

MAGNETIZED BEAM TRANSPORT IN ELECTRON COOLERS WITH OPPOSING SOLENOID FIELDS *

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Abstract

To improve cooling capability of electron coolers magnetized beams in strong solenoid fields are used. To avoid betatron coupling in the ion coupling compensation is required. For the RHIC electron cooler we propose a scheme consisting of two identical solenoids with opposing fields, connected by a quadrupole matching section that preserves the electron beam magnetization. Since the fringe fields of the individual magnets overlap, the matching section can not be designed with standard optics codes. We developed an optimization code based on particle tracking instead. Input for the program are the simulated/measured field maps of the magnets. We demonstrate that the transverse temperature of the electron beam does not increase.

INTRODUCTION

To enhance the average store luminosity of the Relativistic Heavy Ion Collider (RHIC), as well as as part of the proposed electron-ion collider eRHIC, electron cooling of the stored ion beams is foreseen. Since the RHIC ion beams will be cooled at full energy during the store, electron energies of up to 55 MeV are required. Due to this high energy, electrostatic acceleration as in all existing electron coolers is not feasible, and a RF electron linac is required. To limit the electrical power consumption of the electron cooler to reasonable values in spite of the high beam power of 20 MW, this linac will be realized as an energy recovery linac (ERL) [1].

To achieve cooling times of some 30 minutes, use of a magnetized electron beam is foreseen, which requires a 2 Tesla solenoid along the 30 m long cooling section. Besides the difficulty of transporting a magnetized electron beam from the gun to this cooler solenoid without a continuous solenoidal guiding field along the entire beam transport line [2], this long, strong solenoid in the cooling section also causes significant coupling of the stored ion beam, which has to be appropriately compensated.

Since it is foreseen to split the 30 m long solenoid into two sections to ease manufacturing, transport and installation, this opens the possibility of having opposing fields, which provides local coupling compensation. We developed a matching scheme between the two opposing solenoids that preserves electron beam temperatures and magnetization.

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MAGNETIZED BEAM

For efficient cooling it is important that the transverse temperature of the electron beam is minimized. The temperature is defined as:

$$kT_{\perp} = m_e c^2 \gamma^2 \sigma_x'^2 = m_e c^2 \gamma^2 \frac{\epsilon^2}{\sigma^2}$$

where k is Boltzmann's constant, ϵ is the emittance of the beam and σ is the radius. If a cooling solenoid is used the emittance increases due to the rotation of the beam caused by the fringe field:

$$\epsilon_{\text{effective}}^2 = \epsilon_{\text{thermal}}^2 + S^2 \gamma^2 \sigma^4$$

Here, $S = \frac{1}{2} \frac{e}{pc} B_s$ denotes the solenoid strength. This problem can be avoided by using a magnetized beam, i.e. a beam which rotates around the longitudinal axis outside the solenoid. The fringe field will then stop the rotation, leaving only the thermal emittance. A magnetized beam is created by a longitudinal field on the cathode and the magnetization must be preserved by carefully choosing the beam optics.

THIN-LENS APPROXIMATION

The solenoid fringe field generates a correlation between angular coordinates in one plane and the spatial coordinates in the other. This is described by the transfer matrix

$$M_{\text{fringe}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & S & 0 \\ 0 & 0 & 1 & 0 \\ -S & 0 & 0 & 1 \end{pmatrix}. \quad (1)$$

In the case of two opposing identical solenoids, the matrix describing the fringe field at the exit of the first solenoid equals the one that corresponds to the entrance fringe field of the second,

$$M_{\text{exit},1} = M_{\text{entrance},2}. \quad (2)$$

Without an additional matching section between the two solenoids, this leads to an increased electron beam temperature in the second solenoid due to non-zero off-diagonal elements of the product matrix,

$$M_{1,2} = M_{\text{exit},1} \cdot M_{\text{entrance},2} \quad (3)$$

$$= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 2S & 0 \\ 0 & 0 & 1 & 0 \\ -2S & 0 & 0 & 1 \end{pmatrix}. \quad (4)$$

This can be avoided by an appropriate matching section that inverts spatial and angular coordinates in one plane while leaving the other plane intact,

$$M_{\text{match}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}. \quad (5)$$

Such a matching section has a horizontal phase advance of 360 degrees and a vertical phase advance of 180 degrees. The beam is rotated around the transverse axis.

In this case, all off-diagonal elements of the product matrix M_{total} are zero,

$$\begin{aligned} M_{\text{total}} &= M_{\text{exit},1} \cdot M_{\text{match}} \cdot M_{\text{entrance},2} \quad (6) \\ &= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}, \quad (7) \end{aligned}$$

thus preserving electron beam temperatures.

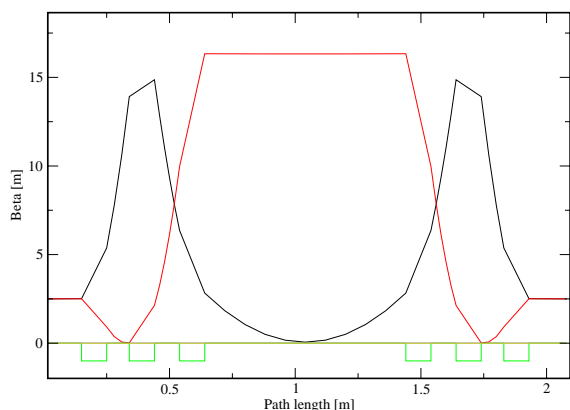


Figure 1: Optics of the matching section between ideal (hard edged) solenoids

The matching section can be realized by a minimum of six quadrupoles, controlling the Twiss parameters α and β as well as the phase advance ψ in both planes. Figure 1 shows the optics of such a matching section.

