FAST BEAM ACCUMULATION BY ELECTRON COOLING IN THE HEAVY ION SYNCHROTRON SIS

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Abstract

An electron cooling system has been designed for the heavy ion synchrotron SIS. The purpose of this device is accumulation of weak injected beams of highly charged ions to the maximum intensity determined by the space charge limit. This is accomplished by repeated multiturn injection and simultaneous cooling at the injection energy. The cooling time has been estimated to be an order of magnitude shorter than the acceleration cycle time. Thus a corresponding increase of the average output intensity by about one order of magnitude is expected. The beam quality of the accumulated beams will also be improved.

1 INTRODUCTION

The GSI accelerator complex [1] provides ion beams over the whole mass range with a maximum energy of 1 GeV/u for the heaviest ions and up to 2.1 GeV/u for the lighter ions with charge to mass ratio $q/A = 0.5$. The ions are injected by multiturn injection into the heavy ion synchrotron SIS filling the horizontal acceptance at a fixed energy of 11.4 MeV/u with beams of highly charged ions from the UNILAC accelerator. For the heaviest ion species the intensity of the injected beams is at present more than two orders of magnitude below the values required to fill the SIS up to the space charge limit. The urgent need for an immediate intensity increase can be met by the installation of an electron cooling system in the SIS which will accumulate higher beam currents at the injection energy. The cooling system has been designed for cooling times short compared to the acceleration cycle time in order to increase the average output current of the synchrotron by approximately one order of magnitude. The cooling process will also improve the quality of the ion beam thus resulting in a higher acceleration efficiency and better transmission to the experiment.

2 INJECTION SCHEME

The standard multiturn injection method at the SIS fills a horizontal acceptance $A_h = 150\ \pi$ mm mrad with a beam of horizontal and vertical emittance of 5 π mm mrad and a momentum spread $\delta p/p = \pm 1 \times 10^{-3}$ which is injected over 150 μs, typically. Thus a maximum intensity gain factor of 30 can be achieved. Electron cooling will reduce the large emittance of the circulating beam to approximately 30 π mm mrad thereby emptying more than 80% of the horizontal acceptance for a new multiturn injection batch. By repeated injection and phase space compression into the inner part of the acceptance the intensity can be successively increased. The fast bumper magnets for the multiturn injection limit this scheme to a maximum repetition rate of 10 Hz in agreement with a transverse cooling time of 0.1 s.

3 INSTABILITY LIMIT AND BEAM LOSS RATE

The number of useful multiturn repetitions might be limited by several effects. The incoherent space charge tune shift drives particle losses when the ratio of beam intensity to beam emittance exceeds a certain value. For intense beams the emittance of the cooled beam depends on the beam intensity as intrabeam scattering prevents a further compression of even more particles into the inner part of the acceptance. For low intensity beams accumulation over time periods of a few seconds can be limited by interaction with the residual gas which is particularly important for partially stripped ions.

The reduction of the beam emittance by cooling lowers the intensity limit by the space charge tune shift for the SIS design values by a factor of approximately three which is mainly determined by the reduction of the horizontal emittance. This results in an upper theoretical limit for the heaviest ions of about 5×10^9 particles per spill assuming an emittance ϵ = 30 π mm mrad in both transverse planes. Proper control of the beam emittance will require techniques such as feedback, rf heating or artificial deterioration of cooling by controlled electron beam misalignment.

For highly charged heavy ions which are not completely stripped at the injection energy of 11.4 MeV/u two major atomic physics processes of similar relevance limit the lifetime of the ions which are circulating in the synchrotron during the repeated multiturn injection. Interaction of the bound electrons with residual gas components causes losses by ionization. The ionization rate in the residual gas can be estimated from the ionization cross-section [2]

$$\sigma_i[\mathrm{cm}^2] = 3.5 \times 10^{(-18+X)} \overline{q}^{-2} \overline{q}_T (\gamma^2 - 1)^{-0.5} (\overline{q}/q)^4 \quad (1)$$

with $X = (0.71 \log Z)^{1.5}$ and $\overline{q}, \overline{q}_T$ the equilibrium charge states of the fast and the target ion, respectively. Residual gas ionization increases strongly for heavier ions and low charge states. For the typical residual gas pressure

