Beam profile measurements and observation of beam cooling at CRYRING@ESR

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Abstract

We report on the first measurements of beam profiles at CRYRING@ESR with cooled and with un-cooled beams. The measurements were performed with ionisation profile monitors that detect interaction vertices of the beam with the residual gas. The storage ring is equipped with two devices, one for each transverse plane. Their main task is the monitoring of the beam cooling process.

Ionisation Profile Monitor and Readout

The ionisation profile monitors (IPM) [1] were originally operated in CRYRING at the Manne-Siegbahn laboratory in Sweden. The entire storage ring has been transferred to GSI as part of the Swedish in-kind contribution to the FAIR facility. The square opening area of the IPM field cage is 100 mm^2, its length 80 mm. When a residual gas molecule is ionised by the beam, the positive reaction product is accelerated towards a stack of two 40 mm multi-channel plates (MCP) in Chevron configuration. The MCP generates a fast timing pulse, while the following resistive-anode encoder splits the electron cloud into four separate signals. These allow for calculation of the interaction vertex by the method of charge division [2]. In order to verify the IPM response, vertex distributions were acquired with a preliminary test setup and an alpha emitter on a linear drive.

A new VME data acquisition system integrates the IPMs into the FAIR-style accelerator control system. It operates under the front-end software architecture (FESA) framework. The output signals of fixed-gain charge-sensitive amplifiers are post processed after ~35 m coaxial transmission by a 16 channel NIM spectroscopy amplifier CAEN N586E with network interface for remote control. Positive semi-Gaussian pulses of total length < 2 µs are generated with a shaping time of 200 ns. A 12 bit peak-sensing ADC CAEN V785N converts all signals within about 6 µs into a set of amplitudes and stores the events for further processing by the FESA software. A satisfactory readout rate of 20 kHz has been observed with a Men A20 2eSST VME controller. The position resolution of 0.3 mm (FWHM) that has been achieved in Sweden is yet to be confirmed at CRYRING@ESR.

Due to the moderate interaction rates, both IPMs are joined in an OR logic and digitised by the same ADC board. Leading edge discrimination of the fast MCP pulses triggers the event latch, i.e. generation of the 2 µs ADC gate pulse and discriminator inhibit signals via the ADC busy signal. For identification of the active IPM in the analysis the discriminator outputs are recorded together with the analogue signals. There is also a possibility to include the MCP output pulses in the readout.

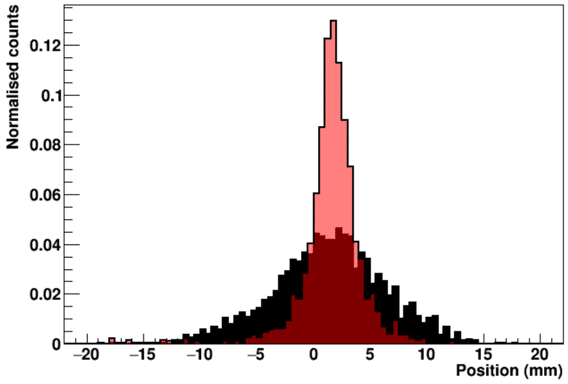

Figure 1: Beam profiles with 0.5 mm bin size at the start of cooling process (black) and at the cycle end (red).

First Operational Experience

During electron cooler commissioning in November 2017 both IPMs were operated together for the first time. The RFQ injector provided a molecular 300 keV/u H_2^+ beam. About 2x10^8 particles were stored at the start of the 5 s long machine cycle, and the resulting MCP count rate reached 50 kHz with a low discriminator threshold. The rates will drop as vacuum conditions are still improving and, at higher energies, due to a smaller specific energy loss dE/dx that drives the ionisation process.

Both IPMs were operated at a field value exceeding 40 kV/m, and the beam was deflected by a few mrad. The resulting orbit shift was not compensated during this beam time.

