Magnetized Electron Cooling Simulations for JLEIC*

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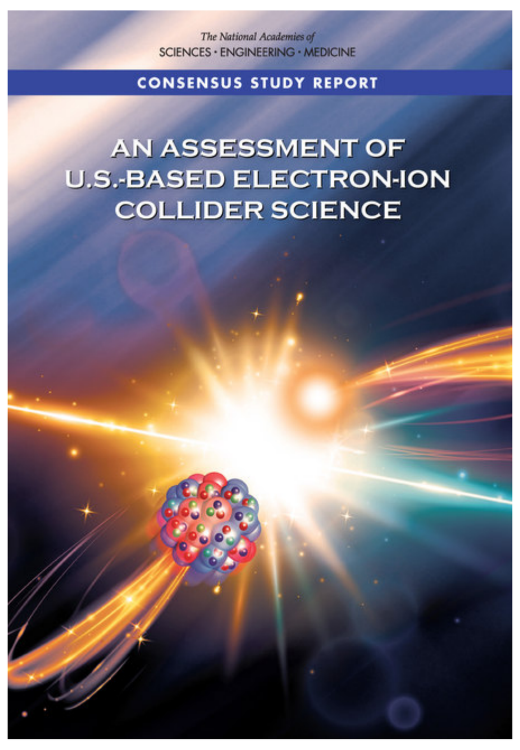
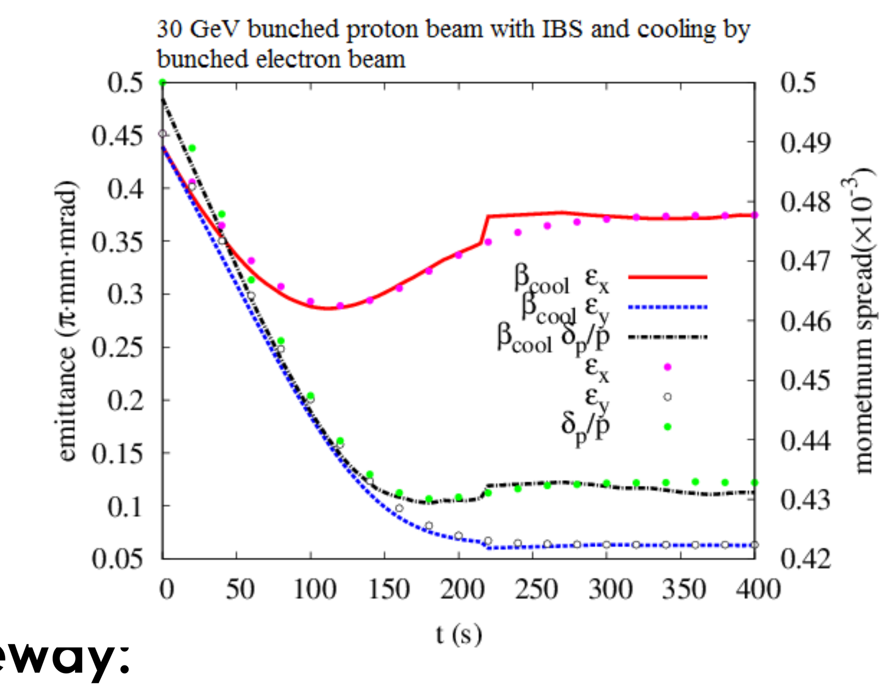
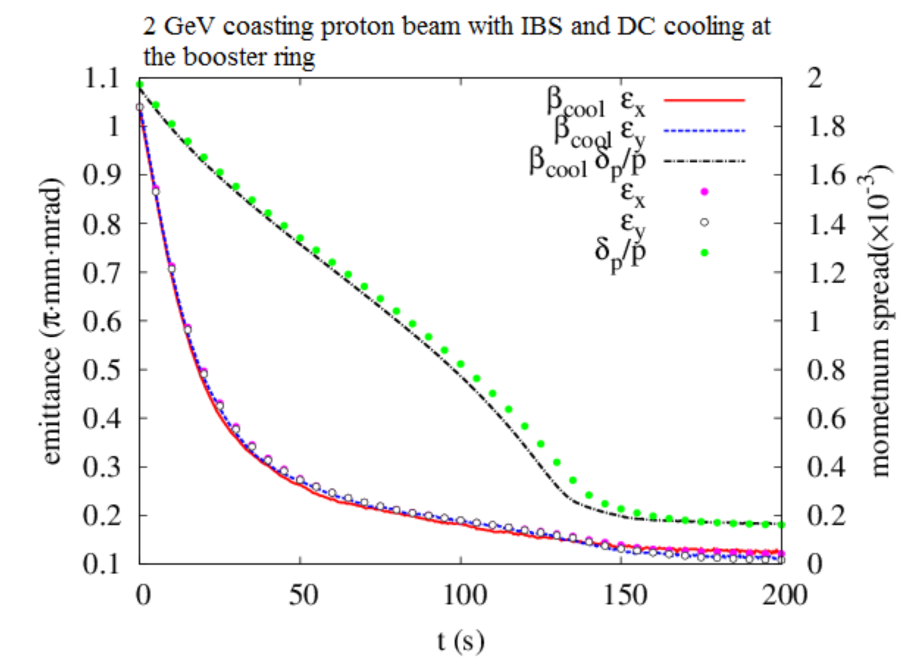


