U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Seeding at LCLS FEL

J. Welch, (SLAC)

Acknowledgements

- SLAC

  J. Amann, J. Arthur, A. Brachmann, F.-J. Decker, Y. Ding, Y. Feng, J. Frisch, D. Fritz, J. Hastings, Z. Huang, R. Iverson, J. Krzywinski, H. Loos, A. Lutman, M. Messerschmidt, D. Ratner, J. Turner, J. Wu, D. Zhu

- ANL

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- DESY/XFEL

  G. Geloni, E. Saldin

- LBNL

  P. Emma

Topics

- Seeding vs SASE
- Description of the HXRSS Installation at LCLS
- Operation and Performance
- New Features
- Next Steps

SASE

- FELs are radiation amplifiers with very high gain:

  $\sim e^{20} = 5 \times 10^{8}$ within a narrow bandwidth $\rho \sim 10^{-4} - 10^{-3}$.

- SASE is simply amplified shot-noise

  X-ray radiation and micro-bunching of the electron beam build up from statistical fluctuations in the density of electrons in the bunch.

  SASE is analogous to turning up the volume of your stereo amplifier to the maximum without connecting it a input source.

- A very narrow bandwidth seed input, narrower than the SASE gain bandwidth, will be greatly amplified and can dominate over the SASE power.

Seeding vs SASE

- Higher spectral brightness

  Users requiring a monochromator will get more intensity.

- Versatile hard x-ray beams

  Near-monochromatic beams of hard x-rays can be manipulated efficiently using bragg reflection, allowing complex beam manipulation such as split and delay, similar to what is done with conventional laser beams.

- Better longitudinal coherence

  low $\sigma_t \sigma_\omega$ pulses make sharper probes.

- High power (potentially)

  Seeded beams may tolerate more energy extraction through additional undulator length and tapering, possibly leading to TW beams.

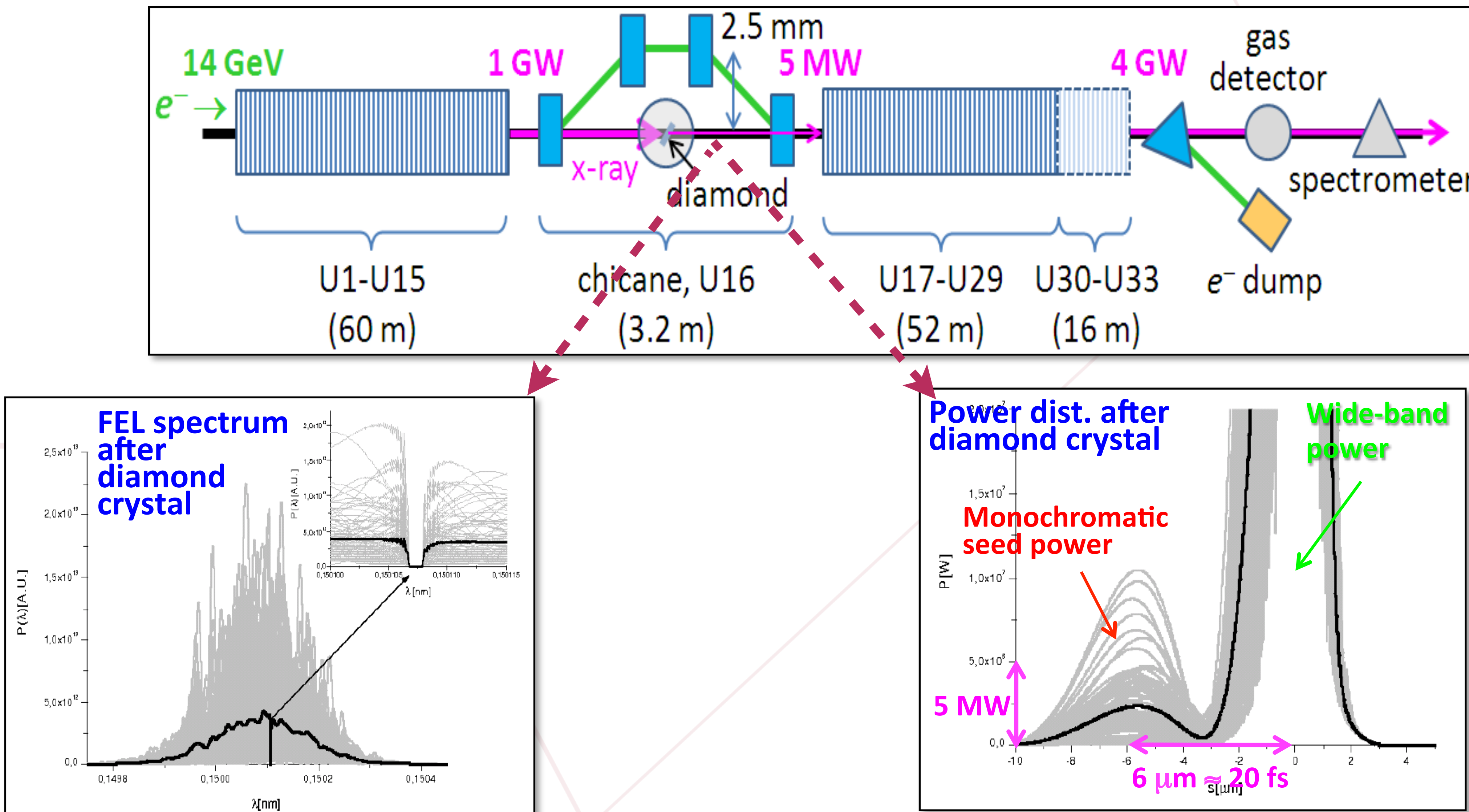
- Fewer photons

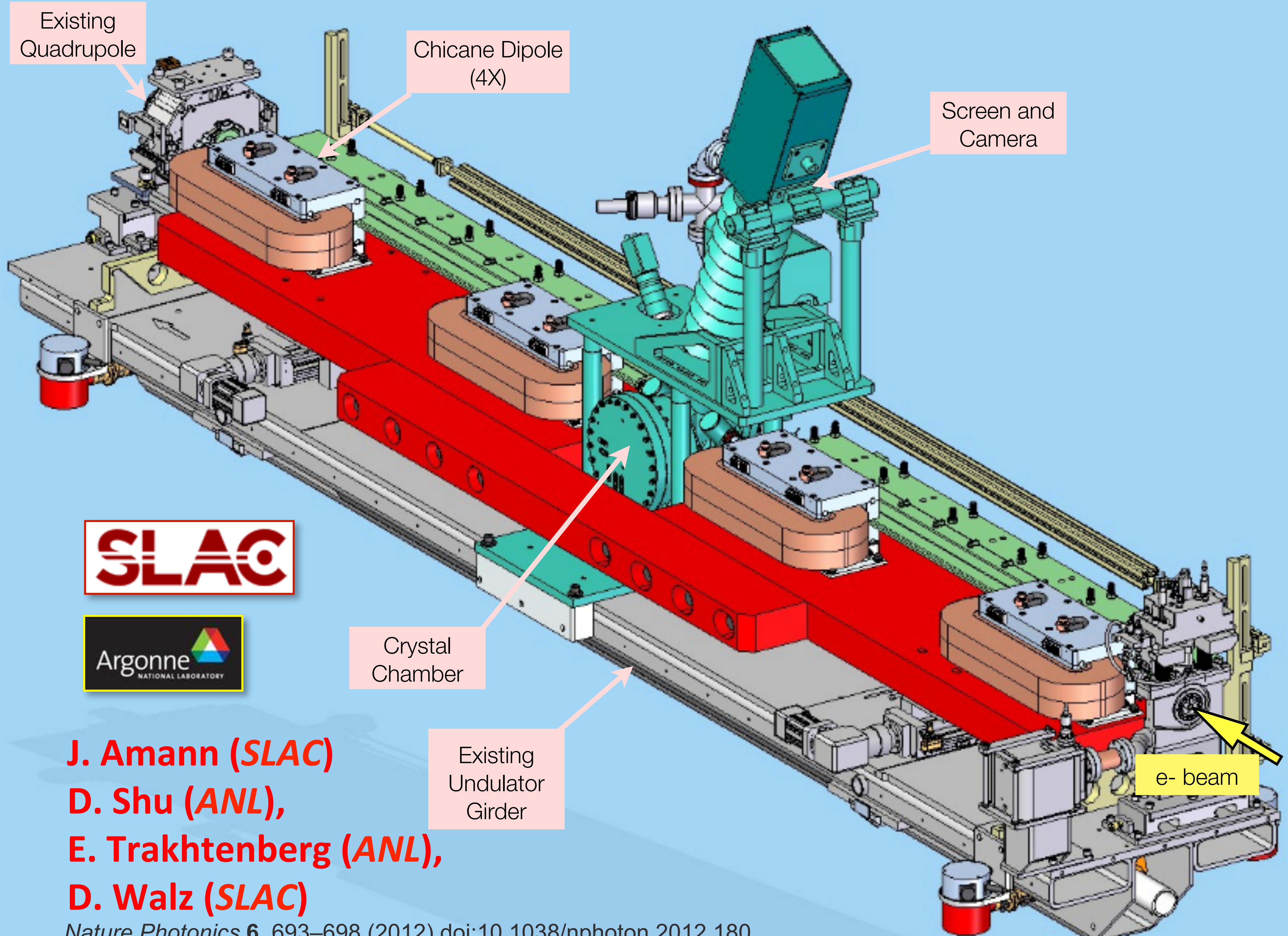
- More intensity jitter

Hard X-Ray Self-Seeding Using a Single Crystal

Great idea from Geloni, Kocharyan, Saldin, (*DESY* 10-133, 2012)

- Filtered SASE pulse can generate a slightly delayed co-axial seed.





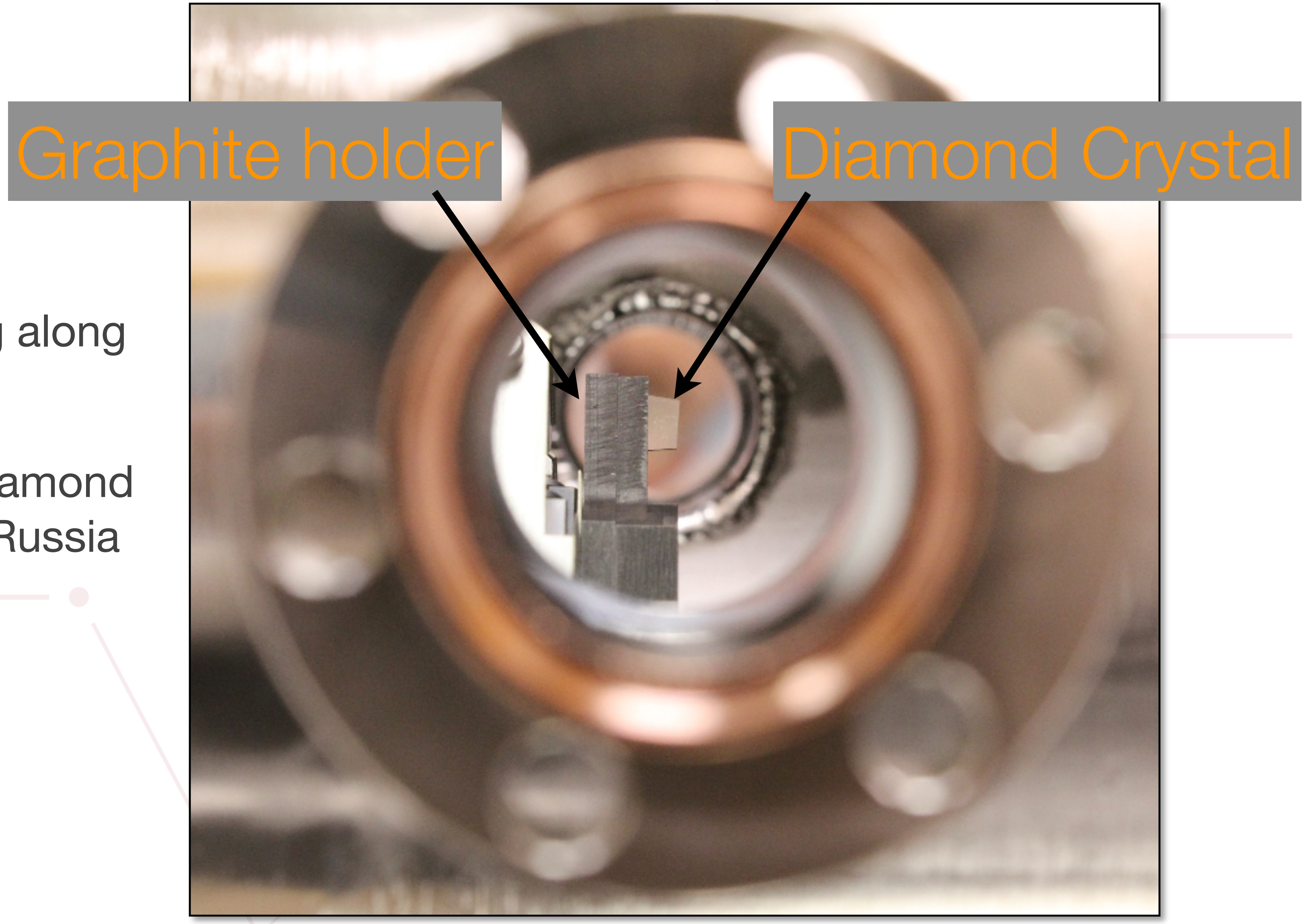
J. Amann (*SLAC*)
D. Shu (*ANL*),
E. Trakhtenberg (*ANL*),
D. Walz (*SLAC*)

Nature Photonics **6**, 693–698 (2012) doi:10.1038/nphoton.2012.180

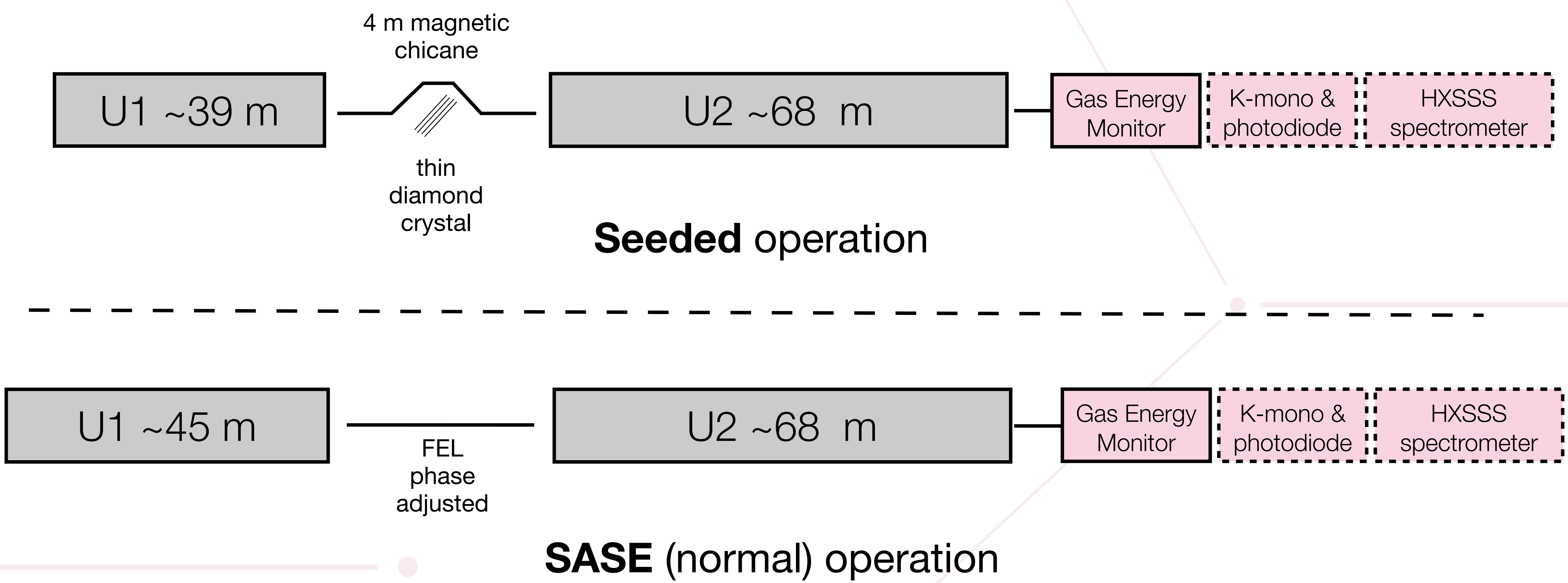
Diamond Crystal

As seen looking along the beam path.

100 μm thick diamond from TISNCM, Russia

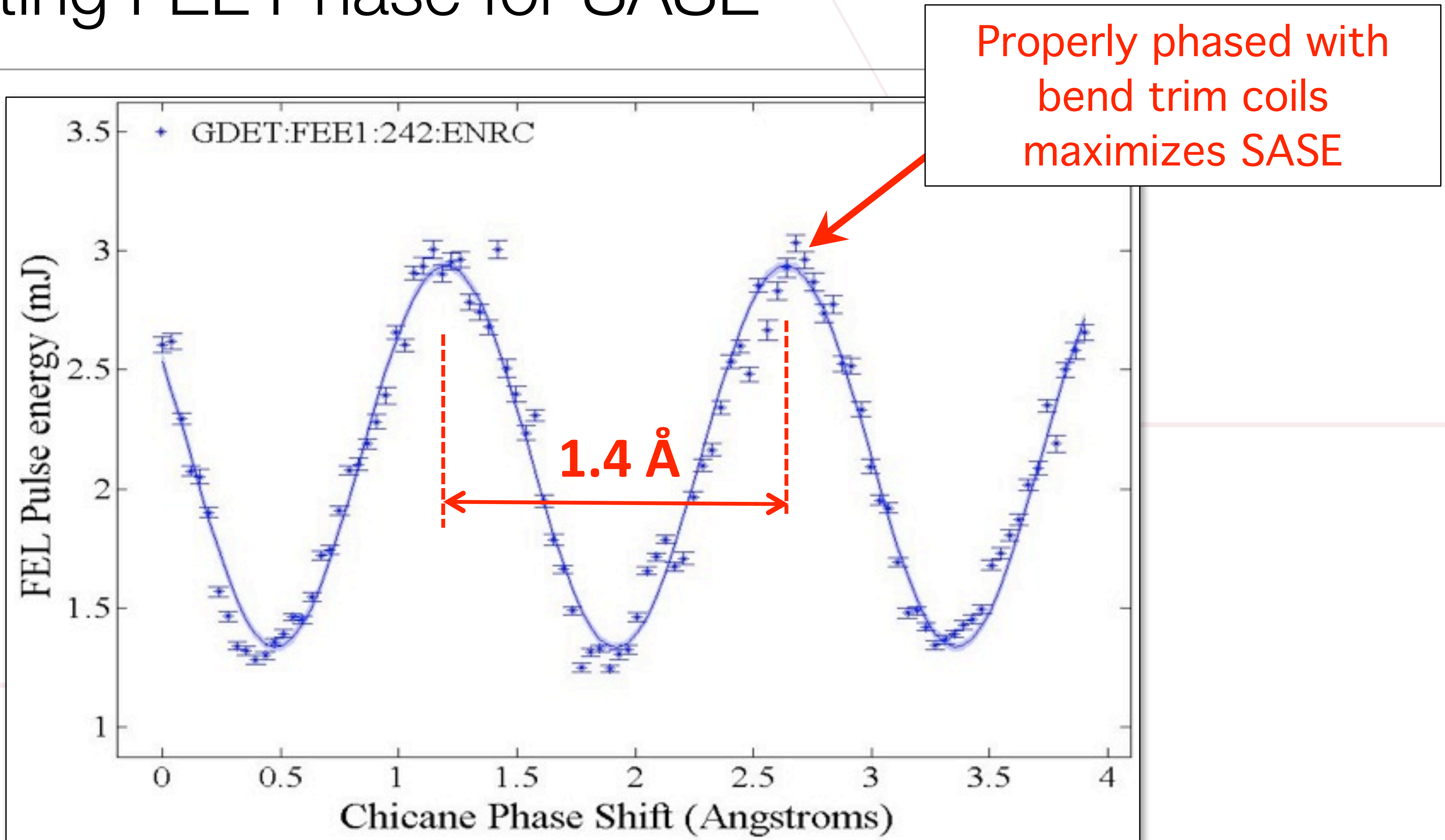


Self-seeding and SASE Operation at LCLS



- **Seeded** operation: turn on chicane, insert crystal and correct residual orbit.
- **SASE** operation: turn off chicane, correct residual orbit, adjust FEL phase between U1 and U2.

