High-Fidelity Modulator Simulations of Coherent Electron Cooling Systems

David L. Bruhwiler[†]

Contributors: G.I. Bell,[†] I. Pogorelov[†] and K. Paul[†]
V.N. Litvinenko,[%] G. Wang[%] and Y. Hao[%]

[†] TECH-X – [%] BROOKHAVEN NATIONAL LABORATORY

DOE-NP SBIR/STTR Exchange Meeting
Gaithersburg MD, Oct. 25, 2011

TECH-X CORPORATION

Tech-X Corporate Overview

Tech-X Corp. is a software and R&D organization with more than 60 employees, roughly 2/3 PhDs

We have multiple offices in the U.S.

Headquarters in Boulder, Colorado

5621 Arapahoe Ave.
Boulder, CO 80303
http://www.txcorp.com

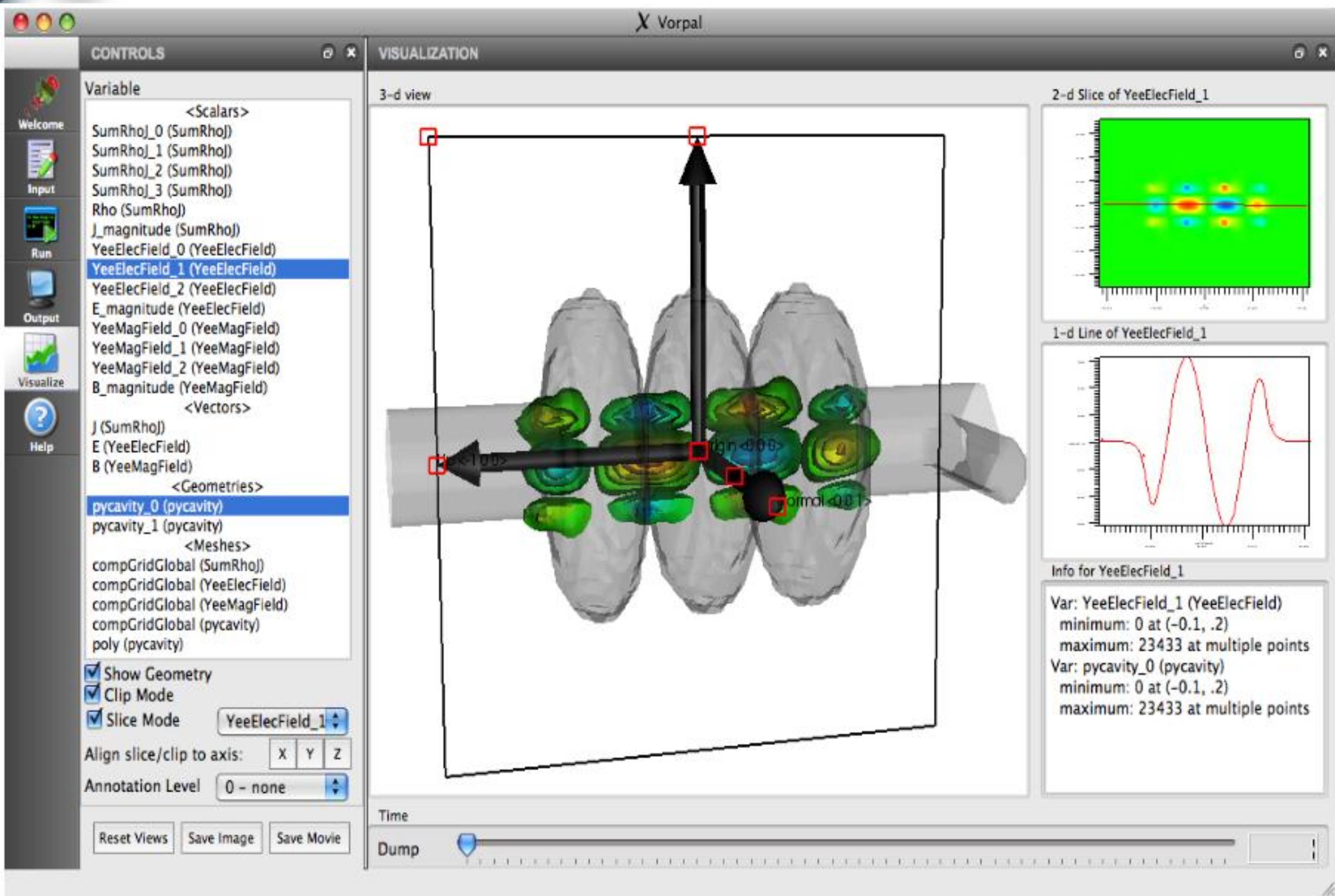
Subsidiary in England: Tech-X UK Ltd

http://txcorp.co.uk/

Resellers: China, India, Korea and Taiwan

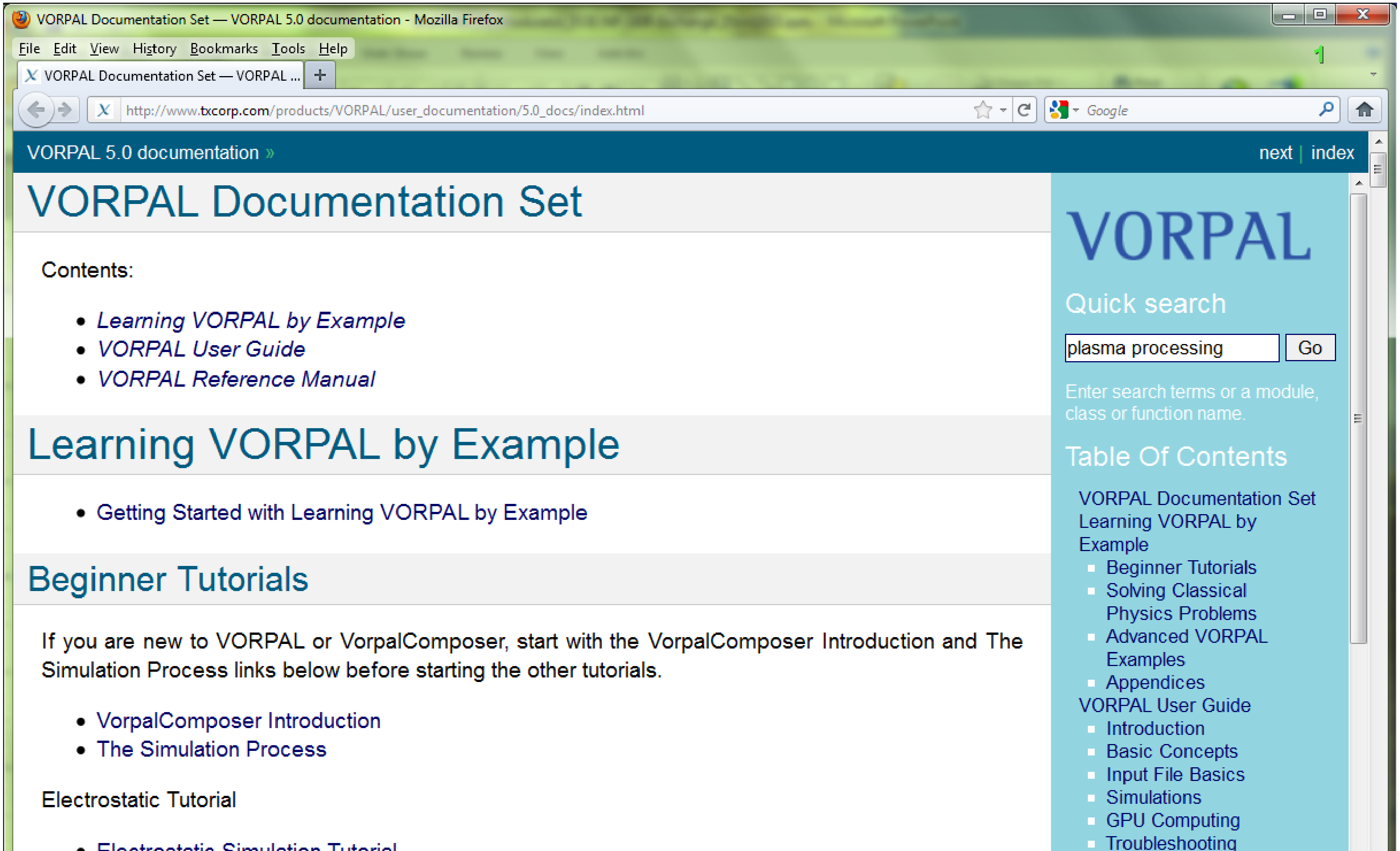
The VORPAL interface is rapidly improving:

http://www.txcorp.com/products/VORPAL/



VORPAL documentation improved & online:

http://www.txcorp.com/products/VORPAL/user_documentation/5.0_docs/index.html



VORPAL training is a new emphasis:

http://spectrum.ieee.org/webinar/1937415

Getting More Benefits From Modeling V...

http://spectrum.ieee.org/webinar/1937415

SPECTRUM WEBCASTS

Getting More Benefits From Modeling Vacuum Electronic Devices

Sponsored by:

Duration: 1 hour
Thu, Oct 27, '11 - 14:00PM (EDT)

Thursday, October 27, 2011
2:00 PM EDT / 11:00 AM PT / 18:00 GMT (Duration: 1 hour)

Learn how simulating the design of your vacuum electronics devices can save money, provide better results, and reduce time-to-market when compared to empirical testing.

PRESENTER:

Dr. David Smithe is a specialist in theoretical and computational electromagnetics and plasma physics. He has extensive experience modeling numerous beam, plasma, and microwave devices using electromagnetic particle-in-cell software. He contributes to algorithm development, and application of multi-physics simulation techniques, to vacuum electronics, accelerator, and fusion science research.

