Simulations of the modulator, FEL amplifier and kicker for coherent electron cooling of 40 GeV/n Au+79

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COOL'11
Workshop on Beam Cooling & Related Topics
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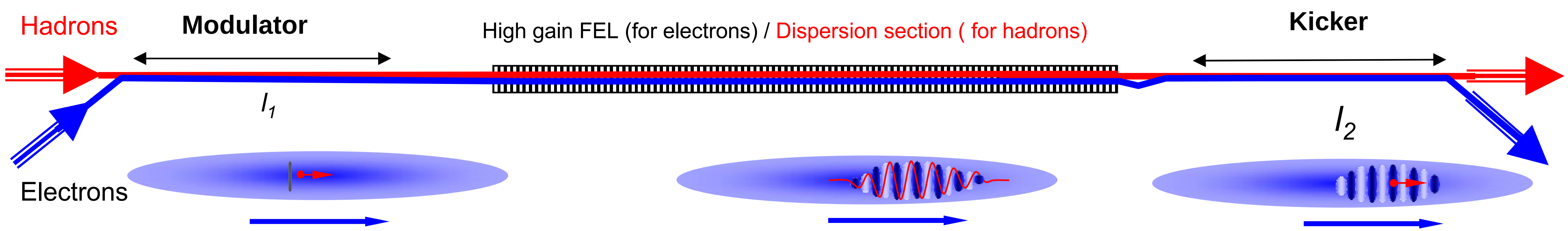
Coherent e- Cooling (CeC) is a priority for RHIC & the future Electron-Ion Collider

- 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

Why coherent electron cooling?

- Traditional stochastic cooling does not have enough bandwidth to cool modern-day proton beams
- Efficiency of traditional electron cooling falls as a high power of hadron's energy
- Synchrotron radiation is too feeble – even at LHC energy, cooling time is more than 10 hours
- Optical stochastic cooling (OSC) is not suitable for cooling hadrons with a large range of energies and has a couple of weak points:
  - Hadrons do not like to radiate or absorb photons, the process which OSC uses twice
  - Tunability and power of laser amplifiers are limited

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.

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

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

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;
      especially from the modulator to the FEL amplifier

Examples of hadron beams cooling

Machine	Species	Energy GeV/n	Trad. Stochastic Cooling, hrs	Synchrotron radiation, hrs	Trad. Electron cooling hrs	Coherent Electron Cooling, hrs 1D/3D
RHIC PoP	*Au*	*40*	-	–	~ 1	*0.02/0.06*
eRHIC	Au	130	~1	20,961 ∞	~ 1	0.015/0.05
eRHIC	**p**	**325**	**~100**	**40,246 ∞**	**> 30**	**0.1/0.3**
LHC	p	7,000	~ 1,000	13/26	∞ ∞	0.3/<1

Potential increases in luminosities:

RHIC polarized pp ~ 6 fold, eRHIC ~ 5-10 fold, LHC ~ 2 fold

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CeC Proof of Principle Experiment at RHIC

Vladimir N. Litvinenko (PI), Ilan Ben-Zvi, Yue Hao, Dmitry Kayran, George Mahler, Wuzheng Meng, Gary McIntyre, Michiko Minty, Triveny Rao, Brian Sheehy, Yatming Roberto Than, Joseph Tuozzolo, Gang Wang, Stephen Webb, Vitaly Yakimenko
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Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Collaboration of BNL, JLab and Tech-X

BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
TECH-X

This is a 5-year project.
The 1st year is underway.

Key system parameters (as originally proposed)

Parameter	Units	
Species in RHIC		**Au ions**
Ion's energy	GeV/u	**40**
Electron beam energy	MeV	**21.8**
Rep-rate	kHz	**78.3**
e-beam power	kW	**1.7**
Length of the CeC straight section	m	**14**
Length of the modulator straight section	m	**3**
Length of the kicker straight section	m	**3**
Length of FEL wiggler	m	**7**
Type of wiggler		**Helical**
Wiggler period	cm	**4**
Wiggler parameter, a_w		**0.437**
FEL wavelength	μm	**10**

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).*

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

  - theory makes certain assumptions:
    - single ion, with arbitrary velocity
    - uniform e- density; *anisotropic* temperature
      - Lorentzian 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; ω_{pe} ~ 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

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Modulator simulations are successfully validated.

