Dynamic friction in electron coolers for relativistic proton beams

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Outline

- The RadiaSoft team
- Motivation
- Overview of Accomplishments & Present Activities
- Recent dynamical friction calculations
- Overview of JSPEC capabilities
- Parameter optimizations to reach a 20-minute cooling time
- RadiaSoft commercialization activities

RadiaSoft staff

- Physics & Data Science
  - machine learning
  - particle accelerators
  - plasma devices
  - control systems

- Science writing
- Product Management
- Operations
- Accounting & HR

- Software Engineering
  - cloud computing
  - browser-based GUIs

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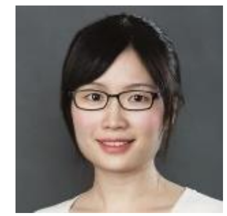

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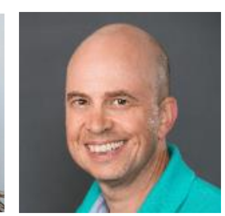


Motivation & Objectives

- Integrate JSPEC cooling code into Sirepo platform
- Develop and test a new conceptual design for both an accumulator ring and high current d.c. cooler
- Incorporate new methods of dynamic friction calculation into a software package
    - risk reduction for high-energy magnetized e- cooling
    - target software package is JSPEC

Image borrowed from the BNL website, https://www.bnl.gov/eic/machine.php

Overview of Project Accomplishments

- Develop a browser-based GUI for electron cooling
  - the GUI has been developed: https://sirepo.com
  - Frank Schmidt (CERN): "We were concerned about an IBS calculation and Markus Steck (GSI/FAIR) suggested we try Sirepo, which immediately gave us the correct rate."
- Preconceptual design of a cooling and accumulator ring
  - completed by P. McIntyre and J. Gerity at Texas A&M on subcontract
  - Yuhong Zhang: "JLEIC implements this idea with a full-size high-energy booster"
- Preconceptual design of an electron cooling system
  - impact ionization physics for the Warp code has been implemented
  - available to the community, via https://github.com/radiasoft/rswarp
- Study equilibrium electron cooling rates
  - this involved much analysis of BETACOOL code & benchmarking with JSPEC
- Generalize friction calculations
  - Developed a new first-principles calculation of magnetized friction for relativistic hadron colliders, where one must consider times less than a plasma period (in the beam frame)
- Develop software to perform dynamic friction calculations
  - includes implementation of our own algorithms, mostly in Python
  - contributions to JSPEC, https://github.com/zhanghe9704/electroncooling

Phase 2a, Year 2: planned activities

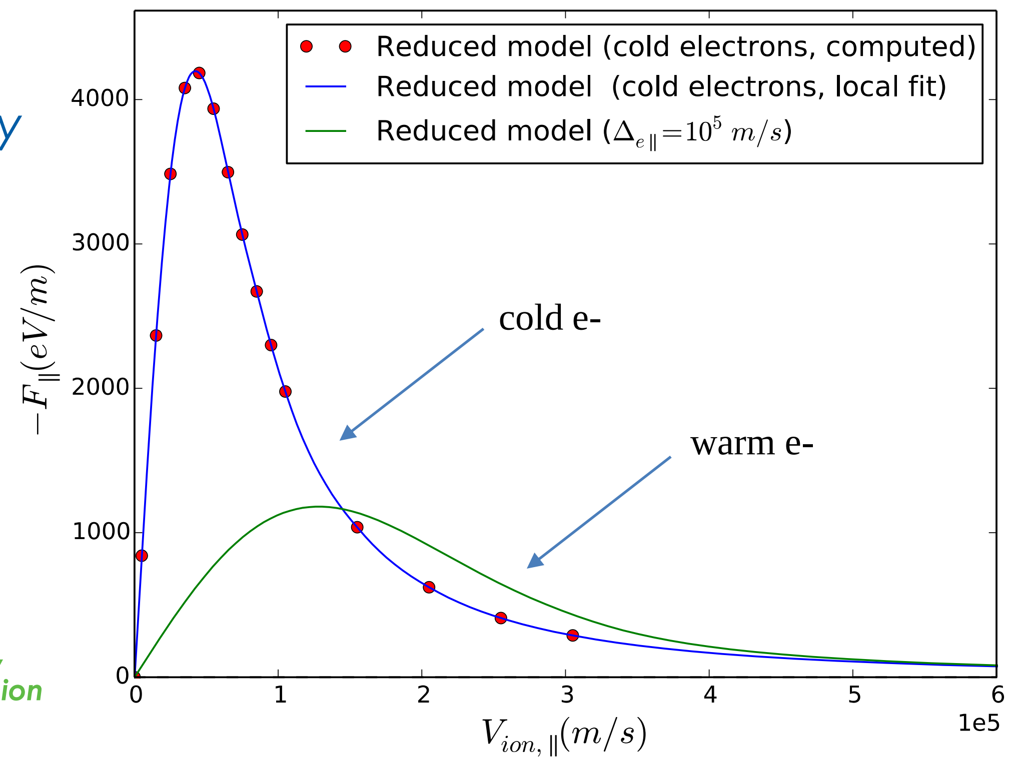
- Develop a browser-based GUI for electron cooling
  - adding standard unmagnetized cooling models (to be available within a week)
  - add modified (short interaction time) variants of the unmagnetized models
  - add the new RadiaSoft models for short-time magnetized cooling
- Preconceptual design of a cooling and accumulator ring
  - address BNL EIC design → 25 GeV protons at injection (magnetized & not)
- Preconceptual design of an electron cooling system
  - address BNL EIC design → 41 GeV protons (lowest collision energy)
- Study equilibrium electron cooling rates
  - dominated by JSPEC/BETACOOL benchmarking in support of tasks 2 & 3
- Generalize friction calculations
  - address BNL EIC design → incorporate short-time effects in unmagnetized models
- Develop software to perform dynamic friction calculations
  - complete new model for transverse magnetized friction
  - incorporate force reduction due to finite magnetic field

How is relativistic cooling different?

