ESR Operation and Development

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The ESR storage ring was operated for physics experiments as well as for FAIR-related machine development.

Internal target experiments included tests of the FOCAL detector and the electron spectrometer. The series of laser cooling experiments was continued successfully, and beams were decelerated for HITRAP.

An experiment on dielectronic recombination (DR) aimed at comparing DR spectra in both ground and isomeric states of $^{235}\mathrm{U}^{89+}$. An almost pure isomeric state was populated through the β^- decay of $^{235}\mathrm{Pa}^{88+}$. The latter was identified among other fragmentation products by Schottky spectroscopy, and a pure $^{235}\mathrm{Pa}^{88+}$ beam was produced by appropriate scraping.

A completely new type of experiments was launched in autumn 2012 with the advent of the first nuclear reaction experiments at the internal gas jet target. In particular, a sufficiently intense secondary $^{56}\mathrm{Ni}^{28+}$ from the fragment separator was accumulated before being used by the experiment. This experiment is covered in a separate contribution to this report [1].

Another nuclear reaction experiment aimed at the measurement of the $^{20}\mathrm{Ne}^{10+}$ (p,d) reaction. This experiment was successfully performed in autumn 2012.

The ESR internal target was run with different types of gases. Hydrogen operation was remarkably reliable, for the first time a helium cluster jet was successfully used for experiments with a density of almost $6 \cdot 10^{12}\ \mathrm{cm}^{-2}$.

An obstacle impeding beam transport into the inner parts of the ESR aperture without dedicated vertical bumps [2] has been identified by now. All stochastic cooling pickup and kicker stations are equipped with resistively coated ceramic cylinders in order to supress undesired higher microwave modes in the beam chamber. Due to mechanical problems which are not yet understood completely, one such cylinder had fallen down into the beam aperture, leading to severe practical problems in beam handling. This obstacle will be removed before the autumn 2013 beam period.

The machine experiments focused on comparative studies of the different longitudinal stochastic cooling systems. These experiment made use of the newly developed optical notch filter [3]. Here the ESR is an important test bench for components of the FAIR project, as a similar device will be installed at the CR of FAIR.

Three different longitudinal stochastic cooling methods are available at the ESR: Palmer cooling, time of flight (TOF) cooling, and notch filter cooling (see [4]). All of these are also planned to be applied at the CR. The components of the optical notch filter worked reliably. The prescise setting of the notch frequencies by changing the position of an optical mirror was a necessary prerequisite for the low momentum width equilibria achieved. The same is true for the optical attenuator settings. First preliminary tests in April confirmed quantitatively the expectation that the momentum acceptance of notch filter cooling is smaller than for TOF or Palmer cooling [5]. Another series of measurements were performed in October with a 400 MeV $^{58}\mathrm{Ni}^{28+}$ beam in order to determine optimum cooling times. The measurements were made with a beam of $6 \cdot 10^6$ particles. The second moment of the momentum distribution $\sigma(t)$ was evaluated and fitted with an exponential decay towards an equilibrium as a model:

$$\sigma(t) = (\sigma_0 - \sigma_\infty)\exp(-t/\tau) + \sigma_\infty$$

A preliminary evaluation of the data confirms the expectation that the equilibrium value for notch filter cooling ($\sigma_\infty = 2.47 \cdot 10^{-5}$) is much lower than for TOF cooling ($\sigma_\infty = 4.33 \cdot 10^{-5}$). Also the cooling time for notch filter cooling ($\tau = 0.18$ s) is much shorter than for TOF cooling ($\tau = 4.33$ s). The latter is mainly due to the much larger amplification (22 dB higher!) which is affordable in the case of notch filter cooling. This is due to the well-known fact that notch filtering reduces largely the random noise in the vicinity of the revolution frequency. It is planned to provide a fast switching from TOF cooling (with its large momentum acceptance in the beginning of the cooling process) to final notch filter cooling in order to profit from both schemes in an optimized fashion..

During the shutdown period in 2013 the high voltage power supply of the electron cooler will be repaired, as the high voltage was less stable than usual from time to time.

It is planned to establish a new model for the supply of data to the quadrupole magnet power supplies during deceleration, because it has turned out that there are deviations between the set values and the measured values of both tunes, particularly during deceleration. A more flexible programming of the rf voltage and frequency ramps during deceleration is under work, as well.

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Radioactive Beam Accumulation in the ESR

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A radioactive $^{56}Ni^{28+}$ was accumulated for the first time in the ESR to an amount usable for a nuclear physics experiment with the ESR internal target. The $^{56}Ni^{28+}$ ions were produced in the fragment separator (FRS) by shooting an intense 600 MeV/u $^{58}Ni^{28+}$ beam from the SIS synchrotron on a fragmentation target. By proper settings of the FRS degrader, contaminants like $^{54}Co^{27+}$ could be reduced to a total fraction of $< 10^{-3}$. Typically $8 \cdot 10^4$ ions were injected at each shot from the SIS. This beam was precooled in two steps (5 s coasting beam + 5 s bunched beam) by stochastic cooling using the newly established time of flight method [1]. The precooled bunched beam was transferred by rf stacking towards an inner orbit of the ESR, where it was neither disturbed by the magnetic field of the injection kicker nor by the rf fields of the stochastic cooling kickers. Here it was gradually moved by electron cooling towards an orbit at a somewhat lower energy. At this orbit, the beam was accumulated using up to 60 injections. The average time between injections was 36 s, as the SIS synchrotron had to serve several different experiments in parallel. Typically $4.8 \cdot 10^6$ secondary $^{56}Ni^{28+}$ ions interacted with the internal target after properly aligning the beam with the (hydrogen or helium) gas jet.

