Optimizing X-ray FEL performance for LCLS at SLAC

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

- Free Electron Lasers
- LCLS Overview
- Deliverable X-Ray Parameters
- Setting Up the Machine
- Tuning Methods
- FEL Performance
- References
- Supplemental Information

Free Electron Lasers

Introduction to Free Electron Lasers

SLAC

FEL uses a bunch of unbound electrons

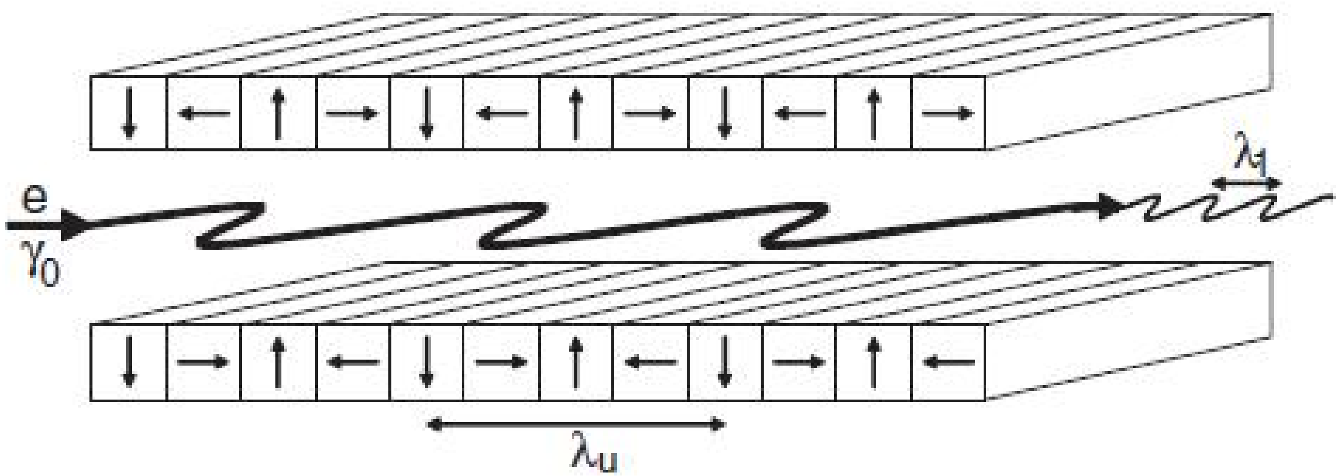
- Amplification of stimulated emission due to a resonance condition
- Resonance condition setup with Electron/Radiation interaction in array of undulator magnets

Why use FEL?

- High Power (GW)
- Coherent Beam
- Short pulses(fs)
- High spatial and temporal resolution of Atomic and Molecular Processes

- Start with electron bunch entering periodic undulator array

- Electron will emit radiation spontaneously as it traverses the undulator

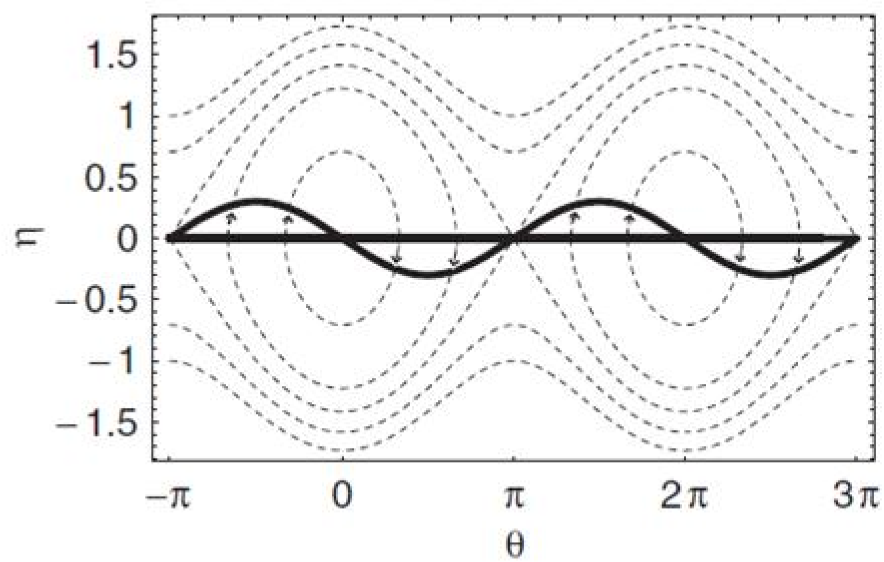


Introduction to Free Electron Lasers

• Once enough X-Rays produced the co-propagating photon bunch will micro-bunch the electron beam

• Micro-Bunched electron beam will then emit radiation coherently to amplify and produce the FEL

• This process of generating an FEL is called Self Amplification by Stimulated Emission(SASE)



Electron motion in the longitudinal phase space (θ, η)

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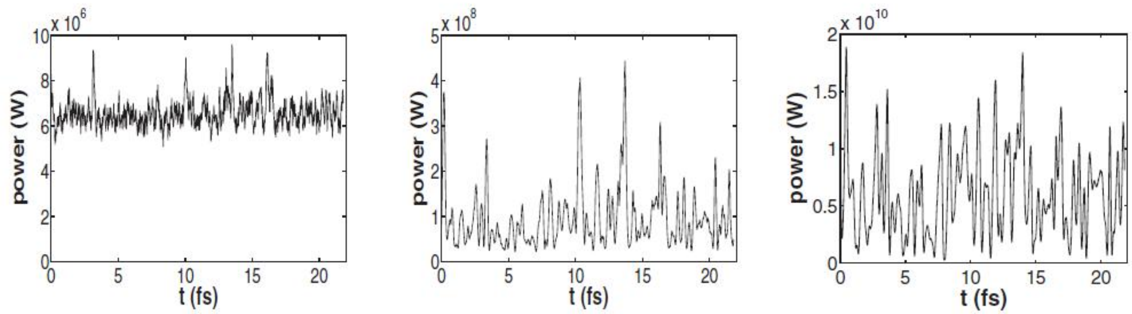
Poor Temporal Coherence(only coherent in each spike):

- Hundreds of ~fs spikes make up FEL pulse due to SASE
- Intensity builds up along length of Undulator

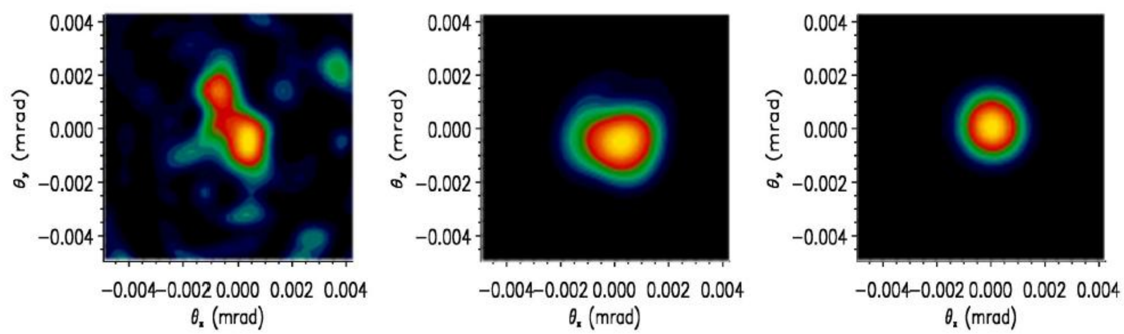


(a) $z = 25$ m (b) $z = 50$ m (c) $z = 75$ m

FIG. 10. Temporal structures of 10% of the LCLS pulse at different z locations.

