High-Fidelity Modulator Simulations of Coherent Electron Cooling Systems

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Getting More Benefits From Modeling Vacuum Electronic Devices

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 Smith 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.”

• 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 $\gamma \sim 9$
    • 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

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

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

Economic option requires: \( 2a_w^2 < 1 \) !!!


V.N. Litvinenko, RHIC Retreat, July 2, 2010
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
  - 2\(^{nd}\) step: equilibrium distribution with space charge
    - constant, external focusing electric field (not realistic)
  - 3\(^{rd}\) step: equilibrium distribution with realistic external fields
    - no focusing (i.e. beam converges to a waist in the FEL)
  - 4\(^{th}\) step: consider beams from electron linac simulations
    - challenge is to convert PIC distribution to \(\delta f\) 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 \(\delta f\) PIC
  - 3D simulations are only practical with \(\delta f\) PIC
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 $\delta f$ 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 $\delta f$ 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.
• 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).  \textit{INVITED TALK}


Comparing $\delta f$ PIC, Vlasov & theory, for Debye shielding in 1D

• both Vlasov & $\delta f$ agree w/ theory
  – $\delta f$ is noisier & slower
  - only $\delta f$ can scale up to 3D simulations

• similar results for Gaussian beam
  - space charge waves are seen
  - amplitude is small at $\frac{1}{2}$ plasma period

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

Theory is the 1D version of W&B’s 3D calculation.
Vlasov simulation results agree well with $\delta f$ PIC (single ion in gaussian e- dist. w/ no space charge)

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

Black: 1/8 plasma period
Blue: 1/4 plasma period
Green: 3/8 plasma period
Red: 1/2 plasma period
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 \( \nabla \cdot E = \frac{\rho(x,t)}{\varepsilon_0} \) 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

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

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

- 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

\[ E = -E'_{sc} x \quad \text{where} \quad E'_{sc} = e n(0)/\varepsilon_0 \]

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

\[ \frac{n(x)}{n(0)} \]

\[ \frac{E'_\text{ext}}{E'_{\text{xc}}} = 1.0001, 1.001, 1.01, 1.1, 2.0 \]
2D $\delta$-f Simulations of the Modulator; Exponential beam (no space charge) is similar to constant density.
3D Simulations of the Modulator have begun, for a longitudinal slice with 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

- 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

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 \(\lambda_0\):
    \[
    \Delta z = \frac{\lambda_0}{2M} \Rightarrow \Delta \phi_0 = \frac{\pi}{M}
    \]
  - with zero bunching, correct spontaneous radiation through the \(M^{th}\) harmonic of the \(\lambda_0\)
  - physical shot noise & initial bunching are obtained by perturbing the initial phases, so that
    \[
    \left\langle \left| \frac{n_e}{M} \sum_{m=0}^{M-1} e^{i(\phi_m + \delta\phi_m)} \right|^2 \right\rangle = n_e
    \]
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 \( \lambda_0 \) and its odd harmonics is the same e-’s & clones
  - correct treatment of odd harmonics requires greater care
  - OK for purposes of CEC simulations

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
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