Simulated e- density agrees with theory [7]

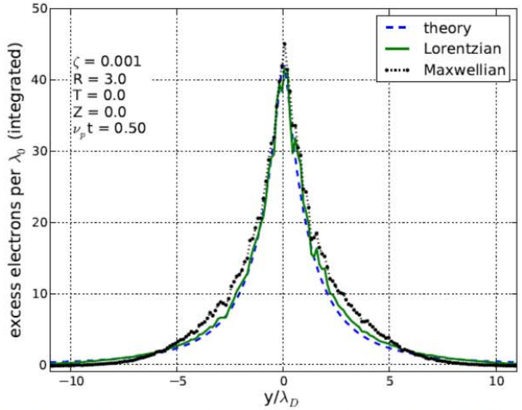

Figure 1: Longitudinal charge density perturbation in the vicinity of the Au^{+79} ion, for the case of a stationary ion in an anisotropic plasma with both Lorentzian and Maxwellian e^- velocity distributions.

Maxwellian wakes can differ from Lorentzian

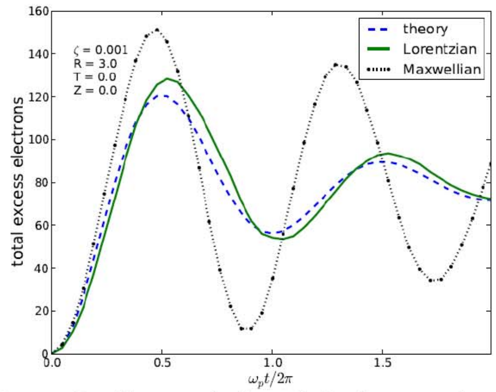

Figure 2: Time evolution of the integrated e^- charge enhancement in the vicinity of the Au^{+79} ion, for the case of a stationary ion in an anisotropic e^- distribution. The time scale is in units of plasma period.

Drifting ion simulations agree w/ theory [7]

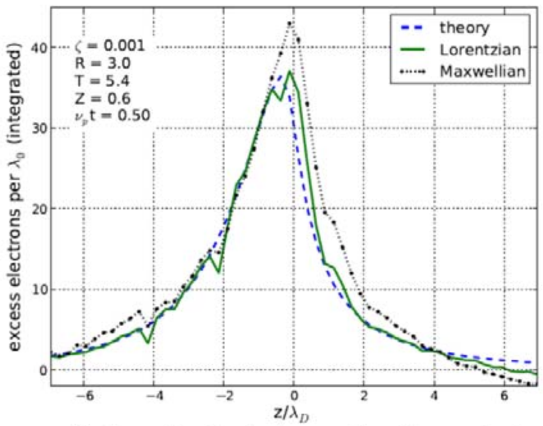

Figure 3: Longitudinal charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

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

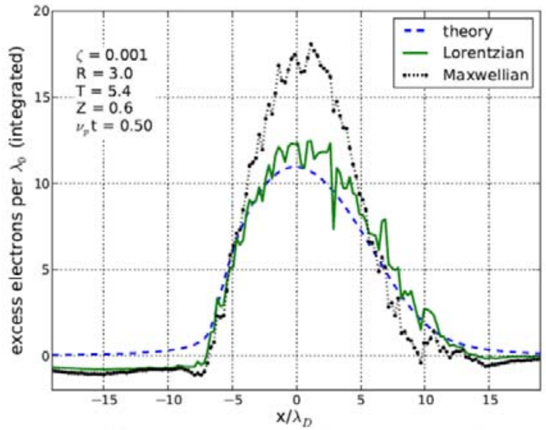

Figure 4: Transverse charge density perturbation of a plasma in the vicinity of a moving Au^{+79} ion.

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Recent work and near-term plans: more realistic modulator simulations

- 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)
- No theory with which to check the simulations
  - hence, we must benchmark different algorithms
- 1D1V Vlasov-Poisson now included in VORPAL
  - successful benchmarking of 1D results with δ-f PIC
  - 3D simulations are only practical with δf PIC

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

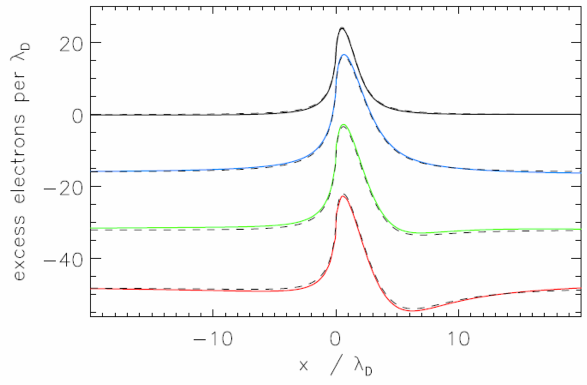

Figure 1: Mountain range plot of the electron response $\tilde{n}_1(x, t)$ from a Vlasov simulation (color) and equation (13) (dashed lines). The curves are snapshots at 0.25 (black), 0.50 (blue), 0.75 (green), and 1.0 (red) plasma periods.