Good Transverse Coherence:

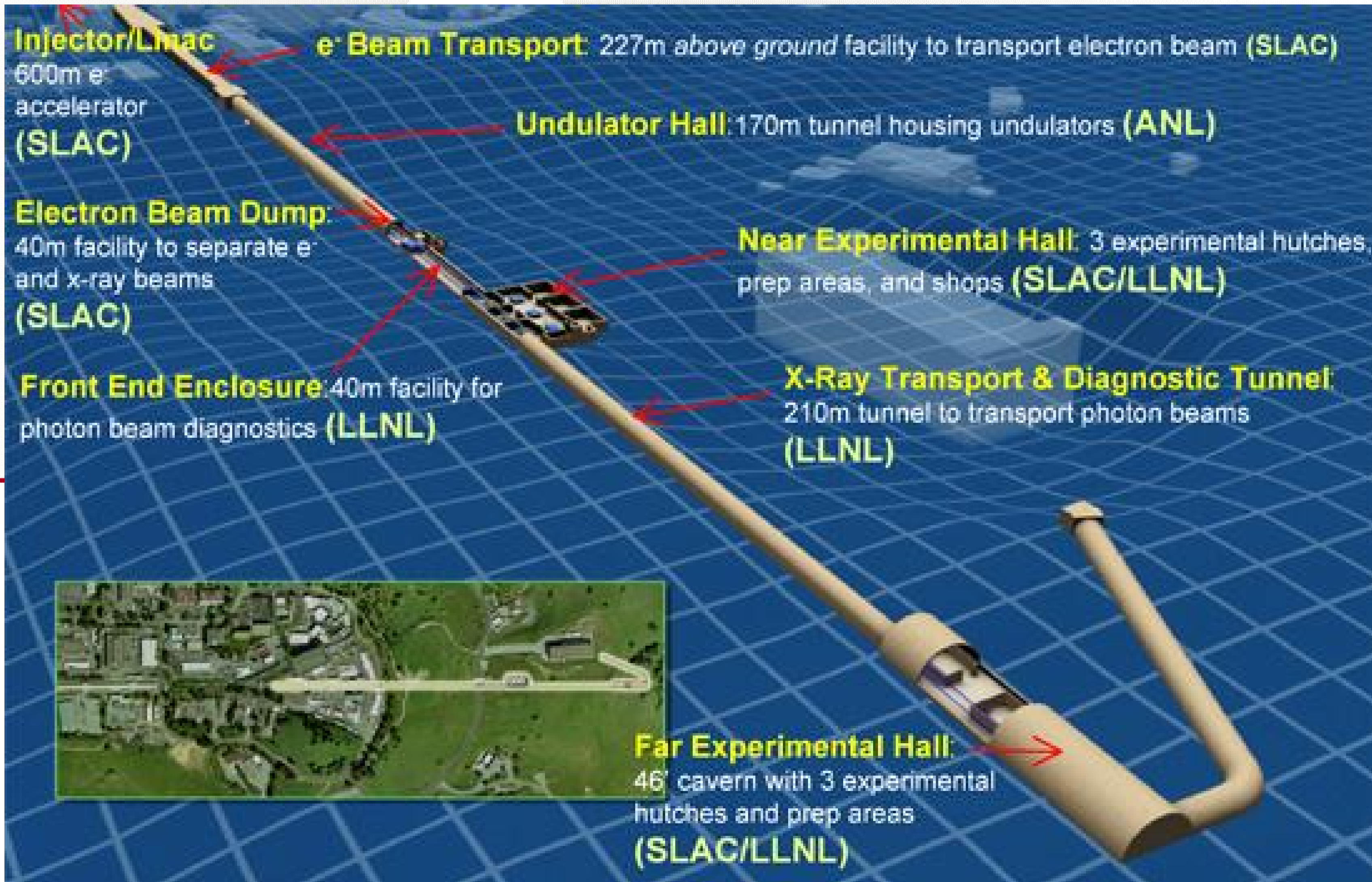
- Coherence builds up along length of the Undulator



(a) $z = 25$ m (b) $z = 50$ m (c) $z = 75$ m

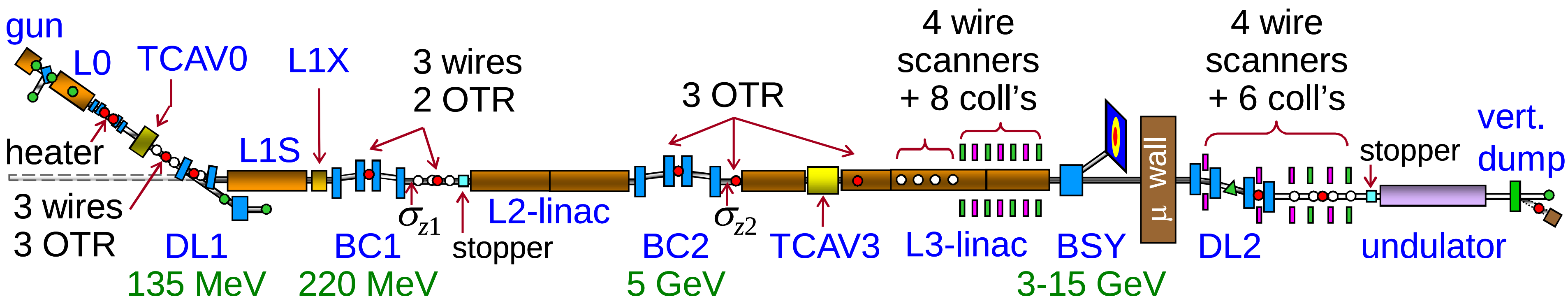
FIG. 9. (Color) Evolution of the LCLS transverse profiles at different z locations (courtesy of Sven Reiche, UCLA).

Introduction to LCLS

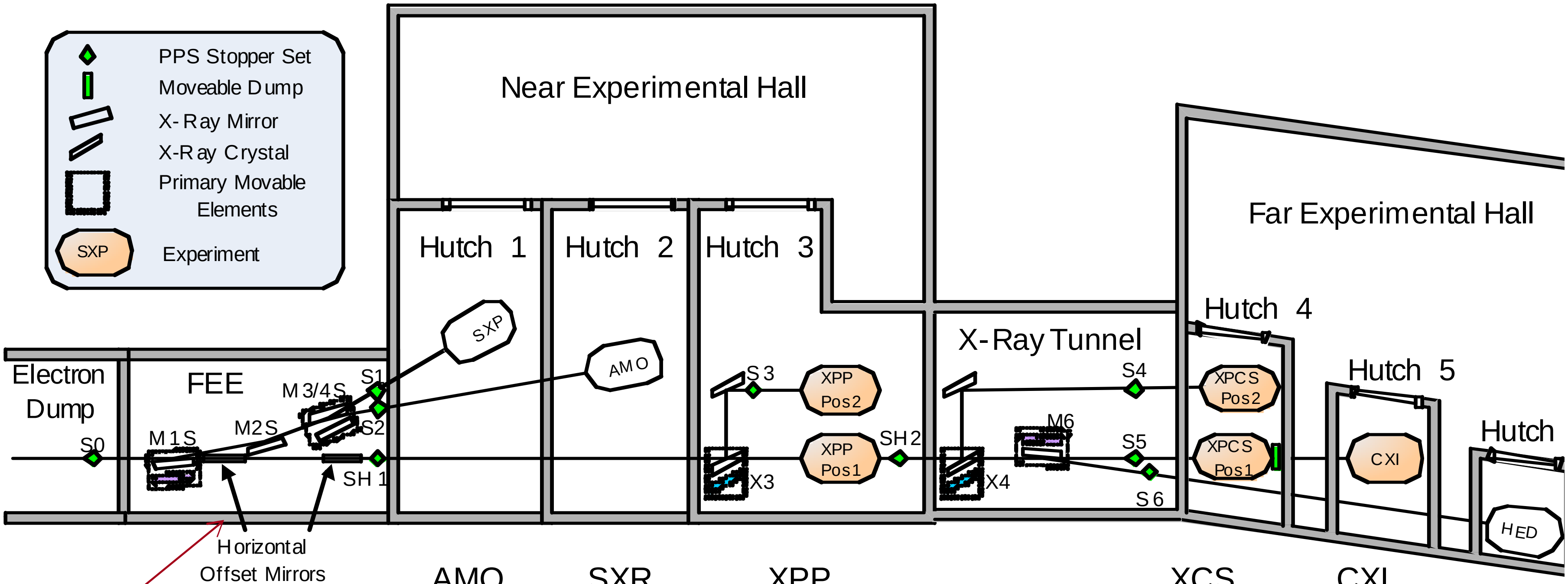


Introduction to LCLS: Electron Transport

•120Hz Pulsed Bunches using 2856MHz RF
• RF Gun(6MeV), UV Drive Laser, Photo-Electric Emission
  Cu Cathode, 20-350pC, 300-600µm Bunch
• Laser Heater(controlling slice energy spread)
• 1st Bunch Compressor(factor of ~10) BC1
• 2nd Bunch Compressor BC2
  Compress down to 0.5-10+µm(2fs-300fs)



