Comparison of Hard X-Ray Self-Seeding with SASE after a Monochromator at LCLS

J. Welch

FEL2012, August 26-31, Nara, Japan

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

  R. Lindberg, Y. Shvydko, A. Zholents

- DESY/XFEL

  G. Geloni, E. Saldin

- LBNL

  P. Emma

Topics

- Seeding and SASE Operation at LCLS
  - motivation
  - K-monochromator
- Spectral Brightness Measurement: Seeded vs. SASE
  - brightness
  - fluctuations
  - electron energy jitter
  - prospects for increasing spectral brightness
- Recent and On-Going Developments
  - two-color seeding using 004 and 220
  - lower energy seeding with 111

Motivation for Seeding

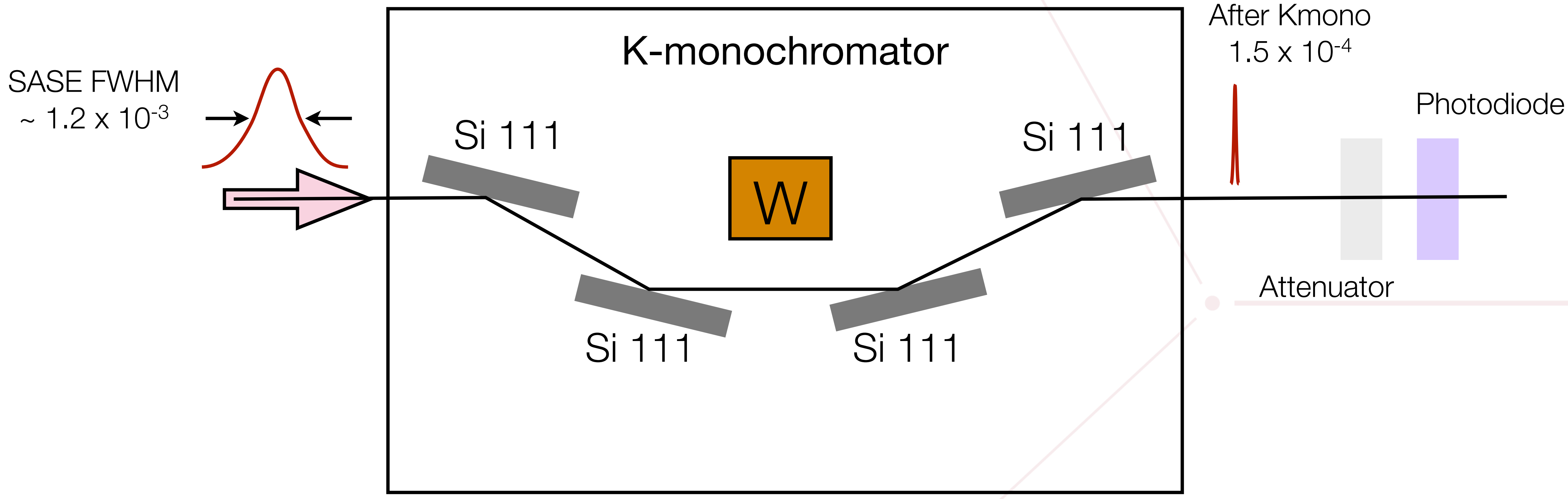
- Higher spectral brightness: Users requiring a monochromator will get more intensity.

- 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.

- Pulses have better longitudinal coherence: low $\sigma_t\sigma_\omega$ pulses make sharper probes.

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

K-monochromator (Kmono)

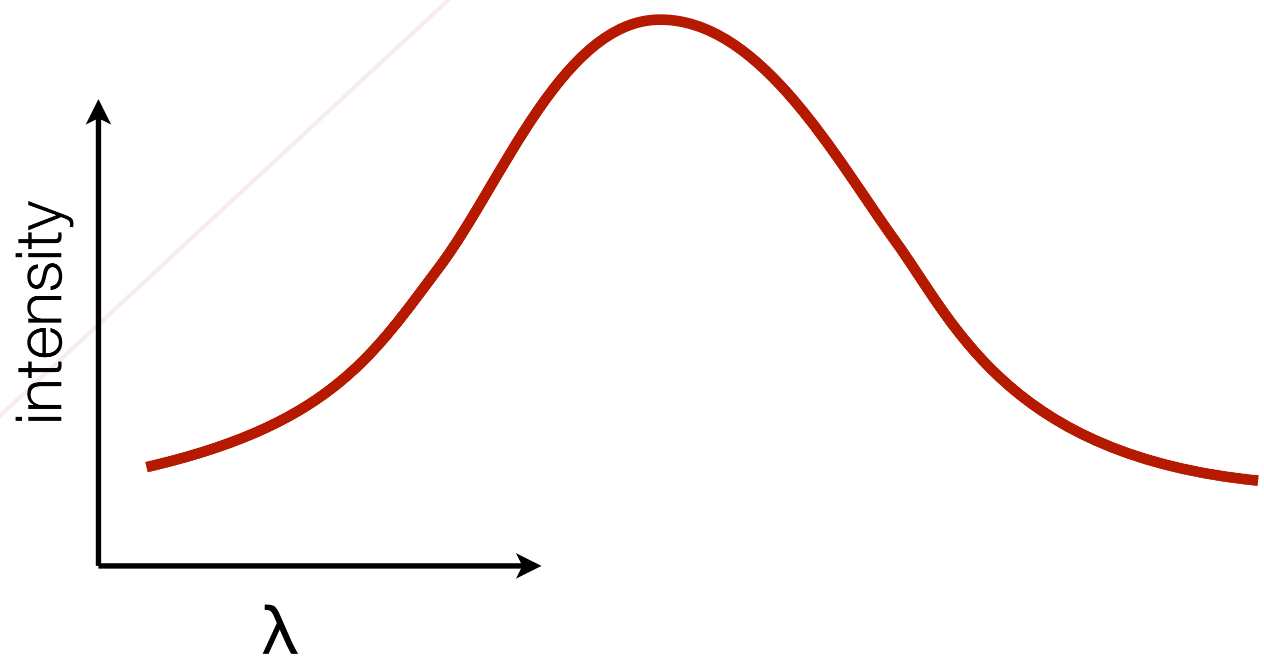


- Four bragg reflections at angle 13.965 degrees for 8194 eV transmission
- Bandwidth measured to be 1.2 eV, FWHM (1.5×10^{-4})
- Only one angle and one energy can pass
- Cleans up spectrum by removing bulk of SASE
- Photodiode provide synchronized data with wide dynamic range

Brightness Comparison Method using the Kmono

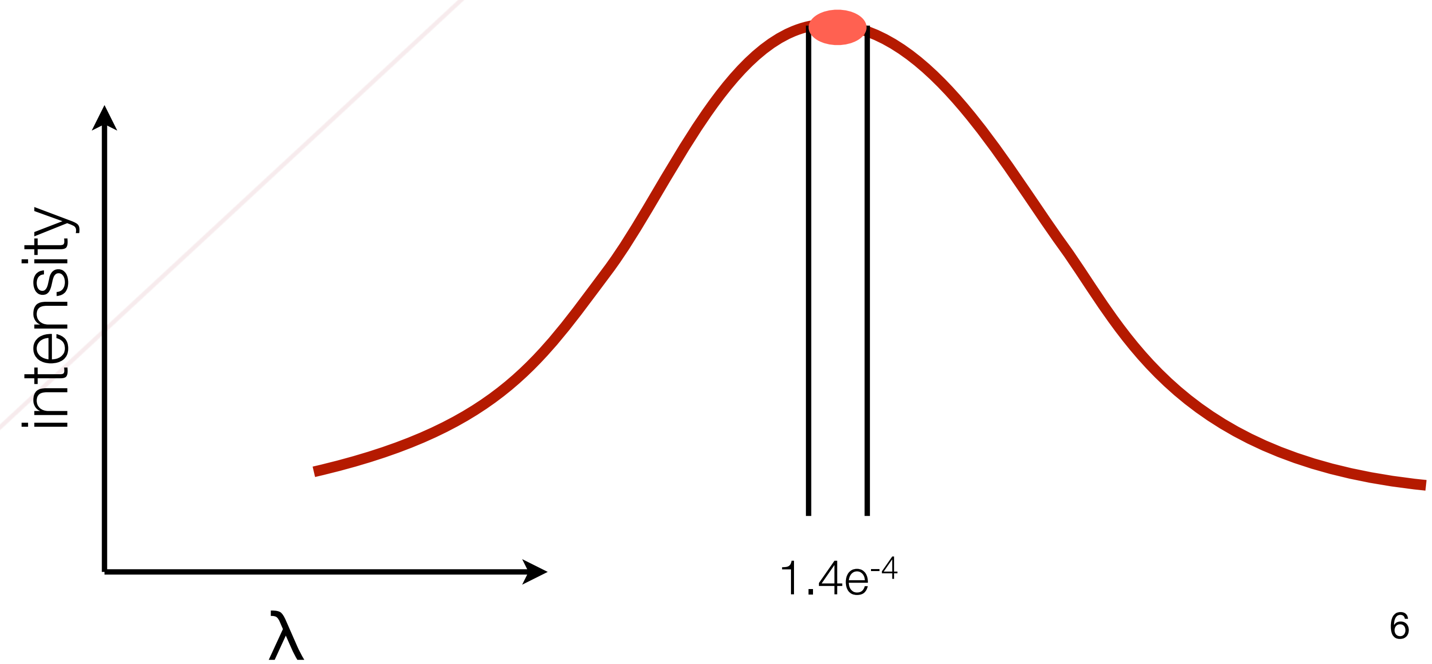
Brightness Comparison Method using the Kmono

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



Brightness Comparison Method using 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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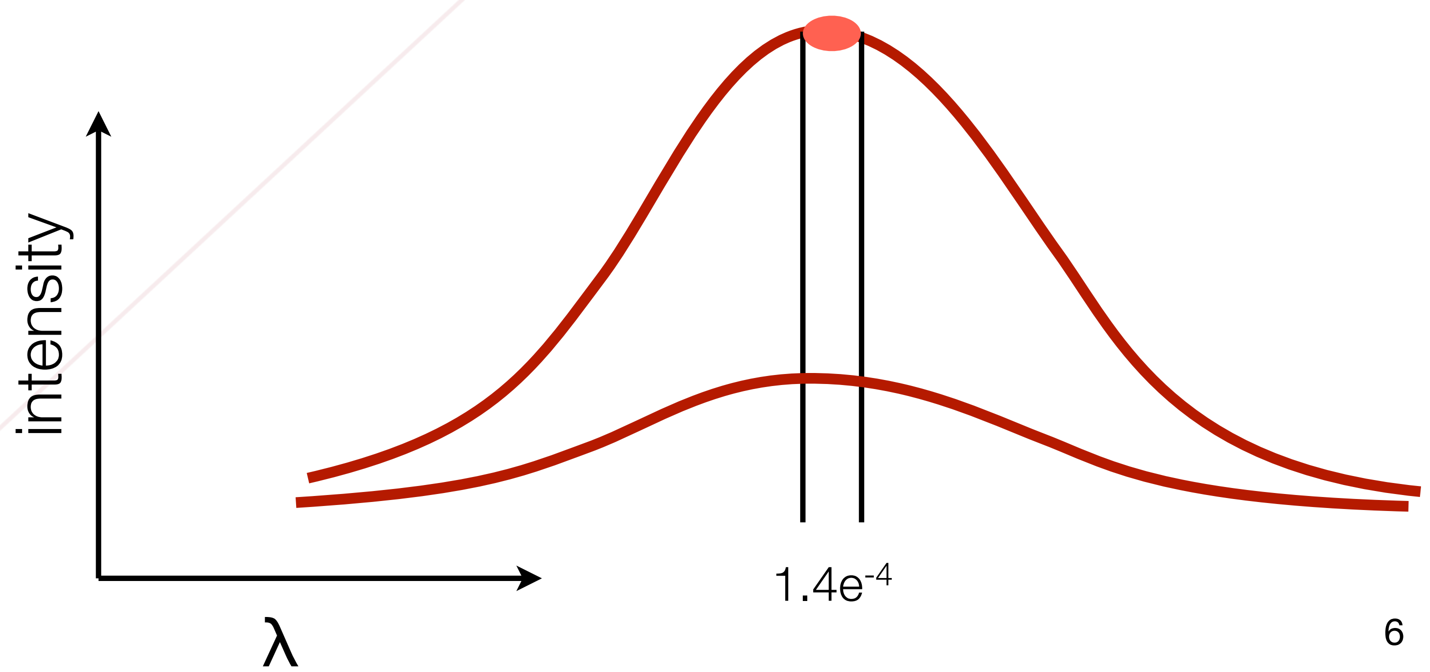
- Turn on chicane.



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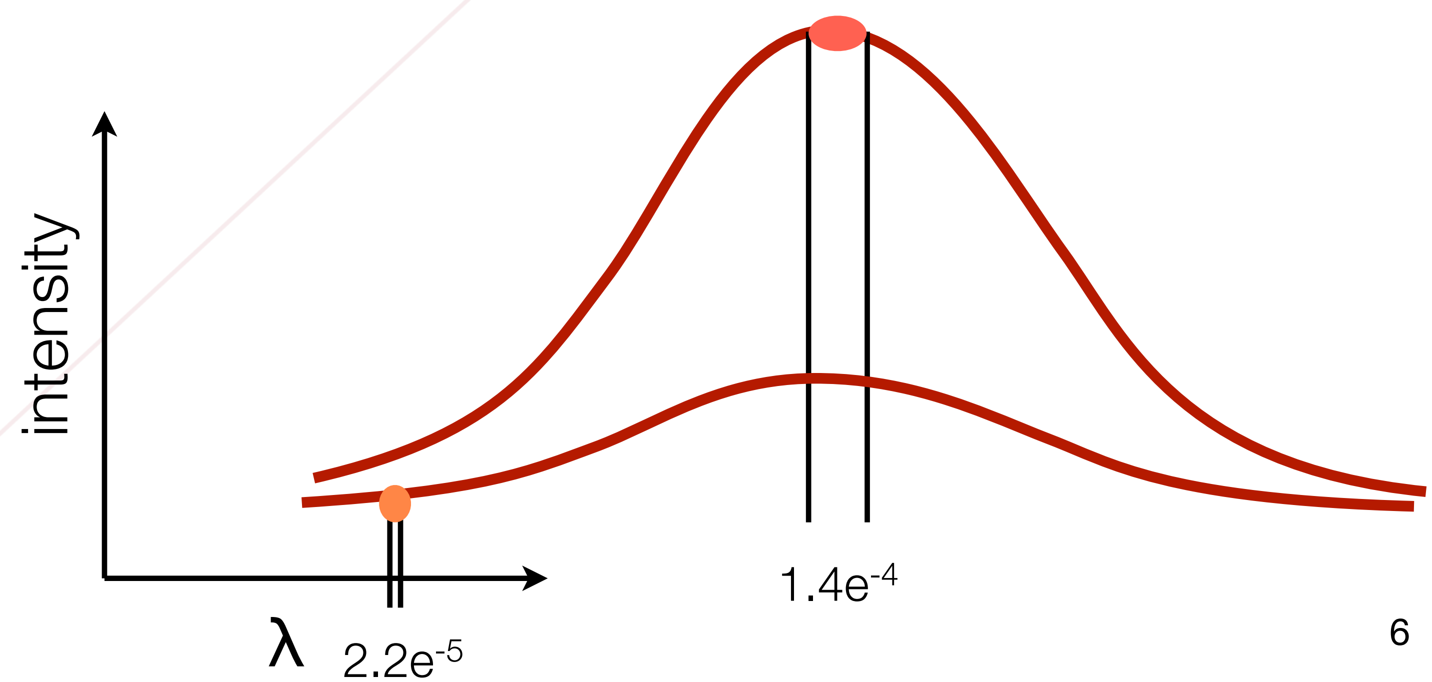
- Insert crystal and tune up to maximize the signal seen through the Kmono.