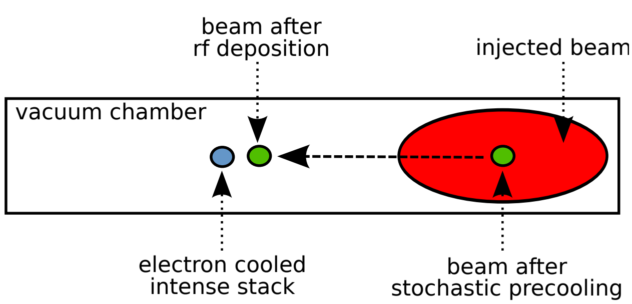

Figure 1: Scheme of beam orbits during accumulation

Fig. 2 shows stochastic precooling of a fresh secondary beam. As long as the beam is coasting the second moment of the momentum width ($\sigma(\delta p/p)$) is decreased by a factor of 3. Due to the non-adiabatic turning on of the rf, $\sigma(\delta p/p)$ increases slightly and is then reduced anew.

Fig. 3 is a waterfall diagram of Schottky spectra (124^{th} harmonic of the revolution frequency) taken just before and after the end of the rf stacking procedure. The distance between stack and deposited beam ($\delta p/p = 4.3 \cdot 10^{-4}$) is chosen such that the two beams are close enough for fast merging by electron cooling without disturbing the stack by the rf. Therefore a low final rf voltage (200 V) was set which corresponds to a full bucket height $(\delta p/p)_{max} = 3.9 \cdot 10^{-4}$.

Fig. 4 displays a series of measured data points from the DC beam current transformer. Although its resolution is limited, the data points are rather linear, indicating that the stacking procedure is working practically lossless.

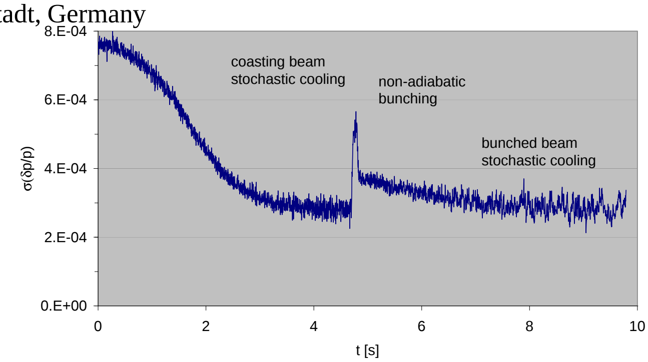

Figure 2: Momentum cooling of freshly injected beam

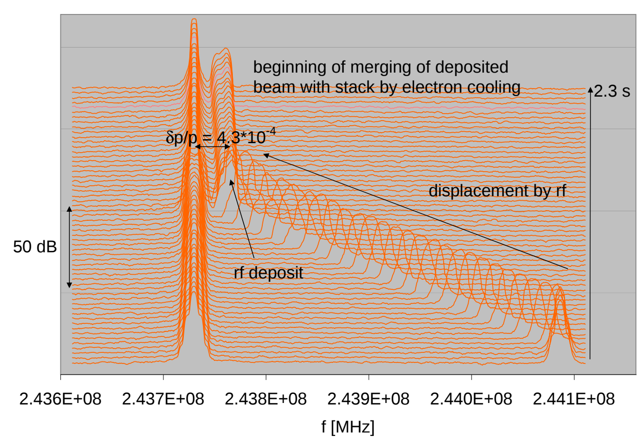

Figure 3: Schottky spectra around beam deposit (see text)

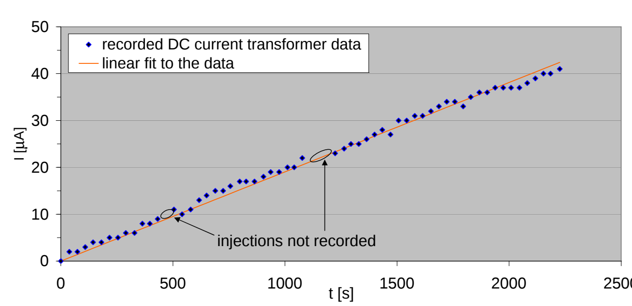

Figure 4: DC beam current transformer data as a function of time

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Sensitivity measurements of the resonant pickup in the ESR

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Qualitative measurements were carried out to determine the sensitivity of the ESR resonant pickup ([1], [2]) using short-lived uranium beams at different energies.

Conventional beam current monitors such as transformers can determine the amount of beam current. But even those devices with high sensitivity suffer from a limited bandwidth which results in reduced performance at higher frequency components of the beam current. To achieve measurements of beams with very few ions, one can make use of the high sensitivity of resonant pickups at a harmonic band of the Schottky signal.

The Schottky process can be shown to be wide sense stationary with the expected (average) value equal to the macroscopic beam current I_B as $\mathsf{E}\left[i(t)\right] = q f_r N = I_B$, where q is the charge, f_r is the revolution frequency and N is the number of particles [2]. Its autocorrelation corresponds to the expected instantaneous power of the signal, which in turn is related to its power spectral density (PSD) via the inverse Fourier transform. The integral under the curve of the PSD shows the total average power in a given frequency band. In this case the area is the same in every (non-overlapping) Schottky band and is equal to

$$\langle I_s^2 \rangle = 2q^2 f_r^2 N = 2q f_r I_B \tag{1}$$

Absolute power values may be difficult to obtain after several stages of signal processing. Also the noise level depends on the number of points within a given frame of sampled data, making it hard to determine at what level signals can be distinguished from noise. A solution is to use an external DC current transformers (DCCT) as a calibration reference to determine I_B and to scale the area under the curve such that it corresponds to it. The number of ions N can also be determined using Eqn. 1.

