FEL Spectral Measurements at LCLS

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THOB5

Acknowledgements

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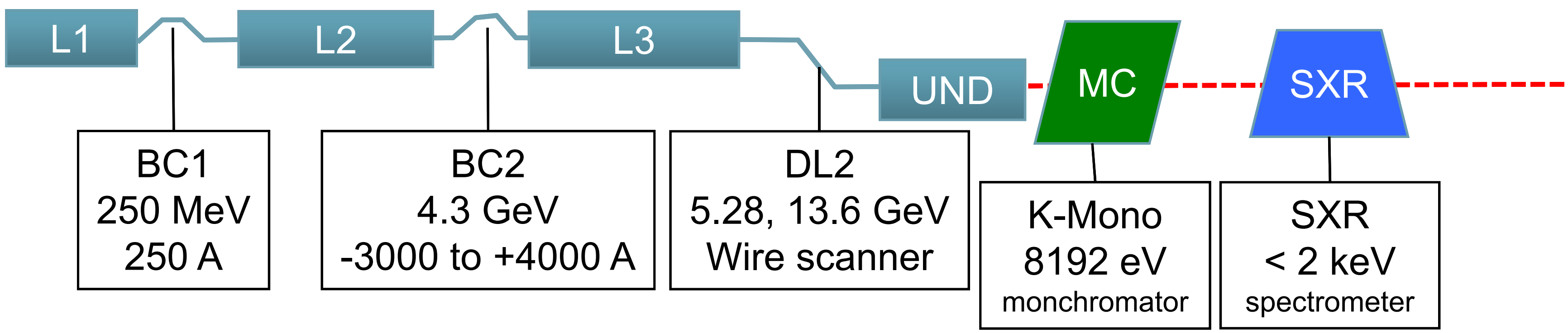
Topics

- Measurements
  - shape vs compression, hard x-rays
    - SASE Spectra – minimum bandwidth
  - fwhm vs compression, soft x-rays,
    - electron energy distributions and single-shot spectra
  - Slotted Foil, quasi-monoenergetic electrons
- Summary
  - FEL spectra at LCLS can be complex
  - 1% chirped hard x-ray FEL can be produced

Measurement Schematic

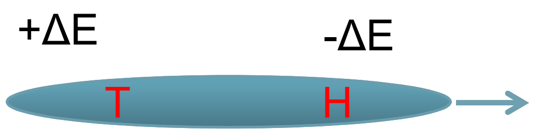


- Spectra measured using either SXR spectrometer, or by scanning the energy across a Monochromator (MC) pass-band.
- Electron energy jitter is measured each shot and for MC measurements the spectrum is shifted accordingly.
- SXR is single shot data, MC is average.
- Compression studies fix beam energy at BC2 but vary the chirp at BC2 by adjusting phase and amplitude in L2
- L3 is held constant during measurements

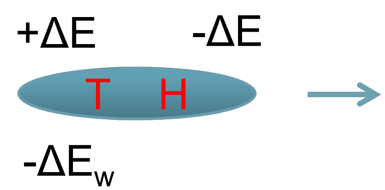
While fixing the beam energy at BC2, vary L2 amplitude (5500 tp 4500 MeV) and phase (-44 to -28 deg) to vary the chirp and therefore the compression at BC2. RF contribution to chirp in L2 goes from 23 MeV to 11 MeV during normal compression

Compression, Wakefields, & Energy Spread

Normal Compression



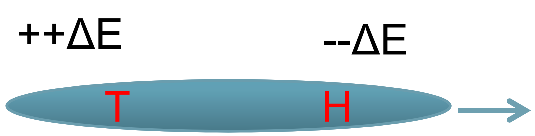
Applied chirp makes Head take a longer path in the chicane and slip toward the Tail



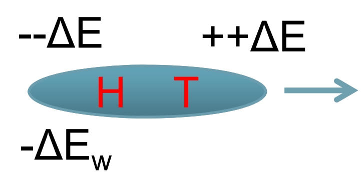
wakefield chirp is partially canceled

Subsequent wakefields in L3 lower Tail energy

Over-Compression



More applied chirp can force Head to slip **past** the Tail



wakefield chirp is reinforced

Subsequent wakefields in L3 lower Tail energy

Should see a step increase in energy spread (~ 2 ΔE) going from normal to over-compression

Spectral Shape vs Compression

Normal Compression

- Compression systematically changed, keeping charge constant.
- Broadening with more compression and higher current.
- Double-humped distributions for intermediate compression
- Max pulse energy 2000-4000A.

