Electron Cooling Code Development

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Electron Cooling Code Development Project

- **Electron Cooling Simulation Development (rows 3,4 – High A),JLAB FY17 Supplemental R&D**

Description:

The high intensity ion beam in the EIC brings challenges to the electron cooling design. Traditional electron cooling technique has to be pushed to an extreme high energy region. Some new elements need to be understood, including cooling with a pulsed (short duration) electron bunch, cooling with electron bunches shorter than the ion bunches, balancing the cooling effect in the three dimensions, repeatedly using the electron bunch in cooling, etc. Electron cooling simulation is essential for a deep *understanding of electron cooling physics* both qualitatively and quantitatively. Simulation study is also needed to *optimize the parameters of the colliding ion beam and the cooling electron beam* for better cooling.

Main Goal:

This project aims to continue development and benchmarking work to allow reliable prediction of electron cooling rates and dependable simulation of the electron cooling process for EIC designs. The codes will address the special physics problems for the high energy electron cooling and need to be sufficiently flexible to allow simulation of either EIC design.

Status : Completed.

Electron Cooling Simulation Development

- Budget

	FY'17	Totals
a) Funds allocated	$84,000	$84,000
b) Actual costs to date	$81,293	$81,293

- Deliverables and schedule

Task	FY'17 Q1	FY'17 Q2	FY'17 Q3	FY'17 Q4
Model for beams of different sizes	×	×		
Code Benchmarking with IMP experiment		X	X	X
Cooling optimization methods			x	x

- The project corresponds to Lines 3,4 "Electron Cooling Simulation Development", Priority High-A of the Jones' Panel report

Contents

- Brief introduction on JSPEC
- Milestone 1: Model for cooling simulation with electron bunch smaller than the ion bunch
- Milestone 2: Code benchmarking with IMP experimental data
- Milestone 3: Study the methods to improve the cooling efficiency
- Extra achievement: User Interface for JSPEC

JSPEC

- **J**lab **S**imulation **P**ackage for **E**lectron **C**ooling
- JSPEC development started in 2015 supported by JLab LDRD 2015-2016 and then supported by EIC R&D fund.

Achievement before this FOA:

- Ion beam model: coasting or bunched
- Electron beam model: DC or bunched with various shapes, *e.g.* Gaussian, Beer can, hollow beam, *etc.*
- Cooling rate and IBS rate calculation.
- Cooling process simulation:
  - RMS model: Ion beam represented by emittance, bunch length, momentum spread, assuming Gaussian distribution.
  - Particle model: Ion beam represented by particles, any distribution.
- Benchmarked with BETACOOL and achieve significant of improvement of efficiency for typical JLEIC cooling simulation.

Milestone 1

Milestone 1: Model for cooling simulation with electron bunch smaller than the ion bunch

- Particle model:

1. Generate particles according to the given emittances.
2. Calculate each particle receives a kick if it sees electrons.
3. Give each particle a random phase advance.
4. Repeat 2-3 till the end of simulation.

- Problems:

1. Does it work without a proper modeling of the betatron oscillation?
2. If works, what is the proper time step?
3. Can it catches non-Gaussian beam profile as expected?

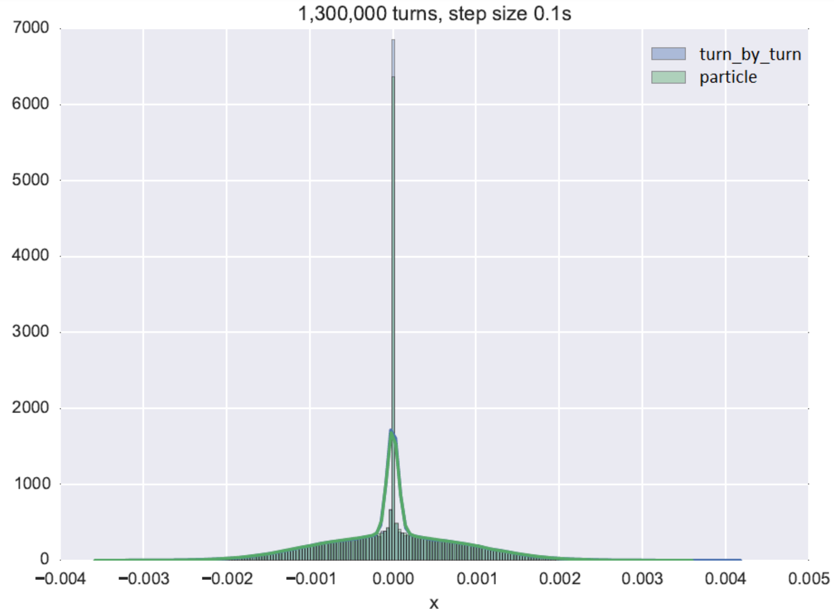
Verify the Particle Model for JLEIC Cooling

