Overview of Computational Challenges for Coherent Electron Cooling

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Collider Accelerator Department Seminar
BNL, September 17, 2010

Office of Nuclear Physics — Exploring Nuclear Matter - Quarks to Stars

NERSC

TECH-X CORPORATION

Outline

- Motivation
  - Future DOE/NP facility: the Electron-Ion Collider
  - Electron cooling is needed to obtain necessary luminosity
- Projects funding Tech-X effort
- Simulating a Coherent e- Cooling (CeC) system
  - Simulating the modulator
  - Simulating the free-electron-laser amplifier
  - Simulating the kicker
- Summary, future plans, acknowledgments

Coherent e- Cooling (CeC) is a priority for RHIC & the future Electron-Ion Collider

- 2007 NSAC Long Range Plan stated:
  - the existing high-energy nuclear physics program will benefit from "…the accelerator modifications needed to implement beam cooling, which will significantly increase the RHIC luminosity…"

    http://www.er.doe.gov/np/nsac/index.shtml
  - stochastic cooling has shown great success with Au^{+79}, but will not work with protons

    Blaskiewicz, Brennan and Mernick, "3D stochastic cooling in RHIC," Phys. Rev. Lett. **105**, 094801 (2010).
  - CeC could yield six-fold luminosity increase for polarized proton collisions in RHIC

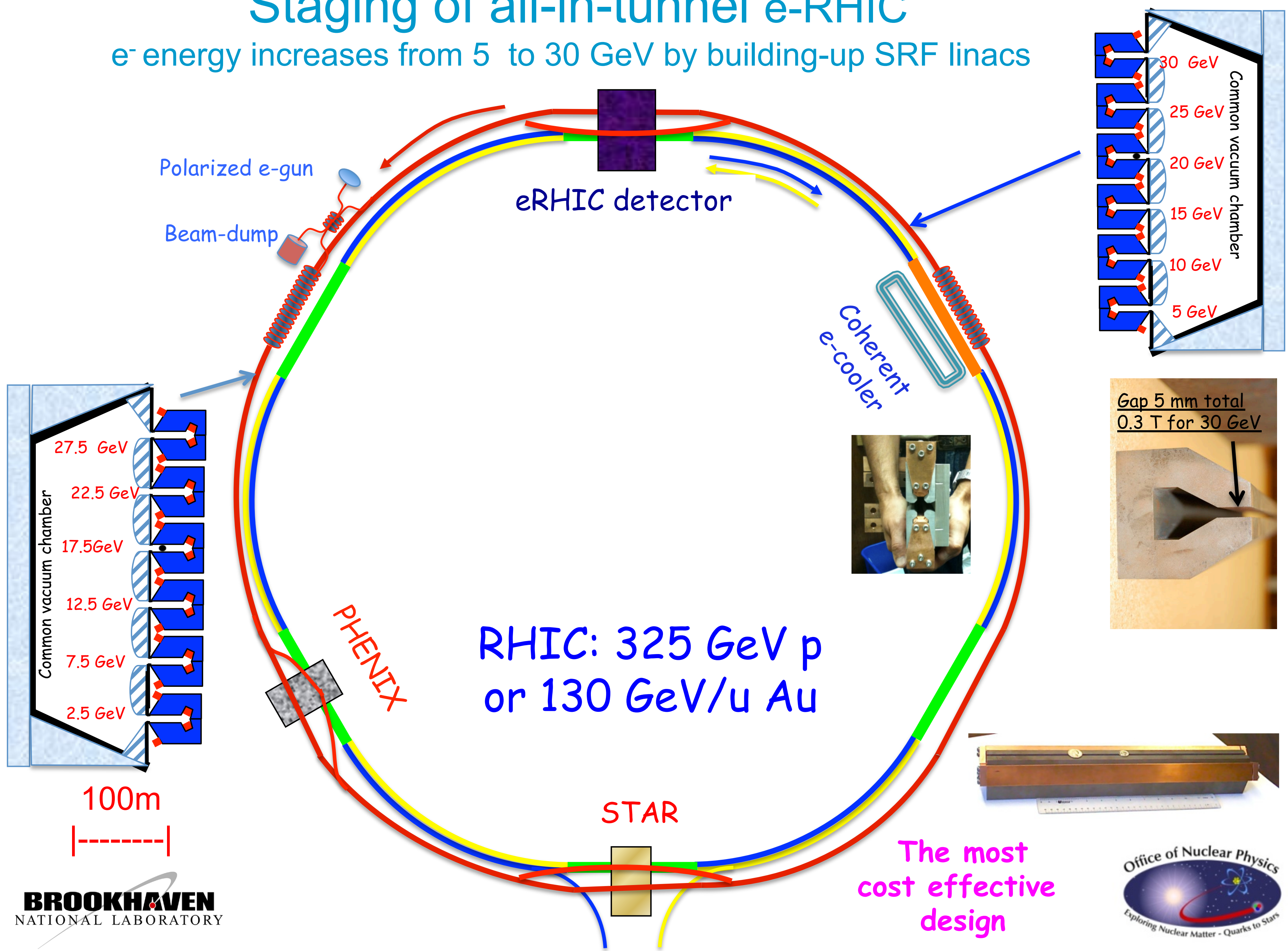
    This would help in resolving the proton spin puzzle.
- Furthermore, the 2007 NSAC Long Range Plan recommends:
  - "…the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider."

    EIC Collaboration website: http://web.mit.edu/eicc/

    Science goals of a future EIC facility:
    - Precision imaging of sea-quarks and gluons to determine spin, flavor and spatial structure of the nucleon
    - Definitive study of the universal nature of strong gluon fields in nuclei
- In November 2009, the Electron-Ion-Collider Advisory Committee (EICAC) selected CeC as one of the highest accelerator R&D priorities.

