

Hard x-ray self-seeding at the LCLS

Ryan R. Lindberg, on behalf of the Hard X-Ray Self-Seeding team
Advanced Photon Source, Argonne National Laboratory

34th International Free-Electron Laser Conference
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- The HXRSS team – a collaboration of SLAC National Lab, the Advanced Photon Source (APS) at Argonne National Lab, and the Technological Institute for Superhard and Novel Carbon Materials (TISNCM, Troitsk, Russia)



J. Amann, F.-J. Decker, Y. Ding, **P. Emma** (LBNL) Y. Feng, J. Frisch, D. Fritz, J. Hastings, Z. Huang, J. Krzywinski, H. Loos, A. Lutman, H.-D. Nuhn, D. Ratner, J. Rzepiela, S. Spampinati (ELETTRA, Basovizza), D. Walz, J. Welch, J. Wu, and D. Zhu



W. Berg, D. Shu, Yu. Shvyd'ko, S. Stoupin, E. Trakhtenberg, and **A. Zholents**



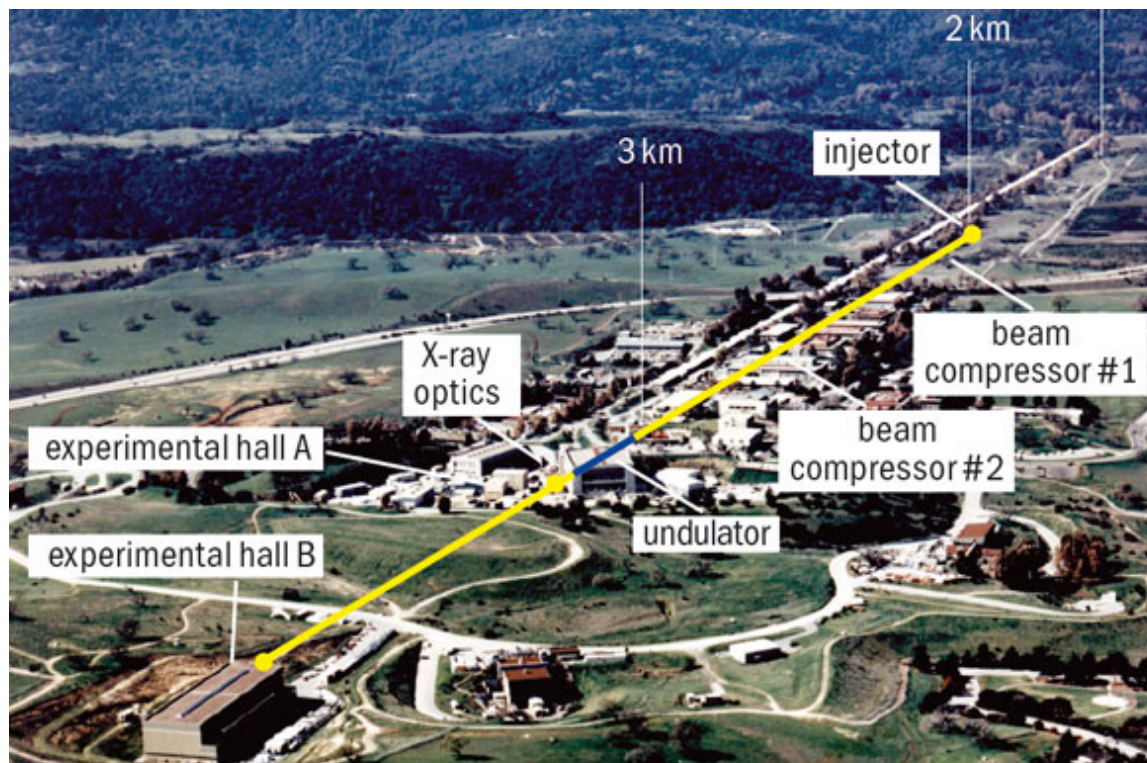
V. Blank and S. Terentiev

- Engineers and technicians @ SLAC & APS, and the LCLS operators
- Colleagues at DESY – G. Geloni, V. Kocharyan, and E. Saldin



The LCLS has produced intense Self-Amplified Spontaneous Emission (SASE) x-rays since 2009

- X-rays with wavelengths from 1.2 – 25 Å
- Up to 3 mJ/pulse ($\sim 10^{12}$ photons/pulse)
- 120 Hz rep rate
- Variable pulse length from few – 100 fs
- $\Delta\omega/\omega \sim 10^{-3}$



Flagship applications include:
Single shot x-ray imaging, Nonlinear physics, and Femtosecond dynamics



The LCLS enables new scientific inquiries/discoveries

LETTER

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Femtosecond X-ray protein nanocrystallography

Henry N. Chapman^{1,2}, Petra Fromme³, Anton Barty⁴, Thomas A. White⁵, Richard A. Kirian⁴, Andrew Aquila⁴, Mark S. Hunter², Joachim Schulz², Daniel P. DePonte¹, Uwe Weierstall⁴, R. Bruce Doak⁴, Filippe R. N. C. Maia⁴, Andrew V. Martin⁴, Ilme Schlichting^{6,7}, Lukas Lomb⁴, Nicola Coppola⁴, Robert L. Shoeman⁴, Sascha W. Epp⁴, Robert Hartmann⁴, Daniel Rolles^{4,8}, Artem Rudenko^{4,9}, Lutz Foucar^{4,10}, Nils Kimmel^{4,11}, Georg Weidenspointner^{12,13}, Peter Holl⁴, Mengning Liang⁴, Miriam Barthelmeß⁴, Carl Caleman⁴, Sebastian Boutet⁴, Michael J. Bogan⁴, Jacek Krzywinski⁴, Christoph Bostedt^{4,14}, Sasa Bajic⁴, Lars Gumprecht⁴, Benedikt Rudek^{4,15}, Benjamin Erk^{4,16}, Carlo Schmidt^{4,17}, Andrei Homke^{4,18}, Christian Reich⁴, Daniel Pietschner⁴, Lothar Strüder^{4,19}, Günter Hauser^{4,20}, Hubert Gorkhov⁴, Joachim Ullrich^{4,21}, Sven Herrmann^{4,22}, Gerhard Schaller⁴, Florian Schopper⁴, Heike Soltan⁴, Kai-Uwe Kühnel⁴, Marc Messerschmidt⁴, John D. Bozek⁴, Stefan P. Hau-Riege⁴, Matthias Frank⁴, Christina Y. Hampton⁴, Raymond G. Sierra⁴, Dmitri Starodub⁴, Garth J. Williams⁴, Janos Hajdu⁴, Nicusor Timneanu⁴, M. Marvin Seibert⁴, Jakob Andreasson⁴, Andrea Rocca⁴, Olof Jönsson⁴, Martin Svenda⁴, Stephan Stern⁴, Karol Nass⁴, Robert Andritschke⁴, Claus-Dieter Schröter⁴, Fatou Krasniqi⁴, Mario Bött⁴, Kevin E. Schmidt⁴, Xiaoyi Wang⁴, Ingo Grotjohann⁴, James M. Holton⁴, Thomas R. M. Barends⁴, Richard Neutze⁴, Stefano Marchesini⁴, Raimund Fromme⁴, Sebastian Schorb⁴, Daniela Rupp⁴, Marcus Adolph⁴, Tais Gorkhov⁴, Inger Andersson⁴, Helmut Hirsemann⁴, Guillaume Poddevin⁴, Heinz Grafsma⁴, Björn Nilsson⁴ & John C. H. Spence⁴

X-ray crystallography provides the vast majority of macromolecular structures, but the success of the method relies on growing crystals of sufficient size. In conventional measurements, the necessary increase in X-ray dose to record data from crystals that are too small leads to extensive damage before a diffraction signal can be recorded¹. It is particularly challenging to obtain large, well-diffracting crystals of membrane proteins, for which fewer than 300 unique structures have been determined despite their importance in all living cells. Here we present a method for structure determination where single-crystal X-ray diffraction 'snapshots' are collected from a fully hydrated stream of nanocrystals using femtosecond pulses from a hard-X-ray free-electron laser, the Linac Coherent Light Source². We prove this concept with nanocrystals of photosystem I, one of the largest membrane protein complexes³. More than 3,000,000 diffraction patterns were collected in this study, and a three-dimensional data set was assembled from individual photosystem I nanocrystals (~200 nm to 2 µm in size). We mitigate the problem of radiation damage in crystallography by using pulses briefer than the timescale of most damage processes⁴. This offers a new approach to structure determination of macromolecules that do not yield crystals of sufficient size for studies using conventional radiation sources or are particularly sensitive to radiation damage.



High-Resolution Protein Structure Determination by Serial Femtosecond Crystallography
Sebastian Boutet et al.
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High-Resolution Protein Structure Determination by Serial Femtosecond Crystallography

Sebastian Boutet^{1,2}, Lukas Lomb^{2,3}, Garth J. Williams², Thomas R. M. Barends^{2,3}, Andrew Aquila⁴, R. Bruce Doak⁴, Uwe Weierstall⁴, Daniel P. DePonte⁴, Jan Steinbrener^{2,3}, Robert L. Shoeman^{2,3}, Marc Messerschmidt², Anton Barty⁴, Thomas A. White⁵, Stephan Kassemeyer^{2,3}, Richard A. Kirian⁴, M. Marvin Seibert⁴, Paul A. Montanez², Chris Kenney², Ryan Herbst², Phillip Hart⁴, Jack Pines⁶, Günther Haller², Sol M. Gruner^{2,4}, Hugh T. Philpott², Mark W. Tate², Marianne Hromalik¹², Lucas J. Koerner^{2,4}, Niels van Bakel^{2,4}, John Morse^{2,4}, Wilfried Ghonsalves², David Arlund^{2,4}, Michael J. Bogan⁴, Carl Caleman⁴, Raimund Fromme⁴, Christina Y. Hampton⁴, Mark S. Hunter^{2,4}, Linda C. Johansson², Gergely Katona², Christopher Kupitz², Mengning Liang⁴, Andrew V. Martin⁴, Karol Nass⁴, Lars Rededeck^{2,3,4}, Francesco Stellato⁴, Nicusor Timneanu⁴, Dingjie Wang⁴, Nadia A. Zatsepin⁴, Donald Schafer⁴, James DeFeaver⁴, Richard Neutze⁴, Petra Fromme⁴, John C. H. Spence⁴, Henry N. Chapman⁴, Ilme Schlichting^{2,3}

Structure determination of proteins and other macromolecules has historically required the growth of high-quality crystals sufficiently large to diffract x-rays efficiently while withstanding radiation damage. We applied serial femtosecond crystallography (SFX) using an x-ray free-electron laser (XFEL) to obtain high-resolution structural information from microcrystals (less than 1 micrometer by 1 micrometer by 3 micrometers) of the well-characterized model protein lysozyme. The agreement with synchrotron data demonstrates the immediate relevance of SFX for analyzing the structure of the large group of difficult-to-crystallize molecules.

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ARTICLES

Femtosecond electronic response of atoms to ultra-intense X-rays

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An era of exploring the interactions of high-intensity, hard X-rays with matter has begun with the start-up of a hard-X-ray free-electron laser, the Linac Coherent Light Source (LCLS). Understanding how electrons in matter respond to ultra-intense X-ray radiation is essential for all applications. Here we reveal the nature of the electronic response in a free atom to unprecedented high-intensity, short-wavelength, high-fluence radiation (respectively 10^{18} W cm⁻², 1.5–0.6 nm, $\sim 10^5$ X-ray photons per Å²). At this fluence, the neon target inevitably changes during the course of a single femtosecond-duration X-ray pulse—by sequentially ejecting electrons—to produce fully-stripped neon through absorption of six photons. Rapid photoejection of inner-shell electrons produces 'hollow' atoms and an intensity-induced X-ray transparency. Such transparency, due to the presence of inner-shell vacancies, can be induced in all atomic, molecular and condensed matter systems at high intensity. Quantitative comparison with theory allows us to extract LCLS fluence and pulse duration. Our successful modelling of X-ray/atom interactions using a straightforward rate equation approach augurs favourably for extension to complex systems.

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PHYSICAL REVIEW LETTERS

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25 JUNE 2010

Ultraintense X-Ray Induced Ionization, Dissociation, and Frustrated Absorption in Molecular Nitrogen

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LETTER

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Single mimivirus particles intercepted and imaged with an X-ray laser

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X-ray lasers offer new capabilities in understanding the structure of biological systems, complex materials and matter under extreme conditions^{1–4}. Very short and extremely bright, coherent X-ray pulses can be used to outrun key damage processes and obtain a single diffraction pattern from a large macromolecule, a virus or a cell before the sample explodes and turns into plasma⁵. The continuous diffraction pattern of non-crystalline objects permits oversampling and direct phase retrieval⁶. Here we show that high-quality diffraction data can be obtained with a single X-ray pulse from a non-crystalline biological sample, a single mimivirus particle, which was injected into the pulsed beam of a hard-X-ray free-electron laser, the Linac Coherent Light Source⁷. Calculations indicate that the energy deposited into the virus by the pulse heated the particle to over 100,000 K after the pulse had left the sample. The reconstructed exit wavefront (image) yielded 32-nm full-period resolution in a single exposure and showed no measurable damage. The reconstruction indicates inhomogeneous arrangement of dense material inside the virion. We expect that significantly higher resolutions will be achieved in such experiments with shorter and brighter photon pulses focused to a smaller area. The resolution in such experiments can be further extended for samples available in multiple identical copies.

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picture of intense x-ray induced

Time-resolved pump-probe experiments at the LCLS

James M. Glownia^{1,2,*}, J. Cryan^{1,3}, J. Andreasson⁴, A. Belkacem⁵, N. Berrah⁶, C. I. Blaga⁷, C. Bostedt⁸, J. Bozek⁸, L. F. DiMauro⁷, L. Fang⁸, J. Frisch⁹, O. Gessner⁵, M. Gühr¹, J. Hajdu¹⁰, M. P. Hertlein¹⁰, M. Hoener^{6,10}, G. Huang¹⁰, O. Kornilov⁵, J. P. Marangos¹¹, A. M. March¹², B. K. McFarland^{1,2}, H. Merdji^{1,13}, V. S. Petrovic⁵, C. Raman¹⁴, D. Ray^{12,15}, D. A. Reis^{1,2}, M. Trigo¹, J. L. White¹, W. White⁸, R. Wilcox¹⁰, L. Young¹²

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Direct Measurements of the Ionization Potential Depression in a Dense Plasma

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The LCLS enables new scientific inquiries/discoveries

LETTER

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X-ray crystallography provides the vast majority of macromolecular structures, but the success of the method relies on growing crystals of sufficient size. In conventional measurements, the necessary increase in X-ray dose to record data from crystals that are too small leads to extensive damage before a diffraction signal can be recorded¹. It is particularly challenging to obtain large, well-diffracting crystals of membrane proteins, for which fewer than 300 unique structures have been determined despite their importance in all living cells. Here we present a method for structure determination where single-crystal X-ray diffraction 'snapshots' are collected from a fully hydrated stream of nanocrystals using femtosecond pulses from a hard-X-ray free-electron laser, the Linac Coherent Light Source². We prove this concept with nanocrystals of photosystem I, one of the largest membrane protein complexes³. More than 3,000,000 diffraction patterns were collected in this study, and a three-dimensional data set was assembled from individual photosystem I nanocrystals (~200 nm to 2 µm in size). We mitigate the problem of radiation damage in crystallography by using pulses briefer than the timescale of most damage processes⁴. This offers a new approach to structure determination of macromolecules that do not yield crystals of sufficient size for studies using conventional radiation sources or are particularly sensitive to radiation damage.



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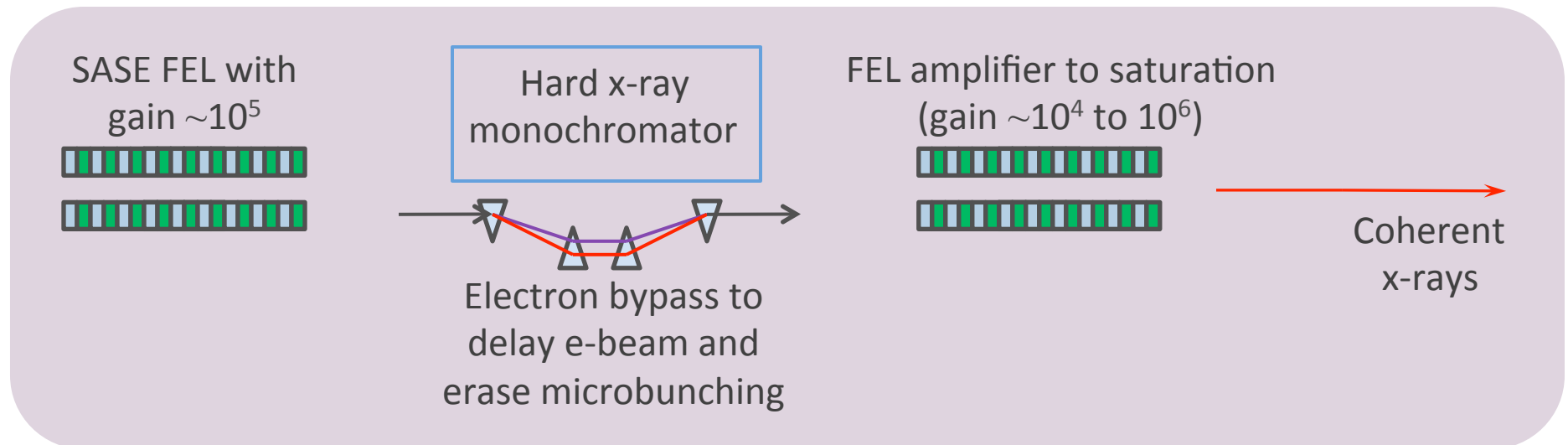
The need to seed

- SASE is initiated by electron beam shot noise
 - ➔ many longitudinal modes & normalized bandwidth $\Delta\omega/\omega \sim \rho$
- Longitudinal coherence/spectral brightness can be improved by seeding the FEL with a coherent signal at the wavelength of interest
- Motivation from experimental users may include
 1. Increase spectral brightness
 - Increase number of photons in a specified narrow bandwidth
 - Decrease noise signals due to nearby spectral components
 2. Produce temporally coherent x-rays
 3. Increase total number of photons by judicious tapering
 - Seeded field saturates more uniformly, and tapering the undulator strength can more efficiently extract additional energy from the e-beam



Self-seeding

Self-seeding uses SASE + monochromator to generate coherent seed



E.L. Saldin, E.A. Schneidmiller, Yu.V. Shvyd'ko, and M.V. Yurkov, *NIMA* **475**, 357 (2001)

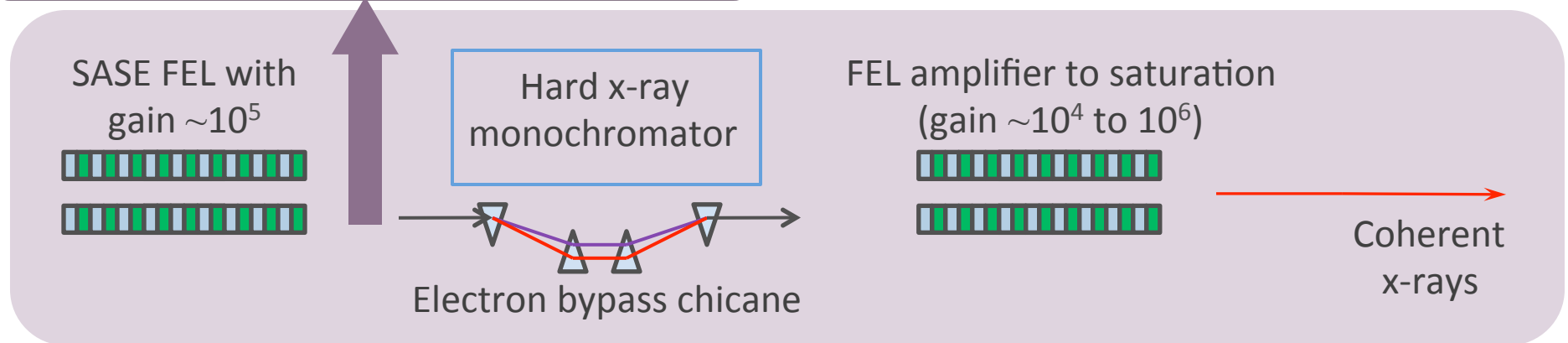
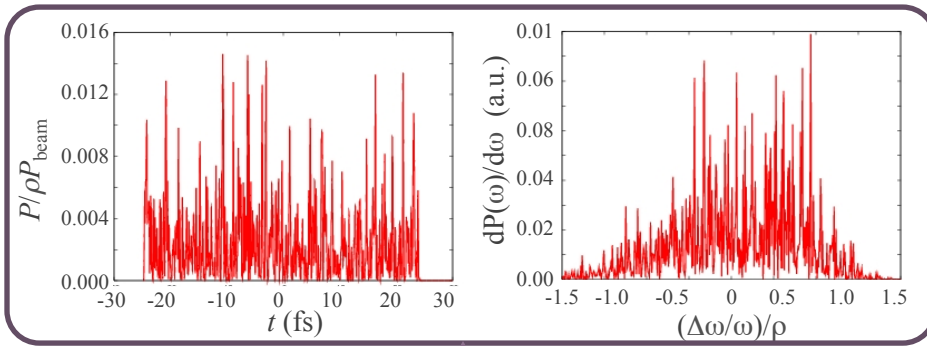
Y. Ding, Z. Huang, and R. D. Ruth, *Phys. Rev. ST Accel. Beams* **13**, 060703 (2010)

