Simulations of an FEL Amplifier for Coherent Electron Cooling

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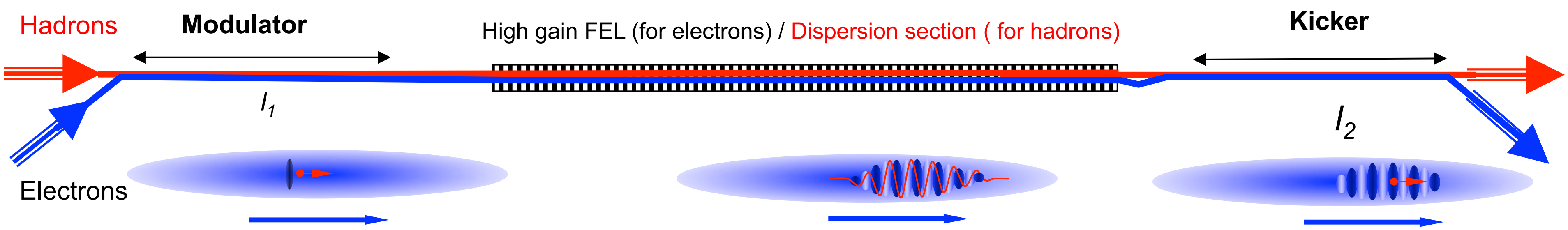
Outline

- Motivation
  - Future DOE/NP facility: the Electron-Ion Collider
  - Coherent e^- Cooling (CeC) proof-of-principle experiment
- Simulating a Coherent e- Cooling system
  - Simulating the modulator and amplifier
  - CeC operates via density and velocity perturbations resulting from anisotropic Debye shielding
  - Coupling the simulations: bunching parameters vs particle-clone pairs
- Simulating the amplifier stage
  - Using 3D distributions of bunching parameters - results
  - Particle-clone pairs approach
  - First results of clone-based simulations
- Work in progress and future plans

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}.

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

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

A multi-stage simulation effort:

1) Couple e- macro-particles from tracking code into VORPAL
2) Full 3D δf-PIC simulations of the modulator (VORPAL)
3) Simulate e- response to ions, including the cases of finite beam size and multiple ions in idealized & non-ideal conditions
5) For each case, perform coupled GENESIS simulations of the FEL amplifier ...
6) ... followed by corresponding PIC simulations of kicker with VORPAL

- This talk: enabling proper 3D *coupling from modulator to the FEL amplifier*, so that all details of the 6D phase space coordinates are retained in the input distribution used in simulations of the amplifier

Coupling modulator results to FEL simulations: coupling VORPAL output to GENESIS input

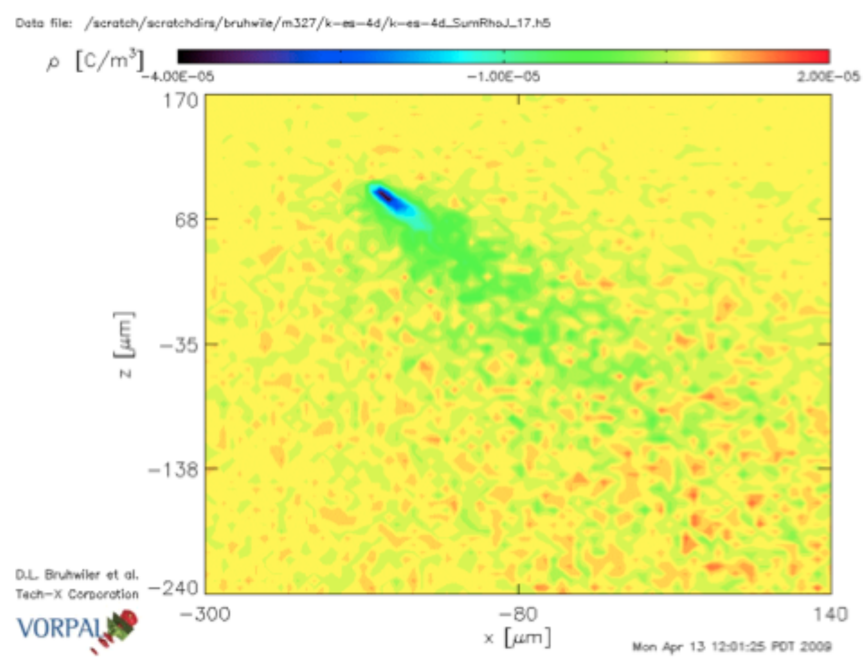
- General scheme:
  - FEL amplifier *in the linear regime* => additive response
  - model one ion at a time (with a zero-noise quiet start) and separately simulate SASE signal starting from shot noise
  - in close analogy with stochastic cooling, the effects of coherent velocity drag accumulate linearly in t with multiple turns, while the larger single-pass contributions from noise accumulate more slowly as $t^{1/2}$
  - coherent term determines the cooling time
- Coherent velocity perturbations: subtle effect, difficult to model by coupling δf PIC and FEL (GENESIS) simulations
- We employ two independent approaches:
  - one based on inferring a distribution of local bunching parameters
  - the other based on the 'clones' technique

