BEAM COOLING SYSTEMS AND ACTIVITIES AT GSI AND FAIR

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Abstract

Efficient and versatile beam cooling (electron and stochastic cooling) has been an indispensable ingredient for beam preparation and physics experiments at the GSI accelerator complex. The hot secondary beams emerging from the production targets can hardly be used, unless they are cooled. Beam stacking of low-abundant species relies on cooling. Cooling enables high-precision experiments with stored beams, counteracts the heating during internal target operation and controls decelerated beams. New challenges lie ahead within the FAIR project like (i) the ongoing integration downstream of the ESR of the low-energy CRYRING with its electron cooler, (ii) the developments for the demanding CR stochastic cooling system, (iii) the stacking scenarios with RF and stochastic/electron cooling in the HESR/RESR/NESR. The function and parameters of the existing and future beam cooling systems are summarized. We report on the latest hardware developments as well as on improvements of the controls and operation software. Recent highlights and results from beam manipulations with cooling at GSI are shown. In focus are those benchmarking experiments, where the concepts for the new FAIR systems are verified.

INTRODUCTION

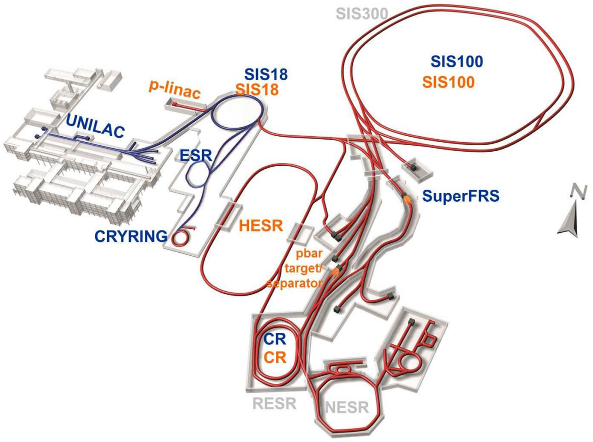

Figure 1: Overview of the GSI and FAIR accelerator complex [1]. SIS300, RESR and NESR will be added later. Orange paths: primary proton/secondary antiproton beam; blue paths: primary stable heavy ion/secondary rare isotope beams (RIBs).

The maximum magnetic rigidity, the main functions and the available/foreseen beam cooling systems of the GSI and FAIR machines are summarized as follows (Fig. 1):
SIS18 (18 Tm, electron cooling), in operation [2]: pre-cooling, accumulation of stable ions.
ESR (10 Tm, stochastic and electron cooling, internal target), in operation [3] : accumulation, storage, deceleration, experiments with stable ions/RIBs.
CRYRING (1.44 Tm, electron cooling), under installation: storage, deceleration, experiments with stable ions/RIBs (also antiprotons as an option).
CR (13 Tm, stochastic cooling): collection, pre-cooling of antiprotons/stable ions/RIBs.
HESR (50 Tm, stochastic and electron cooling, internal target), responsibility of FZJ Jülich [4]: accumulation, storage, acceleration/decelaration, experiments with antiprotons (also stable ions/RIBs).
RESR (13 Tm, stochastic cooling): accumulation of up to 10^{11} antiprotons.
NESR (13 Tm, electron cooling, internal target) [5]: accumulation, storage, experiments with stable ions/RIBs, deceleration of antiprotons/stable ions/RIBs.

PROGRESS ON THE CR SC SYSTEM

The large-acceptance CR is designed to provide fast 3D stochastic cooling (SC) of antiprotons (β=0.97), RIBs and stable heavy ion beams (β=0.83). The SC system operates in the frequency band 1-2 GHz, its main challenges are (i) the cooling of antiprotons by means of cryogenic movable pick-up electrodes and notch filter so as to enhance the signal to noise ratio (ii) the fast two-stage cooling (pre-cooling by the Palmer method, followed by the notch filter method) of the hot RIBs so as to cope with their very large initial undesired mixing. The system design requirements and the simulated physics performance assuming a realistic hardware response, are described in [6, 7]. Intensive in-house engineering and prototyping as well as critical procurements of components are going on.

Prototype Pick-up Tank

The water-cooled linear motor drive units (Fig. 2) have been tested at room temperature with acceleration profiles set by a control software. They fulfill the following specifications: (i) their maximum range of plunging is 70 mm following the shrinking beam size during stochastic cooling and (ii) at the end of the cycle, they move back out to their maximum aperture within 200 ms, before a new beam is injected. Their synchronous operation was recently tested in the tank, long-term tests, also under vaccum, are being prepared.