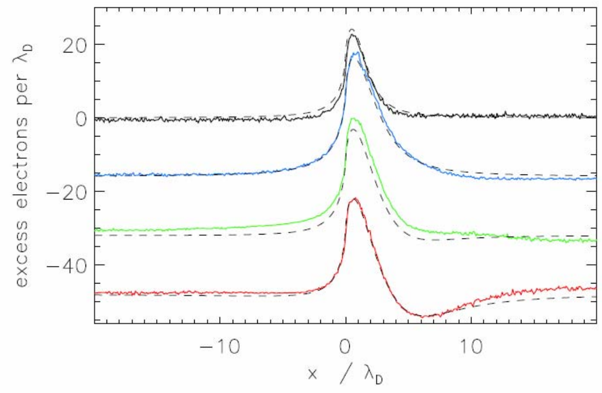

Figure 2: Mountain range plot of $\tilde{n}_1(x, t)$ from a delta-f PIC simulation (color) and equation (13) (dashed lines).

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

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

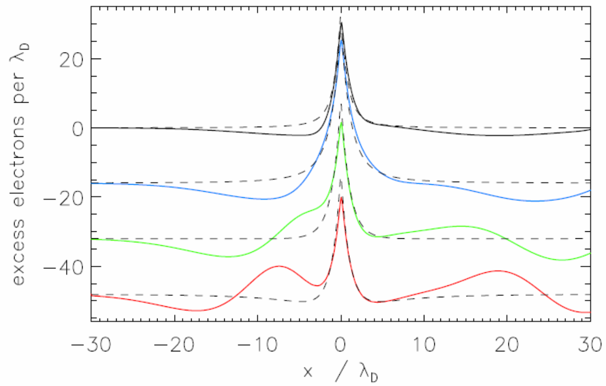

Figure 3: Mountain range plot of $\tilde{n}_1(x, t)$ from a Vlasov simulation in the presence of a density gradient.

- 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

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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)

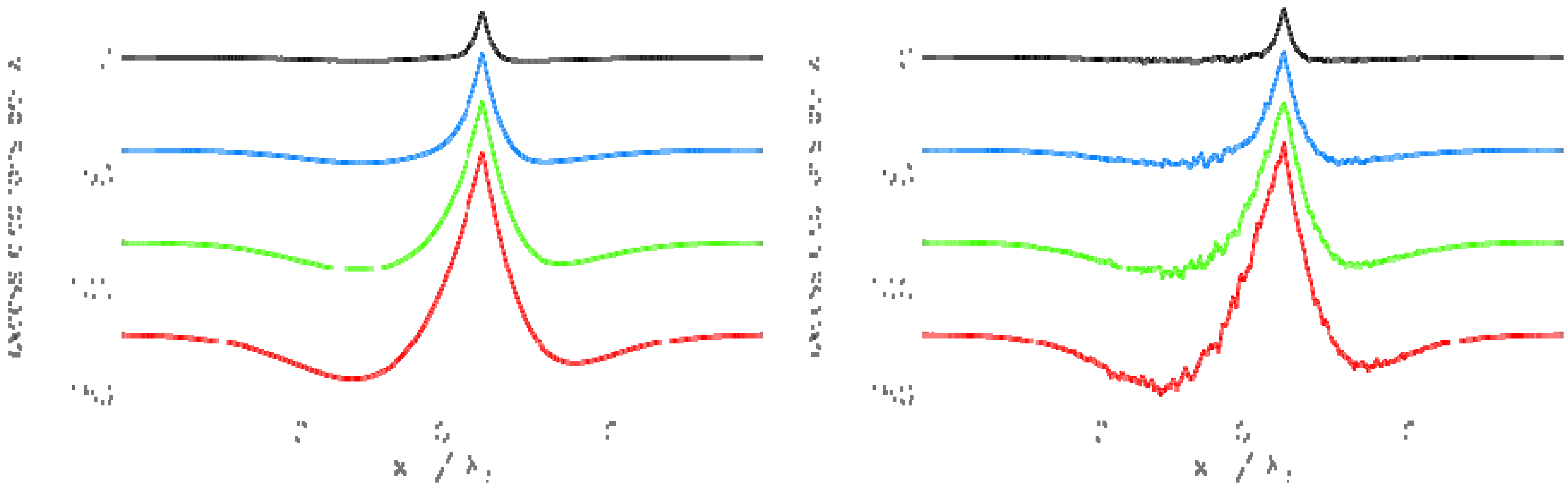
- The perturbation satisfies

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

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

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

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



- no theory available
  - benchmarking Vlasov & δf was helpful
- provides confidence in δf 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 [with space charge]

