First-principles calculation of magnetized dynamic friction & application to cooling for the EIC

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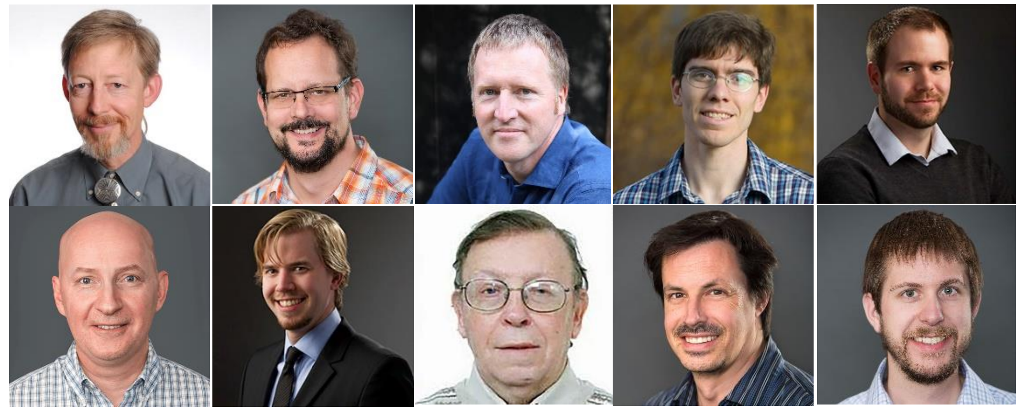
Nuclear Physics SBIR/STTR Exchange Meeting

13 August – Gaithersburg, MD

This work is supported by the US DOE, Office of Science,
Office of Nuclear Physics, under Award # DE-SC0015212.

World-class staff with growing areas of expertise

- Beam & plasma physics
  - *hiring process far along*
    - **3 or 4 hires expected**
  - *additional expertise:*
    - **control systems**
    - **machine learning**
    - **radiation & shielding design**



