THE ELENA ELECTRON COOLER: PARAMETER CHOICE AND EXPECTED PERFORMANCE

G. Tranquille, A. Frassier, L. Joergensen, CERN, Geneva, Switzerland

Abstract

Electron cooling will be central to the success of the ELENA project which aims to increase by a factor of up to 100 the number of antiprotons available for the trap experiments. Because of the tight space constraints, the design of the device will be based on the compact electron cooler in operation on the S-LSR ring in Kyoto.

The biggest challenge will be to generate a cold and stable electron beam at an energy of just 55 eV in order to cool the 100 keV antiprotons. The use of photocathodes is excluded because their relatively short lifetime would require too many vacuum interventions during operation. We present the design parameters of our cooler as well as the results of the cooling performance simulations made with BetaCool and on-going work into "cold" cathodes.

INTRODUCTION

The Extra Low ENergy Antiproton ring (ELENA) project is aimed at substantially increasing the number of antiprotons delivered to the Antiproton Decelerator (AD) physics community. ELENA will be a small machine that receives antiprotons from AD at a kinetic energy of 5.3 MeV and decelerates them further down to 100 keV [1]. Electron cooling will be essential in ELENA in order to reduce or eliminate the emittance blow-up caused by the deceleration process and obtain the small emittance antiproton beams needed for further deceleration and extraction to the trap experiments.

Right after injection into ELENA at 100 MeV/c the beam is decelerated to 35 MeV/c where electron cooling is applied in order to eliminate losses caused by injection mismatch and beam blow up during the deceleration process [1]. Cooling is applied a second time after deceleration to the extraction momentum of 13.7 MeV/c (100 keV kinetic energy) in order to achieve required values of the beam emittances and momentum spread (See Fig.1).

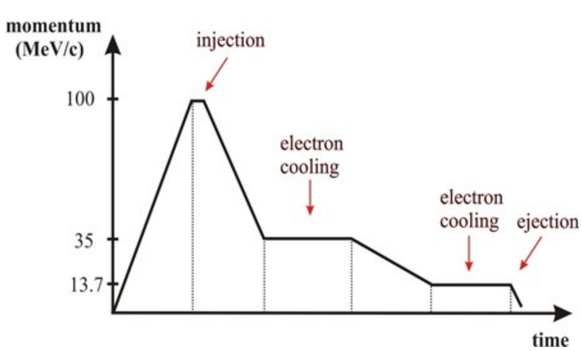

Figure 1: ELENA cycle

THE ELECTRON COOLING DEVICE

The cooler will be installed in long straight section 4 of the machine and will take up almost half the available space. The rest of the section will accommodate the orbit correctors and the compensation solenoids of the cooler. Due to the size limitations of the straight sections in ELENA, the space available for the electron cooler is 1930 mm flange to flange. This makes room for a drift solenoid with a length of 1000 mm. The cooler will have a beam height of 1200 mm as is the standard for the ELENA/AD complex. The electron cooler is envisaged to be mounted horizontally for easier maintenance and access.

Due to the space constraint, we have decided to base our design on the device built by Toshiba Corp. for the S-LSR project at Kyoto University [2]. This compact cooler was also built for use at relatively low energies with very high field uniformity and utilising the latest advances in cooler design (Fig. 2). The main cooler parameters are summarised in Table 1.

Table 1: Main Electron Cooler Parameters

Momentum	35 MeV/c	13.7 MeV/c
Electron beam energy	355 eV	55 eV
Electron current	5 mA	2 mA
B_{gun}	1000 G	
B_{drift}	100 G	
Toroid bending radius	0.25m	
Cathode radius	8 mm	
Electron beam radius	25 mm	
Twiss parameters	β_h=2.103m, β_v=2.186m, D=1.498m	
Cooling (drift) length	1.0 m	
Total cooler length	1.93 m	

The vacuum system will be similar to the one used for the LEIR cooler, namely; NEG cartridges at the gun and collector where the gas load is the highest, NEG coating of the vacuum chambers and NexTorr ion pumps in the cooling section.

For fast and efficient cooling special attention must be paid to the design of the electron gun and the quality of the magnetic field guiding the electrons from the gun to the collector.

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Figure 2: Photo of the S-LSR cooler at Kyoto.