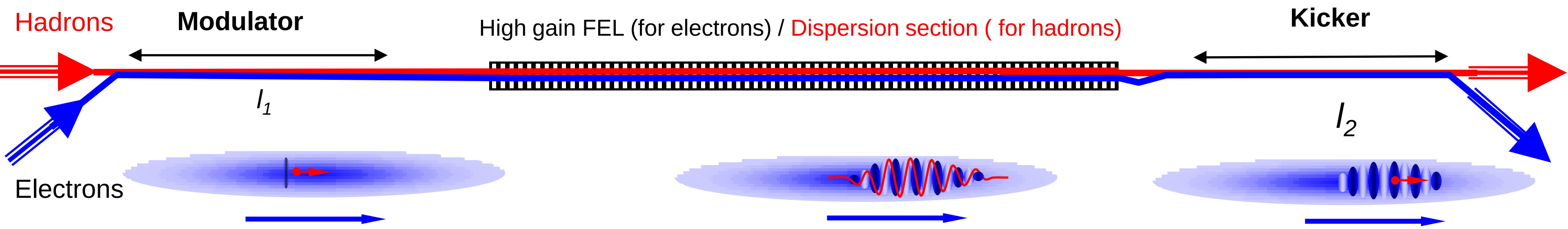
MODERATOR:

Dexter Johnson
Analyst at Cientifica, a business intelligence company for emerging technologies
Author and Editor of several market reports on nanotechnology
Contributing editor for IEEE Spectrum's Tech Talk
Program Director for numerous international conferences on nanotechnology, fiber optic

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
- Alternative cooling approaches
  - 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, it will not work with 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 $\sim 10^3$.

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

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

Motivation: more realistic modulator simulations are required to reduce risk

- Non-ideal modulator simulations
  - finite e- beam size (full transverse extent; longitudinal slice)
  - first step: Gaussian distribution in space; zero space charge
  - 2nd step: equilibrium distribution with space charge
    - constant, external focusing electric field (not realistic)
  - 3rd step: equilibrium distribution with realistic external fields
    - no focusing (i.e. beam converges to a waist in the FEL)
  - 4th step: consider beams from electron linac simulations
    - challenge is to convert PIC distribution to δf macro-particles
- Wang & Blaskiewicz theory valid only for constant n_e
- 1D1V & 2D2V Vlasov-Poisson implemented in VORPAL
  - successful benchmarking of 1D1V results with 1D δf PIC
  - 3D simulations are only practical with δf PIC

BROOKHAVEN NATIONAL LABORATORY

TECH-X CORPORATION

Project tasks & status

- After 1 year, funds are 40% expended
- 1) Implementation of Vlasov-Poisson algorithm in VORPAL
  - 90% complete: Major refactoring of VORPAL to enable coupling of algorithms
- 2) Improve the δf PIC algorithm in VORPAL
  - Complete: Works with variable density beams, open BCs for Poisson
- 3) Couple electron macro-particles from tracking code into VORPAL
  - 50% complete: Works for conventional PIC, not yet for δf PIC
- 4) Simulate electron response to ions near the edge of the beam
  - 40% complete: Code/algorithms are working; need to generate results.
- 5) Simulate e- response to ions in presence of an undulator magnet
- 6) Simulate multiple ions in realistic electron distribution
- 7) GENESIS 1.3 simulations of the FEL amplifier
  - 40% complete: Use of "clones" implemented for improved coupling.
- 8) VORPAL simulations of the kicker
- 9) Generalize parametric representation of the "coherent friction force"
- 10) Generalization of VorpalComposer to support CeC simulations
  - 20% complete: Improvements to GUI are essential for commercialization.

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***

- G.I. Bell , D.L. Bruhwiler, B.T. Schwartz and I. Pogorelov, V.N. Litvinenko, G. Wang and Y. Hao, "Vlasov and PIC simulations of a modulator section for coherent electron cooling," 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", Proc. Particle Accelerator Conf. (2011).

Comparing δf PIC, Vlasov & theory, for Debye shielding in 1D

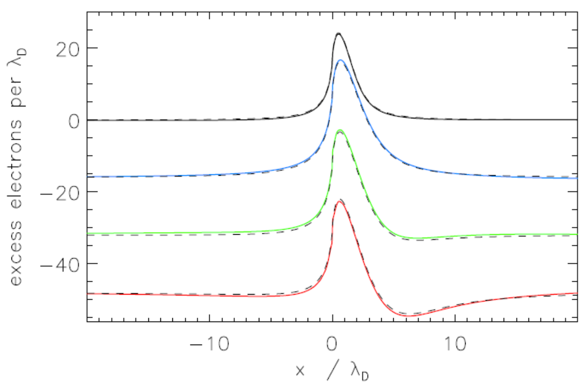


Figure 1: Mountain range plot of the electron response $\tilde{n}_1(x,t)$ from a Vlasov simulation (color) and equation (13) (dashed lines). The curves are snapshots at 0.25 (black), 0.50 (blue), 0.75 (green), and 1.0 (red) plasma periods.

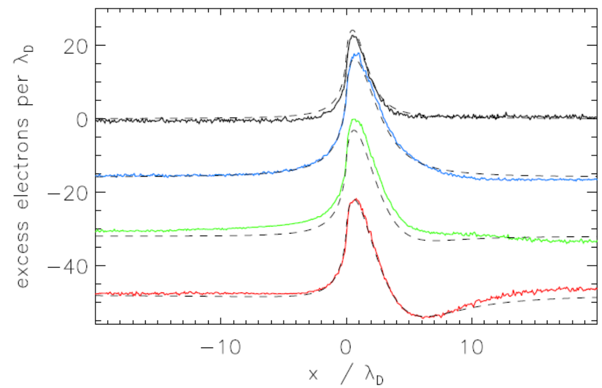


Figure 2: Mountain range plot of $\tilde{n}_1(x,t)$ from a delta-f PIC simulation (color) and equation (13) (dashed lines).

