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TOROIDAL MERGER SIMULATIONS FOR THE JLEIC BUNCHED BEAM ELECTRON COOLER RING*

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Abstract

The bunched beam electron cooler ring for the Jefferson Lab Electron-Ion Collider (JLEIC) requires a merger system to transport magnetized electron beams of two different energies to the same energy recovery linac (ERL) beamline. The system is especially challenging compared to existing mergers for ERL or hadron cooling applications (as at COSY) due to the small separation in energy between the two beams; for the JLEIC bunched beam cooler, the two beam energies may only differ by a factor of 4. An additional complication is the use of a magnetized beam. A toroidal merger system is studied using G4Beamline/GEANT4. Preservation of the quality of the low energy beam from the injector is especially vital for efficient cooling performance and compatibility with the ERL. Effects of the toroidal system on transverse and longitudinal emittances of the magnetized beams, as well as space charge effects, are presented and discussed.

INTRODUCTION

The bunched beam electron cooler ring for the Jefferson Lab Electron-Ion Collider (JLEIC) is envisioned as an ERL-based circulator cooler ring utilizing magnetized electron bunches for strong hadron cooling [1]. The bunched beam cooler ring must provide 20-55 MeV/c electron bunches to cool the 40-100 GeV/c proton bunches during collision for maximum luminosity. One critical component of the bunched beam cooler ring is a merger system to merge both low energy electron beams from the injector and high energy electron beams returning from the cooling section into the same ERL beamline. This merger system is especially challenging due to the small energy separation between the injected beam and the return beam; this energy separation can be as low as a factor of four, much lower than the separation in conventional ERLs. The fields required to preserve the low energy beam quality will likely affect the high energy beam quality as well. The system is further complicated by the magnetized beam.

A toroidal (bent solenoid) merger system is explored as a natural way to preserve the magnetizations of the two beams while bending them into the same beamline. A similar merger system is used in the COSY electron cooler [2], but for the merging of electron and ion orbits at high energies. The preservation of the Larmor emittance of the magnetized beam is the key metric for evaluation of the merger performance, as this emittance component is directly related to the cooling performance. We evaluate the Larmor emittance by evaluating the vertical emittance of the transformed magnetized-to-flat beam.

SIMULATION SETUP

The system is set up in G4Beamline/GEANT4 [3] by placing solenoid coils along an arc with radius of curvature of 1 m. The low energy beam follows the geometric centerline of the toroid section through a bend of 45 degrees in the horizontal plane. An ideal sector bend field is superimposed on the bent solenoid field region to facilitate the horizontal bend. Additional field corrections are applied by tilting individual solenoid coils about their local x and y axes to compensate for vertical drift and guide the low energy beam to the center of the final coil, the exit of the toroidal merger, as in [4]. Figure 1 shows the geometry and the trajectories of the low and high energy beams. The longitudinal field B_z of the merger is 0.1 T, and the sector bend field B_y is 0.0165 T. The coils in the latter half of the merger have larger apertures to accommodate the injection of the high energy beam.

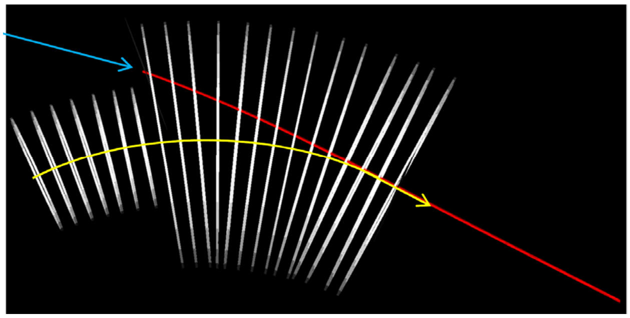

Figure 1: 3D render of the toroidal merger geometry. The yellow arrow indicates the low energy beam trajectory; the blue arrow indicates the high energy beam trajectory.

The magnetic field of the toroidal merger must be matched to the magnetized beam for proper transport. The two are matched when the β of the magnetized beam corresponds to the β of the solenoid, where $\beta_{sol}=2\rho_{Larmor}$. To generate a matched magnetized beam with the proper β as required by the toroidal merger field, we first generate a flat beam ($\varepsilon_x/\varepsilon_y >> 1$) with $\alpha=0$ and apply a flat-beam transform (FBT) [5]:

$$\boldsymbol{T} = \frac{1}{2}\begin{bmatrix} m & \beta p & p & -\beta m \\ -{}^{p}/_{\beta} & m & {}^{m}/_{\beta} & p \\ p & -\beta m & m & \beta p \\ {}^{m}/_{\beta} & p & -{}^{p}/_{\beta} & m \end{bmatrix} \qquad (1)$$

where $m = \cos\mu - \sin\mu$ and $p = \cos\mu + \sin\mu$, and μ is the phase advance. The resultant beam is magnetized and matched to the solenoid field. Figure 2 shows the generated flat beam distribution and the transformed magnetized

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beam distribution in the transverse plane of the beam for $\varepsilon_x/\varepsilon_y = 1000$.

