Simulating IBS and electron cooling (magnetized and unmagnetized) for the Electron Ion Collider

PI: David Bruhwiler*

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Phase 2a SBIR (w/ 5-month NCE) – concludes on Sep. 30, 2021

Scientists: Stephen Coleman, Ilya Pogorelov, Boaz Nash, Dan Abell
Software team: Paul Moeller, Rob Nagler and Evan Carlin

RadiaSoft LLC 6525 Gunpark Dr., Suite 370-411, Boulder, Colorado 80301
*bruhwiler@radiasoft.net

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2021 SBIR-STTR Exchange Meeting *(virtual)*

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Motivation

- Relativistic (γ>25) hadron cooling needed for EIC design luminosity:
  - bunched beam stochastic cooling
  - plan B: conventional e- cooling
  - new: strong hadron cooling (SHC)
- 'Conventional' e- cooling has only been demonstrated for γ<5
  - caveat: BNL's CEC PoP exp't showed ~100 hr cooling time for γ~28
- Dynamic friction for γ>>1 yields short time dynamics
  - asymmetric collisions are essential
  - no time for electron shielding effects
  - existing models are overly optimistic

The EIC Machine

The EIC will be the only electron-nucleus collider operating in the world

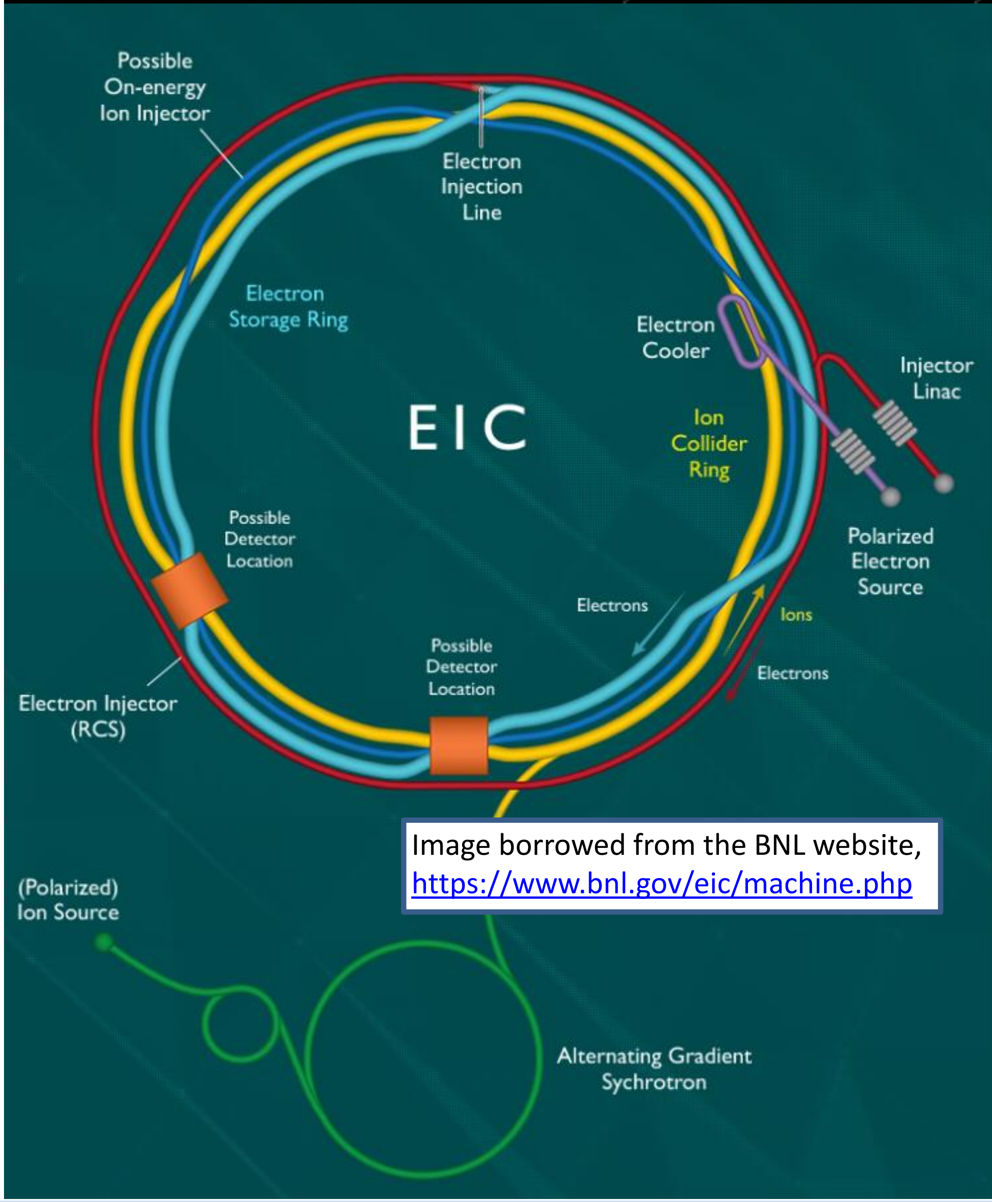

Image borrowed from the BNL website, https://www.bnl.gov/eic/machine.php

Outline

- Motivation
- 20-minute cooling time for EIC protons at injection –
  - challenge posed to RadiaSoft by the BNL EIC cooling team
    - can this be done with 'conventional' relativistic electron cooling?
- Benefits of cooling & IBS simulations with Sirepo / JSPEC
- New dynamic friction model for highly-relativistic coolers
- RadiaSoft team & SBIR commercialization activities
- Conclusions

- Backup slides
  - Sirepo sales brochure for contract GUI development
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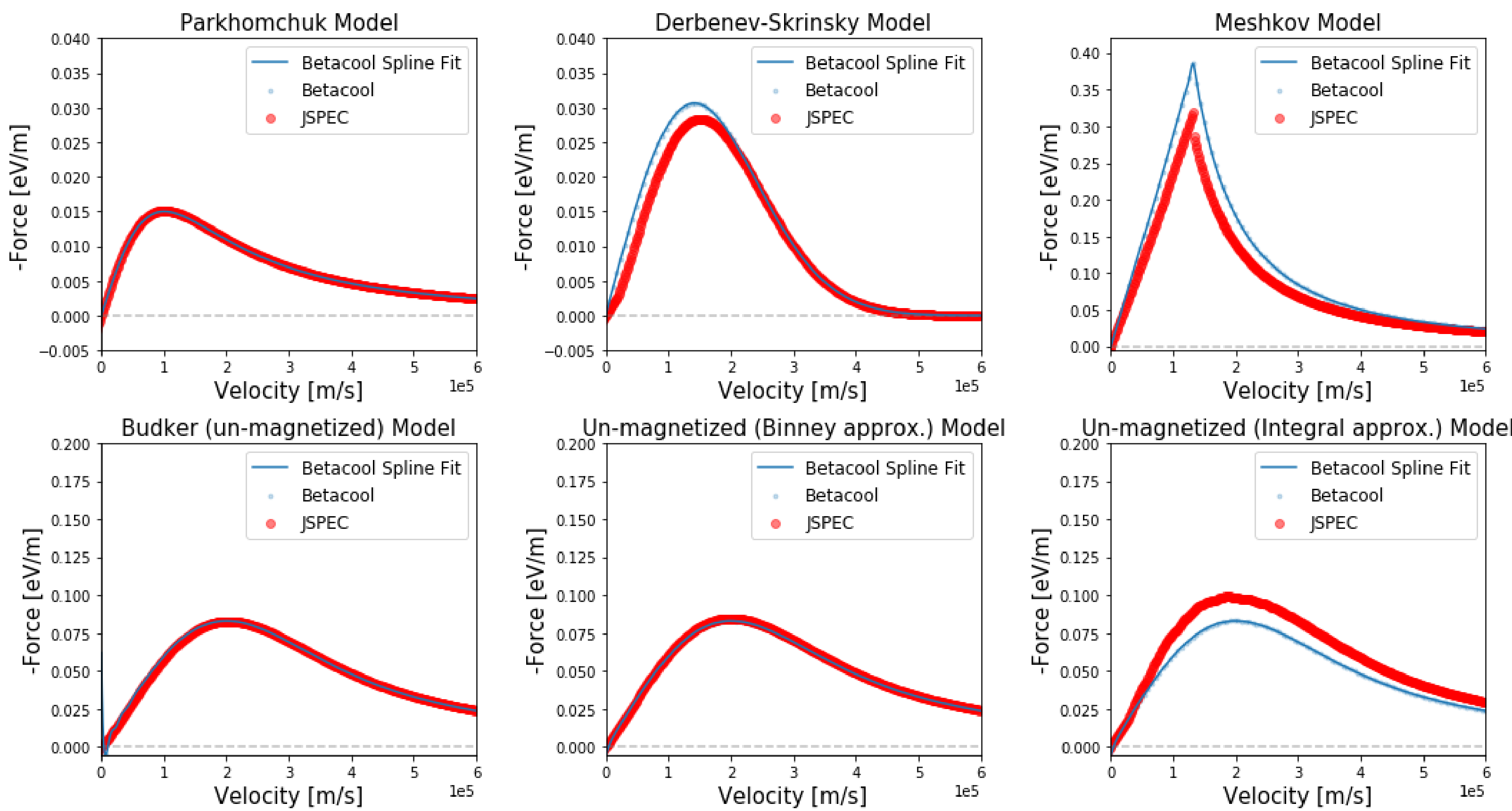
Magnetized configuration with 20 min cooling time