Figures taken from G.I. Bell *et al.*, Proc. 2010 PAC;

Theory is the 1D version of W&B's 3D calculation.

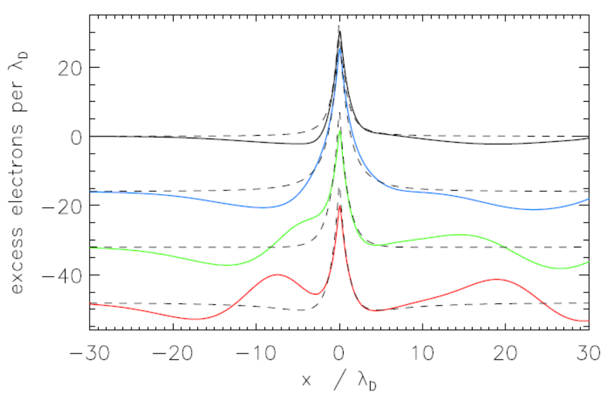
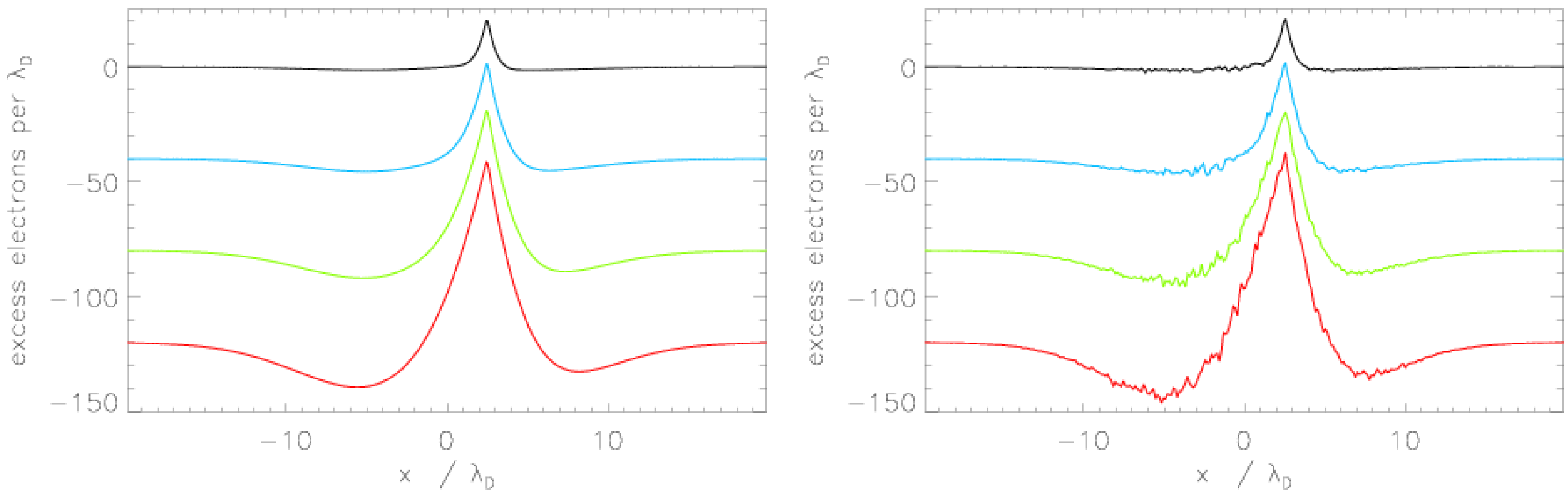


Figure 3: Mountain range plot of $\tilde{n}_1(x,t)$ from a Vlasov simulation in the presence of a density gradient.

- both Vlasov & δf agree w/ theory
  - δf is noisier & slower
  - only δf can scale up to 3D simulations
- similar results for Gaussian beam
  - space charge waves are seen
  - amplitude is small at ½ plasma period

Vlasov simulation results agree well with δf PIC (single ion in gaussian e- dist. w/ no space charge)



Black:	1/8 plasma period
Blue:	1/4 plasma period
Green:	3/8 plasma period
Red:	1/2 plasma period

- no theory available
  - benchmarking Vlasov & δf was helpful
- provides confidence in δf PIC
  - we can now move towards 3D

1D Vlasov equations for the beam density [without space charge]

- We assume that the beam is close to an equilibrium solution which satisfies

$$v \cdot \nabla_x f_0 - \frac{e}{m_e}(E_0 \cdot \nabla_v f_0) = 0$$

  - $f(x,v)$ phase space density
  - $E_0 = E'_0 x$ linear external focusing field (for a Gaussian beam)

- The perturbation satisfies

$$\frac{\partial f_1}{\partial t} + v \cdot \nabla_x f_1 - \frac{e}{m_e}(E_0 \cdot \nabla_v f_1) = \frac{e}{m_e}(E_1 \cdot \nabla_v f_0)$$

where $\nabla \cdot E_1 = \frac{\rho(x,t)}{\varepsilon_0}$ Poisson equation

$$\rho(x,t) = Z\delta(x) + e\int f_1(x,v,t)dv$$

1D Vlasov equations for the beam density [with space charge]

