Simulation of Coherent Electron Cooling for High-Intensity Hadron Colliders

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Abstract

Novel electron-hadron collider concepts are a long-term priority for the international nuclear physics community. Effective beam cooling for intense, relativistic hadron beams will be necessary to obtain the orders-of-magnitude higher luminosities being proposed. Coherent electron cooling (CEC) [1] combines the best features of electron cooling and stochastic cooling, via free-electron laser technology [2], to offer the possibility of cooling high-energy hadron beams much faster. Many technical difficulties must be resolved via full-scale 3D simulations, before the CEC concept can be validated experimentally. The parallel VORPAL framework [3] is the ideal code for simulating the modulator and kicker regions, where the electron and hadron beams will co-propagate as in a conventional electron cooling section. We present initial VORPAL simulations of the electron density wake driven by single ions in the modulator section. Also, we present a plan for simulating the full modulator-amplifier-kicker dynamics, by through use of a loosely-coupled code suite including VORPAL, an FEL code and a beam dynamics code.

[1] Y.S. Derbenev, Proc. COOL07, 149 (2007).
[2] V.N. Litvinenko & Y.S. Derbenev, Proc. FEL07, 268 (2007).
[3] G.I. Bell, D.L. Bruhwiler, A. Fedotov, A.V. Sobol, R.S. Busby, P. Stoltz, D.T. Abell, P. Messmer, I. Ben-Zvi, V.N. Litvinenko, “Simulating the dynamical friction force on ions due to a briefly co-propagating electron beam”, J. Comp. Phys. (2008), doi:10.1016/j.jcp.2008.06.019.

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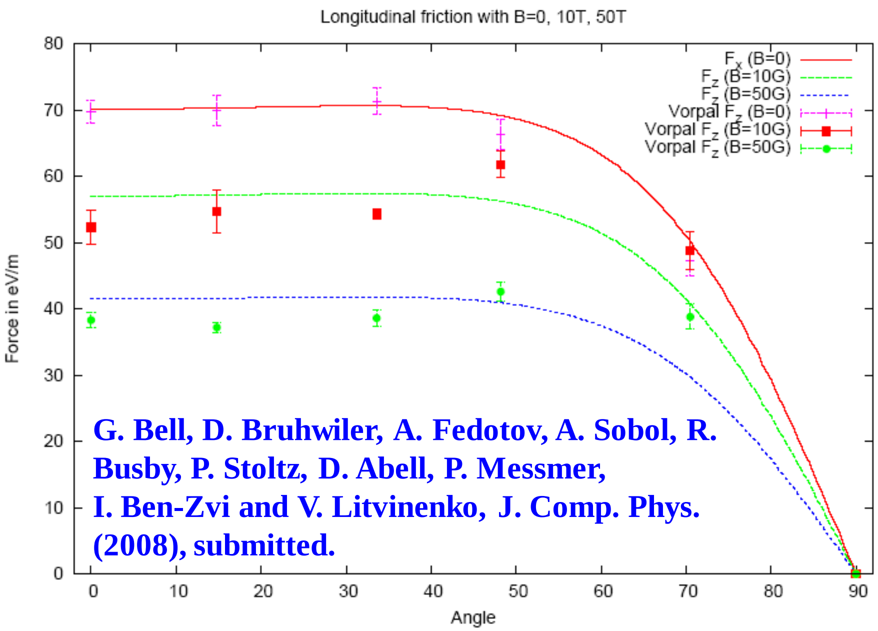
Previous Work

- **Electron cooling of relativistic ion beams is required for high luminosities of electron-ion collider (EIC) concepts**
  - in the mid-term, RHIC luminosity could be increased ~10x

I. Ben-Zvi *et al.*, "Status of the R&D towards electron cooling of RHIC," Part. Accel. Conf. (2007).



G. Bell, D. Bruhwiler, A. Fedotov, A. Sobol, R. Busby, P. Stoltz, D. Abell, P. Messmer, I. Ben-Zvi and V. Litvinenko, J. Comp. Phys. (2008), submitted.

