Modeling the ELENA Electron Cooler with COMSOL Multiphysics®

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The Extra Low Energy Antiproton ring (ELENA) is a small ring at CERN which will be built to increase substantially the number of usable (or trappable) antiprotons delivered to experiments for studies with antihydrogen and antiprotonic nuclei.

The electron cooler plays a key role in ELENA both for efficient deceleration as well as for preparing extracted beam with parameters defined by the experiments.

COMSOL Multiphysics® has been used to complement traditional programs such as EGUN and OPERA to completely model the electron cooling device in 3D. We have taken advantage of the different physics-based modules of COMSOL Multiphysics® to optimize the various components of the cooler (magnetic transport system, electron beam generation, recuperation of the electrons in the collector etc.) and then to integrate the different studies into one model of the complete system.

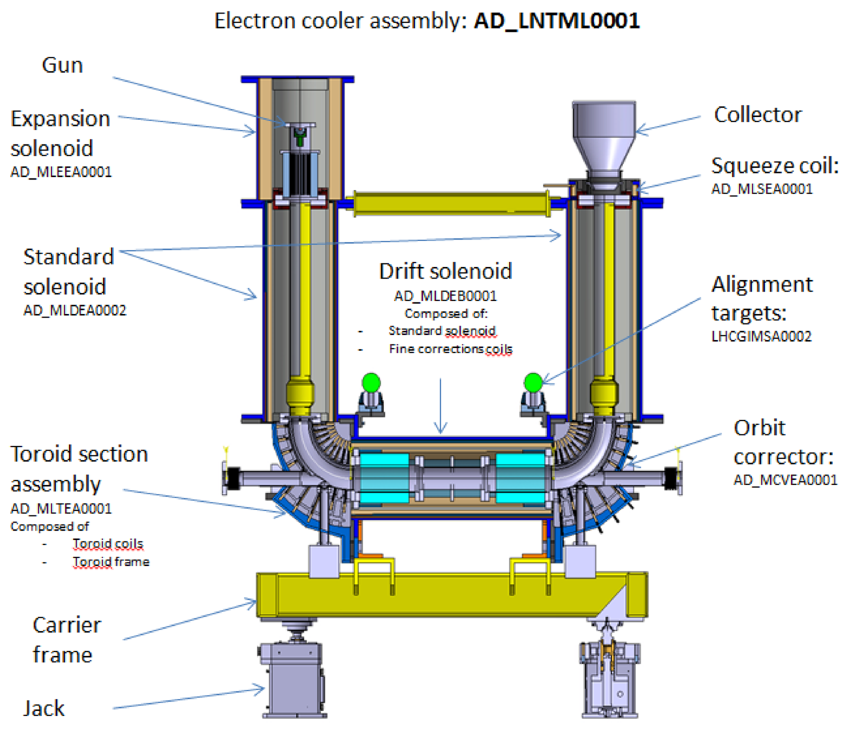
In addition COMSOL Multiphysics® has enabled us to make detailed tracking simulations of the passage of the antiproton beam in the highly non-linear magnetic field of the toroid section of our setup.

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. 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.

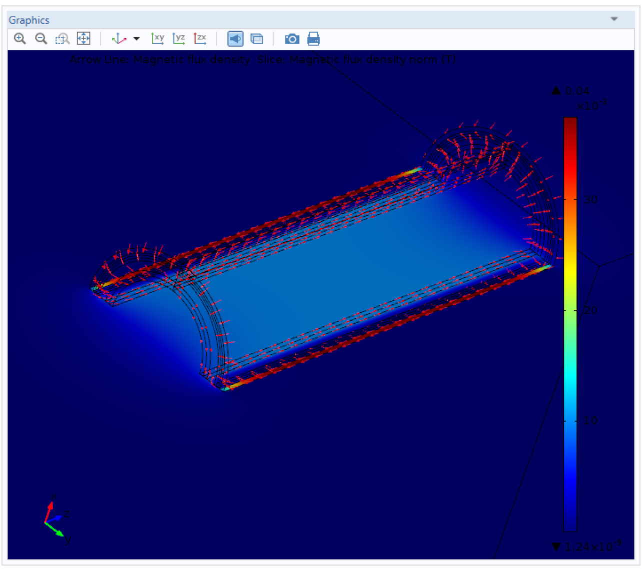
The cooler will be installed in long straight section 4 of the machine and will take up almost half the available space. The rest of the section will accommodate the orbit correctors and the compensation solenoids of the cooler.