Modulator simulations using δf PIC algorithm

- δf PIC uses macro-particles to represent deviation from assumed equilibrium distribution
  - much quieter for simulation of beam or plasma perturbations
  - implemented in VORPAL for Maxwellian & Lorentzian velocities
  - 20 cells per λ_D , 200 ptcls/cell to accurately model temp. effects

Table 1: Ion, electron beam and FEL parameters

ion parameter	value
Lorentz factor, γ_i	43.66
v_z	3.06×10^5 m/s
e-beam parameter	**value**
Lorentz factor, γ_e	43.66
rms energy spread, relative	0.001
rms velocity, v_rms	2.93×10^5 m/s
peak current	100 A
normalized emittance	0.97 mm mrad
amplitude function, $\hat{\beta}$	4.9
electrons per bunch, N_e	1.54×10^9
number density, n_e	5.5×10^{16} m^{-3}
FEL parameter	**value**
wiggler type	helical
wiggler period, Λ	4 cm
wiggler parameter, a_w	0.437
FEL wavelength, λ_FEL	14 μm
FEL bandwidth, $\Delta\nu$	90 GHz



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Coupling modulator results to FEL simulations (coupling VORPAL output to GENESIS input)

- 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:

$$b = \frac{1}{N}\sum_{j=1}^{N} e^{-i\theta_j}$$

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

Modulator output coupled into FEL simulations

- Before: Coupling of 3D e- perturbation from modulator was essentially 1D

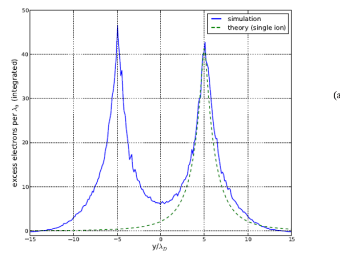
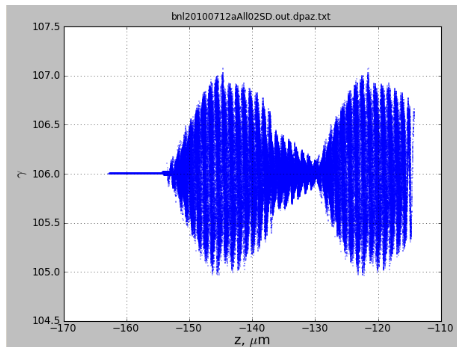
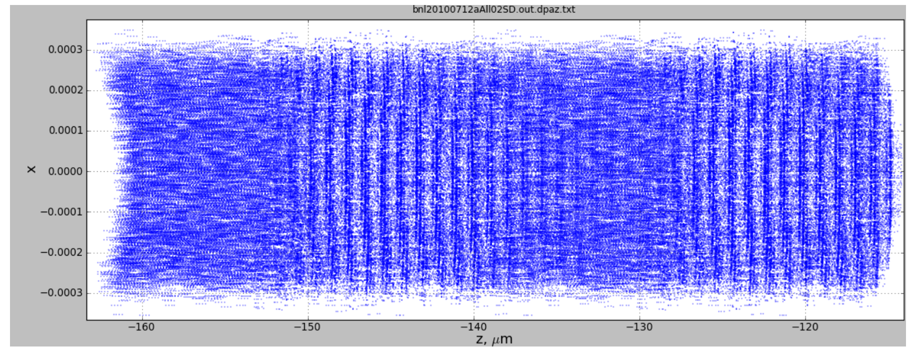


