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DECELERATION OF ION BEAMS – RELATED CHALLENGES AND OPPORTUNITIES

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Abstract

The GSI facilities of CRYRING@ESR and HITRAP are used to decelerate ion beams to low energies. Slow ions are essential for precision experiments in various fields, including atomic physics and nuclear astrophysics. However, producing heavy, highly charged ions is most efficient at high energies, so dedicated ion facilities are needed to match production and experiment. This short overview will highlight the challenges and hint at potential solutions for these facilities.

INTRODUCTION

Heavy, highly charged ions play a central role in numerous physics experiments, especially in atomic physics but also in nuclear and solid-state physics. While for atomic physics investigations it is most interesting to inspect systems with only one, two, or few electrons left (H-like or He-like), nuclear physics experiments profit from the absence of all electrons. To utilise these ions for precise investigations, it is often necessary to reduce their kinetic energy.

Deceleration facilities for heavy, highly charged ions cannot use matter based methods like gas cells or solid degraders for energy reduction since the charge state will be changed and the ions of interest will be lost. Hence, the deceleration of highly charged ions can only be done using the known acceleration principles, using electric fields as in the RF gaps of synchrotron rings or using standard linear accelerator structures.

As the reduction of the centre of mass energy of any ion beam will also increase the beam emittance due to the conservation of the phase space according to Liouville's theorem, which states that the phase space density of a particle beam in a conservative system remains constant. This implies that any reduction in the center-of-mass energy of an ion beam will inevitably lead to an increase in beam emittance. To counteract this effect, the application of cooling methods is essential to reduce the phase space.

In addition, it is important to emphasize that dedicated detectors are key for efficient deceleration. The targeted use of such detectors can optimise beam properties and make the cooling process more effective by close inspection of beam properties even for slow and/or weak ion beams.

An overview of the accelerator chain at the GSI Helmholtz center for heavy ion research is given in Fig. 1 with emphasis on the functional dependencies. Heavy ions are accelerated and stripped, in up to three steps, before they finally reach the Experimental Storage Ring ESR in the desired charge state. Then, two dedicated facilities, the low energy storage ring CRYRING@ESR and the linear decelerator facility HITRAP, are used to provide heavy, highly charged ions at low energies.

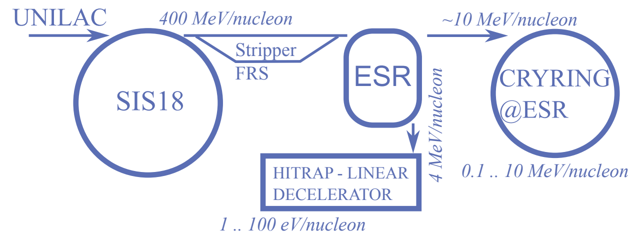

Figure 1: Functional overview of the GSI facilities for slow, exotic, ion beams with indicated beam energy ranges. The machines are not to scale.

Both rely on the ESR for the first deceleration and cooling steps after production. After production, typically at a few 100 MeV/nucleon, the ion beam is stored in the ESR, cooled using electron cooling, proceeded by stochastic cooling in some cases, and then extracted into two different beam lines.

Since the existing beam lines, the so called high energy transfer lines (HEST) were originally designed for high energy beams of up to 10 Tm or beyond, it was not clear that an efficient transfer of low energy ions at only around 1 Tm would be efficient. Reasons are the operation of power supplies at the lower end of their control range and the intermittent use of the same magnet for beams of very different rigidity. After a dedicated campaign in 2020 transfer efficiencies measured as the quotient of stored beam in the ESR and stored beam in CRYRING@ESR of about 40% have been reached eventually for an ion beam of 10 MeV/nucleon and can now be used routinely.

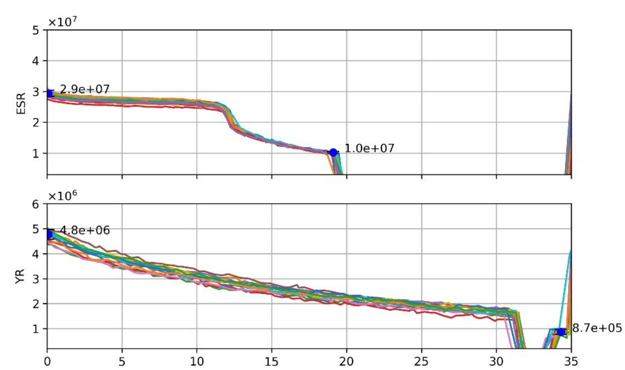

Figure 2: Transfer efficiency ESR – CRYRING@ESR (labelled with "YR") measured to 39(1)%. In the upper graph, the number of particles stored in the ESR are plotted for a number of cycles. The second plot shows the number of particles stored for the corresponding cycle in CRYRING@ESR. The dots with error bars give the number of particles averaged over the analyzed 14 cycles.