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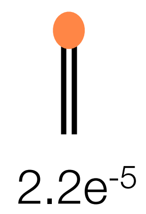

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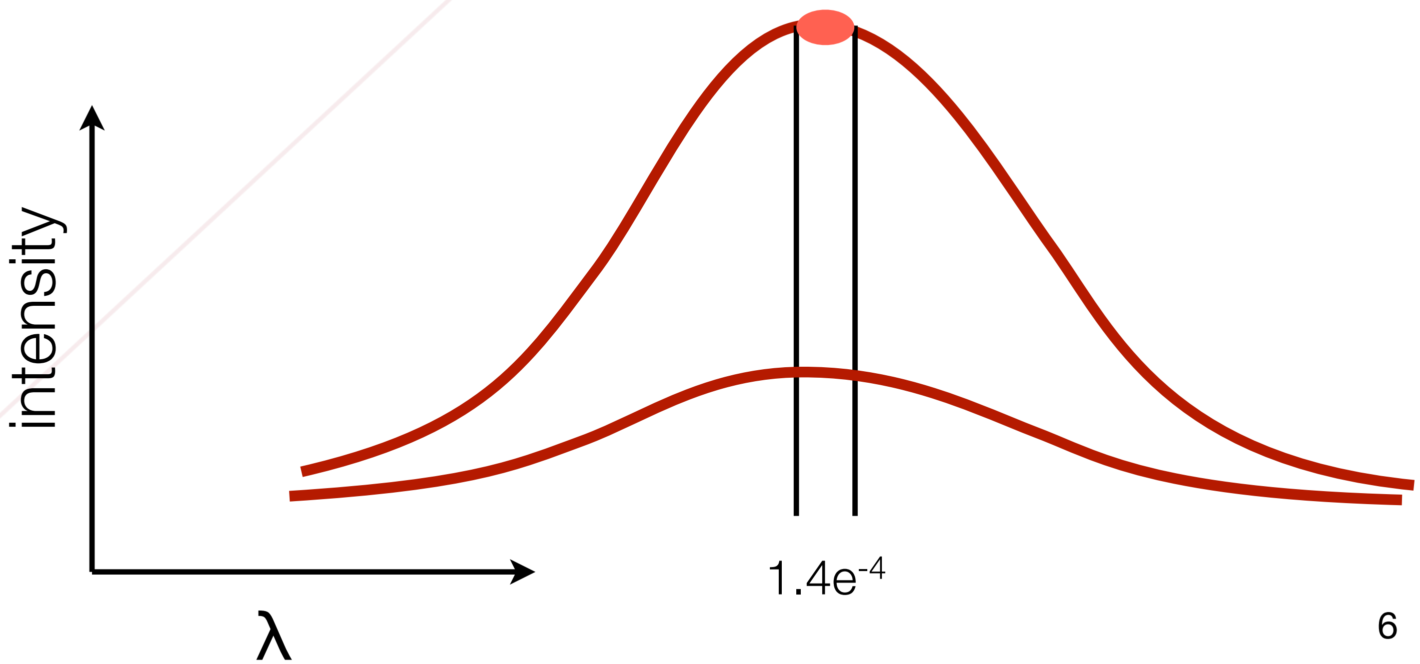

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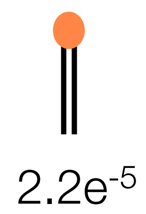

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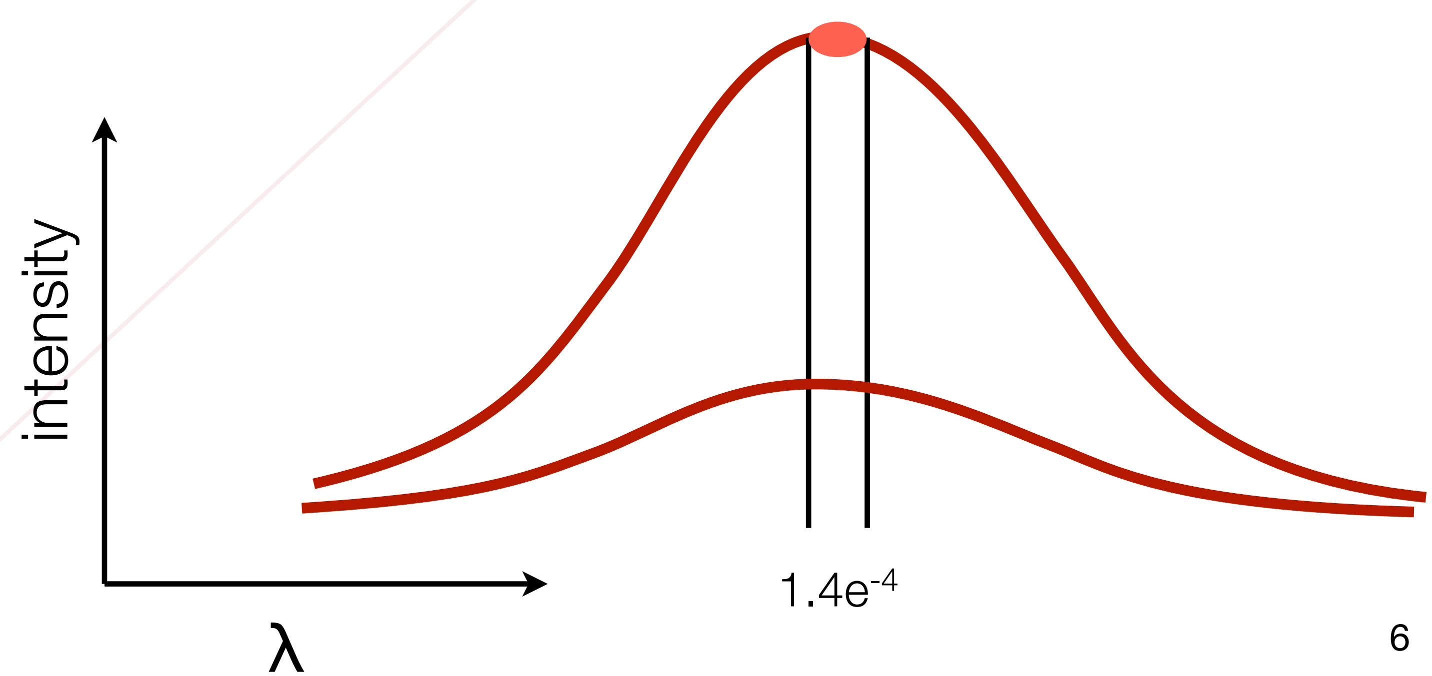
Results typically show at least 3 times more post-Kmono average intensity for Seeded operation.

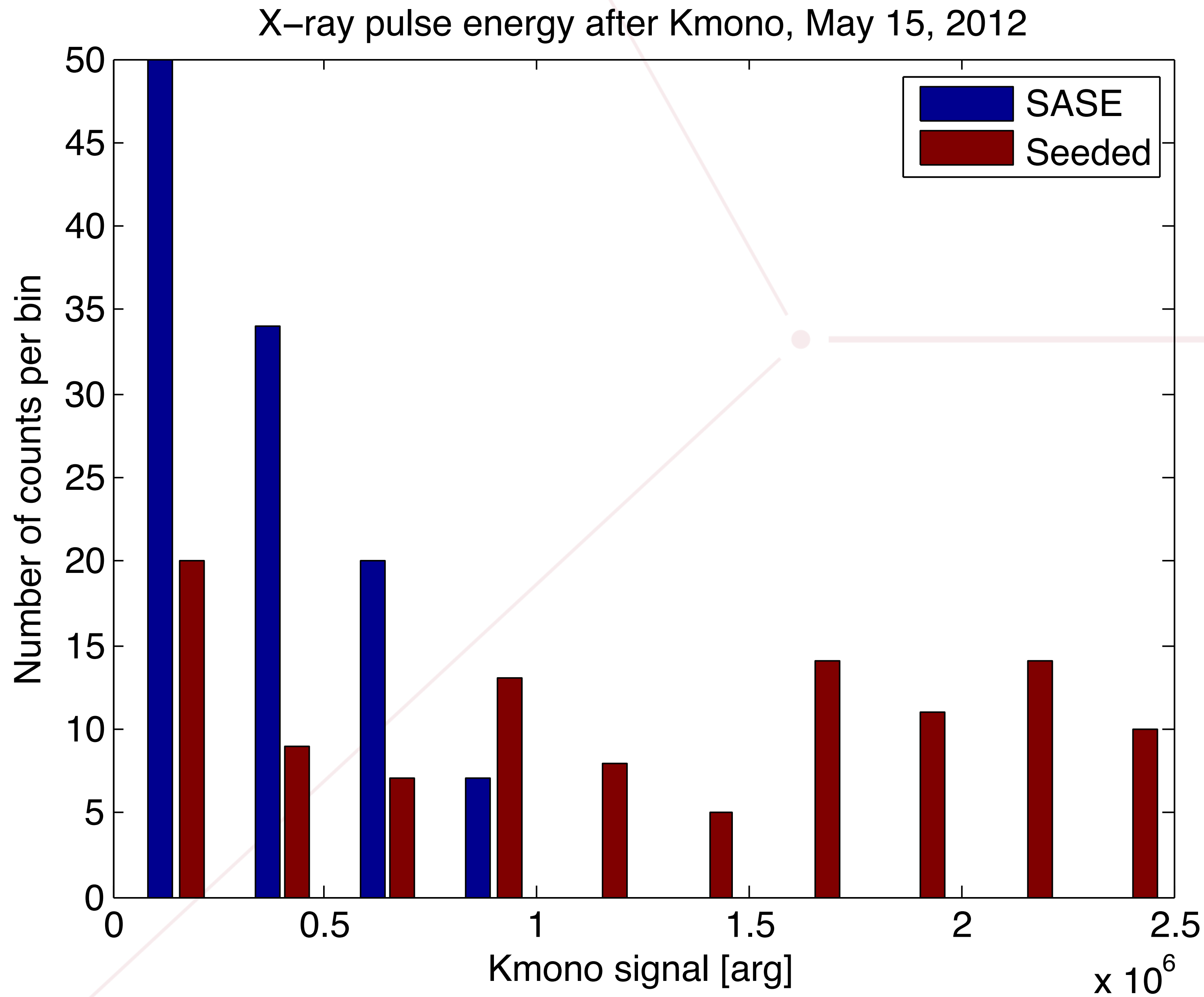
- Turn on chicane.

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



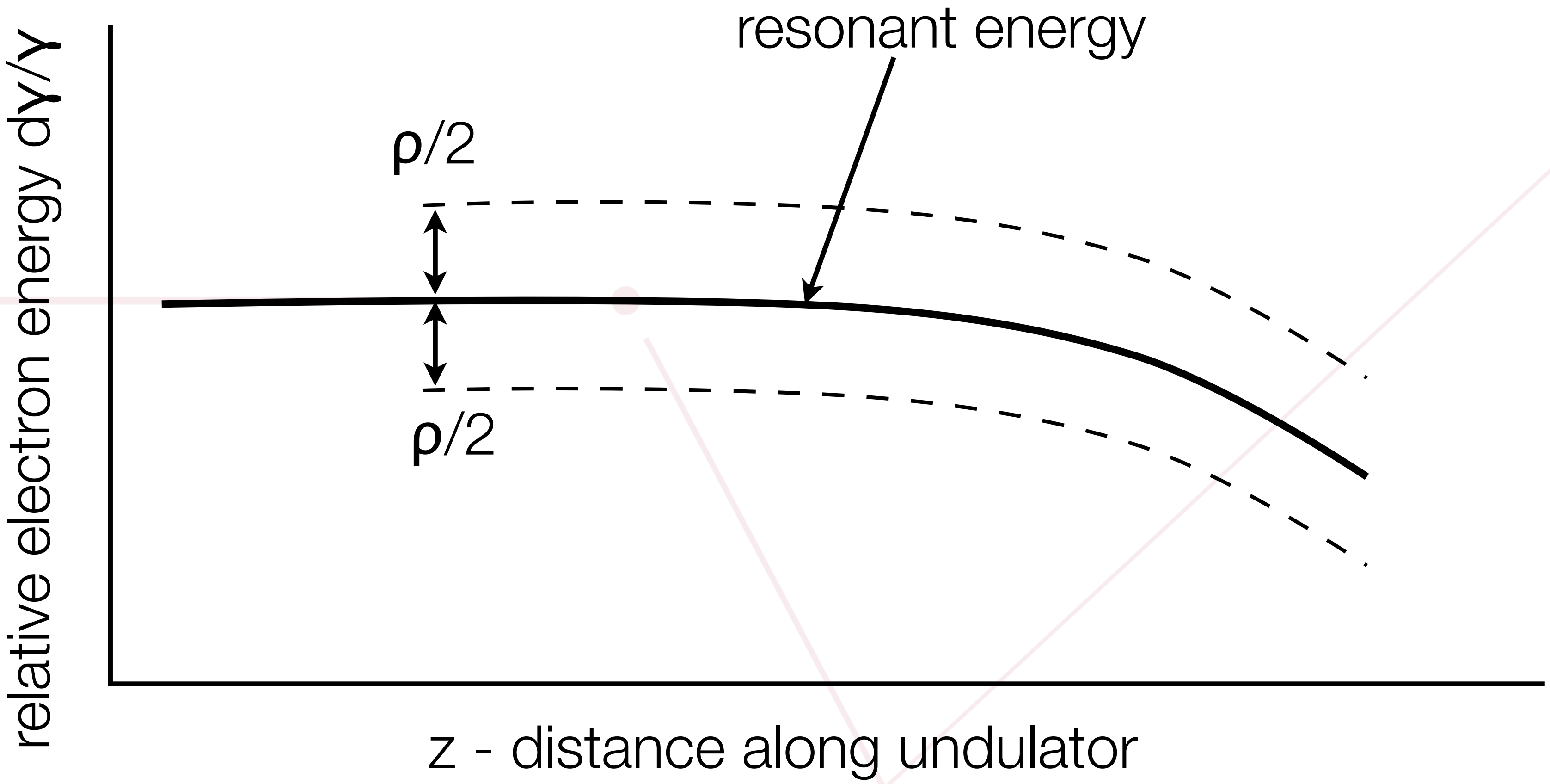
Intensity Fluctuations: SASE vs. Seeded

- Seeded pulses have higher brightness and lower energy fluctuations.



