Coherent electron cooling simulations for parameters of the BNL proof-of-principle experiment

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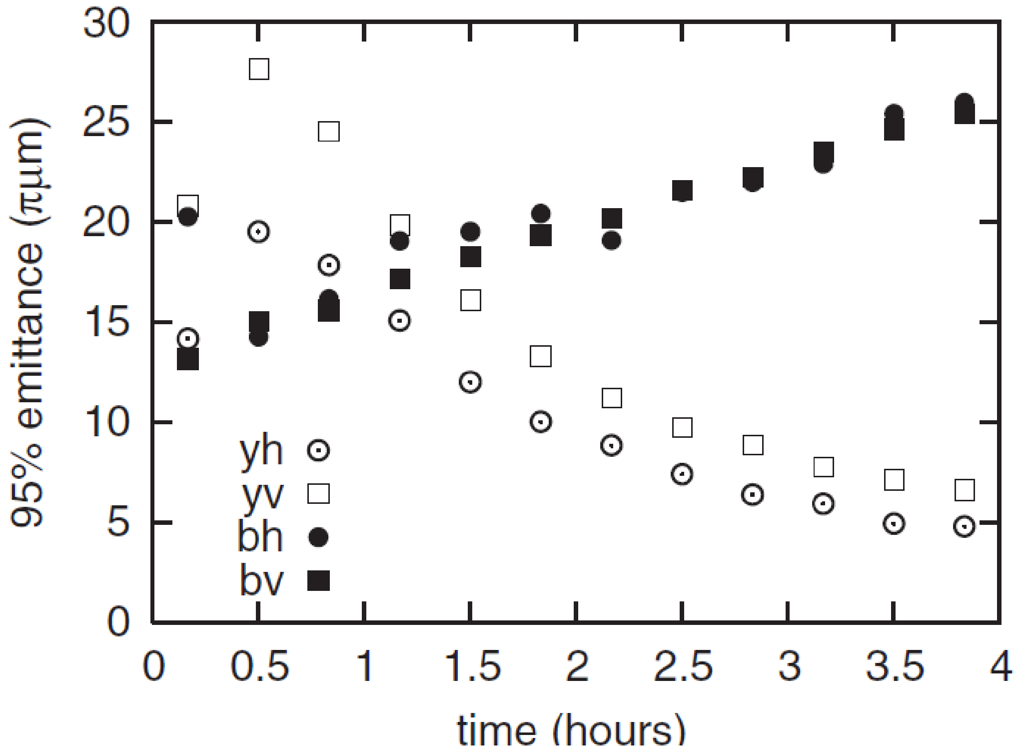
Outline

- The need for cooling of hadron beams
- Electron cooling cartoon
- What is Coherent Electron Cooling (CEC)?
    - Modulator
    - FEL
    - Kicker
- Simulation of the three CEC components
- Dynamical friction ⇨ beam cooling
- Summary and future work

hadron beam cooling

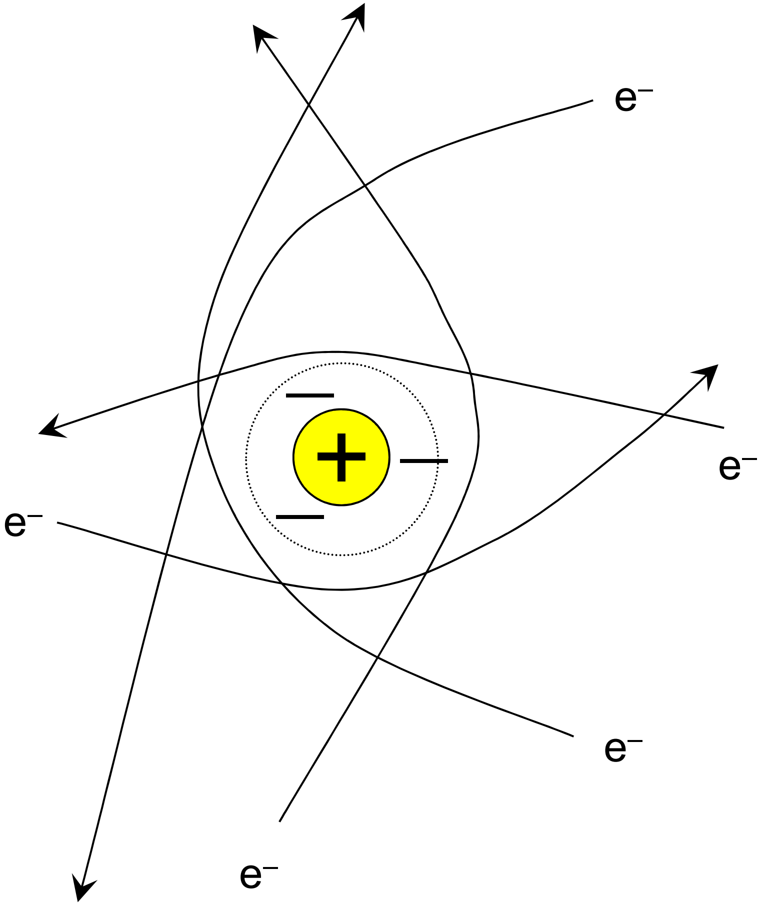
- Many mechanisms can degrade hadron beams in storage rings
  - Intra-beam scattering
  - Beam-beam collisions
  - Scattering off neutral particles
  - Electron cloud

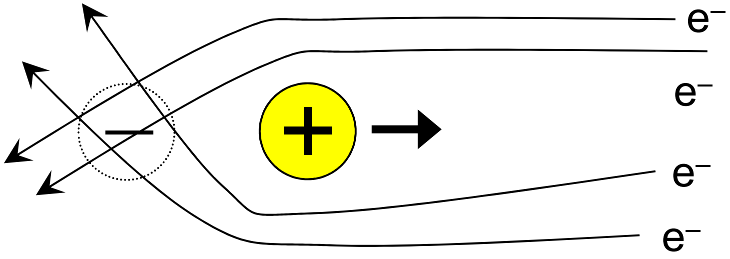


Stochastic cooling success!

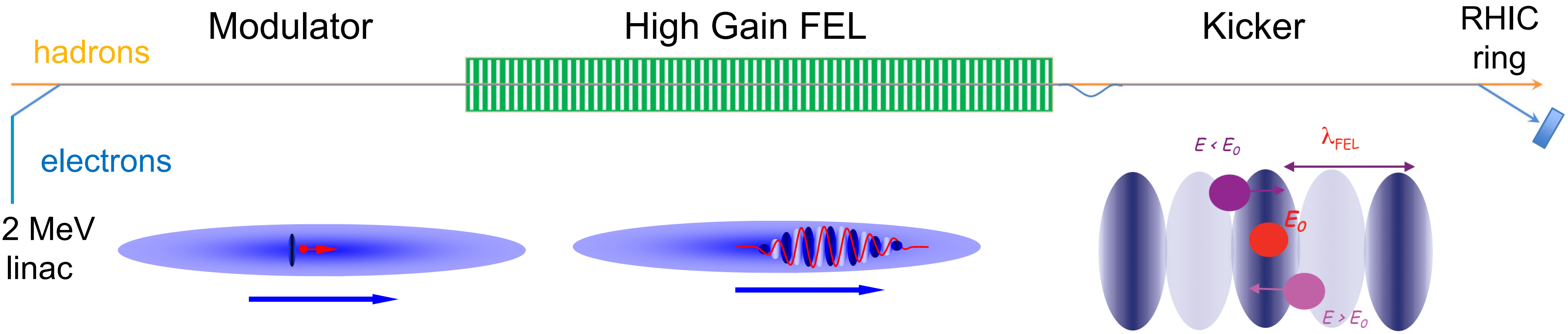
From: Blaskiewicz, Brennan & Mernick, Phys. Rev. Lett. **105**, 094801 (2010)

Electron Cooling Mechanism





Schematic of the BNL Coherent Electron Cooler (Proof-of-Principle)



hadrons

Modulator

High Gain FEL

Kicker

RHIC ring

electrons

22 MeV linac

$E < E_0$

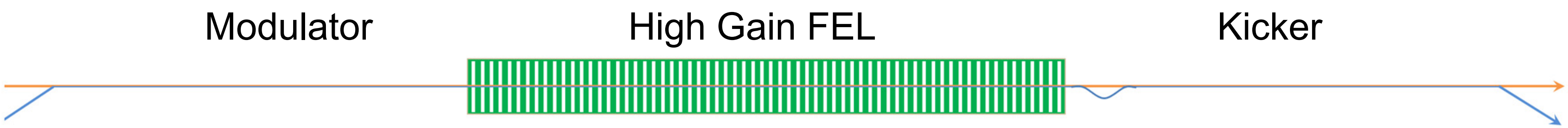
λ_{FEL}

E_0

$E > E_0$

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

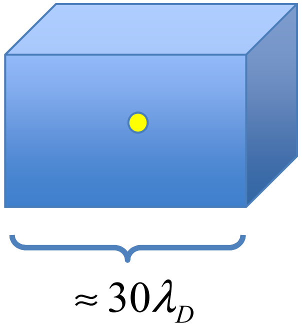
Modeling Coherent Electron Cooling (CEC)

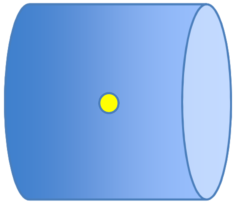


Modulator High Gain FEL Kicker

Section	Code	Frame
Modulator	Vorpal Delta-f PIC	Beam
FEL	Genesis: linear regime, no saturation, ions ignored	Lab
Kicker	Vorpal PIC	Beam

Hierarchy of Modulator Models





- Uniform electron density, infinite plasma, Lorentzian velocity distribution, non-isotropic
  - Exact solution found by *G. Wang and M. Blaskiewicz, Phys Rev E* ***78****, 026413 (2008).*
- Same except Gaussian velocity distribution
- Electron density decreases with radius, external focusing, beam is in equilibrium
- Electron density defined by Twiss parameters, quadrupole focusing, beam is not an equilibrium solution

$$f(\vec{x},\vec{v},t) = \underbrace{f_0(\vec{x},\vec{v},t)}_{\substack{\text{bulk beam} \\ \text{(known solution)}}} + \underbrace{\delta f(\vec{x},\vec{v},t)}_{\text{perturbation}}$$

