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PREPARATION OF LOW-ENERGY HEAVY ION BEAMS IN A COMPACT LINEAR ACCELERATOR/DECELERATOR

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Abstract

High precision tests of fundamental theories can often unfold their full potential only by using highly charged ions (HCI) at very low energies. Although in light of the envisaged energies at FAIR, experiments in the keV to MeV range may sound like backpedaling, these two techniques are in fact complementary, since the production of heavy HCI is virtually impossible without prior acceleration and electron stripping. However, subsequent preparation, transport, storage and detection of low-energy HCI bring new, surprising sets of problems and limitations. Here we will give an overview of the CRYRING@ESR local injector [1] and the HITRAP linear decelerator [2]. These two facilities consist out of one or two accelerator or decelerator stages, with a total length of around 10 meters, making them "compact" in comparison to other GSI accelerators. The following sections describe their main design parameters, the achieved ion numbers, challenges of beam detection, as well as some special features such as multi-turn injection and single-shot energy analyzers. The conclusion will present the current status and will also give an outlook of the planned applications of low-energy ions at the FAIR facility.

WHAT ARE LOW ENERGIES?

Although the term "low-energy" is often used with ease to describe stored ion beams, there is no strict definition of the term and the actual energy can range over several orders of magnitude. In a storage ring, beams of highly charged ions are labeled as slow already below 10 MeV/u, although their velocity still amounts to about 10% the speed of light c. A small-scale linear accelerator brings charged particles to a few hundred keV/u, while in a linear decelerator and a subsequent ion trap, ions can be slowed down almost to rest, pulling the energy over eight orders of magnitude to the sub-eV range. Therefore a more practical description of "low energies" would relate to a diffuse lower limit of a system, behind which a different way of handling ions is necessary, if compared to a "high energy" range of the same system, e.g. an accelerator. It should be noted that the reason for this discrepancy can be both physical, such as scaling of cross sections [3] or beam emittance, and technical, such as device stability or detector noise.

For precision experiments, low energy storage rings like CRYRING@ESR, or Penning traps like HITRAP are the devices of choice. They can provide excellent experimental conditions since effects like Doppler corrections and corresponding uncertainties at low energies are either smaller and/or they can be controlled with higher accuracy, while providing high luminosity or density at the same time. At CRYRING@ESR, electron cooling at comparably low beam energies is enhanced by transversal expansion of the electron beam upon leaving the high magnetic field produced by a superconducting magnet [4]. This process effectively reduces the temperature of the electron beam and consequently of the ion beam, enabling unprecedented experimental accuracy.

Even lower energies can be reached by extracting the ion beam from a storage ring and then employing a linear decelerator, such as HITRAP. Given the energy after multi-stage deceleration is sufficiently low for electrostatic manipulation, ions can be injected into a Penning trap [5], such as the cooling trap of HITRAP, giving the possibility to store ions basically at rest. Trapped ions are then either readily available for experiments, or they can be prepared according to the needs of an experiment and extracted at a desired energy. At this point, for convenience, the energy unit of eV/mass unit (u) commonly used for magnetic beam steering is replaced by eV/charge (q) which is more suitable for electrostatic, low-energy beam manipulation. The HITRAP transport beamline [6] typically operates at 4 keV/q, which requires a separation of doublets around a meter over the full transport length, with diagnostic elements after each pair, before the beam either hits a target or is retrapped by an experiment.

CRYRING@ESR LINEAR ACCELERATOR

The magnetic rigidity ranging from 1.4 Tm down to 0.08 Tm offers the CRYRING@ESR storage ring the possibility to work with very low ion energies. Next to heavy, highly charged ion beams from the GSI accelerator, CRYRING@ESR can also store lighter ions from a local compact injector without the use of the full accelerator chain. The properties of this compact ion source and linear accelerator are given in Table 1.

Typically, a compact electron-cyclotron resonance ion source (ECRIS) is used to deliver up to 50 µA of mass-separated D^+ ions in chopped ion bunches 7 – 50 µs in length. Also multiple charge states like Ne^{3+} are possible, though with considerably lower intensity. A Nielson type ion source (MINIS) is used as a backup, delivering slightly lower ion currents. Both ion sources are constructed in a high voltage cage, allowing extraction energies of up to 40 kV/q.