Figure 1 shows two vertical beam profiles of 0.5 mm bin size and normalised area. The acquisition window was 300 ms long for each profile. The broad distribution represents the beam prior to the cooling process (black) and the narrow one the beam at the end of the cycle (red). At that time the beam was still cooling down. Noteworthy are the quite clean areas outside the beam spot, an indication of the achieved quality of beam and detector setup.

The IPM operational parameters are the high voltage values, discriminator threshold, and spectroscopy amplifier gains to match the signals to the ADC input range. Their optimisation will be studied when longer cycle, and hence cooling, times will produce beam spot sizes in the ~1 mm range.

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Experiment beamline: CRYRING
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Experiment proposal: [none]
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PSP codes: [none]
Grants: [none]
Strategic university co-operation with: [none]

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CRYRING@ESR commissioning – ions stored, cooled, accelerated

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Commissioning of CRYRING@ESR, the low energy storage ring now located at GSI/FAIR has been started in 2016. The commissioning went on during 2017 with establishing stored ion beam, testing beam cooling using the installed electron cooler and first attempts to accelerate.

CRYRING@ESR is the early installation of the low-energy storage ring LSR [1], a Swedish in kind contribution to FAIR, which was proposed as the central decelerator ring for antiprotons at the FLAIR facility.

Status of Commissioning

A local ion source in combination with a radio frequency quadrupole structure is available to provide light ion beams at 300 keV/nucleon for injection into the storage ring. For commissioning this hot cathode type ion source produces singly charged hydrogen molecules. In 2017, the anode voltage was pulsed to prolong the typical operation time until interventions necessary to replace the cathode or the insulators. Now the anode is supplied with voltage for just 1 ms. This shortened considerably the time the ion source plasma burns and led to improved up-times of several weeks. Additionally, a treatment of the Ta cathode wire with triple carbonate spray coating increased the electron emission and hence the ion output. The source is now capable of delivering 1 ms pulses of more than 100 µA peak current of H_2^+ ions for at least a week of continuous operation.

In 2017 three commissioning runs were conducted of about three weeks each. The first run was used mostly for detailed debugging of control system issues. The results from 2016, a first turn, have been reproduced in the remaining three days. Careful analysis of the collected information, a detailed alignment check of all components and the completed bake out of the ring were followed by the second run. In this second run stored ion beam was achieved. The third run ended with successful acceleration and the demonstration of electron cooling.

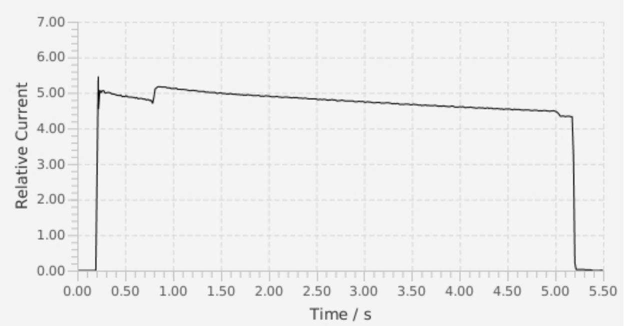

Figure 1: Intensity of stored ion beam versus time during acceleration from injection energy, i.e. 300 keV/nucleon, to 2 MeV/nucleon. Acceleration starts at about 1 s and ends at 5 s.

To test the multi turn efficiency of the local injection, the time between injection and start of the bumper ramp down has been varied. It was found that about 3 turns could be injected [2]. Simulations show that up to ten turns should be achievable. For this the power supply for ramping down the bumpers (orbit distortion) has to be adapted to have more flexibility in choosing the slope.

The storage time strongly depends on the vacuum conditions. Hence, the ring's vacuum system is completely bakeable. The system to heat and bake the ring is at the same time the first large scale installation of the industrial control environment developed for FAIR installations. Several smaller bugs and a serious performance limitation have been identified and solved. Eventually, all ring segments and the last meters of the injection beam line have been heated for about seven days to about 200 degree C. This results an average pressure of $1\cdot10^{-10}$ mbar along the ring directly after the bake out procedure.