CEC Proof-of-Principal experimental parameters

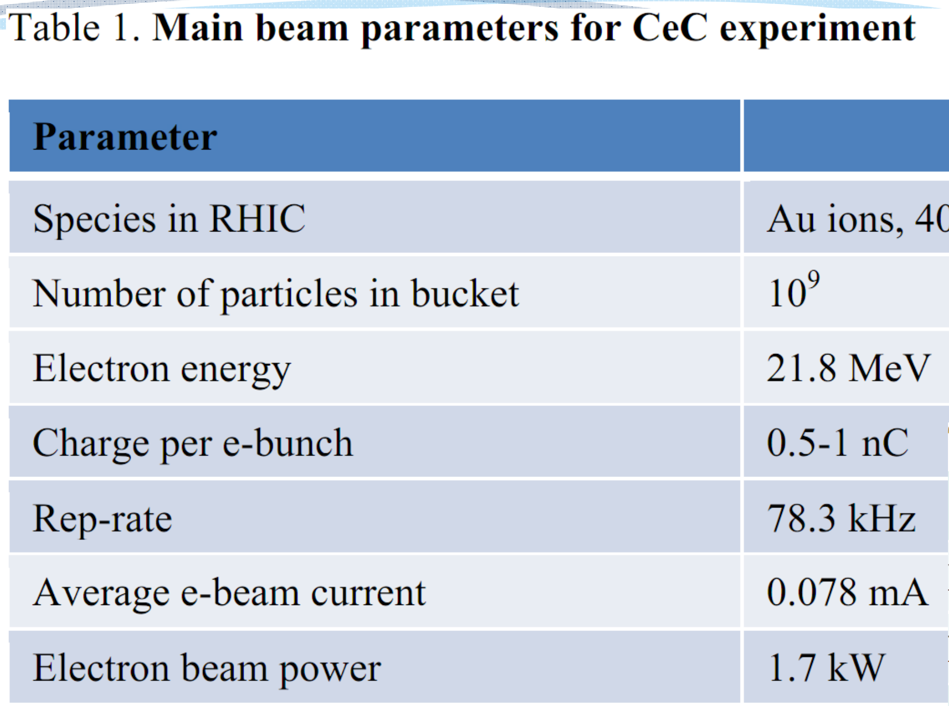


Table 1. **Main beam parameters for CeC experiment**

Parameter	
Species in RHIC	Au ions, 40 GeV/u
Number of particles in bucket	10^9
Electron energy	21.8 MeV
Charge per e-bunch	0.5-1 nC
Rep-rate	78.3 kHz
Average e-beam current	0.078 mA
Electron beam power	1.7 kW

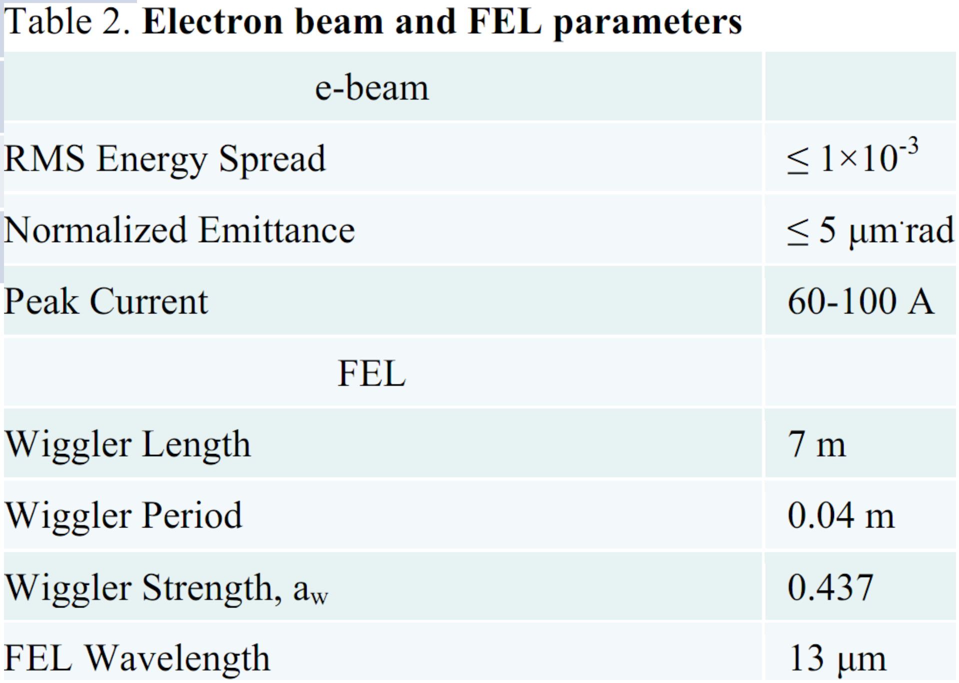


Table 2. **Electron beam and FEL parameters**

e-beam	
RMS Energy Spread	$\leq 1\times10^{-3}$
Normalized Emittance	≤ 5 µm·rad
Peak Current	60-100 A
FEL	
Wiggler Length	7 m
Wiggler Period	0.04 m
Wiggler Strength, a_w	0.437
FEL Wavelength	13 µm

Ref: Litvinenko & Pinayev, “White Paper: Coherent Electron Cooling Experiment at Ip2”, Dec. 27, 2011

Modulator simulations are successfully validated.

Drifting ion simulations agree w/ theory [7]

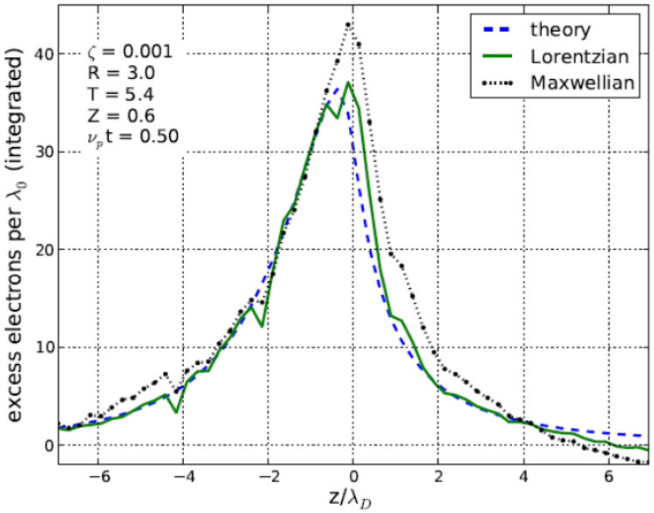


Figure 3: Longitudinal charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

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

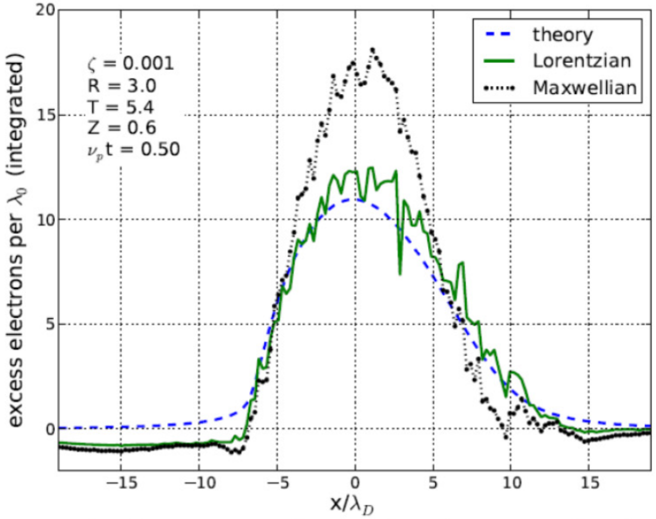
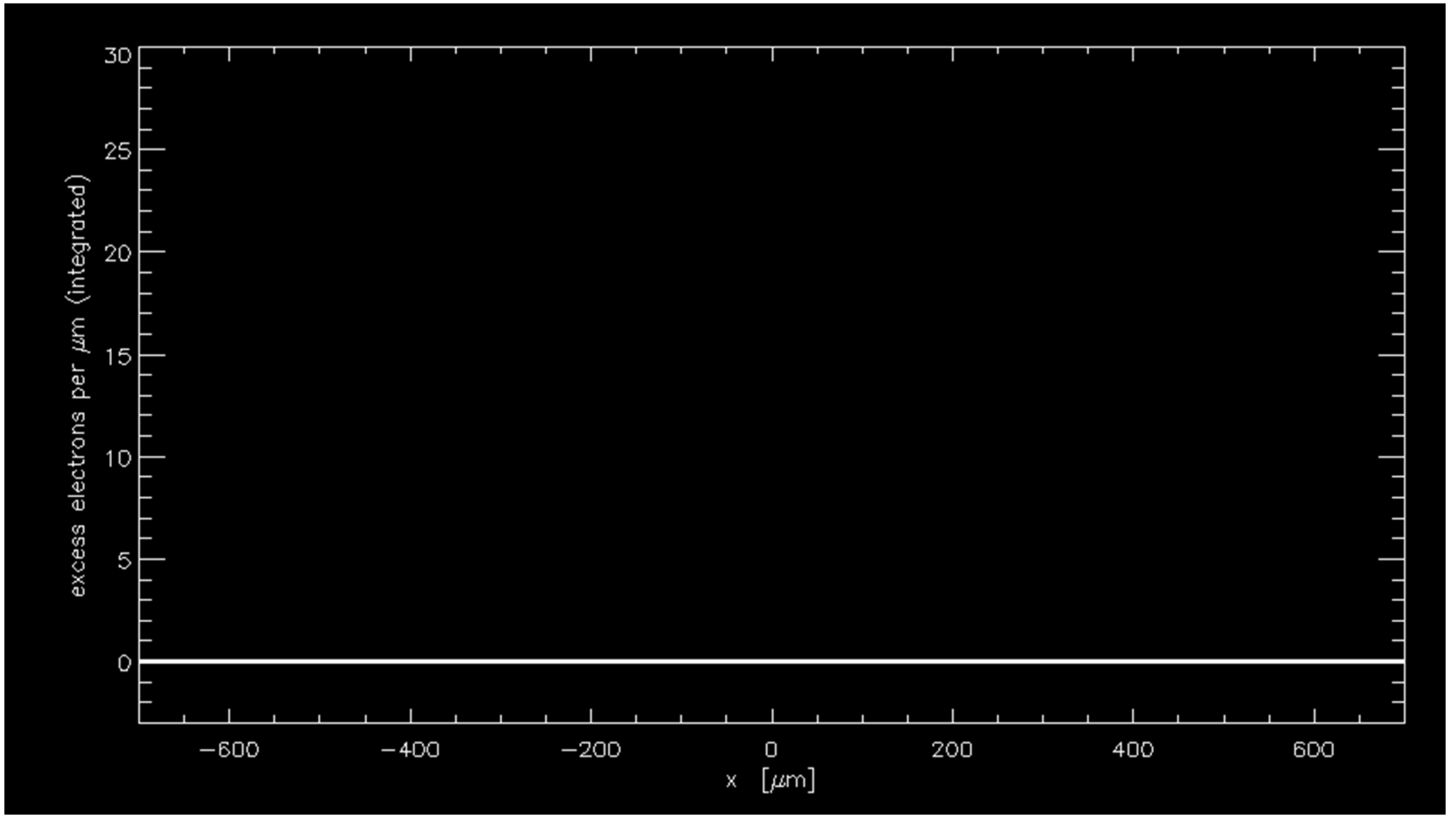