In August 2012 beams of ^{238}U were stored in the ESR at relatively low energies. Signals from both the DCCT and the resonant pickup were corrected for offset and prepared as described in detail in [2]. After scaling, the number of ions were calculated accordingly using the Schottky spectra.

The beams of $^{238}U^{88+}$ were injected at 90 MeV/u. The N_2 gas target was used to reduce the number of ions over several orders of magnitude during the measurement time. Beams of $^{238}U^{28+}$ were injected at energies of 30 MeV/u without gas target. The results can be seen in Fig. 1. The resonant pickup is several orders of magnitude more sensitive than the DCCT, but of course its sensitivity depends on the total charge and energy of the beam. The DCCT has an estimated uncertainty of ± 1 μA which propagates into the calculation of the number of ions, but it is not shown in the figure. Using a high precision DCCT with known uncertainties could improve measurement results in the future.

It is seen in Fig. 1 that the decrease of beam intensity is not strictly exponential. At higher beam intensities coherent Schottky signals cause amplitude suppression, while at lower signal intensities, noise background accounts for loss of precision. A detailed study of these effects may be crucial for in-ring decay studies.

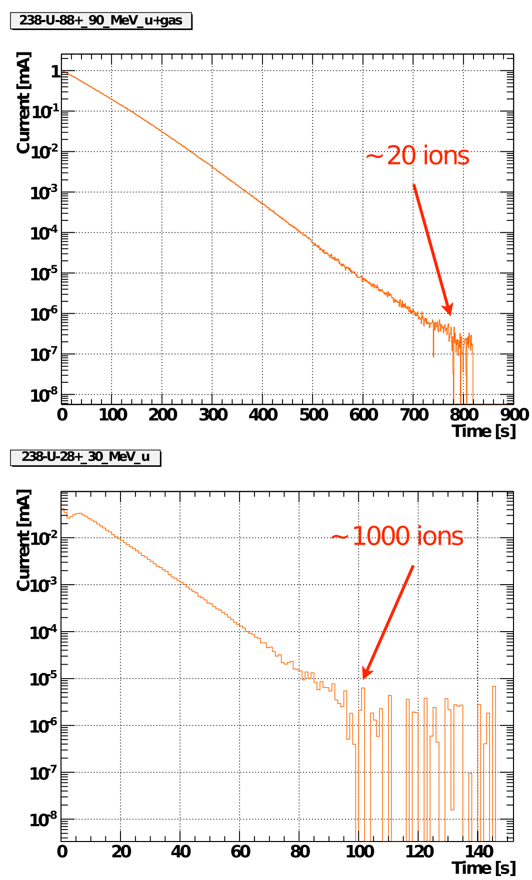

Figure 1: Number of ions after injection for $^{238}U^{88+}$ at 90 and $^{238}U^{28+}$ at 30 MeV/u.

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The CRYRING@ESR Project

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The low energy storage ring LSR shall provide low energy, highly charged ions and antiprotons at FAIR used by two collaborations, SPARC and FLAIR, for precision experiments. The LSR is a Swedish in-kind contribution to the FAIR facility in Darmstadt,

The LSR [1] evolves from the heavy-ion storage ring CRYRING, which has been operated at the Manne Siegbahn Laboratory in Stockholm until 2010. Instead of storing the ring components until installation at the Facility for Antiproton and Ion Research, FAIR, the immediate installation behind the existing Experimental Storage Ring, ESR, has been proposed and worked out in detail by a Swedish-German working group. The estimated efforts for installation and operation of CRYRING at the ESR have been summarized in a report [2] published by that working group in 2012.

A schematic overview of the storage ring and its facilities is shown in fig. 1. CRYRING can decelerate, cool and store heavy, highly charged ions down to a few 100 keV/nucleon. It provides a high performance electron cooler as well as a gas jet target. It is equipped with it's own injector and ion source, to allow for standalone commissioning.

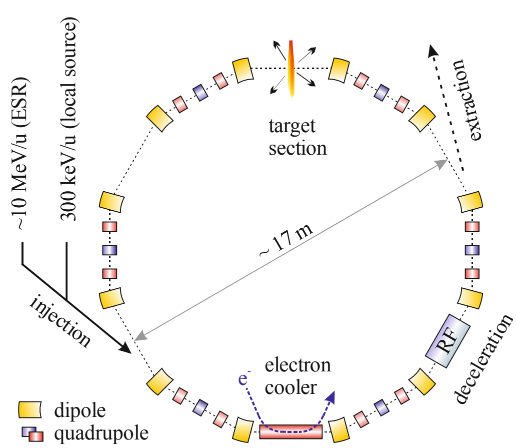

Figure 1: CRYRING at ESR.

The ions are kept in orbit by twelve 30° magnetic dipoles and a number of magnetic quadrupoles and sextupoles (not shown in the figure) in six of the twelve straight sections. The other six sections house an injection and an extraction system, the deceleration and acceleration section, and the electron cooler. One section is used for experimental installations as for instance a gas target.

The storage ring is capable of accelerating ions with mass to charge ratio below four injected at only 300 keV/nucleon from the off-line ion source to the maximum rigidity of 1.44 Tm. It also decelerates ions injected at the maximal rigidity down to the lower rigidity limit of 0.054 Tm. The magnets are designed for fast ramping, such that the whole decelerating (accelerating) process could be done in only 150 ms.

