FUSEE
FUture of SEeded free Electron lasers
Elettra Sincrotrone Trieste
XXVII Users' Meeting
Trieste, Italy / 10 - 11 December 2019

Some current issues regarding achievable spectral quality in high gain, seeded FELs

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11 December 2019

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Spectral Quality in Seeded FELs is a “rich” Field

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Main Topics:

- User expt. requirements for spectral purity
- Classification of types of spectral contamination
- Sideband development in the exponential gain regime
- Observations of spectral contamination at FERMI (HGHG & EEHG) and LCLS (soft x-ray self-seeding)

This talk has benefitted deeply from discussions with R. Schoenlein, C. Callegari, D. Fausti, F. Parmigiani, E. Allaria and F. Bencivenga

Fundamental Questions about User Needs

How good is "good enough" in terms of spectral quality?

If FEL physicists could produce truly ***superb*** spectral quality at meaningful power levels, what new, *really* important user experiments could be enabled?

or ...

hey, where's the FEL-based Nobel Prize???

Seeded FELs: a promise of very, very pure spectral output

But we are much older and, perhaps, a bit wiser now

Both external seeding and self-seeding in *theory* can produce nearly transform-limited, "pure" output

- "Instant" and *z*-enduring transverse and longitudinal coherence
- Strong seed can strongly dominate any SASE growth
- Output wavelength set by input seed wavelength
  - No λ_{out} jitter from e-beam energy jitter
  - Soft limit on $\gamma(t)$ variation: $\Delta\gamma$ < MAX (½ N_w , $\rho/2$)
- Much initial FEL amplifier work in the 1980's was based on seeding; SASE configuration was a late-comer, needed for XUV and X-ray regimes

The actual, present reality is a bit more complex:

- The electron beam is an *active gain medium*!
- HGHG, EEHG, & self-seeding schemes experimentally show spectral contamination surrounding the desired main line
  - Shot-to-shot variable "pedestal" emission appears in all schemes
  - Chirps can strongly afflict HGHG output (but can be useful too!)
  - Self-seeding monochromator optics survivability limits attainable seed-to-SASE contrast

User Experimental Needs: Required Spectral Purity ~ *f* (pulse duration)

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Intrinsic bandwidth of short ($\lesssim$ 20 fs) pulses ~200 meV (FWHM)

- Comparable to FEL gain bandwidth for $\lambda_{RAD} \gtrsim$ 2 nm
- Few expts. in this regime highly sensitive to contamination levels (in both eikonal phase and amplitude) below ~ 20% (norm. intensity)
- Possible exception for strong e-beam energy detuning (SASE problem) (*but why would you do this?*)
- Nonlinear phenomena expts. can be sensitive to pre-pulse "foot"; seeded FELs unlikely to produce such unless anomalously strong SASE

Some expts. requiring longer pulses ($\gtrsim$ 50 fs) may be more sensitive to SASE and sidebands within 0.1 – 1 eV of central line, *e.g.*,

- Very high resolution (~ 200 fs, 30 meV) RIXS expts.: will normally use post-undulator monochromator ➽ pedestal insensitive
- Moderate resolution, time-resolved pump- (FEL) probe RIXS expts.: high pedestal sensitivity ➽ good FEL pedestal background measurements

Different Experiments, Different Sensitivities

- Some experiments might be sensitive to eikonal phase noise
  - gain-medium-sensitive interference between 2 FEL pulses originating from *different* temporal regions of e-beam
  - multicolor (*e.g.*, coherent control) experiments sensitive to phase differences between different harmonics of the seed pulse, especially if they originate from different z-portions of undulator (pedestal growth)
  - non-monochromatized RIXS expts. very sensitive to pedestals
  - quantum coherence state in matter expts. using FEL light as probe

  ➢ E-field coherence factor $g^{(1)}(\tau)$ important as a measure

- Other experiments might be sensitive to intensity fluctuations irregardless of phase noise structure, *e.g.*,
  - nonlinear, strong field susceptibility expts. sensitive to I^n
  - resonance line shape measurements, esp. for K-edge

    ➢ Intensity coherence function $g^{(2)}(\tau)$ important

Spectral Contamination: Two General Categories

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One can categorize background spectral contamination within a worldview of Einstein emission coefficients "A" and "B"

Seed-insensitive, "general" background contamination (i.e., type "A")

- SASE is the dominant, type "A" contribution for high gain FELs
- "Simple" spontaneous emission contaminates "nonlinear" intensity component for afterburner higher harmonic generation expts.
- Probably worse for self-seeding than for external seeding configurations

Seed-sensitive components of pedestals (i.e., type "B")

- Sideband-like phenomena induced by modulation of amplified seed's eikonal phase and/or amplitude

Each component has different relative importance levels depending upon FEL characteristics & particular user experiment

Long Wavelength e-beam Modulations Generate Sidebands

SLAC LCLS work investigating SXR self-seeding pedestal:

- Z. Zhang *et al.* (PRAB **19**, 050701 (2016) + earlier unpublished work by R. Lindberg, ANL) showed energy & current modulations produce upper&lower sideband emission on main seeded line due to frequency mixing
- Long wavelength ($\lambda_M \gtrsim 2\lambda_S / \rho$) modulations $\Rightarrow$ sidebands that lie well within FEL gain bandwidth, little damped by slippage in undulator
- Sideband *E*-field grows ~ linearly with *z* relative to seed
  - ➤ *quadratic* growth in normalized intensity
- Intensity ratio of lower to upper sideband depends on relative size and phases of e-beam energy and current modulations
- Detailed LCLS expt. study (Marcus *et al*., PRAB **22,** 080702 (2019)) of pedestal contamination of SXR self-seeding showed evidence for both SASE and sideband components
  - Relative sideband strength very sensitive to detuning and LH strength

Roussel et al. expt. (PRL **115**, 214801 (2015) on FERMI *purposely* generated FEL sidebands via multipulse LH heating

Two Generic Types of Sidebands: Type I

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Any parameter modulation that periodically modulates output eikonal phase or amplitude induces **sidebands**

When operating FEL near peak exp. gain, any e-beam modulation that directly affects FEL resonance ➽ ~ linear eikonal phase variation with modulation amplitude

- Direct consequence of Kramers-Kronig relation
- Phase variation transfers power from central amplified seed to upper & lower sidebands (i.e., **normalized seed strength fraction *decreases***); coherence factor $g^{(1)}(\tau) < 1$
- Often little temporal variation in FEL intensity; $g^{(2)}(\tau)$ close to 1
- E-beam longitudinal energy variations (e.g., due to microbunching instability growth) are primary offender for seeded FELs
- Resultant phase variations could affect user experiments that depend upon excellent temporal coherence
- Shot by shot spectral measurements that allow binning&filtering can reduce impact on users

Simple Example of Sideband Emission dominated by Eikonal Phase Variation --- GINGER simulation