Introduction to LCLS: Photon Transport



Front End Enclosure(FEE): Gas Detectors, Slits, Attenuators, K-Mono, Direct Imager

Near Experimental Hall Hutches: AMO & SXR (Soft X-Rays) XPP (Hard X-Rays)

Far Experimental Hall Hutches: XCS, CXI & MEC (Hard X-Rays)

6 Total Experiment Sites

Deliverable X-Ray Parameters

LCLS User Parameter Space

- Photon Energy
  480eV to 10.6keV

- Photon Pulse Length
  2 to 300+ fs

- Energy Bandwidth
  0.2% (narrow) or 2%(wide)

•Normally 2+ Configuration Changes Per 24/hours.
For now 1 user at a time, switch every 12 hours

Setting up the Machine

Setting up the Machine

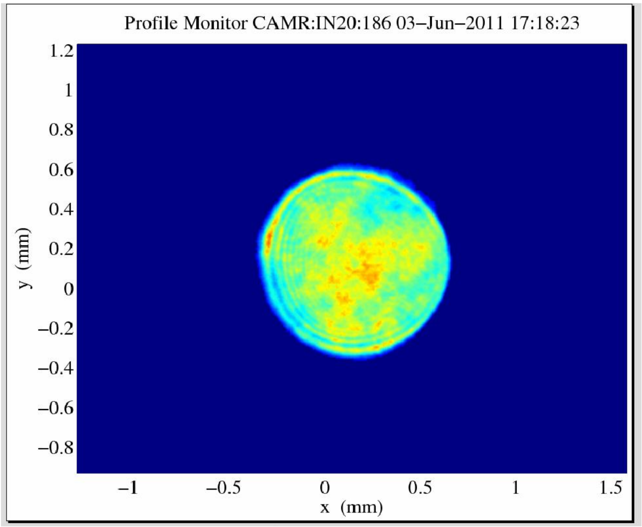
Keys to FEL Performance

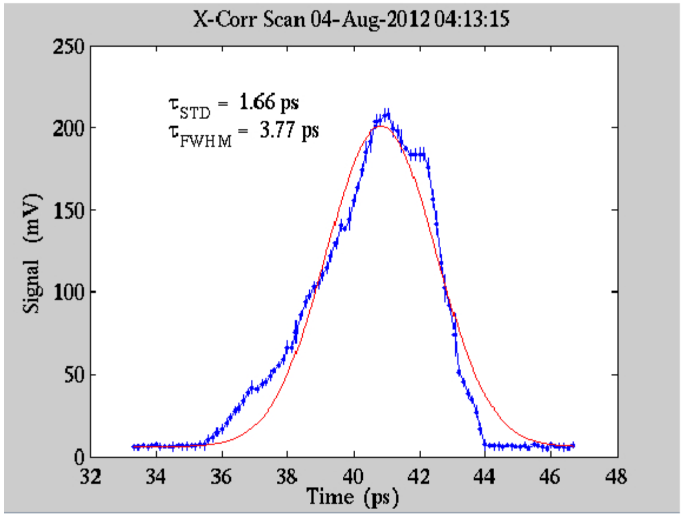
- Lowest Electron Transverse Emittance
- Optimal Electron Bunch Length
- Slice Energy Spread Sufficient to Generate SASE
- Optimal Undulator Configuration

Setting up the Injector

Starting point for good emittance is quality of beam off the cathode

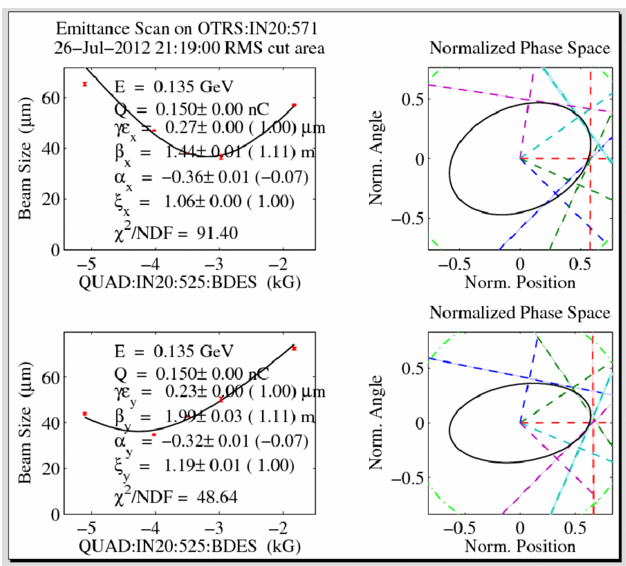
- UV Drive Laser Transverse and Temporal Quality
- Scan Cathode to find optimal QE and Emittance spot

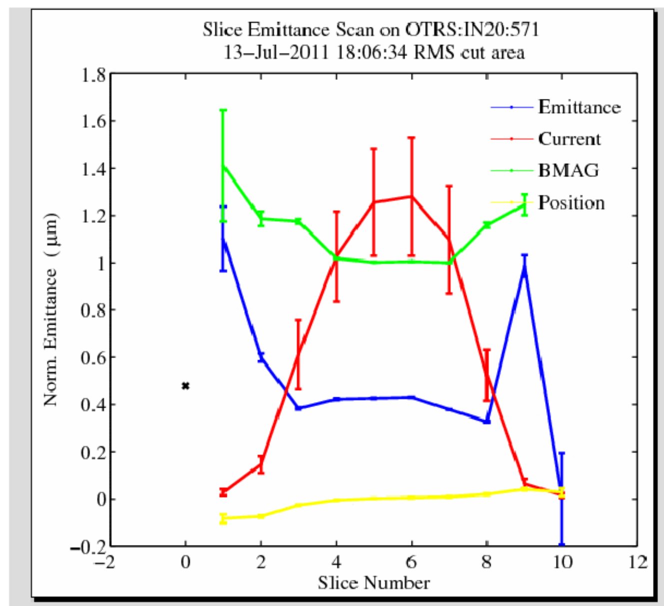




Setting up the Injector

- Use injector optics to tune for best transverse emittance
  - OTR Screens and Wire Scanners for beam size measurements
- Can also examine slice emittance in X plane
  - Clue about temporal quality of laser