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Table 1: Parameters of the CRYRING@ESR Local Injector

Parameter		min.	typ.	max.
MINIS	[µA]	0.2	5	10
ECRIS	[µA]	0.2	10	50
ion pulse	[µs]	1	50	500
RFQ in	[keV/u]	0.8	10	10
RFQ out	[keV/u]	0.8	292	305
dp/p	[%]	0.5	1	1

The radio-frequency quadrupole (RFQ) accelerates ions with mass-to-charge (m/q) ratio of up to 3 to the designed value of 300 keV/u. Depending on the applied RF power, the final energy and the dispersion will vary in a range 292 – 305 keV/u and 0.5 – 1% respectively. Ions with $m/q >$ 3 can be only transported through the RFQ towards the ring with the energy of the ion source. Interestingly, this presents another limit for injection into CRYRING@ESR, since ions with $m/q < 7$ at ion source potential are too slow (i.e. the beam is "too soft") for the lowest possible storage ring rigidity of 0.08 Tm. In summary, the CRYRING@ESR local injector uses two modes of operation:

1. **Acceleration** for ions $m/q < 3$ with $E = 292$ keV/u at injection
2. **Transport** for ions $m/q > 7$ with $E = 40$ keV/q (corresponds to 1 – 6 keV/u) at injection

Ion beam detectors along the injector comprise a combination of a YAG scintillation screen and a Faraday cup driven on the same axis in and out of the ion beam path. The use of micro channel plate detectors, Chromox or Phosphorus fluorescent screens proved to be either too sensitive for the energy range, or not sufficiently sensitive. The destructive detectors are supplemented with an AC and a DC current transformer to monitor the ion source output before and after mass separation by a dipole magnet.

The injection is done with an electrostatic and a magnetic septum as well as an electrostatic bumper to break the closed orbit of the ring. The bumper power supply is a home-made device, constructed with solid-state 15 kV fast switching units, followed by a series of resistors arranged in a switching matrix with high voltage relays. Together with the natural capacity of the electrodes, the resistors slow down the otherwise too fast exponential slope of the rising/falling edge of the bumper voltage, while the switching matrix enables the operator to choose the appropriate slope for a given ion species and energy. Typical fall times (90% to 10%) range between 5 and 10 times the ion revolution time in the ring. Figure 1 shows stored beam intensity as an ion pulse equal to the ring revolution time is stepwise delayed across the falling voltage of the bumper and injected. It shows that by using this multi-turn arrangement around 4 turns (i.e. ion revolution times) can be injected from the local injector with reasonable stored beam intensity, until the bumper voltage becomes either too large or too low for proper injection, or ultimately, until the phase space is completely filled. Efforts are ongoing to improve on this result.

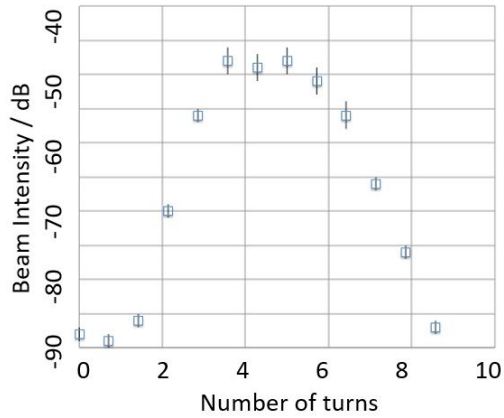

Figure 1: Stored beam intensity as a function of injection time with respect to the bumper trigger. One injection corresponds to one revolution time in the ring (one "turn"). The peak corresponds to ions which were efficiently injected, with the bumper voltage either too low or too high for proper injection outside of this region.

The low energy of the particles injected from the local injector imposes certain restrictions on the diagnostic elements of the storage ring. After the first round is established by using destructive detectors, multi-turn beam storage is typically optimized by observing the beam position monitors (BPM). These are constructed as capacitive pick-up electrodes shaped as diagonally cut hollow cylinders. The noise level of the BPM amplifiers competes with the signal from the stored ion beam and sets the lower intensity limit to about $5 \cdot 10^5$ charges, while reliable measurements significantly above the background noise level require $> 4 \cdot 10^6$. Other non-destructive detectors of coasting beams, such a Schottky noise or DC current transformer offer even lower sensitivity at the given energies. Consequently, the lowest intensity an ion source for the CRYRING@ESR local injector has to deliver amounts to about $3 \cdot 10^7$ charges, in order to reach the minimal storage ring intensity after mass separation and the usual transport losses.

The ion position monitor (IPM) images the beam profile by guiding the residual gas particles, ionized by the circulating beam, towards an MCP with a resistive anode. The field cage of the IPM operates at voltages around 5 kV, which is seen by the incoming particles as a fixed-field electrostatic steerer. If the acceleration mode of the injector's RFQ is used, the kick amounts to 1 mrad and does not significantly influence the stored beam. At higher energies, e.g after acceleration or with beam injected from the GSI accelerator, this angle is even smaller. However, if the transport mode of the RFQ is used, the IPM kick amounts to 143 mrad, which destroys the beam in a single turn. Thus, even though beam profiling would be possible after acceleration, the IPM is effectively not available for low-energy particles which are lost upon injection. Efforts are ongoing to construct a new version of the IPM which will make injection possible by either voltage switching or active compensation.