JSPEC – JLab Simulation Package for Electron Cooling

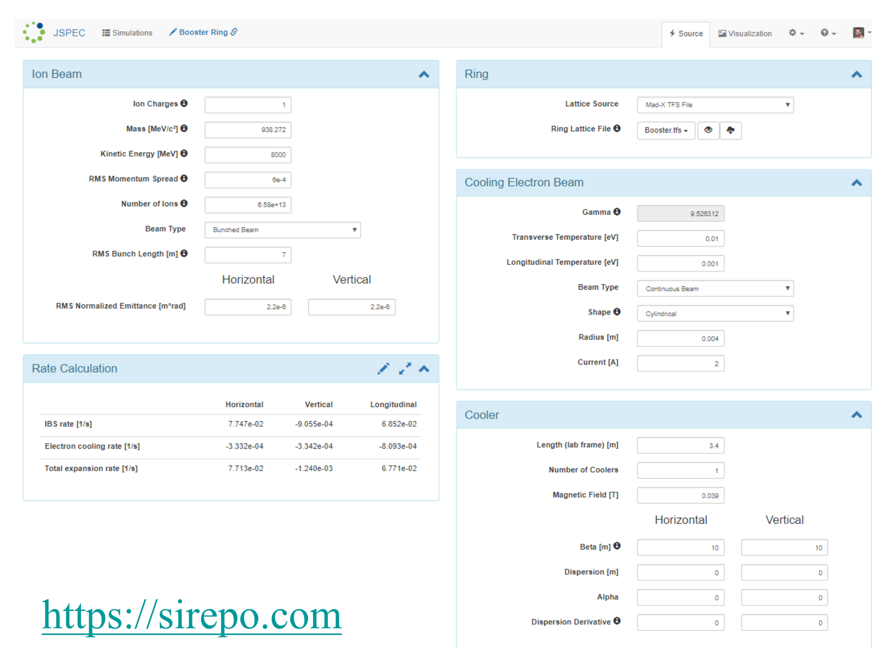
- Considers both IBS and electron cooling
  - *calculate rates, simulate processes for specified ring*
- C++, open source: https://github.com/zhanghe9704/electroncooling
- Successfully benchmarked with BETACOOL →

H. Zhang, J. Chen, R. Li, Y. Zhang, H. Huang and L. Luo, "Development of the electron cooling simulation program for JLEIC," Proc. IPACEPMW014 (2016).