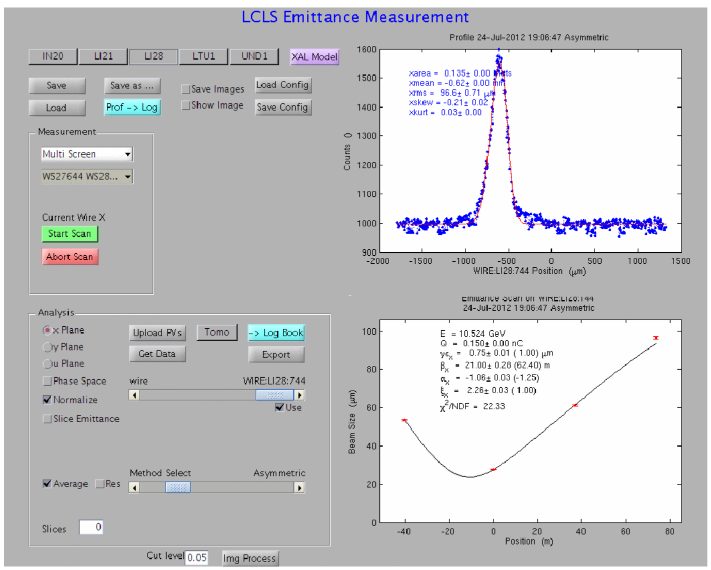


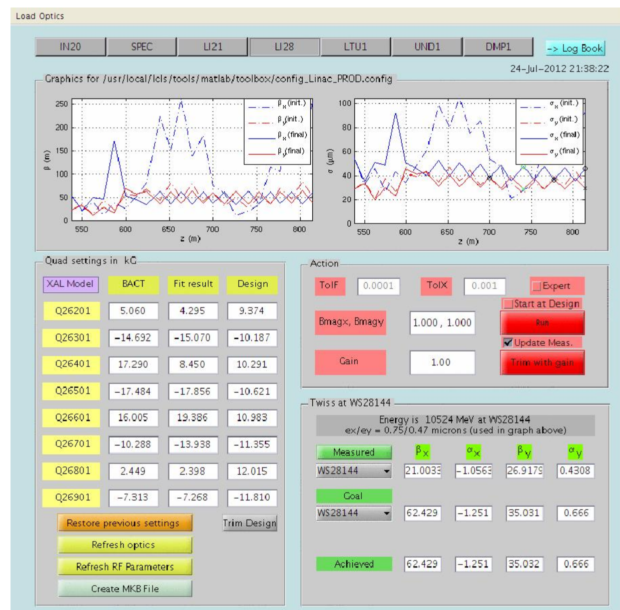


Setting up the Linac

Goal: Preserve Injector Emittance

• Emittance Measurement Points(wires): After 1st and 2nd bunch compressor , then upstream of Undulator
• Steer to Flat Orbit in Linac and Linac to Undulator Region
• Beta and Dispersion Match

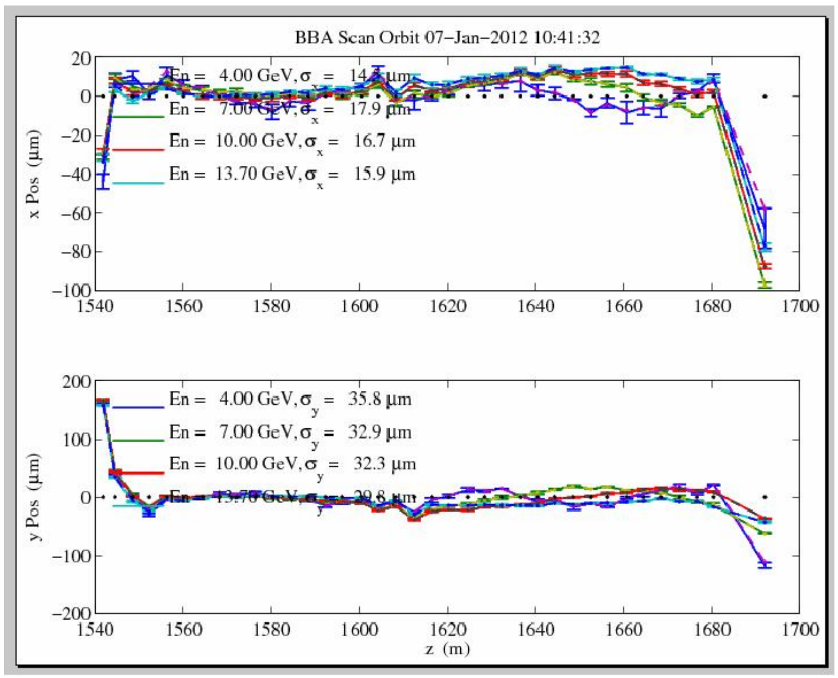


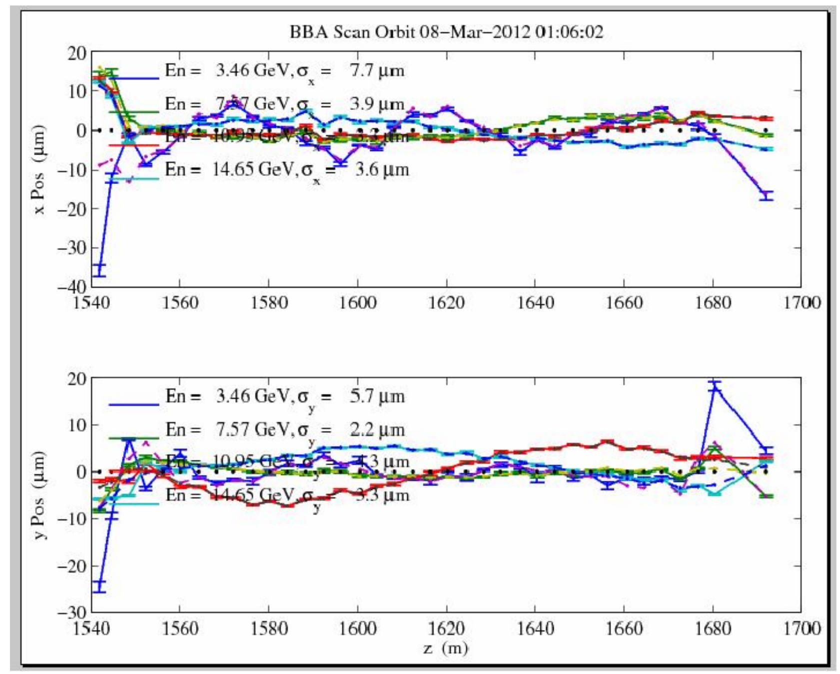


Setting up the Undulator

Goal: Keep the Electrons aligned with the X-Rays

- Beam Based Alignment at 4 energies to find flattest trajectory
  Uses all 33 Undulator BPM's and Undulator Quads
  Offsets in RF BPM's drift due to electronics issues

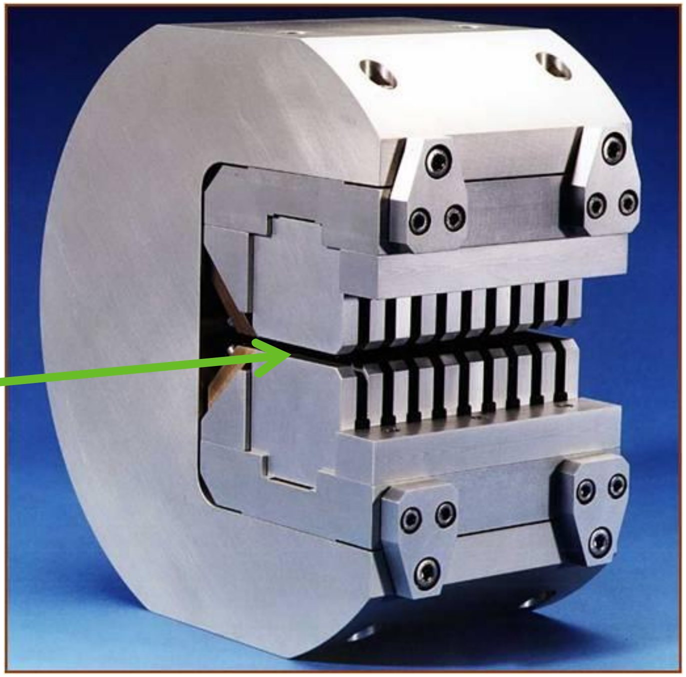




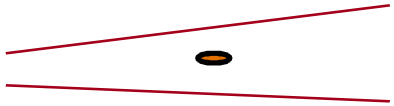
Setting up the Undulator

Undulator Translation Stage: Moves Horizontally to vary magnetic field value in each segment(use for Taper)