During the most recent beam test in November 2017, the exponential decay time constant τ of H_2^+ ions at 300 keV/nucleon has been measured to be about 5 s.

Finally, the ion beam, injected locally at 300 keV/nucleon, has been accelerated to 3 MeV/nucleon. Figure 1 plots the relative intensity during the complete cycle of injection, bunching, and acceleration. This has been recorded by picking up the ion bunch signal on a capacitive pickup during acceleration. While the small increase during the bunching sequence is probably an artefact, the overall decrease is almost entirely due to collisions with the residual gas that limit storage time.

The last part of the commissioning run was dedicated to cooling. The electron cooler has demonstrated its functionality and first cooling has been observed both at injection energy and after acceleration to 1.5 MeV/nucleon [3].

References

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Experiment beamline: CRYRING
Experiment collaboration: APPA-SPARC
Experiment proposal: none
Accelerator infrastructure: CRYRING
PSP codes: 1.3.4.2
Grants: none
Strategic university co-operation with: none

Investigations of different types of current coupling for the new Cryogenic Current Comparator with eXtended Dimensions (CCC-XD)*

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The FAIR project triggers the development of CCCs with larger diameters for the non-destructive, highly-sensitive measurement of charged particle beam intensities. Before the final acceptance test in May 2017 [Fig. 1] different types of current coupling were investigated.

Figure 1: CCC-XD in a wide neck cryostat in front of the magnetic shielded chamber in Jena (l. to r: R. Neubert, T. Sieber, F. Kurian, V. Tympel).

Different types of current coupling

Inside the so-called SQUID-Cartridge the low inductance of the SQUID (Superconducting Quantum Interference Device) has to be coupled with the high inductance of the pickup coil capturing the magnetic field of the charged particle beam. As shown in Fig. 2 three types of coupling were simulated: direct (black), balanced (red) and enhanced (blue). Using the measured inductance values from [1] the simulation shows that the parasitic capacity of the CCC meander shielding leads to resonance peaks above 100 kHz [Fig. 3]. Especially the direct version which is without any matching transformer has a strong peak. A transformer dimensioned with higher inductance values (balanced, enhanced) can generate an additional current magnification at the expense of the bandwidth.

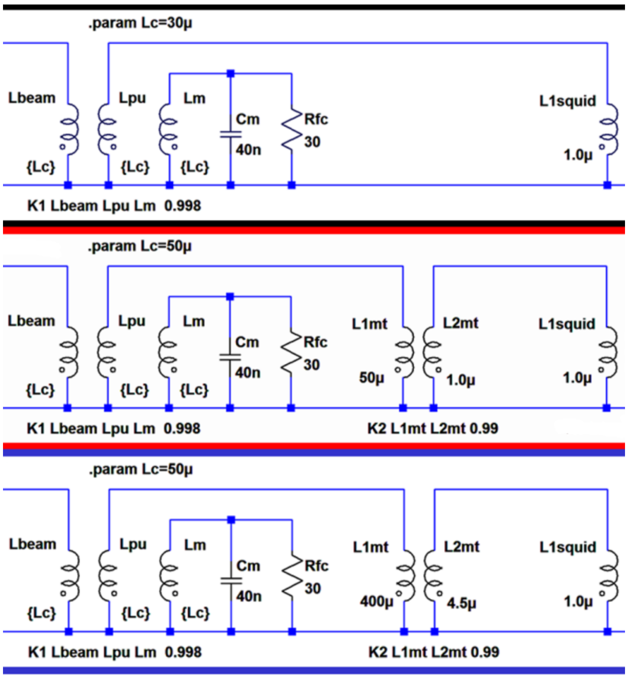

Figure 2: Circuit diagrams of the three coupling types.