One of the key features is an electron cooler with adiabatic expansion of the electron beam. This yields about 100 times lower transversal electron temperature than in the ESR and yields directly higher resolution in recombination spectroscopy with merged ion – electron beams.

The proposed installation behind the ESR in combination with its own injector makes CRYRING@ESR the perfect machine for FAIR related tests of diagnostics, software and concepts on one hand, and atomic physics experiments with heavy, highly charged ions stored at low energy on the other hand.

The new control system of FAIR will be implemented for the first time in a machine that delivers beam and hence will be the perfect occasion to test not only the cooperation of the design concepts but also the performance of the system. Since the ring can be operated any time it is the perfect training ground for operators on the new control system and this allows for valuable feedback on the operational concept well in advance before the commissioning of FAIR's key machines.

Physics applications range from "classical" atomic physics experiments like the determination of the lamb shift using X-ray spectroscopy, but with increased resolution, over measurements at the borderline of atomic and nuclear physics for instance to determine the charge radius, to a yet unexplored energy regime for astrophysically interesting nuclear reactions. The details of planned experiments are laid down in the "Physics book" that is close to completion [3].

Most components have been shipped by now to GSI and on-site tests are on going. CRYRING@ESR will be installed in the existing Cave B and the necessary reconstruction work has been started.

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Department "SPARC Detectors" in the FAIR@GSI Project*

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In the last decades, accelerator-based atomic physics has advanced into hitherto unexplored areas of research, encompassing high energies, high atomic charge states and strong electromagnetic fields. Here, the heavy-ion storage rings play an indispensable role. A worldwide unique research program is being pursued at the experimental storage ring ESR of GSI by conducting precision spectroscopy of relativistic few-electron ions and interaction studies of relativistic ions with atoms, electrons and photons. The atomic physics groups at GSI and HIJ have gained an unparalleled expertise in this field which ensures that the unprecedented possibilities of the future Facility for Antiproton and Ion Research (FAIR) [1] – concerning energy, intensity and experimental tools – can optimally be exploited to provide access to the fundamental facets of relativistic atomic physics and neighbouring fields. Realisation of this rich research program is the main aim of a large international collaboration, the SPARC Collaboration [2].

The envisioned experiments were initially foreseen in several areas of the FAIR complex: in a dedicated APPA multi-purpose cave, at the SIS-100/SIS-300 synchrotrons, at the FLAIR facility and at the New Experimental Storage Ring NESR. However, the SPARC research program was dramatically reduced by the Modularised Start Version (MSV) [3] of FAIR, where the construction of the central facilities for the SPARC experiments, the NESR and the connected FLAIR facility have been moved to later modules. Therefore, intense investigations of various possibilities to rescue the SPARC science at FAIR by using the facilities available within the MSV have been conducted in the last two years.

One of the solutions is to explore the unique opportunity offered by the High Energy Storage Ring (HESR) [4], which was primarily designed for experiments with stored and cooled antiprotons. However, it turned out to be a well-suited facility which can accommodate a range of SPARC experiments with high-energy stored heavy-ion beams [5, 6]. In particular, the HESR can store cooled beams at energies of up to 5 GeV/u and can thus enable unique atomic physics experiments which are not feasible at any other place in the world. Furthermore, installation of the CRYRING – the storage ring which was operated until very recently at the University of Stockholm – at the present ESR facility will open up the possibility of precision experiments with cooled highly-charged heavy ions at low energies already in the MSV of FAIR [7].

A dedicated department within the FAIR@GSI Project, SPARC Detectors, has been organised, the primary task of which is to accomplish working packages assigned by the SPARC collaboration as the GSI contribution to the SPARC experiments at FAIR. These are the integration of the overall SPARC setup including the necessary infrastructure in the HESR and – if required by the collaboration – the construction of SPARC instrumentation, like internal targets, spectrometers, particle detectors, etc.

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* This work is supported by the Helmholtz Association (HCJRG-108) and by Helmholtz Institute Jena

A target station design study for future in-ring applications

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Recent experimental findings [1, 2] led to the elaboration of an internal target design study, which is based on the prototype target station currently deployed at the experimental storage ring (ESR). The initial motivation for starting the redesign process of the former target station, which was assembled in the original setup in 1989 for the first time, was mainly driven by the limited maximum target densities for the light gases helium and hydrogen. Previously, the behavior of cryogenically cooled, thus liquified helium expanded into vacuum through a micrometer sized orifice nozzle was investigated experimentally [3] and set the foundation for the modification process. Therefore, in order to optimize the target performance, the modification of the target inlet chamber started in 2008 by decreasing the working temperature of the target nozzle using a high cooling-power cryostat. In the course of numerous successful target beamtimes performed at the ESR the prototype target setup was further improved in terms of usability and target stability by applying, i.e., a closed-cycle cryostat featuring push-button operation and a trumpet shaped (CERN) nozzle geometry, kindly provided by A. Khoukaz from the Münster University. As a result, an extremely versatile and reliable prototype target station was developed during the past years, capable of providing target beams of all desired species in a wide range of adjustable target densities (see Table 1 below).

Target gas	Area density [cm^{-2}]	T_0 [K]
Helium	1×10^{13}	20
Hydrogen	3×10^{13}	40
Nitrogen	8×10^{12}	130
Argon	3.5×10^{12}	300
Krypton	1.5×10^{12}	300
Xenon	6×10^{12}	300

Table 1: A survey of actual area densities for different target gases achieved at the ESR by employing a 12 ± 1 μm diameter CERN nozzle.