Beam Entrance



Pole Faces are tilted slightly

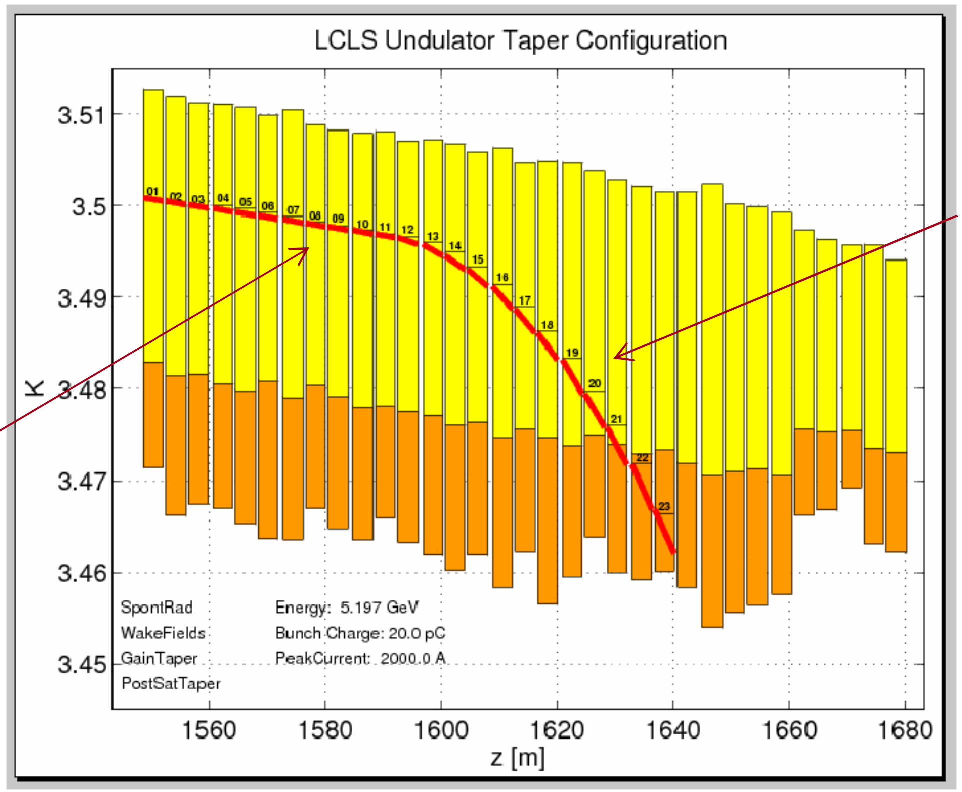


Field varies(K value) Horizontally in position along pole face

Setting up the Undulator

Undulator Taper: Needed to match Undulator Field to electron bunch that is losing Energy to FEL creation

Linear Taper in Exponential Gain Section

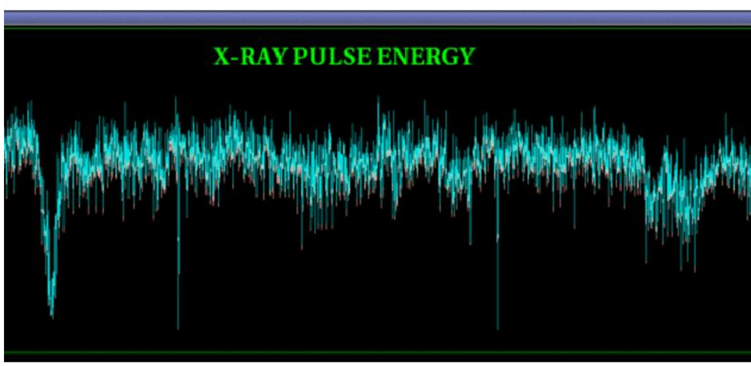


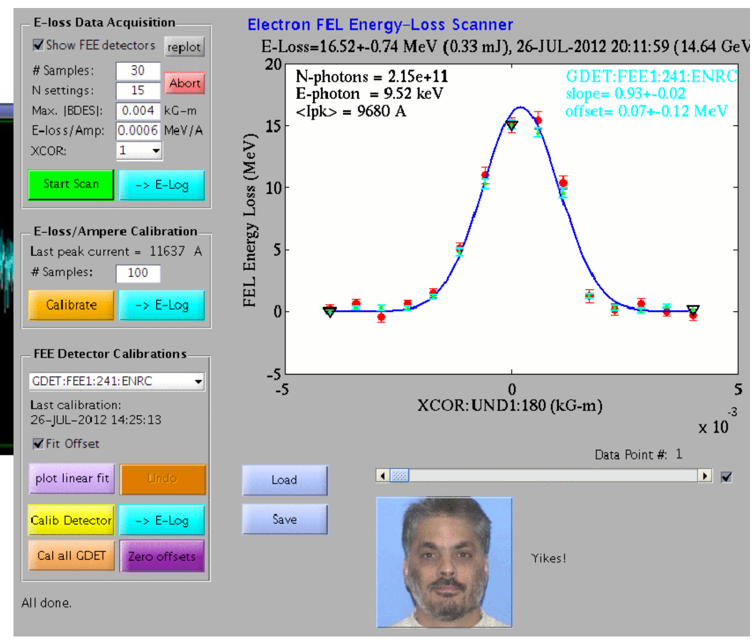
Quadratic taper in post saturation regime

Helps maintain resonance condition after saturation

Measuring the FEL Intensity

- Start by measuring Energy Loss of Electron Bunch across Undulator
  - Suppress FEL by kicking with first corrector in the Undulator
- Then Calibrate the Gas Detectors measuring the FEL pulse
  - FEL interacts with GAS emitting photons picked up by PMT's(minimally invasive)
- Use FEE Gas Detector display for real time Pulse Energy Information, and Tuning





Tuning Methods

Capability for Minimally Invasive Tuning

- Many experiments can handle tuning while beam is delivered
- Most gains are made in FEL pulse energy in this mode

Tuning Methods

Often Design Quad settings do not produce Best FEL

- Start by setting up to design lattice, but sometimes we can double the FEL by going off design
- Use Beta and Dispersion Matching Quads to tune
  Drawback: Reproducibility

Laser Profile Steering

- Start with uniform transverse profile, altering the profile will change bunch profile off of the Cathode

Undulator Taper Tweaks

- The better you can match the energy loss profile the more FEL you can produce
- Has a dependence on charge, energy, and bunch length

Tuning Methods

Pulse Length in BC1 and BC2

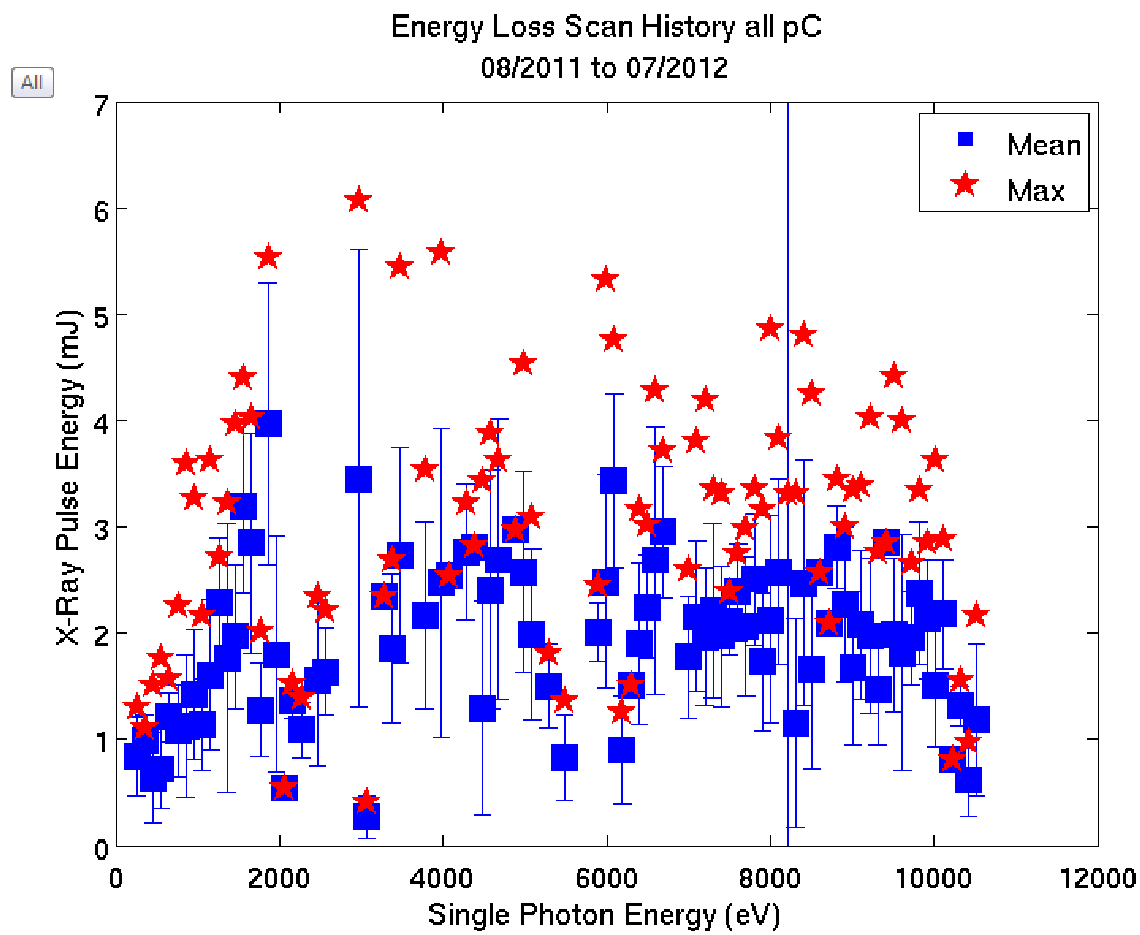
- Can optimize directly on FEL Pulse Energy
  - Difficulties:
    - More Compression leads to more Energy Spread, which leads to more Jitter
    - Pulse lengths of ~10 fs require lower charge which means less FEL power