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HITRAP LINEAR DECELERATOR

The GSI accelerator facility can deliver a large scope of elements at almost any charge state and prepare them for experiments. This process typically involves several acceleration and electron stripping stages, resulting in up to 10^8 highly charged ions stored at the Experimental Storage Ring (ESR). Starting from the initial energy of 30–400 MeV/u, the ions are decelerated to 4 MeV/u, electron cooled and extracted in 1 µs bunches (roughly 1 m long). The full process of preparing the beam takes 30–60 seconds, defining the delivery rate for further deceleration. The extracted ion bunch, comprising typically $10^6 - 10^7$ ions, is guided through several meters of a transport beamline before entering the HITRAP cave. There, the bunch is first reshaped into micro-bunches by two double-drift-bunchers operating at 108 MHz and 216 MHz. Two phase probes monitor the beam energy by measuring the phase advance between individual micro-bunches and overlaying the data for multiple periods. The energy of 4.02(1) MeV/u necessary for injection into the first deceleration stage can then be fine-tuned by adjusting the electron cooler voltage of the ESR.

The interdigital H-structure (IH) is designed to decelerate ions from 4.02 to 0.495 MeV/u with an efficiency of up to 60%. Unlike particle acceleration where the beam successively enters regions with higher magnetic rigidity, in the case of deceleration the subsequent beam steering elements are designed for lower energies while the non-decelerated fraction of the main beam remains unaffected. Therefore a dedicated single-shot energy analyzer was developed in order to set-up deceleration and monitor the efficiency. It consists of a 0.5 T permanent magnet followed by a micro-channel plate (MCP) detector. A narrow slit in front of the energy analyzer increases the accuracy and decreases the non-decelerated beam intensity on the MCP at the same time. With this setup it was possible to separate individual energy components with a resolution of around 0.01 MeV/u. Figure 2 shows the design of the energy analyzer and the energy spectrum directly behind the IH decelerator. The image reveals the non-decelerated beam on the top together with several mid-energy stages, followed by full deceleration to 0.5 MeV/u in the lower part.

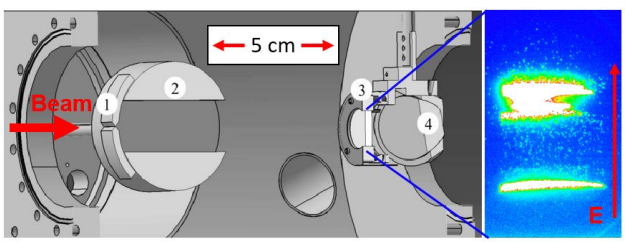

Figure 2: The HITRAP single-shot energy analyzer, comprising a slit (1), a permanent 0.5 T magnet (2), an MCP with a phosphorus screen (3) and a mirror (4) for reflecting the image towards an externally mounted CCD camera (not shown). The image on the right hand side shows the energy spectrum.

After the IH decelerator the particles are rebunched by another beam buncher in order to match the requirements for efficient injection of the decelerated beam into the second deceleration stage - a radio-frequency quadrupole (RFQ). The acceptance in terms of phase and energy are ±3° and 495 ± 5 keV/u respectively, requiring precise tuning of both beam direction and the IH structure. Without prior experience, if the full phase and amplitude ranges are taken into account, this can be a very tedious task with a beam repetition rate of 30-60 seconds. If the correct parameters are set, the ions leave the RFQ with about 6 keV/u. As in the case of IH, the decelerated beam is accompanied by the non-decelerated components at 4 and 0.5 MeV/u. This energy spectrum is analyzed in the same fashion as shown on Fig. 2. The resulting distribution can be seen on Fig. 3.

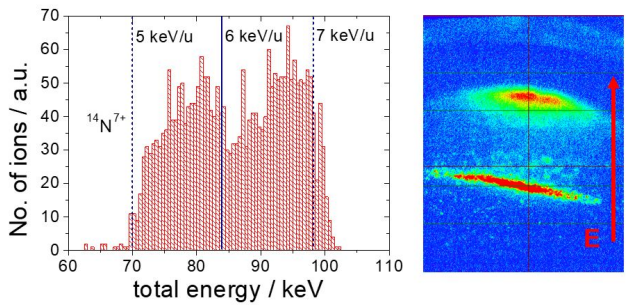

Figure 3: Left: energy distribution of decelerated ions behind the RFQ (simulation). The image on the right-hand side shows the energy spectrum recorded on the RFQ single-shot energy analyzer.

