DESIGN AND CONSTRUCTION OF THE CELSIUS ELECTRON COOLER

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ABSTRACT

The CELSIUS storage ring at the The Svedberg Laboratory is equipped with an electron cooling device. The cooler was taken into operation in May 1990. The paper describes the construction of the device together with some design considerations concerning the electron gun, collector, vacuum and high voltage system.

1. INTRODUCTION

CELSIUS [1] is a cooler-storage ring accelerator for protons and heavy ions from the Gustaf Werner Cyclotron. The ring is particularly suited for nuclear and particle physics with stored and cooled ion beams. The electron cooler for the ring was designed at the Unit for Accelerator Technology of the Royal Institute of Technology in Stockholm as a collaboration with the The Svedberg Laboratory in Uppsala, where the ring is situated.

A drawing of the electron cooler is shown in Fig. 1, the general data of the device in Table 1.

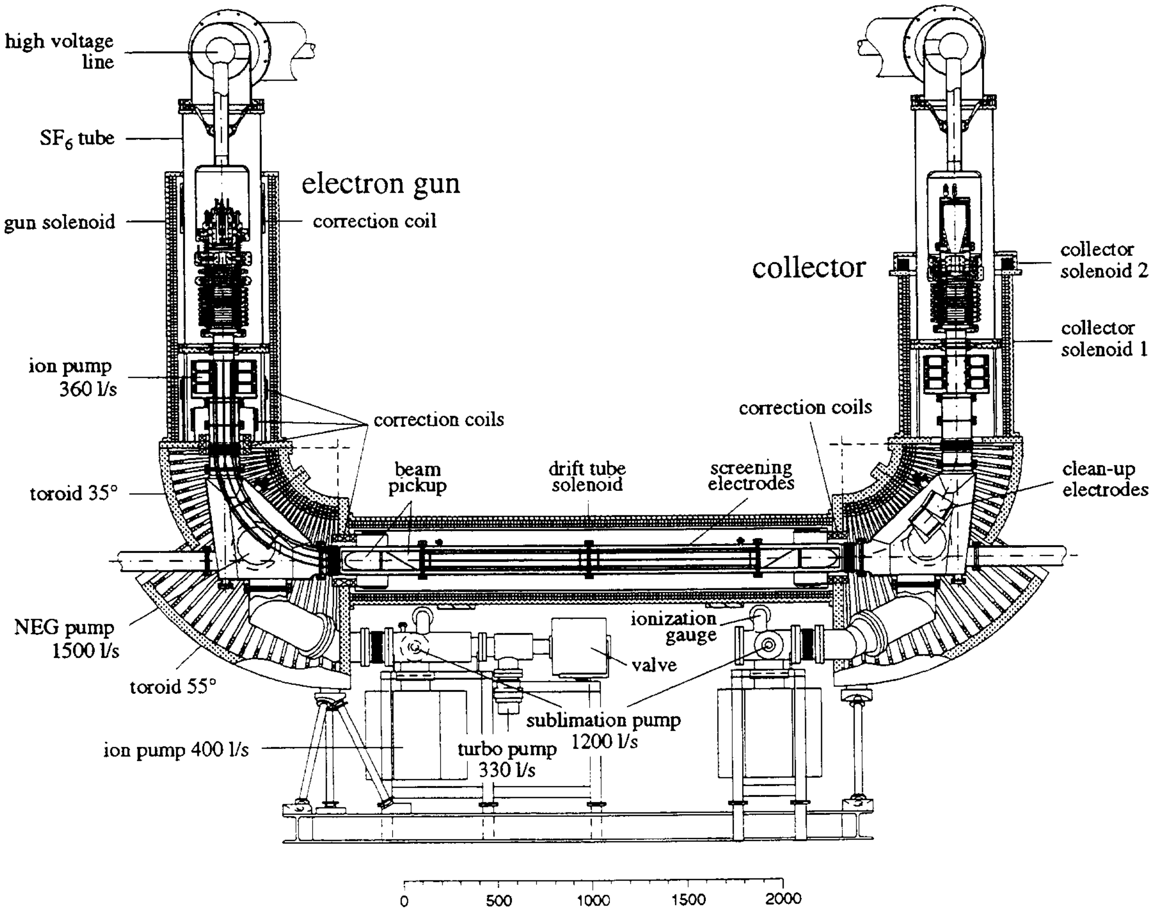

Fig. 1. CELSIUS electron cooler.