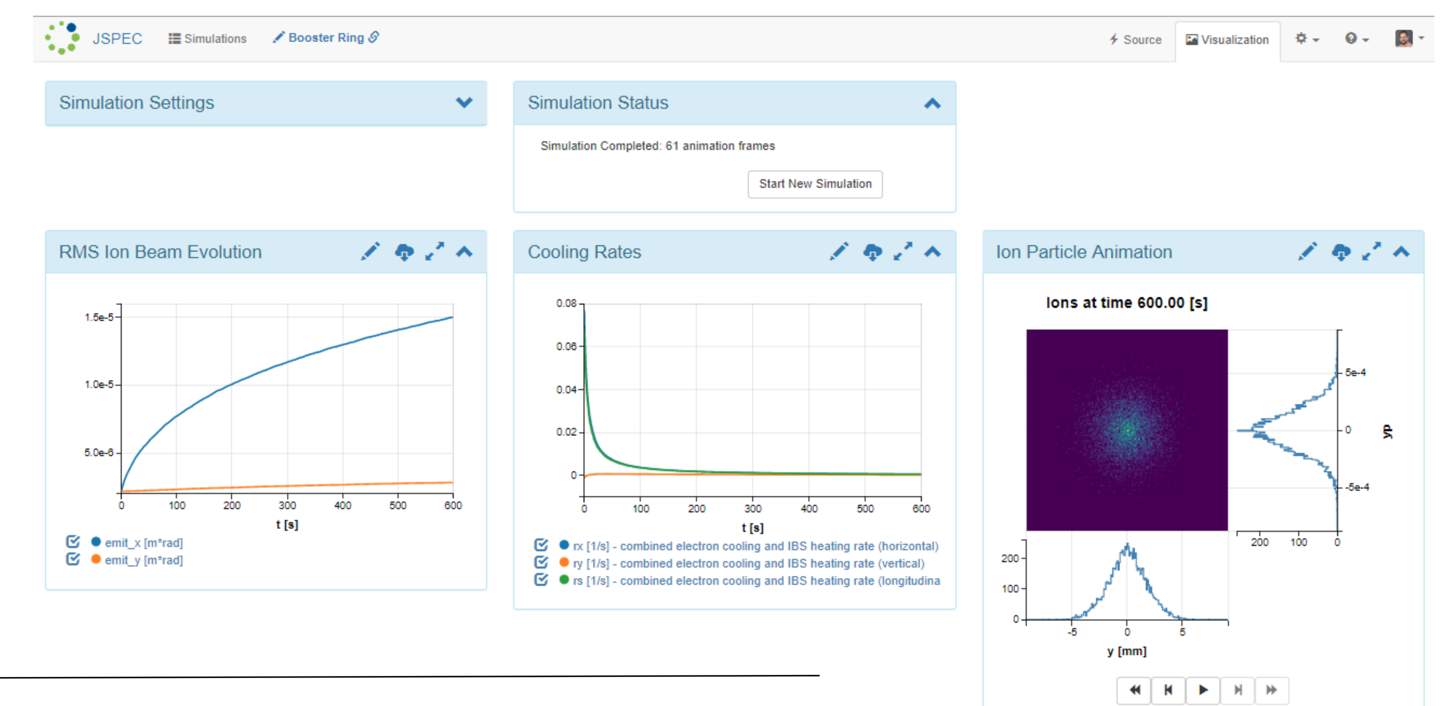




JSPEC is part of the Sirepo Scientific Gateway:

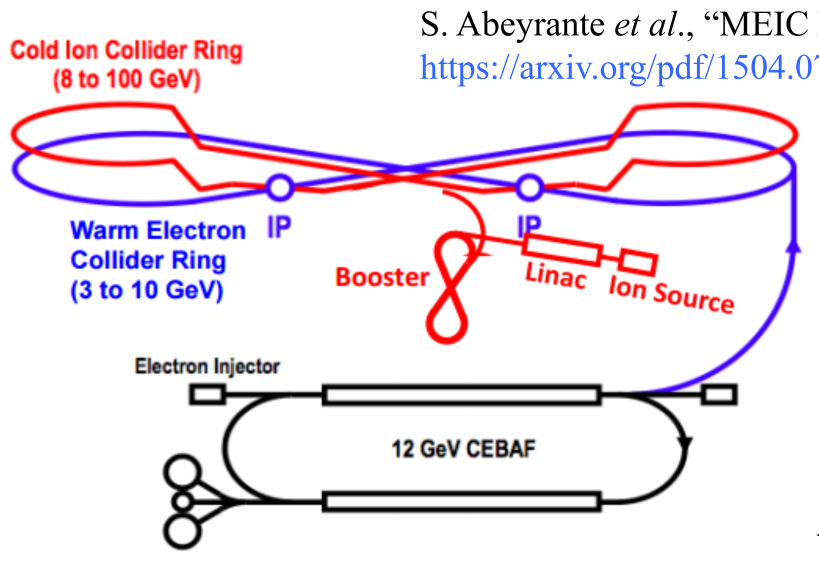


https://sirepo.com



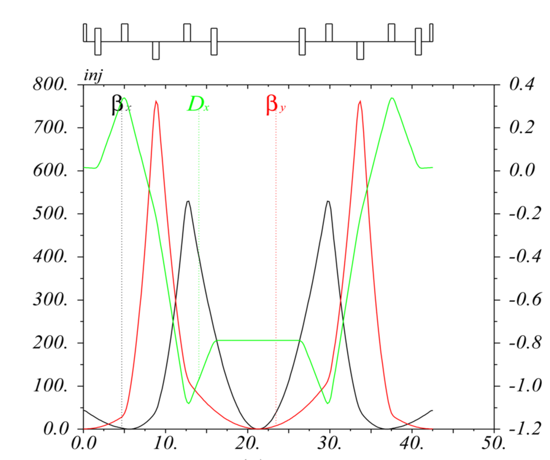
JLEIC Concept from Jefferson Lab

S. Abeyrante *et al.*, "MEIC Design Summary," https://arxiv.org/pdf/1504.07961.pdf

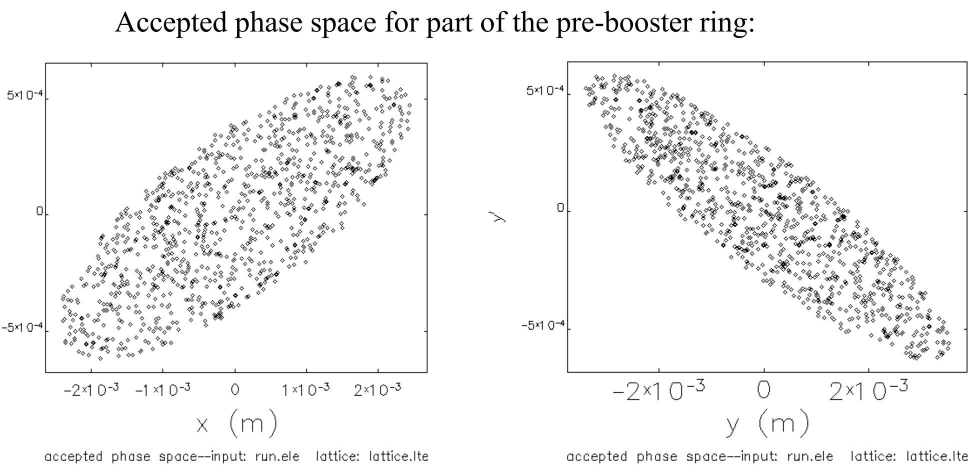


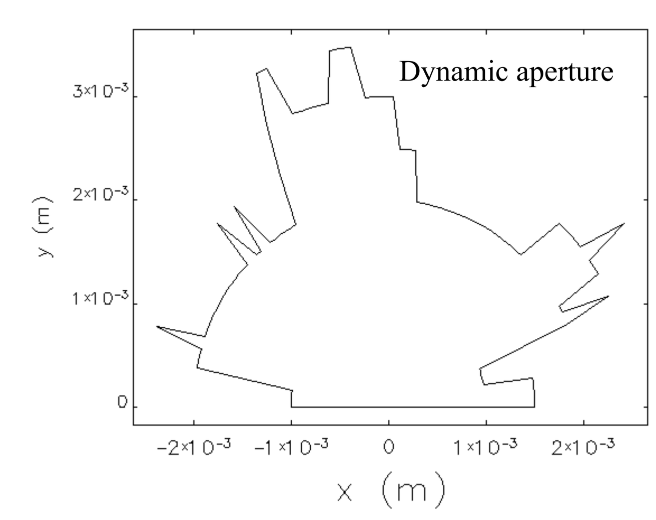
Early concept of pre-booster for accumulation & cooling

