PERFORMANCE TEST AT THE SIS ELECTRON COOLING DEVICE

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Abstract

The new electron cooling device for the heavy ion synchrotron SIS was operated at a test bench before integration in the accelerator. The results of performance tests will be reported. Prior to the tests the magnetic field in the cooling section was mapped and optimized with respect to angular fluctuations. They could be reduced to less than 0.04 mrad. During test operation with electron beam the electron energy, electron current, magnetic field strength and adiabatic expansion factor were varied. Operation with electron currents of 2 A at full beam expansion by a factor of 8 was demonstrated. For different beam parameters the relative loss current was minimized to values lower than 10^{-4}. The requirements for fast transverse beam-cooling were met.

1 PERFORMANCE REQUIREMENTS

In the framework of the intensity upgrade program for the heavy ion synchrotron SIS an electron cooler [1] was prepared for installation in the ring. It is operated simultaneously to repeated multiturn injections for fast compression of the transverse emittance during the injection process at 11.4 MeV/u. An intensity increase of one order of magnitude is desired for heavy and highly charged ions as well as an improvement of the beam quality for all ion species. An optional cooling period is foreseen at an intermediate energy between 50 MeV/u and 65 MeV/u. It can be performed simultaneously during the rebunching process in which the harmonic number for further acceleration can be changed from 4 to 2.

For fast transverse cooling of hot injected ion beams a complete overlap of electron and ion beam is favorable. At the SIS this corresponds to an electron beam diameter of 7 cm which is obtained by adiabatic expansion [2] in the longitudinal magnetic field. For expansion the field strength is reduced along the electron beam line from the emitting cathode to the cooling section by a variable expansion factor f_{exp}. The beam cross section is increased and the transverse electron temperature is decreased by the same factor. At the SIS cooler a maximum field expansion factor $f_{exp} = 8$ is foreseen starting from a cathode diameter of 25.4 mm. To maintain a sufficient electron density even for expanded beams an electron current of up to 1.2 A is required.

The vacuum system is designed for a basic pressure of 1×10^{-11} mbar. During the operation with electron beam 1×10^{-10} mbar should not be exceeded in order to have negligible ion beam loss due to charge changing processes in the residual gas.

2 MAGNETIC FIELD MAPPING

The transverse cooling performance is highly sensitive to the parallelism of the electron and ion beam in the cooling section. The parallelism is distorted by residual transverse components of the solenoid field which cause angular fluctuations of the magnetic field lines. They must be compensated by means of transverse correction coils down to less than 0.1 mrad.

The strength of the longitudinal magnetic field of the SIS cooler is different in the gun, cooling and collector sections. The field in the cooling section is reduced by a factor f_{exp} with respect to the field in the gun section. In the collector section the strength is 2/3 of the gun section strength. Due to this constant ratio the beam diameter in the collector section is independent of the expansion factor.

The cooling solenoid consists of 59 identical circular pancake coils. On a total length of 3.36 m it can provide a field of up to 0.15 T. After field mapping performed at BINP small angles between the single pancake coils were introduced by insertion of proper spacers for first correction of transverse field components. To compensate the remaining components a set of correction coils is integrated in the cooling solenoid in order to superimpose local transverse correction fields. It consists of 20 identical saddle dipole coils for the horizontal and vertical direction, respectively. Their geometric centers are separated along the beam axis by 16.5 cm which corresponds to their effective region of influence. In order to minimize the number of power supplies the 40 coils are subdivided in two circuits. Within the circuits they are connected in series. A variable shunt resistor is connected in parallel with each coil in order to change the current according to the required local correction.

The magnetic field in the cooling section was mapped again at GSI by means of three dimensional Hall probing with an accuracy of better than 2×10^{-6} T. Along the solenoid axis the field was measured over a length of 3.5 m with a step size of 1.0 cm. During the measurements both toroids were also powered. The field strength was set to 0.06 T which is the field level foreseen during standard operation. After field mapping without powering the correction coils the amplitudes of the corrections were adjusted according to maximum compensation of the measured transverse components. The result of the mapping with proper correction settings is shown in Fig. 1. Over an effective length of 2.8 m the mean angular fluctuations could be reduced from 0.24 mrad to 0.034 mrad.

The obtained field quality strongly depends on the hysteresis and the field strength itself. If the hysteresis loop is driven in the direction of decreasing field strength the fluctuations increase by a factor of 6 with respect to the increasing direction. The corrections were made to optimize a field of 0.06 T. For other fields the corrections are scaled linearly which is only a first order approximation. Due to remanent field effects and nonlinearities the fluctuations increase noticeably for fields lower than 0.04 T and higher than 0.09 T. Within this interval they remain below 0.1 mrad.