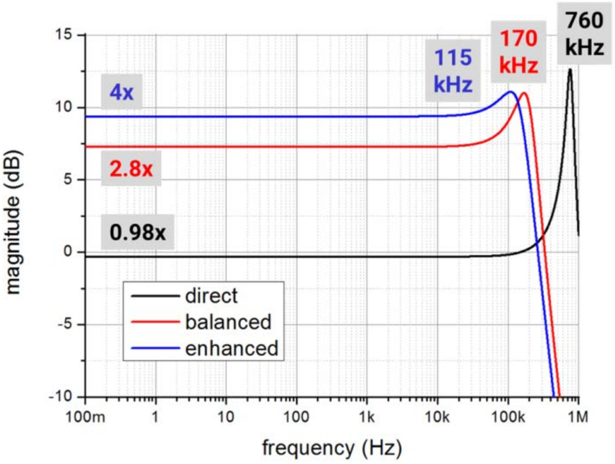

Figure 3: LTspice simulation of the coupling types [2].

Measurement results

The CCC-XD measurements, done in Jena, established that the flux concentrator core surrounded by the pickup coil is the dominant source of current noise. An additional current magnification in front of the SQUID is not necessary. The calculated bandwidths und resonances could be measured. To realize a stable flux-locked-loop working mode with the SQUID the high resonance peak of the direct version has to be damped. Therefor the balanced version was used at the end. This research is supported by the BMBF (project# 05P15SJRBA), the TU Darmstadt and the Leibniz Institute of Photonic Technology.

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* also published in annual HI Jena report 2017

A fluorescence detection system for laser-spectroscopy experiments at CRYRING@ESR

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The low energy storage ring CRYRING is being set up as the first storage ring of the upcoming accelerator facility FAIR at GSI. In order to enable laser spectroscopy experiments with stored ions, a fluorescence detection system has been developed at the Institut für Kernphysik in Münster. Earlier this year, the detector has been set up in section 7 of CRYRING. The detector is designed to measure in a broad wavelength regime between 250 nm to 850 nm.

Several ions of interest have transitions in this wavelength regime. For instance Mg$^+$ (at 280 nm, see [1]) and Be$^+$ (at 313 nm). The latter is a relevant candidate for studying laser induced dielectronic recombination (LIDR).

Status

Initial test and construction of the detector chamber was completed in January 2018 (see fig. 1 and 2). In February 2018, the scrapers were installed and the setup was checked in the vacuum facility of GSI. After baking, a leakage rate of less than $1\text{x}10^{-10}$ mbar l s^{-1} and an outgassing rate of $2\text{x}10^{-12}$ mbar l s^{-1} cm^{-2} were measured.

Also, vertical and horizontal scrapers have been installed. These allow measurement of the beam position directly in front of the detector chamber. As explained in [2] and [3], this is of importance for the detector's working principle. Proper alignment of the beam can be achieved with magnetic steerers. However, the chamber itself also is adjustable, as it is mounted into the CRYRING with metal bellows.

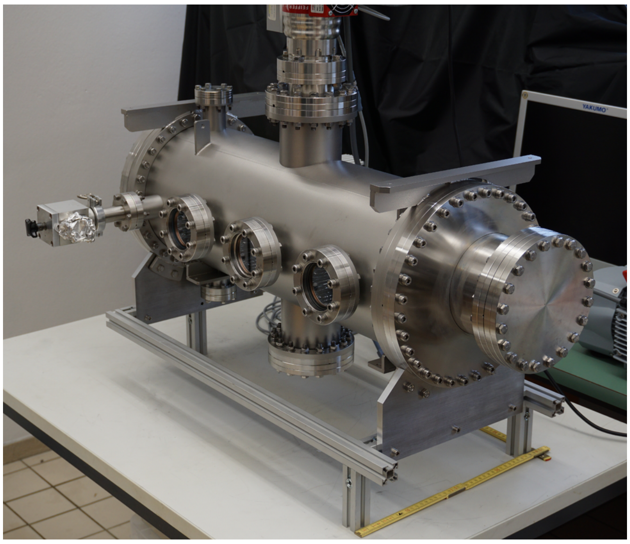

Figure 1: Detector chamber during vacuum test in Münster. At CRYRING site, turbo molecular pump will be substituted by an absorption pump.

