Designing a Coherent Electron Cooling System for High-Energy Hadron Colliders

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DOE-NP SBIR/STTR Exchange Meeting
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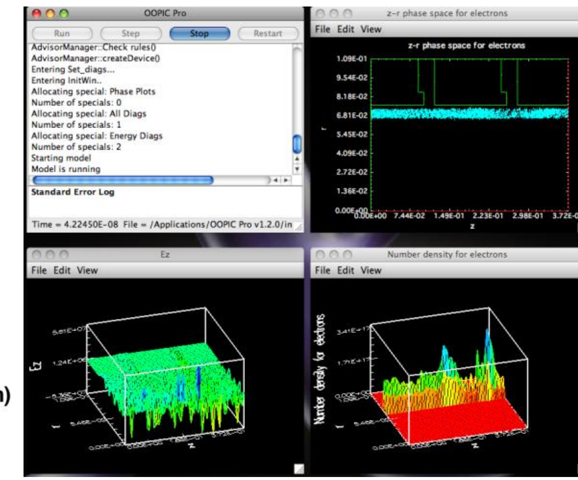
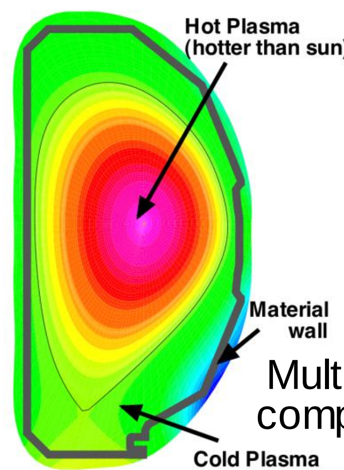
Cover story computations



Interactive modeling; Education

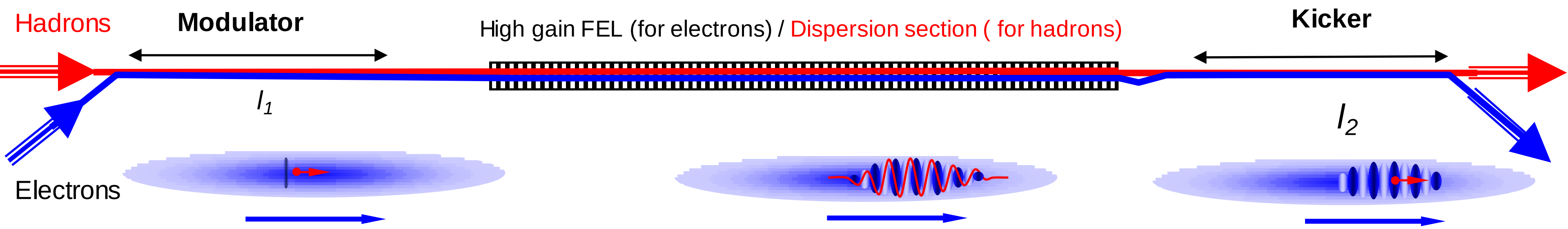


Multiphysics computations

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

- 2007 Nuclear Science Advisory Committee (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."
  - NSAC website: http://www.er.doe.gov/np/nsac/index.shtml
- 2009 Electron-Ion-Collider Advisory Committee (EICAC):
  - selected CeC as one of the highest accelerator R&D priorities
  - EIC Collaboration website: http://web.mit.edu/eicc
- Other cooling approaches have serious limitations
  - stochastic cooling has shown great success with 100 GeV/n Au^{+79} in RHIC
    - Blaskiewicz, Brennan and Mernick, "3D stochastic cooling in RHIC," PRL **105**, 094801 (2010).
    - however, bandwidth of conventional electronics is insufficient for 250 GeV protons in RHIC
  - high-energy unmagnetized electron cooling could be used for 100 GeV/n Au^{+79}
    - S. Nagaitsev et al., PRL 96, 044801 (2006). Fermilab, relativistic antiprotons, with γ~9
    - A.V. Fedotov, I. Ben-Zvi, D.L. Bruhwiler, V.N. Litvinenko, A.O. Sidorin, New J. Physics 8, 283 (2006).
    - cooling rate decreases as $1/\gamma^2$; too slow for 250 GeV protons
  - CeC could yield six-fold luminosity increase for polarized proton collisions in RHIC
    - This would help in resolving the proton spin puzzle.
    - Breaks the $1/\gamma^2$ scaling of conventional e- cooling, because it does not depend on dynamical friction

Coherent e- Cooling: Economic option



Modulator: region 1
(a quarter to a half of plasma oscillation)

Amplifier of the e-beam modulation via High Gain FEL

Longitudinal dispersion for hadrons

Kicker: region 2

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

Electron density modulation is amplified in the FEL and made into a train with duration of $N_c \sim L_{gain}/\lambda_w$ alternating hills (high density) and valleys (low density) with period of FEL wavelength λ. Maximum gain for the electron density of HG FEL is ~ 10^3.

$$v_{group} = (c + 2v_{//})/3 = c\left(1 - \frac{1+a_w^2}{3\gamma^2}\right) = c\left(1 - \frac{1}{2\gamma^2}\right) + \frac{c}{3\gamma^2}\left(1 - 2a_w^2\right) = v_{hadrons} + \frac{c}{3\gamma^2}\left(1 - 2a_w^2\right)$$

Economic option requires: $2a_w^2 < 1$!!!

