FEL Spectral Measurements at LCLS

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Acknowledgements

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
• 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**

- $+\Delta E$  
  - $T$  
  - $H$

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

- $+\Delta E$  
  - $T$  
  - $H$

- $-\Delta E$  
  - $T$  
  - $H$

Subsequent wakefields in L3 lower Tail energy

**Over-Compression**

- $++\Delta E$  
  - $T$  
  - $H$

More applied chirp can force Head to slip past the Tail

- $--\Delta E$  
  - $H$  
  - $T$

- $++\Delta E$  
  - $T$  
  - $H$

Wakefield chirp is reinforced

Subsequent wakefields in L3 lower Tail energy

**Should see a step increase in energy spread ($\sim 2 \Delta E$) going from normal to over-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.

\[ \Delta \omega/\omega [0.1\%] \]
Narrowest Bandwidth

- Narrowest bandwidths are seen in long bunch, low current, weak FEL beams
- SASE theory near saturation
  - $\text{rms } \Delta \omega/\omega \approx \rho = \left[ \frac{1}{16} \frac{I_c}{I_A} \frac{K_0^2}{\gamma_0^3} \sigma_x^2 \kappa_n^2 \right]^{1/3}$
- Width consistent with theory,
  - $\rho = 0.4 \ [0.1\%]$, or $\text{fwhm} \approx 0.7 - 1.0 \ [0.1\%]$
  - 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

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

\[ \Delta \omega / \omega \approx [0.1\%] \]
FWHM vs Chirp – Soft X-rays

- **Normal compression**
  - $fwhm$ increases with compression approximately following $\rho$.

- **Over-compression**
  - $fwhm$ decreases with increasing applied chirp.

- **Step-up in fwhm going across max compression.**

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5.28 GeV, 250 pC.
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 $\rho = 1.1$ [0.1%] or fwhm 3 – 4 [0.1%]
FEL Spectra and e\textsuperscript{-} Energy Distribution
Over-Compression SXR Spectrometer

- Same peak current as previous normal compression case (+1500 vs -1500 A)
- Much larger e\textsuperscript{-} 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

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Slotted Foil Measurement

- 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

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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 $\Delta \omega / \omega \approx \rho = \left[ \frac{1}{16} \frac{I_e}{I_A} \frac{K^2_0[JJ]^2}{\gamma^3 \sigma_x^2 k_u^2} \right]^{1/3}$

• 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 – negligible)
- Laser heater ~ 20 keV before compression ~2 MeV after compression (~1.5 x 10^{-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.
- Shift of spectrum to low energy understandable?
LCLS – Spectral Fluctuations

- Spectrometer at XPP hutch

From David Fritz
Some energy spread estimates

\[ h = \frac{\partial \delta_i}{\partial z_i} \approx \frac{-2\pi}{\chi} \left[ 1 - \frac{E_i}{E_0} \right] \tan \phi \frac{2Ne^2Z_0s_0L}{\pi a^2 \Delta z^2 E_0} \left[ 1 - \left( 1 + \sqrt{\Delta z/s_0} \right) e^{-\sqrt{\Delta z/s_0}} \right] \]

\[ \sigma_\delta \approx \frac{2Ne^2cZ_0s_0L}{\pi \sqrt{12a^2 \Delta z E}} \left[ 1 - \left( 1 + \sqrt{\Delta z/s_0} \right) e^{-\sqrt{\Delta z/s_0}} \right] \]

Relative energy spread from RF only [0.1%]

- over-compressed
- under-compressed

L2 Phase [deg]

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- 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