- When space charge is included, the equilibrium solution must also satisfy a self-consistent Poisson equation

$$v \cdot \nabla_x f_0 - \frac{e}{m_e}\left(\left(E_{sc} + E_{ext}\right) \cdot \nabla_v f_0\right) = 0$$

$$\nabla \cdot E_{sc} = \frac{\rho_0(x,t)}{\varepsilon_0}$$

$$\rho_0(x) = e\int f_0(x,v)dv$$

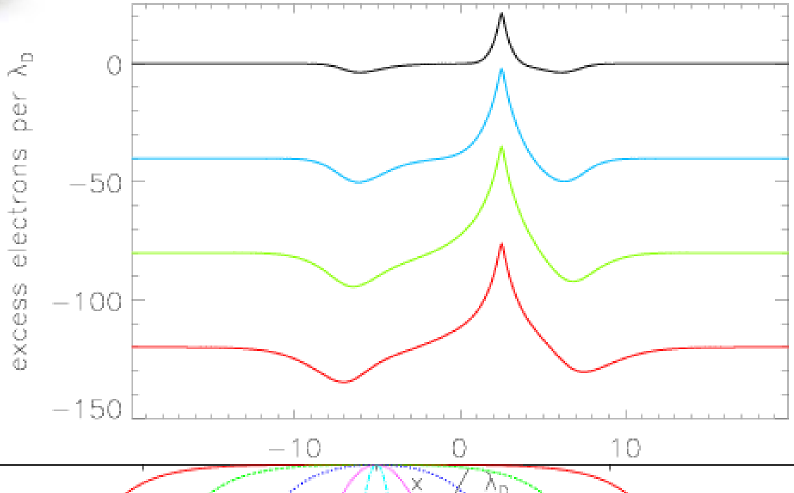
- Can no longer be solved analytically, but numerical solutions are readily calculated (Reiser, 5.4.4)*
  - Assume velocity distribution is Gaussian

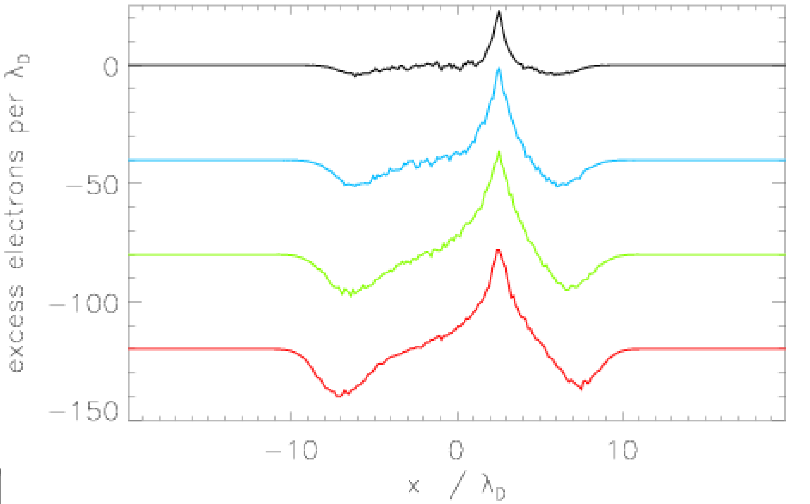
$$f_0(x,v) = \frac{n(x)}{\sigma\sqrt{2\pi}} \exp\left(\frac{-v^2}{2\sigma^2}\right)$$

  - A uniform-density beam generates a linear defocusing electric field $E = -E'_{sc}\, x$ where $E'_{sc} = e\, n(0)/\varepsilon_0$

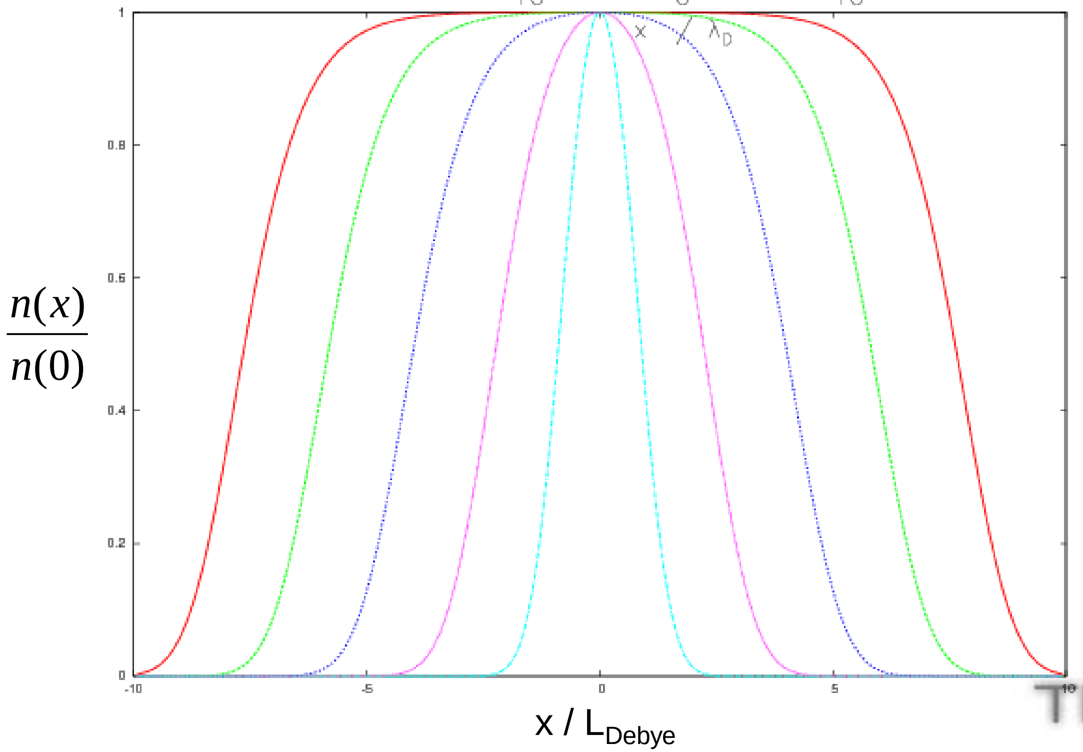
* Martin Reiser, “Theory and Design of Charged Particle Beams”, 2008