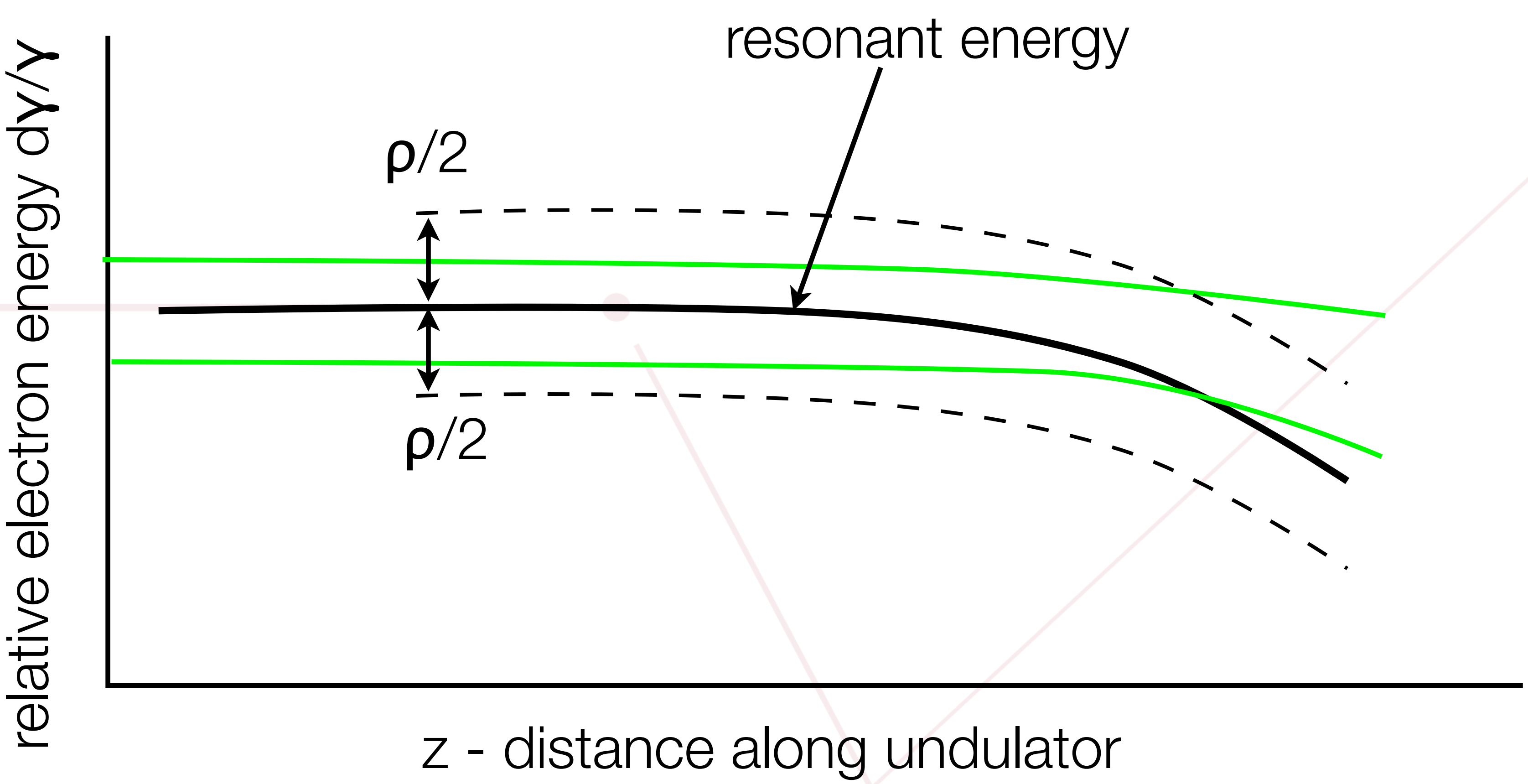
Electron Energy Jitter: Gain Length Fluctuations

- 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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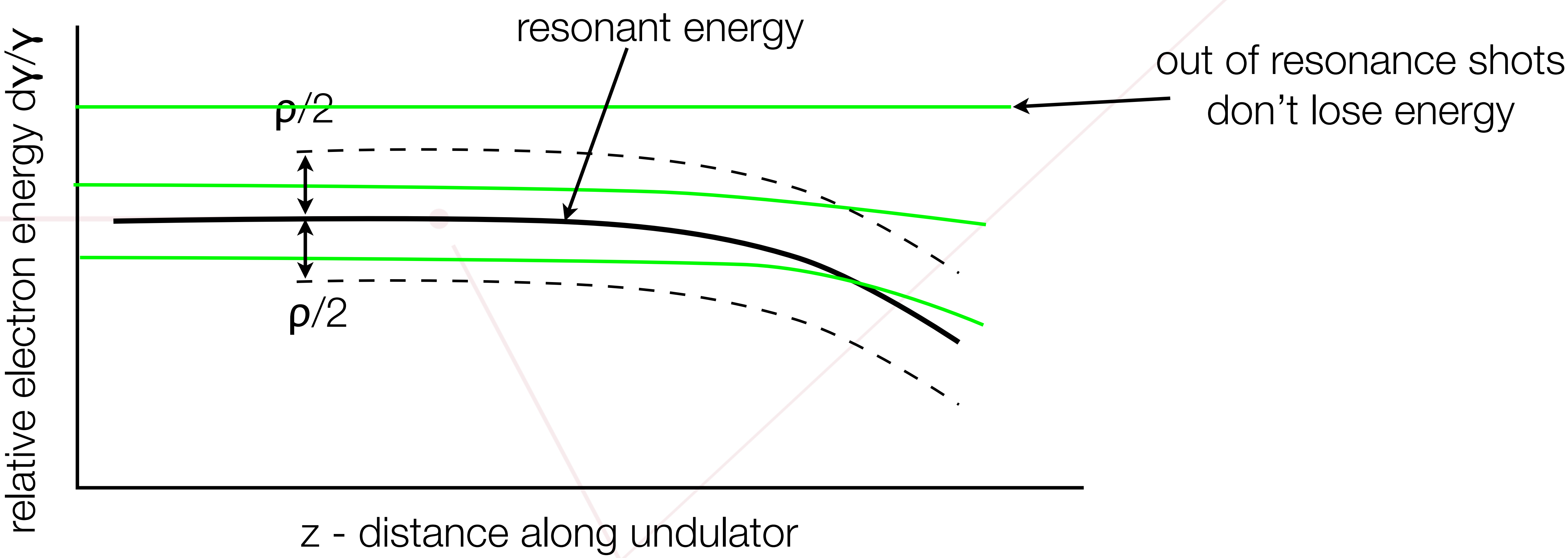

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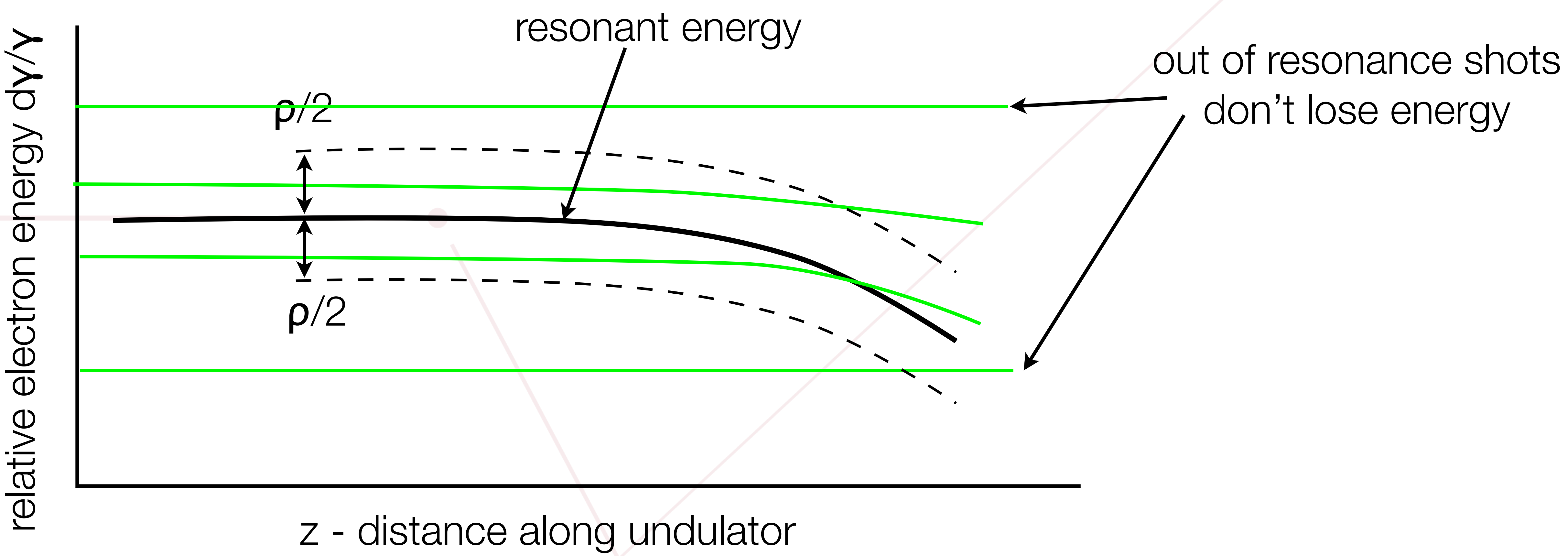

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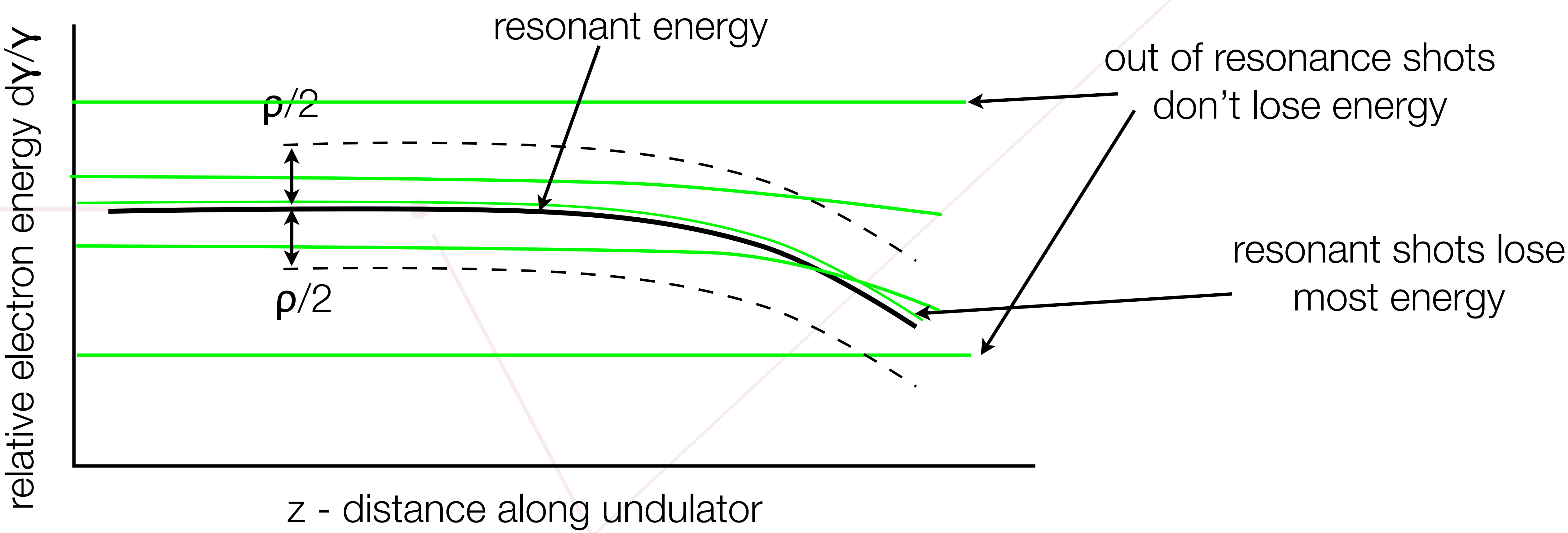
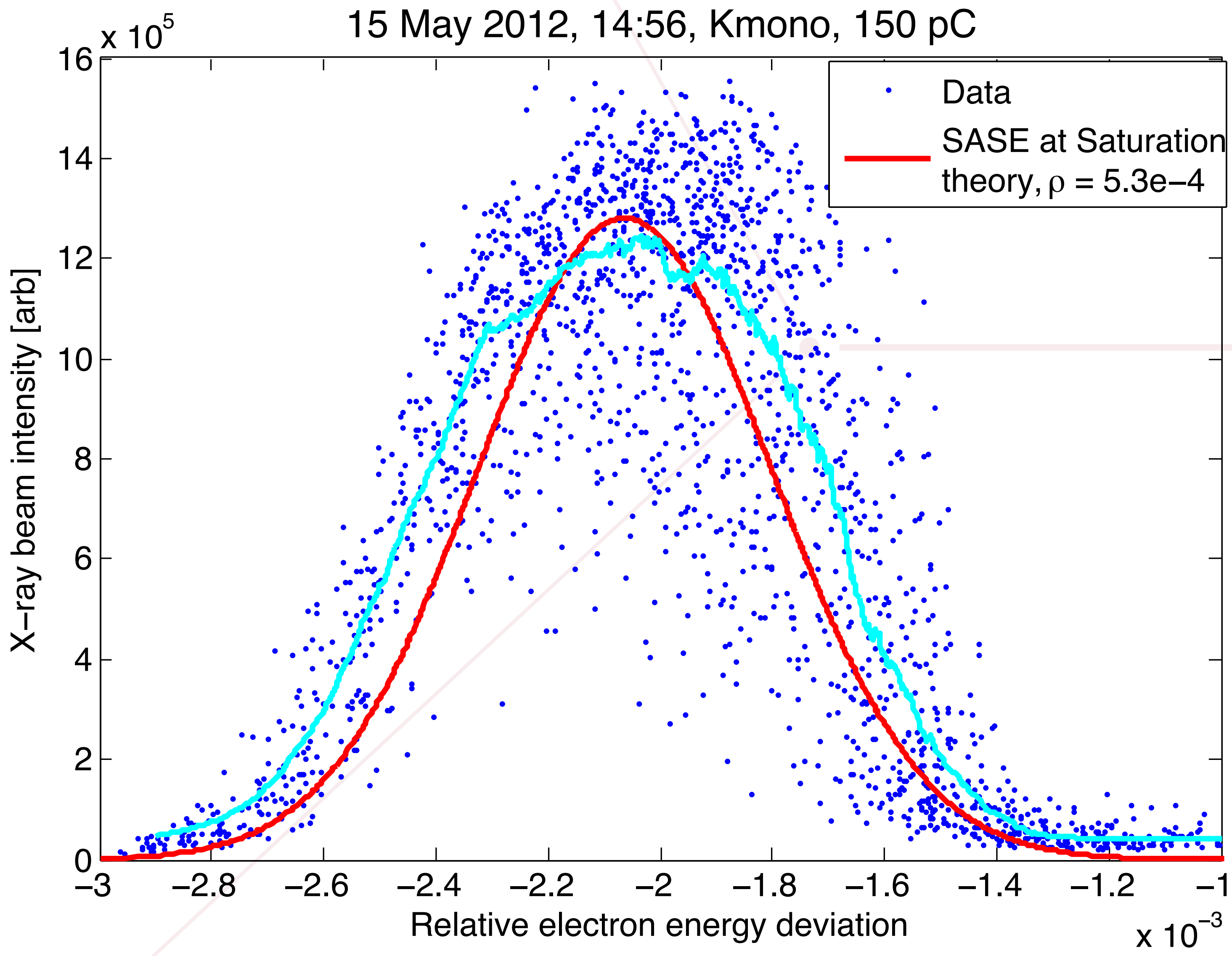


