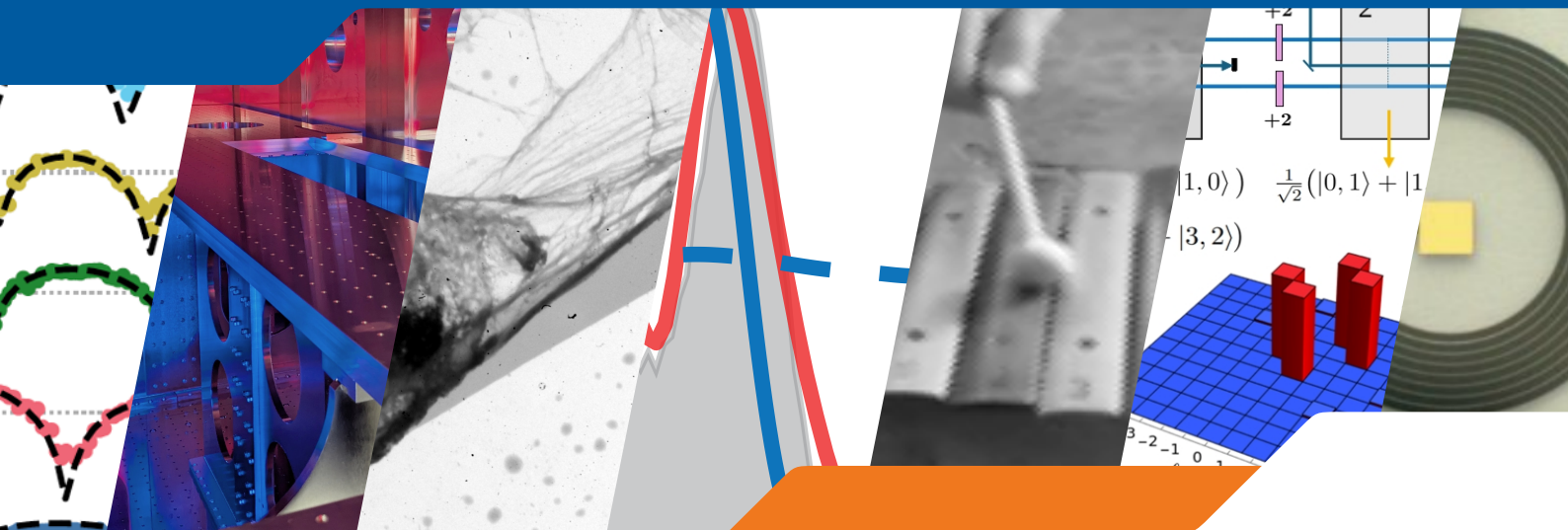


HI JENA

Helmholtz Institute Jena

ANNUAL REPORT 2025



FRIEDRICH-SCHILLER-
UNIVERSITÄT
JENA

HZDR
HELMHOLTZ ZENTRUM
DRESDEN ROSSENDORF



HELMHOLTZ INSTITUTE JENA

ANNUAL REPORT 2025

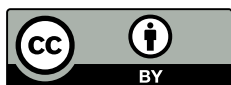
IMPRINT

Publisher: Helmholtz-Institut Jena, Fröbelstieg 3, 07743 Jena, Germany
(<https://www.hi-jena.de>)
@ GSI Helmholtzzentrum für Schwerionenforschung GmbH
Darmstadt, Germany (<https://www.gsi.de>)
GSI is member of the Helmholtz association of national research
centers (<https://www.helmholtz.de>).

Editors: Daniel Seipt and Arno Klenke

DOI: 10.15120/GSI-2026-00759

Publication date: September 2026



The Annual Report 2025 of the Helmholtz-Institut Jena is licensed under
the Creative Commons Attribution BY 4.0 (CC BY 4.0)
<https://creativecommons.org/licenses/by/4.0>

CONTENTS

FOREWORD	10
EDUCATIONAL ENGAGEMENT	14
Status and Updates of the Research School of Advanced Photon Science <i>C. Hahn, G. Weber, and R. Martin</i>	15
Two Balloon Events at the Maximum of Solar Cycle 25 <i>V. Tympel and I. Kadner</i>	16
HIGH POWER LASER DEVELOPMENT	18
Status and Progress of the POLARIS Upgrade <i>M. Hornung, G. A. Becker, M. Hellwing, F. Schorcht, M. B. Schwab, M. Stengel, S. Lauckner, T. Köhler, and M. C. Kaluza</i>	19
Target Area Fraunhofer: Installation and Commissioning of the Beam Shaping System <i>M. Hornung, N. Kohlstruck, T. Köhler, A. Sävert, M. Zepf, and M. C. Kaluza</i>	20
Demonstration of gain-narrowing compensation of a Yb:CaF₂ laser amplifier with tunable spectral filters <i>M. Beyer, and M. C. Kaluza</i>	21
LaserSim: A laser simulation software for the design and performance prediction of diode-pumped solid state laser amplifiers <i>M. Beyer, C. Anschütz, and M. C. Kaluza</i>	22
Recent Progress on the Terawatt mid-IR Laser System CHROME0 <i>C. Anschütz, J. Hein, and M. C. Kaluza</i>	23
A Double Plasma Mirror for JETi200 <i>Stefan Kiesel, Jordan Young, Georg Schäfer, Alexander Sävert, Peter Hilz, and Matt Zepf</i>	24

Development of a Compact Single-Shot Correlator for Femtosecond Jitter Diagnostics	
<i>R. Maskeliūnaitė, A. Sävert, and M. C. Kaluza</i>	25
Spatio-Temporal Characterization of Ultra-Intense Foci via Brewster Wedge Attenuation Under Fast-Focusing Geometries	
<i>A. Thazhathe Peedika and P. Hilz</i>	26
Bright 13.5 nm high-harmonic generation driven by visible laser pulses	
<i>M. Karst, L. Eisenbach, M. Gebhardt, P. Gierschke, T. Sidiropoulos, R. Klas, J. Rothhardt, and J. Limpert</i>	27
Unleashing HHG efficiency: the role of driving pulse duration	
<i>R. Klas, M. Gebhardt, J. Rothhardt, and J. Limpert</i>	28
Integration of Tango-Controls for Polaris	
<i>A. Kessler</i>	29
Status of the Tango control system at JETi200	
<i>D. Hollatz, A. Kessler, A. Sävert, P. Hilz, and M. Zepf</i>	30
Experimental demonstration of efficient ultrashort pulse amplification	
<i>Supriya Rajhans and Christoph Heyl</i>	31
LASER PLASMA ACCELERATION	32
Development of Ionic Liquid Leaf Targets for Laser-Proton Acceleration	
<i>M. C. Nolte, R. Kirmer, and M. C. Kaluza</i>	33
First experimental results from the peeler scheme at JETi200	
<i>I. Salaheldin, L. Reichwein, P. Hilz, A. Sävert, I. Probst, A. Peedika, G. Schäfer, A. Pukhov, and M. Zepf</i>	34
Limitations of emittance and source size measurement of laser-accelerated electron beams using the pepper-pot mask method	
<i>F. C. Salgado, A. Kozan, D. Seipt, D. Hollatz, P. Hilz, M. C. Kaluza, A. Sävert, A. Seidel, D. Ullmann, Y. Zhao, and M. Zepf</i>	35
PHOTON AND PARTICLE SPECTROSCOPY	36
Progress and technological advancements towards quantum logic spectroscopy of highly charged heavy ions	
<i>L. Kau, N. Homburg, H. Hayakawa, L. Bernaerts, and P. Micke</i>	37

Proof-of-Principle Experiment for the Darkfield Detection Concept to Measuring Vacuum Birefringence	
<i>Michal Šmíd, Pooyan Khademi, Naser Ahmadinia, Michal Andrzejewski, Carsten Baetz, Erik Brambrink, Jakub Bulíčka, Tomáš Burian, Samuele Di Dio Cafiso, Jaromír Chalupský, Thomas E. Cowan, Sebastian Göde, Jörg Grenzer, Věra Hájková, Peter Hilz, Willi Hippler, Hauke Höppner, Alžběta Horynová, Lingen Huang, Oliver Humphries, Šimon Jelínek, Libor Juha, Felix Karbstein, Christian Kohlfürst, Alejandro Laso Garcia, Robert Löttsch, Masruri Masruri, Aimé Mathéron, Motoaki Nakatsutsumi, Gerhard G. Paulus, Alexander Pelka, Thomas R. Preston, Sripathi V. Rahul, Lisa Randolph, Alexander Sävert, Hans-Peter Schlenvoigt, Ralf Schützhold, Jan Patrick Schwinkendorf, Thomas Stöhlker, Monika Toncian, Toma Toncian, Maksim Valialshchikov, Vojtěch Vozda, Edgar Weckert, Colin Wessel, Jan Wild, Ulf Zastrau, and Matt Zepf</i>	38
Testing DCCC-xD in GSI warehouse & starting the C4CRY project	
<i>V. Tympel, T. Sieber, B. Voss, and S. Kolbe</i>	39
Dielectronic Recombination of Ne^{3+} at CRYRING@ESR for Astrophysical Plasma Modelling	
<i>V. Tympel, T. Sieber, B. Voss, and S. Kolbe</i>	40
Real-Time Extreme Ultraviolet Ghost Imaging (RT-XUV-GI) for High Throughput and Low-Dose Nanometrology	
<i>Sukyoon Oh and Christian Spielmann</i>	41
Efficient Deep Ghost Imaging with a Compact Physics-Driven Neural Network	
<i>T. Tian, S. Oh, and C. Spielmann</i>	42
Ultrabright MeV Photons and Neutrons from DLA Electrons in Foams	
<i>P. Tavana, M. Gyrdymov, P. Boller, R. Kalla, U. Spillmann, T. Kühl, O. N. Rosmej, and C. Spielmann</i>	43
Stability of the Second-Order Nonlinear Optical Response of Polymer Coated WS_2 Monolayers Investigated Using Dispersion-Scan	
<i>M. Mallick, Z. Xie, M.T. Hossain, P.T. Guerreiro, H.N. Gopalakrishna, R. Romero, A. Turchanin, and C. Spielmann</i>	44
Collective nuclear pulse propagation in single-mode X-ray waveguides	
<i>L. M. Lohse, P. Andrejić, S. Velten, M. Vassholz, C. Neuhaus, A. Negi, A. Panchwatee, I. Sergeev, A. Pálffy, T. Salditt, and R. Röhlsberger</i>	45
Energy-time ptychography for nuclear resonant X-ray spectroscopy	
<i>A. Negi, L. M. Lohse, S. Velten, I. Sergeev, O. Leupold, S. Sadashivaiah, D. Bessas, A. Chumakov, C. Brandt, L. Bocklage, G. Meier, and R. Röhlsberger</i>	46
Single-Frame EUV Imaging with a Randomized Probe	
<i>C. Liu, S. H. Chew, W. Eschen, M. Abdelaal, J. Limpert, and J. Rothhardt</i>	47

Variable brilliant ion sources for strong-field laser and ion applications	
<i>F. Machalett, J. Hacker, B. Ying, Th. Weber, A. Sommerfeld, Th. Stöhlker, and G. G. Paulus</i>	48
A flat field spectrometer for SHHG experiments at JETi200	
<i>I. Probst, S. Kiesel, P. Hilz, and M. Zepf</i>	49
Correlative Soft X-ray and Fluorescence Microscopy for Nanoscale Imaging of Cancer Cell Adhesion	
<i>S. Kaleta, P. Osuchowska, W. Kasprzycka, J. Reinhard, A. Nowak-Stępniewska, J. Abel, Y. Hsu, M. Wünsche, S. Fuchs, and G. G. Paulus</i>	50
Digital Filters for Pulse Shape Analysis of Metallic Magnetic Calorimeters	
<i>J. H. Walch, M. O. Herdrich, D. A. Schnauß-Müller, G. Weber, and Th. Stöhlker</i>	51
Production of $^{229}\text{Th}^{89+}$ and Storage Ring Studies for the HiThor Project	
<i>C. Brandau and Th. Stöhlker for the HiThor project</i>	52
Development of a method for handling disturbed temperature information in Magnetic Metallic Calorimeter data	
<i>D. A. Schnauß-Müller, J. H. Walch, M. O. Herdrich, G. Weber, Th. Stöhlker</i>	53
MMC Signal Artifact Rejection Utilizing Machine Learning	
<i>M. O. Herdrich, T. Mattis, Th. Stöhlker</i>	54
Investigation of Beam Lifetime and Radiative Recombination Rate Coefficient of U^{91+} ions stored in CRYRING	
<i>A. Turelli Khusainova, G. Weber, D. A. Schnauß-Müller, J. H. Walch, M. O. Herdrich, M. Lestinsky, C. Krantz, and Th. Stöhlker</i>	55
Commissioning of a Novel Compton Polarimeter in Telescope Configuration	
<i>T. Over-Winter, A. Kononov, T. Krings, W. Middents, U. Spillmann, G. Weber, and Th. Stöhlker</i>	56
THEORY	58
Impact of background field localization on vacuum polarization effects	
<i>Carl Marmier, Nico Seegert, and Felix Karbstein</i>	59
Limitations of the paraxial beam model in the study of quantum vacuum signals	
<i>Felix Karbstein and Fabian Schütze</i>	60
Self-organized criticality in a relativistic Yukawa theory	
<i>H. Gies and M. Picciao</i>	61

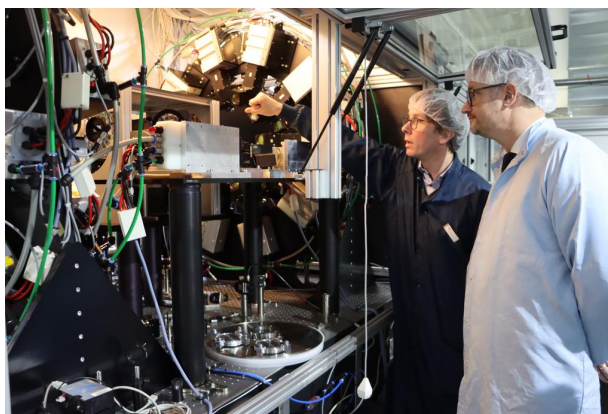
Bound-state Compton scattering of linearly polarized photons <i>Anna Maiorova, Wilko Middents, Jonas Sommerfeldt, Nick M. Mayer, Andrey Surzhykov, Stephan Fritzsche, and Thomas Stöhlker</i>	62
Maximally Entangled Orbital Angular Momentum States via Path Identity <i>R. Bernecker, S. Fritzsche, and B. Baghdasaryan</i>	63
Investigating laser pulse chirping for narrowband x-ray generation using time-frequency analysis <i>N. Larin and D. Seipt</i>	64
Unambiguous vector magnetometer with structured light <i>S. Ramakrishna and S. Fritzsche</i>	65
On The Role of Magnetic Fields in Avalance-Like QED Cascades <i>M. Aleksiejuk and D. Seipt</i>	66
Back-reflection in dipole fields and multi-beam configurations <i>M. Valialshchikov, F. Karbstein, D. Seipt, and M. Zepf</i>	67
Levin Method in Partial-Wave Strong-Field Approximation <i>A. K. Sahoo and S. Fritzsche</i>	68
PUBLICATIONS	70
THESES	83

FOREWORD

Dear friends and members of the Helmholtz Institute Jena,

our current Annual Report documents the Institute's most significant scientific achievements over the past 12 months, which are aligned with its strategic mission: excellence in basic and applied research using on high-power lasers, particle accelerators, and X-ray science. In this context, our research focuses on the interaction of intense light with matter and involves various research and development activities on state-of-the-art measuring instruments for dedicated experiments at the flagship facilities for extreme matter research: the EU-XFEL in Hamburg and the international FAIR project in Darmstadt. We would like to emphasize that the foundation and prerequisite for our activities at the large-scale facilities in Darmstadt and Hamburg are our institute's in-house research facilities on the campus of Friedrich Schiller University in Jena. Since its foundation, the institute has built up an extensive portfolio of state-of-the-art research infrastructures, including the high-power laser systems POLARIS and JETi200, intense HHG photon sources based on fiber lasers, as well as specialized detectors, X-ray and cryogenic laboratories. This was only possible thanks to close collaboration with our partner institutes at the university as well as with local non-university research institutions, notably the Fraunhofer IOF and the Leibniz IPHT.

The year 2026 started with a particular highlight: in January 2026, Thuringia's Minister of Science, Christian Tischner, visited the Helmholtz Institute Jena to learn more about the Institute's cutting-edge research program. The focus of the visit was on future research directions, strategic development, and the institute's advanced infrastructure. A lab tour highlighted internationally relevant work in accelerator technologies and dense plasma research. Tischner praised the institute as a "flagship for science in Thuringia," emphasizing the exceptional precision and the dedication of the teams.



© TMBWK/Andreas Müller

Minister Christian Tischner visited the POLARIS laser as part of his visit to the Helmholtz Institute Jena.

Building on our activities from the past year, preparations for the upcoming POF V funding period (2028–2034) remained the Institute's primary focus. While last year's focus was on the GSI center evaluation—including a detailed assessment of the research conducted at the Institute during the POF IV funding period (2020–2027)—the strategic evaluation of the research field "Matter" took place in Berlin in May 2026. In Berlin, all research programs—involving all centers participating in this research field—underwent a comprehensive and detailed review. Of particular relevance to the institute were the "Matter and Technology" program, with the topics

Accelerator Research and Development” and “Detector Technology and Systems,” as well as the program “From Matter to Materials and Life” with the topic “Matter: Dynamics, Mechanism, and Control”. In summary, the results achieved by HI-Jena were very positive and encouraging. In all categories and for all research topics in which the institute was evaluated, we received either “excellent” or even “outstanding” ratings for our future research plans within the framework of POF V.

With regard to our research projects, the focus at external facilities was particularly on FAIR Phase 0 activities at GSI, on experiments on vacuum birefringence and nuclear quantum optics at the European XFEL, and, in addition, on experiments at our in-house laser facilities. Also worth mentioning are current developments in the field of X-ray optics and detectors based on quantum sensors for X-ray and particle detection. However, GSI suffered a significant setback. In February 2026, the ion injector of the GSI accelerator was severely damaged by a major fire. Due to the resulting damage to the linear accelerator stage (UNILAC), heavy-ion operations at GSI are not expected to be possible until the end of 2030. This has serious implications for various HI-Jena research projects on the GSI campus, including the activities of our early-career research groups and the ERC Advanced Grant project HI-Thor. We would like to particularly highlight GSI’s substantial support in implementing the research programs of the research groups as well as the HI-Thor ERC project, and its support of our strategies to mitigate the delays caused by the fire.

A plethora of scientific endeavors at the institute are made possible by third-party funding that continues to run strong. Dr. Rima Schüssler’s application for a Helmholtz Investigator Group focusing on “Test of Bound-state Quantum Electrodynamics with High-precision Mass Measurements of Heavy Highly Charged Ions” was approved in 2025, and the new research group started in 2026, following 2023’s launch of the already-established Helmholtz Investigator Group “Quantum Logic Spectroscopy of Highly-Charged Ions” led by Jun.-Prof. Dr. Peter Micke. Significant funds could also be attracted from funding lines of the Free State of Thuringia and the European Regional Development Fund. This substantial financial support cannot be overrated and is extremely important for our ongoing research activities in view of the challenges we are facing with re-

gard to the institute’s base budget due to inflation and the general rise in costs. More specifically, financial support of more than 120,000 EUR could be attracted for a joint project with the University of Jena and Jevatec GmbH to develop a brilliant liquid-metal ion source, and more than 540,000 EUR (supplemented by a contribution of 10% of the total project sum coming from the institute’s own budget) to procure two parabolic mirrors, which will dramatically enhance the focusability of the JETi200 and POLARIS laser systems. Further funding was acquired to expand the institute’s EUV imaging research program. A grant of 765,000 EUR, combined with an 85,000 EUR base funding contribution, will enable the procurement of a novel tin target to exper-



© HI-Jena / Marco Hornung

Beam shaping vacuum chamber at the new target-area Fraunhofer, financed by the Free State of Thuringia and the European Social Fund Plus (see contribution to this report).

imentally investigate the in-band EUV conversion efficiency, thereby optimizing driver parameters for laboratory-scale EUV sources. The institute's efforts in this research field are enhanced further by the newly established research group “Nanostructured Optics for Extreme Ultraviolet Light” (NanoEUV) which was set up in collaboration with the Friedrich Schiller University, and for which HI-Jena will receive almost 300,000 EUR over a period of three years from the Free State of Thuringia and the European Social Fund Plus (ESF+).

Last but not least, the training and advancement of early-career researchers is a key focus of the Institute's activities. The Research School for Advanced Photon Science at the Helmholtz Institute Jena, which works closely with the Helmholtz Graduate School for Hadron and Ion Research, is a well-established institution that mentors, trains, and supports early-career researchers during their doctoral studies. Enrollment remains stable at about 60 students, with half of the students receiving direct financial support from HI Jena and the other half funded by third-party grants. With approximately 60% of its doctoral students coming from abroad, the Research School boasts a strong international presence. Similar to the previous reports and due to the wide range of activities related to fostering the next generation of young scientists, we have dedicated a separate contribution of this annual report to our research school, as well as to an example of fascinating public outreach: the “Two Balloon Events” at the peak of Solar Cycle 25.

We hope you will enjoy the overview presented by this annual report on the scientific activities and successes of HI-Jena in 2025.



© GSI / Michael Lestinsky

Group photo of the HI Jena team along with members of the atomic and plasma physics departments of GSI. The photo was taken during the center evaluation at GSI in April 2025.

EDUCATIONAL ENGAGEMENT

Status and Updates of the Research School of Advanced Photon Science

C. Hahn^{*1}, G. Weber¹, and R. Martin¹

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany

Support and promotion of young researchers, as well as science communication to the general public, continue to be core priorities of the Helmholtz Institute Jena. The institute's efforts of graduate education and public outreach are coordinated by the Research School of Advanced Photon Science, now in its 14th year.

Membership in the school has remained steady, with a roster of 50 doctoral projects supported by RSAPS and its partner HGS-HIRE at the end of 2025. Of these, about 20 % are pursued by female scientists, and more than half of the members are foreign students who chose Helmholtz Institute Jena for their doctoral studies. 2025 saw 4 PhD students graduate, marking a return to pre-Covid levels after a number of particularly active years.

The scientific accomplishments of RSAPS members are further highlighted by national and international prizes. Markus Kiffer's PhD thesis, titled "Characterisation and cooling of captured ensembles of highly charged ions in a Penning trap," was recognized with the *Giersch Award for Outstanding Doctoral Thesis 2025* of the *Stiftung Giersch*. Furthermore, Daniel Santiago Penagos Molina was honored with the *Student Talk Award* at the biennial UFO Conference in Furnas on São Miguel Island (Azores, Portugal), for his contribution "Ångström-scale surface metrology enabled by a compact milliwatt-class HHG source."

Beyond the support of young researchers at the institute and its partner universities and research institutions, Helmholtz Institute Jena is increasingly engaged in outreach efforts targeted at high school classes, undergraduate students and the general public. To this end, the institute has invested in a large demonstration cloud chamber, as well as a compact x- and gamma-ray detector. In late 2025, a group of four high school students their one-year *Seminarfacharbeit* (a mandatory requirement for the *Abitur* in Thuringia), using the new detector to investigate radon concentrations in basements of old houses. Additionally, the detector system was used in May 2025 for a workshop for a class of high school students to understand the principles of radioactivity. For this, HI-Jena collaborated with the students' lab of the Department of Physics Education at the University of Jena.

The institute also took part in the traditional *Tag der Physik*, a yearly event organized by the Faculty of Physics and Astronomy of the University of Jena. Various groups prepared a wide range of hands-on experiments, information booths, and public talks, on such diverse topics as infrared cameras, magnetically levitating trains, atomic clocks, laser gyroscopes, and potential prospects of AI use.

In September 2025, the city of Jena, in particular the university and the associated research institutes, hosted

two major science exhibitions simultaneously: the *MINT Festival*, and *Highlights der Physik* (jointly organized by Friedrich Schiller University and the German Physical Society DPG). HI-Jena not only sponsored the *MINT Festival* but also had an information booth at the exhibition. Meanwhile, the newly acquired cloud chamber was displayed at the *Highlights der Physik* and attracted many visitors. Furthermore, three professors from HI-Jena gave popular science presentations, and various members showcased interactive exhibition experiments.



Figure 1: The gyrobus booth of HI-Jena at 2025's *Highlights der Physik*, hosted in the *Goethe Galerie* shopping center. (© Ralf Röhlberger/HI-Jena)

^{*}rsaps@hi-jena.gsi.de

Two Balloon Events at the Maximum of Solar Cycle 25

V. Tympel^{*1,2} and I. Kadner³

¹Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany; ²GSI, Planckstraße 1, Darmstadt; ³NaWiSchool, Verein Naturwissenschaftliche Bildung e.V., Feldstr. 12 b, 16341 Panketal

Balloon flights are a great opportunity to bring science into schools. 2025 was particularly interesting because of the high solar activity. In April, it was possible to carry out a balloon launch at the time of an S2 event, using six partially different Geiger-Müller counters. In October, a test was conducted with a modern replica of the coincidence apparatus with nine counter tubes, as described by Georg Pfofzter in his PhD-theses from 1936, and on whose measurements the current term 'Regener-Pfofzter Maximum' (RP-Max) is based.

In April, an alert launch was carried out during a NOAA S2-level solar radiation storm. The 10 MeV protons were 500 times above the normal level, and the 50 MeV protons were also significantly elevated – which was defined as the launch criterion for the p+50 mission. The payload consisted of two GMC41 units built by students in Dresden and Jena. In addition, there were two test setups of different sensitivity, each with two identical Geiger-Müller tubes, one of which had an additional lead shielding, respectively. The question was: do we see an influence of the S2 event on the RP-Max? The clear answer is: no. Even 50 MeV protons do not penetrate that deeply into the Earth's atmosphere. Simple SRIM simulations show that 500 MeV protons are necessary to generate a RP-Max.

Guided by his doctoral advisor Erich Regener, the Master's student in Physical Engineering, Georg Pfofzter, undertook three balloon flights with Geiger counters in a coincidence arrangement in 1935. He published the results in his PhD thesis in 1936 [2]. Only events that occurred simultaneously in three vertically stacked layers were counted. By blocking radiation coming in from the sides, the penetration depth of cosmic radiation into the atmosphere is measured directly. The modern replica GMC92 naturally used transistors and ICs, but like the original, it used 3x3 Geiger-Müller tubes (Fig. 1 right). The launch took place at a balloon school event of the NaWi School in Dresden, and automatic data reception was ensured in Jena (Fig. 2). The coincidence measurements were confirmed, and it was shown that, with small compromises in the position of the maximum and the sharpness of the peak, it is quite possible to work with just one layer or tube for educational purposes (Fig. 3). More detailed information will appear in [2].

The interesting question is: what is the source of an undirected, energetically quite sharp proton stream? An echo from the time when protons were formed, like with photons and the cosmic background radiation? At this point, however, we are leaving the realm of school-level outreach.

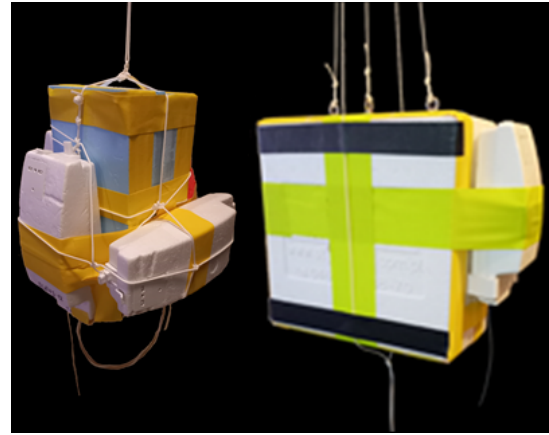


Figure 1: Payloads, left: p+50 mission, right: GMC92.



Figure 2: Two Yagi antennas on the roof of the Institute for Solid State Physics in Jena, oriented towards Dresden.

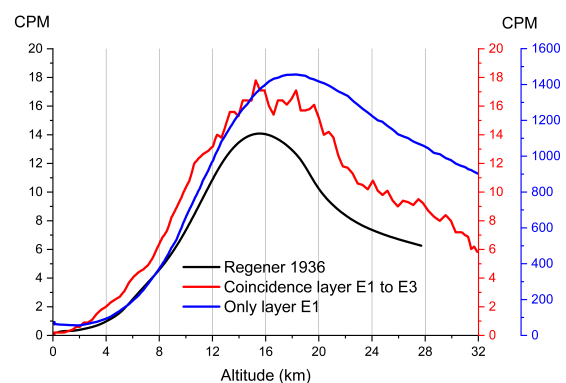


Figure 3: Comparison mean values from five data sets by Pfofzter 1935 and the one data set from 2025 [2].

References

- [1] link.springer.com/content/pdf/10.1007/bf01336829
- [2] V. Tympel, I. Kadner, will be published in CQDL 1/27.

*v.tympel@hi-jena.gsi.de

HIGH POWER LASER DEVELOPMENT

Status and Progress of the POLARIS Upgrade

M. Hornung^{*1,2}, G. A. Becker², M. Hellwing², F. Schorcht¹, M. B. Schwab², M. Stengel², S. Lauckner², T. Köhler², and M. C. Kaluza^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²IOQ, FSU Jena

The pulse stretcher, the pulse compressor and the beam transport system of the POLARIS laser are currently upgraded. The formerly used stretcher-compressor system with 60° angle of incidence was replaced by a newly developed 54°-system, which is capable of compressing more than twice the pulse energy than before. Furthermore, the vacuum connection to the target area Fraunhofer is currently prepared and implemented.

The centerpiece of the ongoing upgrade is the compressor laboratory [1]. This lab was completely gutted to realize a wall breakthrough ($3 \times 1.6 \text{ m}^2$) and to fully reorder and setup the new pulse compressor with the corresponding diagnostic and transfer beamlines. A view into the rearranged lab is shown in figure 1. In the rear right part of the im-



Figure 1: View into the POLARIS compressor laboratory. The vacuum system is located in the left rear area and the optical tables are on the right.

age the black region shows the covered wall breakthrough for the future beamline towards the target area Fraunhofer. The 3-segmented, 5 m large compressor chamber (PEK) was connected to the circular compressor chamber (PRK, obscured in the image) which houses both the first and last grating. An ultra-stable DN500 turning pot (PUT, in front of PEK) was connected to realize the beam transport to the switchyard chamber (PSY, the angular chamber in the background). The breadboards of all three additional chambers (PRK, PUT and PSY) were mounted on massive blocks of granite which were glued and screwed to the floor. This leads to high eigenfrequencies for the boards and hence very stable mounting conditions for the optics. The switchyard is equipped with an adaptive optics system

and will allow to determine whether the beam is directed towards the existing or the new target area. The vacuum connection to the existing target has been completed.

The recently installed optical table with a size of $7.75 \text{ m} \times 1.8 \text{ m}$ will support the input beam expansion telescope, incoupling optics and the laser online diagnostic suite. To finalize the coarse lab work and to make the optical table usable for optics installation and high power operation a cleanroom enclosure is currently prepared to ensure the required cleanliness. All large aperture optics were procured and finally delivered. A first prototype of a large aperture mirror mount is shown in figure 2. This mount is able to handle $320 \times 230 \times 50 \text{ mm}^3$ large mirrors. During construction special attention was paid to the mechanical eigenfrequencies and hence its stability. A single step size of $1 \mu\text{rad}$ can be achieved with a gearbox in front of the stepper motor. The construction of the additionally required grating and mirror mounts is currently ongoing.

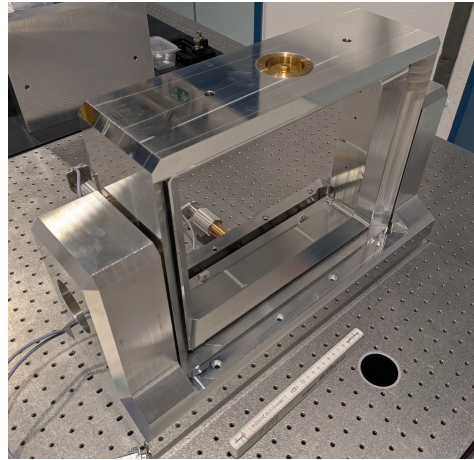


Figure 2: Homemade ultra-stable motorized mirror mount for a $320 \times 230 \times 50 \text{ mm}^3$ turning mirror.

The frontend [2] belonging to the newly designed 54° angle of incidence compressor is already in operation and the construction of the residual compressor and beamline mounts is part of future work.

The authors acknowledge funding from European Union (EFRE, 2022 FGI 0003).

References

- [1] M. Hornung, HI Jena Annual Report 2024, p. 26.
- [2] G. Becker, HI Jena Annual Report 2024, p. 19.

*m.hornung@gsi.de

Target Area Fraunhofer: Installation and Commissioning of the Beam Shaping System

M. Hornung^{*1,2}, N. Kohlstruck³, T. Köhler², A. Sävert^{1,2}, M. Zepf^{1,2}, and M.C. Kaluza^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²IOQ, FSU Jena; ³Pfeiffer Vacuum Components & Solutions GmbH, Göttingen

We report the commissioning of the beam shaping vacuum chamber for the new target-area Fraunhofer (TAF) beamline. This system will be used directly in front of the TAF target chamber to prepare, modify and optimize the three laser beams JETi200, JETiOne and POLARIS. Special attention was paid to the overall stability of the system due to the challenging timing and pointing requirements (fs and sub- μm) for the synchronisation of the high power laser pulses. Finally, the system has been accepted and is operational.

The beam shaping system [1] consists of a vacuum chamber with internal breadboards to realize different optical setups for the JETi200, JETiOne and POLARIS laser pulses. Two photos of the system are shown in figure 1 to visualize the exterior and interior construction.

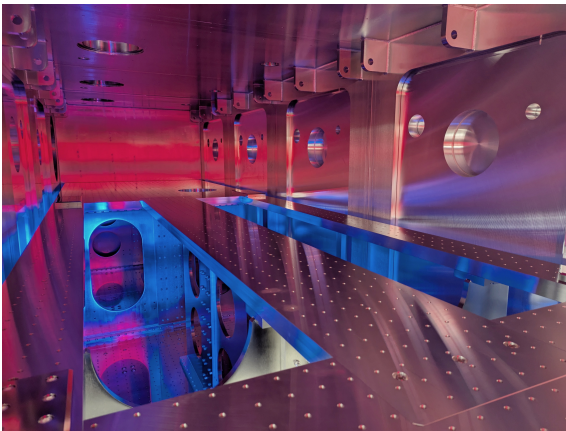


Figure 1: Photographies of the beam shaping system. Top: exterior view, bottom: interior view.

The system was manufactured by Pfeiffer Vacuum Components & Solutions GmbH (Göttingen, Germany) and consists of five segments each having a size of $1.2 \times 1.9 \times 2.3 \text{ m}^3$ resulting in an overall size of $6.2 \times 1.9 \times 2.3 \text{ m}^3$. Together with the internal breadboards and shear walls which were designed in cooperation with Baudynamik Heiland & Mistler GmbH (Bochum, Germany) the system has a total mass of 26 tons.

The vacuum system is bolted onto a specially constructed 75 cm high concrete block and embedded partially in concrete. This leads to an ultra-high mechanical stability to avoid any increase of pointing or timing jitter of the transported pulses. After five months of initial evacuation a final pressure better $8 \times 10^{-8} \text{ mbar}$ has been reached with two turbo pumps and a pumping speed of $1.6 \text{ m}^3 \text{ s}^{-1}$ each. The excellent cleanliness of the 20 m^3 large system is illustrated by the residual gas analysis shown in figure 2 which reveals no significant heavy hydrocarbons approaching the detection limit.

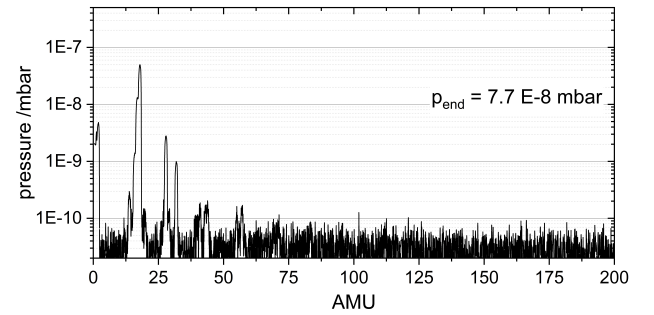


Figure 2: Residual gas analysis of the evacuated vacuum system.

With the realized system a variety of different optical setups could be realized. Possibilities are plasma mirror applications or temporal pulse shortening via nonlinear spectral broadening. Furthermore long range focussing (up to 17 m) will be possible and the polarisation of each pulse could be rotated fully reflectively if required. In any case, the applications are not limited solely to this. The inner breadboard and shear wall system could be disassembled and repositioned if required for other experiments.