Due to the space constraint, we have decided to base our design on the device built by Toshiba Corp. for the S-LSR project at Kyoto University. 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. The main cooler parameters are summarised in Table 1.

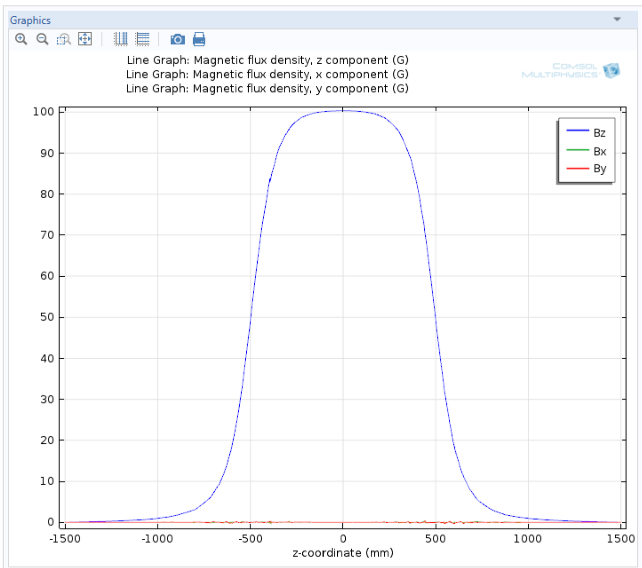
For fast and efficient cooling special attention must be paid to the design of the electron gun and the quality of the magnetic field guiding the electrons from the gun to the collector.



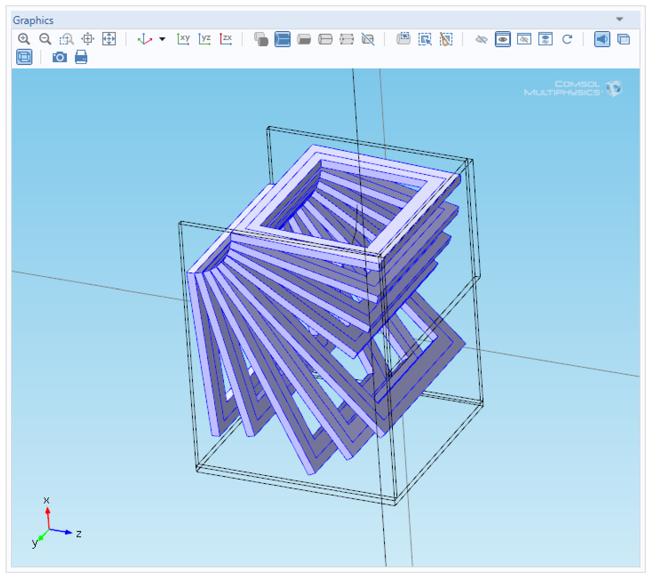
Parameter		
Momentum	35 MeV/c	13.7 MeV/c
Electron beam energy	355 eV	55 eV
Electron current	5 mA	2 mA
B_{gun}	1000 G	
B_{drift}	100 G	
Toroid bending radius	0.25m	
Cathode radius	8 mm	
Electron beam radius	25 mm	
Twiss parameters	β_h=2.103m, β_v=2.186m, D=1.498m	
Cooling (drift) length	1.0 m	
Total cooler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



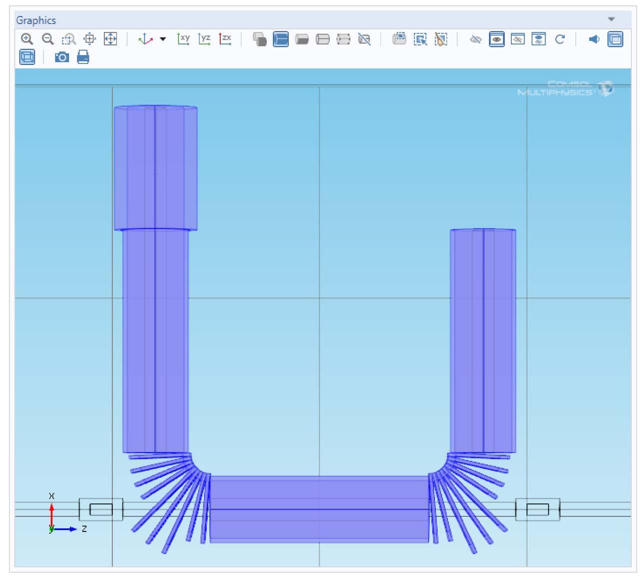
Model of the "standard solenoid" of the cooler.