- Optimized for 25 GeV protons in the BNL EIC collider ring
  - configuration obtained using JSPEC with a nonlinear optimizer
  - running in parallel on Sirepo / Jupyter servers
  - configuration can be imported to Sirepo / JSPEC app for interactive exploration

proton beam		e- beam		cooler	
E	25.0 GeV	$\gamma_e=\gamma_{proton}$	13.6 MeV	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		

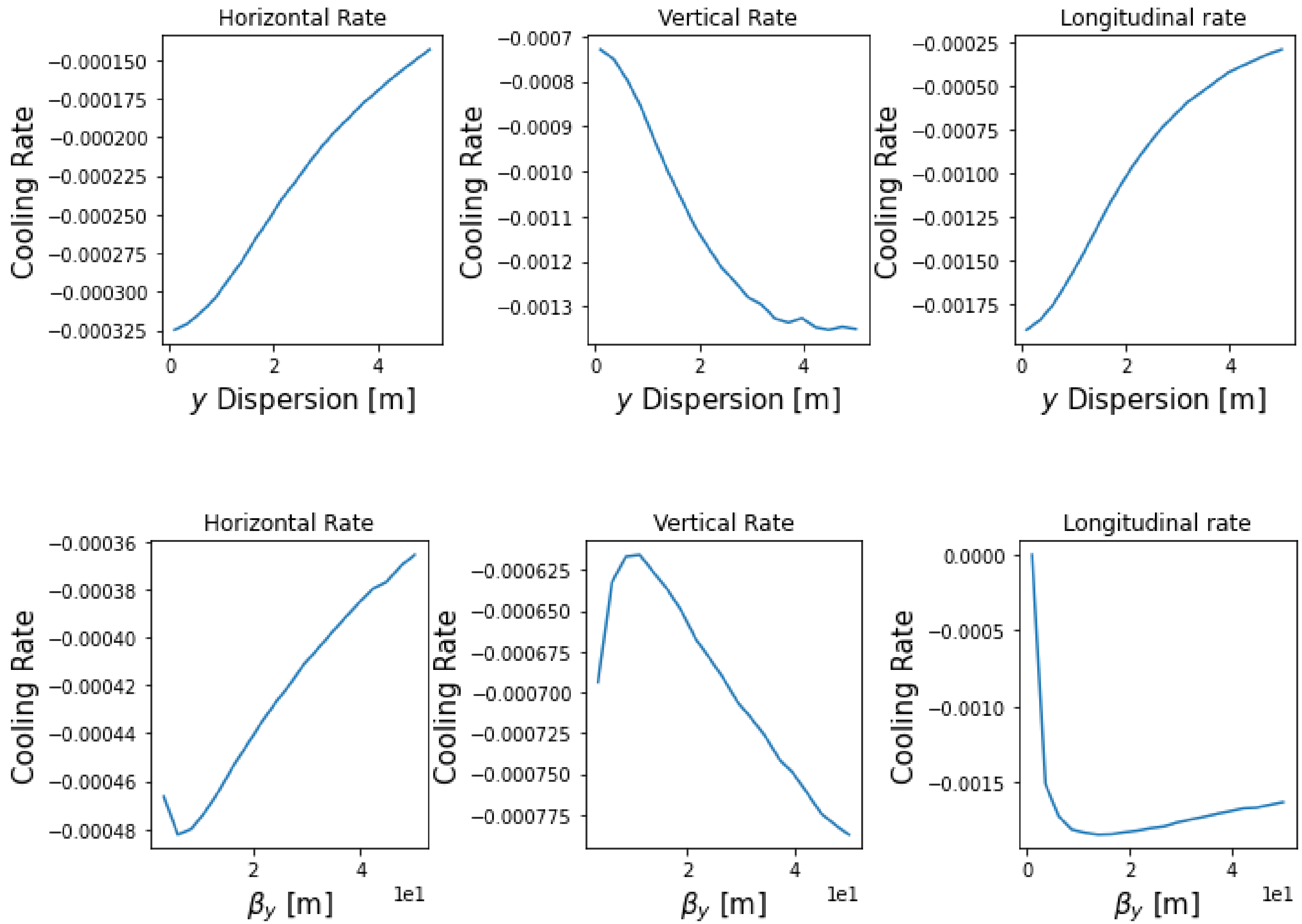
Overview of JSPEC capabilities:

- 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



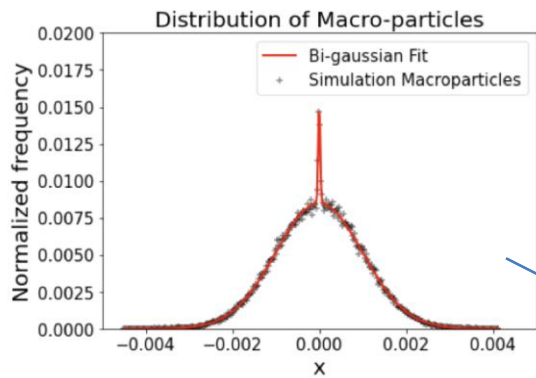
Parameter scans on the Sirepo / Jupyter server

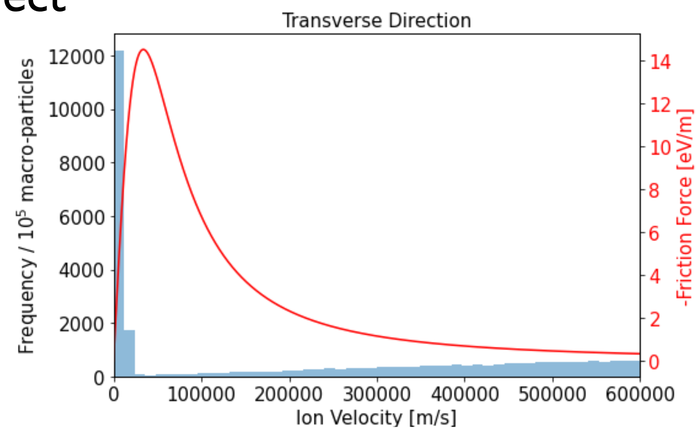
- Cooling rate dependence on parameters can be isolated
  - very difficult to do via BETACOOL

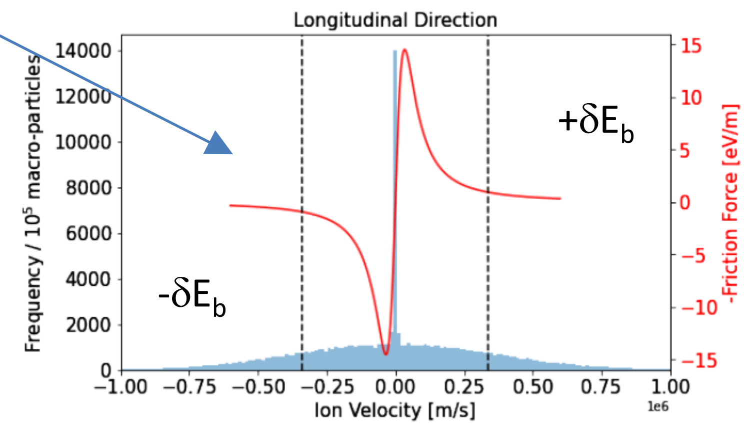


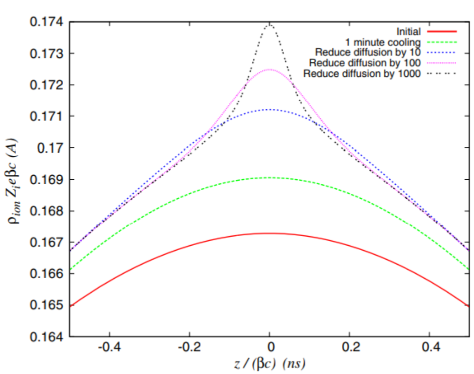
20-minute cooling challenge requires further work

- Simplified RMS treatment of the ion beam yields good results
- Macro-particle treatment of ions → non-Gaussian velocity distributions
  - narrow central peak (seen in previous work) is not acceptable
  - correct non-Gaussian IBS could moderate this effect
  - beam energy jitter could be helpful









Same effect seen in other work, including recent work on strong hadron cooling;
G. Wang, PRAB 22, 111002 (2019)

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Benefits of using Sirepo / JSPEC –

https://sirepo.com

JSPEC   Simulations   BNL EIC Design

SUPPORTED CODES
- ACTIVAIT
- CONTROLS
- ELEGANT
- JSPEC
- JUPYTER
- MADX
- OPAL
- RADIA
- SHADOW
- SRW
- SYNERGIA
- WARPPBA
- WARPVND
- ZGOUBI

Simulation Settings

Total Simulation Time [s]	2000
Total Number of Steps	100
Time Step [s]	20
Model	RMS / Particle
Simulate the IBS Effect	Yes
Simulate Electron Cooling Effect	Yes