THICK LENSES

In the realistic case, the field of the solenoids decays over the length of one bore radius (100 mm), which extends into the region of the matching quadrupoles. The fringe fields of solenoids and quadrupoles also overlap each other. This causes two difficulties:

- The resulting field overlap cannot be handled by traditional beam optics codes like MAD [3], making it impossible to design the matching section using one of these codes.

- The points between which the phase advance must be $360^\circ/180^\circ$ are ill defined. A different figure of merit must be developed

We therefore developed a tracking code capable of tracking particles through magnetic fields described by appropriate field maps [4]. Using field maps for the superconducting solenoid and the superconducting quadrupoles, we tracked four orthogonal particles from a point deep inside the first solenoid to a point inside the second solenoid. Only the linear components of fields and particle coordinates are considered. The four particle vectors are then used to calculate the transfer matrix of the matching section.

The integration of the equations of motion uses simple step functions with a small step size of $1 \mu\text{m}$. While the computation time is still reasonable (in the order of 1 second per step) the results does not change if the step size is decreased further. For optimizing the simulated annealing method described in the "Numerical recipes" collection [5] is used. This method seems to be most able to avoid local minima. Also used is the Powell method which converges much quicker in the vicinity of the absolute minimum.

To address the the question of the phase advance it is useful to describe the rotation of an electron around the longitudinal axis. If $\theta = \text{atan}(\frac{y}{x})$ is the cylindrical coordinate of the electron then the rotation speed is defined as:

$$\theta' = \frac{xy' - yx'}{x^2 + y^2}$$

Starting with $\theta' = 0$ inside the first solenoid the fringe field increases the rotation speed to $\theta' = S$ where S is the above defined solenoid strength. In order to minimize the effective emittance the rotation must be zero inside the second solenoid. This condition replaces the requirement for the phase advance mentioned above. The second matching condition keeps the beam size constant.

It turned out that with these conditions the fitting routines did not converge easily. The convergence was much improved by using the symmetry of the matching section. With $\theta' = S$ at the exit of the first solenoid and $\theta' = -S$ at the entrance of the second solenoid θ' must therefore cross zero in the middle of the matching section. Also, the alpha functions (slope of amplitude functions) must be zero in the symmetry plane.

The matching routine starts therefore in the center of the matching section with a flat beam defined by the following trajectories:

$$\begin{aligned} \vec{x}_0 &= \begin{pmatrix} \sqrt{\epsilon_x \beta_x} \\ 0 \\ 0 \\ 0 \end{pmatrix}, \vec{x}'_0 = \begin{pmatrix} 0 \\ \sqrt{\frac{\epsilon_x}{\beta_x}} \\ 0 \\ 0 \end{pmatrix}, \\ \vec{y}_0 &= \begin{pmatrix} 0 \\ 0 \\ \sqrt{\epsilon_y \beta_y} \\ 0 \end{pmatrix}, \vec{y}'_0 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \sqrt{\frac{\epsilon_y}{\beta_y}} \end{pmatrix} \quad (8) \end{aligned}$$

Due to the fact that the solenoid fringe field leads to “rotation” of the electron beam between quadrupoles the quadrupoles must be rotated around the beam axis to follow the rotation of the beam. This is accomplished by modeling all quadrupoles as overlays of a regular and a skew quadrupole, and varying the ratio of both components during fitting. Using the strength of four two-layer quadrupoles and the initial beta functions as parameters the rotation of each vector inside the second solenoid as well as the aspect ratio of the horizontal and vertical beam size could be matched. Figure 2 shows the traces of the four test particle trajectories.

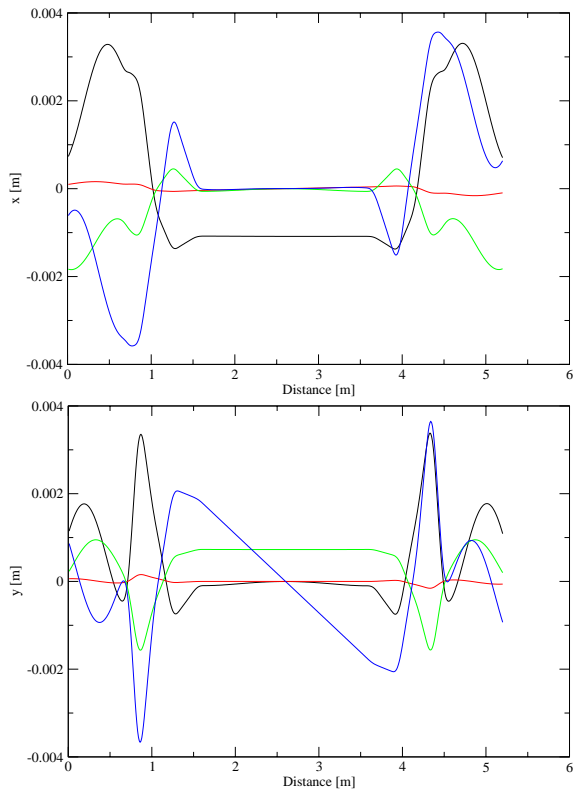


Figure 2: Horizontal (top) and vertical (bottom) trajectories of the test particles

CONCLUSION

We have demonstrated the feasibility of magnetized beam transport between opposing solenoids. This is accomplished by a set of quadrupoles which are rotated around the beam axis to follow the rotation of the beam in the solenoid fringe fields. The appropriate rotation angle of these magnets is found by a matching routine which optimizes the normal and skew components of each individual quadrupole. In the real machine, quadrupoles should therefore also be realized as overlays of (superconducting) regular and skew components to have additional tuning capability.

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