

High-Fidelity Start-to-End Multi-Particle Simulations of Space Charge, IBS and Collective Instabilities

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Injectors and Beam Physics for Future Accelerators

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ENERGY

Office of
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ACCELERATOR TECHNOLOGY &
APPLIED PHYSICS DIVISION



Outline

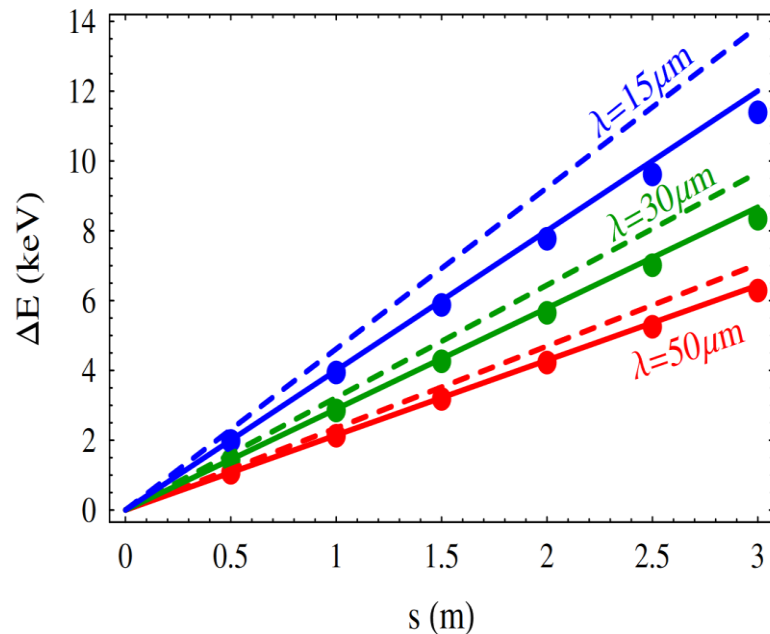
- Introduction to the computational tool
- S-2-E real particle simulation of a LCLS-II-HE design
- Effects of intra-beam scattering
- Summary
- Potential future experiments

Computational Tool: IMPACT Code Suite Is a Multi-Physics High-Intensity and High Brightness Beam Dynamics Code

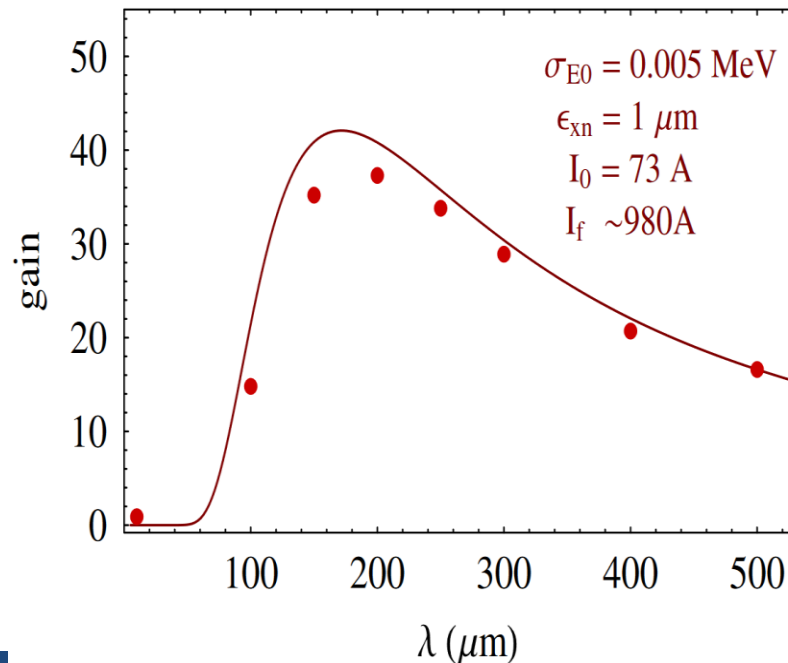
- Key Features include:
 - Time-dependent and position dependent
 - Serial and massive parallelization
 - Detailed 3D RF accelerating and focusing model, dipole, solenoid, multipole, ...
 - Multiple charge states, multiple bunches
 - 3D space-charge effects
 - Structure + resistive wall wakefields
 - Coherent synchrotron radiation (CSR)
 - Incoherent synchrotron radiation (ISR)
 - Gas ionization
 - Photo-electron emission
 - Machine errors and steering

Verification of the IMPACT Space-Charge Model vs. Analytical Calculation Shows Good Agreement