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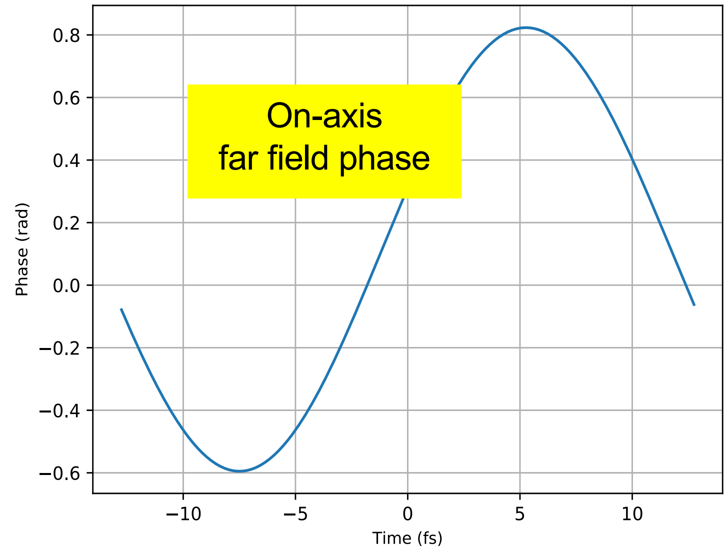
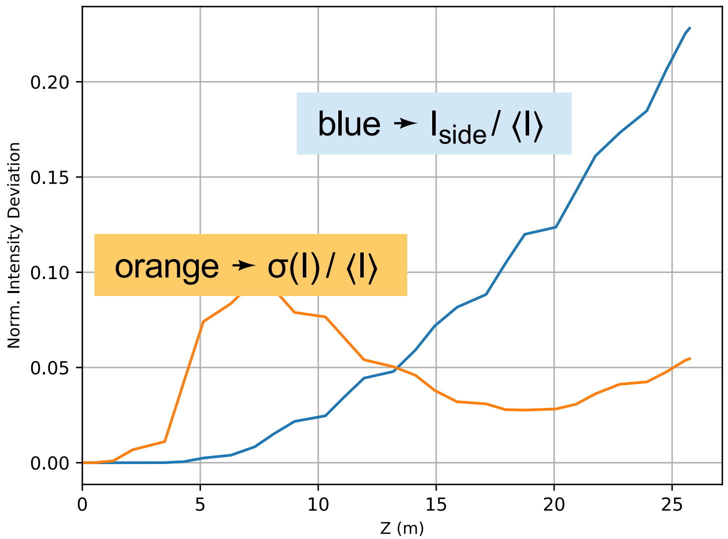
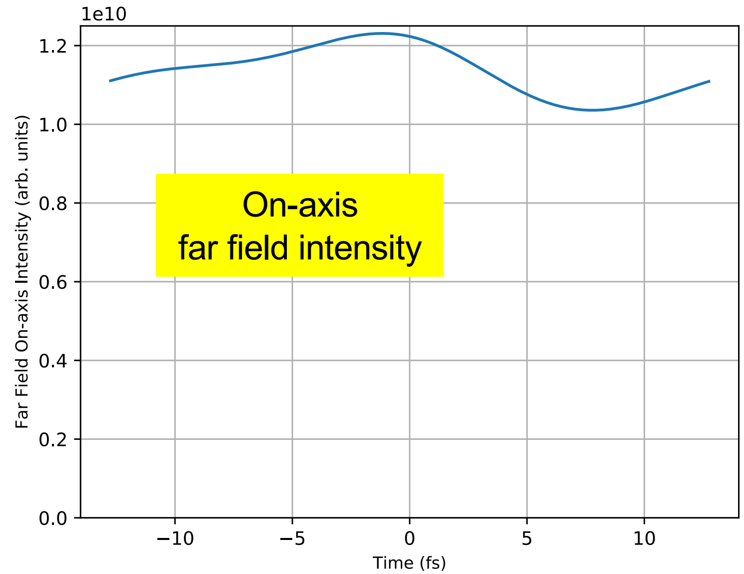
FERMI FEL-2 upgrade-like lattice & e-beam
8-section 2nd radiator, 30-mm period
λ_s=2.2 nm, K=0.9 helical polarization
10 kW seed, no shot noise
E=1.80 GeV I=1.0 kA $\varepsilon_\perp$ = 0.8 mm-mrad
σ_E = 100 keV (slice) $\rho \approx 1.1 \times 10^{-3}$

± 255 keV sinusoidal E_{beam} perturbation,
period = 25.6 fs

At und. exit, sideband spectral intensity > 20% while RMS intensity fluctuation only ≃ 5%







Two Generic Types of Sidebands: Type II

Some e-beam modulation types (e.g., I_B, ε_N, σ_γ) have little or no effect moving the position λ_{RAD} of peak gain

Dominant effect: modulate radiation *intensity* via change in FEL gain Γ

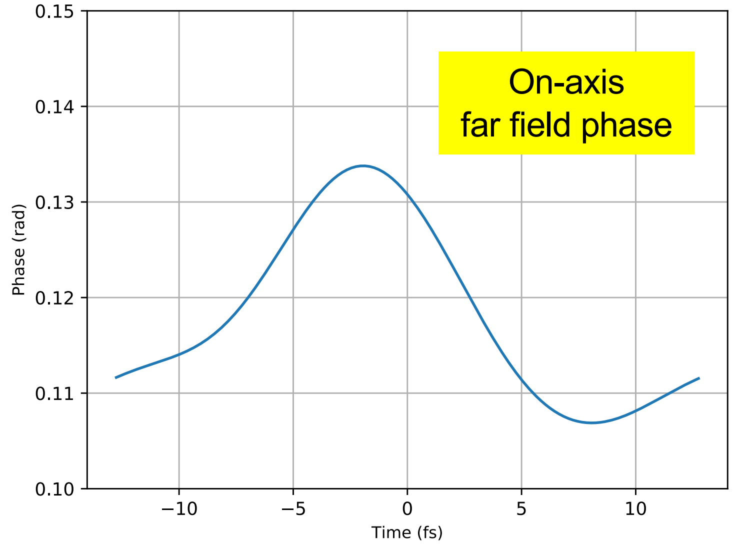
- Much smaller modulation of eikonal phase; $g^{(1)}(\tau) \approx 1$
- Little net transfer of power from fundamental to sidebands
  (i.e., normalized sideband fraction remains ≈ constant)
- Possibly large I(t) fluctuations ; $[\ g^{(2)}(\tau) - 1\ ]$ non-negligible
- Intensity variations might degrade some user experiments examining nonlinear phenomena
- Shot-by-shot intensity measurements allow binning&filtering of expt. data to minimize negative effects for users

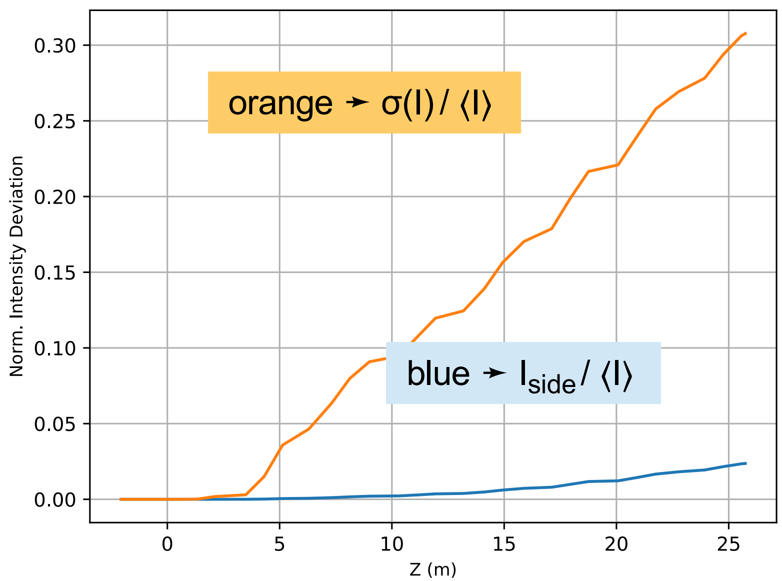
Simple Example of Sideband Emission dominated by Amplitude Variation

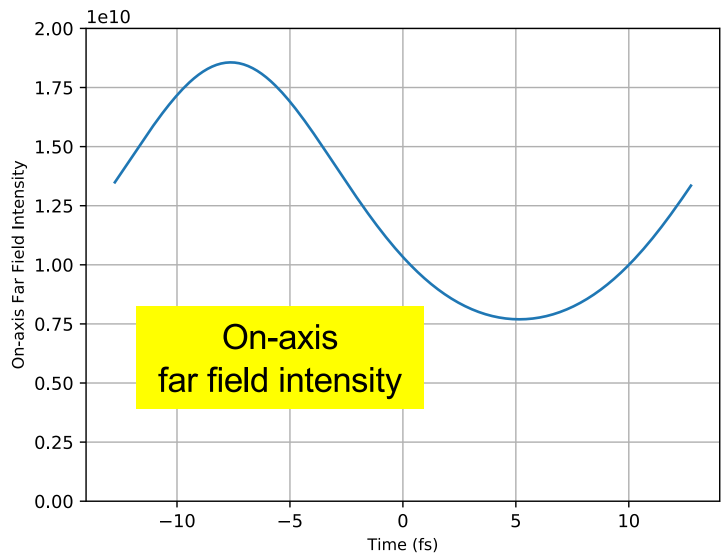
FERMI FEL-2 upgrade-like lattice, e-beam
8-section 2nd radiator, 30-mm period
λ_s=2.2 nm, K=0.9 helical polarization
10 kW seed no shot noise
E=1.80 GeV I=1.0 kA $\varepsilon_\perp$ = 0.8 mm-mrad
σ_E = 100 keV (slice) $\rho \approx 1.1 \times 10^{-3}$

