ULTRA-LOW ENERGY ELECTRON COOLER FOR THE HEIDELBERG CSR

A. Shornikov, D. A. Orlov, M. Grieser, K. Blaum and A. Wolf

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Abstract

As a part of the low energy electrostatic Cryogenic ion Storage Ring (CSR) an ultra-low energy electron cooler is under construction at the MPIK in Heidelberg. The cooler shares the basic CSR ultra-high-vacuum and 2 K cryogenic concept and uses a magnet system installed inside of the CSR isolation vacuum for the electron confinement. Cold electron beams will be provided for both phase space cooling of 300 keV stored ions and for recombination merged beam experiments with typical electron energies of 1-20 eV. A cryogenic photocathode electron source, developed for the Heidelberg Test Storage Ring, is used to achieve the beam quality required for electron cooling at such low energies. A new electron-ion merging scheme together with a decelerating electron optics suitable for both low energy electrons and slow ions will be applied. The production of high-quality electron beams of sub eV energies was studied at the TSR photocathode electron target.

INTRODUCTION

The Heidelberg CSR (see Fig. 1) is an electrostatic ring to be built at the Institute, with no mass limitation and with the capability of storing 20-300 keV ions. The circumference of the ring is about 35 m and it is designed to have a large ring acceptance of about 100 mm mrad.

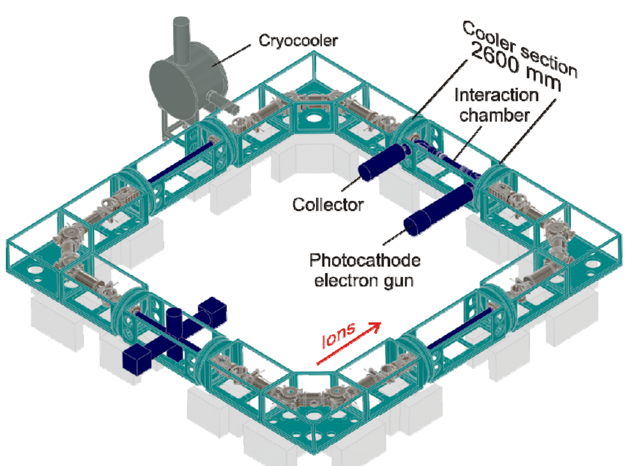

Figure 1: Schematic view of the CSR showing the electron cooler.

The key feature of the ring is the possibility of phase-space cooling of heavy, 100-200 a.m.u., molecular ions. To provide both phase space cooling with a velocity matched electron beam and cold electrons for merged beam recombination experiments, the CSR will be equipped with a dedicated ultra-low-energy electron cooler/target. The ring optics gives us the range of cooling energies we are interested in. The upper limit is given by 300 keV protons and corresponds to 163 eV electrons. For heavier single-charged ions the cooling energy decreases linearly as $1/M_i$ with M_i the ion mass, and corresponds to about 0.8 eV for M_i=200 a.m.u.; the typical electron cooling is foreseen to be a few eV. It is very difficult to cool these slow molecular ions because of the heavy mass and the low density of the electron beam, limited by the gun perveance. Thus, the lowest boundary is defined by the electron beam properties, including electron beam temperature and density.

The cooler will fit in one of the straight 2.6 m long experimental sections (see Fig. 1) and share the basic mechanical and cryogenic concept of the CSR with a two-level vacuum system. The first level is an isolation vacuum protecting the cryogenic environment from convection heat transfer and reducing radiation heat flux by thermal shields and by multilayer thermal isolation [1]. The second one is the 2K cryo-pumped beam vacuum volume at 10^{-13} mbar room temperature density equivalent pressure. The heat emission for the electron cooler has to be minimized and it should withstand bakeout up to 200-300^0 C. The magnetic electron optics of the cooler installed inside of the isolation vacuum has to be compatible with the electrostatic ring optics.

The CSR basic mechanical concept has been tested at the large scale 3-m long cryogenic electrostatic ion trap (Cryogenic Trap for Fast ion beams - CTF) that has been built as a part of the CSR project in 2007-2008. The CTF brought us practical knowledge about design and operation of large-scale cryogenic devices and proved our ability to achieve and measure vacuum with only 1000 rest gas particles per cubic centimetre specified for the CSR [1,2].