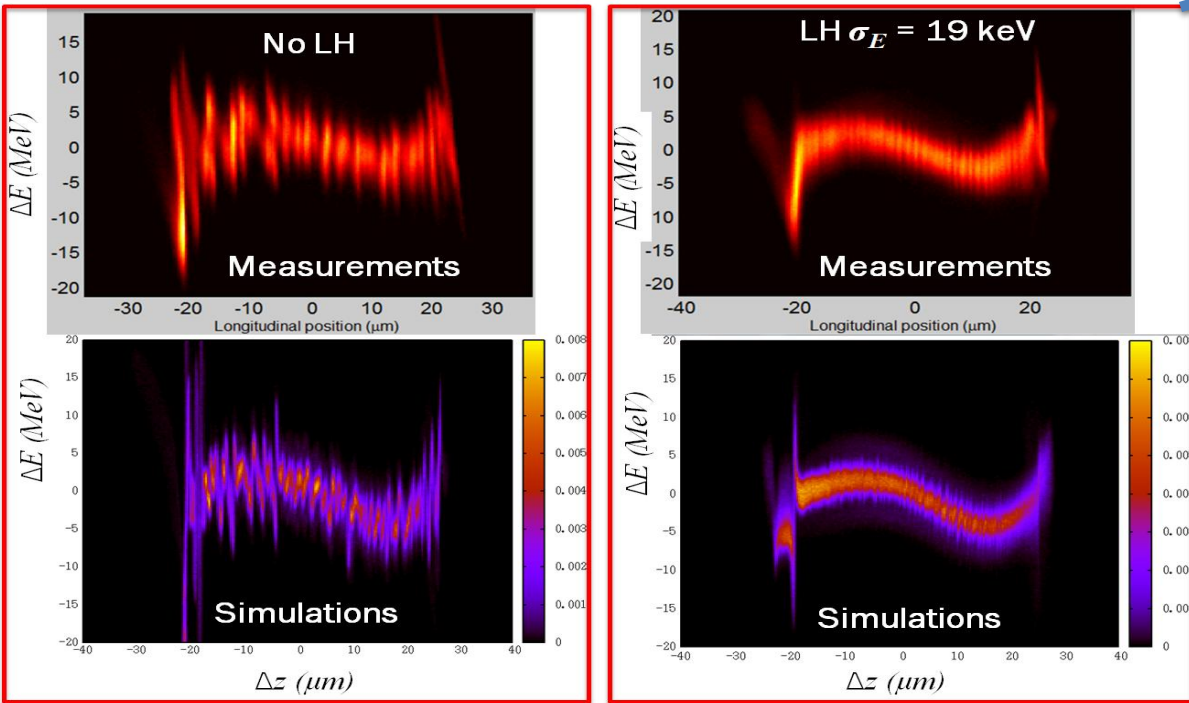
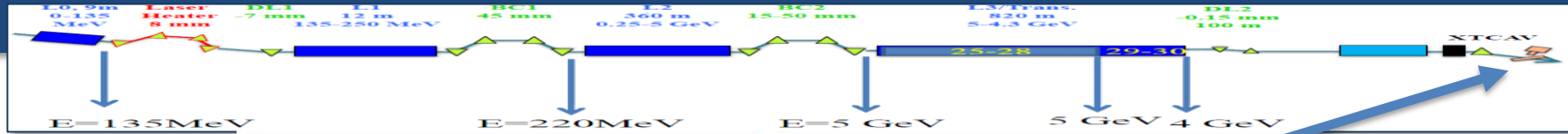
Energy modulation growth from simulations and analytical model



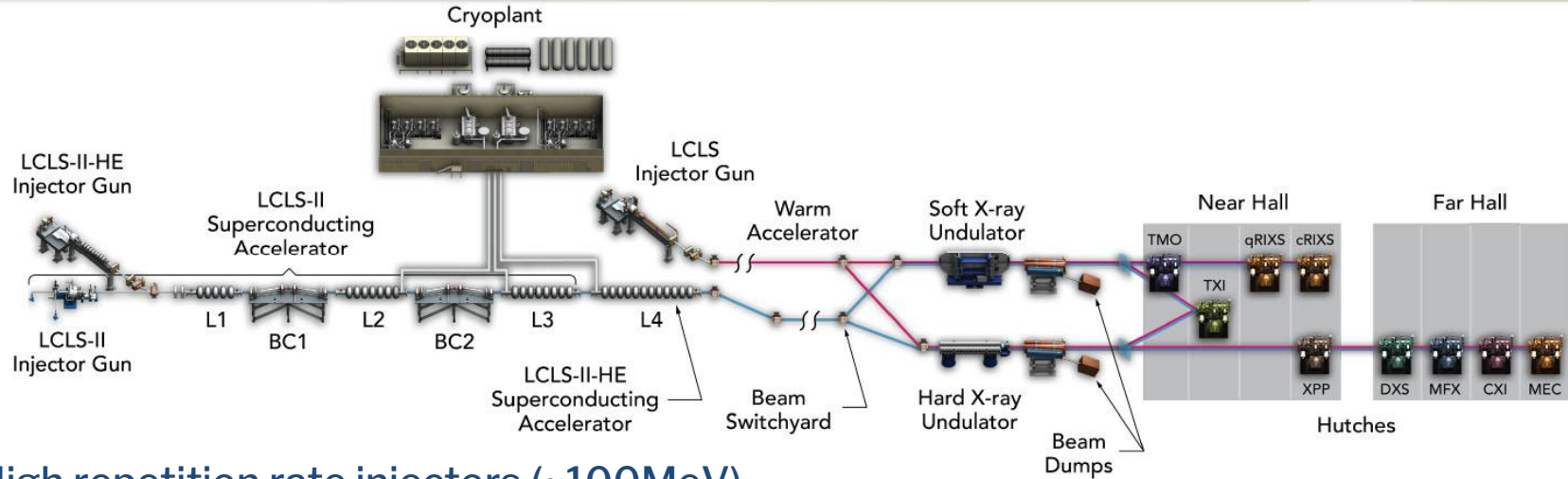
Microbunching instability gain from simulations and analytical model



Start-to-End High Fidelity Simulation Reproduces Experimental Observation of MicroBunching at LCLS



LCLS-II-HE Design Layout



- High repetition rate injectors ($\sim 100\text{MeV}$)
- Laser heater
- Superconducting linac L1, L2, L3, and L4 ($\sim 8\text{GeV}$)
- Two bunch compressors BC1 and BC2 for bunch compression ($> \text{kA}$)
- Two FEL undulators (soft X-ray and hard X-ray)