± 0.1 mm-mrad sinusoidal $\varepsilon_\perp$ perturbation, period = 25.6 fs

Output sideband spectral intensity < 2.4% but RMS intensity fluctuation now ≃ 30%





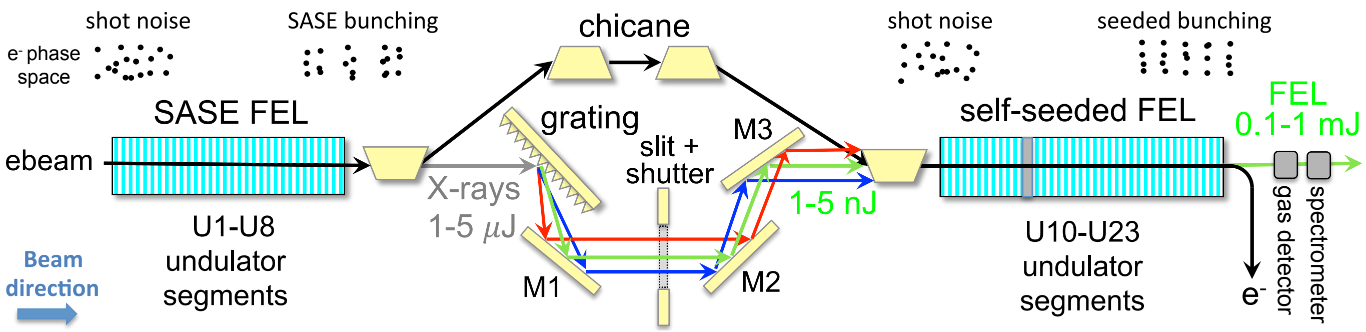


Some Recent LCLS and FERMI Examples of Spectral Contamination

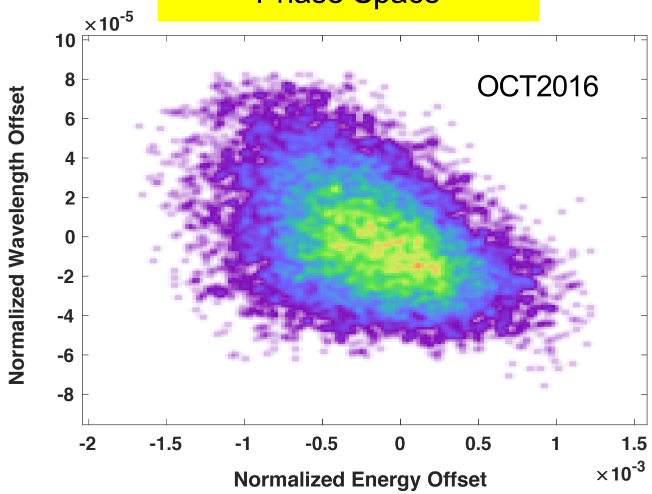
LCLS SXR Self-Seeding --- Configuration & Amplified Seed Wavelength & Power Stability

SLAC team headed by G. Marcus conducted a multishift, multiyear investigation of the LCLS SXR-SS pedestal

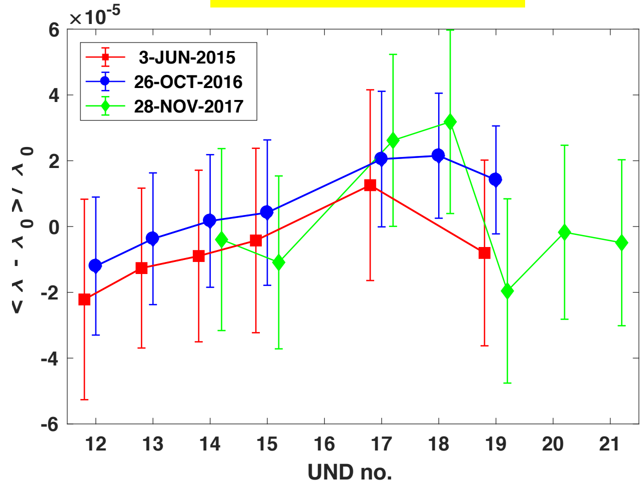
Amplified monochromatized seed extremely stable in wavelength. E_{photon}= 1-keV



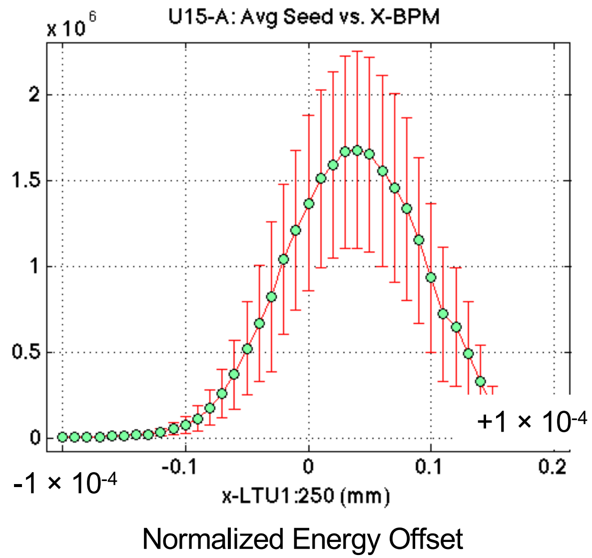
U15 Central Wavelength "Phase Space"



Central Wavelength vs. Eff. Und. No.