- EIC requires cooling at relativistic energies
  - 25 GeV p's → $\gamma \approx 28$ → 14 MeV e- bunches (injection into collider ring)
  - 41 GeV p's → $\gamma \approx 44$ → 22 MeV e- bunches (minimum collision energy)
- Electron cooling at γ~40 requires different thinking
  - friction force scales like $1/\gamma^2$ (Lorentz contraction, time dilation)
    - challenging to achieve the required dynamical friction force
  - normalized interaction time is reduced to order unity
    - $\tau = t\omega_{pe} >> 1$ for nonrelativistic coolers
    - $\tau = t\omega_{pe} < 1$ (in the beam frame), for γ~40
      - violates the assumptions of introductory beam & plasma textbooks
      - breaks the intuition developed for non-relativistic coolers
- Relativistic unmagnetized cooling is now being considered
  - cooling rate can be comparable to a magnetized system
  - to date, all production cooling systems have been magnetized
    - recent experiment: very successful test for low-energy RHIC
  - short-time effects can significantly weaken the cooling; need to be included

New calculation of longitudinal magnetized friction

- Analytic & numerical calc's
  - *Hamiltonian perturbation theory*
    - **gyrokinetic averaging → 1D**
    - **smaller range of time scales**
  - *fast numerical simulations*
    - **complicated hierarchy of 'passing' and 'trapped' orbits**
    - **cannot capture analytically**
  - *numerics agree with theory*
    - **asymptotic calculations agree quantitatively for small, large V_{ion}**
- Approximations being made…
  - *longitudinally cold electrons*
    - **warm e- results obtained via convolution with Gaussian**
  - *longitudinal ion motion*
  - *idealized solenoidal B-field*



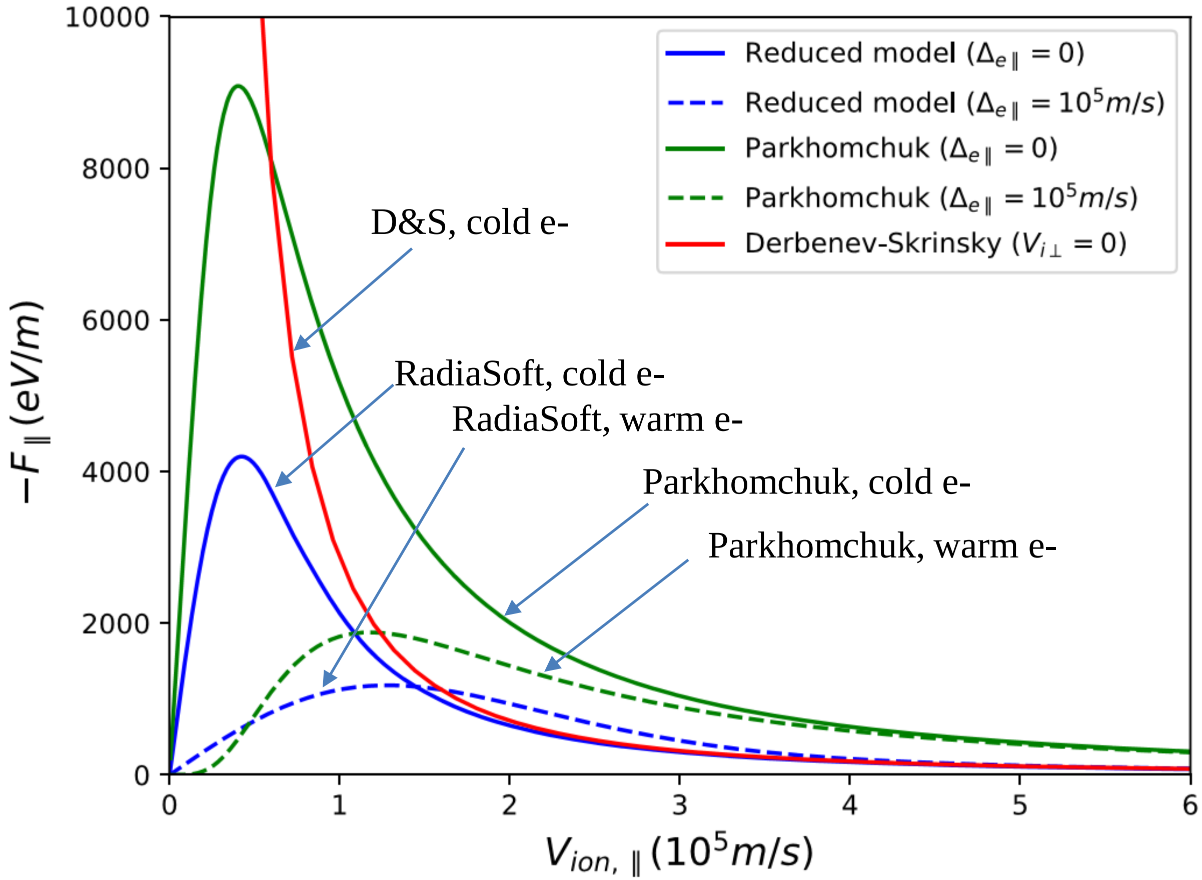
- Correct behavior of $F_{\parallel}(V_{ion,\parallel})$ is seen for both small and large $V_{ion,\parallel}$:

  $\sim V$ *for small V*

  $\sim V^{-2}$ *for large V*

Differences w/ Derbenev-Skrinsky & Parkhomchuk

- We are considering longitudinal friction only
- all ~ $1/v^2$ for large v
  - *our results agree exactly with D&S*
  - *Parkhomchuk is too large in this limit*
- RadiaSoft model is consistently lower than Parkhomchuk
- Parkhomchuk has unphysical inflection as v→0
  - *can be corrected via constant Coulomb log*
  - *no Coulomb log for our model*



Param's are taken from Fedotov, Bruhwiler *et al.*:

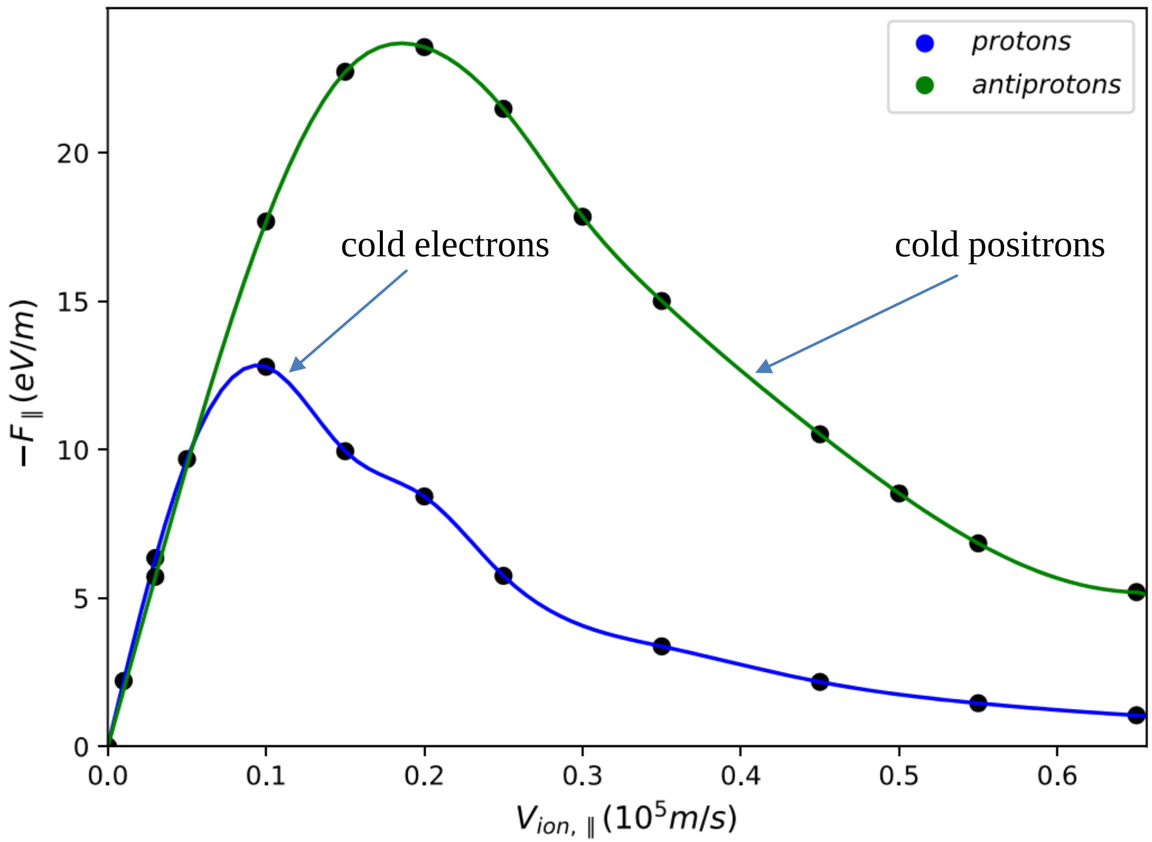
Au^{+79}; γ=107; n_e=10^{15} m^{-3}; B=5 T

τ_{int} = 4x10^{-10} s ~ 56 T_{Larmor} ~ 0.16 T_{plasma}

typical e^- sep. ~ 4.9x10^{-6} m ~ 10 r_{Larmor}

Longitudinal friction due to positrons is stronger

- agreement at small v
  - *consistent with asymptotic theory*
- stronger friction at intermediate v's
  - *trapped e- trajectories lead to phase mixing & lower friction force*
  - *positrons are not trapped*
- ~ $1/v^2$ for large v
  - *stronger e+ friction*
  - *asymptotic theory indicates equality*
  - *this feature is being further investigated*