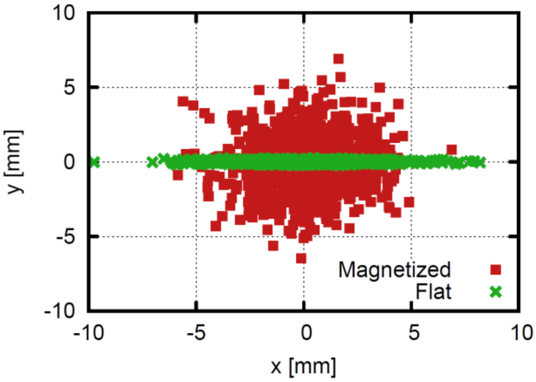

Figure 2: Flat beam and magnetized beam distributions after the flat beam transform.

The magnetized beam exhibits laminar flow while traversing the solenoid to which it is matched – i.e. the beam does not rotate but will follow the magnetic field lines. The transfer matrix for a solenoid can be represented by three matrices that describe the transport through a front fringe field, the solenoid body, and a back fringe field, with the result that the angular momentum of the magnetized beam is removed by the front fringe field and restored by the back fringe field, such that there is no rotational motion within the solenoid body.

In analyzing the motion of the generated magnetized beam in G4Beamline, the beam was found to rotate and experience periodic solenoidal focusing as it traversed the toroidal merger. The solenoid fringe fields do not completely cancel the angular momentum. To best evaluate the effect of the toroidal merger transport on the emittances of the magnetized beams, the fringe field “kicks” at the entrance and exit of the merger are manually applied to the beam distribution. A second flat beam transform is applied to each beam at the merger exit; this converts the magnetized beam back to a flat beam, but with the x and y planes swapped. This allows for a convenient comparison of the horizontal and vertical emittances at the entrance and exit of the merger section.

Table 1 lists the solenoid parameters for matching to the generated magnetized beams for both low and high energy beams. We consider the worst-case scenario in which the energy separation between the low and high energy beams is minimal.

Table 1: Solenoid Parameters

Parameter [unit]	**Low energy beam p=5 MeV/c**	**High energy beam p=20 MeV/c**
B_z [T]	0.1	0.1
ρ_{Larmor} [mm]	166.78	667.13
β [mm]	333.56	1334.25
$\varepsilon_{x,geom}$ [mm-mrad]	20	5.1
$\varepsilon_{y,geom}$ [mm-mrad]	0.2	0.05

SIMULATION RESULTS

Low Energy Beam

The low energy beam traverses the full length of the toroidal merger. The magnetic fields along the trajectory of the low energy beam are plotted in Figure 3. The low energy beam exits the merger at s=0.4 m.

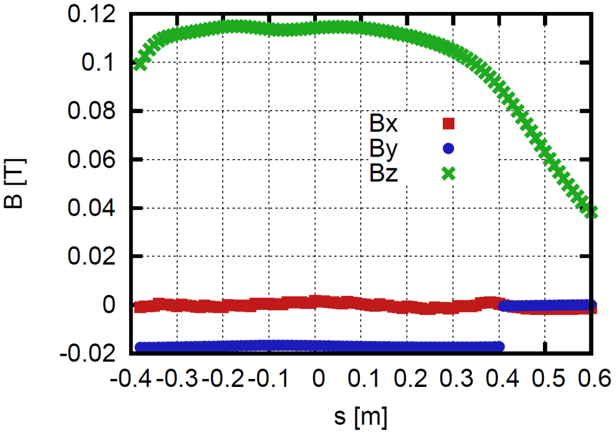

Figure 3: Magnetic fields along reference trajectory for the low energy beam.

Parameters of the magnetized beam distributions at the entrance and exit of the toroidal merger for the low energy beam are listed in Table 2. The emittance ratio $\varepsilon_x/\varepsilon_y = 100$.

Table 2: Low energy beam distribution parameters at entrance and exit of toroidal merger.

Parameter [unit]	**Generated distribution**	**Entrance**	**Exit**
σ_x [mm]	2.58	2.33	2.36
$\sigma_{x'}$ [mrad]	7.75	6.81	6.03
$\varepsilon_{x,geom}$ [mm-mrad]	20	15.86	14.25
σ_y [mm]	0.26	0.27	0.34
$\sigma_{y'}$ [mrad]	0.77	0.95	1.08
$\varepsilon_{y,geom}$ [mm-mrad]	0.2	0.26	0.37
σ_t [ns]	3.33e-2	3.55e-2	3.62e-2
$\sigma_{\Delta p/p}$	1e-3	1.02e-3	1.02e-3

Transit through the merger results in focusing in the horizontal plane as seen in the horizontal emittance at the exit of the merger. At the merger exit, the vertical emittance has grown by a factor of 1.4 when compared to the generated distribution value. We note the discrepancy between the generated distribution and the distribution at the entrance of the merger section; this is likely due to the simulation setup, where the beam must be initialized at a point before the merger entrance plane where the magnetic fields are varying.