In this paper we discuss in more detail the results of numerical simulations, the mechanical and cryogenic concept of the cooler, and recent experiments on ultra-low energy electron beams [3], we have performed at the TSR e-target [4] with the same electron source and at energies we plan to use at the CSR.

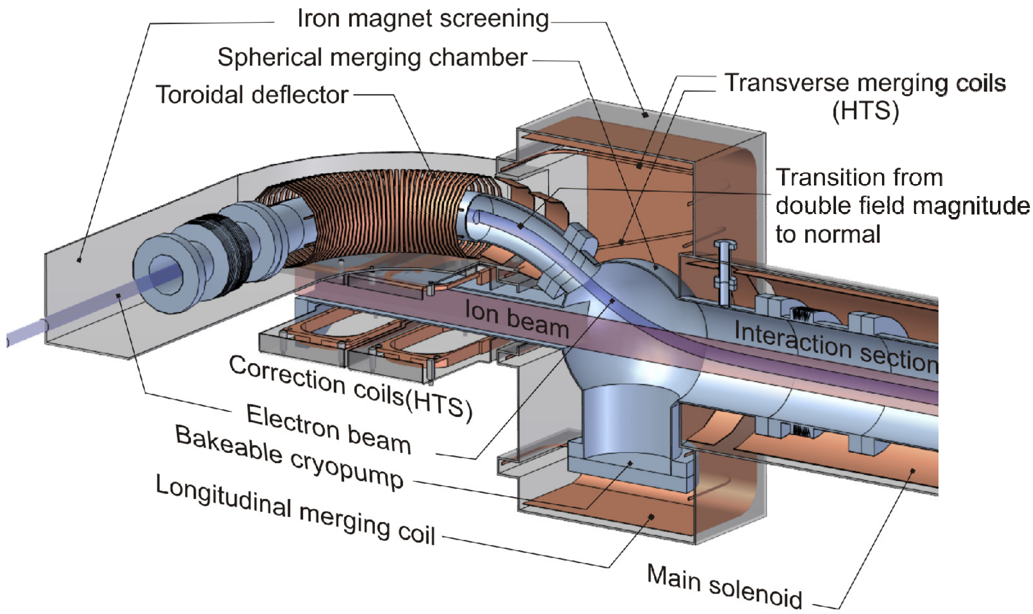

Figure 2: The new mechanical layout of the CSR electron cooler including magnet system inside of the isolation vacuum. The positions of copper magnets (toroidal deflector, main solenoid, longitudinal merging coil) and HTS magnets (correction and transverse merging coils) are also shown.

GEOMETRY AND SIMULATIONS

Recently [5] we have shown that the conventional merging scheme, with ion and electron beams merged in a toroidal section, is not applicable for the CSR because of strong and non-uniform deflection that slow ions suffer in the toroidal region.

The maximum magnetic field allowed in this geometry to keep 20 keV protons within the ring acceptance is below 1-2 Gauss that is not enough to provide a velocity matched high-quality electron beam. A new layout (see Fig. 2), where ions do not pass through the non-uniform toroidal field, has been proposed and numerically simulated by the TOSCA code [5]. In this merging scheme electrons start 140 mm above the ring plane. Then the electron beam is 90^0 deflected in a magnetically screened volume and only after that it is bent down in a rather uniform magnetic field produced by longitudinal and transverse merging coils (see Fig.2). In this geometry ion deflection does not depend on the position of an ion in relation to the beam axis and can be properly compensated by two pairs of magnetic correction coils placed before and after the interaction region. Trying to exclude any possible source of electron beam heating, the merging scheme has recently been designed in detail including the real beam lines, magnets, beam diagnostic tools and other auxiliary equipment. This realistic field geometry has been modelled by the TOSCA code and studied by tracking test electron beams through it. To avoid harmful influence of the magnetic field on the ion beam, the bending regions were completely iron-screened. We also keep the field magnitude in the toroidal sections twice higher than in the merging and interaction regions (see Fig. 2), which allows us to reduce the magnetic field seen by the ions while in the same time we prevent heating of the electron beam in the toroidal sections during bending.