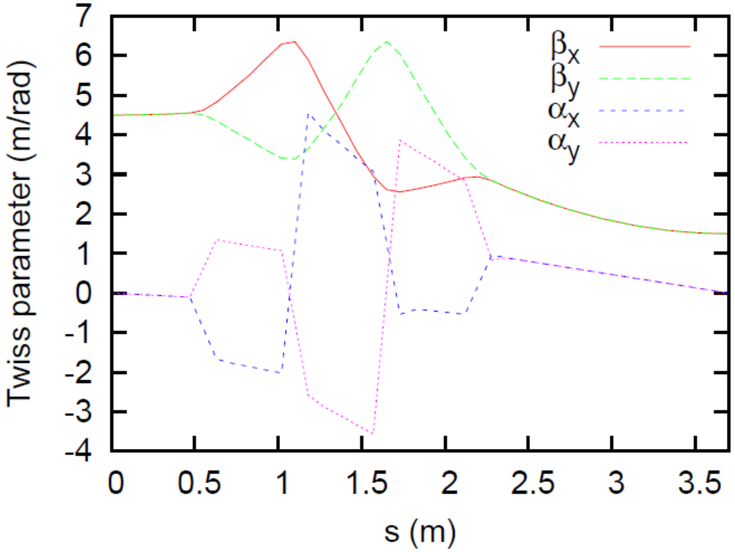
Figure 4: Transverse charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

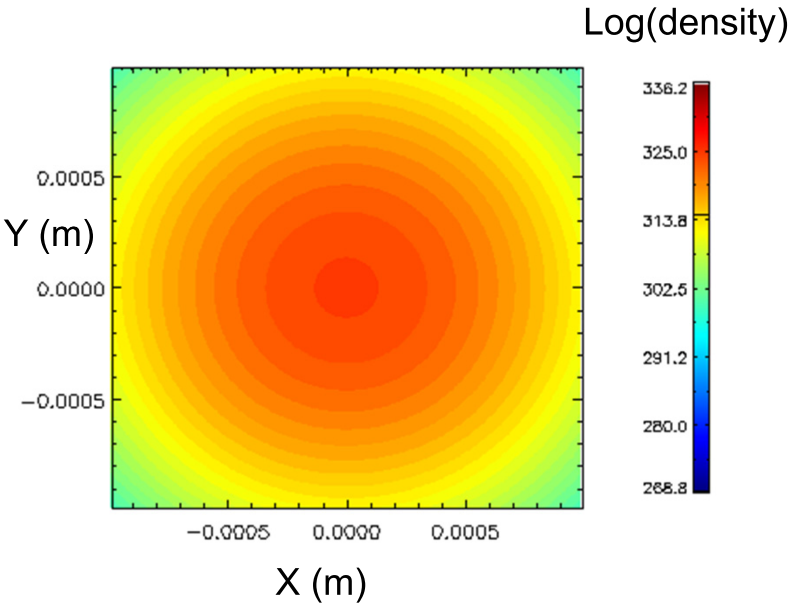
Evolution of a density perturbation (theory vs. simulation)

Dashed curve – Wang and Blaskiewictz theory
Solid curve – Vorpal simulation



A beam defined in terms of Twiss parameters





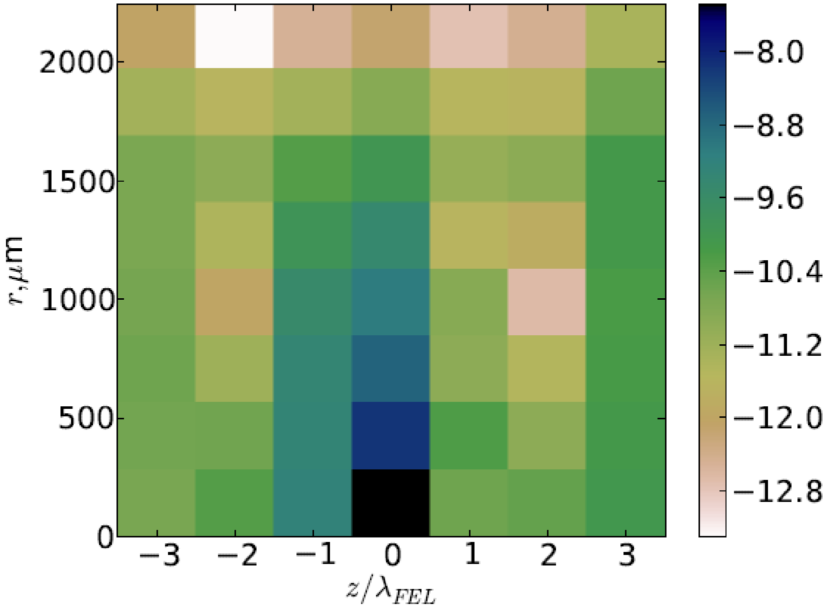
Coupling modulator results to FEL simulations; being explored with multiple approaches

VORPAL → GENESIS 1.3

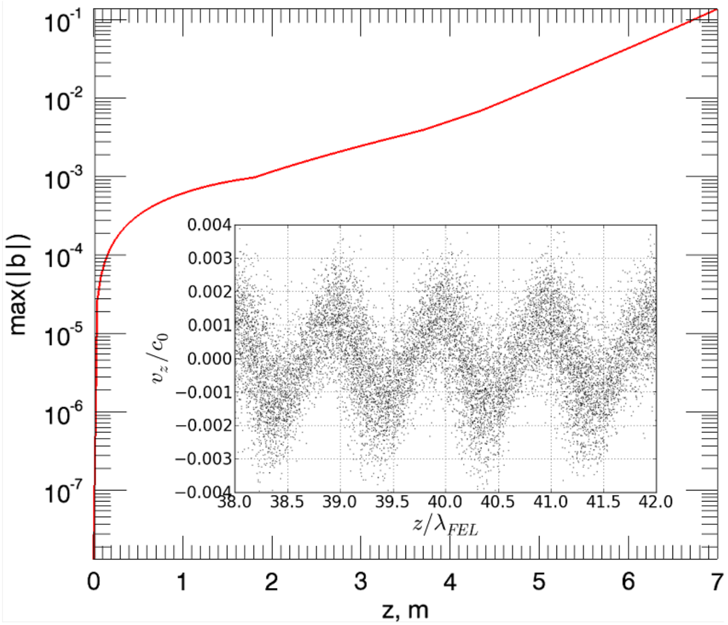
3D modulator simulations
via δf PIC

3D simulations of the high-gain
SASE FEL amplifier

Growth of bunching along FEL for CEC PoP parameters



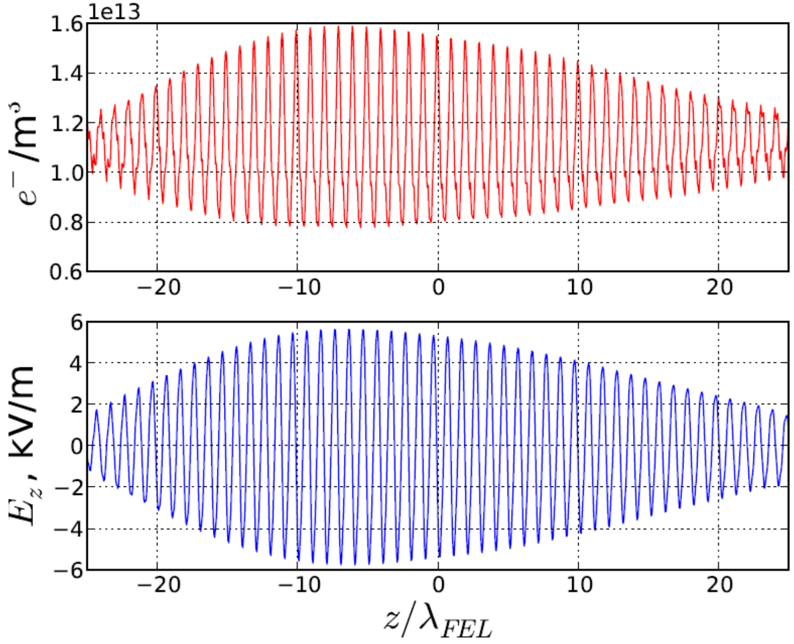
Magnitude of electron beam bunching coefficients b, plotted as log10(|b|), in the vicinity of a shielded ion located at z=0 with positive velocity v_z.