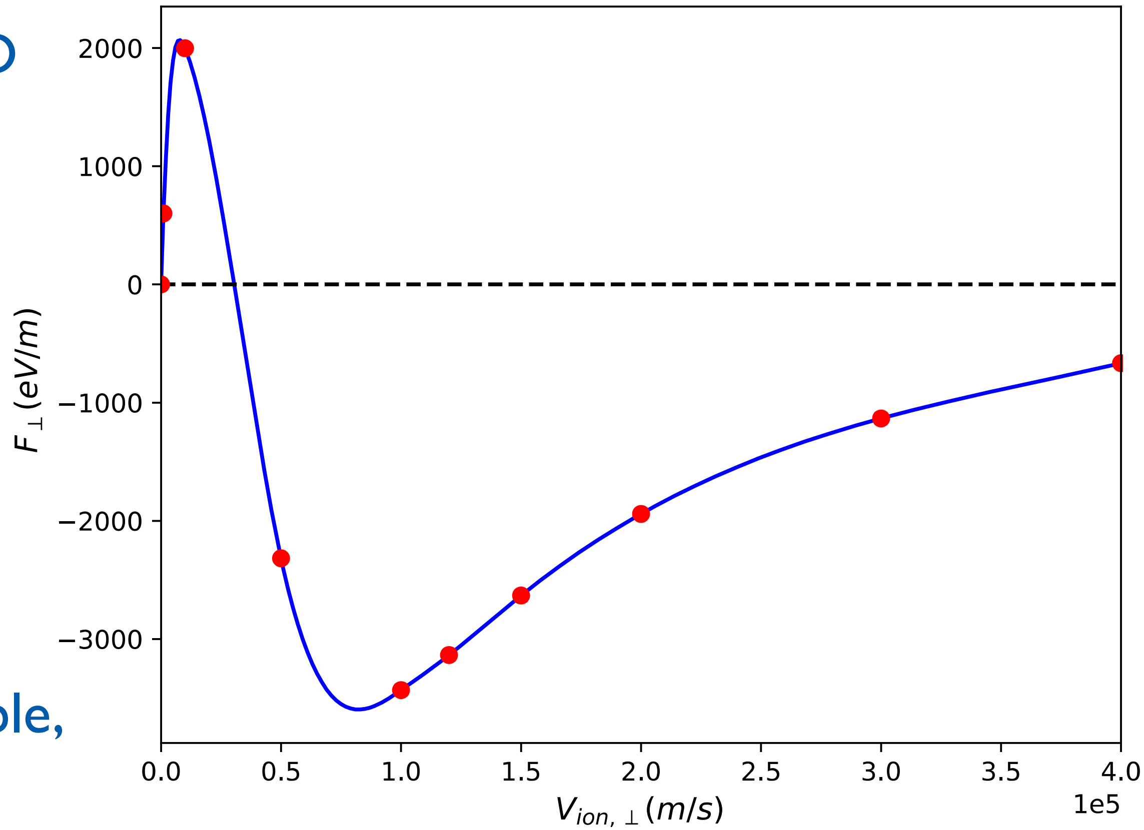


Approach to transverse friction simulations

- Ion velocity assumed constant during interaction, momentum kicks add up
  - *assume ion velocity perpendicular to the field lines of B (→ plane symmetry)*
  - *cold electrons → all have the same initial z velocity component w.r.t. ion*
  - *momentum kicks add up, averaged over T_{int}*
- Dynamical friction comes from ion-induced *density perturbation*
  - *add up the difference between force from e^-'s on perturbed & unperturbed paths*
    - **hence, we track pairs of electrons with identical initial conditions**
  - *this approach eliminates all bulk forces, both physical and numerical*
- Compute ensemble-average expectation value of friction
  - *we assume a locally-uniform electron density n_e*
  - *initial conditions for e^--s are uniformly distributed on lines of constant D*
    - **short interaction time, e-e interactions not included**
  - *longitudinal distribution is uniform in initial z position, z_{ini}*
    - **finite range of z_{ini} values contributes non-negligibly to the friction force**
    - **range depends on: D (impact parameter), V_{ion}, Z (ion charge state)**
- Friction force for warm e^-'s is obtained via convolution