Closed Bumps in Early Linac Orbit

- Possible transverse wake field effects in the early part of Linac
- Can use feedback setpoints or closed orbit bumps to compensate

FEL Performance

FEL Pulse Energy vs. FEL Photon Energy



Note: Gaps around 3 and 5.5keV are due to lack of statistics

Sources of Information and Figures

LCLS Physics:

A. Brachmann, W. Colocho, F. J. Decker, D. Dowell, P. Emma, J. Frisch, Z. Huang, R. Iverson, H. Loos, H.D. Nuhn, J. Turner, J. Welch, J. Wu, F. Zhou

LCLS Control System and Diagnostic GUI's

D. Fairley, J. Frisch, N. Lipkowitz, H. Loos, L. Piccoli, M. Zelazny

MCC Operations Group:

S. Alverson, L. Alsberg, T. Birnbaum, C. Blanchette, A. Egger, M. Gibbs, R. Gold, A. Hammond, C. Hollosi, S. Kalsi, C. Melton, L. Otts, B. Ripman, B. Sampson, D. Sanzone, A. Saunders, P. Schuh, H. Smith, T. Sommer, M. Stanek, E. Tse, J. Warren

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1.) LCLS Undulator PRD 1.4-001-r4, H. D. Nuhn et al. 5/2008

2.) Tapered Undulators for SASE FEL's, W. Fawley, Z. Huang et al. 9/2001

3.) Measurements of the LCLS laser heater and its impact on the

x-ray FEL performance, Z. Huang et al. SLAC-PUB-13854, 2009

4.) X-Band RF Harmonic Compensation for Linear Bunch Compression in the LCLS, P. Emma, 11/2001

5.) Link for LCLS Area Physics Requirement Documents:

http://www-ssrl.slac.stanford.edu/lcls/internals/documents/prd/

6.) A Review of X-ray Free-Electron Laser Theory, Z Huang, K. Kim, ANL-AAI-PUB-2007-002,December 2006

7.) FEL SPECTRAL MEASUREMENTS AT LCLS, J. Welch et al. Proceedings of FEL2011, Shanghai, China

END, Thanks!

Supplemental Information

Bunch Compression at SLAC

Setting Chirp(to create compression in a Chicane)

The head of the bunch needs lower energy than the tail. So RF phase is shifted negative. This will cause the head to take a longer path(effectively slow down), and the tail to take a shorter path(effectively speed up) through the chicane, leading to longitudinal compression.

Horizontal is RF Pulse

Vertical is Z position in DLWG

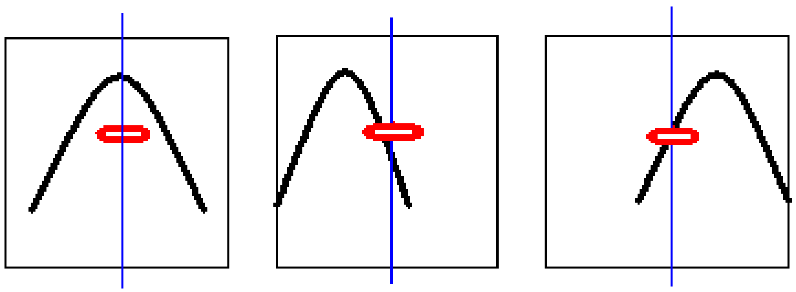


Fig 1: Beam in center of DLWG; RF phase = 0 Deg.

Fig 2: Beam in center of DLWG; RF phase = -20Deg.

Fig 3: Beam in center of DLWG; RF phase = +20 Deg.

Blue line represents arrival of Bunch in center DLWG. Pulse approximates RF distribution in cavity at bunch arrival time.

Note: Beam arrival time in the DLWG does not change(always on blue line when RF is pulsed). The RF phase can shift to align the beam on various parts of the RF pulse.

X-Band Chirp at SLAC

- S-Band DLWG RF at 2.856GHz
- Use X-Band(11.424GHz) for more uniform Chirp

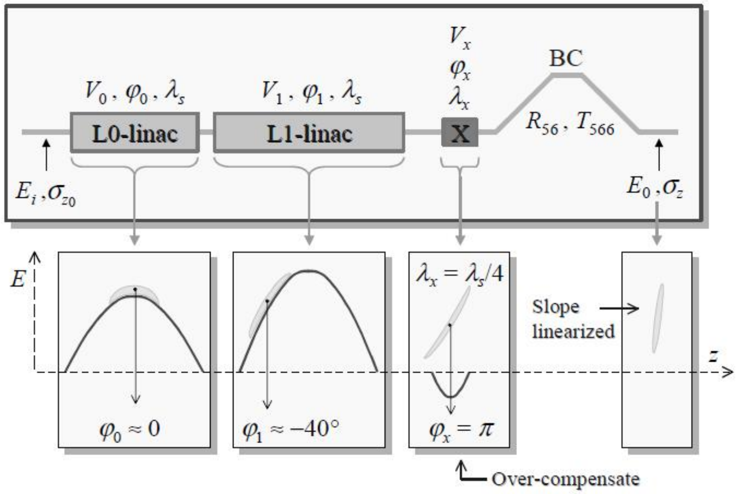
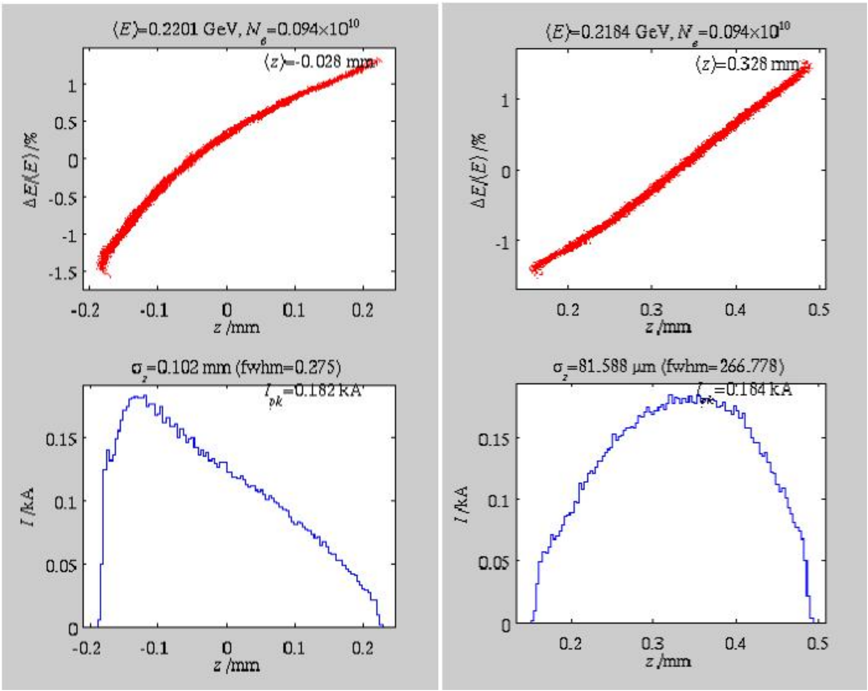


Figure 1. Schematic of two linac segments followed by harmonic RF and compressor chicane. The bunch is compressed from an initial rms length σ_{z0} to a final length σ_z with initial energy E_i and final energy E_0 (bunch head at left: $z<0$).