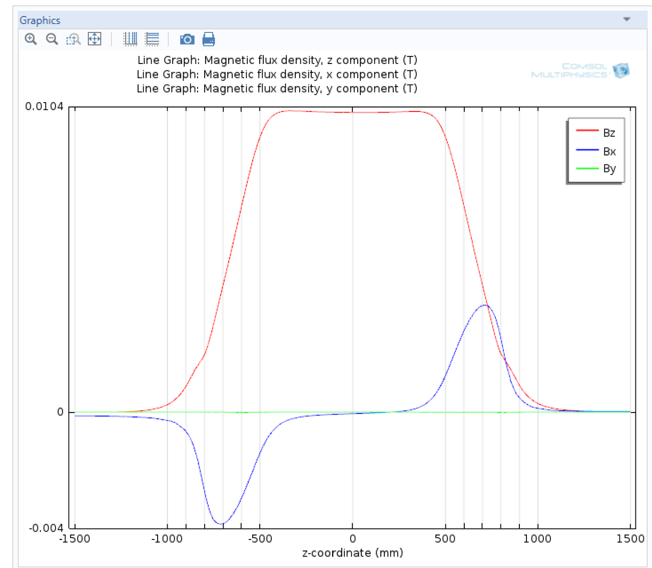
Magnetic field components along the beam axis in a "standard solenoid".



Model of the toroid section.



Complete magnetic model of the electron cooler.

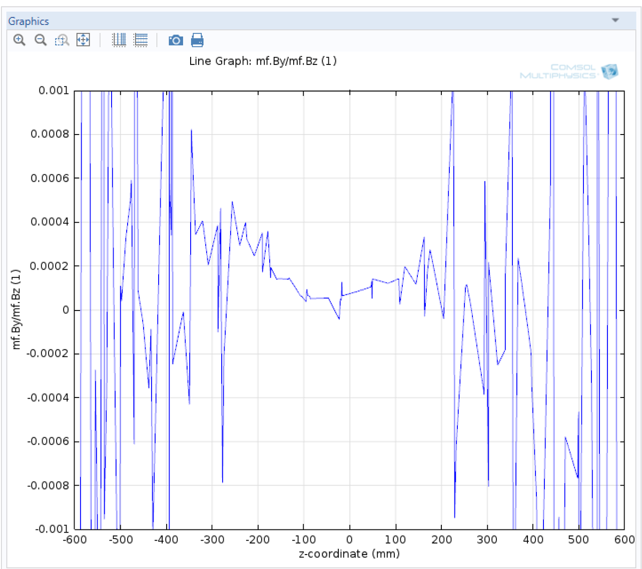


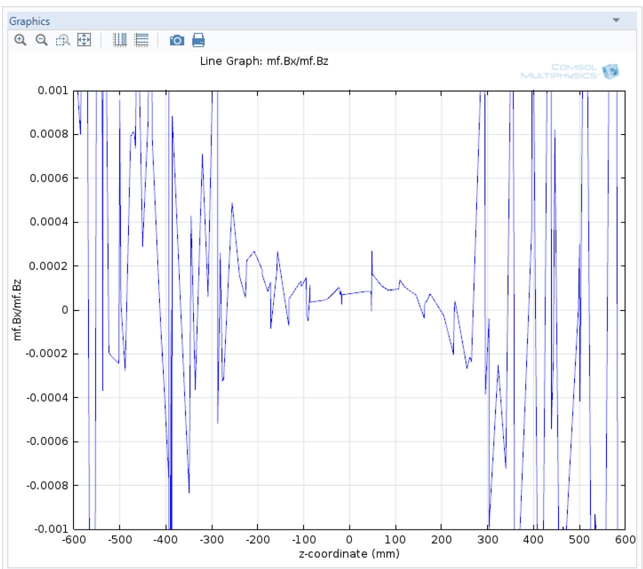
Magnetic field components along the beam axis in the complete cooler.

Three identical standard solenoids are used to guide the electrons from the gun to the collector. The operational field in these magnets is 100 gauss with a maximum field of 300 gauss. Each of the standard solenoids consists of the solenoid winding itself as well as a set of "saddle" coils at each end and two sets of Helmholtz steering coils running the length of the solenoid; one for each transverse direction. To leave sufficient space for the installation of heating jackets around the internal vacuum chamber, the minimum internal diameter of one complete solenoid assembly is fixed at 260 mm. The external diameter is 374 mm. The dimensions of the different layers are as follows; 10 mm for the stainless steel solenoid coil support, 21 mm for the solenoid coils, 6 mm for the saddle coils, 5 mm for the beam steering coils, 5 mm for resin impregnation and 10 mm for the required magnetic shielding. The solenoid coil is made from of two layers of 9×9 mm water cooled copper conductor.

