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RECOMMISSIONING OF THE CRYRING@ESR ELECTRON COOLER

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Abstract

The heavy-ion storage ring CRYRING has been recommissioned downstream of GSI's ESR, which it complements as dedicated low-energy machine. A key element of CRYRING@ESR is its electron cooler, which features one of the coldest electron beams available. This enables efficient phase-space cooling and, in addition, provides very high energy resolution when used as internal electron target. We report on technical upgrades that have been made as part of the re-installation of the cooler at GSI/FAIR and share first results obtained after recommissioning.

INTRODUCTION

After years of successful operation at Manne Siegbahn Laboratory (MSL) [1], the heavy-ion storage ring CRYRING has been transferred to GSI/FAIR. Within the CRYRING@ESR project, the ring can serve precision experiments with ion beams produced by the GSI accelerator complex [2]. Highly-charged heavy ions from the UNILAC/SIS18 accelerator chain can be injected after deceleration in the Experimental Storage Ring (ESR). Weakly-charged ions can be obtained by injection from an independent low-energy linac, followed by synchrotron acceleration in CRYRING.

CRYRING@ESR heavily relies on electron cooling as a means to deliver high-quality stored beams to in-ring experiments. Additionally, the electron cooler itself serves as a platform for low-energy electron-ion collision experiments.

TECHNICAL UPGRADES

Installation of the electron cooler at GSI/FAIR provided the opportunity for a number of technical improvements.

Superconducting Gun Solenoid

Already at MSL, the cooler had been equipped with a down-sized electron gun designed for strong magnetic expansion of the beam by field ratios up to 100, thus enabling very low transverse electron temperature. The high-field region (up to 4 T) at the gun is created by a superconducting solenoid immersed in liquid helium (LHe, c.f. Fig. 1) [3].

Formerly, boiled-off LHe had been re-supplied manually from mobile dewars. To improve operational efficiency and reduce costs, the LHe cryostat has been statically connected

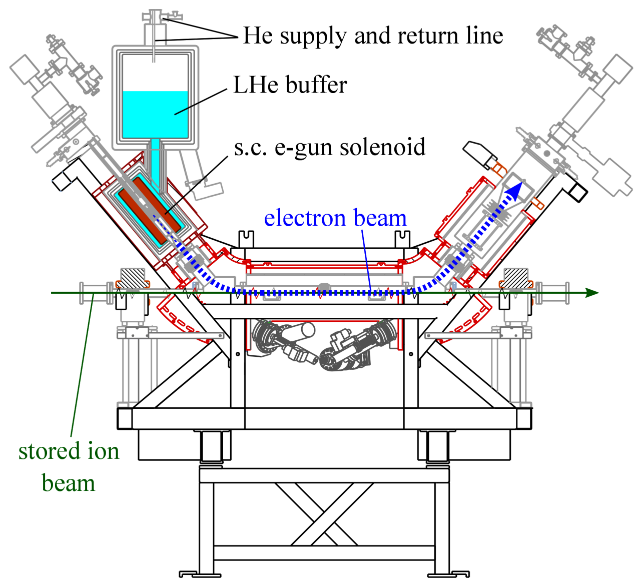

Figure 1: The CRYRING@ESR electron cooler.

to a closed-loop He liquefaction plant run by GSI. The LHe buffer of the solenoid is now refilled once per week, while evaporating He is continuously recuperated via a return pipe that also serves as pre-cooling circuit for the LHe input line. The new refilling procedure requires neither interruption of cooler operation nor personnel to access the CRYRING radiation-protection area.

High-Voltage System

Cooling of highly-charged ions, injected from ESR into CRYRING, typically requires electron energies ≲8 keV, which are possible using the original vacuum electrodes and high-voltage (HV) terminal. However, a number of modifications to the HV system have been made to enhance its capabilities as an experimental platform.

A system enabling fast changes of the electron acceleration voltage has been installed. It consists of a fast HV amplifier (KEPCO BOP-1000M) that, connected in series with the main HV supply, can be used to modulate the nominal terminal voltage by arbitrary waveforms in a range of ±1000 V. For electron-target experiments or cooling force measurements, rapid (~ ms) step-like changes of the energy are normally used. As the emission current of the electron gun depends weakly on the acceleration voltage, a high-bandwidth floating current measurement for the electron

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collector cup has been developed, so that the beam intensity can be measured accurately also during fast energy ramps.

A solid-state HV switch has been installed at the extraction electrode of the electron gun, enabling fast switching of the cooler electron beam controlled by the accelerator timing system.