- conventional wiggler could replace expensive solenoid
  - e- "wiggle" motion suppresses recombination with ~10 Gauss
  - provides focusing; reduces risk
  - friction force should be reduced only by $\rho_{min} \rightarrow \rho_w$ in Coulomb log

$$\rho_w = \frac{\Omega_{gyro}}{k_w^2 v_{beam}} \sim 1.4x10^{-3} \lambda_w^2[m] B_w[G] / \gamma$$

  - suggested independently by V. Litvinenko and Ya. Derbenev
  - confirmed via VORPAL simulations

Motivation for CEC concept

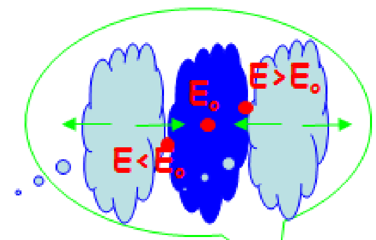
- **Coherent Electron Cooling concept**
  - uses FEL to combine electron & stochastic cooling concepts
    Litvinenko & Derbenev, "Free Electron Lasers and High-Energy Electron Cooling," FEL'07 Proc.
  - a CEC system has three major subsystems
    - **modulator**: the ions imprint a "density bump" on 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
  - standard electron cooling could work well for RHIC II…
  - but CEC could be orders of magnitude better:
    - stronger interaction implies shorter cooling times
    - effectiveness does not scale strongly with ion beam energy
      - could even be relevant to the LHC
  - modulator is now being simulated with VORPAL
    Bell *et al*., "VORPAL simulations relevant to Coherent Electron Cooling," EPAC Proc. (2008).

