Magnetized Electron Cooling –

simulations to support the Electron Ion Collider design effort, including computational reproducibility

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Nuclear Physics SBIR/STTR Exchange Meeting

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U.S. DEPARTMENT OF ENERGY

Office of Science

RadiaSoft Vision

- *Build a world class contract R&D organization*
  - *funded by the SBIR program in the near-term*
  - *develop non-federal customers & a reputation for excellence*
    - *near-term: charged particle beams, plasma and radiation*
  - *long term: diversify and grow (e.g. SAIC, now called Leidos)*
- *Scientific cloud computing services*
  - *the market is large & independent of any particular field*
    - *near-term: accelerator technology can provide initial users*
  - *'Sirepo' is already a brand name in our community*
    - *http://sirepo.com*
  - *near term: Sirepo delivers software solutions to customers*
  - *soon: Sirepo is a freemium subscription-based product*
- *Long term: Sirepo subscriptions exceed contract R&D*
  - *SBIR awards become a small fraction of total revenue*
- *Make computational reproducibility commonplace*

radiasoft Scholarship

RadiaSoft LLC consults regarding the simulation & design of particle beams, plasmas & radiation sources. We have 8 PhD physicists on staff, 3 PhD consultants & 1 COMSOL engineer.

- Helping teach 2 USPAS courses:
  1) *Simulation of Beam and Plasma Systems*, Winter 2018
  2) *Classical Mechanics and Electromagnetism*, Summer 2018
- **Sirepo.com** is a free scientific gateway for cloud-based particle accelerator codes.
  1) *Accelerator Physics*, Summer 2018

Sirepo

- Particle Accelerators
- Synchrotron Radiation
- X-ray Optics
- Vacuum Nanoelectronic Devices
- Electron Cooling
- Free Electron Lasers
- COMSOL Multiphysics

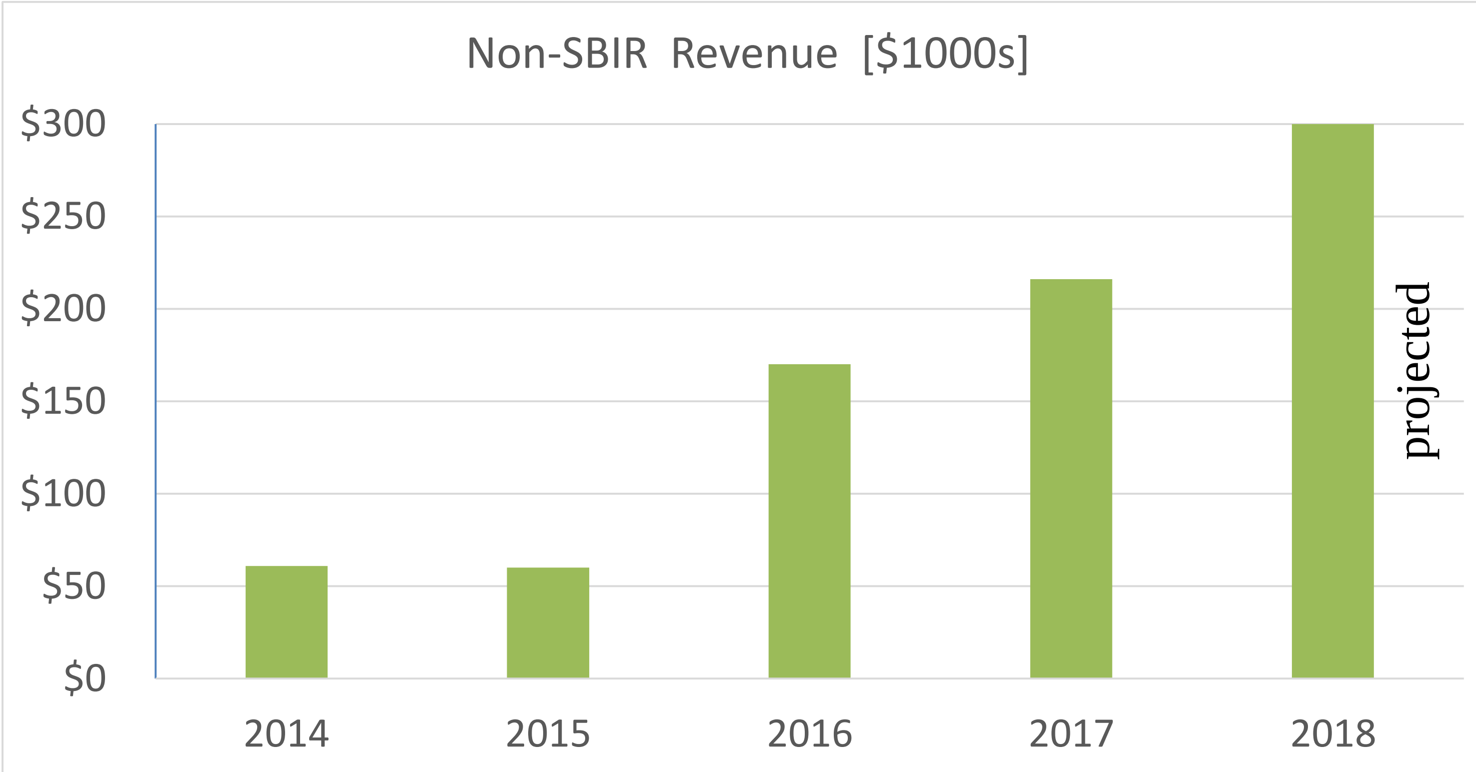
RadiaSoft LLC scholarship this session:

- Pays for class registration and lodging
- Recipient: Maria Simanovskaia (UC Berkeley)

Core Competencies

- *Contract R&D*
  - *particle accelerator modeling (ions, electrons, other)*
    - *lattice design, particle tracking, low-lever RF controls*
  - *x-ray optics, synchrotron radiation, FELs*
  - *ES and EM particle-in-cell (PIC) for beams and plasmas*
  - *hydrodynamics and charged fluids*
  - *machine learning, multi-objective genetic optimization (MOGA)*
- *Community physics codes*
  - *MAD-X, Synergia, elegant, Warp, Zgoubi, PTC*
  - *SRW, Shadow, Genesis, Flash*
- *Computer-aided engineering (CAE)*
  - *COMSOL Multiphysics*
- *GUI development*
  - *design and implement browser-based GUI for any code*
- *Computational reproducibility*
  - *archive full simulation environment for 6 months or 6 years*
  - *rerun previous simulations with same results to machine precision*

Non-SBIR revenue is up year over year



- *Our customer base is diverse*
  - *Air Force Office of Scientific Research, DOE national labs*
  - *high tech hardware companies (some funded by SBIR)*
  - *medical technology; VC-funded hardware startups*

Phase 2 SBIR project – Technical Objectives

- *Integrate JSPEC cooling code into Sirepo platform*
  - *collaboration with He Zhang at JLab*
  - *https://github.com/zhanghe9704/electroncooling*
  - *https://sirepo.com/#/jspec*
  - *important alternative to BetaCool*