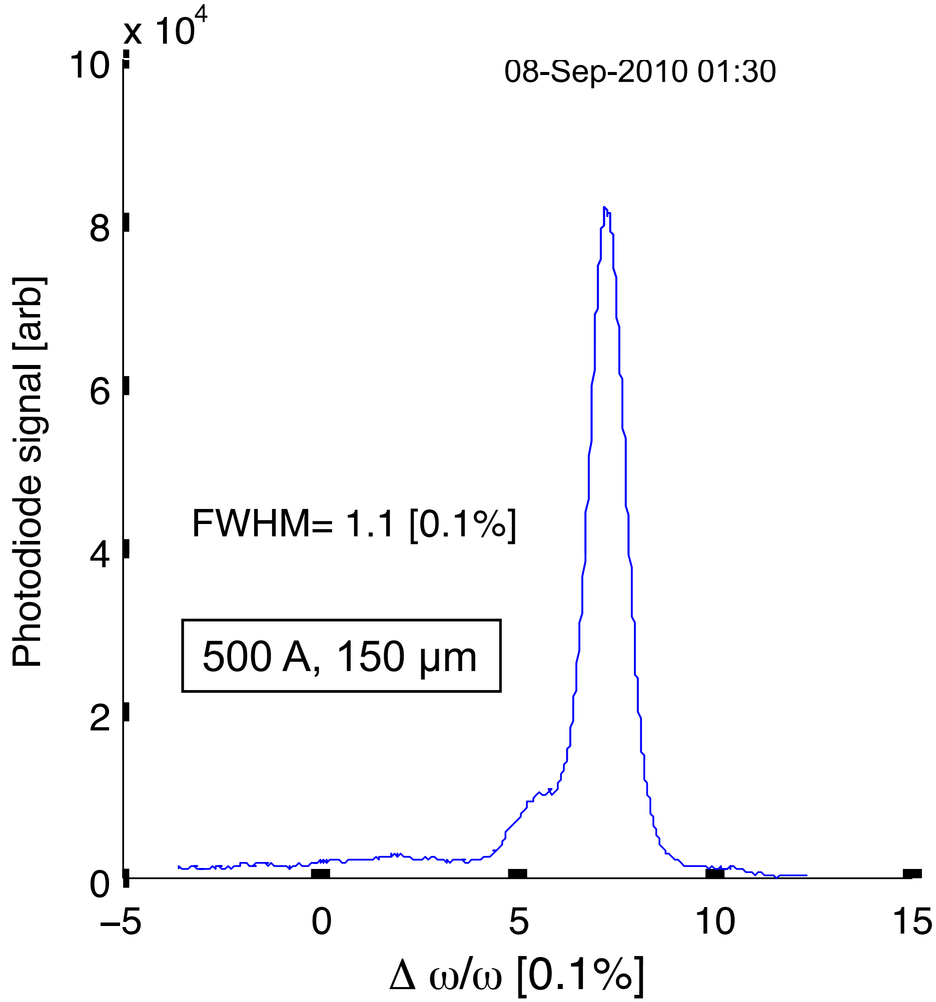
13.6 GeV, 8.2 keV, Q=250 pC
Gain, saturation, and spontaneous contributions to the taper were used, but not a wakefield contribution.

5 0 5 10 15

Δ ω/ω [0.1%]

Narrowest Bandwidth

- Narrowest bandwidths are seen in long bunch, low current, weak FEL beams
- SASE theory near saturation
  - rms Δω/ω ≈ $\rho = \left[\frac{1}{16} \frac{I_e}{I_A} \frac{K_0^2 [JJ]^2}{\gamma_0^3 \sigma_x^2 k_u^2} \right]^{1/3}$,
- Width consistent with theory,
- ρ = 0.4 [0.1%], or fwhm ≈ 0.7 - 1.0 [0.1%]
- Measured FWHM = 1.1 [0.1%]
- Not much correlated electron energy spread



13.6 GeV, MC average spectrum.
Gain, saturation, and spontaneous contributions to the taper were used, but not a wakefield contribution.

Spectral Shape vs Compression

Over-Compression

- Substantially larger widths for beams of same length and current.
- Pulse energy similar to normal compression
- FWHM ~ 10-20 [0.1%] - much larger than SASE
- Spectral shapes are complex

Negative current is the convention for over-compression.
Bunch is more gaussian-like