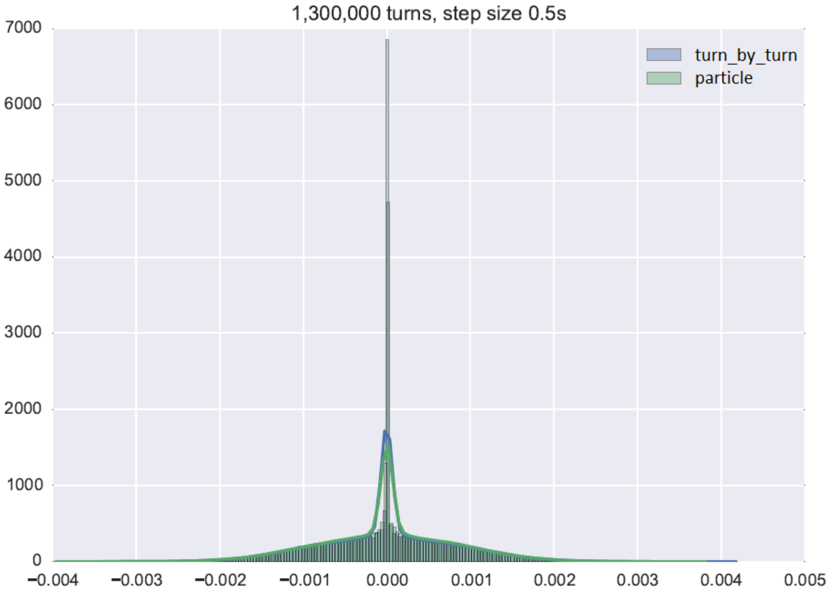
- Turn-by-turn simulation: ~10s, 1,350,000 turns
- Particle: step size 0.1s, 0.5s, 1s
- Parameters:
  - Cooling was artificially increased by 100 times in order to see the deviation from the Gaussian distribution in 10s by turn-by-turn simulation.
  - Beer can shape electron beam covers 2 sigma area at the center of the Gaussian proton beam

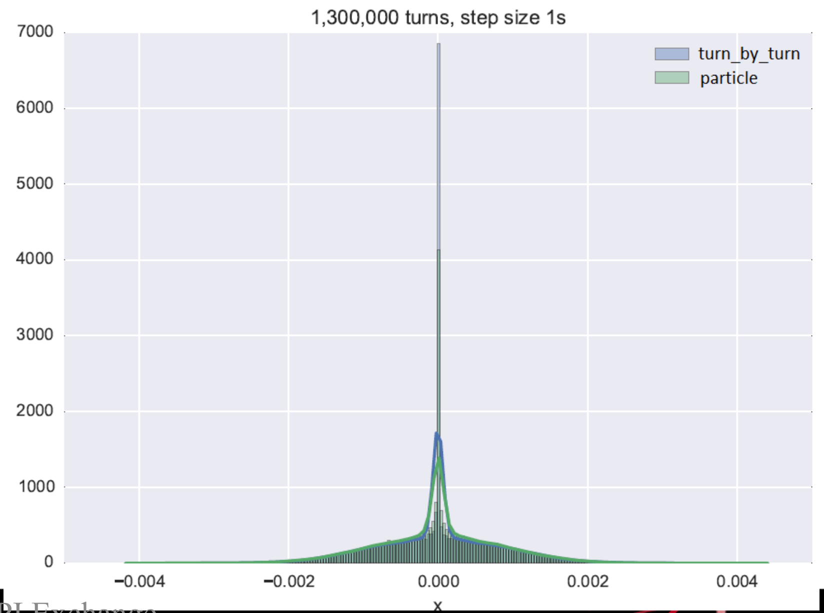
- Proton beam (CM energy 63.5 GeV):
  - Energy: 100 GeV
  - Proton number: 0.998×10^{10}
  - Normalized emit. (rms): 1.25/0.38 μm
  - Beta function in cooler: 60/300 m
  - Bunch size (rms): 0.835/0.841 mm
  - Momentum spread: 8×10^{-4}
  - Bunch length (rms): 2.5 cm

- Cooling electron beam:
  - Charge: 200 nC, Energy 55 MeV
  - Bunch length (total length): 2 cm
  - Length: 2 cm
  - Radius: 0.835 mm
  - Transverse temperature: 0.246 eV
  - Longitudinal temperature: 0.184 eV
  - Cooler: 60m, 1T

Verify the Particle Model for JLEIC Cooling







- dt = 0.1s, results are almost identical.
- dt = 0.5 s, the deviation starts to show, but not large.
- dt = 1s, the deviation becomes larger.

Milestone 1

Summary

1. The particle model is verified with turn-by-turn tracking (slow but accurately models the betatron motion).
2. Given a proper time step (<0.5 s) the particle model agrees with the turn-by-turn tracking and catches the non-Gaussian profile of the beam profile.