Electron Energy Jitter Measurements

- 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

- This data was taken with relatively long pulses ~ 50 fs and 150 pC.



Increasing Spectral Brightness

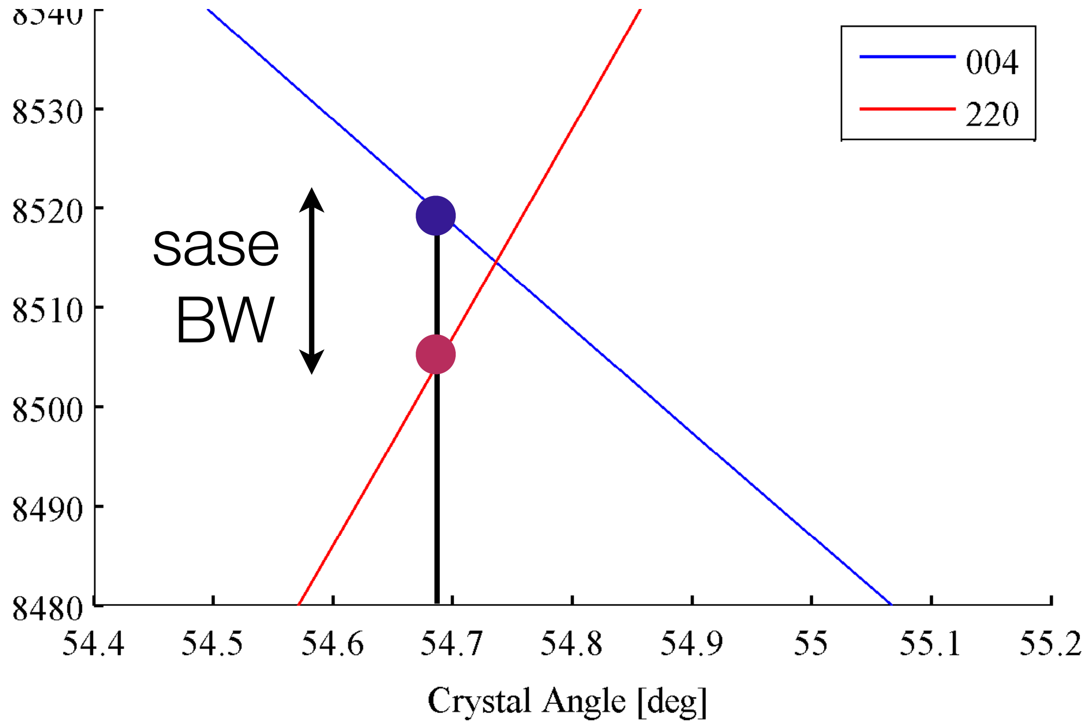
- Reducing electron energy jitter
  - Quickly identifying particular klystrons and removing or adjusting them
  - Optimizing feedback circuits
  - Optimizing the compression ratio at BC1/BC2
  - Developing more stable modulators

- Longer U2 for deeper saturation of seeded beam
  - Developing plans for up to five more segments. Segments are already built.
  - Move the seeding chicane upstream by two segments

- With lower jitter, the taper and other parameters can be better optimized

- Unofficial Goal >~ 1 mJ average seeded pulse energy , < 20% rms/average intensity fluctuations.

Two-color Seeding



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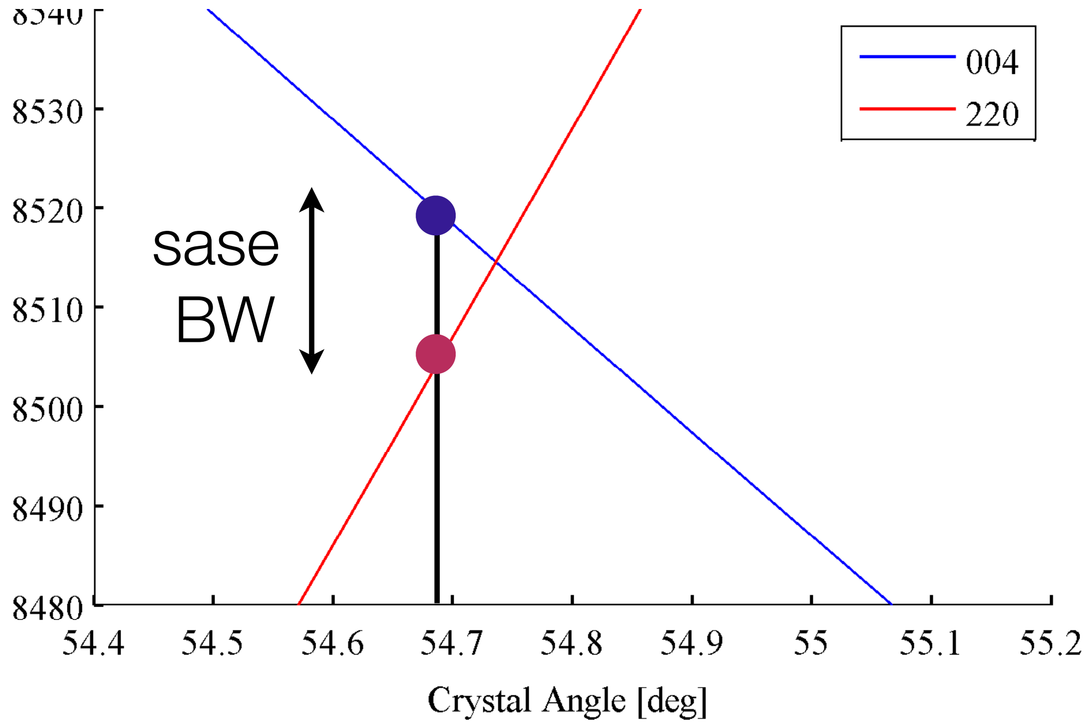