Staging of all-in-tunnel e-RHIC

e⁻ energy increases from 5 to 30 GeV by building-up SRF linacs



Motivations for Tech-X activities:

- Provide computational support, software and new physical insights for the electron cooling design team at BNL

- Reduce technical risk and, if possible, costs for future DOE/NP facilities at BNL
  - Near term: for a proposed proof-of-principle experiment of coherent electron cooling at RHIC
  - Long term: for a full-scale CeC system for eRHIC

SBIR Phase II: "Designing a Coherent Electron Cooling System for High-Energy Hadron Colliders"

40 GeV/n Au^{+79} & 250 GeV protons

1) δf-PIC simulations of the modulator, for range of parameters

   Validated against theory for single ion; boundary issues have been identified and are being addressed; multiple ions are now being simulated

2) GENESIS 1.3 simulations of the high-gain FEL amplifier

   Use of GENESIS well understood, coupling δf-PIC output from VORPAL into FEL amplifier has been done, but new approach will be implemented

3) PIC simulations of kicker, using amplified e- distribution from FEL

   GENESIS particle output is now correctly coupled into VORPAL; strong density ripples are clearly seen; working to resolve boundary issues

4) Characterize effective velocity drag

PI: David Bruhwiler
Grant monitor: Manouchehr Farkondeh
Funded by DOE Office of Science, Office of Nuclear Physics
Grant # DE-FG02-08ER85182

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SBIR Phase II: "High-Fidelity Modulator Simulations of Coherent Electron Cooling Systems"

Physical parameters to be taken from proof-of-principle CeC experiment design

1) Implement Vlasov-Poisson algorithm in VORPAL
    - non-ideal modulator simulations in 2D2V to benchmark δf-PIC
    - full 3D simulations of modulator must be done via δf
2) Improve δf-PIC simulations of the modulator
3) Couple e- macro-particles from tracking code into VORPAL
4) Simulate e- response to ions near edge of beam (i.e. finite beam size)
5) Simulate e- response to ions in presence of external magnetic fields
6) Simulate e- response to multiple ions in idealized & non-ideal conditions
7) For each case, perform coupled GENESIS simulations of the FEL amplifier
8) For each case, corresponding PIC simulations of kicker
9) Generalize effective velocity drag model to include non-ideal conditions

PI: David Bruhwiler
Grant monitor: Manouchehr Farkondeh
Funded by DOE Office of Science, Office of Nuclear Physics
Grant # DE-SC0000835

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SciDAC-2: "ComPASS – Community Petascale Project for Accelerator Science and Simulations"

Tech-X is funded at $80k/year for 5 years to make effective use of supercomputers to support electron cooling simulations and design

Synergistic with SBIR activities / specific to issues of large-scale computing

Multi-institution effort, funded mostly by DOE/HEP

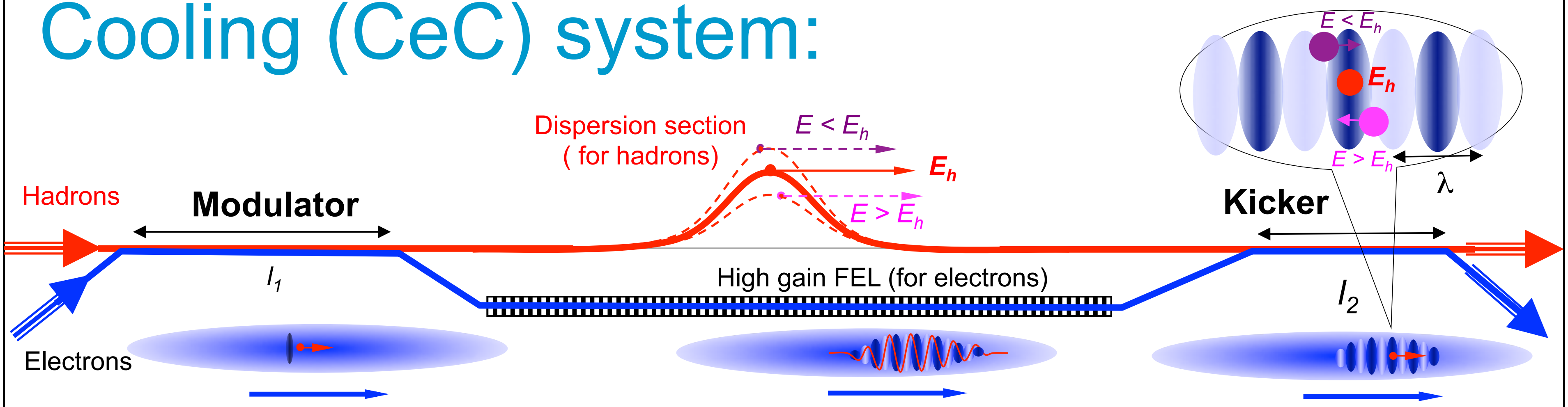
- Fermilab (lead institution), BNL, JLab, LBL, ANL, UCLA, SLAC, Tech-X
- Two years left in the project.
- SciDAC-3 solicitation is expected before the end of 2010, or soon after

Significant supercomputing allocation at NERSC

- Sponsored by DOE/NP
- BNL staff can use this resource for VORPAL simulations or anything relevant to the DOE/NP mission.

Coordinating PI: Panagiotis Spentzouris (Fermilab)
Tech-X PI: John Cary
Funded by DOE Office of Science (HEP, NP, BES)
Tech-X support is from grant # DE-FC02-07ER41499

Schematic of a Coherent electron Cooling (CeC) system:



Litvinenko & Derbenev, "Coherent Electron Cooling," Phys. Rev. Lett. 102, 114801 (2009).