- Suggested a few years ago by P.M. McIntyre *et al.*
  - *further studied as part of this SBIR-funded project*
- Ring design with MAD-X and **`elegant`**
  - **`elegant`** *is also part of the Sirepo Scientific Gateway,* https://sirepo.com



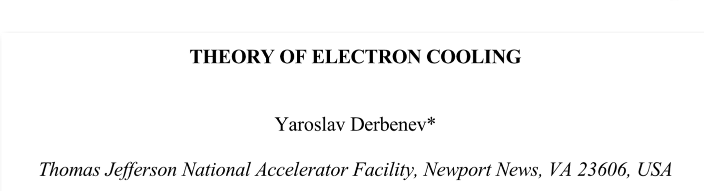
Accepted phase space for part of the pre-booster ring:





Optics for off-momentum injection insertion. Note the dispersion flat-top in the central straight, which permits off-momentum beam to be injected side-by-side with the central orbit in this region.

Dynamic Friction Modeling – general approach


THEORY OF ELECTRON COOLING

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Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

Ya. Derbenev, "Theory of Electron Cooling," arXiv (2017)

- The E-fields associated with friction must be carefully identified
  - -- fields from distribution of e⁻'s perturbed by the presence of the ion

bulk fields | friction | statistical fluctuations

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

- Friction force must be calculated along the ion trajectory:

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

-- we do this numerically for each individual ion-electron interaction
- total force obtained by summing over e⁻ distribution (i.e. no shielding)

-- bulk forces are removed by subtracting force from unperturbed e⁻'s

Gyrokinetic Averaging Yields 1D Nonlinear e⁻ Oscillations

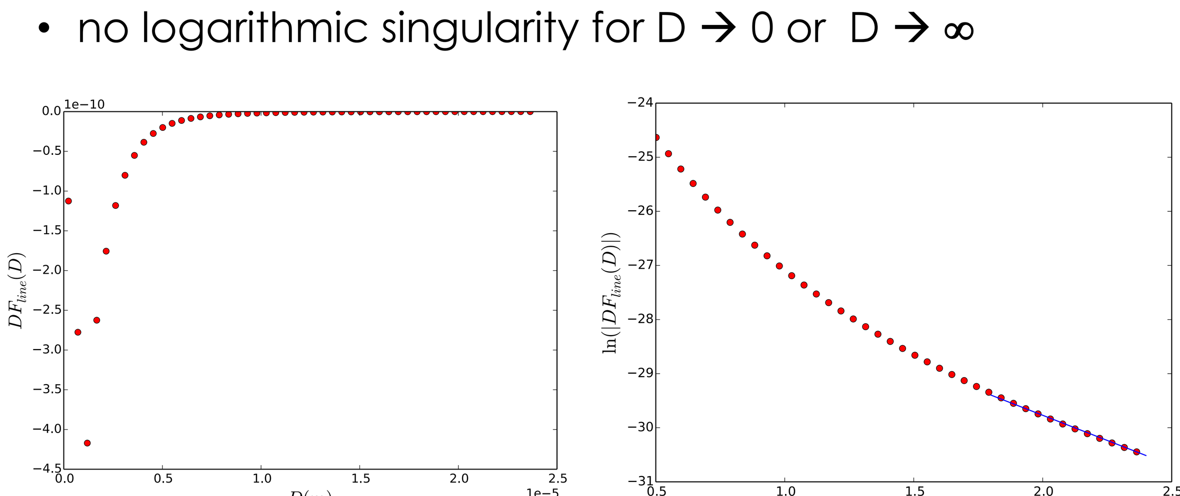
- Hamiltonian perturbation theory for single ion & e⁻
  - *unperturbed motion: drifting ion and magnetized e⁻*
  - *primary assumption: D (impact parameter) >> r_L (Larmor radius)*
  - *longitudinal dynamics: $V_{ion,\perp} = 0$ (to be relaxed in future work)*
- e⁻ gyrocenters stay on cylinder of constant radius
- choose ion to be stationary at the origin (convenient coordinates)
  - *gyrocenters move in a nonlinear 1D potential:*
  - *weak nonlinearity*
    - larger amplitudes => longer periods)

