COOLING OF SECONDARY BEAMS*

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Abstract

Beam cooling is a powerful technique in circular accelerators. It is particularly useful for the operation with high quality secondary beams. In the existing storage ring ESR both stochastic and electron cooling have been developed for the preparation of cooled rare isotope beams with short cooling time. For the new FAIR facility both cooling methods are foreseen. They will be applied in various stages for the generation of intense high quality beams of both antiprotons and rare isotopes.

ACHIEVEMENTS AT THE ESR STORAGE RING

The ESR Storage Ring

The ESR storage ring was designed for a variety of operational modes [1], which benefit from powerful beam cooling [2]. For internal experiments the main installations are the internal gas jet target and the electron cooler. The gas jet target can be operated with various gaseous materials with a target thickness of up to some 10^{13} cm^{-2}, which is mainly limited by the necessity of ultrahigh vacuum conditions in the ESR. The electron cooler can be operated as a target of free electrons with adjustable velocity relative to the circulating ions for the investigation of ion-electron interaction processes.

A well-established technique in the ESR is deceleration of bare ions to low energy (minimum energy 3 MeV/u). The decelerated ions can be used for internal experiments or can be extracted by a slow extraction method employing charge changing processes in the internal target or in the electron cooler. Electron cooling counteracts the adiabatic emittance growth during deceleration as well as any other phase space dilution and provides decelerated beams with high quality.

For precision mass spectrometry of rare isotope beams (RIBs) electron cooling provides low intensity beams with a momentum spread $\delta p/p \leq 10^{-6}$ corresponding to a mass resolution up to about 1×10^6. If shortest cooling time is needed for short-lived isotopes, stochastic pre-cooling reduces the total cooling time to a few seconds.

Stochastic Cooling

A stochastic cooling system was installed at the ESR which was mainly designed for fast pre-cooling of rare isotope beams from the fragment separator FRS. In the meantime it has also proven useful, if only moderate cooling is required to stabilize a stored beam. The system allows cooling in the energy range 400-550 MeV/u. The bandwidth of 0.8 GHz (frequency range from 0.9 to 1.7 GHz) allows a reduction of a typical emittance of 1×10^{-5} m and of an initial momentum spread of $\pm 3.5 \times 10^{-3}$ by about a factor of 5. Depending on the ion charge the damping time can be below 1 second. Because of space restrictions the electrodes of the stochastic cooling system were installed in the vacuum chambers of the main ring magnets (horizontal cooling in the dipole magnets, vertical and longitudinal cooling in the quadrupole magnets). The electrode location was matched to the ion optical lattice.

The expected cooling times could be confirmed experimentally. For a U^{92+} beam at an energy of 400 MeV/u a minimum longitudinal cooling time of the injected beam of 0.3 s was measured. The measured beam parameters of the cooled stored beam in equilibrium with intrabeam scattering correspond to transverse and longitudinal cooling times of about 1 s, albeit the cooling system was not optimized for the prevailing cooled beam parameters. This cooling time is derived from a comparison with simulations with an uncertainty of a factor of two.

In contrast to electron cooling, the cooling time with stochastic cooling is weakly dependent on the ion beam parameters. Therefore stochastic cooling is the method of choice in order to to cool down a hot secondary beam.

Electron Cooling

If the ion beam is already cooled down, electron cooling outperforms stochastic cooling. With the parameters of the ESR cooling systems one to two orders of magnitude higher cooling rates can be achieved by application of electron cooling.

The ESR electron cooling system covers a large range of energies and experimental conditions. In the various experimental conditions ion beams were cooled with electron energies between 1.7 and 230 keV and electron currents between 0.01 and 1 A were applied. The magnetic field of 0.1 T at higher beam energies was reduced down to 0.015 T in order to limit the closed orbit distortion, if ion beams with the lowest magnetic rigidity were cooled. The electron current is usually adjusted according to the required cooling power or to the required recombination rate, which is particularly important for the slow extraction of down charged ions.

The cooling time of electron cooling strongly increases with the ion beam emittance and momentum spread. For hot ion beams at higher energies and for low charge states

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the cooling time can increase to the order of 10 seconds. For cold ion beams, which are always cooled to a value which is limited by intrabeam scattering, cooling times of the order of 10 ms were demonstrated. The equilibrium with intrabeam scattering results in ion beam emittances and momentum spreads which depend on many parameters, such as ion charge and mass, energy, electron current, and more details of the cooling conditions.