The authors acknowledge funding from European Union (EFRE, 2022 FGI 0005).

References

- [1] M. Hornung, HI Jena annual report, p. 27 (2024).

*m.hornung@gsi.de

Demonstration of gain-narrowing compensation of a Yb:CaF₂ laser amplifier with tunable spectral filters

M. Beyer^{*1,2} and M.C. Kaluza^{1,2}

¹Institute of Optics and Quantum Electronics Jena, Germany; ²HI Jena, Fröbelstieg 3, 07743 Jena, Germany

We present the successful demonstration of gain-narrowing compensation in a Yb:CaF₂-based, ultra-short laser amplifier system with pulse energies of less than 1 mJ as a combination of intra-cavity tunable spectral filters (TSF's) and a pre-compensation of the seed spectrum using a Dazzler. In combination, we achieved a significant broadening of the output spectrum from 6 nm to 36 nm (FWHM) at a central wavelength of 1032.5 nm.

The fully diode-pumped laser system POLARIS currently uses Yb:FP15 glass as the active material in its first four amplifier stages. Due to the material's laser induced damage threshold, the output fluence is limited to $\approx 3 \text{ J/cm}^2$. Furthermore, the maximum repetition rate is limited by its poor thermal conductivity, which requires a long cooling period between individual shots. In comparison, Yb³⁺-doped calcium fluoride (Yb:CaF₂) has a significantly larger thermal conductivity supporting higher output fluences and laser repetition rates [1]. However, due to its crystalline structure, the spectral gain profile is more complex and structured, thus making the design of suitable spectral filters for the compensation of spectral gain narrowing effects for broadband laser pulse amplification more challenging.

In order to compensate for gain narrowing effects, we characterized the spectral gain and developed tunable spectral filters (TSF's) [2]. TSF's are dielectric layer systems with a wavelength and angle-of-incidence dependent reflectivity. Placing them in transmission into the laser cavity allows for a precise control of the spectral losses and thus the output spectrum. Due to constraints on the second order phase terms (a required group delay dispersion $\text{GDD} < 500 \text{ fs}^2$), we settled on a Gaussian shaped profile with a maximum reflectivity of 4.5 % and 13 nm (FWHM) bandwidth. Then, four TSF's were put in a regenerative amplifier under different angles ($\varphi = 30.5^\circ, 30.5^\circ, 30^\circ, 26^\circ$). The cavity consists of a Yb:CaF₂ sample with a doping concentration of $3.3 \cdot 10^{20} / \text{cm}^3$ and thickness of 11 mm which was pumped by a 2.5 kW laser diode stack. The amplifier was seeded with nanojoule, picosecond laser pulses provided by a Flint FL1-02 oscillator. Since the spectral gain of Yb:CaF₂ cannot be completely compensated by the TSF's alone, a Dazzler (fastlite) was placed at the entrance of the amplifier to pre-compensate the seed spectrum in a single pass. The result is shown in Figure 1, where the output spectrum of the amplifier is shown to be increased by a factor of 6 in terms of bandwidth (FWHM) from 6.04 nm to 36.3 nm at a central wavelength of $\lambda = 1032.5 \text{ nm}$,

however, the resulting spectral shape is no longer Gaussian. The fourier-transform limited pulse duration is reduced from $\tau = 240 \text{ fs}$ to $\tau = 80 \text{ fs}$ (FWHM).

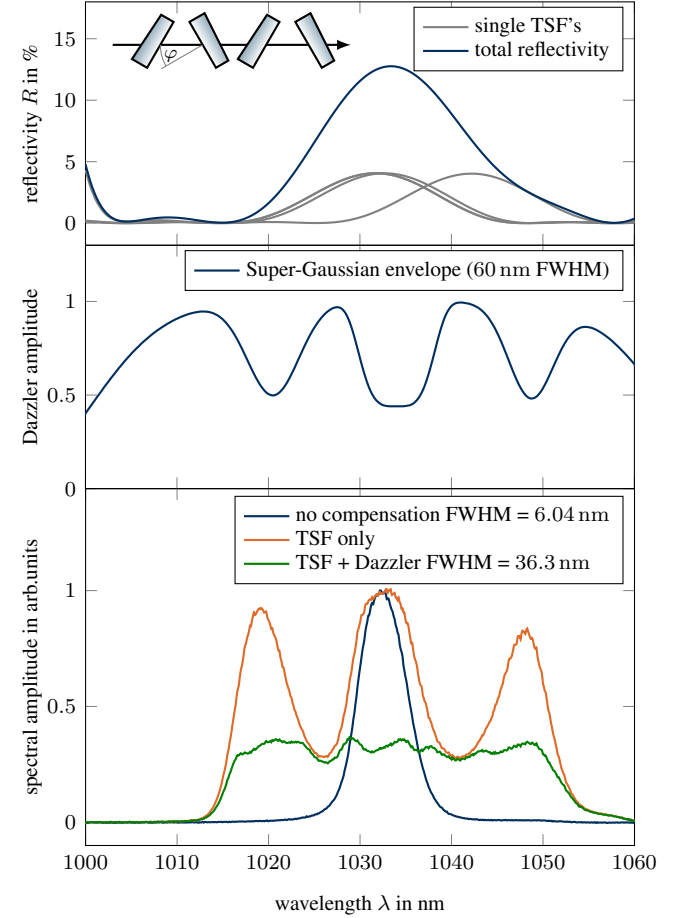


Figure 1: Top: reflectivity profiles of the four TSF's (gray) and their total reflectivity (blue). Middle: Dazzler amplitude function, which was shaped to pre-compensate the seed spectrum. Bottom: output spectrum of the amplifier with no compensation (blue), intra-cavity TSF's only (orange) and TSF's + Dazzler (green).

This demonstration shows that gain compensation is possible in a Yb:CaF₂-based amplifier system, which makes it a promising candidate for the second amplifier stage of POLARIS. Further measurements will show if the amplified pulses can indeed be compressed to the current pulse durations of $< 100 \text{ fs}$.

References

- [1] S. Keppler, PhD thesis, University of Jena, (2017).
- [2] M. Beyer *et al.*, HI Jena annual report, (2025).

*m.beyer@uni-jena.de

LaserSim: A laser simulation software for the design and performance prediction of diode-pumped solid state laser amplifiers

M. Beyer^{*1,2}, C. Anschütz¹, and M.C. Kaluza^{1,2}

¹Institute of Optics and Quantum Electronics Jena, Germany; ²HI Jena, Fröbelstieg 3, 07743 Jena, Germany

For the design and implementation of novel laser materials, a detailed understanding of the laser-matter interaction is important. Based on spectroscopic measurements we can predict the performance of a laser amplifier by solving the underlying coupled rate equations for the pump and laser processes. Therefore, we present a python based, object oriented laser simulation software called *LaserSim* [1] written to simulate diode-pumped solid state laser materials and the spectral/temporal amplification of laser pulses. In simulating the achieved inversion in the laser material, we can successfully predict the spectral gain, as well as saturation, edge steepening and gain narrowing effects in the amplifier.

To achieve laser operation we need a population inversion, i.e. more doping ions in the excited state N_2 than in the ground state N_1 . Real laser materials typically involve multiple energy levels and their transitions can be described via absorption $\sigma_a(\lambda)$ and emission $\sigma_e(\lambda)$ cross sections. However, most materials can be modeled by two manifolds with continuous level distributions. Now, using the photon density $\Phi(t)$ to describe the radiation field, the coupled rate equation describing the complete laser interaction can be written as

$$\frac{dN_2}{dt} = \underbrace{c\Phi_{p/l}(t)[\sigma_a(\lambda_{p/l})N_1 - \sigma_e(\lambda_{p/l})N_2]}_{\text{pump (p), laser (l) process}} - \frac{N_2}{\tau_f},$$

where the second term describes losses due to spontaneous emission with the fluorescence lifetime τ_f . The pump process (p) describes the inversion buildup inside the laser material and includes losses due to spontaneous emission

*m.beyer@uni-jena.de

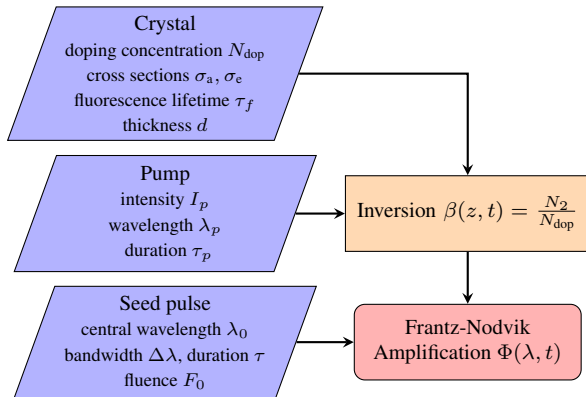


Figure 1: Flowchart of the different implemented classes and the simulation process in *LaserSim*.

(pump duration $\tau_p \approx \tau_f$) and is solved numerically according to [2]. The laser process (l) describes the amplification of the seed pulse (amplification time $\ll \tau_f$) and its solution is described by the Frantz-Nodvik equation [3] modified for a 3-level system [2]. The simulation assumes a one-dimensional laser material of thickness d which is end-pumped by a source with a uniform intensity profile.

The software allows for the implementation of new laser materials by providing the spectroscopic data (c.f. Figure 1, Crystal class). The user can then specify the pump and seed parameters, choose the number of passes through the laser material and simulate the resulting temporal and spectral profile, the total output fluence or pump-related quantities like the pump storage efficiency and the spatio-temporal inversion $\beta(z, t)$. We also implemented a simple graphical user interface (GUI) as shown in Figure 2. Here, we used Yb:YAG as an example material and demonstrated the effect of gain saturation ($I_p = I_{\text{sat}}$, $\tau_p = \tau_f$) when the output fluence reaches the saturation fluence ($F_{\text{sat}} \approx 8 \text{ J/cm}^2$) after 16 passes through the material.

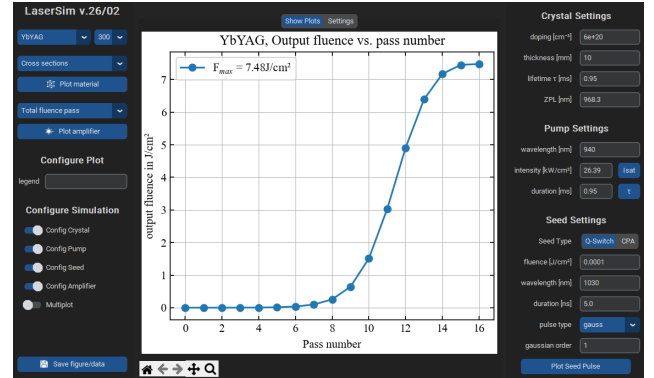


Figure 2: Output fluence of a Yb:YAG laser amplifier simulated with *LaserSim* based on spectroscopic data from [4].

In the future we will further reference the software with experimental data and plan to implement two-dimensional effects such as a spatially varying pump profile and temperature gradients within the laser material.

References

- [1] https://github.com/Tatze99/Laser_Simulation
- [2] J. Körner, PhD thesis, University of Jena, (2014).
- [3] L. Frantz, J. Nodvik, Journal of Applied Physics 34.8 (1963).
- [4] J. Körner *et al.*, Journal of the Optical Society of America B 29.9 (2012).

Recent Progress on the Terawatt mid-IR Laser System CHROMEEO

C. Anschütz^{*1,2}, J. Hein^{1,2}, and M. Kaluza^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²IOQ, FSU Jena

Following the successful implementation of the stretcher-compressor module and the initial cavity design of the CHROMEEO mid-IR laser system, the development has progressed to the setup and optimization of the amplifier chain. By utilizing a cryogenically cooled Tm:YAG pump source, a total gain of 10^5 was achieved in the Cr:ZnSe regenerative amplifier, boosting the seed pulses from the nJ to the sub-mJ level. The amplified pulses exhibit a broad spectrum capable of supporting 100 fs durations, paving the way for high-intensity applications such as high-harmonic generation (HHG) [1, 2].

The complete mechanical construction and optical design of the regenerative amplifier cavity were carried out using our in-house software LaserCAD [1, 4]. Building upon this design, the experimental focus was initially directed towards maximizing the extraction efficiency of the active medium. The cryogenically cooled Tm:YAG pump laser, energized by a 30 W diode pump source, was operated at its point of highest efficiency, delivering an output energy of approximately 3 mJ. This output was subsequently used to pump the Cr:ZnSe crystal within the regenerative cavity.

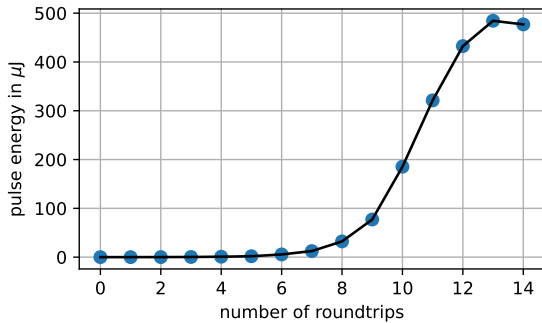


Figure 1: Measured pulse energy within the regenerative amplifier as a function of the round trip number. Early saturation leads to an efficient extraction of the stored energy and a stabilization of the output.

An initial seed pulse energy of 5 nJ was injected into the cavity. Over the course of 15 round trips, corresponding to 30 passes through the active medium, the pulse energy was successfully boosted to 500 μJ , representing a total small-signal and saturated gain factor of 10^5 . The evolution of the pulse energy as a function of the round trip number is depicted in figure 1. Due to the relatively low saturation fluence of Cr:ZnSe, early saturation sets in during the final round trips. This behavior ensures a highly efficient conversion of pump energy into pulse energy, while simul-

taneously stabilizing the output pulse energy against fluctuations of the seed source.

The spectral characteristics of the amplified pulses were characterized and are presented in figure 2. The spectrum exhibits a full width at half maximum (FWHM) of 80 nm. This bandwidth is sufficiently broad to support a Fourier-transform-limited pulse compression down to 100 fs duration. Following successful compression, focusing the beam with an $f/2$ off-axis parabolic mirror is calculated to yield a peak intensity of 10^{16} W/cm^2 . This high-intensity regime is ideally suited to drive secondary sources, particularly for efficient high-harmonic generation (HHG). To the best of our knowledge, this performance represents the highest efficiency in translating diode pump power into focal spot peak intensity achieved so far in this wavelength range.

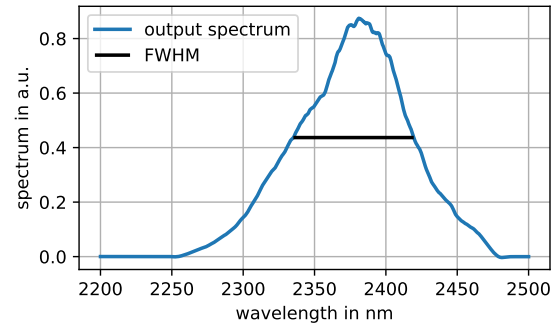


Figure 2: Optical spectrum of the amplified pulses. The FWHM bandwidth of 80 nm allows for compression to the targeted 100 fs pulse duration.

As an outlook, the next phase of development will focus on the subsequent multi-pass amplifier stage, which is designed to scale the pulse energy to the 100 mJ level and then enable relativistic laser-matter interactions. Currently, comprehensive simulations using our newly developed software tool LaserSIM [3] and structural designs for a future 100 TW class mid-IR laser system are in progress.

References

- [1] *Development of a mid-IR regenerative amplifier for the CHROMEEO system*, HI Annual Report 2024
- [2] Popmintchev, T., *et al.*, *Science* **336**(6086), 1287-1291 (2012)
- [3] *LaserSim: A laser simulation software for the design and performance prediction of diode-pumped solid state laser amplifiers*, HI Annual Report 2025
- [4] Anschütz, Clemens, *et al.*, *Appl. Sci.* **15**(22), 11893 (2025)

*clemens.anschuetz@uni-jena.de

A Double Plasma Mirror for JETi200

Stefan Kiesel^{*1}, Jordan Young², Georg Schäfer^{1,3}, Alexander Sävert^{1,3}, Peter Hilz^{1,3}, and Matt Zepf^{1,3}

¹HI-Jena, Fröbelstieg 3, 07743 Jena, Germany; ²CLMI, School of Mathematics and Physics, Queens University Belfast, Belfast, UK; ³IOQ, Friedrich-Schiller-Universität, Fürstengraben 1, 07743 Jena, Germany

Plasma mirrors are an important tool for high power laser physics experiments. In our project, we add a double plasma mirror to the JETi 200 high power laser system in order to enhance temporal pulse contrast. The main objective is interchangeability with a single plasma mirror and operation without a plasma mirror.

Laser intensity-driven optical switches, known as plasma mirrors (PM), have acquired a critical role in high power laser systems worldwide. Their working mechanism relies on striking a plasma on a glass surface, as soon as the laser pulse intensity exceeds the ionization threshold of the underlying material. [1] Free electrons in such a plasma act as an optical mirror, reflecting the beam from there on, and thus increasing the contrast, i.e. the intensity ratio before and during the absolute maximum of the main pulse.

For several years, JETi200 has been equipped with a single plasma mirror (SPM), providing a single reflection of the laser pulse on an ignited plasma. While the current SPM has been a crucial part in the work of recent years, experiments with even higher requirements on the laser contrast have been out of reach so far. One way to increase contrast is adding a second reflection on a plasma surface, a double plasma mirror (DPM). However, a part of the total pulse energy is lost to the plasma. Thus, depending on the experiment, the laser is best operated with a DPM, an SPM, or without a PM. In this infrastructure project we aim for operating a DPM interchangeably with an SPM, or no PM, while keeping the required work for realignment of the laser beam at a minimum.

A sketch of the overall setup is shown in Figure 1. In case no PM is operated, the beam passes the vacuum chamber from the entrance to the exit in a straight line. If a PM is operated, the beam first hits a beamline mirror (M1) and is directed to a parabolic mirror (P1), which focuses the beam towards the first (S1), or, respectively, only (S) plasma mirror substrate. In case a DPM is installed, the beam is further reflected towards the second substrate (S2). A collimating parabolic mirror (P2) and a subsequent flat beamline mirror (M2) directs the beam to the exit. To switch between setups, besides exchanging the PM unit, translations of the mirrors M1, M2 and P2 are necessary.

The DPM and SPM units are shown in Figure 2. SPM and DPM are mounted on separate breadboards with kinematic bases for accurate repositioning. Our DPM design is based on a working device at the CLF Astra Gemini laser facility. For our purpose, the general concept was adapted for compatibility with our kinematic bases, and to add op-

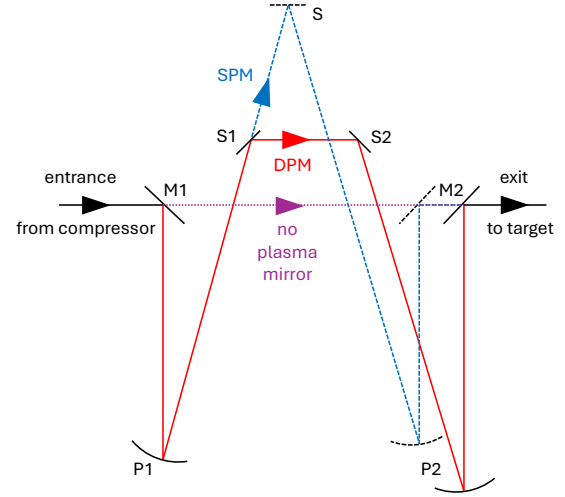


Figure 1: Sketch of the plasma mirror setup in JETi200. The beam can either pass straight through the chamber (dotted purple lines) without plasma mirror interaction, via single plasma mirror (blue dashed lines), or using the new double plasma mirror unit (red solid lines).

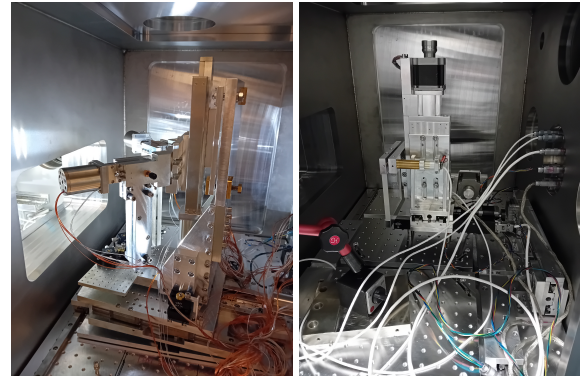


Figure 2: Installed DPM unit (left) and SPM unit (right) inside the JETi200 plasma mirror vacuum chamber.

tional mounting space and relevant motion axes. We have successfully performed first shots with the DPM unit, while further refinement of the system is in the works.

References

- [1] Dromey *et al.*, Rev. Sci. Instrum. 75, 645–649 (2004)

^{*}s.kiesel@hi-jena.gsi.de

Development of a Compact Single-Shot Correlator for Femtosecond Jitter Diagnostics

R. Maskeliūnaitė^{*1}, A. Sävert^{1,2}, and M. C. Kaluza^{1,2}

¹IOQ, FSU Jena, Max-Wien-Platz 1, 07743 Jena, Germany; ²HI Jena, Fröbelstieg 3, 07743 Jena, Germany

Compact single-shot timing diagnostics are being developed for combined JETi200–POLARIS experiments, where the low repetition rate makes it necessary to determine the relative delay between two ultrafast pulses from individual laser shots. As a first step, a non-collinear BBO correlator was used in autocorrelation mode, using two replicas of the same pulse to calibrate the temporal-to-spatial mapping. The generated second-harmonic stripe was recorded on a camera and analysed using live background subtraction, Gaussian fitting, position tracking, and uncertainty checks. The current calibration gives 0.23 fs/px and allows near-transform-limited pulse durations of approximately 13.5 fs to be retrieved. This provides a calibrated preparatory stage for future cross-correlation measurements of timing jitter between the synchronized laser systems.

JETi200 and POLARIS will enable combined ultrafast, high-power experiments at HI Jena [1, 2]. However, their low shot rate, about one shot per minute, requires timing diagnostics that can determine the relative delay between two ultrafast pulses from single laser shots. The diagnostic developed here is intended to support such high-power combined experiments by converting the relative delay between the pulses into the transverse position of a nonlinear optical signal on a camera. As a first step, the device is operated in autocorrelation mode. This provides a controlled and established test for femtosecond pulse characterization [3], while also preparing the setup for later cross-correlation measurements between two independent laser sources.

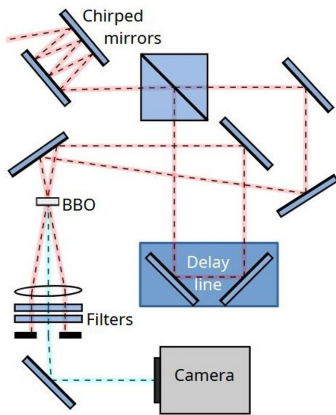


Figure 1: Autocorrelation-mode layout. Two replicas are recombined in BBO, and the filtered SHG signal is imaged onto the camera.

The compact non-collinear correlator uses two pulse replicas crossing in a beta-barium borate (BBO) crystal, as shown in Fig. 1. Their temporal overlap generates a second-harmonic-generation (SHG) signal, which is filtered and imaged onto a camera. A retroreflector delay line imposes a known delay, which is compared with the shift of measured SHG-stripe position on the camera. This gives the spatial-to-temporal calibration of the setup in fs/px.

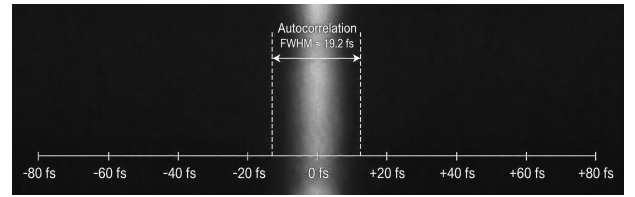


Figure 2: Representative autocorrelation image. The recorded signal corresponds to a pulse duration of 13.6 fs.

A camera-based analysis program performs live acquisition, background subtraction, Gaussian fitting, position tracking, and offline analysis. The measured calibration is 0.23 fs/px, corresponding to sub-femtosecond-per-pixel timing sensitivity. The retrieval model was checked for finite beam size, stripe tilt, satellite features, and camera-region selection, since these effects can change the apparent width in a real single-shot image.

In autocorrelation mode, the calibrated system retrieves near-transform-limited pulse durations of approximately 13.5 fs. A representative camera image is shown in Fig. 2. Although the final cross-correlator will be used to measure relative timing rather than pulse duration, the autocorrelation measurement provides an important controlled test: it verifies that a known signal is correctly mapped onto a spatial position on the camera. The next step is to replace the two pulse replicas with signals from the synchronized JETi200 and POLARIS oscillators and use the same spatial-to-temporal calibration to measure their relative timing stability over timescales from microseconds to seconds.

References

- [1] F. C. Salgado *et al.*, Phys. Rev. Accel. Beams **27**, 052803 (2024).
- [2] M. Hornung *et al.*, High Power Laser Sci. Eng. **2**, e20 (2014).
- [3] P. Simon, H. Gerhardt, and S. Szatmári, Meas. Sci. Technol. **1**, 637 (1990).

^{*}rasa.maskeliunaite@uni-jena.de

Spatio-Temporal Characterization of Ultra-Intense Foci via Brewster-Wedge Attenuation Under Fast-Focusing Geometries

A. Thazhathe Peedika^{*1,2} and P. Hilz^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²FSU Jena

Direct full-power focal diagnostics at intensities exceeding 10^{21} W/cm² remain obstructed by detector damage thresholds and optical distortions from conventional attenuators. We present a non-invasive attenuation framework using a symmetric Brewster-angle wedge system custom-tailored for the 200 TW Ti:Sapphire JeTi beamline. Leveraging polarization-selective reflectivity, this platform yields high-magnitude attenuation while preserving wavefront topography and fs pulse durations, enabling single-shot characterization of spatio-temporal couplings, thermal lensing, and nonlinear phase distortions[1].

Theoretical Framework

The propagation of the ultra-short field envelope $A(r, t)$ with a spatio-temporal phase $\phi(r, t)$ is governed by the paraxial Nonlinear Schrödinger Equation. Near-field phase aberrations influencing the far-field Strehl ratio stem from three primary physical coupling modes:

1. **Thermal Lensing:** Non-radiative relaxation from the crystal quantum defect dictates a radial temperature profile $\Delta T(r)$, resulting in an effective focal length [2]:

$$f_{th} \approx \frac{\kappa_c \pi \omega_p}{\eta_{th} P_{abs} (dn/dT)} \quad (1)$$

2. **Nonlinear Phase Accumulation:** Intensity-dependent index changes ($n = n_0 + n_2 I$) map wavefront deformations quantified via the longitudinal B-integral:

$$B = \frac{2\pi}{\lambda} \int n_2 I(z) dz \quad (2)$$

3. **Gain Refraction:** Following the Kramers-Kronig relation, strong localized gain saturation profiles $\alpha(\omega)$ perturb the local index matrix [3]:

$$\Delta n(\omega) = \frac{c}{\pi} \mathcal{P} \int_0^\infty \frac{\alpha(\omega')}{\omega'^2 - \omega^2} d\omega' \quad (3)$$

Experimental Configuration

The system takes advantage of the zero-reflection threshold for P-polarized light at the Brewster angle (Θ_B) on uncoated fused silica.

To mitigate bandwidth-induced angular dispersion and spatial chirp across the 740–860 nm bandwidth, a symmetric dual-wedge configuration is deployed with equal and

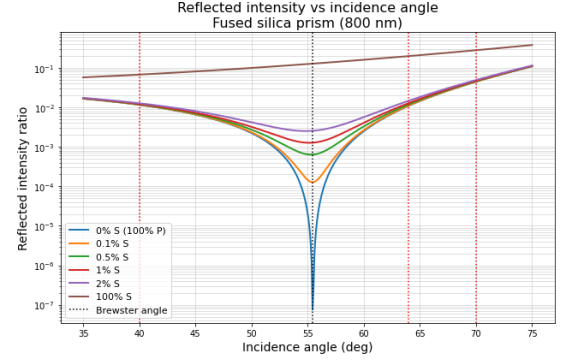


Figure 1: The plot maps Polarization-selective attenuation profile across varying input state purities (pure P- to pure S-polarization). Vertical dotted lines denote specific experimental benchmarks within the multi-wedge cascade.

opposite angular offsets ($\pm \Delta\theta$) relative to Θ_B . To enforce a strict polarization purity tolerance of 1%, two pairs of wedges are cross-coupled with an orthogonal pair of prisms positioned perpendicular to the wedge plane to strip residual S-polarization components. Secondary ghost reflections from the rear wedge faces are suppressed by four orders of magnitude via geometric angle tuning.

The non-distorted sampling channel routes the beam into a comprehensive diagnostic suite: a PHASICS quadriwave lateral shearing interferometer tracks near-field wavefront topography; a gated, high-dynamic-range CCD behind a 20× objective maps far-field focus stability; and a self-referenced spectral interferometer (Wizzler) isolates temporal phase distortion.

Conclusion

The operational deployment of this Brewster-wedge attenuation loop provides an artifact-free diagnostic line for full-power single-shot metrology. By accurately balancing spectral phase evolution and limiting self-lensing, this setup successfully isolates compressor-induced couplings (GC-STCs) and multi-stage gain-saturation mechanics.

References

- [1] B. Shi *et al.*, Opt. Express **31**, 33299 (2023).
- [2] W. Koechner, Solid-State Laser Engineering (Springer, 2013).
- [3] C. Le Blanc *et al.*, Opt. Commun. **131**, 391 (1995).
- [4] G. Doumy *et al.*, Phys. Rev. E **69**, 026402 (2004).
- [5] E. Hecht, Optics, 5th ed. (Pearson, 2017).

*a.thazhathepeedika@hi-jena.gsi.de

Bright 13.5 nm high-harmonic generation driven by visible laser pulses

M. Karst^{1,2,3}, L. Eisenbach^{1,2,3,4}, M. Gebhardt¹, P. Gierschke^{1,4}, T. Sidiropoulos^{1,2,3}, R. Klas^{1,2,3,4}, J. Rothhardt^{1,2,3,4}, and J. Limpert^{1,2,3,4}

¹IAP, FSU Jena, Albert-Einstein-Str. 6, Jena, 07745, Germany; ²HIJ, Fröbelstieg 3, Jena, 07743, Germany; ³GSI, Planckstr. 1, Darmstadt, 64291, Germany; ⁴Fraunhofer IOF, Albert-Einstein-Str. 7, Jena, 07745, Germany

Bright coherent extreme-ultraviolet sources are essential for nanoscale imaging, ultrafast spectroscopy and actinic metrology, but high photon flux near 13.5 nm remains difficult to realize with table-top high-harmonic generation. Here, we demonstrate efficient XUV high-harmonic generation driven by intense visible laser pulses at 516 nm. In helium, the source emits coherent radiation up to approximately 100 eV and delivers more than an order of magnitude higher flux at 13.5 nm than previous table-top high-harmonic sources, using less than 10 W of average driving power. Numerical simulations reproduce the measured XUV spectrum and identify a self-guided high-intensity regime as the origin of the efficient macroscopic buildup at high photon energies.

High-harmonic generation provides coherent XUV radiation on a table-top scale, but its efficiency decreases rapidly at high photon energies. This limits applications that require high photon flux, in particular near the technologically important wavelength of 13.5 nm. In this project, we address this bottleneck using visible driving pulses at 516 nm, combining the favorable microscopic response at shorter wavelength with high-intensity propagation in helium to generate coherent emission extending up to 100 eV. The central experimental result is a photon flux of 2.2×10^{11} photons s^{-1} at 13.5 nm (91.8 eV), measured within a 2% bandwidth and generated with less than 10 W of average driving power. The corresponding conversion efficiency is 4.5×10^{-7} in the 13.5 nm band, while at lower photon energies individual harmonics reach efficiencies of 10^{-6} . These values exceed previous table-top high-harmonic results in this spectral region by more than an order of magnitude [1, 2] and establish visible driving as a practical route towards bright coherent XUV emission at technologically relevant wavelengths [3].

A key aspect of the work is that numerical modeling captures the full nonlinear interaction underlying the experiment. By combining propagation of the intense visible driving pulse with microscopic high-harmonic emission and macroscopic XUV buildup, the simulations reproduce the measured harmonic spectrum and reveal why efficient generation is possible. They show that the driving pulse first undergoes laser-plasma reshaping before evolving into a quasi-stable, self-guided propagation regime. In this region, plasma-induced defocusing balances geometrical focusing and enables phase-matched buildup to persist over an extended distance.

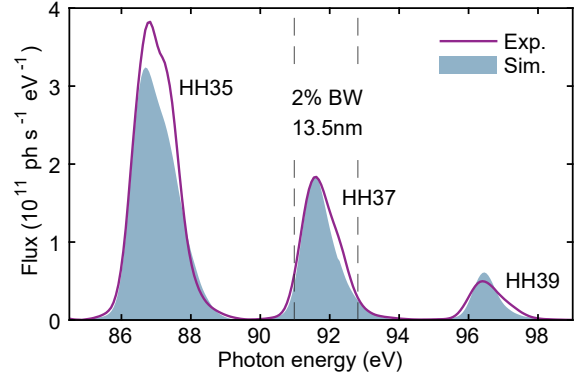


Figure 1: a, Measured and simulated XUV spectrum. Harmonic orders and the lithography-relevant 2% spectral window centered at 13.5 nm are indicated.

The shorter visible driving wavelength plays a decisive role in this behavior, because plasma dispersion is reduced compared with near-infrared drivers, while the microscopic high-harmonic response is more favorable. The present source already delivers application-relevant coherent XUV flux in the 13.5 nm lithography band, directly benefiting metrology applications, spectroscopy and coherent imaging. At the same time, the record result is obtained with less than 10 W of average driving power from a frequency-doubled ytterbium laser system. Scaling this architecture to higher average powers therefore offers a realistic path towards compact coherent XUV sources with orders-of-magnitude higher photon flux, reaching levels otherwise associated with synchrotron-scale infrastructures.

The authors acknowledge funding from the Initiative and Networking Fund of the Helmholtz Association (InnoEUV, KA-TCP-26), the Fraunhofer Cluster of Excellence Advanced Photon Sources (CAPS) and the BMFTR under project EXSAM (13N16673).

References

- [1] R. Klas *et al.*, “Ultra-short-pulse high-average-power megahertz-repetition-rate coherent extreme-ultraviolet light source,” *Photonix* **2**,4 (2021).
- [2] E. J. Takahashi *et al.*, “Low-divergence coherent soft x-ray source at 13 nm by high-order harmonics,” *Applied Physics Letters* **84**, 4–6 (2004).
- [3] M. Karst *et al.* “From Green to EUV: Efficient Coherent Light Generation at 13.5 nm Driven by a 515 nm Source,” *UFO* **132** (2025).

*m.karst@hi-jena.gsi.de

Unleashing HHG efficiency: the role of driving pulse duration

R. Klas^{3,4}, M. Gebhardt³, J. Rothhardt^{*1,2,3,4}, and J. Limpert^{1,2,3,4}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²GSI, Planckstr. 1, Darmstadt, 64291, Germany; ³IAP, FSU Jena, Albert-Einstein-Str. 6, Jena, 07745, Germany; ⁴Fraunhofer IOF, Albert-Einstein-Str. 7, Jena, 07745, Germany

High harmonic generation (HHG) is a key technology for compact, high-brightness extreme ultraviolet (XUV) and soft X-ray sources. While HHG is well-established, novel applications require demanding XUV parameters, mostly higher conversion efficiency and photon flux. In this project the impact of driving laser pulse duration on HHG efficiency is analyzed, and a unified framework linking microscopic dynamics to macroscopic conversion efficiency is established. A scaling law for the single-atom response under phase-matched conditions reveals a τ^{-1} dependence at 515 nm. Furthermore, a novel fundamental limitation, based on the carrier-envelope-phase walk-off, are identified, and experimental results validate the predictions. Practical optimization guidelines are consequently derived.

The efficiency of high harmonic generation is strongly governed by the temporal properties of the driving laser field [1, 2]. High photon flux is essential for many applications, as it enables shorter acquisition times and improves signal-to-noise ratios, while higher efficiency allows comparable performance with more compact and stable laser systems. In this work, the dependence of conversion efficiency on pulse duration is systematically investigated over a broad range of driving wavelengths and photon energies [1]. The analysis is performed on both the microscopic level, considering the single-emitter response, and on the macroscopic level, accounting for collective emission from an extended medium.

First, the theoretically predicted decrease in conversion efficiency with increasing pulse duration is experimentally validated with excellent agreement (Fig.1). For a driving wavelength of 515 nm, photon energies between 20 and 30 eV, and argon as generation medium, a τ^{-1} scaling is observed [1]. This behavior results from higher usable intensities under phase-matched conditions at shorter pulse durations, combined with the strongly non-linear increase of the single-emitter response.