$$\ddot{z}(t) = -\frac{Ze^2}{4\pi\epsilon_0 m_e}\frac{z}{(D^2+z^2)^{3/2}}$$

- shortest oscillation period:
  - *both trapped and passing orbits*
  - *numerical simulations are required to capture these effects*

$$T_{lin} = \frac{2\pi}{c}\sqrt{\frac{D^3}{Zr_e}}$$

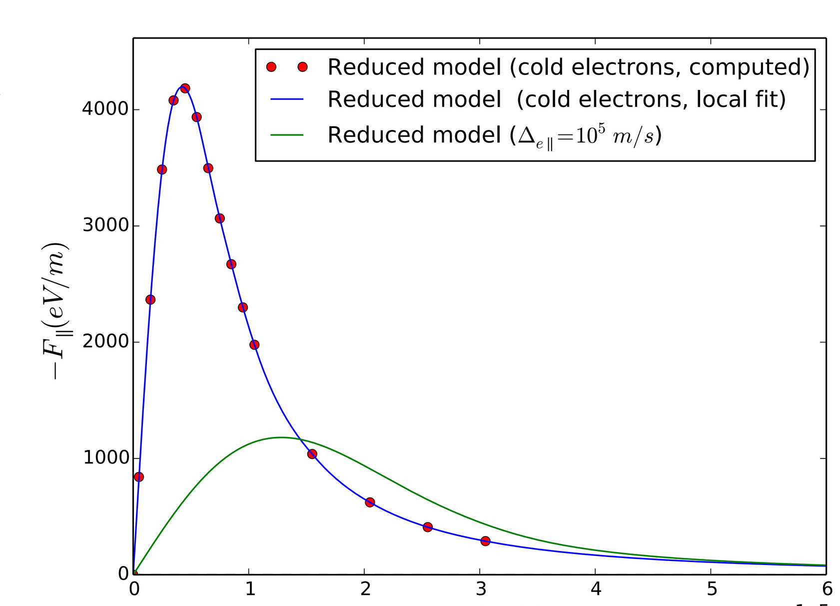
- no logarithmic singularity for D → 0 or D → ∞