- Materials science
- Finite-element design
  - *COMSOL Multiphysics*

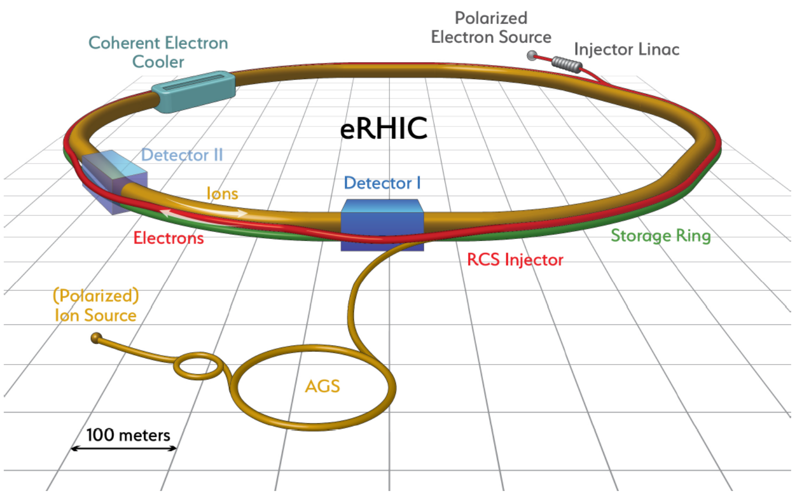
- Software team

- Product management
- Project management
- Accounting & HR

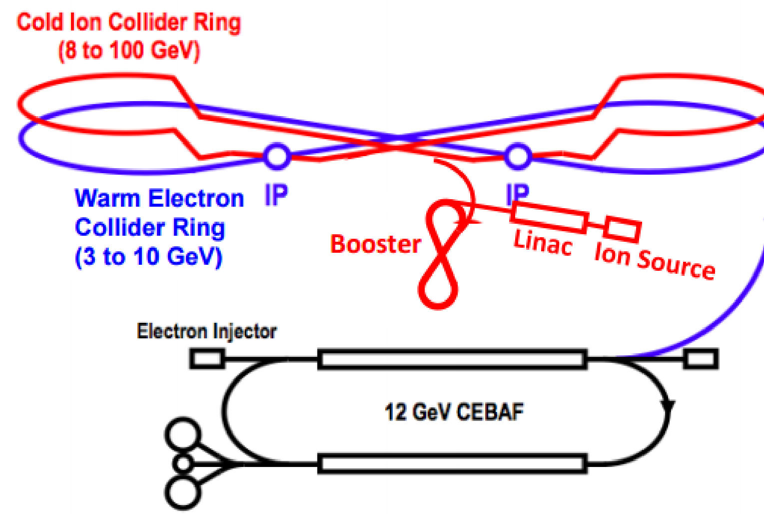
RadiaSoft projects & machine learning initiative

- Office of Nuclear Physics (DOE/NP)
  - *High-energy magnetized e- cooling, Ph 2a, David Bruhwiler*
  - *Spin tracking with the Zgoubi code, Ph 2, Dan Abell*
  - *Toolkit for control system algorithms, Ph 1, Jon Edelen*
- Office of High Energy Physics (DOE/HEP)
  - *MHD modeling of 3D plasma sources, Ph 2, Nathan Cook*
  - *Machine learning for RCS controls, Ph 1, Jon Edelen*
- Office of Basic Energy Sciences (DOE/BES)
  - *Parallel 3D magnet design w/ Radia , Ph 2, Dan Abell*
  - *High-efficiency FEL collab./exp. (ANL), Ph 2, Stephen Webb*
  - *Integrated vacuum chamber modeling, Ph 2, Zhigang Wu – "Michael"*
- Advanced Scientific Computing Research (DOE/ASCR)
  - *Modeling vacuum nanoelectronic devices, Ph 2, Nathan Cook*
- Office of Nuclear Energy (DOE/NE)
  - *Radiation hard plasma-based vibration sensor, Ph 1, Johan Carlsson*
- National Institutes of Health (NIH/NCI)
  - *X-ray treatment plans for prostate cancer, Ph 1, Jon Edelen*

DOE/NP Motivation & Ph 2a Technical Objectives



C. Montag, "eRHIC Accelerator Design Overview,"



S. Abeyrante *et al*., "MEIC Design Summary,"

- 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*

The Ph 2 is completed – Ph 2a work has begun

1. Develop a browser-based GUI for electron cooling code
   - *the GUI has been developed: https://sirepo.com*

   *Frank Schmidt: "**We were concerned about an IBS calculation and Markus Steck suggested we try Sirepo, which immediately gave us the correct rate.**"*
2. 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**"*
3. Preconceptual design of a magnetized electron cooling system
   - *impact ionization physics for the Warp code has been implemented*
   - *available to the community, via https://github.com/radiasoft/rswarp*
4. Study equilibrium electron cooling rates
   - *this involved much analysis of BETACOOL code & benchmarking with JSPEC*
5. Generalize dynamic friction calculations to include space charge and field errors
6. Develop software to perform dynamic friction calculations for electron distributions
   - *includes implementation of our own algorithms, mostly in Python*
   - *contributions to JSPEC, https://github.com/zhanghe9704/electroncooling*

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

- EIC requires cooling at high energy
  - *100 GeV/n → $\gamma \approx 107$ → 55 MeV bunched electrons, ~1 nC*
- Electron cooling at $\gamma \sim 100$ 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
    - $\tau = t\omega_{pe} \sim 1$ (in the beam frame), for $\gamma \sim 100$
      - *violates the assumptions of introductory beam & plasma textbooks*
      - *breaks the intuition developed for non-relativistic coolers*
      - *as a result, the problem requires careful analysis*

