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SIMULATING MAGNETIZED ELECTRON COOLING FOR EIC WITH JSPEC*

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Abstract

We present a possible electron cooling configuration for the proposed Electron Ion Collider (EIC) facility, developed using a Nelder-Mead Simplex optimization procedure built into JSPEC, an electron cooling code developed at Jefferson Lab. We show the time evolution of the emittance of the ion beam in the presence of this cooler evaluated assuming the ion distribution remains Gaussian. We also show that bi-gaussian distributions emerge in simulations of ion macro-particles. We show how intra-beam scattering can be treated with a core-tail model in simulations of ion macro-particles. The Sirepo/JSPEC and Sirepo/Jupyter apps will be presented, with instructions enabling the community to reproduce our simulations.

INTRODUCTION

The eRHIC electron-ion collider conceptual design presents design challenges for controlling intra-beam scattering (IBS) bunch growth in attaining the luminosity targets. Magnetized electron cooling is one possible method for counteracting IBS growth. There are many factors that determine the effectiveness of a magnetized electron cooler, including the length of the cooling section, the magnetic field in which the electrons and ions co-propagate, and the γ of the ions being cooled. Several friction force models exist to calculate the cooling strength based on these parameters. IBS growth calculations of the ion bunch depend on the lattice and the spatial characteristics of the bunch.

JSPEC

JSPEC is an open source C++ package for simulating electron cooling and intra-beam scattering [1,2]. The work shown here has been developed on a fork of JSPEC [3]. JSPEC users may define a set of parameter values defining a ring and a cooler and observe the initial cooling rates (τ_h, τ_v, and τ_{trans}), calculated from the net changes in the emittances of an ion bunch after a single pass through the ring. Or, they may choose to observe the behavior of an ion bunch passing through a cooler through many orbits. In this dynamic simulation, users may choose to make the assumption that all distributions remain Gaussian and time-evolve with the moments of the distributions, or they may choose to initialize a set of macro-particles that start out normally-distributed and evolve over time.

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Friction Forces

In Magnetized electron cooling, ions scatter off of cold electrons confined to helical trajectories due to the cooler's magnetic field. This scattering results in a friction force, slowing the ions velocities relative to the bunch in the beam rest frame. Many models exist to estimate the friction force, some of which require numerical integration in multiple dimensions. In our fork, we have introduced a dependency on the GNU Scientific Library (GSL) [4] to handle these integrations. The friction forces derived from several models in JSPEC were benchmarked against the friction force calculated in the BETACOOL [5] code for identical cooler configurations. Figure 1 shows good agreement between friction force estimation between these two codes. Friction force calculations are available with an online GUI [6].

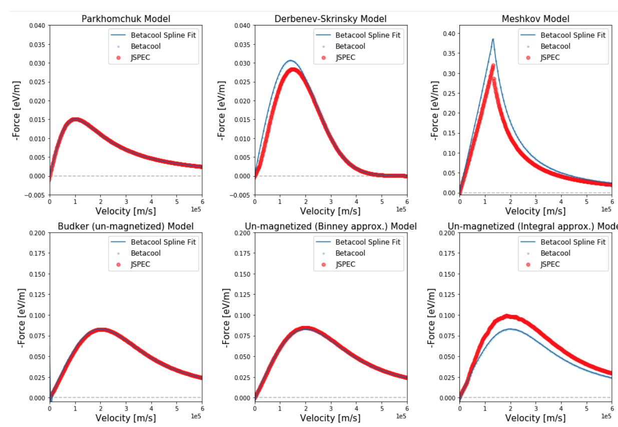

Figure 1: Comparison of friction force calculations in Betacool and in JSPEC.

OPTIMIZATION

There are many different knobs to turn in designing a magnetized electron cooler. A Nelder-Mead Simplex optimization algorithm was introduced to JSPEC, also acquired from GSL libraries. This algorithm minimizes a cost function, here defined to be the difference between a defined target cooling time and the inverse of the initial cooling rate calculated by JSPEC. Users may specify a subset of parameters to be allowed to vary within the optimization algorithm and set their initial values. The algorithm will then insert sampled values for the the floating parameters into JSPEC and calculate initial cooling rates. The output values are not necessarily unique solutions. For example, an equivalent solution may be achieved after one round of optimization by trivially increasing the number of electrons in the cooler and also trivially decreasing the cooler's mag-

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netic field strength. An example of the simple interface for the optimization algorithm is shown in Fig. 2.

```
section_optimization
        sigma_x = 0.0025
        sigma_y = 0.0025
        sigma_s = 0.07
        n_electron = 3.5
        temp_long = 1e-2
        temp_tr = 1e-2
        beta_h = 20
        beta_v = 10
        disp_h = 0.01
        disp_v = 4.0
section_run
        calculate_ecool
        calculate_ibs
        total_expansion_rate
        optimize_cooling
```

Figure 2: Syntax of optimization section in the JSPEC input file. If a parameter is defined within `section_optimization` then it is used as a starting value and may be varied to minimize the cost function. A parameter that is not defined in this section remains fixed. The `optimize_cooling` call at the end initializes the optimization routine.