Figure 5: Transverse charge density perturbation of a plasma in the vicinity of two stationary Au^{+79} ions separated by $10\lambda_D$. Dotted line: theoretical prediction for a Lorentzian velocity distribution.

Two ions in the modulator



Lasing provoked by two ions



FEL-amplified response in e- density distribution

Right:
New approach: compute 2D distribution of bunching parameters, use as input to GENESIS simulations of amplifier stage

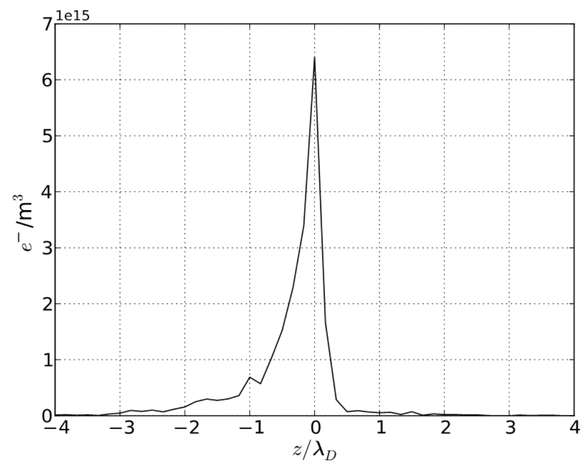


Figure 1: VORPAL δf computation of longitudinal on-axis electron density perturbation near a Au^{+79} ion with longitudinal velocity $v_z\hat{\mathbf{z}}$ in an isotropic plasma. The total number of shielded electrons is N_s=119 and λ_D=22.2 μm.

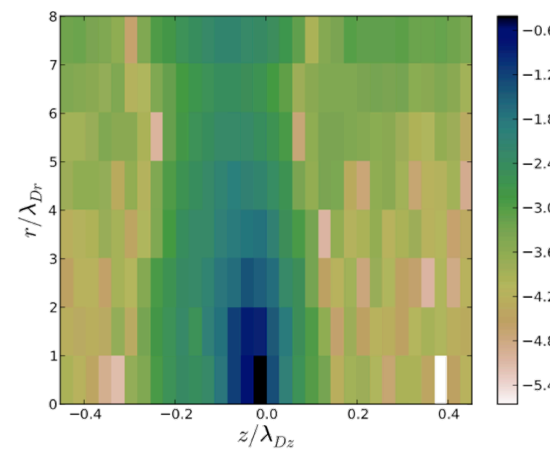
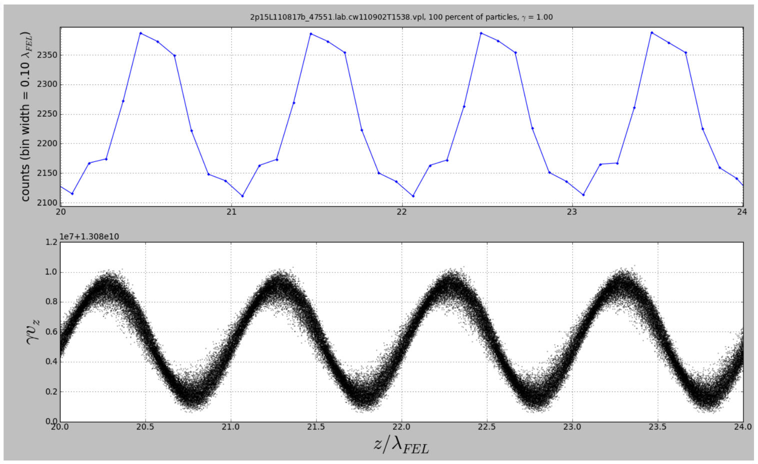
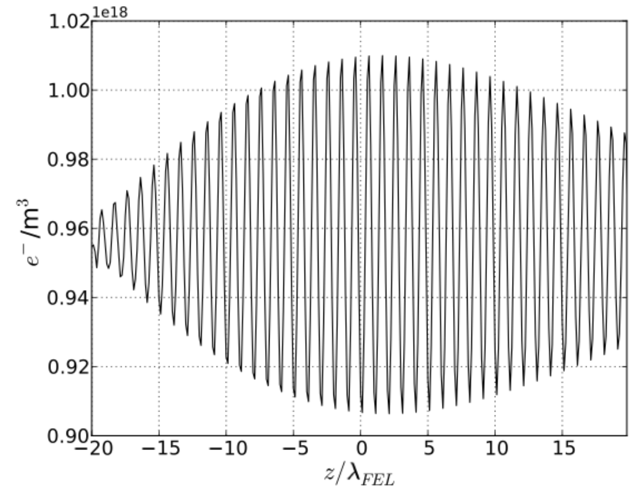