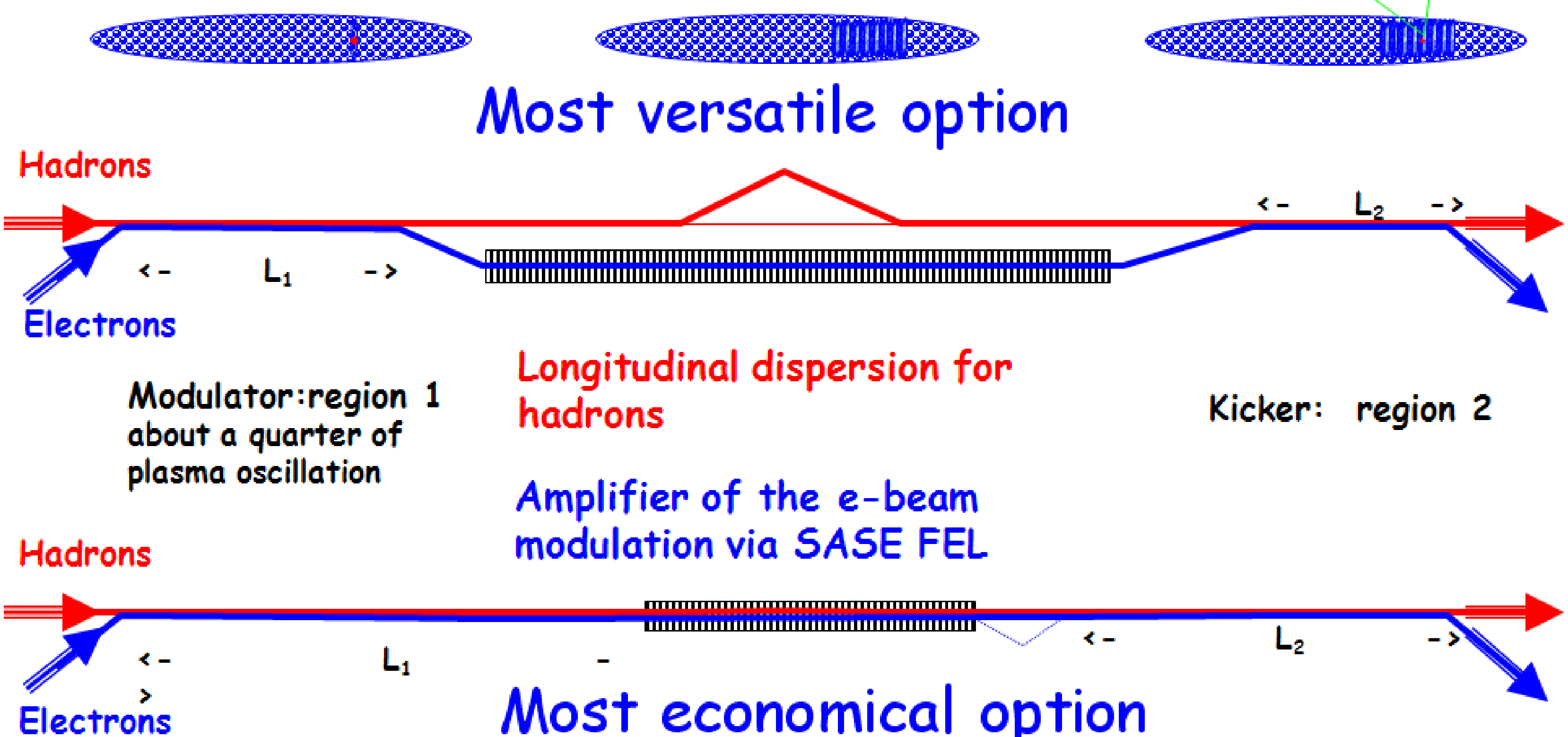
Schematic of the CEC concept

Coherent electron cooling:

ultra-relativistic case (γ>>1), longitudinal cooling

Litvinenko & Derbenev, "FELs and High-Energy Electron Cooling," FEL'07 Proc.





Simulation Overview

- **Using standard electrostatic PIC with VORPAL**
  - single, fully-ionized gold ion at rest
  - 3D domain with constant density thermal electron
    - bulk drift velocity corresponds to relative ion drift
- **Computational noise must be suppressed**
  - each e- represented by ~100 macro-particles
  - correlated e-/e+ pairs yield a perfectly quiet start
- **We assume a semi-infinite e- beam**
  - boundary conditions are difficult
  - Poisson solve is periodic
  - particles are destroyed at the boundaries
  - thermal particle distribution is injected from edges

Dimensionless & Dimensional parameters

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

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	$\zeta \equiv Z_{ion} / (4 \pi n_e R^2 \lambda^3_D)$	Plasma nonlinearity parameter.
	$\zeta = 0.1$ in the following simulations	

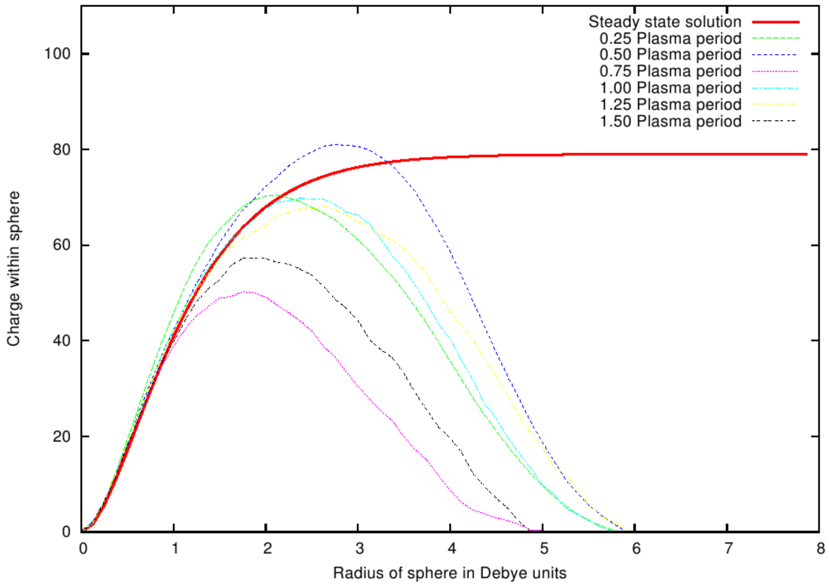
- **VORPAL uses MKS**
  - use parameters relevant to Au^{+79} at RHIC