Maximum value of electron beam bunching magnitude as a function of beam's position in a free-electron laser. Inset: Modulation of electron longitudinal velocities (beam frame) at the end of the FEL.

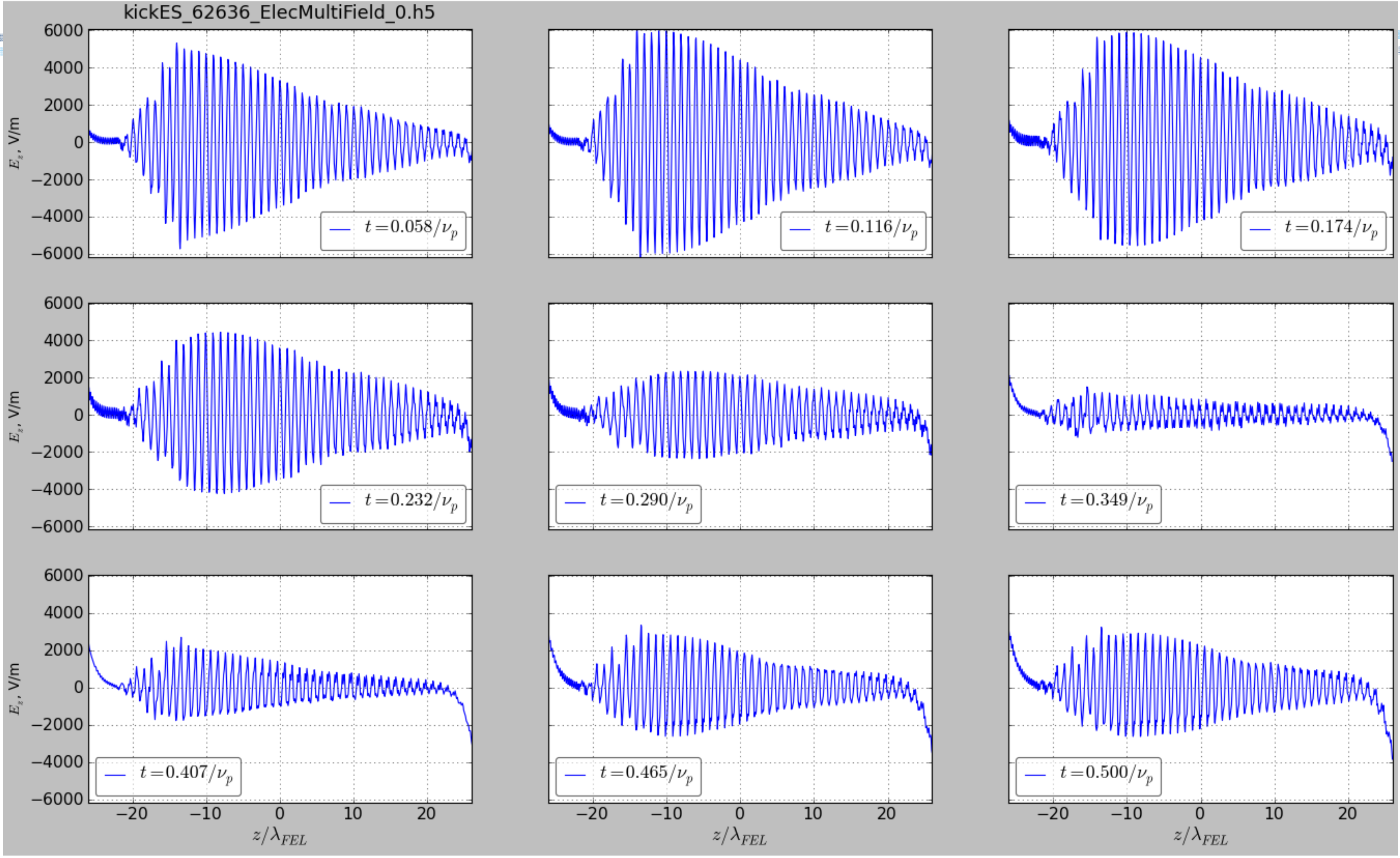
Coupling modulator results to FEL simulations

3D simulations of the high-gain SASE FEL amplifier

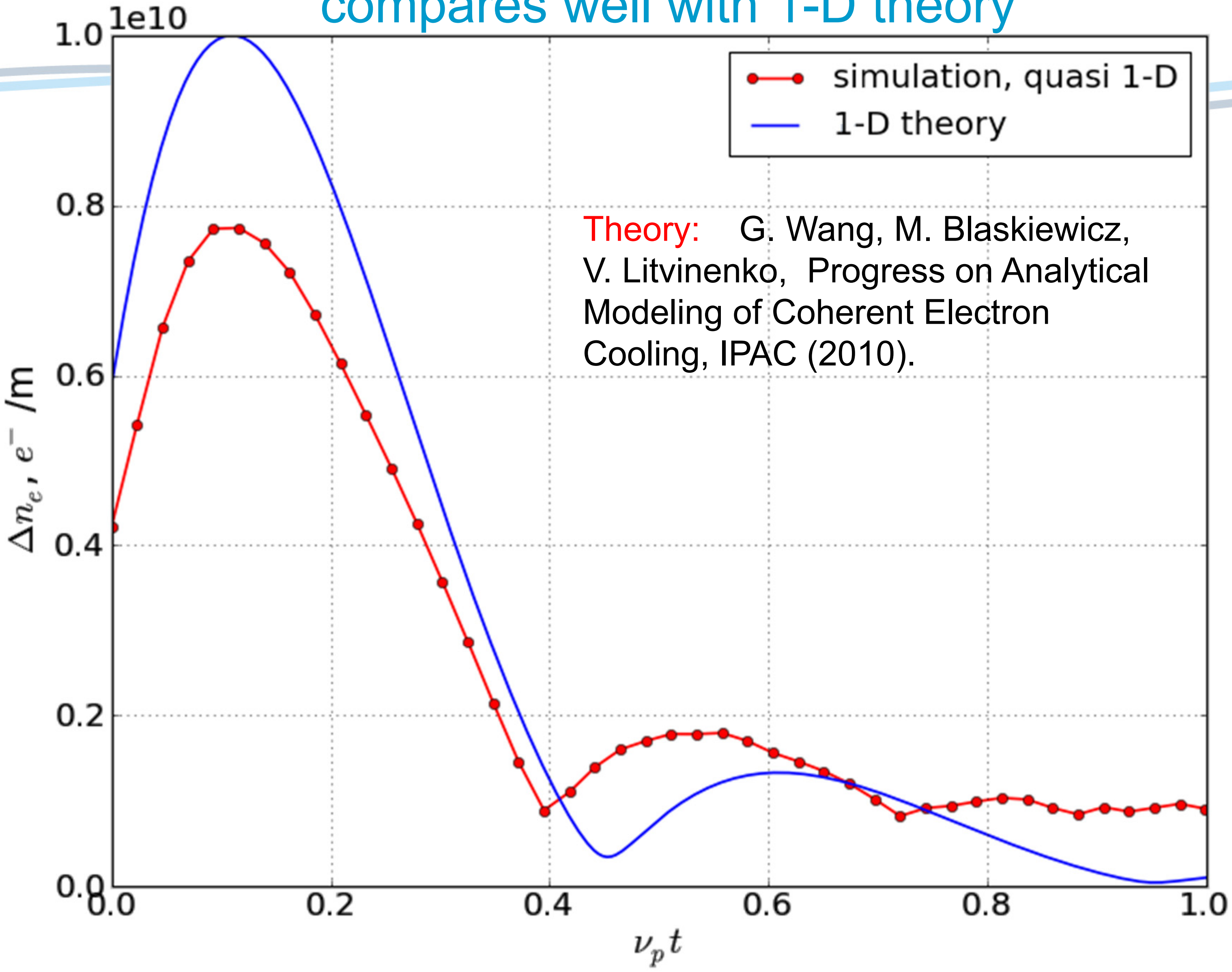


3D kicker simulations via electrostatic PIC (beam frame)

Electric fields in kicker computed in Vorpal for ½ plasma period



Electron density modulation compares well with 1-D theory



Theory: G. Wang, M. Blaskiewicz, V. Litvinenko, Progress on Analytical Modeling of Coherent Electron Cooling, IPAC (2010).

Dynamical friction ➡ beam cooling

- Cooling plus diffusion
  - Cooling kick is obtained by starting with the shielding wake and running through FEL and kicker

$$\left|E^c\right| = 3.91 kV / m$$

  - Diffusive kick is obtained by starting with noise and running through FEL and kicker

$$\left|E^i\right| = 3.24 kV / m$$

- The cumulative effect of cooling and diffusive kicks over many CEC passages
  - Stochastic cooling: cooling time estimate: 1.5 hours
    D. Möhl, Nucl. Instr. Meth. A, **391**, 164-71 (1997)
  - CEC: cooling time estimate: 6 seconds!!
    BUT, this assumes we can cool all ions in a bunch at the same time, which is not the case.