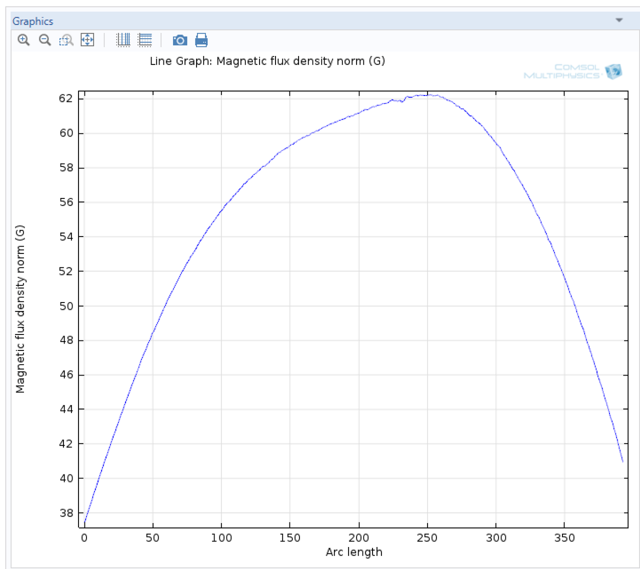
The role of the toroid magnets is to bend the beam of electrons onto the cooling axis and then, after the cooling section, to bend them away from the circulating beam of antiprotons towards the collector. Due to the compact nature of the electron cooler device, the bending radius is fixed at 250 mm. Each toroid is made up of nine coils of 4×4 mm water cooled copper conductor of two layers and of varying size. As for the three main solenoids, the operational is 100 gauss with a maximum field of 300 gauss.

The magnet system consists of 3 standard 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 ($B_\perp/B_l < 2\times10^{-4}$) 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.

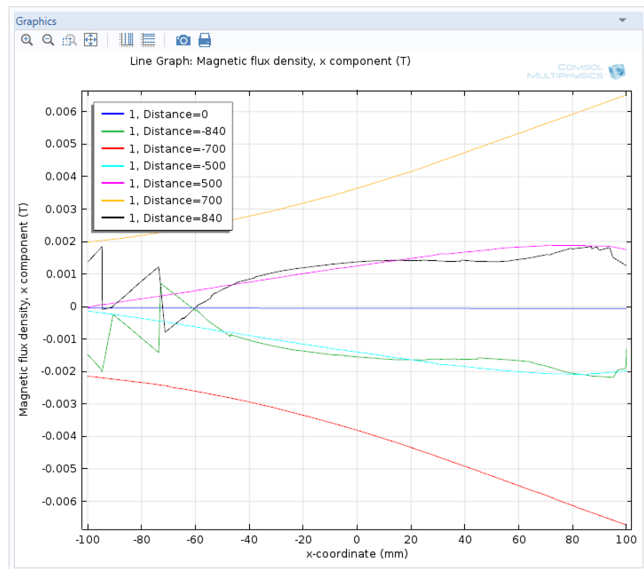


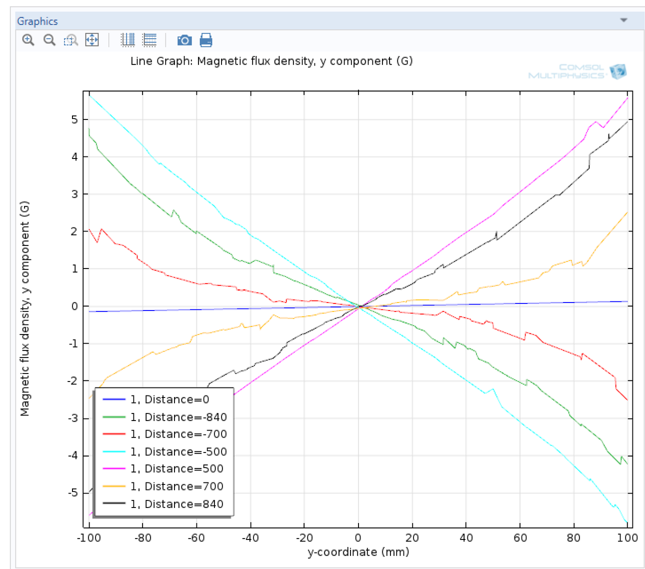


$B_\perp/B_l$ ratio (B_y left, B_x right) in the "standard solenoid". On sees a good field region over ±200 mm even before any correction with the foreseen "saddle coils".