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V.N. Litvinenko, RHIC Retreat, July 2, 2010

Jefferson Lab

3D simulations are being used to provide corrections to 1D and 3D linear theory

- All relevant dynamics in a CeC system is linear
  - modulator
    - 3D anisotropic Debye shielding of each ion (beam-frame Debye length ≈ lab frame FEL wavelength)
    - the coherent density/velocity wake is typically smaller than shot noise
    - there will be other non-coherent perturbations (details of real e- beam with moderate space charge)
  - FEL amplifier
    - high-gain FEL operates in SASE mode; very high-frequency amplifier is critical for success
    - wiggler is kept short enough to avoid saturation ➔ linear density modulation, velocity perturbations
    - amplified noise plus signal from nearby ions >> coherent signal for each ion (as for stochastic cooling)
  - kicker
    - ion responds to fields of amplified electron density perturbation ➔ effective velocity drag
    - linear perturbations of the beam-frame "plasma" evolve for ~0.5 plasma periods
- Role of theory and simulation
  - the entire system is amenable to theoretical calculations
    - many nice papers by V. Litvinenko, Y. Derbenev, G. Wang, Y. Hao, M. Blaskiewicz, S. Webb, others…
    - the subtle coherent/resonant dynamics is assumed to be additive with noise (as for stochastic cooling)
  - simulations are being used to understand 3D and non-idealized effects
    - subtlety of the dynamics is numerically challenging; requires use of special algorithms
    - noise is largely understood, so we suppress/ignore noise and simulate only coherent effects
    - coupling between the three systems is challenging; especially from the modulator to the FEL amplifier

Project tasks & status

- After two years, funds are 80% expended
  - A no-cost extension has been requested (still pending)
- 1) δf-PIC simulations of the modulator, for range of parameters
  - Complete: Validated against theory for uniform-density e-distributions; more realistic e- beam distrib.'s are considered in a separate project
- 2) GENESIS 1.3 simulations of the high-gain FEL amplifier
  - Complete: Use of GENESIS is well understood, 3D coupling of δf-PIC output from VORPAL into the FEL amplifier, with correct shot noise
- 3) PIC simulations of kicker, using amplified e- distribution from FEL
  - 75% complete: GENESIS particle output correctly coupled into VORPAL; time evolution of electric fields in the kicker still being studied
- 4) Characterize effective velocity drag
  - 10% complete: careful comparison of simulation & theory is beginning
- All tasks will be completed, assuming the NCE is approved.

Papers & Presentations

- D.L. Bruhwiler, "Simulations of the modulator, FEL amplifier and kicker for coherent electron cooling of 40 GeV/n Au+79," COOL'11 Workshop on Beam Cooling & Related Topics (Alushta, Ukraine, Sep., 2011). ***INVITED TALK***
- B.T. Schwartz, D.L. Bruhwiler, I.V. Pogorelov, Y. Hao, V. Litvinenko, G. Wang, S. Reiche, "Simulations of a Single-Pass Through a Coherent Electron Cooler for 40 Gev/n Au+79," Proc. Particle Accelerator Conf. (2011).
- V.N. Litvinenko, J. Bengtsson, I. Ben-Zvi, A.V. Fedotov, Y. Hao, D. Kayran, G. Mahler, W. Meng, T. Roser, B. Sheehy, R. Than, J. Tuozzolo, G. Wang, S.D. Webb, V. Yakimenko, A. Hutton, G.A. Krafft, M. Poelker, R. Rimmer, G.I. Bell, D.L. Bruhwiler, B.T. Schwartz, "Proof-of-Principle Experiment for FEL-based Coherent Electron Cooling", PAC Proc. (2011).
- 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 **12**, 093038 (2010).
- 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," Proc. 2010 SciDAC Conference (2011).
- 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, Sep., 2010). ***INVITED TALK***

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).*

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

  - theory makes certain assumptions:
    - single ion, with arbitrary velocity
    - uniform e- density; *anisotropic* temperature
      - kappa-2 (Lorentzian squared) velocity distribution
    - linear plasma response; *fully 3D*
- Dynamic response extends over many λ_D and $1/\omega_{pe}$
  - thermal ptcl boundary conditions are important

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

- δf PIC uses macro-particles to represent deviation from a background 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; $\omega_{pe} \sim v_{th}$ / 2π → ~1,000 time steps
  - 1 μs/ptcl/step → ~30,000 processor-hours for ½ plasma period
  - ~24 hours on ~1,000 proc's

Modulator simulations are successfully validated.