However, this favorable microscopic scaling can only be efficiently transferred to the macroscopic signal under suitable conditions, such as visible driving wavelengths. For infrared drivers required to reach higher photon energies, coherent buildup over extended interaction lengths becomes fundamentally limited.

This limitation originates from a mismatch between phase and group velocities of the driving pulse, inducing a relative shift between carrier and envelope (CEP). As a result, the effective interaction length is significantly reduced, particularly for ultrashort pulses. While this effect has been identified previously [3, 4, 5], its impact on

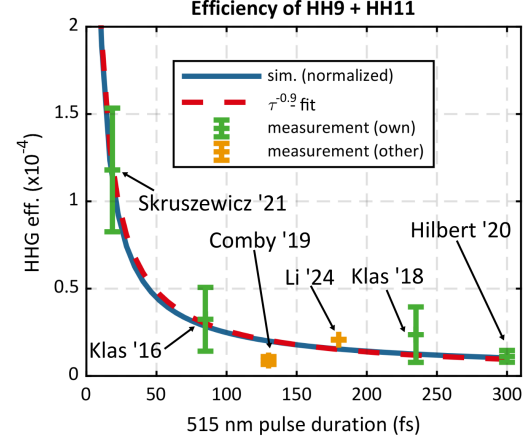


Figure 1: HHG efficiency for the 9th and 11th harmonics generated with a 515 nm driver as a function of pulse duration [1].

macroscopic conversion efficiency and its interplay with absorption-limited regimes have not been systematically analyzed.

The presented framework provides a consistent interpretation of these dephasing mechanisms and enables a quantitative assessment of HHG efficiency across different regimes, including identification of conditions where CEP walk-off becomes the dominant limitation [1].

Finally, the introduced concept paves the way for the development of highly efficient XUV and soft X-ray sources, with potential impact on a wide range of photon-intensive applications in science and technology.

This work was supported by the Fraunhofer Cluster of Excellence (CAPS), the BMFTR (EXSAM), and the Helmholtz Association: Innovation Pool of the Research Field Matter (ECRAPs), APPA R&D (13N12082), and Initiative and Networking Fund (InnoEUV).

References

- [1] R. Klas, *et al.* PhotoniX **7** (2026).
- [2] S. Westerberg, *et al.* APL Photonics **10** (2025).
- [3] C. Hernández-García, *et al.* New J. Phys. **18** (2016).
- [4] D. Kroon, *et al.* Optics letters **39** (2014).
- [5] M. Gebhardt, *et al.* LSA **10** (2021).

*j.rothhardt@hi-jena.gsi.de

Integration of Tango-Controls for Polaris

A. Kessler*¹

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany

The POLARIS control system underwent a software modernisation to adopt state-of-the-art tools, to enable machine learning and artificial intelligence integration, and to eliminate commercial vendor dependencies. In cooperation with S2Innovation we delivered a FAIR (Findable, Accessible, Interoperable, Reusable) data workflow from acquisition to long-term HDF5/NeXus archival with SciCat metadata cataloguing, built exclusively on Free and Open Source Software.

1. HIJ-pyVision: An Integrated GigE Vision Camera Control and Beam Diagnostics System

HIJ-pyVision [1] is a modular software suite for GigE Vision camera control and real-time beam diagnostics within the Tango Controls framework, designed for shot-to-shot laser operation. It consists of a number of different sub-modules, which will be described in more detail below.

1.1. GigE Vision Camera Device Server

The camera-ds controls GenICam-compliant cameras via the Harvesters GenTL interface and supports an HDF5-file-reader mode. It provides background subtraction, ROI masking, and compressed HDF5 storage of recorded camera images with full provenance metadata. Potential connection losses and camera repowers are handled automatically; all user-changed parameters are persisted via Tango memorized attributes and written to the camera at (re)connect.

1.2. Real-Time Image Metrics Device Server

The metrics device server (gigevision-camera-metrics-ds) subscribes to camera events and computes a set of beam metrics on a shot-to-shot basis in a dedicated worker thread, preserving the original frame's timestamp throughout the processing pipeline. Several commonly used analysis algorithms are already implemented via a plugin-based class hierarchy and can be extended by implementing further algorithms.

1.3 Graphical User Interface: imageviewwidget

A Taurus/PyQt5 widget displaying live camera images with overlaid beam diagnostics. Operators define ROIs (rectangle, line, polygon, oval) directly on the image; masks are written back to camera-ds via Tango. HDF5 offline review replays of recorded camera images with the same pipeline.

1.4 Camera Settings Widget

The camera settings widget provides a searchable tree panel for direct access to all GenICam camera hardware parameters. The changed values are persisted through the Tango-memorized-attribute mechanism in camera-ds.

2. Extension of Sardana

Sardana is an SCADA (Supervisory Control and Data Acquisition) and scan framework widely used at synchrotron facilities. Because the workflow of a high-intensity laser experiment requires adjustment of the laser during an experiment, e.g. during a parameter scan, a feature to pause and resume scans has been added. In order to control the camera-ds from a Sardana scan we have implemented a Sardana-2D-Controller [2]. We also extended Sardana controllers with the ability to add user-defined commands [3], as it is standard practice for native TANGO device servers.

3. Improvements of pyTango

Because we had widely used an actor-driven design in our LabVIEW applications, the approach with the latest break due to the implementation of a new laser architecture was to adopt Python's asyncio and multithreading libraries. However, it turned out that the corresponding concurrency mode in PyTango had several issues. We resolved these and contributed the fixes back to the TANGO community [4].

The authors acknowledge funding from European Union (EFRE, 2022 FGI 0022).

References

- [1] A. Kessler, S2Innovation, *HIJ-pyVision*, <https://gitlab.com/hij-s2innovation/hij-pyvision>
- [2] A. Kessler, S2Innovation, *Sardana-pyVision-Controller*, <https://gitlab.com/hij-s2innovation/gigevision-camera-sardana.git>
- [3] A. Justyniarski, S2Innovation, *Sardana-MR2108*, https://gitlab.com/sardana-org/sardana/-/merge_requests/2108
- [4] S. Kupiecki, S2Innovation, *pyTango-MR966*, https://gitlab.com/tango-controls/pytango/-/merge_requests/966

*a.kessler@hi-jena.gsi.de

Status of the Tango control system at JETi200

D. Hollatz^{*1,2}, A. Kessler^{1,2}, A. Sävert^{1,2}, P. Hilz^{1,2}, and M. Zepf^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²IOQ, FSU Jena

The extension building at Helmholtz-Institute Jena offers new opportunities for high intensity laser experiments with JETi200 and POLARIS in the new Target Area Fraunhofer (TAF). The complexity of those experiments with both lasers plus experimental diagnostics and data management as well as the recent trends to utilize artificial intelligence and machine learning necessitate a control system. We present the current status and progress on the Tango control system since last years annual report.

A control system connects laboratory and compute hardware to a software bus to provide supervision, control and data acquisition (SCADA) capabilities. We chose Tango Controls [1, 2] as the framework to build our control system. The software elements can be categorized in 3 major building blocks: hardware drivers, user interfaces and logical control elements. As a first step, we need hardware drivers for all devices at the facility. This includes our in house motor controllers, cameras, gas controllers and spectrometers. Also, the laser itself needs to have a Tango interface.

The motor controller Tango device is our own development. Since July 2025 it is used in the laboratory and replaced the existing LabView control software. We collected data and user experience to mature the Tango device as well as the motor controller software and are now running a robust and working solution.

During the second half of 2025, we worked with a commercial partner to develop Tango device servers for Bronkhorst gas controllers and GigEVision cameras. The device server for Bronkhorst gas controllers was finished last year and was deployed to the laboratory early this year. It is currently being used successfully on an experimental campaign. The device server for GigEVision cameras is currently in development as part of the HIJ-Vision project maintained by A. Kessler. [3]

Hardware support for the JETi200 laser is provided through the Tango gateway, a piece of software purchased from the laser manufacturer that acts as a gateway between the lasers own control system and our Tango control system. The Tango gateway was installed in March 2026 and has since been passed through one iteration of debugging. It is expected to be finalized within the next few months.

Since our last annual report, we started using Tango controls in everyday laboratory activities, specifically the motor and gas controllers. The first experimental campaign to do so was the HILITE experiment at JETi200 Target 1. At the moment, experiments for laser electron and proton acceleration as well as high harmonic generation use the Tango system. An experiment that aims to optimize the

laser electron acceleration via Bayesian optimization is currently underway.

An often overlooked but essential part of operating a control system on a facility with many PC's is the deployment, which describes the process of configuring and installing the required software on the laboratory PC's. Due to the number and accessibility of all the PC's at our facility combined with the number of projects and ongoing software updates, manual deployment on each PC for each project every time an update is made is not practical. Therefore we developed our own automated deployment procedure since we started using Tango everyday in the laboratory. It works by iterating over all PC's via ssh, copying the software and configuring the environments on the target machine. This reduces the maintenance work to a onetime configuration when introducing a new PC to the control system while incremental updates and configuration changes are done automatically.

Although the Tango control system is mainly software engineering, there is a small but essential IT hardware component to it as well, specifically the network. A major amount of our laser diagnostics are cameras, which have a bandwidth requirement up to 1Gbit/s per camera with future cameras up to 5Gbit/s. The network needs to handle this throughput of around 30 to 50 cameras from both lasers and TAF to the control room. We achieve this by building a network composed of 3 major layers. Layer 1 is the ultra high speed connection of the main switches of JETi200, POLARIS, TAF and the control room with up to 3x40Gbit/s optical fiber links. Layer 2 are the high speed individual laboratory networks with 10Gbit/s links to connect high bandwidth components like PC's, databases or large cameras. Inside of the different labs are several smaller layer 3 networks with 1Gbit/s links and 10Gbit/s uplink to the main switch. This network architecture allows full and live access to the entire system including both lasers and TAF from the control room.

The authors acknowledge funding from Freistaat Thüringen and europäischer Fond für regionale Entwicklung (EFRE) with project 2023 FGI 0022 (HIJ) "Künstliche Intelligenz für Hochleistungslaser am Helmholtz Institut Jena".

References

- [1] J-M.Chaize, A.Götz *et al.*, TANGO - an object oriented control system based on CORBA, ICALEPCS (1999).
- [2] S. Feister *et al.*, arXiv.2306.01661, (2023).
- [3] A. Kessler, HIJ annual report, (2025).
- [4] D. Hollatz, HIJ annual reports, (2021-2024).

*dominik.hollatz@uni-jena.de

Experimental demonstration of efficient ultrashort pulse amplification

Supriya Rajhans^{*1} and Christoph Heyl^{1,2,3}

¹Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg; ²HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ³GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstraße 1, 64291 Darmstadt

Key technologies for ultrafast laser source development include multi-pass cell (MPC) based post-compression and optical parametric chirped pulse amplification (OPCPA). Optical parametric amplifiers provides superior temporal contrast and spectral tunability, but are limited by low pump-to-signal conversion efficiency and beam quality. MPCs provide broadband output with excellent throughput and beam quality but they are limited in spectral tunability and temporal contrast. In this work, we present a novel scheme, the optical parametric multi-pass cell amplifier (OP-MPC) combining the advantages of OPCPA and MPCs. We experimentally demonstrate a record pump-to-signal conversion efficiency of 43 % with excellent spatio-temporal pulse quality utilizing a pump at 1030 nm. The developed source centered at 1500 nm exhibits high power and spectral stability and is compressed down to 48 fs, providing a new platform for efficient ultrafast laser source generation.

The generation of high-power, few-femtosecond laser sources is currently primarily driven by two methodologies: multi-pass cell (MPC) post-compression [1], and optical parametric chirped pulse amplification (OPCPA) [2]. In order to overcome the limitations inherent to each approach, a hybrid architecture, the optical parametric multi-pass cell amplifier (OPMPC), was recently proposed [3] and experimentally demonstrated [4]. The OPMPC scheme showcases parametric amplification within an MPC utilizing the cell architecture to suppress the idler beam, effectively overcoming the traditional bandwidth and efficiency limitations of OPAs. In this work, we explore the potential of this scheme in terms of higher pulse energies, shorter pulse durations, and higher conversion efficiencies approaching the theoretical quantum limit [6].

We present experimental results which are supported by our (3+1) D simulations using the chi3D software [5]. A pump laser centered at 1030 nm provides 227 fs pulses at a repetition rate of 1 kHz. A small fraction of the pump energy undergoes filamentation in a YAG crystal to generate broadband seed pulses. The OPMPC setup is driven by 174 μ J of pump energy and a 10 nJ seed. The setup comprises a non-collinear OPMPC geometry with the seed and pump propagating in two MPCs. Both beams overlap spatially and temporally inside a 1.5 mm thick nonlinear KTA crystal placed at the focus of the cell [6]. This setup geometry enables the use of off-the-shelf dielectric mirror for pump and seed while ejecting the idler each pass through the cell.

The pump-to-signal conversion efficiency reaches a

^{*}supriya.rajhans@desy.de

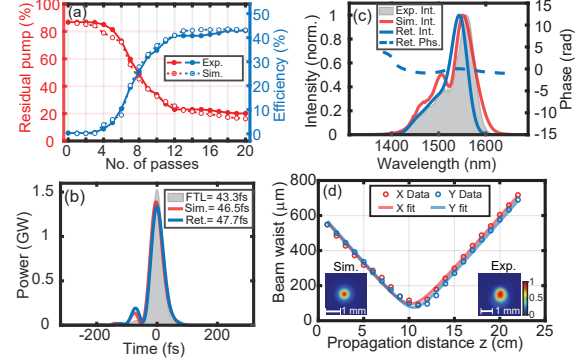


Figure 1: (a) Simulated (Sim.) and experimentally measured (Exp.) residual pump (including 13.3 % linear losses in the cell), and conversion efficiency from the pump to the signal beam as a function of the number of passes in the OPMPC. (b) Sim. and Exp. compressed temporal output pulse profile retrieved from the FROG traces along with the FTL pulse. (c) Retrieved spectrum and spectral phase along with the Exp. and Sim. spectrum. (d) Beam quality measurement of the signal output. The Sim. and Exp. beam profiles are shown as insets.

record value of 42.9 % (Fig. 1(a)) with the amplified signal spectrum shown in Fig. 1(c). Our simulations matches very well with the experimental results as shown in Figure 1. The pulses were compressed down to 48 fs with the retrieved pulse and corresponding spectrum shown in Fig. 1(b) and Fig. 1(c), respectively. The output signal exhibits excellent spatio-spectral homogeneity, a power stability of 0.2 % rms and a spatially homogeneous beam with an M^2 of 1.29×1.01 in the x- and y-axes respectively utilizing $1/e^2$ beam diameters (Fig. 1(d)).

In conclusion, we demonstrate an ultrafast laser source utilizing the optical parametric multi-pass scheme. High pump-to-signal conversion efficiencies approaching the quantum limit can be achieved, paving way for a new generation of laser sources.

The authors acknowledge funding from BMFTR, under grant 13N16678, and DFG, under grant 54561252

References

- [1] Viotti *et al.*, *Optica* **9**, 197-216 (2022).
- [2] Fattahi *et al.*, *Optica* **1**, 45-63 (2014).
- [3] Rajhans *et al.*, *CLEO*, p. SS147.3 (2025).
- [4] Nägele *et al.*, *Nature* **647**, 74-79 (2025).
- [5] Rajhans *et al.*, accepted for publication in *Optica* (2026).
- [6] Lang *et al.*, *Opt. Express* **21**, 949-959 (2013).

LASER PLASMA ACCELERATION

Development of Ionic Liquid Leaf Targets for Laser-Proton Acceleration

M. C. Nolte^{*1}, R. Kirmer¹, and M. C. Kaluza^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²FSU Jena

Liquid leaf targets are attractive for laser-plasma accelerators because they support high repetition rates, enable continuous operation, and are cost-effective due to liquid recirculation. For that, ionic liquids (ILs) are interesting target materials because of their negligible vapor pressure under laser-plasma vacuum conditions. In the following we report on our setup and progress in creating leaf targets. First, stable leaves were created using ethanol. The shape and thickness of the leaf was measured using white light interferometry. In addition, a temperature control system was implemented for future studies with ionic liquids.

Liquid leaf targets are mainly generated by colliding two liquid jets under an angle, or by forcing a liquid through a converging nozzle. Since it is easier to align and replicate, the second approach was chosen. The used nozzles were the "Micro1" nozzles by "Micronit". These consist of two glass plates with etched-in channels, which are then bonded together. To connect them to the tubing, a custom adapter was developed. The liquid was supplied by a HPLC pump that supports up to 350 bar of pressure. To reduce the pressure fluctuations during the pump cycle, a sample cylinder initially filled with air was installed between the pump and the nozzle.

White light interferometry was used to measure the thickness and shape of the leaf. The target gets illuminated by white light, which is reflected at the back and front surfaces. Since the transmission intensity depends on the wavelength dependent interference, the thickness of the target can be determined by measuring the transmission at every wavelength with a spectrometer. By moving the target and measuring at different positions the thickness profile can be retrieved, which can be seen in Fig. 1. The leaves develop a thick rim going around the whole leaf. Due to the strong curvature of that rim it is difficult to measure its thickness with white light interferometry, and therefore it is not resolved in Fig. 1. The leaf is thickest at the interaction point right after the nozzle, where the flow from the nozzle converges. As the liquid spreads out, it gets thinner further away from the nozzle [2].

The thinnest point was measured at the lowest point of the leaf, which is the furthest away from the nozzle, with a thickness of 335nm. The driving pressure can be increased to also increase the size of the leaf, which will lead to a thinner point at the lowest part of the leaf. However, due to the Rayleigh-Plateau-instability the leaf will break up into droplets eventually, which limits the achievable thickness.

The ionic liquid 1-ethyl 3-methylimidazolium dicyanamide (also referred to as EMIM DCA) was chosen for our experiments, because it has a rela-

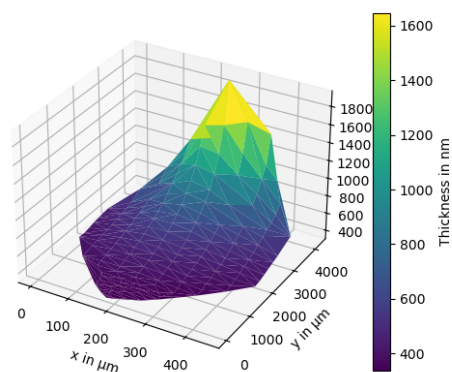


Figure 1: Thickness plot of the feaf created with pure ethanol. The flow rate was 2.1 ml min^{-1} .

tively low viscosity of $\eta = 16.8 \text{ mPa s}$ at room temperature [1]. A low viscosity and surface tension should lead to a larger and thinner leaf [3]. Further, the viscosity and surface tension of EMIM DCA can be significantly reduced by raising its temperature, while the vapor pressure does not change significantly up to 150°C . Therefore, the adapter in which the nozzle is fixed, as well as the tubing in front of it, can be heated with two $22\ \Omega$ -resistors. In a feedback loop with a PT100 temperature sensor, temperatures above 100°C for the ILs can be reached. This enables future investigations of ionic liquid leaves and their shape depending on viscosity and surface tension.

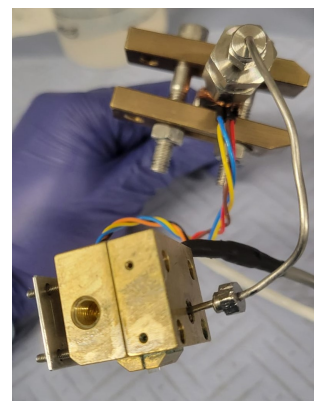


Figure 2: Nozzle adapter with nozzle and heating elements. One heating resistor is mounted to the adapter, one is mounted to the tubing in front of it.

References

- [1] J. Safarov *et al.*, J. Mol. Liq. **332**, 115552 (2021).
- [2] D. Hasson, R. E. Peck, AIChE J. **10**, 752 (1964).
- [3] R. Li and N. Ashgriz, Physics of Fluids **18**, 087104 (2006).

^{*}mathis.nolte@uni-jena.de

First experimental results from the peeler scheme at JETi200

I. Salaheldin^{*1}, L. Reichwein², P. Hitz¹, A. Sävert¹, I. Probst¹, A. Peedika¹, G. Schäfer¹, A. Pukhov², and M. Zepf¹

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²Heinrich Heine University Düsseldorf, 40225 Düsseldorf, Germany

We report on proton acceleration from the edge of a 1 μm thick parylene-coated silicon bridge irradiated by a laser pulse focused to a 1.5 μm FWHM spot size. The laser propagates along the target surfaces toward the rear edge, similar to the peeler scheme proposed in Ref [1]. Proton energies of up to 16 MeV were observed. To investigate the acceleration mechanism, measurements with s- and p-polarized laser pulses were compared together with shots on thick plastic foils.

Surface plasma waves (SPWs) can be excited at the plasma-vacuum boundary when an intense laser pulse interacts with a sharp edge of an overdense plasma. The generation of the SPWs require a steep density profile, which is maintained when the plasma scale length is significantly shorter than the laser wavelength. Under these conditions, the plasma surface remains sufficiently sharp to support efficient SPW excitation [2]. The experimental implementation of the peeler target requires precise alignment, as the laser focal spot size is comparable to the dimensions of the bridge edge. To minimize the impact of shot-to-shot pointing fluctuations, the jitter was characterized over hundreds of shots and the target was aligned to the mean $x - y$ focus position.

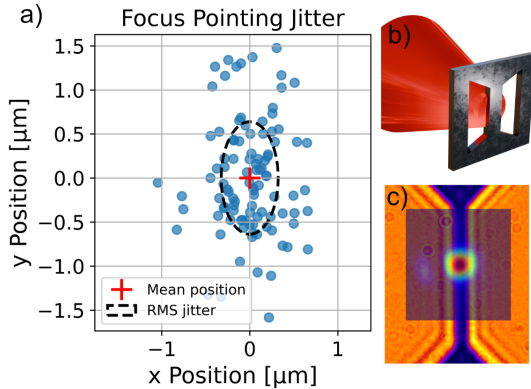


Figure 1: (a) Scatter plot of the focus jitter. The dashed ellipse indicates the rms pointing fluctuations ($\text{rms}_x = 0.32 \mu\text{m}$, $\text{rms}_y = 0.64 \mu\text{m}$), the red cross marks the mean focal position for target alignment. (b) 3D model of the experimental geometry. (c) Overlay of the measured focal spot on the 1 μm -thick bridge, illustrating the relative dimensions of the focus and target.

To investigate the role of SPWs, the peeler target was irradiated with both p- and s-polarized laser pulses. Contrary to expectations, the proton spectra obtained with s-

polarization remained within the shot-to-shot variation of the p-polarized measurements. Reference experiments using thick plastic foils yielded reproducible exponentially decaying spectra with cutoff energies below 6 MeV (Fig. 2).

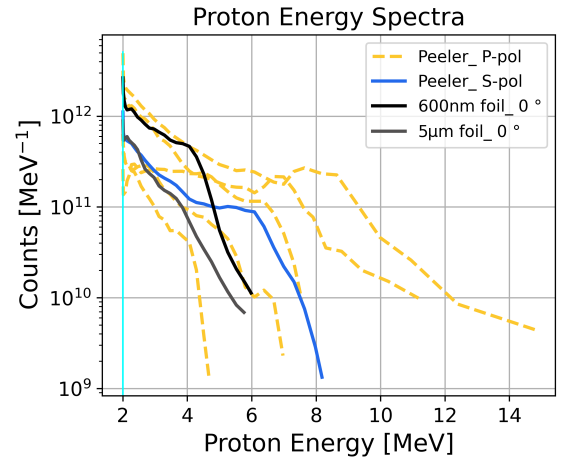


Figure 2: Experimental proton energy spectra for different target and polarization conditions. The dashed yellow curves correspond to p-polarized irradiation of the peeler target, yielding maximum proton energies between 4.5 and 16 MeV. The solid blue curve shows the spectrum obtained under s-polarized irradiation, which falls within the shot-to-shot variation of the p-polarized measurements. For comparison, the solid black and gray curves represent spectra from 600 nm and 5 μm thick plastic foil targets, respectively. Cyan-vertical line represents the spectrometer cut-off.

The obtained spectra, together with the transmission diagnostics, indicate target pre-expansion, likely compromising the sharp plasma-vacuum interface required for efficient SPW excitation in the peeler regime. Further laser contrast enhancement will be required for future investigations of the peeler scheme. See report of S. Kiesel for the implementation of double plasma-mirror (DPM) at JETi200.

The author acknowledges the company NORCADA for producing the targets.

References

- [1] X.F. Shen *et al.*, Phys. Rev. X **11**, 041002 (2021).
- [2] A. Macchi, Phys. Plasmas **25**, 031906 (2018).

*i.salaheldin@gsi.de

Limitations of emittance and source size measurement of laser-accelerated electron beams using the pepper-pot mask method

F. C. Salgado^{1,2}, A. Kozan^{1,2}, D. Seipt^{*1,2}, D. Hollatz^{1,2}, P. Hilz^{1,2}, M. C. Kaluza^{1,2}, A. Sävert^{1,2}, A. Seidel^{1,2}, D. Ullmann^{1,2}, Y. Zhao^{1,2}, and M. Zepf^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²Institute of Optics and Quantum Electronics, FSU Jena, Germany

Extraordinarily bright electron beams, characterized by small emittance and source size, are fundamental requirements for driving advanced light sources (including FELs), as well as reaching the required luminosities for future electron-positron colliders. The pepper-pot method is a widely employed technique for measuring the emittance of electron beams at conventional accelerator facilities. In an experiment at the JETi-200 laser facility, together with simulations of the diagnostic, we have demonstrated and characterized the inherent limitations of the pepper pot method for measuring the emittance for low-emittance electron beams that are produced in wakefield acceleration (LWFA).

The pepper-pot (PP) consists of a high-density material with a grid of holes that samples the electron beam into smaller, emittance-dominated beamlets, which then propagate toward a scintillation screen positioned downstream, where they are imaged. The emittance of the beam is then inferred from the sizes and positions of the beamlets [1]. The design parameters of the PP—e.g. the hole diameter d , their distance pitch Λ , or the parameters for the imaging system—are very much constrained [2]. While these conditions are easily fulfilled for RF photoinjector beams, it is hardly possible to satisfy all constraints for LWFA beams simultaneously, as our analysis shows [2].

We measured the beam emittance of 73 MeV, 5.6 pC LWFA beams at JETi-200 via the PP method [2]. The PP used was a Tungsten mask with optimized parameters: thickness of 200 μm , with a grid of 33×33 holes with $d \approx 50 \mu\text{m}$ and $\Lambda = 120 \mu\text{m}$, yielding a measured geometric emittance of $(26.2 \pm 7.3) \mu\text{m mrad}$ from averaging over 100 shots using the standard inference [1], see Fig. 1. However, from our analysis, we hypothesize that the PP can only provide an upper bound for the true beam emittance for our LWFA beams.

This is evidenced by a large number of PP simulations using GEANT4, keeping the experimental geometry constant but varying beam emittances (purple squares in Fig. 1). These simulations help identify three regions, labeled I, II, and III. Only in region III (gray shaded) can the true beam emittance be retrieved with better than 10% accuracy.

In region I, the true beam emittance is overestimated by the PP method (see Ref. [2] for a detailed discussion and mitigation options). The simulated PP results can be fitted as $\varepsilon_{\text{rms,PP}} = \sqrt{\Omega^2 \theta_x^2 + \varepsilon_{\text{rms,true}}^2} \rightarrow \Omega \theta_x$ as $\varepsilon_{\text{rms,true}} \rightarrow 0$, where Ω depends only on the geometric parameters.

To further support our hypothesis, we performed particle-

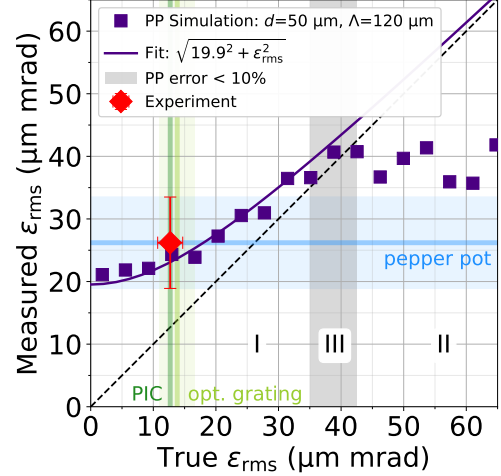


Figure 1: Comparison of experimental and simulated emittance. The PP measurement yields $(26.2 \pm 7.3) \mu\text{m mrad}$ (blue region, red diamond). GEANT4 simulations of the PP diagnostic (purple symbols and fit) indicate that the measurement lies in region I, where the PP method overestimates the true emittance. The green vertical shaded regions represent the expected beam emittance from PIC simulations and from the laser grating diagnostic of Ref. [3]. Using these as input for the PP simulations yields results consistent with the PP measurement.

in-cell simulations of the LWFA using FBPIC with the same laser and plasma parameters as in the experiment, which yielded an RMS beam emittance of about 12.7 $\mu\text{m mrad}$. Moreover, we have obtained in an independent experiment with the same LWFA setup, but using a novel laser grating method, an rms emittance of $(13.8 \pm 2.8) \mu\text{m mrad}$ [3]. We took these values as input for PP diagnostic simulations, and the simulation results agree with the experimentally measured value within the experimental uncertainty (red diamond). We conclude that the limitations of the pepper-pot method prevented a proper determination of the true beam emittance in our experiment. However, our GEANT4 simulations of the diagnostic establish a consistent picture with those emittance values obtained via better-suited low-emittance diagnostic methods [3], and PIC simulation results.

References

- [1] M. Zhang, Report No. Fermilab-TM-1988, (1996).
- [2] F. C. Salgado *et al.*, PRAB **29**, 022801 (2026).
- [3] F. C. Salgado *et al.*, PRAB **27**, 052803 (2024).

*d.seipt@hi-jena.gsi.de

PHOTON AND PARTICLE SPECTROSCOPY

Progress and technological advancements towards quantum logic spectroscopy of highly charged heavy ions

L. Kau^{1,2}, N. Homburg^{1,2}, H. Hayakawa^{1,2}, L. Bernaerts², and P. Micke^{*1,2,3,4}

¹Helmholtz Institute Jena; ²GSI Helmholtz Center for Heavy Ion Research, Darmstadt; ³Institute of Optics and Quantum Electronics, Friedrich Schiller University Jena; ⁴Abbe Center of Photonics, Jena

We are developing a novel optical clock experiment based on quantum logic spectroscopy of accelerator-produced highly charged heavy ions in a cryogenic linear Paul trap. The experiment aims to enable unprecedented tests in fundamental, atomic, and nuclear physics. During 2025, substantial progress was achieved in establishing the laboratory infrastructure, developing the laser and control systems, and finalizing the design of the cryogenic trapping apparatus. Furthermore, prototypes of a superconducting trap resonator were successfully tested, and the ion-transfer beamline concept was developed.

Quantum logic spectroscopy of accelerator-produced highly charged heavy ions requires a complex set of advanced instrumentation and methods, as well as a laser laboratory connected to an accelerator facility capable of decelerating the ions after production and providing a sufficient number of ions at low kinetic energy and with a sufficiently small energy spread for recapture in a Paul trap. Furthermore, the high charge states necessitate a cryogenic trap environment. In 2025, the infrastructure of the laser laboratory, located downstream of the HITRAP decelerator at GSI in Darmstadt, was further developed, and major progress was achieved on key components of the experiment.

The laboratory was commissioned with the installation of the first optical table and preparations for the first laser setups. Commercial lasers (one scientific diode laser and four high-power fiber lasers), purchased the previous year, were brought into operation, providing the fundamental beams for sum-frequency mixing and second-harmonic generation. Initial characterization using new instrumentation, including a high-precision wavemeter, confirmed that the require specifications for wavelength, beam quality, and output power were met or exceeded. In addition, we began commissioning a laser and experimental control system based on Sinara hardware and the ARTIQ real-time control framework for quantum physics experiments.

At the heart of the experiment is a Paul trap operated at a cryogenic temperature of 4 K. The finalized monolithic trap design is ready for manufacture in collaboration with the Physikalisch-Technische Bundesanstalt (PTB) and the Leibniz University Hannover (LUH). The concept and design of the low-vibration cryostat, based on Ref. [1], have been finalized. Commercial components are currently being procured, while the majority of the large number of custom parts is being machined at the Max Planck Institute

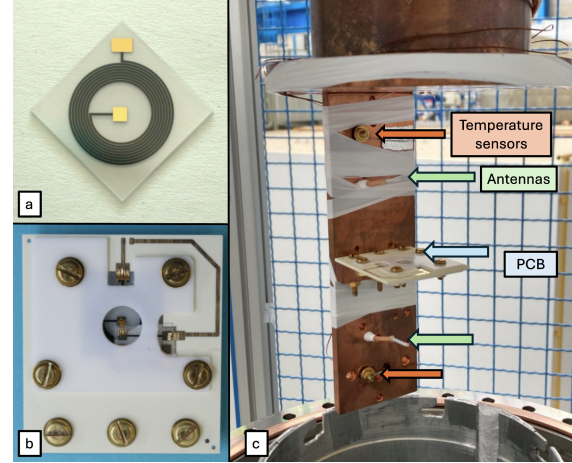


Figure 1: Test setup for the superconducting trap resonator. (a) The YBCO resonator on the sapphire wafer (provided by PTB), (b) mounted on a Rogers printed circuit board, and in (c), installed on the 4 K stage of a cryogenic test stand.

for Nuclear Physics (MPIK). In parallel, flexible cryogenic links are being developed together with the GSI technology laboratory and prepared for implementation. These components are crucial as they provide the thermal coupling while minimizing the transmission of mechanical vibrations from the cold head to the ion trap.

Major progress has also been achieved towards a high-quality-factor step-up resonator for a low-noise radio-frequency trap drive. As part of a master's project and in collaboration with the PTB, a test setup for planar coils made from the high-temperature superconductor YBCO was established. The coils were characterized on a cryogenic test stand (see Figure 1) using different capacitors to simulate the trap capacitance and employing two methods (scattering parameter and ring down measurements). Highly promising quality factors of several thousands were obtained.

Furthermore, the ion-transfer beamline connecting the Paul trap to the accelerator chain and offline ion sources was conceptually developed together with the responsible accelerator department at GSI.

This work is supported by the Initiative and Networking Fund of the Helmholtz Association under the call Helmholtz-Nachwuchsgruppen (VH-NG-19-23).

References

- [1] P. Micke *et al.*, Rev. Sci. Instrum. **90**, 065104 (2019).

*p.micke@gsi.de

Proof-of-Principle Experiment for the Darkfield Detection Concept to Measuring Vacuum Birefringence

Michal Šmíd¹, Pooyan Khademi^{2,3,4}, Naser Ahmadianiaz¹, Michal Andrzejewski⁵, Carsten Baehtz¹, Erik Brambrink⁵, Jakub Bulíčka^{6,7}, Tomáš Burian⁶, Samuele Di Dio Cafiso¹, Jaromír Chalupský⁶, Thomas E. Cowan^{1,8}, Sebastian Göde⁵, Jörg Grenzer¹, Věra Hájková⁶, Peter Hilz^{2,3,4}, Willi Hippler^{2,3,4}, Hauke Höppner¹, Alžběta Horynová^{6,9}, Lingen Huang¹, Oliver Humphries⁵, Šimon Jelínek^{6,7}, Libor Juha⁶, Felix Karbstein^{*2,3,4}, Christian Kohlfürst¹, Alejandro Laso Garcia¹, Robert Löttsch^{2,3,4}, Masruri Masruri⁵, Aimé Matheron^{2,3,4}, Motoaki Nakatsutsumi⁵, Gerhard G. Paulus^{2,3,4}, Alexander Pelka⁵, Thomas R. Preston⁵, Sripati V. Rahul⁵, Lisa Randolph⁵, Alexander Sävert^{2,3,4}, Hans-Peter Schlenvoigt¹, Ralf Schützhold^{1,8}, Jan Patrick Schwinkendorf^{1,5}, Thomas Stöhlker^{2,3,4}, Monika Toncian¹, Toma Toncian¹, Maksim Valialshchikov^{2,3,4}, Vojtěch Vozda⁶, Edgar Weckert¹⁰, Colin Wessel^{2,3,4}, Jan Wild⁷, Ulf Zastrau⁵, and Matt Zepf^{2,3,4}

¹HZDR, Germany; ²HI Jena, Germany; ³GSI, Germany; ⁴FSU Jena, Germany; ⁵EuXFEL, Germany; ⁶Czech Academy of Sciences, Czech Republic; ⁷Charles University, Czech Republic; ⁸TU Dresden, Germany; ⁹Czech Technical University, Czech Republic; ¹⁰DESY, Germany

Vacuum fluctuations give rise to effective nonlinear interactions between electromagnetic fields. These generically modify the characteristics of light traversing a strong-field region. X-ray free-electron lasers (XFELs) constitute a particularly promising probe, due to their brilliance, the possibility of precise control and favourable frequency scaling. However, the non-linear vacuum response is very small even when probing a tightly focused high-intensity laser field with XFEL radiation. Achieving a sufficiently good signal-to-background separation is key to a successful quantum vacuum experiment.