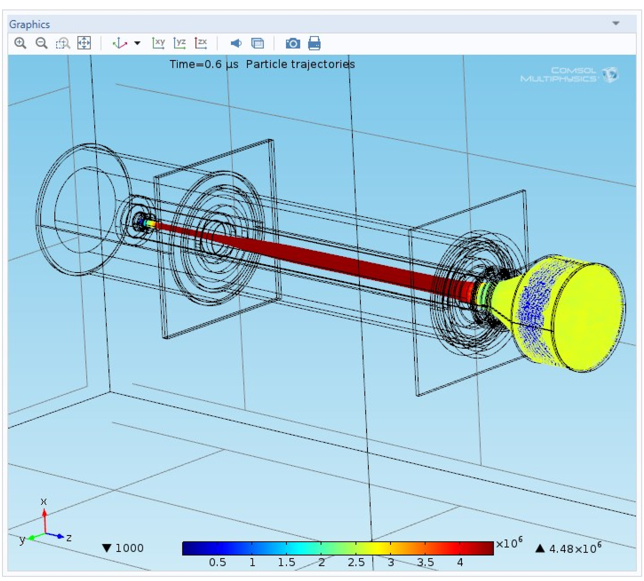


Magnetic field along the bending radius in the toroid section.

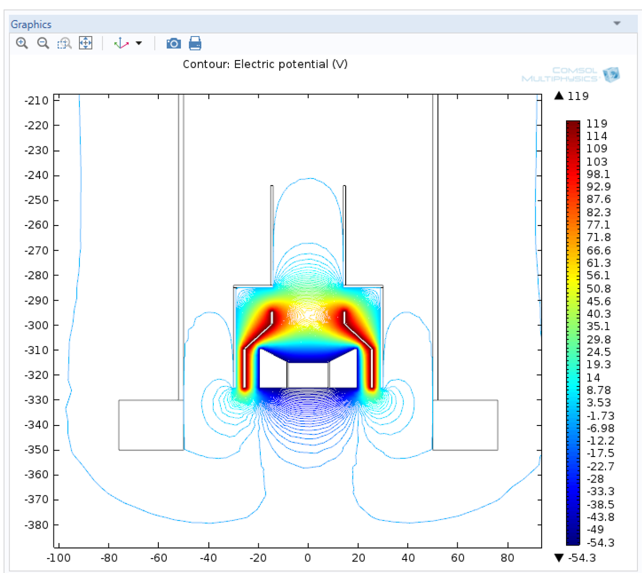




B_x (left) and B_y (right) field components at various longitudinal positions in the cooler. One notices an asymmetric behaviour of B_x giving rise to a skew deflection of the circulating particle beam.

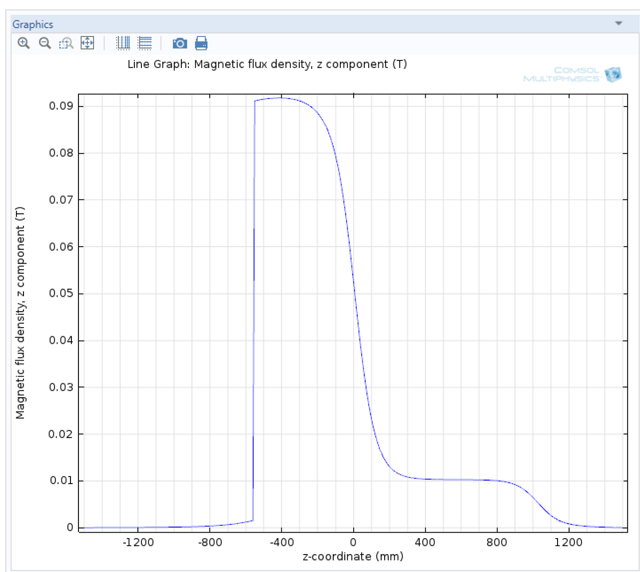


Electron trajectories from cathode to collector in a linear test stand model.