Previous work – asymptotic model for cold elec's

$$F_{\parallel} = -2\pi Z^2 n_e m_e \left(r_e c^2\right)^2 \left[3\left(\frac{V_\perp}{V_{ion}}\right)^2 \ln\left(\frac{\rho_{\max}^A}{\rho_{\min}^A}\right) + 1 \right] \frac{V_\parallel}{V_{ion}^3}$$

$$r_L = V_{rms,e,\perp} / \Omega_L\left(B_\parallel\right)$$

$$\rho_{\min}^A = \max\left(r_L, \rho_{\min}\right)$$

$$\rho_{\max}^A = \min\left(r_{beam}, \rho_{\max}\right)$$

$$\rho_{\max} = V_{rel} / \max\left(\omega_{pe}, 1/\tau\right)$$

$$V_{rel} = \max\left(V_{ion}, V_{e,rms,\parallel}\right)$$

$$V_{ion}^2 = V_\parallel^2 + V_\perp^2$$

for large V_{ion} parallel to B:

$$F_{\parallel}\left(V_\perp = 0\right) = -2\pi Z^2 n_e m_e \left(r_e c^2\right)^2 \frac{1}{V_\parallel^2}$$

diverges as $V_{ion} \rightarrow 0$

Ya. S. Derbenev and A.N. Skrinsky, "The Effect of an Accompanying Magnetic Field on Electron Cooling," Part. Accel. **8** (1978), 235.

Ya. S. Derbenev and A.N. Skrinskii, "Magnetization effects in electron cooling," Fiz. Plazmy **4** (1978), p. 492;   Sov. J. Plasma Phys. **4** (1978), 273.

I. Meshkov, "Electron Cooling; Status and Perspectives," Phys. Part. Nucl. **25** (1994), 631.

Previous work: parametric model for warm elec's

$$\mathbf{F} = -4Z^2 n_e m_e \left(r_e c^2\right)^2 \ln\left(\frac{\rho_{\max} + \rho_{\min} + r_L}{\rho_{\min} + r_L}\right) \frac{\mathbf{V}_{ion}}{\left(V_{ion}^2 + V_{eff}^2\right)^{3/2}}$$

$$\rho_{\min} = \left(Ze^2/4\pi\varepsilon_0\right)/m_e V_{ion}^2$$

$$\rho_{\max} = V_{ion}/\max\left(\omega_{pe}, 1/\tau\right)$$

$$r_L = V_{rms,e,\perp}/\Omega_L\left(B_{\|}\right)$$

$$V_{eff}^2 = V_{e,rms,\|}^2 + \Delta V_{\perp e}^2$$

V.V. Parkhomchuk, "New insights in the theory of electron cooling," Nucl. Instr. Meth. in Phys. Res. **A 441** (2000).