G. Geloni, V. Kocharyan, and E.L. Saldin, *J. Modern Optics* **58**, 1391 (2011)



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Self-seeding

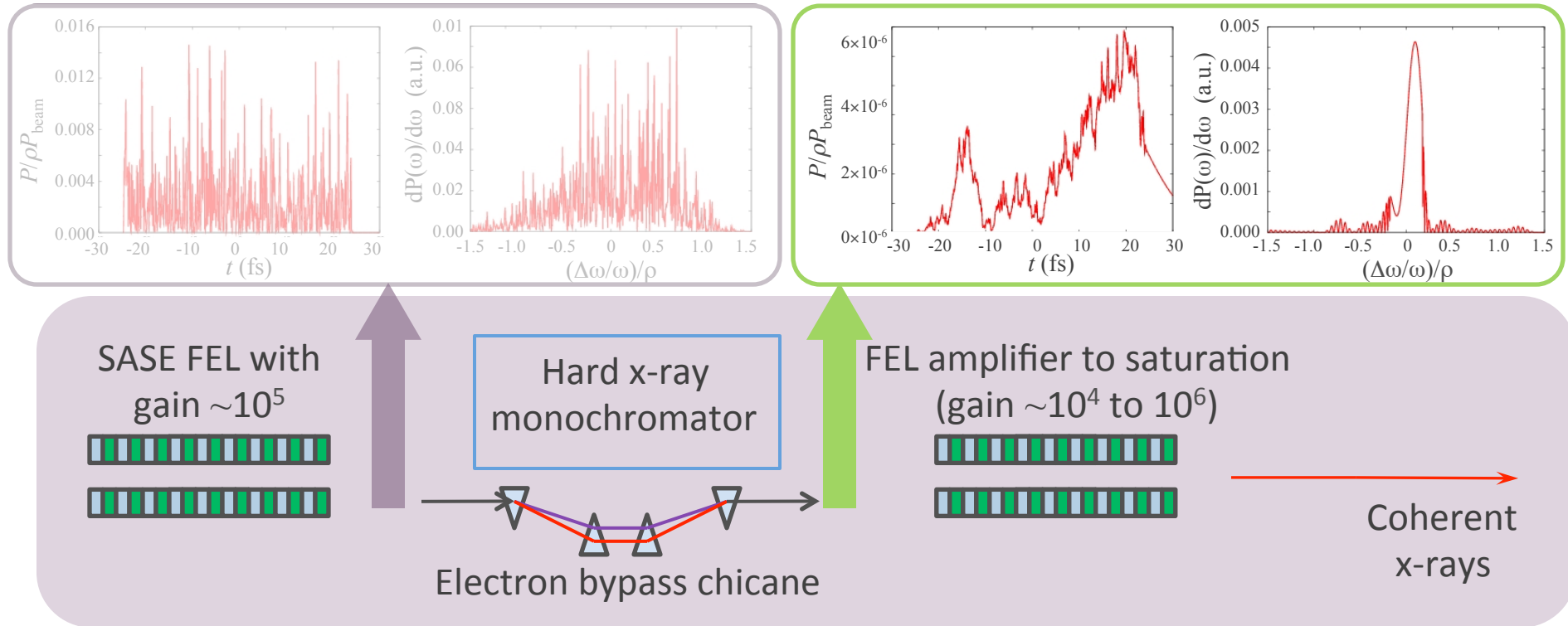


- Power large enough so that monochromatic signal dominates the seeding of SASE by electron beam shot noise
- FEL-induced energy spread on beam must remain small (well before nonlinear regime)

Example uses LCLS-type parameters with $\rho = 5 \times 10^{-4}$ and $(\Delta\omega/\omega)_{\text{mono}} = 2 \times 10^{-5}$



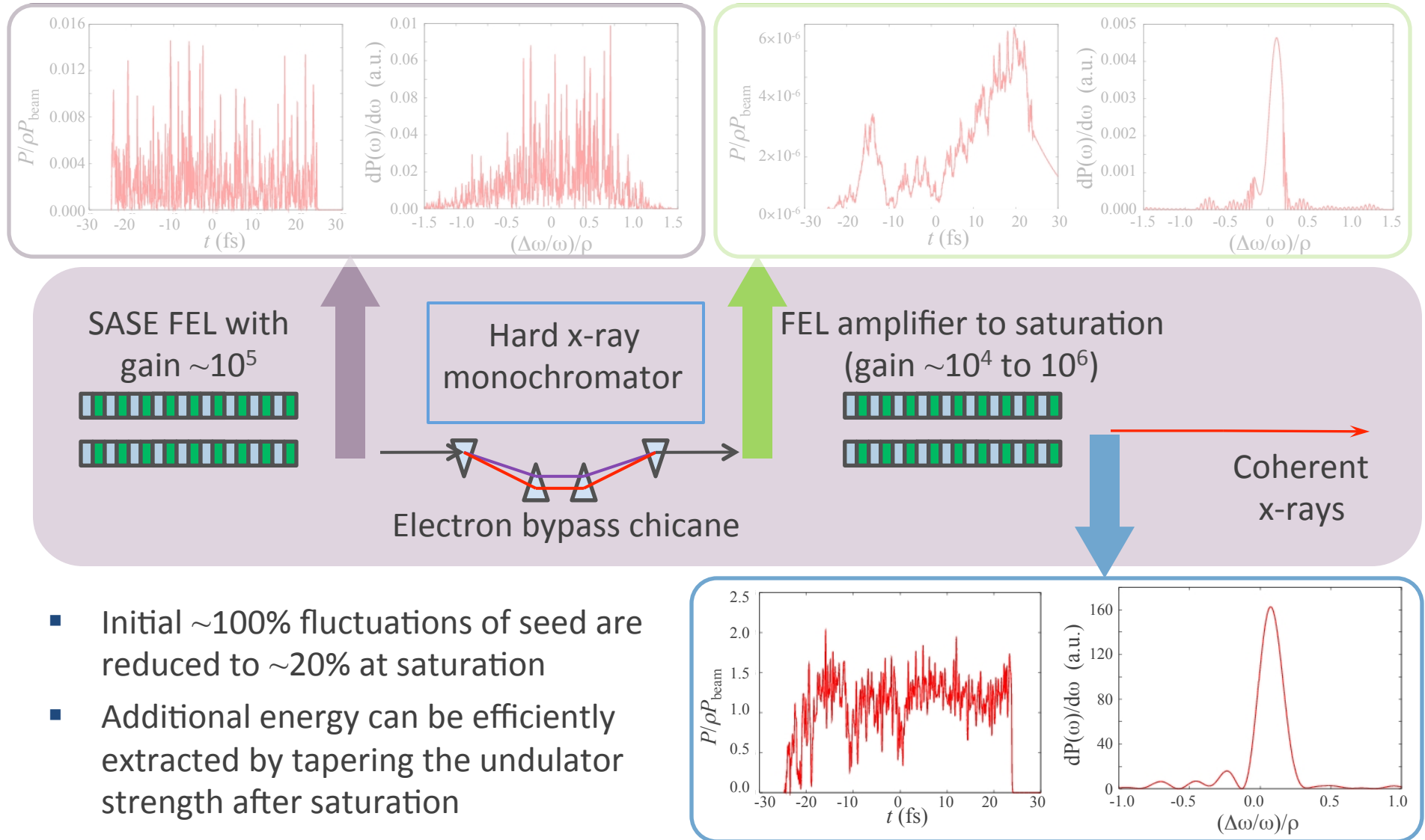
Self-seeding



- Monochromator selects narrow bandwidth seed whose energy fluctuates by $\sim 100\%$
- Electron beam is delayed to overlap and amplify radiation in downstream undulator
- Chicane erases microbunching of SASE

Example uses LCLS-type parameters with $\rho = 5 \times 10^{-4}$ and $(\Delta\omega/\omega)_{\text{mono}} = 2 \times 10^{-5}$

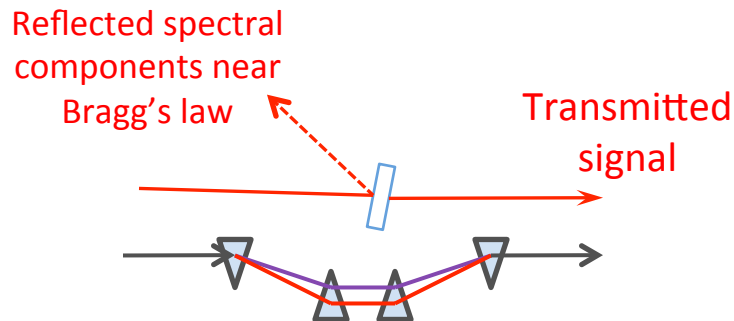
Self-seeding



Wake monochromator for self-seeding of short x-ray pulses

Produces seed using time dependence of forward Bragg diffraction from a single crystal, i.e., time response of the crystal transmission function

Single crystal wake mono



~3-4 m chicane washes out microbunching and delays electrons requires tens of fs

† G. Geloni, V. Kocharyan, and E.L. Saldin, *J. Modern Optics* **58**, 1391 (2011)



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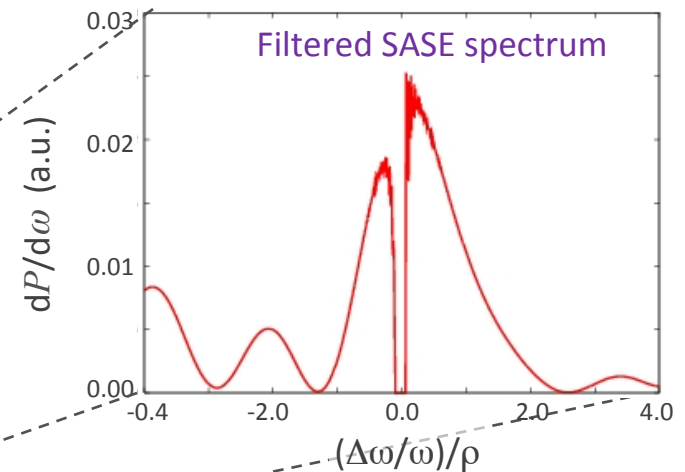
Produces seed using time dependence of forward Bragg diffraction from a single crystal, i.e., time response of the crystal transmission function

Single crystal wake mono

Reflected spectral components near Bragg's law

Transmitted signal

~3-4 m chicane washes out microbunching and delays electrons requires tens of fs

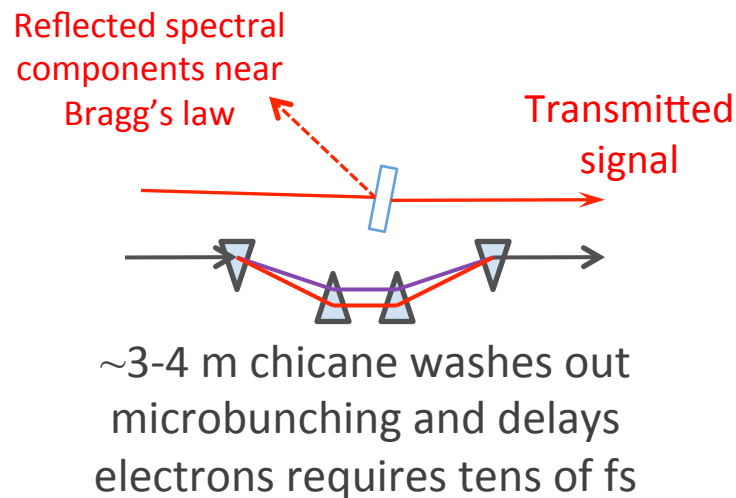


† G. Geloni, V. Kocharyan, and E.L. Saldin, *J. Modern Optics* **58**, 1391 (2011)

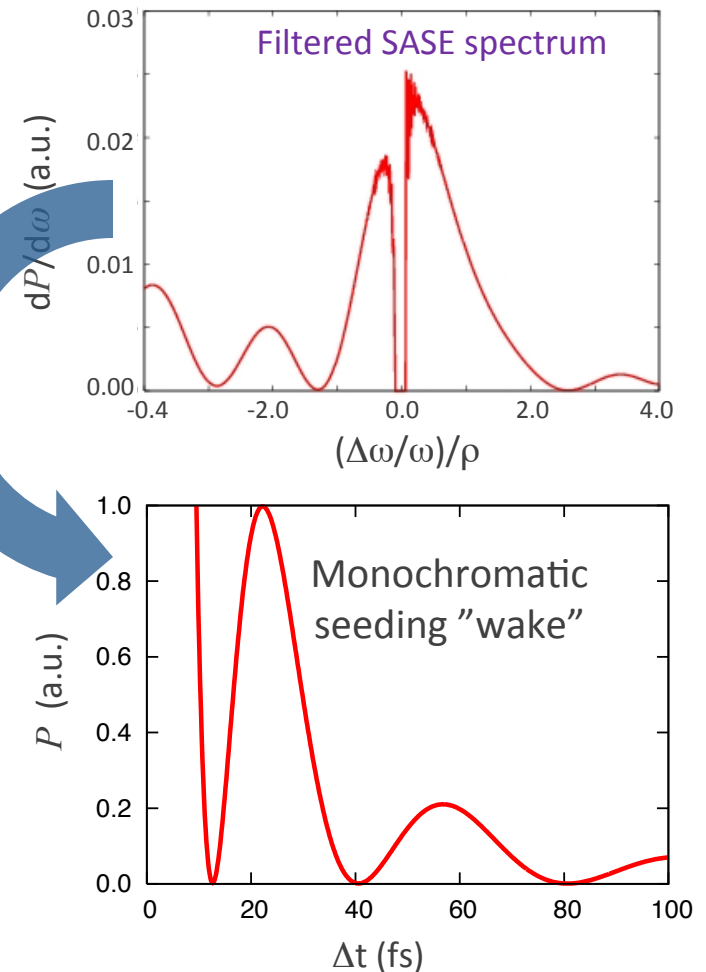
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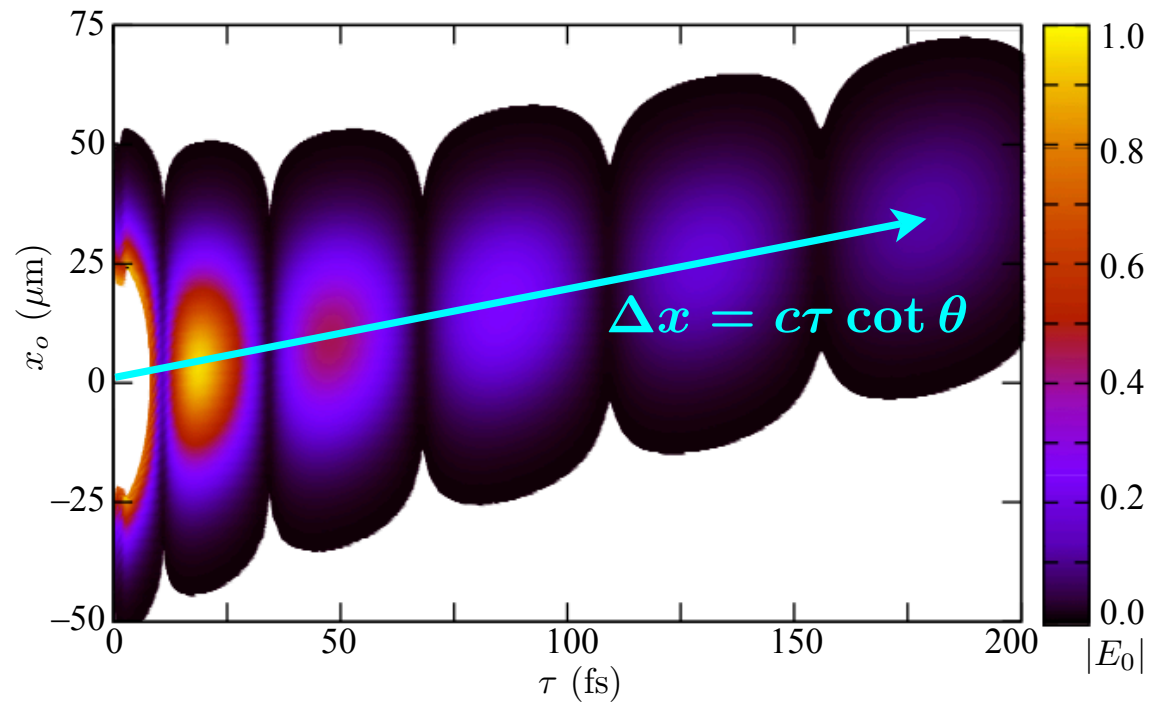


Transmission function gives rise to broad and delayed temporal features



† G. Geloni, V. Kocharyan, and E.L. Saldin, *J. Modern Optics* **58**, 1391 (2011)

Transverse displacement of self-seeding “wake”



Delayed seeding field is also transversely displaced
according to $\Delta x = c\tau \cot \theta$

† R.R. Lindberg and Yu. Shvyd'ko, *Phys. Rev. ST-Accel. Beams* **15**, 050706 (2012)

Implementation at the LCLS

Great synthesis of wake monochromator idea with the fact that the LCLS can benefit from its conservative design – there's enough undulators for self-seeding to both produce and subsequently amplify its signal[†]

[†] G. Geloni, V. Kocharyan, and E.L. Saldin, “Cost-effective way to enhance the capabilities of the LCLS baseline,” DESY 10-133, arXiv:1008.3036 (2010)



Implementation at the LCLS

Great synthesis of wake monochromator idea with the fact that the LCLS can benefit from its conservative design – there's enough undulators for self-seeding to both produce and subsequently amplify its signal[†]

Requirements for monochromator position:

1. Require enough SASE undulators to produce sufficient seeding power (1 MW $\gg$ 10 kW of effective SASE seeding from e-beam shot noise)
2. Limit SASE section so as to minimize energy spread increase/beam quality degradation due to the FEL process

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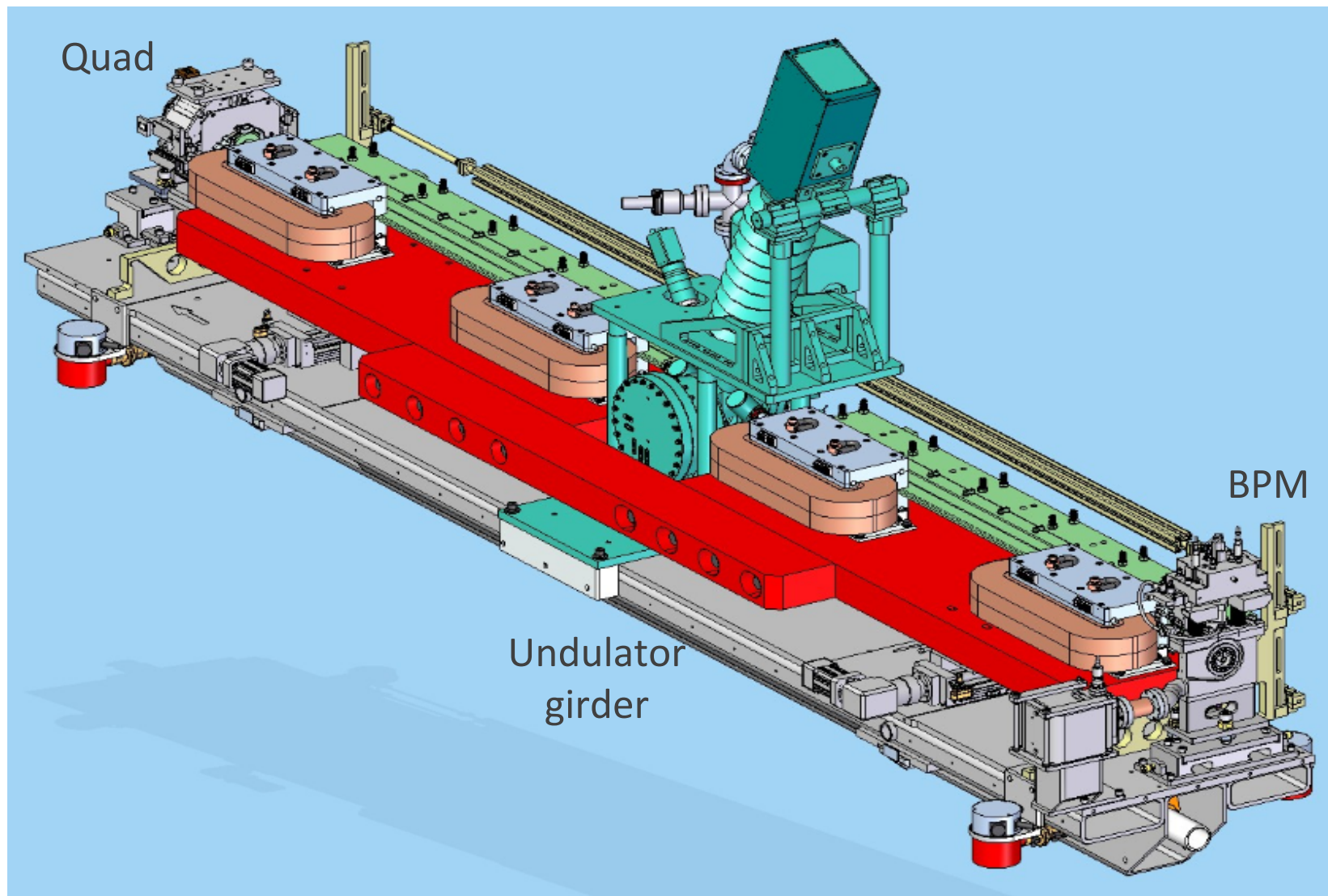
1. Require enough SASE undulators to produce sufficient seeding power (1 MW $\gg$ 10 kW of effective SASE seeding from e-beam shot noise)
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It was chosen to replace Undulator 16 with the monochromator system:
4-dipole chicane and the x-ray wake monochromator including
diamond crystal in Bragg transmission