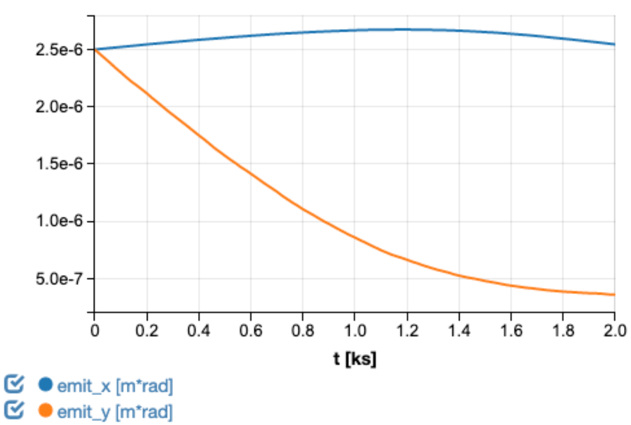
Simulation Status

Simulation Completed

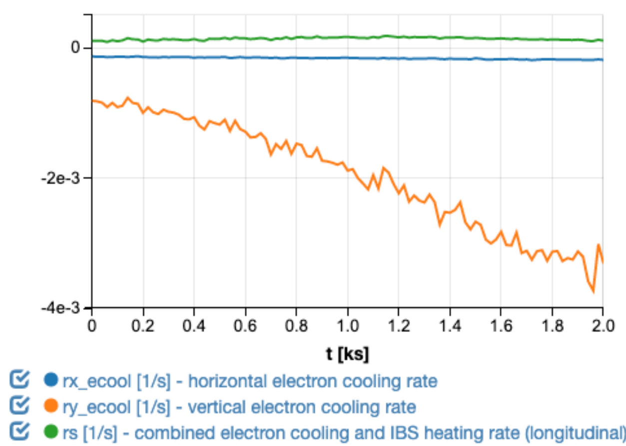
Start New Simulation

- **Interactive visualization**
  - User sees y emittance decreasing, witch constant x emittance