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



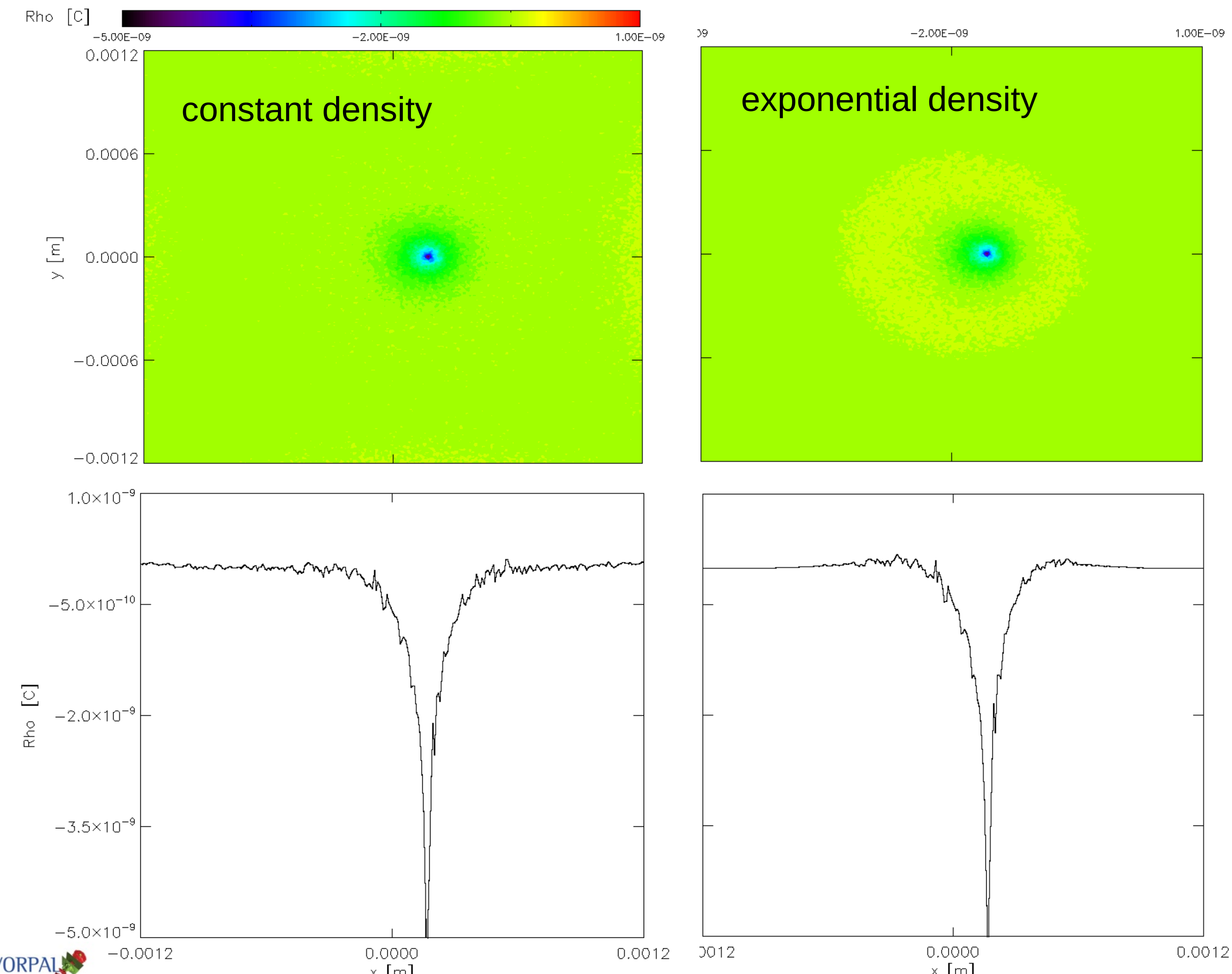


Black: 1/8 plasma period
Blue: 1/4 plasma period
Green: 3/8 plasma period
Red: 1/2 plasma period



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

2D δ-f Simulations of the Modulator; Exponential beam (no space charge) is similar to constant density