To master this challenge, a darkfield (DF) detection concept has been proposed [1]. The idea underlying the DF concept is to choose an experimental set-up, where the desired signal is contained in an angular range which is essentially free from any background, thereby maximising the signal to background ratio [2]. In the specific case of the x-ray DF scenario devised for the measurement of the nonlinear quantum vacuum response, the probe beam is modified with a well-defined obstacle such as to exhibit a shadow in both the converging and expanding beam while retaining a peaked focus profile; see Fig. 1 for an illustration.

Wave optics implies that in the focus the information about the shadow in the beam is encoded in pronounced side peaks. The number of x-ray signal photons induced in the collision with the high-intensity pump scales linearly (quadratically) with the intensity of the probe (pump). In line with that, the product of the transverse focus profile of the probe and the squared pump focus profile determines the signal source distribution. Appropriate tuning of the pump and probe waists allows the source distribution of the quantum vacuum signal to be modified. In particular the side-lobes can be significantly reduced relative to central peak. Effectively erasing the side-lobes in the source

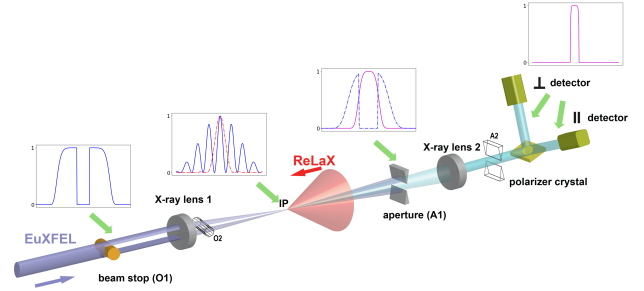


Figure 1: Idealized darkfield set-up. The central shadow is imprinted onto the x-ray probe beam by inserting an opaque beam stop, transforming the initial distribution with a central maximum. In the focal plane a peaked distribution reappears with the shadow encoded in side-lobes. At the interaction-point (IP) the central peak overlaps with the high intensity laser (ReLaX) focus. For matched x-ray and laser waists the resulting quantum vacuum signal (magenta line in the aperture plane) is peaked on axis.

distribution of the quantum vacuum signal ensures that the signal does not inherit any information about the shadow in the incident probe beam. This results in a signal distribution that is peaked in the DF region.

The experimental results presented in [3] show that a sufficiently good background suppression can be achieved in a beam-line with real-world optical components, opening the path to measuring the non-linear response of the vacuum.

References

- [1] F. Karbstein, D. Ullmann, E. A. Mosman and M. Zepf, Phys. Rev. Lett. **129**, 061802 (2022).
- [2] BIREF@HIBEF Collaboration, High Power Laser Sci. Eng. **13**, e7 (2025).
- [3] M. Šmíd, *et al.*, Phys. Rev. A **112**, 6 (2025).

*f.karbstein@hi-jena.gsi.de

Testing DCCC-xD in GSI warehouse & starting the C4CRY project

V. Tympel^{*1,2}, T. Sieber², B. Voss³, and S. Kolbe³

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²Institute of Optics and Quantum Electronics, FSU Jena, Germany;

³Uni App. Sci. Jena

The planned installations of large DCCC-xD systems in the FAIR project require continuous operation with liquid helium [1]. To ensure this, a long-term test was carried out over several months. Like-wise, it was investigated how low-frequency acoustic disturbances from the helium re-liquefier couple into a Double-core CCC sensor. In July, the BMFTR project "Compact Cryo-Current Comparator for the CRYRING@ESR," briefly called C4RAY, was launched at the University of Jena, with HI-Jena being significantly involved.

Tests of the DCCC-xD system with a helium re-liquefier HeRL15 (15 litres/day) at CRYRING@ESR and in transport sections had shown that it only works on a weekly basis. Therefore, the cryostat was redesigned and the re-liquefier replaced with a more powerful HeRL 25. The system was then set up in the 'SD Testing Hall' (Fig. 1) and operated uninterrupted for 6 months. The increased cooling capacity even makes it possible to install a control loop for further temperature regulation using a small resistance heater in the cold head of the HeRL25 pulse tube cooler.

In January, a measurement campaign was conducted to investigate the microphonic effects caused by the re-liquefier. For this purpose, the two sensitive SQUID channels were used, which deliver the signals from the two pickup coils of the DCCC-xD (called Red and Yellow). As expected, the 1.4 Hz frequency of the pressure change in the cooler's pulse tube tubes was the main source of disturbance. Unexpected was the large difference (factor of 10, see Fig. 2) between the two coils, even though they are actually built identically.

In July, the BMFTR project to develop a special CCC system for the CRYRING@ESR began with the start of the tenders. Unfortunately, the PhD position will not be filled until 2026. However, the tender for the development was successful in 2026, and ILK Dresden has started the work, so that the first milestone with the approval of the planning could already be achieved in December.

In November a long-term liquefaction test has been started to check the possibility of using the HeRL25 to produce liquid He fed from gas bottles to the system. If this is possible, the CCC in the FAIR tunnels would not only work as a standalone system, but would additionally be independent from LHe filling and mobile He recovery schemes. It could be demonstrated, that the cryogenic system can reach LHe temperatures. However, the cooling time is realistically two months, mainly caused by accumulation of N₂ at the HeRL25 cold head, which requires several regeneration breaks of two or three days (cold head warm up and pumping). Nonetheless, the result shows that the liquefier

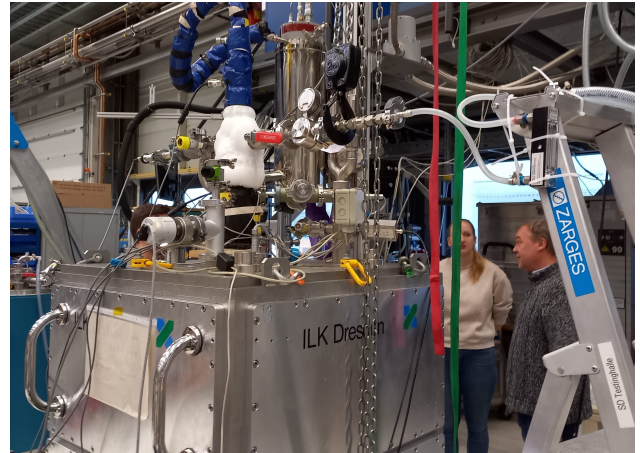


Figure 1: DCCC-xD system with a HeRL25 helium re-liquefier running at the GSI 'Testing Hall'.

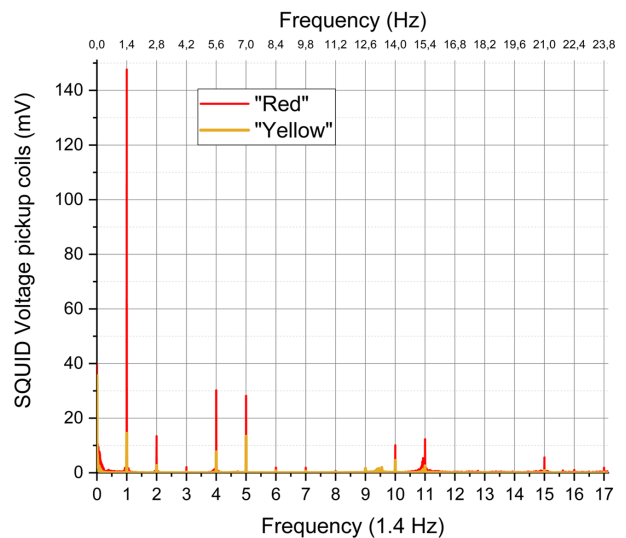


Figure 2: The significant difference at 1.4 Hz eluded perception in the laboratory.

has sufficient cooling power for our needs, and that standing time problems stem from gas contamination in the first place, which can be avoided with appropriate measures. This would reduce the required time, a cool down time of a month could be acceptable, if long-er preparation periods are scheduled.

The authors acknowledge funding from BMFTR: 05P21SJRB1, 05P24SHA, 05K25SJA.

References

[1] <https://doi.org/10.18429/JACoW-IBIC2025-M0BC01>

*v.tympel@hi-jena.gsi.de

Dielectronic Recombination of Ne^{3+} at CRYRING@ESR for Astrophysical Plasma Modelling

E.-O. Hanu^{*1,2,3}, M. Lestinsky², C. Brandau², M. Fogle⁷, P.-M. Hillenbrand², M. Looshorn^{4,5}, E. B. Menz^{2,6}, S. Schippers^{4,5}, S. Wang^{4,5}, and T. Stöhlker^{1,2}

¹HI Jena, 07743, Jena; ²GSI, 64291, Darmstadt; ³IKP, Goethe Universität, 60438, Frankfurt am Main; ⁴I. Physikalisches Institut, Justus-Liebig-Universität Giessen, 35392 Giessen; ⁵HFHF, 35392, Campus Giessen; ⁶Institut für Kernphysik, Universität zu Köln, 50937 Köln; ⁷Department of Physics, Auburn University, 36832 Auburn, USA

This study investigates the dielectronic recombination (DR) of Nitrogen-like Ne, using the ultra-cold electron beam at CRYRING@ESR [1]. The experiment aims to improve the accuracy of modeling charge state distributions in cold photoionized plasma by investigating low-energy dielectronic recombination rate coefficients, with a particular emphasis on resonances below 0.5 eV.

The experiment was conducted at the CRYRING@ESR, storage ring at GSI in Darmstadt, where beams of specific elements and charge states are stored, cooled, and merged with a monoenergetic electron beam for DR measurements [1]. Accurate DR rates are essential for reliable charge state distributions calculations and abundance determinations from nebular emission lines. The present CRYRING@ESR measurement addresses this need by delivering new, state-of-the-art DR data for Ne^{3+} , covering collision energies from 0 to 25 eV. $\Delta N = 0$ resonance clusters are identified below ~ 25 eV, with series limits at 5.11 eV, 7.74 eV and 22.91 eV (see upper panel Figure 1). Above ~ 9 eV, good overall agreement is found between experiment and theory for both resonance positions and strengths, within the $\pm 1\sigma$ level. At lower energies (0.5–9 eV), however, noticeable discrepancies appear in the integrated resonance strengths, partly attributed to limited statistics. In the near-threshold region (< 0.25 eV), eight individual DR resonances were fitted to extract precise energies, strengths, and widths. Field ionisation of high- n Rydberg states was accounted for by supplementing the experimental spectrum with theoretical contributions up to $n = 1000$.

From the merged-beams data, the temperature-dependent plasma recombination rate coefficient (PRRC) $\alpha(T)$ for DR was derived. In the temperature range where Ne^{3+} is abundant in collisionally ionised plasmas ($kT \approx 6.8$ –34 eV), the experimental PRRC shows good agreement with previous theoretical calculations (e.g. Badnell), while in the low-temperature regime relevant to photoionised plasmas [2] such as planetary nebulae ($kT \approx 0.68$ –1.46 eV), the experimental rate is slightly higher than theory, consistent with the experimental statistics (see lower panel Figure 1). To make these results directly applicable, parametrised analytic fits of the PRRC [3] are provided for straightforward implementation in astrophysical plasma modelling codes (e.g. CLOUDY).

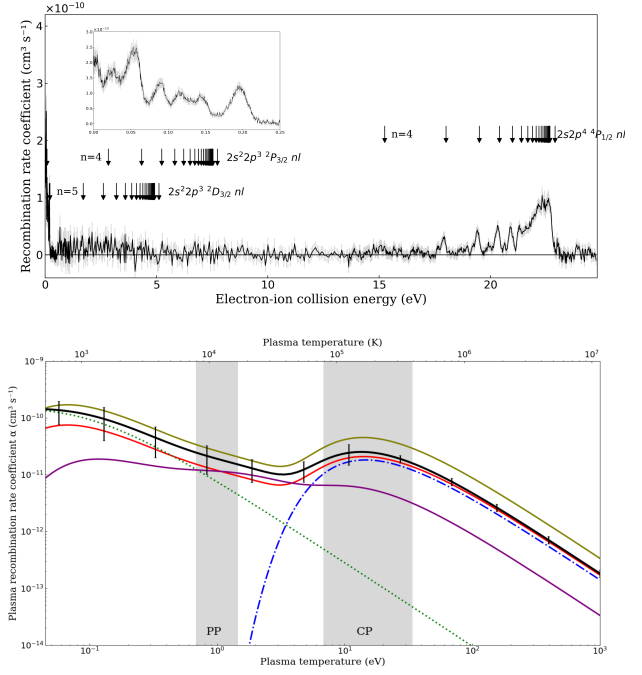


Figure 1: Upper panel: summary of the merged beam recombination rate coefficient $\alpha(E)$ covering a collision energy range between 0 and 25 eV. Lower panel: the experimentally derived total DR PRRC $\alpha(T)$ is represented by the black lines, with the associated total uncertainty. A comparison with the theoretical calculations is provided: the red line corresponds to a weighted sum over the individual metastable levels, while the green line represents the contribution arising solely from the pure $4S_0$ ground level. The individual components constituting the experimentally derived DR PRRC are also shown separately: the low-energy resonance fit (dashed green line), the overview spectrum contribution (magenta line), and the field ionization contribution from high- n Rydberg levels (dot-dashed blue line).

References

- [1] M. Lestinsky *et al.*, Phys. Rev. Let. **100**, 033001 (2008).
- [2] M. Lestinsky *et al.*, Eur. Phys. J. Special Topics **225**, 797–882 (2016).
- [3] N. R. Badnell *et al.*, Astrophys. J. **804**, 100 (2015).

*e.hanu@gsi.de

Real-Time Extreme Ultraviolet Ghost Imaging (RT-XUV-GI) for High-Throughput and Low-Dose Nanometrology

Sukyoon Oh^{*1,2} and Christian Spielmann^{1,2}

¹IOQ, Friedrich-Schiller-Universität Jena, Max Wien Platz 1, D-07743 Jena, Germany; ²HI Jena, Fröbelstieg 3, 07743 Jena, Germany

Real-time extreme ultraviolet ghost imaging (RT-XUV-GI) breaks the critical trade-off between acquisition speed and sample damage in nanoscale metrology. Utilizing a 1 kHz tabletop high-harmonic generation (HHG) source and a fast-rotating mask disk patterned with a track-adapted 2D Hadamard matrix, we demonstrate a lensless high-throughput imaging platform. Non-iterative reconstruction via the Fast Walsh-Hadamard Transform (FWHT) yields a target spatial resolution of 200 nm over a large field of view ($\geq 70 \mu\text{m}$) in under one minute, while maintaining an exceptionally low radiation dose ($\leq 1 \text{ kGy}$ per frame) for non-destructive industrial inline analytics.

Motivation: Modern semiconductor nanometrology faces physical limits: electron-beam methods cause critical dimension (CD) shrinkage in sensitive EUV photoresists [1], while optical XUV approaches like ptychography suffer from long, iterative reconstruction times and high radiation doses ($> 10 \text{ kGy}$) due to lossy optics [2]. The RT-XUV-GI framework bypasses these challenges by completely eliminating focusing optics and distributing the photon load over a large area. Rapid, non-iterative reconstruction based on spacetime correlations guarantees high photon efficiency and minimal radiation damage ($\leq 1 \text{ kGy}$), securing entirely non-destructive inline inspection [3, 4].

Experimental Configuration: The tabletop system synchronizes a 1 kHz HHG source with a dynamic modulation module containing an Al/Cr transmission mask (200 nm minimum feature size) on a fast-rotating disk ($\sim 8.4 \text{ rpm}$) (Fig.1). Through a designated aperture, 25,111 deterministic patterns are recorded within $\sim 25 \text{ s}$ by a high-speed XUV single-bucket detector. A digital geometric routine corrects rotation-induced distortions to remap the raw data into a precise cartesian grid prior to computational reconstruction. The transmission mask comprises a bilayer system of Al/Cr (100 nm each) with a minimum feature width of 200 nm, fabricated using electron beam lithography (EBL) and precise dry etching down to a $\pm 10 \text{ nm}$ critical dimension tolerance. To achieve loss-free high-speed data acquisition, the rotational framework is phase-locked to the 1 kHz driving laser via a dedicated FPGA trigger module, ensuring an exact single-pulse-to-pattern correlation.

Performance and Results: End-to-end simulations validate that scaling the correlation matrix to the full set of 25,111 patterns effectively eliminates motion artifacts and restores high-fidelity sample dynamics (Fig.2). Utilizing

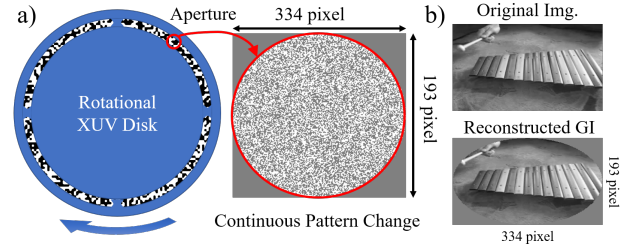


Figure 1: Principle of RT-XUV-GI imaging. a) Rotating XUV mask disk (Hadamard track, 2D pattern). b) Real object and image reconstruction.

the FWHT algorithm, the pipeline resolves a 334×193 pixel image covering an $\text{FOV} \geq 70 \mu\text{m}$ in under one minute. This rapid, low-dose performance confirms that the RT-XUV-GI architecture successfully breaks the trade-off between throughput and sample damage, establishing a robust baseline for high-throughput, non-destructive inline quality control and photomask defect inspection.

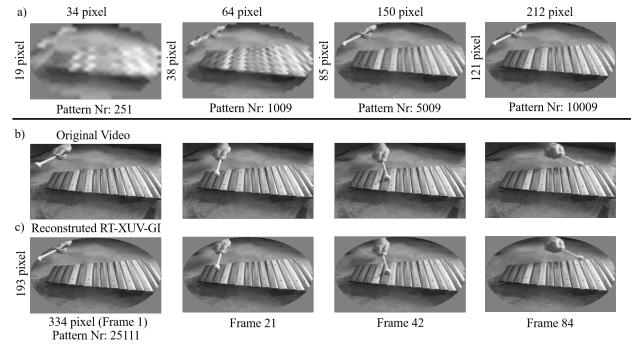


Figure 2: Performance simulation of the dynamic RT-XUV-GI reconstruction. a) Top row: Representation of the increasing spatial resolution resulting from an increasing number of correlation patterns (from left to right). b) Middle row: Individual frames of the original video sequence as a reference. c) Bottom row: Reconstructed individual frames based on 25,111 correlation patterns (corresponding to the full pixel count).

References

- [1] B. Bunday *et al.*, J. Micro/Nanolithog. **11**, 023007 (2012).
- [2] Howells, Malcolm R *et al.*, 170.1-3 (2009): 4-12..
- [3] S. Oh *et al.*, Sci. Rep. (2026, under review).
- [4] R. Henderson, Proc. R. Soc. Lond. B **241**, 6 (1990).

*sukyoon.oh@uni-jena.de

Efficient Deep Ghost Imaging with a Compact Physics-Driven Neural Network

T. Tian^{*1,2}, S. Oh^{1,2}, and C. Spielmann^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²IOQ, FSU Jena

Ghost imaging reconstructs images from known illumination patterns and bucket detector measurements. While deep-learning-based methods have improved reconstruction quality, they often rely on complex networks with limited interpretability. We propose a compact physics-guided neural network for ghost imaging and validate it experimentally. Its lightweight architecture facilitates the investigation of underlying imaging mechanisms and provides a basis for future single-pixel phase imaging applications.

Ghost imaging originated from quantum-entanglement-based imaging and emerged at the end of the twentieth century. Since the beginning of the twenty-first century, classical light sources have been introduced into ghost imaging implementations, sparking steadily growing interest in the research community. Today, ghost imaging has evolved into a versatile imaging technique capable of operating across a wide range of wavelengths. In addition, it has become a computational imaging framework that tightly integrates hardware implementation with advanced reconstruction algorithms.[1]

Ghost imaging reconstructs images from known illumination patterns and bucket detector measurements. Early methods relied on correlation-based algorithms, followed by compressed sensing around 2010, which improved reconstruction efficiency.[2] Since around 2020, deep-learning-based approaches have rapidly advanced the field.[3]

Early deep-learning ghost imaging methods required extensive pretraining, limiting their practical use. In 2022, F. Wang et al. proposed the physics-driven framework called Ghost Imaging using Deep neural network Constraint (GIDC), enabling training-free ghost imaging.[3] In GIDC, the reconstructed image generated by the network is correlated with the illumination patterns, and the resulting bucket signals are compared with experimental measurements. The squared error serves as the loss function for network optimization. By establishing a nonlinear mapping between measurements and images, deep learning significantly improves reconstruction quality.

However, existing deep-learning ghost imaging methods often rely on complex network architectures with limited interpretability and generalization. Understanding the nonlinear mapping process and its relationship to image formation has therefore become an important research direction for developing more efficient and physically meaningful reconstruction methods.

To address this challenge, we propose a compact and ef-

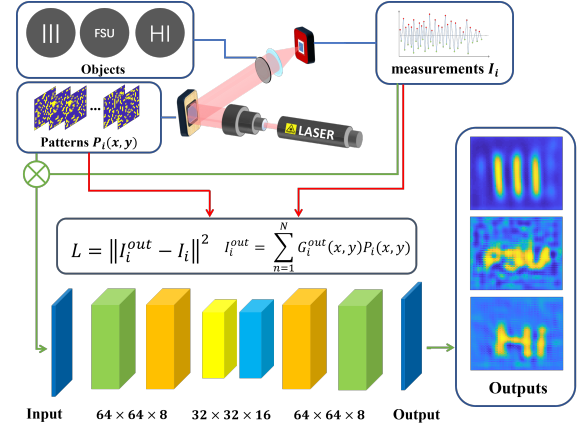


Figure 1: The experimental setup and the proposed network structure.

ficient neural network that has been experimentally validated to achieve high-quality image reconstruction. Compared with GIDC, our network can achieve reconstruction performance of comparable quality using only 22% of its network size. The overall experimental setup, network architecture, and data flow are illustrated in Figure 1.

We constructed a computational ghost imaging system using a digital micromirror device (DMD) as the illumination modulator. The core of the software framework is a neural network consisting of six convolution layers. Its architecture adopts a front-back symmetric design inspired by U-Net. The input to the network is the correlation result between the speckle patterns displayed on the DMD and the corresponding bucket detector measurements.

Furthermore, if some reconstruction quality can be sacrificed, the network size can be reduced to below 10% of that of GIDC. Such a compact architecture greatly facilitates the investigation of the underlying nonlinear mapping process. At the same time, it provides a solid foundation for further adapting the network to more advanced applications, such as single-pixel phase imaging.

References

- [1] T. Tian *et al.*, Vicinageth 2, 4 (2025).
- [2] M. F. Duarte *et al.*, IEEE Signal Process. Mag. **25**, 83 (2008).
- [3] F. Wang *et al.*, Light Sci. Appl. **11**, 1 (2022).

*tong.tian@uni-jena.de

Ultrabright MeV Photons and Neutrons from DLA Electrons in Foams

P. Tavana^{*1,2,4}, M. Gyrdymov^{2,4}, P. Boller^{3,4}, R. Kalla^{3,4}, U. Spillmann⁴, T. Kühl⁴, O. N. Rosmej^{2,4}, and C. Spielmann¹

¹Institute of Optics and Quantum Electronics (IOQ), Friedrich Schiller University Jena, Jena, Germany; ²Institute for Applied Physics (IAP), Goethe University Frankfurt, Frankfurt am Main, Germany; ³Institute for Applied Physics, Technical University of Darmstadt, Darmstadt, Germany; ⁴GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

We demonstrated an ultrabright, directional source of MeV bremsstrahlung by combining direct laser acceleration (DLA) in preionized polymer foams with a high-Z converter. A 200 TW, sub-picosecond PHELIX laser pulse drove high-current superponderomotive electron beams in long-scale near-critical plasmas formed by a controlled nanosecond prepulse. Conversion of these electrons in a few-millimeter Ta/Au stack produced multi-MeV photons with energies up to about 70 MeV and a laser-to-photon efficiency above 1% for $E_\gamma > 7$ MeV.

Ultrabright MeV photon sources are of strong interest for high-energy-density (HED) radiography, photonuclear studies, activation studies, and laboratory astrophysics. In this work, a controlled nanosecond prepulse was used to preionize low-density CHO polymer foams and form a long-scale near-critical plasma. The subsequent 200 TW, sub-picosecond PHELIX laser pulse efficiently accelerated high-current, superponderomotive electrons by DLA.

The generated electron beams reached effective temperatures of approximately 26–29 MeV, with electron energies extending beyond 100 MeV. A total charge of about 300 nC was measured for electrons above 1.5 MeV, while the directed high-energy fraction above 7.5 MeV reached 20–30 nC within a narrow cone around the laser axis. These high-current relativistic electrons were then converted into bremsstrahlung radiation in a millimeter-scale Ta/Au converter attached to the rear side of the foam target.

The MeV photon emission was characterized by combining nuclear activation diagnostics with gamma spectroscopy and autoradiography. Photonuclear reactions in Au, Ta, and Cu confirmed photon production in the giant dipole resonance region. In particular, the detection of high-threshold reaction products such as ¹⁹⁰Au and ¹⁷⁴Ta confirmed the presence of photons above 55 MeV. In control shots without foam, no comparable high-energy activation was observed, showing that the bright MeV photon emission comes from the DLA electrons generated in the preionized foam plasma.

On average in each shot, approximately 2×10^{11} photons per steradian were produced within the FWHM of the beam for $E_\gamma > 7$ MeV. The mean photon energy above 7 MeV was about 16 MeV, and the laser-to-photon conversion efficiency exceeded 1%. Autoradiography of activated Cu foils showed a stable and directional MeV photon beam

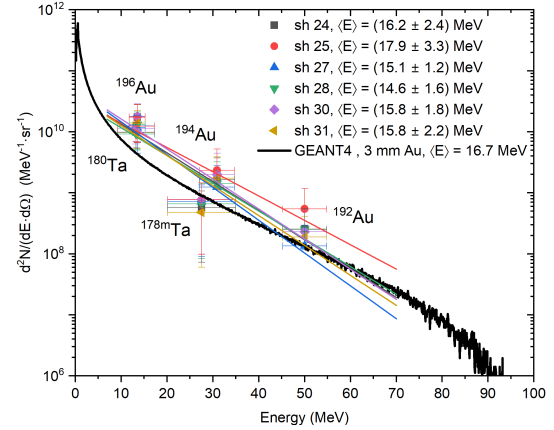


Figure 1: Reconstructed MeV bremsstrahlung spectra from Au and Ta activation measurements, showing a reproducible photon source extending up to about 70 MeV. The black curve shows the corresponding GEANT4 simulation [1].

with an average half-angle of about 22° in the 14–21 MeV energy range. In addition, more than 2×10^9 photoneutrons per shot were produced through photonuclear reactions in the high-Z converter.

Compared with laser-wakefield-acceleration-based photon sources, the present scheme does not rely on GeV electron beams but instead benefits from the exceptionally high charge of DLA electrons. This is especially advantageous for photonuclear applications in the giant dipole resonance region, where high photon flux in the 10–30 MeV range is required.

This work follows our earlier studies on bremsstrahlung generation from DLA electrons in high-Z converters [2] and extends this source to photonuclear diagnostics and neutron production. In the same experiment, this ultrabright bremsstrahlung source was also used for on-shot detection of fission products from ²³⁸U [3], making it a useful platform for laser-driven nuclear physics studies.

References

- [1] P. Tavana *et al.*, Phys. Rev. Applied **25**, 034003 (2026).
- [2] P. Tavana *et al.*, Front. Phys. **11**, 1178967 (2023).
- [3] R. Kalla *et al.*, Phys. Plasmas **32**, 073106 (2025).

*p.tavana@uni-jena.de

Stability of the Second-Order Nonlinear Optical Response of Polymer-Coated WS₂ Monolayers Investigated Using Dispersion-Scan

M. Mallick^{*1,2}, Z. Xie^{1,2}, M.T. Hossain², P.T. Guerreiro³, H.N. Gopalakrishna², R. Romero³, A. Turchanin², and C. Spielmann^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²Friedrich-Schiller-University Jena, Max-Wien-Platz 1, 07743 Jena, Germany; ³SphereUltrafast Photonics, SA, Rua do Campo Alegre, 1021, Porto, Portugal

We experimentally investigate broadband second harmonic generation (SHG) from polymer-coated WS₂ monolayers using dispersion-scan (d-scan) measurements. Stable performance after long-term storage and continuous laser exposure demonstrates the potential of protected WS₂ monolayers for nonlinear photonic applications.

Monolayer WS₂ exhibits strong light-matter interaction and efficient second-harmonic generation (SHG), making it attractive for ultrafast nonlinear photonic applications. However, photo-induced oxidation under ambient conditions leads to a gradual degradation of its optical properties [1]. To address this challenge, we investigate the long-term stability of the second-order nonlinear optical response of CVD-grown monolayer WS₂ wet-transferred onto fused silica and then spin coated with a cyclic olefin copolymer (COC) on top. The COC layer was selected for its high optical transparency, low water permeability, excellent chemical resistance, and electrical insulating properties [2].

The nonlinear optical response was characterized using broadband SHG measured via a d-scan technique driven by few-cycle laser pulses from hollow core fiber pulse compression (≈ 7 fs, 600–925 nm, 1 kHz). While conventional SHG measurements primarily quantify conversion efficiency, d-scan additionally retrieves the spectral phase and pulse characteristics, providing a more sensitive assessment of the material's suitability for nonlinear photonic applications. To evaluate the impact of encapsulation on device-relevant performance, the coated WS₂ monolayers were benchmarked against a standard nonlinear crystal (10- μ m-thick β -BBO). The retrieved pulse characteristics show good agreement with the β -BBO reference, with dscan trace retrieval errors below 5%. As shown in Fig. 1 (a–c), only minor differences are observed in the measured d-scan traces, yielding pulse durations between 6.4 to 7 fs, well within the experimental uncertainty. Furthermore, no measurable degradation of the SHG response was observed after five months of storage or during continuous laser exposure for up to 5 hours, as shown in Fig. 1 (d). The preserved nonlinear response and β -BBO-comparable performance demonstrate the potential of protected WS₂ monolayers for future integrated photonic applications.

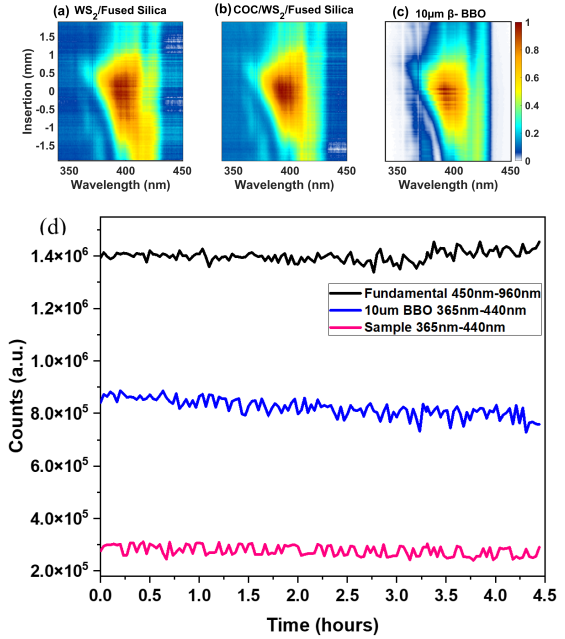


Figure 1: d-scan traces of (a) monolayer WS₂ on fused silica, (b) COC-coated monolayer WS₂ on fused silica, and (c) a 10- μ m-thick β -BBO reference crystal. (d) Long-term stability of SHG signals from β -BBO and COC-coated WS₂ shown with laser power.

References

- [1] Jian Gao et. al, ACS Nano **10**, 2, (2016).
- [2] S.B Kalkan et.al, Adv. Opt. Mat. **112**, 2201653 (2023).

*monalisa.mallick@uni-jena.de

Collective nuclear pulse propagation in single-mode X-ray waveguides

L. M. Lohse^{1,2,3}, P. Andrejić⁴, S. Velten^{2,3}, M. Vassholz¹, C. Neuhaus¹, A. Negi^{2,3}, A. Panchwane³, I. Sergeev³, A. Pálffy⁵, T. Salditt¹, and R. Röhlberger^{6,2,3}

¹Georg-August-Universität Göttingen, Göttingen, Germany; ²The Hamburg Centre for Ultrafast Imaging CUI, Hamburg, Germany; ³DESY, Hamburg, Germany; ⁴Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany; ⁵Julius-Maximilians-Universität Würzburg, Würzburg, Germany; ⁶Helmholtz Institute Jena, GSI Helmholtzzentrum, and Friedrich-Schiller-Universität Jena, Germany

Ensembles of identical atoms or nuclei that share a common light field do not simply behave like the sum of their parts: they can emit collectively, faster and into preferred directions. We have realised such collective behaviour with Mössbauer nuclei coupled to X-ray photons that travel *inside* a nanometre-thin waveguide, establishing a new platform for waveguide quantum electrodynamics in the hard X-ray regime [1].

When many identical quantum emitters couple to the same radiation field, their response becomes cooperative. Hallmarks of this collective regime are superradiance—an accelerated, directed decay—together with collective frequency shifts, and they appear already for as little as a single shared photon. Nuclear resonances are ideal for studying these effects: the 14.4 keV transition of the Mössbauer isotope ^{57}Fe is extraordinarily narrow, which makes nuclear ensembles exceptionally clean quantum-optical systems and a long-standing testbed for cooperative emission.

Until now, such experiments relied on three geometries: forward scattering through thin foils, Bragg diffraction from crystals, and grazing-incidence reflection from thin films. What had remained unexplored is a genuine *waveguide*, in which the nuclei are coupled to photons that propagate in a confined, guided mode. This is the hard X-ray analogue of waveguide quantum electrodynamics—a field that, in the optical domain, has attracted enormous interest. but which had so far been restricted to much longer wavelengths.

In our experiments at the PETRA III beamline P01 (DESY), 100 ps pulses of 14.4 keV synchrotron radiation excite a film only a few atomic layers thick of ^{57}Fe , embedded in the core of a planar X-ray waveguide. The delayed photons leaving the waveguide exit are recorded with avalanche photodiodes, time-gated to separate the nuclear signal from the prompt synchrotron flash. Two complementary ways of feeding the pulse into the guide were studied: (a) In *front-coupling*, the pulse enters the front face and travels in the fundamental guided mode, see Fig. 1. The nuclear ensemble then emits the characteristic “dynamical beats” of coherent pulse propagation through a resonant medium, just as in nuclear forward scattering, see Fig. 2. By cutting the waveguide into a triangular shape we tuned its length from about 0.1 to 2 mm and confirmed that the resonant optical depth grows in strict proportion to the length. (b) In *resonant-beam-coupling*, a long waveguide is excited at grazing incidence. Here the exciton decays

exponentially, but with a pronounced superradiant speedup of up to 30 times the natural rate, together with a shifted resonance—both tunable simply by adjusting the incidence angle.

A single theoretical framework based on a real-space Green’s-function description captures both observations. Whenever one guided mode dominates, the coupled nuclei behave exactly like a homogeneous slab whose effective thickness is rescaled by a single nucleus–mode coupling constant. Optically thin guides then produce dynamical beats, while optically thick guides produce superradiant exponential decay.

Beyond confirming this unified picture, the work points to applications: “harvesting” the guided beam at the waveguide exit yields a highly coherent, narrow-band X-ray source only 20 nm across. Multi-mode guides could enable two-beam control and the deliberate engineering of collective radiation patterns, opening promising routes for quantum optics with hard X-rays.

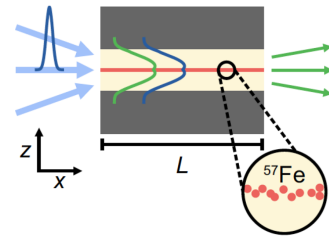


Figure 1: A short X-ray pulse enters a planar waveguide and excites a thin ^{57}Fe layer. The collective nuclear excitation emits delayed resonant photons into the guided mode.

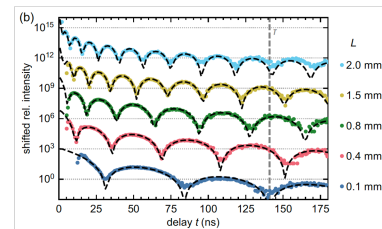


Figure 2: Delayed emission from waveguides of different length L , demonstrating coherent collective pulse propagation through the nuclear layer.