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The rightmost dot (8.7×10^5 particles) measures the average background of the used parametric current transformer.

The transfer into the HITRAP beam line is much more straight forward but still challenging and has proven to work equally well. However, it turned out quickly that the standard wire based beam profile monitors ("wire grids") are not sensitive enough for a detailed beam profile measurement of the 1 μs short macro bunch containing in the beginning of the beam transport optimization process only 10^6 ions. The most used diagnostic system for beam shape inspection is a Ce-doted YAG crystal read with a standard CCD camera.

THE CRYRING@ESR PROJECT

CRYRING@ESR is a low energy synchrotron [1] dedicated to in-ring experiments but also capable of fast and slow extraction towards a fixed target station [2]. A schematic overview is given in Fig. 3. The ring consists of 12 sections, 6 of which contain quadrupoles and sextuples and 6 are used for injection, electron cooling, radio-frequency cavity, extraction and laser interaction, in ring gas and electron target and Schottky detection. See Fig. 2 for an overview of the optical and functional layout. The ring's circumference is 54 m, a slight increase from its first installation in Stockholm, in order to meet just half the ESR circumference. It can handle beams between 0.055 and 1.44 Tm rigidity. Two strong points are the very good vacuum required for long-term storage of even very slow ions and the high-performance electron cooler [3]. A local injector can deliver light ions for commissioning and also some physics experiments based on a permanent magnet electron cyclotron resonance (ECR) ion source [4] and a 4-rod RFQ [5].

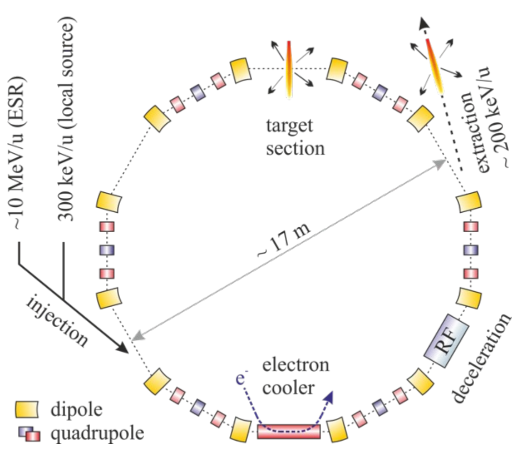

Figure 3: Overview of the low-energy synchrotron CRYRING@ESR in the layout used at GSI, Darmstadt.

The low energy storage ring part of the CRYRING@ESR project is an in-kind contribution by Sweden to FAIR. It has been brought to GSI/FAIR in 2012/2013 and subsequently renovated, installed, and recommissioned. Notably, in addition to the refurbishment of many devices, fast injection and fast extraction systems were added. By 2021, routine operation has been established, serving the FAIR Phase-0 physics programme with heavy, highly charged ions produced in the accelerator chain via the ESR or light ions produced locally [6].

To set up a well-controlled ion beam, a sensitive and conclusive detection of the beam and its properties is essential. CRYRING@ESR is hence equipped with all the standard beam detection systems for storage rings, i.e. Schottky detector, beam position monitors and parametric and integrating current transformers. However, slow ion also means low signal on many of those systems hence more sensitive equipment needs and was installed and tested. Especially when comparing current sensitive detection schemes using induced magnetic fields ("parametric current transformer") it is worth mentioning that the signal for the same amount of ions is proportional to their velocity.

CRYRING@ESR has been operated as part of the GSI accelerator chain during the last years and a long list of different ion species has been stored, cooled, accelerated or decelerated and delivered to experiments. The local source and injector delivered H, D, Li, C, O, F, Ne, Mg, S ions in different charge states to experiments. Using the GSI accelerator chain and the ESR for first deceleration and cooling experiments at CRYRING@ESR were provided with highly-charged U, Pb and Au ions at energies between 10 and 4 MeV/u.

Table 1. Overview of ion species delivered to experiments with CYRING@ESR. If no isotope mass given, the most abundant was used.