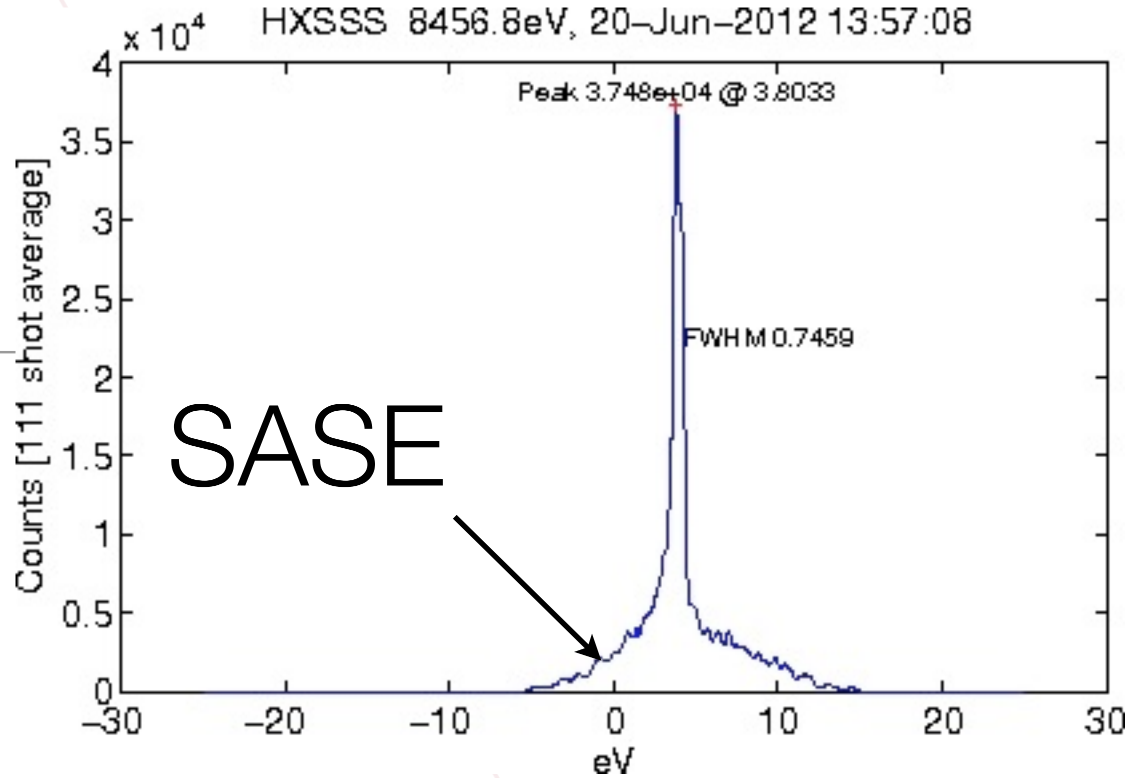
Adjusting FEL Phase for SASE



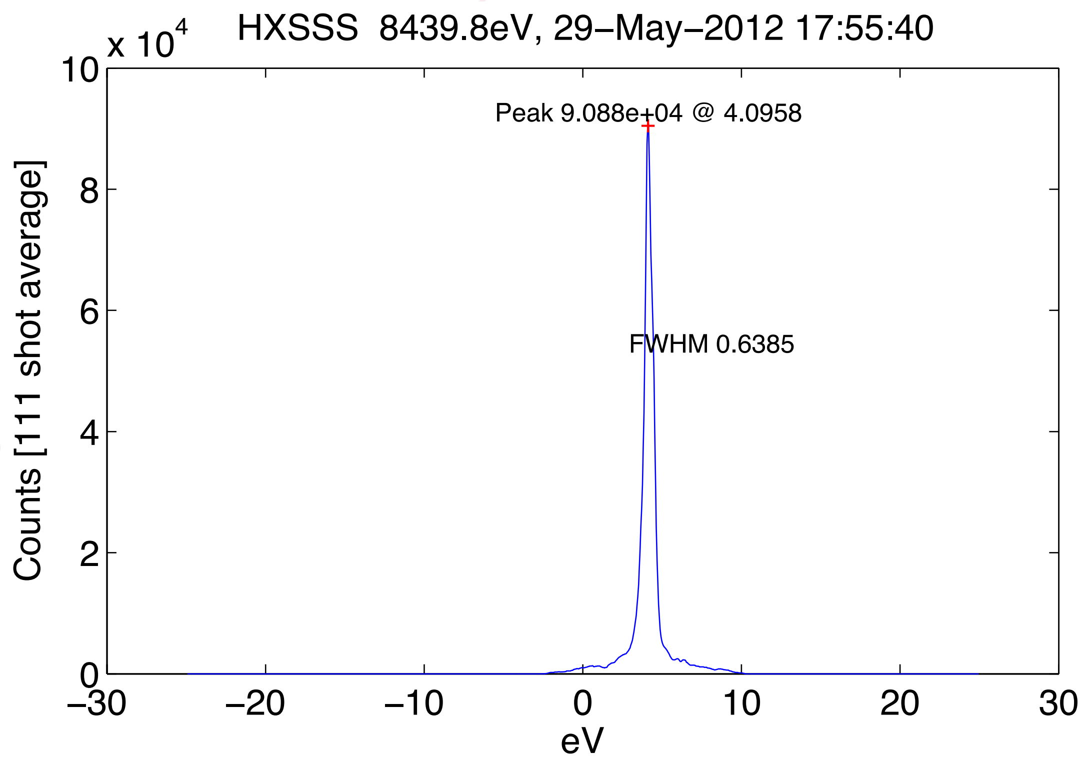
- Use trim coils on chicane dipoles. Main current is off.

Tuning Notes

- Need to precisely correct orbit change introduced by chicane (to < 5μm).
- Large intensity fluctuations require a lot of averaging.
- Tune on peak spectral intensity, not pulse energy (SASE)
- Tune-up takes (at least) 2 hrs, but it should be possible to reduce it to ~15 minutes.

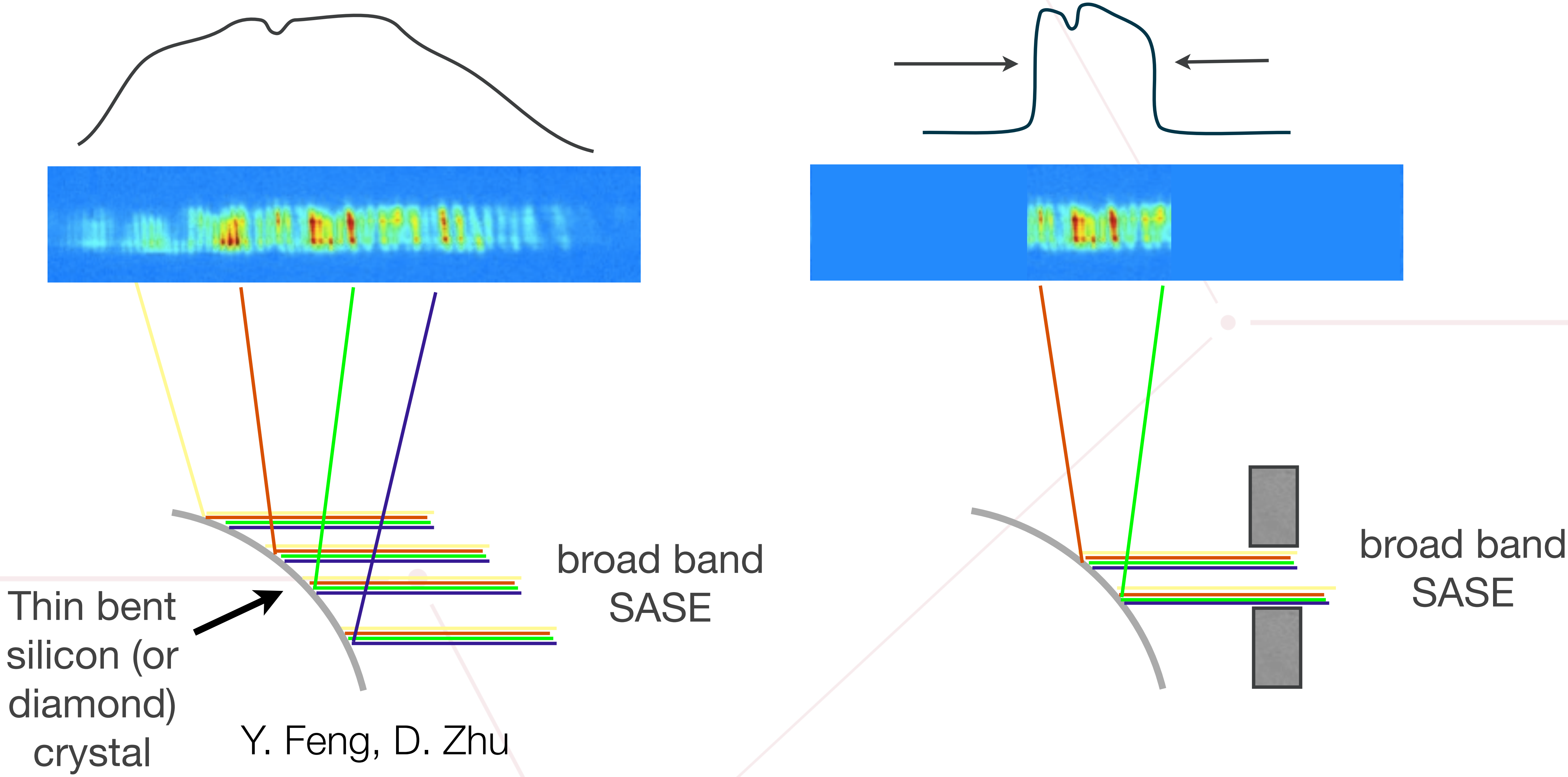


Not well-tuned beam showing substantial energy in SASE bandwidth.



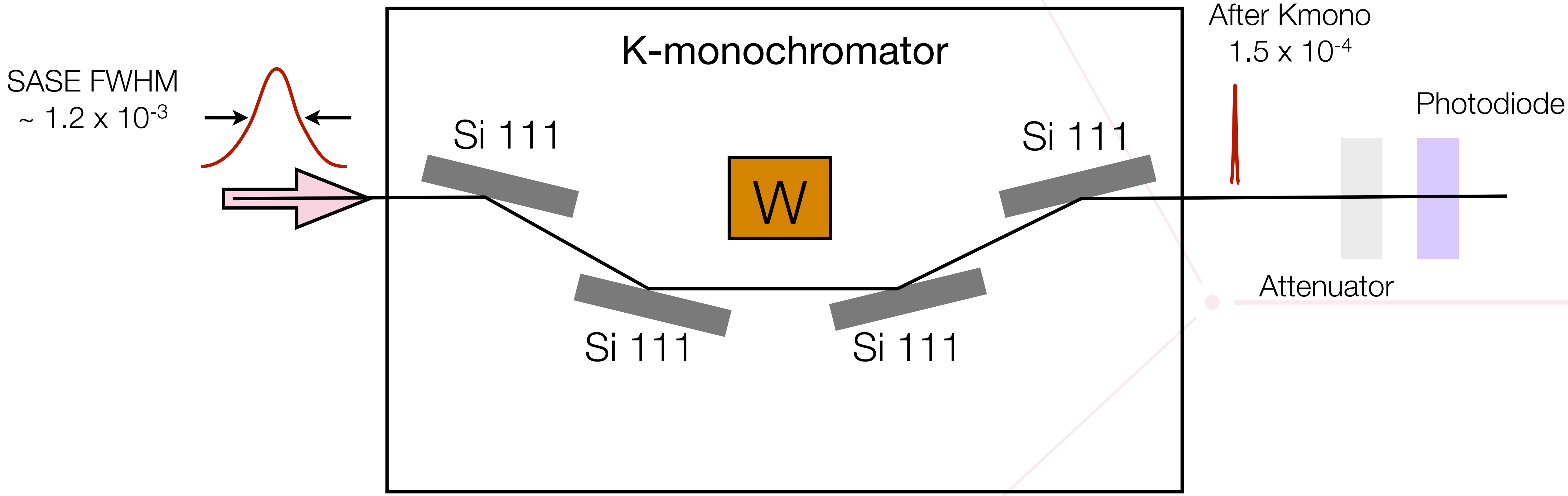
Well-tuned beam. Most energy is in the narrow peak.

HXSSS - bent crystal spectrometer



- Resolution is very good, but range and response can depend on vertical beam size, especially for the relatively broad band SASE beams

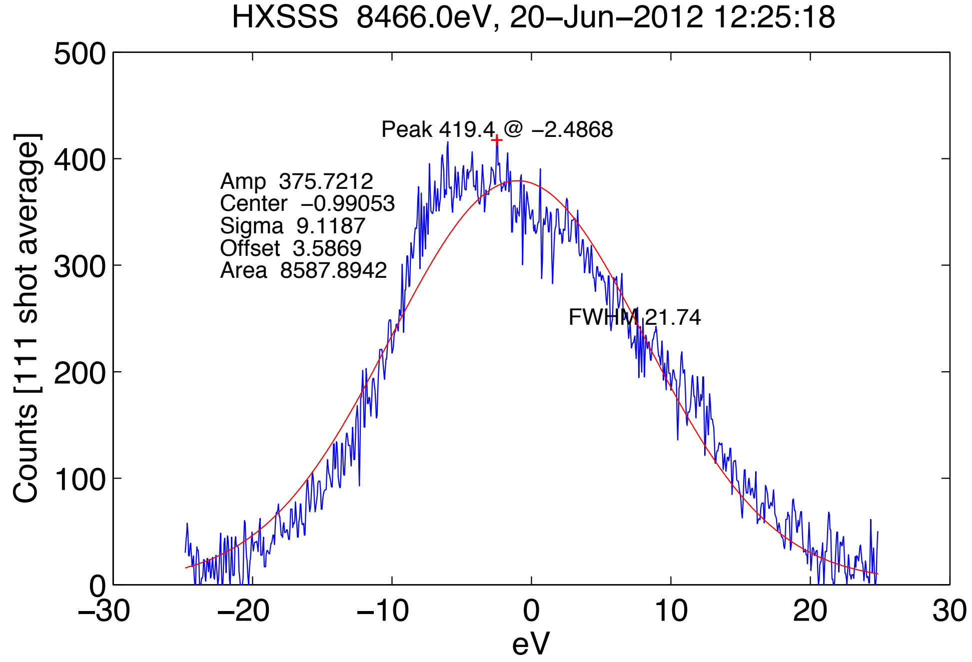
K-monochromator (Kmono)



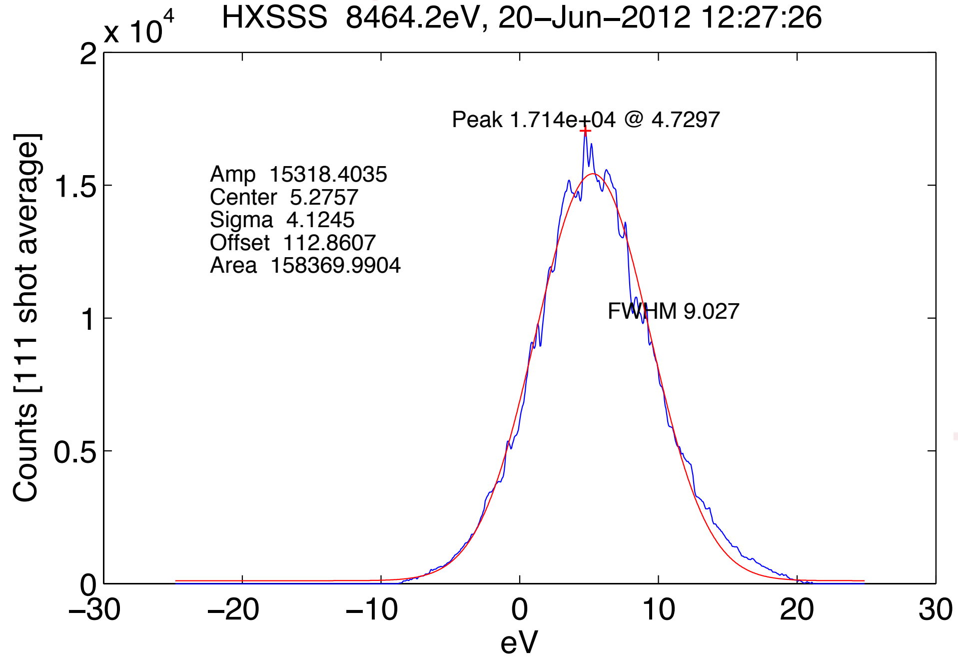
- Four bragg reflections at angle 13.965 degrees for 8194 eV transmission
- Bandwidth measured to be 1.2 eV, FWHM (1.5×10^{-4})
- Only one angle and one energy can pass
- Cleans up spectrum by removing bulk of SASE
- Photodiode provide synchronized data with wide dynamic range