Summary and Next Steps

- We have simulated the passage of ions through all three CEC stages
  - Modulator calculations are the most computationally intensive
  - Modulator can now be simulated with realistic beam profiles, including beam focusing
  - Simulations agree with analytical estimates
    - In the modulator (Wang-Blaskiewicz, 2008)
    - In the kicker (Wang-Blaskiewicz-Litvinenko, 2010)
- Next Steps
  - Run many 3D delta-f PIC simulations with different velocities and positions
  - Insert parameterized kicks into BETACOOL, which can then simulate beam cooling

Acknowledgments

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

ComPASS – *Community Petascale Project for Accelerator Science and Simulation*

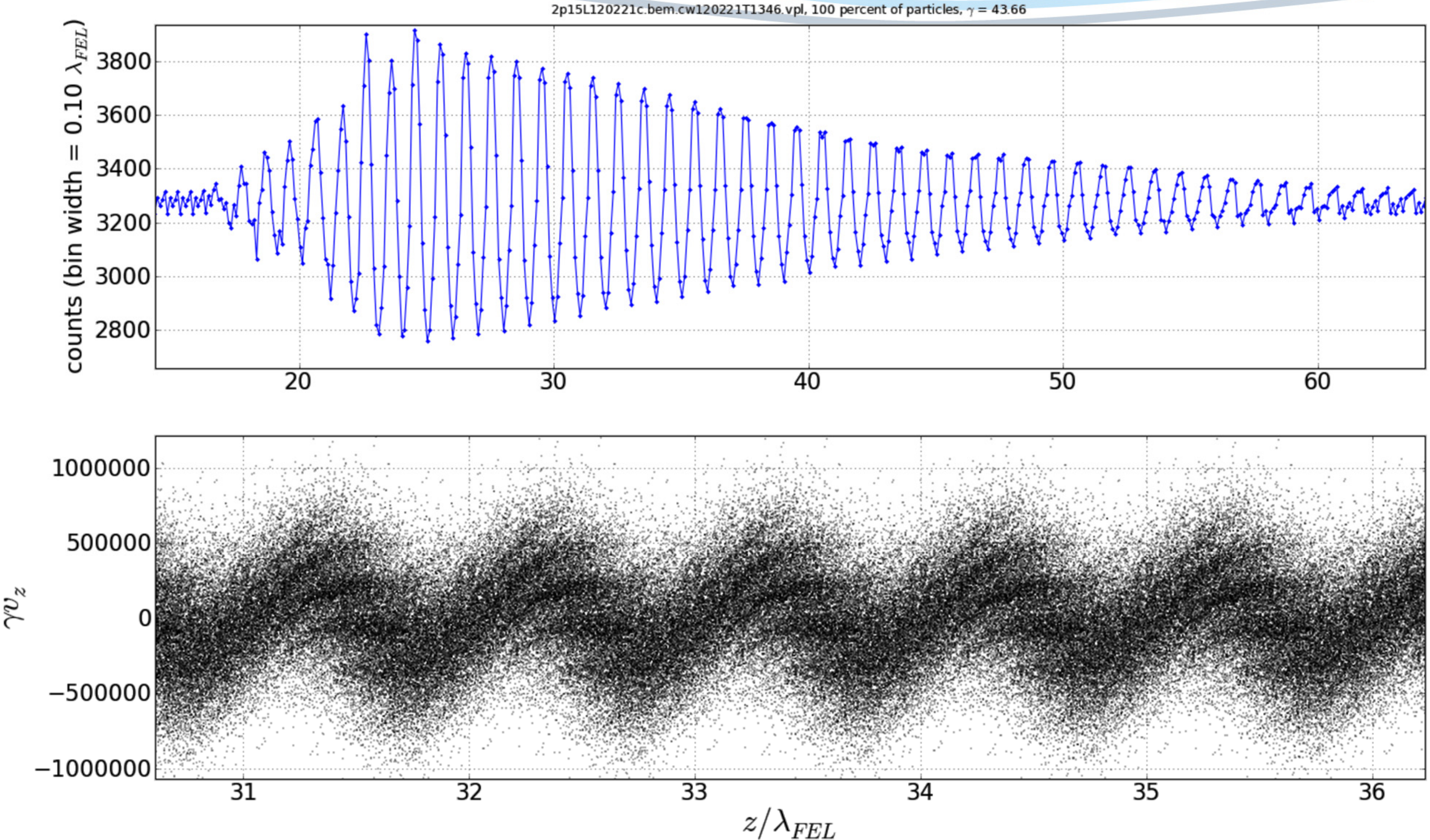
Boulder, Colorado USA

Extra Slides

TECH-X

SIMULATIONS EMPOWERING
YOUR INNOVATIONS

Electron density & γ modulation at FEL output



Overview

- 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

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

- Analytic results for e- density perturbations

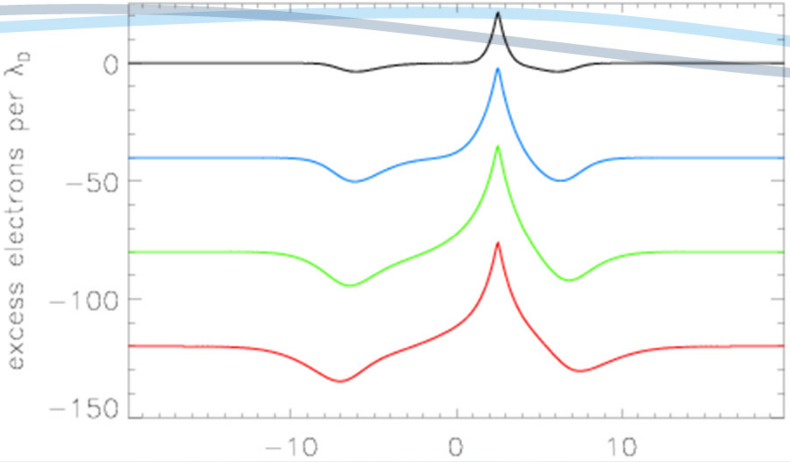
*G. Wang and M. Blaskiewicz, Phys Rev E **78**, 026413 (2008).*

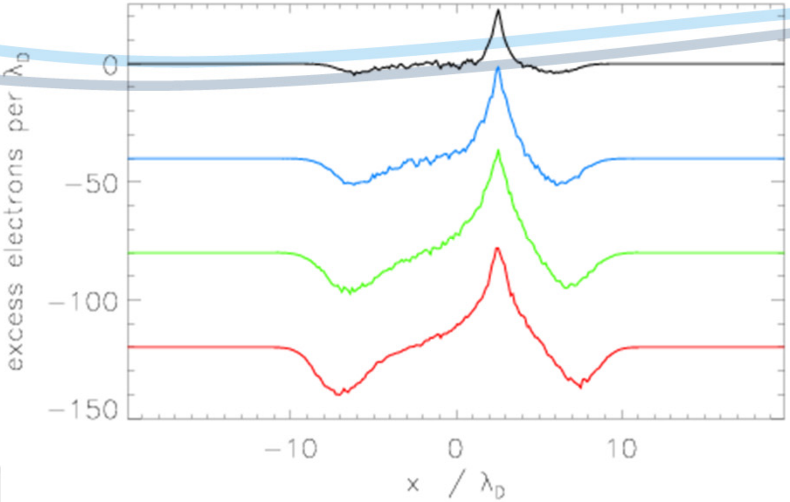
$$\delta n(\mathbf{x},\mathrm{t})=\frac{Zn_o\omega_p^3}{\pi^2\sigma_{\mathrm{v}x}\sigma_{\mathrm{v}y}\sigma_{\mathrm{v}z}}\int_0^{\omega_p t}\frac{\tau\ \sin(\tau)\ d\tau}{\left(\tau^2+\left(\left(\mathrm{x}-\mathrm{v}_{\mathrm{th,x}}\tau/\omega_p\right)/r_{Dx}\right)^2+\left(\left(\mathrm{y}-\mathrm{v}_{\mathrm{th,y}}\tau/\omega_p\right)/r_{Dy}\right)^2+\left(\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

  - theory makes certain assumptions:
    - single ion, with arbitrary velocity
    - uniform e- density; *anisotropic* temperature
      - Lorentzian velocity distribution
    - linear plasma response; *fully 3D*
- Dynamic response extends over many λ_D and $1/\omega_{pe}$

rmal ptcl boundary conditions are important

Vlasov compares well with δf PIC (single ion in 1D beam with space charge)