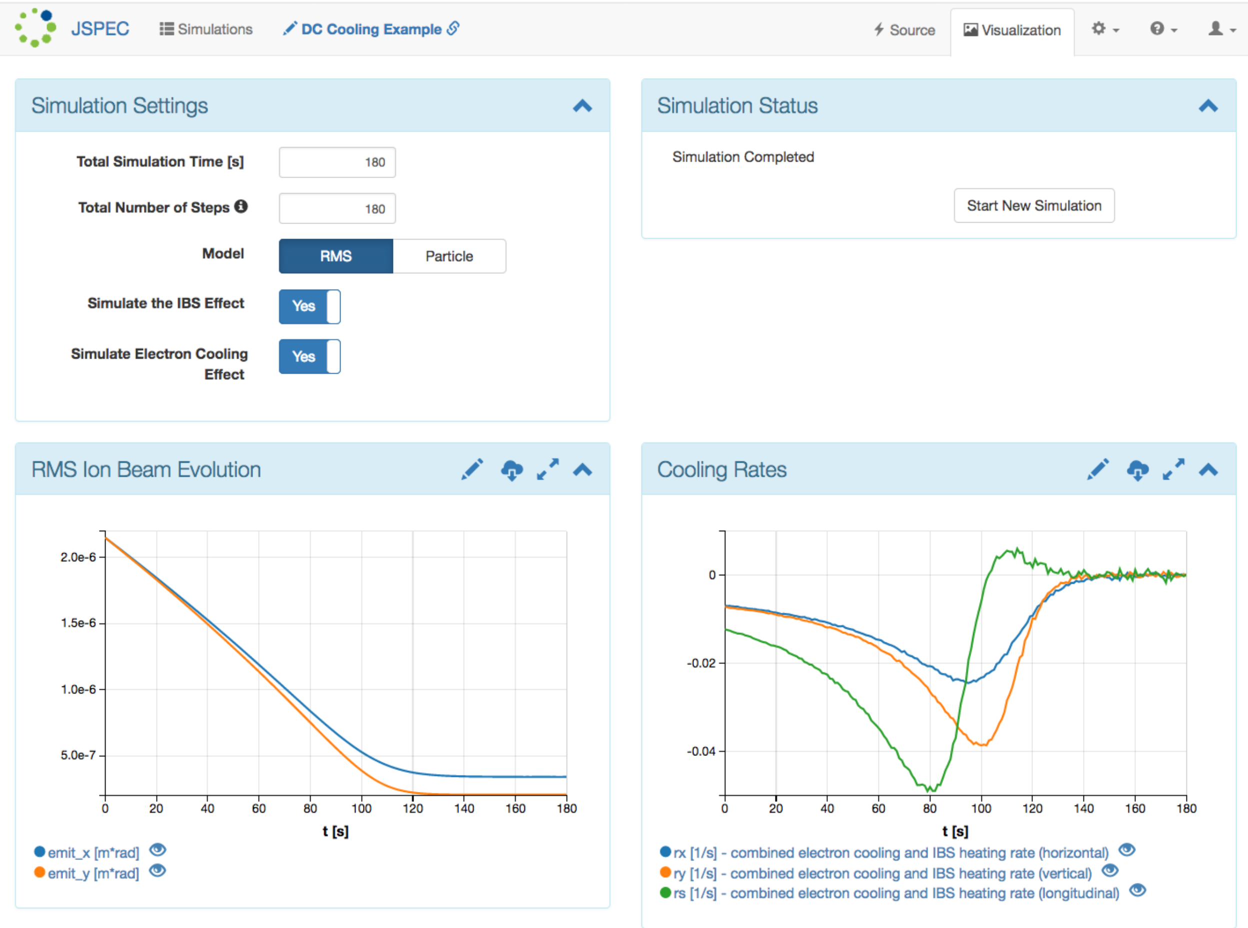
- *Develop and test a new conceptual design for both an accumulator ring and high current d.c. cooler*
  - *collaboration with P. McIntyre and J. Gerity at Texas A&M*

- *Incorporate new methods of dynamic friction calculation into a software package*
  - *risk reduction for high-energy magnetized e- cooling*
  - *target software package is JSPEC*

Task 1 – *Develop browser-based GUI for e- cooling code*

- *Good progress has been made*
  - *He Zhang (JLab) is collaborating with us*
  - *https://sirepo.com/#/jspec*

- *I. Ben-Zvi (BNL) & M. Steck (GSI) have tested:*
  - *both provided good feedback*
  - *M. Steck simulated GSI cooler params with good results*



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Task 2 – Preconceptual Design of a Cooling and Accumulator Ring

- *JLEIC ion collider ring is a figure-8 layout*
  - *includes low-energy DC electron cooling*
  - *also, high-energy bunched electron cooling, using ERL*
    - *this includes significant technical risk*
- *consider e- cooling at intermediate energy: 6 GeV/u*
  - *less risky then high-energy cooling*
  - *new figure-8 design conforming to updated JLEIC design*
    - *the arc cells have twice the periodicity of those found in JLEIC ring*
    - *yields transition energy $\gamma_T \sim Q_X$ higher than collision ring, $\gamma_T = 12.46$*
    - *allows for acceleration after cooling, so beam can enter collision ring above transition*
  - *designed using MAD-X*
    - *basic lattice parameters:*