Simulated e- density agrees with theory [7]

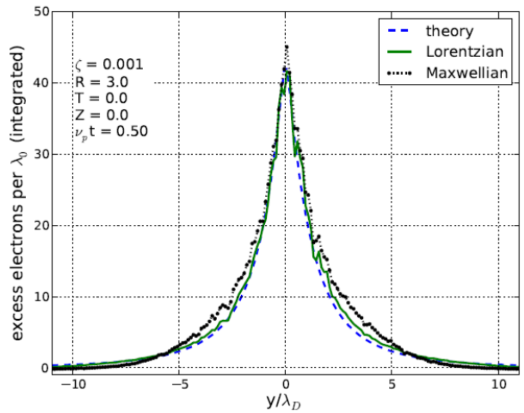


Figure 1: Longitudinal charge density perturbation in the vicinity of the Au^{+79} ion, for the case of a stationary ion in an anisotropic plasma with both Lorentzian and Maxwellian e^- velocity distributions.

Maxwellian wakes can differ from Lorentzian

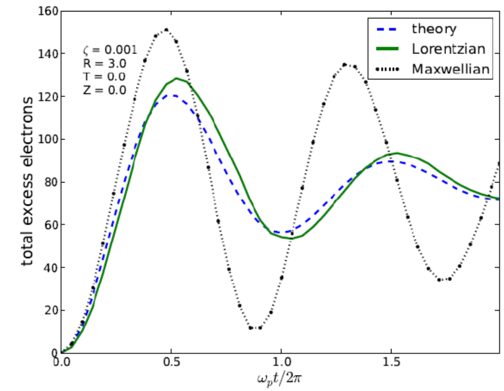


Figure 2: Time evolution of the integrated e^- charge enhancement in the vicinity of the Au^{+79} ion, for the case of a stationary ion in an anisotropic e^- distribution. The time scale is in units of plasma period.

Drifting ion simulations agree w/ theory [7]

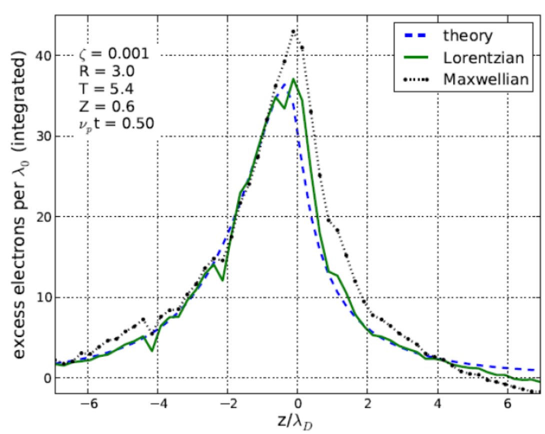


Figure 3: Longitudinal charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

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

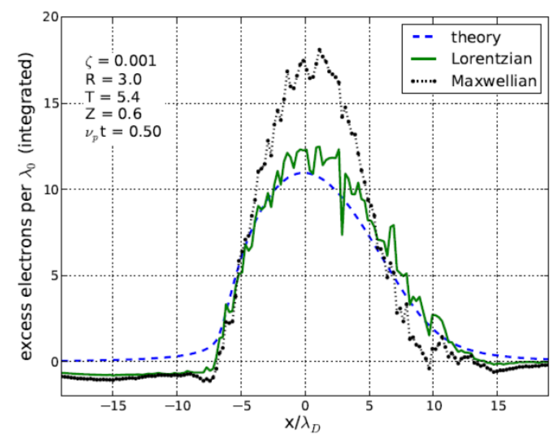


Figure 4: Transverse charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

Coupling modulator results to FEL simulations (coupling VORPAL output to GENESIS input)

- Convert δf macro-particles to constant weight GENESIS particles
- GENESIS reads particle file
  - No coherent response to electron perturbations
  - Must define bunching coefficients and phases
- Get longitudinal bunching parameters from electron ponderomotive phases

Definition of bunching parameters:

$$b = \frac{1}{N}\sum_{j=1}^{N} \mathrm{e}^{-\mathrm{i}\theta_j}$$

McNeil and Robb, *J. Phys. D: Appl. Phys.* **31**, 371 (1998).

$$\theta = (k_{FEL}+k_u)*z - ct*k_{FEL}$$ (pond. phase)

– GENESIS divides slices of width λ_{FEL}

– Must specify bunching *b* for each slice

– GENESIS modifies phase of each ptcl:

$$\theta' = \theta - 2*|b|\sin(\theta - \arg\{b\})$$

VORPAL → GENESIS 1.3

Coupling VORPAL output into GENESIS now works in 3D (density only)