From local injector	From GSI via ESR
H_2^+, D^+	Ar^{18+}
C^+, $O^{2+,5+}$, F^{6+}, $Ne^{2,3,7+}$ (gas based)	Pb^{78+}, Au^{78+}
$^{6,7}Li^{+,2+}$, $^{24,25}Mg^+$, S^{3+} (oven based)	U^{91+}

THE HITRAP FACILITY

HITRAP, a linear decelerator and ion trap facility, has been conceived to stop heavy, highly charged ions in an ion trap. For this, the initial energy after the deceleration in the experimental storage ring ESR of 4 MeV/nucleon has to be reduced to typical trapping energies of eV/nucleon and below. In a first step, the about 1 microsecond long macro bunch of ions has to be bunched into nanosecond sub bunches to be suitable for deceleration in 108 MHz RF structures. A double drift buncher, at 108 and 216 MHz, is used for this. The next step is an interdigital H-Type (IH) structure including one inner tank lens. This structure reduces the energy to 500 keV/nucleon. After rebunching to bridge the longish flight pad towards the next structure, a 4-rod radio frequency quadrupole (RFQ) reduces the energy further to 6 keV/nucleon. Then the ions are trapped dynamically in a Penning-Malmberg trap by rapid switching its electric trapping potentials by a few kV.

Every step along this process is prone to inefficiencies. The typical losses for accelerator structures also happen during deceleration, i.e. phase mismatch (ions arrive at the wrong time in between drift tubes) and transversal loss due to beam halo or just misalignment. However, due to the increase in transversal and longitudinal phase space, they are more severe as the ions reach lower and lower energies.

A further complication is the detection of the decelerated ion beam. Ions that gradually move out of phase with the correct decelerating RF oscillation will travel further at initial energy and not be removed from the beam. Hence, an energy selective detection is required at each step and considerable development effort was invested to establish suitable diagnostic systems. I want to give two examples, one for energy selective detection at 500 keV/nucleon and another one at 6 keV/nucleon.

The conventional method for energy selection in analysing ion beams involves using dispersive optics. By altering the dispersion while recording the ion intensity, an energy spectrum of the ion beam is obtained. However, this approach requires time, as each step necessitates a new beam bunch. Since HITRAP is supplied from the ESR, and the cooling and deceleration required in this storage ring take approximately 20 to 40 seconds, we sought a solution to obtain energy spectra for each individual bunch—a one-shot energy analyzer. Initial tests employed diamond detectors, which were fast enough for the extremely short ion bunches but lacked the capacity to handle high rates (between 1×10^6 and 1×10^7 ions per bunch). A retractable permanent magnet, coupled with a very narrow (0.1 mm) slit and a multi-channel plate (MCP) detector, effectively addressed this limitation [7]. It has been implemented in 2010 and used since.

An overview of this detection system, which is used in both positions, between the IH and RFQ as well as after the RFQ, is depicted in Fig. 4. The system after the RFQ is slightly different because it uses a weaker magnet of only 0.1 T adopted to the lower energy range between 500 and 6 keV/nucleon.

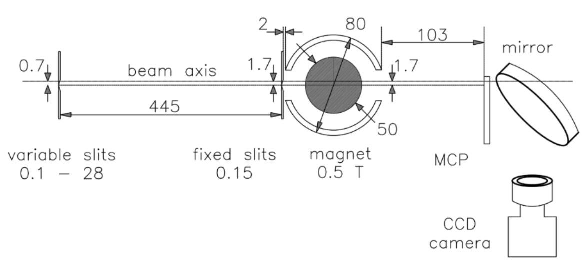

Figure 4: Geometry of the one-shot energy analyzer as used after the IH to separate mainly the initial 4 MeV/nucleon from the target energy of 0.5 MeV/nucleon. All dimensions are in mm.

For the very low energy end, where remaining beam fragments at 4 MeV/nucleon are present along with the final energy of 6 keV/nucleon an electrostatic energy selection is used in order to separate the fast background from the desired slow ions. Based on the original idea by N. R. Daly [8] for an off axis detection to suppress background, a version suitable for 6 keV/nucleon ion beams has been developed in order to suppress the background of the 4 MeV/nucleon beam [9]. See Fig. 5 for a sketch.

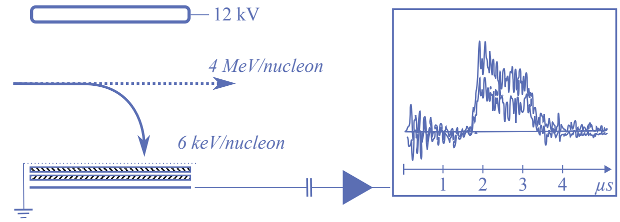

Figure 5: Functional overview of the background suppressing detection setup for 6 keV/nucleon ions. The low energy ions are deflected onto a MCP and the electronic signal is schematic depicted to the right. Very low background is due to secondary electrons the fast ion beam creates during passage or by hitting material in the surroundings.

HITRAP has seen a number of commissioning beam times in the last two years, after a long interruption from 2014 to 2022. During the recent commissioning periods, heavy, highly-charged ions were eventually transported to the cooling Penning trap and their life time in the trap was measured [10]. In 2025 a first experiment was supplied with bare gold ions, Au^{79+}, to irradiate different surfaces. This marks the first ever experiment with decelerated, heavy, highly-charged ions.

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