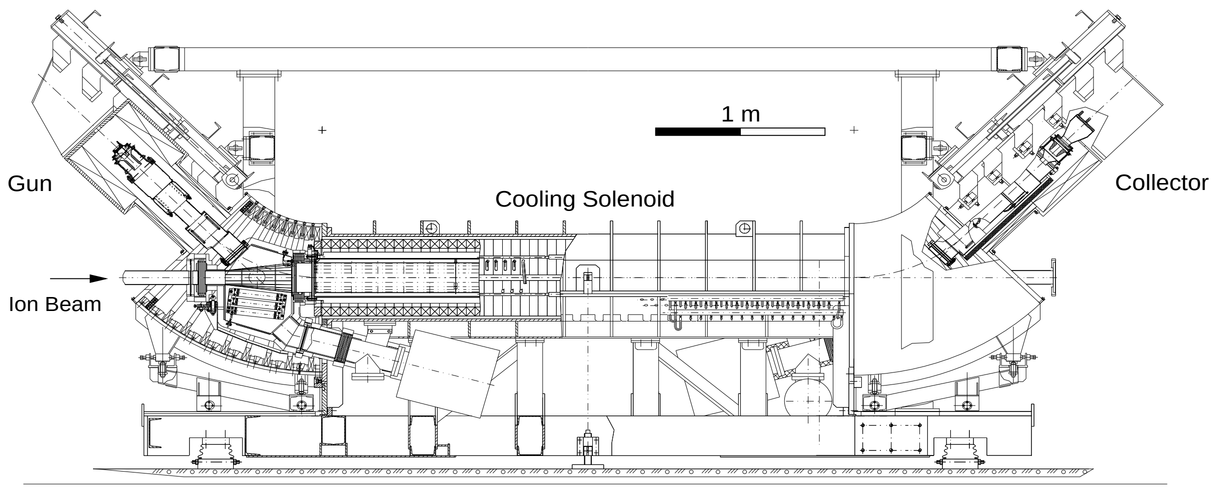

Figure 1: Layout of the SIS electron cooler.

($p \simeq 1 \times 10^{-10}$ mbar) the beam lifetime for incompletely stripped heavy ions with the optimum charge state after stripping has been determined experimentally to be on the order of a few tens of seconds. For lighter ions which usually are completely stripped fast ionization losses are not expected. Losses due to recombination with the residual gas constituents can be neglected.

Another even more important loss mechanism is recombination with the velocity matched electrons of the cooling beam. The radiative electron capture increases proportional to the square of the ion charge q^2. The lifetime of the ions with respect to radiative recombination is on the order of minutes due to completely or partially filled inner atomic shells. Recent experimental results, however, indicate that additional resonances close to zero relative energy, e. g. by dielectronic recombination, lead to enhanced recombination rates which can exceed the radiative recombination rate considerably (by factors of ten and even more). These fast recombination processes seem to be associated with particular electronic configurations [3]. As the stripping process in thin foils normally provides two or three similarly populated charge states the longest-lived charge state with respect to recombination in the electron beam can be selected for injection into the synchrotron.

Considering all relevant loss mechanisms it can be concluded that storage times of a few seconds at the injection energy are feasible even for partially stripped heavy ions.

4 COOLING TIME AFTER INJECTION

The typical SIS acceleration cycle lasts 1-3 s, therefore a cooling time on the order of 0.1 s is mandatory to accumulate the ion beams efficiently. The overall intensity gain mainly depends on the time interval that is required to compress the hot injected beam from a horizontal emittance $\epsilon_h = 150\ \pi$ mm mrad to an emittance $\epsilon_h \leq 30\ \pi$ mm mrad. The transverse cooling time for a hot ion beam can be estimated according to [4]

$$\tau_\perp\ [\mathrm{s}] = 1.225 \cdot 10^{16}\ \frac{A}{q^2} \frac{\gamma^5 \beta^3 \theta^{c3}}{\eta_c n_e} \qquad (2)$$

with the usual relativistic notation for β, γ, the ion mass and charge numbers A and q, the ion beam divergence θ^c in the cooling section and the electron density n_e in [cm^{-3}].

The theoretical formula does not include the benefit from a reduced transverse temperature which can be accomplished by magnetic expansion of the electron beam [5] as foreseen in the design of the SIS electron cooling system. Experimental investigations at the storage ring TSR [6] with similar beam parameters resulted in cooling times which were by a factor of two shorter than expected from formula (2). This was attributed to the high quality of the electron beam which has a reduced transverse temperature after expansion in the magnetic field. Thus for ions with mass numbers $A \geq 100$ the fast transverse cooling time of 0.1 s can be achieved with an electron density $n_e = 4 \times 10^7$ cm^{-3}.