The results on electron beam heating for the optimized cooler design are presented in Fig. 3 where the transverse beam temperature is shown as a function of electron energy for different magnetic fields.

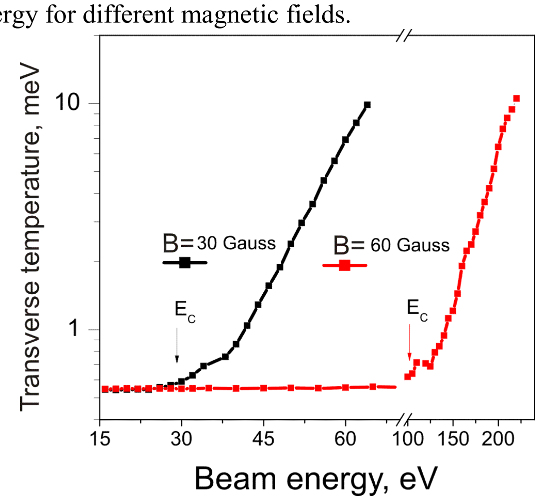

Figure 3: Transverse electron temperature as a function of beam energy for two values of the solenoidal field strength B. Due to non-adiabatic transport at high energies the transverse heating starts at critical energies E_C.

The initial transverse electron temperature of 0.5 meV is defined by the temperature of the electrons emitted from the cryogenic photocathode (about 10 meV) reduced by the factor of magnetic expansion α=20. It is seen that for a fixed guiding magnetic field the transverse heating becomes important in comparison to the initial temperature at critical energies E_c at ~ 30 eV and 100 eV for B=30 Gauss and B=60 Gauss. Above these energies the heating rises exponentially and at higher beam energies a stronger magnetic field is required to provide adiabatic beam transport. As a function of the electron beam energy E the scaling rule for the minimum guiding magnetic field, required to suppress the heating for the considered cooler geometry, is found to be

$$B_{MIN}(E) = 30\,G \times \sqrt{\frac{E}{30\,eV}}$$

The effective length of the cooler for the planned magnetic field geometry is obtained from the points where the angle between the electron beam and the cooled ion beam, due to the magnetic field angle, amounts to about 0.5 mrad, that is much below the natural electron beam divergence $\sqrt{kT_\perp/E}$ for E≤20 eV and $kT_\perp$ =0.5 meV. This way the effective cooling length of the CSR electron cooler is found to be at least 780 mm that is 2.2 % of the ring circumference.

MECHANICAL AND CRYOGENIC CONCEPT

The basic mechanical concept of the electron cooler is the same as for the entire ring. The CSR is a double vacuum system, where the XHV beam line is housed in a cryostat kept under 10^{-6} mbar pressure. The cooling system of the CSR is based on a commercial refrigeration system [6] with helium cooling lines of 2 K, 5 K, 40 K and 80K going around the ring inside the CSR cryostat volume, and with a 5 K line available for room temperature operation of the CSR. For cryogenic operation the XHV beam line is kept below 10 K with some stations cooled below 2 K to provide good pumping of hydrogen from the residual atmosphere. The distribution of the cooling power for the 10 K inner chambers will be realized by thermal conductivity of stainless steel-chamber walls with thin copper coating or oxygen-free copper foil attached to the chamber connected to the 2 K line by oxygen-free copper bands. At room temperature ultra-high vacuum will be reached by high temperature (200-300°C) bakeout of the inner chamber and with a help of NEG, cryo- and ion-getter pumps [7].

The electron cooler consists of the photocathode chamber, the gun chambers, the toroid and merging chambers, the interaction region, and the collector chamber (see Fig. 1). The toroid, merging and interaction regions are placed inside of the 2600 mm long 800×800 straight section of the CSR cryostat with 800*800 mm cross-section and will be cooled together with the ring. All magnets in these sections will be also inside of the cryostat and have to fit cryogenic and 10^{-6} mbar vacuum requirements.