[†] G. Geloni, V. Kocharyan, and E.L. Saldin, "Cost-effective way to enhance the capabilities of the LCLS baseline," DESY 10-133, arXiv:1008.3036 (2010)



HXRSS design for Undulator 16

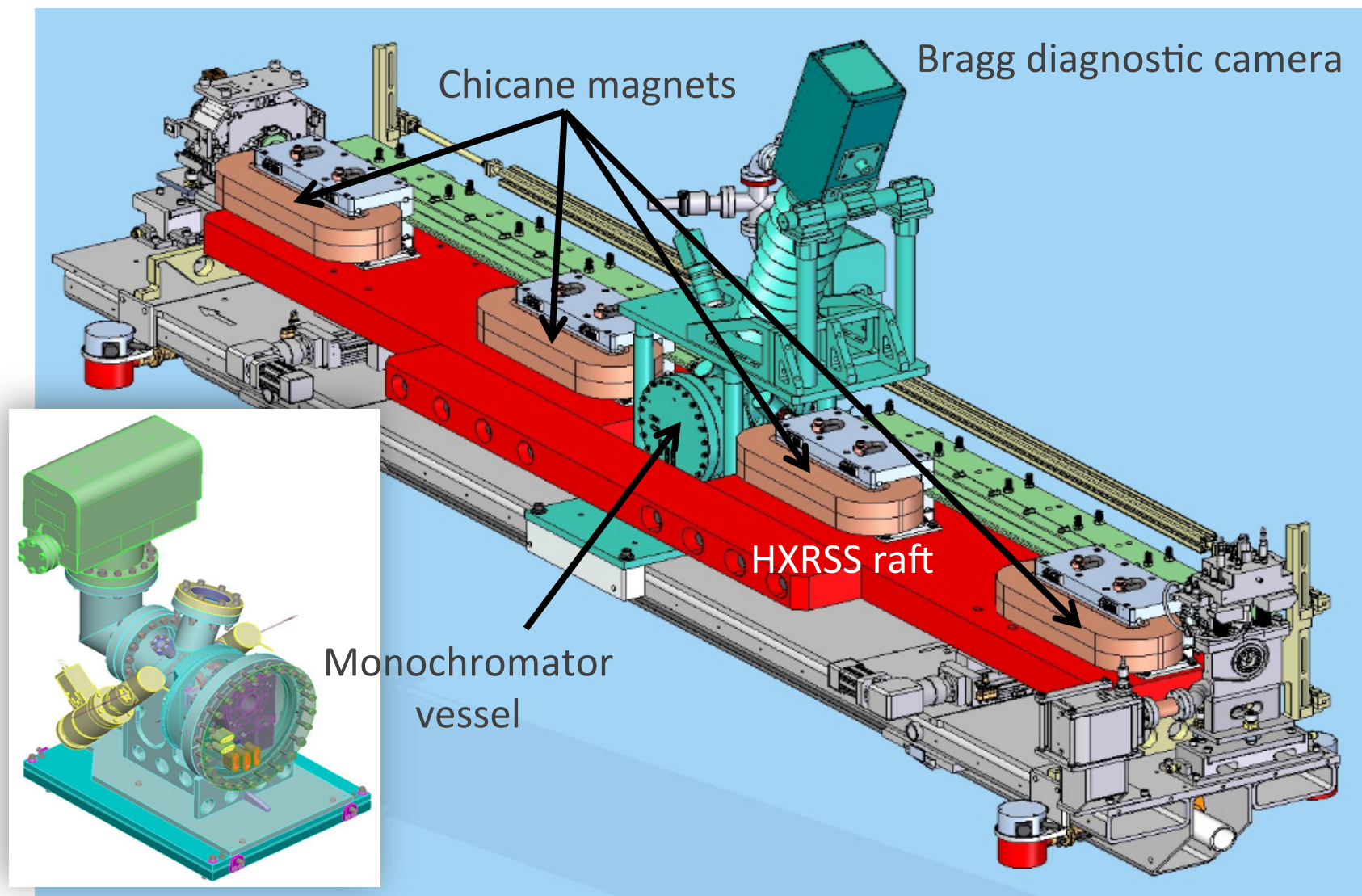


† Amman, Shultz, Trakhtenberg

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HXRSS design for Undulator 16

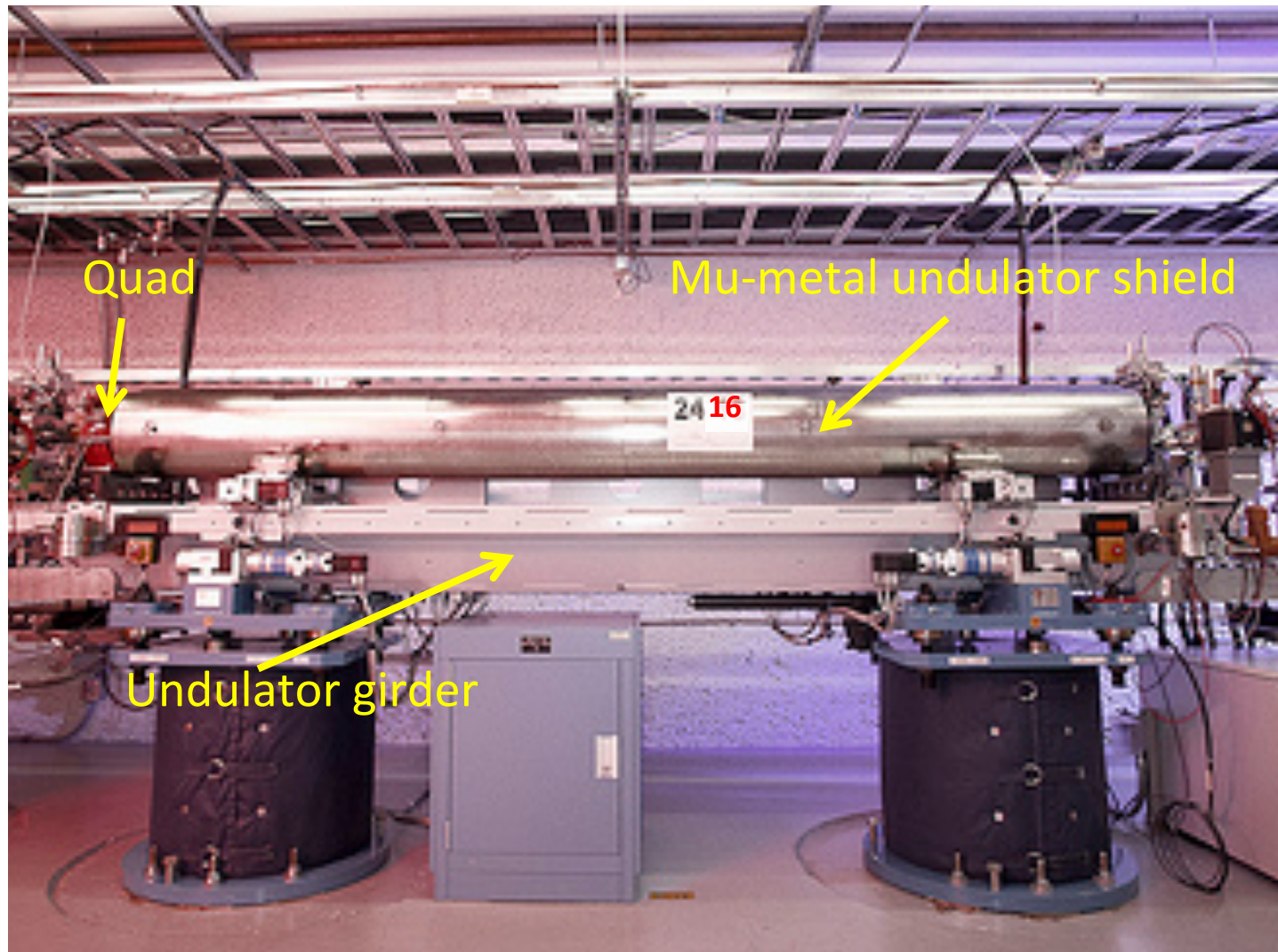


† Amman, Shultz, Trakhtenberg

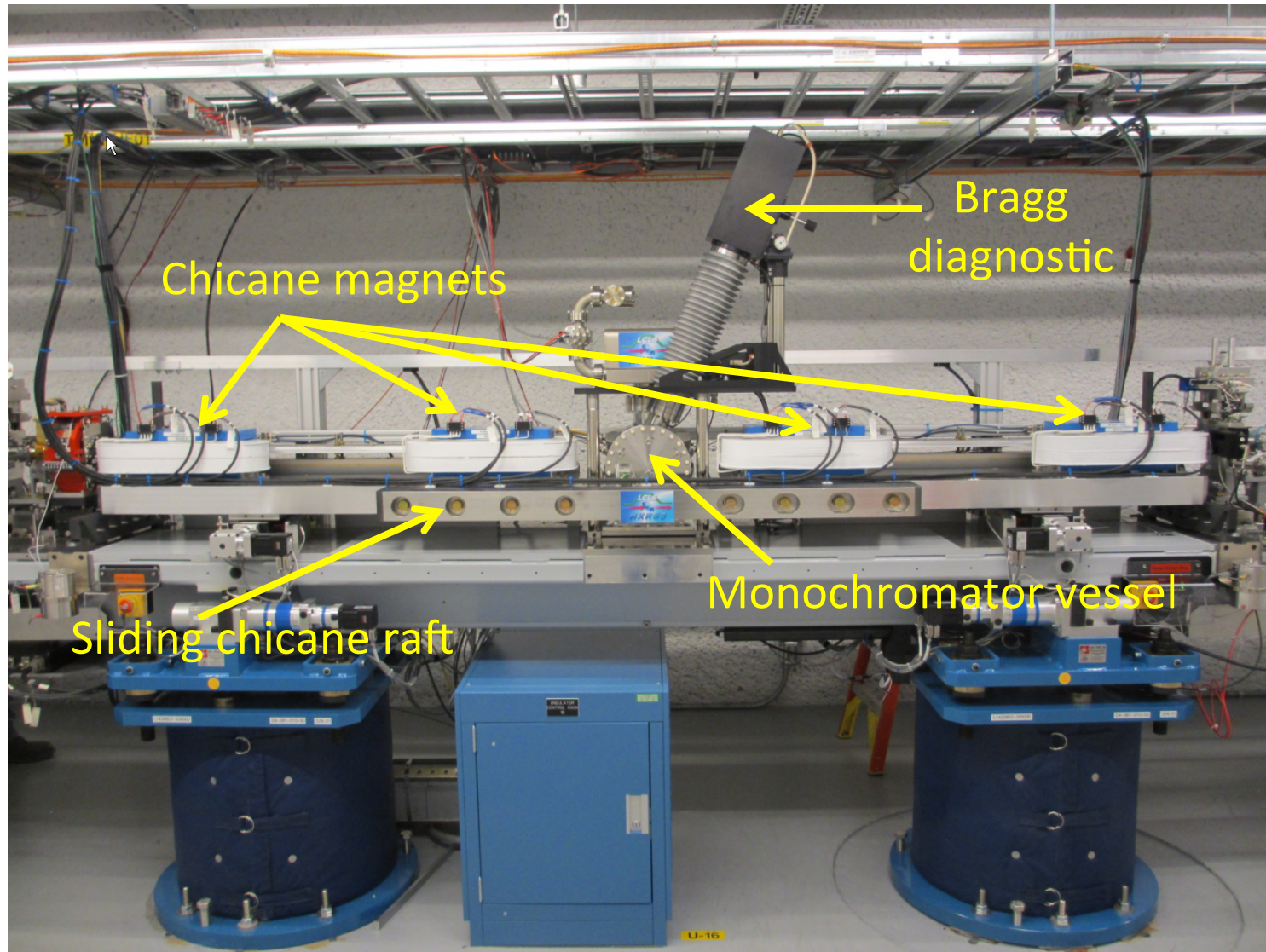
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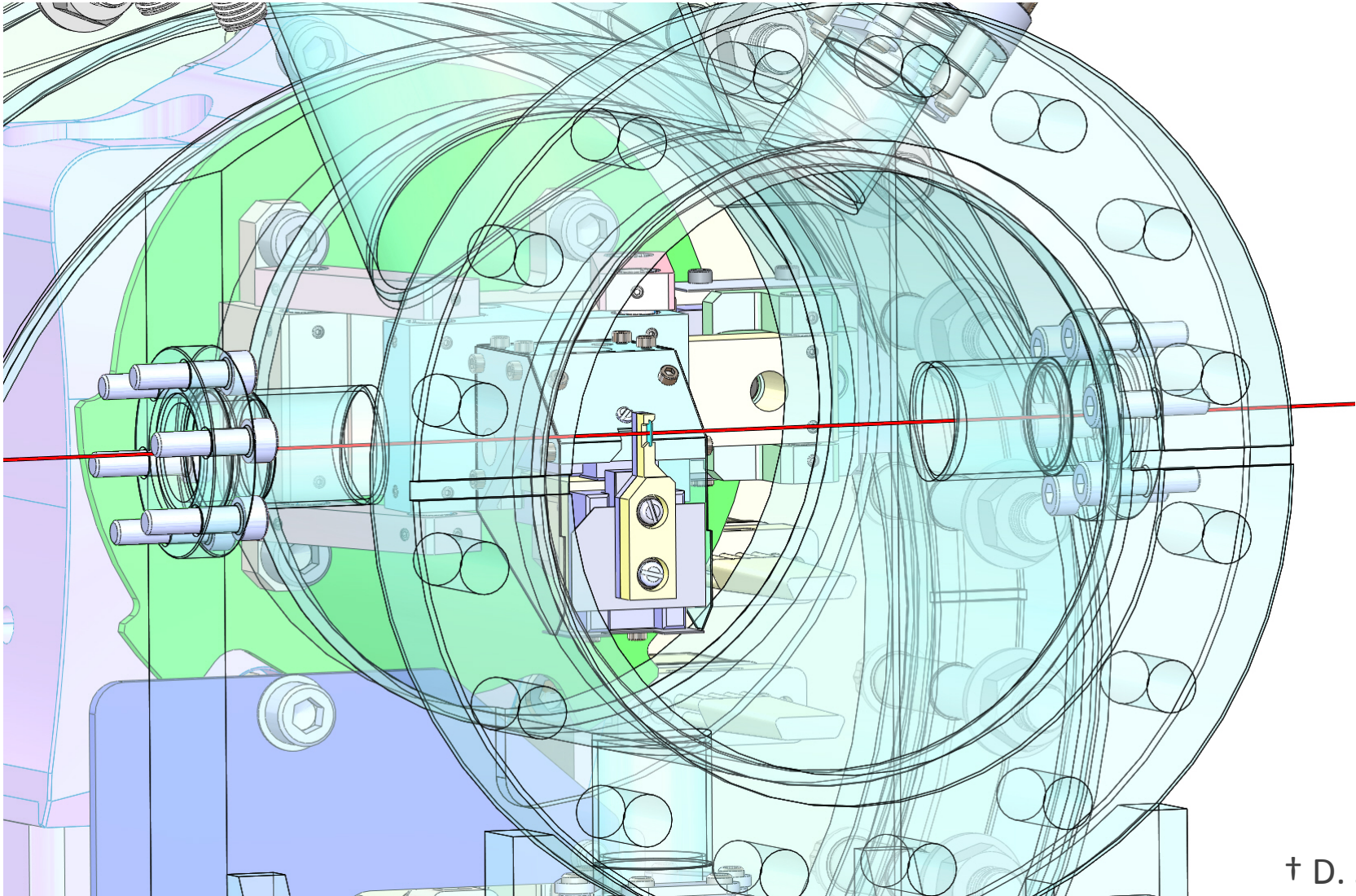
Standard LCLS undulator (of 33 total)