The expansion factor of the SIS electron cooler will be variable thus allowing to optimize the cooling time as a trade-off between higher electron density for a smaller expansion factor and a broader overlap cross section area between ion and electron beam for a larger expansion factor. As the cooling time is proportional to the third power of the ion beam divergence it might be advantageous to reduce the emittance of the ion beam after multiturn injection. In this case the reduced ion beam intensity after a single multiturn injection can be balanced by faster cooling with a smaller diameter of the electron beam and correspondingly higher electron density.

5 BEAM QUALITY

Electron cooling at the injection energy will increase the phase space density of the accelerated beam. The beam emittances and momentum spread will be determined by intrabeam scattering which limits the quality of cooled highly charged ions. For the maximum beam intensity the emittance can not be reduced below the space charge tune shift limit. For a smaller particle number N, however, the emittance can be reduced approximately proportional to $N^{0.6}$ and the momentum spread proportional to $N^{0.3}$ as has been found experimentally [7]. This offers the opportunity to provide beams of much better quality at the expense of reduced beam intensity. During the acceleration process mainly the longitudinal degree of freedom will be heated due to two processes. Heating by intrabeam scattering transfers heat from the hotter transverse degree of freedom to the longitudinal one. Bunching with the rf system can be an additional heating source. The transverse and longitudinal emittances will shrink adiabatically during the acceleration process. Even higher phase space density can be achieved by cooling at an intermediate energy of 60 MeV/u which has the advantage of less stringent constraints by the space charge limit.

6 ELECTRON COOLING SYSTEM

The electron cooler will be installed in a free straight section of the synchrotron which offers a maximum length for the installation of the electron cooler of 6.5 m. Assuming an effective length of the cooling section of 3 m a fraction η = 0.014 of the ring circumference is used for cooling. The electron cooler layout is shown in Fig. 1 and its main parameters are listed in Table 1. The required electron density and the size of the ion beam in the cooling section determine the electron current and the beam diameter. The electrons are extracted from a 2.5 cm diameter cathode in a strong longitudinal magnetic field. The reduction of the field strength by a factor of 8 results in an electron beam of 7 cm diameter in the cooling section which is matched to the size of the injected ion beam.

Table 1: Parameters of the electron cooler for SIS.

ion beam momentum spread $\delta p/p$	$\pm 1 \times 10^{-3}$
ion beam emittance ϵ_x, ϵ_y	150, 5 π mm mrad
Twiss parameter β_x^c, β_y^c	8.0, 15.0 m
ion beam divergence θ_x^c, θ_y^c	4.3, 0.6 mrad
electron energy	5 - 35 keV
electron current at 6.2 keV	1.2 A
maximum electron current	2 A
useful relative cooler length η_e	0.014
cathode diameter	25.4 mm
gun perveance	2.2 μP
magnetic field expansion factor	1 - 8
maximum magnetic field in gun	0.4 T
magnetic field in cooling section	0.04 - 0.15 T
length of cooling solenoid	3.36 m
field parall. $B_\perp/B_\parallel$ in cool. section	$\leq 1 \times 10^{-4}$
maximum power dissip. in collector	8 kW
collector perveance	10 μP
collection inefficiency $\delta I/I$	$\leq 3 \times 10^{-4}$
basic vacuum pressure	10^{-11} mbar

6.1 Electron Gun

The electron gun is designed as a standard diode type geometry with an extraction gap and a separated acceleration gap. The whole gun section is immersed in a homogeneous longitudinal magnetic field. The electrodes have been designed by computer simulations for minimum radial electric field components. The field strength in the extraction gap determines the electron current, the second gap accelerates the electrons to the final energy. After acceleration the electron beam is expanded. This scheme requires a strong magnetic field in the gun section (typically $B \simeq 0.3$ T) which suppresses any transverse electron motion efficiently. After the magnetic expansion the transverse motion in the intense electron beam is determined by a balance between the weaker magnetic field ($B \simeq 0.04 - 0.1$ T) and space charge forces.

6.2 Collector

The expanded electron beam will be compressed before the collector section to about 1.5 times the cathode area (typical magnetic field strength $B \simeq 0.2$ T) in order to have a beam cross section in the collector which is independent of the expansion factor and only related to the cathode size. The apertures of the collector electrodes allow some variation of this recompression factor. For efficient collection of the electrons the magnetic field decreases again inside the collector. This reduces the power density in the collector and reflects slow secondary electrons which are emitted from the collector surface. An electrostatic suppressor configuration which forms an electrostatic barrier for reflected or secondary emission electrons is assumed to reduce the beam loss to a level of a few 10^{-4} of the main electron current. The water cooled collector supports a maximum power of 8 kW deposited on the inner collector surface. If necessary, the magnetic field strength in the collector can be varied in order to increase the collector efficiency.

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