Seed Energy vs. linac energy



LCLS SXR Self-Seeding Seed & Pedestal: Graphical Representation

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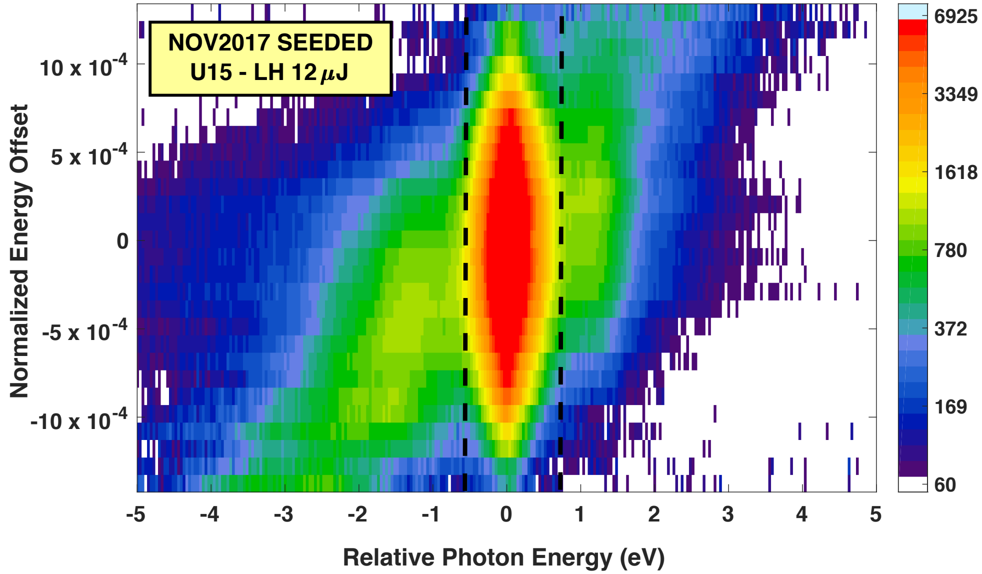
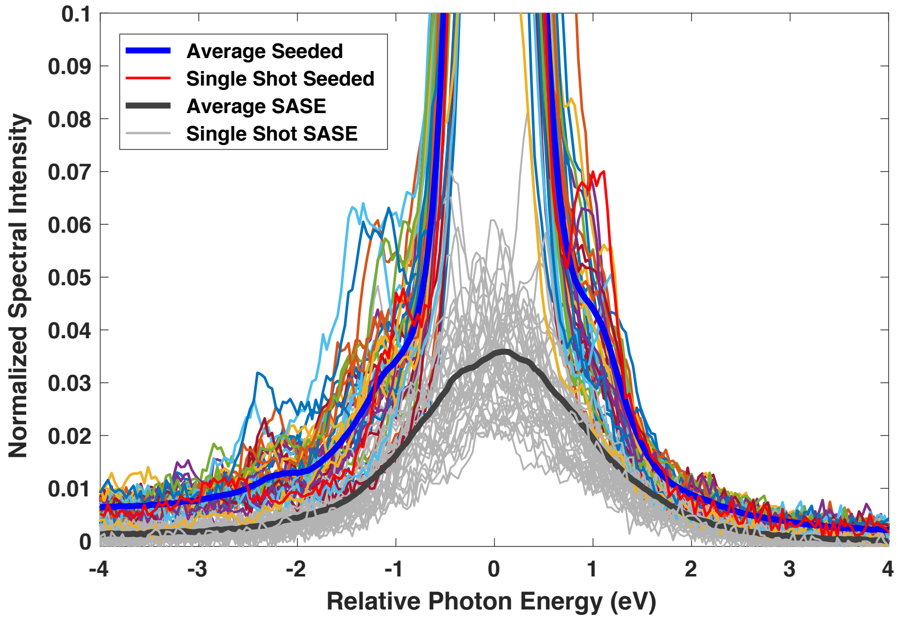
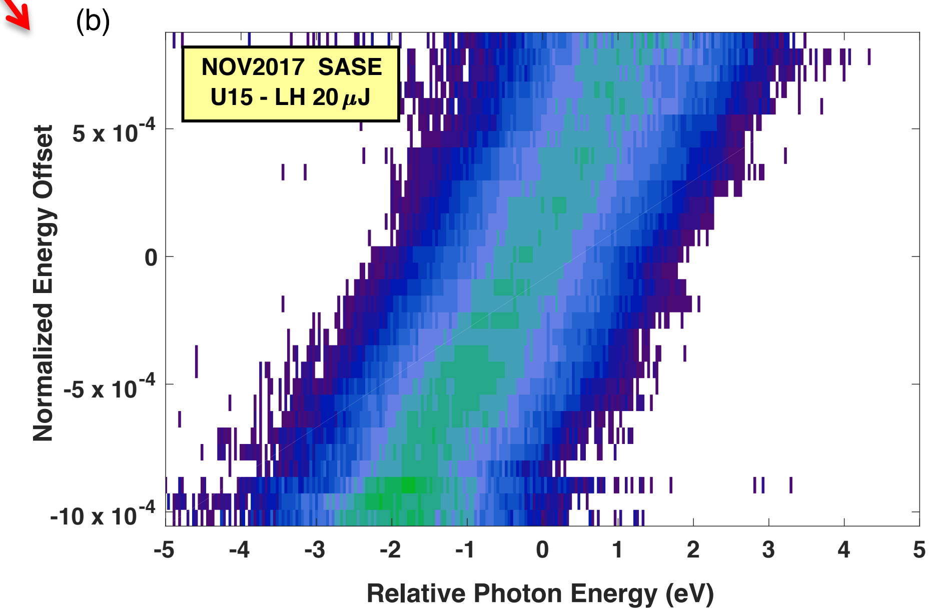
Binning spectral intensity against shot e-beam energy ("Lutman plot") makes generic SASE, amplified seed and pedestal apparent nonlinear color map (sinh function)

1 keV photon energy , $\rho \approx 1 \times 10^{-3}$, well-aligned LH, flat long. phase space U15 eff. undulator length ~ 6 segments of amplification beyond SS mono (well before obvious saturation effects)

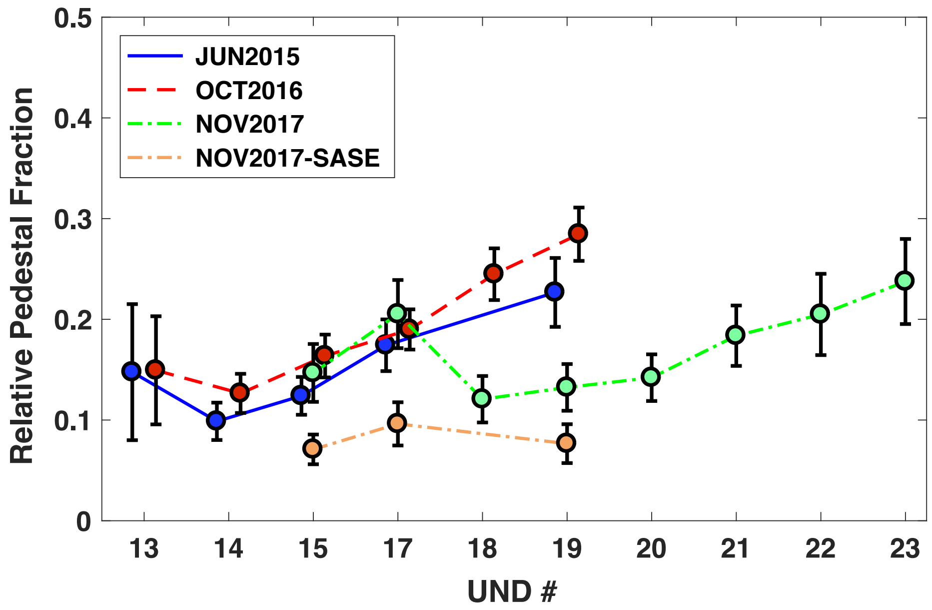


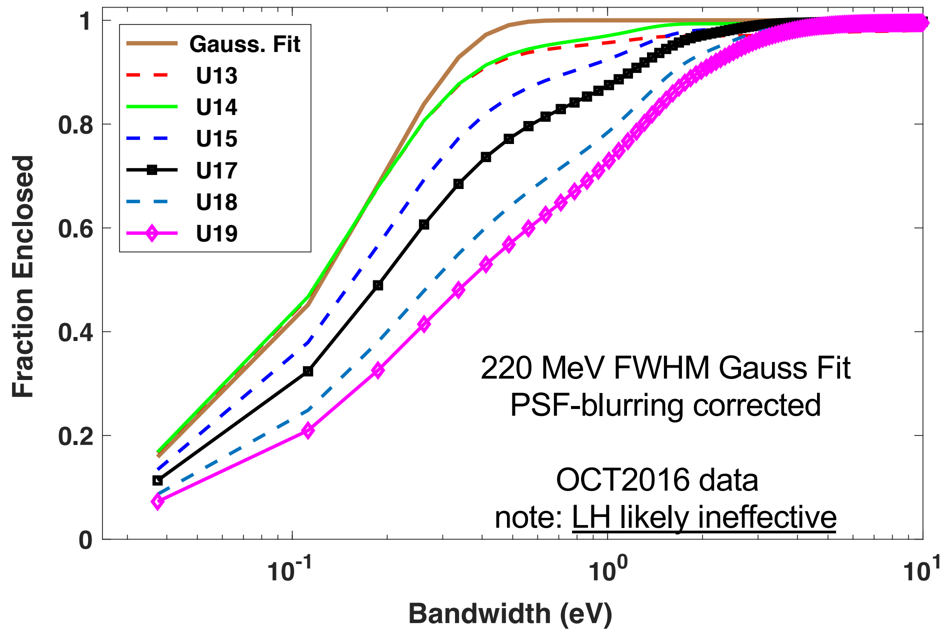
NOV2017 U19: Seeded and SASE shots (filtered in e-beam energy) 12μJ LH energy





LCLS 1-keV SXR Self-Seeding: Growth of Pedestal Fraction & Bandwidth with z





JUN2015 --- moderate seed, LH not optimized
OCT2016 data --- very strong seed, LH not optimized, CCD sat. problems ≳ U17
NOV2017 data --- rel. weak seed, good LH optimization, no CCD sat. issues
(SASE ≡ monochromatized seed blocked by aperture)

Point spread function (PSF) determined both directly *and* indirectly by quantifying correlations between seed and offset wavelengths for energy-mistuned shots

Pedestal Contamination Widens Spectral Bandwidth for both FERMI external- and LCLS self-Seeding