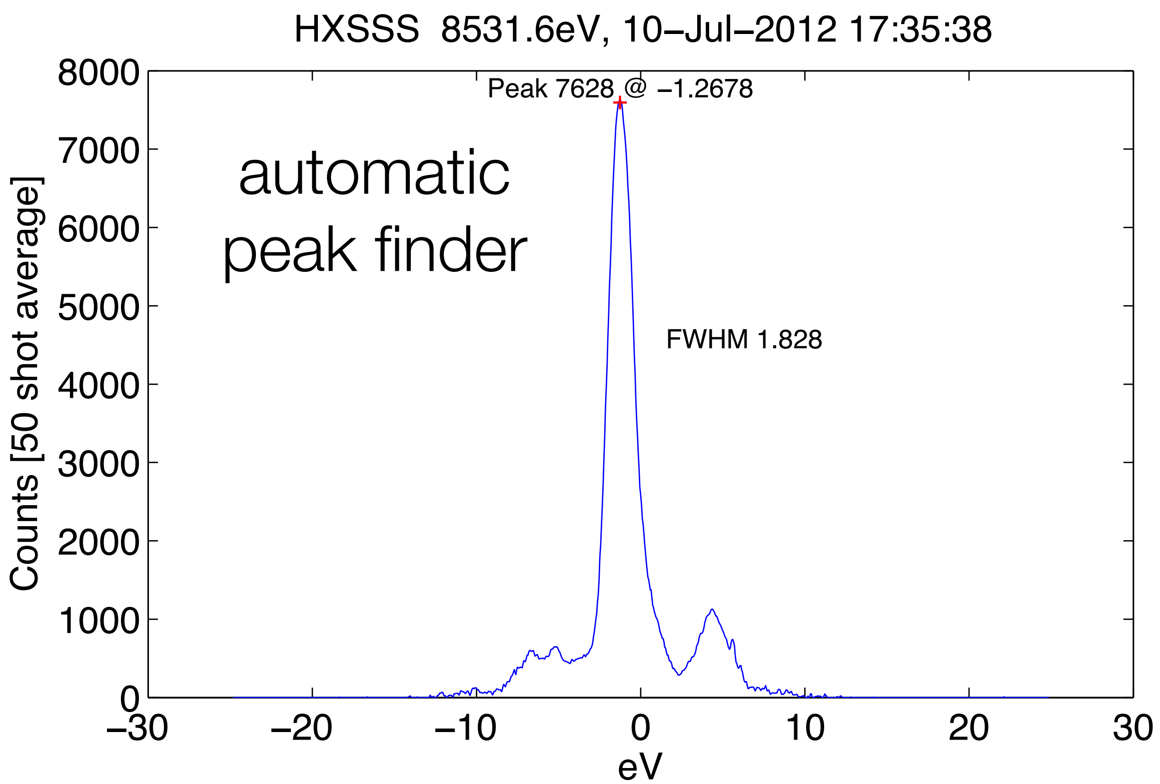

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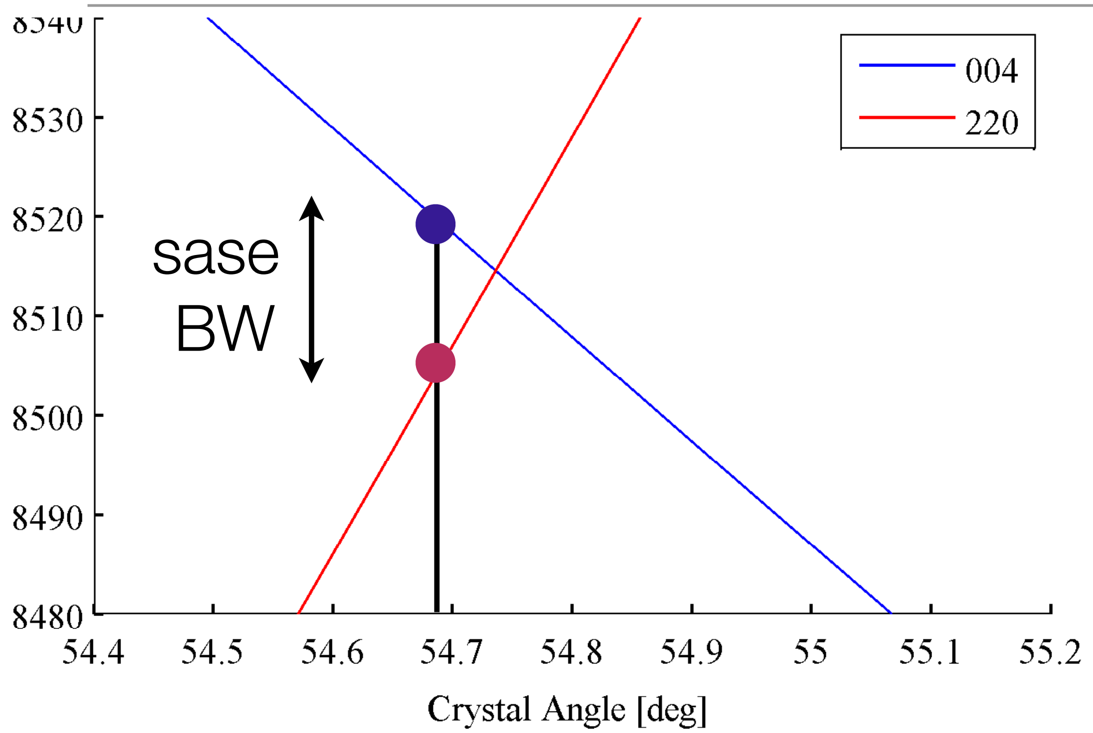
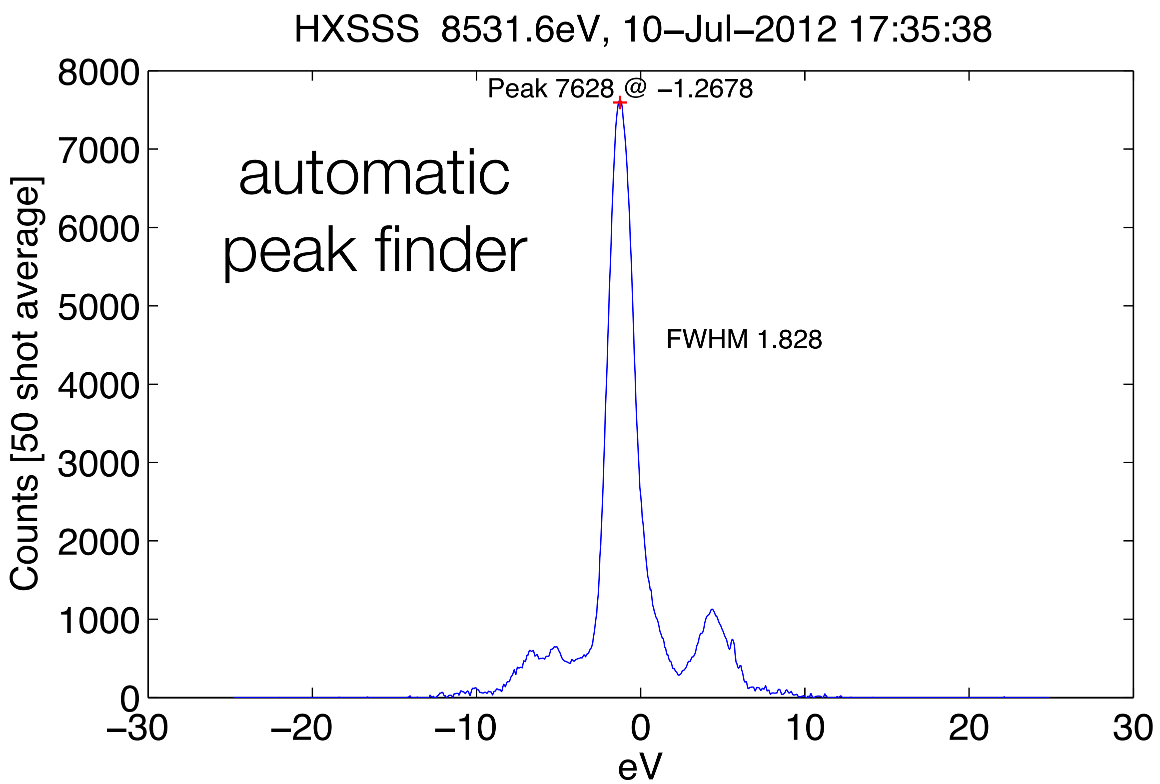
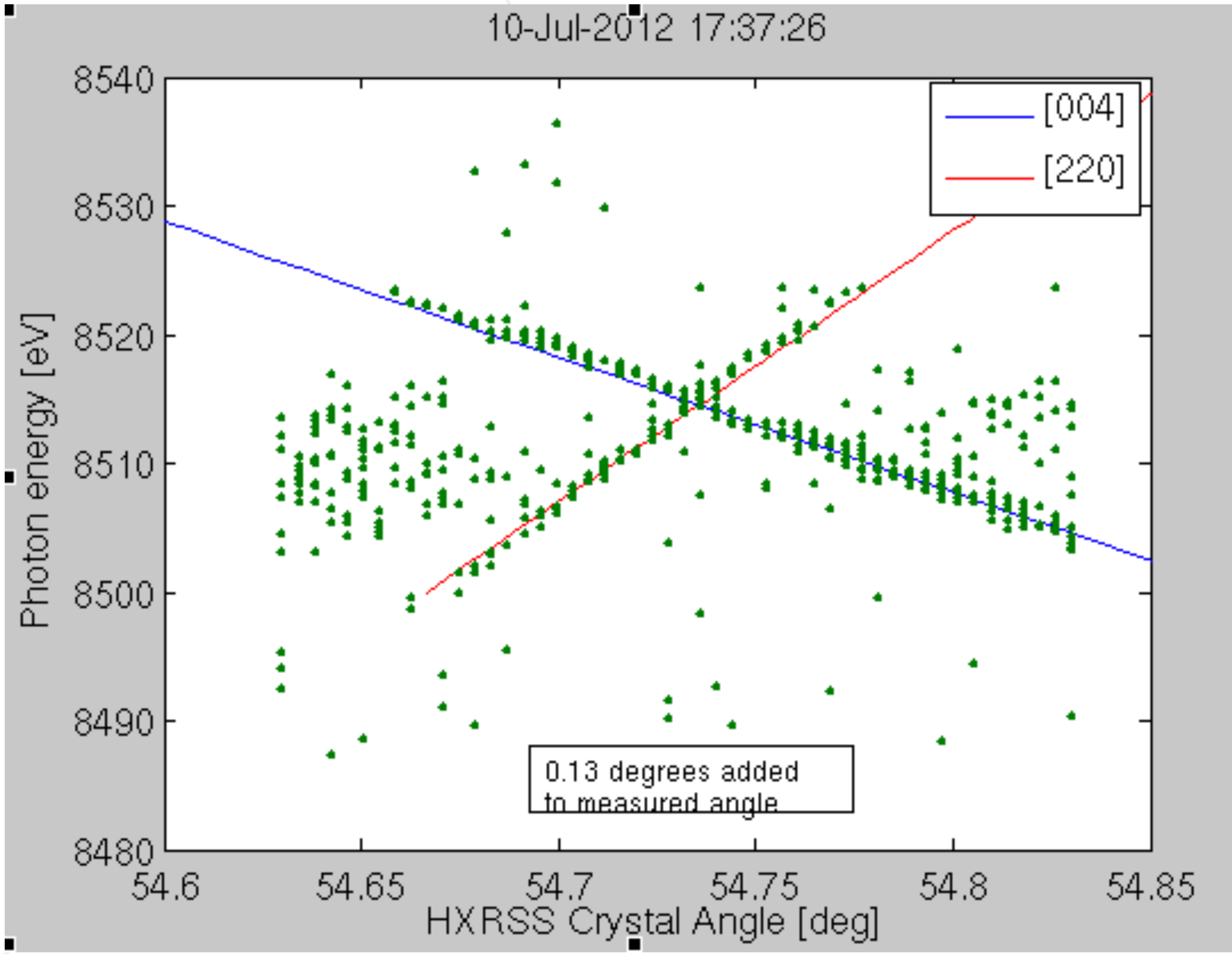
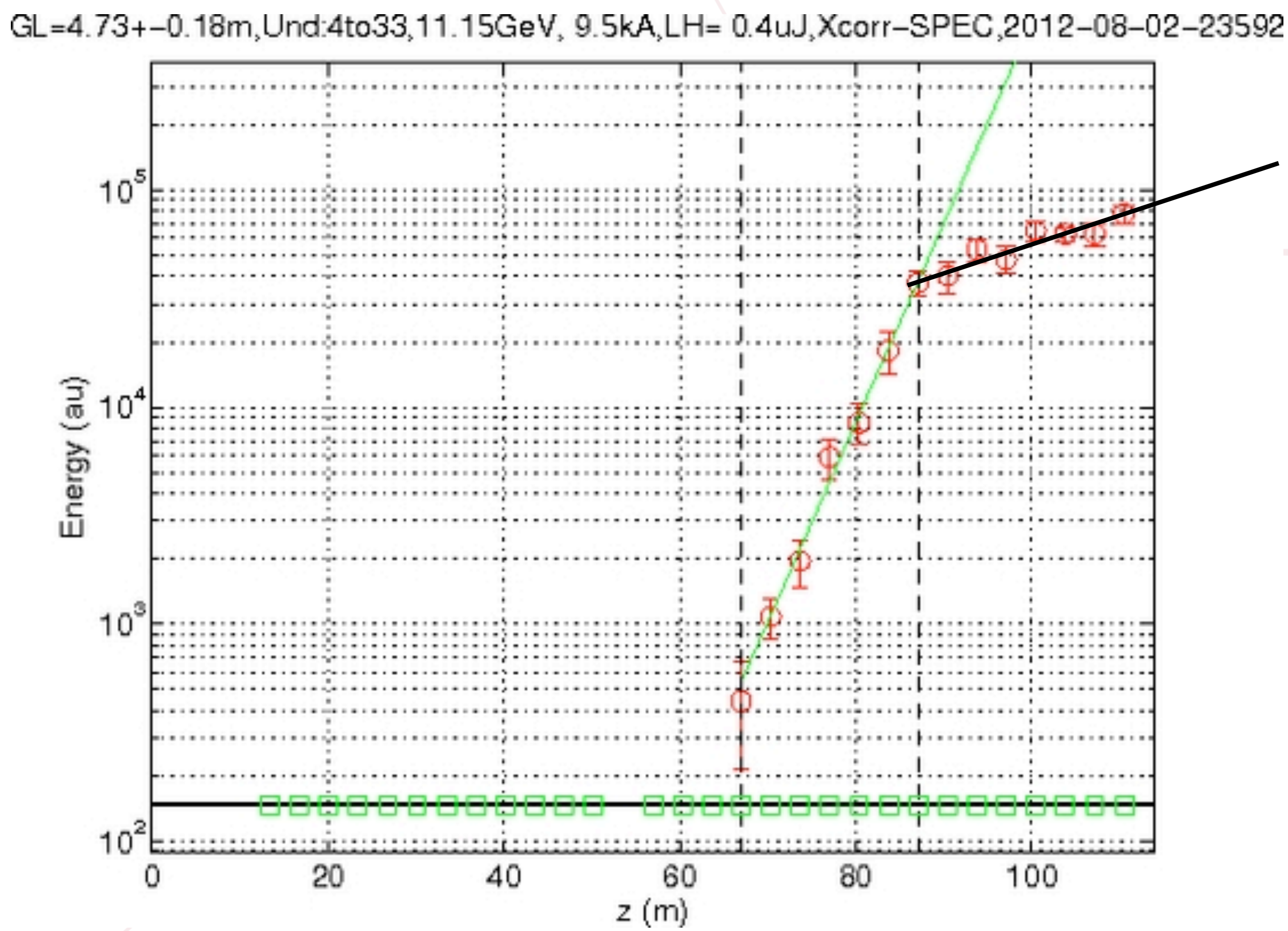






5.5 keV Studies Using 111 Plane

- Going to lower energy was mentioned by Saldin et. al., in DESY preprint.
- We found a way to to do it without changing the seeding crystal.
- Lower energy leads to shorter gain lengths and makes deeper taper and saturation studies possible.
- Very preliminary gain curve measurement shows more the undulator length is in saturation.