Spectra

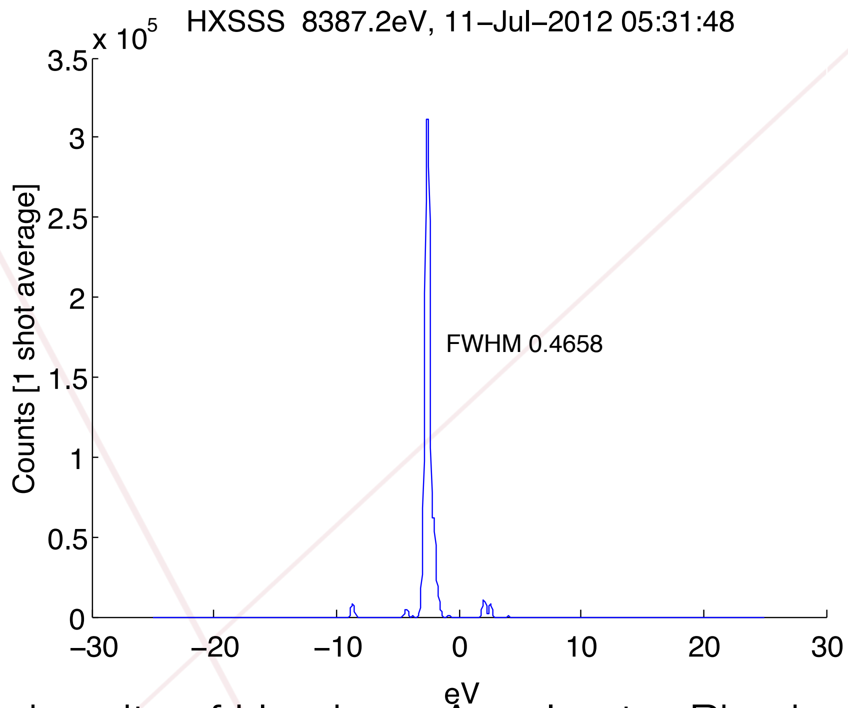
SASE at chicane



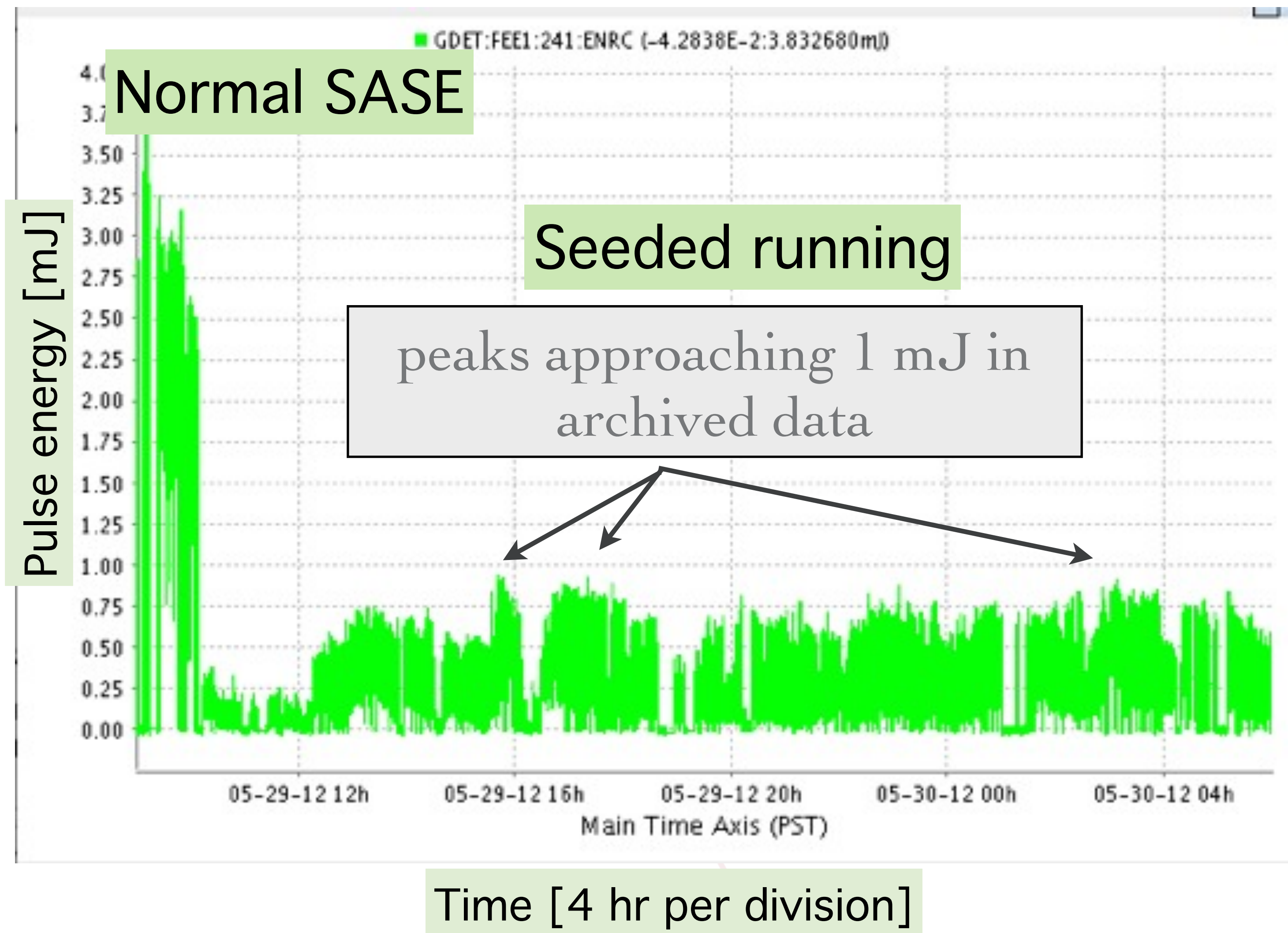
SASE at output of LCLS



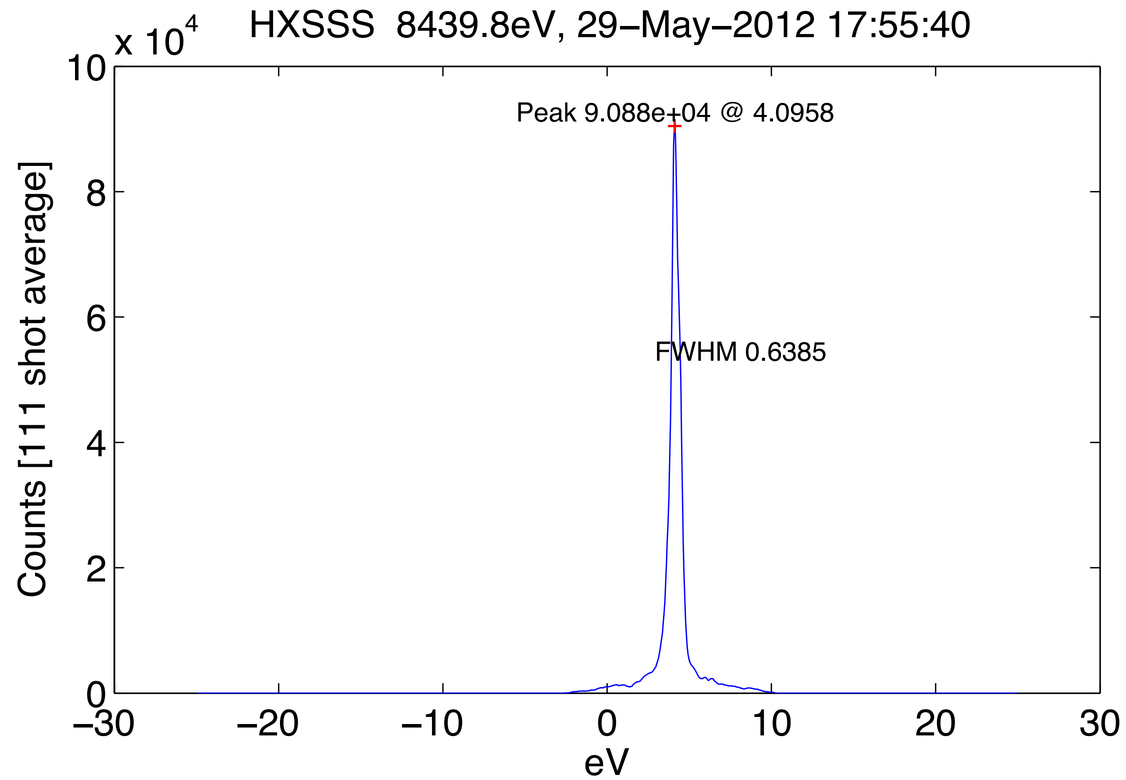
Seeded at output of LCLS (004)



Energy and Bandwidth Performance



150 pC bunch average energy loss ~300 uJ, or 1.5 x 10^{-4} relative energy loss (~1/3 ρ).

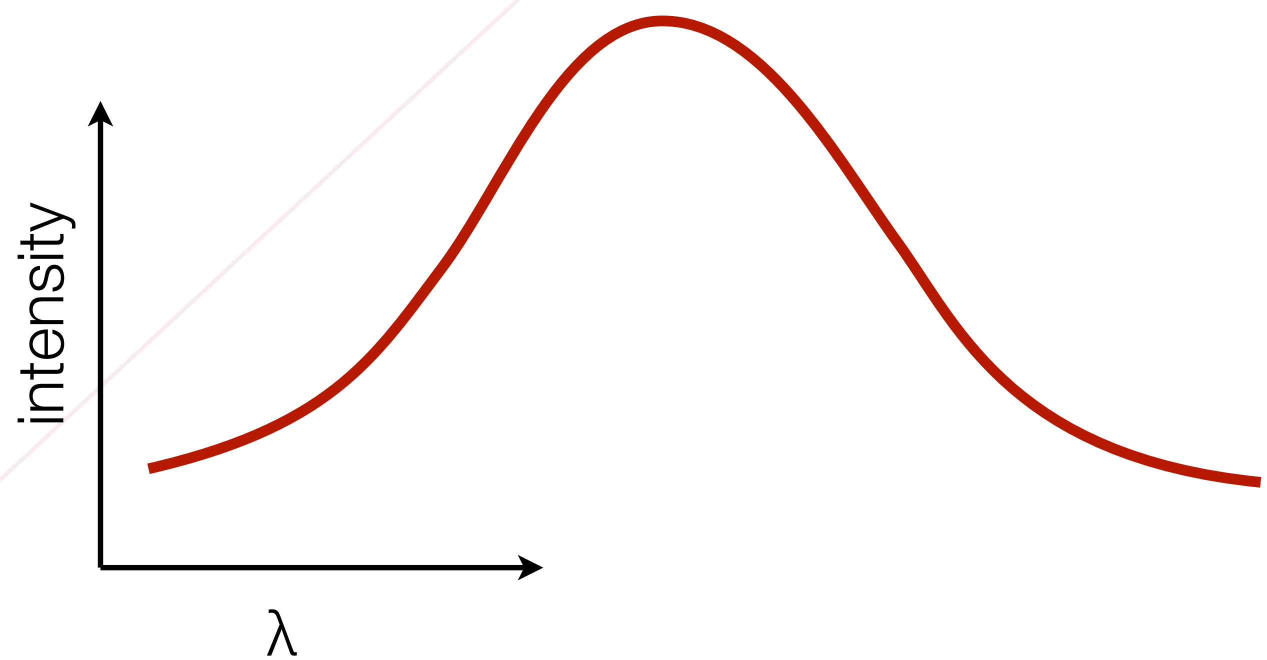


FWHM 0.8 x 10^{-4} (average for 004). SASE FWHM ~2 x 10^{-3} ≈ spectrometer range.

Relative Brightness, Measured with the Kmono

Relative Brightness, Measured with the Kmono

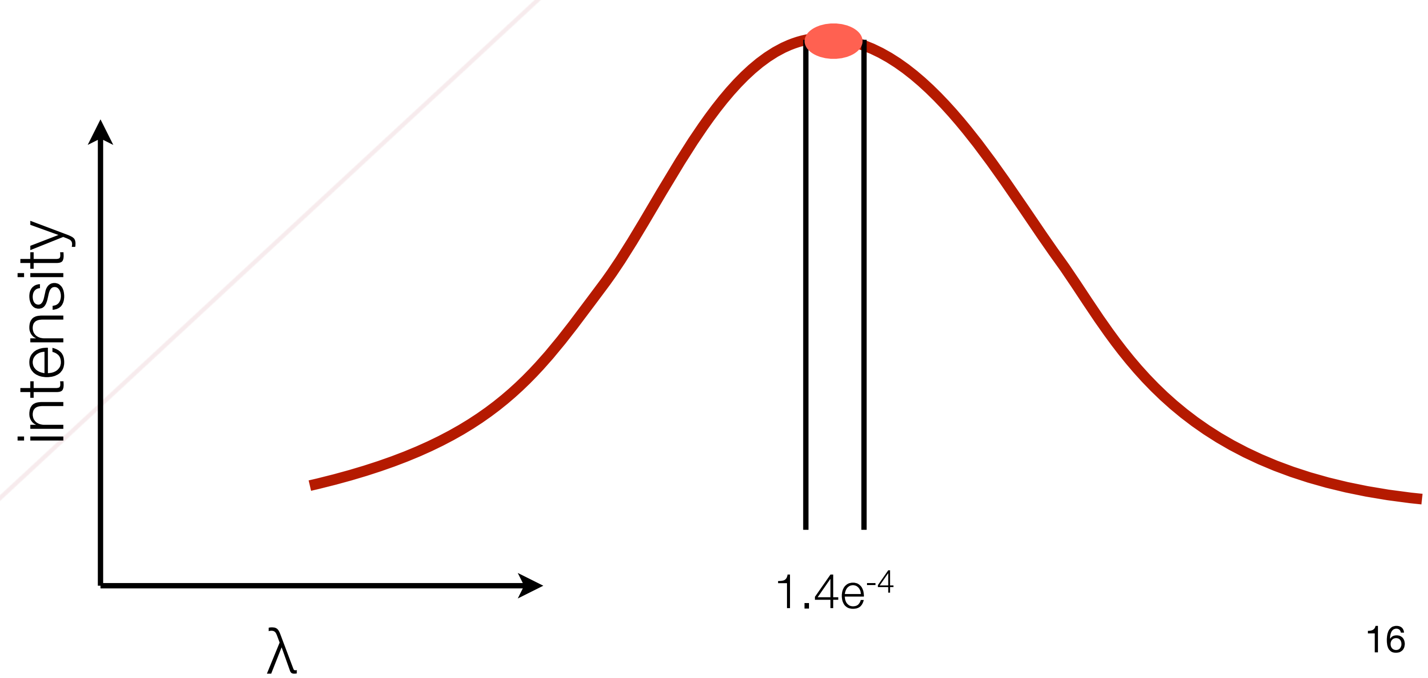
- Tune up SASE for normal operation for maximum pulse energy, e.g. 2 mJ. Self-seeding chicane is off.



Relative Brightness, Measured with the Kmono

- Tune up SASE for normal operation for maximum pulse energy, e.g. 2 mJ. Self-seeding chicane is off.

- Insert Kmono and adjust electron energy to maximize the output. This is the peak SASE brightness



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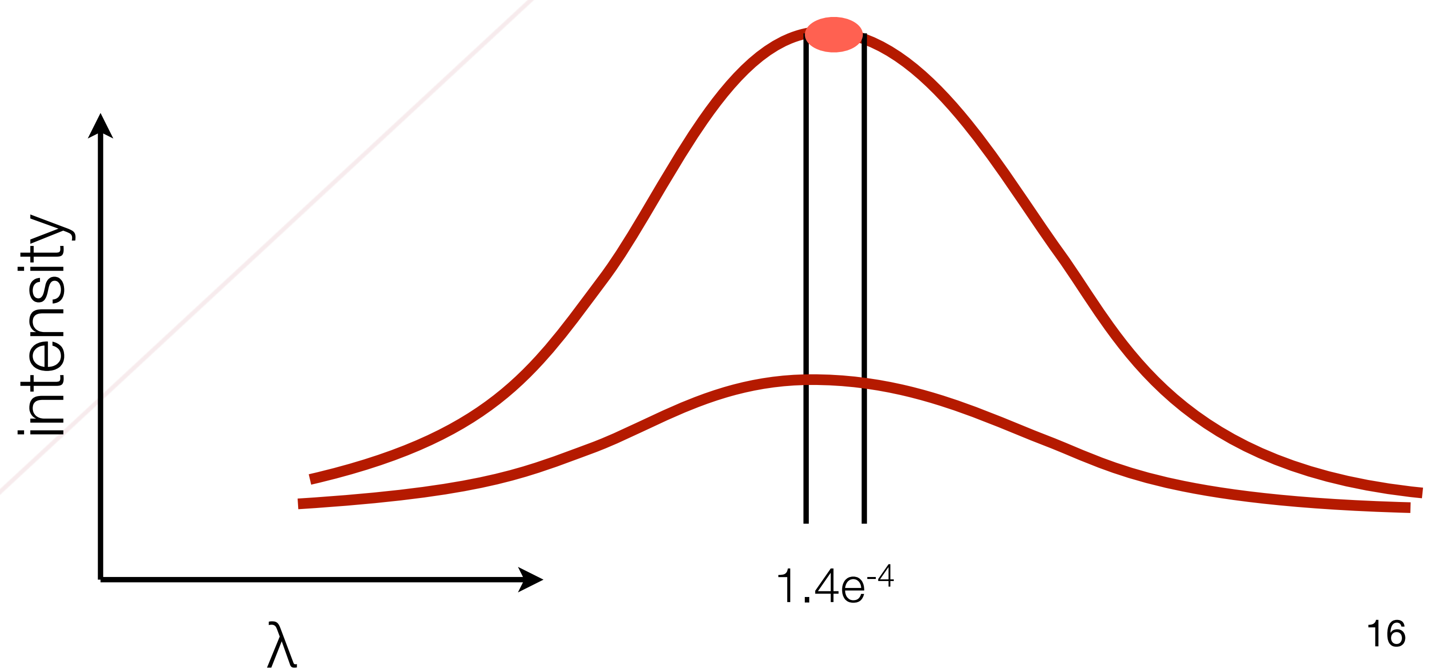
- Insert Kmono and adjust electron energy to maximize the output. This is the peak SASE brightness
- Turn on chicane.



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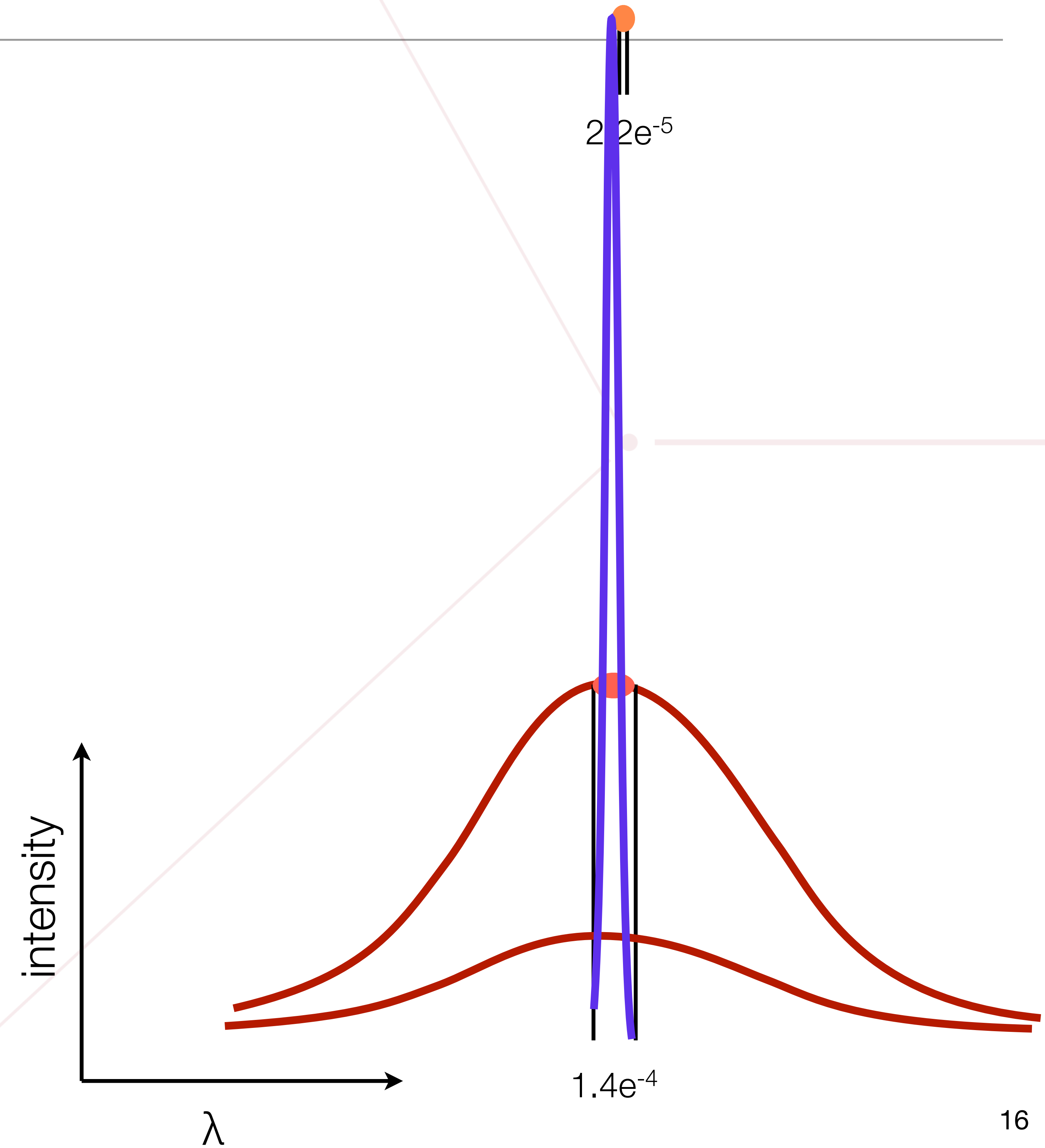
- Insert crystal and tune up to maximize the signal seen through the Kmono.