Physical Model and Numerical Parameters Used in the S2E Simulation

Physical Model:

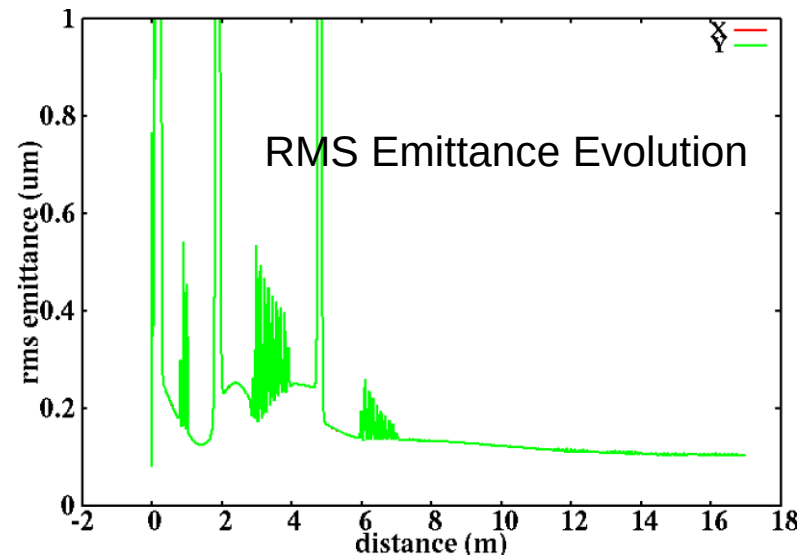
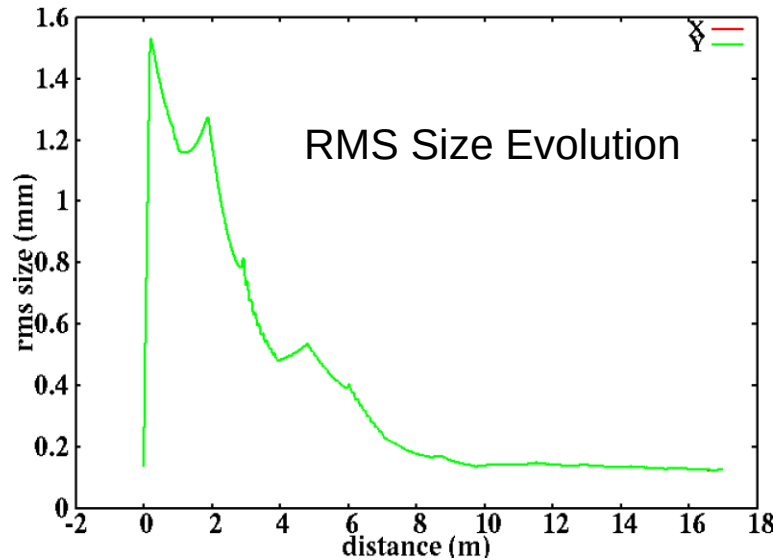
- Superconducting RF gun LEI with 30MV/m at cathode; 0.6 $\mu\text{m}/\text{mm}$ thermal emittance, transverse truncated Gaussian, longitudinal flattop with $\sim 2\text{ps}$ rise time
- 2021 LEI-HE lattices: HXR and SXR (include transverse focusing of LH undulator)
- 3D space-charge
- 1D CSR
- ISR
- longitudinal structure and resistive wall wakefields
- IBS (distributed analytical model including beam distribution dependent, G. Penn, LBNL Report 6762, 2014.)
- laser heater (0 keV)

Numerical Parameters:

- 1 macroparticle = 1 electron
- 64x64x2048 grid

Transverse RMS Size and Emittance Evolution through Superconducting Gun, Bunchers, and Booster Cavities

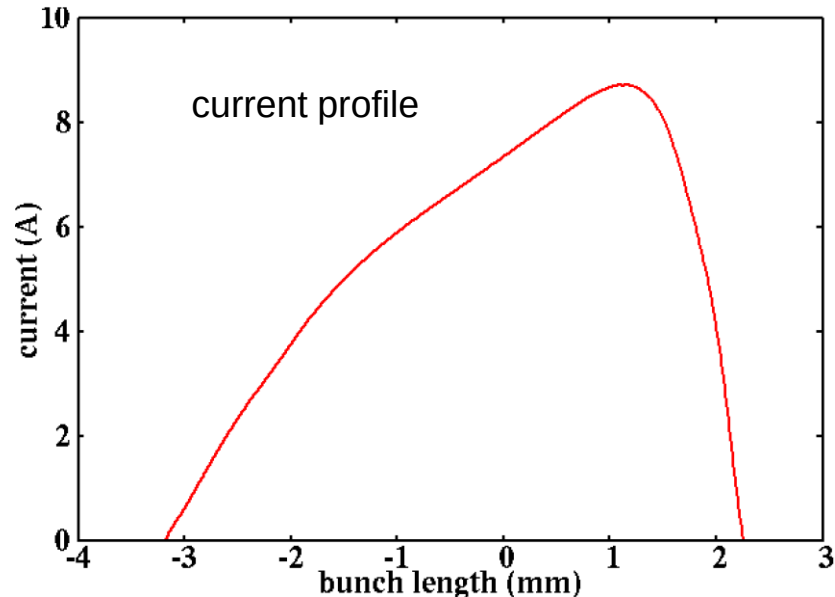
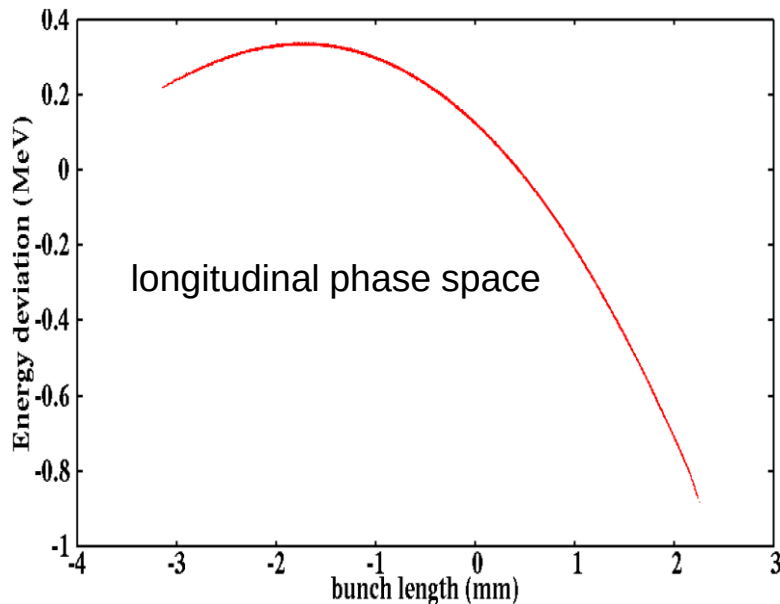
from Impact-T simulation



