# DESIGN OF A LOW ENERGY ELECTRON COOLER FOR THE HEIDELBERG CSR

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#### Abstract

A new electron cooler/target is being designed for the Heidelberg CSR. This device will serve the double purpose of phase space compression of the stored particles and of an electron target for recombination experiments. In this paper, we will present our results of a design for the magnetic confinement of the electron beam, stressing the demands specific to operation of such a device with low energy ion beams.

### THE HEIDELBERG CSR

The electrostatic Cryogenic Storage Ring (CSR) is currently being designed at MPI-K in Heidelberg [1]. This ring will utilise electrostatic deflectors and focusing elements to store ions with kinetic energies in the range 20 - 300 keV (E/Q) and will be mainly utilised for atomic and molecular physics experiments. Electrostatic deflection is used because it is more efficient at low energies and poses in principle no limitation on the stored particle mass. The CSR will be equipped with a compact mag-



Figure 1: Overview of the Heidelberg CSR. This cryogenic storage ring will be equipped with an electron cooler/target for recombination experiments as well as with a reaction microscope for neutral beam ion interaction detection.

netic electron cooler, which will serve the double purpose of phase space compression of the stored ion beam [2] as well as an electron target for recombination experiments. The cryogenic photo-cathode electron source, developed for the Heidelberg TSR [3], will be used to provide extremely cold magnetically guided electrons. The maximum cooling electron energy of 165 eV corresponds to 300 keV protons and the usual operation energy for 20 keV protons will be about 10 eV. The cooler will fit in the 2.8 m straight section of the ring. Since the entire device will be installed inside the cryostat (CSR outer vacuum chamber), we will use High Temperature Superconductor wires for the coils, which will be operated at temperatures of 40 - 80 K. An initial model of the CSR electron cooler was presented [4], but we have subsequently found that an important change to the layout of the cooler magnets was necessary in order to prevent non-linear excitation of the stored ions. In a typical cooler layout, electrons are created in an electron gun and guided by a solenoid field, after which they are bent in a magnetic toroid in order to merge them with the circulating ions. The ions penetrate through an opening in the toroid where they suffer some deflection. Usually this deflection is almost independent of the ion coordinate, but in the case of a low energy beam, e.g 20 keV protons, we have found that there is a strong dependence of this deflection on the coordinate. This effect will be shown to introduce strong coupling between the horizontal and vertical motions in the ring, and a new layout for the CSR electron cooler is presented which solves this problem.

#### ION DEFLECTION IN THE TOROID

When an ion moves through a toroid magnet the particle will experience a vertical kick caused by the horizontal component  $B_t$  (the CSR cooler will be mounted horizontally) of the tangential magnetic field  $B_s$  as shown in Figure 2. The dipole component is given by  $B_t = B_s \sin \phi$ , and

$$B_s = \frac{B_0 R_0}{R}, R = \frac{R_0 - x}{\cos\phi} \tag{1}$$

where,  $R_0$  is the equilibrium orbit radius of the electrons, x is the horizontal coordinate of the ion and  $\phi$  is the angle of the ion relative to the x-axis. Therefore the dipole component of the toroid field is given by

$$B_t(x) = \frac{B_0 R_0}{R_0 - x} \sin \phi \cos \phi \tag{2}$$

The total deflection angle  $\delta(x)$  of the ion due to the toroid field is then found by integrating  $B_t(x)$  divided by the magnetic rigidity of the ion beam  $B\rho$  and expressing  $\phi_{max}$  in

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Figure 2: Horizontal magnetic field  $B_t$  experienced by the ion during its motion through the toroid section (the CSR electron cooler is mounted horizontally).

terms of  $R_{max}$ , and we get finally

$$\delta(x) = \int_0^{\phi_{max}} \frac{B_t(x)}{B\rho} = -\frac{B_0 R_0}{B\rho} \ln \cos(\frac{R_0 - x}{R_{max}}) \quad (3)$$

The vertical deflection y' of the ion in the toroid can then be expressed as

$$y'(x) = \delta(x) = \delta(0) + x \left(\frac{d}{dx}\delta\right)_{x=0} + \dots$$
 (4)

The zero-order term  $\delta(0)$  is usually corrected in a storage ring with two sets of dipole coils before and after the electron cooler while the first-order term is usually small enough to be neglected. For the CSR we find however that

$$\left(\frac{d}{dx}\delta\right)_{x=0} = -\frac{B_0 R_0}{(B\rho)R_{max}} \tan\frac{R_0}{R_{max}}$$
(5)

cannot be neglected due to the low energy of the ion (small  $B\rho$ ). The immediate remedy to this is to the lower the confinement magnetic field of the electron beam  $B_0$  as much as possible. This however will have a detrimental effect on the efficiency of electron cooling due to the non-magnetisation of the electron beam. Also, for small magnetic field, the relaxation process between the transverse and longitudinal temperatures of the electron beam becomes important and will lead to an increase of the longitudinal electron temperature. In addition, the adiabatic condition for electron motion is difficult to satisfy at low  $B_0$ .