A cooler was optimized for a toy beam configuration consisting of a 25 GeV proton bunch with a bunch length of 70 cm, transverse emittances $\epsilon_{h,v} = 2.5 \times 10^{-6}$ m rad, and a single 130 m cooler section, using the Parkhomchuk friction force model [7], with a target cooling time in the vertical dimension of 30 minutes (so, a target cooling rate of $\tau = -5.56 \times 10^{-4}$ sec). With these parameters fixed, an optimum cooler configuration is shown in Table 1. This solution was validated by matching the inputs with a Betacool simulation and observing the cooling time minimum while scanning values for individual parameters. An example comparison of a parameter scan is shown in Fig. 3.

Table 1: Optimized Parameters

Parameter	Value	Parameter	Value
β (horiz., vert.)	16 m, 28 m	B Field	5 T
# of Electrons	1×10^{10}	e^- RMS Size	200 µm
e^- T_{trans}	0.01 eV	e^- T_{long}	0.01 eV
e^- Bunch Len.	6.8 cm	Horiz. Disp.	0.31 m

BI-GAUSSIAN IBS

Simulations with strong friction forces often lead to an over-cooled core in ion distributions that does not disperse with standard Bjorken-Mtingwa (B-M) IBS calculations [8]. B-M assumes that particles are Gaussian distributed, where the distributions appear to be the sum of two Gaussian distributions, with an over-cooled core and the remainder in the tail:

$$f(x) = A_c \exp\left[-\frac{1}{2}\left(\frac{x}{\sigma_c}\right)^2\right] + A_t \exp\left[-\frac{1}{2}\left(\frac{x}{\sigma_t}\right)^2\right], \quad (1)$$

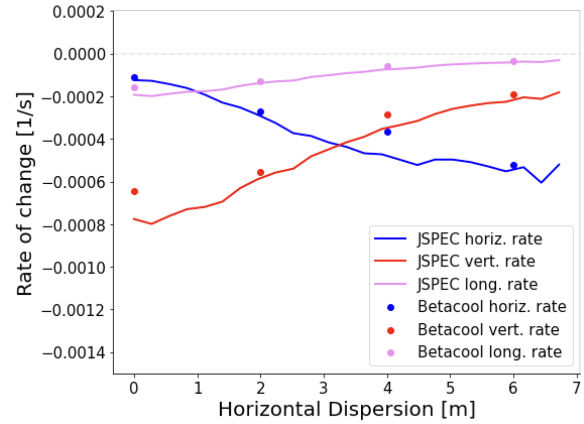

Figure 3: Comparison of JSPEC and Betacool for scans of horizontal dispersion and its effect on cooling rates.

where (A_i, σ_i) are the amplitude and standard deviation for Gaussians with mean 0 for the core (c) and tail (t). The Betacool code implements a bi-gaussian approximation to B-M in which particles in the tail experience heating rates induced by the tail distribution, where particles in the core experience heating rates induced by both the core and the tail. Thus the core is dispersed more strongly through scattering, corresponding to the increased density. The effective core rate in Betacool is [5]:

$$\frac{1}{\tau_{\rm eff}} = \frac{1}{\tau_c}\left(\frac{N_c}{N}\right)^2 + \frac{1}{\tau_t}\left(\frac{N_t}{N}\right)^2 \frac{\epsilon_c}{\epsilon_t}, \quad (2)$$

where N is the total number of macro-particles partitioned into the core (N_c) and tail (N_t). In JSPEC, the distributions are fit to this bi-Gaussian model using routines in GSL and the (A_c, σ_c) and (A_t, σ_t) values are extracted (see Fig. 4). However, the approximate heating rate applied to the core is modified. By examining the Betacool effective rate, and observing that in the limit of a true Gaussian distribution $N_c = N_t = N/2$, $\epsilon_c = \epsilon_t$, and also the $\tau_c \rightarrow \tau_{\rm eff}/2$, it appears that there is an inconsistency that could lead to a contradiction, $1/\tau_{\rm eff} = 1/(4\tau_{\rm eff})$. To correct this, we also consider applying a scale factor:

$$\frac{1}{\tau_{\rm eff}} = 4\frac{1}{\tau_c}\left(\frac{N_c}{N}\right)^2 + 4\frac{1}{\tau_t}\left(\frac{N_t}{N}\right)^2 \frac{\epsilon_c}{\epsilon_t}. \quad (3)$$

Additional theoretical work will be required to determine if this ad hoc scaling is justified, or if we can independently calculate heating rates that should be applied to the core and tail distributions separately.

CONCLUSION

The JSPEC electron cooling modeling code has been modified to include new features to more accurately model magnetized electron cooling and IBS heating. Users may now utilize optimization algorithms to select cooling parameters to achieve target cooling times given some subset of fixed beam parameters. Users may also model and visualize their cooling designs using a cloud-based GUI [6].

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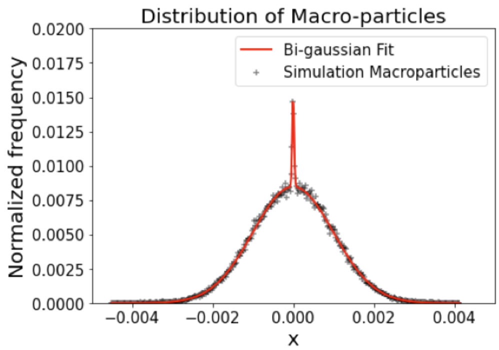

Figure 4: A Bi-Gaussian distribution of macro-particles in JSPEC, together with the fit performed to extract the core and tail amplitudes and standard deviations.

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