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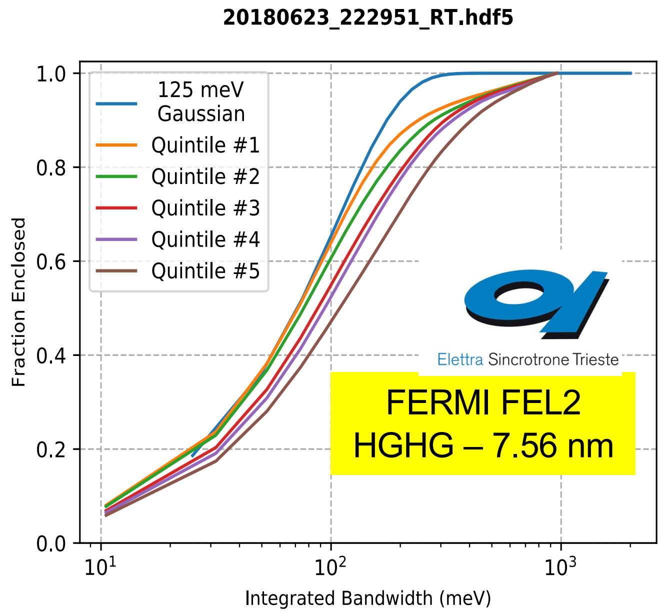
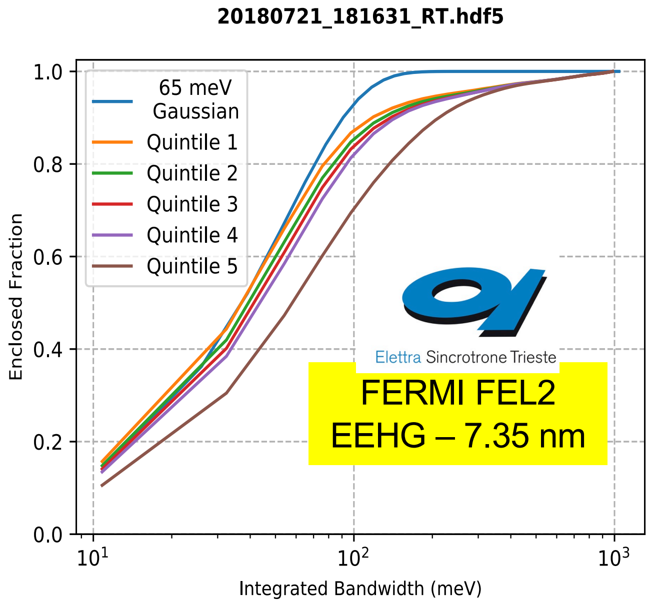
Normalized spectral intensity fraction as a function of enclosed bandwidth

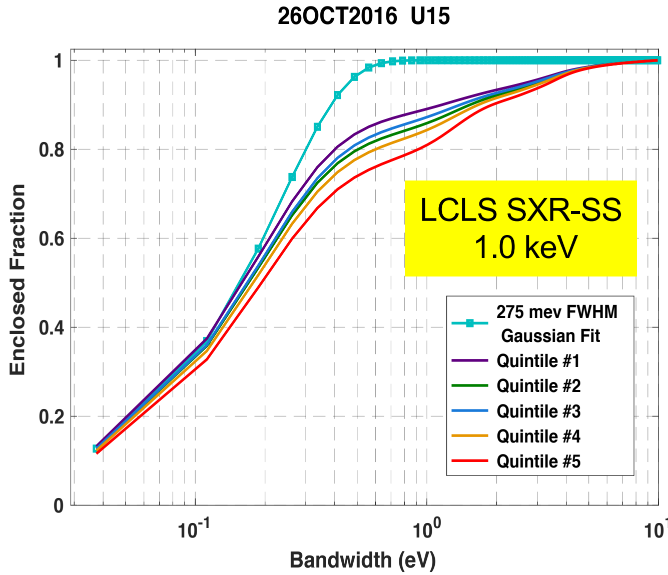
Eff. FWHM defined by min. bandwidth that encloses 76% of total power

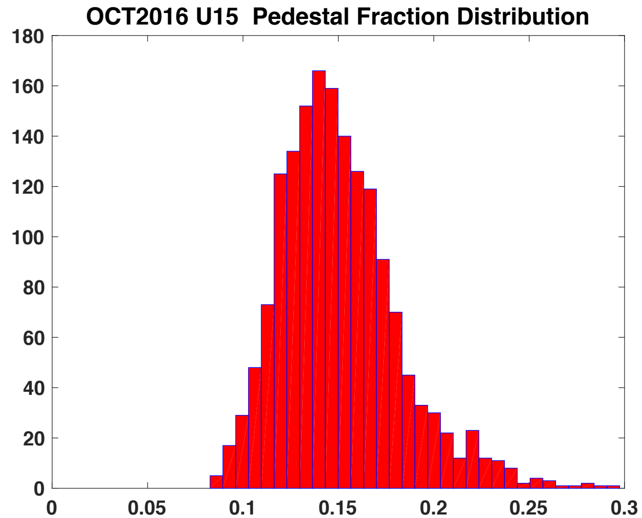
FERMI: EEHG has much better central core; 80% of pulses are quite good; 2-stage HGHG only 40% fraction very good

LCLS SXR-SS: ~20% of pulse energy extends beyond 550 meV = 2 σ_{FWHM}









LCLS self-seeded data shows shot-to-shot correlation between upper and lower sideband strength

NOV2017 data taken at 1 keV

12 μJ LH energy
 $\rho \approx 1.1 \times 10^{-3}$;

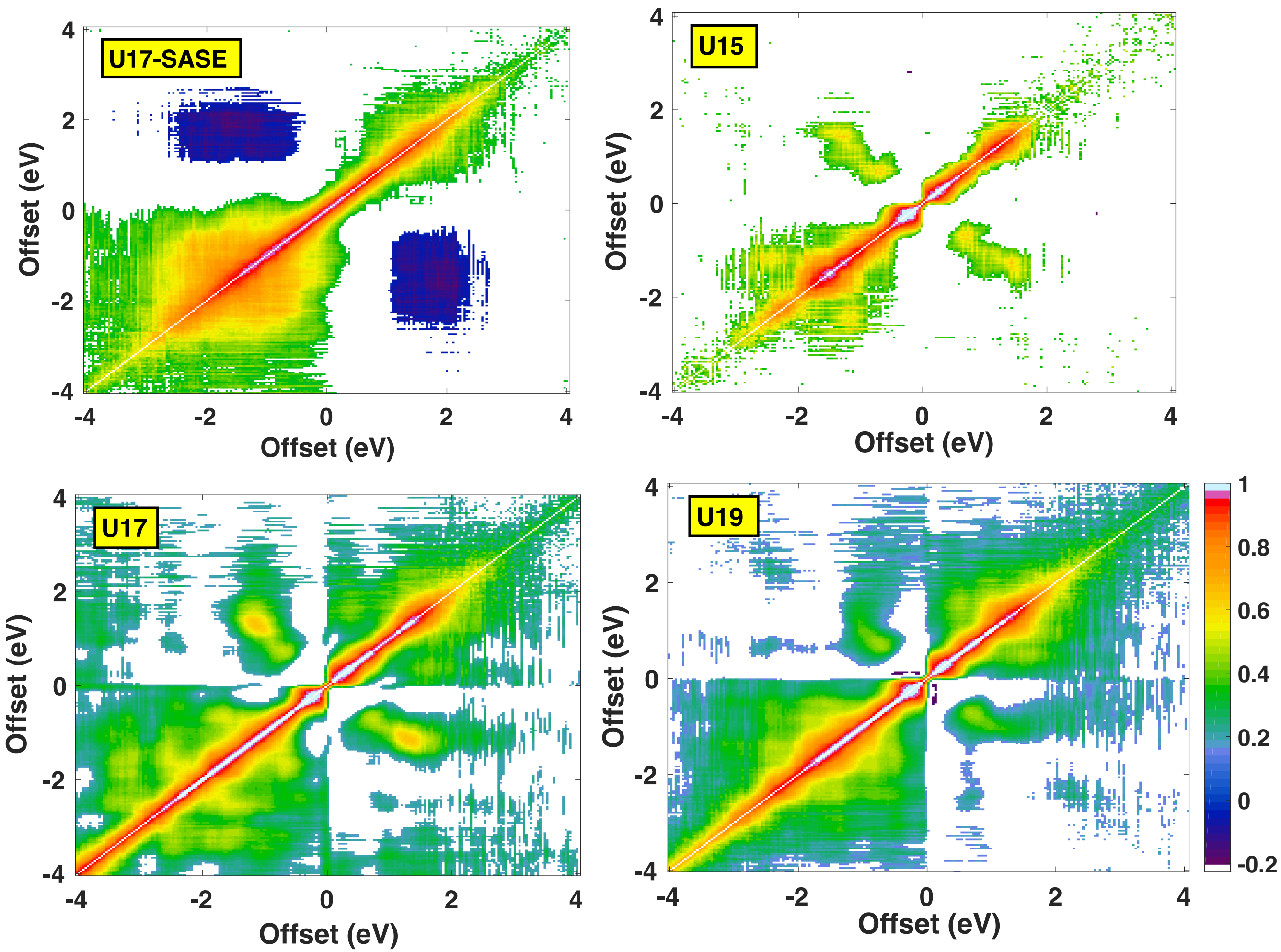
Indiv. shot E_b filtering:
 self-seeded: ± 0.8-1.6×10^{-4} ;
 SASE: $\pm 1.6 \times 10^{-4}$