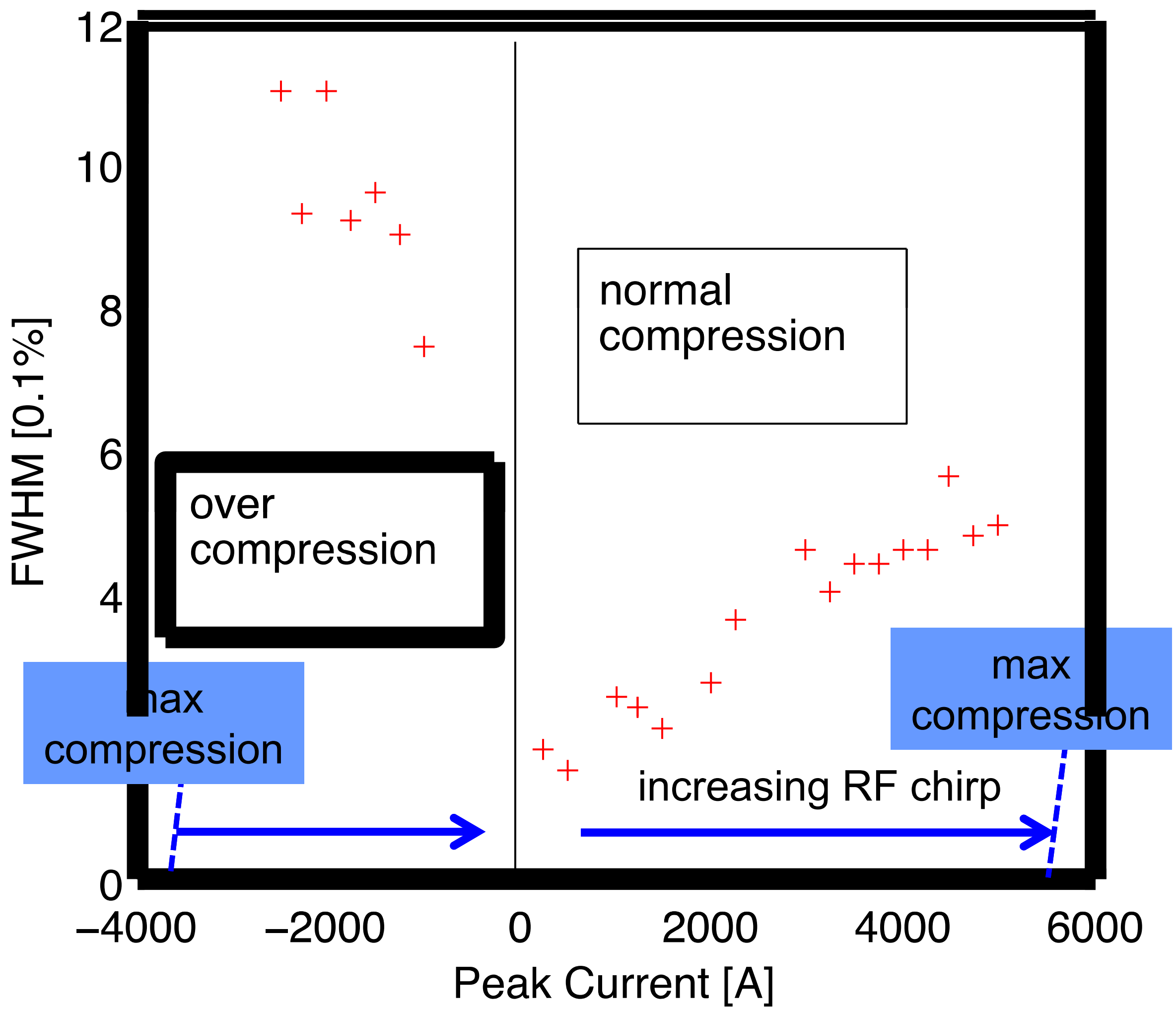
$\Delta\ \omega/\omega$ [0.1%]

13.6 GeV, 8.2 keV, 250 pC
Gain, saturation, and spontaneous contributions to the taper were used, but not a wakefield contribution.

FWHM vs Chirp – Soft X-rays

- Normal compression
  - fwhm increases with compression approximately following ρ.
- Over-compression
  - fwhm decreases with increasing applied chirp
- Step-up in fwhm going across max compression.

5.28 GeV, 250 pC.



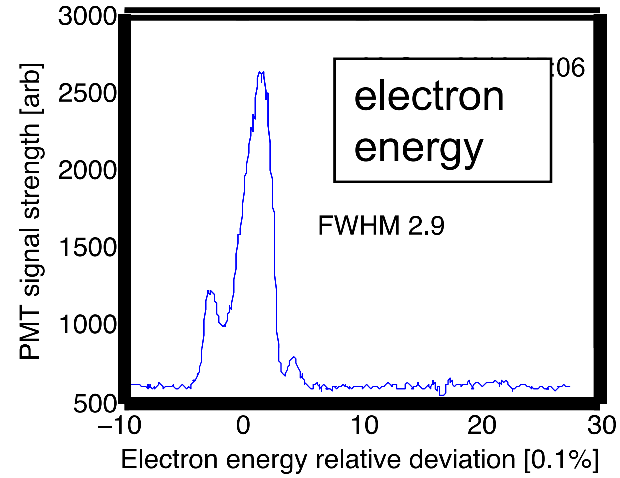
FEL Spectra and e$^-$ Energy Distribution

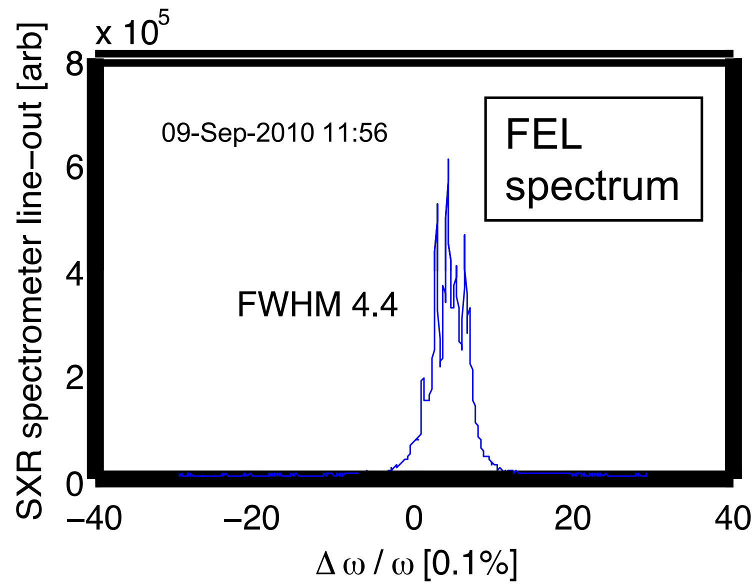
Normal Compression SXR Spectrometer

- Electron energy distribution and FEL spectrum taken sequentially

- FEL spectrum is less than 2x electron distribution width
  - FEL spectrum fwhm 4.4 [0.1%]
  - Electron distribution: FWHM 2.9 [0.1%], (includes energy jitter).
  - not much energy spread effect