ELECTRON GUN DESIGN

The electron gun must produce a cold ($T_\perp < 0.1$eV, $T_\parallel <$ 1meV) and relatively intense electron beam (ne ≈ 1.5x10^{12} cm^{-3}). The use of a photocathode has been briefly considered but for operational reasons was rejected as it is complicated to operate, has stability issues and also a relatively short lifetime. Instead a conventional thermionic cathode will be used and the electrodes will be designed to minimize the transverse temperature after acceleration to the desired energy. The gun is immersed in a longitudinal field of 1000 G which is adiabatically reduced to a maximum field of 100 G in the transition between the gun solenoid and the toroid. In this manner the transverse temperature is reduced further through an adiabatic beam expansion. The design of this gun is on-going using the EGUN code and the COMSOL multi-physics package.

THE MAGNETIC FIELD

The magnet system consists of 3 main solenoids: the gun, drift and collector solenoids, as well as an expansion solenoid to increase the magnetic field around the electron gun which is needed for the adiabatic expansion of the electron beam. The toroid sections are made up of 9 racetrack coil which come in 3 different sizes; two medium sized coils near the drift solenoid, 3 large coils to allow access by the antiproton beam as well as access for pumps etc. and finally 4 small coils near the gun and collector solenoids, respectively. In order to compensate for the larger size the two outer large coils have 1 extra turn whilst the centre large coil has 2 extra turns. The coil setup can be seen in Figure 3. There are also a number of larger correction coils needed to (i) improve the good field ($B_\perp/B_\parallel < 2\times10^{-4}$) region in the drift solenoid, (ii) guide the electron beam through the solenoid magnets, and (iii) compensate the kick experienced by the circulating beam in the toroids.

The magnetic field of the electron cooler has been modelled using the OPERA software package. At present the main goal of our simulations is to extend the good field region in the drift section. This should be possible if we install more Helmholtz coils in the drift section and move the field of the expansion solenoid as far away as possible. Figure 4 shows the effect on the longitudinal field if the gun solenoid is extended by 50 cm, effectively moving the expansion field 50 cm away from the drift.

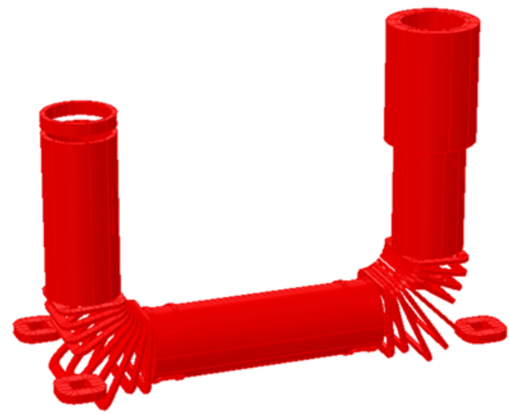

Figure 3: OPERA modelling of the magnetic fields for the ELENA cooler.

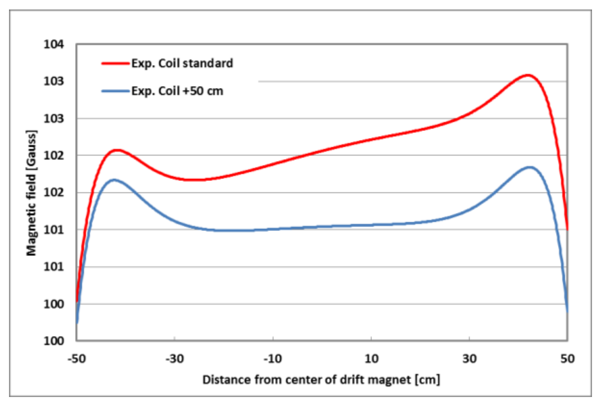

Figure 4: Influence of the expansion coil on the longitudinal field inside the drift solenoid.

EXPECTED COOLING PERFORMANCE

We have used Betacool [3] to investigate and optimise the performance of the cooler at the two momenta at which electron cooling will be used.

At the first plateau of 35 MeV/c, the initial parameters for the transverse emittances and longitudinal momentum spread were set at $\varepsilon_h = \varepsilon_v = 50\ \pi$ mm mrad and $\Delta p/p = \pm2\text{x}10^{-3}$. These values are somewhat pessimistic as they assume that the beam is injected into ELENA with emittances of 15 π mm mrad and that there is some extra blow up during the first deceleration. In practice we hope to obtain transverse emittances closer to 15 π mm mrad at this intermediate plateau.

Based on the results of the simulations an electron current of 5 mA with an electron temperature of 10 meV (110 K) appeared to be the optimum achievable. The results indicate that we should be able to achieve approximately a factor of 20 reduction in the emittances

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and a factor of 8 reduction in the momentum spread. With such large initial emittances tails can be seen in the cooled beam distribution (Fig. 5). This is explained by the fact that particles with large betatron amplitudes see a weaker cooling force and take much longer to be cooled to the core. In fact simulations with more realistic values for the emittances gave cooling times of less than 2 seconds with equilibrium emittances of the order of 1 π mm mrad in both planes.