- Coherent Electron Cooling concept
  - uses FEL to combine electron & stochastic cooling concepts
  - a CEC system has three major subsystems
    - **modulator**: the ions imprint a "density bump" on e- distribution
    - **amplifier**: FEL interaction amplifes density bump by orders of magnitude
    - **kicker**: the amplified & phase-shifted e- charge distribution is used to correct the velocity offset of the ions

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VORPAL simulations of the modulator: validation against theory for a simple case

- Analytic results for e- density perturbations

  *G. Wang and M. Blaskiewicz, Phys Rev E **78**, 026413 (2008).*

$$\delta n(\mathbf{x},t)=\frac{Zn_o\omega_p^3}{\pi^2\sigma_{vx}\sigma_{vy}\sigma_{vz}}\int_0^{\omega_p t}\frac{\tau\ \sin(\tau)\ d\tau}{\left(\tau^2+\left(\left(x-v_{th,x}\tau/\omega_p\right)/r_{Dx}\right)^2+\left(\left(y-v_{th,y}\tau/\omega_p\right)/r_{Dy}\right)^2+\left(\left(z-v_{th,z}\tau/\omega_p\right)/r_{Dz}\right)^2\right)^2}$$

  - theory makes certain assumptions:
    - single ion; arbitrary velocities
    - uniform e- density; *anisotropic* temperature
      - Lorentzian velocity distribution
      - now implemented in VORPAL
    - linear plasma response; *fully 3D*
- Dynamic response extends over many λ_D and $1/\omega_{pe}$
  - thermal ptcl boundary conditions are important

For semi-infinite e- distributions, modulator has 4 dimensionless param's

- Infinite e- beam size
  - only 4 dimensionless parameters
  - finite beam size will be simulated in future

- VORPAL uses MKS
  - use param's relevant to Au^{+79} at RHIC

Parameter	Definition	Description
R	$R \equiv \sigma_{vx} / \sigma_{vz} = 3$	Ratio of transverse to longitudinal RMS velocity spread.
T	$T \equiv v_{ix} / \sigma_{vz}$	Ratio of transverse ion velocity to RMS velocity spread.
Z	$Z \equiv v_{iz} / \sigma_{vz}$	Ratio of longitudinal ion velocity to RMS velocity spread.
ζ	$\zeta \equiv Z_{ion} / (4 \pi n_e R^2 \lambda^3_D)$ $\zeta = 0.1$ in the following simulations	Plasma nonlinearity parameter.

Parameter	Value	Definition
n_e	1.60×10^{16} e-/m^3	Electron Density
$\omega_p = (2\pi)8.98\, n_e^{1/2}$	7.14×10^9 radians/second	Plasma frequency in radians per second
$f_p = 8.98\, n_e^{1/2}$	1.14×10^9 cycles/second	Plasma frequency in cycles per second
$1/f_p$	0.88 nanoseconds	Plasma frequency time scale
$\lambda_D = \sigma_{vz}/\omega_p$	1.26 microns	Nominal longitudinal Debye radius
$(\sigma_{vx}, \sigma_{vy}, \sigma_{vz})$	$(27, 27, 9) \times 10^3$ m/sec	RMS electron velocity spread

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Modulator simulations use δf PIC algorithm; run in parallel at NERSC

- δf PIC uses macro-particles to represent deviation from assumed equilibrium distribution
  - much quieter for simulation of beam or plasma perturbations
  - implemented in VORPAL for Maxwellian & Lorentzian velocities
- Maximum simulation size
  - 3D domain, 40 λ_D on a side; 20 cells per λ_D → ~5 x 10^8 cells
  - 200 ptcls/cell to accurately model temp. effects → ~1 x 10^{11} ptcls
  - dt ~ $(dx/v_{th,x})$ / 8; ω_{pe} ~ v_{th} / 2π → ~1,000 time steps
  - 1 μs/ptcl/step → ~30,000 processor-hours for ½ plasma period
  - ~24 hours on ~1,000 proc's; or ~30 minutes on ~60,000 proc's