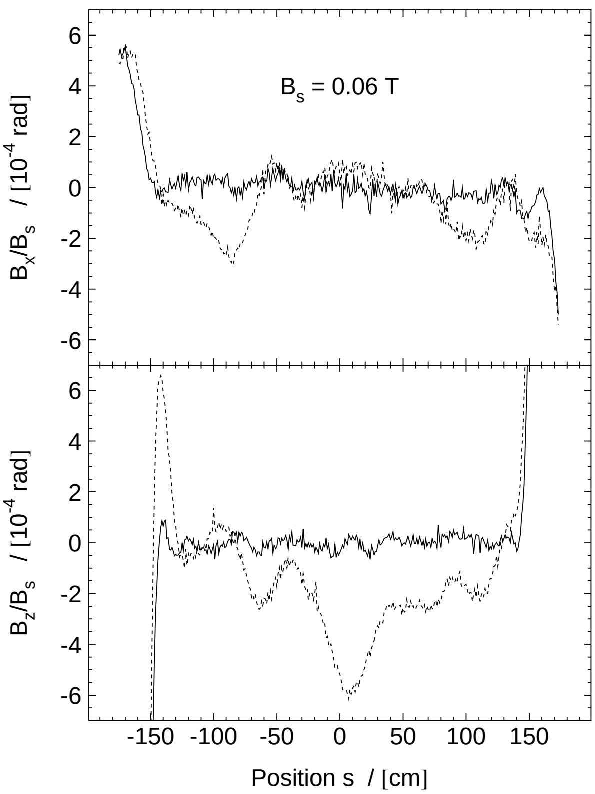

Figure 1: Horizontal and vertical angular fluctuations at a field strength of 0.06 T with (solid line) and without (dashed line) powering the correction coils.

3 OPERATION WITH ELECTRON BEAM

In preparation of the intended operation for beam accumulation at the SIS injection energy of 11.4 MeV/u the cooler was mainly operated with an electron energy of 6.3 keV. The electrons are extracted from a thermionic cathode by means of two acceleration gaps which determine independently the beam current and energy, respectively. In order to preserve good vacuum conditions during the operation of the cooler the loss current must be minimized for each setting of the electron beam parameters. For stable operation conditions a ratio of loss current to primary beam current of less than 10^{-4} should be maintained.

During the test operation stable electron beams could be achieved for currents up to 2 A with a maximum expansion factor of 8. Significant beam instabilities were observed only for magnetic fields lower than 0.03 T. An unstable electron beam mainly raises from loss currents caused by electrons which are not recuperated. They drift backwards along the magnetic field lines and affect the electrostatic field distribution. In addition, the vacuum pressure is increased when these electrons hit the vacuum chamber at almost full energy. The collection efficiency is determined by the electrostatic potentials in the collector section. Figure 2 shows the electrode configuration in the collector section of the SIS cooler. The calculated electrostatic potential along the beam line [3] is also shown. The electrons reach the collector section with full energy and are decelerated by the collector anode potential U_{CA} down to almost zero velocity in the vicinity of the suppressor which is on potential U_S. They hit the surface of the collector end plate with a kinetic energy of $e \cdot U_C$ and are partially reflected. To prevent those electrons from drifting backwards to the cooling section a potential barrier is formed by means of the three electrodes. In addition the strongly expanded magnetic field lines in the collector form a magnetic bottle which serves as a repeller for secondary electrons as well. The shape and depth of the potential barrier determines the collection efficiency, i.e. the loss current. During the test operation the electrode potentials for minimum loss current were determined. The

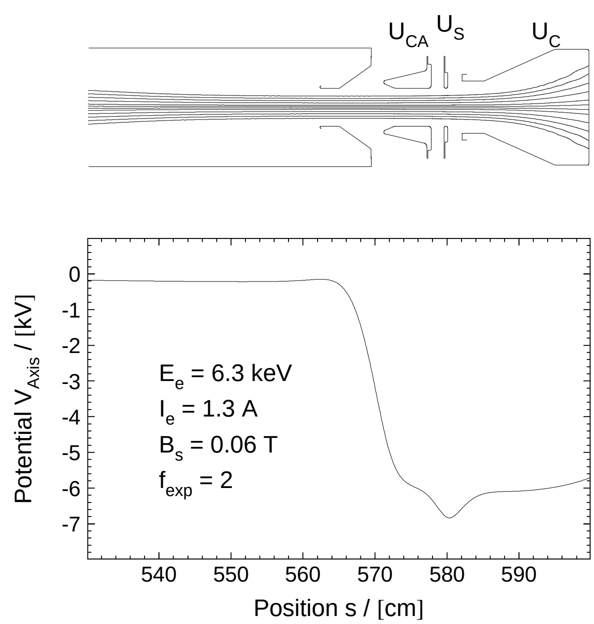

Figure 2: The electrode configuration in the collector section and the calculated electrostatic potential along the electron beam axis for typical test operation parameters. The electrode potentials U_{CA}, U_S and U_C refer to the cathode potential of -7.0 kV.