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

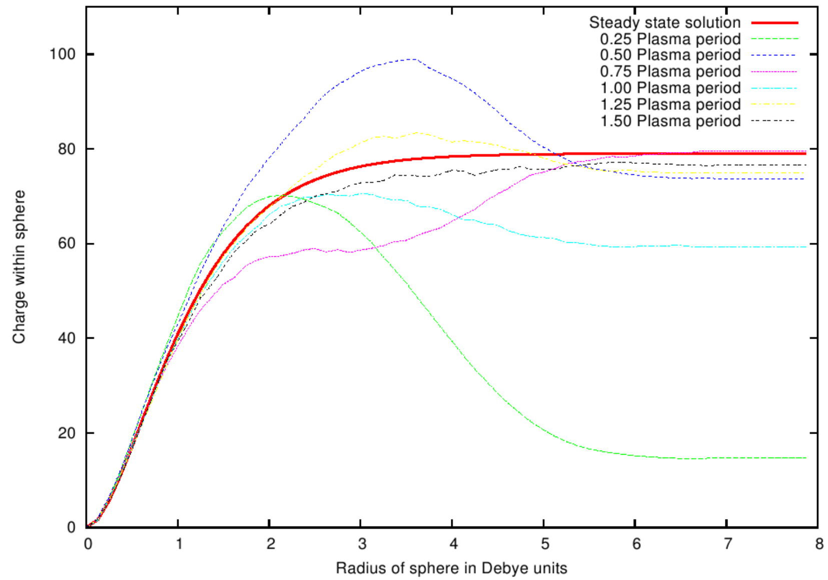
Effects of Boundary Conditions

- **Isotropic, Gaussian e- velocities**
  - steady-state, linear theory predicts e- charge distrib.
  - VORPAL simulations show reasonable agreement
    - cannot use periodic BCs for the electrons
    - time required to reach steady-state is seen