X-Band OFF: After BC1

X-Band ON: After BC1



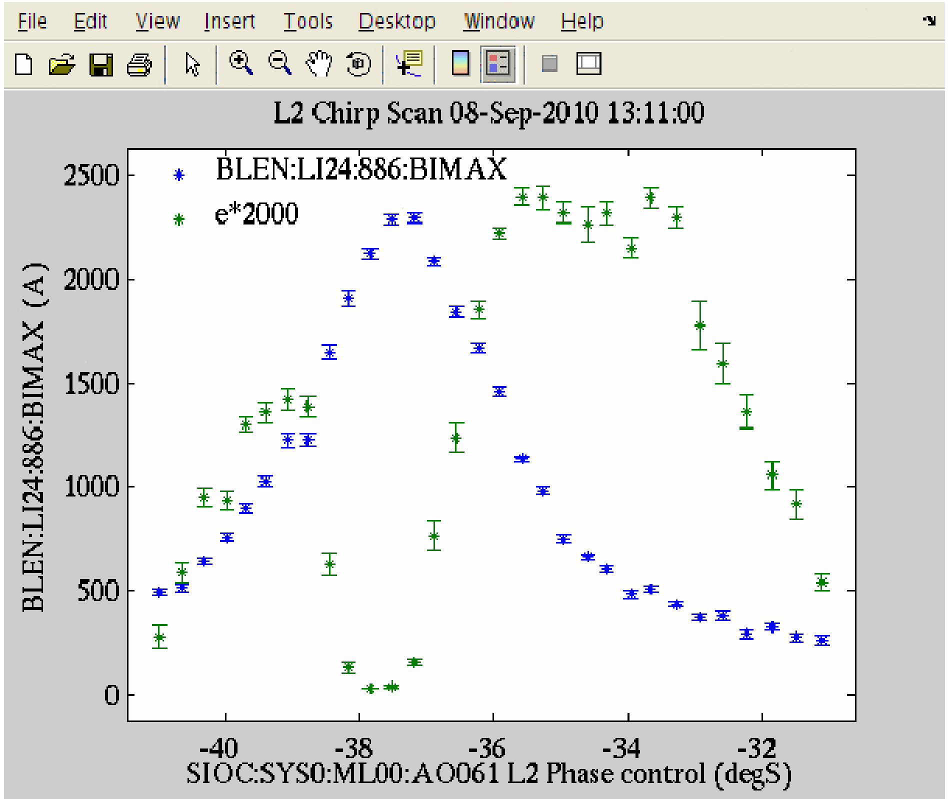
Bunch Length Optimization

Choosing Bunch Length

• Optimize on FEL Pulse Energy, Stability or Bandwidth

Blue: Bunch Length(A)
Green: FEL Pulse Energy(arb)
X-Axis: Klystron Chirp

FEL Goes to Zero at Max Compression

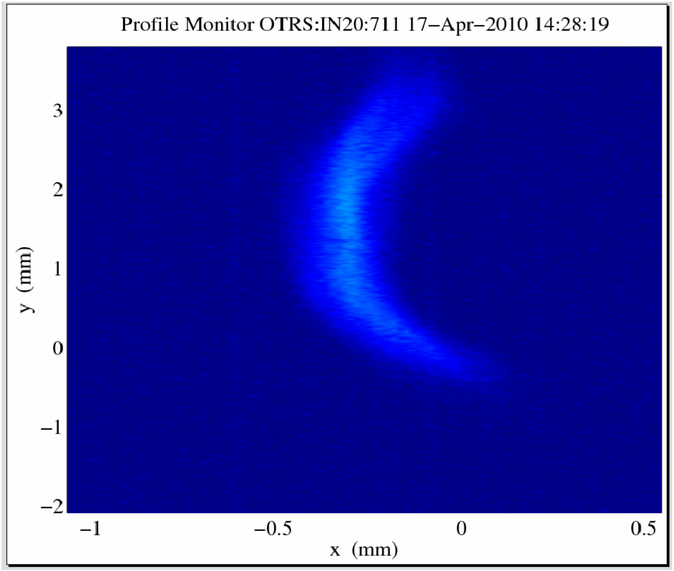


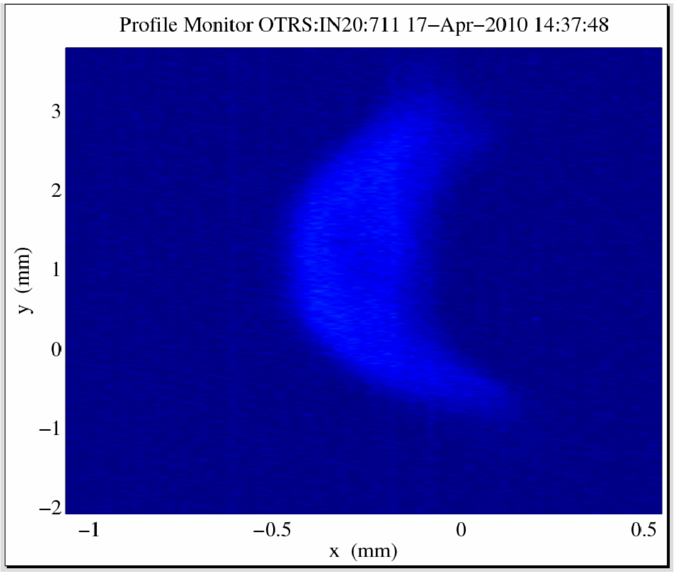
Injector Laser Heater

•Use IR Laser "Heater" to blow up and randomize initial slice energy spread

•Optimize to eliminate Micro-Bunching induced from Bend Magnets in Compressors which will suppress SASE effect

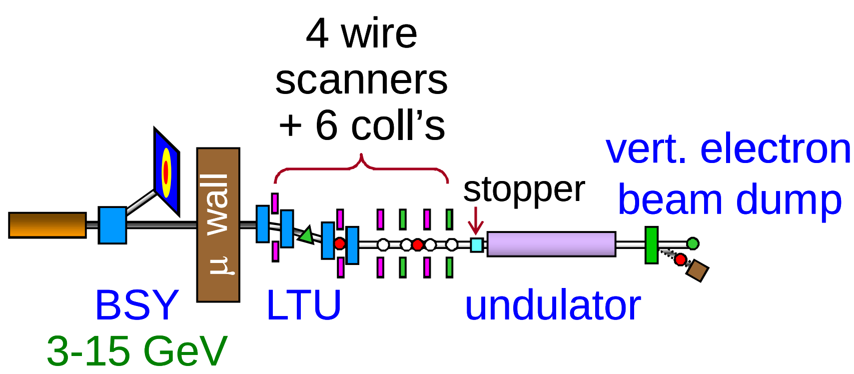
• Setup: Use Transverse Cavity to streak Beam in Y Plane, then send beam in X-Dispersive region to observe uniform slice energy spread increase





Introduction to LCLS: Undulator Transport

- Undulator Hall(100M)
- 33 total Segments, each containing fixed magnets
- 6.8mm Vertical Gap, Bend in Horizontal Plane
- ~100 3cm periods per segment