Table 1
Electron cooler data

Electron energy	5 - 300 keV
Cathode diameter	20 mm
Gun anode voltage	0 - 40 kV
Perveance	0.38 μP
Beam current	0 - 3 A
Magnetic field	0.1 - 0.18 T
Design magnetic field	0.15 T
Transverse energy	<0.2 eV @ 300 keV
Interaction space	2.5 m
Length	4.6 m
Height	4.3 m

2. MAGNETIC CIRCUIT

A homogeneous longitudinal magnetic field in the electron cooler confines the electron beam. The magnetic circuit consists of solenoids, toroids, correction, steering and dipole coils. The gun and collector solenoids have a larger diameter then the drift tube solenoid in order to accommodate the SF_6 chambers, with the high voltage insulation. The toroids consists of a 35° and a 55° section. To be able to adjust the position of the electron beam steering coils for the two perpendicular directions are included in all solenoids. Dipole coils in both toroids compensate for the drift of the electron beam.

All solenoids and toroids are connected in series to the main power supply. To compensate for differences between the necessary amperetums in the solenoids and the toroids an additional power supply is connected to each solenoid and toroid winding. By adjusting the currents from these power supplies the same value of the longitudinal magnetic field can be obtained in the centre of each solenoid or toroid. The design value of the longitudinal field is 0.15 T.

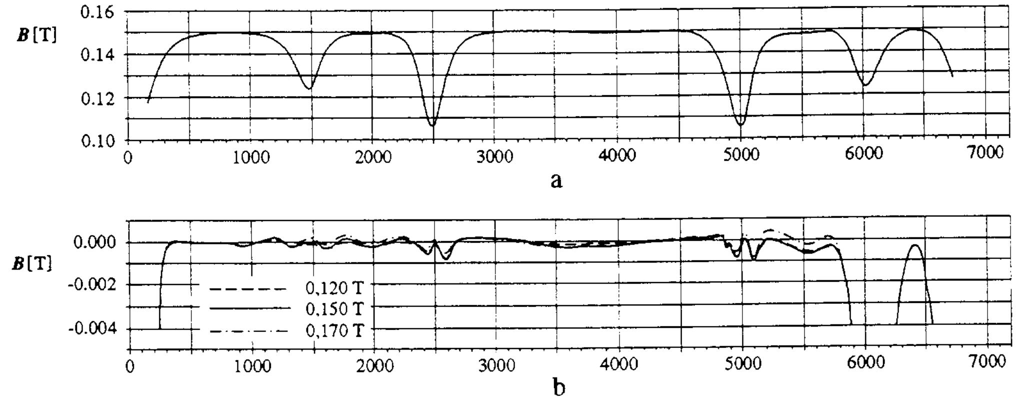

Fig. 2. Longitudinal magnetic field. **a.** Magnetic field along the axis without correction coils. **b.** Expanded corrected magnetic field at three excitations corresponding to nominal field of 0.12, 0.15 and 0.17 T.

At the transitions between the solenoids and the toroids there are missing ampereturns. The magnetic field shows a dip at these transitions, Fig. 2.a. Extensive computer simulations using the program POISSON [2] were made in order to find the number of correction coils, their shape and the number of ampereturns necessary to decrease the dips to an acceptable level.

The correction coils are necessary also for another reason. The dip in the magnetic field at the transition introduces scallop in the electron beam. Using the POISSON program a solenoidal system, where the toroids were replaced by solenoids of large diameter, was simulated. The computed field was then used as input data in a modified version of the E-GUN program [3] and a simulation of the transit of an electron beam with different energies was made. At a beam current of 2.5 A and a beam energy of 300 keV the computed transverse energy of the outermost orbit in the drift tube was 12 eV. When all correction coils were included, the increase of the transverse energy inside the drift tube was negligible, of the order of 0.1 eV.