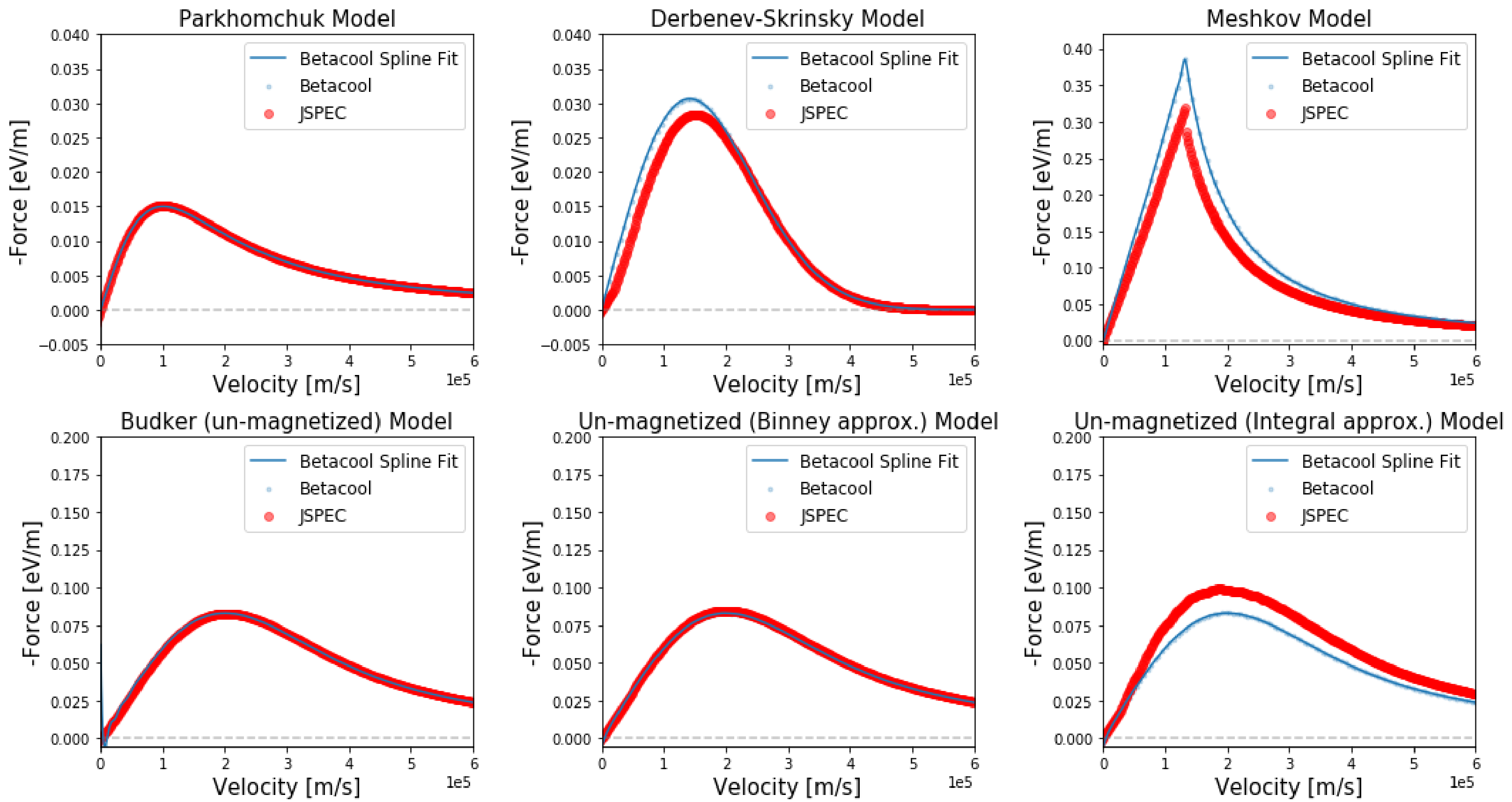
Initial simulation results for transverse friction

- Xverse simulations are 2D and, hence, ~100x slower than the longitudinal case
- Still working to obtain analytical results in a meaningful limit for code verification
- Initial results are reasonable, especially at high V
  - "anti-friction" is sometimes seen at low velocities
  - Derbenev & Skrinsky also saw anti-friction