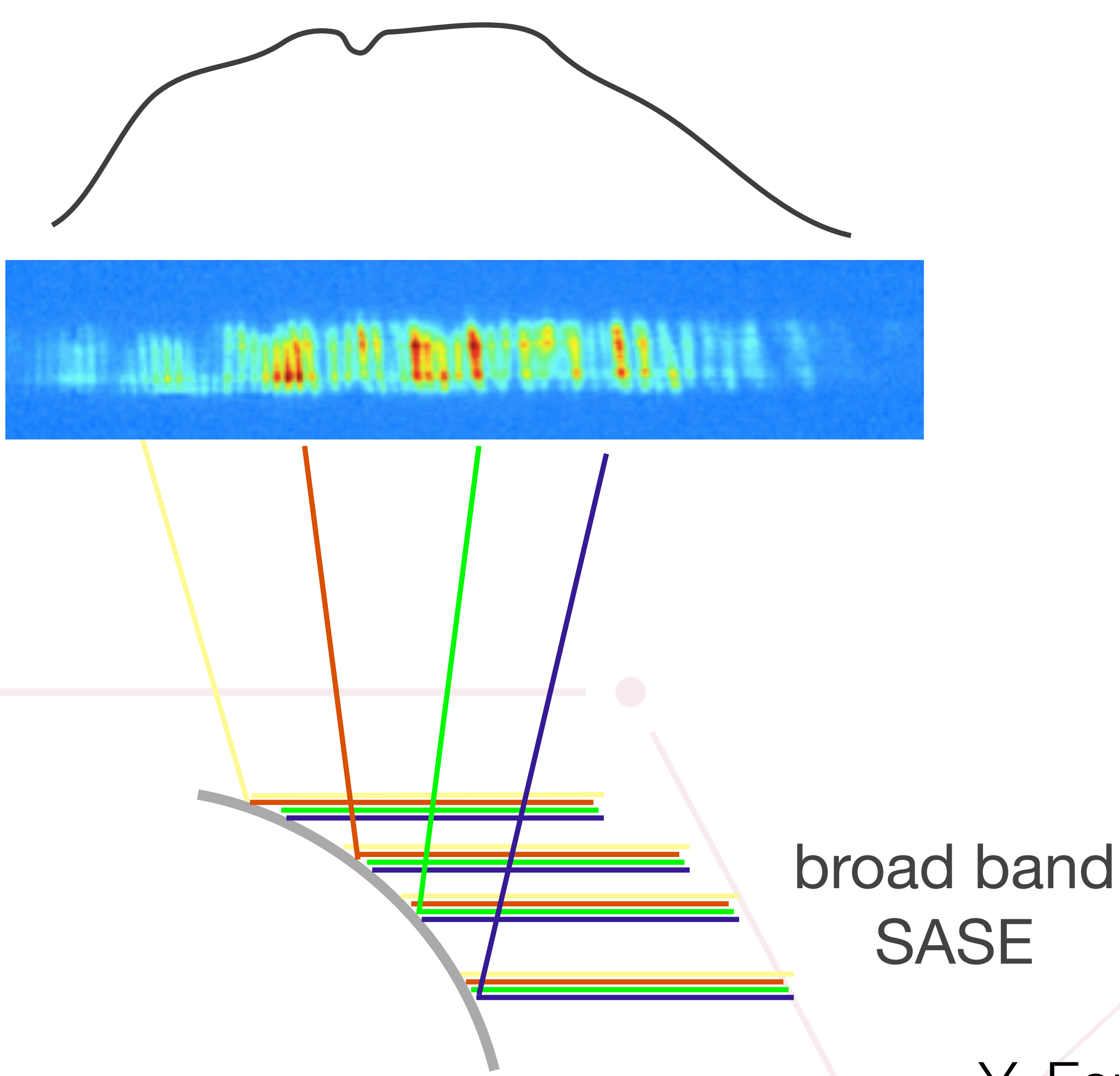
Summary

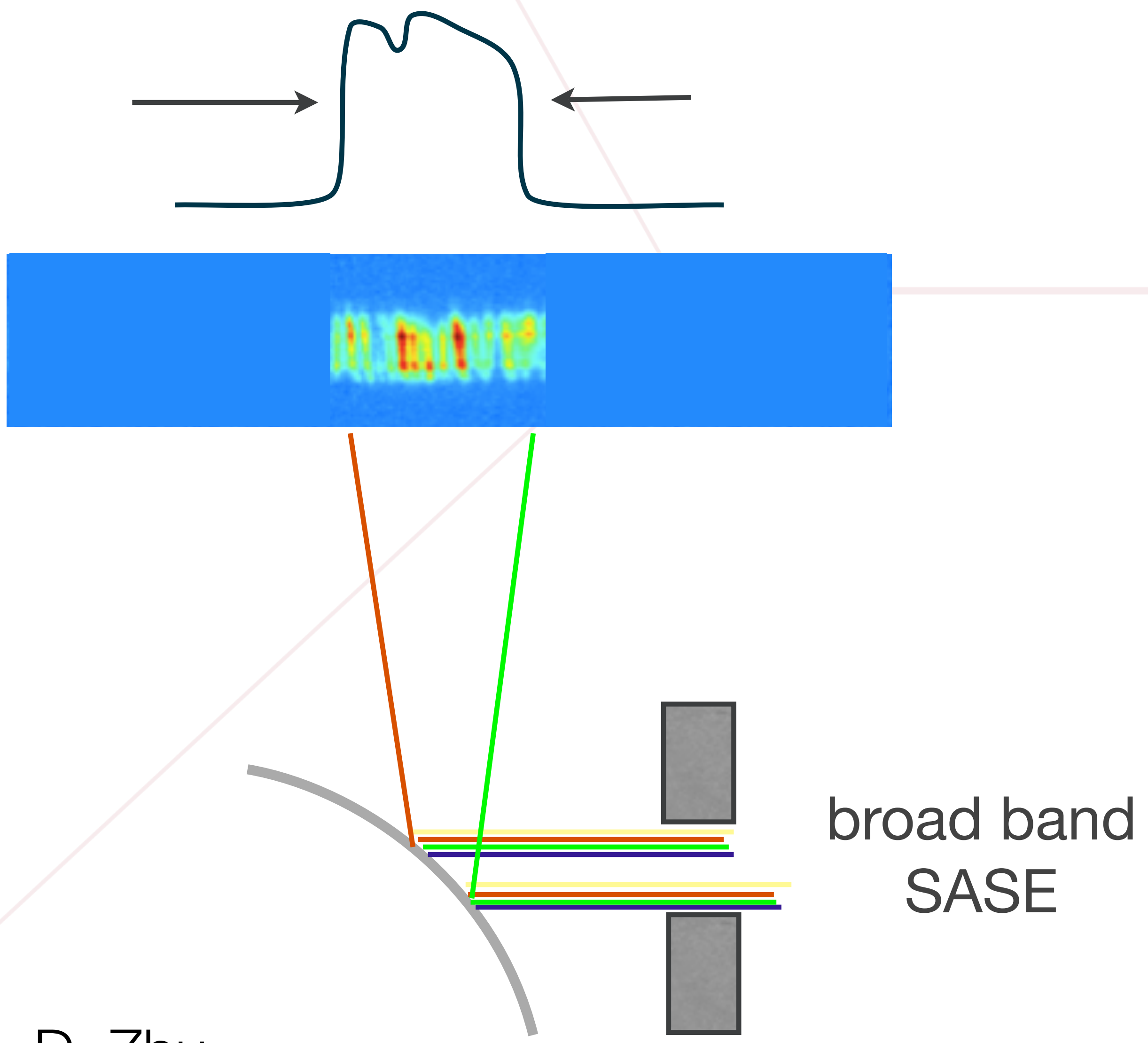
- Kmono is useful for tuning up and studying seeded beams.
- Seeded operation can provide monochromator users at least 3 times more intensity than SASE operation
- There are good prospects for increasing the average brightness further
- New configurations of seeded operation are still being explored.

. . . that's all for now. Thank you for your attention.

HXSSS - bent crystal spectrometer

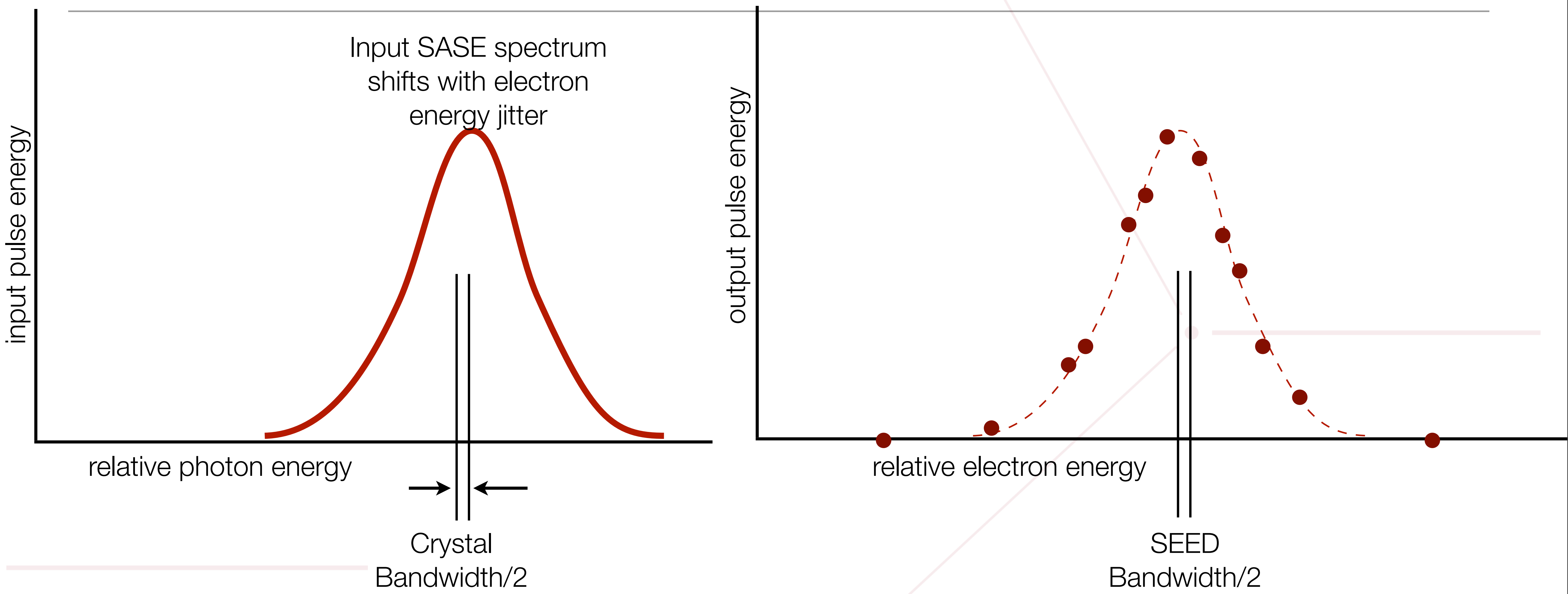
- Resolution is very good, but range and response can depend on vertical beam size, especially for the relatively broad band SASE beams





Y. Feng, D. Zhu

Electron Energy Jitter: Seed Power Fluctuations



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

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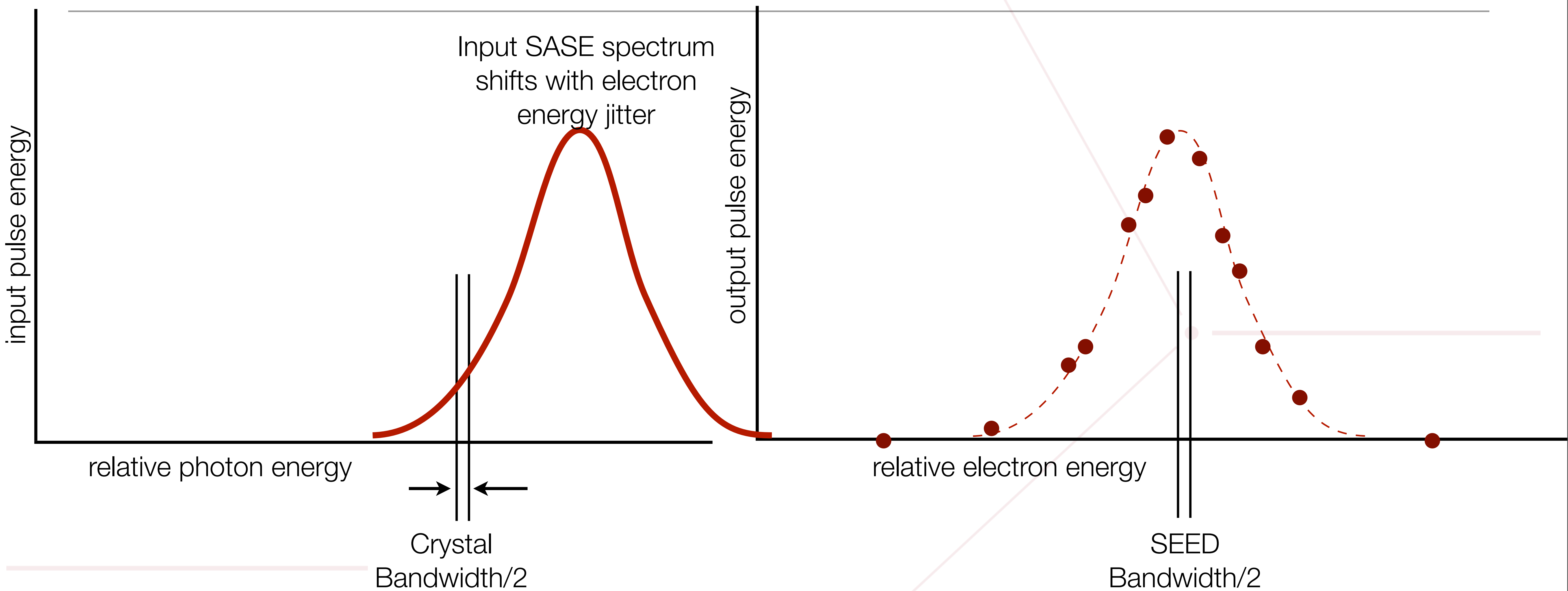

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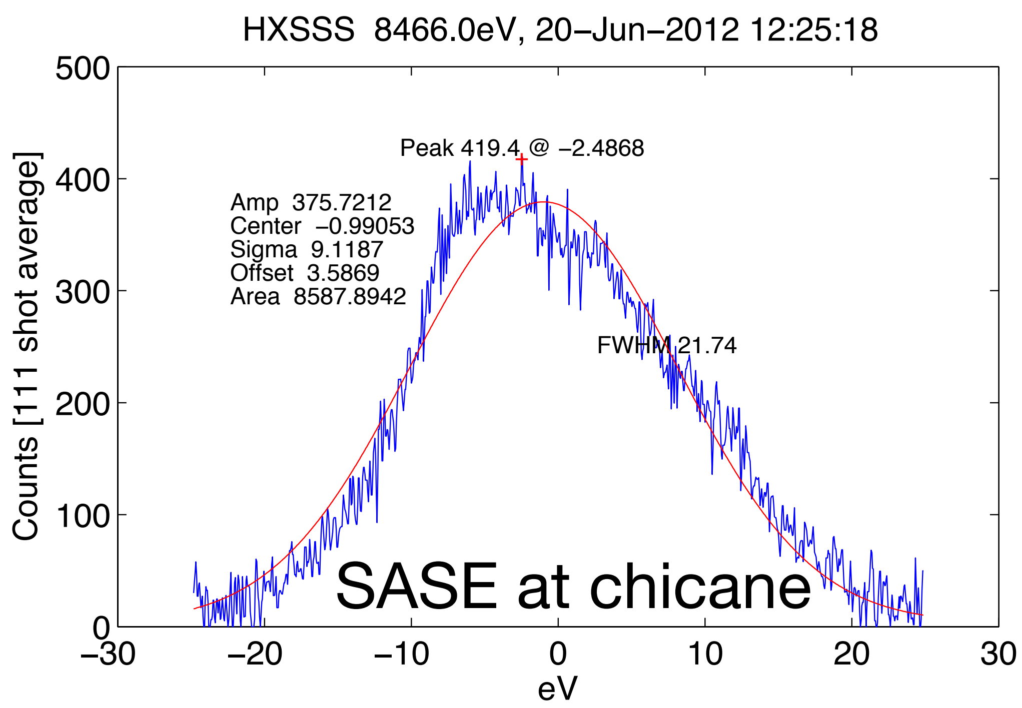
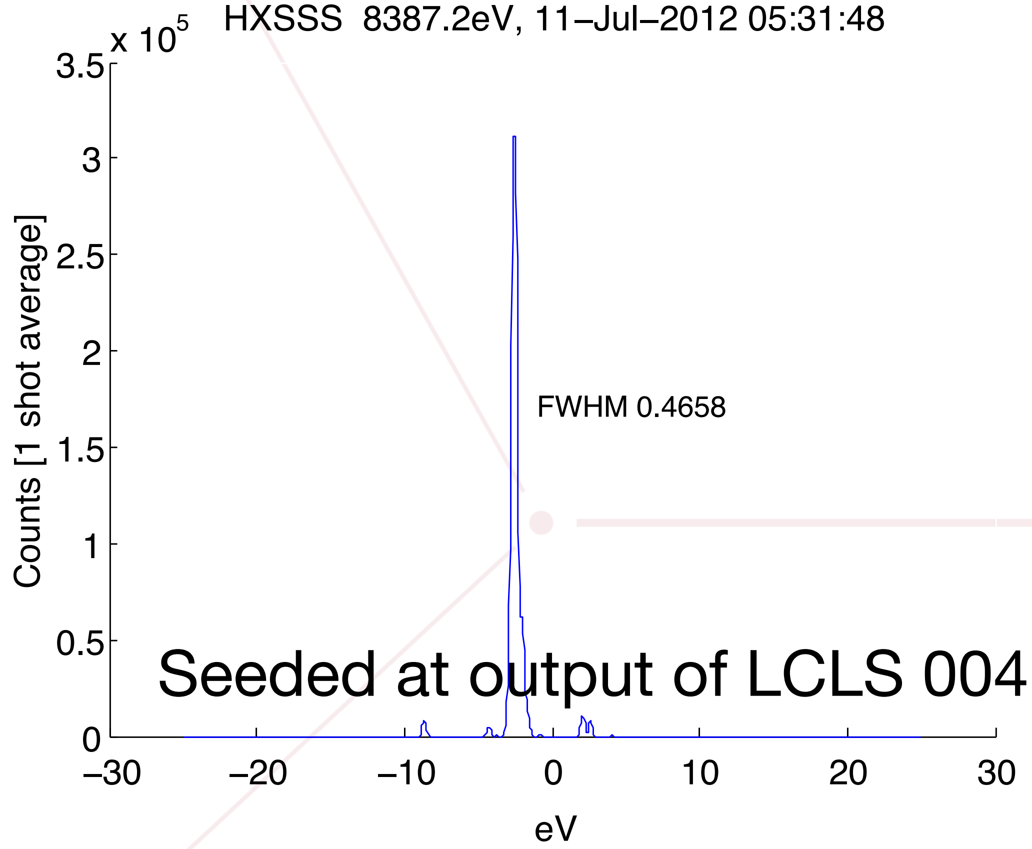
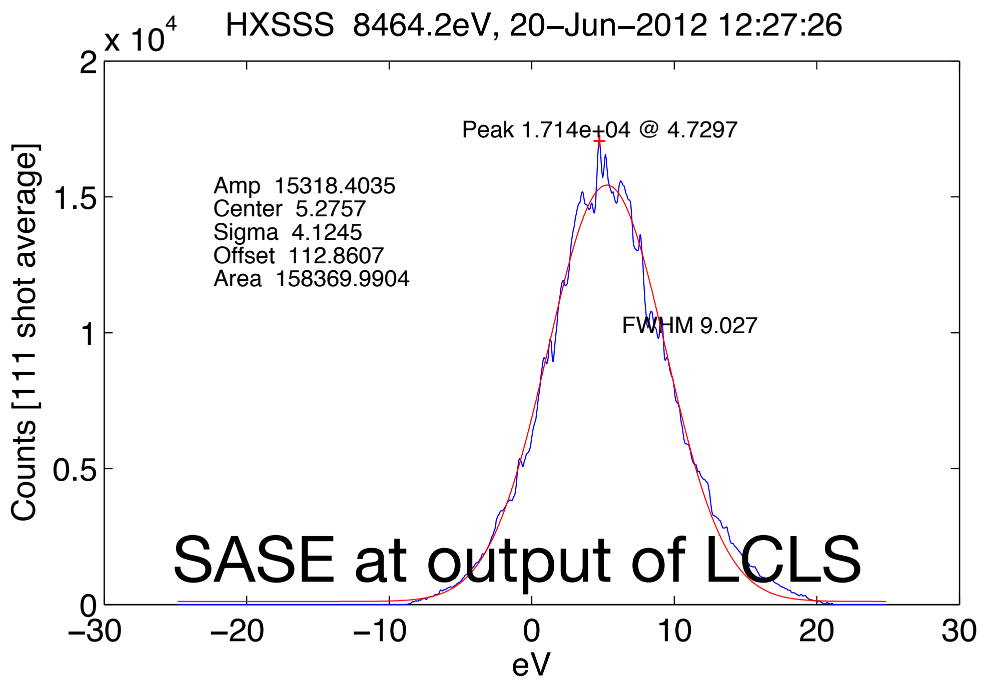
Spectra