3. We also tested another model, which groups the particles according to their dynamic invariants and applies an averaged kick in each group. However, this model is outperformed by the particle model with a proper time step size.

Milestone 2

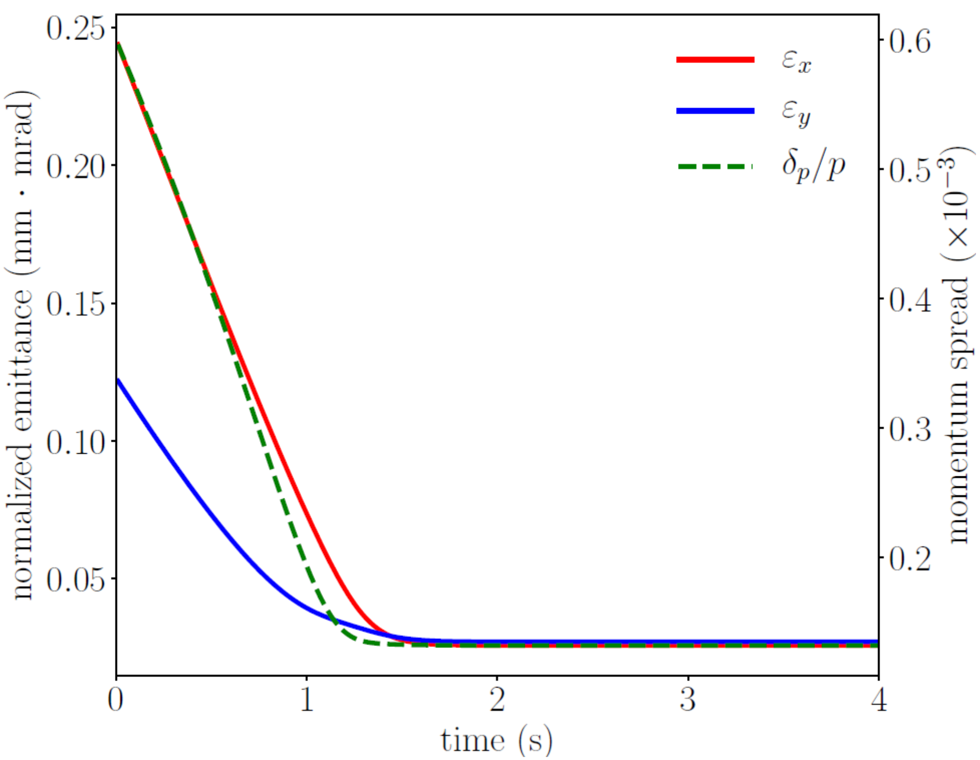
Milestone 2: Code benchmarking with IMP experimental data

- In the IMP experiment, electron cooling and IBS reaches equilibrium very fast (<1s). It can be simulated by turn-by-turn tracking.

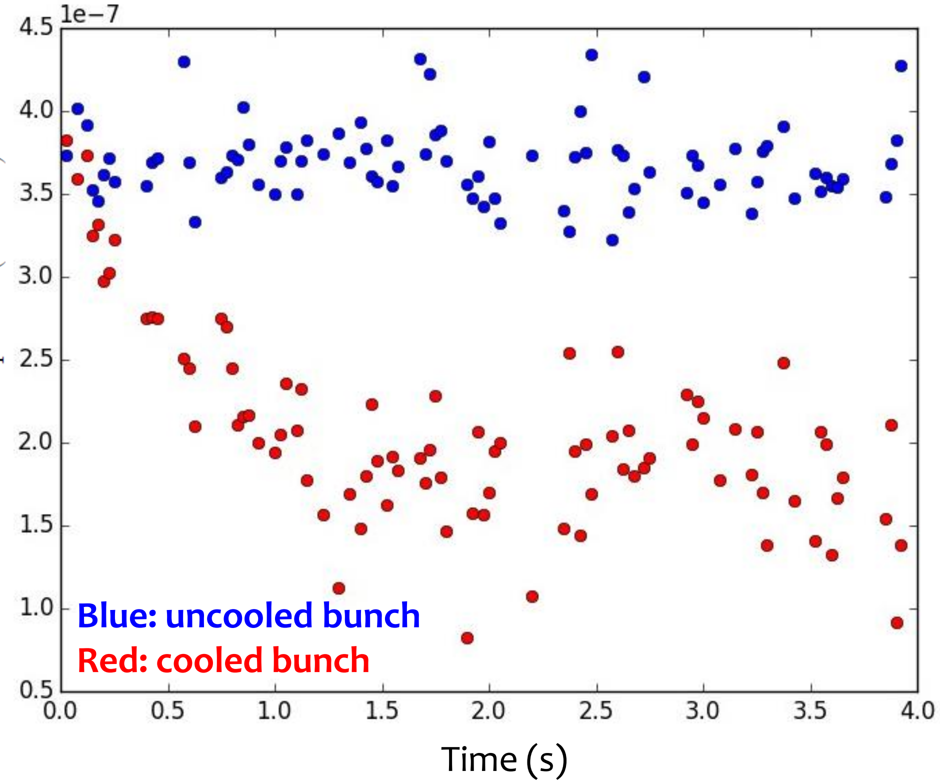
1. A turn-by-turn tracking module with an RF cavity model for longitudinal motion has been developed for JSPEC. (Has been used to verify the particle model.)
2. Preliminary result (cooling time) agrees with the experimental data.
3. More reliable benchmarking will be carried out after the second electron cooling experiment at IMP with calibrated beam measurement, which will be performed in later 2018.