Monochromator and chicane @ Undulator 16

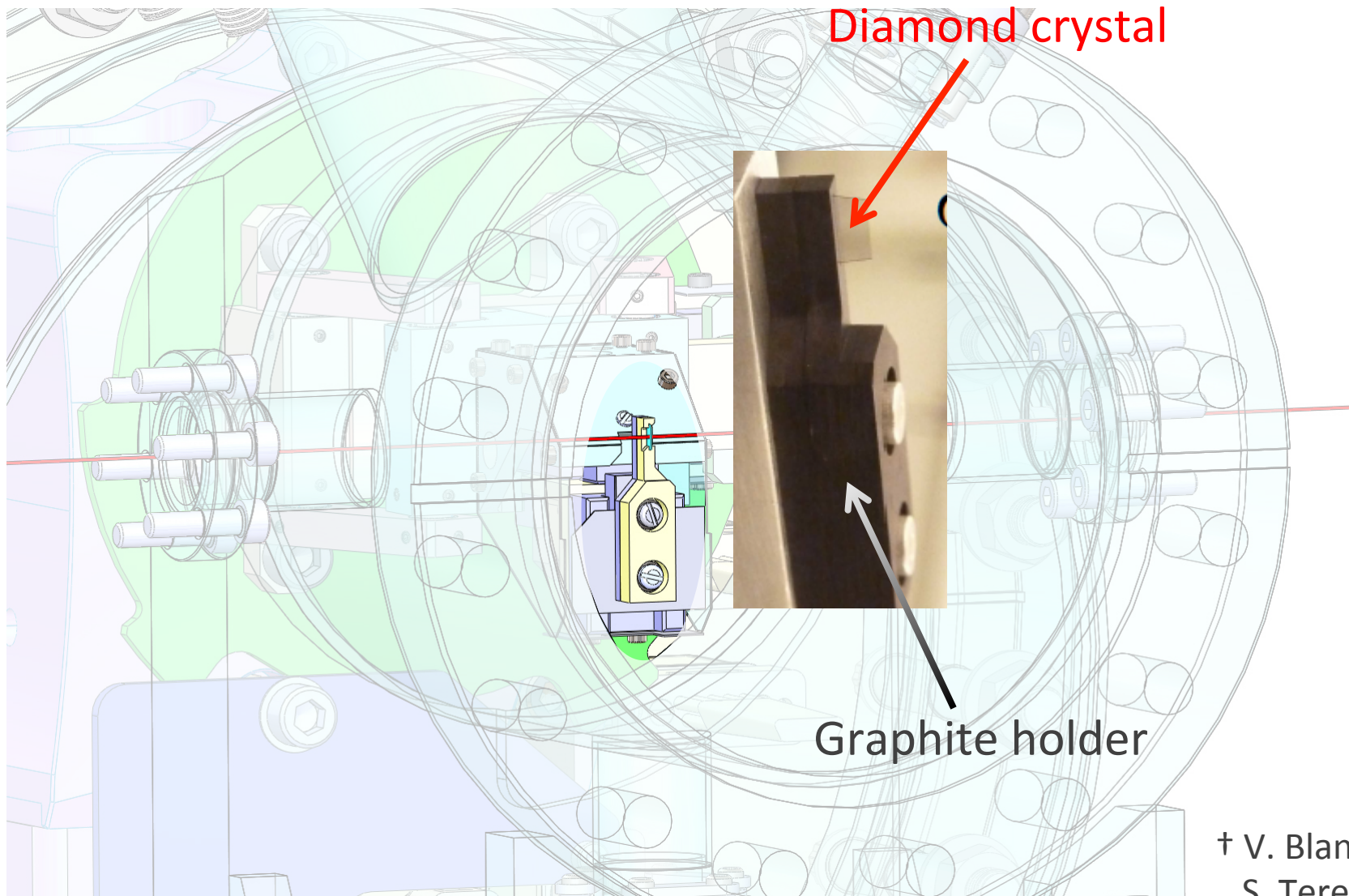


Diamond holder and positioning system



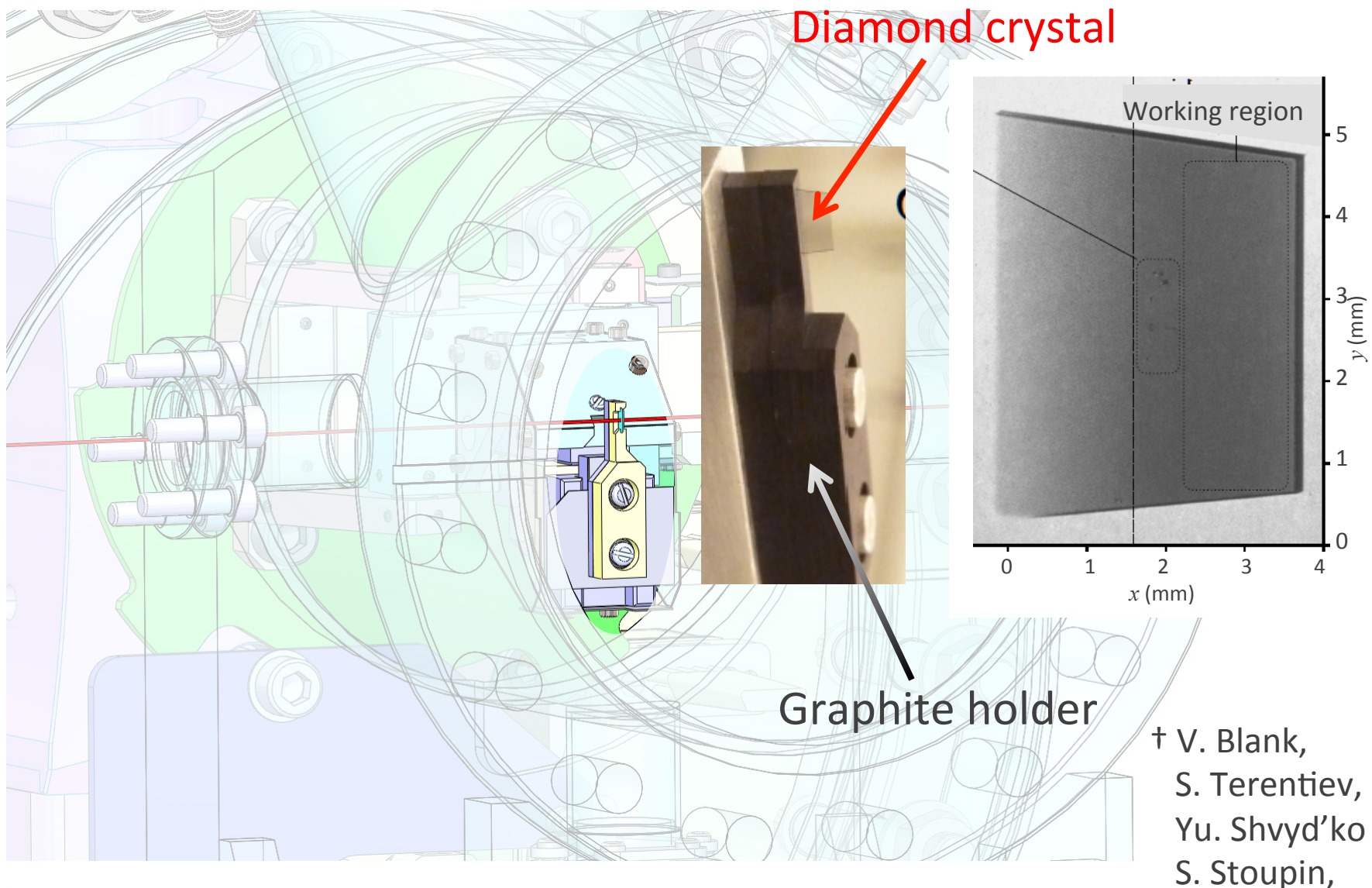
† D. Shu

Diamond holder and positioning system



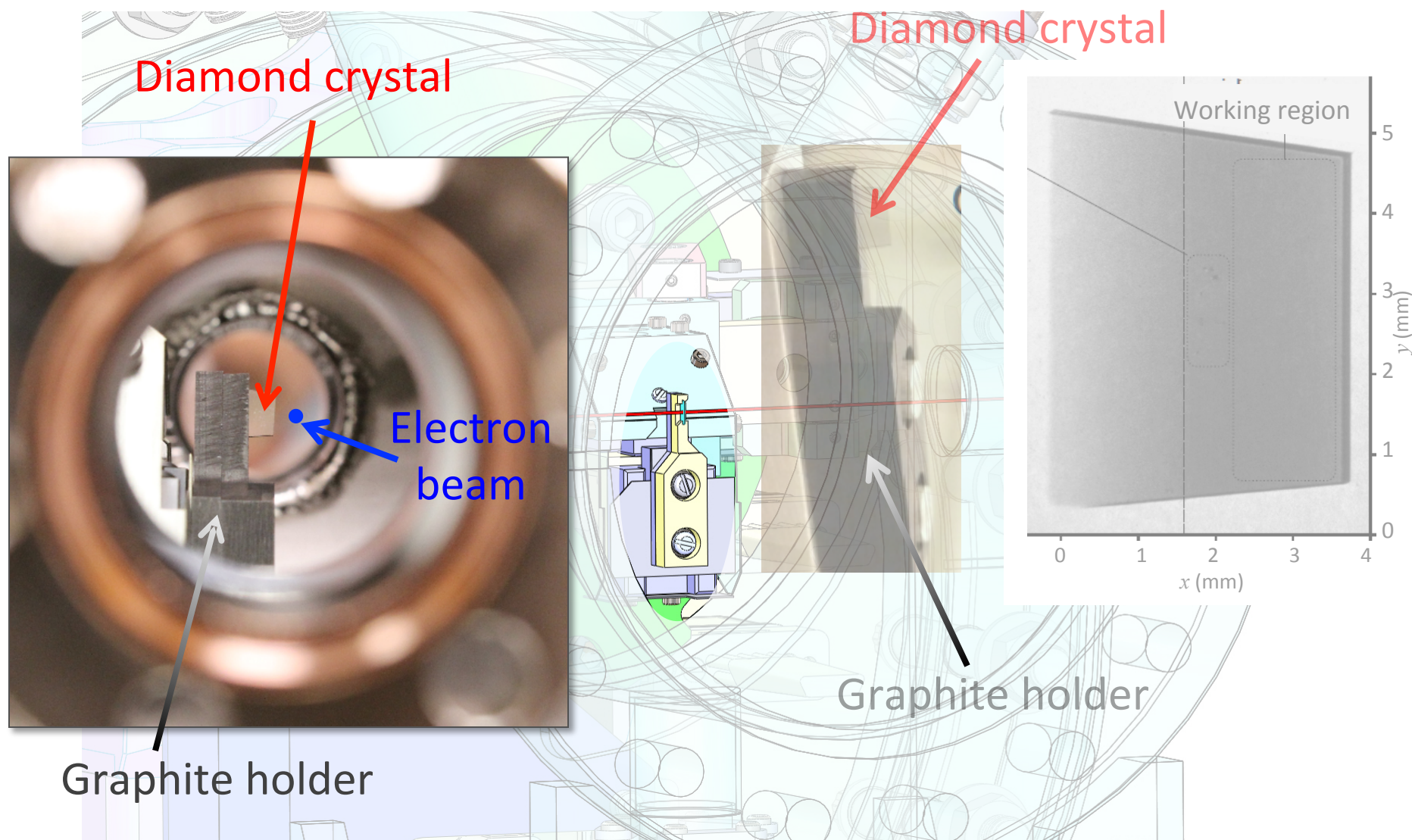
† V. Blank and
S. Terentiev

Diamond holder and positioning system

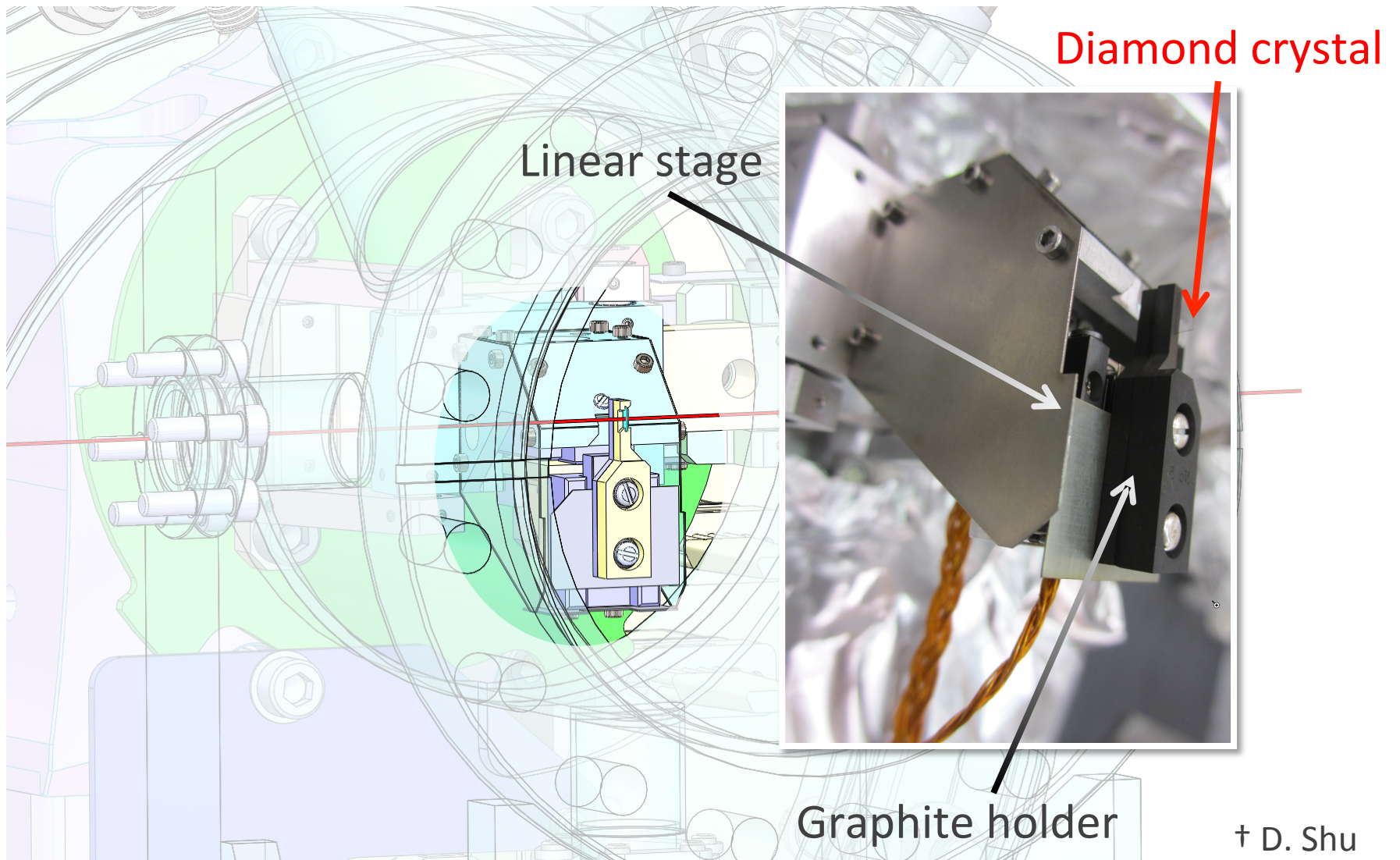


† V. Blank,
S. Terentiev,
Yu. Shvyd'ko
S. Stoupin,

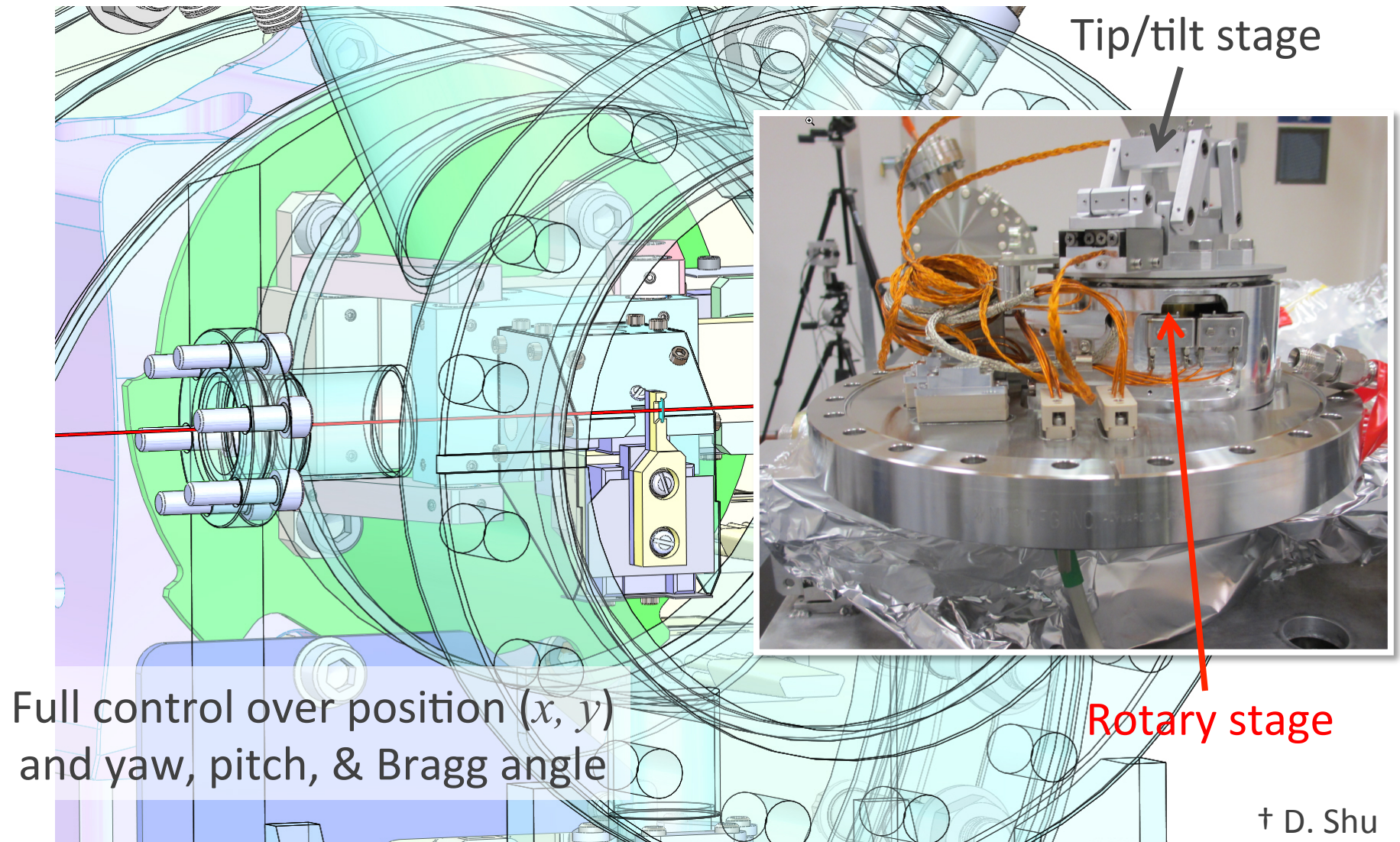
Diamond holder and positioning system



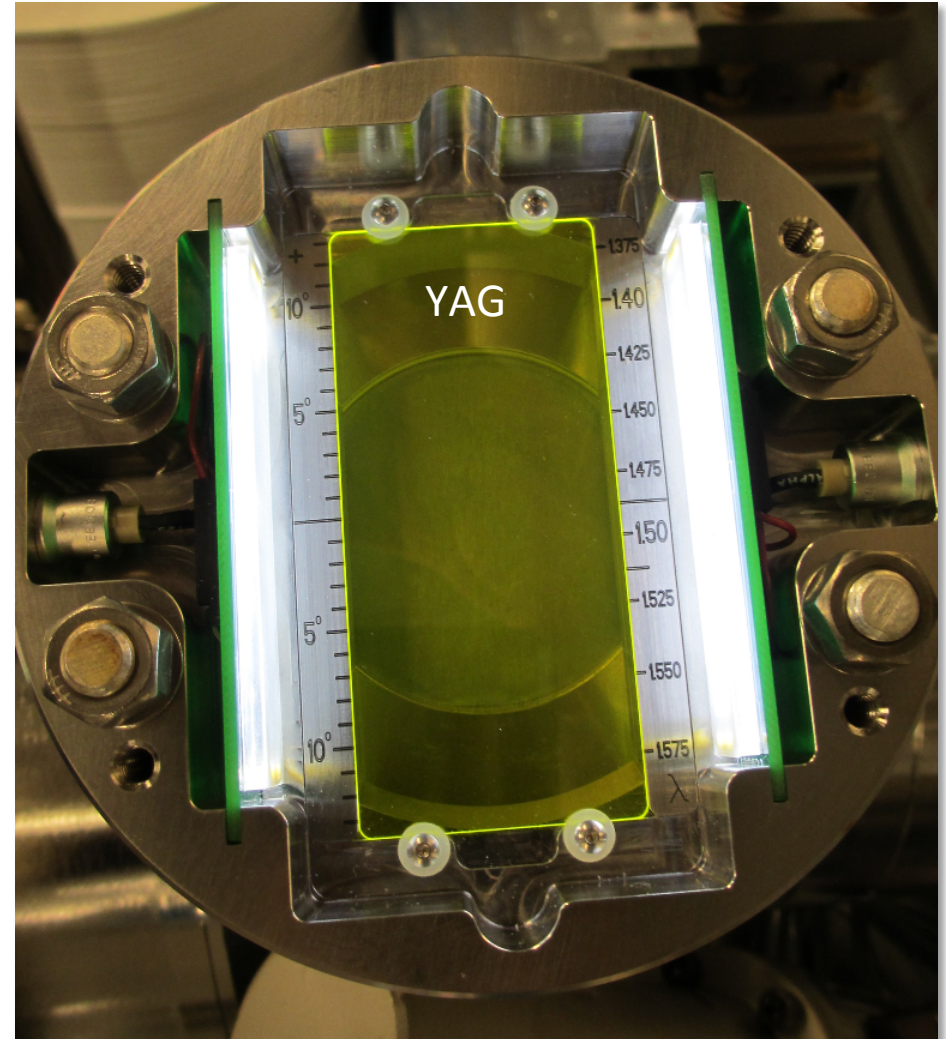
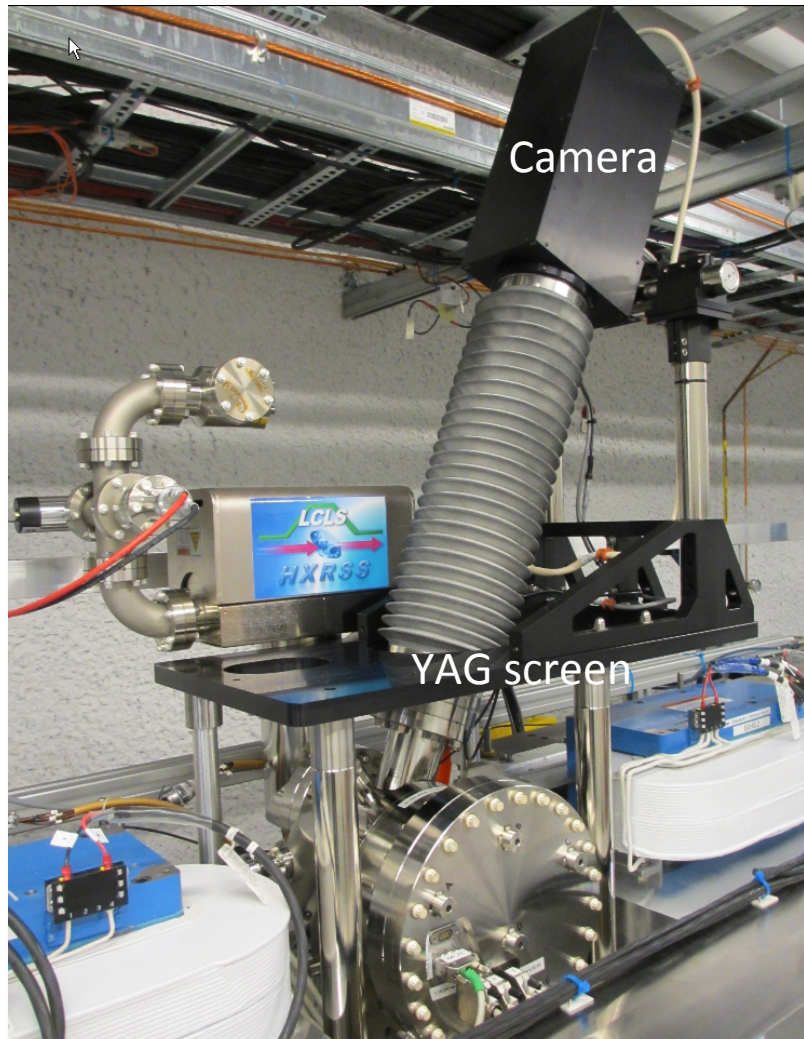
Diamond holder and positioning system