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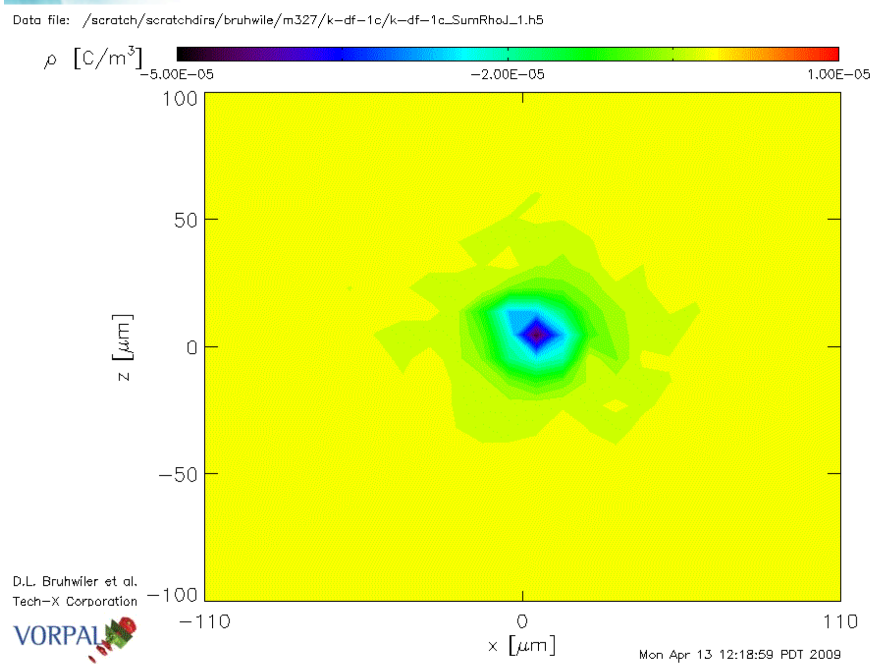
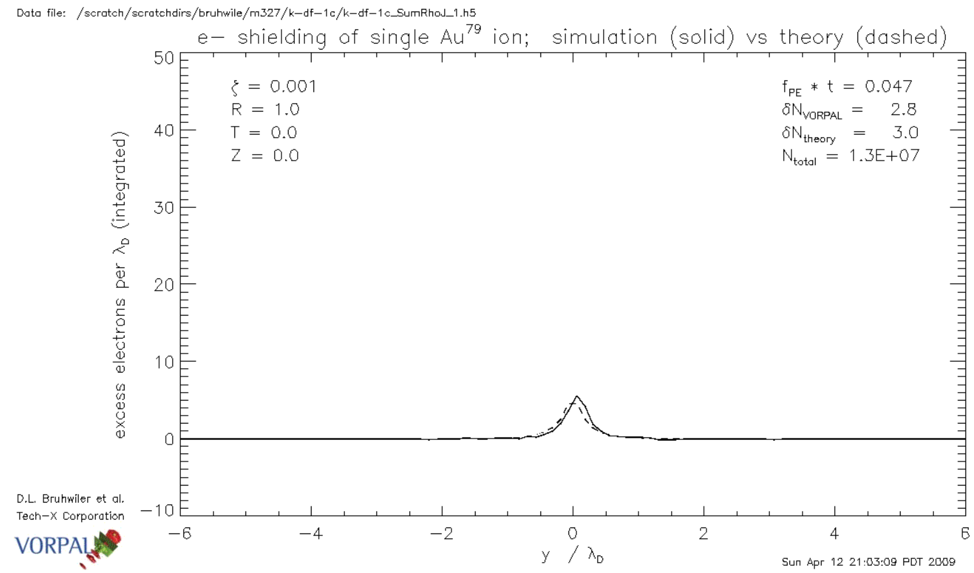
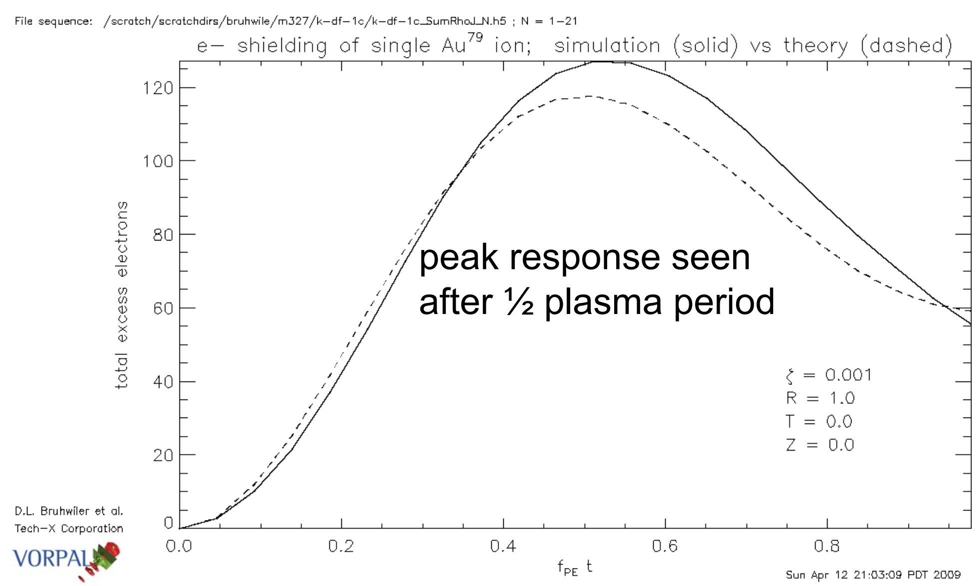
δf PIC shows ~10% deviations from theory

(understood BC effects; they will be resolved)







- Top right movie: 1D integral of e- density perturbation

$$F(z) = \int f_e(\vec{\rho} - \hat{z} \cdot Z\tau, \vec{v}, \tau) d\vec{v}^3 dx dy$$

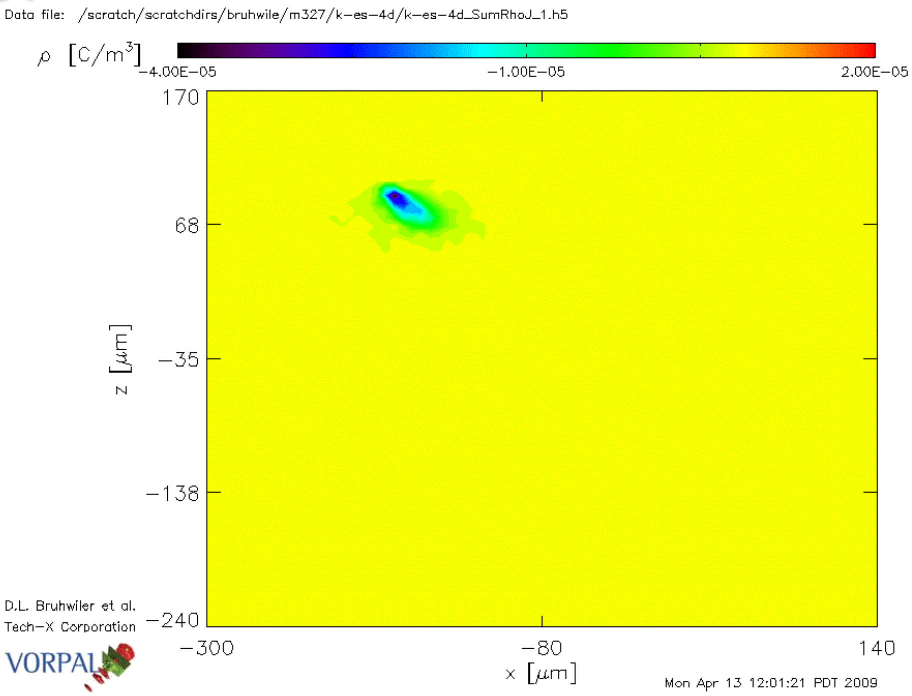
  - R=1 (isotropic e- temperatures)
  - T=Z=0 (stationary ion)