Milestone 2

Simulation: emittance, dp/p vs. time



Experiment: rms bunch length vs. time



- Cooling time to reach the equilibrium agrees.
- But more accurate experimental data are needed to eliminate the uncertainties in the simulation.

Milestone 3

Milestone 3: Study the methods to improve the cooling efficiency

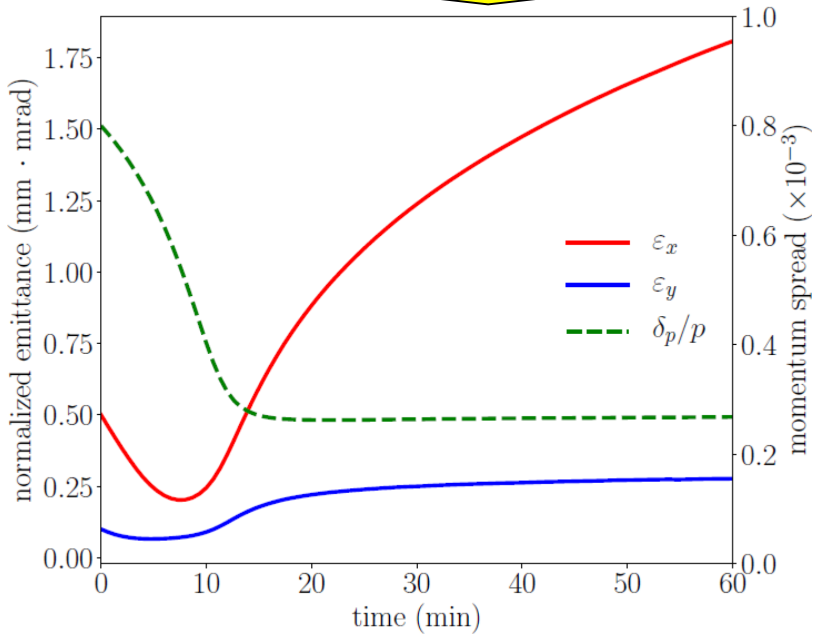
- Challenge of JLEIC cooling: mismatch between cooling and IBS
- Investigated methods to improve the overall cooling or to redistribute the cooling in different directions.

1. Using a flat electron beam (with the same emittance as the round electron beam) increases the overall cooling rate.
2. Maintain a constant bunch length helps to mitigate the overcooling in the longitudinal direction.
3. Maintain a constant momentum spread (how?) can remove the overcooling in the longitudinal direction.
4. A new module that allows to use arbitrary electron beam is developed for future simulations on advanced cooling techniques: dispersive cooling, cooling with electron velocity gradient, sweeping effect.

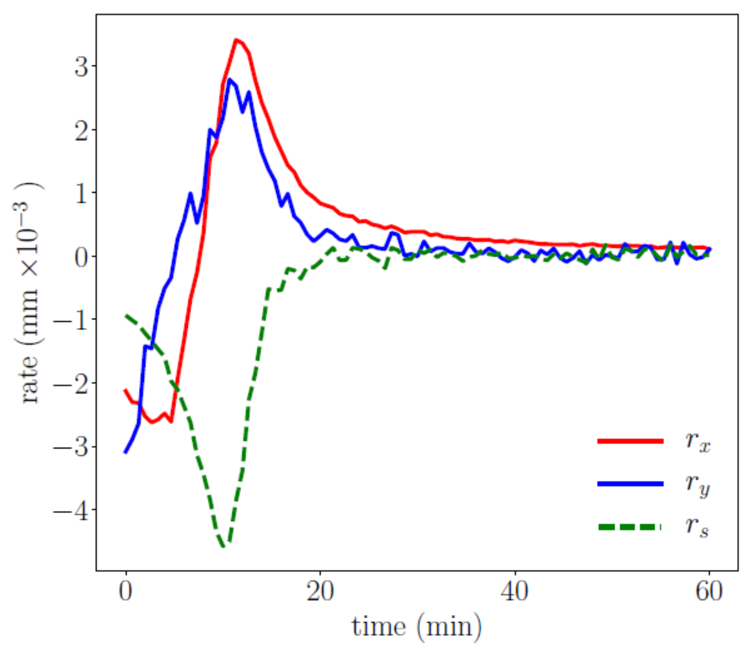
Fixed bunch length or momentum spread

- Proton beam (CM energy 44.7 GeV):
  - Proton number: 0.98×10^{10} *0.3
  - Dispersion: 0.9 m/ 0.9 m
  - Coupling: 70%