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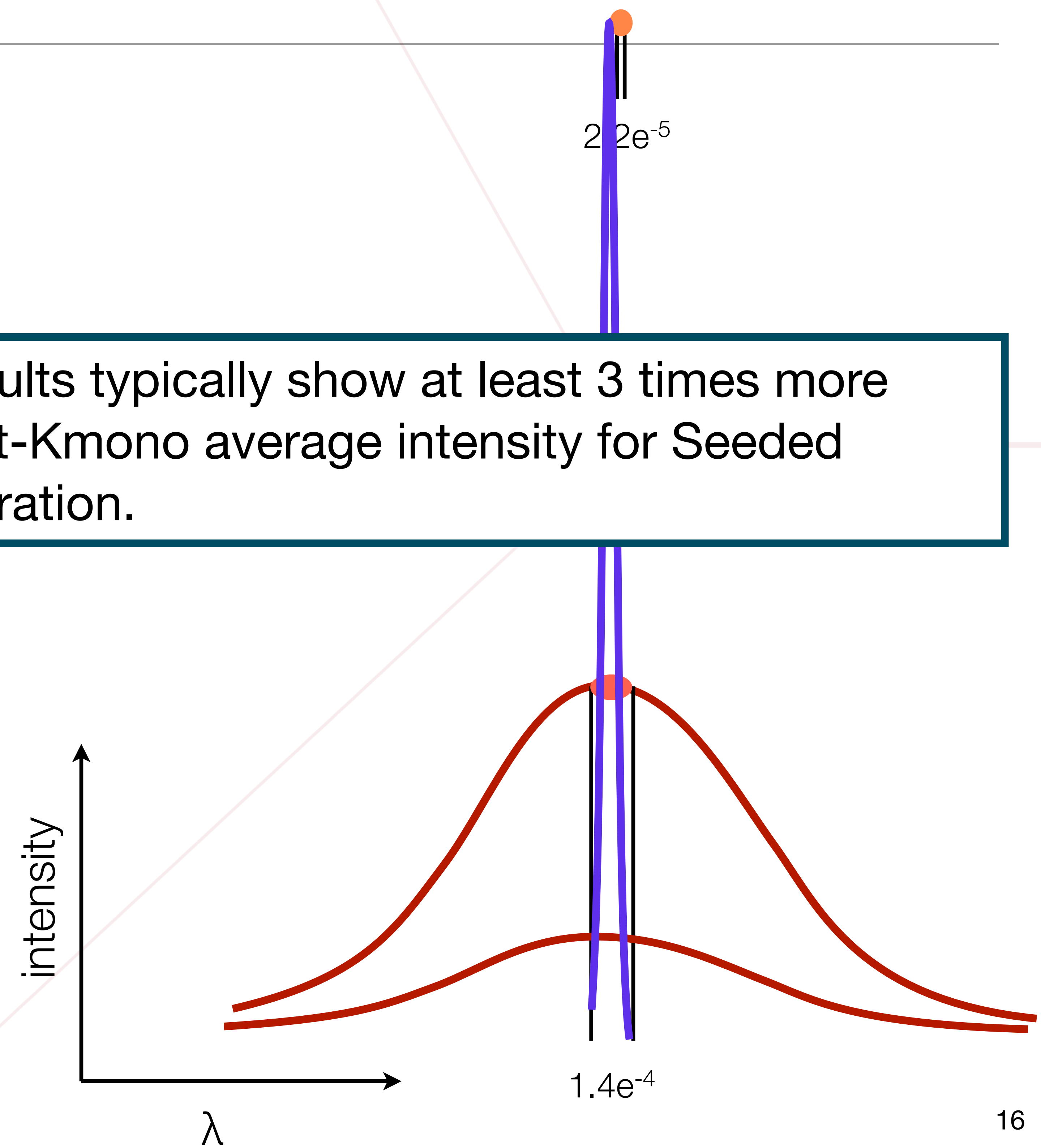
Results typically show at least 3 times more post-Kmono average intensity for Seeded operation.



Fluctuations: SASE vs. Seeded

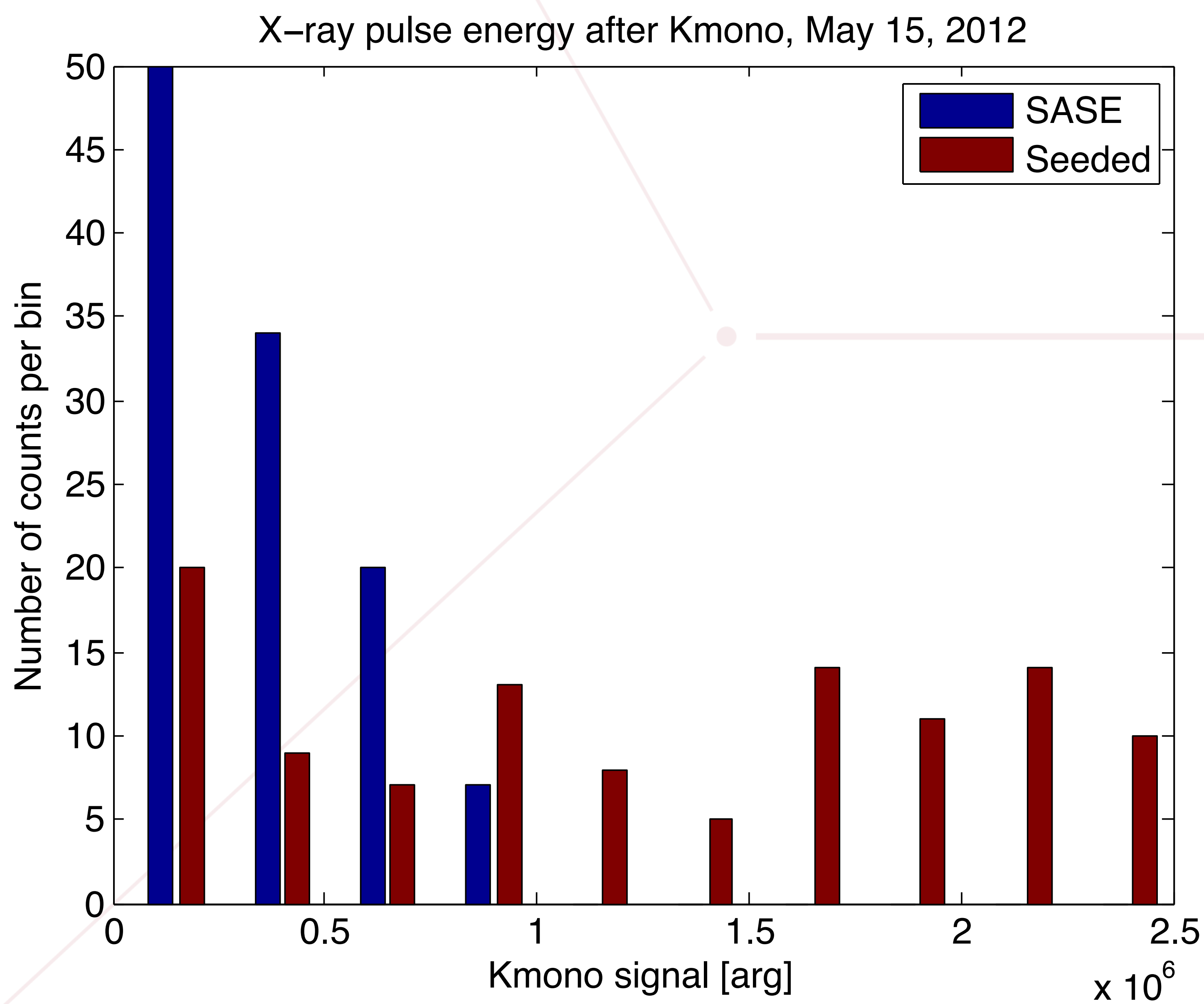
- SASE measured after Kmono and compared with Seeded.

- Unsaturated SASE pulse energies should have an exponential pulse height distribution.

$$p \sim e^{-u/u_0}$$

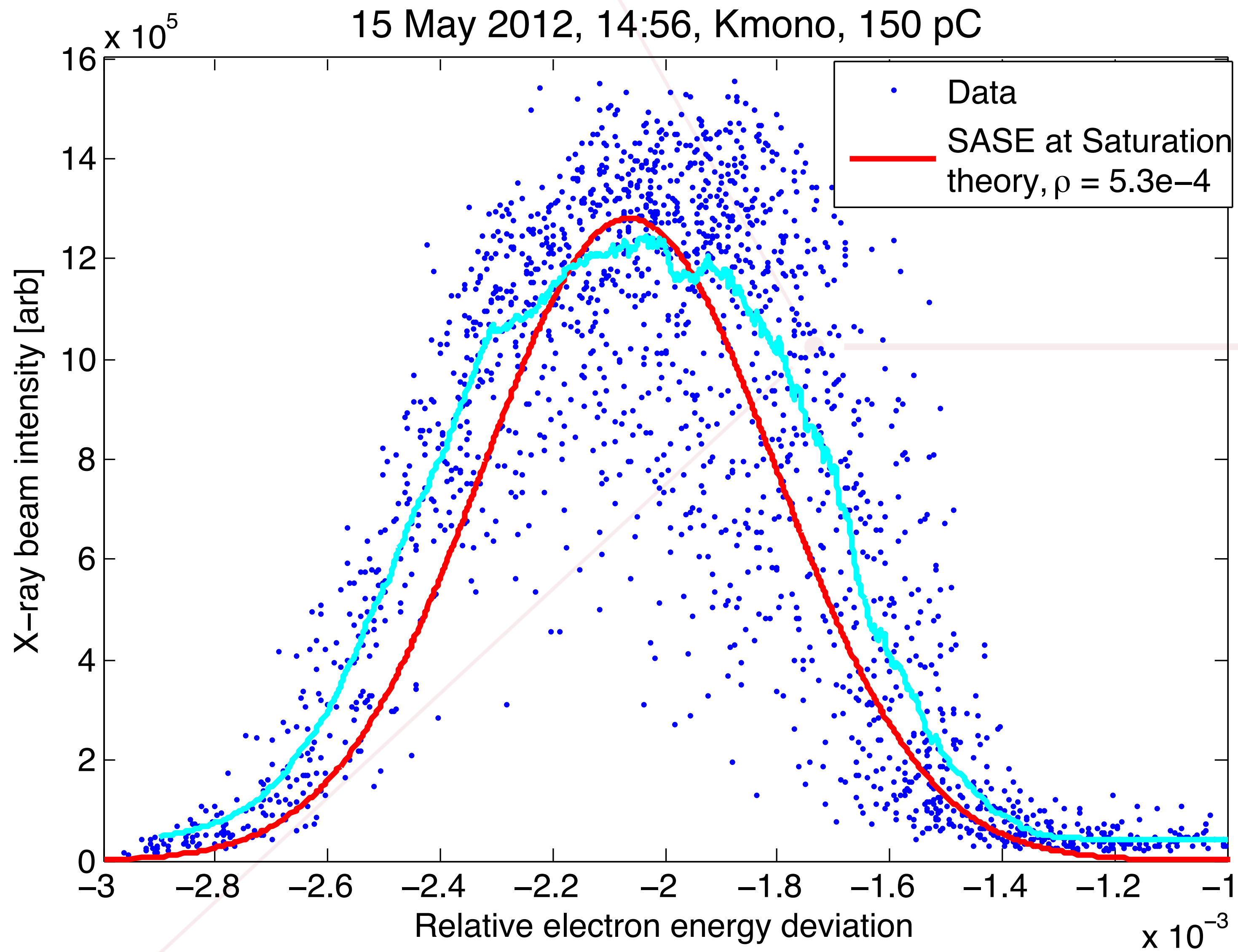
$$\sigma_u = \bar{u} = u_0$$

- Seeded monochromatized pulses have lower pulse energy fluctuations.



Electron Energy Jitter Measurements

- If only shots within ρ/2 of the peak is included, intensity fluctuations are reduced from 71% to 21% and average intensity doubles.
- Typical electron energy jitter is of order ρ. We want it to be less than ~ρ/2.
- This data was taken with relatively long pulses ~ 50 fs and 150 pC.



Bunch Length

- Original design, short pulse ~5 fs, optimizes around 20 fs delay
- We found long pulses 40 fs, 150 pC, optimize well around 25-30 fs delay.
- Long pulse theory* qualitative agreement with observation

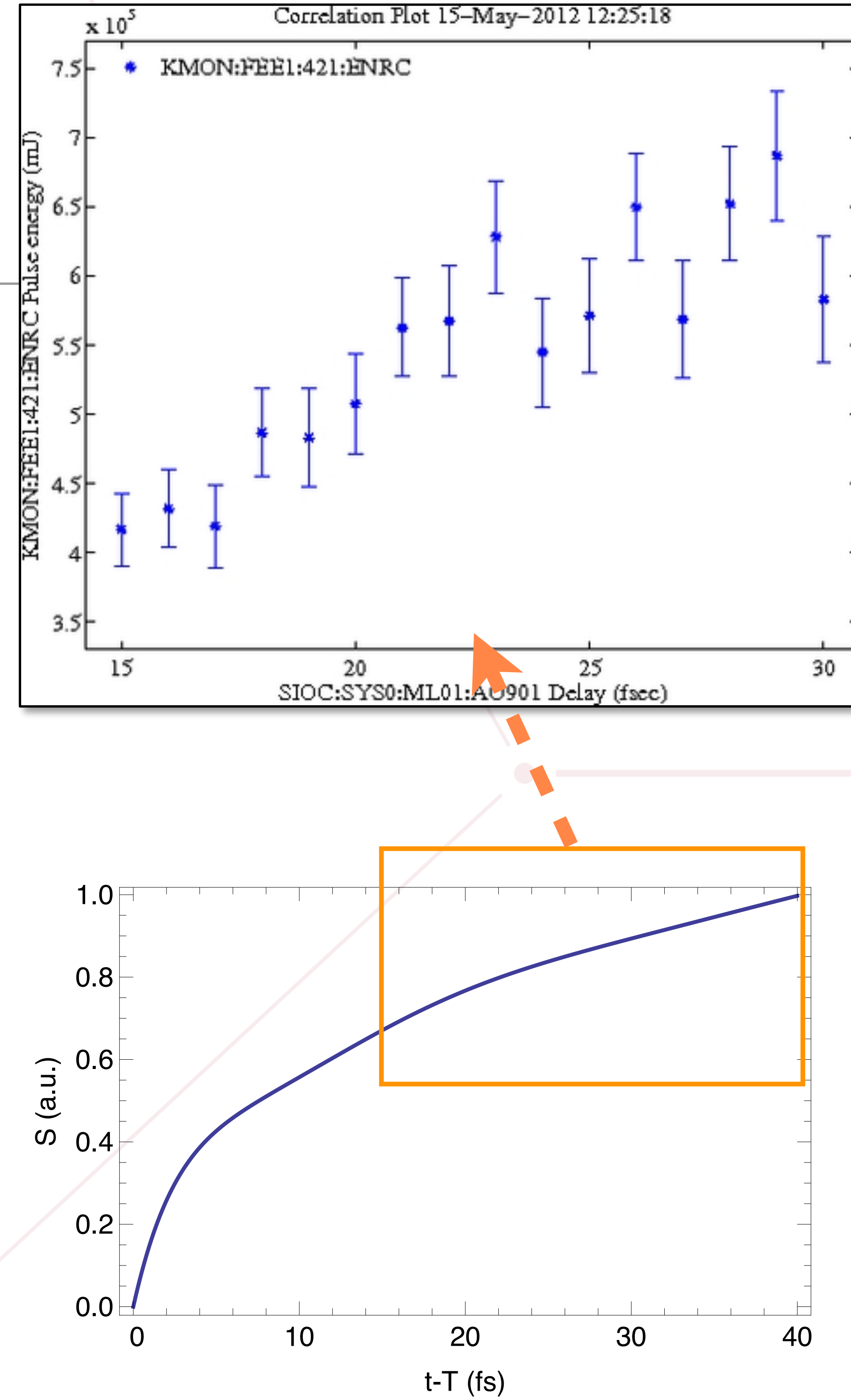
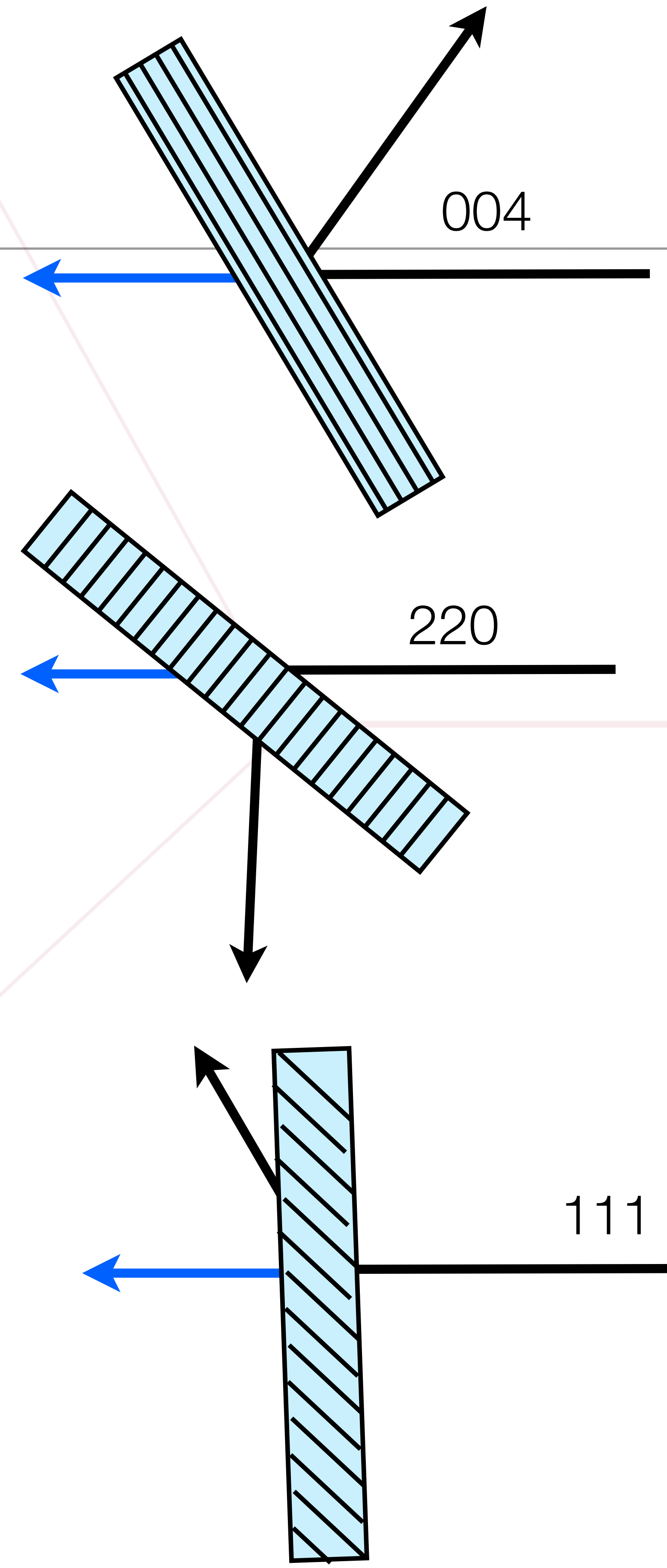


FIG. 3. Integrated seed powere (in arbitrary units) versus the overlapping time.

