# THE ELECTRON COOLING DEVICE FOR THE HEAVY ION STORAGE RING TSR*

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## Summary

An electron cooling system for the heavy ion storage ring TSR is being developed for electron energies of 3-20 keV according to the ion energies available in the first phase of operation of the TSR. The electron gun has a Pierce geometry and is immersed in a longitudinal magnetic field. By use of resonant focusing for acceleration it can deliver cold electron beams with variable gun perveance and small guiding magnetic field. Transverse energies smaller than 0.2 eV were calculated for magnetic fields below 600 G. A collector for the electron beam was designed and tested in a linear arrangement which showed an excellent current collection efficiency of up to 0.99999. Measurements of the magnetic confinement system which can be operated at a maximum field strength of 3 kG are in progress. First results indicate that the cooling solenoid was produced with a good field parallelity $B_t/B_l \leq 1.5\cdot10^{-4}$.

## Introduction

Electron cooling is a method to increase the phase space density of charged particle beams which has been demonstrated to work very efficiently for low and medium energy proton beams. Because of the $Z^2/A$ dependence of the cooling force it is expected to cool high intensity heavy ion beams even more efficiently. The cooling of heavy ion beams will be studied with the heavy ion storage ring TSR which has recently come into operation [1]. The heavy ions are injected from the tandem-postaccelerator combination [2] which can provide a large variety of heavy ions from protons to uranium ions. Heavy ion beams with intensities of some mA at energies of 5-30 MeV/u are expected to circulate in the TSR. The velocity of the electrons has to be matched to the ion velocity; therefore cold electron beams in the range 3-20 keV are required.

## Electron gun design

The electrons to be used for cooling of ions need to have small transverse energy. Therefore a longitudinal magnetic field is applied to accelerate the electrons from the Pierce shaped cathode with negligible heating and to guide them during their drift through the electron cooling system. Resonant focusing is employed to operate the cooler with relatively small magnetic guiding field and therefore with minimum influence on the ion beam optics.

An electrostatic five electrode system is employed to accelerate the electrons to variable energy with small transverse velocity components. With the SLAC program [3] for the calculation of electron trajectories different

| | | | | | |
|---|---|---|---|---|---|
| gun perveance | [$\mu$P] | 6.63 | 1.67 | 0.69 | 0.37 |
| cathode voltage | [kV] | -3.0 | -7.0 | -12.7 | -20.0 |
| magnetic field | [G] | 556 | 552 | 394 | 292 |
| max. transv. energy | [eV] | 0.01 | 0.02 | 0.17 | 0.08 |

Tab. 1 calculated modes of electron gun to produce an electron beam of intensity I≈1A

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modes of operation were found which allow to accelerate a beam of 2 inch diameter and a typical intensity $I_{el} \approx 1$ A. The calculated modes are listed in Table 1. All modes show good beam quality as is obvious from the calculated maximum thermal transverse energy which was found close to the beam edge.

For the first electron cooling experiments in the TSR the mode at a perveance of 1.67 $\mu$P will be preferable. The high perveance mode is foreseen for experiments with low energy ions particularly after deceleration in the ring. The lower perveance modes will be favoured for experiments with ions after acceleration in the ring or for proton beams.

A calculation of the trajectories of electrons which are emitted from the 2 inch diameter cathode through the electrostatic lens system is shown in Fig. 1 for the 1.67 $\mu$P mode demonstrating that the divergence of the electrons after emission from the cathode is counteracted by the combined focusing action of the electrodes and the magnetic field.

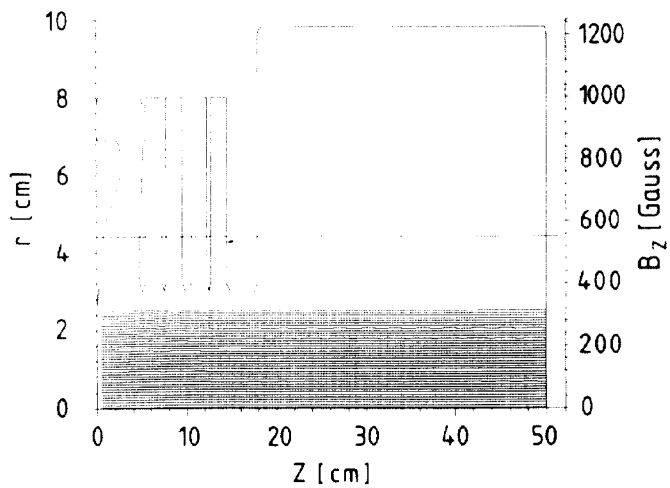


Fig. 1 Calculation of electron trajectories in the gun

## Collector design considerations

The strict vacuum demands for operation of a heavy ion storage ring make the collection efficiency for the electrons after interaction in the cooling section a parameter of major importance. Electrons which hit the vacuum chambers cause gas desorption from the surface. The vacuum in the device is expected to scale proportionally to the electron loss current.