Figure 2: Magnitude of electron beam bunching coefficients b, plotted as $\log_{10}(|b|)$, at λ_0 = 12.5 μm in vicinity of a shielded ion located at z=0 with positive velocity $v_z\hat{\mathbf{z}}$.

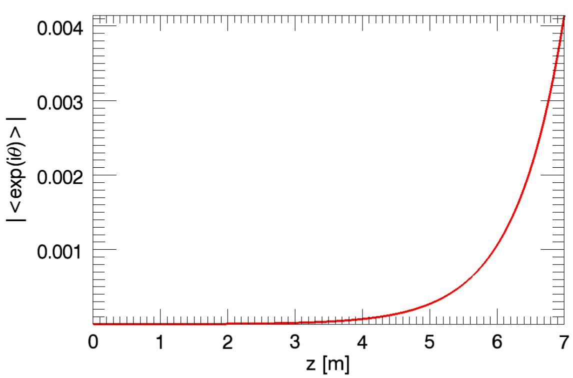
Simulation results (GENESIS)



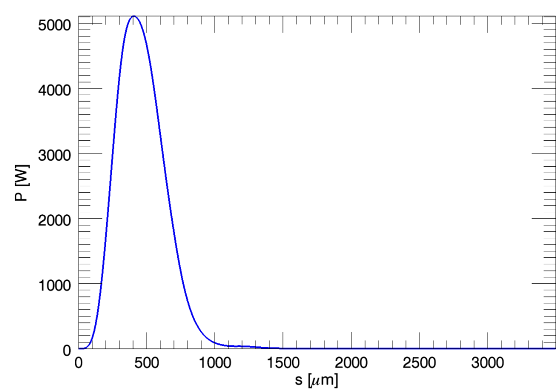
Binned current (top) and p_z (bottom), lab frame: growing bunching, as seen from phase shift



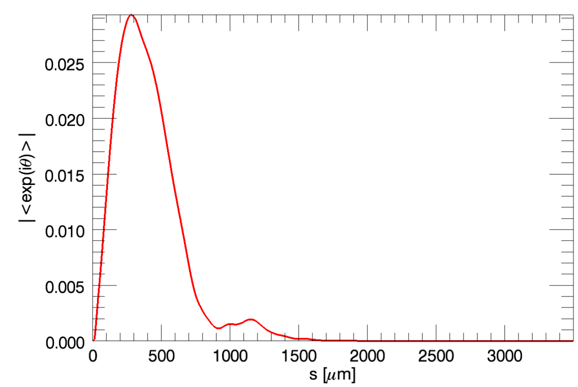
e^- density after a single pass through the FEL, max(δn_e)~5.3 10^{16} m^{-3}.