The movable slotline electrode modules are thermally coupled to flexible silver-plated copper beryllium sheets which are cooled by helium cryoheads to about 20-30 K. The intermediate cryoshield, which will be held at 80 K inside the pick-up tank, was inserted into the tank at room temperature (Fig. 2). It consists of 4 half-shells, each 1 m long, and bears holes for the motor drives and for assembling, it is made of oxygen-free copper Afterwards, its pieces were galvanically gold plated, so as to reach very low thermal emissivity ($\leq$ 2% at 100°C; 7-16 μm expected from lab measurements).

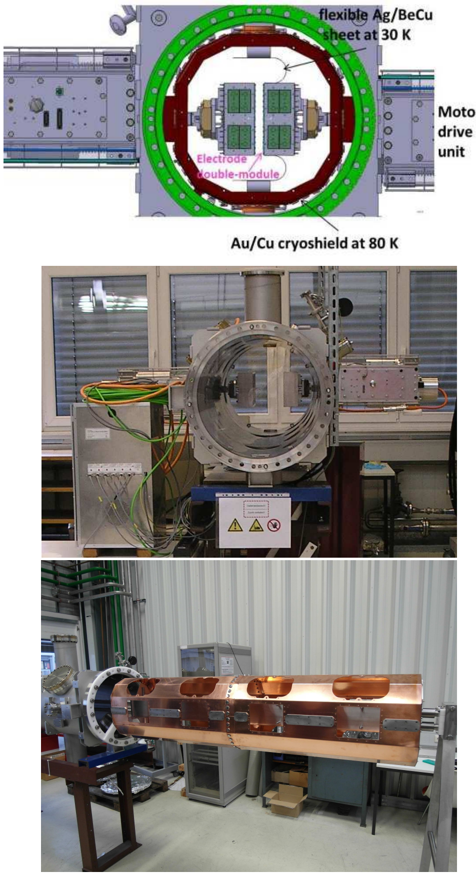

Figure 2: Section of the prototype pick-up tank, where the mechanical and thermal concepts are being tested. The cryoshield (up) and the movable electrode modules fixed on the linear motor drive units are shown (up at 20-30 K/middle at room temperature). Down: Cryoshield (made of Cu) before mounting in the tank.

Slotline Electrodes

The designed [8] slotline pick-up electrodes were further optimized, first ceramic electrode plates have been delivered, their metallisation is underway. In the mean time, dummy electrode modules with equivalent RF properties are used for testing purposes.

Faltin Electrodes for the Palmer Pick-up

Simulations with the HFSS code have converged to possible designs of the Faltin-type electrodes of the Palmer pick-up optimized for (i) maximum pick-up impedance coupled to the beam, (ii) linear output signal phase with respect to the particle pulse and (iii) flat frequency response, avoiding resonances [9]. Plunging of the electrodes is not needed for pre-cooling of RIBs, but the sensitivity of the pick-up is limited because of their large vertical aperture (± 66 mm with respect to the beam axis), so as not to intercept the injected beams. Consequently, the Palmer cooling performance in the CR with such electrodes has been confirmed using a Fokker-Planck approach and engineering work started (Fig. 3).

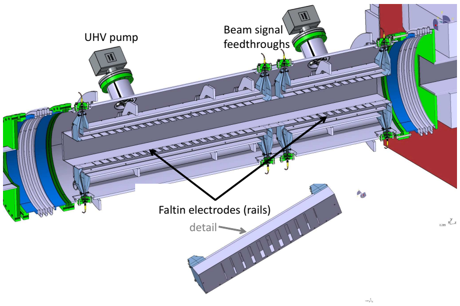

Figure 3: One half the Palmer pick-up vacuum tank (about 2 m long) housing the Faltin electrode rails.

RF Signal Processing

The RF block diagram of the complete SC system and its integration into the building has been refined [10] so as to save electrical length, since the flight time of the quasi-relativistic particles from pickup to kicker is very short.

The design and assembly, including the thermally stabilized delay line, of the optical CR notch filters was finalized (Fig. 4), their measured RF properties fulfill the specification i.e. notch depth below -30 dB within 1-2 GHz.

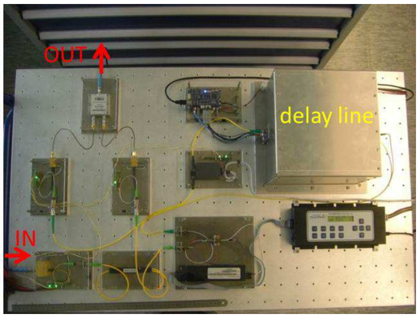

Figure 4: CR optical notch filter layout (1.0x0.6 m^2).

Recently, the procurement contract for the water cooled 1-2 GHz power amplifiers at the kickers has been awarded. Because of the very demanding antiproton cooling a total cw microwave power of 8 kW (32 250 W units) is required, in combination with stringent requirements on amplitude

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flatness and phase linearity as well as very short (≤ 4.8 m i.e. 16 ns) allowed electrical length for each unit.