B_{dip}	1.0 T
G_{quad}	7.02 T/m
Q_x, Q_y	49.43, 48.83
$B_{solenoid}$	>1 T

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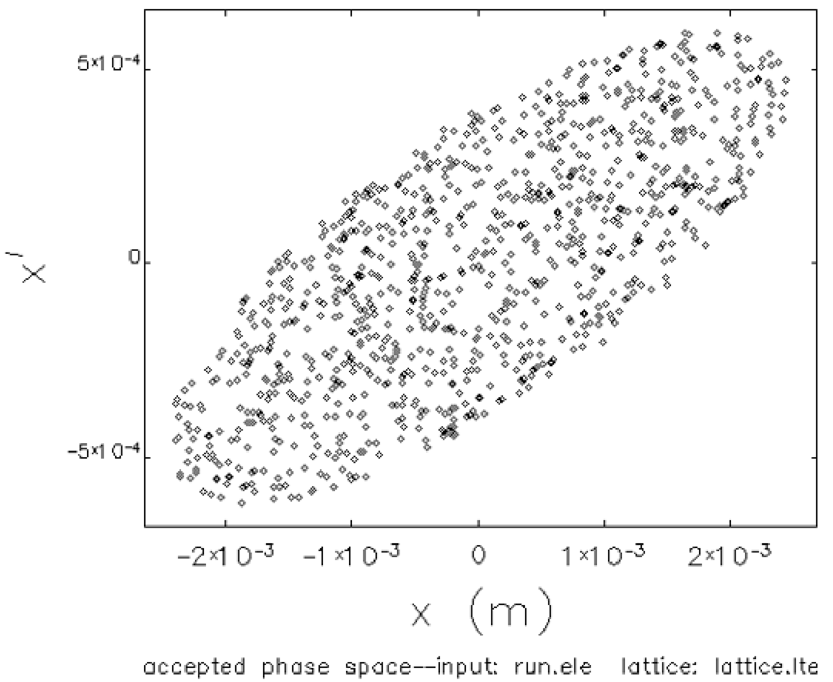
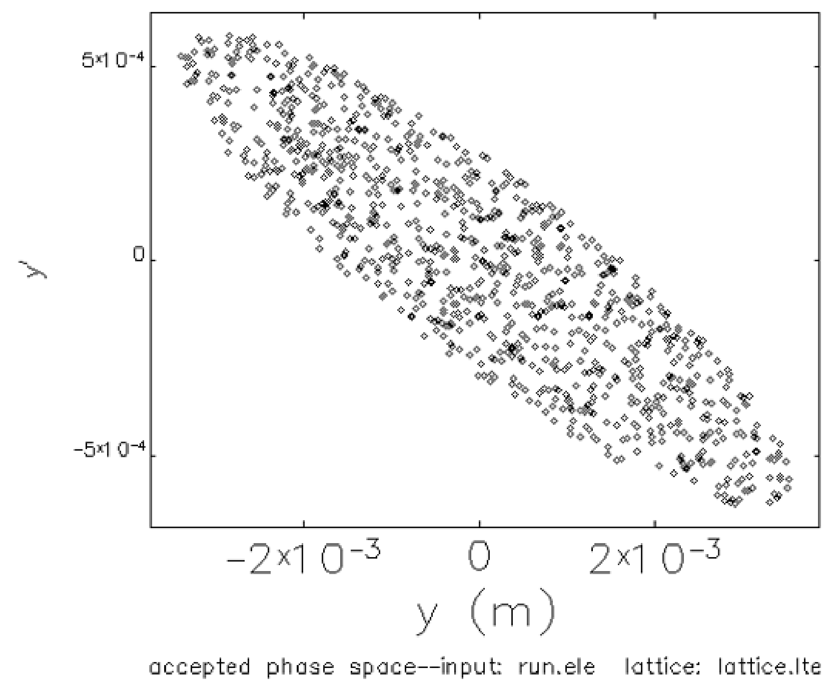
Task 2 – Preconceptual Design of a Cooling and Accumulator Ring

- *Ongoing lattice improvements, using MAD-X*
  - *matching regions between arcs and straight sections*
    - *same matching conditions met with fewer magnets*
- *Particle tracking studies with 'elegant' code*
  - *initial results are consistent between the two codes*