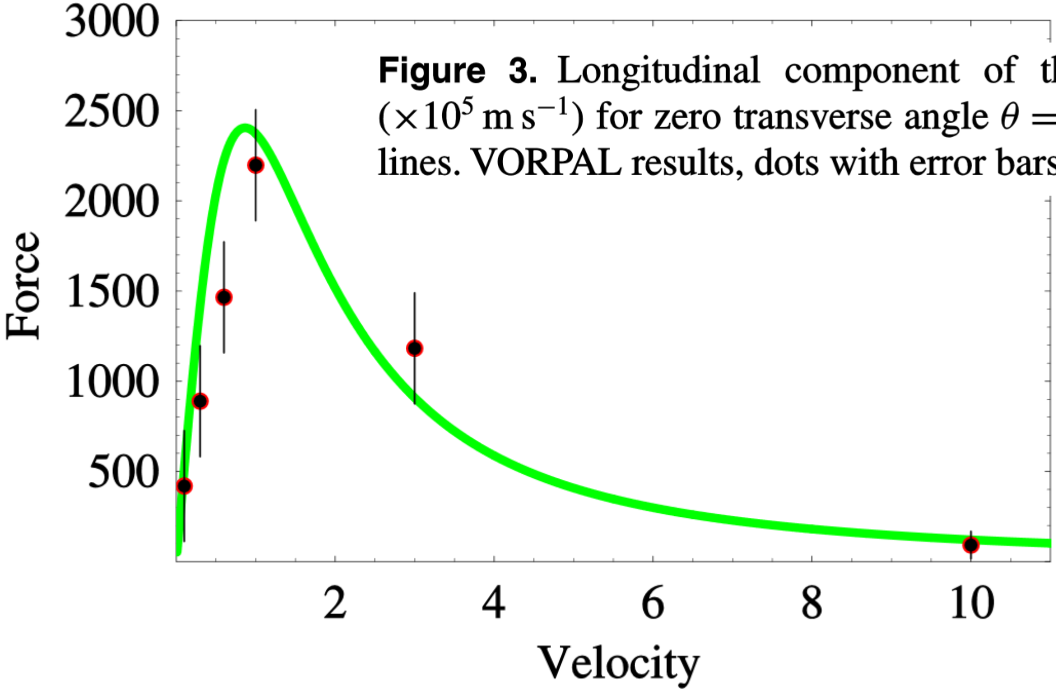


Figure 3. Longitudinal component of the force (eV m^{-1}) versus velocity ($\times 10^5$ m s^{-1}) for zero transverse angle $\theta = 0$ with respect to the magnetic field lines. VORPAL results, dots with error bars; empirical fit from [18], solid line.

New Journal of Physics

The open-access journal for physics

High-energy electron cooling in a collider

A V Fedotov[1,4], I Ben-Zvi[1], D L Bruhwiler[2], V N Litvinenko[1] and A O Sidorin

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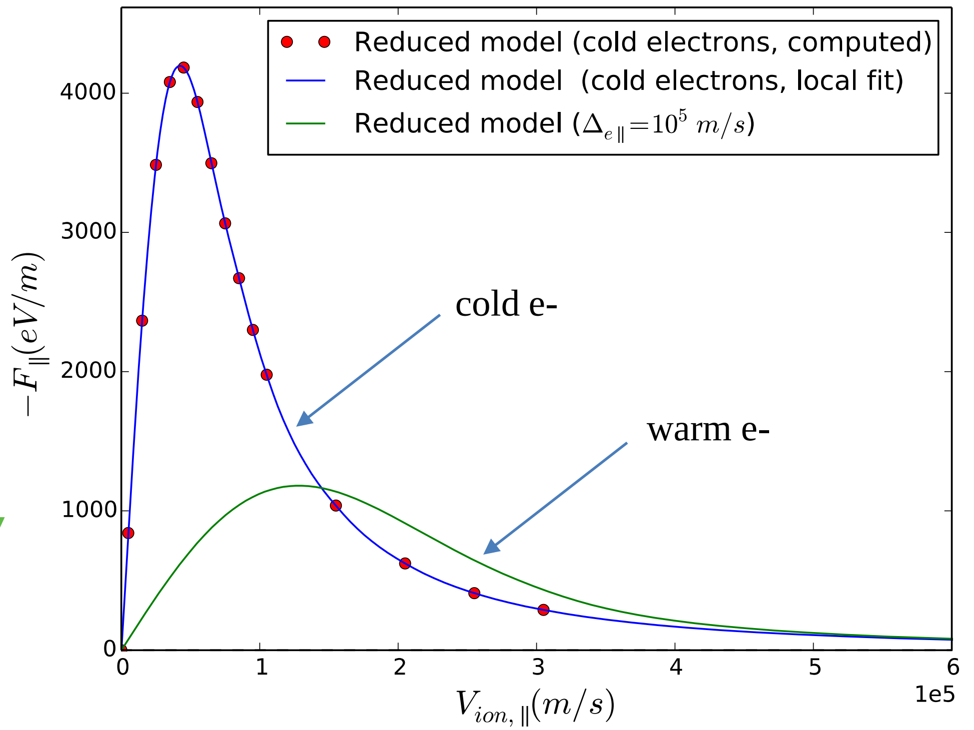
New Journal of Physics **8** (2006) 283

New approach to calculating magnetized friction

- Semi-analytic calculation
  - *Hamiltonian perturbation theory*
    - **gyrokinetic averaging**
    - **reduces dimensionality**
    - **reduces range of time scales**
  - *fast numerical simulations*
    - **complicated hierarchy of 'passing' and 'trapped' orbits**
    - **cannot be captured analytically**
- Approximations
  - *longitudinally cold electrons*
    - **warm e- results obtained via convolution with Gaussian**
  - *longitudinal ion motion*
  - *idealized solenoidal B-field*
  - *no other external forces*
- Approximations will be relaxed