Precision experiments need to monitor the long-term stability of the electron energy with high accuracy. Thus, two new precision HV dividers have been developed. The first, named 'G35', is a variant of the 35-kV precision divider designed for the KATRIN experiment [4]. During electron cooling, it allows one to measure the electron acceleration potential with relative accuracy $<10^{-5}$. As a dedicated DC device, the G35 cannot be used during electron-target experiments involving fast energy ramps. It is hence complemented by a second, frequency-compensated voltage divider, the 'FC20', suitable for measurements on <10-ms time scales [5]. The FC20 reaches the same level of precision, but has lesser long-time stability compared to the G35. It is therefore designed to be calibrated against the latter on regular basis.

Control Systems

Mostly, the original MSL power converters and HV supplies are still used for defining the cooler magnetic fields and electric potentials. They have however been equipped with new front-end CPUs and DACs for integration into the FAIR accelerator control system developed at GSI.

In electron-target operation, an independent experimental micro-controller/DAC combination, interfacing the fast HV amplifier and synchronised with the FAIR timing system of CRYRING, generates the fast voltage ramps for modulation of the cooler base potential. Fast correction of further cooler parameters, like electron beam steerers, under authority of the experiment is foreseen. This hybrid control system allows set-up of the electron cooler base parameters via the standard CRYRING@ESR operator interfaces while providing maximum flexibility to experiments with regard to arbitrary fast energy variations.

OPERATIONAL EXPERIENCE

Electron Cooling

Figure 2 shows characteristics of a beam of $^{238}U^{91+}$ stored and cooled in CRYRING at 10.3 MeV/u. Accelerated in UNILAC and SIS18, the ions were stripped to the desired charge state at 300 MeV/u and injected into the ESR storage ring. ESR decelerated the particles to 10.3 MeV/u, and, subsequently, they were transferred to CRYRING.

The CRYRING electron cooler operated at 5.63 kV acceleration voltage and at a current of 30 mA. An intermediate magnetic expansion factor of 33.3 was used (1 T at the gun vs. 0.03 T in the cooler solenoid), yielding an electron beam of ~2.3 cm diameter and a particle density of $\sim 1\times10^{7}$ cm^{-3}.

The ring operated in coasting-beam mode, so that the electron cooler defined the storage velocity of the ions. This is visible in Fig. 2(a) (top frame), displaying the evolution

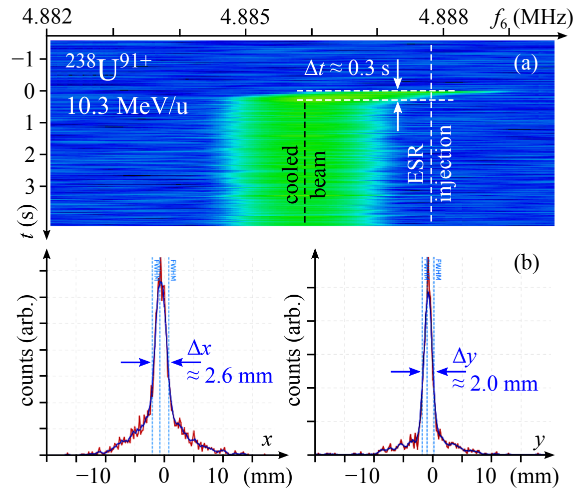

Figure 2: Electron cooling of an ESR-injected beam of $^{238}U^{91+}$ at 10.3 MeV/u. Top (a): 6th harmonic of Schottky spectrum vs. storage time. Bottom (b): Final horizontal (x) and vertical (y) beam profiles measured at the IPMs.

of the Schottky noise spectrum as a function of storage time, measured at the 6th harmonic of the revolution frequency. Within 0.3 s after injection (at $t = 0$ s), the revolution frequency changed by ~0.3 kHz under the effect of electron cooling.

Although the $^{238}U^{91+}$ beam was pre-cooled in the ESR, time-dependence of the kicker fields and imperfect injection matching led to significant emittance blow-up upon transfer to CRYRING. Within ~1 s, electron cooling reduced the transverse beam diameters back to below 3 mm, as measured via residual-gas-ionisation beam profile monitors (IPMs). The steady-state horizontal and vertical beam profiles after cooling are displayed in Fig.2(b) (lower two panels).

Weakly-charged heavy ions require very different electron cooler parameters. Figure 3 displays measurements on cooled beams of $^{24}Mg^{+}$ and $^{25}Mg^{+}$. The ions were injected from a local ECR source at 35 keV and accelerated in CRYRING to the maximum rigidity allowed by the ring magnets. The latter limited the flat-top ion energies to 0.168 MeV/u and 0.155 MeV/u, respectively.

To match the low ion velocities, the cooler needed to operate at acceleration potentials around ~100 V, space-charge limiting the emission current from the electron gun to ~1.7 mA. At a magnetic expansion factor of 33.3, this resulted in a beam density of $\sim 5\times10^{6}$ cm^{-3}.

Rf-bunching of the beams was maintained also at the final ion energy. Within ~3 s, electron cooling reduced the bunch length to a final value of ~110 ns – close to what is expected for space-charge-limited bunch size at the given ion current, rf amplitude, and harmonic number [cf. Fig. 3(a)].