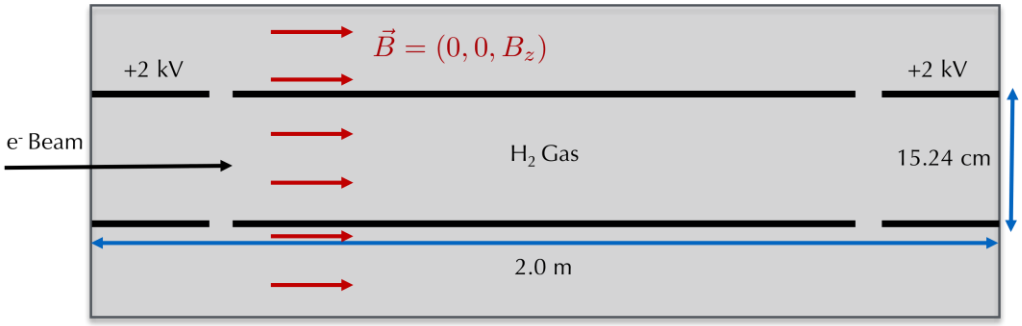




Task 3 – Preconceptual design of a magnetized e- cooling system

- *We consider parameters of Task 2 accumulator ring*
- *Consider space charge neutralization of ~1 A e- beam*
  - *lower space charge forces means stronger dynamic friction*
- *Initial simulations have been run using Warp*
  - *space charge neutralization of the electron beam is observed*
  - *the neutralization time is ~15 μs*
    - *this requires 3.6 million simulation time steps*

Quantity (Units)	Simulation Value
Beam Energy (MeV)	3.2
Beam Current (mA)	10
Beam Density (cm^{-3})	6.75e+5
Gas Density (cm^{-3})	1.06e+14
Interaction Cross Section (Approx.) (cm^2)	1.8e-20
H_2^+ T_p (μs)	8.2
e^- T_p (μs)	0.1
e^- T_{cycle} (ps)	50
Time step (ps)	5



Task 3 – Preconceptual design of a magnetized e- cooling system

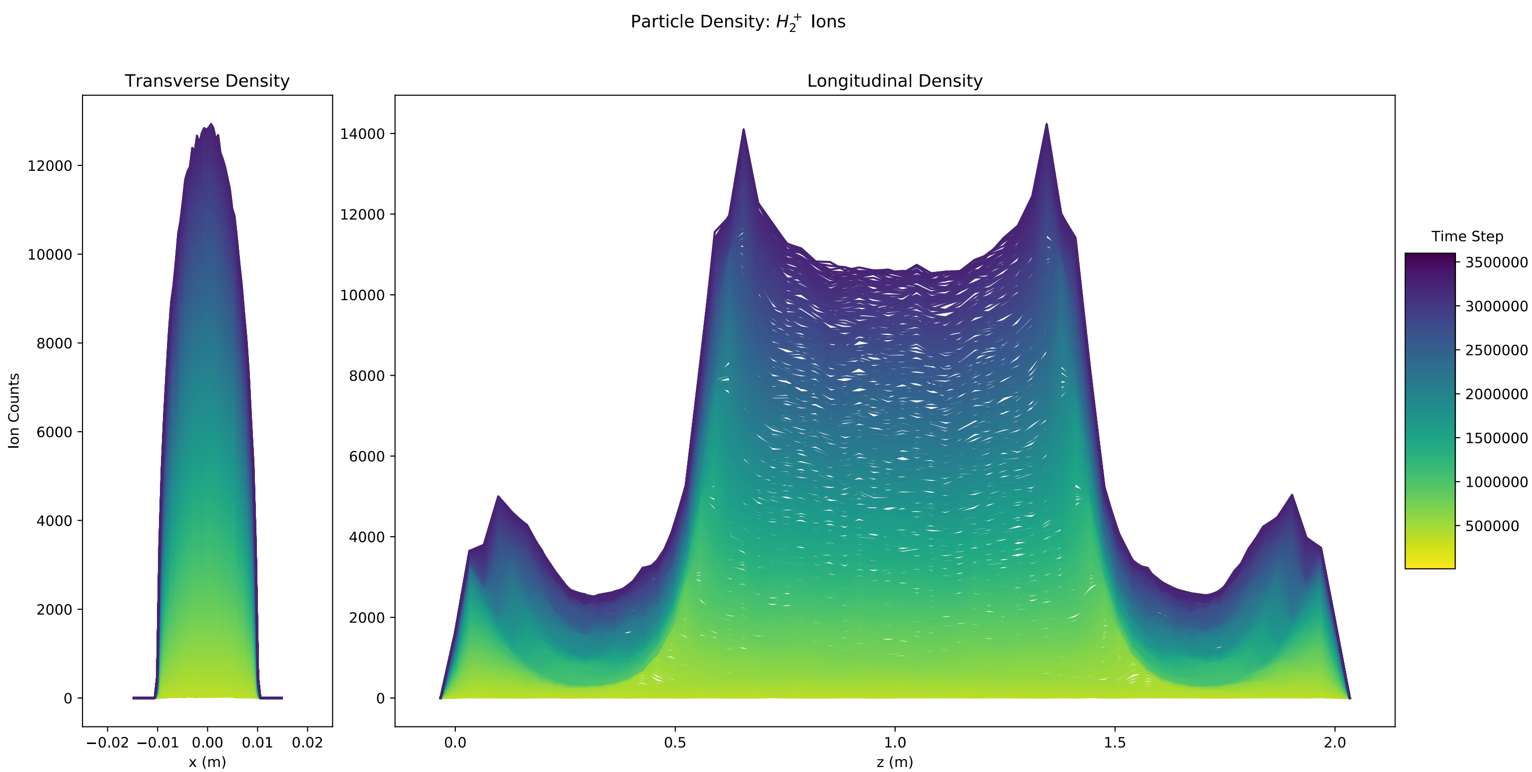
Space charge neutralization is provided by impact ionization of the e- beam on residual H_2:

$$e^- + H_2 \rightarrow 2e^- + H^2{}_+$$

The neutralization time depends on the interaction cross section, beam velocity and gas density as:

$$\tau_n = \frac{1}{\sigma_c v_e n_H}$$

Calculated neutralization time of 17 μs matches well with simulations:



Task 4 – Study equilibrium electron cooling rates

- *Now that Task 2 and Task 3 are nearing completion, work on this task has recently begun.*
- *We'll use BETACOOL and JSPEC, with benchmarking*

- *BETACOOL: simulates long time (millions of turns) evolution of the ion beam phase space, including many physics models*
  - *developed in early 2000's at JINR (Dubna, Russia)*
  - *coupled ODEs for modeling RMS dynamics of 6D Gaussian distributions or Langevin-type simulation tacking a sample of ion macroparticles*
  - *particle loss (recombination) and multiple beam heating and cooling processes:*
    - *unmagnetized (Derbenev, Meshkov) and magnetized (Derbenev-Skrinsky-Meshkov, Parkhomchuk) asymptotic and/or parametrized electron cooling models*
    - *IBS (Bjorken-Mtingwa, Martini)*
    - *other effects (e.g., scattering on residual gas)*
  - *IBS calculation requires detailed knowledge of the optics structure of the ring*

Task 4 – Study equilibrium electron cooling rates

- *The BETACOOL GUI (so-called Bolide Interface) is required to prepare input files and for postprocessing*
  - *a multi-window GUI, only available as a pre-compiled executable for Windows*
  - *difficult to set up (from scratch) the simulation of a new ring*
  - *it would be prohibitively difficult to add and use new capabilities without access to the GUI source code*
    - *far easier to work with JSPEC in this regard*
  - *Windows-only GUI necessitates working in a Windows VM, while most of our development and simulation cycle is on Linux and MacOS*
- *Benchmarking JSPEC and BETACOOL*
  - *we will understand and document the differences*
  - *new capabilities will be added to JSPEC*

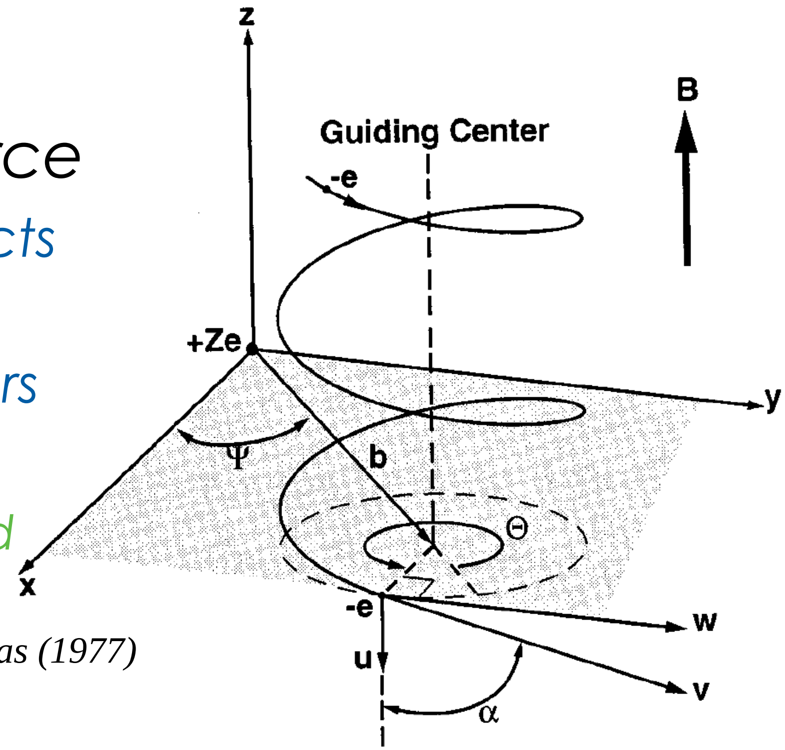
Task 5 – Generalize dynamic friction calculations to include space charge and field errors