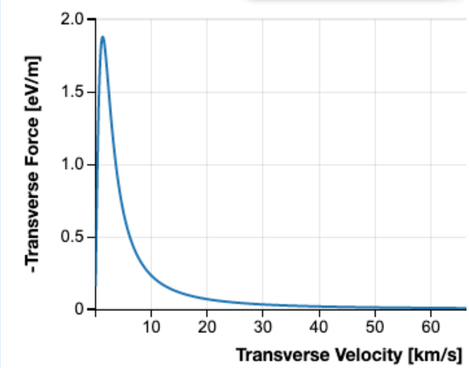
RMS Ion Beam Evolution



IBS & Cooling Rates



Friction Force



New model for short-time magnetized friction force

$$F_{\|}(v) = -\frac{Av}{(\sigma^2 + v^2)^{3/2}}$$

$$A = 2\pi Z^2 n_e m_e (r_e c^2)^2$$

$$\sigma \approx (\pi Z r_e c^2 / T_{int})^{1/3}$$

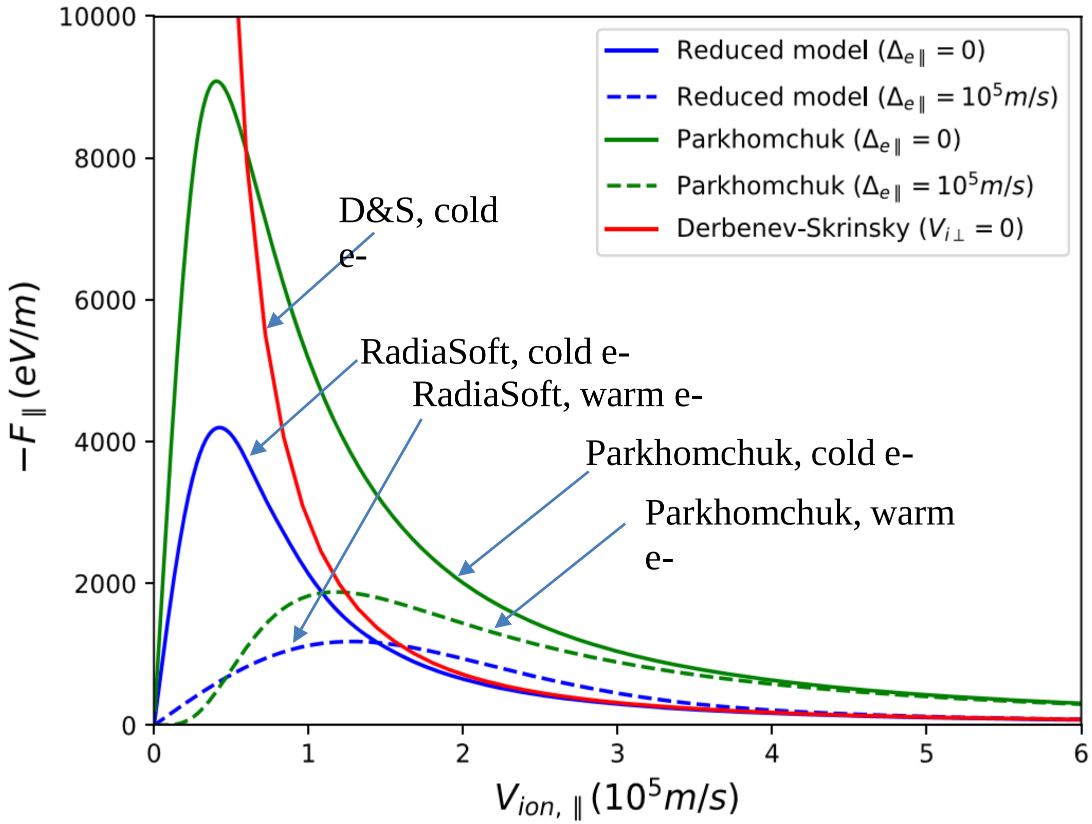
- Large v (v >> σ):
  - *$F_{||} \sim A / v^2$*
  - *A is from asymptotics & dim. analysis*
  - *agrees exactly with Derbenev & Skrinsky*
  - *Parkhomchuk is too large in this limit*
- Small v (v << σ):
  - *$dF/dv \sim A / \sigma^3$*
  - *σ is from asymptotics & dim. analysis*

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}



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The RadiaSoft team provides unique capabilities:

- Software Engineering
  - cloud computing
  - distributed computing
  - browser-based GUIs
- Physics & Data Science
  - computational physics
  - parallel computing
  - machine learning
  - nonlinear optimization
  - particle accelerators
  - plasma devices
  - x-ray optics
  - control systems
  - radiation modeling
- Operations
  - project management
  - technical writing
  - accounting

Rob Nagler

Paul Moeller

Evan Carlin

Mike Keilman

Kevin Bruhwiler

David Bruhwiler

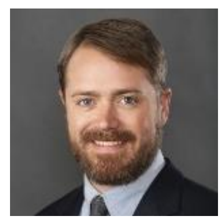
Nathan Cook

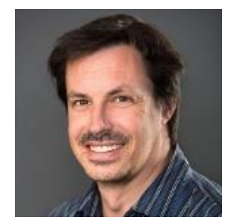
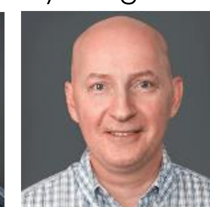
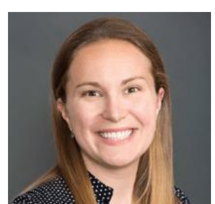
Jon Edelen