- SASE theory ρ = 1.1 [0.1%] or fwhm 3 – 4 [0.1%]



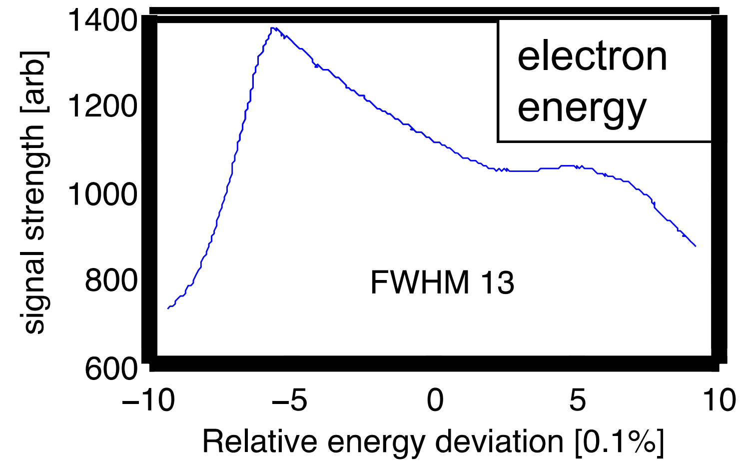


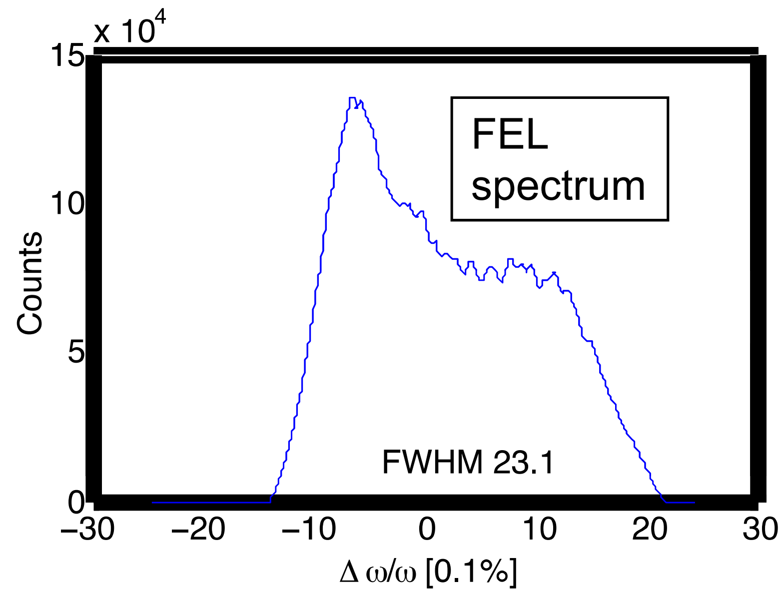
5.28 GeV, 1500 A

FEL Spectra and e$^-$ Energy Distribution

Over-Compression SXR Spectrometer

- Same peak current as previous normal compression case (+1500 vs -1500 A)
- Much larger e$^-$ energy spread: (2.9 vs 13 [0.1%])
- Photon fwhm is approximately 2X electron and features match
- Conclude bandwidth is primarily due to electron energy spread, and FEL beam is probably chirped.