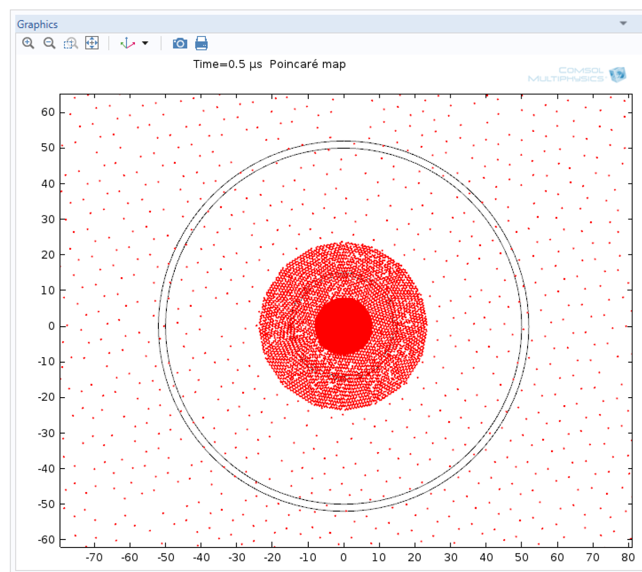


Equipotential lines in the electron gun. Careful choice of the "Pierce" angle results in flat equipotential lines at the cathode surface.

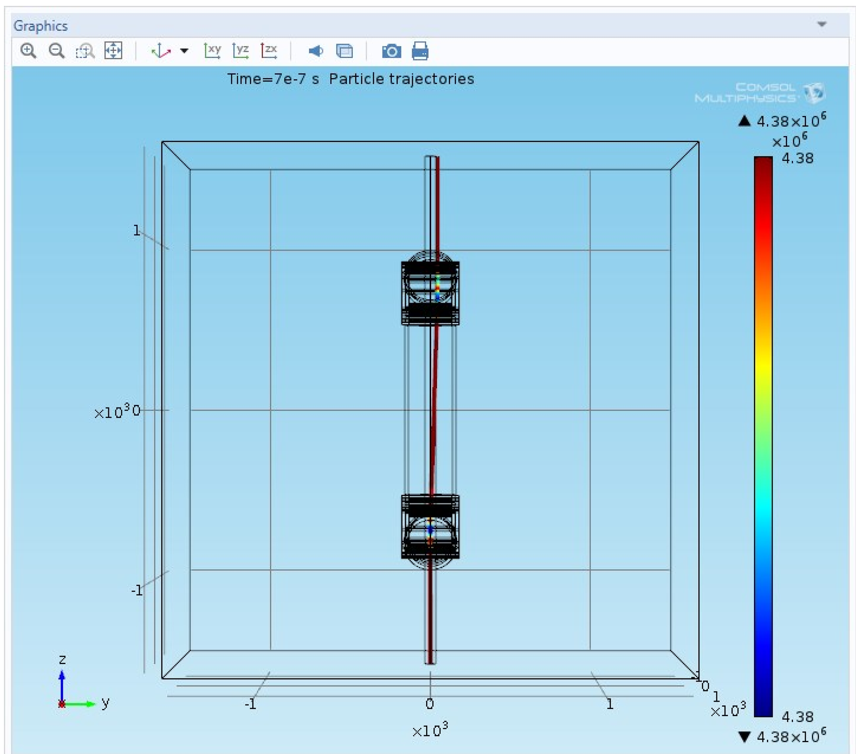
The electron gun must produce a cold ($T_\perp < 0.1$eV, $T_\parallel < 1$meV) and relatively intense electron beam (ne $\approx 1.5\times10^{12}$ m^{-3}). The use of a photocathode has been briefly considered but for operational reasons was rejected as it is complicated to operate, has stability issues 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.