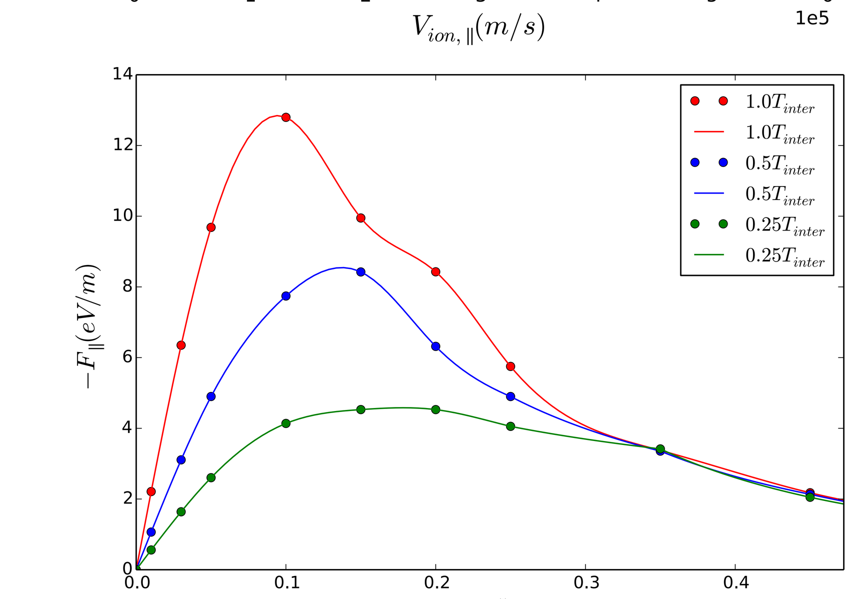


$$F_{\|}(V_{\perp}=0) = 2\pi n_e \int_0^{\infty} dD\,DF_{line}(D) \equiv 2\pi n_e \int_0^{\infty} dD\,D \int_{-\infty}^{\infty} dz_{ini} F_{i-e}(z_{ini}, D)$$

$F_{\|}(V_{ion,\|})$ for cold e-, short times: scaling in Z, T_{int}

- Considered protons and Au^{+79} ions
  - *with different interaction times in the cooler*
  - *for small V, $dF_{\|}(V)/dV \approx 2Z\, n_e m_e r_e c^2 T_{int}$*
  - *at large V, $F_{\|} \approx 2\pi Z^2 n_e m_e (r_e c^2)^2 / V^2$*
    - with no dependence on T_{int}
  - *for a given T_{int}, peak friction force scales as $Z^{4/3}$*
- For $T_{int} < T_{plasma}$ and small-to-moderate V_{ion} $F_{\|}(V_{ion,\|})$ increases with interaction time, while the large-V tail is independent of T_{int}
- $F_{\|}(V_{ion,\|})$ is linear in n_e by construction
- Thermal effects are computed via convolution of $F_{\|}(V_{ion,\|})$ with warm longitudinal electron distribution