A bad case: strong cooling in the longitudinal direction reduces the proton beam phase space density, which increases the transverse IBS and leads to transverse emittance explosion.



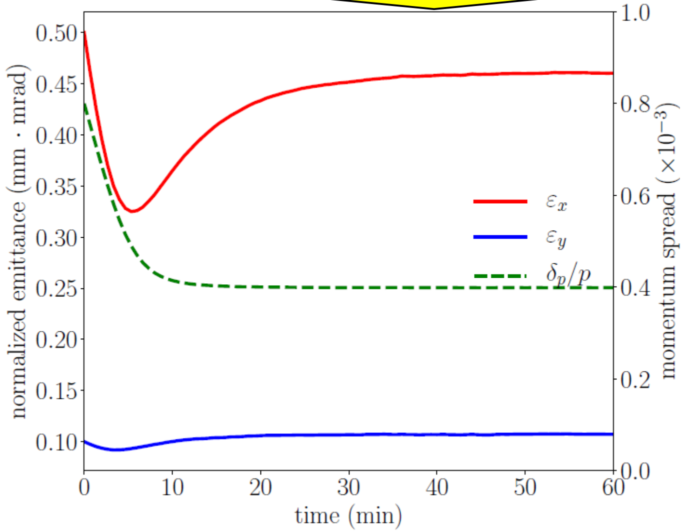
Emittances

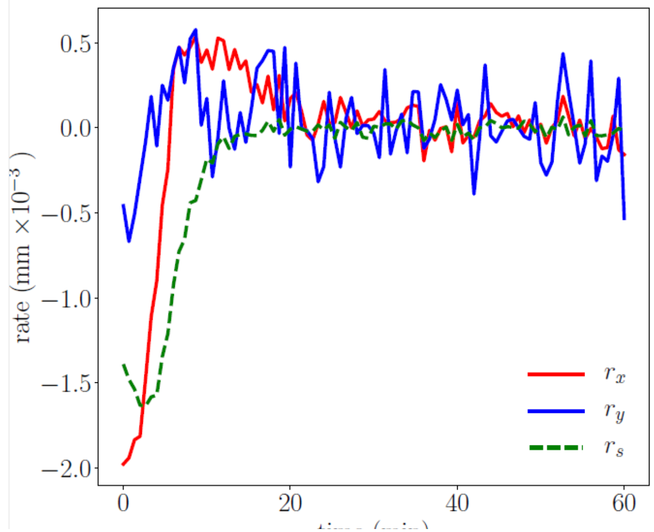


Rates

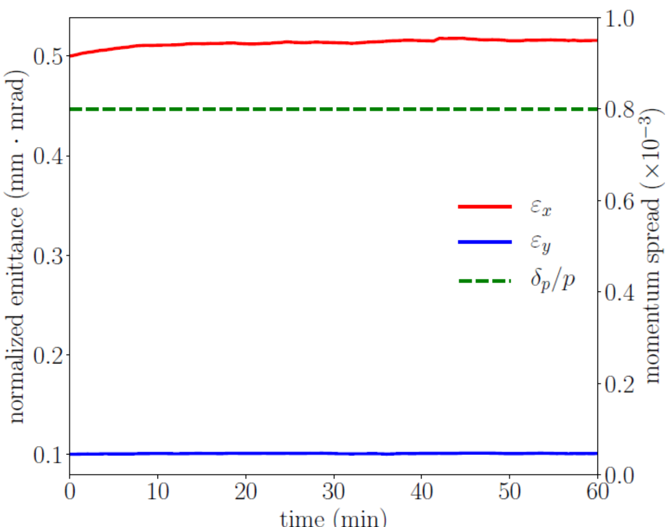
Fixed bunch length or momentum spread