The collector chosen for the electron cooler is of the Faraday-cup type which has been shown to offer high collection efficiency [4]. The electrons are decelerated in a homogeneous magnetic field whereas the collector is located in the decreasing magnetic field which prevents the electrons from escaping from the collector. Electrons which start with an angle larger than $\alpha = \arctan\,(B_{max}/B_{min}-1)^{-1/2}$ from the collector surface will be repelled due to the adiabatic invariant of motion in a magnetic field. Additionally by setting the electrodes in front of the collector to negative repelling potentials slow secondary electrons can be captured electrostatically.

## Experimental test of electron gun and collector

The feasibility of the gun and collector design were studied in a linear test bench arrangement [5] which is shown in Fig. 2. The vacuum system which is bakeable to 400°C is installed in a 1.5 m long solenoid magnet that provides the longitudinal magnetic field. An additional solenoidal coil at the collector end allows for proper shaping of the decrease of the axial magnetic field in the collector.

The electrons are emitted from a 2 inch diameter barium oxide coated tungsten cathode which is positioned in the homogeneous part of the magnetic field. After acceleration in the five electrode system the electrons drift through a cylindrical vacuum tube which is used as a microwave resonator to detect the microwave radiation emitted by the electrons. The electrons are decelerated in an electrode system which is a mirror image of the gun.

The linear test bench was operated in a vacuum in the $10^{-10}$-$10^{-8}$ mbar range. The vacuum conditions did not effect the properties of the electron beam and the collection efficiency. The basic pressure after bakeout was measured to 5 $10^{-11}$ mbar with the rest gas consisting to over 90% of hydrogen. The cathode was operated at 930°C in the space charge limited regime thus increasing the pressure to 1-2 $10^{-10}$ mbar.

From startup stable operation was possible for all calculated modes independent of the collector parameters with the exception of the 6.6 μP mode which could be adjusted to a perveance of 5 μP easily, but the full perveance was obtained only after a delicate tuning of the collector parameters. Table 2 gives a list of the values of beam intensity and the best achieved collection efficiency.

| | | | | | |
|---|---|---|---|---|---|
| calc.perveance | [μP] | 6.6 | 1.67 | 0.69 | 0.37 |
| cathode voltage | [kV] | -2.8 | -7.0 | -12.7 | -19.3 |
| beam current | [mA] | 875 | 925 | 929 | 996 |
| meas. perveance | [μP] | 6.1 | 1.58 | 0.65 | 0.37 |
| opt. coll. eff. | [%] | 99.998 | 99.999 | 99.997 | 99.997 |

Tab. 2 measured parameters for operation of the linear test section

The collector voltage was in the experiments usually set to + 2 kV with respect to the cathode. The entrance electrodes were optimized independently. The collector perveance at optimum collection efficiency was determined to 18 μP by variation of the collector potential.

The action of the magnetic repeller was proved by variation of the magnetic field in the collector. For vanishing magnetic field a minimum of the loss current was found. With increasing collector field the loss current also rises. For a reversal of the magnetic field direction in the collector electrons are reflected in the magnetic field and reduce the primary beam intensity because of the formation of a space charge cloud. A further reduction of loss current and therefore better collection efficiency can be achieved if the electrodes in front of the collector are set to voltages repelling slow secondary electrons.

The microwave spectra recorded with the antenna in the drift section cavity did not show the expected proportionality of emitted power to beam intensity. Therefore the main contribution to the emitted microwave power is attributed to a cloud of hot electrons which are captured between cathode and collector. Furthermore the antenna in this linear arrangement is also sensitive to radiation emitted during acceleration and deceleration of the electrons. Quantitative estimates gave an averaged thermal transverse energy of $E_t = 3.4$eV which is only an upper limit. The transverse energy of the primary electron beam appeared to be at least an order of magnitude smaller.