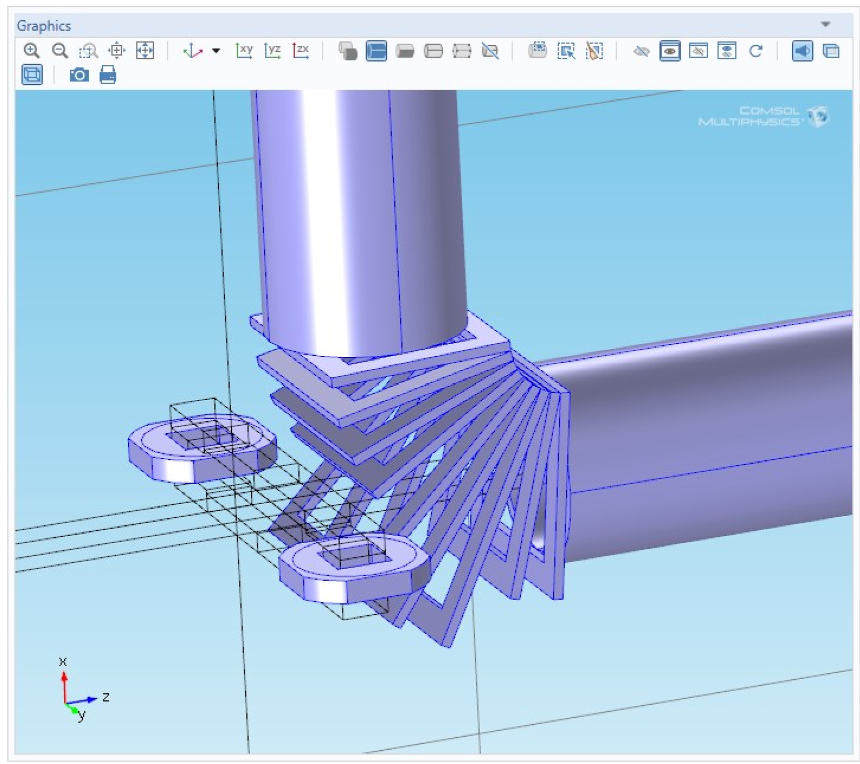
Longitudinal field in the linear test stand model. The field is adiabatically reduced by a factor of ten to increase the beam size and to reduce the transverse temperature.



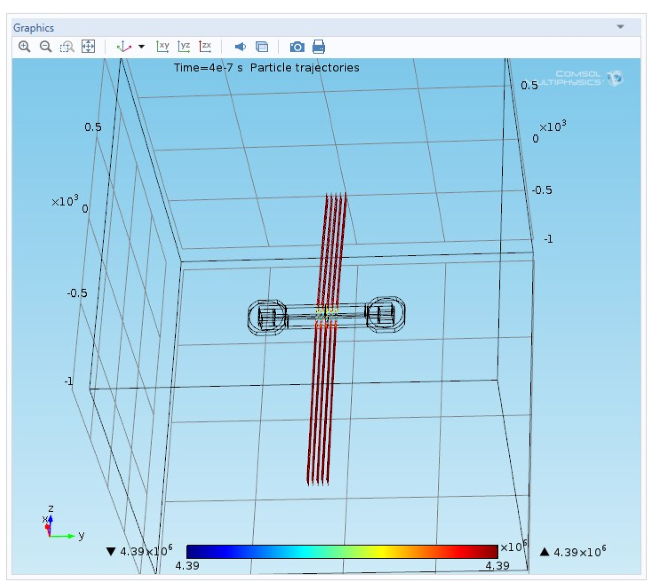
Electron beam size at the cathode, after expansion and in the collector. The increase in beam size by the factor $\sqrt{(B_{exp}/B_{sol})} = 3.16$ after expansion is observed.



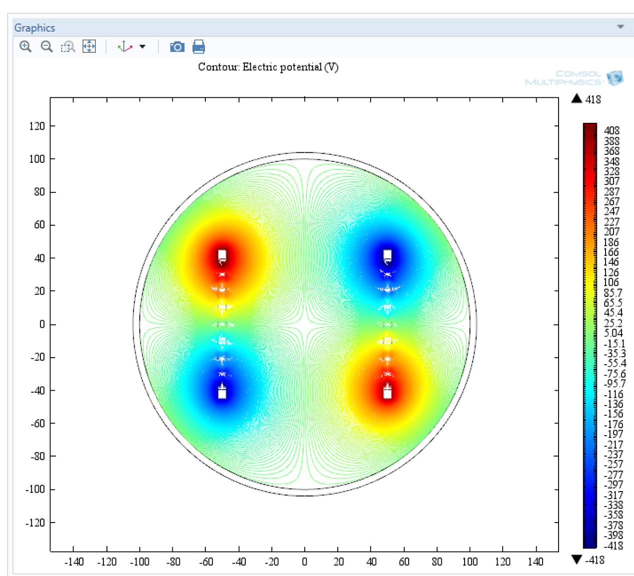
Antiproton trajectories in the electron cooler showing the effect of the deflection due to the toroids.