- Before: coupling of 3D e- perturbation from modulator was essentially 1D

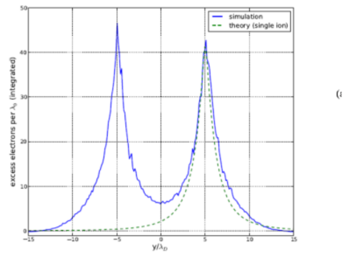
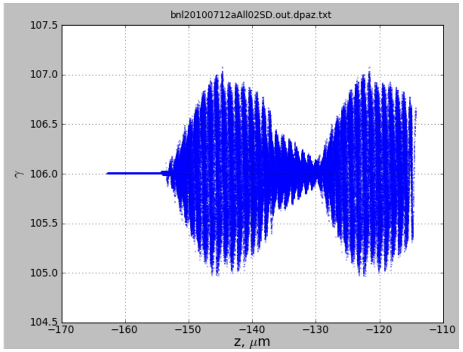
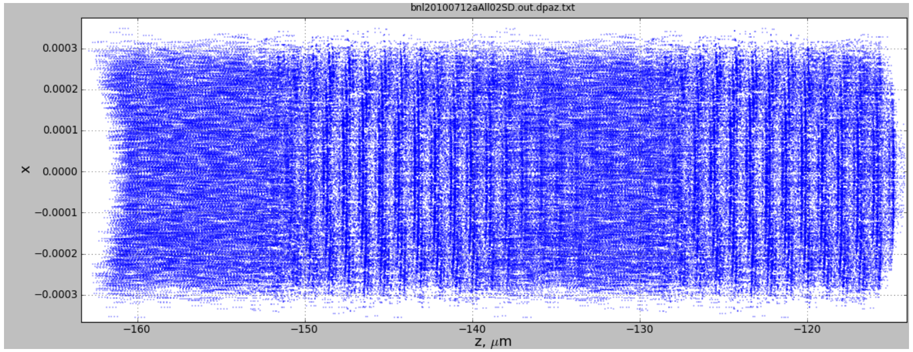


Figure 5: Transverse charge density perturbation of a plasma in the vicinity of two stationary Au^{+79} ions separated by $10\lambda_D$. Dotted line: theoretical prediction for a Lorentzian velocity distribution.

Two ions in the modulator



Lasing provoked by two ions



FEL-amplified response in e- density distribution

New approach:

a) compute 3D distribution of bunching parameters;

b) apply to ptcl. phases in initial distrib. for GENESIS

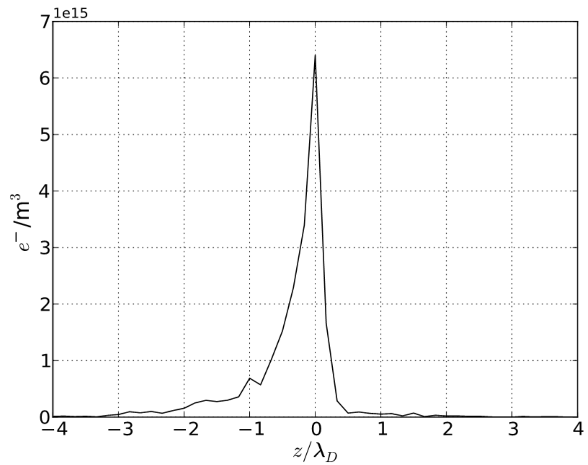


Figure 1: VORPAL δf computation of longitudinal on-axis electron density perturbation near a Au^{+79} ion with longitudinal velocity $v_z\hat{\mathbf{z}}$ in an isotropic plasma. The total number of shielded electrons is N_s=119 and λ_D=22.2 μm.

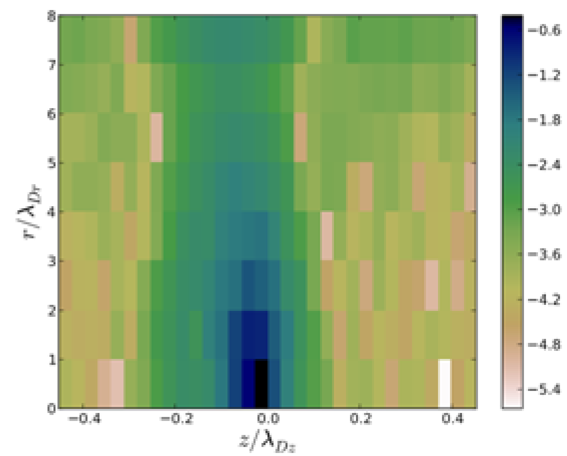


Figure 2: Magnitude of electron beam bunching coefficients b, plotted as $\log_{10}(|b|)$, at λ_0 = 12.5 μm in vicinity of a shielded ion located at z=0 with positive velocity $v_z\hat{\mathbf{z}}$.