Diamond holder and positioning system



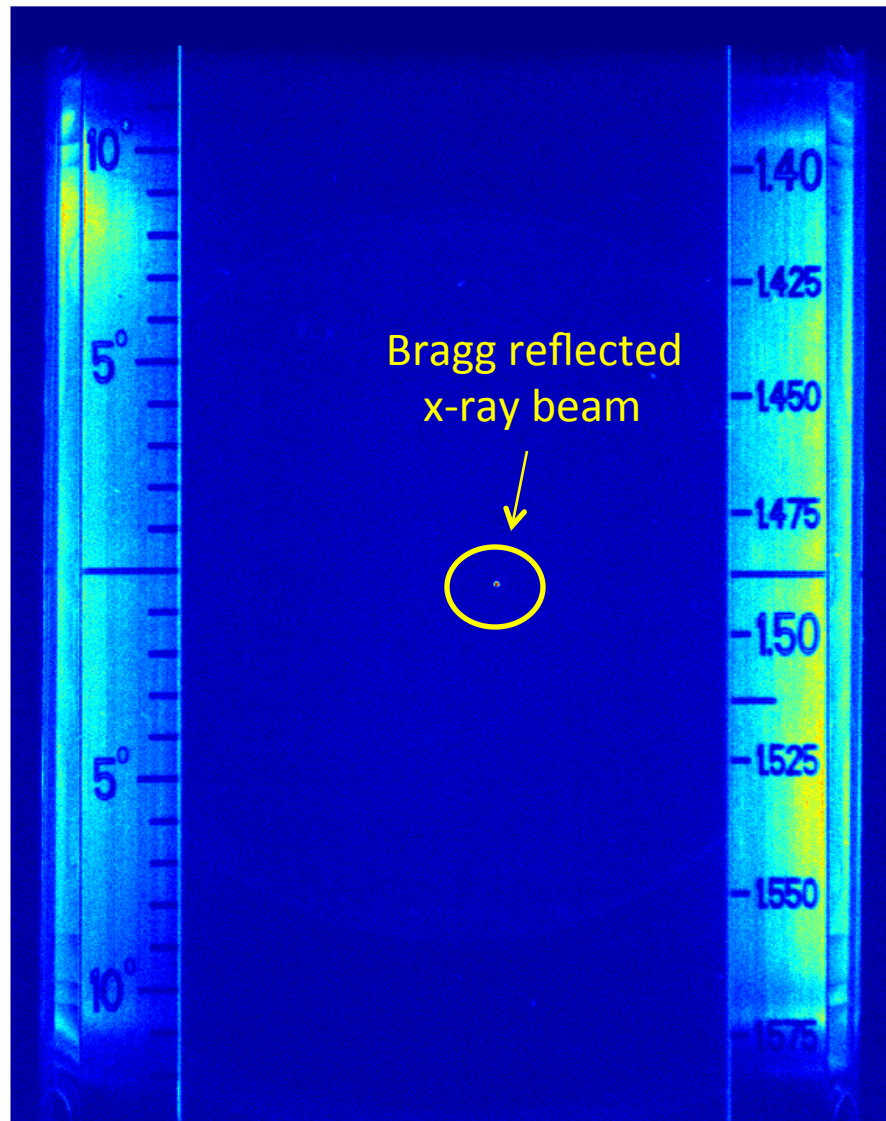
Bragg reflection diagnostic



As suggested in G. Geloni, V. Kocharyan, and E.L. Saldin, DESY 10-133, arXiv:1008.3036 (2010)

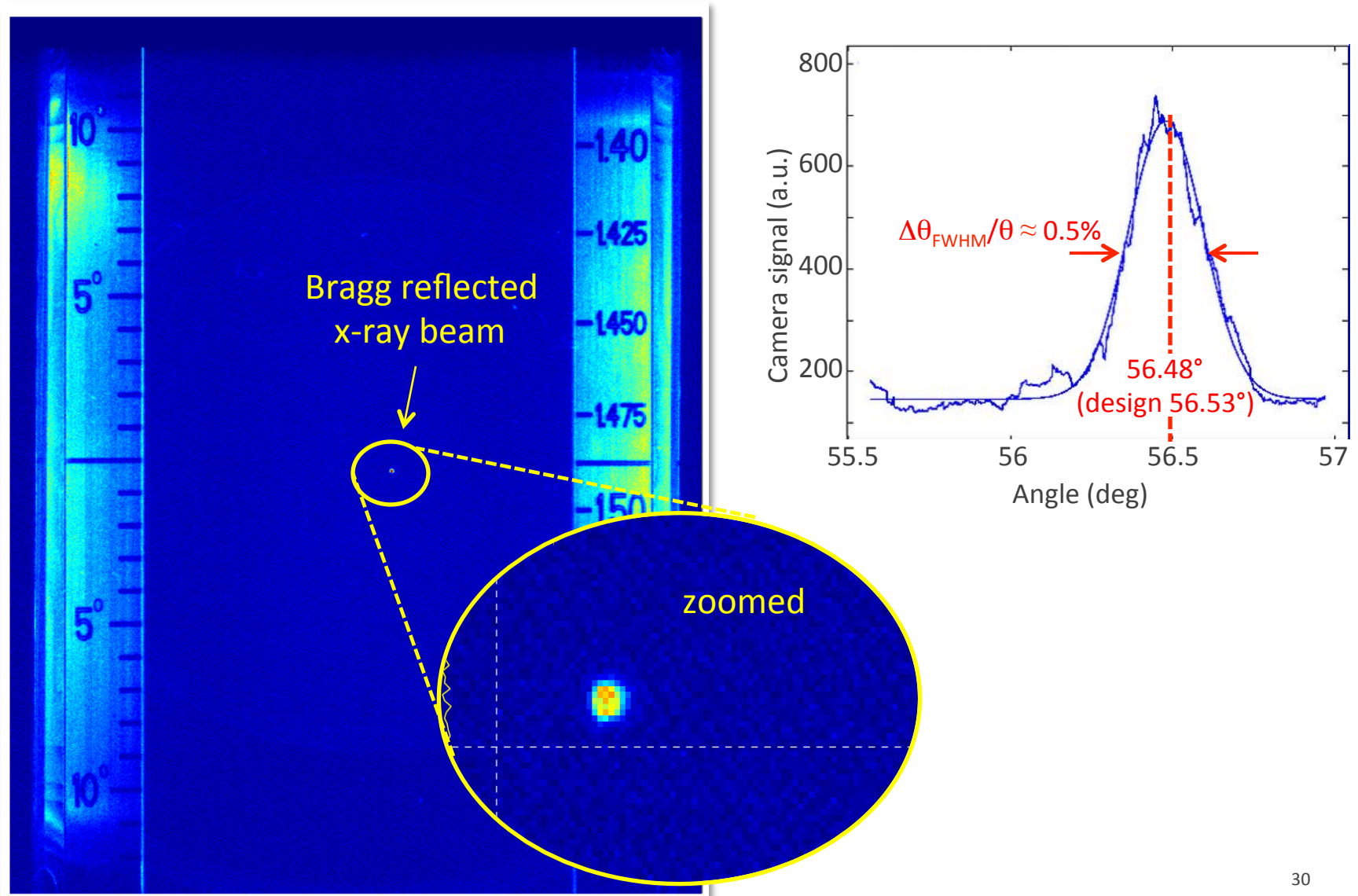
† B. Berg

First signal of successful mono operation

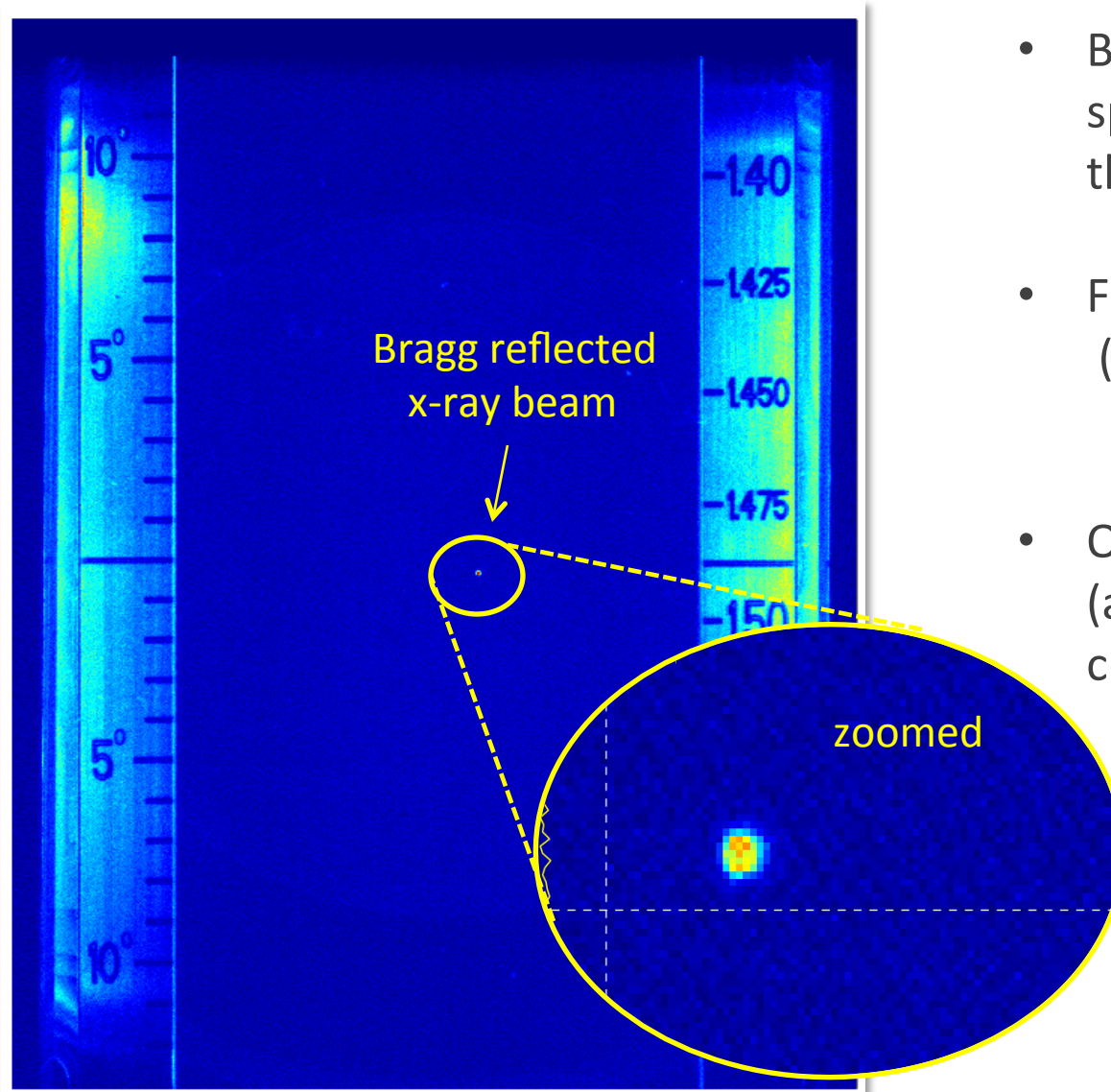


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First signal of successful mono operation



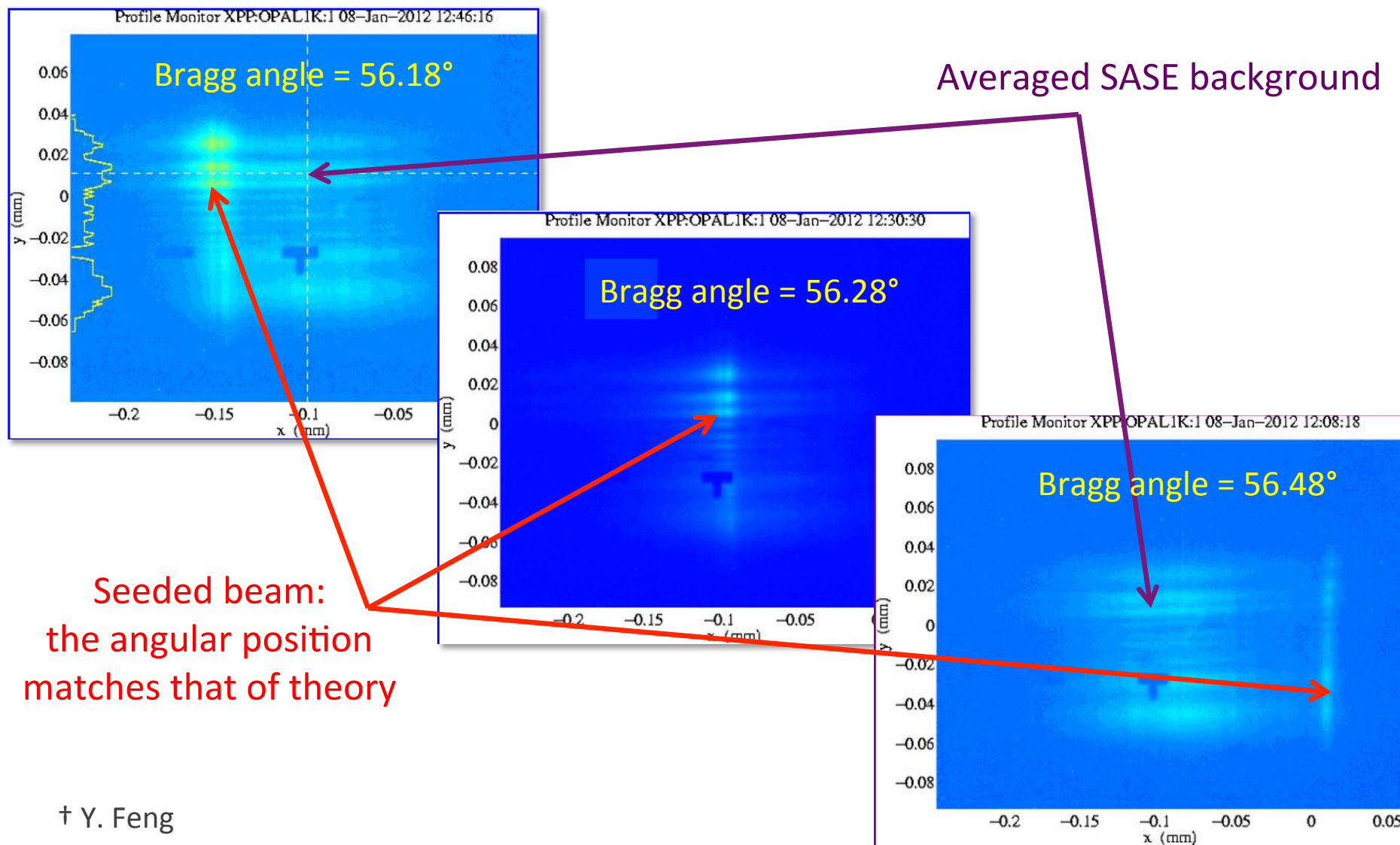
First signal of successful mono operation



- Bragg reflected signal of spectral components in the transmission “notch”
- Fluctuations are 100% (single spectral mode before saturation)
- Of limited use for other (asymmetric or Laue) crystal reflections

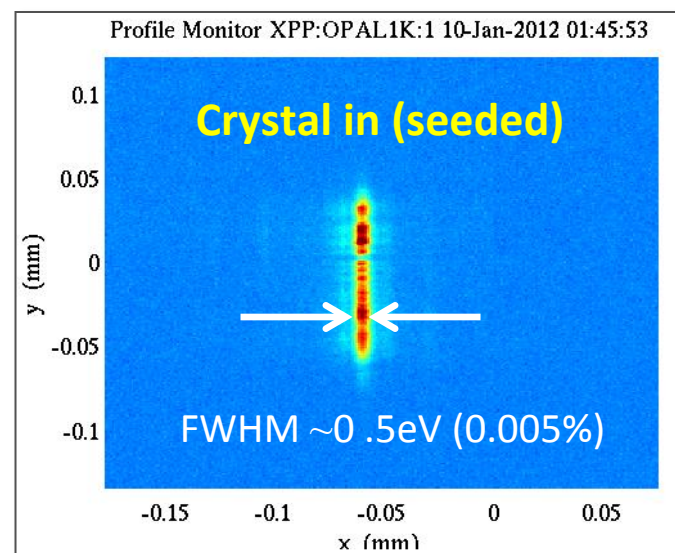
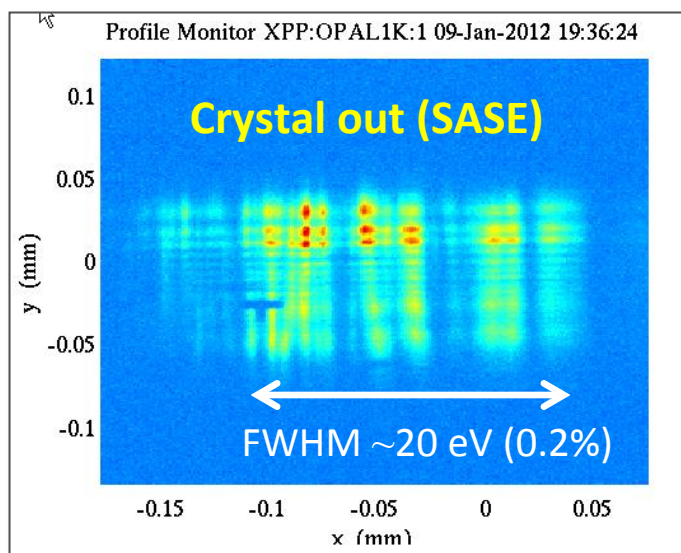


First indications of seeding from averaged spectra



† Y. Feng

Slow improvements in power of seeded signal

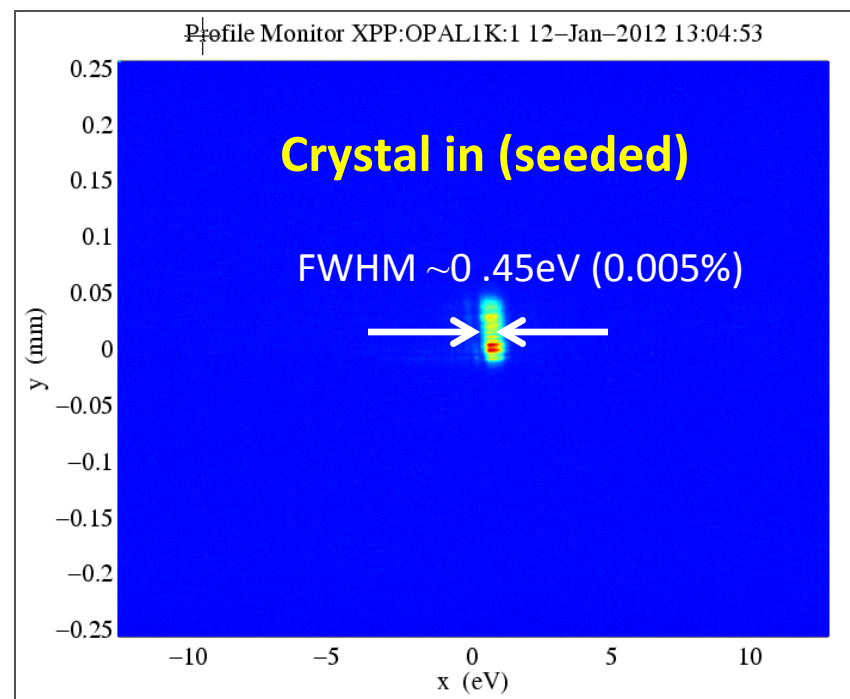
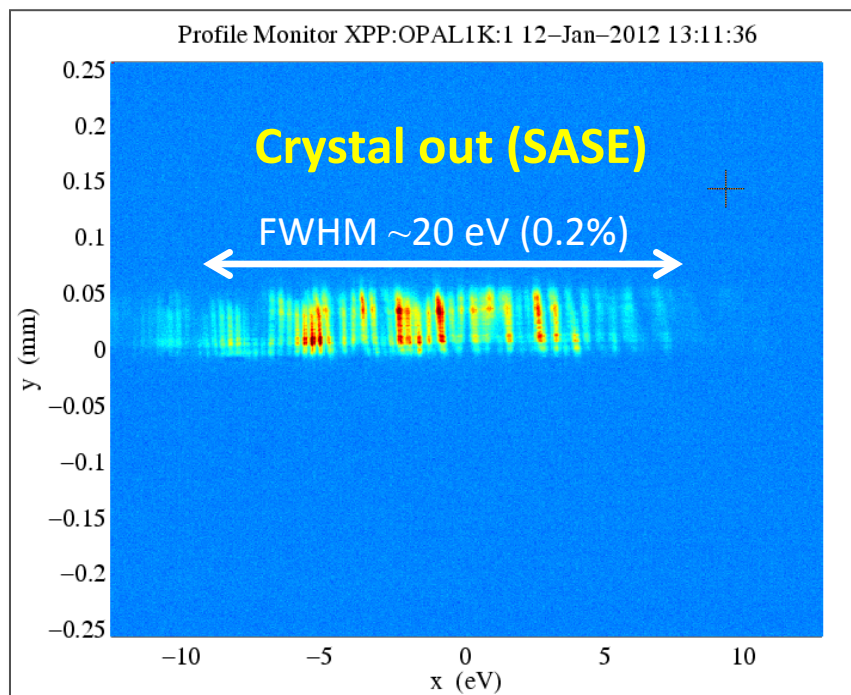