Periodic BCs for particles



Thermal emission at boundaries

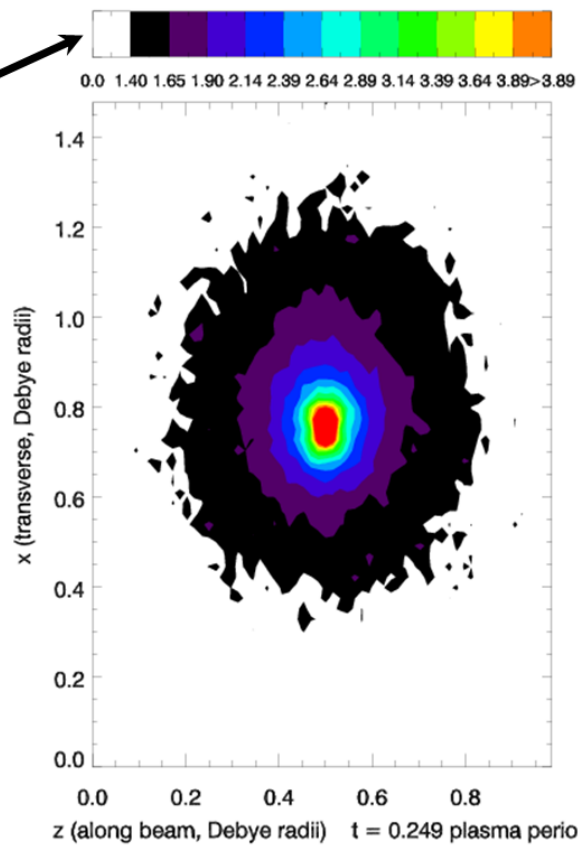


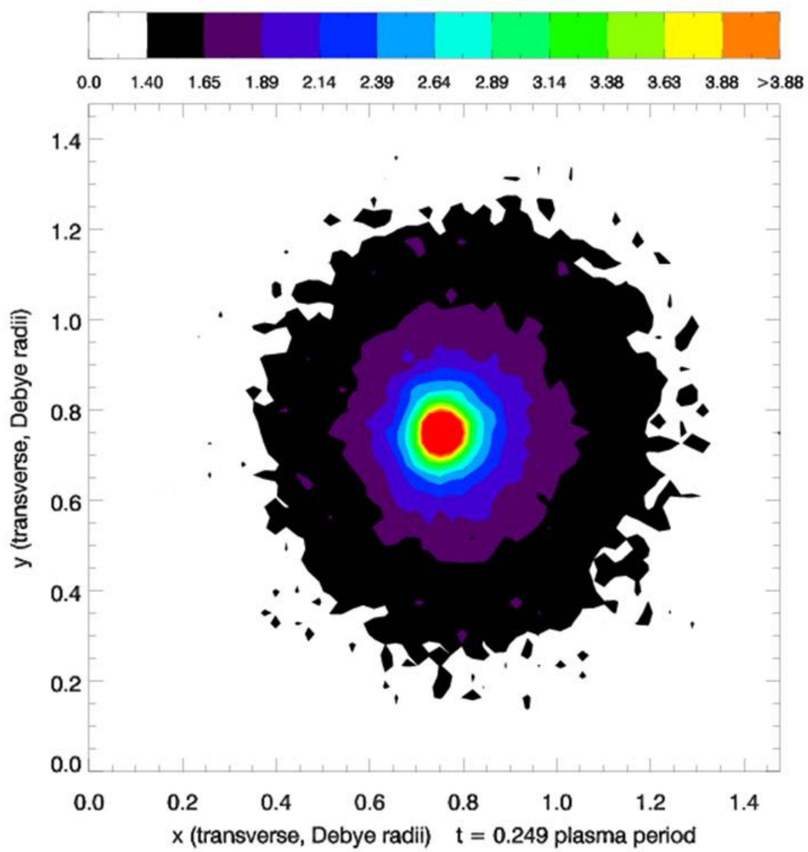
Effects of temperature anisotropy

Stationary ion

R = 3 (non-isotropic); T = 0 ; Z = 0

density enhancement color scale



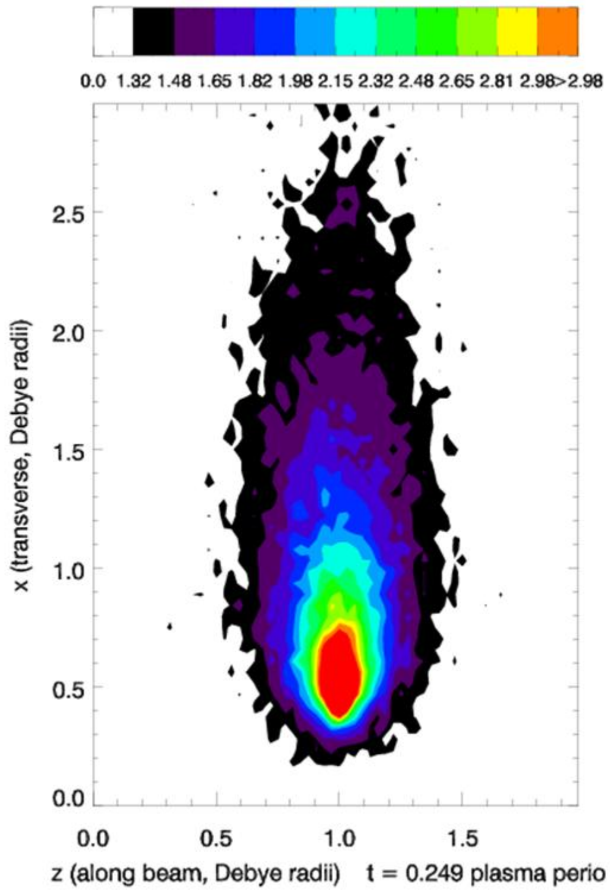


Effects of ion motion

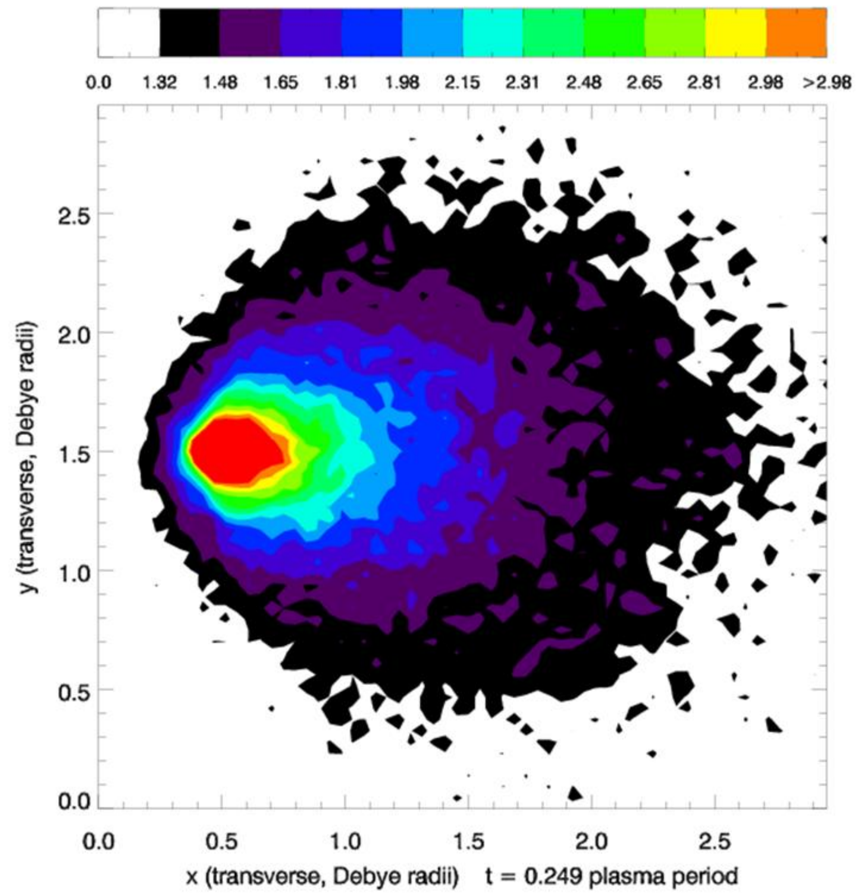
Ion moving transversely

R = 3; T = 5.6 ; Z = 0

Z (along beam) vs. X (transverse)



X (transverse) vs. Y (transverse)

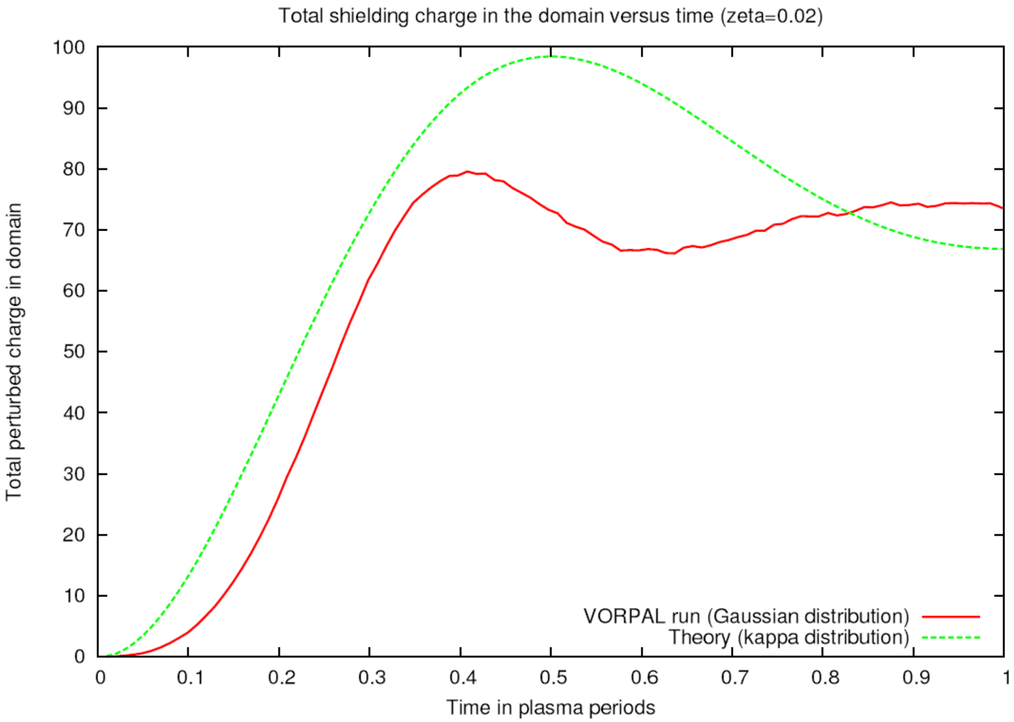


Comparison with theory

- **Dynamical friction vs. details of e- density wake**
  - conventional electron cooling
    - key metric is dynamical friction force on ions
    - interaction time small compared to plasma period
  - Coherent Electron Cooling (CEC); modulator & kicker
    - dynamical friction is irrelevant
    - key metric is size/shape of e- density wake
    - very little theory available until recently
- **New analytical results for e- density wake**
  - Wang & Blaskiewicz, Phys. Rev. E (2008), in press.
  - many details for “kappa” or Lorentzian velocity distrib.
    - “kappa=1” distribution now implemented in VORPAL
    - for slow ions, results are very similar for Gaussian