- Transverse rms beam size is focused by three solenoids and RF boosting cavities.
- The final 100% projected rms emittances attain around (0.105, 0.105) μm with initial 0.6 $\mu\text{m}/\text{mm}$ thermal emittance.

Longitudinal Phase Space Distribution and Current Profile at the Exit of the new SRF Gun Injector

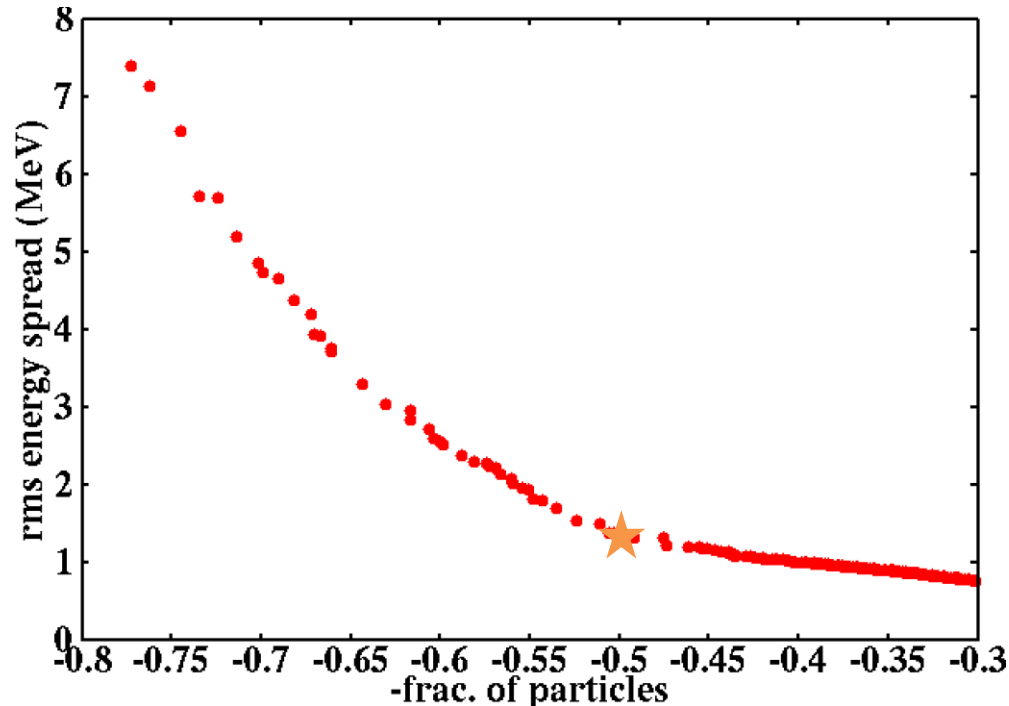
from Impact-T simulation



- RMS longitudinal energy spread is $\sim 0.3\%$.
- Initial core peak current is under 9 A.

Multi-Objective Optimization of Final Electron Beam Quality to Attain High Brightness