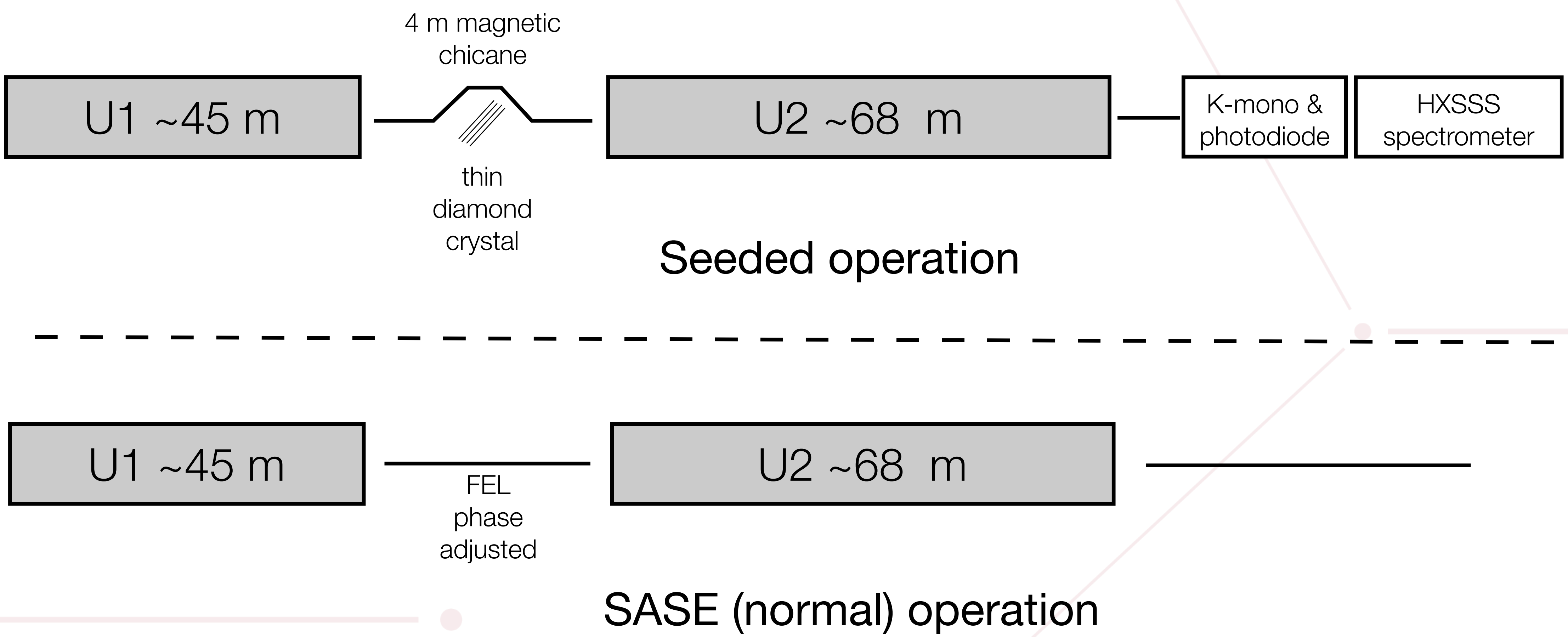






- SASE spectra may be affected by beam size correlations

Self-seeding and SASE Operation at LCLS



- For Seeded operation, turn on chicane, insert crystal and correct residual orbit.
- Adjust FEL phase between U1 and U2 for normal SASE operation.

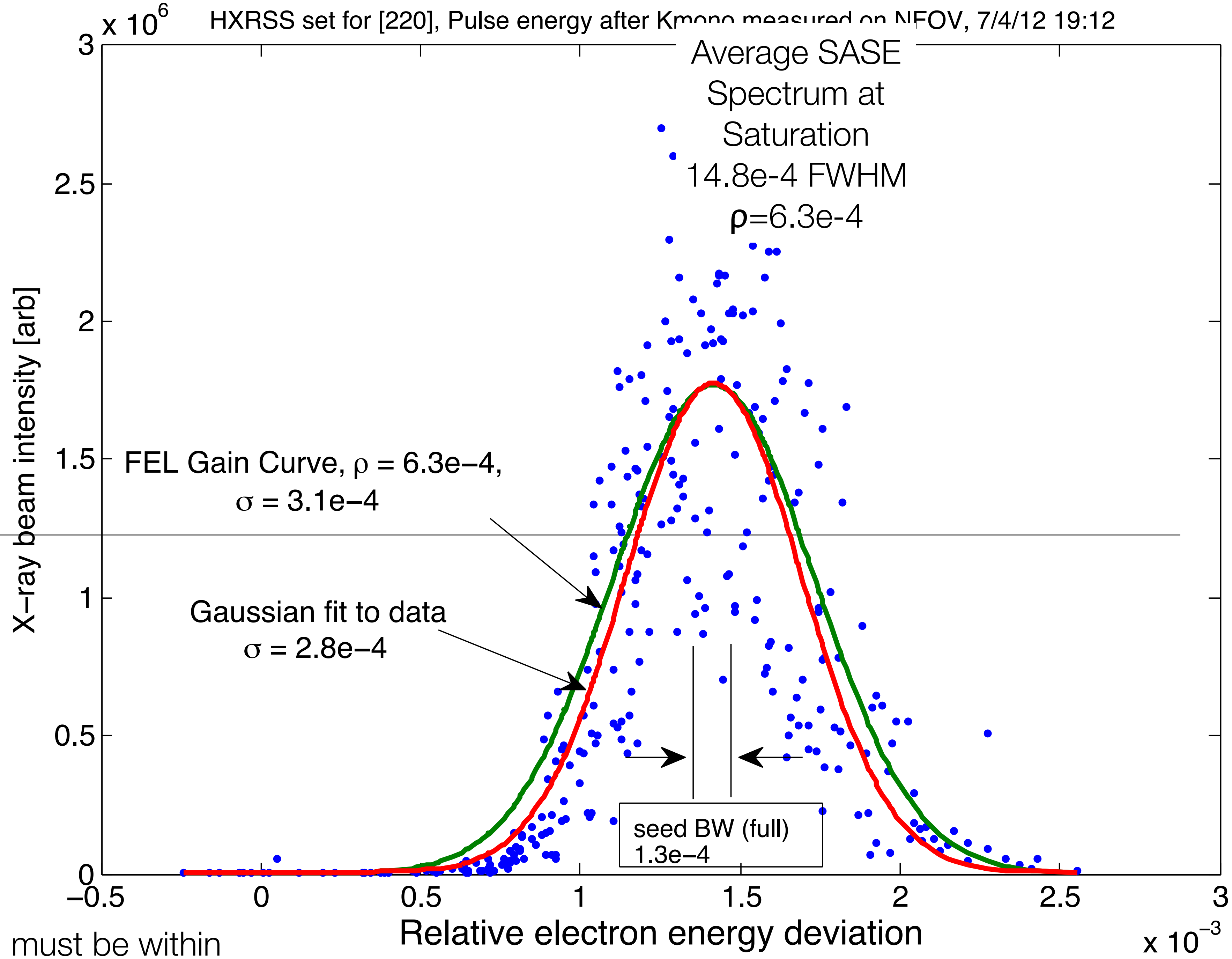
- At saturation the rms bandwidth is expected to be about ρ, the Pierce, parameter.

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.

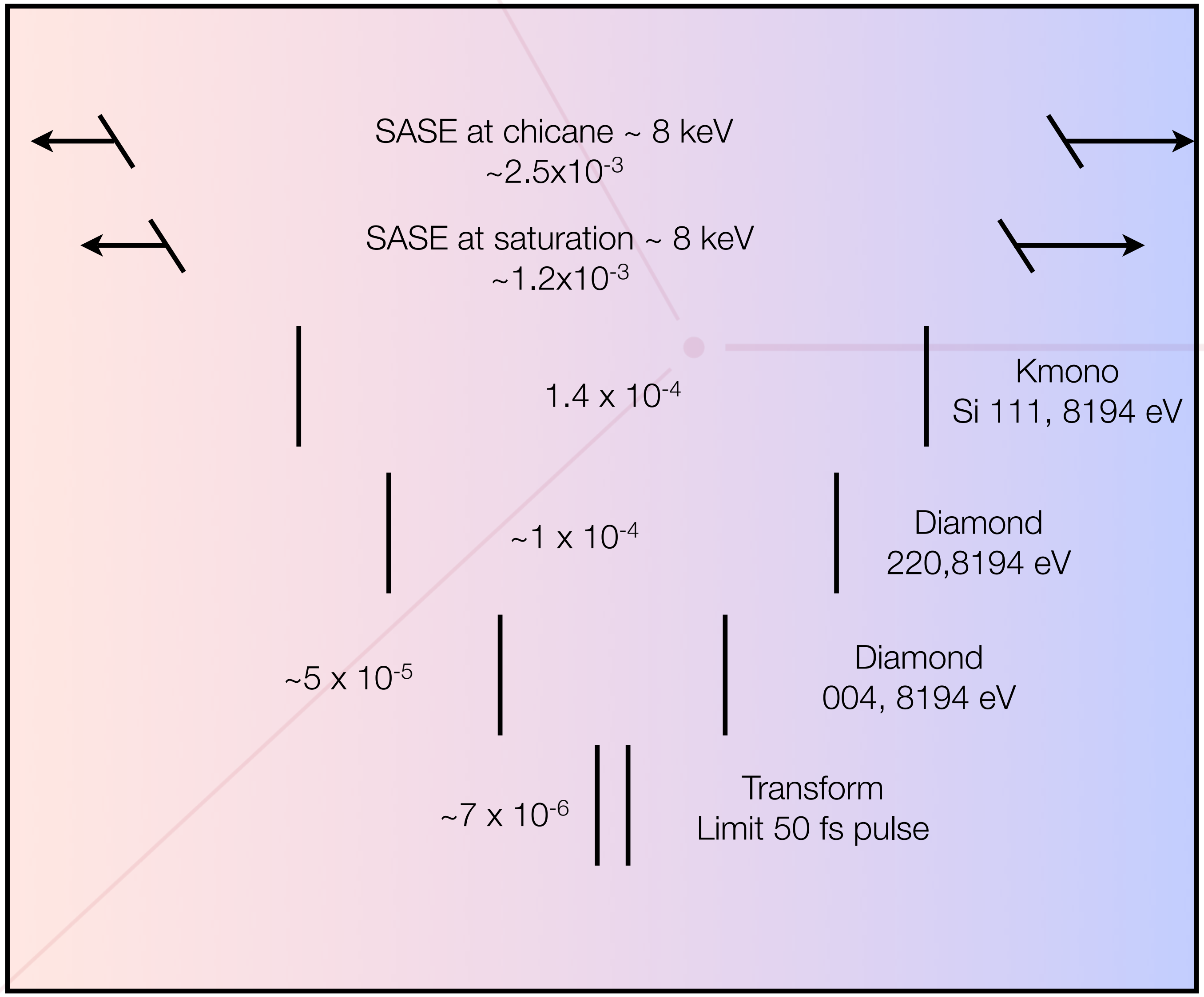


The relative energy of the electron beam must be within about ρ/2 for effective seeding. If the resonance wavelength is too far from the seeding wavelength, the emitted sase won't reinforce the sase already present and gain will suffer. That is why we observe the relative width of the intensity when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

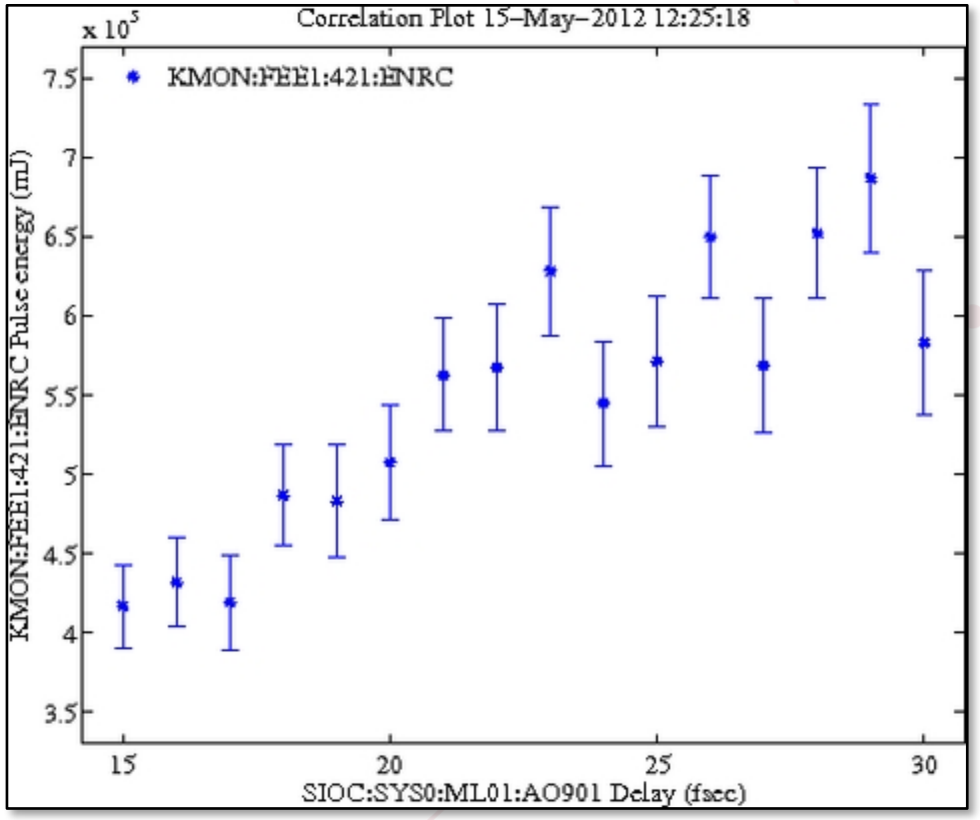
- Operational range is generally smaller than given in the table.
- Quoted range is limited by the crystal angular range 47 to 93 degrees, and machine energy.