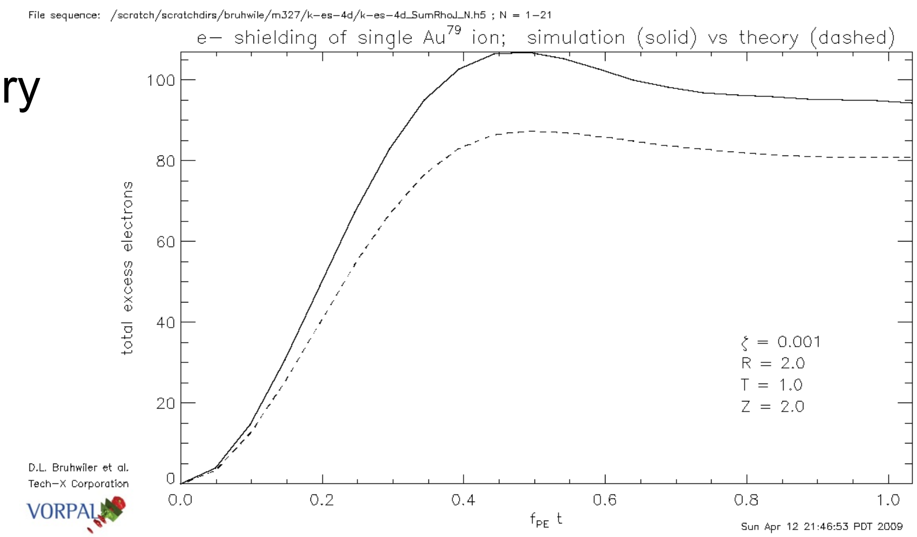
Simulated e- response to ion moving in x & z; anisotropic e- temp.

- Au^{+79} ion is moving in both x & z
  - R=2 (transverse e- temp. 4x larger)
  - T=1 ($v_x = -1 * v_{e,x,rms}$)
  - Z=2 ($v_z = 2 * v_{e,z,rms}$)

- Total e- shielding is shown in figure below
  - peak response is seen after ½ of a plasma period
  - subsequent oscillation (for stationary ion) is not seen

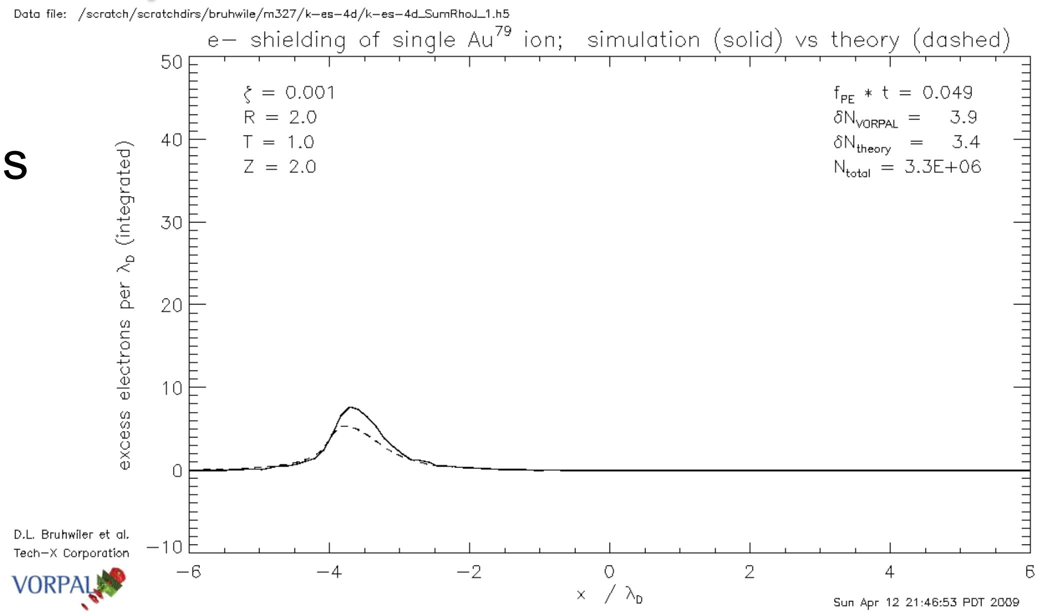
- Deviations from theory ~20%
  - δf algorithm is not yet working in VORPAL for moving ion