collector potential U_C was kept constant at 3 kV but the potentials of the collector anode U_{CA} and the suppressor U_S were varied. Detailed measurements were performed for beam currents up to 1.5 A, expansion factors ranging from 1 to 8 and magnetic fields from 0.03 to 0.06 T. The results for 0.06 T are shown in Fig. 3. The relative loss current is below 10^{-5} for expansion factors higher than 2. For small expansion factors the losses are caused by primary beam reflection at the suppressor. At high expansion factors they are mainly due to reflection at the collector end plate. In

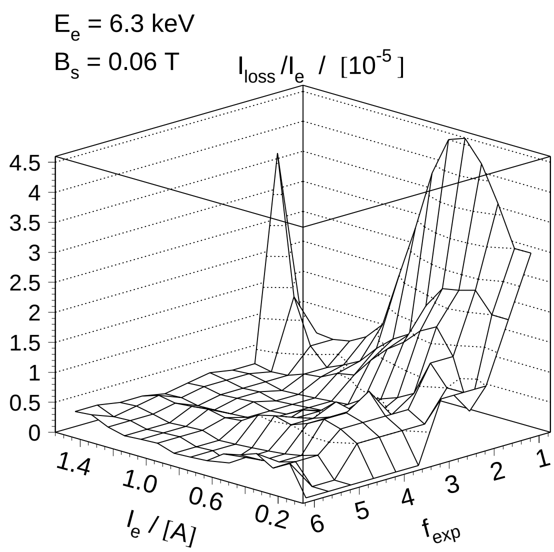

Figure 3: Minimized relative loss current as a function of electron current and magnetic expansion factor for operation at SIS injection energy and a magnetic field strength of 0.06 T.

the intermediate range of $3 \leq f_{exp} \leq 6$ the losses depend only weakly on the potential settings and raise from both kinds of reflection. By reducing the magnetic field to 0.03 T the relative loss current increases roughly by a factor of 3 whereas for fields higher than 0.06 T even lower losses have been observed.

The cooler was also operated at electron energies up to 32 keV corresponding to an ion energy of 60 MeV/u. In this case stable operation conditions could be achieved for currents up to 1.2 A and expansion factors higher than 2. At the highest available electron energy of 35 keV the maximum electron current is reduced to 0.5 A and the maximum expansion factor to 4 due to increased loss currents, i.e. unstable operation conditions. For stable operation conditions the vacuum pressure remained below 10^{-10} mbar at all settings of the beam parameters.

The results of the performance test are summarized in Table 1. The reduction of the maximum electron current with increasing energy might be due to the relative increase of the dipole field in the toroids with respect to the longitudinal guiding field with increasing beam energy. This dipole field compensates the transverse drift motion of the electrons caused by the radial field gradient in the toroid field. For electrons reflected in the collector section, which move in opposite direction with respect to the primary beam, the dipole field causes a drift which is twice the value without this correction. The resulting displacement increases the loss current. This assumption is supported by the fact that higher primary currents can be obtained by increasing the longitudinal field strength, i.e by decreasing the displacement in the toroids.

Table 1: Experimentally achieved parameters of the SIS electron cooler after performance test

max. electron energy	35 keV
magnetic field expansion factor	1 – 8
max. electron current at 6.3 keV	2.0 A
gun perveance	2.9 μPerv
effective relative cooler length	0.013
field parall. in cool. section	$\leq 4 \times 10^{-5}$ rad
max. collector perveance	12 μPerv
collection inefficiency $\delta I/I$	$\leq 1 \times 10^{-4}$
vacuum pressure	$\leq 1 \times 10^{-10}$ mbar

4 OUTLOOK

After almost all design parameters were reached and even partially exceeded the cooler was integrated in the synchrotron. Fast transverse beam-cooling during the injection was successfully demonstrated [4]. The cooler is now ready to be used routinely to supply experiments with cooled ion beams.

5 REFERENCES

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