ELECTRON COOLING IN COSY–JÜLICH

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Abstract

In the Cooler Synchrotron COSY, electron cooling will be applied to reduce the phase space volume of proton or ion beams after injection at low energy, before acceleration to the demanded final energies. Electron cooling of protons at the injection energy of 40 MeV leads to short cooling times, 1 to 2 s, and to small equilibrium emittances of the order of 1 π mm mrad. For the definition of optimum cooler and ring parameters for electron cooling in a fast cycling synchrotron the simulation code SPEC [1] was used. The design of the electron cooler, following from those calculations, is presented.

Introduction

The electron cooler, Fig. 1, will be installed in the cooler telescopic section of COSY. The ring has the shape of a race track with 184 m circumference. The free length for installing the electron cooler and the necessary ion beam correction elements (steerer and compensation solenoids) is about 7 m. The active cooling section is 2 m long. Table 1 gives a selection of important parameters of the lattice and the electron cooler. The cyclotron JULIC, being upgraded in the moment, will serve as injector providing H_2^+ ions of 80 MeV with a current of up to 10 μA. Using stripping injection, more than 10^{10} particles can be expected within the full aperture of the ring (50 – 150 π mm mrad). The maximum energy is designed to be 2.5 GeV. The main purpose of the COSY electron cooler is to prepare cooled ion beams at injection energy before acceleration to the demanded energies in order to provide maximum phase space density and particle number.

Stripping injection and electron cooling

Emittance and number of particles

It is easy to obtain emittances far below 1 π mm mrad with electron cooling [2]. However, such a beam can carry only a restricted number of particles due to various instabilities. At low energies, as the 40 MeV p injection energy in COSY, the Laslett tune shift ΔQ due to the space charge of the beam is the dominating limitation [3]. Qualitatively, Fig. 2 shows the dependence of the number of particles on the emittance with the beam energy as parameter. Additionally, the growth of the emittance of a 40 MeV p beam after n turns through the stripper foil (20 $\mu g/cm^2$ C) is shown. If injection is stopped after, e.g., 100 turns and the beam then fully cooled down to its natural equilibrium below 1 π mm mrad transversely and 10^{-4} longitudinally, more than 90 % of the particles would be lost again. A typical experimental situation would initially require 10^{10} particles in 3 π mm mrad which, during acceleration, would adiabatically shrink to a sufficiently low value. Due to the specific behaviour

Table 1. COSY electron cooler design parameters

Tune horizontal, vertical	3.38, 3.38 [+]	
Betatron amplitudes horizontal, vertical	4.3, 4.8	m
Dispersion	0	m
Transition energy	1.0	GeV
Free length	7.16	m
Cooling section length	2.00	m
Beam tube inner diameter	0.15	m
Electron beam diameter	2.54	cm
Max. solenoidal field	165	mT
Electron gun perveance	0.53	μP
Electron beam energy range, step I	20 – 30	keV
Electron beam current	1.5–2.7	A
Magnetic field for 22 keV, 1.7 A	84	mT
Electron beam energy range, step II	20–100	keV
Electron beam current	1.5–5	A
Magnetic field for 100 keV, 5 A	150	mT
Electron beam current loss	$\leq 5\times10^{-4}$	
Vacuum	1×10^{-10}	hPa