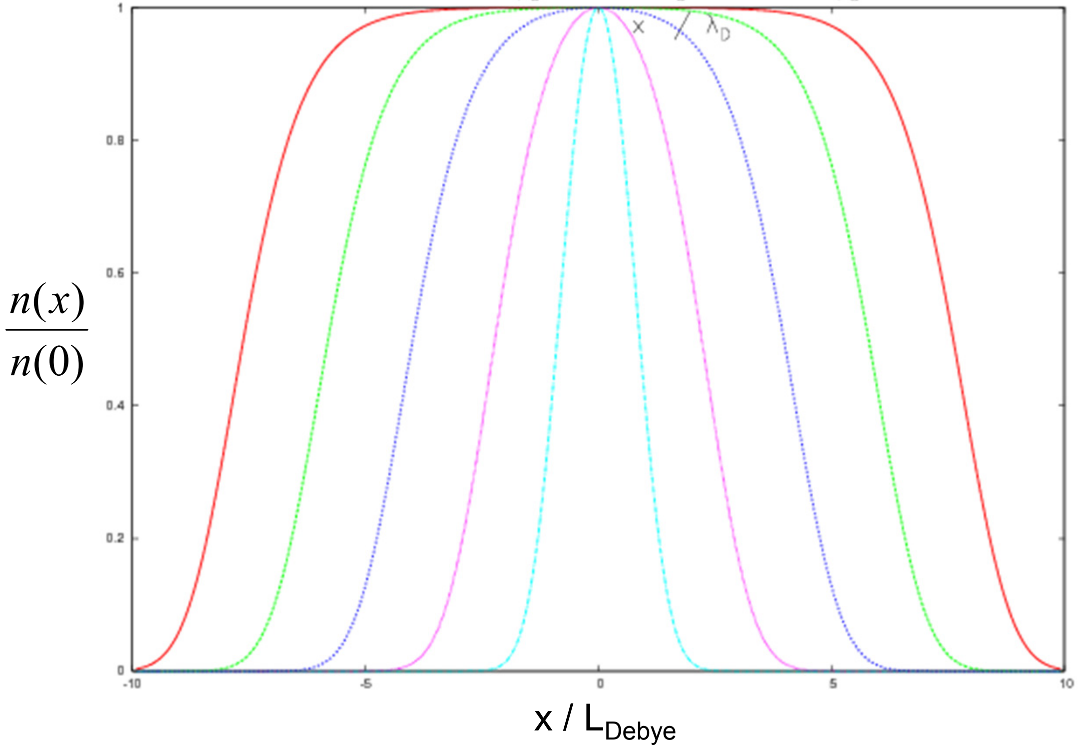


Black: 1/8 plasma period

Blue: 1/4 plasma period

Green: 3/8 plasma period

Red: 1/2 plasma period

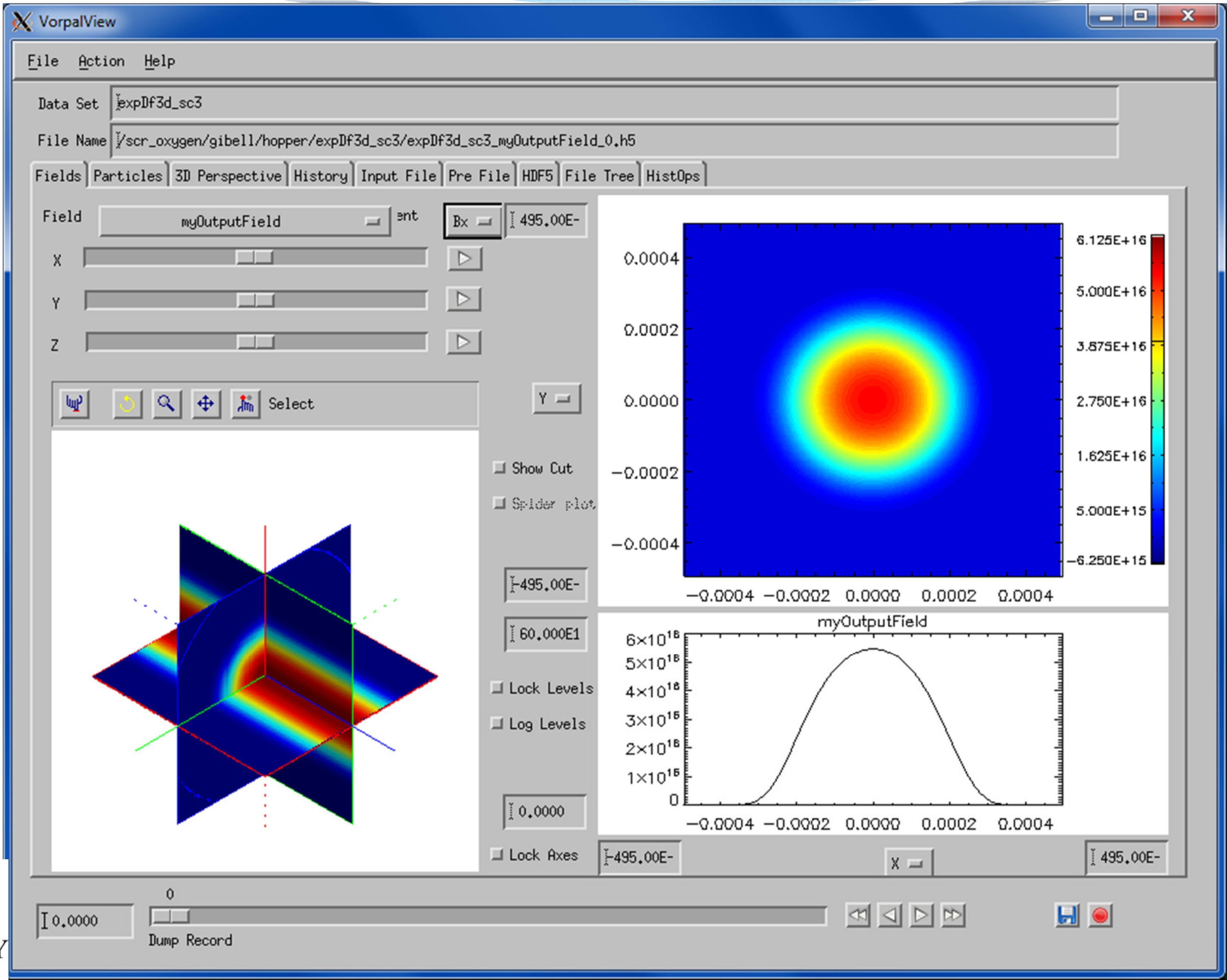


$$\frac{E'_{ext}}{E'_{sc}} = 1.0001 \quad 1.001 \quad 1.01 \quad 1.1 \quad 2.0$$

3D Delta-f simulations

- Equilibrium beam has radial symmetry transversely, with a linear focusing field $E_{ext} = E_0' r$
- In z we model a thin slice of the beam, 0.88 mm thick
- The equilibrium beam has uniform density in z, and Gaussian in r
- Beam width is 0.6mm (artificially narrow to keep the domain reasonably small)
- Field solve is periodic in z, and Dirichlet in x and y

3D Delta-f Beam Simulation



Data Set expDf3d_sc3

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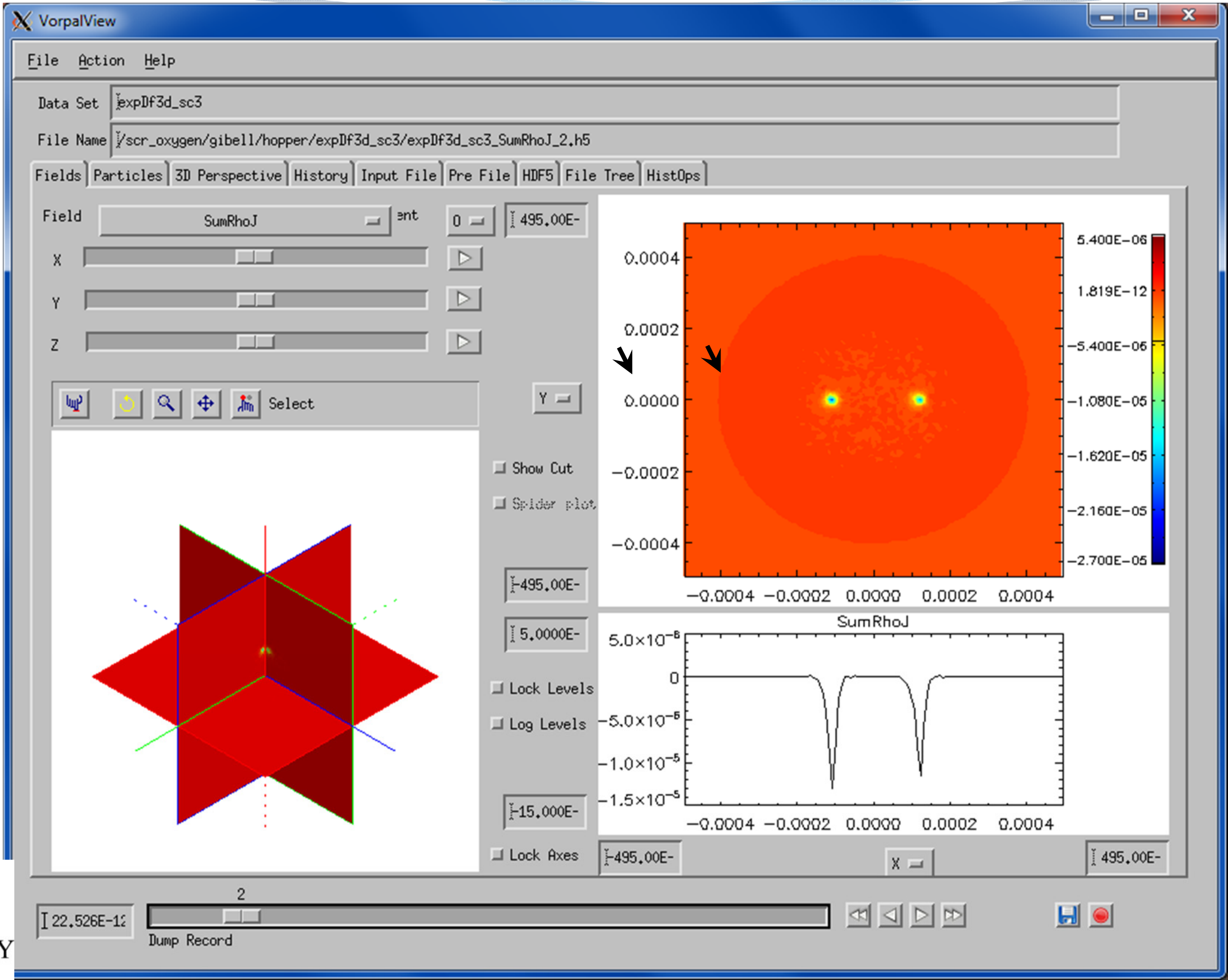
Field myOutputField

Two Ions moving longitudinally



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Field: SumRhoJ

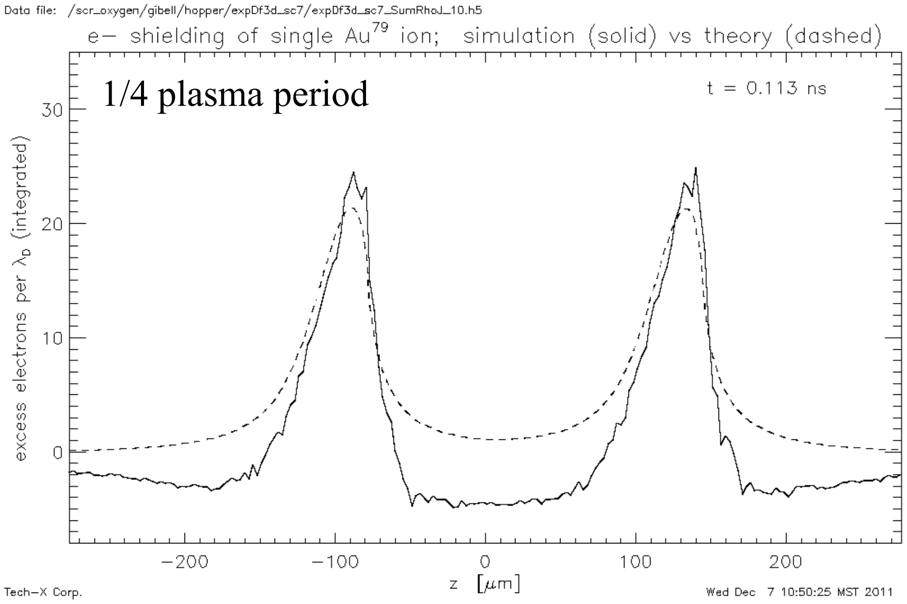
3D δf Simulations of the Modulator, with two ions moving longitudinally