* G. Stupakov, “HXRSS for long bunches”, informal note, May 31, 2012

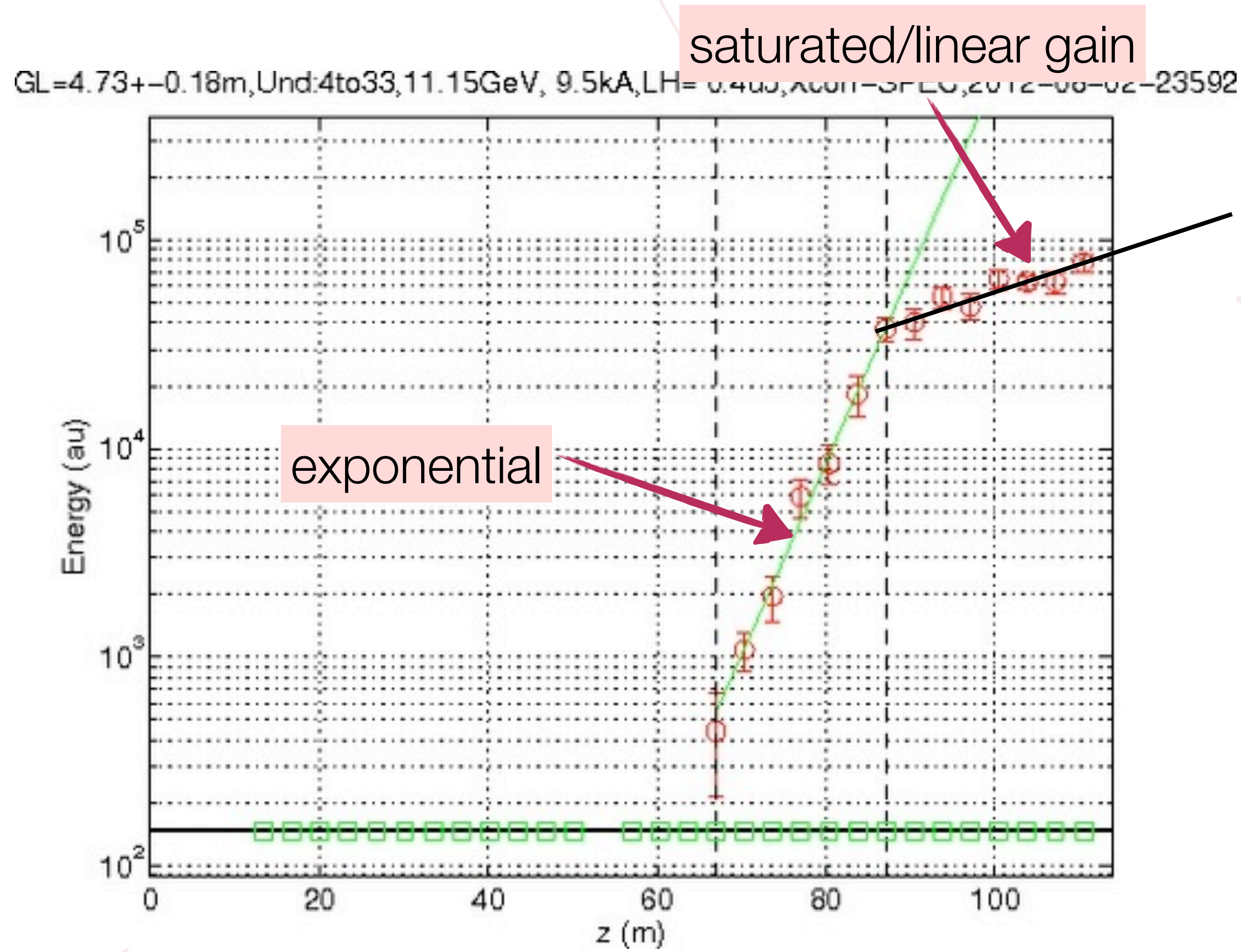
Bragg and Laue Reflections

- Original scheme: Bragg 004 reflection. Only one axis of crystal rotation available over significant range.
- Y. Schvydko suggested 220 Laue (forward Bragg reflection)
- Other reflections work too: e.g 111 reflects out of plane of paper
- Net result: more bandwidths and wavelength are accessible.

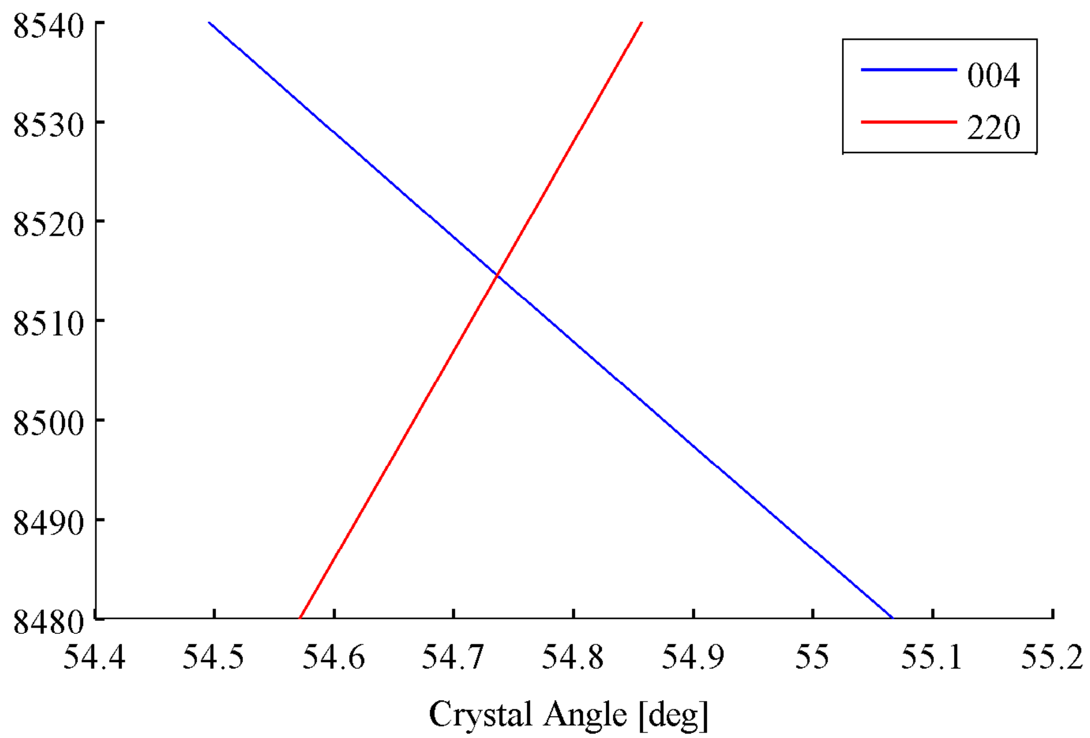


5.5 keV Studies Using 111 Plane

- Lower energy leads to shorter gain lengths and makes deeper taper and saturation studies possible.
- Very preliminary gain curve measurement shows saturation in last 7 segments.



Two-color Seeding



Photon energy versus crystal angle for 004 (Bragg) and 220 (Laue) reflection

Tune machine energy for photon energy to match 004/220 intersection, then scan the crystal angle.

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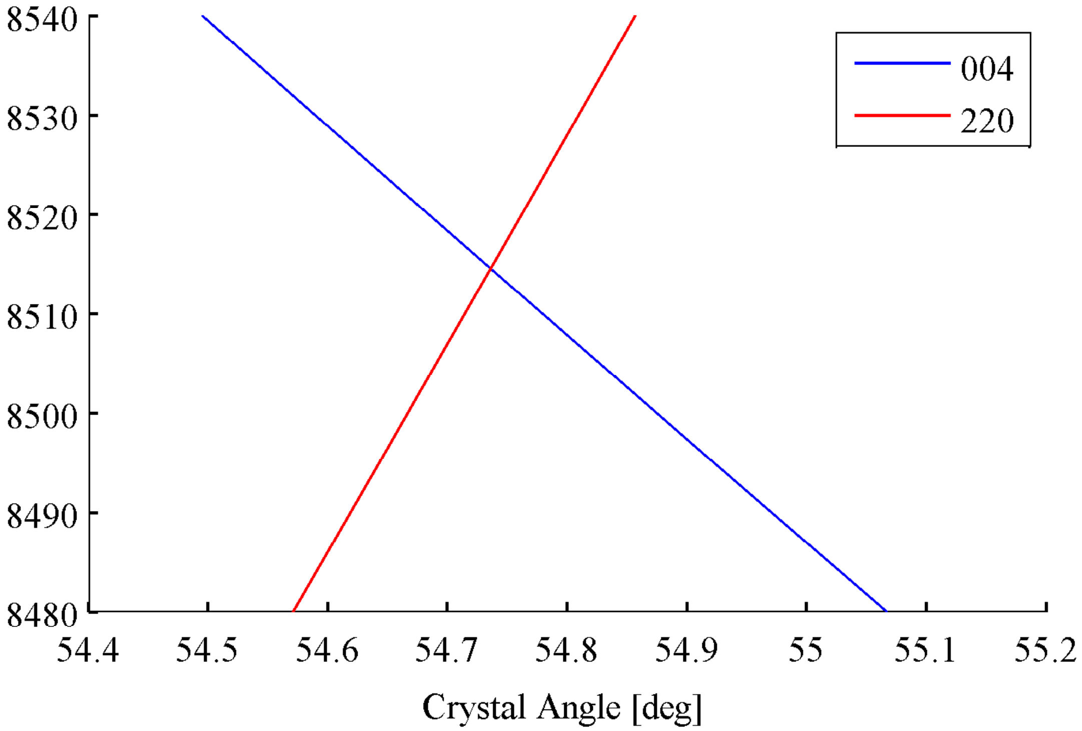

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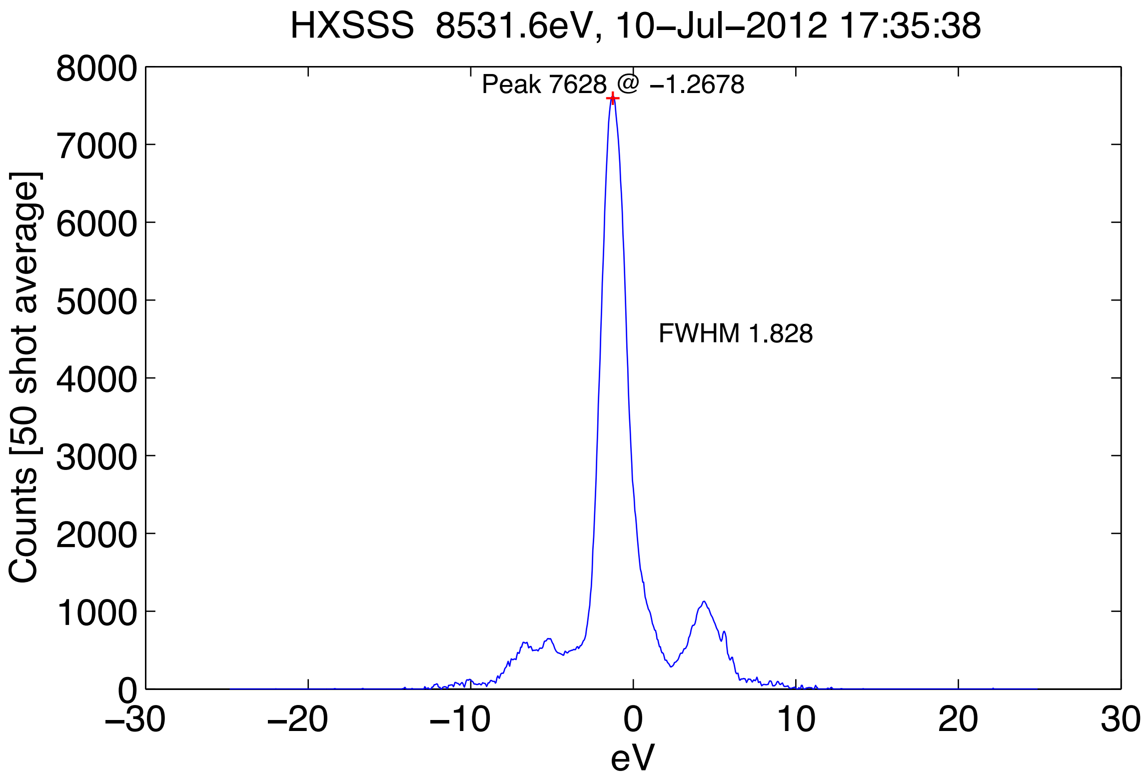

automatic peak finder tracks peak as Crystal angle is scanned

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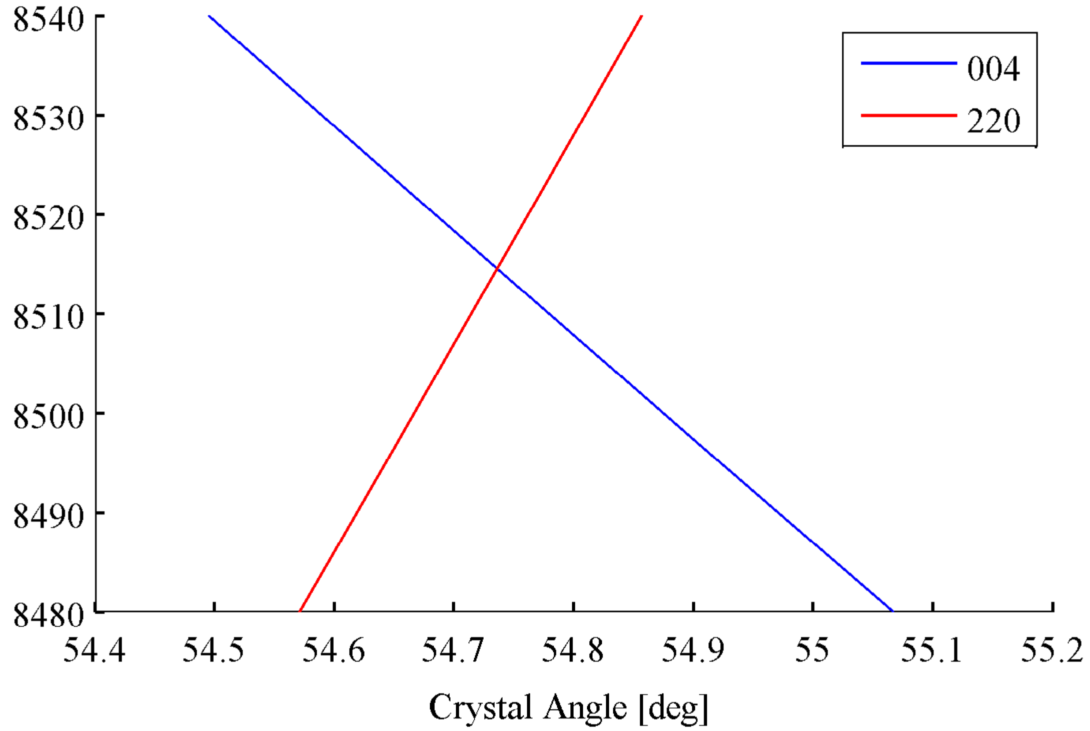

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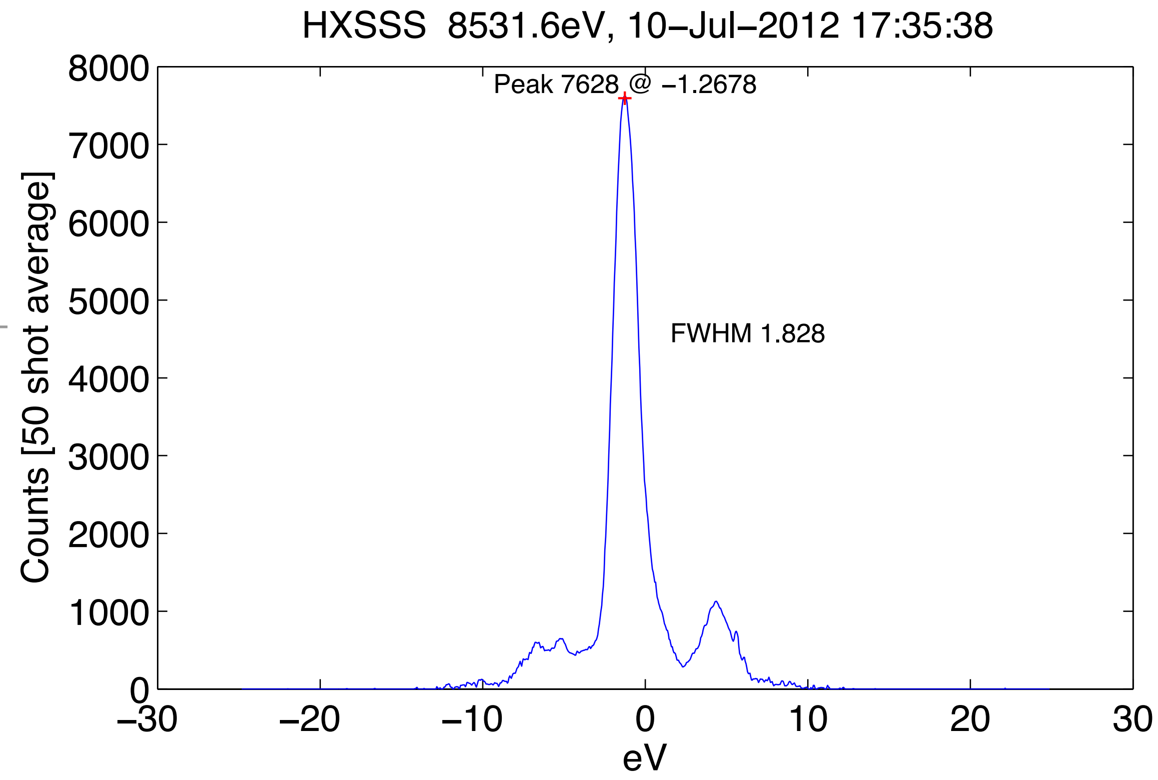