## Magnet system

The magnetic confinement system for the electron cooling device in the TSR consists of five solenoid and two toroid magnets with a bending angle of 45 degrees (Fig. 3). Two pairs of C-shaped correction dipoles will correct the closed orbit distortion caused by the toroids.

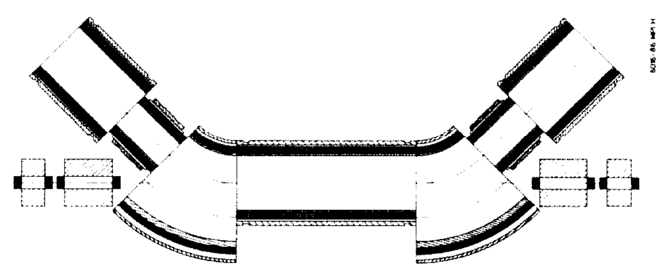

Fig. 3 Schematic sketch of the magnetic system of the cooler

All solenoids have the same number of conductor turns per length and are connected in series to one power supply; the toroids will be powered by a second one. The magnet system can be operated at a maximum field of 3 kG. Technical details of cooling solenoid and toroid are listed in Table 3.

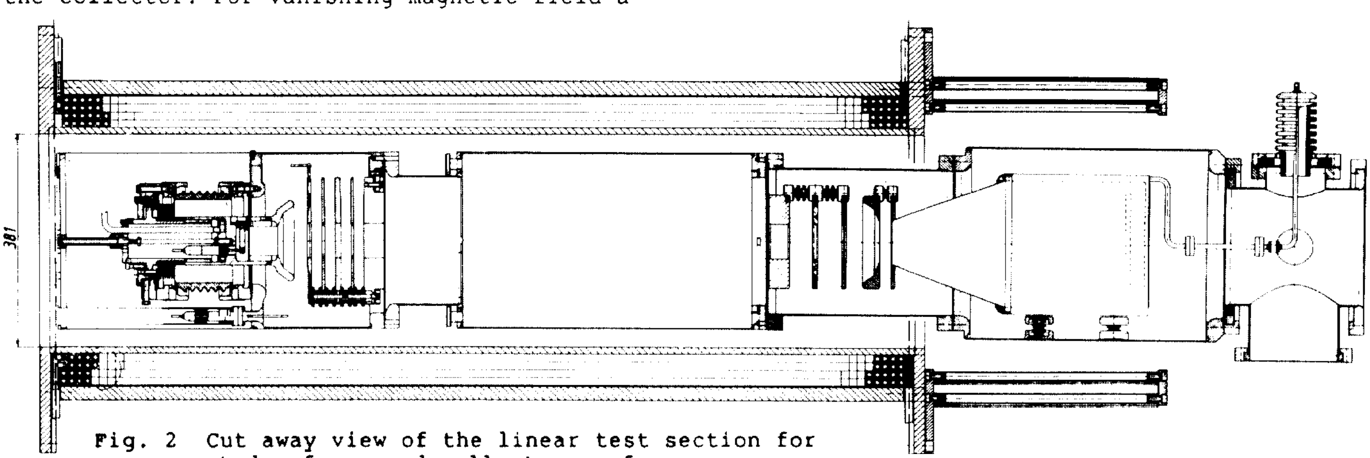


Fig. 2 Cut away view of the linear test section for study of gun and collector performance

| Cooling Solenoid | |
|---|---|
| length | 1.5 m |
| inner coil diameter | 0.5 m |
| conductor (4 layers) | 13 x 13 $mm^2$ $\phi$ 9mm |
| maximum current | 900 A |
| coil resistance | 118 mΩ |
| **Toroid** | |
| bending angle | 45 degrees |
| curvature radius | 0.8 m |
| small diamters | 0.5 m |
| conductor (4 layers) | 13 x 13 $mm^2$ $\phi$ 9mm |
| max. current | 1500 A |
| coil resistance | 43 mΩ |

Tab. 3 parameters of main magnets

First measurements of the components of the magnetic system have been performed. To study and minimize field variations at the transition between the individual coils the longitudinal and transversal field components from the outer side of the gun solenoid to the cooling section end of the toroid have been recorded with a Hall probe. Fig. 4 shows this measurement of the field components for the optimized relative positioning of the coils.