3D Simulations include:

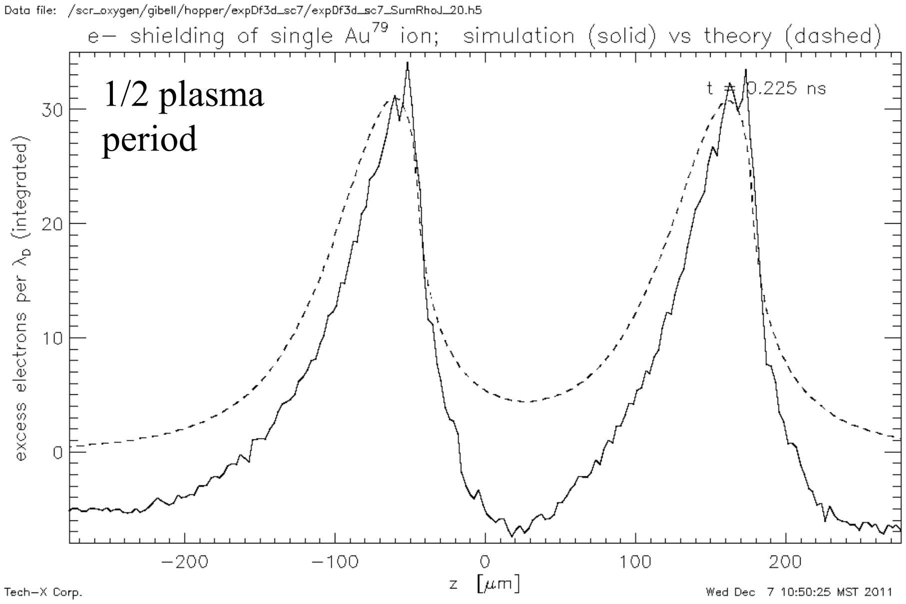
- Entire beam (0.6mm in diameter)
- Equilibrium maintained by external focusing
- Gaussian velocity distrib.

Theory is from Wang and Blaskiewicz

- Constant e- density (out to infinity)
- No external fields
- kappa-2 (Lorentzian squared) velocity distrib.



1/4 plasma period

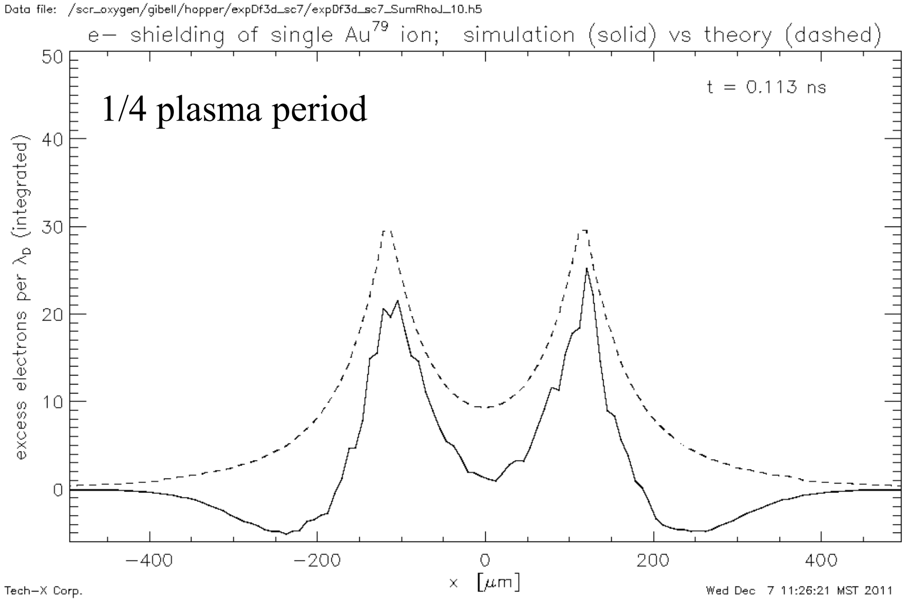


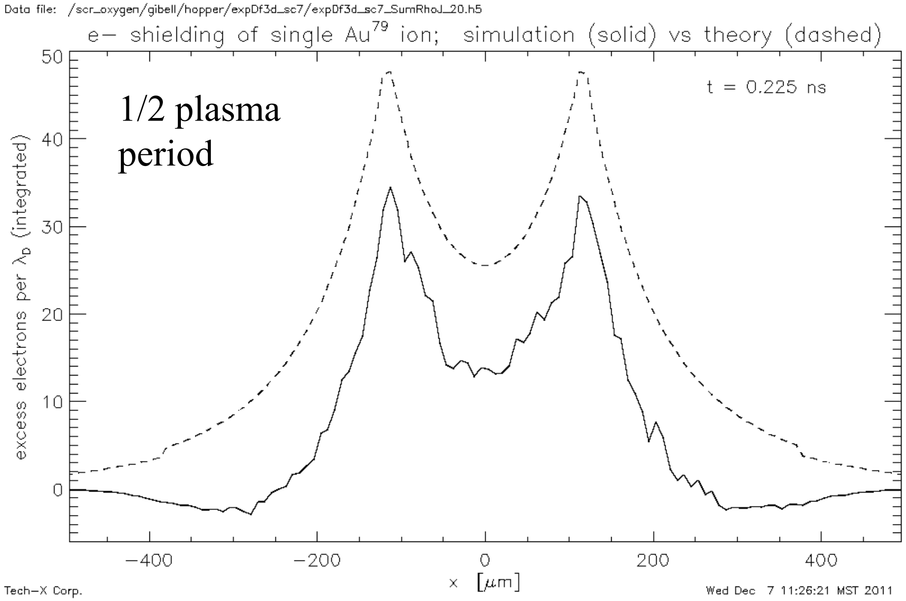
1/2 plasma period

Longitudinal variation of the density is shown

3D δf Simulations of the Modulator, with two ions moving longitudinally

Parameter	Value	Parameter	Value
Density	5.48×10^{16} e-/m^3	Debye x,y	66μ
Density at ion	82% of peak	Debye z	22μ
Plasma Freq.	1.32×10^{10} rad/sec	R = Debye x / Debye z	3
Beam radius	$0.3mm = 300\mu$		