References

- [1] L. M. Lohse *et al.*, Phys. Rev. Lett. **135**, 053601 (2025).

Energy-time ptychography for nuclear resonant X-ray spectroscopy

A. Negi^{1,2}, L. M. Lohse^{1,2}, S. Velten¹, I. Sergeev¹, O. Leupold¹, S. Sadashivaiah^{3,4}, D. Bessas⁵, A. Chumakov⁵, C. Brandt⁶, L. Bocklage^{1,2}, G. Meier^{7,2}, and R. Röhlberger^{3,4,8,1,2}

¹DESY, Hamburg, Germany; ²The Hamburg Centre for Ultrafast Imaging CUI, Hamburg, Germany; ³Helmholtz Institute Jena, Jena, Germany; ⁴GSI Helmholtzzentrum GmbH, Darmstadt, Germany; ⁵ESRF - The European Synchrotron, Grenoble, France; ⁶University of Greifswald, Greifswald, Germany; ⁷Max Planck Institute for the Structure and Dynamics of Matter, Hamburg, Germany; ⁸Friedrich-Schiller-Univ. Jena, Germany

Phase retrieval is a central problem in photon science: detectors count photons, but the phase of the wave field is lost. We have demonstrated an energy-time ptychography method that recovers this missing phase for nuclear resonant scattering from Mössbauer nuclei. The approach converts time-resolved nuclear forward scattering into a phase-sensitive route towards complex energy spectra, with applications in high-resolution spectroscopy and hard X-ray quantum optics [1].

The phase problem is well known from crystallography and coherent X-ray imaging. In one dimension it is especially difficult, because a single intensity measurement usually does not define a unique complex spectrum. This limitation also appears in synchrotron Mössbauer spectroscopy. A short X-ray pulse excites an ensemble of resonant nuclei; the delayed nuclear forward scattering signal contains quantum beats that reveal the hyperfine structure. However, the detector records only intensity as a function of time, while the phase of the scattered field is missing.

Our work transfers ptychography from spatial imaging to the coupled energy-time domain. A broad nuclear “probe” resonance is placed in front of the sample under investigation. By moving one of the foils with a Doppler drive, the probe spectrum is shifted relative to the object spectrum. Each velocity setting therefore probes a different, but overlapping, energy range of the object. This overlap provides the redundancy needed to retrieve the complex transmission spectrum computationally.

The proof-of-principle experiment was performed at PETRA III beamline P01 using the 14.4 keV transition of ⁵⁷Fe. A ⁵⁷Fe-enriched stainless-steel foil served as the probe and a magnetized iron foil as the object. For each Doppler detuning, avalanche photodiodes recorded delayed photons after the synchrotron pulse. The resulting two-dimensional ptychogram, shown in Fig. 1, contains phase-sensitive interference between the probe and object responses. From these data we reconstructed the complex nuclear transmission spectrum of iron. The retrieved line positions agree with an independent synchrotron Mössbauer source measurement within the numerical grid resolution, giving a magnetic hyperfine field of about 32.6 T, as expected for iron.

This method avoids scanning a narrow single-line source through the spectrum. Instead, it uses the full time-domain response of a coupled nuclear system and retrieves the missing phase by exploiting measurement redundancy. It

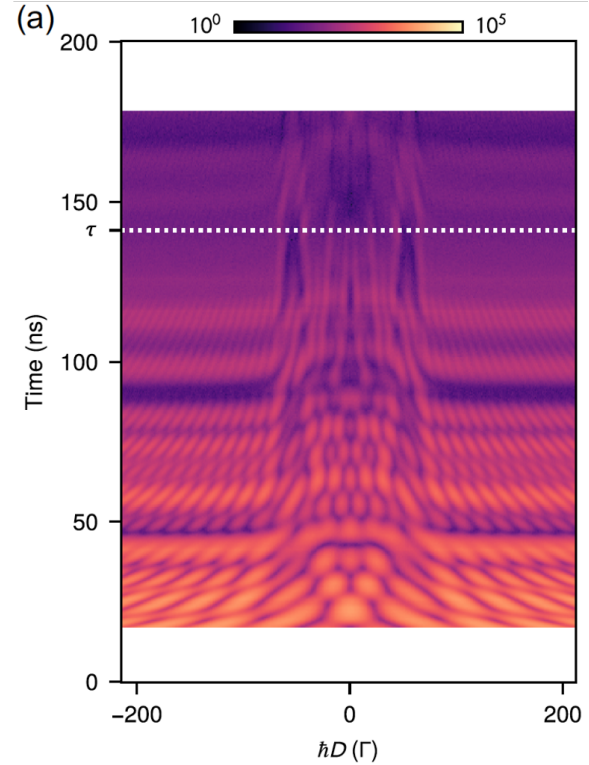


Figure 1: Energy-time ptychogram for nuclear resonant scattering. The horizontal axis is the Doppler detuning of the probe in units of the natural linewidth Γ , while the vertical axis gives the photon arrival time after pulsed X-ray excitation. The rich interference pattern is the energy–time analogue of a ptychographic diffraction dataset and encodes the missing spectral phase. The dotted line marks the natural lifetime τ of the 14.4 keV level in ⁵⁷Fe.

is therefore attractive for Mössbauer isotopes and sample environments where conventional energy-domain spectroscopy is difficult or where no suitable synchrotron Mössbauer source exists. With longer bunch spacings and improved timing modes, nuclear ptychography should enable sub-linewidth energy resolution and provide a new tool for coherent control, nanostructured materials, and nuclear quantum optics with hard X-rays.

References

- [1] A. Negi *et al.*, *Optica* 12, 1529 (2025).

Single-Frame EUV Imaging with a Randomized Probe

C. Liu^{*1,2}, S. H. Chew^{2,3}, W. Eschen^{1,2}, M. Abdelaal², J. Limpert^{1,2,3}, and J. Rothhardt^{1,2,3}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²IAP, FSU Jena, Albert-Einstein-Str. 6, 07745 Jena, Germany;

³Fraunhofer IOF, Albert-Einstein-Str. 7, 07745 Jena, Germany

Fast nanoscale EUV imaging is important for studying dynamic processes, but established lensless methods often require isolated samples or time-consuming scans. Here, we demonstrate single-frame randomized probe imaging (RPI) at 13.5 nm using a table-top high-order harmonic source. A structured EUV probe is first characterized by ptychography and then used to reconstruct the complex object transmission from one diffraction pattern. Comparing smooth, spiral and speckle-like illuminations shows that structured probes are essential for robust single-frame reconstructions. The best RPI image reaches 110 nm half-pitch resolution, while averaging a few independently reconstructed frames improves the resolution below 100 nm. These results establish RPI as a promising approach for rapid EUV imaging in pump-probe experiments.

Coherent lensless imaging in the EUV and soft-X-ray regimes enables nanoscale microscopy with material-specific contrast, and compact high-order harmonic generation (HHG) sources now make such experiments possible in the laboratory. However, established methods often require either isolated samples or multi-position acquisitions. Ptychography is highly flexible and quantitative, but its scanning nature becomes a bottleneck for pump-probe measurements or rapid experimental feedback. Randomized probe imaging (RPI)[1] addresses this limitation by first characterizing a structured illumination function and then using it to reconstruct the object from a single diffraction pattern. The structured probe adds spatial-frequency diversity, making the single-frame phase retrieval problem sufficiently constrained for extended samples. In this way, RPI retains the flexibility of ptychography for extended samples while reducing the acquisition to a single exposure.

We demonstrate RPI with a 13.5 nm HHG-EUV source driven by sub-10 fs, 1030 nm laser pulses. To tailor the illumination, a mask was positioned approximately 200 μm upstream of the sample. Three probe types were investigated: a smooth pinhole beam, a vortex-like beam generated by a spiral mask, and a highly randomized speckle beam produced by an EUV diffuser. For each case, a conventional ptychographic scan with 200 diffraction patterns was first used to retrieve the complex probe and a constant background. These calibrated quantities were then supplied to the RPI algorithm to reconstruct the complex object transmission function from individual diffraction patterns.

The single-frame RPI results at maximum detector dynamic range are shown in Figure 1 for the spiral and EUV diffuser illuminations [2]. In both cases, the main object

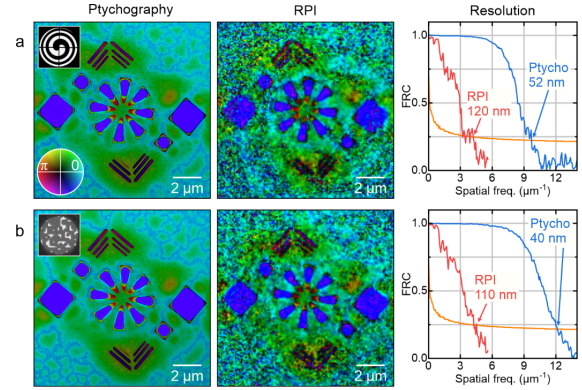


Figure 1: Ptychography and single-frame RPI reconstructions using (a) spiral and (b) EUV diffuser illumination.

features are recovered from one selected diffraction pattern. Fourier ring correlation gives half-pitch resolutions of 120 nm for the spiral mask and 110 nm for the EUV diffuser, compared with 52 nm and 40 nm from ptychography, respectively. The slightly better performance of the diffuser is attributed to its broader and more randomized angular spectrum, which spreads the diffraction signal more efficiently across the detector and provides stronger diversity for single-frame phase retrieval. Averaging independently reconstructed RPI frames further improves the resolution below 100 nm, providing a tunable trade-off between acquisition time and image quality.

Overall, this work establishes single-frame RPI as a robust and experimentally simple route to fast EUV imaging of arbitrary extended samples. Compared with CDI or Fourier-transform holography, RPI does not require isolated objects or reference holes and directly reconstructs the quantitative object transmission function. Since the probe needs to be calibrated only once, the method can be integrated naturally into existing ptychography beamlines and HHG microscopes. It is therefore promising for pump-probe studies, on-the-fly scans and real-time experimental feedback, where acquisition time is the limiting resource.

The authors acknowledge funding from the Freistaat Thüringen, Thüringer Aufbaubank, the Helmholtz Association, the Fraunhofer Cluster of Excellence Advanced Photon Sources, ERC project SALT, the European Social Fund Plus and the Helmholtz Innovation Pool project FISCOV.

References

- [1] A. Levitan *et al.*, Opt. Express **28**, 37103-37117 (2020).
- [2] S. Chew *et al.*, Opt. Express **34**, 7496-7508 (2026).

*c.liu@gsi.de

Variable brilliant ion sources for strong-field laser and ion applications

F. Machalett^{*1,2,3}, J. Hacker², B. Ying², Th. Weber², A. Sommerfeld², Th. Stöhlker^{1,2,3}, and G. G. Paulus^{1,2}

¹Helmholtz Institute Jena, 07743 Jena; ²Institute of Optics and Quantum Electronics, Friedrich Schiller University Jena, 07743 Jena; ³GSI Helmholtz-Zentrum für Schwerionenforschung, 64291 Darmstadt, Germany

Brilliant liquid metal ion sources (LMIS) are characterized by small emission sites and high emission current densities. In addition to their use in focused ion beam (FIB) systems, they are well suited for generating narrow, collimated ion beams required for ionic laser targets. These properties make LMIS promising for a range of future applications.

For new applications we developed and tested a variable ion source, which can controllably change characteristic parameters during operation. Using the newly developed preparation and vacuum test chamber, we were able to fabricate ion emitters and examine emitter materials on a microscopic scale. The same setup makes it possible to measure and vary the operation properties of the entire variable ion source.

Fig. 1 (a) shows the new UHV test chamber for the preparation, testing and optimization of ion emitters, and (b) shows a part of the new variable source with the emitter (blue), movable in 3 directions relative to the extractor electrode (below at the bottom).

In general, these developments make it possible to improve and meet the requirements of important quality factors of LMIS [1] such as: high brilliance of $10^6 \text{ A cm}^{-2} \text{ sr}^{-1}$, long service life (approx. 1000 h per emitter), low melting metals / alloys, ion currents of $5 \mu\text{A}$ – max. 1 mA, continuous and triggered beams are possible.

The newly designed variable ion source enables several opportunities to vary source characteristics and enables a better adaption to the requirements of specific applications. Fig. 2 shows just a very small selection of the options available for optimizing various source parameters. For example in Fig. 2 (a) the axial angular ion intensity is increasing with ion source current I_s , but depends on distance a of the emitter tip to extractor, and (b) the extraction voltage U depends strongly on the distance a and shows a minimum at $a = -1 \text{ mm}$ for all ion source currents I_s .

The strong-field laser experiments are continued with new developed systems using the brilliant LMIS. The experiments are focused on the ultrafast laser-induced fragmentation of dimer and cluster ions as well as on the ionization to higher charge states. Further experiments will be carried out with ions of other materials, such as eutectic systems.[2]

The authors acknowledge support from GSI Innovation Fund as an internal funding instrument for technology transfer of GSI. The creative and productive collaboration with JEVATEC GmbH Jena is specifically acknowledged.

*f.machalett@gsi.de

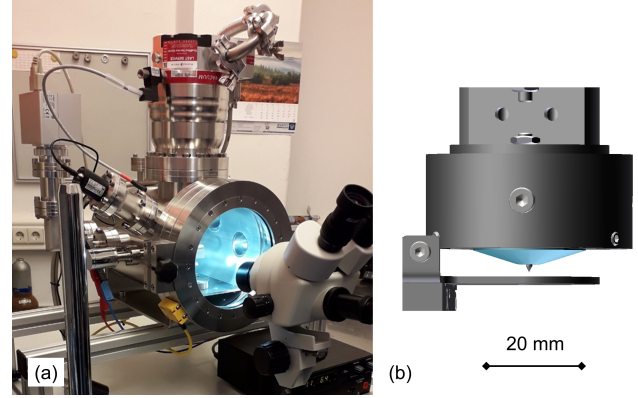


Figure 1: (a) UHV test chamber for the preparation, testing and optimization of ion emitters down to the microscopic scale and (b) the new emitter, movable in x-, y- and z- directions to vary the source characteristics during operation.

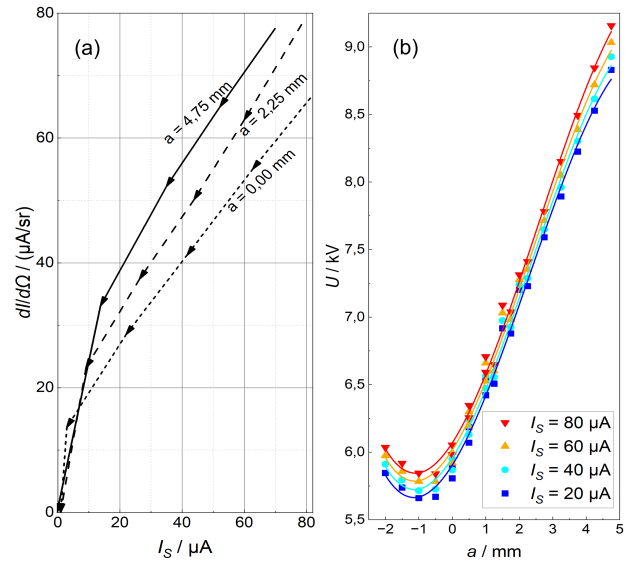


Figure 2: (a) The axial angular intensity of ions from a Au-Si LMIS, measured in a Faraday cup, is shown as a function of ion source current I_s for different distances a between emitter tip and extractor, (b) Extraction voltage U as function of the distance a for different ion source currents I_s .

References

- [1] F. Machalett, P. Seidel, Focused Ion Beams and Some Selected Applications, EAP, Wiley (2019)
- [2] B. Ying, *et al.*, J. Phys. B: At. Mol. Opt. Phys. **54** (2021)

A flat field spectrometer for SHHG experiments at JETi200

I. Probst^{*1,2}, S. Kiesel¹, P. Hilz^{1,2}, and M. Zepf^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²IOQ, Friedrich-Schiller-Universität Jena, Germany

For solid target High Harmonic Generation (SHHG) experiments at JETi200 we are working on a custom flat field spectrometer for target area 2. We report the implementation of a first version optimized for wavelengths between 20 nm and 80 nm and the ongoing design process of a more elaborate version for a wider range of harmonics.

The design of the spectrometer is based on the spectrometer presented in Kita *et al.*[1]. Its main component is a concave grating with varied line spacing. Each wavelength λ is diffracted at a different angle $\beta = \sin(\sin \alpha - \frac{m\lambda}{d})^{-1}$ depending on the incident angle α , diffraction order m and distance d between grating lines. In addition, the rays are focused by the concave shape of the grating. The variation of the line spacing is optimized so that the focal points of each wavelength lie on a plane instead of the Rowland circle. In comparison to the original design by [1], we do not use an entrance slit, but directly image the source to enhance light collection. Furthermore, the grating is placed in a separate chamber attached to our main target chamber to achieve better shielding from stray light and maintain the alignment between experimental campaigns. Due to the constraints of the experimental layout, the grating must be placed at a greater distance than the design distance of the grating. Therefore, we calculated the focal curves for possible distances in our set-up via ray tracing to determine the optimal grating angle and camera position.

A preliminary version of the spectrometer (see Figure 1) is currently installed in target area 2 and will be used in an upcoming SHHG experiment with the recently installed double plasma mirror at JETi200. It is designed for a grating with a line spacing of $N = 300 \frac{\text{lines}}{\text{mm}}$ and is optimized to fit into a conventional 160 ISO-K cross attached to the target chamber. The grating angle and positions are optimized to achieve a flat focal curve that is perpendicular to the incoming beam. The corresponding focal curves are shown in Figure 2 and the beam paths for the optimal incident angle $\alpha = 86.1^\circ$ and selected wavelengths in Figure 3. This design allows for the detection of the 10th harmonic (=80 nm) to the 40th harmonic (=20 nm) of the fundamental wavelength of 800 nm in one shot with a CCD camera. To detect even higher harmonics, we are working on a set-up where the grating with $N = 300 \frac{\text{lines}}{\text{mm}}$ is interchangeable with a grating with $N = 1200 \frac{\text{lines}}{\text{mm}}$. This second grating is optimized for 5 nm to 20 nm, which is equivalent to the 40th and 160th harmonics. In addition to that, we are designing a custom chamber for the spectrometer and intend to motorize the grating angle and position to enable alignment in vacuum.

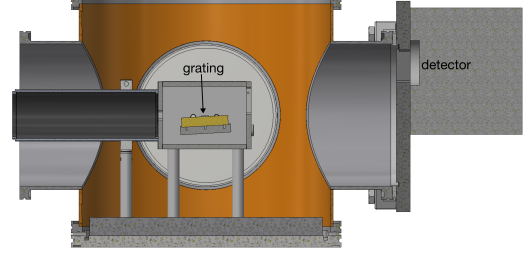


Figure 1: Drawing of the flat field spectrometer currently installed in target area 2 at JETi200.

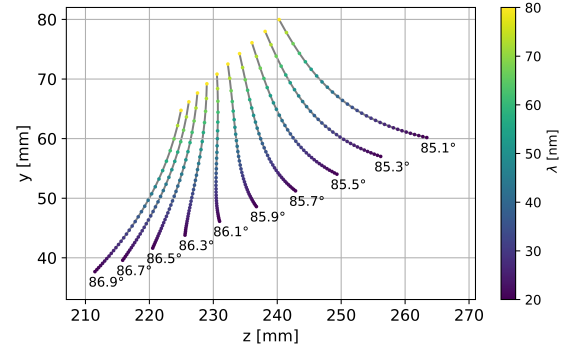


Figure 2: Calculated focal curves for different wavelengths λ diffracted by a grating with a line spacing of $N = 300 \frac{\text{lines}}{\text{mm}}$ placed 662 mm after a point source. Each curve corresponds to a different incident angle α .

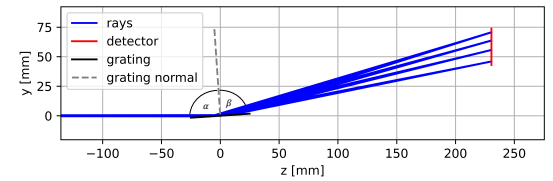


Figure 3: Beam path for selected wavelengths (80 nm, 60 nm, 40 nm and 20 nm, top to bottom) diffracted by a grating ($N = 300 \frac{\text{lines}}{\text{mm}}$) placed 662 mm after a point source with an incident angle $\alpha = 86.1^\circ$.

References

- [1] T. Kita *et al.*, Appl. Opt. **4**, 512 (1983).

* i.probst@hi-jena.gsi.de

Correlative Soft X-ray and Fluorescence Microscopy for Nanoscale Imaging of Cancer Cell Adhesion

S. Kaleta^{*1,2}, P. Osuchowska³, W. Kasprzycka³, J. Reinhard^{1, 2}, A. Nowak-Stępniewska³, J. Abel², Y. Hsu^{1,2}, M. Wünsche², S. Fuchs⁴, and G. G. Paulus^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²IOQ, FSU Jena; ³WAT, MUT Warsaw; ⁴HS Mittweida

To investigate metastatic mechanisms in triple-negative breast cancer, we employ a correlative soft X-ray and fluorescence microscope. It allows for the direct alignment of functional protein labeling with structural nanoscale imaging. We successfully visualized the internal architecture of focal adhesions in HCC38 cells, demonstrating that our integrated vacuum-compatible setup offers unique insights into the mechanical drivers of cancer cell migration.

Understanding the complexities of cellular mechanisms requires the ability to visualize biological specimens at the nanoscale. The "water window" (WW) spectral region, defined by the absorption edges of carbon and oxygen (280–530 eV / 2.3–4.4 nm), is particularly well suited to meet this demand. Within this range, oxygen-rich water remains highly transparent, allowing the radiation to penetrate up to 25 μm deep, whereas organic, carbon-dense structures strongly absorb the radiation. This creates a high natural structural contrast, enabling intact, whole-cell imaging at the nanoscale without the need for artificial contrast agents.

We use this spectral range by operating a correlative soft X-ray (SXR) and visible light fluorescence microscope [1]. The WW radiation is generated by a laser-produced plasma source. We generate a strong single-line emission at a wavelength of 2.88 nm by focusing nanosecond laser pulses into a nitrogen gas jet and use a zone plate for high-resolution imaging. We achieve a spatial resolution of 50 nm half-pitch, verified with a Siemens star test target.

Although the SXR modality provides a structural image of the sample, understanding cellular functionality requires targeted labeling. To provide this functional context, a wide-field fluorescence microscope has been integrated directly into the SXR vacuum chamber. The SXR microscope's zone plate and the fluorescence microscope's objective share a single stage, enabling correlative microscopy. This allows us to locate specifically labeled cellular components via fluorescence and, immediately afterward, take a high-resolution SXR structural image of the same position without the need to move the specimen or break the vacuum environment.

In our most recent collaborative study [2], we applied this correlative approach to investigate the adhesion of triple-negative breast cancer (TNBC) cells, specifically the HCC38 line. TNBC is a highly aggressive subtype in which metastasis is driven by the cells' ability to adhere to and migrate through the extracellular matrix via focal adhe-

sions (FAs). These complex multi-protein structures link the actin cytoskeleton to the cell's exterior. By using fluorescence to identify key proteins like paxillin, we can pinpoint the exact locations of these functional centers.

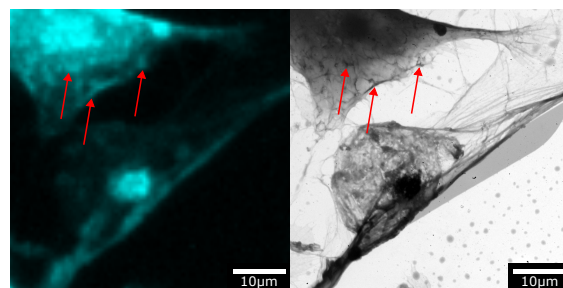


Figure 1: Triple-negative breast cancer cells imaged with the correlative microscope. Left: Fluorescence image with labelled paxillin to locate focal adhesions. Right: Corresponding SXR image to image the structural shape of the focal adhesions.

Our SXR imaging then reveals the underlying structural "core" of these FAs, which often appear as spherical, dot-like subunits clustered at the terminals of actin stress fibers as visible in Fig. 1. Unlike previous methods where fluorescence and X-ray images had to be obtained from different sample sets [3], our integrated system ensures that the functional signal and the high-resolution structural map correspond to the exact same adhesive complex. Although the vacuum environment requires the cells to be imaged in a dried state, the high density of the actin-protein networks, such as actin fibers and adhesion complexes, remains well-preserved. This allows us to resolve the internal packing of adhesive complexes and their organization within the cytoskeleton, providing crucial data on the migratory potential and invasive strength of cancer cells at the nanoscale.

This project is funded by the EU's Horizon Europe programme under grant agreement number 101131771 Lasers4EU [37863 – HIJ (JE)]. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. The European Union cannot be held responsible for them.

References

- [1] J. Reinhard, S. Kaleta *et al.*, *Microsc. Microanal.* **10**, 84 (2023).
- [2] P. N. Osuchowska, S. Kaleta *et al.*, in preparation.
- [3] P. N. Osuchowska *et al.*, *Int. J. Mol. Sci.* **22**, 7279 (2021).

*s.kaleta@hi-jena.gsi.de

Digital Filters for Pulse Shape Analysis of Metallic Magnetic Calorimeters

J. H. Walch^{*1,2,3}, M. O. Herdrich^{1,2}, D. A. Schnauß-Müller^{1,2,3}, G. Weber^{1,2}, and Th. Stöhlker^{1,2,3}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²GSI, Darmstadt; ³IOQ, FSU Jena

In the last years novel metallic magnetic calorimeters (MMC) have been utilised in the field of precision x-ray spectroscopy, for example X-ray spectroscopy of helium-like uranium [1] or light muonic atoms [2]. In order to perform an optimal data analysis for the recorded MMC detector signals, various digital pulse shape analysis filters were tested in terms of their ability to accurately determine the amplitudes of simulated MMC pulses with different properties. For a detailed offline analysis the Optimal Filter (OF) was found to deliver the best resolving power while for online analysis the Integral Filter (IF) revealed the best compromise between achievable spectral resolution and processing time.

To exploit the outstanding performance MMC detectors require a complex data analysis which contains among other features a pulse shape analysis, a temperature correction, an analysis of the coincident measurement, a reconstruction and produces finally a physically interpretable spectrum. This report concentrates on the aspect of the pulse shape analysis and the comparison of several pulse shape analysis filters. For this propose a typical pulse shape and noise (restricted to a combination of white and pink noise) of MMC signals including digitalisation effects of an ADC were simulated. These synthetic pulses were fed into four digital pulse shape analysis filters to test their resolving power: the Maximum Filter (MF), the Integral Filter (IF), the Moving Average Deconvolution combined with a Moving average Filter (MWDMAF) [3] and the Optimal Filter (OF) [4]. The performance of a filter was defined to describe the resolving power in a more descriptive way as $1 - \sigma_{\text{spec}}/\sigma_{\text{noise}}$, where σ_{spec} is the spectral width of the pulses in the spectrum and σ_{noise} is the standard deviation of the additive signal noise.

The filters were analysed with datasets containing signals with a fixed energy but one varied property. These properties are the uncertainty of the arrival time, an uncertainty in the determination of the decay time, a varying proportion of pink noise to the total noise and a variation in the signal to noise ratio (SNR). The results for the latter can be found in Figure 1. It is illustrated that all filters despite the MF (depicted in blue) show a constant performance up to a SNR of three. Thereby the actual noise of an MMC detector is located at the very bottom of the shown scale (≈ 0.2 keV for signals with an amplitude of 60 keV). For interpretation of the figure it is important to be aware that the performance is normalised to the amount of noise superimposed to the signal. Therefore the filters, respectively, are able to filter the same percentage of noise regardless of the SNR. It was

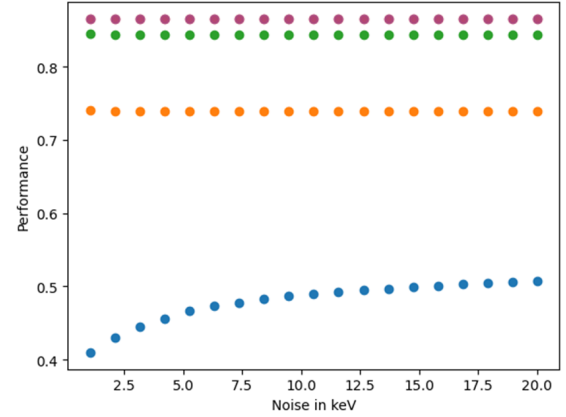


Figure 1: Performance of the digital pulse shape analysis filters evaluating pulses with a decreasing signal to noise ratio (left to right). blue: MF; orange: IF; green: MWDMAF; purple: OF.

demonstrated that the OF shows the best performance of the filters. The increasing performance expressed by the MF is an artefact related to the chosen implementation of the determination of the pulse maximum. Thus it does not indicate a real increase in the performance of the filter.

The analysis of the pulse shape analysis filters applied to datasets with varying simulation parameters revealed that for all realistic pulses the OF demonstrates the best performance of the filters and thus is advised to be utilised for a detailed offline analysis to gain the best possible FWHM in the spectrum. The inclusion of a correction method for the trigger jitter of the signals increased the filter stability in a wider range of simulated scenarios. However a runtime benchmark showed that for an online analysis during the experiment, where a fast analysis is more important than the most precise results, the IF should be used. These findings will be utilised in the data analysis of following experiments featuring an MMC detector. *This work was in part supported by "Quantum Sensing for Fundamental Physics (QS4Physics)", funded by the Innovation pool of the research field Helmholtz Matter of the Helmholtz Association.*

References

- [1] Ph. Pfäfflein *et al.*, Phys. Rev. Lett. **134**, 153001 (2025).
- [2] B. Ohayon *et al.*, Physics **6**, 206-215 (2024).
- [3] M. O. Herdrich, PhD thesis (2023)
- [4] A. Fleischmann, PhD thesis (2003)

*j.h.walch@hi-jena.gsi.de

Production of $^{229}\text{Th}^{89+}$ and Storage Ring Studies for the HiThor Project

C. Brandau^{*1} and Th. Stöhlker^{1,2,3} for the HiThor project

¹GSI, Planckstraße 1, Darmstadt; ²HI Jena, Fröbelstieg 3, Jena; ³Uni Jena, Max-Wien-Platz 1, Jena

Within the ERC-awarded HiThor project (“Highly Ionized Trapped $^{229}\text{-Thorium}$: A New Paradigm To-towards a Nuclear Clock”) [1] we plan to follow an alternative pathway towards a clock based on a nuclear transition. The sole candidate for such a clock with an excitation energy that is within the reach of present laser systems is the thorium isotope with $A=229$. Complementary to existing concepts (for a recent review, cf. [2]) in HiThor it is foreseen to use $^{229}\text{Th}^{q+}$ -ions in their highest charge states, in particular H-like ($q = 89+$) and bare ($q = 90+$) ions. Here, $^{229}\text{Th}^{89+}$ is the door-opener for further developments since it exhibits the unique mechanism of nuclear hyperfine mixing (NHM) [3] where, induced by the strong magnetic field due to the 1s electron, the nuclear decay is vastly accelerated by 5 to 6 orders of magnitude compared to the bare nucleus. As a consequence, also the probability for laser excitation is correspondingly enhanced.

HiThor rests on 3 pillars: (1) production, accumulation and first experiments to experimentally verify and characterize NHM in the storage ring ESR of GSI, (2) deceleration of and first precision experiments with trapped $^{229}\text{Th}^{q+}$ ions at the SPECTRAP set-up on the HITRAP platform, (3) development of powerful and tuneable VUV frequency comb. Eventually, and in the follow up phase of HITHOR, the realization of a quantum logic spectroscopy (QLS) laboratory at HITRAP may result in uttermost precision.

In 2025, at the ESR a beamtime was conducted with 2 major goals, firstly, the production, unambiguous identification, separation, accumulation and deceleration of $^{229}\text{Th}^{89+}$, and, secondly, in-ring laser spectroscopy of $^{229}\text{Th}^{89+}$, in order to evidence NHM.

$^{229}\text{Th}^{89+}$ is an unstable nucleus that needs to be artificially synthesized. This was accomplished by impinging a high-energy ^{238}U primary beam with more than 900 MeV/u on a dedicated composite production / stripper target that consists of a thick Al block and a thin Cu stripper. With this combination a high yield of the wanted H-like ions could be obtained and at the same time contaminants from the isobar $^{229}\text{Pa}^{89+}$ largely suppressed. After the production the hot cocktail of isotopes was subsequently injected into the ESR, stochastically cooled and accumulated using an RF stacking approach. This already cleans the stored beam of many unwanted species. After deceleration to about 190 MeV/u

the beam was electron cooled and purified using mechanical scrapers in the ring. Using this approach, we could prepare about $4\text{--}6 \times 10^4$ $^{229}\text{Th}^{89+}$ ions ready for the laser experiment. This is about an order of magnitude smaller than initially expected. The reasons are in parts due to a rather moderate primary beam intensity due to problems of the SIS cooler, and parts due to very unstable operation of a long list of accelerator devices in the transfer beamlines and at the ESR ring it-self (RF, magnets etc.) largely due to the very high temperatures at the time of the experiment. The experimental set-up including data acquisition, laser system and detectors worked very well, however, given the low ion beam intensity and unstable boundary conditions, the laser resonance could not be found.

A new attempt was originally scheduled for autumn 2026 but had to be canceled: Due to a severe fire at GSI no operation with heavy ion beams at SIS/ESR will be possible for the next 3 to 4 years. Of course, this severe incident has a strong impact on the whole HiThor project since the ESR related experimental work has to be postponed. In order to mitigate the problem, major parts of HiThor such as the development of the VUV frequency comb, a VUV laser beamline on the HITRAP platform or the built-up of the QLS laboratory can be realized in the meantime. These works will be complimented with commissioning of the equipment at SPECTRAP and in the QLS lab with surrogate ions from the local EBIT ion sources on the HITRAP platform. In parallel, we have imitated the development of a dedicated ^{232}Th ion source at the UNILAC to be used as a future complementary primary beam at GSI alongside with ^{238}U . With ^{232}Th we expect an enhancement of the $^{229}\text{Th}^{q+}$ secondary-ion yield by more than two or more orders of magnitude and thus have ideal conditions to pick up experimental work with $^{229}\text{Th}^{89+}$ at the ESR.

This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (Grant agreement No.101142155).

References

- [1] <https://cordis.europa.eu/project/id/101142155>; <https://doi.org/10.3030/101142155>.
- [2] A. Derevianko *et al.*, arXiv:2606.11048; <https://doi.org/10.48550/aXiv.2606.11048>.
- [3] V. Shabaev *et al.*, Phys. Rev. Lett. **128**, 043001 (2022).

^{*}c.brandau@gsi.de

Development of a method for handling disturbed temperature information in Magnetic Metallic Calorimeter data

D. A. Schnauß-Müller^{*1,2,3}, J. H. Walch^{1,2,3}, M. O. Herdrich^{2,3}, G. Weber^{2,3}, and Th. Stöhlker^{1,2,3}

¹IOQ, FSU Jena, 07743 Jena; ²HI-Jena, Fröbelstieg 3, 07743 Jena; ³GSI, 64220 Darmstadt

Spectroscopy with Magnetic Metallic Calorimeters (MMCs) can overcome limitations of traditional X-ray spectroscopy methods. They allow measurements with the flexibility of semiconductor detectors while providing a resolution approaching crystal spectrometers. A new MMC detector system was deployed to study strong field QED effects during the GSI beamtime 2025. The high sensitivity makes the system vulnerable to environmental disturbances. In this contribution we present first attempts to mitigate artifacts in the data.

Photons absorbed in the absorber of an MMC detector cause a temperature increase which is measured by a magnetisation change of a paramagnetic sensor material. The resulting signal amplitude is proportional to the energy of the absorbed photon. But variations in the temperature of the detector can cause a change in the signal amplitude as well. In order to utilise the full potential of MMCs, it is crucial to mitigate even small temperature changes. In order to do this it is necessary to have a precise information about the temperature of the detector. Since the detector itself basically is a thermometer, it is possible to construct a few pixels of the array in a way that they encode the temperature in a DC offset on the signal. This allows to correct the signal amplitudes of detected photons for temperature changes.

While this method is well established [1], it relies on a good information about the temperature. Since the output of the temperature sensitive pixels is not absolute, the given information is only a proxy for the temperature and not an actual value. Due to the readout scheme it is possible that the value of this proxy jumps without an actual temperature change. Those jumps are a result of the periodic response of the two stage superconducting quantum interference device (SQUID) readout system. The origin of the jumps can be photons hitting part of the readout system, or external disturbances that are coupled into the system. While a jump in a single temperature sensitive pixel can be easily identified and corrected for, it is more difficult to deal with events, where multiple of the temperature sensitive pixels produce a non continuous temperature signal simultaneously.