A specific feature of electron cooled ion beams is the suppression of intrabeam scattering at very low beam intensity (below a thousand stored ions, typically). The cooling rate exceeds the heating rate and results in extremely low ion beam temperature, both longitudinally and transversely. Ion temperatures slightly below 1 meV correspond to momentum spreads of order 10^{-7}. This small momentum spread is the precondition for high resolution in Schottky mass spectrometry which allows the measurement of the mass of rare isotopes by measurement of their revolution frequency using Schottky noise analysis.

Combination of Stochastic Cooling and Electron Cooling

Stochastic cooling and electron cooling have been integrated into the operation of the ESR in various ways. The straightforward combination is stochastic pre-cooling of the hot ion beam after a fragmentation or stripping target and switching to electron cooling as soon as stochastic cooling has come to its limits or when electron cooling is faster than stochastic cooling (Fig. 1). The combination is favorable in order to reach lowest ion beam temperature in minimum time.

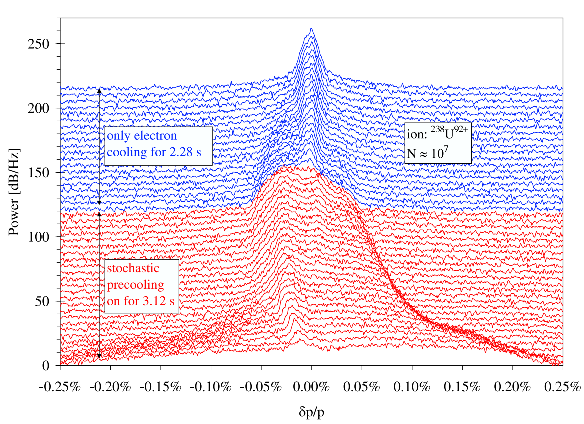

Figure 1: Longitudinal Schottky noise signal of combined stochastic and electron cooling of 10^7 U^{92+} ions injected at an energy of 400 MeV/u. The stochastic pre-cooling is switched of after 3.1 s and electron cooling cools to minimum momentum spread.

As the stochastic cooling system acts only over a fraction of the ring acceptance (less than half the momentum acceptance) on the ion beam, stochastic cooling and electron cooling were combined to cool and accumulate injected ions. After stochastic cooling on the injection orbit (positive momentum deviation $\Delta p/p = +1$ % relative to the central orbit) the pre-cooled ions were transported to the stack orbit ($\Delta p/p = -1$ %) in a few hundred milliseconds by the rf system. Electron cooling was applied to accumulate beam and to cool the stack continuously at the lower momentum.

In contrast to methods where stochastic cooling and electron cooling are applied at constant field of the ring magnets, in the future also cooling at larger energies differences within a deceleration cycle is foreseen. Stochastic cooling at the injection energy will prepare a small emittance and momentum spread beam for deceleration with fast ramp rate, electron cooling at lower energy avoids the time consuming ramping of the accelerating voltage of the electron cooler. Both aspects allow a significant reduction of the total time for a deceleration cycle.

BEAM COOLING AT THE NEW FAIR STORAGE RINGS

General Concepts

Amongst the main features of the new Facility for Antiproton and Ion Research (FAIR) [3], [4] are production and cooling of secondary beams, rare isotope beams produced by fast heavy ion projectiles and antiprotons converted in a target from a primary proton beam. The high intensity beams from the new synchrotron SIS100 will bombard special target set-ups and the secondary beams will be selected in magnetic separators.

The secondary beams will be further treated in various stages, i.e. pre-cooling, accumulation, and final cooling for the experiment, which can also include deceleration to lower energy. These different preparation steps are linked to dedicated storage rings. These storage rings are designed for a magnetic bending power of 13 Tm, which allows the storage of antiprotons at an energy of 3 GeV and the storage of RIBs at 740 MeV/u. This storage ring concept is shortly described hereafter.

Stochastic Pre-cooling in CR

The collector ring CR is a large acceptance storage ring with a circumference of 212 m. Short bunches of secondary beams (25 ns length for antiprotons, 60 ns for RIBs) are injected after the production target and the separator. Full aperture kickers allow the usage of the full acceptance for injection. An rf system with a total voltage of 200 kV operating at harmonic $h = 1$ will reduce the momentum spread by fast bunch rotation and adiabatic debunching. This procedure allows fast cooling by the stochastic cooling system, which is specially designed for hot beams. The different velocities of antiprotons ($\beta = 0.97$) and RIBs ($\beta = 0.83$) are taken into account in the electrode design. Different working points of the focussing structure of the ring provide optimized conditions with respect to the frequency slip factor η and the desired and undesired mixing for the stochastic cooling system, also maintaining large transverse and longitudinal acceptance for the hot secondary beams.