Pareto Front of the Optimal Solutions



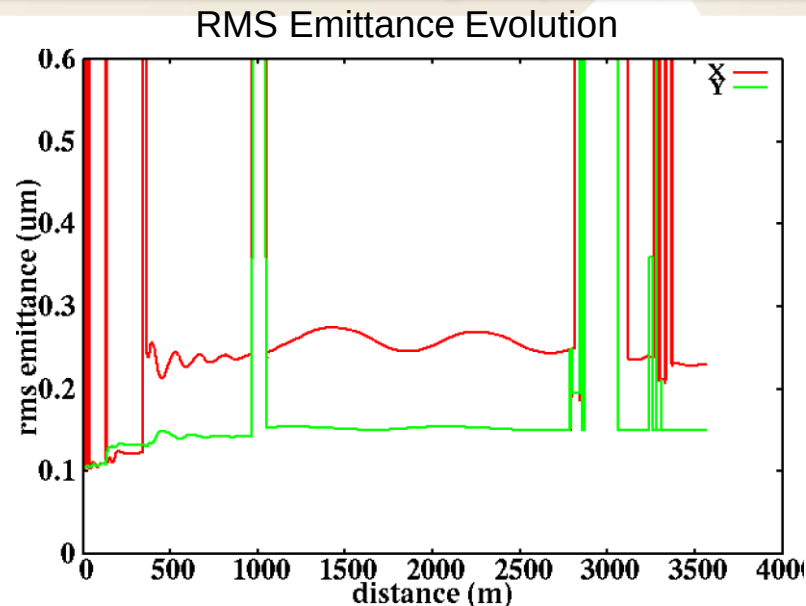
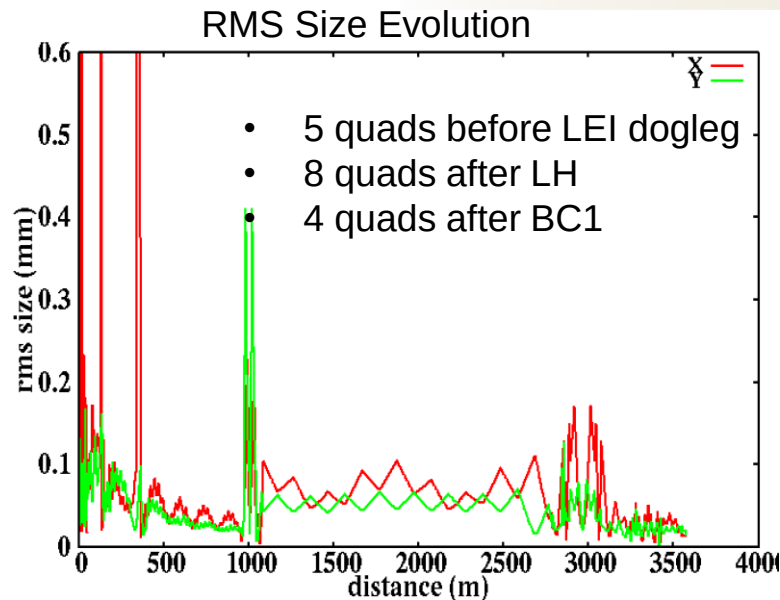
2 objective functions

- Negative fraction of particles inside the core
- RMS energy spread of the particles inside the core

10 linac control parameters

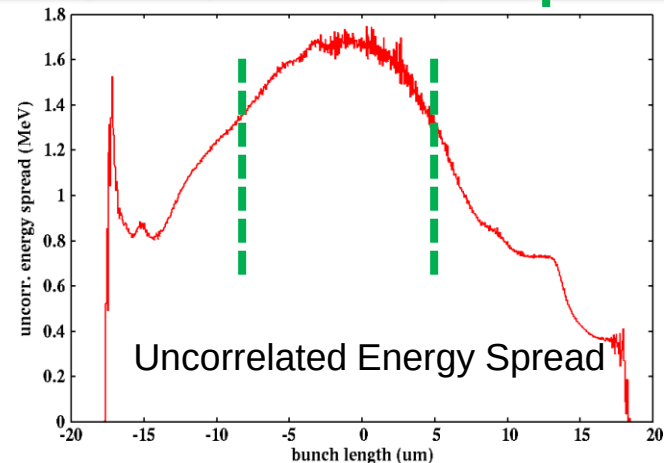
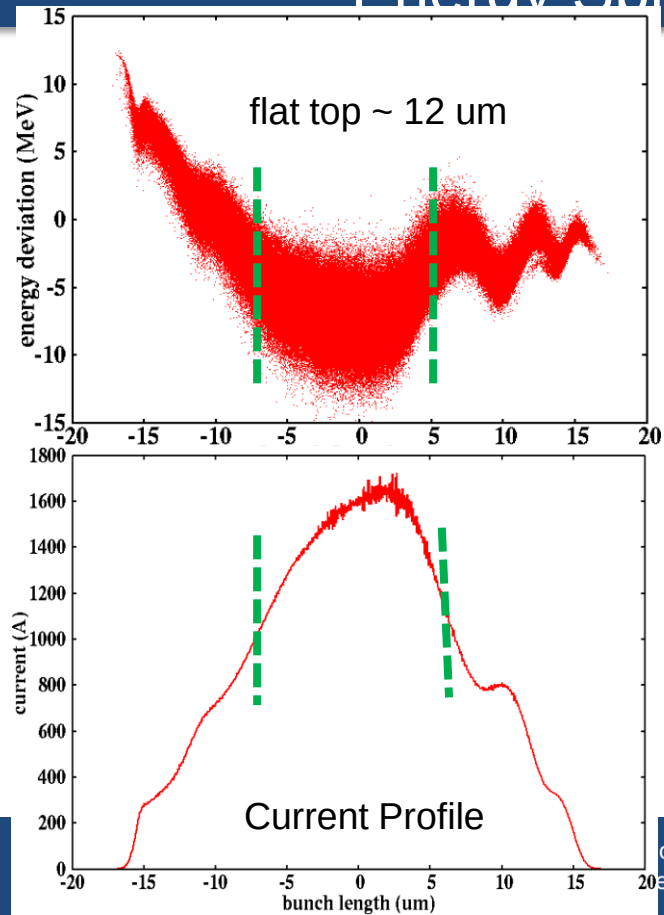
- L1 amplitude + phase
- HL amplitude + phase
- BC1 R56
- L2 amplitude + phase
- BC2 R56
- L3 amplitude + phase