 intensity filtering:
 $0.8 \leq I^{(n)} / \langle\langle I \rangle\rangle \leq 1.2$

False color maps of Pearson correlation coefficient between $\Delta\omega_1$, $\Delta\omega_2$;
negative values clamped to ≥ -0.2

Anti-correlation in SASE due to central λ sensitivity to linac energy jitter

Positive correlation for $\Delta\omega_1 = -\Delta\omega_2$ seen in multiple shifts for seeded shots

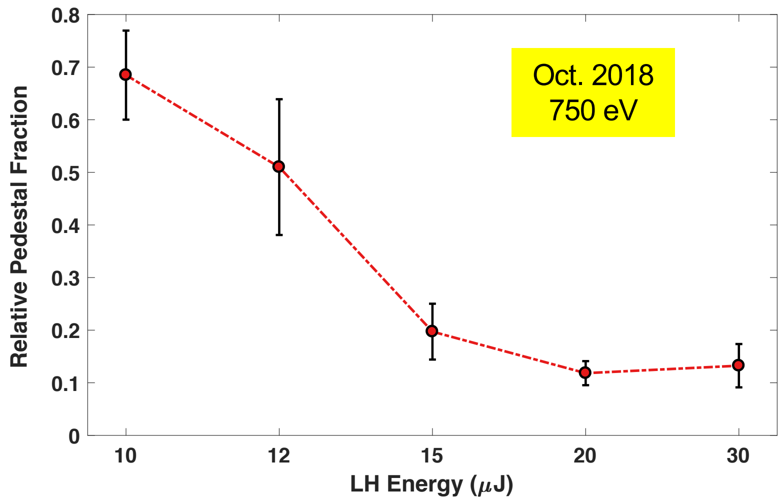


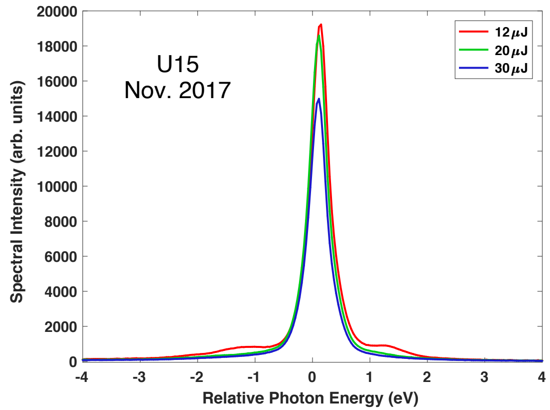
Spectral Purity Sensitivity to Laser Heater - LCLS

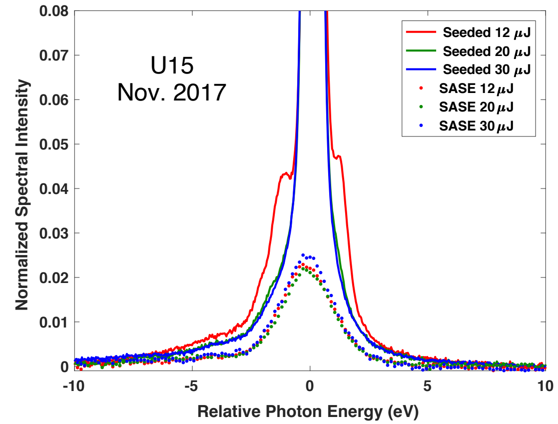
Both FERMI and LCLS self-seeded data show that optimizing LH strength can improve spectral purity

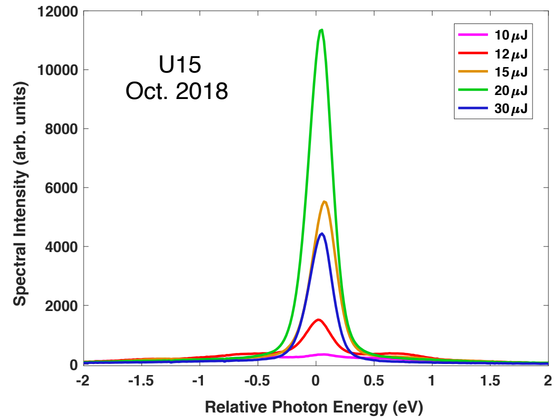
- LCLS 1-keV & 750 eV data, 1.3 kA, 140 pC, 0.6 mm-mrad U15 -- 6 und. segments post-SS chicane
- Shots filtered in e-beam energy
- Diagnostic spectrometer PSF ⇒ minimum pedestal fraction ≃ 0.07