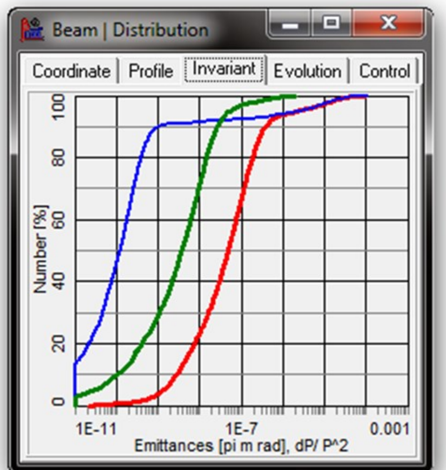

Figure 5: Beam distribution after 8 seconds of cooling at 35 MeV/c.

The simulations at 13.7 MeV/c were made with initial conditions of $\varepsilon_{h,v}$ = 15 π mm mrad and ΔP/P = ±1x10^{-3} (again very pessimistic values). The results are summarised on Table 2 and show that good beam characteristics can be obtained within 2 seconds of cooling with an electron current of 2 mA.

Table 2: Selected Results From Betacool at 13.7 MeV/c

Ie	kT	ε_h	ε_v	Δp/p
mA	eV	π mm mrad	π mm mrad	10^{-3}
1	0.03	2.4	1.5	±0.6
1	0.01	2.1	1.3	±0.5
2	0.01	1.9	1.1	±0.5

Studies have indicated that it may be necessary to continue with electron cooling during bunching prior to ejection to the experiments at the end of the 13.7 MeV/c plateau in order to prevent excessive beam blow-up that could be problematic for the acceptance of the electrostatic transfer lines. Test studies of this have been performed at the AD with encouraging results [4]. For ELENA, first simulations with Betacool show that an extension of the cooling during the bunching process will be beneficial for the beam parameters of the ejected beam.

COLD ELECTRON BEAM SOURCES

Thermionic cathodes limit the performance of electron coolers due to the high transverse temperature of the emitted beam. Adiabatic expansion helps to reduce this temperature but requires an additional solenoid to generate a large magnetic field at the gun. Photocathodes have been used in many set-ups but for reasons evoked previously cannot be used on ELENA.

We have started to look at alternative solutions for a cold electron beam source and at the moment two technologies look very promising:

- Micro-channel plates (MCP) / Electron generator array (EGA)
- Field emission carbon nanotubes

MCPs operate on the principle of secondary electron emission. When a charged particle, electron or photon impinges on the input side of the channel with sufficient energy, a few secondary electrons are produced. The resultant electrons continue to cascade down the channel until a charge cloud exits the channel. If one uses a UV diode as a photon generator and controls the MCP gain with the high voltage [5], a relatively intense electron beam can be generated.

In an EGA, the microstructure within the channel is altered creating spontaneously emitted electrons which initiate the cascade of secondary electrons [6]. The emission current can be varied over a broad range by controlling the rate of spontaneous emission and the gain of the device.

Carbon nanotubes have many potential applications. One of these is their use as an intense cold electron beam source. Applying a voltage to such an object causes electrons to be field emitted off the end due to an intense electric field concentrated at the tip of the nanotube. By producing an array of such tubes it should be possible to fabricate a viable field-emission electron beam source.

A test bench is being set up to investigate the possible use of the above techniques. If successful, a new gun could be designed and installed in the future on the ELENA electron cooler.

REFERENCES

[1] S. Maury et al. "Progress in ELENA Design", IPAC13, Shanghai, China, May 2013, p.2651.
[2] T. Shirai et al.,"S-LSR, Cooler Ring Development at Kyoto University", Proc. of Cool05, AIP Conf. Proc. 821, 103(2006).
[3] A. Sidorin et al., "Betacool Program for Simulation of Beam Dynamics in Storage Rings", NIM A 558 (2006) 325-328.
[4] P. Belochitskii, Private communication.
[5] B. Laprade et al., "The Development of a Novel Cold Electron Source", 50th ASMS Conference on Mass Spectrometry and Allied Topics, Orlando, FL, USA, June 2-6, 2002, paper 238.
[6] Hyun Sik Kim et al., "Cold Electron Source With an Electron Multiplier Illuminated by Ultraviolet Photons", Anal Chem. 2012, 84, 3635-3639.

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