During the analysis we encountered two different types of jumps. The first type is a jump of one whole flux quantum in the readout SQUID. Those jumps produce a jump of the same DC offset. When calculating the difference between two consecutive temperature information and looking for peaks in the resulting distribution, those jumps can be easily identified and their size determined.

The second type are smaller jumps which can originate from changing operation point in readout system. To clearly identify those jumps one can leverage another feature of the data. During the experiment a multitude of radioactive sources were used to continuously calibrate the detector. By identifying those peaks in the data, one can calculate the deviation of events from the expected peak position. This deviation is a result of changing detector temperature and provides an additional information. By looking at the correlation of this data with the temperature proxy one can identify time intervals where the information is consistent. To do this we plot (Figure 1) the data against each other and rotate the resulting distribution to align the correlation with one of the axis.

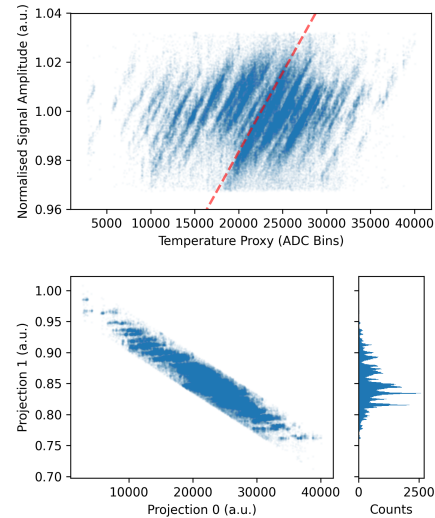


Figure 1: Amplitude dependency of the temperature proxy.

The projection on this axis is now evaluated over time where the python library ruptures [2] can be used to identify steady time areas. By correcting and then rotating back the data, we can mitigate the effect of those jumps and generate a consistent temperature information for the whole data set. By then comparing the different temperature information from different temperature sensitive pixels, we can identify remaining outliers and correct for them as well.

This work was conducted in the framework of the SPARC collaboration, experiment E134 of FAIR Phase-0 supported by GSI.

References

- [1] S. Allgeier, Dissertation, Universität Heidelberg (2024).
- [2] C. Truong *et al.*, Signal Processing **167**, 107299 (2020).

*daniel.aaron.mueller@uni-jena.de

MMC Signal Artifact Rejection Utilizing Machine Learning

M.O. Herdrich^{*1,2,3}, T. Mattis⁴, and Th. Stöhlker^{1,2,3}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²IAP, FSU Jena; ³GSI, Planckstr. 1, 64291 Darmstadt, Germany;

⁴HPI, Prof.-Dr.-Helmert-Str. 2-3, 14482 Potsdam, Germany

Metallic Magnetic Calorimeters (MMCs) are highly sensitive detectors used for high-precision X-ray spectroscopy. Their sensitivity makes them susceptible to artifacts in the recorded data. This work presents a novel approach to artifact rejection in MMC data using Machine Learning (ML) techniques. The method involves an auto-label-discovery scheme, followed by training a classification model to identify artifacts. This approach has the potential to significantly speed up and eliminate human bias of the filtering process.

MMCs have been established as a powerful tool for high-precision X-ray spectroscopy and successfully applied in various experiments in the past (e.g. in the context of Lamb-shift measurements of highly charged ions at GSI/FAIR [1, 2]). However, due to their high sensitivity, MMCs are also susceptible to external sources of noise, which can lead to the presence of artifacts in the recorded data. These artifacts, together with other deformations of the pulse shape – e.g., from direct sensor hits – can significantly affect the quality and reliability of the results obtained from MMC measurements. Therefore, it is crucial to develop effective methods for identifying and rejecting malformed pulses. Traditionally, artifact rejection in MMC data has been performed using rule-based approaches, which rely on predefined criteria and thresholds. This requires a detailed understanding of the signal shape and time-consuming analysis of the parameter space.

A novel approach to artifact rejection in MMC data is the use of ML techniques, which learn complex patterns and identify and reject artifacts in the data, without the need for predefined criteria. To implement this approach, though, the utilized ML models first need to be trained on a representative dataset of both pulse shapes stemming from real photon events, and artifacts, which are labeled accordingly. Labeling the data manually can be a time-consuming and labor-intensive process, especially when dealing with large datasets. Therefore, an efficient method for auto-label-discovery of the data is required.

The method proposed in this work is based on several steps. First, a combination of linear – e.g., principle component analysis (PCA) – and non-linear – e.g., uniform manifold approximation and projection (UMAP) – dimensional reduction techniques is applied to the data, with the goal of finding a projection that captures the highest variance in both the local and global structure of the data. The resulting low dimensional embedding of the data can then be analyzed by a clustering algorithm – e.g., hierarchical density-based spatial clustering (HDBSCAN) – to identify clusters of similar events. The largest cluster corresponds

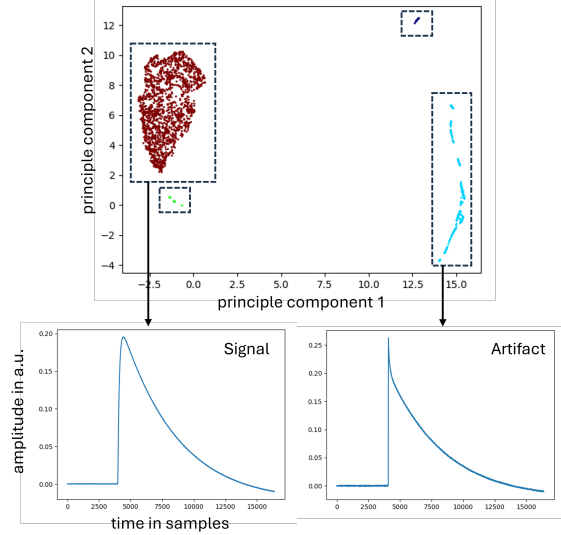


Figure 1: The upper part of the figure shows the result of the dimensional reduction and clustering process applied to a single channel of the MMC data recorded during the E135 experiment. Each point in the plot represents an event, with the color indicating the cluster assignment. The lower part of the figure shows the average signal shape for two representative clusters.

to real photon events, while smaller clusters are comprised of the various occurring artifacts (see for example figure 1). Thus, by including the results of several trivial pre-filters, a set of training labels for a subset of the data can be generated. Finally, a classification model – e.g., Random Forest – can be trained on the labeled data to automatically identify and reject artifacts in the full dataset. This has been successfully applied to the data recorded during the E135 experiment at GSI and shows promising results for example for the generation of a template signal for the optimal filtering of the data.

In the future, we plan to include a pre-experiment period to train the ML model on a representative dataset of both real photon events and artifacts. This will allow us to have a well-trained model ready for use during the actual experiment. The classifier model can then be included in the online analysis toolchain to enable more efficient and reliable real-time artifact rejection during data acquisition.

References

- [1] M. O. Herdrich, *Ph.D. Thesis*, FSU Jena (2023).
- [2] Ph. Pfäfflein *et al.*, *Phys. Rev. Lett.* **134** (2025) 153001

*m.o.herdrich@hi-jena.gsi.de

Investigation of Beam Lifetime and Radiative Recombination Rate Coefficient of U^{91+} ions stored in CRYRING

A. Turelli Khusainova^{*1,2}, G. Weber^{1,3}, D. A. Schnauß-Müller^{1,2}, J. H. Walch^{1,2}, M. O. Herdrich^{1,3}, M. Lestinsky³, C. Krantz³, and Th. Stöhlker^{1,2,3}

¹HI Jena; ²IOQ, FSU Jena; ³GSI, Darmstadt

We report on an investigation of ion beam lifetimes and charge-exchange rate of U^{91+} ions interacting with electrons in the electron cooler of CRYRING. The contributions of collisions with the residual gas and radiative recombination (RR) in the electron cooler to the beam lifetime are disentangled. Moreover, the RR rate coefficient is evaluated.

For experiments using highly-charged ions at relatively low beam energies the beam lifetime can be a limiting factor as beam losses due to electron capture from the residual gas strongly increase with decreasing ion velocity [1]. In this report, data on beam lifetimes as well as charge-exchange rates from a 2025 beam time using decelerated, highly-charged ions U^{91+} in the low-energy storage ring CRYRING at a kinetic energy of 11.5 MeV/u is investigated.

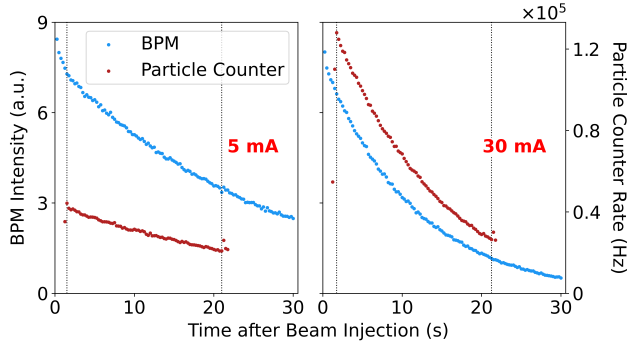


Figure 1: Signals of the beam profile monitor (BPM) and the particle counter as a function of time for two different electron cooler currents. The particle counter is moved into and out of the beam line, indicated by the dashed line. Both signals are proportional to the ion beam intensity.

Fig. 1 presents the intensity of the beam profile monitor (BPM) of CRYRING as well as hits of down-charged ions on a particle counter located downstream of the electron cooler as a function of time and for two different electron cooler currents. The latter is mainly the result of radiative recombination (RR) between stored ions and cooler electrons. Both the BPM signal and the rate of down-charged ions is expected to exhibit a proportional relation to the ion beam intensity I , thus their decrease over time t reveals the beam lifetime $\tau = 1/\lambda$ according to $I(t) = I(0) \cdot e^{-t/\tau}$.

By measuring the electron cooler current it is possible to disentangle the beam loss contributions from charge-changing collisions in the residual gas and the contribution

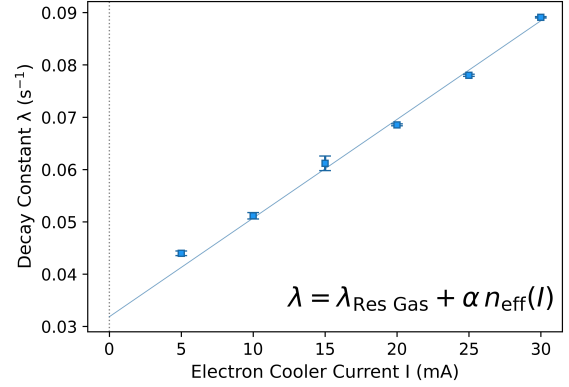


Figure 2: Decay constant of the ion beam as a function of the electron cooler current. α is the RR rate coefficient. n_{eff} is obtained scaling the electron density n_e by the ratio of the interaction length and the circumference of the storage ring. Extrapolating to $n_{\text{eff}} = 0$ yields an estimate for the beam loss solely due to collisions with the residual gas.

of RR in the electron cooler. This is illustrated in Fig. 2. From this we estimate a beam lifetime solely due to the residual gas of about 30 s, which demonstrates a clear improvement of the vacuum conditions in CRYRING compared to the 2021 value of 15 s for the same ion species at a very similar beam energy of 10.25 MeV/u.

Moreover, both the beam lifetimes as a function of electron cooler current as well as the rate in the particle counter provide access to the RR rate coefficient. The resulting values are $3.316 \cdot 10^{-7} \text{ cm}^3/\text{s}$ and $3.288 \cdot 10^{-7} \text{ cm}^3/\text{s}$ respectively. The good agreement of both values is a strong indicator that now the particle counter records close to 100 % of all ions that underwent RR in the cooler. This is a big improvement compared to roughly 60 % efficiency in 2021. It is noteworthy that the well-known enhancement of the rate coefficient at close to zero collision velocities between ions and electrons as it is the case in the electron cooler is still not fully understood [2]. In the present case, an enhancement factor of 1.65 is found compared to the prediction of basic RR theory.

This work was conducted in the framework of the SPARC collaboration, experiment E134 of FAIR Phase-0 supported by GSI.

References

- [1] F. M. Kröger *et al.*, Phys. Rev. A **102**, 042825 (2020).
- [2] K. Q. Shi *et al.*, Phys. Rev. A **111**, 042828 (2025).

*aliya.turelli.khusainova@uni-jena.de

Commissioning of a Novel Compton Polarimeter in Telescope Configuration

T. Over-Winter^{*1,2,3}, A. Kononov², T. Krings⁴, W. Middents^{1,2,3}, U. Spillmann², G. Weber^{1,2}, and Th. Stöhlker^{1,2,3}

¹HI Jena, Germany; ²GSI, Darmstadt, Germany; ³IOQ, FSU Jena, Germany; ⁴FZ Jülich, Germany

Fundamental radiative processes in the hard x-ray regime can be investigated with Compton polarimetry. Optimized for photon energies between 60 keV and 1 MeV a new polarimeter with two double-sided segmented planar crystals was developed within the SPARC collaboration. For this, an already used detector system with a Si(Li) crystal was upgraded by an additional HPGe crystal. A first test of the novel setup is planned in a scattering experiment at a high-intensity γ -source.

Compton polarimetry is an effective tool to determine the (linear) polarization of a hard x-ray photon beam. This allows for deep insight in the directionality and anisotropy of radiative processes in the hard x-ray regime (>10 keV). The anisotropy of Compton scattering distribution with respect to the electric field vector of the analyzed photon beam is exploited to determine the polarization. For this purpose, the entirety of various Compton events need to be resolved. This is realized by a simultaneous registration of the recoil electron and absorption of the scattered photon with precise positional and energy resolution. Dedicated Compton polarimeters, which are based on 2D sensitive semiconductor crystals have been developed for this purpose within the SPARC collaboration [1]. The latest advancement is a new Compton polarimeter in telescope configuration consisting of two semiconductor crystals, both segmented on front and back side. This detector setup is based on an already used Compton polarimeter [2], which was upgraded by the additional installment of a HPGe crystal behind the already installed Si(Li) crystal.. Due to the additional detector crystal, the effective energy range of the Compton polarimeter is extended from previously 200 keV up to the MeV range. For a detailed description of the novel detector see [3].

The main advancement of this detector setup is the increased detection efficiency of Compton scattering events across the above mentioned energy range. This is achieved from two factors. First, the probability for photon absorption in germanium is higher than in silicon, especially for photon energies above a few 100 keV. Secondly, the setup of two crystals allows to measure Compton scattering events in new geometries. Beside the case where the Compton scattered photon and the recoil electron are both measured in either the Si(Li) or the HPGe crystal, it is now possible to detect the Compton scattered photons with the HPGe crystal which escaped from the Si(Li) crystal and vice versa.

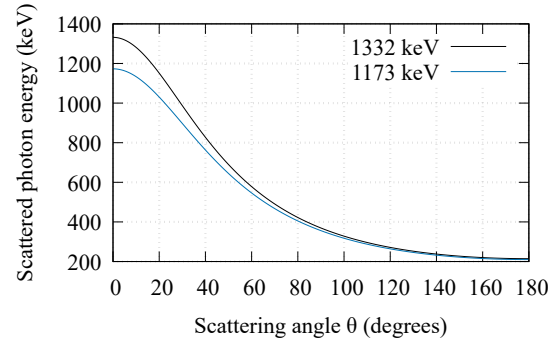


Figure 1: Energy of the Compton scattered photons for the initial photon energies of the two γ -lines at 1173 keV and at 1332 keV.

A first experiment to test the performance of the new Compton polarimeter, especially of the extended energy range, is planned. To perform an experiment at these high energies, a high-intensity γ -source out of ^{60}Co was chosen to deliver the desired photon energies. ^{60}Co has two prominent γ -lines at 1173 keV and at 1332 keV. The source targeted is a 40 cm long rod source with an approximated activity of several TBq and located at the Institute of Experimental Physics II of the Justus Liebig university in Gießen, Germany. In the planned experiment, the photons emitted by the γ -source will be scattered from a solid target, e.g. a gold foil, and the linear polarization of the scattered photons will be measured with the new Compton polarimeter in telescope configuration. By analyzing the Compton scattered photons under different scattering angles a broad energy range can be covered. It is planned to use scattering angles between 40° and 90° . This results in an energy range of roughly 350 keV and 800 keV (see Figure 1) in which the Compton polarimeter can be tested. The measurable degree of linear polarization varies between approximately 0.2 and 0.4.

References

- [1] Th. Stöhlker *et al.*, Nucl. Instrum. Methods Phys. Res. B **365**, 680 (2015).
- [2] M. Vockert *et al.*, Nucl. Instrum. Methods Phys. Res. B **408**, 313 (2017).
- [3] W. Middents *et al.*, HJAR **44** (2023).

*t.over@hi-jena.gsi.de

THEORY

Impact of background field localization on vacuum polarization effects

Carl Marmier^{1,2,3}, Nico Seegert^{2,3}, and Felix Karbstein^{*2,3}

¹*École Normale Supérieure Paris-Saclay, France;* ²*Helmholtz Institute Jena, Germany;* ³*Theoretisch-Physikalisches Institut, FSU Jena, Germany*

We aim at insights about how localization of the background field impacts nonlinear quantum vacuum signatures probed by photons in purely magnetic, electric and crossed fields. The starting point of our study are the one-loop results for the Heisenberg-Euler effective action and the photon polarization tensor in quantum electrodynamics (QED) evaluated in a uniform constant electromagnetic field. As is well known and often employed, within certain restrictions these results also allow for the reliable analysis of vacuum polarization effects in slowly varying background fields. Here, our main interest is in manifestly non-perturbative effects. To this end, we make use of the fact that for the particular case of background field inhomogeneities of Lorentzian shape with $0 \leq d \leq 3$ inhomogeneous directions analytical insights are possible. We study the scaling of conventional nonlinear QED signatures, such as probe-photon polarization flip and probe-photon induced electron-positron pair production, with relevant parameters. Special attention is put on the d dependence of the considered effects.

Charged particle-antiparticle fluctuations give rise to effective interactions between electromagnetic fields. Within the Standard Model of particle physics these are mainly governed by QED, i.e., are driven by virtual electrons and positrons. The fluctuations in particular affect the propagation of probe photons (four-potential a^μ) sent through strong macroscopic electromagnetic fields (field strength tensor $F \equiv F^{\mu\nu}$) via the photon polarization tensor $\Pi^{\mu\nu}$. The latter encodes vacuum fluctuation mediated corrections to photon propagation at linear order in the fine-structure constant α and beyond. In position space, the effective action at quadratic order in a^μ relevant for the study of probe photon propagation effects can be expressed as [1]

$$\Gamma[a] \Big|_{\sim a^2} = -\frac{1}{4} \int_x f_{\mu\nu}(x) f^{\mu\nu}(x) - \frac{1}{2} \int_{x'} \int_x a_\mu(x') \Pi^{\mu\nu}(x', x|F) a_\nu(x),$$

with probe field strength tensor $f^{\mu\nu}(x) = \partial^\mu a^\nu - \partial^\nu a^\mu$. Here, the polarization tensor specifically mediates an – in general non-local – interaction between in- and outgoing probe photons.

Currently, only one-loop results for the photon polarization tensor in the presence of an external electromagnetic field F are known explicitly, namely in uniform constant and plane-wave backgrounds. In momentum space the photon polarization tensor is conventionally expressed

as $\Pi^{\mu\nu}(k', k|F)$, where $k' \equiv k'^\mu$ and $k \equiv k^\mu$ denote the four-momenta of the in and out going photon, respectively. We emphasize that $\Pi^{\mu\nu}(k', k|F)$ does not feature any explicit x dependence via $F = F(x)$ in inhomogeneous fields because its derivation involves an integration over x . The vacuum-fluctuation-induced effective couplings to $F(x)$ generically break the translational invariance of the vacuum and thereby result in a finite overlap between in and out states with $k'^\mu \neq k^\mu$. Moreover, these may change the polarization properties of probe light because for two polarization vectors $\epsilon^\mu(k)$, $\epsilon_\perp^\mu(k)$ fulfilling $\epsilon_\perp^{*\mu}(k) \epsilon_\mu(k) = 0$ the forward amplitude $\epsilon_\perp^{*\mu}(k) \Pi_{\mu\nu}(-k, k) \epsilon^\nu(k)$ can be non-vanishing.

In Ref. [2], we analyzed how the localization of the background field influences the scaling of the photon polarization tensor with various parameters relative to the well-studied constant-field results. To this end, we focused on parameter regimes where reliable approximate results can be obtained and limited our analysis to background field inhomogeneities of Lorentzian shape with $0 \leq d \leq 3$ inhomogeneous directions, for which closed-form calculations are possible [3, 4].

We are convinced that such a study is very relevant, because it can provide us with important new insights in phenomena that are inaccessible with constant-field and plane-wave studies. This becomes particularly evident for electromagnetic fields reaching near or above critical peak field strengths: especially in infinitely extended, constant electromagnetic fields, the regimes of perturbative weak and non-perturbative strong fields are conventionally clearly separated and amount to two complementary limits. Conversely, probe light sent through localized inhomogeneous field configurations reaching non-perturbative peak field strengths inevitably experience both perturbative and non-perturbative field strengths. As to be expected, this results in modifications of the strong-field scaling of quantum vacuum phenomena that affect the propagation of probe light.

This work has been funded by the DFG under Grant No. 416607684 within the Research Unit FOR2783/2.

References

- [1] W. Dittrich and M. Reuter, *Lect. Notes Phys.* **220**, 1-244 (1985).
- [2] C. Marmier, N. Seegert and F. Karbstein, *Phys. Rev. D* **111**, 016005 (2025).
- [3] H. Gies, F. Karbstein and N. Seegert, *New J. Phys.* **15**, 083002 (2013).
- [4] F. Karbstein, *Phys. Rev. D* **95**, 076015 (2017).

*f.karbstein@hi-jena.gsi.de

Limitations of the paraxial beam model in the study of quantum vacuum signals

Felix Karbstein^{*1,2} and Fabian Schütze^{1,2}

¹Helmholtz Institute Jena, Germany; ²Theoretisch-Physikalisches Institut, FSU Jena, Germany

Studies of nonlinear quantum vacuum signals often model the driving laser fields as paraxial beams. This in particular holds for analytic approaches. While this allows for reliable predictions in most situations, there are also notable exceptions. A prominent example is the overestimation of the polarization-flipped signal photon yield in the collision of two equally focused, parallel polarized laser beams by a factor of about six. In the present work, we identify the origin of this deficiency and devise a strategy to obtain accurate closed-form expressions also in cases challenging the conventional (leading order) paraxial beam model. We demonstrate the potential of our approach on the example of two linearly polarized laser pulses colliding at a generic collision angle.

Quantum vacuum fluctuations give rise to effective nonlinear couplings between macroscopic electromagnetic fields [1]. So far, these nonlinearities could not be verified in a controlled laboratory experiment. However, recent progress in laser technology has brought their experimental detection in reach. All-optical signatures of quantum vacuum nonlinearity in laser beams collisions can be conveniently analyzed within the vacuum emission picture. This provides direct access to the directional emission characteristics and polarization properties of the signal far outside the interaction region of the laser fields. To be experimentally accessible, the signal needs to differ in key-parameters, such as propagation direction, frequency or polarization, from the background of the driving *laser photons*. In the context of the vacuum emission picture, the most advanced laser beam model numerically evolves the laser fields from an input configuration according to the linear Maxwell equations in vacuum [2]. On the other hand, analytical considerations typically model the laser beams as zeroth-order paraxial Gaussian beams supplemented with a temporal pulse envelope [3]. It has been shown that this simplification allows for an accurate prediction of quantum vacuum signals in various experimentally relevant scenarios, like vacuum birefringence measurements. However, by unveiling that it significantly overestimates the yield of polarization-flipped signal photons in the collision of two equally focused, parallel polarized laser beams, [2] identified a serious issue; see Fig. 1. Exactly the same problem arises for perpendicular polarized laser beams.

In Ref. [4] we clarified the origin of this deficiency and to put forward a strategy allowing to overcome it while retaining the possibility of analytical insights. For simplicity,

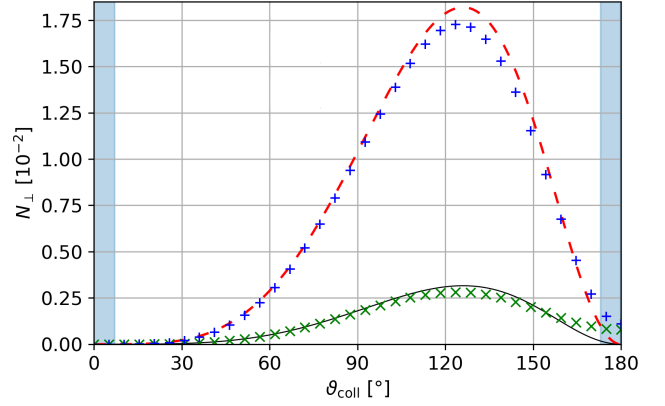


Figure 1: Number of polarization-flipped signal photons $N_{\perp}$ as a function of the collision angle ϑ_{coll} for colliding laser fields that are parallel polarized in the focus. The green crossed ($\times$) data points are obtained from a fully numerical calculation modeling the laser beams as solutions of the linear Maxwell equations. The blue crossed ($+$) data points are for the collision of two pulsed Gaussian beams at zeroth order in the paraxial approximation. The red dashed and black solid lines are plots of the analytical approximation devised in [4] at leading order and next-to-leading order. The values of ϑ_{coll} outside the regime of validity of our analytic approximation are shaded in blue.

in this work we limited our discussion to two linearly polarized laser beams colliding at an angle ϑ_{coll} and only focused on the dominant polarization-flipped signal component, which originates in a quasi-elastic scattering process. Our approach can be readily and systematically extended to higher orders in the paraxial approximation, and be generalized to the collision of more than two laser beams. We are convinced that a well-controlled analytical approach as put forward here will be essential for understanding and unveiling the physical processes underlying the quantum vacuum signatures predicted by first-principles numerical approaches.

This work has been funded by the DFG under Grant No. 416607684 within the Research Unit FOR2783/2.

References

- [1] W. Heisenberg and H. Euler, Z. Phys. **98**, 714 (1936).
- [2] A. Blinne, H. Gies, F. Karbstein, C. Kohlfürst and M. Zepf, Phys. Rev. D **99**, 016006 (2019).
- [3] H. Gies, F. Karbstein and C. Kohlfürst, Phys. Rev. D **97**, 036022 (2018).
- [4] F. Karbstein and F. Schütze, Phys. Rev. D **111**, 096026 (2025).

*f.karbstein@hi-jena.gsi.de

Self-organized criticality in a relativistic Yukawa theory

H. Gies^{*1,2} and M. Picciani²

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²TPI, FSU Jena

Analogies between the dynamics of quantum fields and statistical physics have been a driving force for the development of both fundamental physics and the theory of emergent critical phenomena. The present project has identified for the first time a relativistic quantum field theory that exhibits self-organized criticality, a phenomenon so far only known from statistical physics and complex systems subject to external driving. Our Yukawa-type model features a natural scale separation and universal long-range observables. We determine nonperturbative estimates for the latter including the scalar and fermionic mass gaps.

Yukawa models are ubiquitous in quantum field theory and statistical physics, including nuclear physics, condensed matter physics, many-body atomic physics, and elementary particle physics. They often arise as effective low-energy theories of more fundamental interactions, which is also related to the fact that the massive perturbation of the scalar excitations is a relevant operator in the renormalization group (RG) sense; i.e. a large scale separation between a microscopic UV scale and the long-range observables requires a fine-tuning of the bare mass parameter. In the particle-physics context, this is known as the hierarchy or naturalness problem [1].

Our project [2] has identified a Yukawa-type model involving a real scalar field ϕ and a relativistic Luttinger fermion ψ , a novel fermionic field with quadratic derivative kinetic term. The interaction part of the action is given by

$$S_{\text{int}} = \int_x \left[-h\phi\bar{\psi}\gamma_{11}\psi + \frac{1}{2}m^2\phi^2 + \frac{\lambda}{8}\phi^4 \right], \quad (1)$$

where γ_{11} is a matrix that anticommutes with all elements of the Abrikosov algebra of the Luttinger fermions. The model exhibits intriguing properties rather different from conventional Yukawa models: (1) The fermions have a lower canonical dimension, (2) their self-interactions are perturbatively renormalizable in $d = 3 + 1$ dimensions, (3) can be asymptotically free, (4) the scalar field develops a large anomalous dimension, such that (5) the scalar mass term m^2 becomes an RG marginal operator.

A nonperturbative RG analysis of the model reveals that all other couplings such as the Yukawa coupling h and the scalar coupling λ are irrelevant and approach a non-trivial (partial) fixed point towards the infrared. This feature is reminiscent of self-organized criticality [3] known from statistical systems. The role of the external driving in such statistical models is now played by the marginal scalar mass term, which is naturally driven to criticality $m^2 \rightarrow 0$ by the RG flow.

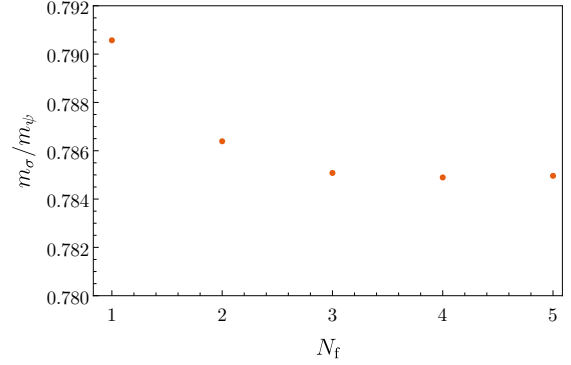


Figure 1: Ratio between the scalar σ -type mass m_σ and the fermion mass m_ψ as a function of the flavor number N_f .

Because of RG marginality, the scalar mass runs only logarithmically such that a large scale separation between the microscopic UV scale and the long-range observables can be achieved naturally without fine-tuning. The low-energy phase is always in the symmetry-broken phase, exhibiting a nonvanishing scalar condensate and a fermion mass gap, as well as a scalar σ -type excitation with a mass gap m_σ . All dimensionless ratios are universal and can be predicted from the nonperturbative RG flow.

As an example, we plot the ratio between the scalar σ -type mass m_σ and the fermion mass m_ψ as a function of the fermion flavor number N_f in Fig. 1. From a viewpoint where the scalar can be interpreted as a bi-fermionic bound state, we conclude that the mass ratio near $m_\sigma / m_\psi \simeq 0.79 < 2$ points to a deeply bound relativistic state where the binding energy exceeds the mass gap of a single fermionic constituent.

Our model is the first example of a relativistic quantum field theory featuring self-organized criticality. The existence of such examples has been envisaged for a long time [4], but it was not clear whether such theories can be formulated in a generic way without tuning of parameters and matter content. Our model is a proof of principle that such theories do exist.

The authors acknowledge funding from the DFG.

References

- [1] G. 't Hooft, NATO Sci. Ser. B **59**, 135-157 (1980).
- [2] H. Gies and M. Picciani, Int. J. Theor. Phys. **64**, no.10, 282 (2025).
- [3] P. Bak, C. Tang and K. Wiesenfeld, Phys. Rev. A **38**, 364-374 (1988).
- [4] S. Bornholdt and C. Wetterich, Phys. Lett. B **282**, 399-405 (1992).

*holger.gies@uni-jena.de

Bound-state Compton scattering of linearly polarized photons

Anna Maiorova^{*1,2}, Wilko Middents^{1,2,3}, Jonas Sommerfeldt^{4,5}, Nick M. Mayer^{6,7}, Andrey Surzhykov^{6,7}, Stephan Fritzsche^{1,2,8}, and Thomas Stöhlker^{1,2,3}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²GSI, Darmstadt, Germany; ³IOQ, FSU Jena, Germany; ⁴Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, Paris, France; ⁵MPIK, Heidelberg, Germany; ⁶PTB, Braunschweig, Germany; ⁷TU Braunschweig, Germany; ⁸TPI, FSU Jena, Germany

We present a theoretical study of Compton scattering of X- and γ -rays by a K -shell electron. We investigate the double-differential cross section and polarization of the scattered photons for linearly polarized incident radiation within the framework of the scattering matrix (S -matrix) theory and the relativistic Green's function approach. Furthermore, the S -matrix results are compared with predictions of the free-electron (FEA) and impulse (IA) approximations.

Compton scattering of a photon by a bound electron is one of the fundamental processes of light-matter interaction. In this process, the photon is scattered with a lower frequency, while part of its energy is used to eject the electron [1]. Compton scattering finds important applications in medicine, materials science, astrophysics, and atomic and plasma physics. Of particular interest in the present work is the sensitivity of the Compton cross section and, especially, the polarization of the scattered photons to the linear polarization of the incident radiation. These investigations were motivated by the recent development of polarization-sensitive detectors as well as the availability of highly polarized X-ray beams at modern synchrotron facilities, such as PETRA III at DESY in Hamburg. Detailed numerical calculations have been performed for Compton scattering by a K -shell electron in hydrogen-like Ne^{9+} (Fig. 1) and Pb^{81+} ions [2].

In our study, special attention is paid to comparing the S -matrix calculations with the predictions of the IA, which is widely employed for simplified calculations of Compton scattering. As seen from Fig. 1, the S -matrix and IA results generally agree well in the vicinity of the Compton peak. However, away from the peak, the two approaches begin to diverge. This discrepancy becomes more pronounced as the kinematic parameter p_b/q increases. This parameter, defined as the ratio of the characteristic momentum of the bound electron to the photon momentum transfer, is traditionally used to characterize the strength of electron binding effects [3]. The figure clearly demonstrates that for large p_b/q values, the IA significantly underestimates the cross section and overestimates the polarization of the scattered photons compared to the rigorous S -matrix calculations. These findings clearly highlight the importance of an accurate accounting of electron binding effects for a precise description of bound-state Compton scattering.

In conclusion, our relativistic S -matrix analysis establishes the limitations of standard approximation schemes,

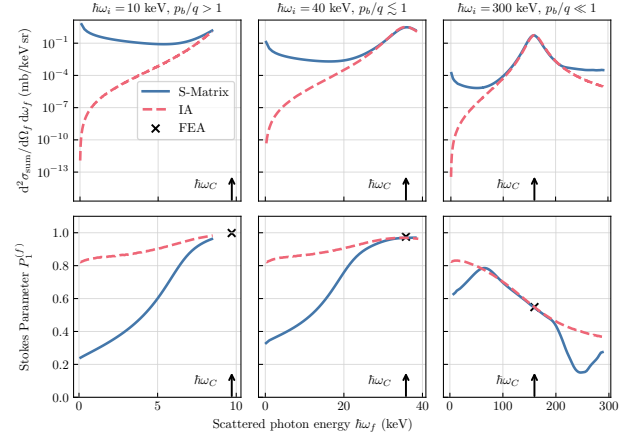


Figure 1: Double-differential Compton cross section (upper panels) and linear polarization (lower panels) for photons scattered by hydrogen-like neon, $\text{Ne}^{9+}(1s)$, at the scattering angle $\theta_f = 120^\circ$. Results of the relativistic S -matrix (blue solid line) and impulse approximation (red dashed line) calculations are compared with predictions of the free-electron model (cross). The figure is from Ref. [2].

such as the IA, in describing Compton scattering by strongly bound electrons. The demonstrated sensitivity of both the cross section and the polarization of scattered photons to electron binding effects underscores the need for rigorous theoretical models in interpreting future experiments. These results are particularly timely given the ongoing development of advanced polarization-sensitive detectors and the availability of high-brilliance radiation at modern light sources. Looking forward, the developed approach can be extended to investigate electron screening corrections, as well as to explore Compton scattering of vortex photon beams.

References

- [1] C.-K. Qiao, J.-W. Wei, and L. Chen, *Crystals* **11**, 525 (2021).
- [2] J. Sommerfeldt, N. M. Mayer, A. Maiorova *et al.*, <https://arxiv.org/abs/2604.14748>
- [3] P. M. Bergstrom, T. Surić, K. Pisk, and R. H. Pratt, *Phys. Rev. A* **48**, 1134 (1993).