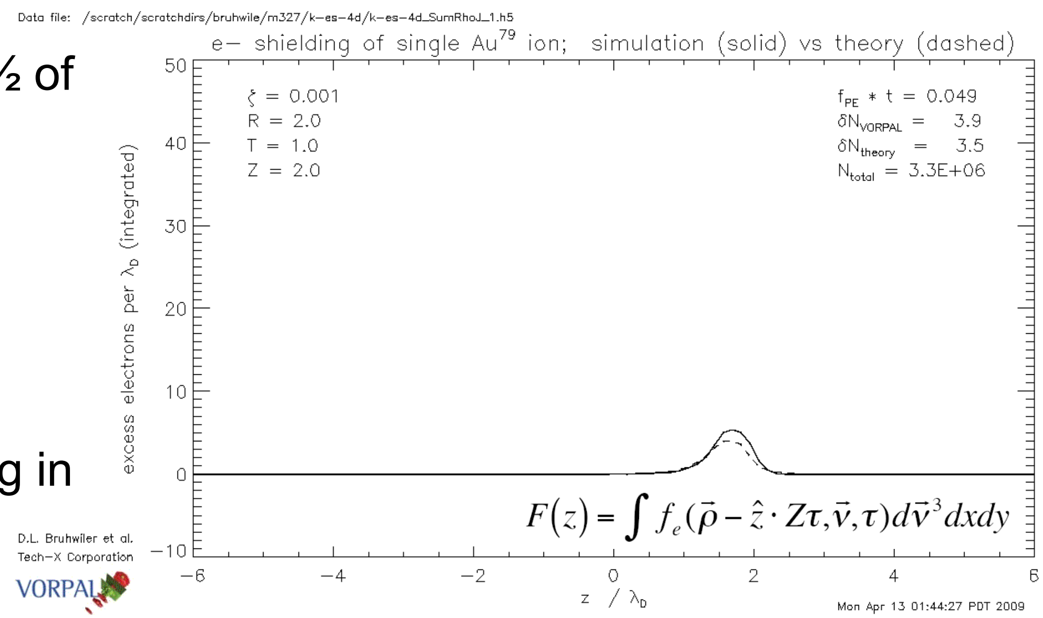




Simulated e- response to ion moving in x & z; anisotropic e- temp.

- Au^{+79} ion is moving along z-axis
  - R=2 (transverse e- temp. 4x larger)
  - T=1 ($v_x = -1 * v_{e,x,rms}$)
  - Z=2 ($v_z = 2 * v_{e,z,rms}$)
- Total e- shielding is shown in lower figure
  - peak response is seen after ½ of a plasma period
  - subsequent oscillation (for stationary ion) is not seen
- Deviations from theory ~30%
  - δf algorithm is not yet working in VORPAL for moving ion





Modulator simulations are successfully validated.

Simulated e- density agrees with theory [7]

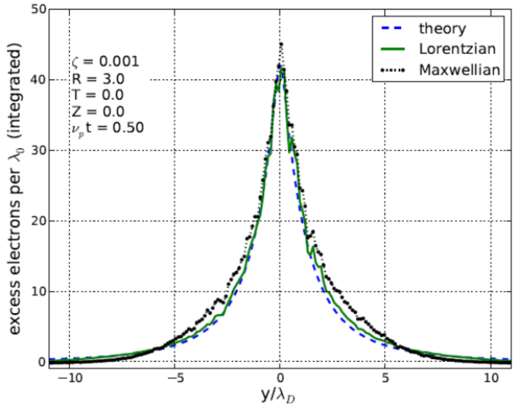


Figure 1: Longitudinal charge density perturbation in the vicinity of the Au^{+79} ion, for the case of a stationary ion in an anisotropic plasma with both Lorentzian and Maxwellian e^- velocity distributions.

Maxwellian wakes can differ from Lorentzian

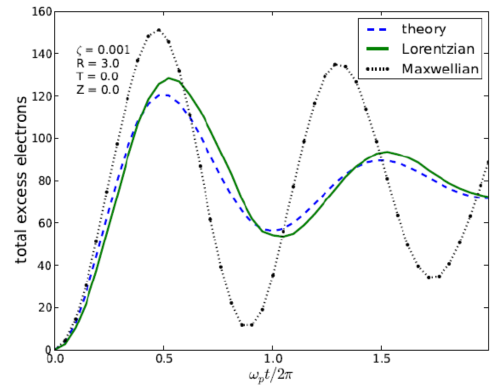


Figure 2: Time evolution of the integrated e^- charge enhancement in the vicinity of the Au^{+79} ion, for the case of a stationary ion in an anisotropic e^- distribution. The time scale is in units of plasma period.

Drifting ion simulations agree w/ theory [7]

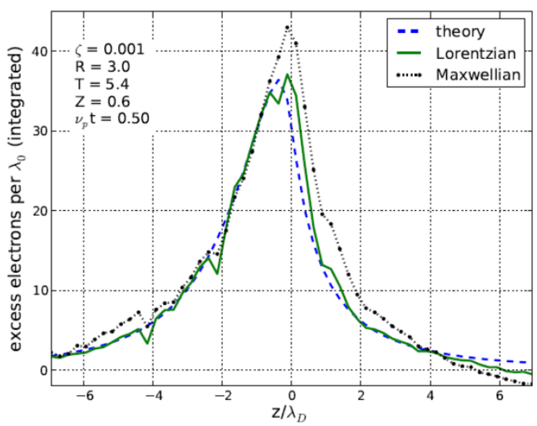


Figure 3: Longitudinal charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

Large transverse drift velocity yields strongly perturbed wakes over many Debye lengths

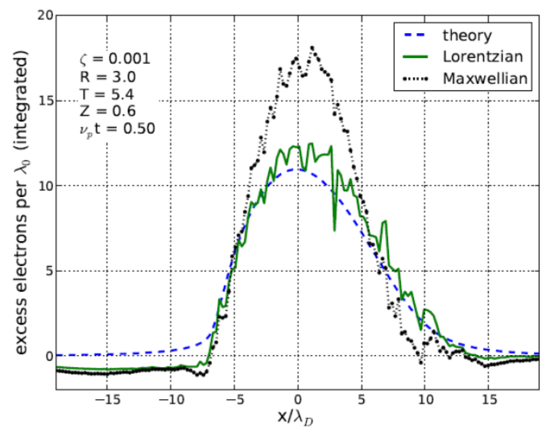


Figure 4: Transverse charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

Modulator output coupled into FEL simulations.

http://pbpl.physics.ucla.edu/~reiche/

Spectrogram of longitudinal e-density perturbation in modulator yields 'bunching' parameters and phases for GENESIS input file.