† Y. Feng



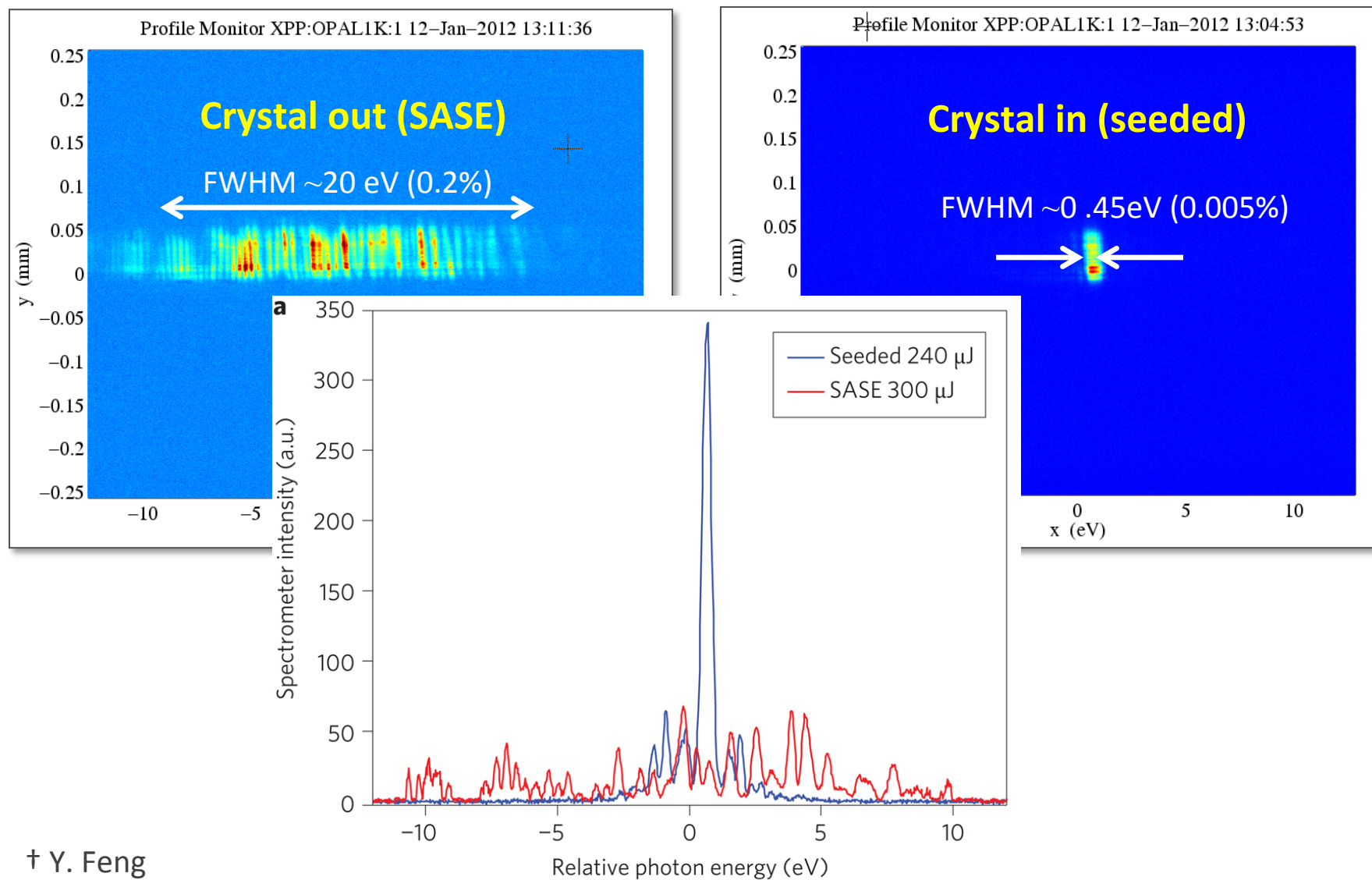
The Advanced Photon Source is an Office of Science User Facility operated for the U.S. Department of Energy Office of Science by Argonne National Laboratory

Slow improvements in power of seeded signal



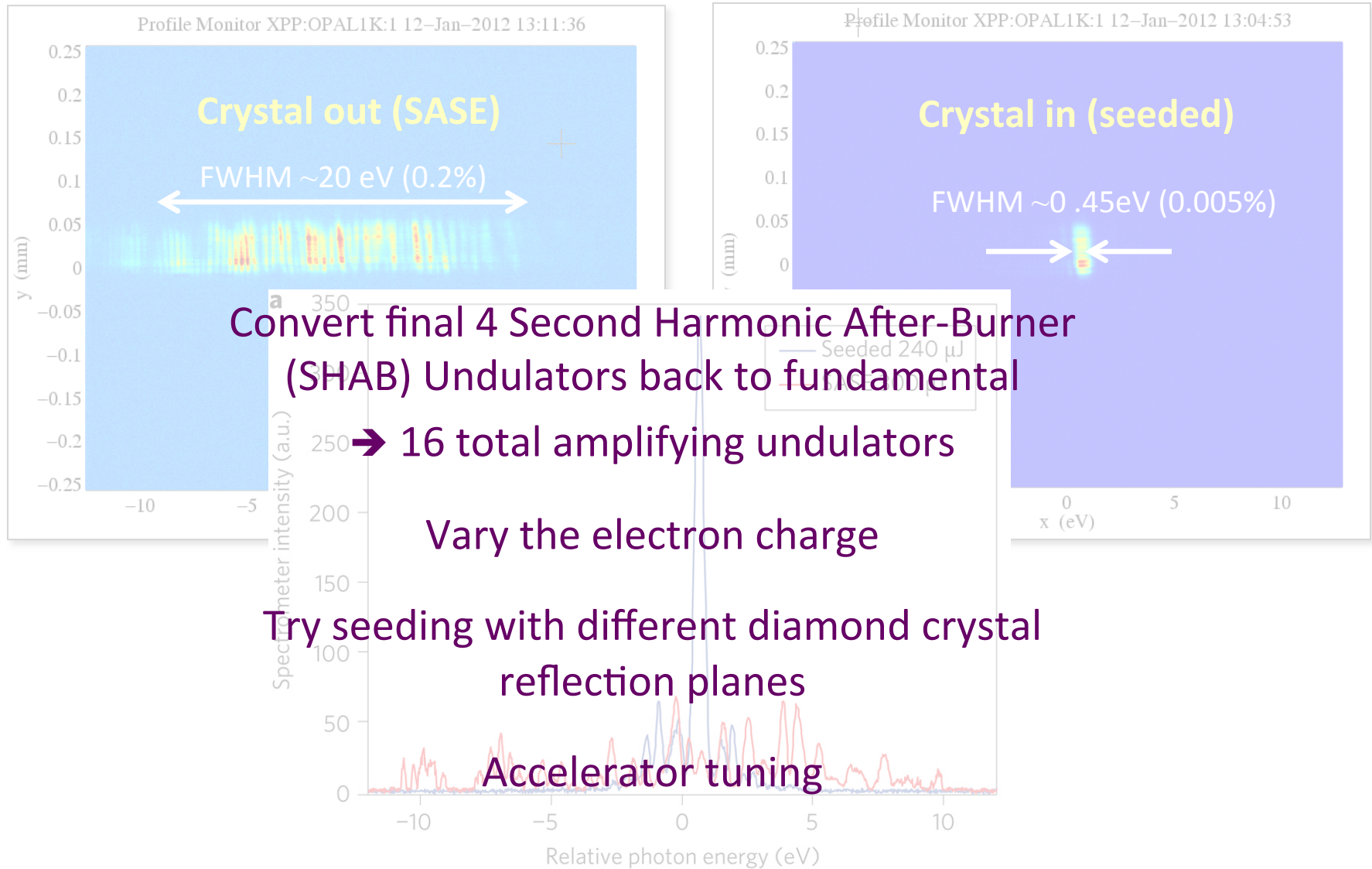
† Y. Feng

Slow improvements in power of seeded signal



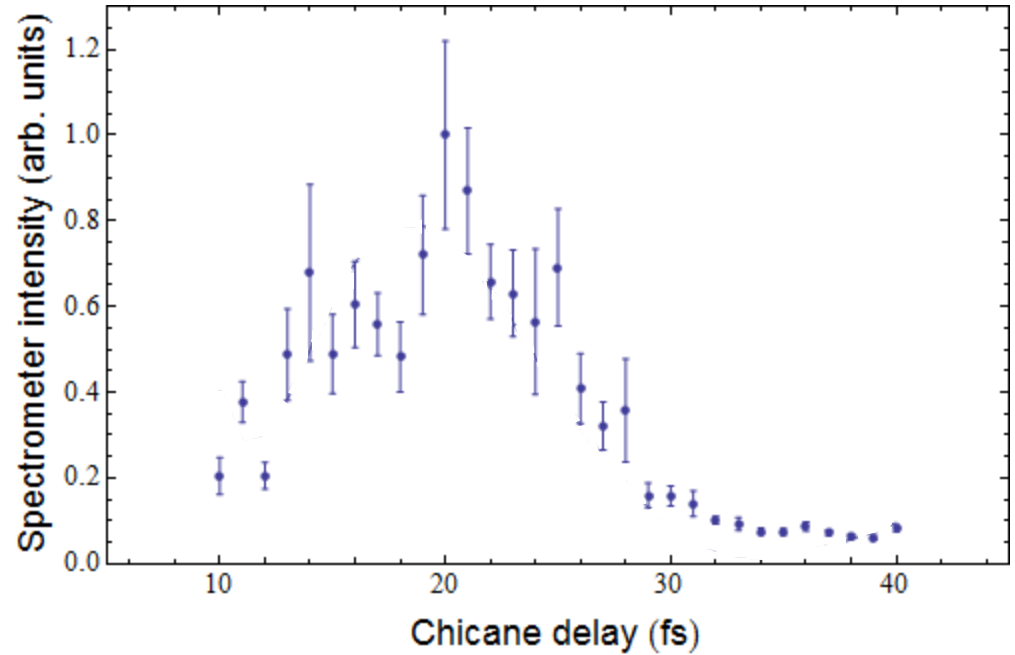
† Y. Feng

Slow improvements in power and stability



Delay scan of seeding “wake”

Measure the seeded output as a function of the chicane time delay



Delay scan of seeding “wake”

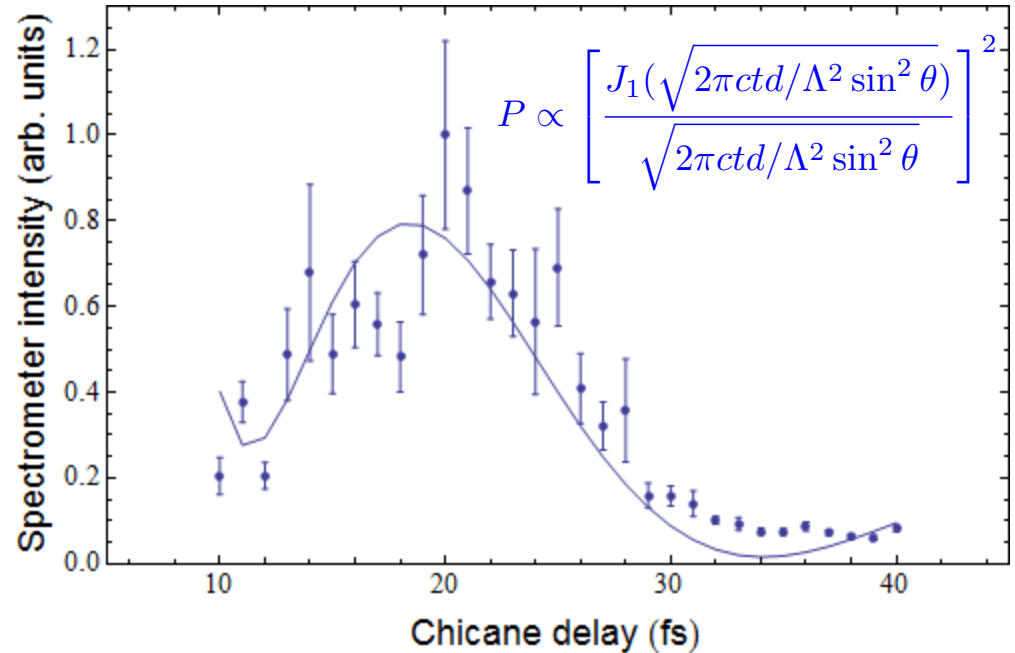
Measure the seeded output as a function of the chicane time delay

Fit measurement to the predicted wake dependence using the dynamical theory of x-ray diffraction assuming:[†]

KNOWN: The time delay
C(004) reflection
properties at 56.53°

FREE PARAMETERS:

Crystal thickness d
SASE pulse profile



† A. Zholents



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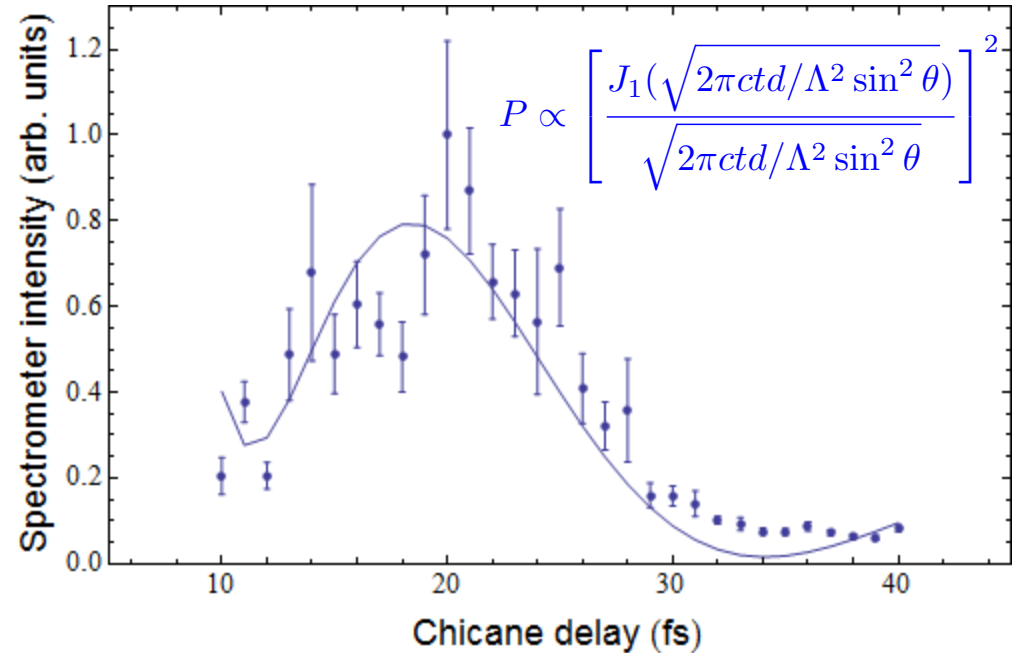
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Crystal thickness d

SASE pulse profile

Best fit rather insensitive to beam shape; predicts crystal thickness equal to 104 microns and the SASE FWHM to be 3.5-5.5 fs



Pulse shape	d (μm)	T_{FWHM} (fs)
Flat-top	104	5.5
Gaussian	104	3.5
Parabolic	104	4.9

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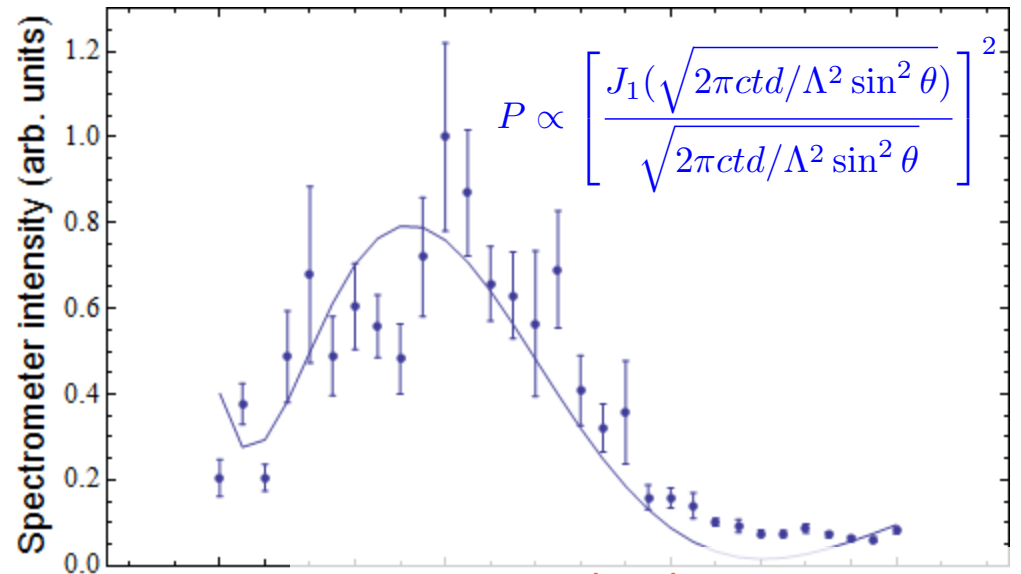
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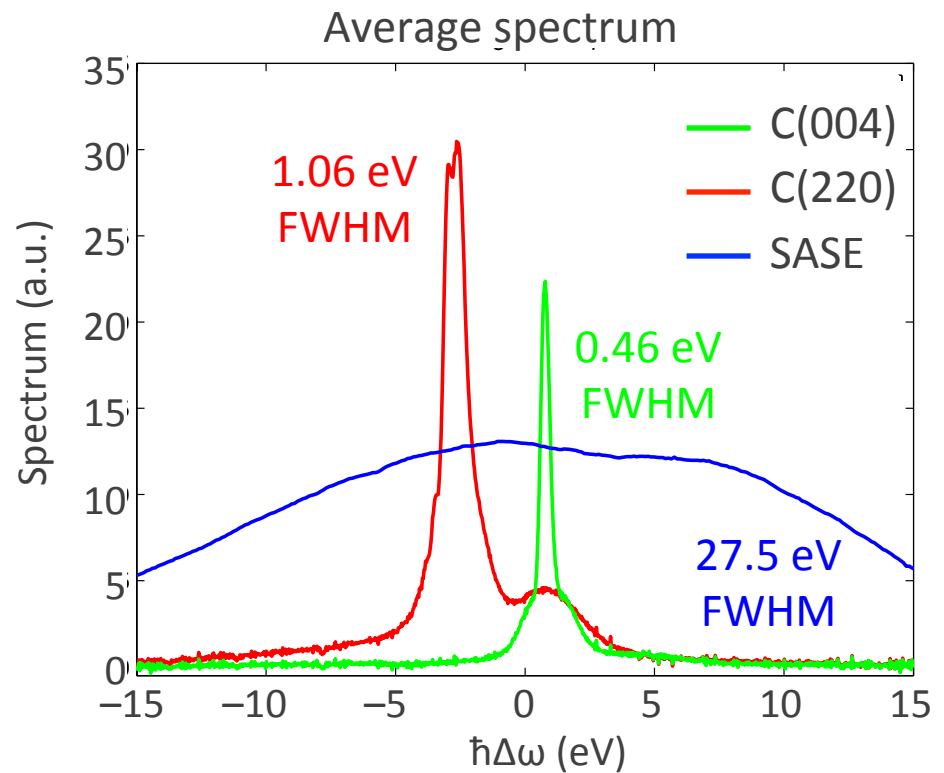
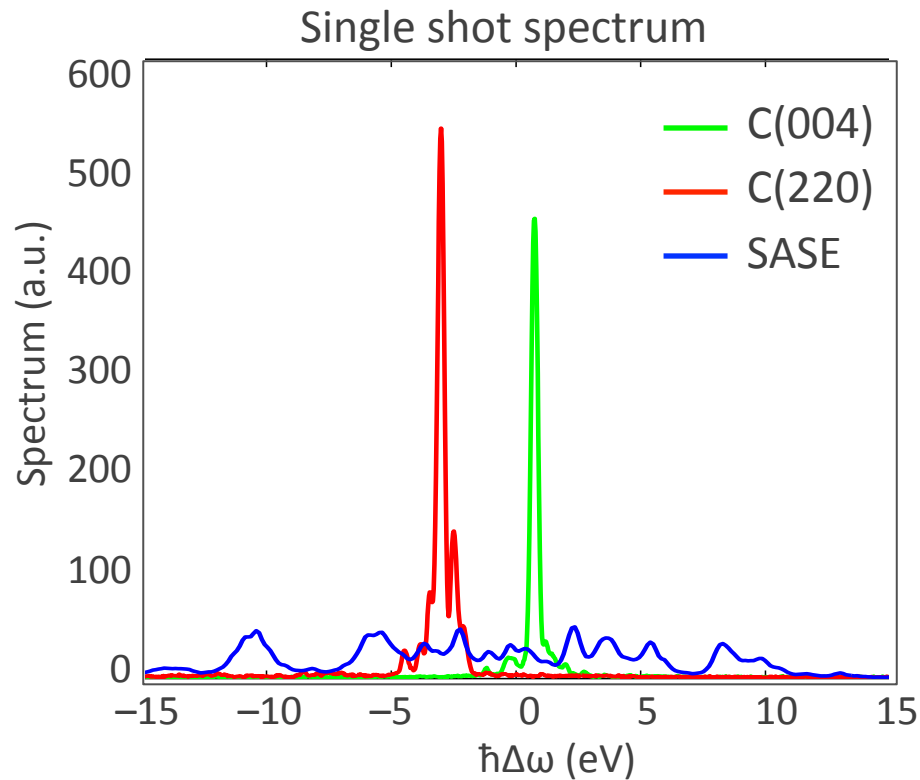