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

  $\sim V$ for small V

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

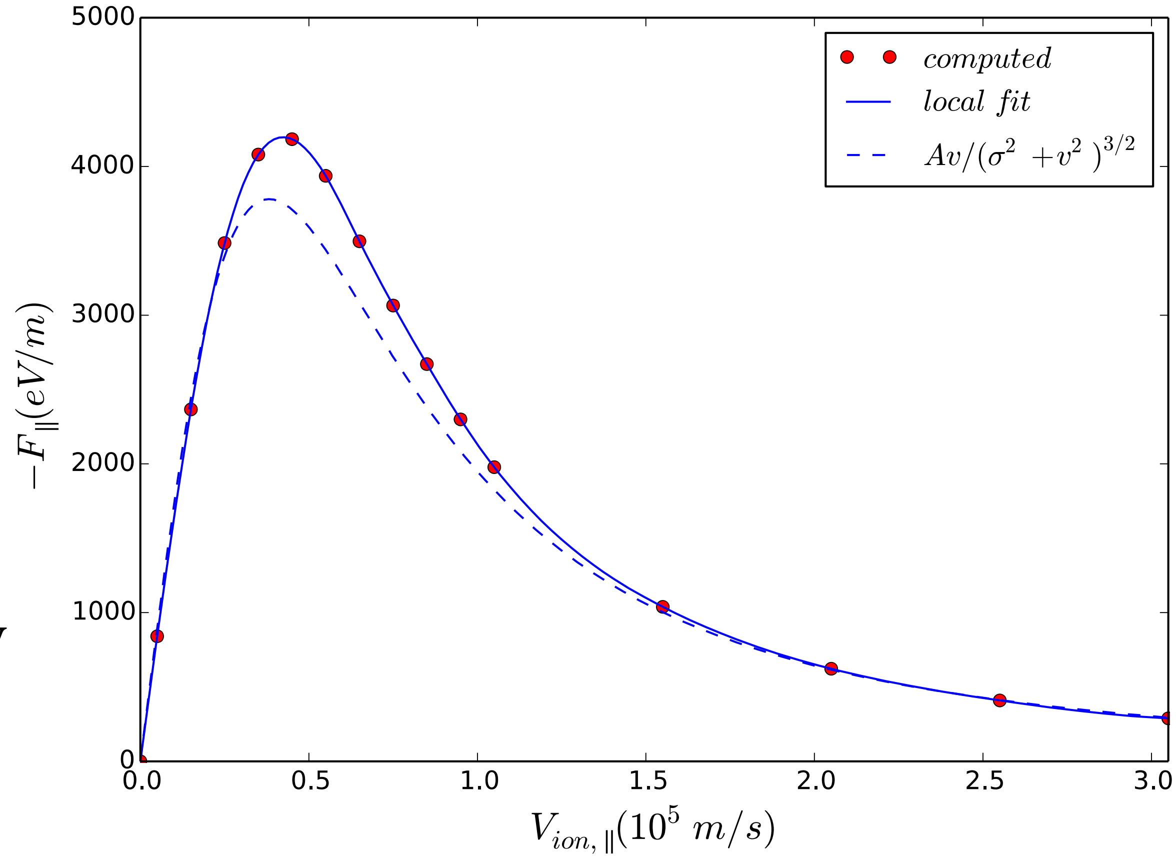
Dimensional analysis yields 2-parameter model