- *JLEIC requires cooling at high energy*
  - *100 GeV/n → $\gamma \approx 107$ → 55 MeV bunched electrons, ~1 nC*

- *Electron cooling at γ~100 requires different thinking*
  - *friction force scales like $1/\gamma^2$ (Lorentz contraction, time dilation)*
    - *challenging to achieve the required dynamical friction force*
    - *not all of the processes that reduce the friction force have been quantified in this regime → significant technical risk*
  - *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~100*
      - *violates the assumptions of introductory beam & plasma textbooks*
      - *breaks the intuition developed for non-relativistic coolers*
      - *as a result, the problem requires careful analysis*

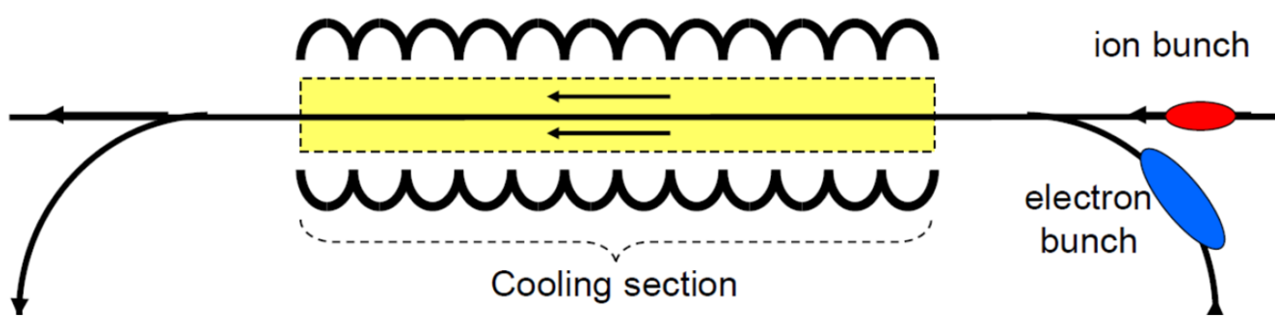
Goals

- Simulate magnetized friction force
  - include all relevant real world effects
    - e.g. incoming beam distribution
  - include a wide range of parameters
  - cannot succeed via brute force
    - improved understanding is required



from Geller & Weisheit, Phys. Plasmas (1977)

- Include key aspects of magnetized e- beam transport
  - imperfect magnetization
  - space charge
  - field errors



from Zhang et al., MEIC design, arXiv (2012)

Serious difficulties with dynamic friction calculations

- *Can we quantify the required solenoidal field quality?*
  - *Parkhomchuk formula provides a parametric knob*
  - *Derbenev and Skrinsky do not offer quantitative guidance*
  - *No*
- *Can we quantify the effects of space charge forces?*
  - *No*
- *Can we quantify the effects of non-Gaussian e- beam phase space distributions?*
  - *No*
- *New friction force calculations are important*
  - *Otherwise, technical risk will be high*

A new dynamical friction calculation is underway…

- *We follow the approach described by Y. Derbenev*
- *However, we begin from a new starting point*
  - *analytic momentum transfer between ion and magnetized e-*
  - *proceed step by step with calculation*
- *Calculation is defined by the following considerations:*

$$\vec{E}(\vec{r},\vec{v},t) = \langle \vec{E}^0 \rangle(\vec{r},t) + \langle \Delta\vec{E} \rangle(\vec{r},\vec{v},t) + \vec{E}^{fl}(\vec{r},\vec{v},t) \quad (1.1)$$

$$\vec{F} = -ze\langle \Delta\vec{E} \rangle(\vec{r},\vec{v},t)\Big|_{\vec{r}=\vec{r}(t),\dot{\vec{r}}(t)=\vec{v}} \quad (1.2)$$