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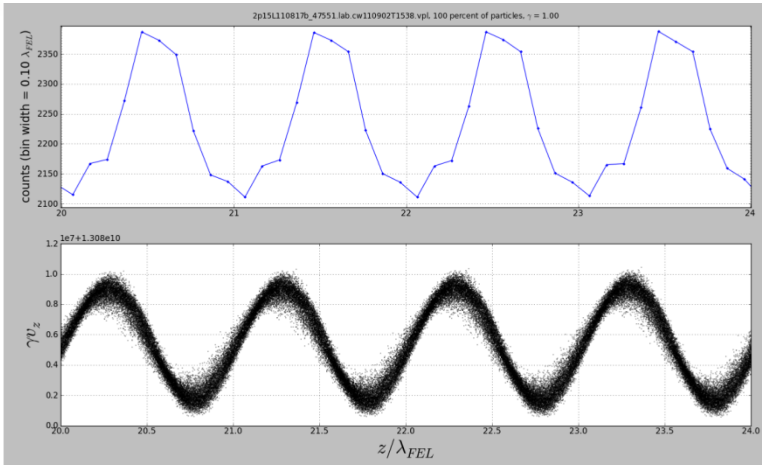
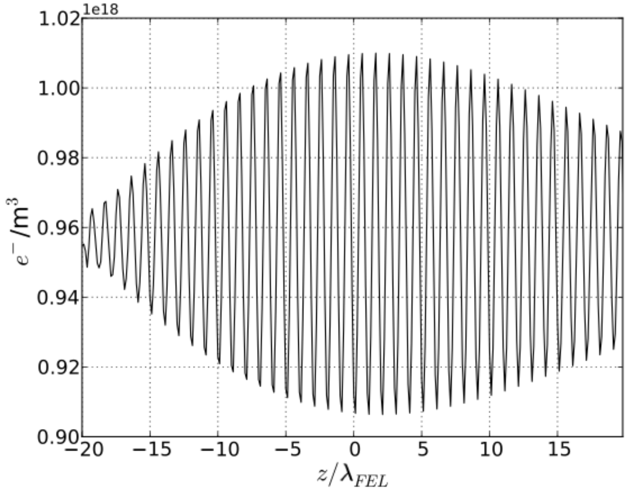
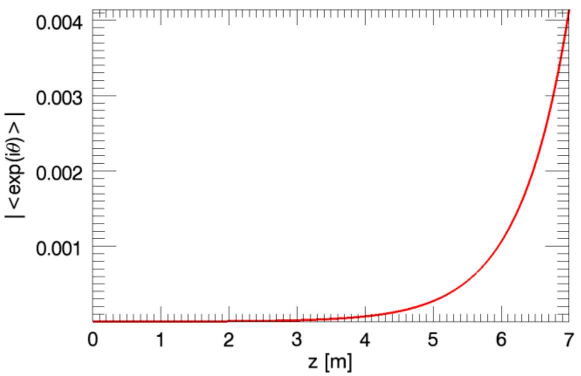
Characteristic output from GENESIS is consistent with theoretical work at BNL



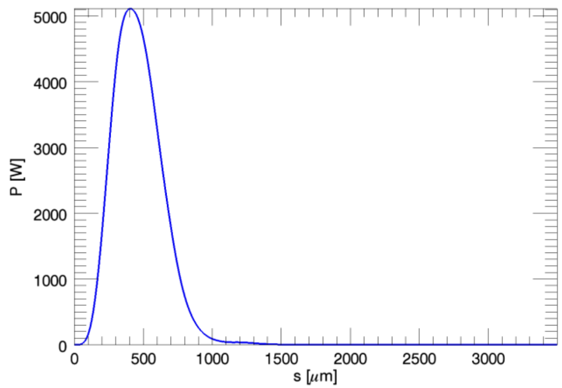
Binned current (top) and p_z (bottom), lab frame: growing bunching, as seen from phase shift



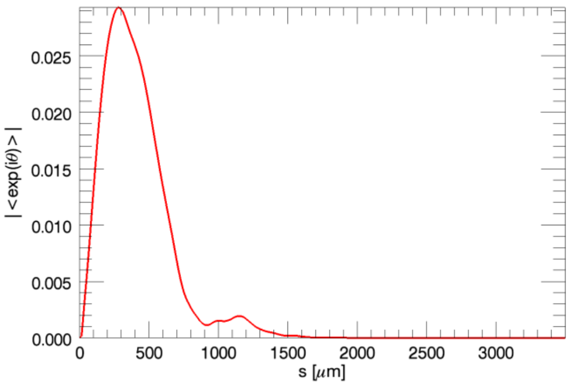
e$^-$ density after a single pass through the FEL, max(δn_e)~5.3 10^{16} m^{-3}.