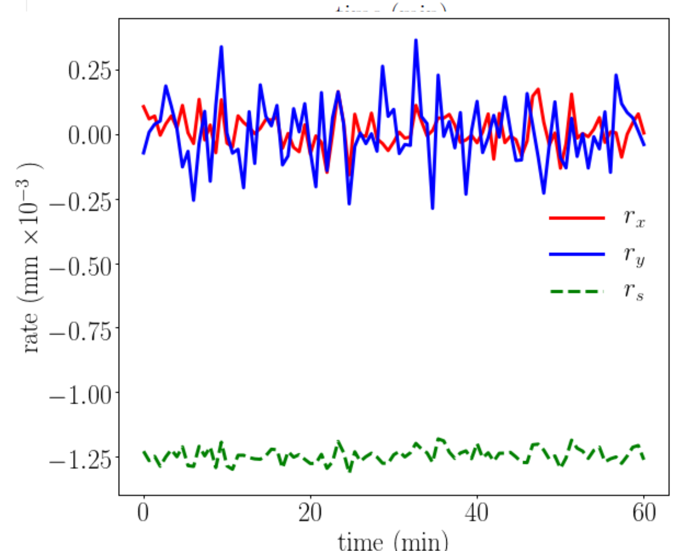
Fixed bunch length or momentum spread helps to maintain the equilibrium with even higher proton current





- Fixed bunch length
- Proton number: 0.98x10[10] *0.5
- Dispersion: 0.9 m/ 0 m
- Coupling: 55%

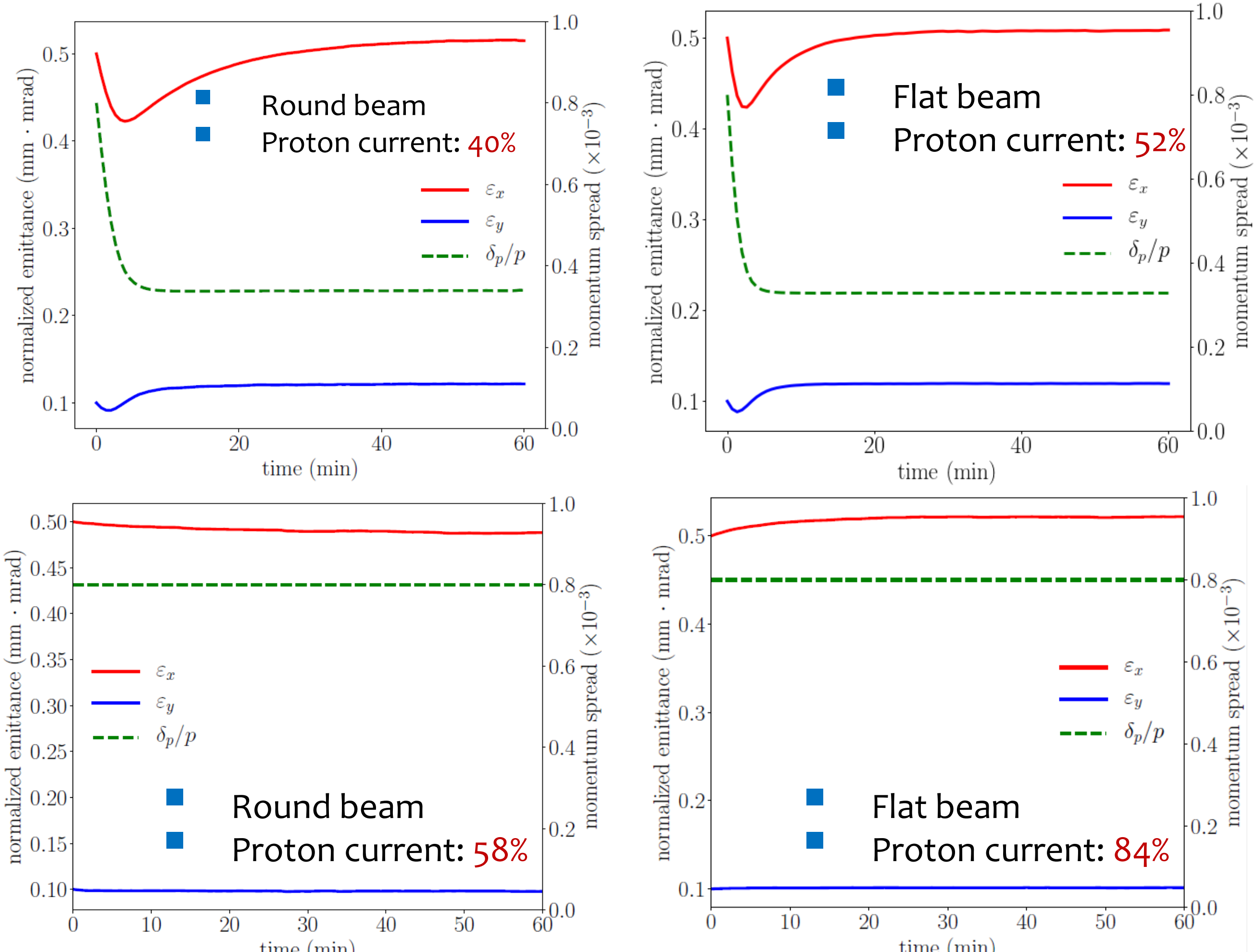




- Fixed dp/p and bunch length
- Proton number: 0.98x10[10] *0.76
- Dispersion: 0.9 m/ 0 m
- Coupling: 40%