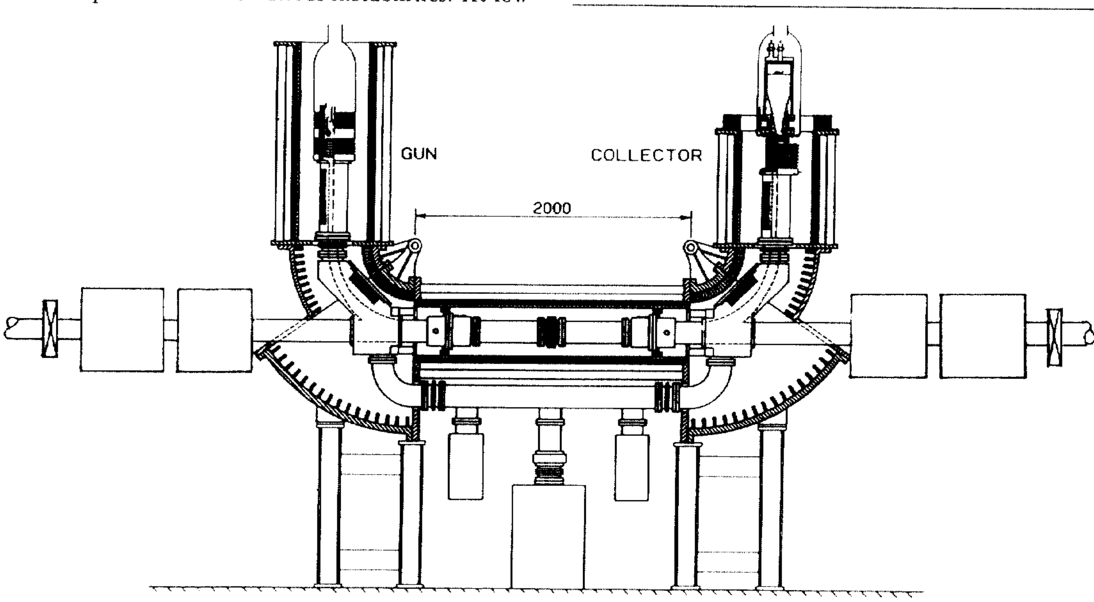

Fig. 1. Cross sectional view of the COSY electron cooler with proton beam correction magnets.

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[+] The final tune will range between 3.34 and 3.66.

of the cooling process – the cooled beam grows out from the "halo" of the uncooled beam [2] – it is not possible to stop cooling after some time. The only way to define a desired emittance and its related particle number is to artificially influence the emittance equilibrium in a controlled manner. In practice, this can be done by applying RF noise, which heats up the beam and counteracts the cooling power of the electron beam. It is important to note that a "poor electron beam", which would also result in a higher equilibrium, is not appropriate due to the longer cooling time in this case. Heating and cooling the ion beam independently leaves the cooling time more or less unchanged.

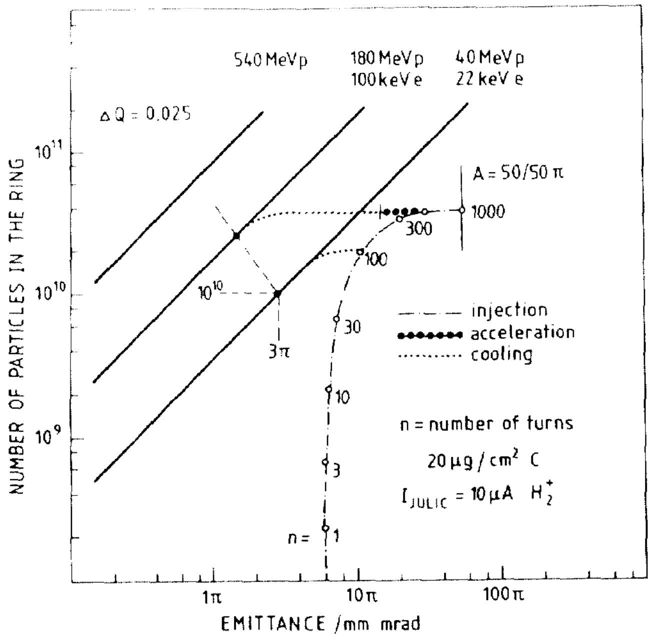

Fig. 2. Space charge limits in COSY for a coasting proton beam for three different beam energies, solid straight lines. Stripping injection increases the initial beam emittance depending on the number of turns through the stripper foil. Cooling at an intermediate energy yields a higher particle number at the same normalized emittance. The emittance is chosen to include 95 % of the beam, $E_{2\sigma}$.

Cooling time

Basically, the cooling time constant τ_c is determined by the relative velocity $v_{rel} = |\vec{v}_p - \vec{v}_e|$ of protons and electrons in the center of mass system, the electron density n_e, and the ratio η of cooling length and ring circumference [4].

$$\tau_c \propto v_{rel}^3/(n_e\,\eta) \qquad (1)$$

In COSY $\eta \approx 10^{-2}$, therefore we have decided to use a small diameter of the electron beam, 25 mm, in order to make n_e high with respect to a not too high total electron beam current. As long as the β functions in the cooling section are in the order of 5 m there is sufficient overlap of proton and electron beam. The v_{rel}^3 dependence of τ_c is a complicated mixture of p and e beam divergence, space charge of the e beam, magnetic field, and

Table 2. Transverse cooling time constants, SPEC simulations

T_e/keV	B/mT	I_e/A	β/m	$E_{0,\sigma}/\pi$ m rad	$(\Delta p/p)_\sigma$	$\tau_{c\perp}$/s
22	84	1.5	3.5	15×10^{-6}	6×10^{-4}	0.4
100	150	5.0	3.5	15×10^{-6}	6×10^{-4}	1.5

beam energy. To study τ_c in detail, SPEC [1] simulations were carried out. Typical results on the transverse cooling time constant relevant for our case are shown in Table 2. The longitudinal time constants τ_c are comparable to the transverse ones. The total cooling time to reach equilibrium is roughly $t_c \approx 2\,\tau_c$.