The prototype target station, with which those improvements were accomplished, essentially consists of the former target station including the important modifications, i.e. the cryostat and the nozzle. Hence, in order to exploit the full potential of the implemented parts, a dedicated and specialized inlet chamber design is crucial. For instance, geometrical considerations regarding the skimmer geometry suggest an improvement in target density at shorter distance of the nozzle to the interaction point (assuming equal

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Investigation and Optimization of Transverse Beam Dynamics in HESR@FAIR for Experiments with Highly-Charged Heavy Ions*

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Introduction

The High-Energy Storage Ring (HESR) was primarily designed for experiments with stored and cooled antiprotons. But it also appeared to be most suitable facility to maintain a wide range of experiments with high-energy stored heavy-ion beams. In this study the transverse nonlinear beam dynamics for heavy ions in the HESR were investigated.

Beam optics optimization for heavy ion experiments

Within PHELIX project at FAIR@GSI an appropriate place for an experiment, where laser and ion beams are overlapped, has to be found. Available free space and flexible optics are important factors in search for the right location. As an optimal solution a place in the straight section in between two quadrupole triplets is proposed. To maximize the brightness of the ion beam in the above-mentioned location (which is crucial for the experiment) we have to minimize a beam profile as much as possible. For this purpose with the help of MIRKO code an algorithm for decreasing the beam transverse profile was developed.

The technique of variation the quadrupole magnets strengths along the ring allowed to locally decrease the β_x-function in the place of beams interaction. As a result, in modified ring optics in the location of interaction the β_x-function was reduced to the value of 3.1 m, which is 7 times less than in standard optics. Optics variation didn't require any change of the designed quadrupoles parameters.

The emittance of a transferred (from the CR to the HESR) beam is about $\epsilon_{x,y}$ = 0.5 mm mrad and the momentum spread about $7 \cdot 10^{-4}$ [1]. Thus one can calculate the size of the beam. The following results are obtained: the horizontal and the vertical beam widths after changing the optics equal to 1.2 mm and 1.5 mm correspondingly.

With the existing set of sextupoles the chromaticities ξ_x = -14.35 and ξ_y = -13.71 can be corrected up to 0.

Frequency map analysis

Frequency map analysis for both ring optics has been performed. The field errors of dipole and quadrupole magnets [2] were included. An ordinary tracking was used to define the dynamic aperture (DA). From the DA plot for modified optics (see figure 1): A_x = 3.1 mm, A_y = 15.0 mm. The emittances which correspond to the dynamic aperture are ϵ_x = 0.7 mm mrad and ϵ_y = 17.8 mm mrad. For standard optics we have ϵ_x = 11.2 mm mrad and ϵ_y = 13.3 mm mrad. One can see that the horizontal DA decreased significantly (from 11.2 mm mrad to 0.7 mm mrad). The betatron tunes are: Q_x = 7.94, Q_y = 7.62 for modified and Q_x = 7.62 Q_y = 7.62 for standard optics. Further investigation and analysis are needed in order to find out and possibly eliminate the causes of DA shrinking.

A revised Fourier technique [3] with data windowing was used in order to obtain a frequency map with a diffusion coefficient (see figure 2).

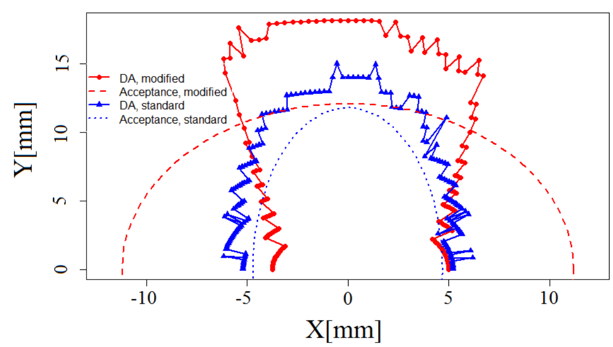

Figure 1: Calculated dynamic aperture for modified (β_x = 13.7 m, β_y = 12.6 m) and standard optics (β_x = 2.4 m, β_y = 11.9 m) for Δp/p = 0.

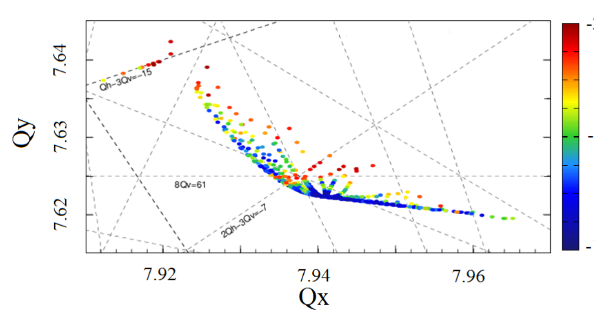

Figure 2: Frequency diagram for modified optics

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* This work is supported by the Helmholtz Association (HCJRG-108), Helmholtz Institute Jena, and GSI F&E program

HITRAP – Status of On-Line Commissioning and Installations

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Heavy, highly charged ions (HCI) are interesting systems for many different experiments as for instance precision tests of the theory of quantum electrodynamics (QED). In order to transform heavy HCI produced at 400 MeV/u to stored and cooled HCI at low energy the linear decelerator facility HITRAP has been conceived behind the experimental storage ring (ESR). Its setup has been started in 2006 and commissioning is underway [1].

In the ESR ions are decelerated from 400 to 4 MeV/nucleon, cooled and extracted; meanwhile a routine operation. Up to ten million ions can be extracted at 4 MeV/nucleon and sent to HITRAP.