A special program was written to simulate the transition of the electron beam through the toroid. This program used the two-dimensional planar field obtained by POISSON computation, in the transverse direction the field was assumed constant. The space-charge of the electron beam was taken into account in a simplified way, treating the beam as concentric cylinders with variable diameter. The computations have shown two important results. The transition introduces some scallop in the electron beam, larger for higher energies. Up to about 100 keV the scallop seems to be negligible. At 300 keV the transverse energy, depending on the magnitude of the magnetic field, can reach a few electron volts. By varying the magnetic field a resonant condition can be obtained. This speaks for an electron gun construction which does not use resonant focusing to obtain a low scallop at the exit of the gun.

The longitudinal magnetic field was measured with a Hall probe connected to a Bell 600 Gaussmeter. The probe, mounted in a brass block, was pulled along the optical axis of the cooler by a synchrone motor, the output of the Gaussmeter was connected to a precision digital voltmeter and a recorder. The design value of the longitudinal magnetic field of 0.15 T was chosen for the adjustments of the correction coils. Between 0.12 and 0.17 T the differences are smaller than 0.2 mT from the gun cathode to the end of the drift tube, Fig. 2.b. All currents can be scaled proportionally to the desired magnetic field without changing the field distribution and its straightness in the drift tube solenoid.

The transverse field was measured using a small pencil beam. An electron gun with a tungsten cathode and a copper anode was placed inside the collector solenoid. The laser drilled hole in the anode was 0.05 mm in diameter. The acceleration voltage was 4.5 kV, which in a field of 0.15 T gives a Larmor radius in microns. The pencil beam is therefore forced to follow the magnetic field lines. The position of the narrow beam was monitored on a screen by a telescope, mounted on a table with digital read-out of the position. The screen was moved along the axis of the drift tube. By taking the average of a few measurements it was found that this zero method gives an accuracy of ±0.02 mm. Fig. 3 shows the result of these measurements.

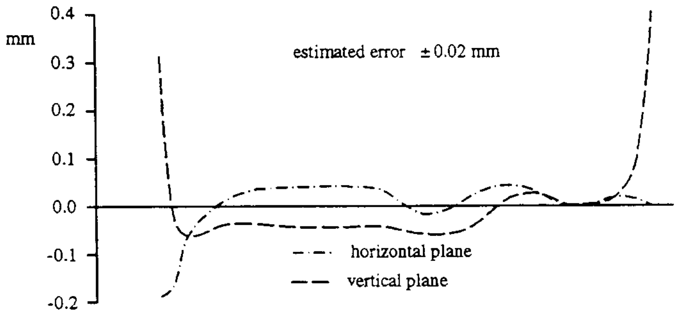

Fig. 3. Transverse magnetic field in the drift tube. Deviation from the geometric axis of the solenoid.

3. ELECTRON GUN

The design of the electron gun should result in an electron beam with a low transverse electron energy, it should be possible to vary the beam energy, the current and the magnetic field independently of each other. This speaks for an adiabatic focusing design.

A schematic drawing of the CELSIUS electron gun is shown in Fig.4. The whole gun system is placed inside a stainless steel tank filled with SF_6 in order to withstand the highest operating voltage of 300 kV. The gun uses a dispenser cathode with a diameter of 2 cm surrounded by a Pierce electrode. Two rings, the so called guard electrodes, are controlling the potential distribution in front of the cathode in order to obtain an even current density distribution across the cathode area. After passing the gun anode the electron beam is accelerated in two Large High Gradient accelerating columns made by National Electrostatic Co., a short one with 6 and a long one with 18 electrodes. A potential divider with a total resistance of 940 MΩ takes care of the potentials on all electrodes in the accelerating column. Corona rings are mounted around the electrodes. The osmium coated dispenser cathode is mounted on a holder consisting of three laser-welded Mo-Re cylinders which act as a thermal shield. The outermost cylinder is welded to a stainless steel cylinder with grooves to decrease the thermal conductivity losses. The cathode is heated by a pyrolytic graphite cylinder pressed against the inner cathode surface by a nimonic spring. The advantage of this kind of heating is an extremely low magnetic field at the surface of the cathode, low outgassing and a negative temperature coefficient of the material. A Mo-Re tube is the current lead. At the normal working temperature of about 1050°C the heater power is about 65 W. The power supply is power regulated. The holder of the Pierce electrode is made massive so that the outermost of the Mo-Re cylinders can be centred by three molybdenum spacers. The Pierce electrode has a standard 67.5° angle, its innermost part near the cathode is made of molybdenum, the outer part of copper. Both parts are brazed together. The electrode is mounted insulated from the holder by ceramic spacers. A ss-Cu-Ti transition connects the third Large High Gradient tube with the rest of the accelerating structure.