Duty factor

Considering the space charge limit, it is obvious that cooling at 180 MeV p would yield 2.5 times more particles in the ring, Fig. 2. On the other hand the cooling time becomes larger at increased energy, resulting in a poorer duty factor. With the inverse of the duty factor

$$\frac{1}{D.F.} = V = \frac{t_m + t_c + t_{exp}}{t_{exp}}, \qquad (2)$$

t_m the machine time, t_c the total cooling time, t_{exp} the experiment time, we describe the time duration of an external experiment. Since

$$t_{exp} = N/n, \qquad (3)$$

$$V = 1 + \frac{t_m + t_c}{N/n} \qquad (4)$$

with N the number of particles in the ring and n the number of particles per second on the external target. In COSY $t_m \lesssim 4$ s and total cooling times t_c in the range 1 s < t_c < 4 s can be expected. For low intensity beams, N/n >> 1, cooling at 40 MeV is always efficient. Only in a rapid cycling mode, N/n ≈ 1, a higher cooling energy might have some advantage.

Taking into account the technical limitations of the electron beam current, it is useless to go above 100 keV electron beam energy since the cooling time grows at least proportional with the beam energy. Our design goals for the COSY electron cooler are therefore:

- Shortest possible cooling times using an electron beam of 25 mm diameter.
- Reliable operation of a 22 keV electron gun and collector system with optimum electron beam current $\lesssim$ 1.7 A, stage I.
- Layout of the magnetic guide field and the high voltage system for 100 keV electron beam energy.
- Later development of a gun and collector system for 100 keV and 5 A, stage II.

Design Concepts

Magnetic guide field

The magnetic system consists of drift solenoid, gun solenoid, collector solenoid, two 55° toroids, and two 35° toroids arranged in the geometry of an upright U, Fig. 1. The double–layered solenoid coils are wound on 20 mm thick Al mandrels. The coils in the toroids are single pancake coils with four windings. The coil material is 15 x 15 mm Cu with a 10 mm bore. The free diameter of the drift solenoid is 340 mm and 500 mm for gun and collector solenoid. For the flux return at the solenoids we use rods [3] instead of a closed iron configuration. Outer correction and steering coils can thereby easily be mounted. In order to make the effective cooling length in the drift solenoid as long as possible, we use field clamp plates at the ends of the drift solenoid with the hole for the beam line as small as possible, 280 mm. The field bump at these transitions between drift solenoid and 55° toroid is compensated by an inner gap coil with about 4000 A windings. This relatively low value is achieved by deeply submerging the ends of the solenoid coil into the 50 mm thick endplates of the 55° toroid.

The currents for a nominal field of 150 mT are 960 A for the solenoids and 1085 A for the toroids. The total power consumption for all seven coils is then 175 kW. All coils, including the coils of the compensating solenoids, I ≈ 1020 A, will be connected in series with active shunts in parallel in order to guarantee synchroneous fields in the cooler magnets and the compensating solenoids.

Proton beam corrections

The longitudinal field in the drift solenoid and the 55^0 toroids cause transverse coupling and –in the case of a polarized beam–spin rotation and, therefore, rapid loss of polarization. Two symmetrically placed so–called compensating solenoids will counterbalance the cooler magnetic fields better than 5 x 10^{-5}. The coil of such a compensating solenoid will be 0.55 m long and have six layers of a 15 x 15 mm conductor.

The second perturbation – the more serious one for the primary operation of a ring – is the closed orbit distortion by the vertical magnetic field component in our upright 55^0 toroids. Usually, a symmetric pair of two horizontal steerers close together adjust the proton beam such that the cooler is "invisible" to the beam.