Pulse shape	d (μm)	T_{FWHM} (fs)
Flat-top	104	5.5
Gaussian	104	3.5
Parabolic	104	4.9

Agrees with measurements made at TISCNM

[†] A. Zholents

FEL spectra at 40 pC



Single shot bandwidth reduction by a factor ~ 50

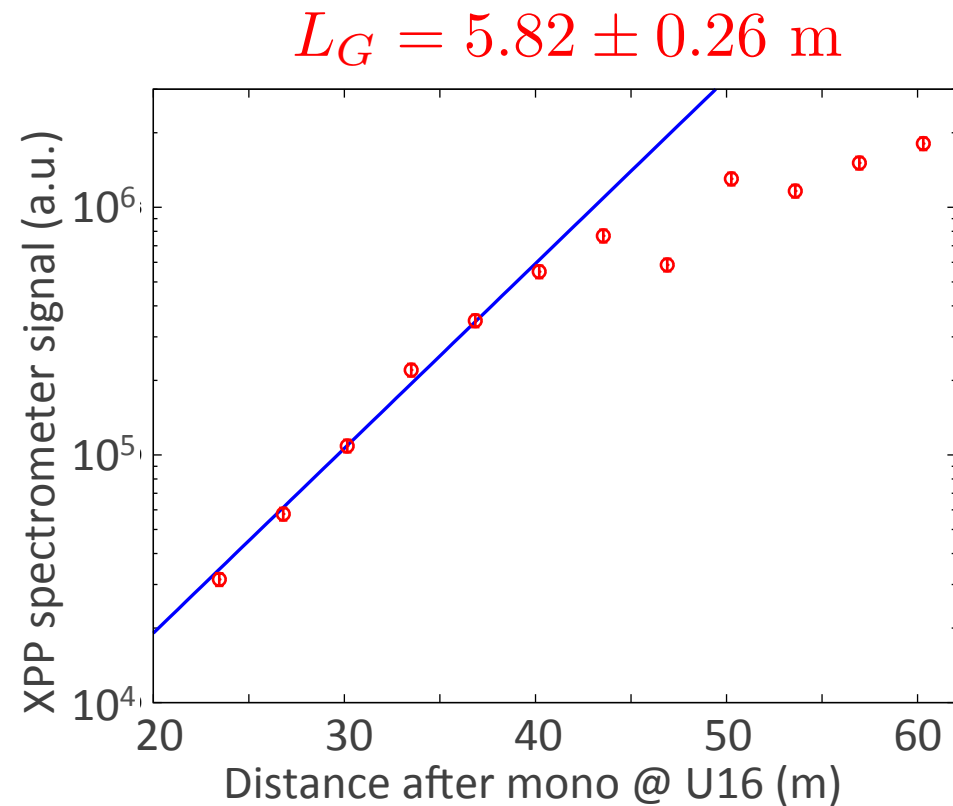
Averaged bandwidth reduction ~ 25 to 50 depending on crystal reflection
(different acceptances leads to different tolerances to fluctuations)

† A. Lutman

Gain and saturation of seeded signal

Using SASE produced by upstream **Undulators 1-15 IN** (None OUT)
plot power in downstream Undulators 17-33

$$P(z) \propto e^{6.4} \exp\left(\frac{z}{5.8 \text{ m}}\right)$$



† D. Ratner

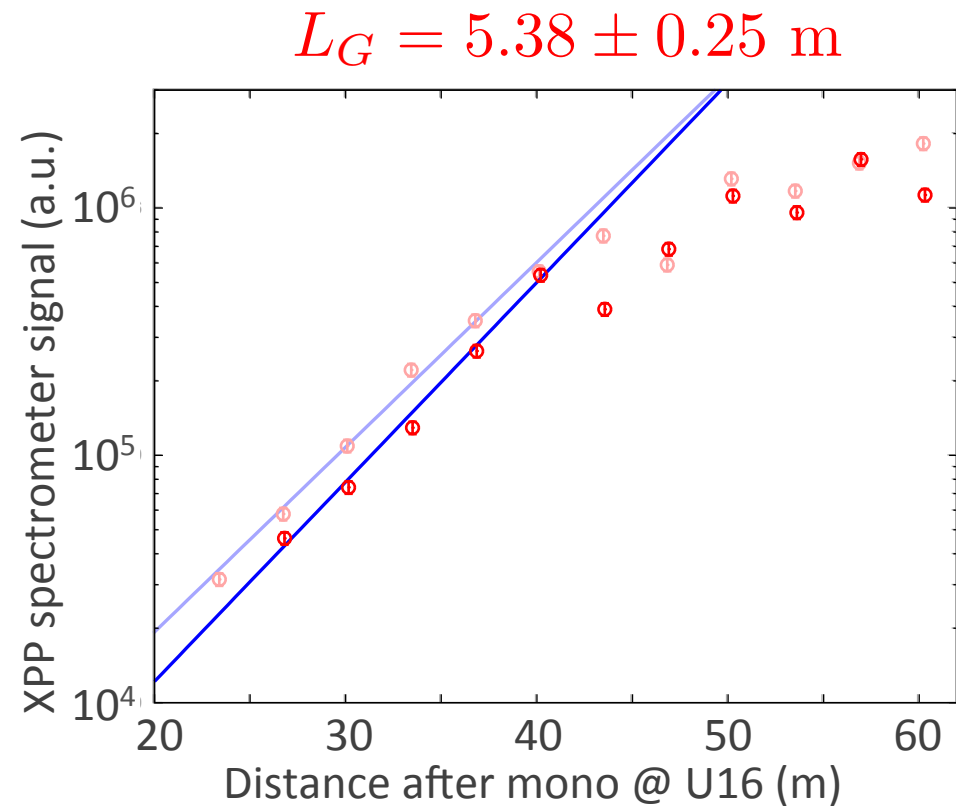


Gain and saturation of seeded signal

Using SASE produced by upstream **Undulators 2-15 IN** (One OUT)
plot power in downstream Undulators 17-33

$$P(z) \propto e^{6.4} \exp\left(\frac{z}{5.8 \text{ m}}\right)$$

$$P(z) \propto e^{5.7} \exp\left(\frac{z}{5.4 \text{ m}}\right)$$



† D. Ratner



Gain and saturation of seeded signal

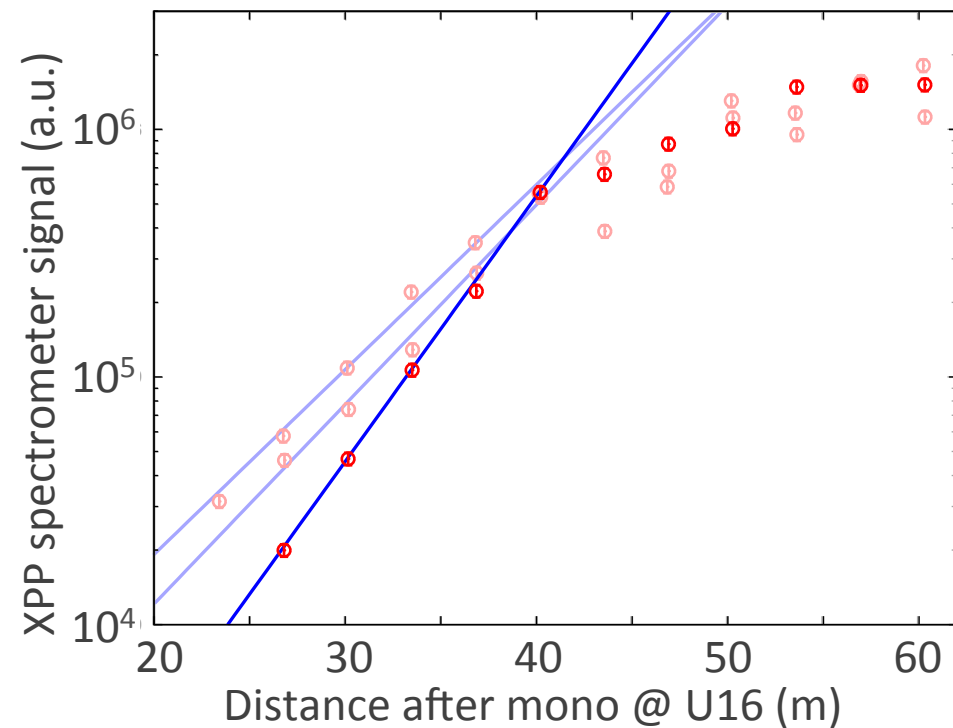
Using SASE produced by upstream **Undulators 3-15 IN** (Two OUT)
plot power in downstream Undulators 17-33

$$L_G = 4.05 \pm 0.07 \text{ m}$$

$$P(z) \propto e^{6.4} \exp\left(\frac{z}{5.8 \text{ m}}\right)$$

$$P(z) \propto e^{5.7} \exp\left(\frac{z}{5.4 \text{ m}}\right)$$

$$P(z) \propto e^{3.3} \exp\left(\frac{z}{4.1 \text{ m}}\right)$$



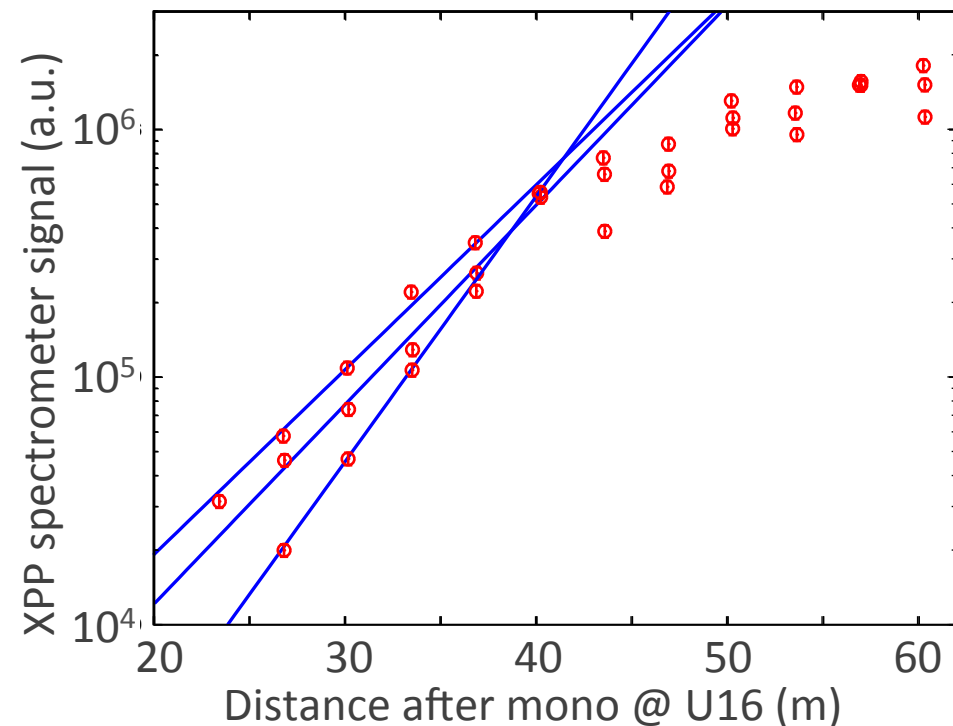
† D. Ratner



Gain and saturation of seeded signal

Ideally, one would like the SASE seeding undulator section to be ~ 14 gain lengths long to produce sufficient seeding power with minimal increase in energy spread

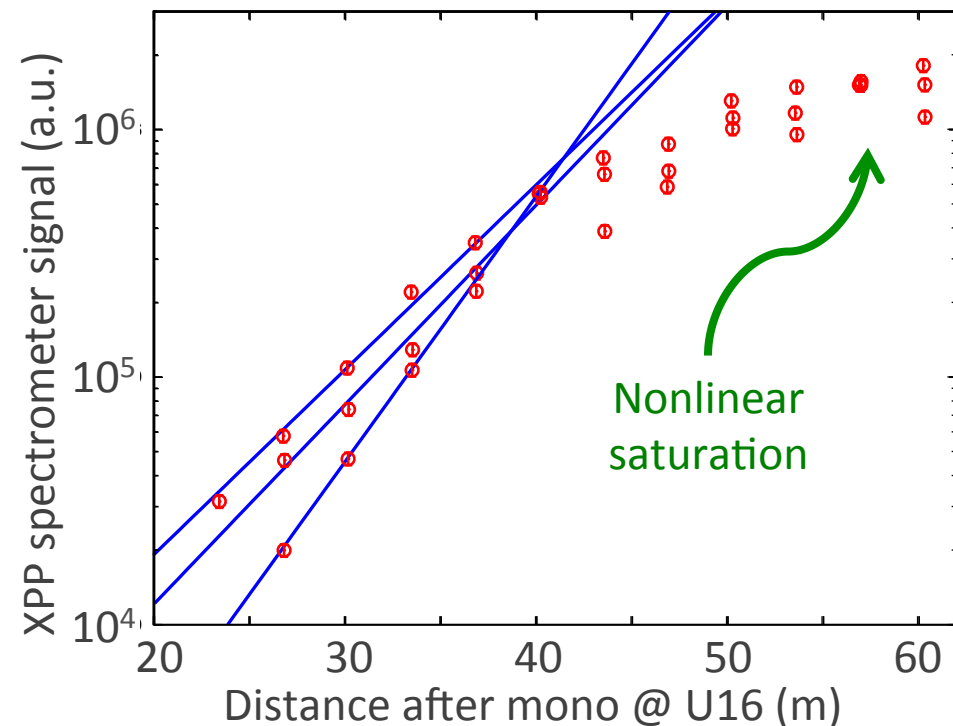
Optimal position of monochromator probably at Undulator 14 or 15 (depends on machine conditions, tuning)



Gain and saturation of seeded signal

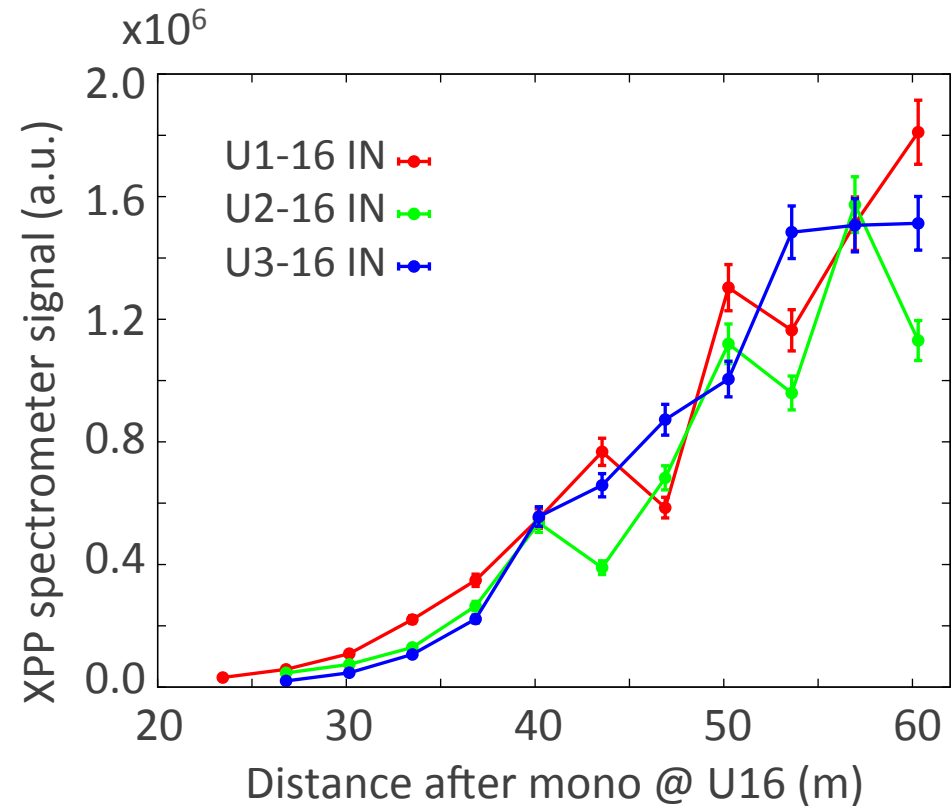
Ideally, one would like the SASE seeding undulator section to be ~ 14 gain lengths long to produce sufficient seeding power with minimal increase in energy spread

Optimal position of monochromator probably at Undulator 14 or 15 (depends on machine conditions, tuning)



“Soft” saturation with some evidence for oscillations in the power

- Synchrotron oscillations?
- Non-uniform amplification across the bunch? (i.e., the “current horns”)?
- Other variations/ fluctuations?
- What does this mean for post saturation taper?