Stephen Webb

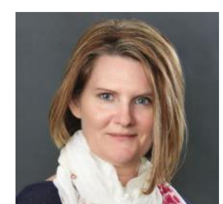
Dan Abell

Abdou Diaw

Stephen Coleman

Chris Hall

Boaz Nash

Ilya Pogorelov

Joan Danver

Jessie Hansen

Claudia Behnke

Beck Cotter


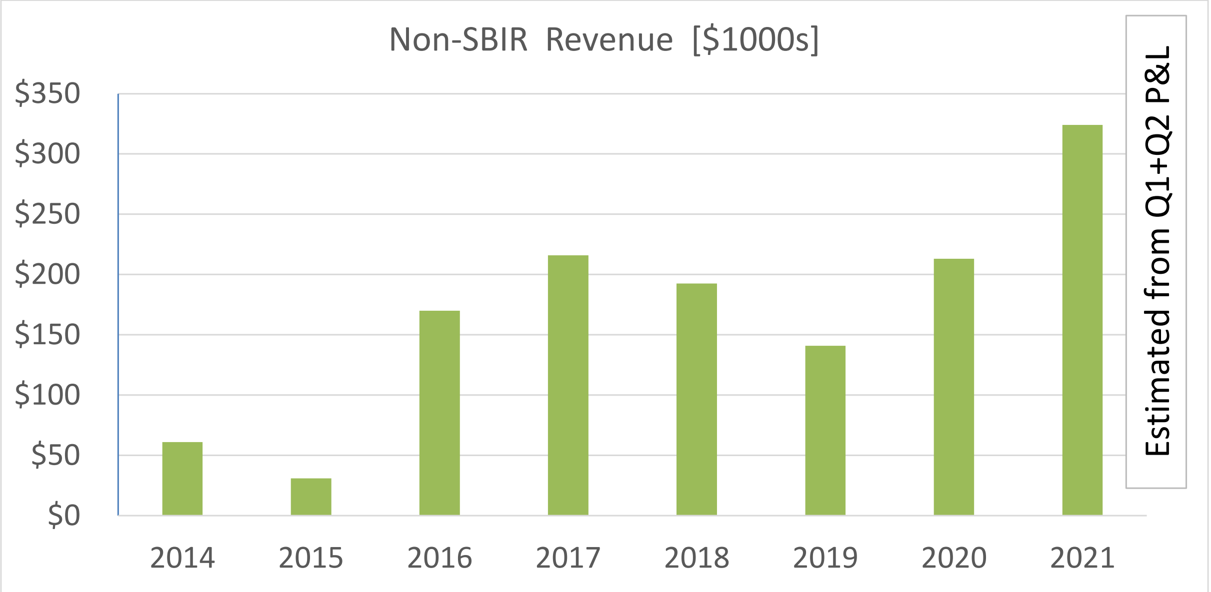
RadiaSoft provides contract R&D services, as well as Sirepo-specific services:

Overview of recent Sirepo-specific sales –

- 3-year $100k subcontract from BNL, NSLS-II (to be renewed)
  - Sirepo / SRW development
- Annual support contract with USPAS/Fermilab (Year 1 concluded)
  - Years of USPAS students using Sirepo will have important long-term benefits
- Lawrence Livermore National Lab (12-week project underway)
  - Developing a Sirepo-based GUI for ITAR protected internal codes
  - Will evolve into a "Sirepo Private Cloud" contract
- Sirepo Premium sales to individuals are now active:
  - 3 customers so far: 1 each in Korea, Japan & Italy

RadiaSoft is supporting the US accelerator industry:

- Range of customers (2019 to 2021) –
  - US companies: 2 (medical accelerator design)
    1 (isotope production)
    1 (food irradiation)
  - DOE laboratories: 1 (shielding design) + 1 (education)
    1 (light sources; beams / vacuum chambers)
    2 (Sirepo 'private cloud' & GUI development)
    1 (PIC code development & simulations)
  - DOD subcontracts:
    1 (light source)
  - University:
    1 (magnetic horn)
  - International labs:
    1 (vacuum chamber)
  - SBIR subcontracts:
    3 (various topics)



Conclusions

- The open source JSPEC code (originated at JLab) has been improved
  - parallelized for fast performance
  - generalized for parameter sweeps and design studies
  - Several new friction force models & 1 bi-Gaussian IBS model were added
- Sirepo / JSPEC is freely available on GitHub and via **Sirepo.com**
  - now a viable US alternative to the aging (PC-based) Russian code BETACOOL
  - easy to use for a much broader segment of the particle accelerator community
- An EIC design question (20-minute cooling times) is being addressed
  - a complete answer is beyond the scope of this SBIR project…
  - but the tools are now available.
- Sirepo improvements & RadiaSoft marketing is increasing sales!
  - example Sirepo improvement: previous versions of the Sirepo framework & a specified version of the 'application container' can be pulled from GitHub and instantiated
  - this is required for 'computational reproducibility', which is important for a long-lived facility like the EIC

Thanks! … any questions?

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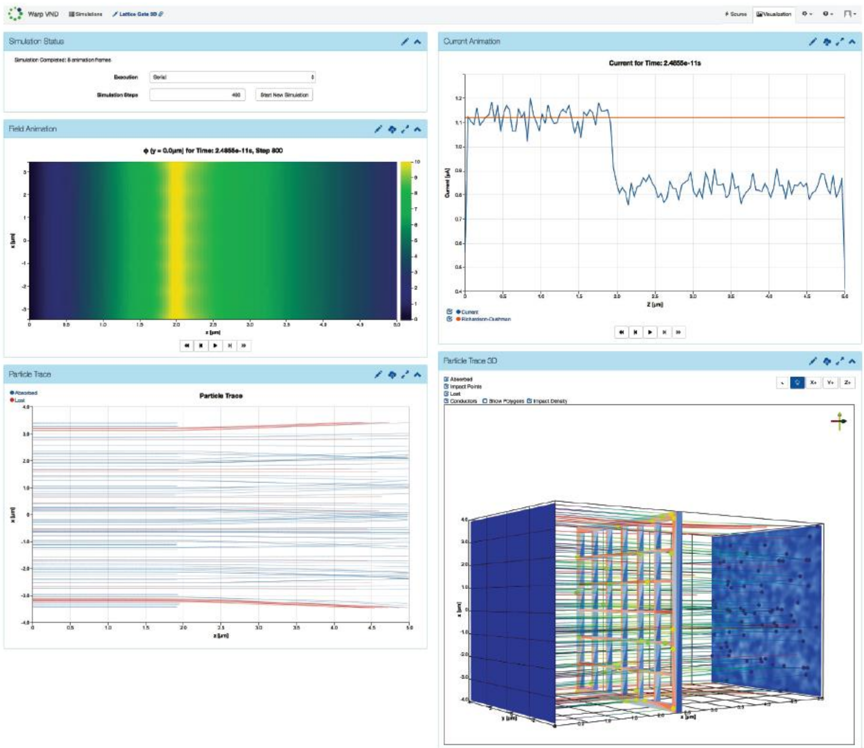
The Sirepo sales brochure for GUI development –