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

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

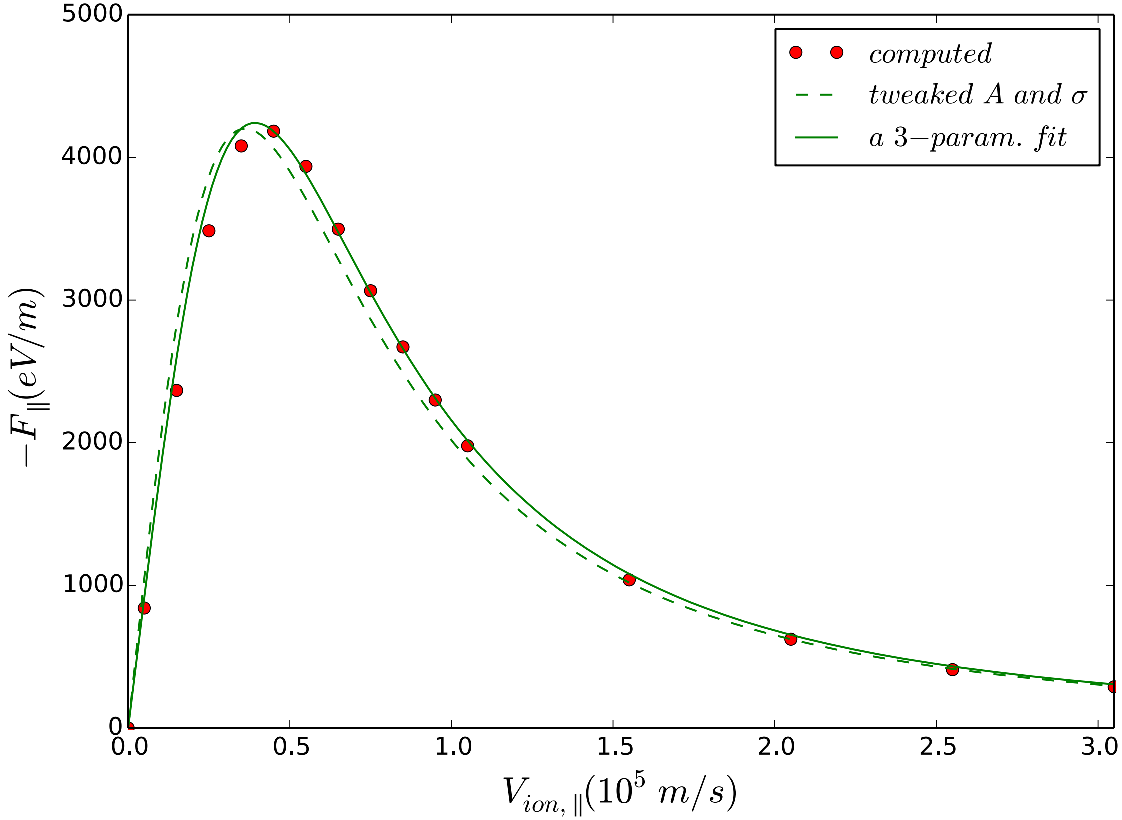
$$\sigma \approx (\pi Z r_e c^2 / T_{int})^{1/3}$$

- Large v:
  - *$F_{\parallel} \sim A/v^2$*
  - *Derbenev & Skrinsky*
- Small v:
  - *$dF/dv \sim A/\sigma^3$*
- Peak force is low by ~10%