*a.maiorova@gsi.de

Maximally Entangled Orbital Angular Momentum States via Path Identity

R. Bernecker^{*1,2}, S. Fritzsche^{1,2}, and B. Baghdasaryan³

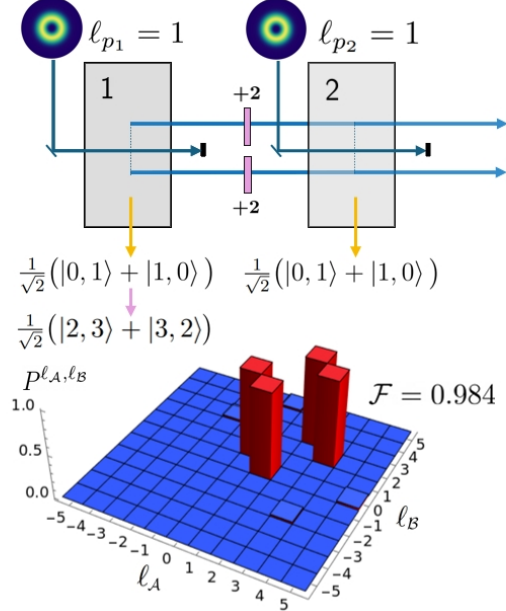
¹HI Jena; ²TPI, FSU Jena; ³IAP, FSU Jena

High-dimensional entangled photon states are a crucial resource for secure and high-capacity quantum communication and future quantum networks. We investigate the preparation of maximally entangled orbital angular momentum (OAM) states using the concept of path identity, where photon pairs from multiple indistinguishable nonlinear sources interfere coherently. By combining path identity with spatial engineering of the pump-beam, we identify new strategies to create high-dimensional entangled states. Furthermore, we establish fundamental fidelity bounds for OAM-entangled states and show that our scheme exhibits a more favorable scaling of the accessible dimensionality than previous approaches. Based on these results, we propose an experimentally feasible scheme for the preparation of four-dimensional maximally entangled states.

Entangled photons carrying orbital angular momentum (OAM) provide access to a discrete, high-dimensional Hilbert space to encode quantum information and are promising for quantum communication, quantum networking, and distributed quantum computing. In spontaneous parametric down-conversion (SPDC), entangled photon pairs are produced when a pump beam interacts with a nonlinear medium. The resulting OAM distribution of the pair is generally nonuniform, which limits the direct preparation of maximally entangled states (MESs). Here, we address this challenge by combining path identity with spatial pump-beam engineering to tailor the OAM distribution of photon pairs.

Path identity relies on the coherent overlap of photon pairs originating from different nonlinear crystals [1]. If the pair creation process is made indistinguishable by maintaining coherence conditions [2], the quantum state becomes a coherent superposition of all possible pair-creation events. We developed a theoretical framework for such multicrystal configurations and investigated how OAM shifts induced by spiral phase plates, relative phase shifts, and relative pump powers can be exploited to tune the final quantum state [3]. In particular, we demonstrate that state preparation based on path identity can be equivalent to pump-beam engineering with a superposition of Laguerre-Gaussian modes.

A central result of this work is the identification of fundamental fidelity bounds for OAM-entangled states produced with pump modes of $\ell_p \geq 2$. We show that the conservation of OAM inevitably introduces additional OAM contributions that cannot be eliminated through optimizing the pump beam or the experimental configuration. As a result, maximally entangled target states with dimensions larger



$$|\psi_{\text{tar}}\rangle = \frac{1}{2}(|0, 1\rangle + |1, 0\rangle + |2, 3\rangle + |3, 2\rangle)$$

Figure 1: Sketch of a path-identity setup comprising two coherently pumped nonlinear crystals for the preparation of a four-dimensional maximally entangled OAM state. Here, ℓ_A and ℓ_B denote the OAM number of photons detected along paths $\mathcal{A}$ and $\mathcal{B}$, respectively. Each crystal triggers a Bell state in OAM. Since OAM provides a high-dimensional alphabet, the OAM values of the photon pair emitted by the first crystal can be shifted by $\Delta\ell = +2$. The resulting state, $|\psi_{\text{tar}}\rangle$, approximates the desired target state with near-unity fidelity.

than two cannot be prepared with unit fidelity in a single SPDC process.

For a setup consisting of n nonlinear crystals, we find that the optimal dimensionality scales as $d = 2n$. As a concrete example, we propose experimentally feasible two-crystal schemes for the preparation of maximally entangled ququart states ($d = 4$) with near-unity fidelity, see Fig. 1. Our results provide practical design principles for scalable sources of high-dimensional entanglement.

References

- [1] M. Krenn *et al.*, Phys. Rev. Lett. **118**, 080401 (2017).
- [2] J. Kysela *et al.*, Proc. Natl. Acad. Sci. U.S.A. **117**, 42 (2017).
- [3] R. Bernecker, B. Baghdasaryan, and S. Fritzsche, Phys. Rev. A **112**, 063701 (2025).

*richard.bernecker@uni-jena.de

Investigating laser pulse chirping for narrowband x-ray generation using time-frequency analysis

N. Larin^{*1} and D. Seipt¹

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany

Inverse Compton scattering (ICS) is a well-established mechanism of producing high brightness X-ray and γ -ray radiation. However, achieving the necessary large photon yield requires operation at relativistic laser intensities, which introduces ponderomotive broadening. This effect directly limits the desired spectral brightness. To mitigate this constraint and enhance the performance of ICS-based sources, chirped laser pulses have been proposed as a compensation strategy. In this work, we use novel time-frequency analysis method to gain insights into how different previously suggested chirping prescriptions work.

When an ultrarelativistic electron propagates through the intense laser pulse with $a_0 = eE/m\omega_0 \sim 1$ (E and ω_0 are the laser strength and frequency, correspondingly), it emits radiation with a distinct harmonic structure. The frequencies of the emitted harmonics in head-on collision is approximately given by

$$\omega_n(\eta) \approx \frac{4n\gamma^2\omega_0}{1 + \gamma^2\vartheta^2 + 4n\gamma\frac{\omega_0}{m} + a_{\text{rms}}^2(\eta)}, \quad (1)$$

where ϑ is the photon emission angle, n is the harmonic number and $a_{\text{rms}}(\varphi)$ is a root mean square of the field potential over the carrier period with $\eta = t - z$ is being a light-front time.

The time dependence of the ponderomotive potential $a_{\text{rms}}(\eta)$ results in a frequency chirp of the emitted radiation, leading to a significant broadening of the harmonics. To compensate this effect, frequency-chirping of the incident laser pulse has been proposed [1]. Analysis of the nonlinear Compton scattering amplitude has demonstrated that an ideal chirping prescription can, in theory, fully compensate for ponderomotive broadening [2]. While an ideal chirp is difficult to realize experimentally - since $\omega(\eta)$ in this case is a highly nonlinear function of time - a linear chirp is much more easily implemented. This linear prescription, given by $\omega(\eta) = \omega_0(1 + \beta\eta/\tau)$ has been shown to be highly effective as well [3, 4], despite the stark differences between the two approaches.

Since it was shown that various chirp prescriptions lead to the full or partial compensation of ponderomotive broadening, it is desirable to understand how they work and what are their differences and similarities. To do so, we study Husimi joint probability distribution (JPD) of ICS, which provides simultaneous access to the time-frequency structure of the emitted radiation. The Husimi JPD may be derived from the ICS joint distribution by means of the Husimi transform [5]

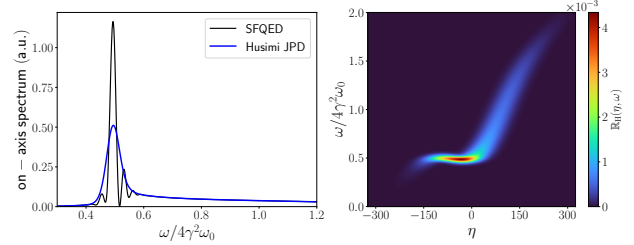


Figure 1: Husimi JPD (right panel) with $\sigma_\eta = 25$ for the on-axis ICS in circularly polarized linearly chirped pulse with $\beta = 0.18\omega_0$ and $a_{\text{rms}}(\eta) = a_0/\cosh(\eta/\tau)$, $\tau = 40\pi/\omega_0$ and $a_0 = 1$, $\omega_0 = 1.55$. The left panel shows corresponding exact spectrum (black line) and Husimi marginal (blue line).

$$\mathbb{R}_H(\eta, \omega) \propto \iint \mathcal{R}(\eta', \omega') e^{-\frac{(\eta-\eta')^2}{2\sigma_\eta^2}} e^{-\frac{(\omega-\omega')^2}{2\sigma_\omega^2}} d\eta' d\omega', \quad (2)$$

where corresponding Gaussian dispersions are linked via $\sigma_\eta\sigma_\omega = 1/2$, ensuring the non-negativity of the result distribution [5].

In Fig. 1 we show Husimi JPD of ICS within the linearly chirped laser pulse. The Husimi JPD reveals that linear laser chirp compensates ponderomotive broadening on the one slope of the envelope, resulting into pronounced peak in the emission spectrum (see, left panel in Fig. 1). In turn, the other slope stretches to the high-energy region and gives the characteristic plateau feature of the spectrum. The Husimi JPD is symmetric w.r.t. substitution $\beta \rightarrow -\beta$ as long as radiation reaction (RR) is negligible, meaning that linearly increasing and decreasing chirps lead to the same emitted spectrum. However, if RR is significant this symmetry breaks and spectra are different. Influence of the RR could be investigated in future study.

References

- [1] I. Ghebregziabher *et al.*, PRSTAB **16**, 030705 (2013).
- [2] D. Seipt *et al.*, Phys. Rev. A **91**, 033402 (2015).
- [3] V. Kharin *et al.*, Phys. Rev. Lett. **120**, 044802 (2018).
- [4] M. Valialshchikov *et al.*, Phys. Rev. A **106** L031501 (2022)
- [5] N. Larin and D. Seipt, arXiv:2606.05203v1 (2026).

^{*}nikita.larin@uni-jena.de

Unambiguous vector magnetometer with structured light

S. Ramakrishna^{*1,2} and S. Fritzsche^{1,2}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²TPI, FSU Jena

Absorption profiles of vector light upon interaction with atomic vapor carries distinct signatures of external magnetic field vector. However, this signature becomes ambiguous for anti parallel magnetic field vectors of equal magnitude, which makes their absorption profiles visually indistinguishable. To resolve this ambiguity, we present theoretical analysis of the interaction of vector light with optically polarized atoms immersed in reference and test magnetic fields. Furthermore, we demonstrate the complete characterization of the arbitrarily oriented test magnetic field via Fourier analysis of the absorption profile. This analysis reveals a one-to-one correspondence between the magnetic field properties and the profile's contrast and rotational angle. Our findings open an avenue to design an optical vector atomic magnetometer based on structured light fields.

Recent works [1, 2, 3] have established the advantages of structured light based atomic magnetometers in retrieving magnetic field information by observing the absorption profile.

However, in this kind of magnetic field detection scheme the absorption profiles are indistinguishable for anti-parallel magnetic fields. This leads to difficulties in realizing vector atomic magnetometer which can determine both strength and direction of the external magnetic fields. In this work [4], we provide theoretical framework which shows how to overcome this limitation. Furthermore, we analyze the absorption profiles for a 3D test magnetic field and show that one could obtain unique absorption profiles for any arbitrarily oriented magnetic field. To realize this, we propose the rubidium atomic vapor to be placed at a room temperature of 30 degree celcius, exposed to a combination of reference and test magnetic fields. Moreover, the atomic system interacts with counter propagating pump and probe light fields. Here, linearly polarized plane wave is considered as pump and vector light constructed in Bessel modes will act as probe light field. To understand the interaction between light and atomic system, we choose the total magnetic field as our quantization axis, which will be suspended in the free space. Then, one could define the total Hamiltonian of the system composed of three parts: unperturbed atomic Hamiltonian, light-atom interaction Hamiltonian, and magnetic field-atom interaction Hamiltonian. This Hamiltonian, can be later utilized to study the dynamics of the atomic system, with the help of the Liouville-von Neumann equation based on density matrix theory. We primarily track the population of the atomic excited state over the time until the system has reached steady state condition. The underlying reason being that

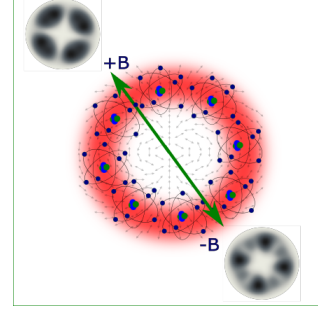


Figure 1: Absorption profiles of vector Bessel light beams interacting with Rb atomic vapor. The absorption profiles for anti-parallel magnetic fields are visually distinguishable.

the absorption profile formed by the vector light atom interaction displays four dark lobes which represents maximum absorption of light by atoms. Thus, at these regions in the beam cross section of the vector light, one would observe maximum atomic population in the excited state.

The pump light field polarizes the atomic ground state population. Mainly, the magnetic sublevel $F_g = 1, M_g = 0$ will have relatively maximum population in comparison to other two sublevels. Thus, the probe, vector light field predominantly couples $M_g = 0$ and $M_e =$ sublevels. In other words, the dark regions in the absorption profile are formed in the cross section of vector light where the local electric field is parallel to the quantization axis. Therefore, as we vary the test magnetic field, the quantization axis changes and this leads to subsequent rotation and reduction in contrast of the absorption profile, as seen in Fig. 1.

The fundamental reason for the unique absorption profile one would obtain in our case is the presence of the reference magnetic field. Otherwise, the quantization axis would be symmetric for anti-parallel magnetic fields, leading to indistinguishable absorption profiles. Our method also allows one to obtain the absorption profile for any arbitrarily oriented magnetic field, without any ambiguity, a scenario not considered in earlier studies.

The authors acknowledge funding from research School of Advanced Photon Science of the HI Jena.

References

- [1] F. Castellucci *et al.*, Phys. Rev. Lett. **127**, 233202 (2021).
- [2] S. Ramakrishna *et al.*, Phys. Rev. A. **110**, 043101 (2024).
- [3] S. Ramakrishna and S. Fritzsche, Phys. Rev. A. **111** 063110 (2025).
- [4] S. Ramakrishna and S. Fritzsche, Phys. Rev. A. (Letter) **113**, L031102 (2026).

*shreyas.ramakrishna@uni-jena.de

On The Role of Magnetic Fields in Avalanche-Like QED Cascades

M. Aleksiejuk^{*1} and D. Seipt¹

¹ *Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany*

We investigate the effect of an external magnetic field on the dynamics of QED cascades as an extension of the rotating electric field model. Our numerical simulations reveal a non-trivial dependence of the asymptotic particle growth rate on the magnetic field strength.

It has long been conjectured that the formation of QED cascades may limit attainable electromagnetic field strengths of high-power lasers long before the Schwinger field is reached [1]. In the high-power laser context, cascade formation was studied in detail using a rotating electric field as a toy model that approximates the fields at the magnetic nodes of two counter-propagating circularly polarised laser pulses. More detailed investigations of QED cascades in high-power laser interactions aim to include magnetic field effects and particle migration due to field inhomogeneities [2]. This motivates us to extend the rotating electric field model by a static magnetic field as follows:

$$\mathbf{E} = E_0(\cos \omega t, \sin \omega t, 0), \quad \mathbf{B} = (0, 0, B_0).$$

This model could serve as benchmark for simulations of cascades in realistic focus geometries, where magnetic field effects are intrinsically more complicated [3].

Moreover, QED cascades are also relevant in extreme astrophysical environments such as the polar caps pulsars and magnetars [4], where the fields are dominantly magnetic. In the astrophysics context, our set-up resembles a strong electromagnetic wave propagating along a pulsar magnetic field lines [2].

The cascade evolution is modeled kinetically, using Boltzmann-type equations for the distribution functions f_q of electrons, positrons and photons (charge $q = \pm 1, 0$)

$$\left[\frac{\partial}{\partial t} + q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_{\mathbf{p}} \right] f_q(t, \mathbf{p}) = \mathcal{C}_q(\chi; \{f_{q'}\}),$$

where the right-hand side are the QED collision operators describing the QED effects of photon emission via non-linear Compton Scattering and pair production via non-linear Breit-Wheeler rates calculated in the LCFA. The Boltzmann equations are conveniently solved numerically by adopting a frame that is co-rotating with the electric field vector. Then, the collision operators depend on the angle $\varphi = \angle(\mathbf{E}, \mathbf{p})$ only parametrically via the quantum parameter $\chi \propto |\beta + \sin \varphi|$. The angle φ is conserved during the quantum processes.

The main effect of the magnetic field is a symmetry breaking between the electron and positron dynamics, affecting their steady state phase spaces distributions. QED cascades eventually reach a quasi-steady exponential growth phase, $f_q(t, \mathbf{p}) \sim e^{\Gamma t}$, with growth rate $\Gamma = \Gamma(a_0, \beta)$.

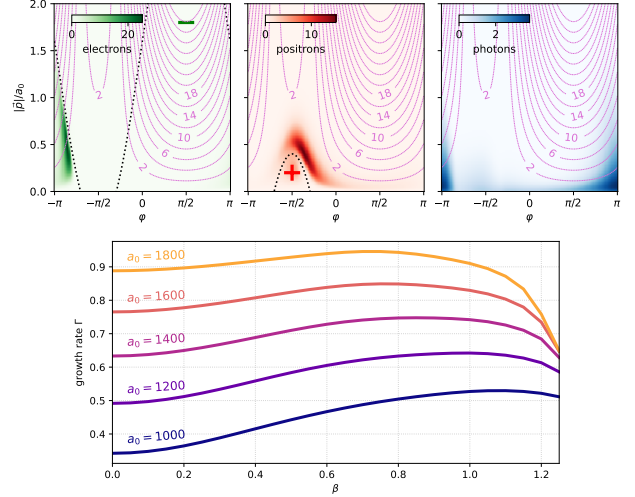


Figure 1: Upper panels: distribution functions f_q in the steady state plotted in the co-rotating frame. Parameters are $a_0 = eE_0/m\omega = 1800$ and $\beta = B_0/E_0 = 0.8$. Also shown are the χ iso-contour lines (magenta) as well as the phase space separatrices (black dotted). The lower panel shows the dependence of the growth rate over a wide range of parameters.

In Fig. 1, the particle distribution functions are exhibited, showing the asymmetries between e^+ and e^- due to the magnetic field effect. The lower panel of Fig. 1 shows the dependence of the growth rate on β for a different values of a_0 . For small β the growth rate first increases, before it eventually starts decreasing for large β . The location of the maximum is a_0 -dependent and can even occur at $\beta \gtrsim 1$ (where the field is magnetically dominated) for small values of a_0 . The location of the maximum moves towards smaller β with increasing a_0 , and above $a_0 > 2500$ it occurs at $\beta = 0$. The growth rate monotonically decreases with increasing β .

Future work will include the effects of particle polarisation which are expected to be amplified by magnetic field symmetry breaking [5]. Moreover, the numerical investigations should scan over the electric field frequency, particularly toward significantly lower frequencies that are relevant for e.m. waves in astrophysical plasmas.

References

- [1] A. M. Fedotov *et al.*, Phys. Rev. Lett. **105**, 080402 (2010).
- [2] M. Lyutikov, MNRAS **529**, 2180 (2024).
- [3] A. Mercuri-Baron *et al.*, Phys. Rev. X **15**, 011062 (2025).
- [4] F. C. Michel and H. Li, Phys. Rep. **318**, 227 (1999).
- [5] D. Seipt *et al.*, New J. Phys. **23**, 053025 (2021).

^{*}m.aleksiejuk@hi-jena.gsi.de

Back-reflection in dipole fields and multi-beam configurations

M. Valialshchikov^{*1}, F. Karbstein¹, D. Seipt¹, and M. Zepf¹

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany

Quantum reflection is a fascinating signature of the quantum vacuum that emerges from inhomogeneities in the electromagnetic fields. Pursuing the prospective real-world implementation of quantum reflection in the back-reflection channel, we provide the first numerical estimates for the light-by-light scattering with dipole pulses, which are known to provide the tightest focusing of light possible.

Strong-field QED predicts that in the presence of strong electromagnetic fields the quantum vacuum starts to behave like a medium and affects light propagation. In Ref. [1] it was shown that light could experience quantum reflection: an incoming probe photon could be reflected from the electromagnetic field of sufficient intensity and localization. Dipole pulses [2] have high focusing efficiency and have been argued to benefit e^+e^- pair creation and light-by-light scattering effects. Motivated by this, we consider a dipole pulse to be a promising candidate for quantum reflection.

In the vacuum emission picture [4], the zero-to-single photon transition amplitude (with wave vector $\mathbf{k}$, energy $\omega = |\mathbf{k}|$ and polarization vector $\epsilon_{(p)}^\mu$) is given by

$$S_{(p)}(\mathbf{k}) = \frac{\epsilon_{(p)}^{\mu}(k)}{\sqrt{2k^0}} \int d^4x e^{ik_\nu x^\nu} j_\mu(x) \Big|_{k^0=\omega}, \quad (1)$$

where

$$j_\mu(x) = 2\partial^\nu \frac{\partial \mathcal{L}_{\text{HE}}}{\partial F^{\nu\mu}} \quad (2)$$

is the signal-photon current generated by the external macroscopic electromagnetic fields $F^{\mu\nu}$ and $\mathcal{L}_{\text{HE}}$ is the Heisenberg-Euler Lagrangian.

The numerical algorithm to calculate quantum vacuum signals was originally put forward in [3]: 1) a linear Maxwell solver is used to describe the evolution of external electromagnetic fields, 2) the vacuum emission picture is used for the calculation of the quantum vacuum signals (Eq. 1). We use our code *quvac* that follows the same basic algorithm and has a range of new features [5].

Figure 1 shows the angular signal spectrum, $d^2N/d^2\Omega = \int \sum_p |S_p(\vec{k})|^2 \omega^2 d\omega / (2\pi)^3$, for different dipole moment orientations. Extended ring-like structures around the dipole axis originate from the dipole self-scattering. Back-reflected signature at $(\vartheta, \varphi) = (90^\circ, 180^\circ)$ is more pronounced for some configurations [compare (b) with (a) and (c)]. Unfortunately, huge dipole background renders the signal indiscernible.

In [5] we investigate in detail dipole and various multiple beam configurations that maximize the back-reflected signal and make it potentially discernible. Among all considered scenarios, the three pulse setup appears to be the most

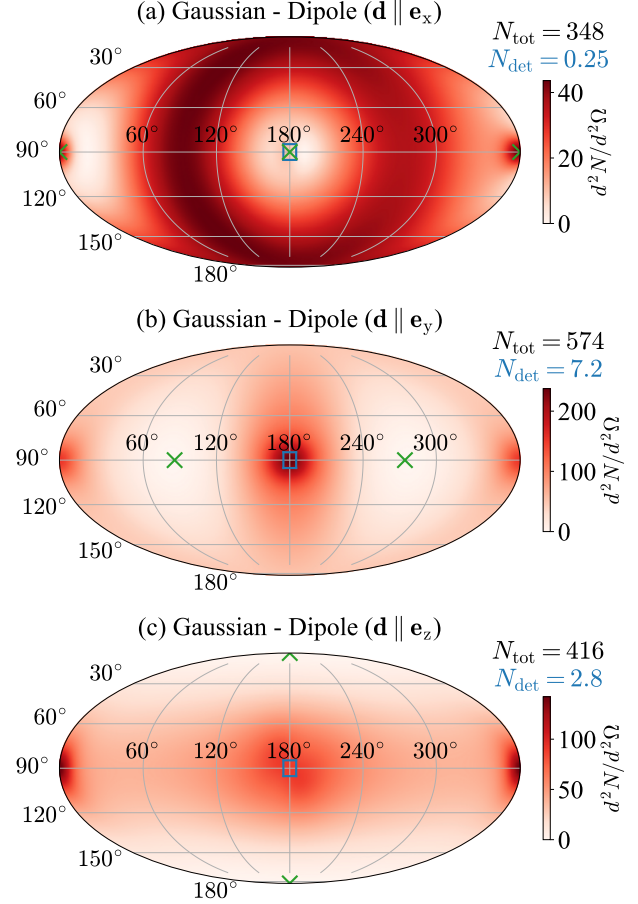


Figure 1: Angular signal photon spectrum from the collision of a Gaussian probe with a dipole pump. Both pulses have $\lambda = 800$ nm, $\tau_{\text{FWHM}} = 20$ fs. Probe pulse with $W = 20$ J, $w_0 = 2\lambda$, $\beta = 0^\circ$ propagates along x-axis. The probe collides with the magnetic dipole pulse ($W = 40$ J) with different dipole moment orientations. Green crosses show the dipole moment axis. The blue square shows a $10^\circ \times 10^\circ$ detector for which we calculate the signal propagating opposite to the probe (N_{det}): it is a mixture of back-reflected signal and dipole self-scattering.

experimentally accessible, though it still remains challenging to implement in practice.

References

- [1] H. Gies *et al.*, New J. Phys. **15**, 083002 (2013).
- [2] I. Gonoskov *et al.*, Phys. Rev. A **86**, 053836 (2012).
- [3] A. Blinne *et al.*, Phys. Rev. D **99**, 016006 (2019).
- [4] F. Karbstein *et al.*, Phys. Rev. D **91**, 113002 (2015).
- [5] M. Valialshchikov *et al.*, Phys. Rev. D **112**, 116012 (2025).

^{*}maksim.valialshchikov@uni-jena.de

Levin Method in Partial-Wave Strong-Field Approximation

A. K. Sahoo^{*1,2} and S. Fritzsche^{1,2,3}

¹HI Jena, Fröbelstieg 3, 07743 Jena, Germany; ²GSI GmbH, Planckstraße 1, 64291 Darmstadt, Germany; ³TPI, FSU Jena, 07743 Jena, Germany

The strong-field approximation (SFA) has been widely employed to model the interaction of atomic systems with intense-laser pulses. However, the standard SFA formulation requires an orbital-specific analytical treatment when describing ionization from states with nonzero angular momentum. Furthermore, the application of the saddle-point approximation to multi-color pulses requires careful identification of the contributing saddle points. In this work, we implemented the Levin method within a partial-wave formulation of the SFA. This approach overcomes the aforementioned limitations and provides a unified, computationally efficient framework for modelling strong-field ionization processes from orbitals with nonzero angular momentum and for treating multi-color pulses.

The partial-wave formalism of the strong-field approximation (SFA) [1] expands the continuum electron in partial waves and employs a spherical tensor representation of the interaction operators. This formalism treats ionization from orbitals with nonzero angular momentum without orbital-specific analytical derivations. We implement the Levin method [2, 3] within this framework to evaluate the oscillatory pulse-shape integrals, which eliminates the need to determine the complex saddle points for multi-color pulses and provides a computationally efficient framework.

The vector potential for the two-color pulses is usually expressed as

$$\mathbf{A}_c(t) = A_1 f(t) e^{-i(\omega_1 t + \varphi_1)} \hat{\mathbf{u}}_1 + A_2 f(t) e^{-i(\omega_2 t + \varphi_2)} \hat{\mathbf{u}}_2$$

where ω_1 and ω_2 are the angular frequencies, A_1 and A_2 are the peak amplitudes of the vector potentials, φ_1 and φ_2 are the carrier-envelope phases, and $\hat{\mathbf{u}}_1$ and $\hat{\mathbf{u}}_2$ are the unit polarization vectors of the respective pulses. The interaction Hamiltonian within the dipole approximation and velocity gauge is $V_{le} = \mathbf{A} \cdot \mathbf{p} + \mathbf{A}^2/2$. For a two-colour pulse, the interaction operator takes the form

$$V_{le} = \frac{1}{2} [\mathcal{A}_1 \cdot \mathbf{p} + \mathcal{A}_1^* \cdot \mathbf{p} + \mathcal{A}_2 \cdot \mathbf{p} + \mathcal{A}_2^* \cdot \mathbf{p} + \mathbf{A}^2].$$

Here, we will focus only on the direct ionization amplitude $\langle \chi_p | V_{le} | \psi_{nlm} \rangle$. Following the work of Böning and Fritzsche [1], the transition amplitude can be separated into temporal and spatial components. The temporal contributions, referred to as pulse-shape integrals, are given by

$$\begin{aligned} \mathbf{F}_i^{(1)}[\pm\omega, f(t), \mathbf{p}] &= A_i \int_{t_i}^{t_f} f(t) e^{-i(\varepsilon \pm \omega_i \pm \varphi)t + iS_V(t)} dt \\ \mathbf{F}^{(2)}[\pm\omega, \mathbf{p}] &= \int_{t_i}^{t_f} \mathbf{A}^2(t) e^{-i\varepsilon t + iS_V(t)} dt \end{aligned}$$

*a.k.sahoo@hi-jena.gsi.de

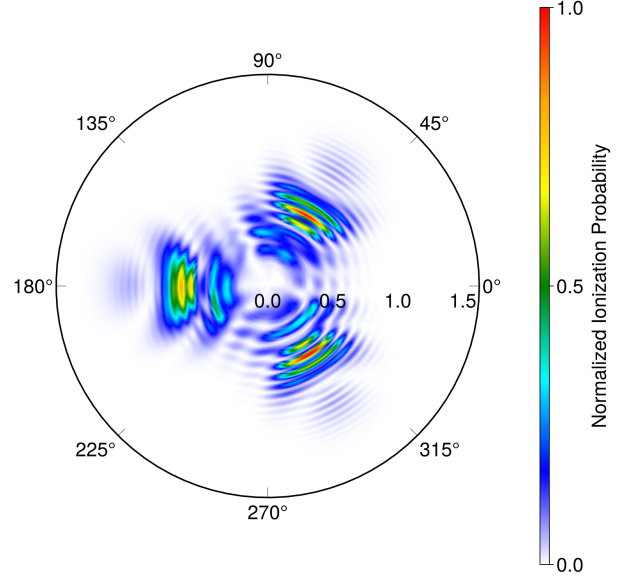


Figure 1: Photoelectron momentum distribution in the polarisation plane for ionization of Ar by a counter-rotating, circularly polarised two-colour laser pulse, computed within the partial-wave SFA using the Levin method. The 800 nm and 400 nm components each have a Gaussian pulse envelope with a full-width at half-maximum duration of ≈ 200 a.u. and a peak electric field amplitude of 0.053 a.u.

These pulse-shape integrals can be easily cast into the Levin integral form [2],

$$I = \int_a^b h(t) e^{ig(t)} dt.$$

Levin-type integrals were solved using a computationally efficient collocation method. In conclusion, this theoretical framework provides an efficient treatment of strong-field ionization processes for several pulse shapes, chirped pulses, and multi-color pulses.

References

- [1] B. Böning, and S. Fritzsche, Phys. Rev. A **102**, 053108 (2020).
- [2] D. Levin, Mathematics of Computation **38**(158), 531 (1982).
- [3] D. Levin, J. Comput. Appl. Math. **67**(1), 95 (1996).

PUBLICATIONS

R. BERNECKER, B. BAGHDASARYAN, AND S. FRITZSCHE

Engineering of maximally entangled orbital angular momentum states via path identity

Physical Review A **112**, 063701 (2025)

10.1103/9qrm-chgg

C. ANSCHÜTZ, J. HEIN, H. ZHUANG, AND M. C. KALUZA

LaserCAD – A Novel Parametric, Python-Based Optical Design Software

Applied Sciences **15**, 11893 (2025)

10.3390/app152211893

S. RAMAKRISHNA AND S. FRITZSCHE

Interaction of a Poincaré beam with optically polarized atoms in the presence of a constant magnetic field

Physical Review A **111**, 063110 (2025)

10.1103/5r63-5h11

N. LARIN AND D. SEIPT

Extended locally monochromatic approximations of strong-field QED processes

Physical Review A **112**, 032819 (2025)

10.1103/cmp-rt2g

H. GIES, F. KARBSTEIN, AND L. MAIWALD

Phase transition analogs in laser collisions with a dark-field setup

Physical Review D **111**, 016027 (2025)

10.1103/PhysRevD.111.016027

F. KARBSTEIN AND F. SCHÜTZE

Limitations of the paraxial beam model in the study of quantum vacuum signals

Physical Review D **111**, 096026 (2025)

10.1103/bmxl-776l

S. FRITZSCHE

Atomic input for modeling ionic mixtures in astrophysical plasma

European Physical Journal A **61**, 63 (2025)

10.1140/epja/s10050-025-01535-3

S. FRITZSCHE, H. K. HUANG, AND A. K. SAHOO

Empirical Atomic Data for Plasma Simulations

Plasma **9**, 2 (2025)

10.3390/plasma9010002

S. RINGLEB, M. KIFFER, TH. STÖHLKER, AND M. VOGEL

Collisional thermalisation behaviour of highly-charged-ion plasmas in a Penning trap

Journal Of Physics B-Atomic Molecular And Optical Physics **58**, 095202 (2025)

10.1088/1361-6455/adcf65

H. GIES AND M. PICCIAU

Mean-field theory for self-interacting relativistic Luttinger fermions

Physical Review D **111**, 085001 (2025)

10.1103/PhysRevD.111.085001

H. GIES AND M. PICCIAU

Self-Organized Criticality in a Relativistic Yukawa Theory with Luttinger Fermions

International Journal Of Theoretical Physics **64**, 282 (2025)

10.1007/s10773-025-06132-0

S. RAMAKRISHNA AND S. FRITZSCHE

Interaction Between Atoms and Structured Light Fields

Atoms **13**, 20 (2025)

10.3390/atoms13020020

D. F. DAR AND S. FRITZSCHE

Comparison between Jacobi-Anger and saddle point methods to treat above-threshold ionization

Journal Of Physics B-Atomic Molecular And Optical Physics **58**, 215202 (2025)

10.1088/1361-6455/ae187b

T. OVER-WINTER, W. MIDDENTS, G. WEBER, AND TH. STÖHLKER

Polarization Reconstruction Based on Monte Carlo Simulations for a Compton Polarimeter

Atoms **13**, 65 (2025)

10.3390/atoms13070065

Y. F. CHEN, T. TIAN, X. LU, C. LI, R. L. ZHU, Z. SUN, AND X. L. LI

Attention-enhanced computational ghost imaging

Science China-Information Sciences **68**, 162104 (2025)

10.1007/s11432-024-4434-5

Y. HIKOSAKA AND S. FRITZSCHE

Amplified Collective Auger Decay of Double Inner-Shell Vacancy in Xe

Physical Review Letters **134**, 103001 (2025)

10.1103/PhysRevLett.134.103001

M. SCHMELZ, V. SHVAB, K. PEISELT, J. KUNERT, V. ZAKOSARENKO, TH. STÖHLKER, G. OELSNER, AND R. STOLZ

Highly Sensitive DC SQUID Arrays for the Readout of Optical TES at mK Temperatures

Ieee Transactions On Applied Superconductivity **35**, 0600704 (2025)

10.1109/TASC.2025.3543941

D. F. DAR, A. WEBER, S. RAMAKRISHNA, AND S. FRITZSCHE

Photoionization dynamics in intense few-cycle twisted laser pulses

Physical Review A **111**, 053113 (2025)

10.1103/PhysRevA.111.053113

M. VALIALSHCHIKOV, F. KARSTEIN, D. SEIPT, AND M. ZEPF

Back reflection in dipole fields and beyond

Physical Review D **112**, 116012 (2025)

10.1103/1291-c43n

A. L. HARRIS AND S. FRITZSCHE

A distorted-wave approach to the elastic scattering of twisted electrons

Journal Of Physics B-Atomic Molecular And Optical Physics **58**, 095201 (2025)

10.1088/1361-6455/add1a0

J. GEBHARD, P. HILZ, F. BALLING, J. KALIS, M. SPEICHER, L. DOYLE, A. SÄVERT, G. SCHÄFER,
P. KHADEMI, B. LIU, M. ZEPF, AND J. SCHREIBER

Efficient laser-plasma acceleration of protons via near-critical mass limited targets

Physical Review E **112**, 035204 (2025)

10.1103/z7y1-1zbz

C. MARMIER, N. SEEGERT, AND F. KARBSTEIN

Impact of background field localization on vacuum polarization effects

Physical Review D **111**, 016005 (2025)

10.1103/PhysRevD.111.016005

C. HEYL AND M. HANNA

Ultrashort laser pulse amplified by back-and-forth propagation

Nature **647**, 45 (2025)

10.1038/d41586-025-03449-y

H. GIES, R. SCHMIEDEN, AND L. ZAMBELLI

Interplay of chiral transitions in the standard model

European Physical Journal C **85**, 56 (2025)

10.1140/epjc/s10052-024-13689-3

W. WANG, S. FRITZSCHE, AND Y. LI

Search for variations of the fine-structure constant via the hyperfine electronic bridge in highly charged ^{229}Th ions

Physical Review A **112**, 022811 (2025)

10.1103/64n6-9b44

D. WANG, Y. LI, T. Y. WANG, S. FRITZSCHE, AND Z. W. WU

Lightning spectra of collisionally excited N II ions: Role of the ion alignment

Physical Review A **112**, 052809 (2025)

10.1103/ptnp-wh9t

B. LI, Y. SONG, Y. MA, AND S. FRITZSCHE

Electron-impact multiple ionization in JAC: integration and application

European Physical Journal D **79**, 79 (2025)

10.1140/epjd/s10053-025-01031-9

J. SPÄTHE, S. HELL, M. WÜNSCHE, R. KLAS, J. ROTHHARDT, J. LIMPET, T. SIEFKE, G. G. PAULUS,
AND M. KÜBEL

Laser-driven high-flux source of coherent quasi-monochromatic extreme ultraviolet radiation for coincidence spectroscopy

Review Of Scientific Instruments **96**, 123009 (2025)