Y. Derbenev, "Theory of Electron Cooling," arXiv (2017); https://arxiv.org/abs/1703.09735

THEORY OF ELECTRON COOLING

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The required steps are straightforward in principle:

- *Calculate the perturbed e- velocities*
  - *due to a single ion*
  - *initially, we consider purely longitudinal motion*
- *Obtain time-derivative of perturbed E-field*
  - *via Poisson and continuity equations*
- *Integrate in time to get δE*
  - *initially, this is for only a single value of e- velocity*
  - *it is necessary to integrate over thermal e- velocities*
- *Integrate δE along ion trajectory to obtain <F>*
  - *hence, this is a 2nd-order effect, $\sim(Ze^2)^2$ xx*
- *Present efforts:*
  - *find best way to integrate <F> over e- distribution functions*
  - *consider transverse ion motion*
  - *numerical approaches, testing, etc.*

Hamiltonian for 2-body magnetized collision:

$$H(\vec{x}_{ion}, \vec{p}_{ion}, \vec{x}_e, \vec{p}_e) = H_0(\vec{p}_{ion}, y_e, \vec{p}_e) + H_C(\vec{x}_{ion}, \vec{x}_e)$$

$$\vec{B} = B_0\,\hat{z} \qquad \vec{A} = -B_0 y\,\hat{x} \qquad p_{e,x} = m_e\left(v_{e,x} - \Omega_L y_e\right)$$

$$H_0(\vec{p}_{ion}, y_e, \vec{p}_e) = \frac{1}{2m_{ion}}\left(p_{ion,x}^2 + p_{ion,y}^2 + p_{ion,z}^2\right) + \frac{1}{2m_e}\left[\left(p_{e,x} + eB_0 y_e\right)^2 + p_{e,y}^2 + p_{e,z}^2\right]$$

$$H_C(\vec{x}_{ion}, \vec{x}_e) = \frac{-Ze^2}{4\pi\varepsilon_0} \Big/ \sqrt{\left(x_{ion} - x_e\right)^2 + \left(y_{ion} - y_e\right)^2 + \left(z_{ion} - z_e\right)^2}$$

D.L. Bruhwiler and S.D. Webb, "New algorithm for dynamical friction of ions in a magnetized electron beam," in *AIP Conf. Proc.* **1812**, 050006 (2017); http://aip.scitation.org/doi/abs/10.1063/1.4975867

After many steps we obtain an approximate friction force:

Let $z_e = v_{i,z}T$ *and then integrate over* T *to obtain*:

$$< F > = (n_0 e)\frac{n_0(Ze^2)^2}{m_e v_{rel} T}\left\{\frac{T}{v_{rel}} ln\left(\left[\rho_{gc}^2 + \left(v_{i,z}T\right)^2\right]^{1/2} + v_{i,z}T\right) - \frac{v_{e,z}}{v_{i,z}^2 v_{rel}}\left(\left[\rho_{gc}^2 + \left(v_{i,z}T\right)^2\right]^{\frac{1}{2}} - \rho_{gc}\right)\right.$$

There is an integrable singularity for cold electrons.
The challenge now is to integrate over thermal velocities

Task 6 – Develop software to perform dynamic friction calculations for e- distributions

- *Now that Task 5 is nearing completion, work on this task will begin soon.*

Enabling reproducibility for accelerator codes

- A single code with simple workflow
  - *scientist #2 will* ***initially*** *get the same results as scientist #1*
  - *if simulation is properly archived, then many scientists can benefit*
- What is required (*assuming minimum effort from scientists*)?
  - make community codes publicly available, pre-installed
  - provide a state-of-the-art GUI
    - ease of use (required for adoption)
    - constrain the workflow (always enable export to Python CLI)
  - cloud computing
    - control the execution environment
    - minimize development and maintenance costs (sustainability)
- *Advantages of using the browser as your scientific UI*
  - *enables "instantaneous collaboration" via URL sharing*
    - *the first sharing event corresponds to first bullet above*
    - *collaborative use case: multiple back-and-forth sharing events*
  - *cross-platform development pain is confined to JavaScript issues*