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

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

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

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

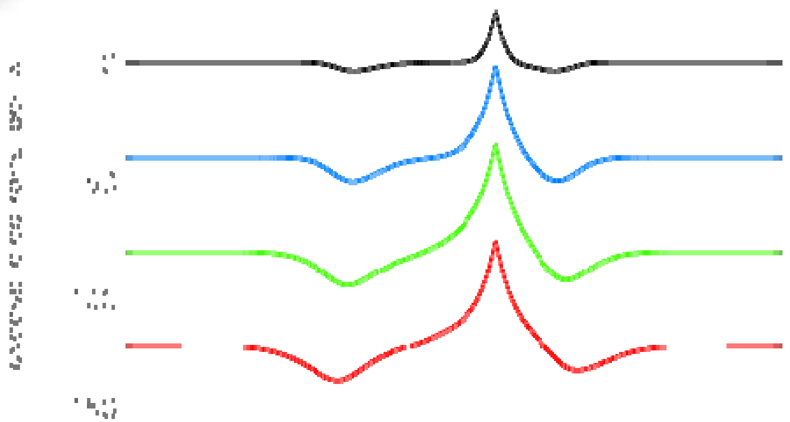
- Can no longer be solved analytically, but numerical solutions are readily calculated (Reiser, 5.4.4)*
  - Assume velocity distribution is Gaussian

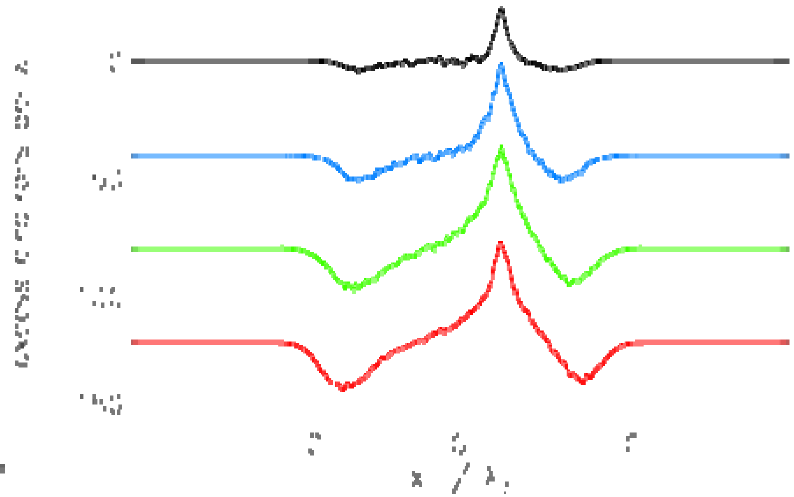
$$f_0(x,v) = \frac{n(x)}{\sigma\sqrt{2\pi}} \exp\left(\frac{-v^2}{2\sigma^2}\right)$$