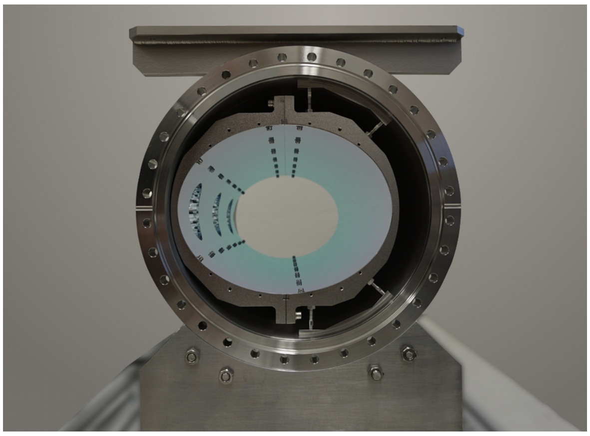

Figure 2: Elliptical mirror chamber. For better visibility, front and end mirror caps are not mounted. The beam will be aligned along the right focus point of the ellipse.

The fluorescence light will be detected by two sets of three PMTs each, one for UV and visible wavelengths (Type 9235QBA by Electron Tubes) and one red-sensitive set (Type 9658BA). In order to allow for single photon counting, air-cooled housings will be used to reduce the dark count rate, especially for the IR-sensitive PMTs. The 2-inch PMTs and cooling housings will be delivered in early April.

References

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Experiment beamline: CRYRING / ESR
Experiment collaboration: APPA-SPARC
Experiment proposal: none
Accelerator infrastructure: ESR / CRYRING
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Strategic university co-operation with:
other: University Münster

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First electron cooled beam in CRYRING after electron cooler commissioning

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In 2017 the activities at the CRYRING electron cooler focussed on commissioning the device and investigating the proper operation parameters. The cooler was operated remotely in DC mode, via newly developed application software, embedded into the new FAIR control system.

Standalone commissioning

After a short bake-out of the cooler vacuum system, a first electron beam was guided from the gun to the collector, confirming the function of all hardware and controls. After a longer bake-out 10^{-10} mbar without electron beam (< 9 10^{-9} mbar with 12 mA electron current in the collector) was reached. The newly mounted cathode, heated according to the supplier instructions at 1200 K (measured with a pyrometer), was fully activated for electron emission. Following the data from former operation in Sweden, the electrode voltages, the guiding magnetic fields and the electron steerers were quickly set so as to extract and guide an electron beam from the gun to the collector. All optimizations were carried out by minimizing the electron beam loss to the ground (and on all anode electrodes) and maximizing the electron current reaching the collector. Operation settings were systematically studied, for cooler voltages ranging from 100 V up to 5 kV and magnetic expansion factors between 30 and 100, as relevant for CRYRING operation with beams from the local injector and from the ESR. Finally, the cooler was ready to be brought into operation with ion beam during the CRYRING beam time in November/December 2017.