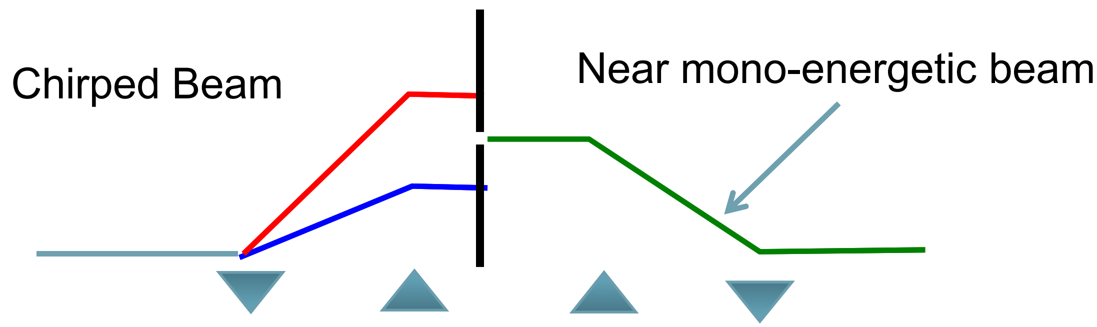




5.28 GeV, -1500 A
Point was excluded from fwhm plot

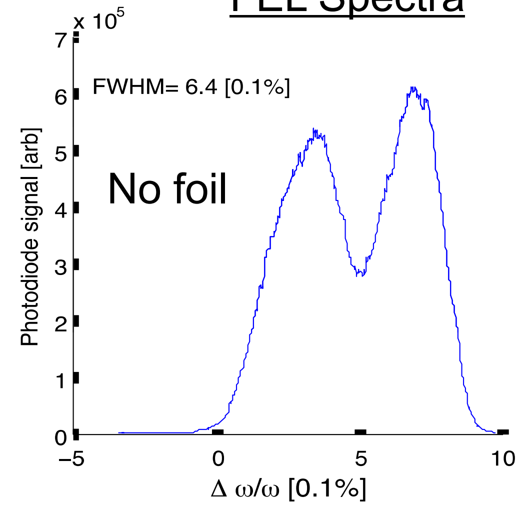
Slotted Foil Measurement

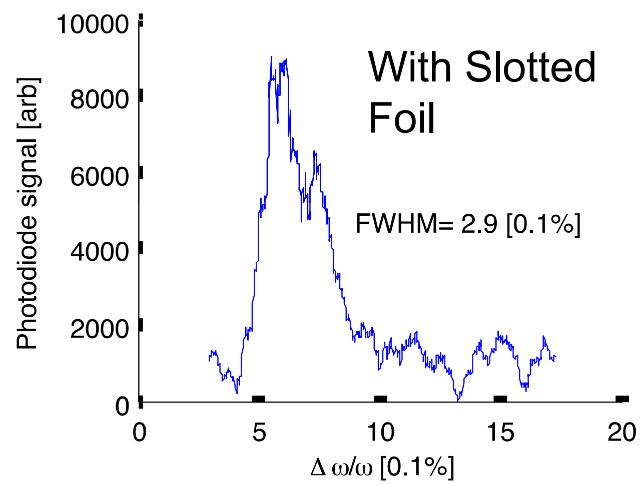
Slotted Foil in BC2



- Mainly designed for generated short bunches P. Emma et al. / Proceedings of the 2004 FEL Conference, 333-338
- Slotted foil in chicane insures minimal electron energy spread of lasing electrons.
- Spectrum approaches SASE bandwidth ~2 [0.1%]
- Could be used for wakefield studies
  - shift in spectra as function of slot position

FEL Spectra





250 pC, 3000 A, 13.6 GeV, monochromator

Summary

- FEL spectral shapes are complex and often double humped
- Smallest bandwidth for long pulse, normally compressed beam, consistent with SASE theory.
- Over-compressed beams have broad spectra without substantial loss of gain,
  - implies we can produce over-compressed FEL beams chirped at 1% level.

Thank you!

Underlying Physics of FEL Spectra

- SASE process
  - near saturation rms Δω/ω ≈ $\rho = \left[\frac{1}{16} \frac{I_e}{I_A} \frac{K_0^2 [\mathrm{JJ}]^2}{\gamma_0^3 \sigma_x^2 k_u^2} \right]^{1/3}$,
- Electron energy distribution
  - Each time slice of the e$^-$ bunch generates FEL photons independently
  - Energy – time correlation in the bunch is imposed on the FEL spectrum mainly through RF and wakefields
  - Gain varies along the bunch and this effect modulates the spectrum shape.
- Undulator tuning (taper)