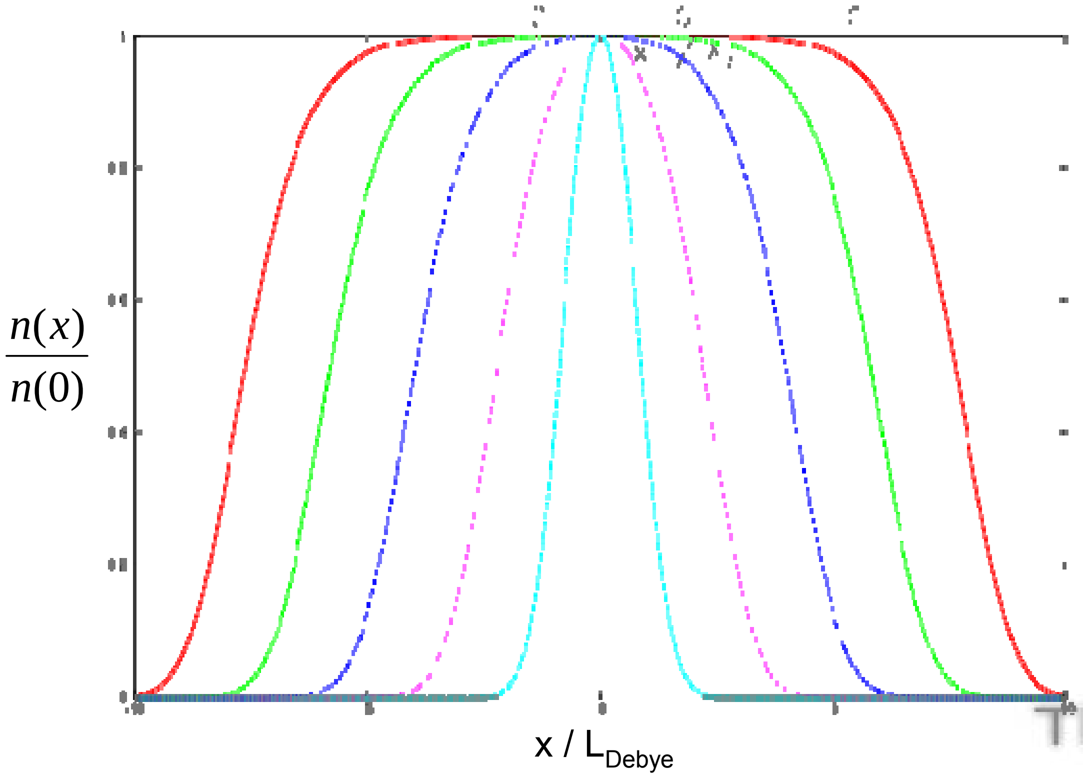
  - A uniform-density beam generates a linear defocusing electric field $E = -E'_{sc}\, x$ where $E'_{sc} = e\, n(0)/\varepsilon_0$