Commissioning with ion beam

From the local injector, a molecular hydrogen H_2^+ beam was injected and stored into the CRYRING at a kinetic energy of 300 keV/u (β=0.025, revolution frequency= 140 kHz). The operation cycle was about 8.5 s, limited by the ion beam lifetime under the given vacuum residual gas pressure in the ring. This was sufficient to demonstrate the reduction of the phase space volume of the ion beam under electron cooling. Figure 1 shows the evolution of the vertical ion beam size during cooling. The profiles were recorded with an ionization profile monitor (IPM) after optimization of the x and y electron cooler steerers in the cooling section, to provide fastest cooling (best alignment to the ion beam). In figure 2 the corresponding longitudinal cooling is shown. This waterfall Schottky spectrum was recorded for a coasting ion beam of $2 \cdot 10^8$ ions (5µA current) at the 20th harmonic (2.8 MHz). The settings of the electron cooler were: cooler voltage 168 V, electron density $1.3 \cdot 10^6$ cm^{-3}, adiabatic magnetic expansion factor 100 (gun at 2 T, cooling solenoid at 0.02 T). Thus, the electron beam expands from the cathode (4 mm diameter) to a diameter of 40 mm in the cooling section. This electron beam fully overlaps the ion beam in the cooling section. This was confirmed by the measured ion beam spots on the IPMs and the known lattice functions. Partial horizontal overlap between electrons and ions was seen for smaller electron beam diameter (28.3 mm, for expansion factor 50).

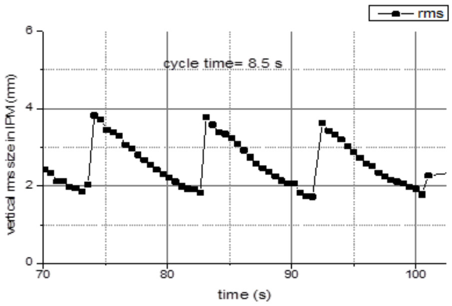

Figure 1: Due to electron cooling the transverse ion beam size (i.e. the transverse emittance) decreases with time. Vertical rms beam size as recorded with an IPM. Simultaneous reduction of the horizontal beam size was observed with a separate IPM in a similar way.

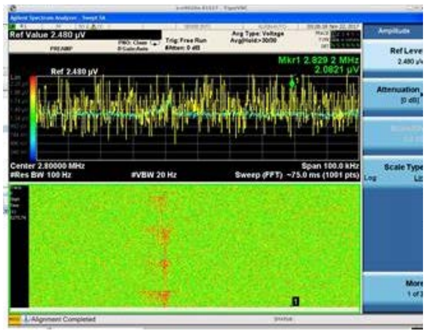
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Figure 2: Schottky spectrum showing the evolution of the frequency distribution i.e. of the momentum distribution of the stored ion beam (horizontal axis) with time (vertical axis) under the action of electron cooling.

The cooling effect was further verified by slightly varying the cooler voltage (i.e. velocity mismatch between the electron and the ion beam) and observing in the Schottky spectrum that the ion beam distribution was pulled towards the velocity of the electrons.

The superconducting gun solenoid worked at the required fields (up to 3 T) but its Helium consumption was extremely high, so that the cryostat had to be filled every 30 hours. This indicates a thermal leak inside the cryostat system which is presently under investigation.

In summary, the CRYRING electron cooler and its dedicated control software were successfully put into operation with stored ion beams at fixed energy. In 2018, the ramped operation mode will be implemented so as to apply cooling at variable beam energies within the machine cycle (i.e. accelerated/decelerated ion beams), as requested by physics experiments. In general, the cooler needs further runs with stored ion beams of sufficient lifetime compared to the expected cooling times.

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Progress on the construction of the precision high voltage divider for the electron cooler at CRYRING

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[1]Institut für Kernphysik, WWU Münster; [2]Institut für Kernphysik, TU Darmstadt

In high precision experiments at ion storage rings the velocity of the ions is a critical quantity. For measurements at CRYRING the electron cooler determines the ion velocity and momentum spread of the ions by superimposing the ion beam with a monoenergetic electron beam. Consequently, a precise knowledge of the acceleration voltage of the electron beam is essential for the accuracy of the experiments. Therefore, we construct a high-precision voltage divider for voltages up to 35 kV which will be similar to the ultrahigh-precision voltage dividers which have been constructed in Münster in cooperation with PTB for use at the KATRIN experiment [1, 2]. The precision of the divider will be in the low ppm range.