Mean bunching as a function of z along the undulator: no saturation at exit from the wiggler



FEL power distribution along the bunch, at exit from the undulator



Magnitude of the bunching parameter along the bunch

3D coupling to FEL simulations: using ‘clone’ macroparticles

- One fundamental difficulty of GENESIS bunching parameters is that they are derived from sums over the δf macroparticles, and so the coupling is somehow indirect
- Another fundamental difficulty with GENESIS bunching parameters is that they capture coherent density perturbations, but not the velocity perturbations
- Use of clones [*] promises to remove both of these difficulties, plus it provides the very important possibility of benchmarking two different algorithms
- Correct statistics of shot noise, by construction

* 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
  - W.M. 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

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

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 α = 0, including FEL interaction, initial shot noise is zero
- When α = 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)

Complex-weight clone multiplets

- More generally, not just clone pairs, but complex weight multiplets can be constructed for modeling high harmonics, with $q_n = |q_n| e^{i\psi_n},\ m_q = m_e |q_n/e|$
- To keep FEL equations correct

$$\sum_{n=1}^{N} c_n^h |q_n| e^{i(h+1)\psi_n} = e n_e$$

- Local 6D neutrality + density fluctuations:

$$\sum_{n=1}^{N} c_n^h q_n = e\delta n_e;\ \ h = 0, 1, 2, \ldots$$

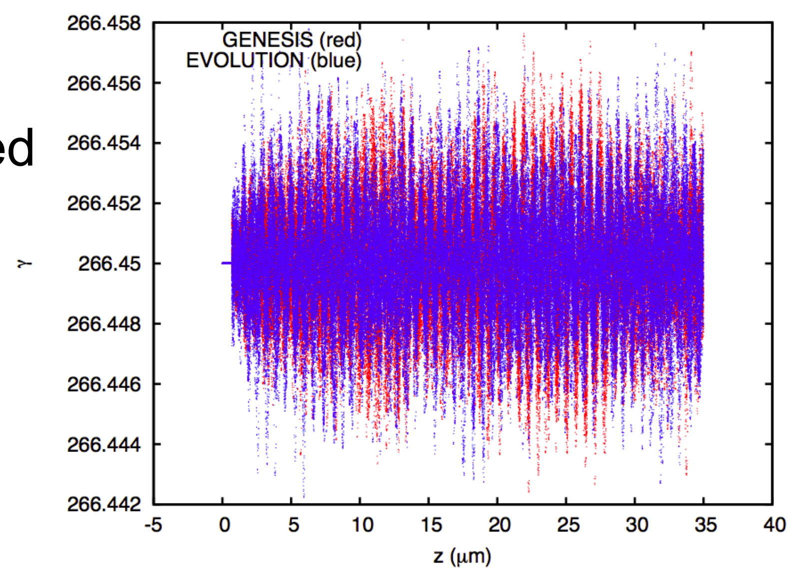
- Exact power and spectrum of spontaneous radiation when

$$\langle \delta n_e^2 \rangle = n_e$$

- Simple clone pairs: $c_n^h = 1,\ q_1 = e\dfrac{n_e + \delta n_e}{2},\ q_2 = -e\dfrac{n_e - \delta n_e}{2},\ \psi_1 = 0,\ \psi_2 = \pi$

Implementing particle-clone pairs approach in GENESIS

- Clone macroparticles have already 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

Work in progress and future plans

- Enabling direct coupling of the VORPAL *δf* simulation putput into the 3D distribution of particle-clone pairs
- Exploring the use of complex-weight clones for modeling high harmonics
- Careful comparisons of fully 3D amplifier simulations performed with the clone-based approach vs GENESIS simulations with distribution of bunching parameter as input
- More realistic simulations that account for the finite beam size and multiple ions; accounting for ion's transverse velocity and modeling cooling for anisotropic plasmas