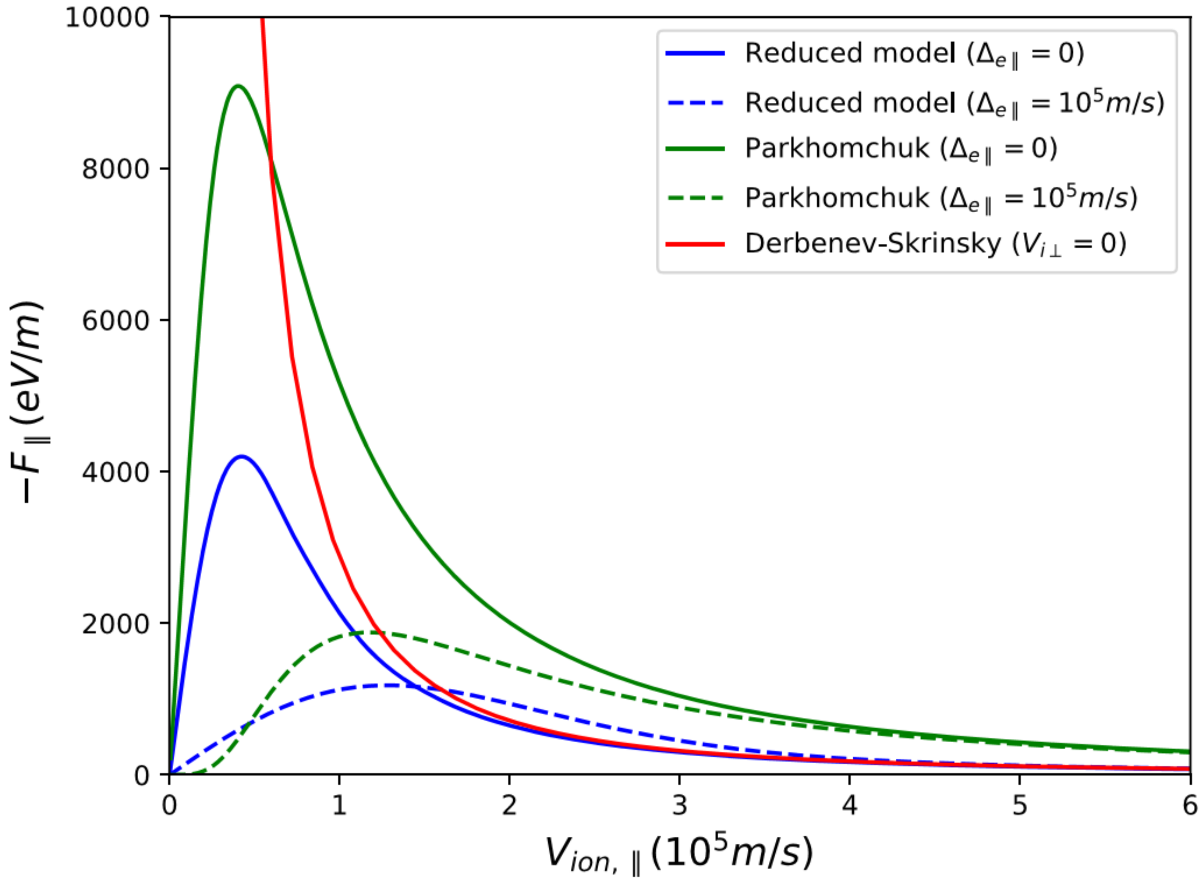
3-parameter model fits the calculations closely

- The physical system depends on 3 parameters:
  - *n_e, Z, T_{int}*
- 3-parameter model works well
  - *3rd parameter is small*
  - *optimal parametric form is still under consideration*
- will implement in JSPEC code



Differences w/ Derbenev-Skrinsky & Parkhomchuk

- all ~ $1/v^2$ for large v
  - *our semi-analytic model agrees exactly with D&S*
  - *Parkhomchuk is too large in this limit*
- Our semi-analytic model is consistently lower than Parkhomchuk
  - *may not always be so*
- Parkhomchuk has unphysical inflection as v→0
  - *can be corrected via constant Coulomb log*
  - *no Coulomb log for our model*



- Param's taken from Fedotov, Bruhwiler *et al.*:
  - Au^{+79}; $\gamma=107$; $n_e=10^{15}\ m^{-3}$; $B=5\ T$
  - $\tau_{int} = 4x10^{-10}\ s$ ~ $56\ T_{Larmor}$ ~ $0.16\ T_{plasma}$
  - typical e^- sep. ~ $4.9x10^{-6}\ m$ ~ $10\ r_{Larmor}$

Future plans

- Theory and analysis
  - *correct treatment of perpendicular friction is in process*
  - *including the effect of space charge forces & B-field errors*
    - Parkhomchuk handles this parametrically with v_{eff}
    - Derbenev & Skrinsky approach cannot include these effects
- Software development
  - *parallelize our Python code*
    - benchmark brute force simulations with semi-analytic model
    - more data for parametric models
    - quantify effects of weaker B-fields
  - *implement models in JSPEC*
    - compare with BETACOOL
- Supporting EIC design work
  - *use JSPEC to study EIC designs*