Flat beam

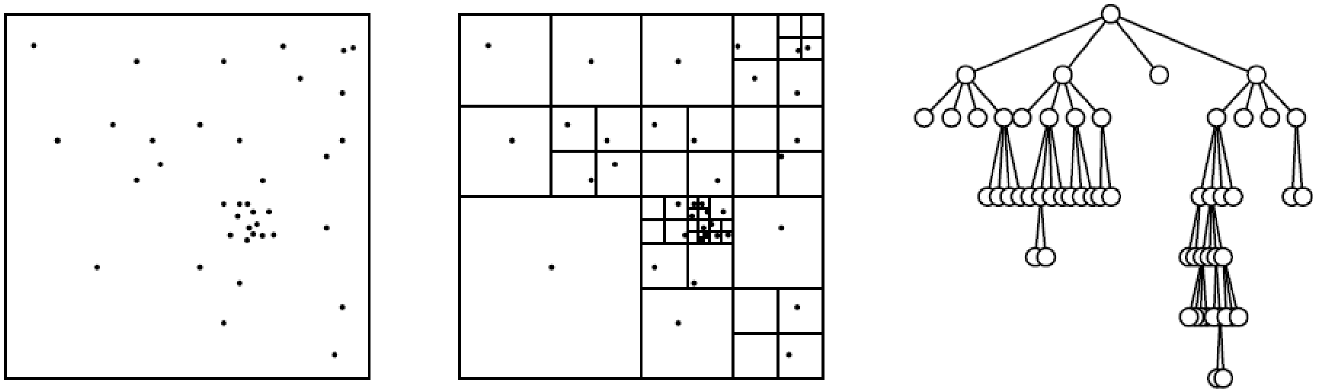
Flat beam with the same emittance provides strong cooling than the round beam.



- Assuming no dispersion at the cooler, we will have to reduce the proton current due to the very strong horizontal IBS.
- Assume constant bunch length (top) or constant momentum spread and bunch length (bottom), which helps to mitigate overcooling in the longitudinal direction.
- If compared with the round beam, we received a significant gain (higher proton current) using the flat beam.
- Flat beam is preferred to round beam for JLEIC cooling.

JSPEC Updates: User-Defined Electron Bunch

- The electron bunch is defined by sample particles with 6D coordinates (x, y, z, vx, vy, vz) saved in a asci/binary file. (x, y, z) is the position of a sample particle in the lab frame. (vx, vy, vz) is the velocity of the a sample particle in the beam frame.
- JSPEC read the file and use the electron bunch in friction force calculation.
- A tree based algorithm to calculate the local electron density and temperature enhances the efficiency by orders.
- New modules has been benchmarked with ideal Gaussian bunch.



Extra Achievement

Extra achievement: user interface

- Text-based user interface
- An input file is composed of three kinds of sections.

Section name	Category	Usage
section_scratch	scratch	Define variables and do calculations with the variables. The variables defined in this section can be used in definition sections.
section_ion	definition	Set parameters for the ion beam
section_ring	definition	Set parameters for the ion ring
section_e_beam	definition	Set parameters for the cooling electron beam
section_cooler	definition	Set parameters for the cooler
section_ibs	definition	Set parameters for IBS rate calculation
section_ecool	definition	Set parameters for electron cooling rate calculation
section_run	operation	Create the objectives (ion beam, ion ring, electron beam, cooler) and perform the calculation and/or the simulation.