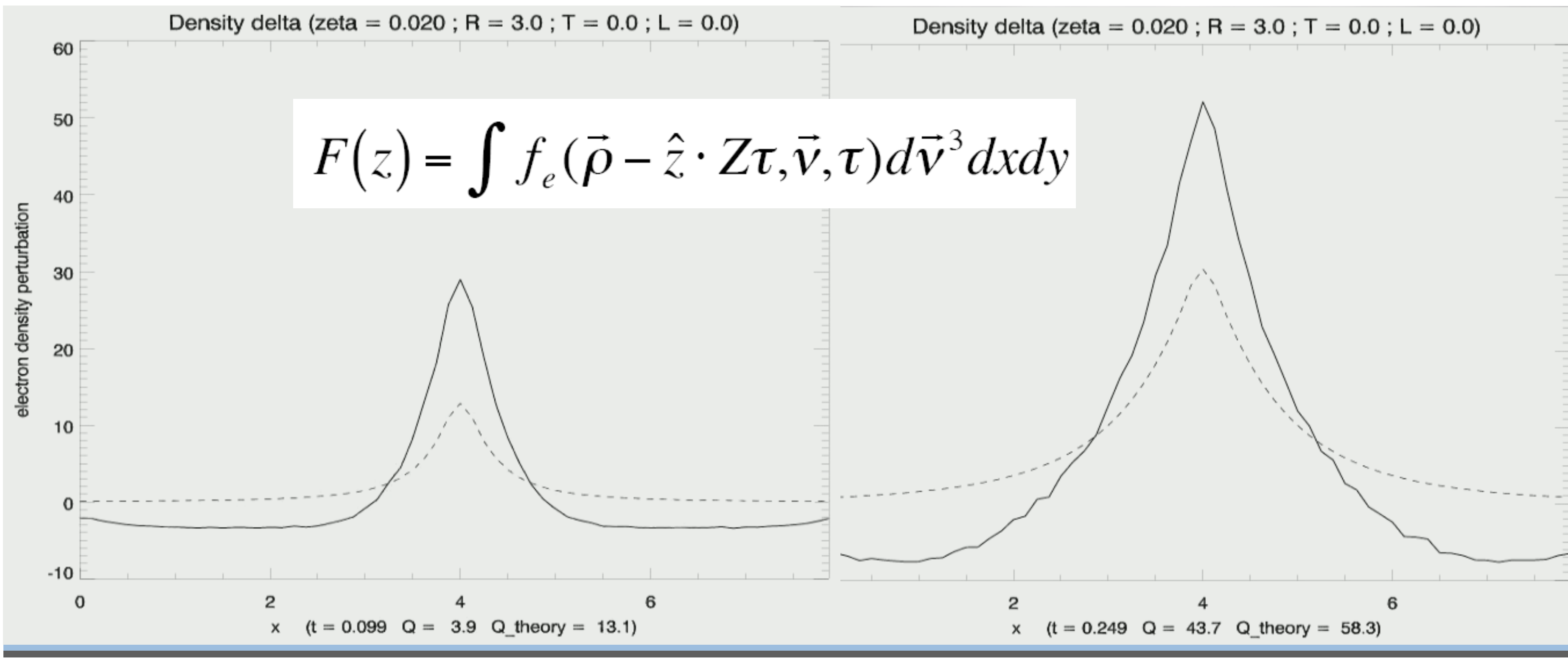
Shielding charge within 4 λ_D of the ion

- **Analysis of W&B provides more detail**
  - anisotropic e- temperatures
  - time dependence
- **VORPAL simulations do not agree closely**
  - BCs are suspect; limited particle influx
  - larger domains, and kappa velocity distributions will be explored