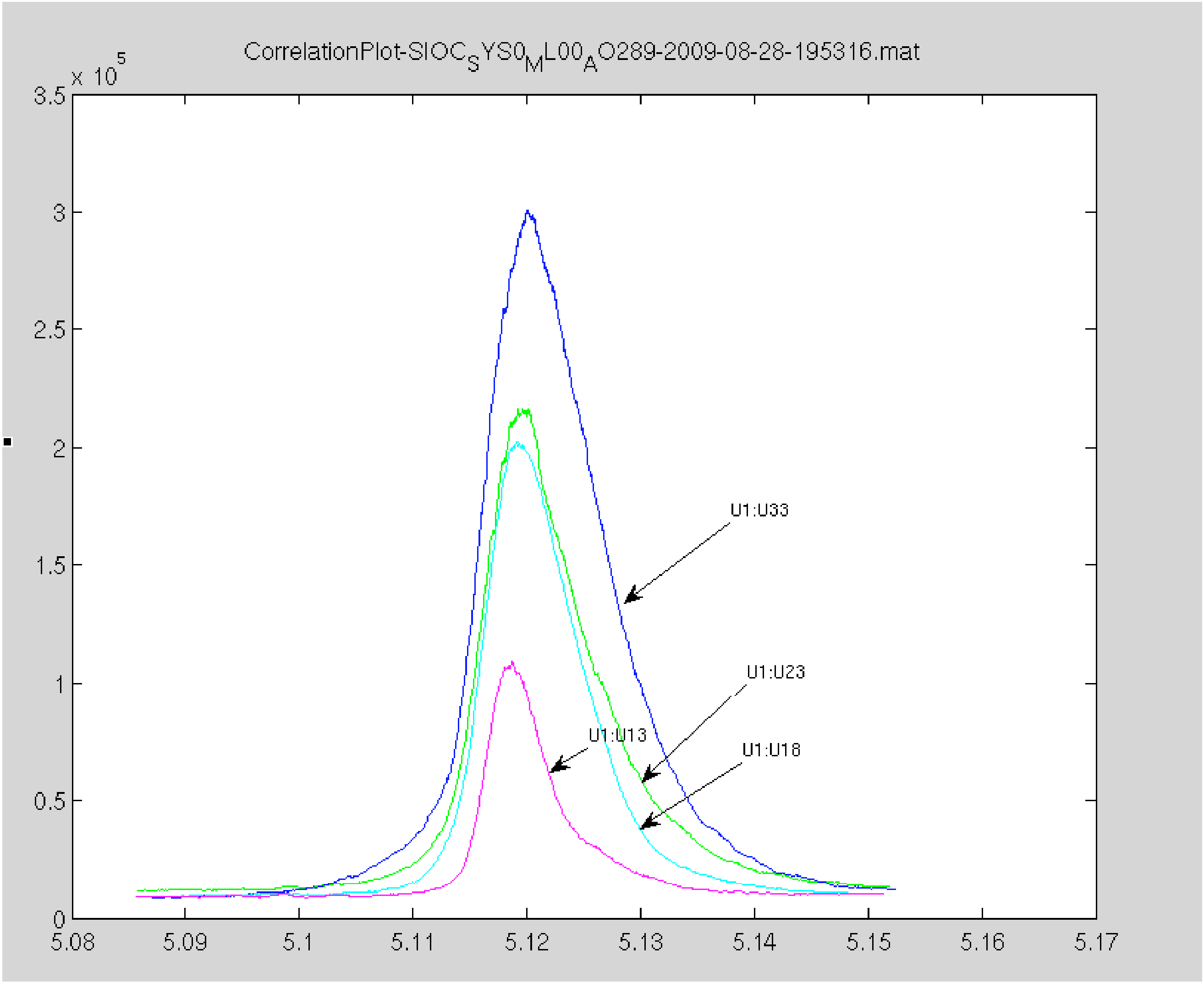
Electron Energy Drivers

- Intrinsic ~ few keV before compression ~ few hundred keV after compression (~10^{-5} at 13 GeV – neglible)
- Laser heater ~ 20 keV before compresion ~2 MeV after compression (~1.5 x10^{-4} rms at 13 GeV – almost significant)
- RF acceleration (applied chirp) (~ 1-5 MeV after compression (1 - 4 x 10^{-4} at 13 GeV)
- Spontaneous radiation (1.3 x 10^{-4} at 13.6 GeV)
- Wakefields....can be strong and complex
- CSR ... try to avoid

Spectra vs Length of undulator

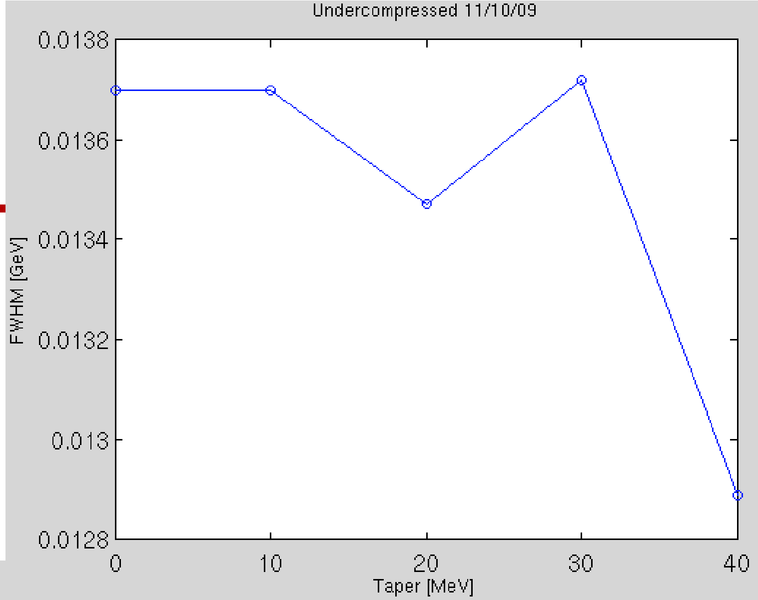
- Amplitude and BW grow with undulator length
- BW grows toward longer wavelength

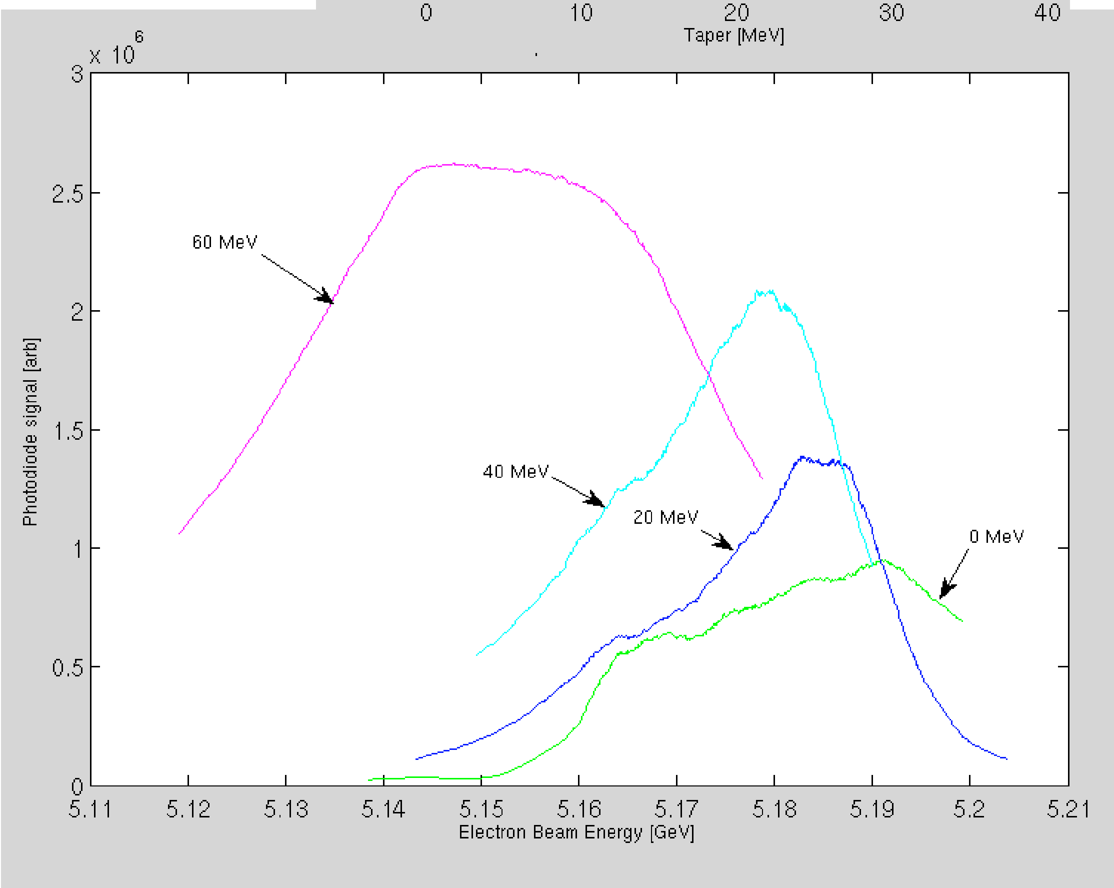
Spectrum of 5th harmonic used here.