The ions are then matched to an interdigital H-type structure (IH) using a double drift buncher, decelerated from 4 to 0.5 MeV/nucleon in the IH, and then down to 6 keV/nucleon in a radio frequency quadrupole (RFQ).

About one million highly charged ions are typically decelerated with the IH from 400 MeV/nucleon to about 0.5 MeV/nucleon per cycle. However, the optimization of the combination of two bunchers (combined in the double drift buncher) and the IH is still difficult and not completely understood. The large parameter space given by three RF amplitudes and two phases requires the investigation of many different settings.

In 2012, the rebuncher between IH and RFQ structures was taken into operation. With a measured loaded Q-value of about 5000 and an effective impedance of 29 MΩ□ it yields a gap voltage of 100 kV for A/q=3. For $^{50}Ti^{22+}$ ions the effective gap voltage of 80 kV corresponds to a change in energy of less than 35 keV/nucleon.

To measure the action of the buncher on the beam, the phase of the rebuncher RF was changed relative to the master oscillator driving the IH radio frequency (fig. 1). Effectively, this makes the ions experience different gap voltages. The largest measured dispersion on the energy analysing detector of about 0.8 mm corresponds to an approximate change in energy of 40 keV/nucleon, pretty close to the expected value.

The full-width-half-maximum of the peak on the detector is 45 keV/nucleon. This is the result of a convolution of geometrical spread due to imaging, slit size and camera issues with the actual energy spread of the ion beam. This has not yet been disentangled, but first estimates show that at least half of that spread is due to the energy spread.

All efforts to decelerate the beam further with the RFQ structure failed so far. The most probable reason is a slight mismatch of the IH output energy distribution and the energy range accepted by the RFQ. This was found in recently updated simulations of the RFQ structure using

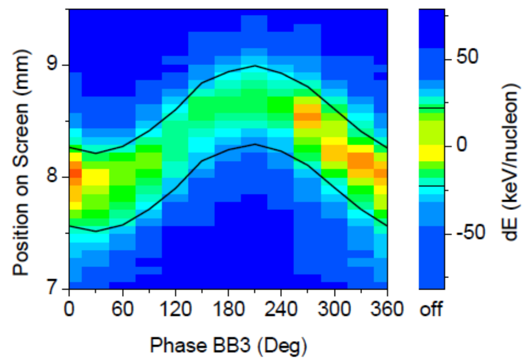

Figure 1: Commissioning of the spiral rebuncher between IH and RFQ. Shown are position on the screen, corresponding energy shift, and intensity (in arbitrary units) of the beam on the energy analysing detector versus the phase of the radio frequency driving the buncher cavity. A power of 1.1 kW was used for all phases. The lines are the FWHM limits of a Gaussian fit of the beam profile at each phase.

the code DYNAMION accompanied by detailed 3D measurements of the electrodes and verified in off-line test. Consequently, a new electrode set has been designed, built and tested off-line [2,3,4] with an on-line test pending autumn 2013.

The cooler Penning trap was tested offline with deuterium ions from a cross beam ion source, an electron source to provide the electrons for the electron cooling scheme and medium heavy, highly charged ions from a compact, room temperature electron beam ion trap (EBIT) [5]. Finally, O^{8+} ions have been stored for an extended period of time. The simultaneous storage of ions and electrons is the next item on the test schedule.

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Simulation of Resistive Cooling in cylindrical Penning Traps*

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The simulation of ion clouds in traps taking ion-ion interaction into account is associated with large computational effort. This applies especially for the simulation of cooling methods like e.g. resistive cooling, where the cooling force has a complex structure. In [1] a simulation method for the resistive cooling was presented, using a particle in cell code. There the ion-ion interaction was treated by a mean-field approximation which, however, neglects the influence of ion-ion correlations on the dynamics. We thus developed an algorithm for the simulation of resistive cooling including the complete ion-ion interactions.
Charged particles moving between two conductive electrodes induce a surface charge Q on both of them and cause a potential imbalance u. Connecting the electrodes to an external RLC-circuit leads to an electrical current i. Energy dissipation in the resistor of the circuit then leads to changes in the induced charges on the electrodes and the related electric field which acts back on the ions as a cooling force $\vec{F}_D$. This non-trivial coupling between the circuit and the ion motion is described by the equations:

$$\frac{d^2u}{dt^2} + \frac{R}{L}\frac{du}{dt} + \frac{1}{LC}u \quad = \quad \frac{1}{C}\left(\frac{R}{L}\frac{di}{dt} + i\right) \qquad (1)$$

$$i \quad = \quad \sum_{k=1}^{N} \frac{d}{dt} \cdot \Delta Q(\vec{r}_k)$$

$$\ddot{\vec{r}}_j \quad = \quad \frac{1}{m_j} \cdot \Big(\vec{F}_E(\vec{r}_j) + \vec{F}_B(\dot{\vec{r}}_j) + \cdots \qquad (2)$$

$$+ \vec{F}_C(\vec{r}_1, \cdots, \vec{r}_N) + \vec{F}_D(\vec{r}_j, u)\Big)$$

R represent the resistance, C the capacitance and L the inductance of the circuit which is driven by the current i and ΔQ is the difference of the induced charges on the Pick-Up electrodes. $\vec{F}_E$, $\vec{F}_B$, $\vec{F}_C$ and $\vec{F}_D := -q_j \vec{\nabla} V_D$ represents the forces from the electrical field, magnetic field, the Coulomb interaction and the induced Potential. N is the number of ions and $\vec{r}_j$ the position vector of the j-th particle. The induced charge on one of the Pick-Up electrodes is given by the equation:

$$Q = a \cdot \sum_{k=1}^{N} \int_{z_<}^{z_>} \int_0^{2\pi} \epsilon_0 \frac{\partial V(r, \phi, z; r_k, \phi_k, z_k)}{\partial r}\bigg|_a d\phi dz, \qquad (3)$$

where $z_<$, $z_>$ representing the z coordinates of the electrode, V_k the potential of the k-th ion using cylindrical coordinates and a the radius of the trap.