Transverse RMS Size and Emittance Evolution after Retuning Lattice Focusing Parameters with Space-Charge (100pC HXR)



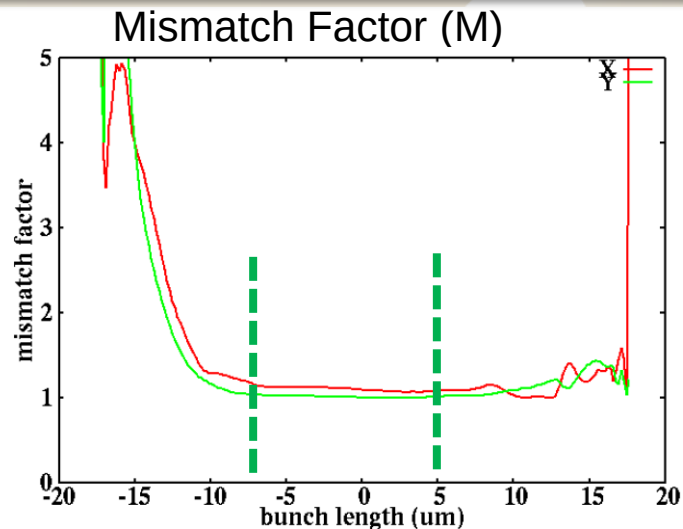
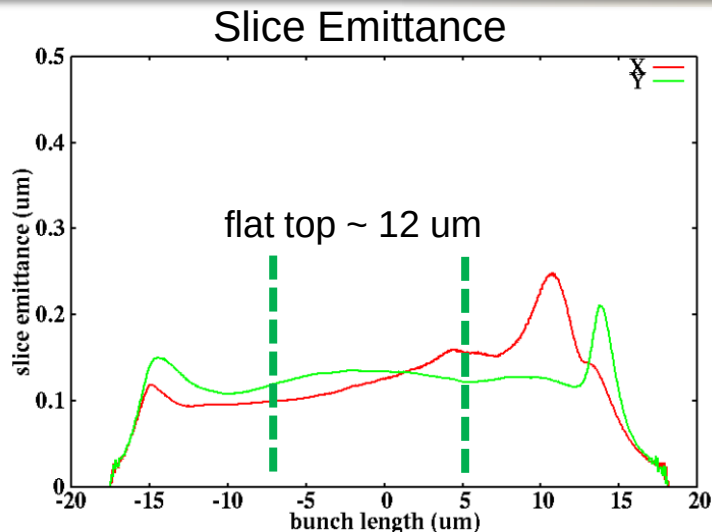
- Transverse rms beam size is reasonably matched through the accelerator after matching with SC.
- The longitudinal compression factor after BC1 is about 4 and about 45 after BC2.
- The major horizontal emittance growth occurs after BC2 due to the CSR effects, the vertical emittance growth after BC1.
- The final rms emittances are around (0.22, 0.15) μm .

Final Longitudinal Phase Space, Current Profile, Uncorrelated Energy Spread Profile (100pC HXR)



- Final longitudinal phase space is reasonably flat.
- Final core peak current is about 1.6 kA.
- Final peak uncorrelated energy spread is about 1.6 MeV.

Final Transverse Slice Emittance and Mismatch Factor (100 pC HXR)



- Core slice emittance is good ($<0.15 \mu\text{m}$).
- Horizontal and vertical planes are well matched inside the core.
- Somewhat mismatched near the beam head and tail.

$$M = (\beta\gamma_0 - 2\alpha\alpha_0 + \gamma\beta_0) / 2$$

Summary of cathode-to-undulator simulation results

Low Emittance Injector – LCLS-II-HE (30 MV/m at cathode)

IMPACT Studies	I_core (A)	σ_E (keV)	Proj. ϵ_x / ϵ_y (mm-mrad)	Slice ϵ_x / ϵ_y (mm-mrad)
100 pC	1453	1590	0.23/0.15	0.13/ 0.13
	1451	1598	0.19/0.15	0.13/0.13

HXR

SXR

LCLS-II injector – LCLS-II-HE (20 MV/m at cathode)

IMPACT Studies	I_core (A)	σ_E (keV)	Proj. ϵ_x / ϵ_y (mm-mrad)	Slice ϵ_x / ϵ_y (mm-mrad)
100 pC	1238	1025	0.58 / 0.45	0.24/ 0.27
	1251	1034	0.53/0.43	0.25/0.27

HXR

SXR

IBS Models: Self-Consistent Fokker-Planck Solver and Semi-Analytical Model

- Fokker-Planck-Landau Equation with Rosenbluth Potentials:

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = -\frac{\partial}{\partial \mathbf{v}} \cdot \mathbf{F}_d f + \frac{1}{2} \frac{\partial^2}{\partial \mathbf{v} \partial \mathbf{v}} : \mathbf{D} f$$

$$\mathbf{F}_d = \left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{4\pi e^4}{m^2} \lambda \frac{\partial H}{\partial \mathbf{v}}$$

$$\mathbf{D} = \left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{4\pi e^4}{m^2} \lambda \frac{\partial^2 G}{\partial \mathbf{v} \partial \mathbf{v}}$$

$$H = 2 \int d^3 \mathbf{v}' \frac{f(\mathbf{v}')}{|\mathbf{v} - \mathbf{v}'|}$$

$$G = \int d^3 \mathbf{v}' f(\mathbf{v}') |\mathbf{v} - \mathbf{v}'|$$

$$\lambda = \ln\left(\frac{b_{max}}{b_{min}}\right)$$

- Langevin solution of the Fokker-Planck-Landau equation:

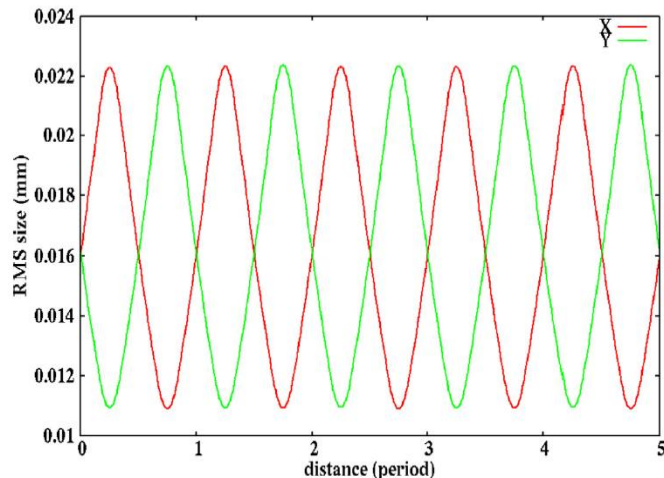
$$\mathbf{v}' = \mathbf{F}_d + \Gamma(t)$$

- Semi-analytical multi-slice model assuming a Gaussian velocity distribution and transverse Gaussian density distribution :

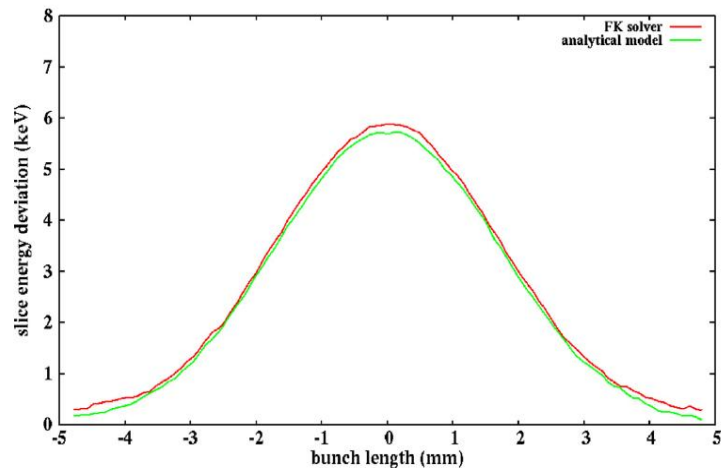
$$\langle \Delta \gamma^2 \rangle = 2\pi^{3/2} r_e^2 n_e(x, y, z) \ln \Lambda \frac{1}{\sigma_\beta(z) \gamma_b} s$$

Benchmark the FK Solver against the Semi-Analytical Solver

Transverse RMS size evolution through the FODO lattice

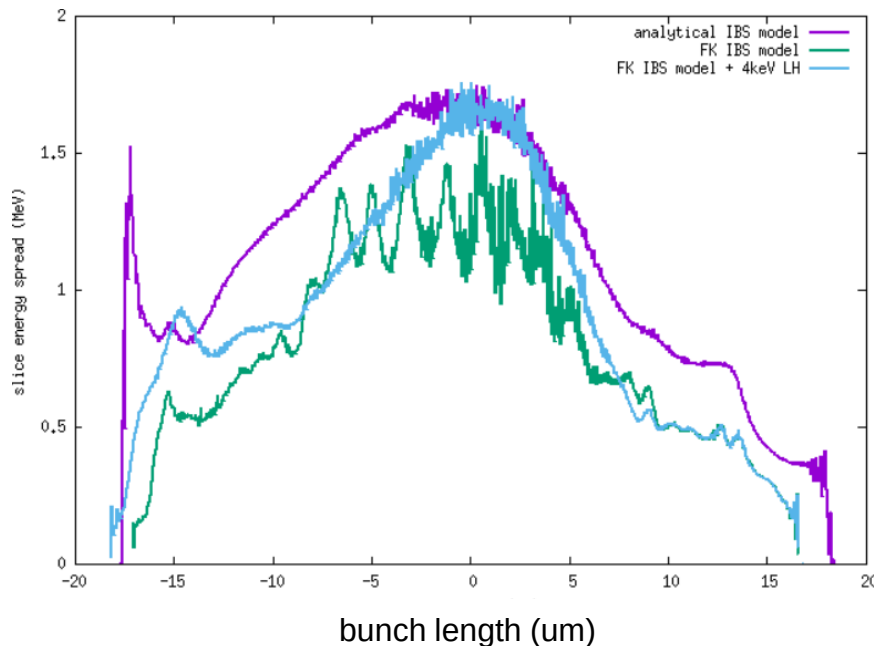


Slice uncorrelated energy spread profile at the exit of the FODO lattice



- Good agreement is attained between the two solvers for an initial 6D Gaussian distribution

Final Slice Energy Spread from the FK Solver w/o Laser Heater



- FK IBS model predicts less energy spread and 4 keV uncorrelated energy spread from LH is needed to mitigate uBI.