An Example of the Text-Based UI

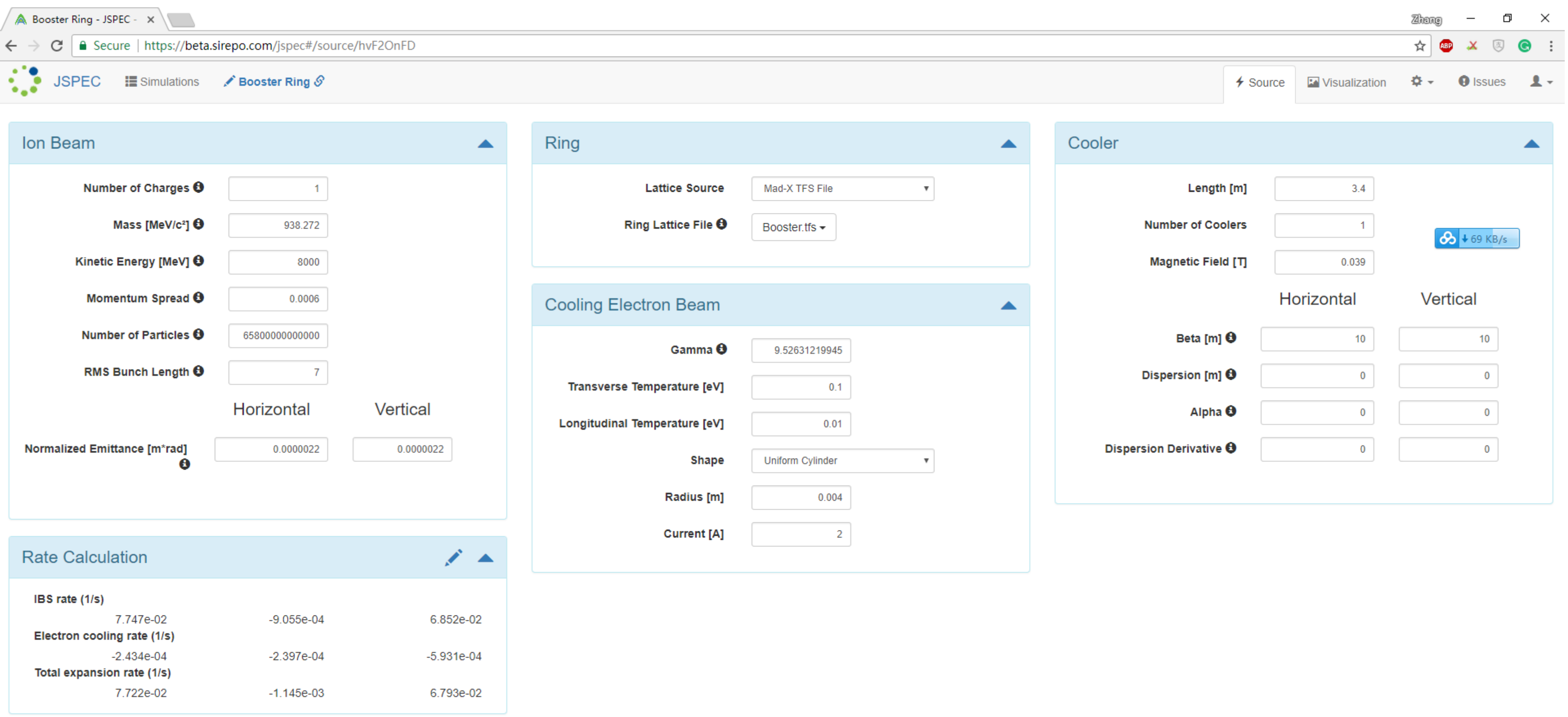
```
section_ion                           # Define the ion (proton) beam
        charge_number = 1       # Charge number
        mass = 938.272          # Mass of the ion
        kinetic_energy = 8000   # Kinetic energy
        norm_emit_x = 2.2e-6    # Normalized emittance in horizontal direction
        norm_emit_y = 2.2e-6    # Normalized emittance in vertial direction
        momentum_spread = 0.0006        # Momentum spread
        particle_number = 6.58e11       # Total ion number (per bunch)
        rms_bunch_length = 7            # Rms bunch length of the bunched ion beam
section_ring                                                    # Define the ring
        lattice = MEICColliderRedesign1IP.tfs   # file that saves the lattice of the ring
section_ibs #define the arguments for IBS calculation
        nu = 100                # Grid number in horizontal direction for IBS integration
        nv = 100                # Grid number in vertial direciton for IBS integration
        nz = 40                 # Grid number in longitudinal direction for IBS integration
        log_c = 20.6    # Define Coulomb logrithm. nz is ignored after log_c is defined.
        coupling = 0    # No coupling
section_cooler                        # Define the cooler
        length = 3.4                  # Cooler length
        section_number = 1            # Number of coolers
        magnetic_field = 0.039  # Magnetic field
        bet_x = 10                            # Twiss parameter at the cooler
        bet_y = 10
        #disp_x = 0                           # If the values are zero, the command can be omitted.
        #disp_y = 0
        #alpha_x = 0
        #alpha_y = 0
        #disp_dx = 0
        #disp_dy = 0
```

Anything follows a "#" is a comment.

A list of the key words for all the sections can be found in the user manual on Github.

Online JSPEC and GUI

- Developed by Radiasoft with our support.
- Configure, run and share a simulation using JSPEC using a brower.



Summary

- Milestone 1: We verified that the particle model with time steps below 0.5 s works for our purpose.
- Milestone 2: New module added to JSPEC for IMP experiment simulation. Preliminary benchmarking performed. Waiting for more accurate data (expected in late 2018) for future benchmarking.
- Milestone 3: A few schemes have been studied to enhance the cooling. New module developed for future study on advanced cooling scheme.
- For easier usage of the program, a test-based UI has been developed. A browser-based GUI and an online JSPEC has been developed by Radiasoft with support from JLAB.