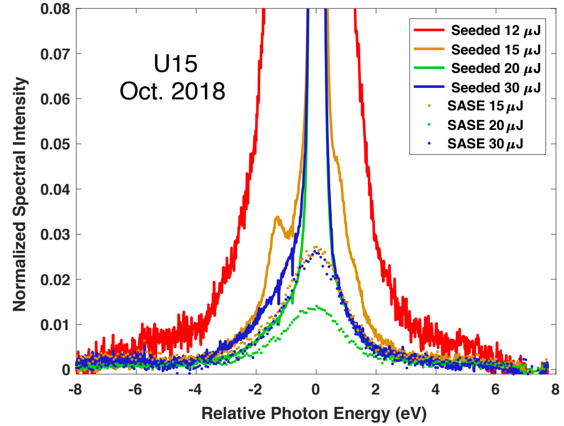
U15 Pedestal Fraction vs. LH strength





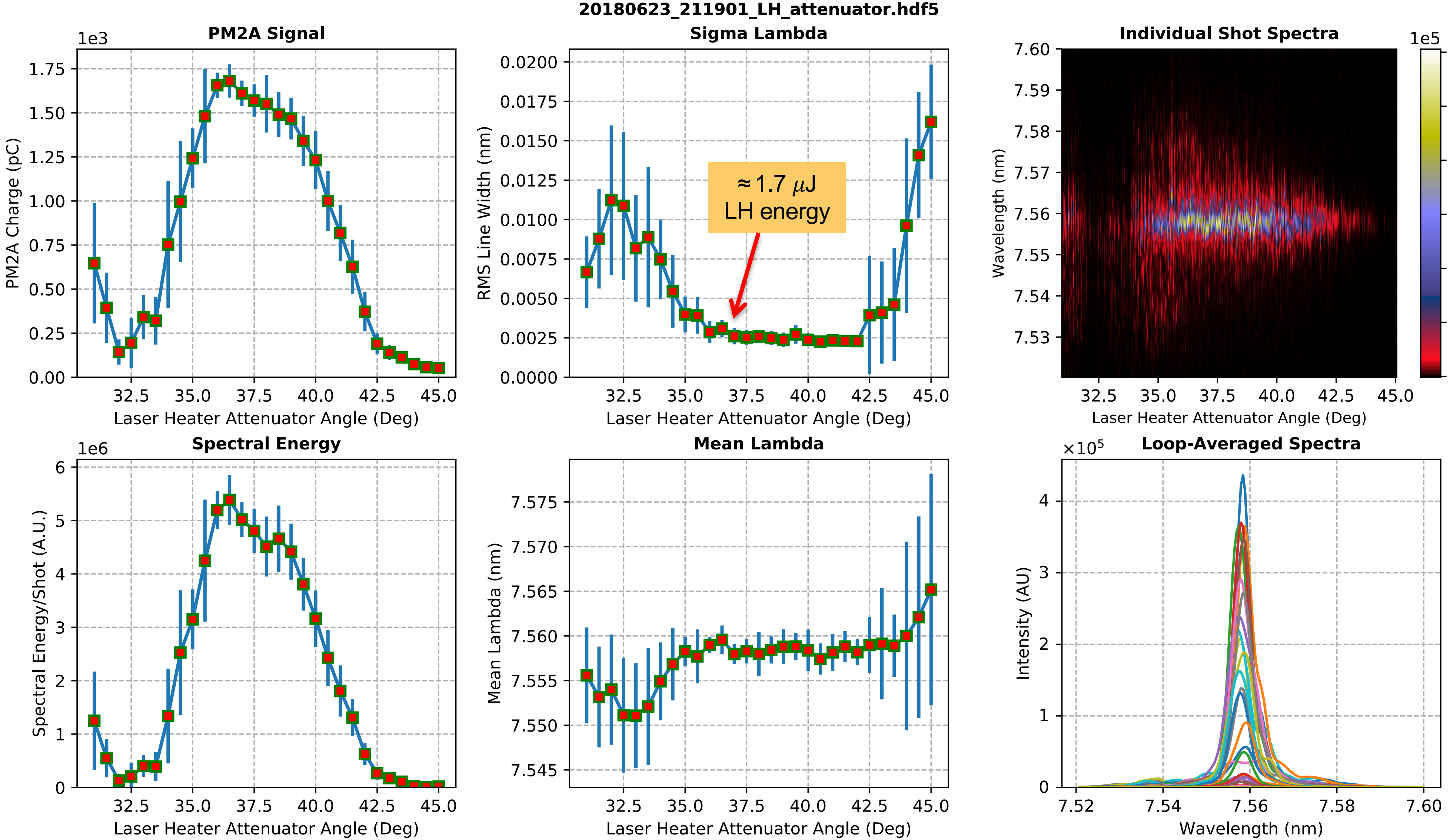






FERMI Spectral Purity Sensitivity to Laser Heater –23JUNE2018 FEL-2 HGHG Data at 7.5 nm

Elettra Sincrotrone Trieste



Note that FEL power is optimized at LH energy of ~1-2 μJ

FERMI Spectral Purity Sensitivity to Laser Heater – 15JULY2018 FEL-2 EEHG Data at 7.5 nm

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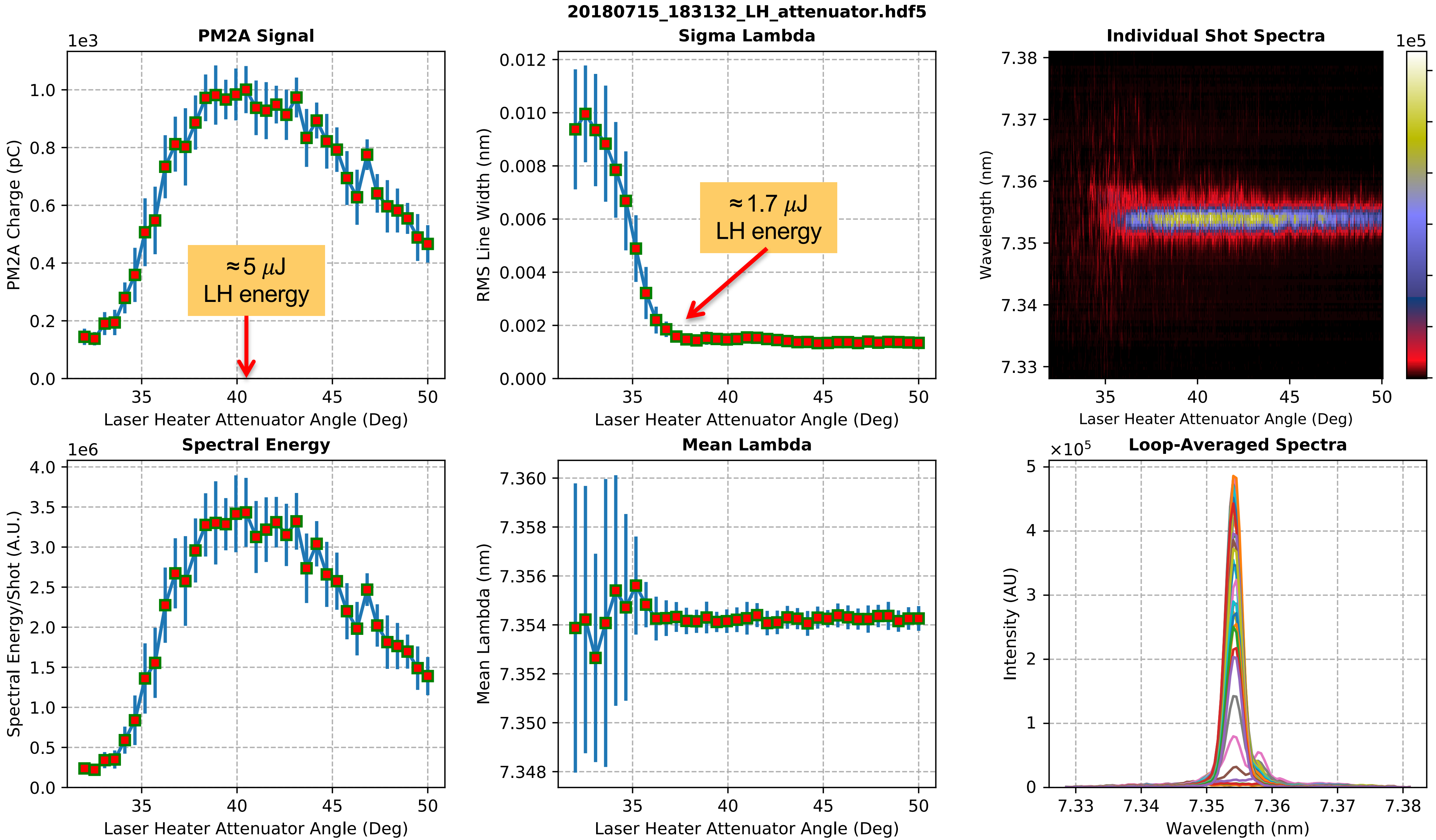
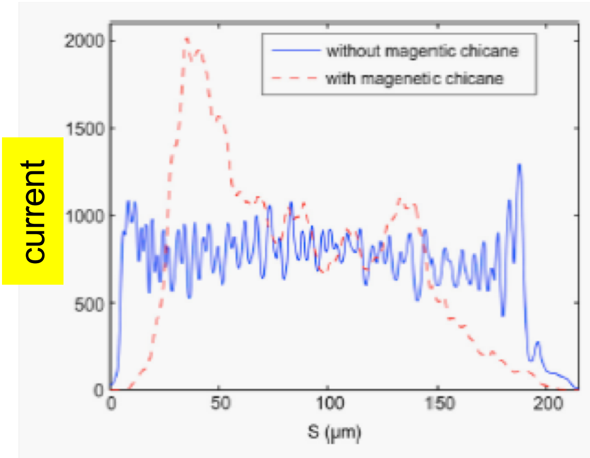


Note that FEL power insensitive over LH energy range of ~2 to 8 μJ --- very different behavior than HGHG result

Control of Microbunching Instability

- Photocathode surface and photoinjector laser can seed microbunching
- Laser heater found essential to control μBI growth (LCLS & FERMI)
  - consider reducing net gain for better μBI suppression & improved spectral purity

- K. Zhang *et al.* (Shanghai; NIMA, **882**, 23 [2018]): use strong chicane before 1st undulator to reduce μBI modulations
  - Good damping for $\lambda \lesssim 5\,\mu m \times (R_{56} / 10\ mm)\ (\sigma_E / 200\ keV)\ (E_B / 2\ GeV)$
    (however: is damping truly exponential in λ^{-2} ?!)
  - Significant risk of making high current horns and accompanying strong SASE contamination
  - Advantage of providing possible diagnostic region



- Sidebands in 0.3 -1.5 eV offset region (λ ≈ 0.8 – 4 μm) most important for XUV and SXR output radiation
  - near-to-moderate IR-sensitive diags needed to monitor CTR output and/or ≲2.5-fs resolution in deflection cavity to directly measure long. phase space

FERMI FEL-1 @ 20.5 nm   25NOV2019: Little Sensitivity to LH energy, is μBI vanquished?!