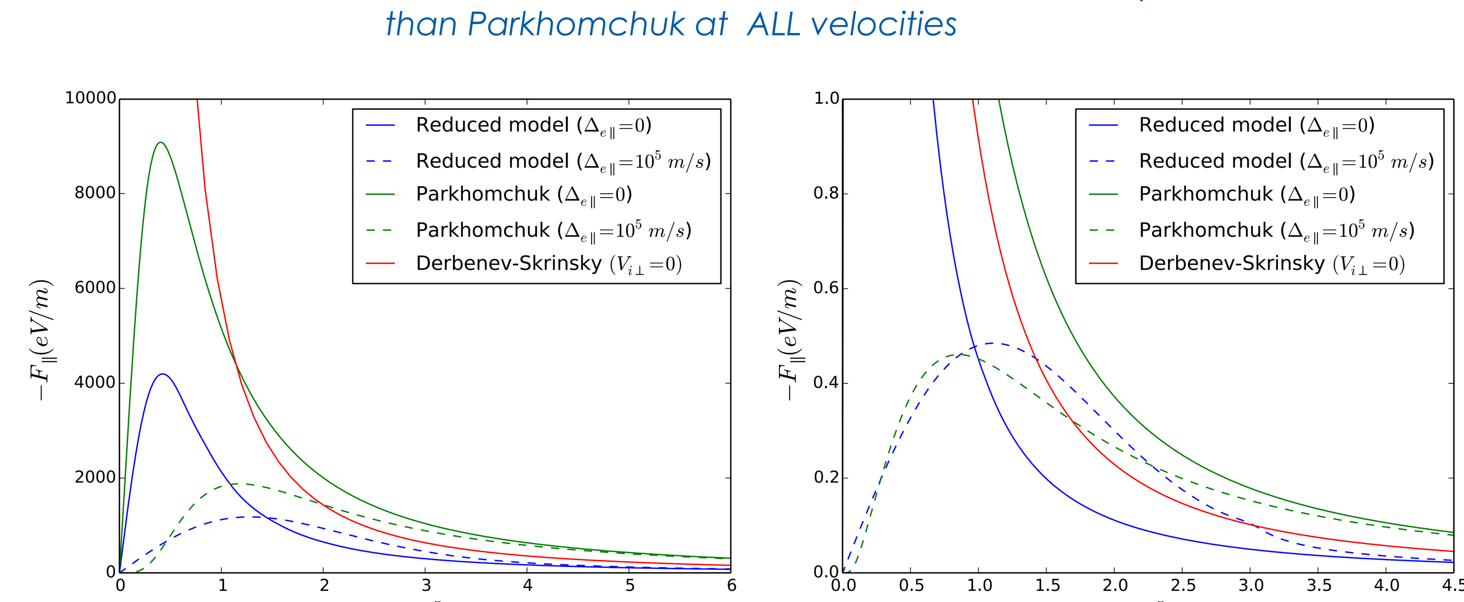




Upper panel: Gold ion, cold and warm e⁻'s;
Lower panel: Protons, cold e⁻'s, varying T_{int}

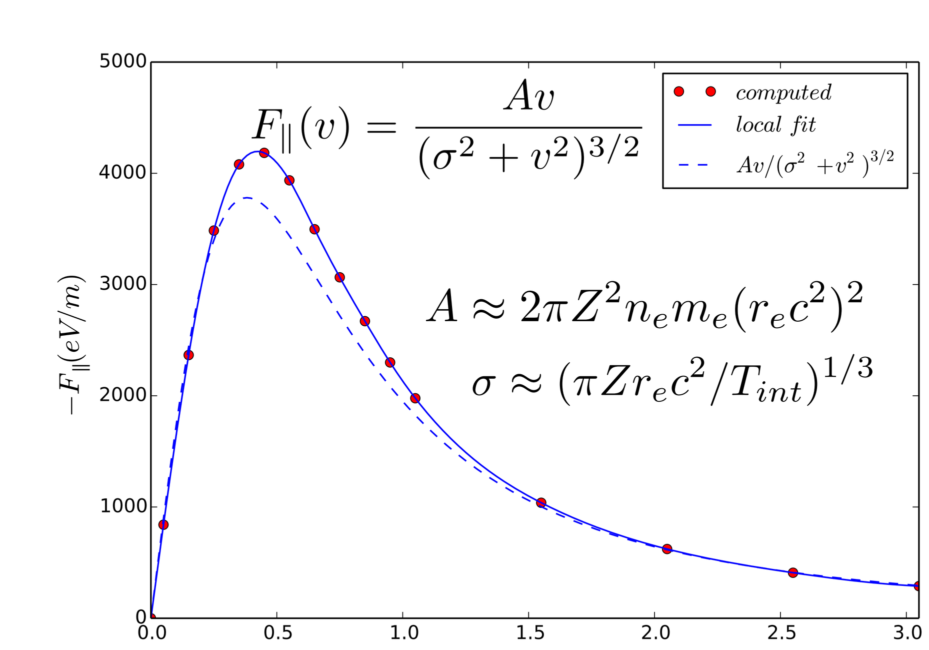
Comparison with Derbenev-Skrinsky and with Parkhomchuk models

- Comparison of new model for Au^{+79} ions and protons with:
  - *Derbenev and Skrinsky (D-S) for $V_{ion,\perp} = 0$ and large $V_{ion,\|}$*
    - Ya. S. Derbenev and A.N. Skrinsky, Part. Accel. 8 (1978), 235
  - *Parkhomchuk (P) with 0 and finite effective long. e⁻ temp*
    - V.V. Parkhomchuk, Nucl. Instr. Meth. in Phys. Res. A 441 (2000), p. 9
- Consistently lower force than D-S and P for larger $V_{ion,\|}$
  - *for lower ion velocity, details depend on Z*
  - *for cold electrons, new model shows consistently lower force values than Parkhomchuk at ALL velocities*



Left panel: Gold ion, cold and warm e⁻'s; Right panel: Protons, cold and warm e⁻'s

Parametric fit yields physical insight



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

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

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

International Particle Accelerator Conference – Melbourne – May 20, 2019

*This material is based upon work supported by the U.S. Department of Energy, Office of Science, through the SBIR program of the Office of Nuclear Physics under Award No. DE-SC0015212, with partial support from RadiaSoft LLC.