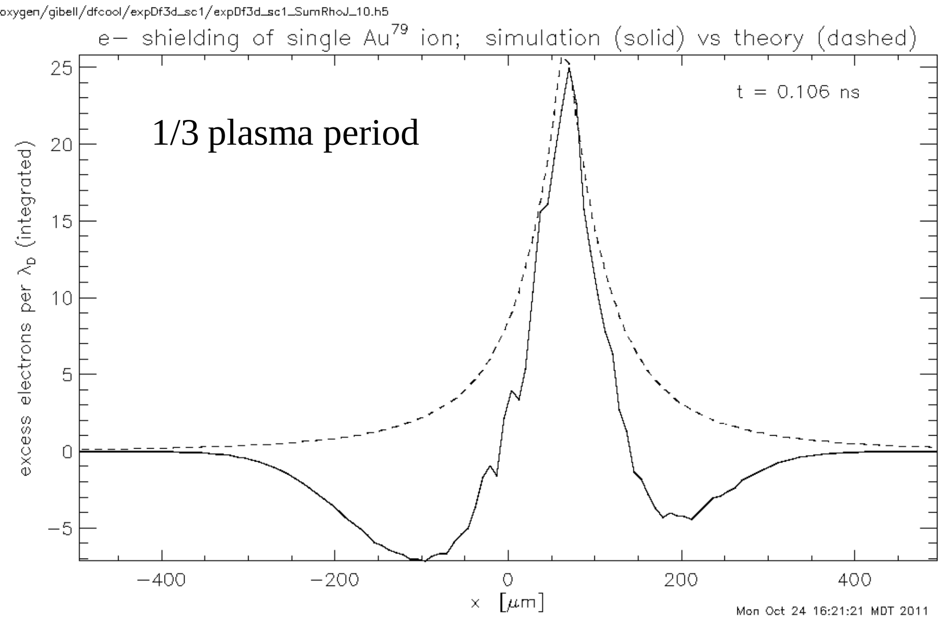
3D δf Simulations of the Modulator have begun, for a longitudinal slice w/ self-consistent space charge

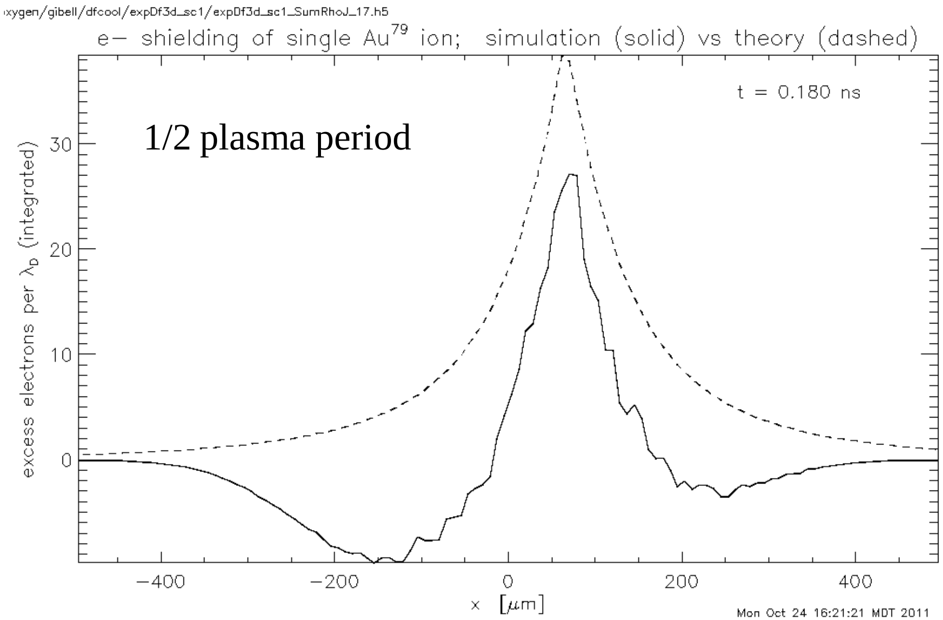
3D Simulations include

- Entire beam (0.4mm 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.





Transverse variation of the density is shown; e- beam is artificially narrow

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

3D modulator sim's via δf PIC → 3D sim's of high-gain SASE FEL amplifier

VORPAL → GENESIS 1.3

- Serious difficulty in coupling to GENESIS via bunching parameters:
  - GENESIS creates specialized particle distribution
  - bunching parameters are used to slightly modify initial longitudinal phases
  - "bunching" is derived from sums over the δf macroparticles
  - this is expected to capture coherent density perturbations
  - coherent velocity perturbations are lost
- We are implementing in GENESIS a recent idea [1], where electron macroparticles are paired with positron-like "clones"
  - yields correct shot noise, by construction
  - makes direct use of macroparticle distribution provided by other codes
  - enables coupling of both velocity and density perturbations

[1] V.N. Litvinenko, "Macro-particle FEL model with self-consistent spontaneous radiation", unpublished (2002).