Mean bunching as a function of z along the undulator: no saturation at exit from the wiggler



FEL power distribution along the bunch, at exit from the undulator



Magnitude of the bunching parameter along the bunch

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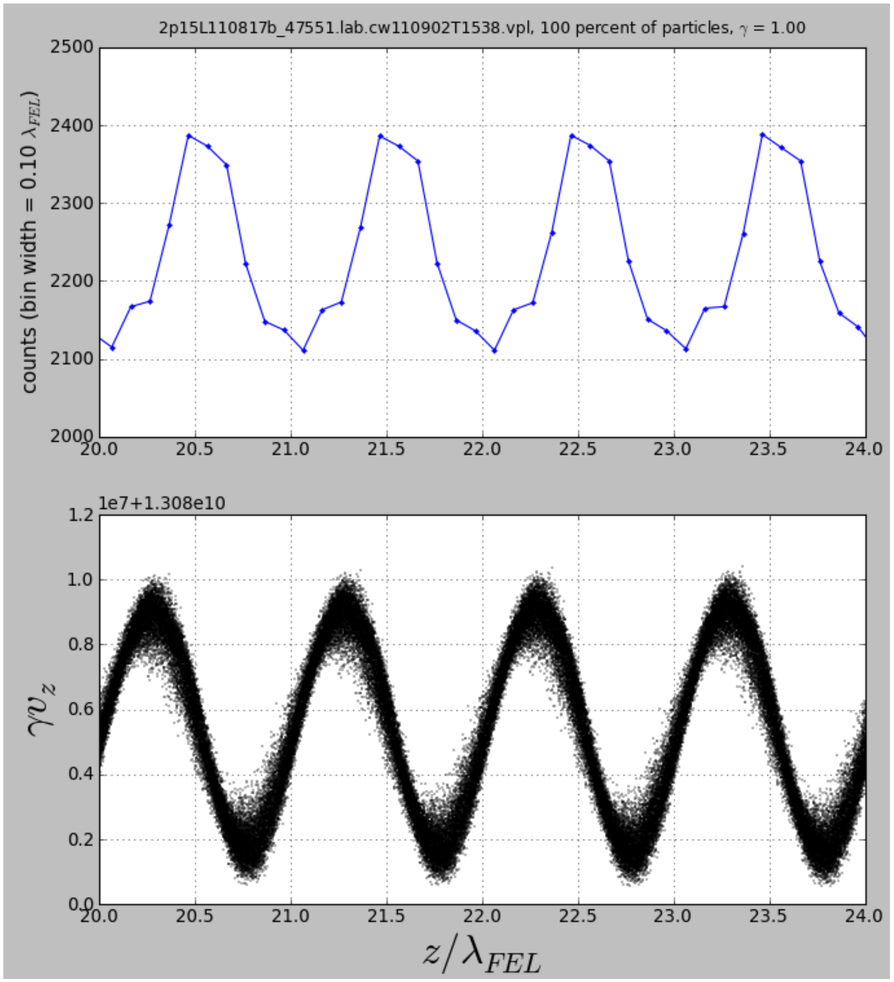
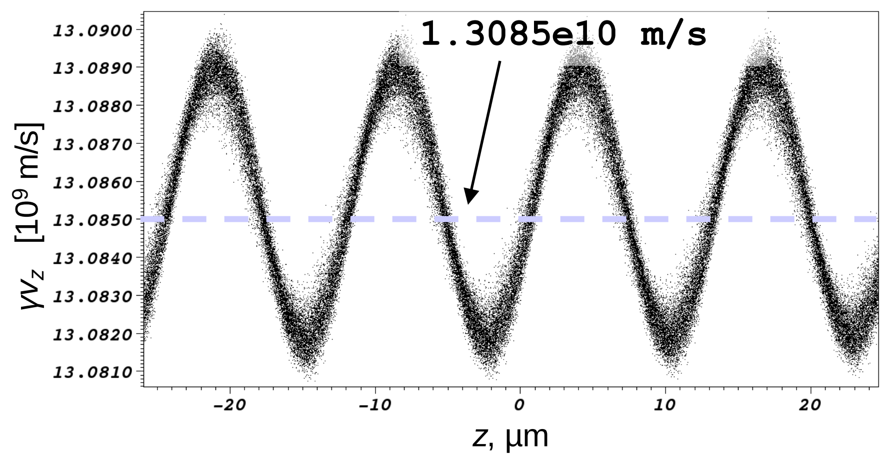
Coupling GENESIS particles into VORPAL for beam-frame electrostatic PIC sim's of the kicker is subtle; appears to be correct now

Particles at end of FEL, from GENESIS



- Direct coupling from an FEL code to a PIC code doesn't work without careful treatment –
- Particles per cell must be increased (without changing density or velocity distrib.'s
- High-order spline-based macro-particle shapes must be used for charge deposition (to reduce noise)
- must Lorentz transform from lab to beam frame
- not yet clear if EM fields must be included