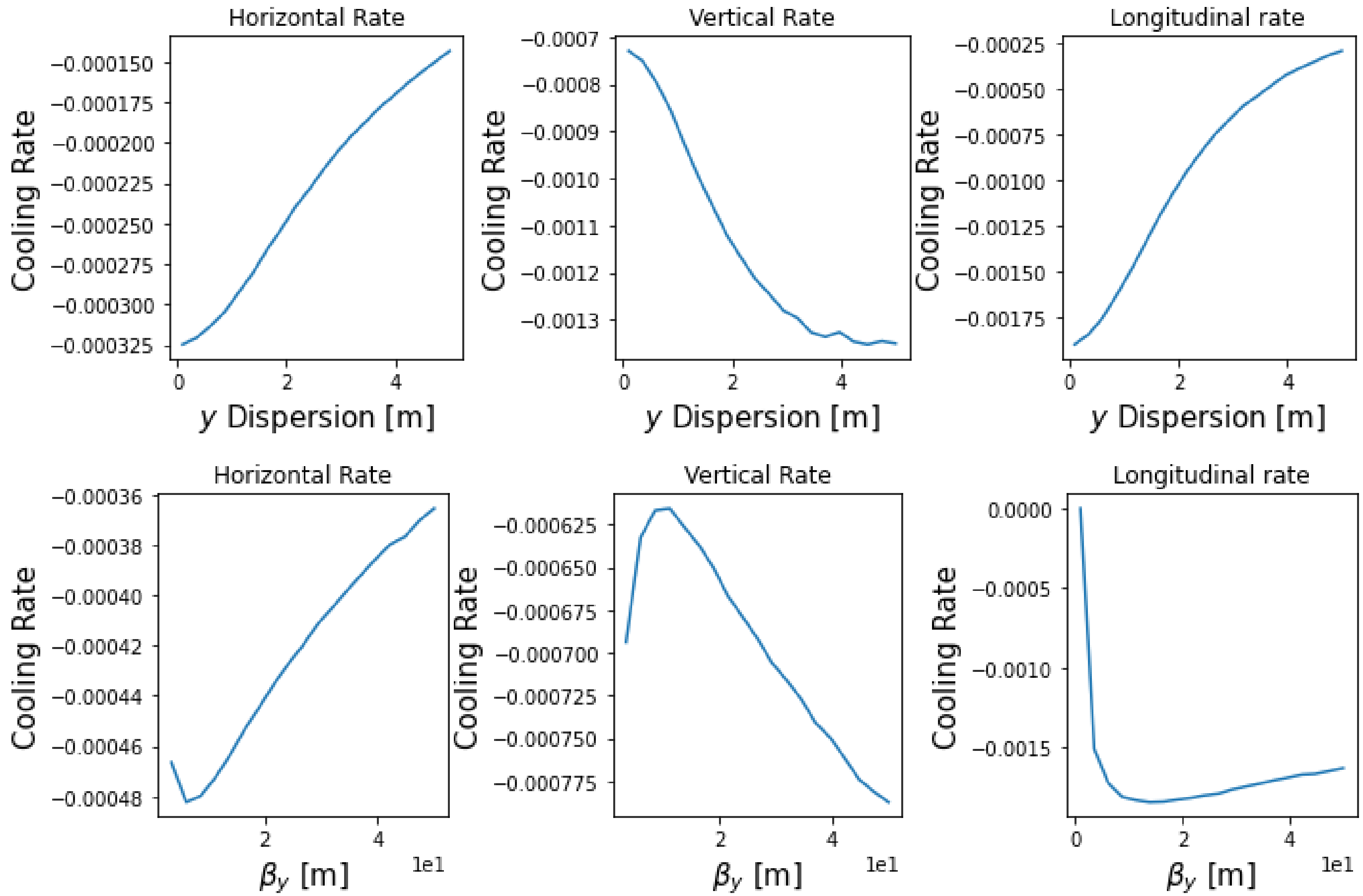
Overview of JSPEC capabilities

- A C++ package for intrabeam scattering (IBS) and electron cooling simulations
  - developed by He Zhang (JLAB)   https://github.com/zhanghe9704/electroncooling
- The friction force models have been benchmarked against BETACOOL
- Modified with a Nelder-Mead optimization method for minimizing the cooling time



Parameter Scans on the Jupyter server

- Cooling rate dependence on parameters can be isolated
  - very difficult to do via BETACOOL
  - scope out the problem, using the Sirepo GUI: https://sirepo.com
  - export files and move to https://jupyter.radiasoft.org for command-line scripting