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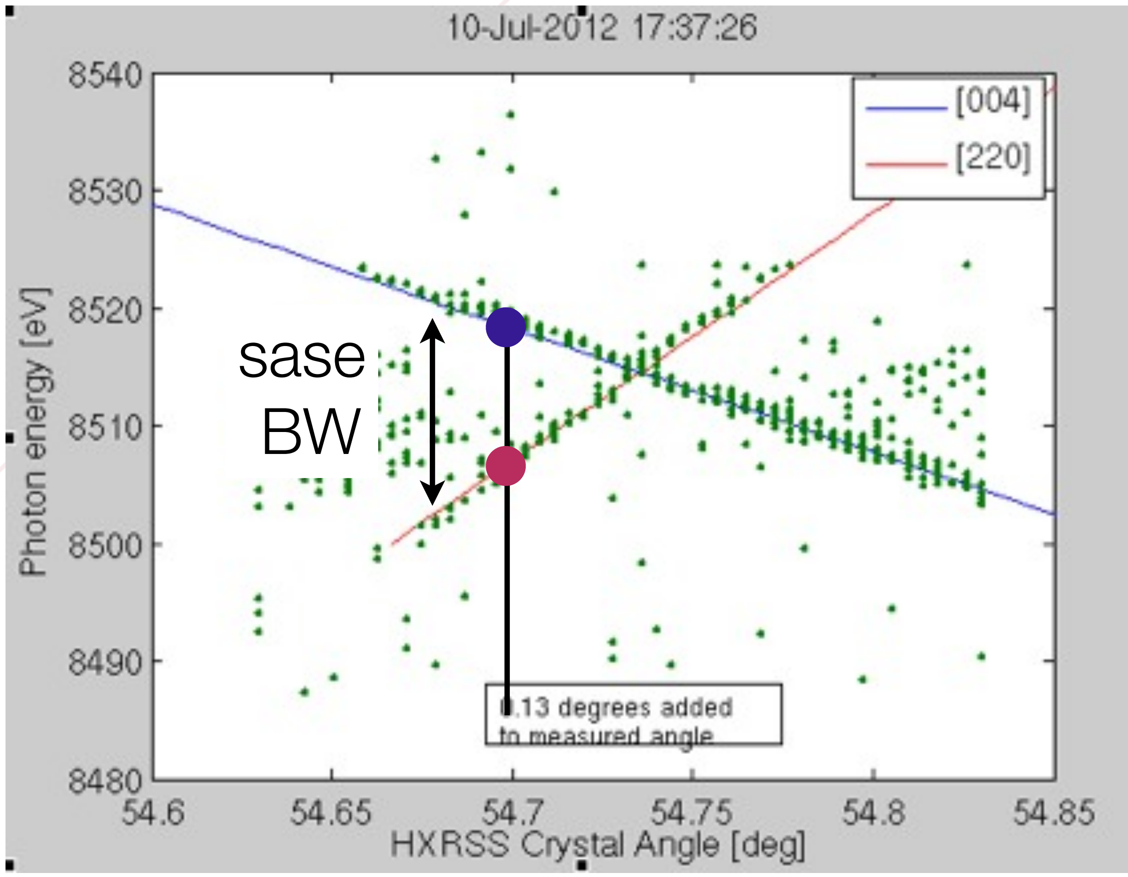
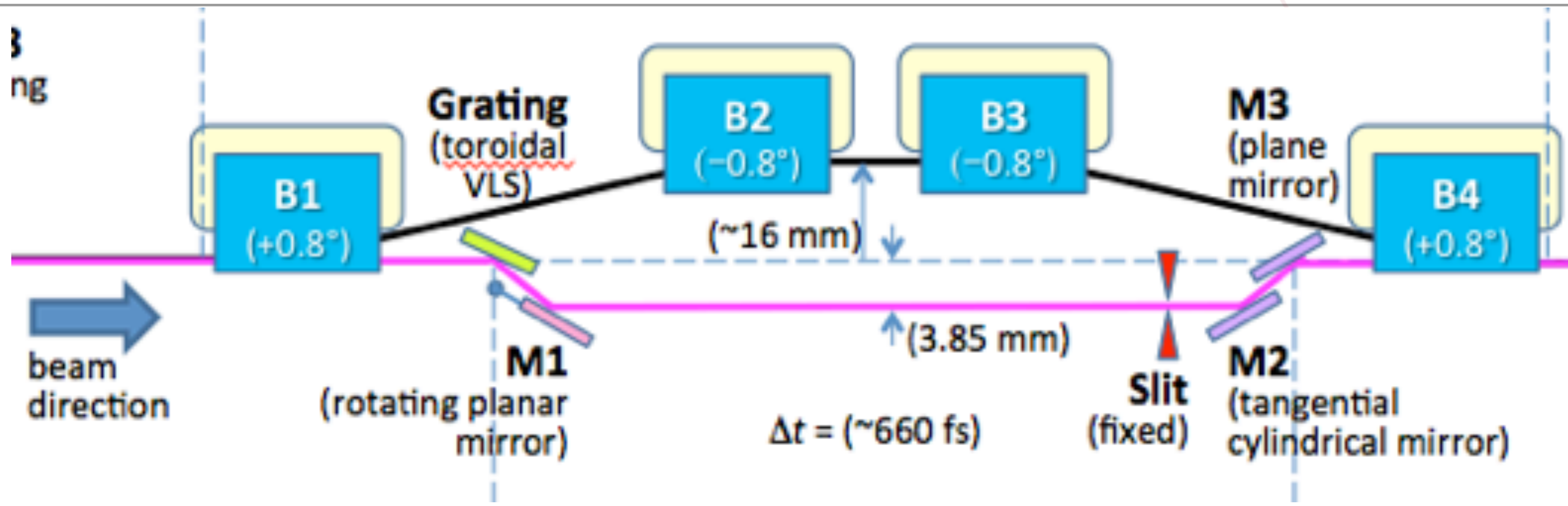
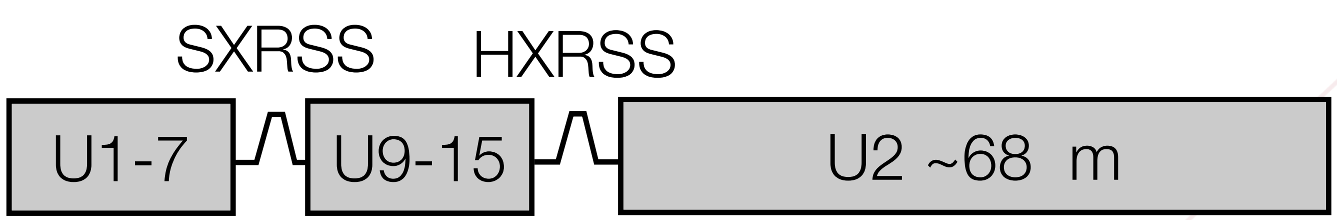


Next Steps: Increase Spectral Brightness

- Reducing electron energy jitter
  - Quickly identifying particular klystrons and removing or adjusting them
  - Optimizing feedback circuits
  - Optimizing the compression ratio at BC1/BC2
  - Developing more stable modulators
  - With lower electron energy jitter, other parameters can be better optimized
- Unofficial Near-term Goal >~ 1 mJ average seeded pulse energy , < 20% rms/ average intensity fluctuations, 15 minute tune-up.
  - higher charge? more taper?
- Longer term: Deeper and longer taper, pulse compression
  - Systematically replacing last segments with retuned segments matched for deeper taper.
  - Move the seeding chicane upstream by two segments
  - Plans for adding up to 5 more segments
  - X-ray pulse compression using chirped seeded beams? (Bajt et. al. J. Opt. Soc. Am. A / Vol. 29, No. 3 / March 2012.)

. . . and Soft X-ray Self-Seeding





- 500-1000 eV, BW 2×10^{-4}
- Grating used to generate dispersion
    - X-ray mirrors to get beam back on axis
    - Delay up to 1000 fs needed.
- Fit is same length space as HXRSS (~4 m)
- Dipoles (< 7 kG) quite reasonable (lower energy helps)
- SLAC, LBNL, PSI collaboration. Near design completion.

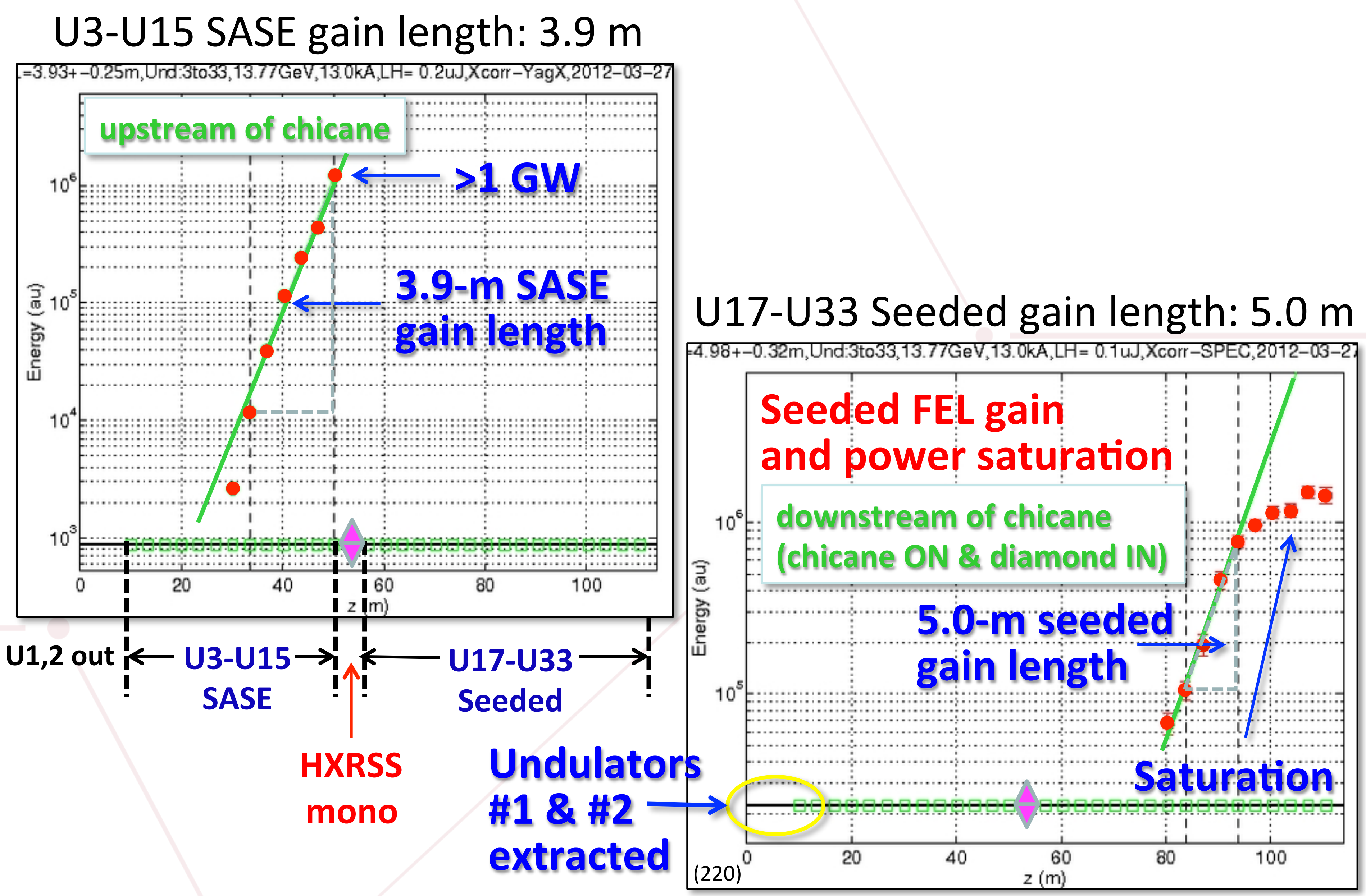
Summary

- Seeded operation can provide monochromator users at least 3 times more intensity than SASE operation, with somewhat reduced intensity fluctuations.
- Since initial commissioning, brightness has increased and fluctuations are decreased mainly through the use of higher charge longer bunches, and better tuning. There are good prospects for increasing the average brightness further.
- New seeding ideas are always welcome.

. . . the end

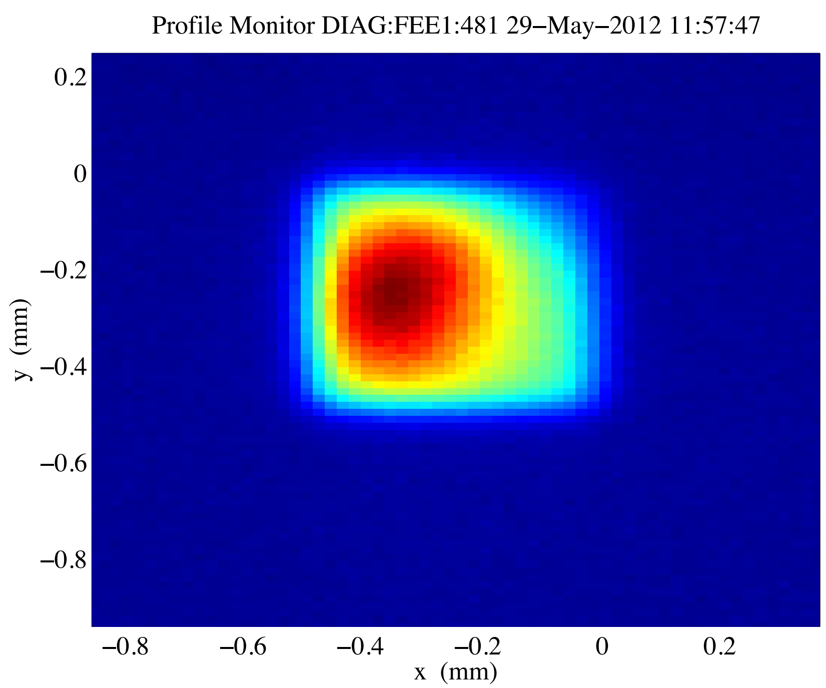
Seed Power

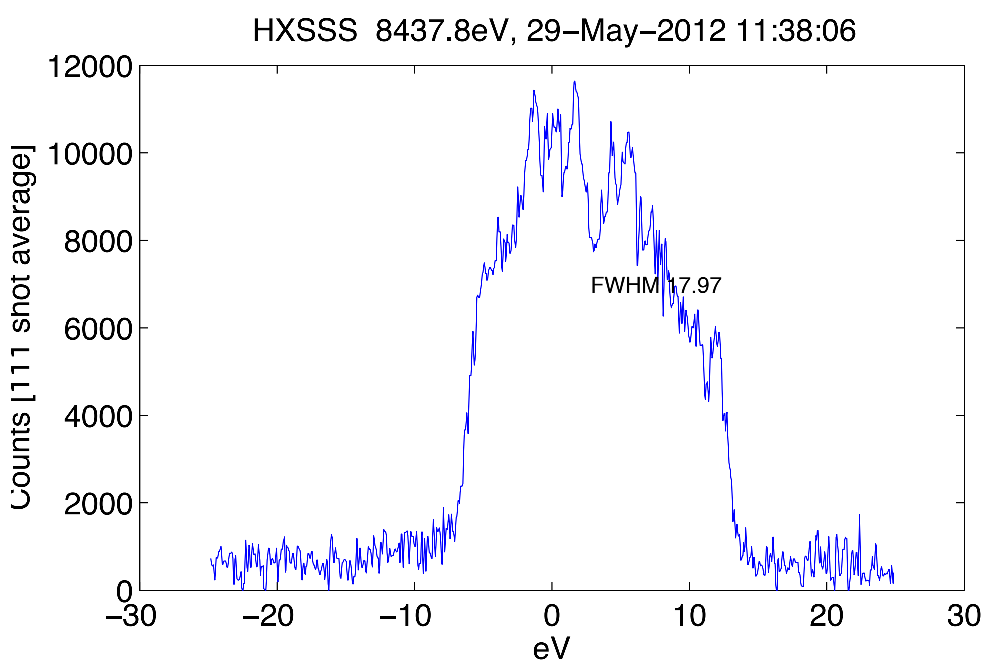
- Generating seed power also generates energy spread and degrades beam quality
- Too much seed leads to excess SASE power and lower peak spectral brightness
- 12-13 segments is optimum



Spectrometer and Slit Effect on SASE Spectrum

0.5 x 0.5 mm slit





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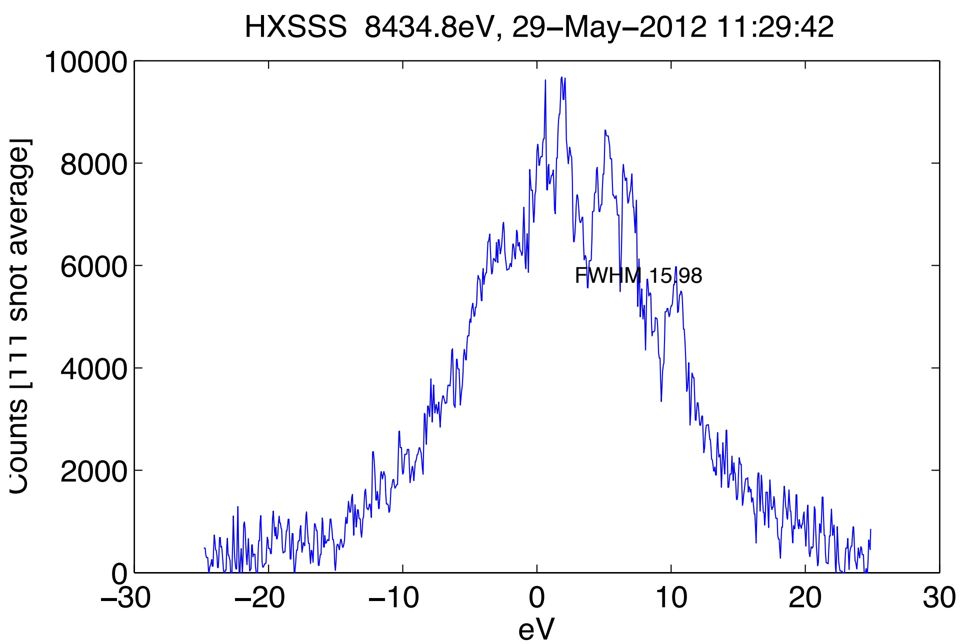
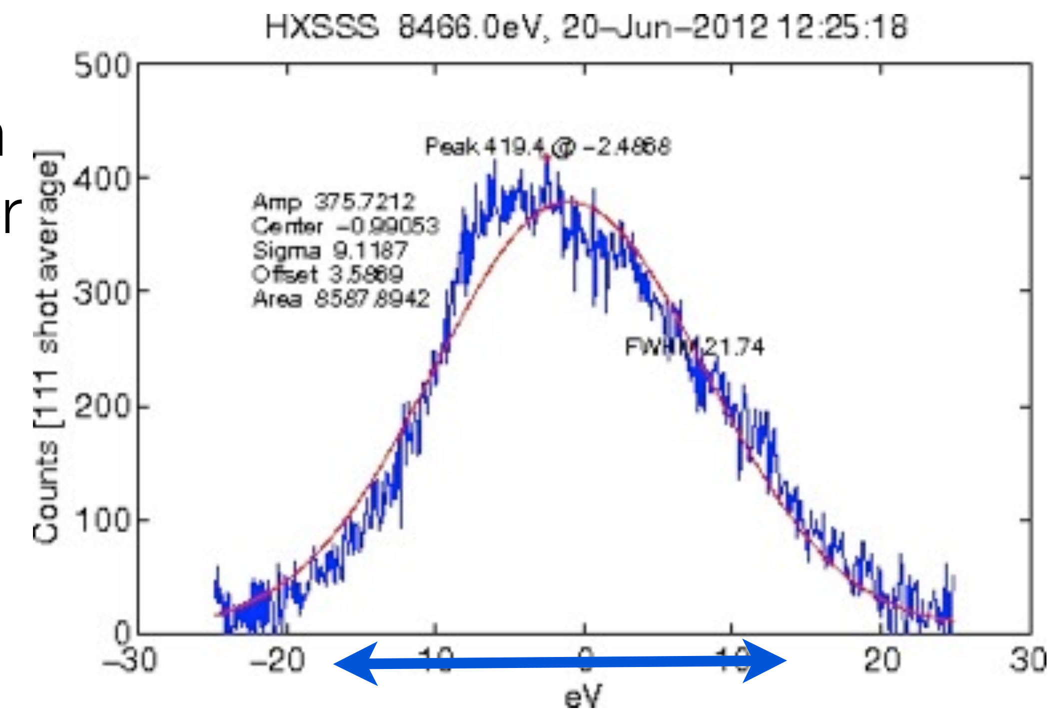