10.1063/5.0289040

D. SEIPT, M. SAMUELSSON, AND T. BLACKBURN

Nonlinear Breit-Wheeler pair production using polarized photons from inverse Compton scattering

Plasma Physics And Controlled Fusion **67**, 035002 (2025)

10.1088/1361-6587/adaa77

A. MAIOROVA, S. FRITZSCHE, A. SURZHYKOV, AND TH. STÖHLKER

Diagnostics of Spin-Polarized Ions at Storage Rings

Atoms **13**, 15 (2025)

10.3390/atoms13020015

W. MIDDENTS, A. GUMBERIDZE, T. KRINGS, T. OVER-WINTER, P. PFÄFFLEIN, N. SCHELL, U. SPILLMANN, M. VOCKERT, G. WEBER, AND TH. STÖHLKER

Linear polarization properties of energetic x-rays being Compton-scattered off atomic targets

New Journal Of Physics **27**, 073204 (2025)

10.1088/1367-2630/adf140

A. SCHÖNBERG, S. RAJHANS, E. ESCOTO, N. KHODAKOVSKIY, V. HARITON, B. FARACE, K. PÖDER, A. K. RAAB, S. WESTERBERG, M. MERDANOV, A. L. VIOTTI, C. L. ARNOLD, W. P. LEEMANS, I. HARTL, AND C. M. HEYL

Compact, folded multi-pass cells for energy scaling of post-compression

Photonics Research **13**, 761 (2025)

10.1364/PRJ.540977

D. S. P. MOLINA, W. ESCHEN, C. LIU, J. LIMPert, AND J. ROTHHARDT

Multiplexing information limits in multi-beam ptychography

Optics Express **33**, 12925 (2025)

10.1364/OE.542608

A. KLENKE, C. JAUREGUI, M. BAHRI, J. NOLD, S. KÜHN, N. HAARLAMMERT, T. SCHREIBER, AND J. LIMPert

High-power ytterbium-doped multicore fibers

Optical Fiber Technology **96**, 104471 (2025)

10.1016/j.yofte.2025.104471

C. JAUREGUI, Y. M. TU, S. KHOLAIF, F. MOLLER, G. PALMA-VEGA, N. HAARLAMMERT, T. WALBAUM, T. SCHREIBER, AND J. LIMPert

Recent developments in the understanding and passive mitigation of transverse mode instability

Optical Fiber Technology **96**, 104496 (2025)

10.1016/j.yofte.2025.104496

Y. M. TU, C. JAUREGUI, S. KHOLAIF, AND J. LIMPert

Real-time modal decomposition of fiber laser beams using a spatial mode multiplexer

Optics Letters **50**, 690 (2025)

10.1364/OL.546209

- M. LENSKI, Q. XU, P. GIERSCHE, Z. Y. WANG, T. HEUERMANN, C. JÁUREGUI, AND J. LIMPET
Average-power scaling of in-band pumped, Tm-doped, fiber laser systems for high peak power pulsed operation
Optics Express **33**, 16029 (2025)
 10.1364/OE.553640
- S. KHOLAIF, C. JAUREGUI, J. NOLD, N. HAARLAMMERT, S. KÜHN, T. SCHREIBER, AND J. LIMPET
Influence of core size on the transverse mode instability threshold of fiber amplifiers
Optics Express **33**, 54245 (2025)
 10.1364/OE.580001
- C. LIU, W. ESCHEN, D. S. P. MOLINA, L. LICHT, M. ABDELAAL, AND J. ROTHHARDT
Purity-based self-calibration in ptychography
Optics Letters **50**, 1581 (2025)
 10.1364/OL.543865
- S. HELL, J. SPÄTHE, M. FORRE, R. KLAS, J. ROTHHARDT, J. LIMPET, R. MOSHAMMER, C. OTT, G. G. PAULUS, S. FRITZSCHE, AND M. KÜBEL
Coincidence measurement of two-photon double ionization of argon through an autoionizing resonance
Physical Review Research **7**, L032030 (2025)
 10.1103/f63d-4hrh
- Y. LI, Z. Q. TIAN, J. Q. WANG, C. Z. DONG, S. FRITZSCHE, AND Z. W. WU
Effect of the Breit interaction on spin polarization of Auger electrons following electron-impact excitation of Be-like ions
European Physical Journal D **79**, 26 (2025)
 10.1140/epjd/s10053-025-00980-5
- S. FRITZSCHE, A. K. SAHOO, L. SHARMA, AND S. SCHIPPERS
Simulated Photoabsorption Spectra for Singly and Multiply Charged Ions
Atoms **13**, 77 (2025)
 10.3390/atoms13090077
- Y. F. CHEN, H. J. AN, Z. SUN, T. TIAN, M. L. CHEN, C. SPIELMANN, AND X. L. LI
Large model enhanced computational ghost imaging
Science China-Technological Sciences **68**, 2120403 (2025)
 10.1007/s11431-025-3062-3
- R. CHAKMA, S. FRITZSCHE, K. HAUSCHILD, AND A. LOPEZ-MARTENS
GEANT4 atomic relaxation data for transfermium nuclei (Z=101–104)
Nuclear Instruments & Methods In Physics Research Section A-accelerators Spectrometers Detectors And Associated Equipment **1072**, 170144 (2025)
 10.1016/j.nima.2024.170144
- Y. C. WANG, J. MA, L. G. JIAO, AND S. FRITZSCHE
Singly differential cross section in the generalized binary-encounter-Bethe model for electron impact ionization of polyatomic molecules
European Physical Journal D **79**, 63 (2025)
 10.1140/epjd/s10053-025-01009-7

C. CHEUNG, M. G. KOZLOV, S. G. PORSEV, M. S. SAFRONOVA, I. I. TUPITSYN, AND A. I. BONDAREV
pCI: A parallel configuration interaction software package for high-precision atomic structure calculations

Computer Physics Communications **308**, 109463 (2025)

10.1016/j.cpc.2024.109463

J. S. ANDREWS, A. I. BONDAREV, P. JÖNSSON, J. GRUMER, S. RAEDER, S. FRITZSCHE, AND J. BIERON
Ab initio multiconfigurational calculations of experimentally significant energy levels and transition rates in Lr I (Z=103)

Physical Review A **112**, 062802 (2025)

10.1103/9p1l-xx4b

W. ESCHEN, R. KLAS, D. S. P. MOLINA, S. FUCHS, G. G. PAULUS, J. LIMPET, AND J. ROTHHARDT
Coherent nanoscale imaging and chemical mapping with compact extreme ultraviolet and soft x-ray sources: Review and perspective

APL Photonics **10**, 050901 (2025)

10.1063/5.0254017

S. MORRIS, D. O. GERICKE, S. FRITZSCHE, J. MACHADO, J. P. SANTOS, AND M. AFSHARI
Recombination effects in laser-driven acceleration of heavy ions

Physical Review E **111**, 065209 (2025)

10.1103/PhysRevE.111.065209

S. FRITZSCHE, H. K. HUANG, Z. K. HUANG, S. SCHIPPERS, W. Q. WEN, AND Z. W. WU
Dielectronic recombination into high-n Rydberg shells

European Physical Journal D **79**, 22 (2025)

10.1140/epjd/s10053-025-00969-0

L. M. LOHSE, P. ANDREJIĆ, S. VELTEN, M. VASSHOLZ, C. NEUHAUS, A. NEGI, A. PANCHWANEE, I. SERGEEV, A. PÁLFFY, T. SALDITT, AND R. RÖHLSBERGER

Collective Nuclear Excitation and Pulse Propagation in Single-Mode X-Ray Waveguides

Physical Review Letters **135**, 053601 (2025)

10.1103/r2hf-9qn9

H. G. RINDERKNECHT, E. DILL, A. J. MACLEOD, B. KING, K. SOW, S. W. BAHK, I. A. BEGISHEV, F. KARBSSTEIN, J. SCHREIBER, M. ZEPF, AND A. DI PIAZZA

On measuring stimulated photon-photon scattering using multiple ultraintense lasers

Physics Of Plasmas **32**, 083301 (2025)

10.1063/5.0272791

M. S. SANJARI, Y. A. LITVINOV, S. LITVINOV, B. PETER, R. J. CHEN, D. DMYTRIIEV, C. FORCONI, J. GLORIUS, G. W. HUDSON-CHANG, H. HUETHER, E. B. MENZ, Z. NUNNS, T. OHNISHI, Z. PODOLYAK, J. STADLMANN, TH. STÖHLKER, Q. WANG, T. YAMAGUCHI, Y. YAMAGUCHI, X. YAN, A. YANO, AND Y. YU

Software defined radio for on-line interaction with beam processes in the heavy ion storage ring ESR

Chinese Physics C **49**, 074005 (2025)

10.1088/1674-1137/adcc01

- H. K. HUANG, Y. YUAN, N. HOSEA, R. SI, AND S. FRITZSCHE
Dielectronic and tri-electronic recombination strengths of low-lying resonances and plasma rate coefficients for beryllium-like argon ions
European Physical Journal D **79**, 18 (2025)
 10.1140/epjd/s10053-025-00961-8
- S. BERNITT, S. KÜHN, M. TOGAWA, R. STEINBRÜGGE, C. SHAH, M. A. LEUTENEGGER, P. MICKE, TH. STÖHLKER, AND J. R. C. LÓPEZ-URRUTIA
Laboratory X-ray astrophysics at ultrabright light sources with PolarX-EBIT
Journal Of Instrumentation **20**, C03030 (2025)
 10.1088/1748-0221/20/03/C03030
- A. NEGI, L. M. LOHSE, S. VELTEN, I. SERGEEV, O. LEUPOLD, S. SADASHIVAIAH, D. BESSAS, A. CHUMAKHOV, C. BRANDT, L. BOCKLAGE, G. MEIER, AND R. RÖHLSBERGER
Energy-time ptychography for one-dimensional phase retrieval
Optica **12**, 1529 (2025)
 10.1364/OPTICA.568949
- P. BOLLER, J. HORNING, A. DUMITRU, C. KANSTEIN, E. OEZALP, J. B. OHLAND, L. WEGERT, AND V. BAGNOUD
Prepulse-induced changes in ion acceleration direction: Insights from TNSA regime experiments and simulations at PHELIX
Physics Of Plasmas **32**, 083105 (2025)
 10.1063/5.0278103
- L. J. SPIESS, S. Y. CHEN, A. WILZEWSKI, M. WEHRHEIM, J. GILLES, A. SURZHYKOV, E. BENKLER, M. FILZINGER, M. STEINEL, N. HUNTEMANN, C. CHEUNG, S. G. PORSEV, A. I. BONDAREV, M. S. SAFRONOVA, J. R. C. LÓPEZ-URRUTIA, AND P. O. SCHMIDT
Excited-State Magnetic Properties of Carbon-like Ca^{14+}
Physical Review Letters **135**, 043002 (2025)
 10.1103/p88p-brnx
- A. A. PULS, J. KUSKE, C. J. HANSEN, L. LOMBARDO, G. VISENTIN, A. ARCONES, R. F. DE MELO, M. REICHERT, P. BONIFACIO, E. CAFFAU, AND S. FRITZSCHE
Chemical Evolution of R-process Elements in Stars (CERES)
Astronomy & Astrophysics **693**, A294 (2025)
 10.1051/0004-6361/202452537
- L. SILLETTI, A. BIN WAHID, T. F. GRIGOROVA, L. PRATOLLI, A. O. E. SILVA, N. HERMELLIN, T. MULLINS, A. TRABATTONI, C. M. HEYL, C. BRAHMS, V. WANIE, J. C. TRAVERS, AND F. CALEGARI
Multi-pass cell driven multi-kHz dispersive wave emission of broadband deep-UV pulses
APL Photonics **10**, 070801 (2025)
 10.1063/5.0268188
- P. HESSELBACH, J. LÜTGERT, V. BAGNOUD, R. BELIKOV, O. HUMPHRIES, B. LINDQVIST, G. SCHAU-MANN, A. SOKOLOV, A. TAUSCHWITZ, D. VARENTSOV, K. WEYRICH, B. WINKLER, X. YU, B. ZIELBAUER, D. KRAUS, D. RILEY, Z. MAJOR, AND P. NEUMAYER
Platform for laser-driven X-ray diagnostics of heavy-ion heated extreme states of matter
Matter And Radiation At Extremes **10**, 017803 (2025)
 10.1063/5.0233548

R. FITZGARRALD, J. A. CARDARELLI, P. T. CAMPBELL, S. FOURMAUX, M. D. BALCAZAR, A. F. ANTOINE, N. F. BEIER, Q. QIAN, A. E. HUSSEIN, B. KETTLE, S. R. KLEIN, K. KRUSHELNICK, Y. F. LI, S. P. D. MANGLES, G. SARRI, D. SEIPT, V. SENTHILKUMARAN, M. J. V. STREETER, A. G. R. THOMAS, AND Y. MA

Angularly resolved spectral reconstruction of x rays via filter pack attenuation

Review Of Scientific Instruments **96**, 023103 (2025)

10.1063/5.0248972

B. F. LEI, H. ZHANG, D. SEIPT, A. BONATTO, B. QIAO, J. RESTA-LOPEZ, G. X. XIA, AND C. WELSCH
Coherent Synchrotron Radiation by Excitation of Surface Plasmon Polariton on Near-Critical Solid Microtube Surface

Physical Review Letters **135**, 205001 (2025)

10.1103/cnym-16hc

N. AHMADINIAZ, C. BÄHTZ, A. BENEDIKTOVITCH, C. BÖMER, L. BOCKLAGE, T. E. COWAN, J. EDWARDS, S. EVANS, S. F. VIÑAS, H. GIES, S. GÖDE, J. GÖRS, J. GRENZER, U. H. ACOSTA, T. HEINZL, P. HILZ, W. HIPPLER, L. G. HUANG, O. HUMPHRIES, F. KARBSTEIN, P. KHADEMI, B. KING, T. KLUGE, C. KOHLFÜRST, D. KREBS, A. LASO-GARCÍA, R. LÖTZSCH, A. J. MACLEOD, B. MARX-GLOWNA, E. A. MOSMAN, M. NAKATSUTSUMI, G. G. PAULUS, S. V. RAHUL, L. RANDOLPH, R. RÖHLSBERGER, N. ROHRINGER, A. SÄVERT, S. SADASHIVAIAH, R. SAUERBREY, H. P. SCHLENNVOGT, S. M. SCHMIDT, U. SCHRAMM, R. SCHÜTZHOLD, J. P. SCHWINKENDORF, D. SEIPT, M. SMÍD, TH. STÖHLKER, T. TONCIAN, M. VALIALSHCHIKOV, A. WIPF, U. ZASTRAU, AND M. ZEPF

Towards a vacuum birefringence experiment at the Helmholtz International Beamline for Extreme Fields (Letter of Intent of the BIREF@HIBEF Collaboration)

High Power Laser Science And Engineering **13**, e7 (2025)

10.1017/hpl.2024.70

J. SÖDERSTRÖM, M. AGÅKER, J. C. LIU, T. TOKUSHIMA, A. GHOSH, C. SÄTHE, J. WANG, A. P. F. KOUDOURIDIS, M. GRUNWALD-DELITZ, T. M. BAUMANN, M. MEYER, M. HARDER, Z. YIN, O. BJÖRNEHOLM, J. NORDGREN, S. FRITZSCHE, V. KIMBERG, J. E. RUBENSSON, AND F. GEL'MUKHANOV

Interference between One-and Two-Electron Channels in Resonant Inelastic X-Ray Scattering

Physical Review Letters **135**, 233001 (2025)

10.1103/c5mk-trlz

M. S. SANJARI, Y. A. LITVINOV, G. W. HUDSON-CHANG, S. NAIMI, D. DMYTRIIEV, J. GLORIUS, E. MENZ, T. OHNISHI, Z. PODOLYAK, TH. STÖHLKER, T. YAMAGUCHI, Y. YAMAGUCHI, AND A. YANO
Schottky detection techniques for ultra-rare short-lived ions in heavy-ion storage rings

Chinese Physics C **49**, 084007 (2025)

10.1088/1674-1137/adcc00

M. ŠMÍD, P. KHADEMI, N. AHMADINIAZ, M. ANDRZEJEWSKI, C. BAEHTZ, E. BRAMBRINK, J. BULICKA, T. BURIAN, S. D. CAFISO, J. CHALUPSKY, T. E. COWAN, S. GÖDE, J. GRENZER, V. HÁJKOVÁ, P. HILZ, W. HIPPLER, H. HÖPPNER, A. HORYNOVÁ, L. E. HUANG, O. HUMPHRIES, S. JELÍNEK, L. JUHA, F. KARBSTEIN, C. KOHLFÜRST, A. L. GARCIA, R. LÖTZSCH, M. MASRURI, A. MATHERON, M. NAKATSUTSUMI, G. G. PAULUS, A. PELKA, T. R. PRESTON, S. RAHUL, L. RANDOLPH, A. SÄVERT, H. P. SCHLENVOIGT, R. SCHÜTZHOLD, J. P. SCHWINKENDORF, TH. STÖHLKER, M. TONCIAN, T. TONCIAN, M. VALIALSHCHIKOV, V. VOZDA, E. WECKERT, C. WESSEL, J. WILD, U. ZASTRAU, AND M. ZEPF

Proof-of-principle experiment for the dark-field detection concept for measuring vacuum birefringence

Physical Review A **112**, 063512 (2025)

10.1103/xpxy-ntwz

P. PFÄFFLEIN, G. WEBER, S. ALLGEIER, Z. ANDELKOVIC, S. BERNITT, A. I. BONDAREV, A. J. R. BOROVIK, L. DUVAL, A. FLEISCHMANN, O. FORSTNER, M. FRIEDRICH, J. GLORIUS, A. GUMBERIDZE, C. HAHN, F. HERFURTH, D. HENGSTLER, M. O. HERDRICH, P. M. HILLENBRAND, A. KALININ, M. KIFFER, F. M. KRÖGER, M. KUBULLEK, P. KUNTZ, M. LESTINSKY, Y. A. LITVINOV, B. LÖHER, E. B. MENZ, T. OVER, N. PETRIDIS, S. RINGLEB, R. S. SIDHU, U. SPILLMANN, S. TROTSSENKO, A. WARCZAK, B. ZHU, C. ENSS, AND TH. STÖHLKER

Quantum Electrodynamics in Strong Electromagnetic Fields: Substate Resolved K_{α} Transition Energies in Heliumlike Uranium

Physical Review Letters **134**, 153001 (2025)

10.1103/PhysRevLett.134.153001

H. K. HUANG, W. Q. WEN, Z. K. HUANG, Y. YUAN, C. Y. ZHANG, R. SI, S. J. WU, C. Y. CHEN, S. FRITZSCHE, S. SCHIPPERS, H. B. WANG, S. X. WANG, C. LIU, W. L. MA, X. P. ZHOU, M. Y. WAN, L. J. MAO, J. LI, M. T. TANG, K. Y. YAN, Y. B. ZHOU, Y. J. YUAN, J. C. YANG, S. F. ZHANG, L. F. ZHU, AND X. MA

Absolute Rate Coefficients for Dielectronic Recombination of Sodium-like Iron Ions: Experiment and Theory

Astrophysical Journal Supplement Series **278**, 44 (2025)

10.3847/1538-4365/adcc25

O. TRAVNIKOVA, F. TRINTER, M. AGÅKER, G. VISENTIN, J. ANDERSSON, L. KJELLSSON, I. ISMAIL, N. VELASQUEZ, D. KOULENTIANOS, M. HARDER, Z. YIN, J. SÖDERSTRÖM, T. MARCHENKO, R. GUILLEMIN, O. D. MCGINNIS, H. ÅGREN, S. FRITZSCHE, M. SIMON, J. E. RUBENSSON, AND J. NORDGREN

Neutral Sulfur Atom Formation in Decay of Deep Core Holes in SF₆

Physical Review Letters **134**, 063003 (2025)

10.1103/PhysRevLett.134.063003

C. HOFER, D. BAUSCH, L. FÜRST, Z. WEI, M. HÖGNER, T. P. BUTLER, M. GEBHARDT, T. HEUERMAN, C. GAIDA, K. S. MAITI, M. HUBER, E. FILL, J. LIMPET, F. KRAUSZ, N. KARPOWICZ, AND I. PUPEZA

Linear field-resolved spectroscopy approaching ultimate detection sensitivity

Optics Express **33**, 1 (2025)

10.1364/OE.536543

M. C. NOLTE, G. A. BECKER, M. BEYER, M. B. SCHWAB, M. HORNUNG, M. HELLWING, AND M. C. KALUZA

Characterization of Liquid Micro-Droplets for Laser-Driven Proton Acceleration

Journal Of Physics-Conference Series **3124**, 012019 (2025)

10.1088/1742-6596/3124/1/012019

M. BEYER, Y. AZAMOUM, M. C. NOLTE, G. A. BECKER, M. B. SCHWAB, M. HORNUNG, M. HELLWING, T. WEICKHARDT, AND M. C. KALUZA

Shadowgraphy of the plasma evolution around water micro-droplets irradiated by high-power laser pulses

Journal Of Physics-Conference Series **3124**, 012022 (2025)

10.1088/1742-6596/3124/1/012022

P. BIESTERFELD, A. SCHÖNBERG, M. SEITZ, N. E. VEGA, T. LANG, M. SEIDEL, P. BALLA, L. WINKELMANN, J. K. SUNNY, S. FRÖHLICH, P. MOSEL, I. HARTL, F. CALEGARI, U. MORGNER, M. KOVACEV, C. HEYL, AND A. TRABATTONI

Post-compression of a Q-switched laser in a glass-rod multi-pass cell

Journal Of Physics-Photonics **8**, 015013 (2025)

10.1088/2515-7647/ae1fc4

F. WIESNER, J. J. ABEL, M. HUSSAIN, V. KRISHNA, A. R. CADORE, J. P. G. FELIPE, A. M. VALENCIA, M. WÜNSCHE, J. REINHARD, M. GRUENEWALD, C. COCCHI, G. G. PAULUS, G. SOAVI, AND S. FUCHS
Optical Coherence Tomography of Van Der Waals Heterostructures Using Extreme Ultra-violet Light

Advanced Materials Interfaces **12**, 2400534 (2025)

10.1002/admi.202400534

M. HORST, Z. ANDELKOVIC, C. BRANDAU, R. J. CHEN, D. F. FERNÁNDEZ, C. GEPPERT, J. GLORIUS, V. HANNEN, R. HESS, P. IMGRAM, S. KLAMMES, K. KOENIG, G. LECKENBY, S. LITVINOV, Y. A. LITVINOV, B. LORENTZ, J. MEISNER, K. MOHR, P. MÜLLER, S. PASSON, T. RATAJCZYK, S. RAUSCH, J. ROSSBACH, R. SÁNCHEZ, S. SANJARI, R. S. SIDHU, U. SPILLMANN, M. STECK, TH. STÖHLKER, K. UEBERHOLZ, C. WEINHEIMER, D. WINTERS, AND W. NOERTERSHÄUSER

Storage-ring laser spectroscopy of accelerator-produced hydrogen-like $^{208}\text{Bi}^{82+}$

Nature Physics **21**, (2025)

10.1038/s41567-025-02885-x

R. WATT, B. KETTLE, E. GERSTMAYR, B. KING, A. ALEJO, S. ASTBURY, C. BAIRD, S. BOHLEN, M. CAMPBELL, C. COLGAN, D. DANNHEIM, C. GREGORY, H. HARSH, P. HATFIELD, J. HINOJOSA, D. HOLLATZ, Y. KATZIR, J. MORTON, C. D. MURPHY, A. NURNBERG, J. OSTERHOFF, G. PÉREZ-CALLEJO, K. PÖDER, P. P. RAJEEV, C. ROEDEL, F. ROEDER, F. C. SALGADO, G. M. SAMARIN, G. SARRI, A. SEIDEL, C. SPINDLOE, S. STEINKE, M. J. V. STREETER, A. G. R. THOMAS, C. UNDERWOOD, W. WU, M. ZEPF, S. J. ROSE, AND S. P. D. MANGLES

Bounding elastic photon-photon scattering at $\sqrt{s} \approx 1$ MeV using a laser-plasma platform

Physics Letters B **861**, 139247 (2025)

10.1016/j.physletb.2025.139247

S. SCHIPPERS, C. BRANDAU, S. FUCHS, M. LESTINSKY, S. X. WANG, C. Y. ZHANG, N. R. BADNELL, A. J. R. BOROVIK, M. FOGLE, V. HANNEN, Z. HARMAN, P. M. HILLENBRAND, E. B. MENZ, Y. ZHANG, Z. ANDELKOVIC, F. HERFURTH, R. HESS, A. KALININ, C. KOZHUHAROV, C. KRANTZ, S. LITVINOV, B. LORENTZ, U. SPILLMANN, M. STECK, G. VOROBYEV, D. BANAS, S. FRITZSCHE, E. LINDROTH, X. MA, A. MÜLLER, R. SCHUCH, A. SURZHYKOV, M. TRASSINELLI, K. UEBERHOLZ, C. WEINHEIMER, AND TH. STÖHLKER

Testing Strong-Field QED to Second Order in the Highly Correlated Atomic System Berylliumlike Pb⁷⁸⁺ by Electron-Ion Collision Spectroscopy

Physical Review Letters **135**, 113001 (2025)

10.1103/6j3v-lwxj

R. J. CHEN, G. LECKENBY, R. S. SIDHU, J. GLORIUS, M. S. SANJARI, Y. A. LITVINOV, F. C. AKINCI, M. BAI, K. BLAUM, F. BOSCH, C. BRANDAU, T. DICKEL, I. DILLMANN, D. DMYTRIIEV, T. FAESTERMANN, O. FORSTNER, B. FRANCAK, B. S. GAO, H. GEISSEL, R. GERNHÄUSER, C. J. GRIFFIN, A. GUMBERIDZE, E. HAETTNER, R. HESS, P. M. HILLENBRAND, P. KIENLE, W. KORTEN, C. KOZHUHAROV, N. KUZMINCHUK, S. LITVINOV, E. MENZ, T. MORGENROTH, C. NOCIFORO, F. NOLDEN, N. PETRIDIS, U. POPP, S. PURUSHOTHAMAN, R. REIFARTH, C. SCHEIDENBERGER, U. SPILLMANN, M. STECK, TH. STÖHLKER, Y. K. TANAKA, M. TRASSINELLI, S. TROTSSENKO, L. VARGA, M. WANG, H. WEICK, P. J. WOODS, T. YAMAGUCHI, Y. H. ZHANG, AND J. ZHAO

Half-life determination of heavy ions in a storage ring considering feeding and depleting background processes

European Physical Journal A **61**, 130 (2025)

10.1140/epja/s10050-025-01597-3

M. SGUAZZIN, B. JURADO, J. PIBERNAT, J. A. SWARTZ, M. GRIESER, J. GLORIUS, Y. A. LITVINOV, J. ADAMCZEWSKI-MUSCH, P. ALFAURT, P. ASCHER, L. AUDOUIN, C. BERTHELOT, B. BLANK, K. BLAUM, B. BRÜCKNER, S. DELLMANN, I. DILLMANN, C. DOMINGO-PARDO, M. DUPUIS, P. ERBACHER, M. FLAYOL, O. FORSTNER, D. FREIRE-FERNÁNDEZ, M. GERBAUX, J. GIOVINAZZO, S. GRÉVY, C. J. GRIFFIN, A. GUMBERIDZE, S. HEIL, A. HEINZ, R. HESS, D. KURTULGIL, N. KURZ, G. LECKENBY, S. LITVINOV, B. LORENTZ, V. MÉOT, J. MICHAUD, S. PÉRARD, N. PETRIDIS, U. POPP, D. RAMOS, R. REIFARTH, M. ROCHE, M. S. SANJARI, R. S. SIDHU, U. SPILLMANN, M. STECK, TH. STÖHLKER, B. THOMAS, L. THULLIEZ, M. VERSTEEGEN, AND B. WLOCH

First Measurement of the Neutron-Emission Probability with a Surrogate Reaction in Inverse Kinematics at a Heavy-Ion Storage Ring

Physical Review Letters **134**, 072501 (2025)

10.1103/PhysRevLett.134.072501

G. LECKENBY, M. TRASSINELLI, R. J. CHEN, R. S. SIDHU, J. GLORIUS, M. S. SANJARI, Y. A. LITVINOV, M. BAI, F. BOSCH, C. BRANDAU, T. DICKEL, I. DILLMANN, D. DMYTRIIEV, T. FAESTERMANN, O. FORSTNER, B. FRANCAK, H. GEISSEL, R. GERNHÄUSER, B. S. GAO, C. J. GRIFFIN, A. GUMBERIDZE, E. HAETTNER, R. HESS, P. M. HILLENBRAND, P. KIENLE, W. KORTEN, C. KOZHUHAROV, N. KUZMINCHUK, S. LITVINOV, E. B. MENZ, T. MORGENROTH, C. NOCIFORO, F. NOLDEN, N. PETRIDIS, U. POPP, S. PURUSHOTHAMAN, R. REIFARTH, C. SCHEIDENBERGER, U. SPILLMANN, M. STECK, TH. STÖHLKER, Y. K. TANAKA, S. TROTSSENKO, L. VARGA, M. WANG, H. WEICK, P. J. WOODS, T. YAMAGUCHI, Y. H. ZHANG, AND J. W. ZHAO

Bayesian and Monte Carlo approaches to estimating uncertainty for the measurement of the bound-state β - decay of ²⁰⁵Tl⁸¹⁺

Chinese Physics C **49**, 114001 (2025)

10.1088/1674-1137/ade956

Y. MA, M. J. V. STREETER, F. ALBERT, N. BOURGEOIS, S. CIPICCIA, J. M. COLE, S. J. D. DANN, K. FALK, E. GERSTMAYR, I. G. GONZÁLEZ, A. HIGGINBOTHAM, A. E. HUSSEIN, D. A. JAROSZYNSKI, A. S. JOGLEKAR, B. KETTLE, K. KRUSHELNICK, N. LEMOS, N. C. LOPES, C. LUMSDEN, O. LUNDH, S. P. D. MANGLES, K. G. MILLER, W. MORI, Z. NAJMUDIN, Q. QIAN, P. P. RAJEEV, D. SEIPT, M. SHAHZAD, M. SMÍD, R. SPESYVTSEV, D. R. SYMES, G. VIEUX, L. WILLINGALE, J. C. WOOD, AND A. G. R. THOMAS

Single-Shot Reconstruction of Electron Beam Longitudinal Phase Space in a Laser Wake-field Accelerator

Physical Review X **15**, 031062 (2025)

10.1103/sxqf-16mp

S. F. DELLMANN, J. GLORIUS, Y. A. LITVINOV, R. REIFARTH, L. VARGA, M. ALIOTTA, F. AM-JAD, K. BLAUM, L. BOTT, C. BRANDAU, B. BRÜCKNER, C. G. BRUNO, R. J. CHEN, T. DAVINSON, T. DICKEL, I. DILLMANN, D. DMYTRIEV, P. ERBACHER, O. FORSTNER, D. FREIRE-FERNÁNDEZ, H. GEISSEL, K. GÖBEL, C. J. GRIFFIN, R. E. GRISENTI, A. GUMBERIDZE, E. HAETTNER, S. HAG-MANN, T. HEFTRICH, M. HEIL, R. HESS, P. M. HILLENBRAND, C. HORNUNG, R. JOSEPH, B. JU-RADO, E. KAZANSEVA, K. KHASAWNEH, R. KNÖBEL, D. KOSTYLEVA, C. KOZHUHAROV, I. KULIKOV, N. KUZMINCHUK, D. KURTULGIL, C. LANGER, G. LECKENBY, C. LEDERER-WOODS, M. LESTINSKY, S. LITVINOV, B. LÖHER, B. LORENTZ, E. LORENZ, J. MARSH, E. MENZ, T. MORGENROTH, I. MUKHA, N. PETRIDIS, U. POPP, A. PSALTIS, S. PURUSHOTHAMAN, E. ROCCO, P. ROY, M. S. SANJARI, C. SCHEI-DENBERGER, M. SGUAZZIN, R. S. SIDHU, U. SPILLMANN, M. STECK, TH. STÖHLKER, A. SURZHYKOV, J. A. SWARTZ, Y. TANAKA, H. TOERNQVIST, D. VESCOVI, M. VOLKNANDT, H. WEICK, M. WEIGAND, P. J. WOODS, T. YAMAGUCHI, AND J. ZHAO

First Proton-Induced Cross Sections on a Stored Rare Ion Beam: Measurement of $^{118}\text{Te}(p,\gamma)$ for Explosive Nucleosynthesis

Physical Review Letters **134**, 142701 (2025)

10.1103/PhysRevLett.134.142701

L. VARGA, J. GLORIUS, M. ALIOTTA, K. BLAUM, L. BOTT, C. BRANDAU, B. BRÜCKNER, C. G. BRUNO, X. CHEN, R. CHEN, S. DABABNEH, T. DAVINSON, D. DMYTRIIEV, S. F. DELLMANN, I. DILLMANN, P. ERBACHER, S. FIEBIGER, O. FORSTNER, T. GASSNER, K. GÖBEL, S. GORIELY, C. J. GRIFFIN, R. E. GRISENTI, M. GROOTHUIS, A. GUMBERIDZE, G. GYÜRKY, M. HEIL, R. HENSCH, R. HESS, P. M. HILLENBRAND, P. HILLMANN, O. HINRICHS, R. JOSEPH, B. JURADO, T. KAUSCH, K. KHA-SAWNEH, A. KHODAPARAST, T. KISSELBACH, N. KLAPPER, C. KOZHUHAROV, D. KURTULGIL, G. J. LANE, C. LANGER, G. LECKENBY, C. LEDERER-WOODS, M. LESTINSKY, Y. A. LITVINOV, S. LITVINOV, B. LÖHER, E. LORENZ, B. LORENTZ, P. MARINI, J. MARSH, E. MENZ, T. MORGENROTH, T. T. NGUYEN, F. NOLDEN, N. PETRIDIS, U. POPP, A. PSALTIS, M. REED, R. REIFARTH, M. S. SAN-JARI, D. SAVRAN, M. SGUAZZIN, H. SIMON, R. S. SIDHU, Z. SLAVKOVSKÁ, U. SPILLMANN, M. STECK, TH. STÖHLKER, J. STUMM, A. SURZHYKOV, J. SWARTZ, T. SZÜCS, A. T. ZADEH, B. THOMAS, S. Y. TO-RILOV, H. TÖRNQVIST, M. TRÄGER, C. TRAGESER, S. TROTSSENKO, D. VESCOVI, M. VOLKNANDT, H. WEICK, M. WEIGAND, C. WOLF, P. J. WOODS, Y. M. XING, AND T. YAMAGUCHI

Nuclear Astrophysics in the Storage Ring: Background Suppressed Simultaneous Measure-ment of (p,γ) and (p,n) Reactions

Physical Review Letters **134**, 082701 (2025)

10.1103/PhysRevLett.134.082701

G. SARRI, B. KING, T. BLACKBURN, A. ILDERTON, S. BOOGERT, S. S. BULANOV, S. V. BULANOV, A. DI PIAZZA, L. JI, F. KARBSTEIN, C. H. KEITEL, K. KRAJEWSKA, V. MALKAL, S. P. D. MANGLES, F. MATHIEU, P. MCKENNA, S. MEUREN, M. MIRZAIE, C. RIDGERS, D. SEIPT, A. G. R. THOMAS, U. UGGERHOJ, M. VRANIC, AND M. WING

Input to the European strategy for particle physics: strong-field quantum electrodynamics
European Physical Journal Plus **140**, 1151 (2025)
[10.1140/epjp/s13360-025-07057-7](https://doi.org/10.1140/epjp/s13360-025-07057-7)

THESES

FELIX KRÖGER

**High-resolution X-ray spectroscopy of fast-moving ions:
Towards intrinsic Doppler correction**

Dissertation

Friedrich-Schiller-Universität Jena, November 2025.

DANISH FUREKH DAR

Theoretical study of atomic ionization under intense laser pulses

Dissertation

Friedrich-Schiller-Universität Jena, November 2025.

FABIAN SCHÜTZE

Quantum vacuum signatures in high-intensity laser experiments

Dissertation

Friedrich-Schiller-Universität Jena, October 2025.

YUYANG WANG

Towards Studies of the Polarization Correlation for the Annihilation Radiation of Na-22

Master-Thesis

Friedrich-Schiller-Universität Jena; Physikalisch-Astronomische Fakultät, July 2025.

MARKUS KIFFER

**Characterisation and cooling of captured ensembles of highly charged ions in a
Penning trap**

Dissertation

Friedrich-Schiller-Universität Jena, May 2025.

DANIEL AARON SCHNAUB-MÜLLER

**Mitigation of Signal Digitisation Artefacts on the Spectral Performance of
Metallic Magnetic Calorimeters**

Master-Thesis

Friedrich-Schiller-Universität Jena; Physikalisch-Astronomische Fakultät, January 2025.