Tools are meant to be shared.



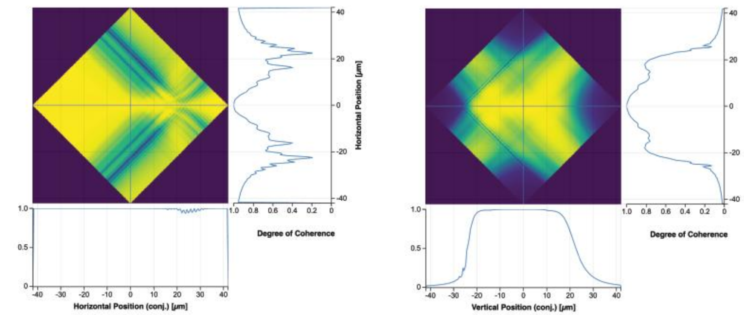
Scientific labs invest significant time and money into developing codes, but getting a good ROI is difficult. Command line interfaces (CLIs) are tough to master, hard to share within teams, and look dated.

They can also present other challenges:

- Difficultly onboarding new hires because they can't immediately contribute to projects dependent on CLI code.
- Unnecessary rework and rebuilds because CLI dependence fostered siloing and inaccessibility.
- Inefficient and wasteful investment in new code development because employees don't share tools.
- Extra time and cost around employee transitions because code documentation is sparse or nonexistent.

RadiaSoft Consulting

GUI Conversion Services for Companies and Scientific Labs

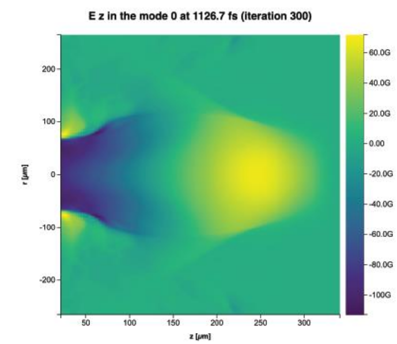


Our GUI Conversion services enable labs to unlock the full potential of their command-line codes

- Transforming command-line codes into fully functional GUI tools makes solutions instantly accessible to your entire lab.
- Wrapping CLI code in a GUI enables knowledge reuse, freeing up valuable resources.
- New hires and scientists benefit from better accessibility, improving productivity and retaining valuable legacy knowledge.
- GUIs remove the expense and burden of documentation, uncomplicating succession planning.

Share your tools

Our expert team of software engineers, scientists, and project managers offers a unique blend of skills, experience, and ingenuity necessary to take your legacy codes to the next level. We welcome the opportunity to collaborate with you.



Learn more:

info@radiasoft.net
720-502-3928
radiasoft
www.radiasoft.net

Overview of project accomplishments by task:

- #1 - Develop a browser-based GUI for electron cooling
  - the GUI has been developed: https://www.sirepo.com – look for JSPEC
  - parallel execution via command-line is also supported – look for Jupyter
- #2 - Preconceptual design of a cooling and accumulator ring
  - Ph 2: completed by P. McIntyre at Texas A&M on subcontract
  - Ph 2a pivot: 25 GeV protons in EIC (at injection); 20-minute cooling times…?
- #3 - Preconceptual design of an electron cooling system
  - Ph 2: ionization physics in Warp, https://github.com/radiasoft/rswarp
  - Ph 2a pivot: 41 GeV protons in EIC (minimum collision energy)
- #4 - Study equilibrium electron cooling rates
  - JSPEC benchmarked with BETACOOL
  - For 20-minute cooling times, non-Gaussian IBS becomes a serious issue
- #5 - Generalized 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)
- #6 - Develop software to perform dynamic friction calculations
  - includes implementation of our own algorithms, mostly in Python
  - contributions to JSPEC, https://github.com/zhanghe9704/electroncooling