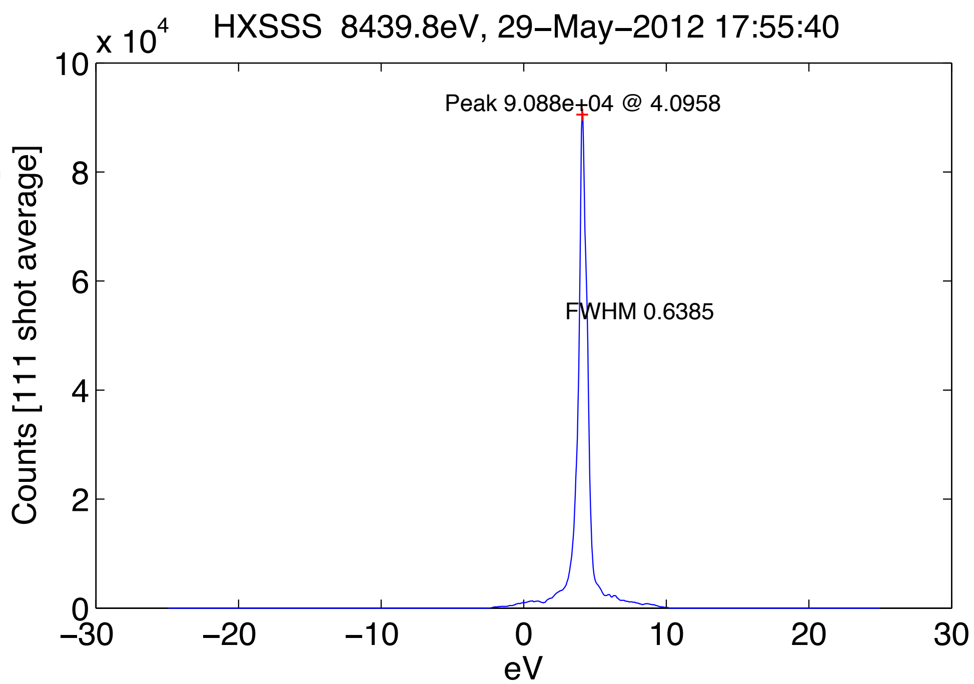
0.5 x 2.0 mm slit

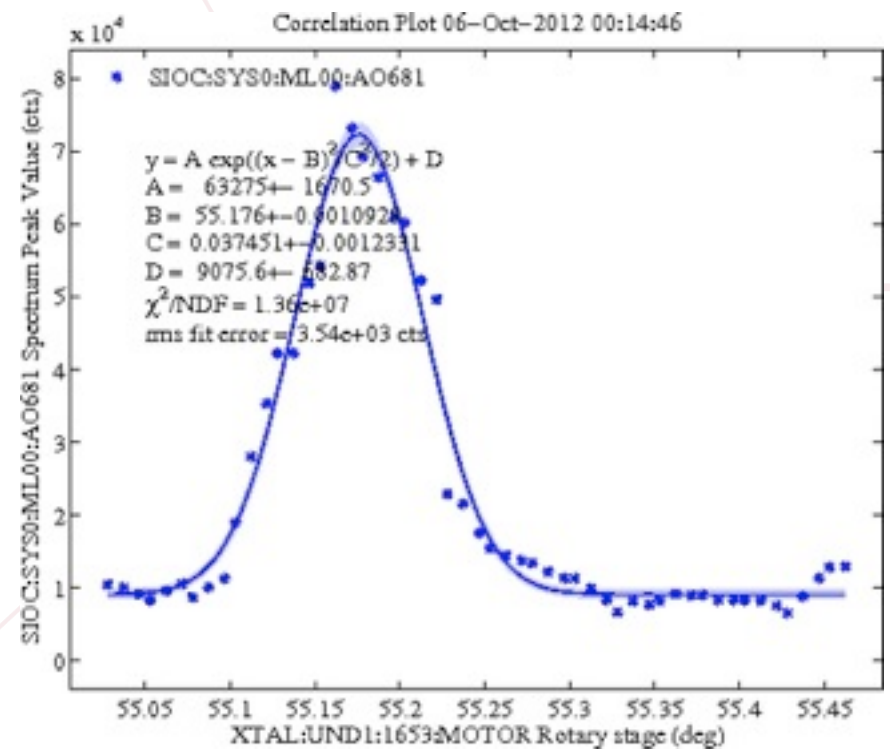
Tuning Example

1. Adjust beam energy to center SASE on spectrometer



2. Continuously measure peak spectral density





3. Fine tune crystal angle to maximize peak spectral density

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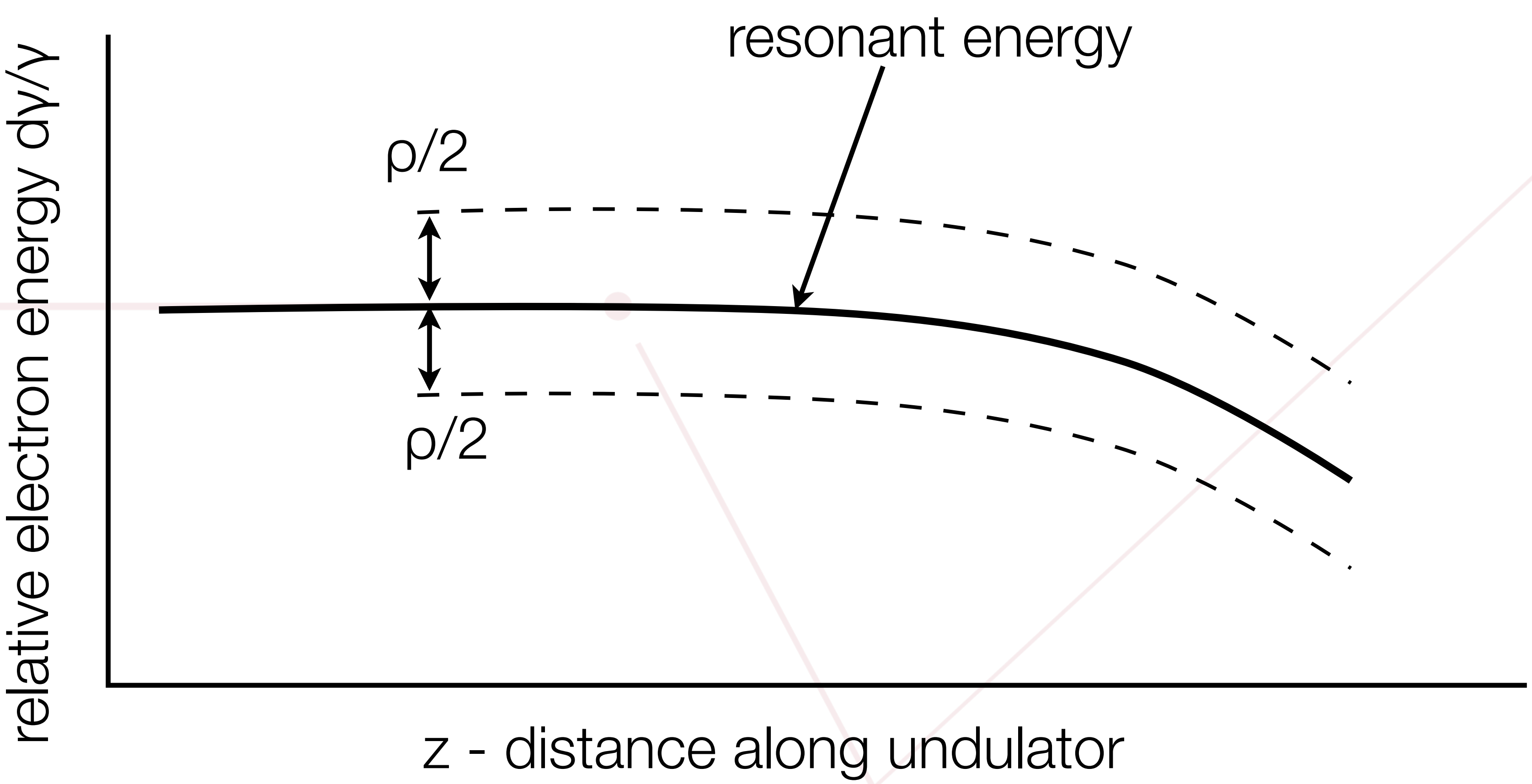
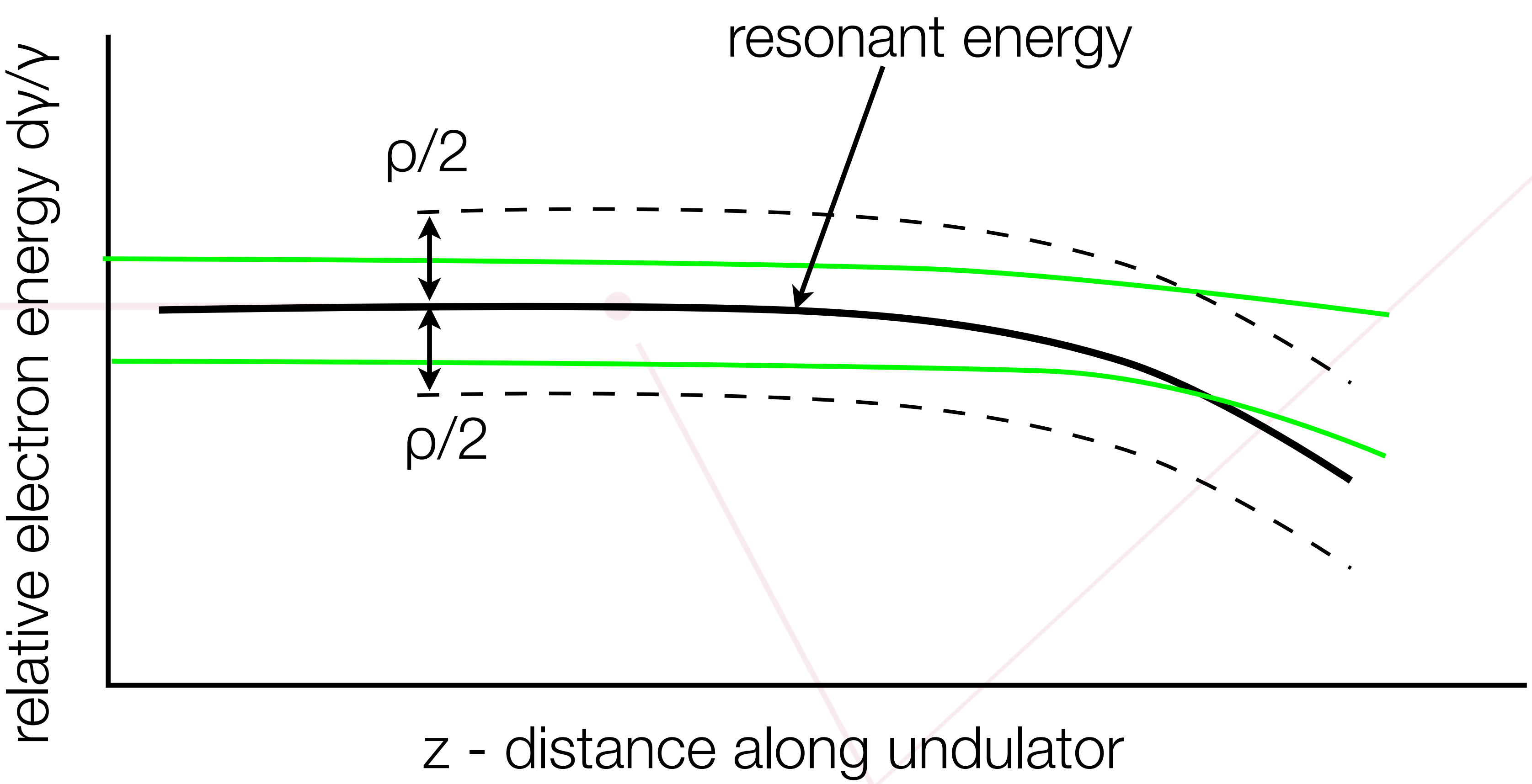
Electron Energy Jitter: Gain Length Fluctuations

- A taper is applied to the undulator to match the resonant energy with electron beam energy which is decreasing along the undulator.



Electron Energy Jitter: Gain Length Fluctuations

- A taper is applied to the undulator to match the resonant energy with electron beam energy which is decreasing along the undulator.
- Only shots with energy within about ρ/2 of the resonant energy will have good gain at seeding wavelength. ρ is the FEL Pierce parameter and is typically 5-6 x 10^{-4}. The rms bandwidth at saturation is typically ρ.



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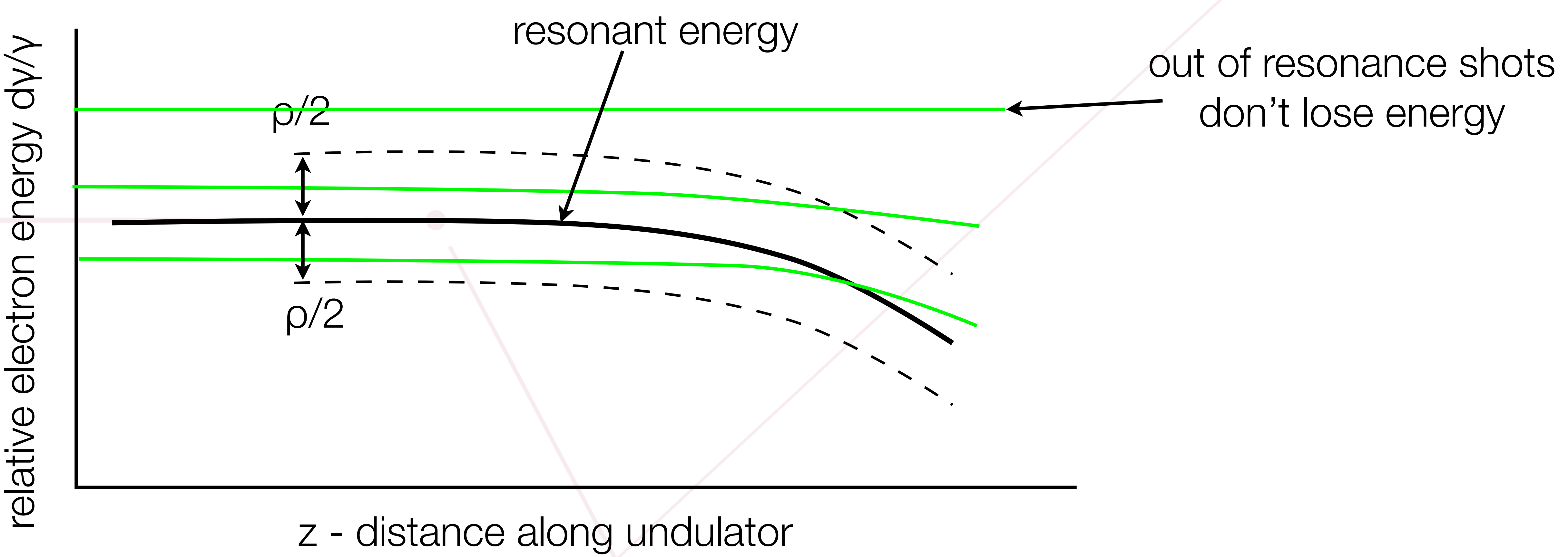

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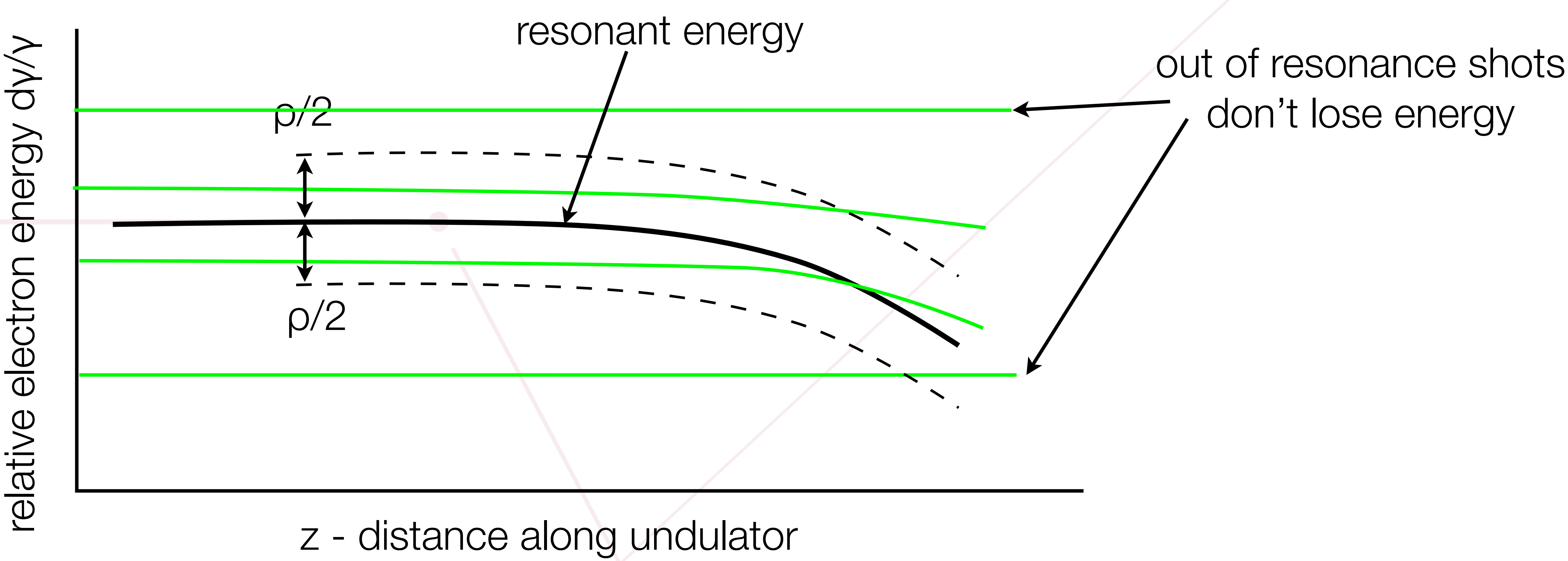