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

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



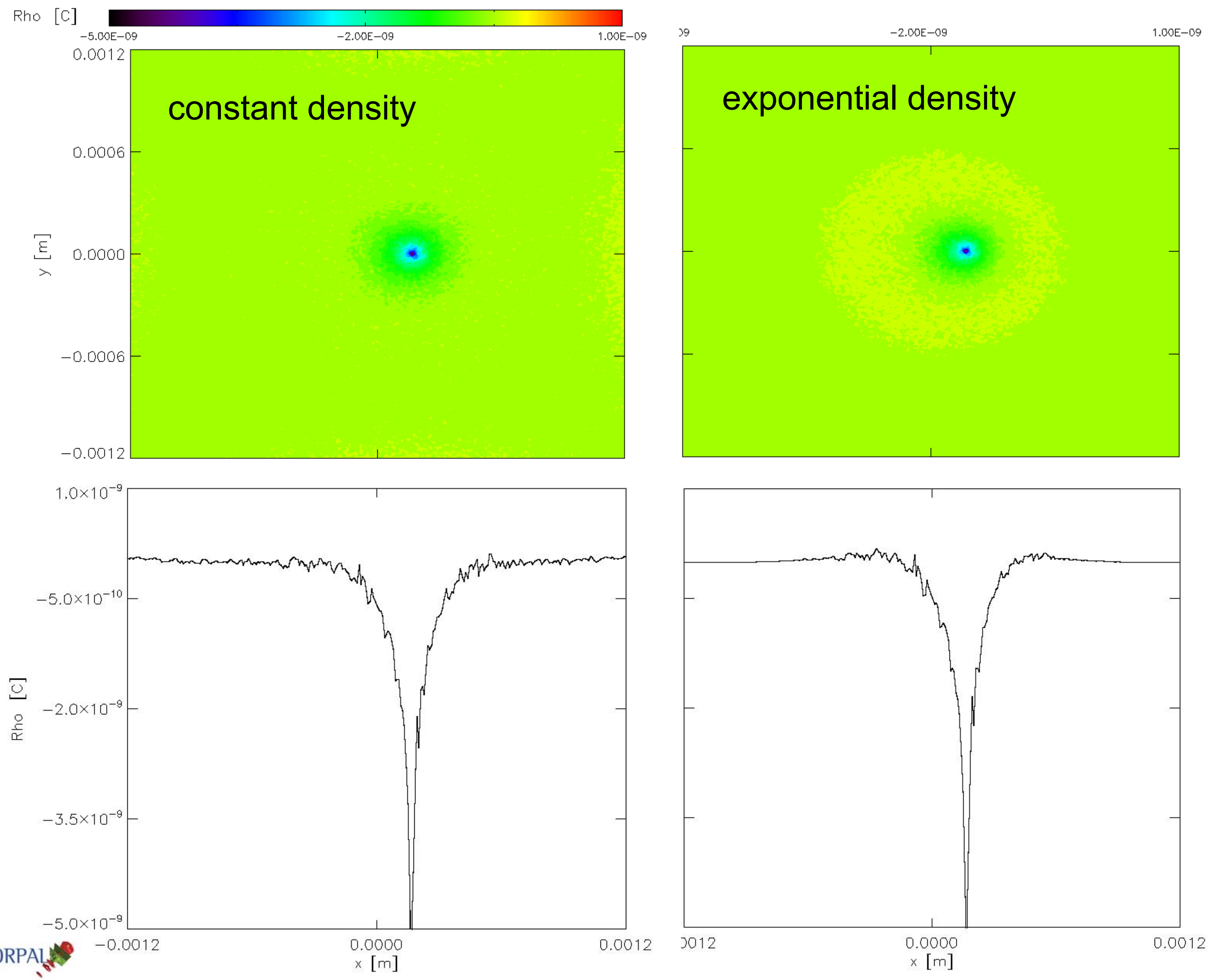




Black: 1/8 plasma period
Blue: 1/4 plasma period
Green: 3/8 plasma period
Red: 1/2 plasma period

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

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



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

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3D modulator simulations via δf PIC

GENESIS 1.3

3D simulations of the high-gain SASE FEL amplifier

Please see next presentation by Ilya Pogorelov

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

GENESIS 1.3 → VORPAL

3D simulations of the high-gain SASE FEL amplifier

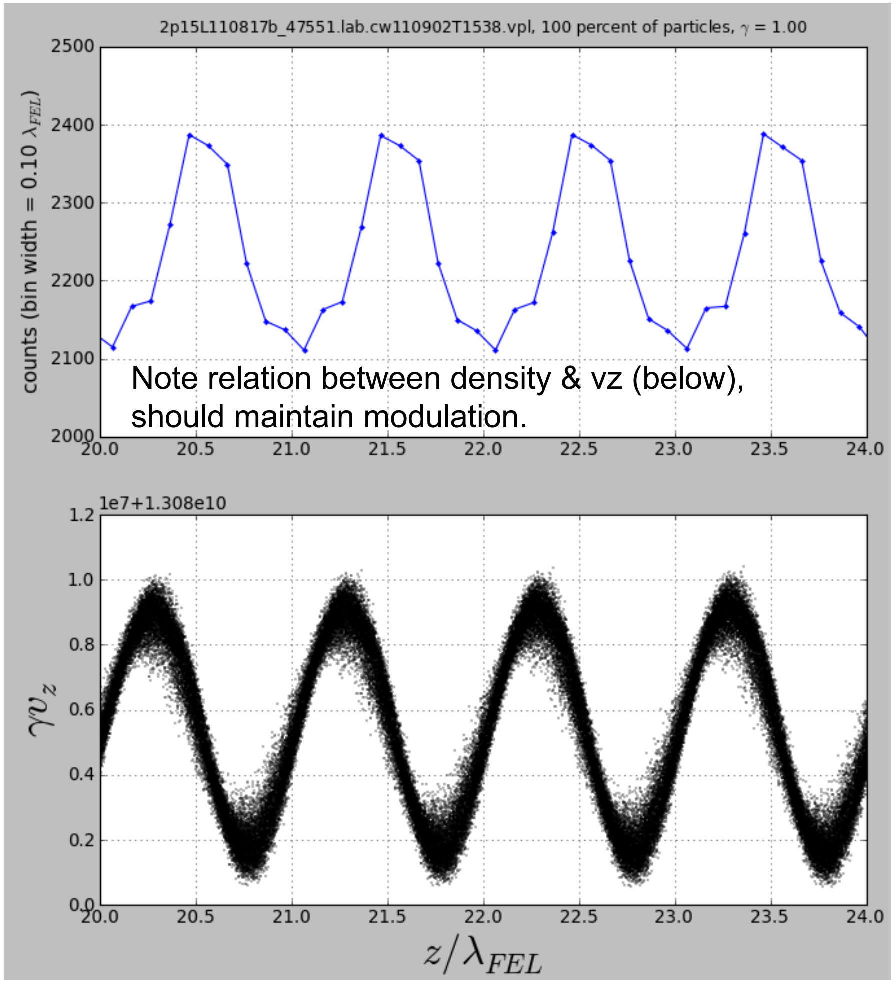
3D kicker simulations via
electrostatic PIC (beam frame)
or
electromagnetic PIC (lab frame)