In figure 1, the workflow of the resistive cooling algorithm is shown. The algorithm starts with an inital distribution of the positions and velocities of the ions, while the electrical Potential V_D caused by the induced current is neclegted at first. Next equation (2) is solved numerically to calculate a new set of positions, velocities and accelerations from which the right hand side of equation (1) is evaluated. After solving equation (1), finally the electrical potential V_D is calculated and serves together with the new positions and velocities as a starting point for the subsequent cycle.

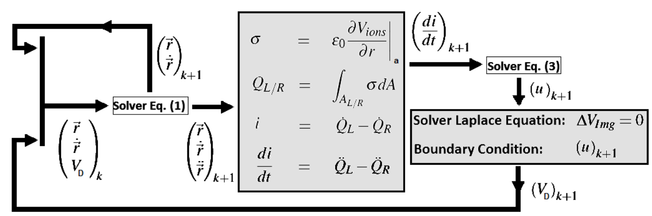

Figure 1: Workflow of the resistive cooling algorithm

Currently we work on the implementation of this algorithm into our existing code [2]. First simulations done with single ions show the expected cooling behavior. Figure 2 shows the simulation result of a single $^{12}C^{5+}$ ion in a cylindrical geometry with radius of $3.5\ mm$. The parameters of the circuit were chosen as $(R,\ L,\ C) \approx (10\ \Omega,\ 1.22\ mH,\ 14.22\ pF)$. The simulation was done on a GPU device using an parallelized Adam-Bashforth method of fourth order.
Next steps are the comparsion of the simulation results with experimental data were the circuit parameters are well known and investigating the cooling behavior for an increasing ion number.

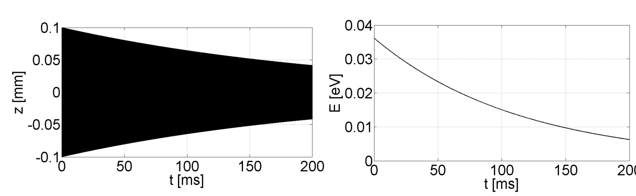

Figure 2: Left: Amplitude of the axial motion, Right: Total axial energy of the ion during resistive cooling.

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* Work supported by FE, Project-Number DAGROS1012.

Demonstration of the Sensitive Schottky-System for CR *

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Introduction

This report summarizes the development of a sensitive longitudinal and transversal Schottky-Sensor for the Collector Ring CR at FAIR. Based on the equivalent circuit model, numerical simulations with CST Microwave Studio, controlled by MATLAB were accomplished to optimize the performance of the sensor structure to the needs of the CR. To demonstrate the performance, a scaled non-hermetic demonstrator was optimized, fabricated and characterized.

Schottky-System Design

Resonant cavities exhibit excellent performances with moderate size for schottky measurements at the ESR [1]. The evaluation of the monopole mode TM_{010} and the dipole mode TM_{110} allows longitudinal as well as transversal schottky measurements. Due to the weak excitation of the dipole mode, both modes need to be coupled out independently and, to suppress the monopole mode for the extraction of the transversal signal, rectangular waveguide resonators are foreseen for the CR [2, 3].

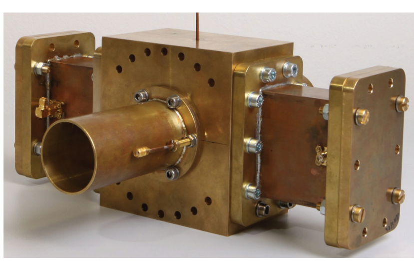

Figure 1: Non-hermetic demonstrator with a beampipe dimension of 46.5 mm.

Structure Optimization

Due to the strong inter-dependence of the relevant parameters and the complex structure, the sensor system cannot be separated into subsystems. To optimize the coupling geometry, the simulations with CST Microwave studio are iteratively controlled by MATLAB. The algorithm optimizes the length of the waveguide for maximum coupling between the pillbox and the waveguide resonators under condition that the monopole mode is kept constant at 200 MHz, which can be adjusted by the radius of the pillbox. The algorithm closes with the adaption of the coupling geometry, until the goal, the maximum gradient of the $\frac{R}{Q}$-value of the dipole mode is achieved.

* Work supported by BMBF: 06DA90351

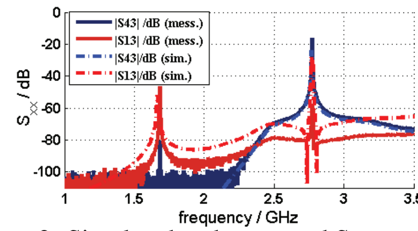

Figure 2: Simulated and measured S-parameters.

Non-hermetic demonstrator

To prove the simulation results, a non hermetic demonstrator scaled down by a factor of 8.6 was realized at TU Darmstadt (see fig.1). S-parameter results exhibit very good agreement between simulation and measurement (fig. 2). Preliminary perturbation measurements of the system exhibits good agreement with the expected behavior for both, the longitudinal and transversal detection (fig. 3).