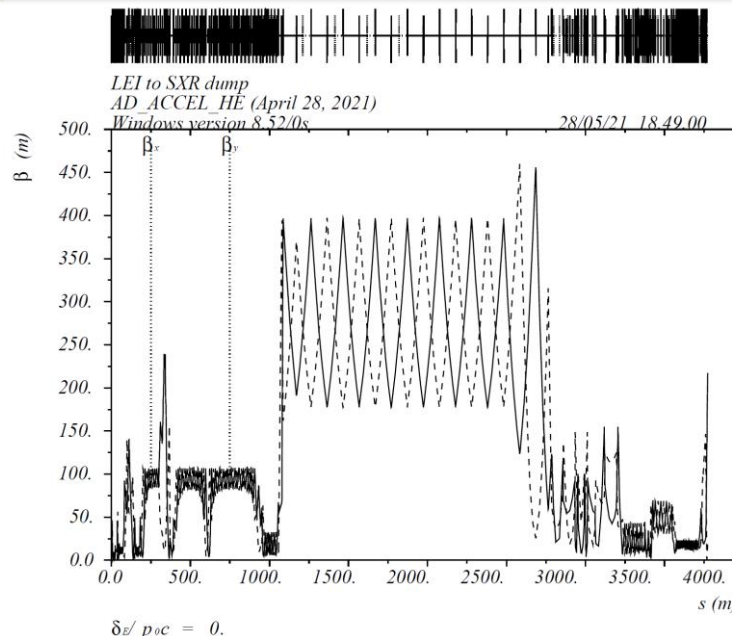
Mitigation of Intra-Beam Scattering (IBS) Effects

$$\sigma_{\gamma}^2 = (\sigma_{\gamma 0}^2) + \frac{2r_e^2 N_b}{\langle \sigma_x \rangle \varepsilon_x^n \sigma_z} \Delta s,$$

- Lower transverse emittance from LEI can result in larger energy spread from IBS effects
- Larger transverse beam size helps reduce the IBS induced energy spread
- Less compression also helps mitigate the IBS induced energy spread

Ref: Z. Huang, "Intrabeam Scattering in an X-ray FEL Driver," SLAC-TN-05-026, 2002.

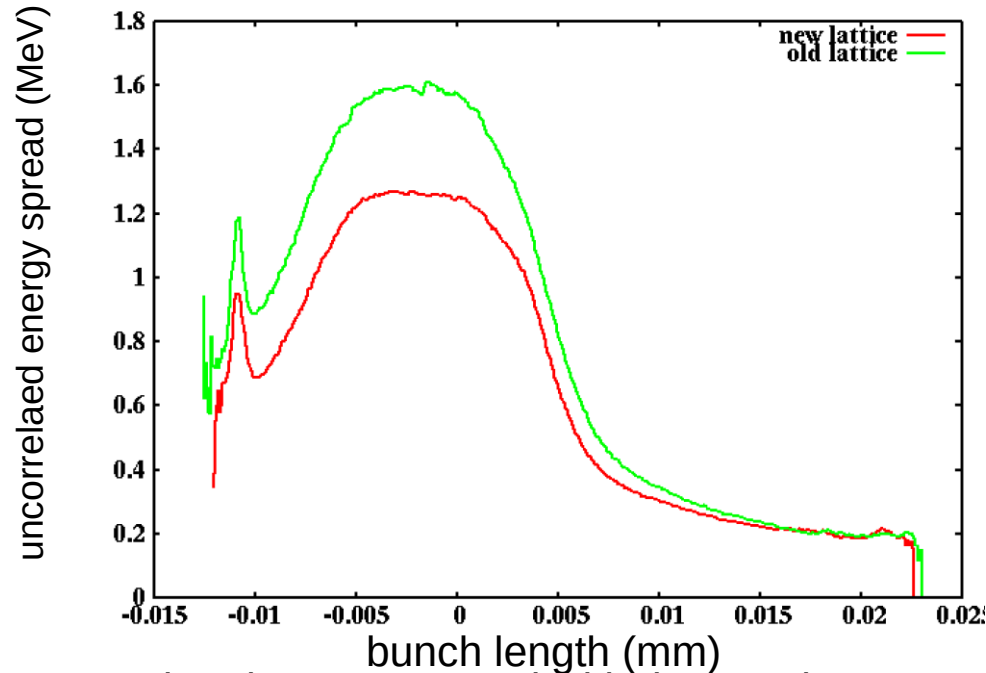
Larger Beta Function Values in the Modified Test Lattice



- L1B beta function increased by a factor of 2
- L2B, L3B, and L4B phase advance lowered from 30 degrees to 15 degrees
- Rematched all other lattice parameters

From M. Woodley

Final Uncorrelated Energy Spread from the New Lattice and the Old Lattice



- ~20% smaller uncorrelated energy spread with the new larger transverse size test lattice
- Larger transverse emittance growth observed through the new test lattice

Summary

- S-2-E real electron number simulations through an LCLS-II LEI-HE HXR/SXR lattice yield reasonable final peak current, longitudinal and transverse phase space, and emittances.
- The low emittance beam from the LEI is reasonably preserved through the linac accelerator beam delivery system with about 100% projected emittance growth and 30% sliced emittance growth including space-charge, IBS, ISR/CSR, wakefields, and microbunching instability.
- The final uncorrelated slice energy spread might be lowered with appropriate lattice design.

Potential Future Beam Physics Experiments

- Validate the project emittance at the exit of injector dependency on peak electric field at cathode.
- Measure the transverse space-charge effects on beam emittance growth after in LH and BC1 regions.
- Study the IBS effects and uBI on SES after injector.
- Test the mitigation of uBI with transverse – longitudinal coupling.
- Benchmark the final electron beam emittances, energy spread before undulators from simulations and measurements.

Thank You for Your Attention!