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

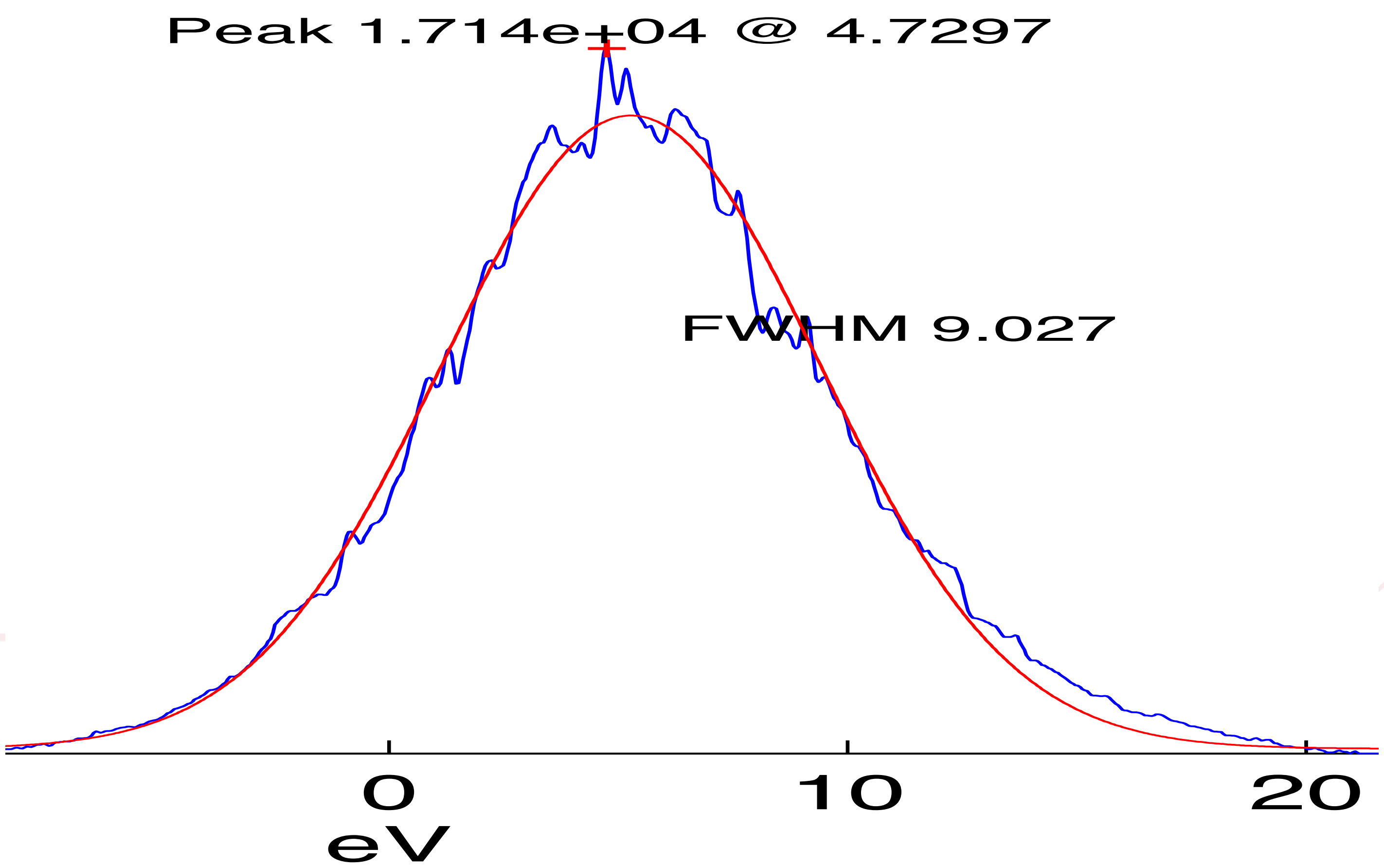
Spatial Profiles

- Kmono cleans up spatial profile and the transmitted beam resembles seeded radiation.

Delay scan

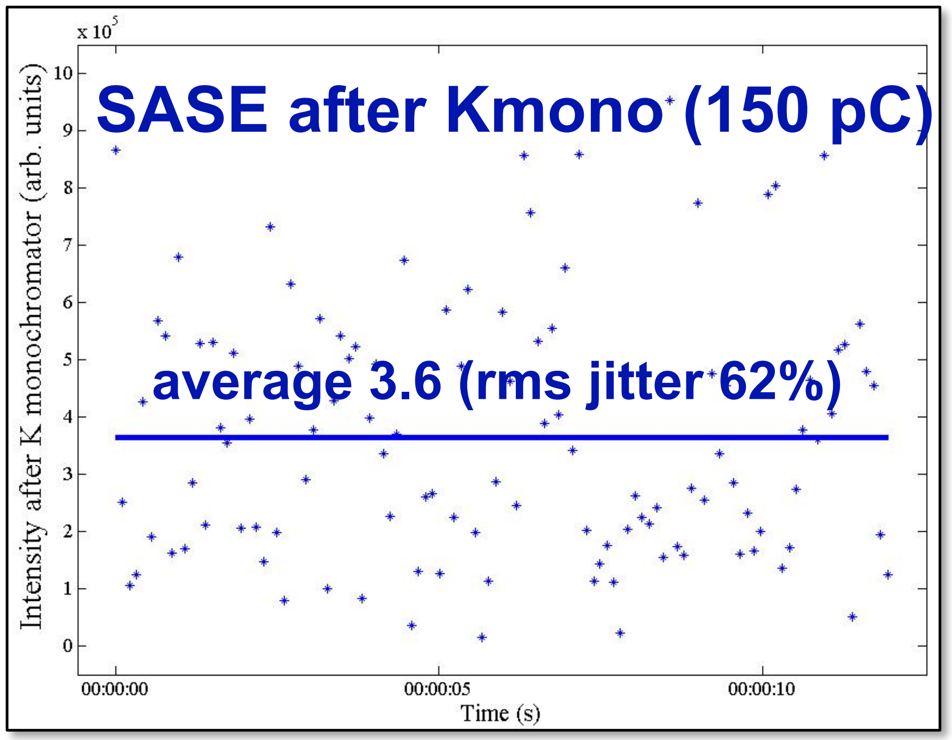


Correlation Plot 15–May–2012 12:25:18
x 10^5
KMON:FEE1:421:ENRC
KMON:FEE1:421:ENRC Pulse energy (mJ)
7.5
7
6.5
6
5.5
5
4.5
4
3.5
15
20
25
30
SIOC:SYS0:ML01:AO901 Delay (fsec)

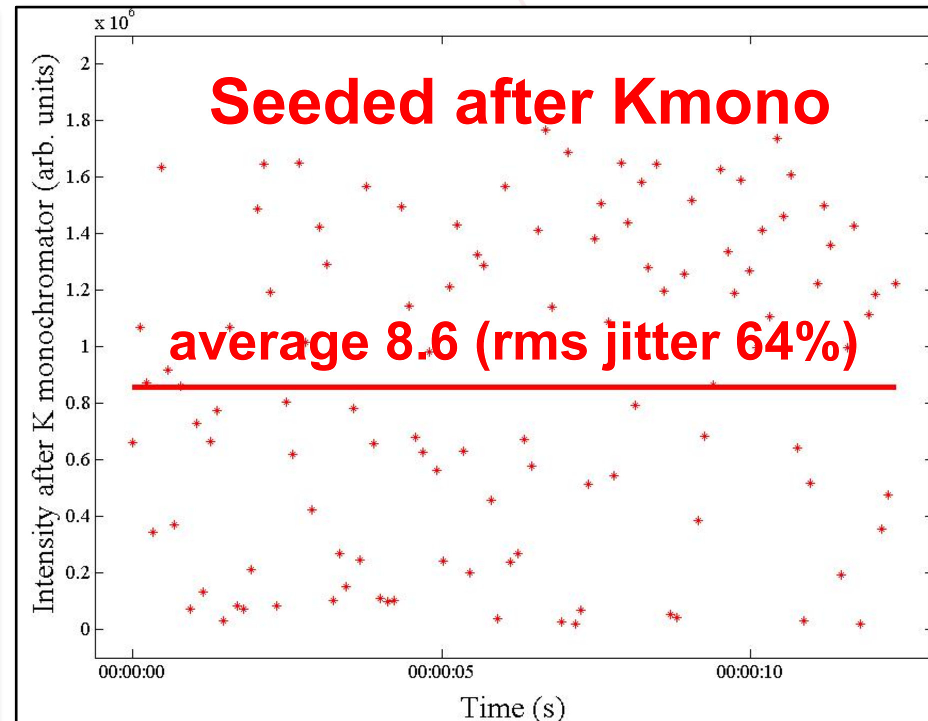

Peak 1.714e+04 @ 4.7297
FWHM 9.027
0
10
20
eV

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



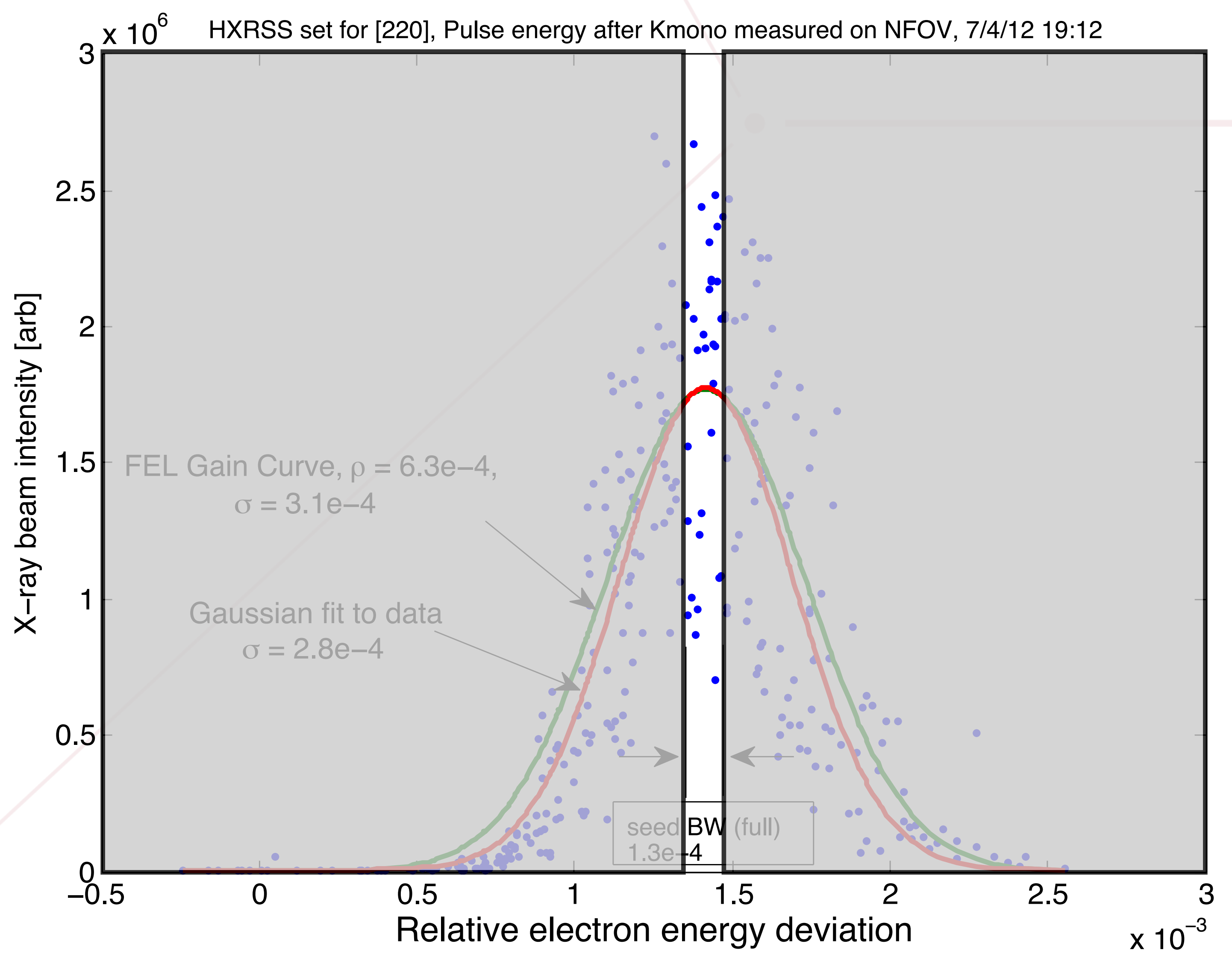
Tuned seeded (U1-2 out) after K-mono Solid attenuator 1-6, 8, 9 in, foil 9 in



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

SASE jitter



HXRSS set for [220], Pulse energy after Kmono measured on NFOV, 7/4/12 19:12
x 10^6
3
2.5
2
1.5
1
0.5
0
X−ray beam intensity [arb]
FEL Gain Curve, ρ = 6.3e−4,
σ = 3.1e−4
Gaussian fit to data
σ = 2.8e−4
seed BW (full)
1.3e−4
−0.5
0
0.5
1
1.5
2
2.5
3
Relative electron energy deviation
x 10^−3