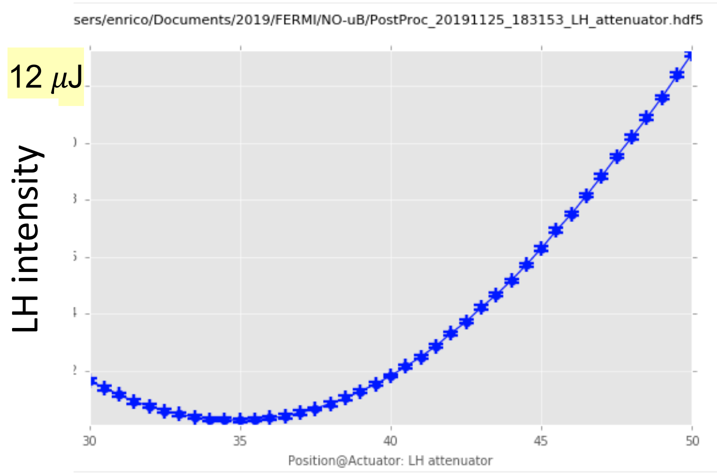
Elettra Sincrotrone Trieste

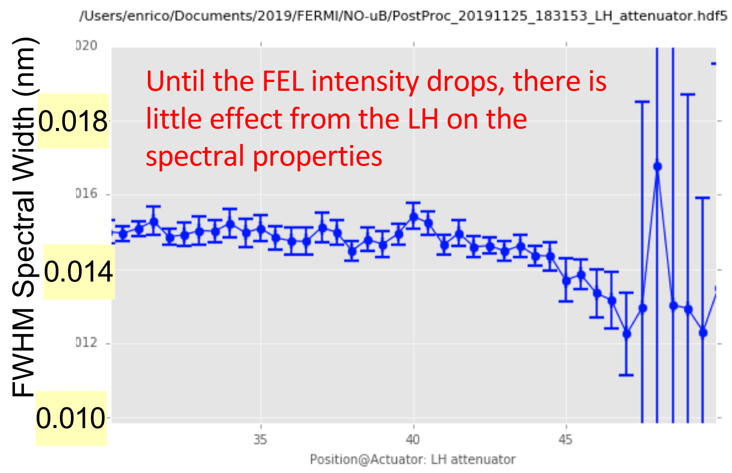
After summer 2019 shutdown, FERMI has operated with a new photocathode, new linac tune with fewer large β-function excursions, and perhaps a better PIL beam

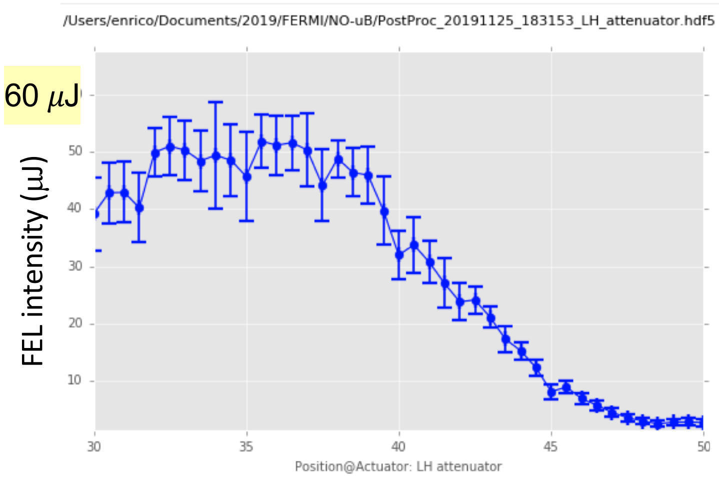
In the 20-40+ nm wavelength regions evidence of μ-bunching has disappeared!!!

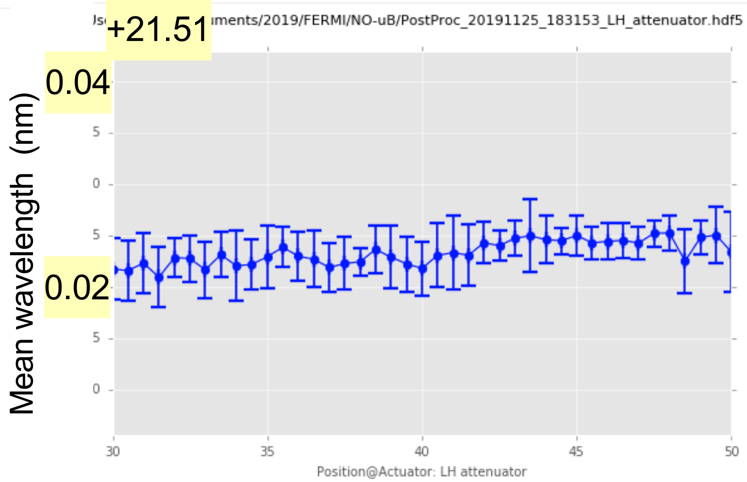
More specifically, no increase of slice energy spread is needed to optimize FERMI FEL power --- very different behavior than in the past

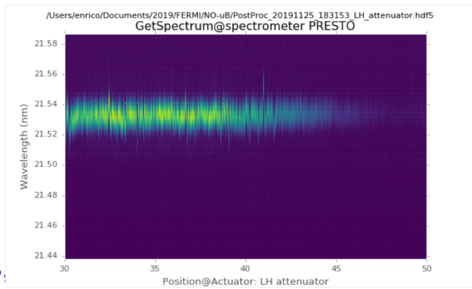
Why???



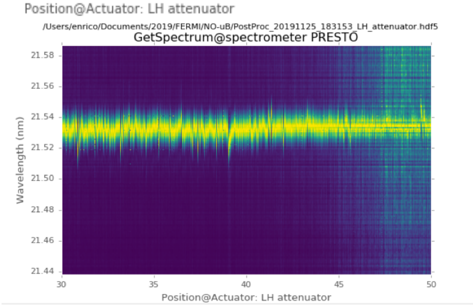








courtesy E. Allaria



Possible Topics for Future Investigations - Pedestal

With FERMI and soon LCLS-2 (warm linac line only in 2020), additional experimental investigations of pedestal physics are possible

- LCLS-2 with XTCAV can correlate long. phase space structure with pedestal strength
- Both FERMI and LCLS-2 can purposely mistune energy to see pedestal response as seed amplification is reduced
- Deeper analysis of FERMI data can perhaps find relevant correlations between pedestal and beam parameters (e.g., orbit in undulator, compression strength, spreader dispersion, photocathode laser spot position, etc. *vs.* spectral purity)
- Additional LCLS-2 study of LH-pedestal interaction is warranted, especially with simultaneous spectra and post-undulator XTCAV measurements
- Intentional wake field excitation in FERMI linac and effects on FEL spectrum could be illuminating, esp. when modelled by S2E calculations
  - on upgraded FEL-1, can examine comparative microbunching sensitivity between HGHG and EEHG modes

Possible Topics for Future Investigations – Spectral Quality

- Can cross-correlation analysis of spectral data separate wanted RIXS signal from SASE/pedestal contamination (D. Fausti)? Other applications?
- For high rep-rate machines like XFEL & LCLS-II, can machine learning algorithms significantly optimize spectral quality?
- Can EEHG experiments with FERMI upgraded FEL-1 in 5+ nm region accurately predict spectral quality for upgraded FEL-2 @ 2.2 nm? CSR scaling? IBS?

- *etc., etc.* --- far more clever people than me will improve present methods and invent new ones to further advance FEL radiation characteristics

FEL physicist ⇔ User scientist collaboration is critical

Fundamental Questions about User Needs

To return to the beginning...

How truly good is "good enough" in terms of spectral quality?

If FEL physicists could produce superb spectral quality at meaningful power levels, what *really, REALLY* important user experiments could be enabled?