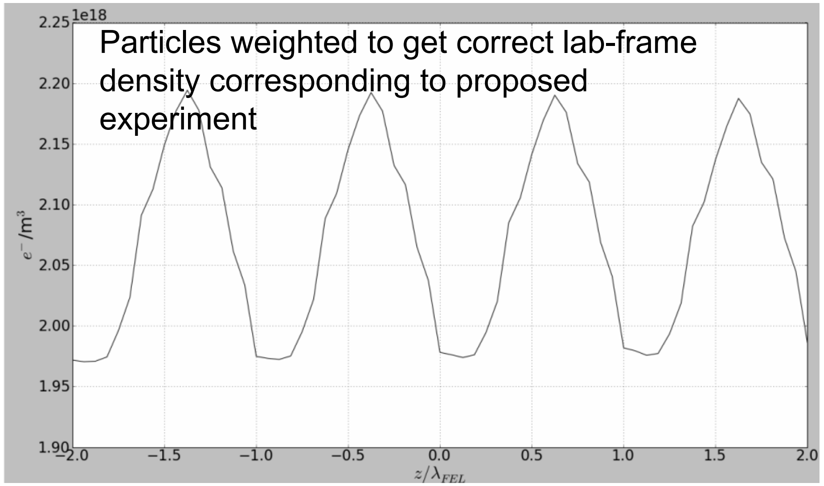
work in progress

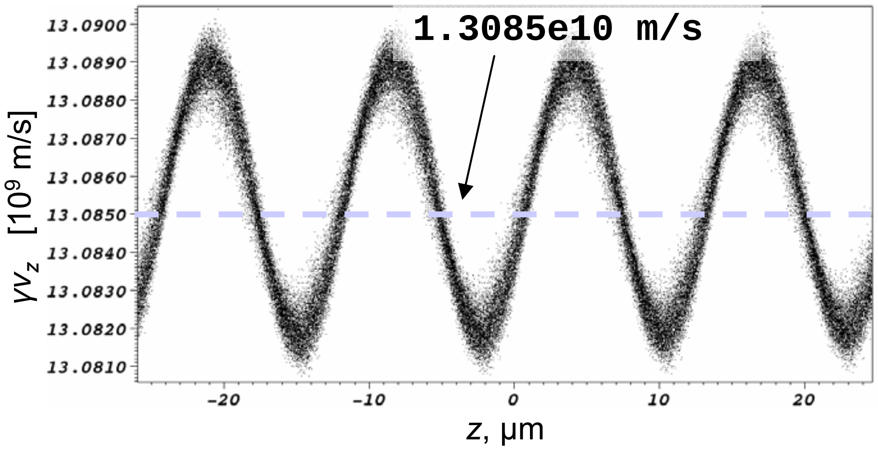
Lab frame simulations of the Kicker

Particles at end of FEL GENESIS output

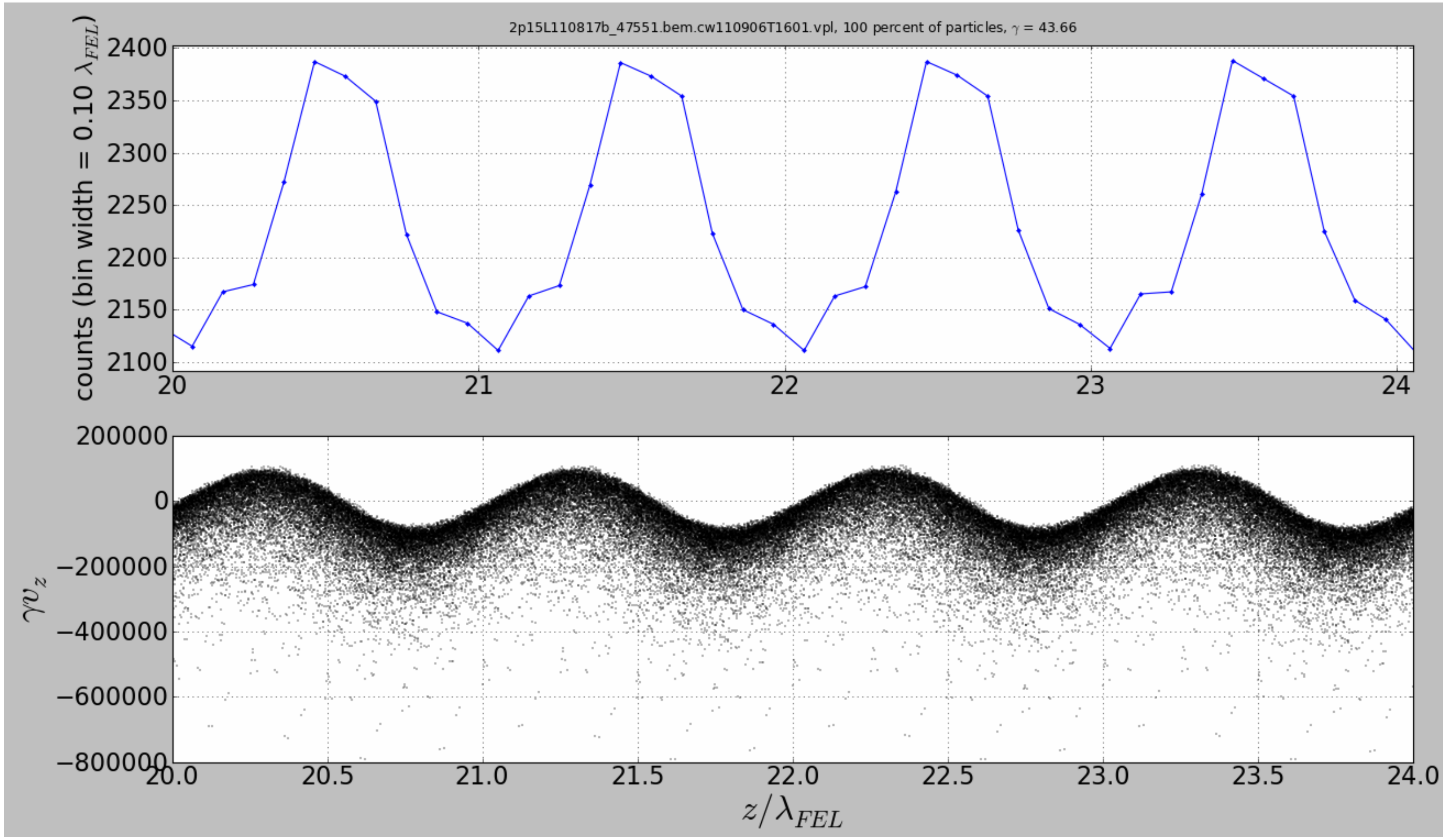
Particles are transferred via file I/O to VORPAL





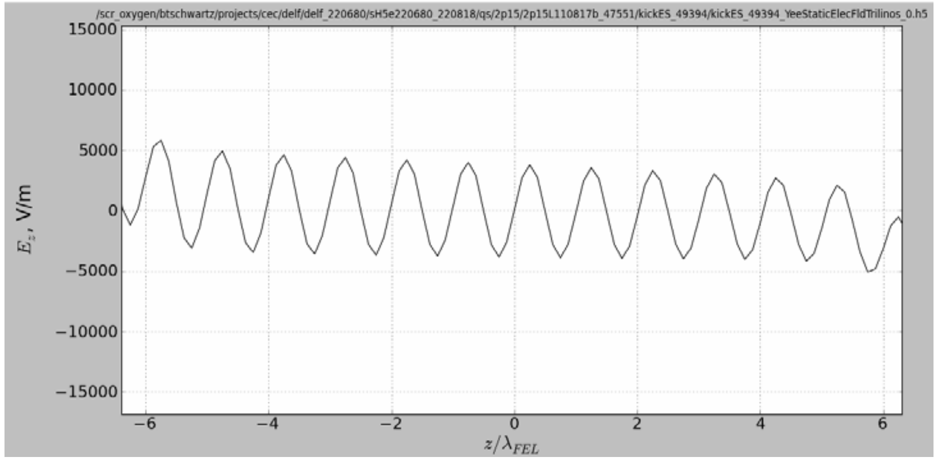


Beam frame simulations of the Kicker



- Longitudinal electron velocities are appropriately centered around zero.
- Phase relation between density and v_z maintained.
- Transverse beam-frame velocities are ~γ times lab frame velocites, as expected.

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: $g = eZl_k E_{\text{max}}^{\text{c}}/\Delta\mathcal{E} = 1.7 \times 10^{-4}$
- 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: $M^{-1} = 2\delta\nu(L_{\text{kp}}/c)\eta \cdot \delta\gamma_{\text{i-rel}}$

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

With present parameters, $\tau = 27$ seconds.

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

Future Plans – Enable full cooling simulations

- We are simulating micro-physics of a single CeC pass
  - full e- cooling simulations requires many 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
- Near term:
  - run many 3D δf PIC sim's for equilibrium beam distribution
  - determine if Wang & Blaskiewicz theory is sufficiently accurate
  - determine importance of beam evolution in the kicker
- Mid-term:
  - study more general, realistic fields in the modulator (e.g. zero)
  - complete implementation of 2D2V Vlasov for benchmarking δf

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