Present approach to control of shot noise

- Randomly distributed macroparticles yield artificially strong spontaneous radiation in FEL simulations, increasing shot noise by factor $(N_{mp})^{1/2}$
  - power of spontaneous radiation goes up by factor N_{mp}
- Special seeding of macroparticles is used in GINGER and GENESIS
  - WM Fawley, PRST-AB **5,** 070701 (2002).
  - *2M* macroparticles seeded at equal intervals within the fundamental wavelength λ_0:

$$\Delta z = \frac{\lambda_0}{2M} \Rightarrow \Delta\phi_0 = \frac{\pi}{M}$$

  - with zero bunching, correct spontaneous radiation through the M^{th} harmonic of the λ_0
  - physical shot noise & initial bunching are obtained by perturbing the initial phases, so that

$$\left\langle \left| \frac{n_e}{M} \sum_{M-1}^{m=0} e^{i(\phi_m + \delta\phi_m)} \right|^2 \right\rangle = n_e$$

Alternate idea of 'clone' macroparticles will enable direct 3D coupling from into FEL

- "positron" clone macroparticles are created for each electron, with precisely the same initial phase space coordinates
  - weight/charge of macro-particles are set as follows

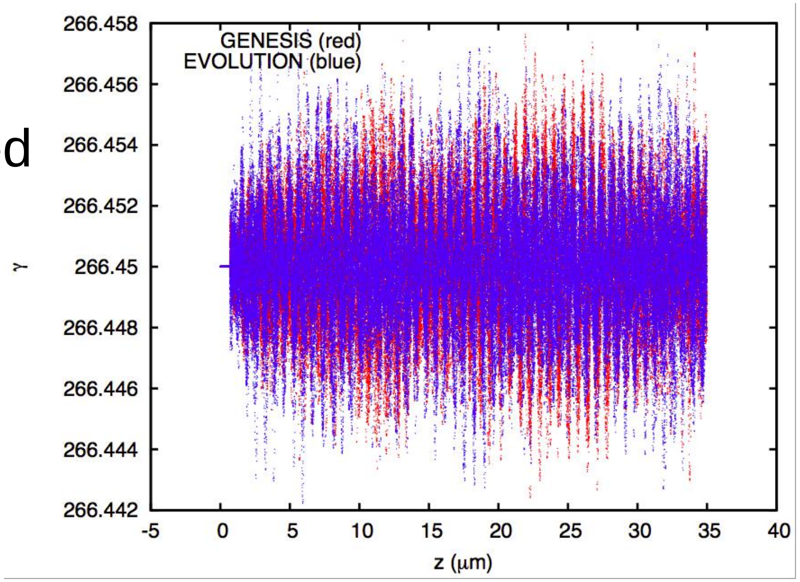
$$q_{mp} = e\frac{n_{np}}{2}\left(1+\frac{\alpha}{\sqrt{n_{np}}}\right) \quad \text{and} \quad q_{cl} = -e\frac{n_{np}}{2}\left(1-\frac{\alpha}{\sqrt{n_{np}}}\right)$$

- In absence of FEL interaction, with sign of magnetic field switched, clone trajectories are identical to electron
- When $\alpha = 0$, including FEL interaction, initial shot noise is zero
- When $\alpha = 1$, physically correct shot noise is obtained
  - FEL interaction results in separation of electrons and clones
  - the bunching leads to induced radiation in the FEL
- Induced radiation for λ_0 and its odd harmonics is the same e-'s & clones
  - correct treatment of odd harmonics requires greater care
  - OK for purposes of CEC simulations

V.N. Litvinenko, unpublished (2002)

The particle-clone pairs algorithm has been successfully implemented in GENESIS

- Clone macroparticles have been implemented
  - GENESIS procedures for overwriting the input distribution are bypassed, can use distributions generated by RNG (no need for Fawley's algorithm)
  - pass all basic tests like no lasing when a perfect quiet start distribution is used
- Benchmarked clone-based simulations of SASE with RNG-generated distributions against GENESIS with internally generated distributions (with noise)
  - varied the number of particles per slice, used uncorrelated energy spread for comparison
  - agreement at the 10% level ($\sigma_\gamma \sim 2.2 \pm 0.2$ in clones runs compared to $\sigma_\gamma \sim 2.4 \pm 0.5$ in original GENESIS
  - no $N^{1/2}$ dependence of growth rate on the number of simulation particles



Longitudinal phase space at exit from the undulator in simulations with the original (red) and modified, clone-based (blue) versions of GENESIS

Near-Term Future Plans

- Major challenge is to consider very realistic e- beams
  - first, remove the constant focusing field required for equilibrium
  - find δf PIC representation of beams from e- linac simulations
- Complete implementation of 2D2V Vlasov-Poisson
  - allows flexible coupling with other algorithms for beams, plasmas
- FEL simulations, based on new modulator sim. results
  - explore benefits of clone-based approach to coupling
- Commercialization
  - look for contract opportunities in FEL modeling with GENESIS
  - support VORPAL GUI development to improve sales
  - coupling of VORPAL to GENESIS will help drive upgrade sales
    - laser-plasma accelerator groups want to drive compact FEL light sources

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 S. Reiche of PSI for helpful discussions regarding GENESIS. Dr. Reiche does not endorse our modifications to the source code.

We thank D. Smithe and T. Austin for assistance with the δf PIC algorithm and other members of the VORPAL development team for assistance and useful discussions.

Work at Tech-X Corp. is supported by the US DOE Office of Science, Office of Nuclear Physics under grant No. DE-SC0000835.

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