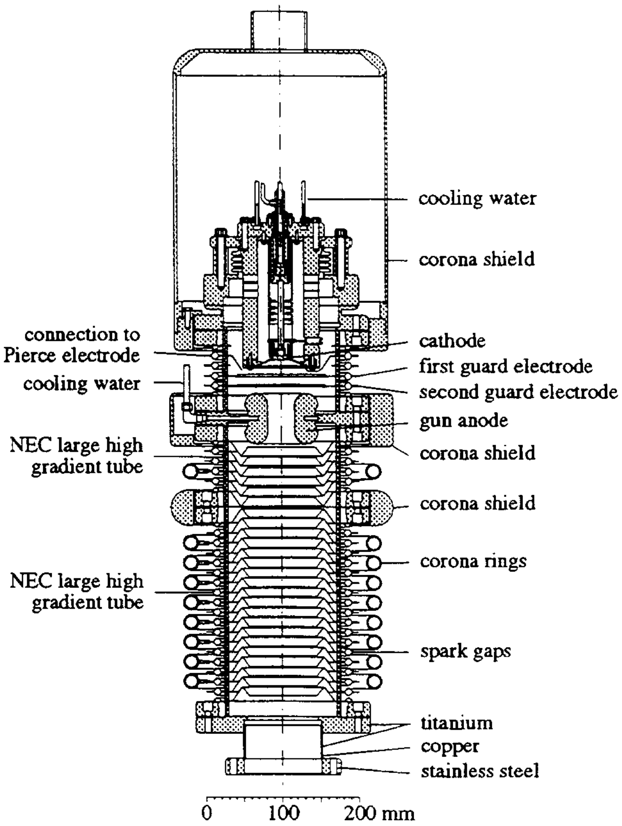

Fig. 4. Electron gun

Inside the high voltage terminal there are three power supplies connected to the gun side of the electron cooler: the gun anode, the gun bias (guard 1) and the Pierce electrode power supply. The potential of the gun anode, the gun bias and the Pierce electrode power supply can be varied independently of the acceleration voltage on the high voltage power supply (HVPS). The voltage of the gun bias electrode can be varied between 0 and −10 kV in order to cut-off the beam current. Each power supply is connected via a series resistor and has an overvoltage spark gap in parallel. The power supplies inside the high voltage terminal are connected to the gun and to the collector side of the electron cooler by large coaxially mounted tubes insulated by SF_6.

4. COLLECTOR

A schematic drawing of the CELSIUS collector is shown in Fig. 5. Like the electron gun, the whole collector system is placed in a stainless steel tank filled with SF_6 and immersed in a magnetic field.

Table 2
Collector efficiency at 30 keV and 0.13 T

Beam current [mA]	100	200	500	1000
Gun anode voltage [kV]	3.7	5.7	10.3	16.3
Collector anode voltage [kV]	0.15	0.20	0.38	0.58
Computed minimum [kV]	0.34	0.55	1.01	1.60
HVPS current [mA]	0.049	0.049	0.063	0.124
HVPS loss current [mA]	<1 bit	0.003	0.023	0.094
Collector efficiency [per cent]	99.999	99.998	99.995	99.991
Pressure [10^{-8} Pa]	0.9	1.2	1.5	1.7

The electron beam is retarded in one Large High Gradient column, passes the collector anode and is accelerated into the collector. The column has a potential divider with equal resistors resulting in a constant field gradient. The collector is biased positive with respect to the cathode potential, like the collector anode. The potential of the collector anode is adjusted to be high enough to avoid a formation