Conformal to the standards of the FAIR control system, a new operation program with an interface based on the RF block diagram has been implemented to the existing hardware of all cooling branches at the ESR. This is a major step towards preparing such codes for the CR.

PROGRESS AT THE ESR

Stochastic Cooling

A compact correlation notch filter based on optical components has been developed and integrated into the ESR stochastic cooling system [11] (band 0.9-1.7 GHz). Thus, longitudinal cooling of ion beams with the notch filter and with the time of flight (TOF) methods was demonstrated. Together with the Palmer method, 3 different longitudinal SC methods are now available. Notch filter cooling is very fast and leads to the best beam quality for experiments. TOF cooling is useful alone for moderate cooling requirements or, due to its larger momentum acceptance, as pre-cooling before the notch filter takes over. The experience gained from this notch filter [12] was used to optimize the CR setups.

Low-noise preamplifiers at the pick-ups, fulfilling the specification of NF≤0.8 dB (T≤59 K) and amplitude/phase variation ≤1 dB/≤10° in the band 0.9-1.7 GHz have replaced the old series. Subsequently, the pick-up to kicker RF signal processing chain has been re-adjusted and commissioned with beam.

Electron Cooling

The ESR electron cooler [13] has been the working horse for beam preparation, precision experiments as well as delivery of decelerated beams downstream. The versatile operation relies on the high stability of the velocity of the electron-cooled ion beams i.e. adjustable, highly stable (within ±1 V) accelerating voltage for the electron beam in the whole operation range of 2-220 kV (i.e. ion beam kinetic energy in the range 4-400 MeV/u). Several experiments like for example, the laser spectroscopy of Bi ions [14] and the precise energy matching to the HITRAP decelerating linac demand also the absolute determination of the applied HV accelerating the electron beam. Considerable efforts have been made in 2013-2014 to acquire and calibrate against the PTB standards highly-precise HV dividers, allowing a real-time monitoring of the output of the -320 kV power supply applied to the HV terminal of the cooler (Fig. 5). First HV tests and physics experiments using such dividers have been performed, analysis is underway. Unfortunately, the HV power supply, which had repeatedly suffered damage during transportation for maintenance, was unacceptably unstable for the operation of most experiments. It will be repaired in situ so as to recover its value of relative stability and thus fully profit from the combination with the HV dividers in the next beam time.

Figure 5: The Ohmlabs 250 kV (250 MΩ) dc HV divider specified for 10^{-4} precision, installed in the HV terminal of the electron cooler.

Beam Manipulations with Cooling

In a pioneering experiment [15] a low-abundant ^{56}Ni^{28+} RIB produced in the fragment separator was accumulated in the ESR profiting from its large transverse acceptance: 3D stochastic cooling (with the TOF method longitudinally) was used to pre-cool the beam on the outer injection orbit. The pre-cooled beam was deposited by RF on an inner stack orbit where the electron cooling was applied. In this way, the required secondary beam intensity was accumulated (up to 60 injections) for experiments with the internal gas target.

Longitudinal RF stacking (beam compression either by short barrier bucket RF pulses or by successive injections onto the unstable fixed point of the RF bucket at h=1) supported by cooling has been demonstrated in the ESR [16,17]. Depending on the injection energy, continuous application of electron or 3D stochastic cooling merges the stack fast with the newly injected bunch. These benchmarking experiments provided the proof of principle for the fast accumulation (i) of antiprotons/ions in the HESR [18], as foressen in the first stage of FAIR, in the absence of RESR/NESR, respectively. Longitudinal stacking is particularly suitable to the large, small-acceptance HESR; (ii) of RIBs in the NESR; (iii) of heavy ions at NICA [19]. A dedicated barrier bucket cavity will provide the necessary voltage for efficient standard stacking e.g. of RIBs.

ELECTRON COOLER AT CRYRING

The CRYRING was transported from Sweden and is being reinstalled at GSI to serve as a low-energy storage ring for experiments and further deceleration of ions (possibly also antiprotons) [20]. The electron cooler provides an optionally very cold electron beam up to 20 keV and 3 A (typical operation at ≤8 keV and ≤0.1 A), emerging from a ∅ 4 mm cathode followed by an adiabatic magnetic expansion by up to a factor 100 (typically from 3 T in the gun to 0.03 T in the cooling section). Particular care is being taken in laying out the 20 kV HV terminal, in checking/upgrading the sensitive UHV and baking equipment (10^{-11}-10^{-12} mbar) as well as the He-cooled cryogenic components (superconducting gun solenoid, cryopumps).

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