Acknowledgments

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

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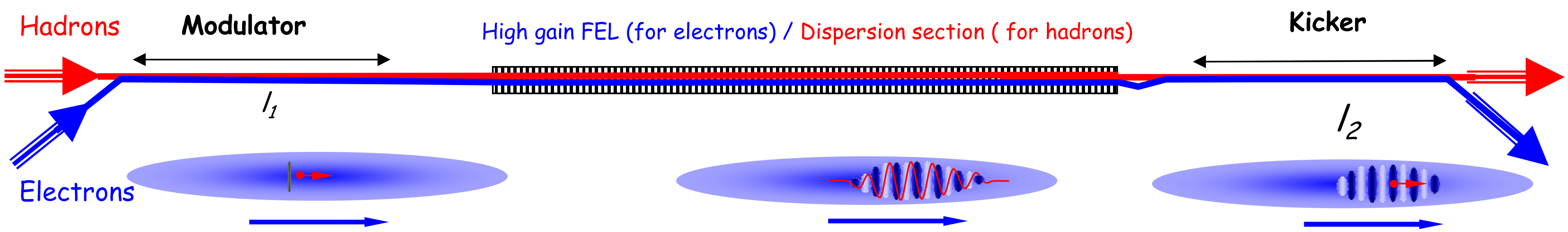
CeC: Economic option



Electrons

Modulator: region 1
a quarter to a half of plasma oscillation

Amplifier of the e-beam modulation via High Gain FEL and
Longitudinal dispersion for hadrons

Kicker: region 2

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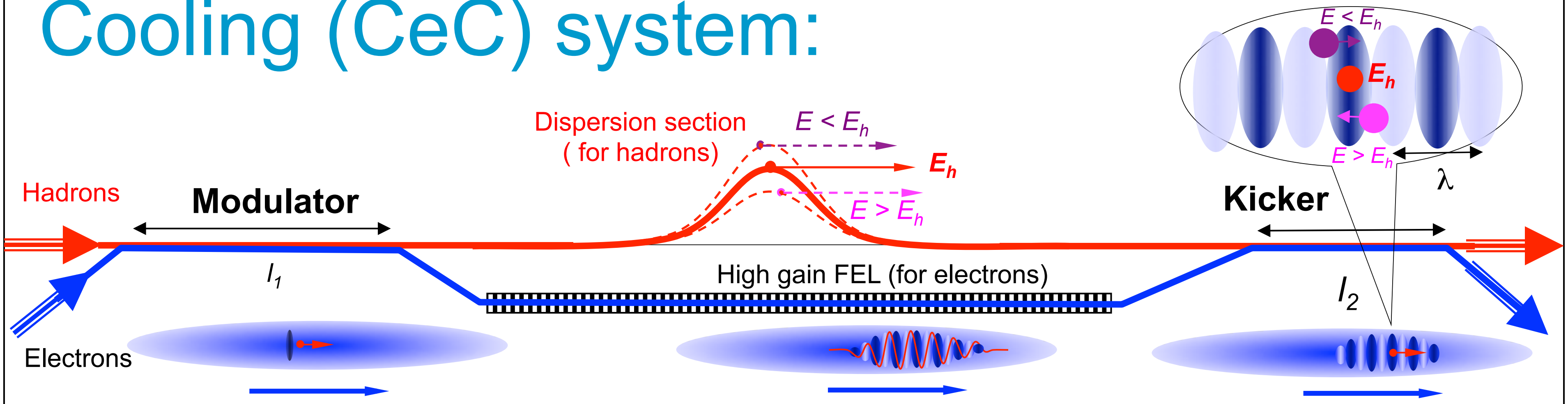
Schematic of a Coherent electron Cooling (CeC) system:



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

- Coherent Electron Cooling concept
  - uses FEL to combine electron & stochastic cooling concepts
  - a CEC system has three major subsystems
    - **modulator**: the ions imprint a "density bump" on e- distribution
    - **amplifier**: FEL interaction amplifies density bump by orders of magnitude
    - **kicker**: the amplified & phase-shifted e- charge distribution is used to correct the velocity offset of the ions

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Modulator simulations use δf PIC algorithm; run in parallel at NERSC

- δf PIC uses macro-particles to represent deviation from assumed 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; or ~30 minutes on ~60,000 proc's

VORPAL

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