High Energy Beam

The high energy beam does not traverse the full length of the toroidal merger, instead entering the merger at an angle to the low energy beam trajectory as shown in Figure 1. The magnetic fields along the trajectory of the high energy beam are plotted in Figure 4.

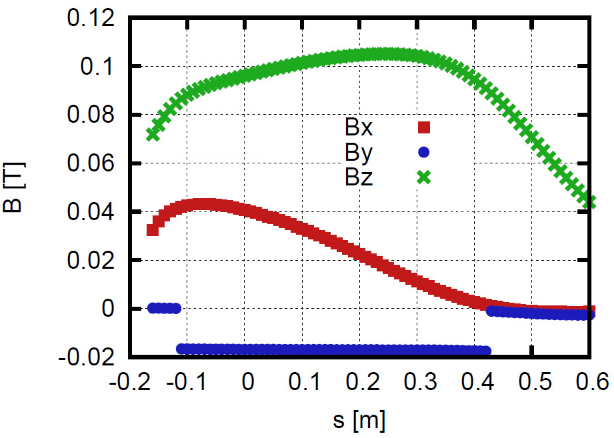

Figure 4: Magnetic fields along reference trajectory for the high energy beam.

Parameters of the high energy magnetized beam distributions at the entrance and exit points of the toroidal merger are listed in Table 3.

Table 3: High energy beam distribution parameters at entrance and exit points of toroidal merger.

Parameter [unit]	**Generated distribution**	**Entrance**	**Exit**
σ_x [mm]	2.61	2.72	2.39
$\sigma_{x'}$ [mrad]	1.96	2.97	3.13
$\varepsilon_{x,geom}$ [mm-mrad]	5.1	8.09	7.5
σ_y [mm]	0.26	0.77	1.33
$\sigma_{y'}$ [mrad]	0.2	0.28	0.4
$\varepsilon_{y,geom}$ [mm-mrad]	0.051	0.22	0.52
σ_t [ns]	3.33e-2	3.21e-2	3.2e-2
$\sigma_{\Delta p/p}$	1e-3	9.76e-4	9.76e-4

While the horizontal emittance sees some growth (1.5x), the vertical emittance grows by an order of magnitude by the time it reaches the exit plane of the merger; this is likely due to the relatively large magnitude transverse magnetic fields that the high energy beam sees as it enters the merger.

Space Charge Effects

The JLEIC bunched beam cooler design calls for high bunch charge electron bunches, as much as 3.2 nC per bunch. This high bunch charge will cause emittance growth in the injector region of the cooler ring. The space charge module in G4Beamline [6] was enabled to observe the effect of the high bunch charge on the low and high energy beams. Table 4 compares the generated distributions with the distributions at the exit of the merger for low energy beams with and without space charge. For the high energy beam case, the inclusion of space charge had no effect on the exit distribution, as expected.

Table 4: Low energy beam distribution parameters at the exit plane of the toroidal merger, with and without space charge effects.

Parameter [unit]	**Generated distribution**	**Exit, no space charge**	**Exit, 3.2 nC bunch charge**
σ_x [mm]	2.58	2.36	2.41
$\sigma_{x'}$ [mrad]	7.75	6.03	6.15
$\varepsilon_{x,geom}$ [mm-mrad]	20	14.25	14.82
σ_y [mm]	0.26	0.34	0.37
$\sigma_{y'}$ [mrad]	0.77	1.08	1.12
$\varepsilon_{y,geom}$ [mm-mrad]	0.2	0.37	0.41
σ_t [ns]	3.33e-2	3.62e-2	3.61e-2
$\sigma_{\Delta p/p}$	1e-3	1.02e-3	2.88e-3

The high bunch charge causes additional growth in the vertical emittance but has its largest effect on the energy spread of the beam, increasing the energy spread by nearly a factor of three.

SUMMARY AND FUTURE WORK

A toroidal merger is evaluated as a possible injector merger design for the JLEIC bunched beam electron cooler. The preservation of the vertical emittance of the low energy beam is critical to efficient hadron cooling. Simulation results show that the low energy beam vertical emittance grows by a factor of two when space charge effects are included. Space charge effects also result in growth of the energy spread by a factor of three. The large transverse magnetic fields seen by the high energy beam cause an order of magnitude increase in its vertical emittance; this may affect the energy recoverability of the high energy beam.

Future work will focus on more realistic particle distributions from the upstream injector region, and better separation of the magnetic fields near the high energy beam entrance point to the merger.

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