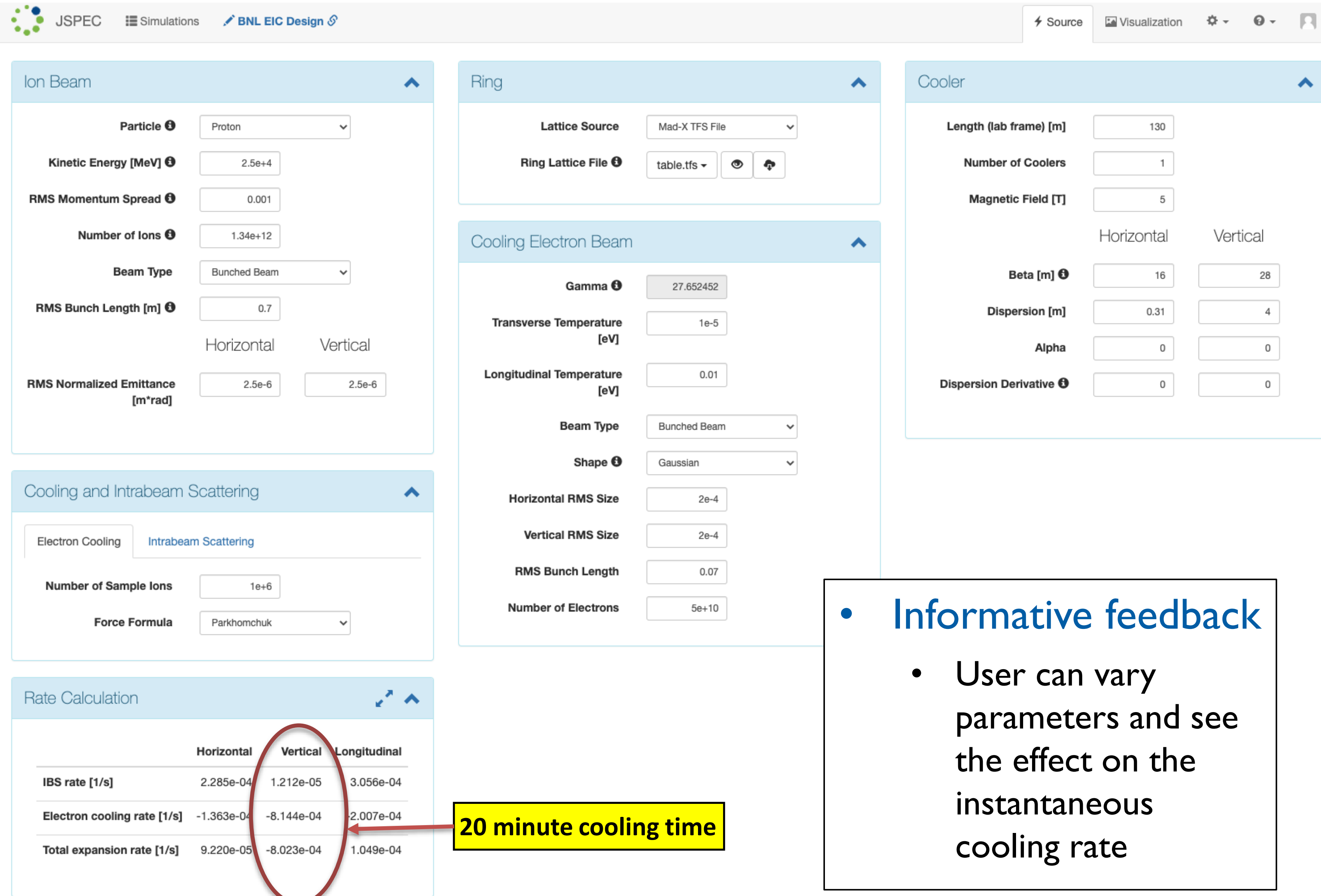


Magnetized configuration with 20 min cooling time

- Optimized for 25 GeV protons in the BNL EIC collider ring
  - configuration obtained using JSPEC with a nonlinear optimizer
  - this is a starting point → collaborate with BNL design team to move forward
  - initial indications are that an unmagnetized approach is as good or better

proton beam		e- beam		cooler	
E	25.0 GeV	$\gamma_e=\gamma_{proton}$	27.652	L	140 m
$N_{protons}$	1.34e12	Q_{tot}	8 nC	B-field	5 T
z_{RMS}	7 cm	z_{RMS}	7 cm	horiz. disp.	0.3 m
$\varepsilon_{x,y,norm}$	2.5 μm	x_{RMS}	2 mm	vert. disp.	4 m
β_x	16 m	$T_{x,y}$	1e-5 eV		
β_y	28 m	T_z	0.01 eV		

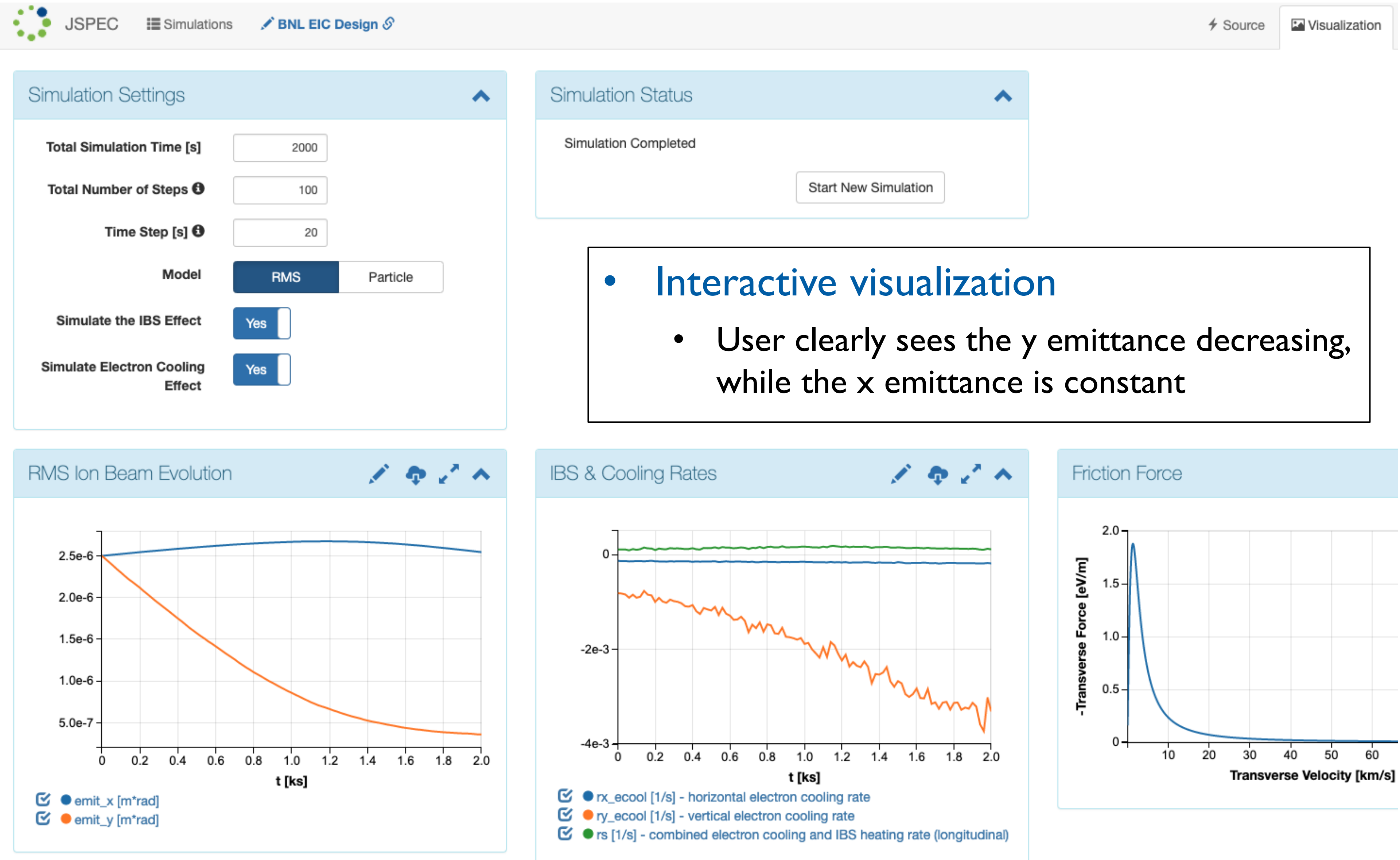
Benefits of using Sirepo/JSPEC



- Informative feedback
  - User can vary parameters and see the effect on the instantaneous cooling rate