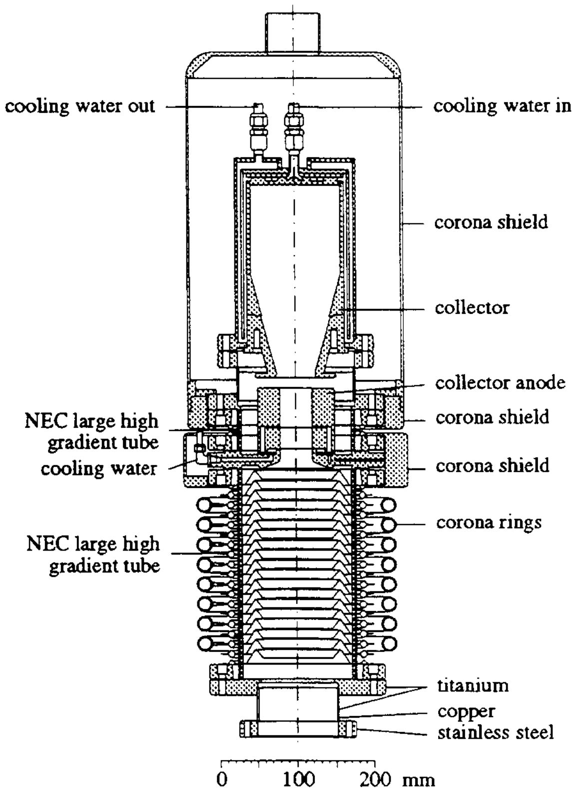

Fig. 6. Collector

of a virtual cathode and a reflection of electrons. The length of the anode ensures that a potential valley is created where positive ions, a result of the ionisation of the residual gas, are trapped [4]. The trapped ions neutralize the space-charge of the electron beam and reduce the lowest potential of the anode. The measured potential on the collector anode, Table 2, is lower than the minimum necessary to avoid the reflection of the electrons because of the space-charge depression, which confirms the formation of an ion cloud. The collector perveance is 58 μP. To optimize the collector efficiency the distribution of the magnetic field in the collector region can be changed by adjusting the current in the collector solenoid 2, Fig. 1.

Based upon the current distribution obtained from the simulation of electron orbits inside the collector, the power density and the maximum expected temperature was computed by the POISSON program. At a maximum current of 3 A the power density amounts to about 800 W/cm^2 at the centre of the collector. At a cooling water temperature of 30°C the temperature on the inside of the collector is 158°C.

5. VACUUM SYSTEM

The CELSIUS ring operates under ultra high vacuum conditions, at pressures below 10^{-7} Pa. The main pumping of the cooler is performed by a combination of ion pumps, NEG pumps and sublimation pumps, Fig. 1. A differential pumping is included on the gun and on the collector side by ion pumps, which use the gun and collector solenoid to generate the necessary magnetic field. With the valves towards the ring closed, the pressure in the cooler, as measured at the ionisation gauge mounted above the ion pump on the collector side, is $2 \cdot 10^{-9}$ Pa. With the cathode heated it increases by a factor of three. The pressure increases to about $2 \cdot 10^{-8}$ Pa with an electron current of 1 A.

All materials used in the cooler match the ultra high vacuum requirements. Stainless steel parts are made of LN316 steel, which has been fired. Other used materials are copper, titanium and ceramic. Heating jackets are wrapped around the whole vacuum system, the gun and the collector side have special baking hats. Most of the vacuum tubes have an inner diameter of 150 mm. The screening electrodes, which carry mirror charges inside the drift tube and the gun toroid chamber, are made of eight rods. This construction makes the electrodes transparent from the vacuum point of view. An estimate was made to check the possible deformation of the equipotential surfaces at the edge of the beam and found negligible.

The residual gases are ionised by the electron beam. Resulting ions and electrons drift inside the cooler along the magnetic field lines. Two clean-up electrodes are placed inside the collector toroid chamber to deflect the particles in an B×E field. Low conductance ceramic plates (zirconia) are connected by two stainless steel plates. The steel plates are connected to two power supplies, with variable voltage between zero an 10 kV. The electrodes are 100 mm long.

References:

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