GENESIS 1.3

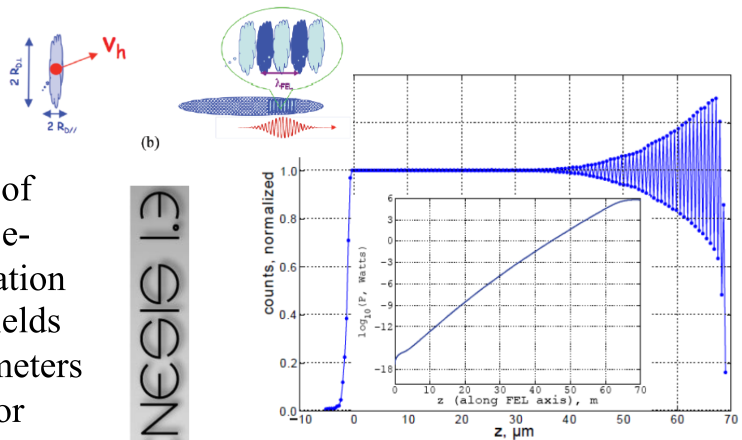
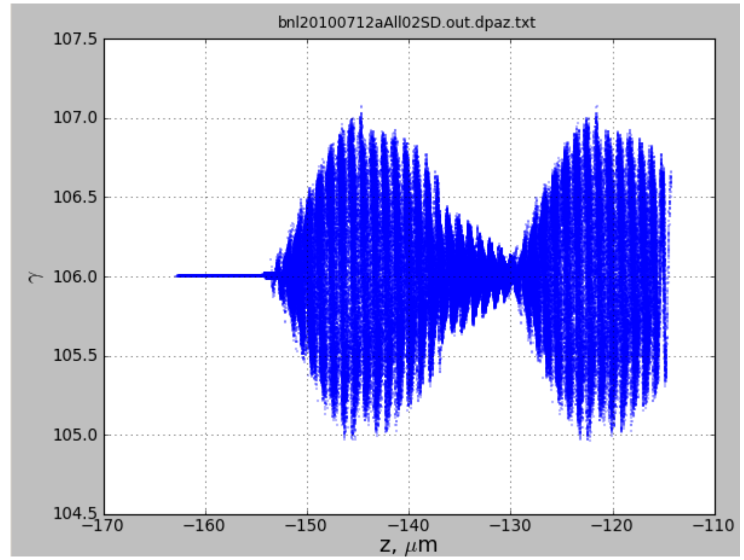


Figure 6: Histogram of electron beam particle counts after propagating 60 meters in an λ_0=700 nm FEL, bin width = $\frac{\lambda_0}{2}$. Inset: Optical power along FEL axis.

Lasing provoked by two well-separated ions (in the modulator) drives energy modulations



Effect of two ions in the modulator

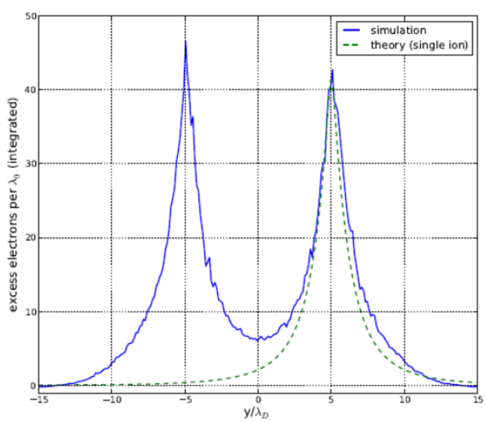
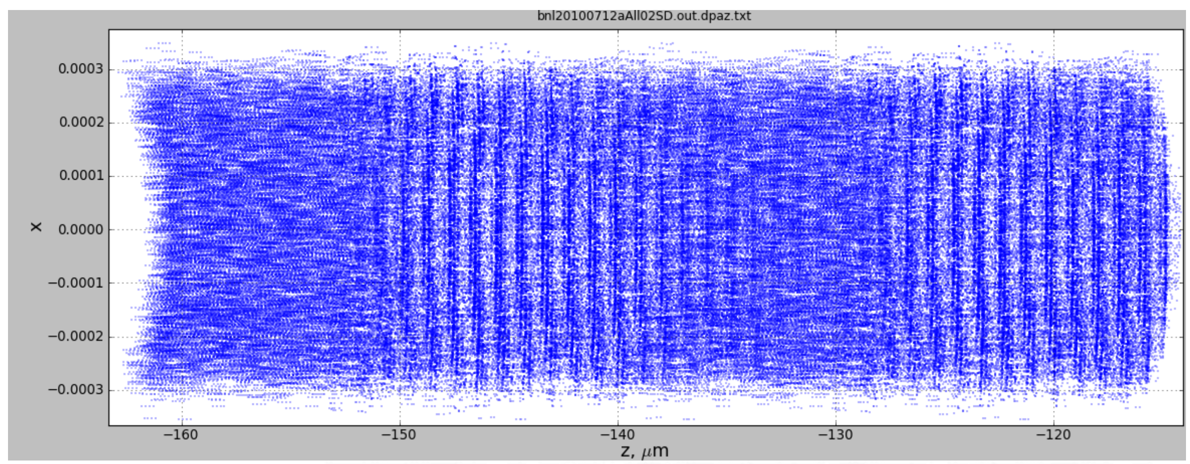


Figure 5: Transverse charge density perturbation of a plasma in the vicinity of two stationary Au^{+79} ions separated by $10\lambda_D$. Dotted line: theoretical prediction for a Lorentzian velocity distribution.