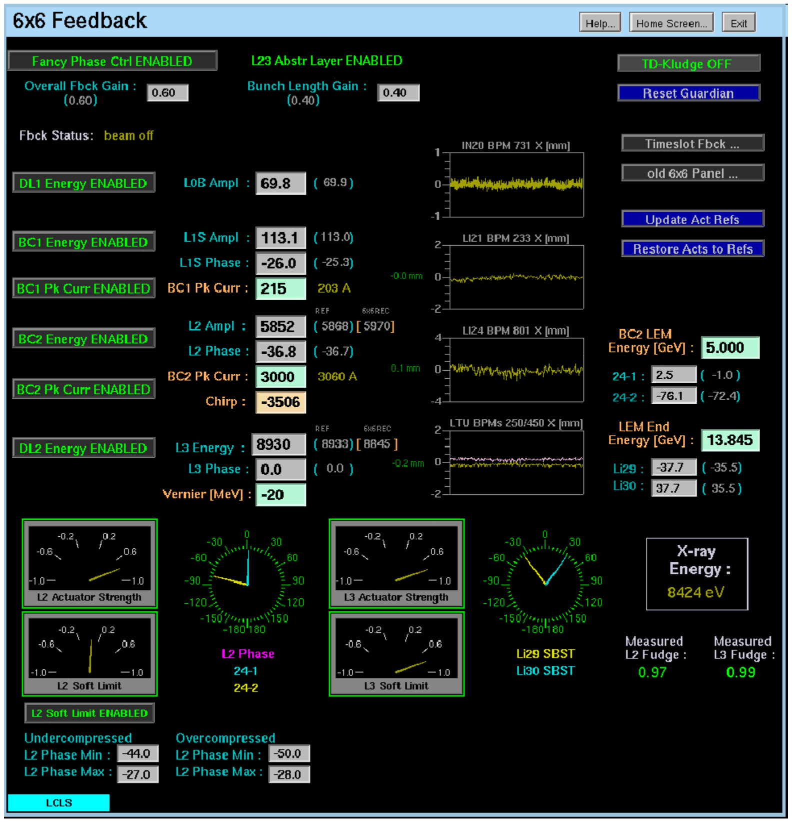
Soft X-Ray Operation

- Soft X-Rays for LCLS < 2keV
- Emittance Requirements less demanding
- Optimal FEL at Longer Pulse Lengths
- Shorter Gain Length
- Laser Heater has stronger effect
- Energy Jitter in Linac is a problem at shorter pulse lengths

Feedback Displays

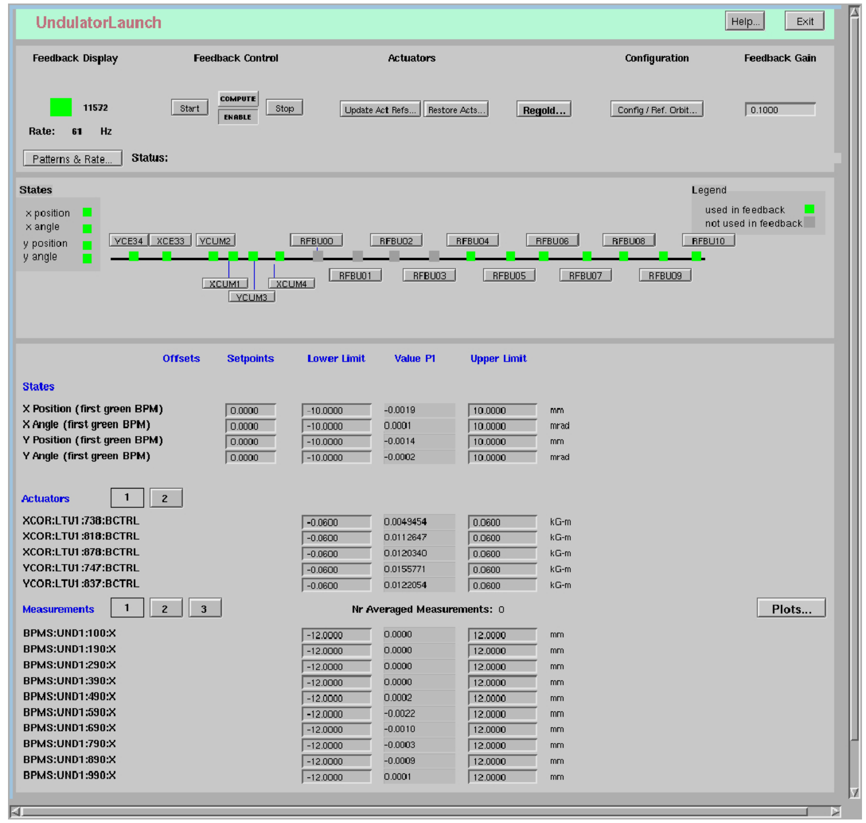
Longitudinal Feedbacks

Matlab Based, ~5Hz
Energy Setpoints
Pulse Length Control

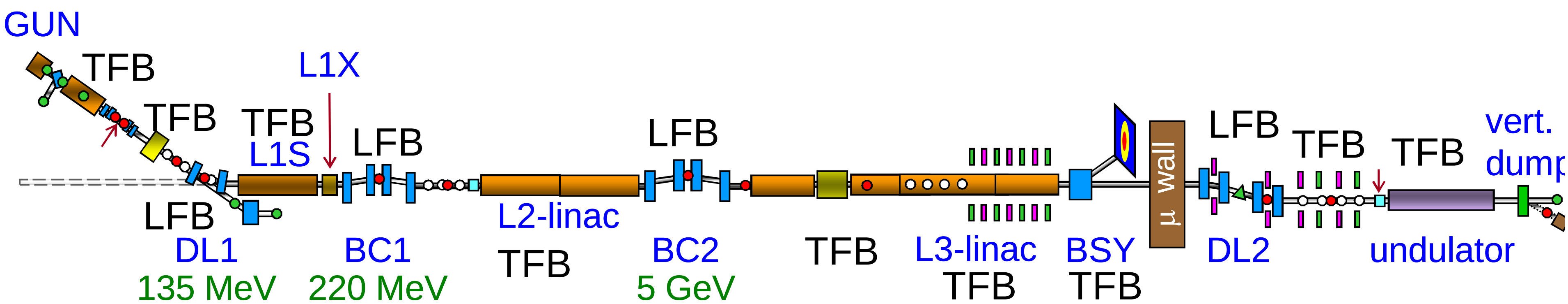


Transverse Feedbacks

EPICS Based, up to 120Hz
Ex: Injector Launch,
Launch into Undulator



Feedback Locations



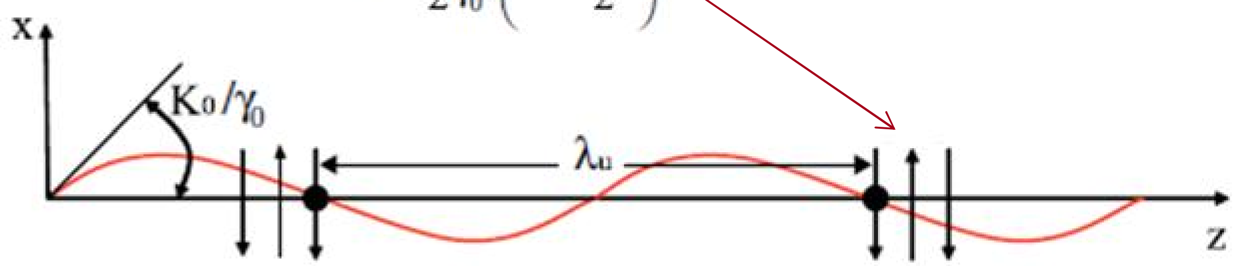
TFB - Transverse Feedback in region
LFB – Longitudinal Feedback in region

Free Electron Lasers

• Setting up resonance condition Undulator

$$\lambda_1 = \frac{\lambda_u}{2\gamma_0^2}\left(1 + \frac{K_0^2}{2}\right)$$

Electron(black dot) co-propagating with seed pulse



• As electron travels 1 period in the undulator, it slips behind a distance equal to one wavelength of the resonant X-Ray emitted

FEL Spot Size in FEE

8.4keV FEL Spot Size