Benefits of using Sirepo/JSPEC

- Interactive visualization
  - User clearly sees the y emittance decreasing, while the x emittance is constant



Benefits of working with JSPEC

- It makes the open source ecosystem available for e- cooling analysis
  - GNU Scientific Library (GSL) is used for monte carlo integration & optimization
- Most functionality available to users through the Sirepo GUI
  - easy to use; nothing to install; instantaneous collaboration
- We have identified many configurations with a 20-minute cooling time
  - Some parameters are (anti-)correlated, so turning two knobs at once can achieve the same result

- Caveat: we are using standard friction force algorithms
  - These are "state-of-the-art", but not correct in the relativistic regime
  - We will soon implement more accurate models as described above

Increased sales & marketing effort is paying off

From https://www.radiasoft.net/services

GUIs for Code

We develop intuitive browser-based GUIs for open-source, high-performance codes.

Our algorithms and software solutions drive major improvements in accelerator design and research productivity

More about GUIs for Code

ML for Science

Our researchers and scientists bring years of experience to design and develop custom machine learning (ML) algorithms.

Whether it's tracking performance or preempting faulty conditions, ML can help.

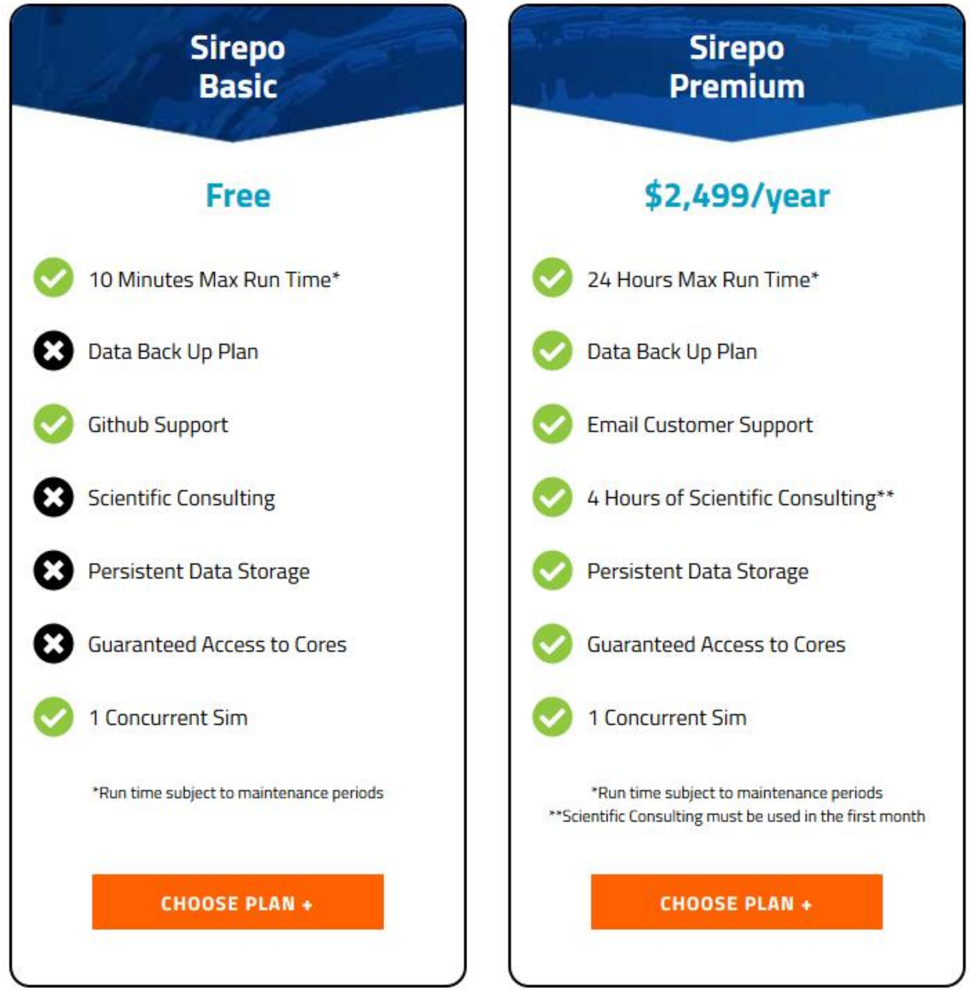
More on ML for Science

- 3-year $100k subcontract from BNL, NSLS-II
  - Sirepo/SRW development
- Annual support contract with USPAS/Fermilab (in negotiations)
  - For both Sirepo and Jupyter server access, including support/consulting
  - Years of USPAS students using Sirepo will have important long-term benefits
- Lawrence Livermore National Lab (in negotiations)
  - Develop a Sirepo-based GUI for proprietary internal codes
  - Initial effort is likely to be extended: support & ongoing improvements

We have begun to productize Sirepo

- Sirepo Premium is live next week
  - 1 customer so far: Korea University
- Increased marketing:
  - monthly Sirepo webinars
  - using Mailchimp to communicate
  - frequent social media postings
- 500 Sirepo users and growing
  - fraction who will pay for Premium is still an unknown
  - we will introduce "Jupyter Premium" in the next 6 to 12 months

From https://www.sirepo.com/en/plans.html



Thanks!

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