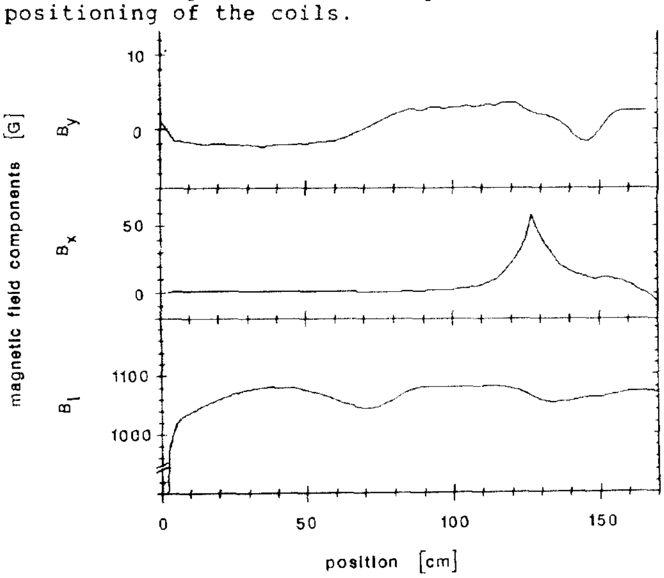


Fig. 4 Measurement of the magnetic field from electron gun end into the toroid

The field in the toroid was measured along a straight line and corrected for the 1/r-dependence and the geometrical angle between probe and field direction to obtain the field along the ideal electron trajectory. Without any correction coil a variation of -3.4% was achieved. Computer calculations proved that the variation of the measured guiding field will not cause excitation of additional transverse motion of the electrons.

Transverse components were studied by a Hall probe which was mechanically aligned on the axis and the readings of which where corrected for effects of improper alignment of the sensitive area. Inside the solenoids uniform transverse components of $B_t/B_l \leq 1.5\cdot10^{-3}$ were measured which can be compensated by a set of steerer coils.

To detect transverse components in the cooling solenoid with high sensitivity the technique of the magnetic pointer is employed [6]. A soft magnetic needle is cardanically suspended in two axis which are perpendicular to each other. The needle will align almost frictionless along the field lines. The change of the field line direction can be detected by a mirror attached to the needle which is controlled by an electronic autocollimation system. The sensitivity of this device was found adequate to detect changes of the field direction as low as $1\cdot10^{-5}$.

A survey of the cooling solenoid by this method showed an excellent field homogeneity in a 1 m long interior part. Deviations from the field direction in the center of the coil amount to $B_t/B_l \leq \pm1.5\cdot10^{-4}$. The increase towards the ends of the coil are due to the magnetically open ends of the coil.

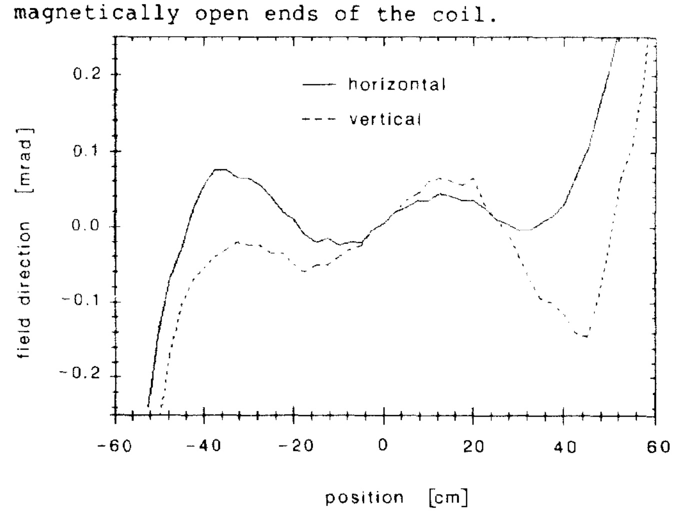


Fig. 5 Deviations of the magnetic field direction in the interior part of the cooling solenoid from the central direction

## Vacuum system

Most of the construction work of the vacuum system is completed and the main vacuum chambers are in industrial production. Great care is taken to avoid the use of any magnetic material in the vacuum system.

The ultra high vacuum ( < $10^{-10}$mbar) is maintained by non evaporable getter modules which are grouped in five sections, two in front of the collector, one behind the gun and one in each toroid chamber. This way a total pumping speed of more than 15000 l/s for hydrogen at room temperature is distributed along the electron cooler. Additional ion sputter pumps will supply pumping of those rest gas constituents not pumped by the getter modules.

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