Due to lack of space each pair of steerers had to be split. The first steerer bending back the proton beam (70 mrad for 40 MeV p and B_c = 150 mT) is located right after the toroid. The second steerer bending the proton beam into the axis is located after the inner quadrupole family. Consequently, the proton beam passage through the compensating solenoid is bent which makes necessary also vertical steering. Here, the deflection angles are smaller by more than a factor of 10. TRANSPORT calculations [5] have shown that only in the vertical direction ramping with beam energy is necessary. The technical solution will be a combined horizontal/vertical steerer about 0.5 m long.

Gun and collector

The technological challenge for the COSY electron cooler is to build a gun which delivers 1.7 A at 22 kV and which can also operate at 100 kV and 5 A. After first attempts to follow the concept of the resonant, compact multigap gun type, we will now realize an adiabatic gun with a single extraction anode plus an acceleration tube, Fig. 3. Besides less high voltage problems such a design features the advantage of varying the beam current independently from beam energy and magnetic field. EGUN [6] calculations on perveance and beam ripple show the expected results. The main reasons for the good beam quality are the smooth contours of anode and drift tube end, as well as appropriate ratios of lengths and diameters [7].

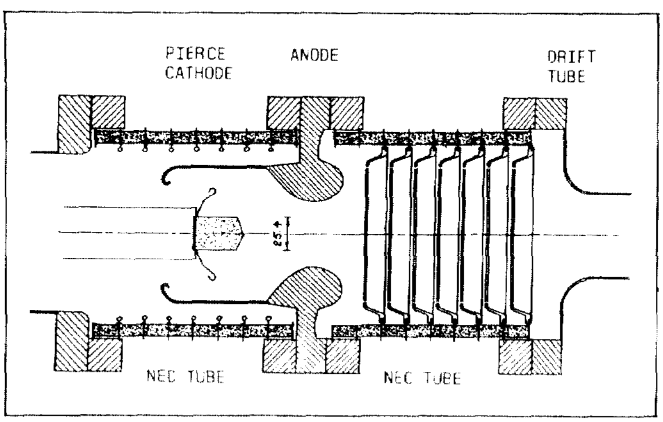

Fig. 3. Tentative design of the COSY electron cooler 1" gun.

The electron collector has been devised to be feasible for both the 30 keV and the 100 keV electron beams. A mirror image of the gun acceleration structure will form the deceleration optics in front of the collector. The collector will operate as Faraday cup with relatively low specific heat loads and at a perveance around 15 μP.

High voltage system

In view of the planned upgrading to 100 kV, we have choosen the conventional set–up with gun and collector at high potential supplied from a HV terminal in a Faraday cage which will be located about 7 m aside the electron cooler. In the terminal shell is space for four 19" racks containing the power supplies and the water cooling systems for gun and collector. All mechanical dimensions are choosen according to 100 kV, i.e. minimum distances of 0.3 m between HV and ground in order to ensure small corona currents. The connection between HV terminal and the heads of gun and collector will consist of a 0.8 m diameter coaxial structure with a 0.1 m diameter inner pipe carrying electric cables and water tubes.

The collector power supply needs 5 kV for 5 A. The isolation transformer will have 50 kVA. The high voltage power supply will be specifically choosen for 22 or 100 kV operational voltage.

Vacuum

The vacuum system has to be designed such that it fulfills the requirements of 10^{-10} h Pa, also with full power of the electron system. NEG pump modules situated around the electron beam nearby gun and collector and in the toroid vacuum chambers take over the task of differential pumping. Noble gases will be pumped by two 400 l/s ion pumps located near the toroids. Initial pumpdown is done with a turbopump set. The whole 7 m section can be separated from the beamline by two valves. The system will be bakeable between 200 and 300 ^{0}C.

Diagnostics

Two pick–up units for determining proton and electron beam position as well are forming part of the beam tube in the cooling section, Fig. 1. Besides standard Schottky signals available from COSY diagnostics, the well–proven method of neutral particle extraction , H^0 diganostics, will be used. A 50 mm diameter 50 μm thick stainless steel window at the end of the cooling straight section allows the detection of divergence and total intensity of the neutral particles. Proton beam emittance and electron beam temperature can thereby be determined [8].

Construction status

Solenoids and toroids have been ordered recently. Delivery is due end of April 1991. The design of all the other components is in good progress. First production of an electron beam is to be expected near the end of 1991. Integration of the electron cooler into the COSY ring shall occur mid 1992.

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