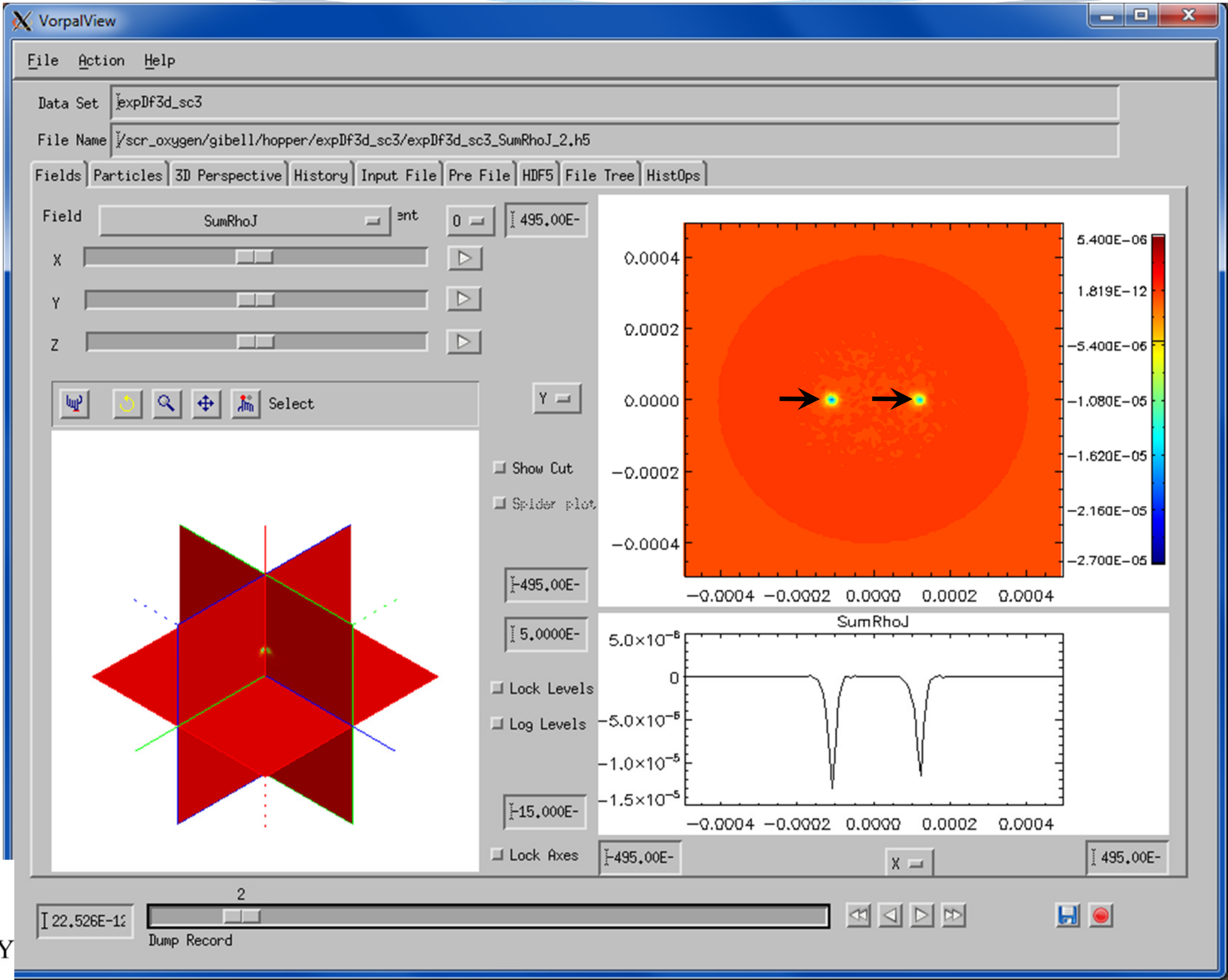




Transverse variation of the density is shown

e- beam is artificially narrow

Two Ions moving transversely



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Field: SumRhoJ

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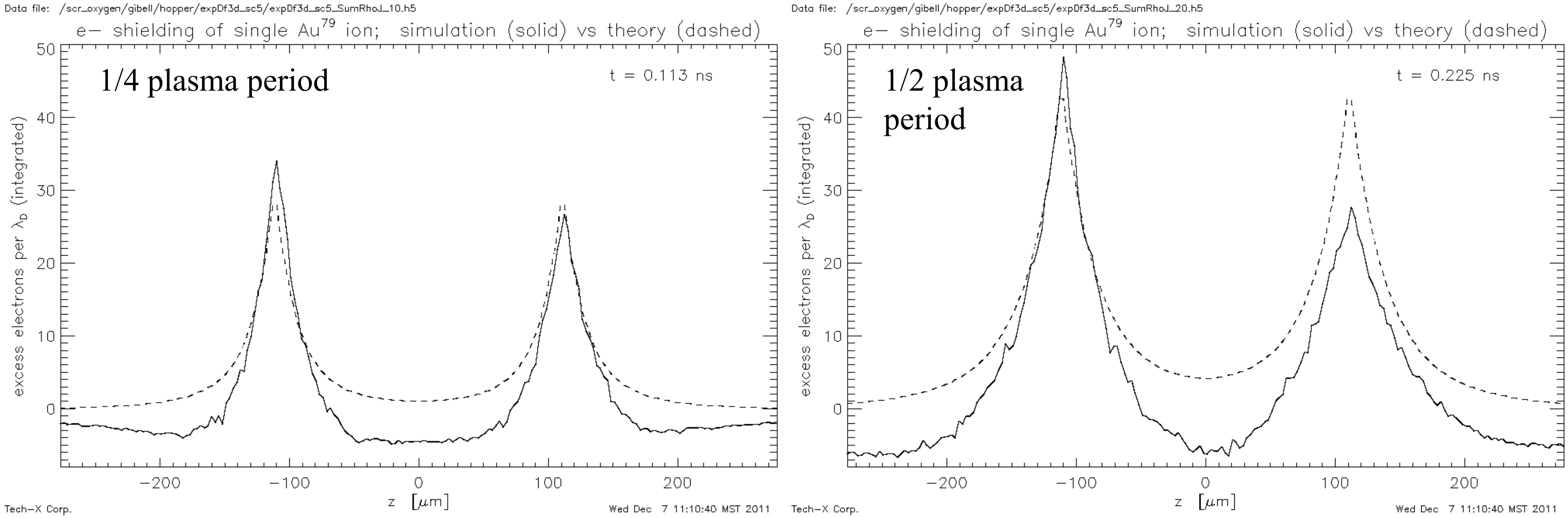

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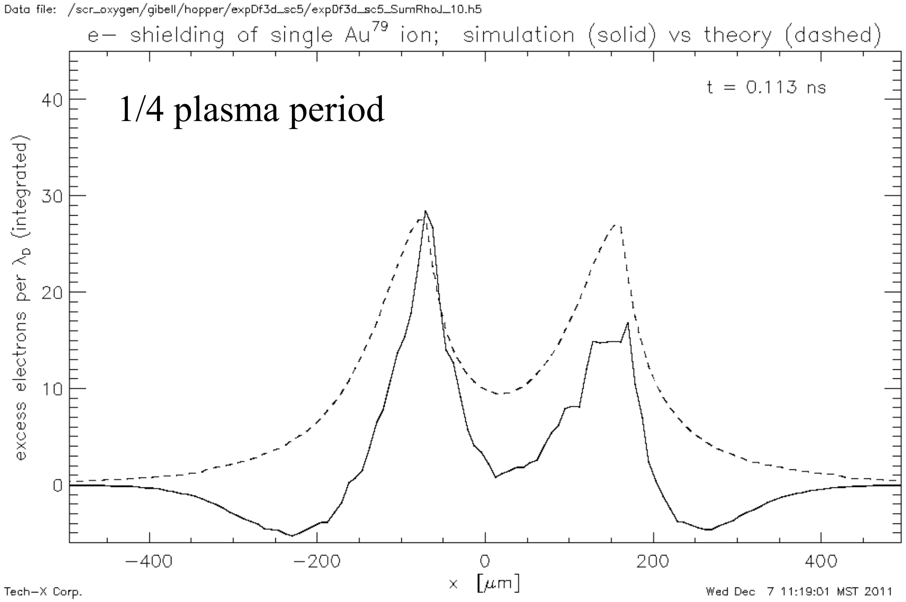

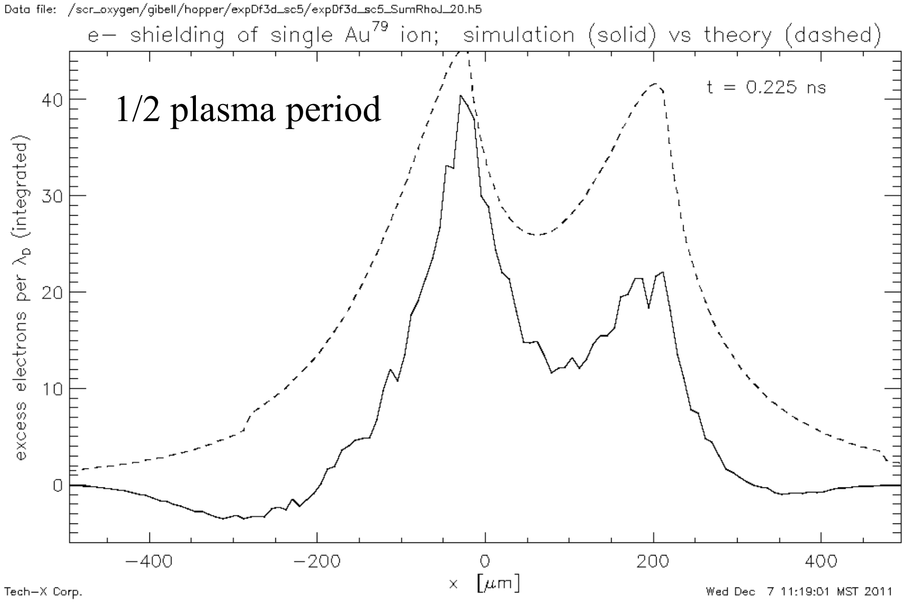

Transverse variation of the density is shown

e- beam is artificially narrow

TECH-X

Addition of finite 'bunching parameters' to FEL quiet start particles

- 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

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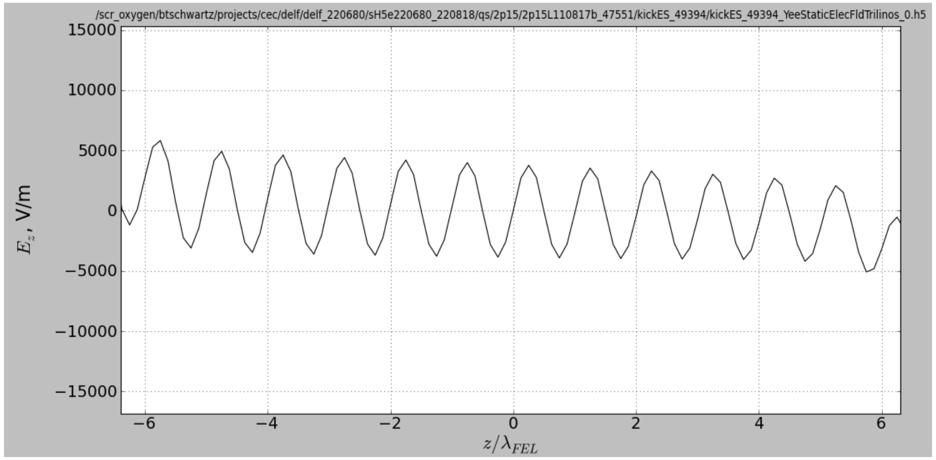
Kicker E-fields are solved via the Poisson equation & advanced w/ standard PIC



- run FEL w/ bunching from ion, no shotnoise → coherent E_z= 3.7 kV/m
- run FEL w/ shot noise → incoherent E_z= : 14.3 kV/m

Input parameters

- kicker of length: l_k= 3 m
- relative energy spread: $\delta\gamma_{\text{i-rel}} = \Delta\mathcal{E}/\mathcal{E}_{\text{k}}^{\text{ion}} = 3.4 \times 10^{-4}$
- relative energy correction per turn: $g = eZl_k E^{\text{c}}_{\text{max}}/\Delta\mathcal{E} = 1.7 \times 10^{-4}$
- electron beam transition energy: $\gamma_{\text{t}} = 23$
- distance from kicker to modulator (pickup): L_{kp}=3834 m (RHIC)

Cooling time†

phase slip factor: $\eta = |{\gamma_{\text{t}}}^{-2} + \gamma^{-2}|$
mixing rate, cooling: $\tilde{M}^{-1} = 2\delta\nu(l_{\text{k}}/c)\eta \cdot \delta\gamma_{\text{i-rel}}$
mixing rate, heating: $M^{-1} = 2\delta\nu(L_{\text{kp}}/c)\eta \cdot \delta\gamma_{\text{i-rel}}$

$$\tau^{-1} = \frac{\Delta\nu}{N_i}[2g(1-\tilde{M}^{-2}) - g^2(M + U/Z^2)]$$

D.Möhl, The status of stochastic cooling. *Nucl. Instrum. Methods A*, 391(1):164 -- 171, 1997.