With a stochastic cooling system operating in the frequency band 1-2 GHz and using cryogenic slotline electrodes, a cooling time for antiprotons of less than 10 s and for RIBs of 1.5 s have been found in beam dynamics simulations. The corresponding emittance reduction is about a factor of 50 for antiprotons and a factor of 400 for RIBs.

By doubling the rf voltage of the bunch rotation system and an extension of the stochastic cooling system to the frequency range 2-4 GHz a two times faster pre-cooling is expected. This is presently considered an option for a future extension.

Antiproton Accumulation in RESR

For the accumulation of batches of typically 1×10^8 antiprotons after pre-cooling in the CR, the storage ring RESR has been designed. It will be installed in a common hall with the CR, with its circumference of 245.5 m it can surround the CR. A stochastic cooling system operating in the 1-2 GHz range allows longitudinal stacking of up to 1×10^{11} antiprotons accumulated over 3 hours. Pre-cooled antiprotons from the CR are injected to an inner orbit and captured in a matched rf bucket. After a slight acceleration to a handover orbit, the antiprotons are debunched and cooled by the tail cooling system, which also shifts the antiprotons to a larger momentum orbit. The final cooling with a reduced system gain is performed on the stack orbit, which corresponds to the highest beam momentum within the ring acceptance. The cooling scenario in the RESR is supported by a matched ion optical lattice, which provides proper dispersion and beta functions.

Additionally, the RESR can also decelerate RIBs after pre-cooling in the CR for experiments in the subsequent NESR storage ring. A ramp rate of 1 T/s is particularly valuable for experiments with decelerated short-lived isotopes. For an intended operation of the NESR in a mode to study collisions between RIBs and antiprotons, the RESR can be equipped with an electron cooling system in order to cool the antiprotons at an intermediate energy during deceleration.

Cooled Beams for Experiments in NESR

The New Experimental Storage Ring (NESR) will be used for a large variety of experiments in atomic and nuclear physics. Experiments can be performed internally, employing set-ups like internal target, electron cooler, electron target or an interaction region with a second smaller storage ring for collision experiments. After special preparation, particularly deceleration of secondary beams, the beams can be extracted from the NESR.

The NESR has a circumference of 222 m and four straight sections of 18 m length. The maximum bending power is 13 Tm as for the other storage rings. After deceleration of antiprotons from 3 GeV and intermediate electron cooling at about 800 MeV a minimum energy of 30 MeV before extraction is planned. Ions, particularly short-lived RIBs, will be decelerated with a maximum ramp rate of 1 T/s from 740 MeV/u to a minimum energy of 4 MeV/u, optionally also with intermediate electron cooling. The decelerated beams will be transferred to the dedicated Facility for Low-energy Antiproton and heavy-Ion Research (FLAIR) of the FAIR project.

The electron cooling system of the NESR needs a large flexibility, cooling of the pre-cooled RIBs and the intermediate cooling for antiprotons requires a maximum electron energy of 450 keV. High precision mass measurements at the injection energy of 740 MeV/u8 will also require extreme stability of ring magnet power supplies and electron energy.

A special requirement for the electron cooling system is fast ramping during deceleration. Cooling after injection for ions and at the intermediate energy for antiprotons requires electron energies of 400-450 keV, after deceleration the electron energy must be lowered to a few keV. As a consequence an active method of discharging and charging the high voltage section is required to be able to ramp the accelerating voltage in 1.5 s between upper and lower value.

According to simulations, cooling times of the precooled RIBs of less than 0.5 s are feasible. However, the cooling time for antiprotons after deceleration from 3 GeV to 800 MeV will strongly depend on the antiproton beam parameters after stochastic cooling. For the present design values, even assuming a 2 A electron beam, the cooling time is estimated to 180 s. If faster cooling is required, either pre-cooling has to be improved or significant beam losses during deceleration have to be accepted.

For cooling of ion bunches in the collider mode, the requirements are also very demanding. To achieve high luminosity in the collider mode with counter-propagating electron bunches, about 40 bunches of 0.15 m length with a transverse emittance not exceeding 1×10^{-7} m will be circulating with an intensity of 1×10^7 ions per bunch.

To achieve the ambitious cooling rates the electron beam should be designed for a maximum electron current of 2 A and variable operation of the electron beam diameter, this allows an optimization of the electron beam size to the ion beam emittance. This will be adjusted by transverse magnetic expansion or compression of the electron beam.

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