Theory & numerics differ at early times

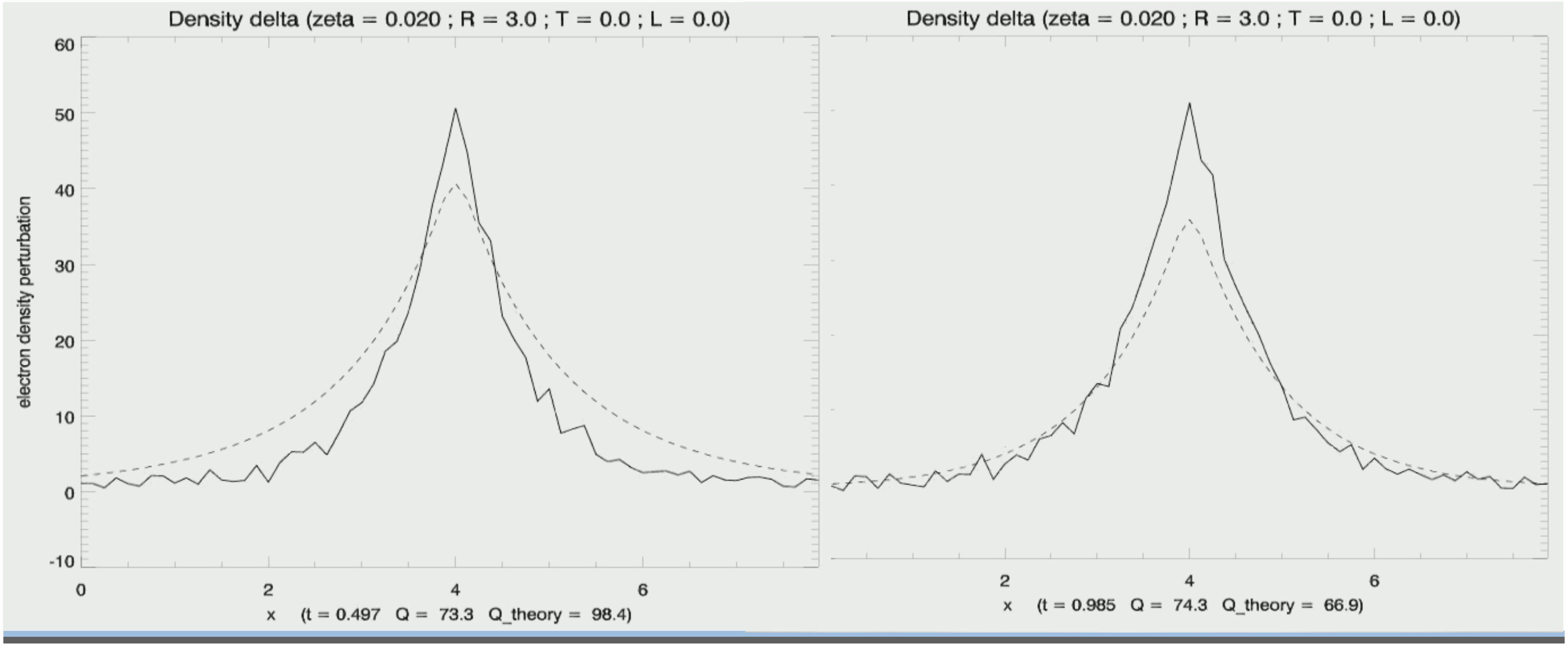
- **W&B assume infinite domain**
  - this e- reservoir moves inward at early times
  - VORPAL assumes external fields are zero



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

Theory & numerics agree at later times

- **after $t \sim 1/\omega_{pe}$, BCs become less important**
  - sufficiently close to ion, dynamics remains nonlinear
    - possibly exaggerated by cell size in simulations



Future work

- **Modulator / Amplifier / Kicker**
  - simulate modulator with VORPAL
    - 1D integrals of e- wake provide input to FEL theory
    - particle files converted for input to other codes
  - simulate FEL amplifier with GENESIS
  - simulate particle transport with MaryLie/IMPACT
    - phase shift of ions wrt electrons is critical
  - simulate kicker with VORPAL
- **Modulator simulations**
  - consider effects of finite e- beam size
    - wakes will be asymmetric
  - consider effects of multiple ions
    - dynamics is nonlinear in immediate vicinity of ion