To produce the magnetic field, high-temperature superconductor (HTS) coils and cryogenic cooled oxygen-free copper coils will be used. The space to build the correction and transverse merging coils (see Fig. 2) is strongly limited leading to the use of HTS coils. Both resistive and superconductive magnets will be cooled to about 30-40 K using a separate low-pressure 30 W Ne-refrigerator developed for the electron cooler [8] and powered by a commercial Leybold cold head. The basic idea for the superconductor magnets is that the HTS coil is mounted inside of a compact welded titanium vessel flooded with Ne cooling gas. Resistive 50 A magnetic coils are made of a 6 mm thin-wall copper tube combining conductor and cooling-line functions. Due to the low resistance of oxygen-free copper at 30-40 K, the resistive power is strongly reduced. This solution in particular strongly simplifies the design of the solenoids and reduces the required space. It should be also mentioned that the copper magnets have higher bakeout temperature of about 200°C (defined by the used isolation coating) whereas the temperature of the superconductor wire should not exceed 150°C. This allows us to keep the bakeout temperature of the inner chamber at about 200-300°C (depending on position), which is crucial for achievement of XHV conditions.

ULTRA LOW ENERGY BEAM

To cool 300 keV atomic and molecular beams stored at the CSR, electron beams with energies down to <1 eV are required. For successful operation at such low energies, properties of the electron beam such as temperature and intensity are crucial.

To deliver ultra-cold electron beams the cryogenic photocathode electron source, developed for the TSR electron target [3,9], will be used together with dedicated electron optics providing adiabatic electron transport. Transverse temperatures below 1 meV for magnetically expanded (α=30) electron beams from GaAs photocathode sources were demonstrated [10]. We also have shown that the longitudinal temperature from this source is below 30 meV, which can be further reduced by acceleration due to kinematic transformation to about 0.05-0.1 meV in the used energy range [10]. In contrast, the broad energy distribution of 100-120 meV from thermocathode source causes the longitudinal temperature of slow (≤10 eV) electron beams to be about a few meV, which increases strongly the cooling time of the stored ions.

Another key point is the electron beam density. It goes down linearly with electron energy and is limited by the gun perveance which is typically 1-2×10^{-6} A/V$^{3/2}$. To improve the beam perveance we performed the measurements with decelerated beams using the TSR electron target (Fig. 4). Here the electrons are extracted at higher voltages (typically ~ 20 eV) and decelerated by a drift tube in the interaction region down to sub-eV energies. Behind the interaction region the electron beam is accelerated to its original energy and transported to the collector where its 2D current density profile was analyzed. We implemented beam deceleration as a diagnostic and experimental tool to calibrate the electron kinetic energy taking into account space charge effects and the difference of contact potentials with an accuracy of 0.1 eV.

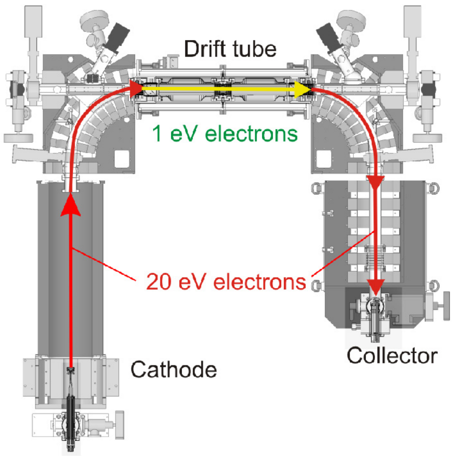

Figure 4: Scheme of the beam deceleration experiment at the TSR e-target with typical electron energies of a few eV

In these measurements, monitoring the electron beam profile, we found that the electron beam perveance could be increased by a factor of 10 up to 9-12$\times10^{-6}$ A/V$^{3/2}$, keeping a high quality of the electron beam. At higher deceleration voltages (with a threshold found to be very sensitive on the level of 10-20 meV) reflection of electrons caused strong inhomogeneity in the beam profile as well as a decrease of the photocathode lifetime. The measurements demonstrated that a strong increase of the electron current at a given low beam energy can be achieved using the deceleration scheme, which will strongly improve performance of the CSR electron cooler at lowest energies to be used.

CONCLUSIONS

The design concept of the ultra-low energy electron cooler for the CSR has been developed. Numerically and experimentally studied electron beam transport and field geometry allow us to foresee that electron cooling down to 1 eV can be provided by the photocathode electron beams for stored 300 keV molecular and atomic ions. Construction of the CSR electron cooler and the cryogenic magnetic optics is in progress.

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