FEL amplified response in electron density distribution, from two well-separated ions (in the modulator)



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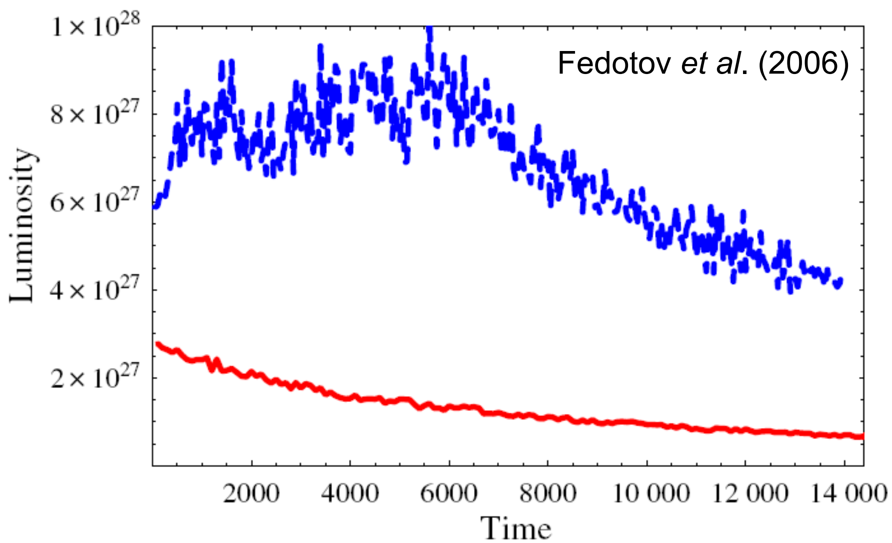
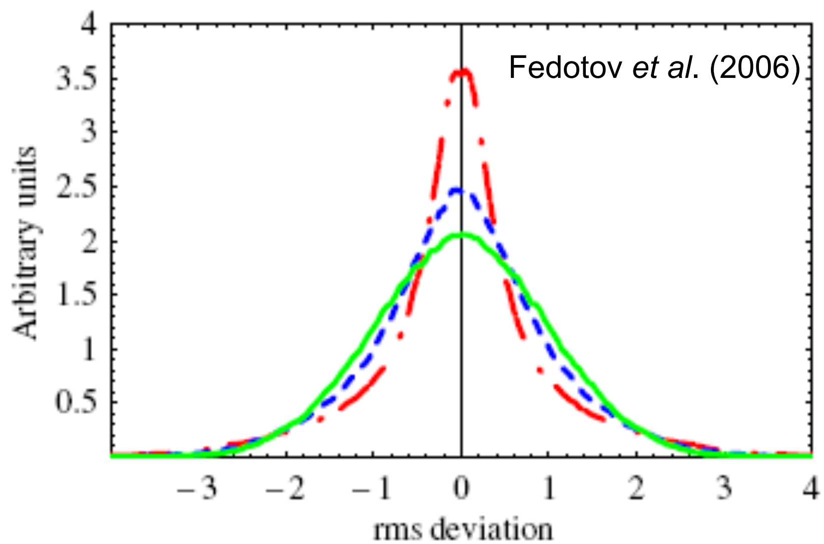
Reminder: full e- cooling sim's are distinct from simulating micro-physics of a single pass

- BETACOOL code is used to model many turns
  - A. Sidorin *et al.*, *Nucl. Instrum. Methods* A **558**, 325 (2006).
  - A. Fedotov, I. Ben-Zvi, D. Bruhwiler, V.N. Litvinenko, A. Sidorin, New J. Phys. **8**, 283 (2006).
  - variety of "conventional" electron cooling algorithms are available
    - i.e. simple models for dynamical friction and diffusion
  - various models for "heating" are included
    - intra-beam scattering (IBS), beam-beam collisions, etc.
- Never used for CeC





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Plans for future work

- Modify GENESIS to use 'clone' ptcl's (Litvinenko, unpublished)
  - will enable proper 3D coupling from modulator to FEL amplifier
- Demonstrate coupled simulations of complete system
  - next, macro-particles from GENESIS coupled into VORPAL, with phase shifted ions, to model the kicker section
- Characterize effective velocity drag
  - need to develop a parametric model
    - e.g. from 'conventional' magnetized cooling:

$$\mathbf{F} = -\frac{1}{\pi}\omega_{pe}^2 \frac{(Ze)^2}{4\pi\varepsilon_0} \ln\left(\frac{\rho_{\max} + \rho_{\min} + r_L}{\rho_{\min} + r_L}\right) \frac{\mathbf{V}_{ion}}{\left(V_{ion}^2 + V_{eff}^2\right)^{3/2}}$$

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

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

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

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

V. Parkhomchuk, Nucl. Instr. Meth. in Phys. Res. A **441** (2000), p. 9.

- Non-ideal modulator simulations
  - multiple ions
  - finite e- beam size; external magnetic fields

Recent Papers & Presentations

A.V. Sobol, D.L. Bruhwiler, G.I. Bell, A. Fedotov and V.N. Litvinenko, “Numerical calculation of dynamical friction in electron cooling systems, including magnetic field perturbations and finite time effects,” New Journal of Physics (2010), in press.

Partially supported by previous SBIR and by ComPASS SciDAC project.

B.T. Schwartz, D.L. Bruhwiler, V.N. Litvinenko, S. Reiche, G.I. Bell, A. Sobol, G. Wang and Y. Hao, “Massively parallel simulation of anisotropic Debye shielding in the modulator of a coherent electron cooling system and subsequent amplication in a free electron laser,” Journal of Physics: Conference Series (2010), in press.

Partially supported by ComPASS SciDAC project.

Invited talk at HB2010:

D.L. Bruhwiler, “Overview of Computational Challenges for Coherent Electron Cooling,” 46th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (Morschach, Switzerland, September, 2010).

Acknowledgments

We thank I. Ben-Zvi, A. Fedotov, M. Blaskiewicz, A. Herschkowitz and other members of the BNL Collider Accelerator Department for many useful discussions.

We thank J.R. Cary, P. Stoltz and other members of the VORPAL development team for assistance and useful discussions.

Work at Tech-X Corp. was supported by the US DOE Office of Science, Office of Nuclear Physics under grant #DE-FG02-08ER85182.

We used computational resources of NERSC, BNL and Tech-X.