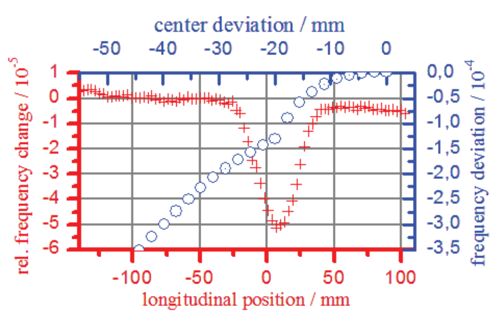

Figure 3: Preliminary results of the perturbation measurements.

Summary and Outlook

An iterative optimization algorithm based on Matlab controlled CST Microwave Studio simulations have been verified by a realized non-hermetic demonstrator. The optimization of the sensor geometry for the CR is ongoing.

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Studies for the radioactive waste management of copular air filters

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One of the main tasks of the radiation protection department at GSI is the radioactive waste management. Among the duties around the radioactive waste management (see other annual reports of 2012) are the inspection and utilization of used air filter systems, fig. 1 a). As the filters could contain radioactive isotopes, it is mandatory to analyze the possible radioactive nuclides and their activities within the filter. The isotopes emitting distinctive γ ray decay lines allow identification using a High Purity Germanium (HPGe) detector. The remaining difficulty is the determination of the efficiency calibration and thus the determination of the minimum detectable activity (MDA) [1]. In the following we introduce results from simulation and experimental studies of the MDA determination.

The main difficulty for the determination of the MDA is the complicated internal structure of the copular air filter. Each filter consists of an inlet and an outlet section, see fig. 1 b) and c).

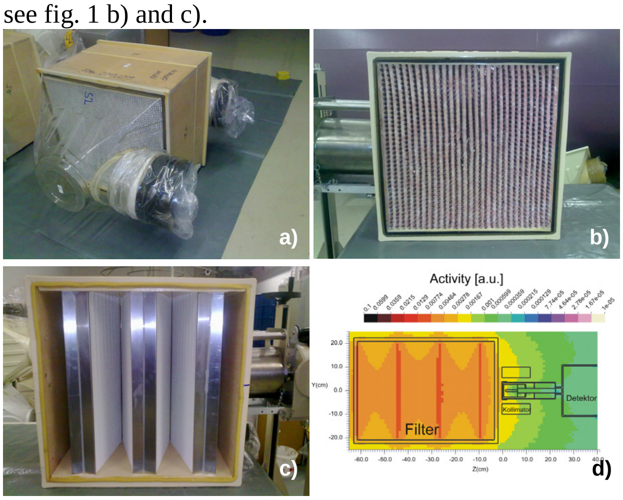

Figure 1: a) Copular air filter. b) charcoal filter of the incoming air section. c) Micro structure filter fins of exhaust section. d) Simulated activity distribution of the air filter.

The HPGe detector is used with a tungsten collimator reducing the background counts. To determine the MDA we used several calibration point sources (^{241}Am, ^{152}Eu, ^{210}Pb) in combination with an unused copular air filter (fig.1). These sources were placed behind and in the middle of the filter, while the detector was placed right in front. The experimental results are compared to the simulation using the Monte Carlo radiation transport code FLUKA [2]. The comparison of the results from FLUKA and the experiment for the point sources shows relative agreement with 20% discrepancy means the differences in the ideal to real terms of the detector-filter system. Additional simulations were done for expanded sources to be compared with point sources. Figure 1 d) shows example of the simulated activity distribution for expanded sources related to the activated filter fins. Figure 2 shows the detector efficiency as a function of the γ ray energy.

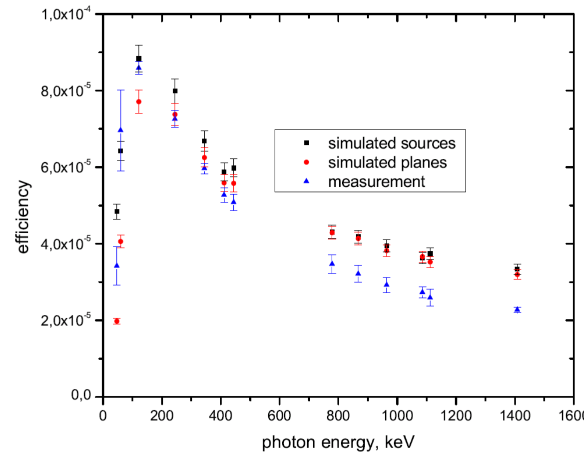

Figure 2: Detector efficiency as a function of γ ray energy.

The difference between the efficiency of a point source and an expanded source is not significant with a discrepancy of less than 5%. So, for future measurements of copular air filters we can use point sources for the efficiency calibration instead of complicated expanded sources.

Nuclide	Energy keV	Iγ %	MDA (Bq)	
			Middle	Behind
Pb-210	46,54	4,25	1,13E+02	2,58E+03
Cs-137	661,66	85,10	4,04E+00	5,65E+01
K-40	1461,00	10,67	6,04E+01	4,43E+02
Tl-208	2614,53	99,16	1,04E+00	7,53E+01

Table 1: MDA of different background lines of detector-filter system. The detector efficiency was used in terms of the calibration using point sources in the middle and the back of the filter element.

Table 1 shows the MDA of the detector-filter system for the γ ray lines of naturally occurring isotopes. It demonstrates the high accuracy for the determination of a low MDA for different γ decay lines using the mentioned results.

The consolidated results of the detector efficiency study lead to the determination of isotopes with very low activities satisfying the DIN norms [1]. Furthermore, future measurements of used copular air filters can be done with high accuracy which lead to a proper and routine radioactive waste management.

References:

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[2] http://www.fluka.org