Taper

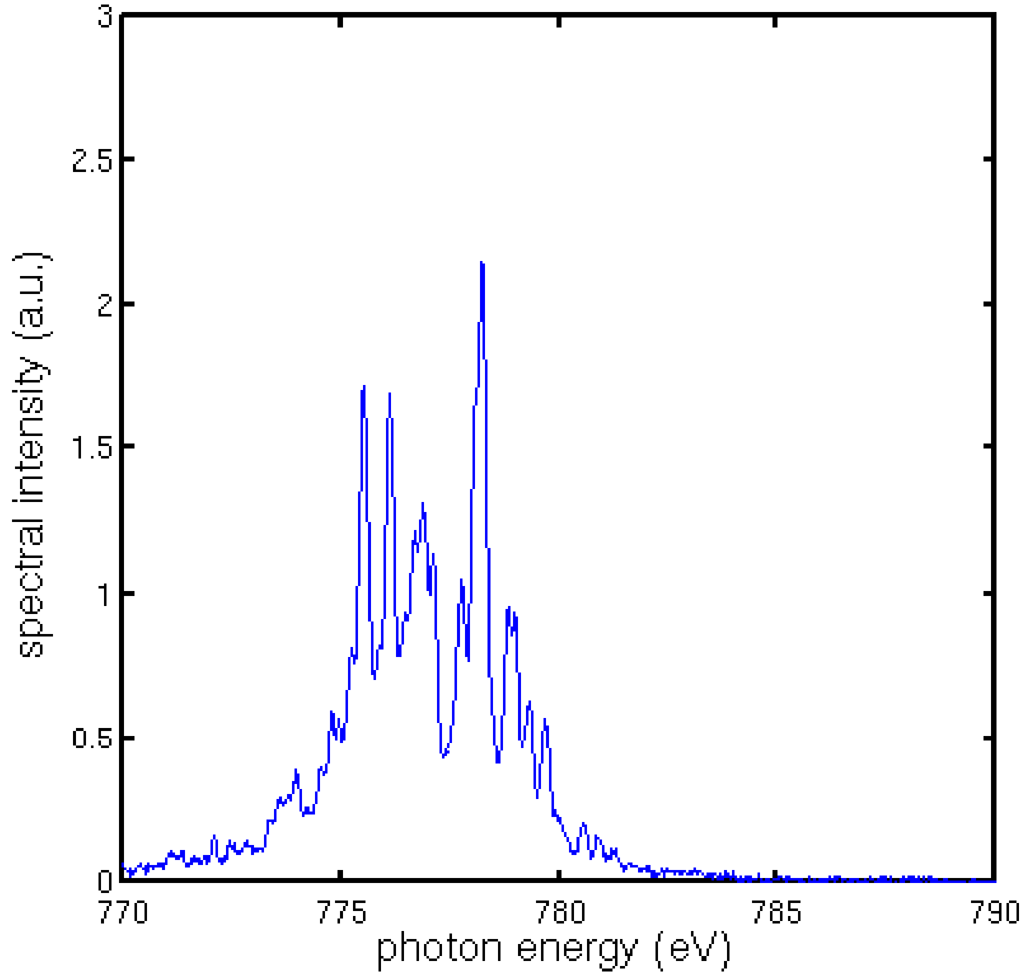
- Shift of spectrum to low energy understandable?