The low electric rigidity of the Mg^{+} beams at injection prohibited use of the IPMs, as they caused excessive orbit perturbations. However, the beam diameters could be measured indirectly by imaging of neutral Mg atoms from charge-exchange with the residual gas [cf. Fig. 3(b)]. Using the known beta functions of CRYRING, the beam size

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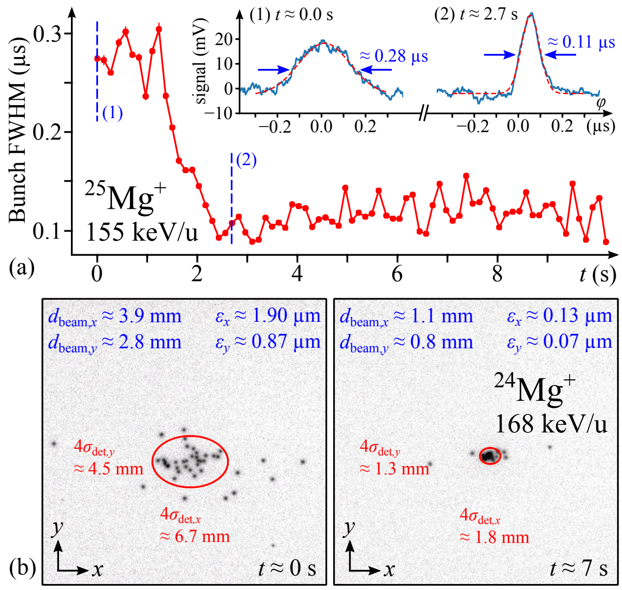

Figure 3: Electron cooling of slow, rf-bunched beams of Mg$^+$. Top (a): Evolution of the ion bunch length (15th harmonic) as a function of cooling time t. Bottom (b): Transverse beam sizes (d_{beam}) and 95%-emittances (ε) before ($t \approx 0$ s) and after ($t \approx 7$ s) cooling, measured by imaging of neutral Mg atoms from charge-exchange (black dots).

in the straight section preceding the imaging detector can be inferred from the measured distribution of neutral hits. Within ~7 s, electron cooling decreased the horizontal and vertical beam diameters from several mm after acceleration to ≃1 mm, corresponding to 95%-emittances of the order of 100 nm.

Electron Target Operation

Several experiments on resonant recombination have used the cooler in electron-target mode. De-tuning of the electron velocity with respect to that of the cooled ions was used to induce collisions at specific energies. To prevent re-acceleration of the ions under the effect of the cooling force, the terminal voltage alternated rapidly between the values corresponding to "cooling" and "target" electron energies.

The voltage measurement in Fig. 4 shows a typical modulation of the cooler potential during such an experiment. In the example, the scanned voltage intervals on both sides of the "cooling" point correspond to electron-ion collision energies between 9.1 eV and 16.6 eV.

SUMMARY AND OUTLOOK

The CRYRING electron cooler has been recommissioned at GSI/FAIR and has been used successfully for cooling of, both, highly- and singly-charged heavy ions. Several technical upgrades have been implemented to improve operational performance and flexibility as experimental platform.

Further improvements of the cooler are planned. The ageing main HV supply as well as some vacuum and bake-out system components will be replaced in upcoming maintenance shutdowns. We are investigating the possibility of

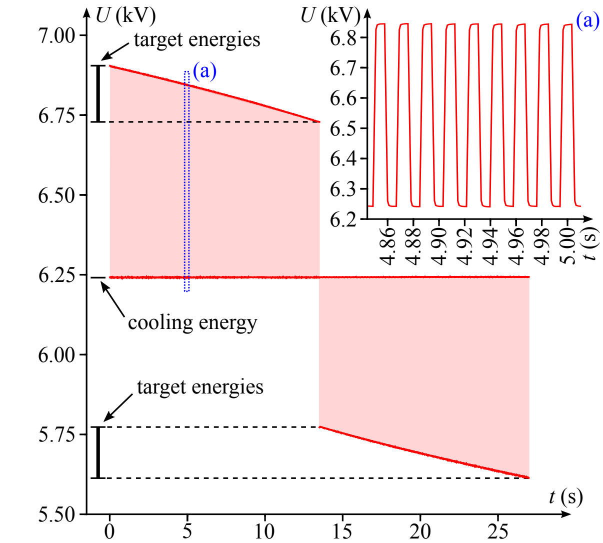

Figure 4: A typical ramp of the terminal voltage U during an experiment using the cooler as electron target. The inset (a) shows a magnified view of the 15-ms cycling between cooling and target energies, unresolved in the main plot.

additional electron beam diagnostics providing information about the transverse current distribution.

Dedicated machine experiments are planned to measure cooling forces and energy resolution in target experiments.

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