## **DESIGN OF THE ELECTRON COOLER**

An initial design of the electron cooler was investigated where the ions go through a toroid of radius  $R_0 = 0.1$  m with a guiding field of  $B_0 = 30$  G, using 3-dimensional finite elements calculations (TOSCA code). The calculated dependence of the vertical kick y' on the horizontal coordinate x of the ion is shown in Figure 3 (black circles). We see that the zero-order deflection is corrected to



Figure 3: Upper: calculated dependence of the vertical kick in the centre of the CSR electron cooler on the horizontal coordinate of the ion for the initial model (black circles); and for the improved cooler layout (white circles). Lower: the horizontal and vertical phase space plots show clearly the non-linear and coupled motion due to the toroid field for the old model (300 keV p,  $B_0 = 30$  G).

 $y'|_{x=0} \approx 0$ , but the first order term is reflected by the almost linear dependence of y' on x. A linear fitting to this data gives

$$\left(\frac{d}{dx}\delta\right)_{x=0} = -0.1mrad \cdot mm^{-1} \tag{6}$$

The formula 5 estimated for  $B\rho = 0.02$  Tm (20 keV proton) and  $R_{max} = 0.14$  m gives the consistent value of -0.09 mrad/mm. As a result of this coupling the beam dynamics in the ring were found to be highly non-linear. A finite elements model of the entire CSR ring was calculated which allowed us to study the particle dynamics in the real fields of the ring elements by tracking test particles for many turns [5]. The magnetic field from the electron cooler was also added to the electrostatic solution of the ring and the effect of the toroid field was investigated. A typical result is shown in Figure 3 (lower). For this tracking the particle was initially started at the coordinates  $(x_i, y_i) = (30, 0)$ . If the horizontal and vertical



Figure 4: Layout of the CSR electron cooler/target; the electrons start initially at 14 cm above the ring plane, and after a  $90^{\circ}$  deflection in the toroid they are bent down with a dipole field, therefor the ions are subjected only to the much more homogeneous dipole field.

motions are decoupled we should see no vertical motion  $(y = y_i = 0)$ , but the result shows clearly that this is not the case; both motions are coupled and non-linear due to the toroid effect. Therefore we have changed the cooler layout as shown in Figure 4. The orbit of the electrons as



Figure 5: The betatron motions are linear and decoupled with the new cooler layout (300 keV p,  $B_0 = 30$  G).

they leave the gun has been shifted to 14 cm above the ring plane. A toroid of radius  $R_0 = 20$  cm then bends the electrons by 90° before they enter into a transition solenoid of length 30 cm where an additional transverse magnetic field superimposed to the solenoid field, shifts them down to the ion orbit level. The toroid is iron shielded and the ions cross completely bellow it, so that they experience only the much more uniform dipole field of the transition area. The deflection they suffer there is corrected by the two correction coils as shown in the layout. The maximum solenoid field strength of the device is 300 G. The linear dependence of the deflection angle on position has been removed with this layout as seen in Figure 3 (upper part; white circles). Particle tracking for the same initial coordinates as before shows that the motion is now linear and that the horizontal and vertical betatron motions are decoupled as shown in Figure 5. Tracking of a 20 keV proton was also performed and shows that a magnetic field of up to 100 G can be applied while keeping the particle successfully stored. This study shows that special care should be paid to the lay-

out of the magnetic elements of an electron cooler and the effect its magnetic field can have on the dynamics of low energy ions in a storage ring.

## REFERENCES

- [1] A. Wolf et al., Proc. COOL05 (2005) pp. 473-477.
- [2] G. I. Budker, Proceedings of the International Symposium on Electron and Positron Storage Rings, Saclay, 1966, p. II-1-1
- [3] D.A. Orlov et al., J. Physics: Conference Series 4 (2005) 290.
- [4] H. Fadil et al., Proc. COOL05 (2005) pp. 346-350.
- [5] H. Fadil et al., these proceedings.