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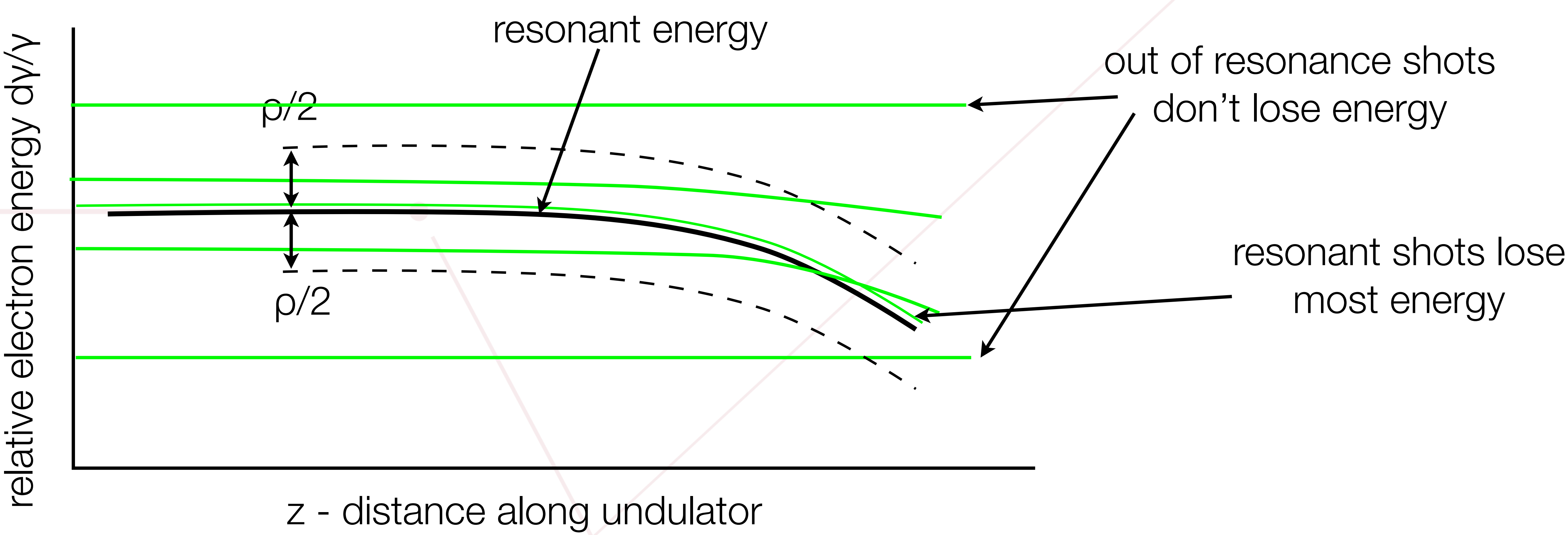
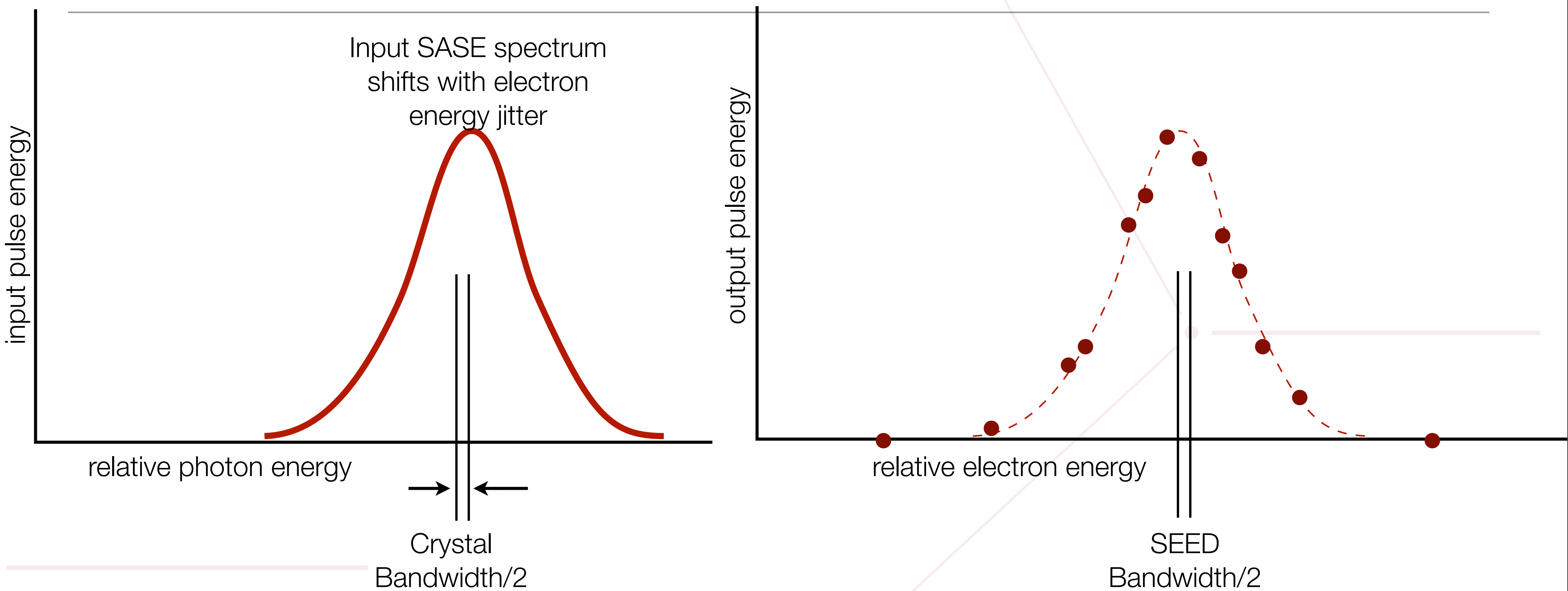
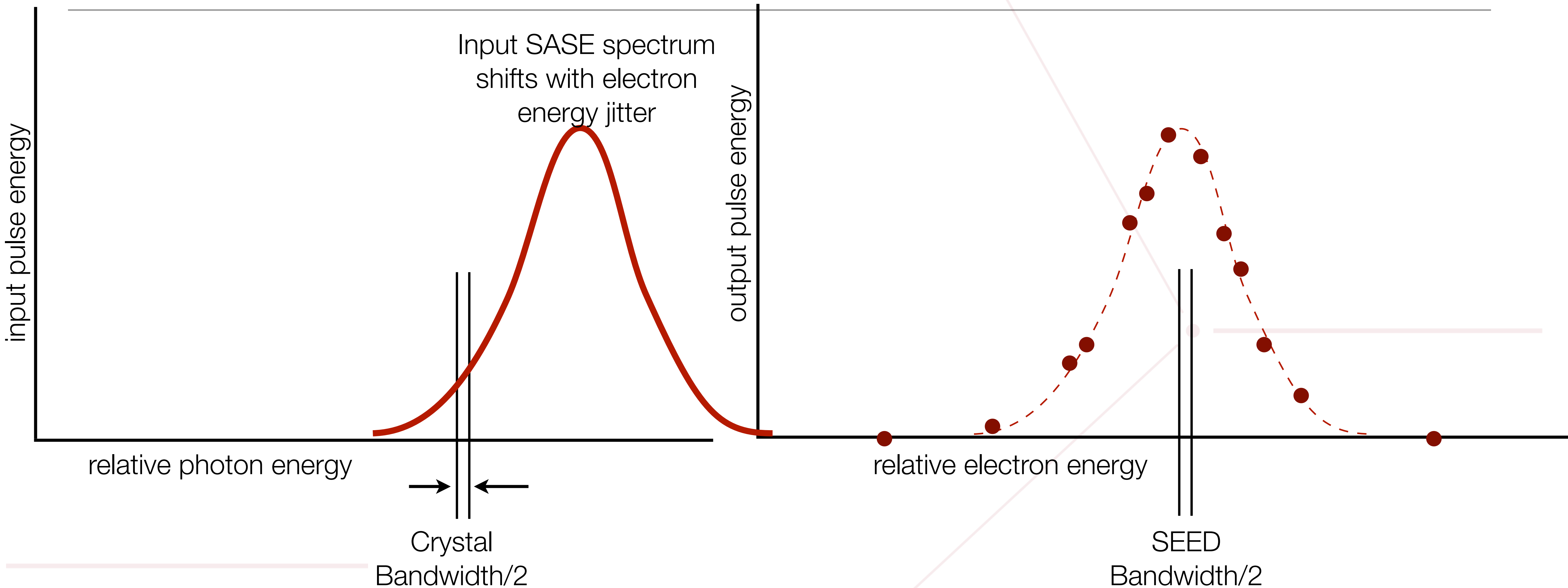


Electron Energy Jitter: Seed Power Fluctuations



Jitter induced seeding power fluctuations depend on the ratio of jitter to input SASE bandwidth.

Electron Energy Jitter: Seed Power Fluctuations



Jitter induced seeding power fluctuations depend on the ratio of jitter to input SASE bandwidth.

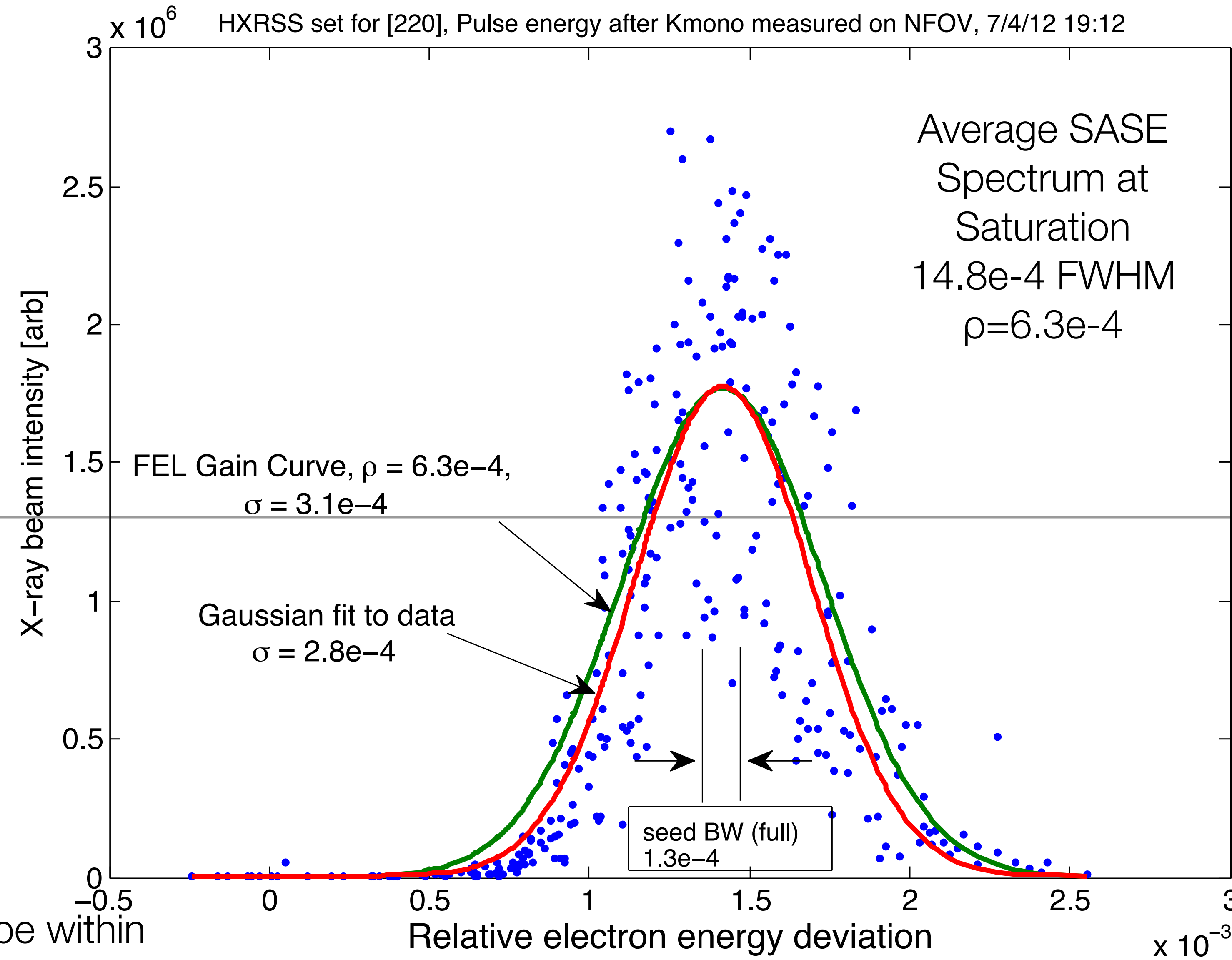
- At saturation the rms bandwidth is expected to be about ρ, the Pierce, parameter.

Seed BW is approximately rectangular

adding seed BW/2 with FEL Gain in quadrature gives 2.9 e-4 --- in agreement with measurement.

Kmono BW is 1.5e-4 (full)

Intensity is measured at end of LCLS after seed is amplified.

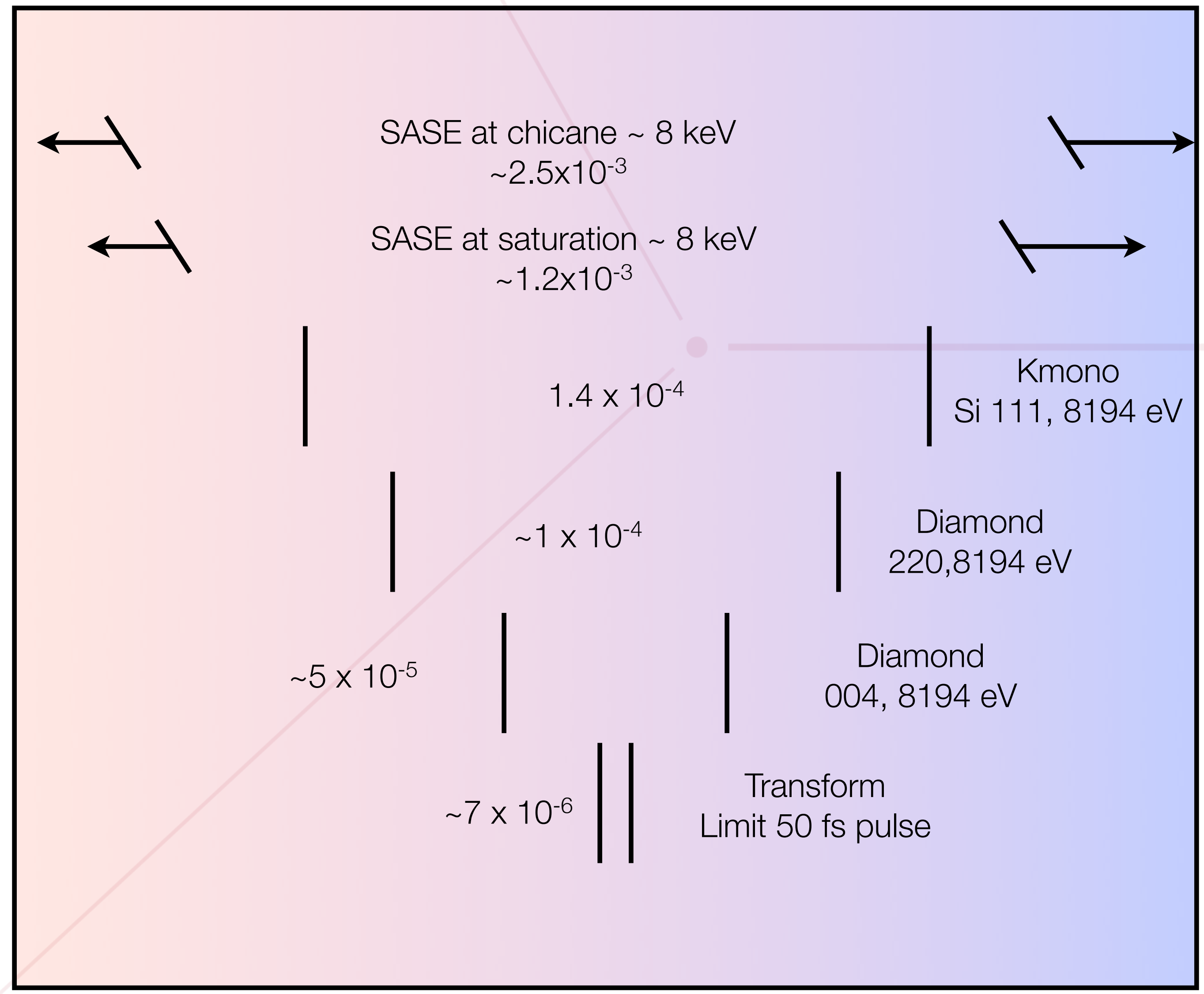


The relative energy of the electron beam must be within about ρ/2 for effective seeding. If the resonance wavelength is too far from the seeding wavelength, the emitted sase won't reinforce the sase already present and gain will suffer. That is why we observe the relative width of the intensity when plotted against the relative electron energy is about rho/2.

Theoretical SASE spectrum at saturation point follows exp(-0.5*(ephoton/rho)^2); expressed in relative electron energy deviation, is half as broad.

Relative Bandwidths

- Kmono BW is much less than SASE, but substantially more than the seeded beams.
- Bandwidth of SASE at saturation is expected to be ~ ρ RMS and higher before saturation.
- Bandwidths of seeded beam are approximate.
- SASE spectra shift with the square of the electron beam energy.



Relative bandwidths: FWHM

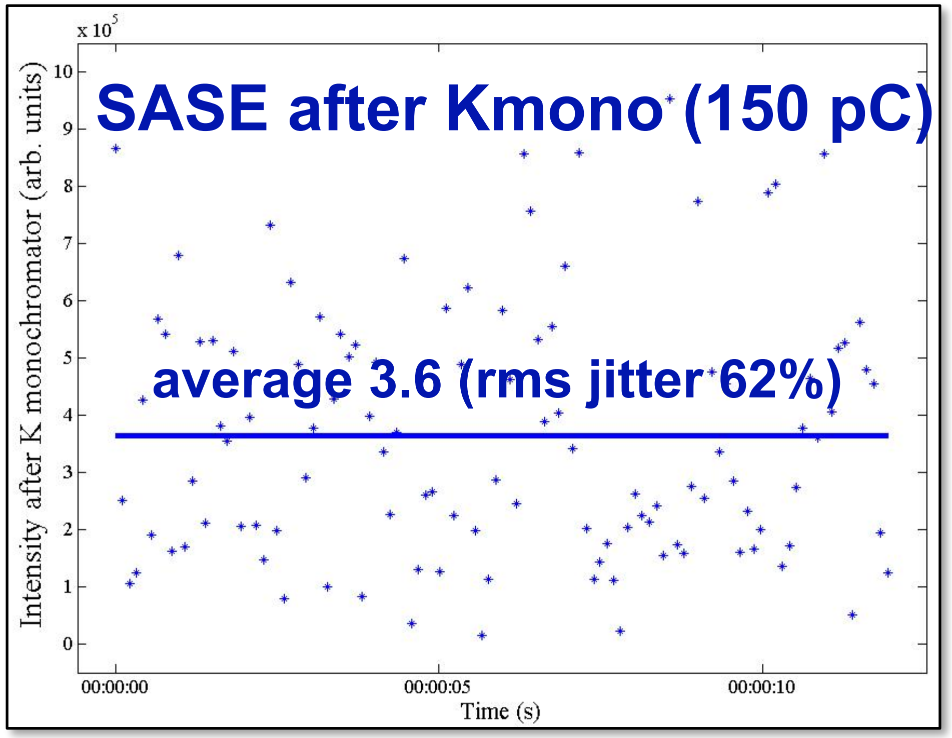
Ultimate Range of Performance

- Operational range is generally smaller than given in the table.
- Quoted range is limited by the crystal angular range 47 to 93 degrees, and machine energy.

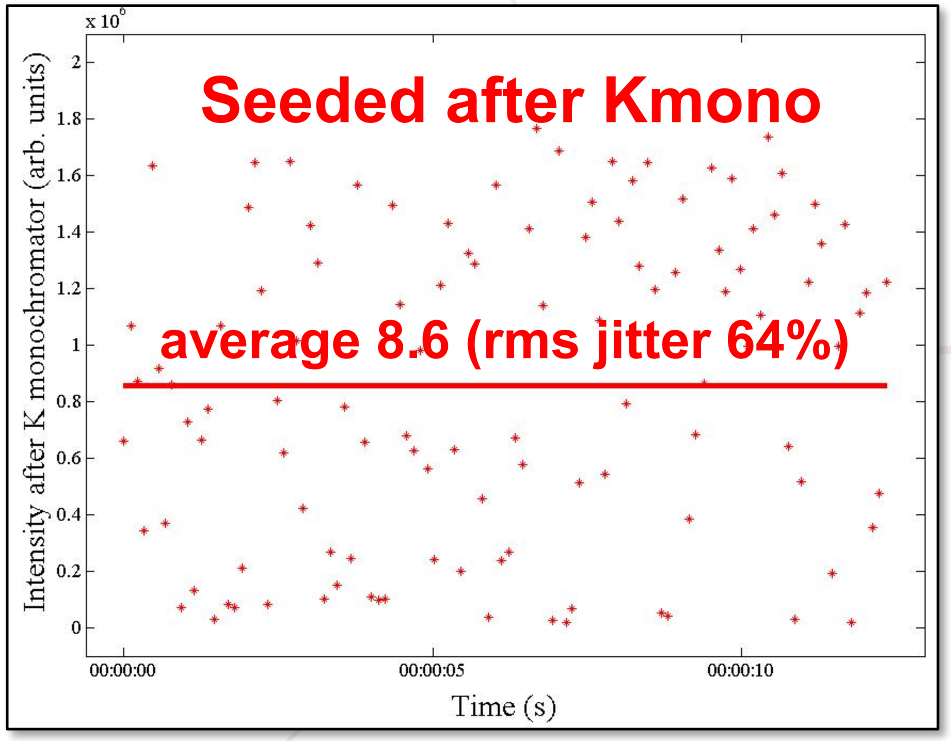
Plane	Min eV	Max eV	FWHM (relative,theo)
[004] design	7000	9505	2.20E-05
[220]	7208	~10,000	2.70E-05
[111]	4861	~10,000	6.60E-05

Seeded vs. SASE intensity after a narrow-band mono

SASE 2 mJ after K-mono (1eV BW @8 keV) Solid attenuator 6, 8, 9 in, foil 9 in



Tuned seeded (U1-2 out) after K-mono Solid attenuator 1-6, 8, 9 in, foil 9 in



Adjusting for the additional attenuation of the seeded beam (8.6/0.7=12.3), its intensity is **3.4 x SASE**.

J. Welch et al., to be presented at FEL2012