Particles loaded into VORPAL



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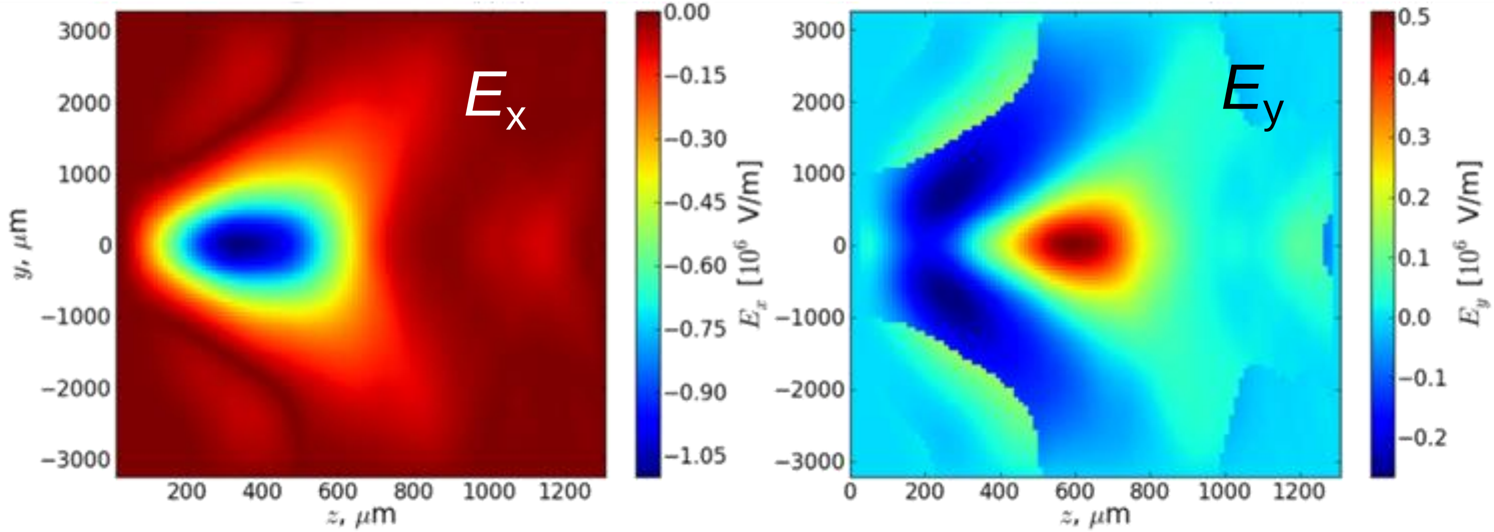
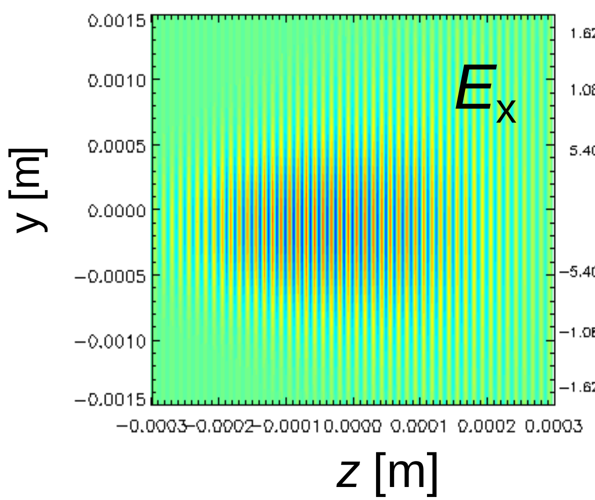
FEL electric fields can be coupled correctly from GENESIS to VORPAL in the lab frame

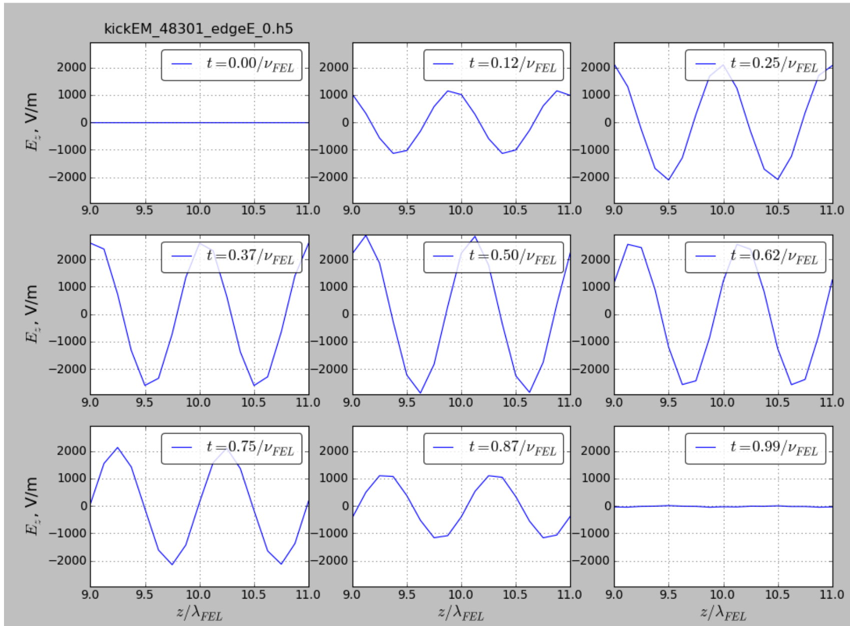
GENESIS output:



GENESIS outputs only E_x & E_y envelopes for FEL field. In VORPAL, fast oscillations are added; then E_z evolves self-consistently:

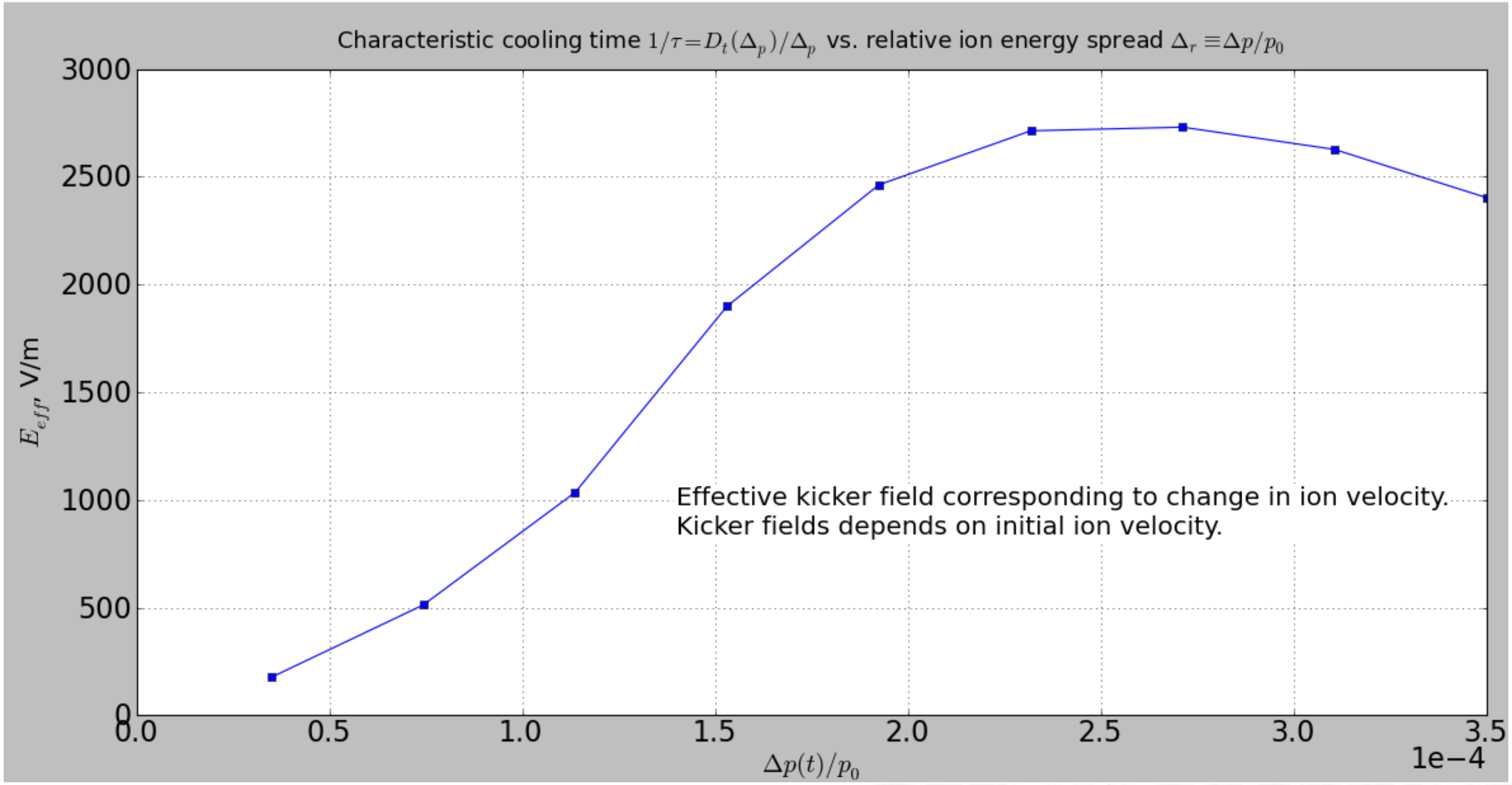


Longitudinal E-field



The "effective" kicker field must be known to obtain cooling rate

The "effective" electric field experienced by the drifting ion depends on
a) its relative velocity with respect to the electron beam, and
b) the time and space evolution of the longitudinal electric field.



Future Plans – Enable full cooling simulations

- We are simulating micro-physics of a single CeC pass
  - full e- cooling simulations requires $>10^4$ turns
    - inclusion of IBS and other effects to see evolution of luminosity
    - detailed evolution of the ion beam phase space
  - detailed VORPAL-GENESIS simulations are too slow
- Need to characterize the effective drag force for CeC
  - theoretical work at BNL provides a semi-analytic result
  - our 3D simulations capture effects that reduce cooling rate
  - community code BETACOOL can be used for integrated sim's
- Wrapping up:
  - determine importance of e- beam evolution in the kicker
  - all software tools/techniques in place; compare with theory
  - characterization of drag force will be mod's of BNL theory

Acknowledgments

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GENESIS 1.3

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