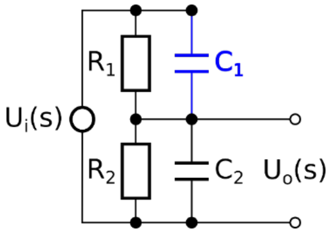

Figure 1: Compensation of a capacitance C_2 by introducing a capacitance C_1 that fulfils the compensation condition $R_1C_1 = R_2C_2$.

Besides static electron cooler voltage measurements, periodic detuning of the electron cooler voltage on time scales of several ms is necessary for electron-ion merged-beam experiments [3]. Hence the voltage at the voltage taps of the HV-divider has to settle in an appropriate timing window to be able to measure the applied voltage with the desired precision. Since the divider is not an ideal ohmic divider (Vishay precision resistors have a capacitance of approximately 0.5 pF [4], stray capacitances, etc.), the settling time of the voltage at the voltage taps is frequency-dependent. A method to optimize the timing behaviour of the high voltage divider has been developed based on the all-pass filter principle. The principle is illustrated for a simple ohmic-capacitive divider as shown in Fig. 1 with a transfer function of:

$$\frac{U_o(s)}{U_i(s)} = \left(\frac{R_2}{R_1 + R_2}\right) \cdot \frac{sR_1C_1 + 1}{s(R_1 \parallel R_2)(C_1 + C_2) + 1}$$

By dimensioning the capacitance C_1 according to the all-pass compensation condition $R_1C_1 = R_2C_2$, the system becomes frequency independent. By applying this method, the transient response of the HV-divider could be optimized in simulations as shown in Fig. 2. For the real setup this method is limited by unknown stray capacitances which have to be determined experimentally.

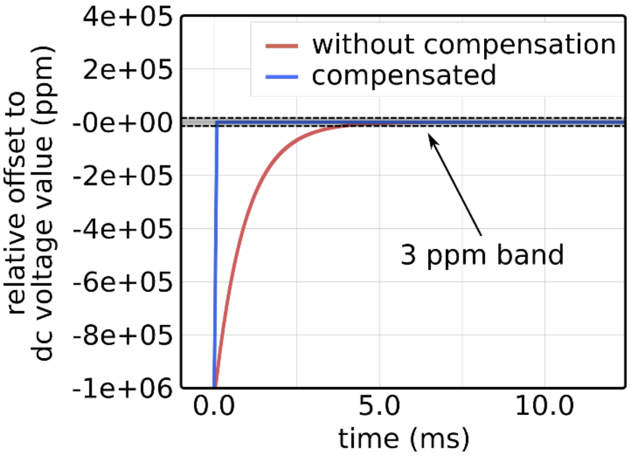

Figure 2: LTspice XVII transient response simulation to 1 kV amplitude ramp with 12µV/s ramping speed for 100:1 voltage tap of the HV-divider [5].

The construction of the high voltage divider has started end of 2017 (see Fig. 3) and is expected to be finished in February/March 2018. Subsequently calibration and characterization measurements will be conducted before integration of the HV-divider into the CRYRING framework.

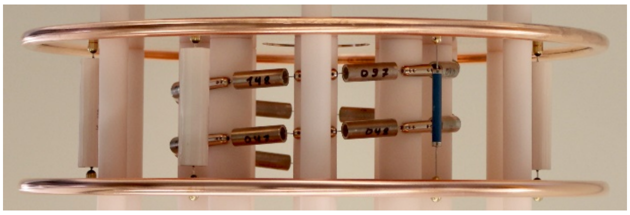

Figure 3: Setup of one of the precision resistor planes of the new HV-divider.

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[5] T. Dirkes, Bachelor Thesis, Münster 2017.

Experiment beamline: CRYRING
Experiment collaboration: APPA-SPARC
Experiment proposal: none
Accelerator infrastructure: CRYRING
PSP codes: 1.3.1.5.8.2
Grants: BMBF contract No. 05P15PMFAA
Strategic university co-operation with: WWU Münster