LCLS – Spectral Fluctuations

- Spectromet
  at XPP hutc

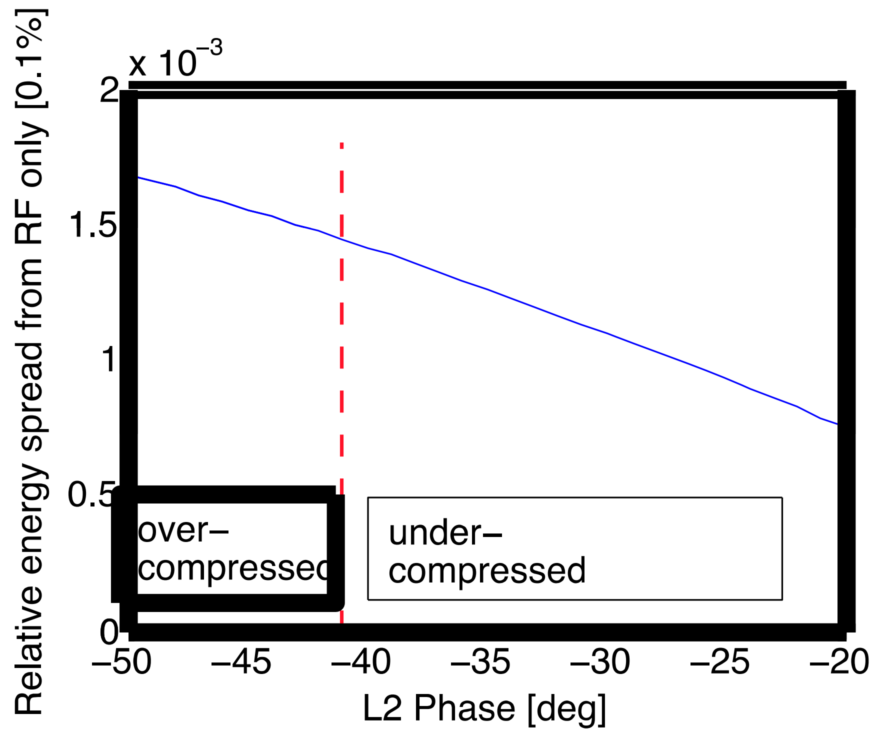


From David Fritz

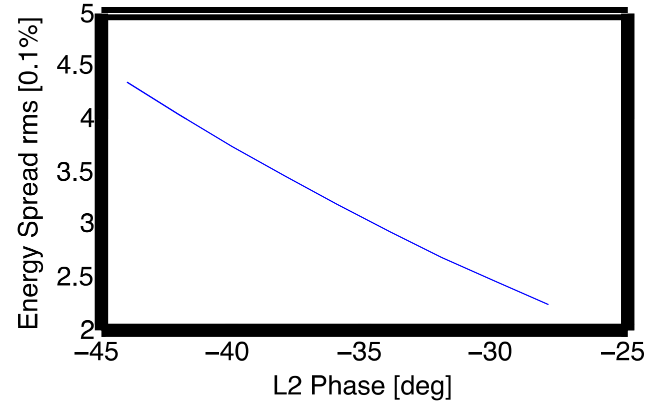
Some energy spread estimates

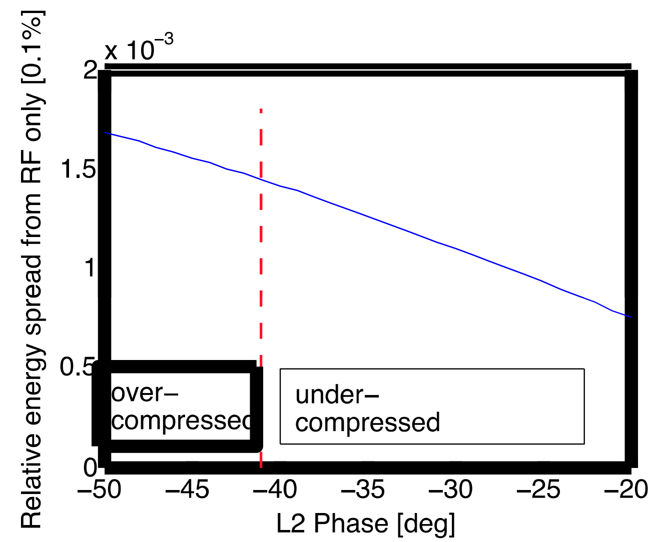
$$h = \frac{\partial \delta_i}{\partial z_i} \approx -\frac{2\pi}{\lambda}\left[1 - \frac{E_i}{E_0}\right]\tan\phi - \frac{2Ne^2 Z_0 c s_0 L}{\pi a^2 \Delta z^2 E_0}\left[1 - \left(1 + \sqrt{\Delta z / s_0}\right) e^{-\sqrt{\Delta z / s_0}}\right]$$

$$\sigma_\delta \approx \frac{2Ne^2 c Z_0 s_0 L}{\pi \sqrt{12} a^2 \Delta z E}\left[1 - \left(1 + \sqrt{\Delta z / s_0}\right) e^{-\sqrt{\Delta z / s_0}}\right]$$



- upper figure is emmas calculator
- lower figure is welch analytic using Frisch generated amplitudes and phases
- Qualitative and quantitatively different.
- Initial energy spread is not a significant factor in emma's calculation.
- Emma's calc includes wakefield effects.
- 13.6 GeV assumed.





Why Study FEL Spectra?

- Delivered spectrum matters to experiments...
  - High spectral brightness – narrow bandwidth
  - Large bandwidth for absorption edges, nano-crystal imaging

- ... and as a diagnostic for accelerator physics
  - pulse duration measurements (WFOA2 Alberto Lutman)improve power and spectral brightness, e.g. tuning linearization and compression, deep taper studies, avoid CSR degradation
  - develop new types of beams e.g. chirped hard x-ray FEL

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