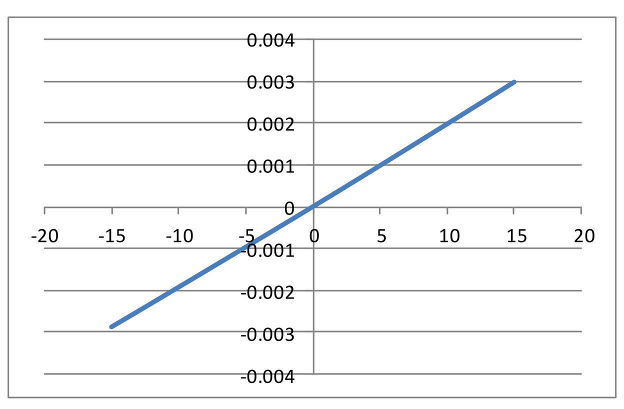
Position of the proposed closed orbit corrector.



Antiproton trajectories through the orbit corrector. The integrated field of this element gives the required 26 mrad deflection (below) needed to compensate for the toroid kick.



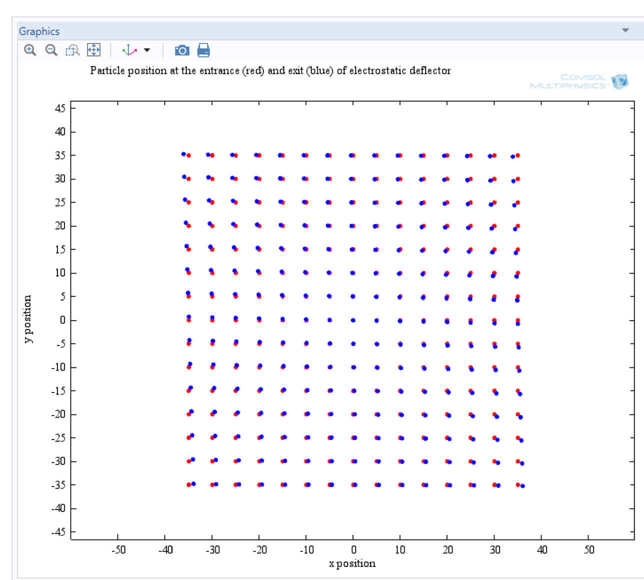
Electric potential contour of the proposed electrostatic deflector. A more refined model is being prepared to correctly simulate a resistive plate which would give a more uniform distribution.



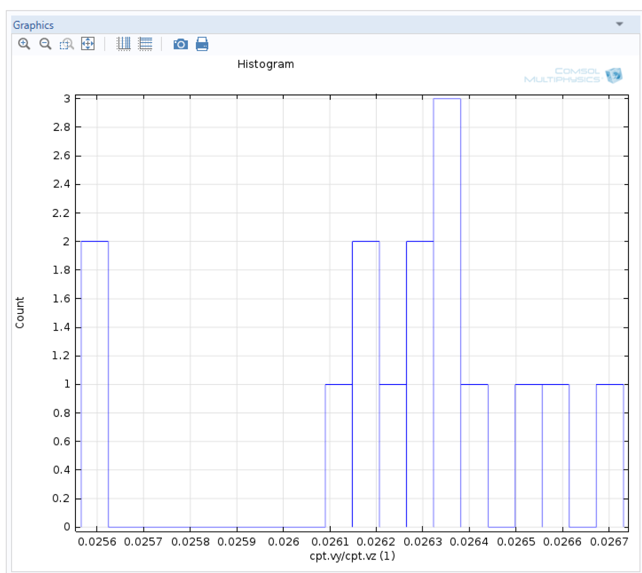
Residual kick angle (rad) as a function of vertical offset in the toroid magnet.

As the circulating antiproton beam passes through the electron cooler, the antiprotons experience a net vertical field due to the toroids, which results in a horizontal kick to the antiproton beam. In order to correct this kick, two sets of orbit correctors (one at either end of the electron cooler) are added to the system. These orbit correctors are be outside of the electron cooler shielding so as not to disturb the electron beam, while being as close to the shielding as possible to minimize the size of the antiproton excursion from the central orbit.

In addition, we have observed a dependence of the kick amplitude on the vertical position of the beam in the toroid section (see above). This means that our orbit corrector is not able to fully compensate this residual deflection and that an additional skew deflector needs to be designed. We are investigating the possibility of using resistive plates to create an electric field gradient that will give opposite deflections depending on the vertical offset in the toroid.



Skew deflection of the beam after passing through the electrostatic deflector. One clearly sees that at the exit (blue dots) the particles are deflected in opposite horizontal directions depending on their vertical positions.



Excerpt from the Proceedings of the 2014 COMSOL Conference in Cambridge