Transport between the RFQ and the ion trap is realized with six einzel lenses operating at voltages up to −40 kV, guiding the beam through two pumping barriers and some 2.5 m of beamline. Figure 4 shows the simulations of such an ion beam with an energy distribution of 18 ± 2 keV/q and an emittance of 200 π mm mrad.

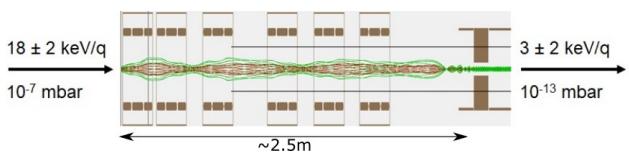

Figure 4: Simulation of the transport beamline between RFQ and entrance of the trap. Beam trajectories in different colors represent different energies.

However, with the dispersion of 30% and a very large emittance, the decelerated beam leaving the RFQ is very challenging for further transport and requires cooling. This is realized by the so-called HITRAP cooling trap, a seven-electrode, nested Penning trap, designed to capture and cool the decelerated HCI by mixing them with externally produced, pre-cooled electrons [7]. Energy is transferred via Coulomb-interaction from HCI to the electrons, which are being constantly cooled by emitting synchrotron radiation in the strong 4 T magnetic field of the Penning trap. Finally,

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the cooled ions are extracted and can be transported via a low-energy beamline [6] towards various experiments.

Besides the heavy HCI provided by the GSI accelerator infrastructure, a small dedicated electron beam ion trap (EBIT) [8] attached to the low-energy beamline is used as an offline ion source, in a similar fashion as the local injector described in the previous section provides ions for CRYRING@ESR. The EBIT has a typical output of about 10^6 charges, usually bringing up to 10^5 mass separated, medium-heavy highly charged ions, available for cooling trap commissioning or experiments.

CURRENT STATUS AND PLANS

Since its commissioning in 2016 the local accelerator has produced and injected into CRYRING@ESR the following ion species: H_2^+, D^+, $^7Li^+$, $^{12}C^+$, $^{16}O^{2\ldots6+}$, $^{20}Ne^{2\ldots3+}$, $^{24}Mg^+$, $^{25}Mg^+$, $^{40}Ar^+$, with D^+ being by far the simplest and most used ion, mostly for commissioning and machine experiment purposes. Typical intensities at injection range between 10 µA for singly charged, gaseous elements like D^+, over 1 µA for higher charge states like $^{20}Ne^{3+}$, to a few 100 nA for $^{25}Mg^+$, as a less abundant natural isotope from an ion source oven. Translated into number of particles, this corresponds to $10^8 - 10^9$ stored D^+ to $10^6 - 10^7$ stored Mg^+, both coming close to the space-charge limit of the storage ring due to the incoherent tune shifts. The injector has thus proven to be a versatile tool for operation of CRYRING@ESR without the use of the GSI accelerator chain, both for commissioning and for experiments with low-energy ion beams.

The last time ions were injected into HITRAP was 2014, before the FAIR shutdown and upgrade period of the GSI accelerator. The linear decelerator has remained in standby for several years, with only the low-energy beamline and the ion trap seeing some operation with ions produced by the local EBIT. The ion trap has also been modified to accommodate higher stability and easier operation [7]. Recommissioning in 2022 brought both deceleration stages back into operation and ions at 6 keV/u were reestablished, while the low-energy beam transport and ion trapping still remain as open tasks for the online beam. Nevertheless, efforts are ongoing to establish ion cooling offline by experimenting with ions from the EBIT. At the same time the FAIR control system is being expanded to include the full HITRAP facility, ensuring continuity and making further commissioning more effective.

As a part of FAIR, a new low-energy facility is planned within the framework of NUSTAR collaboration. The MATS-LaSpec facility [9] will be located at the very end of the superconducting fragment separator (SFRS), taking decelerated rare isotopes produced online by nuclear reactions. These short-lived isotopes will be directed at 5 keV/q through several meters of beamline, a cooler and buncher RFQ, to reach experimental setups for in-trap mass measurements (MATS) or in-flight laser spectroscopy (LaSpec). As commonly the case with low-energy experiments, new challenges of ion handling are mostly compensated by the prospect of both high precision measurements of shortest-lived isotopes and decay studies, as well as high sensitivity and accuracy for the study of very exotic nuclides that will be possible only at the FAIR facility.

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