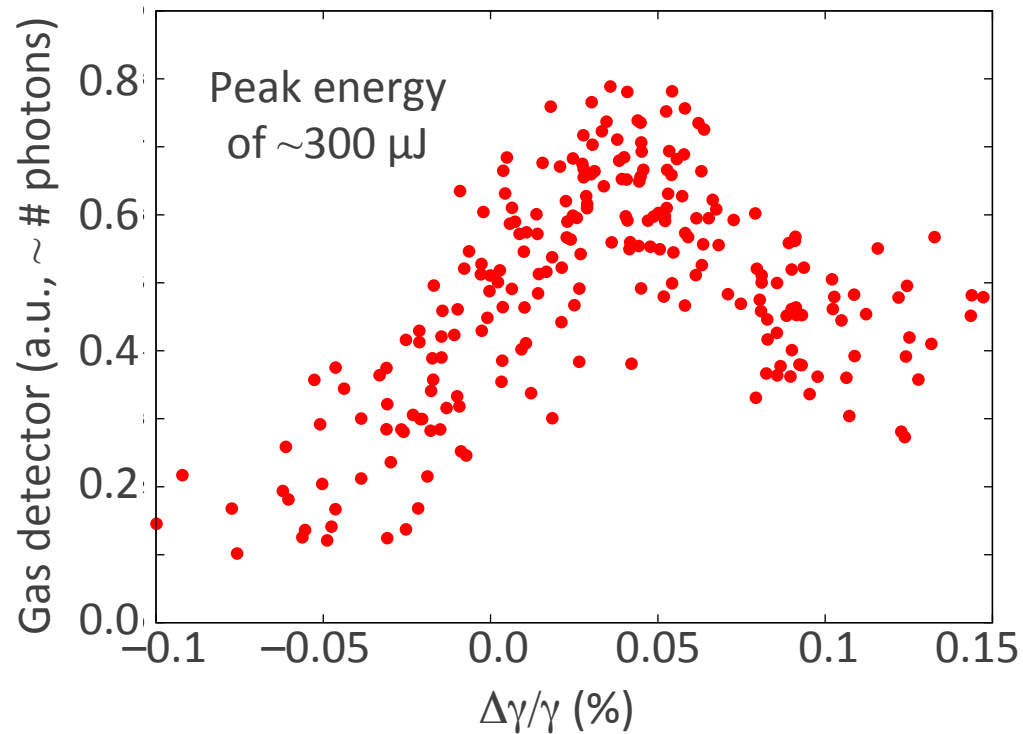
Energy in the seeded output

In addition to the usual requirements for SASE
(small emittance & energy spread, large peak current)
stable seeding requires precise control over
the longitudinal e-beam phase space



Energy in the seeded output

Jitter in mean e-beam energy maps onto variations in gain of seeded signal and thus in output photon number



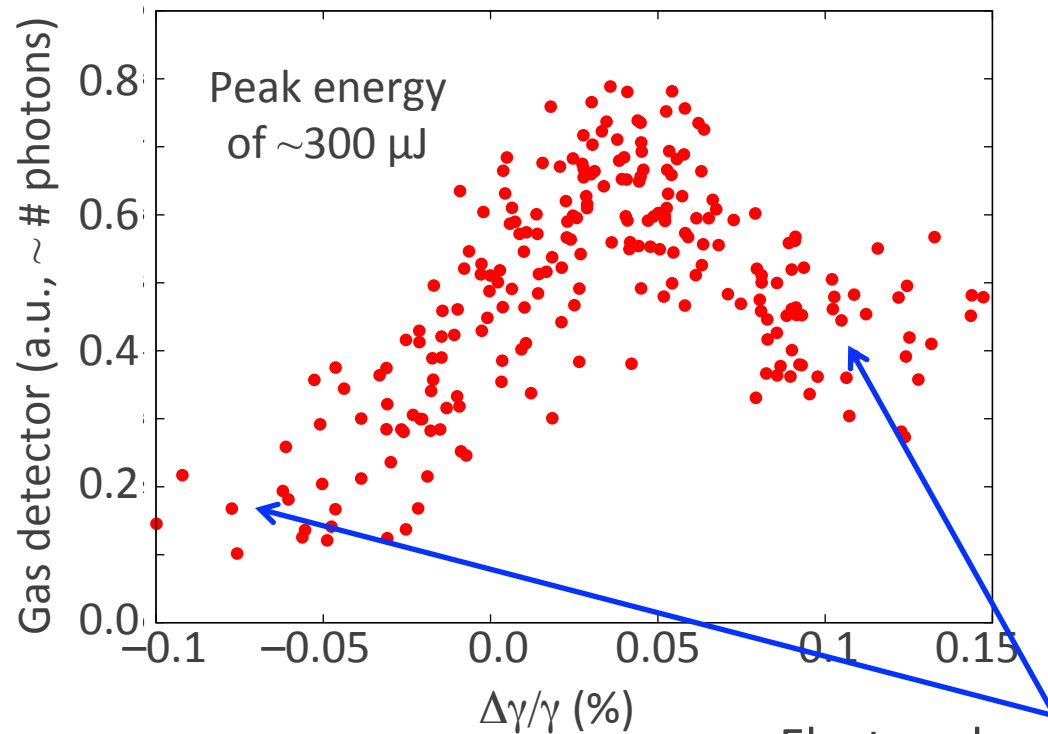
† J. Welch, F.-J. Decker



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Energy in the seeded output

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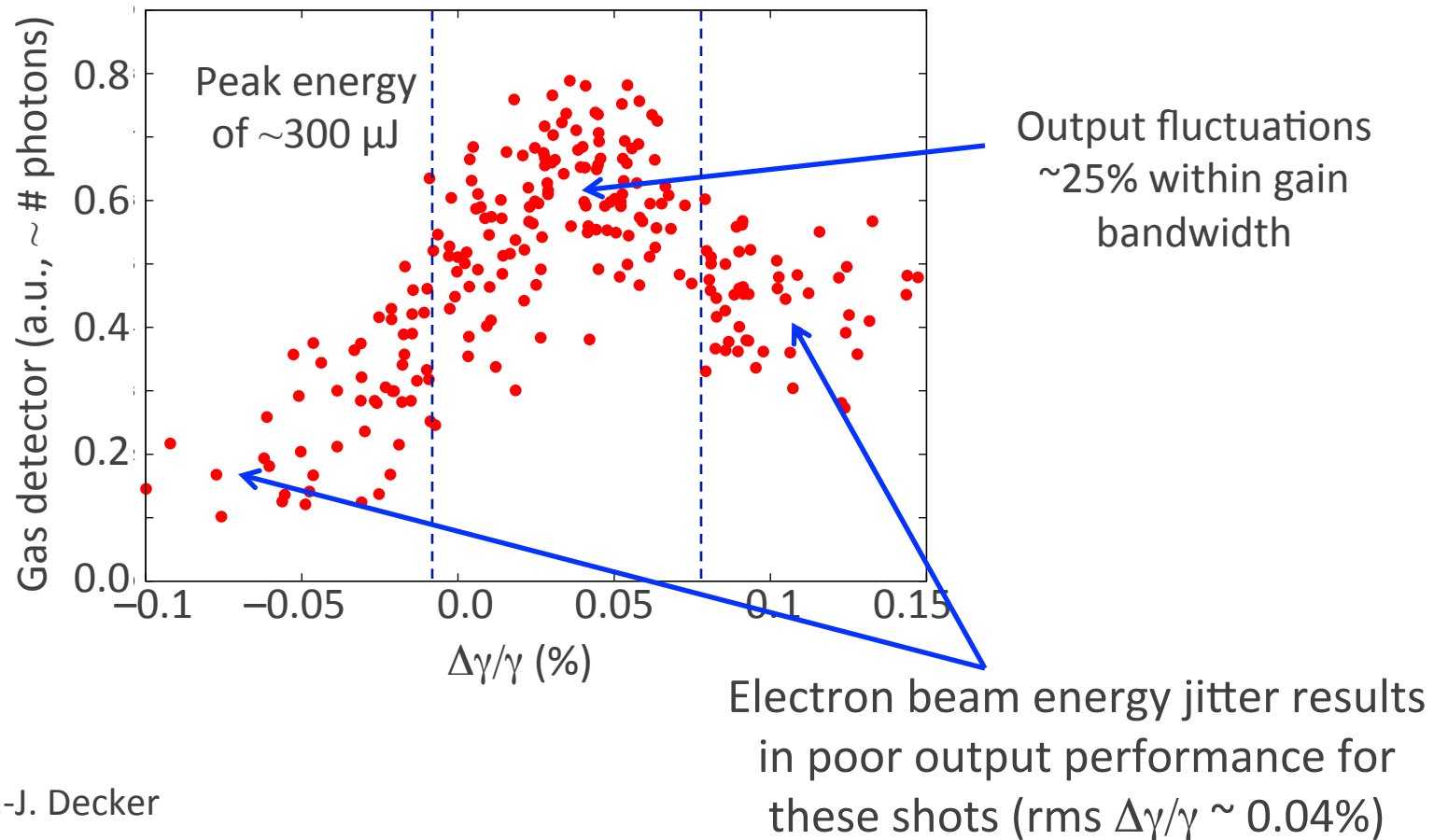


Electron beam energy jitter results in poor output performance for these shots (rms $\Delta\gamma/\gamma \sim 0.04\%$)

† J. Welch, F.-J. Decker

Energy in the seeded output

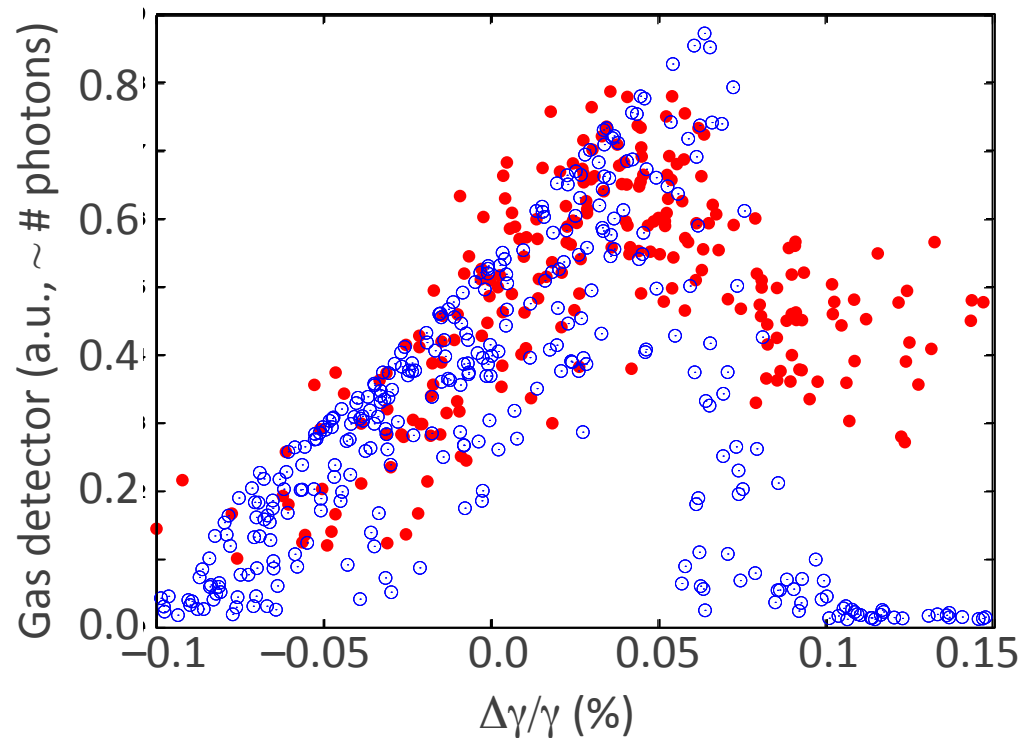
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Energy in the seeded output

Jitter in mean e-beam energy maps onto variations in gain of seeded signal and thus in output photon number



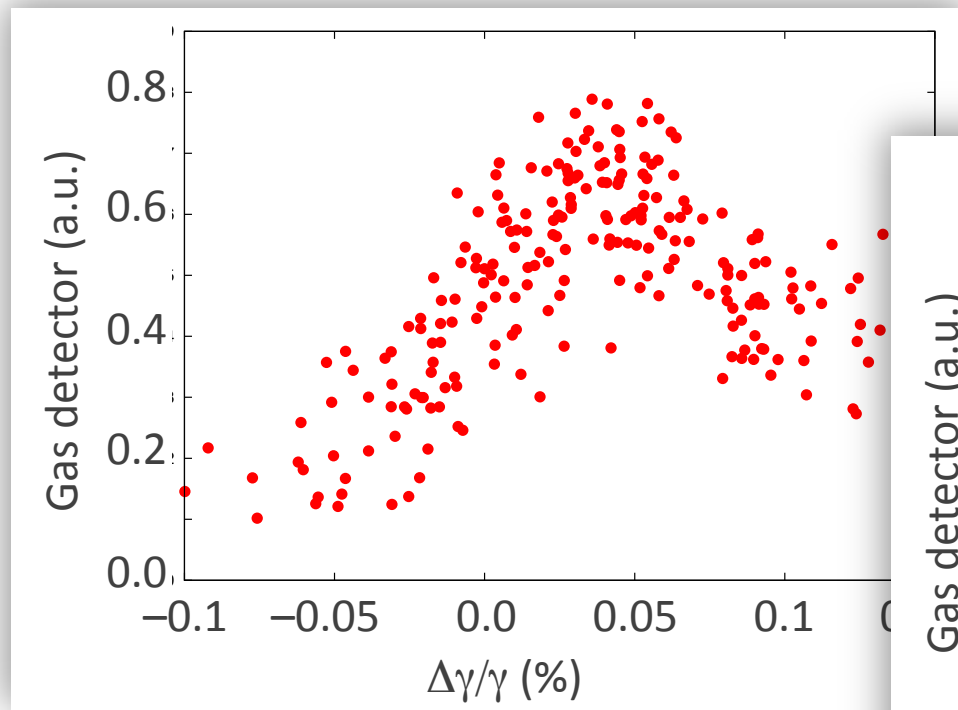
Compares reasonably well with simulations that reach saturation using $\rho \sim 6 \times 10^{-4}$ and an rms energy jitter $\Delta\gamma/\gamma = 4 \times 10^{-4}$



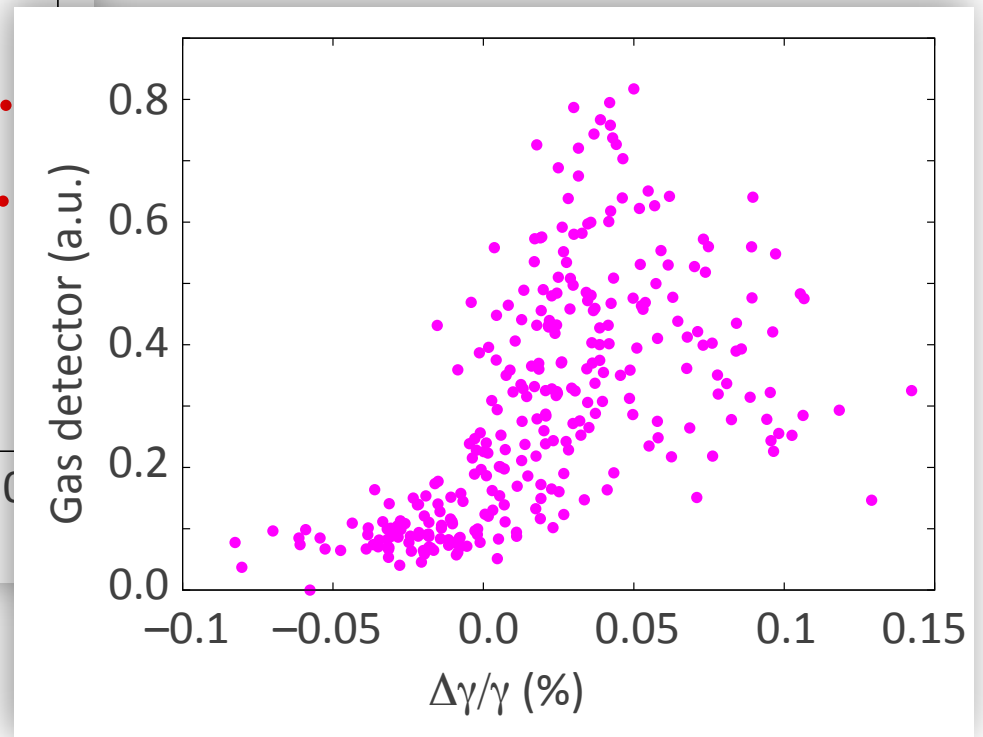
Energy in the seeded output

Depends strongly on machine parameters/tuning

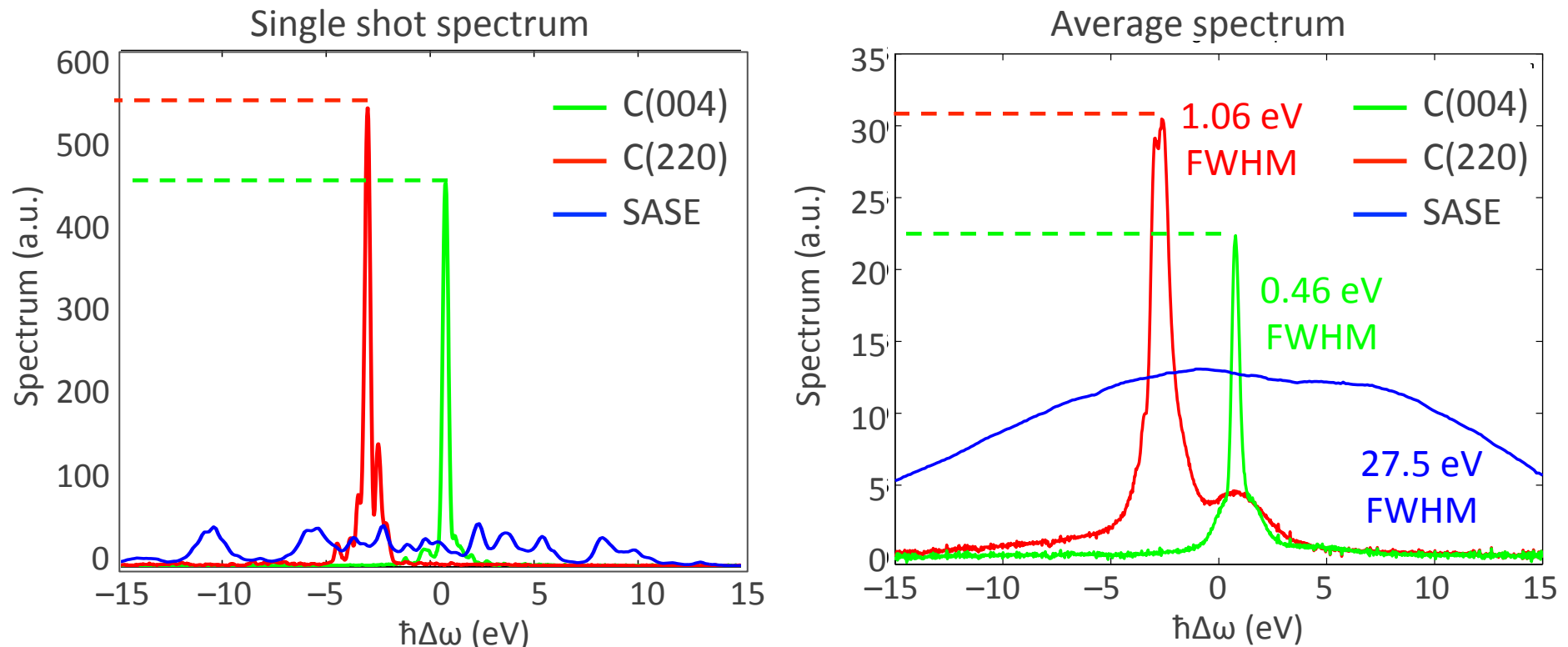
Output fluctuations ~25% within
gain bandwidth



Output fluctuations ~50% within
gain bandwidth



Fluctuations and spectral brightness for two diamond crystal reflections



Fluctuations reduce ensemble averaged seeded spectral brightness by a factor ≥ 18 from its peak value

BUT, seeded spectral brightness still larger than SASE

Depends on accelerator conditions, tuning

† A. Lutman

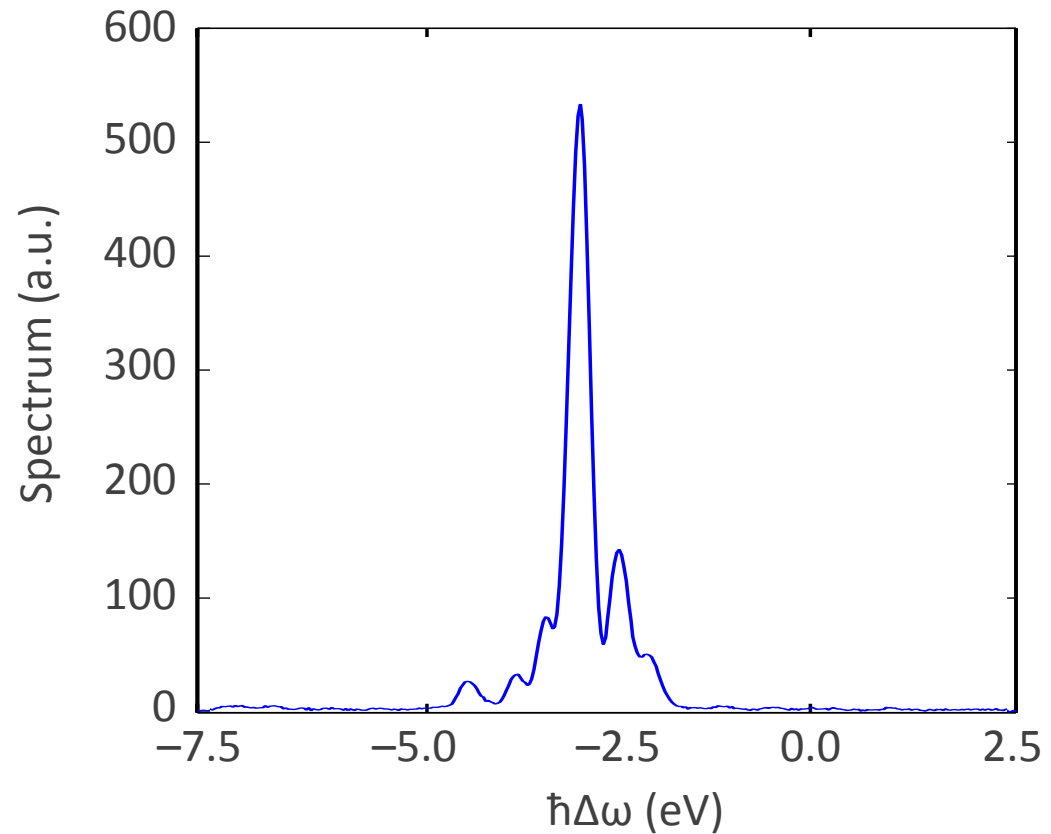
Other variations can be mapped onto spectrum

Variations in current?
("current horns")

Energy modulations?

Crystal vibrations?

???



† A. Lutman



Conclusions

- The wake monochromator concept can be experimentally realized
- Hard x-ray self-seeding has been implemented at the LCLS with a measured output bandwidth $\Delta\omega/\omega \sim 5 \times 10^{-5}$ at 1.5 Å
- Clear signs of seeded saturation have been observed
- Fluctuations in output still somewhat high

Most are attributable to the “large” e-beam energy jitter ($\Delta\gamma/\gamma \sim 4 \times 10^{-4}$), but are there other sources?

- Nevertheless, seeding improves (ensemble averaged) spectral brightness within narrow seeded bandwidth
- Seeded mode available for user operations (J. Welch’s talk today)
- First step towards a terawatt FEL

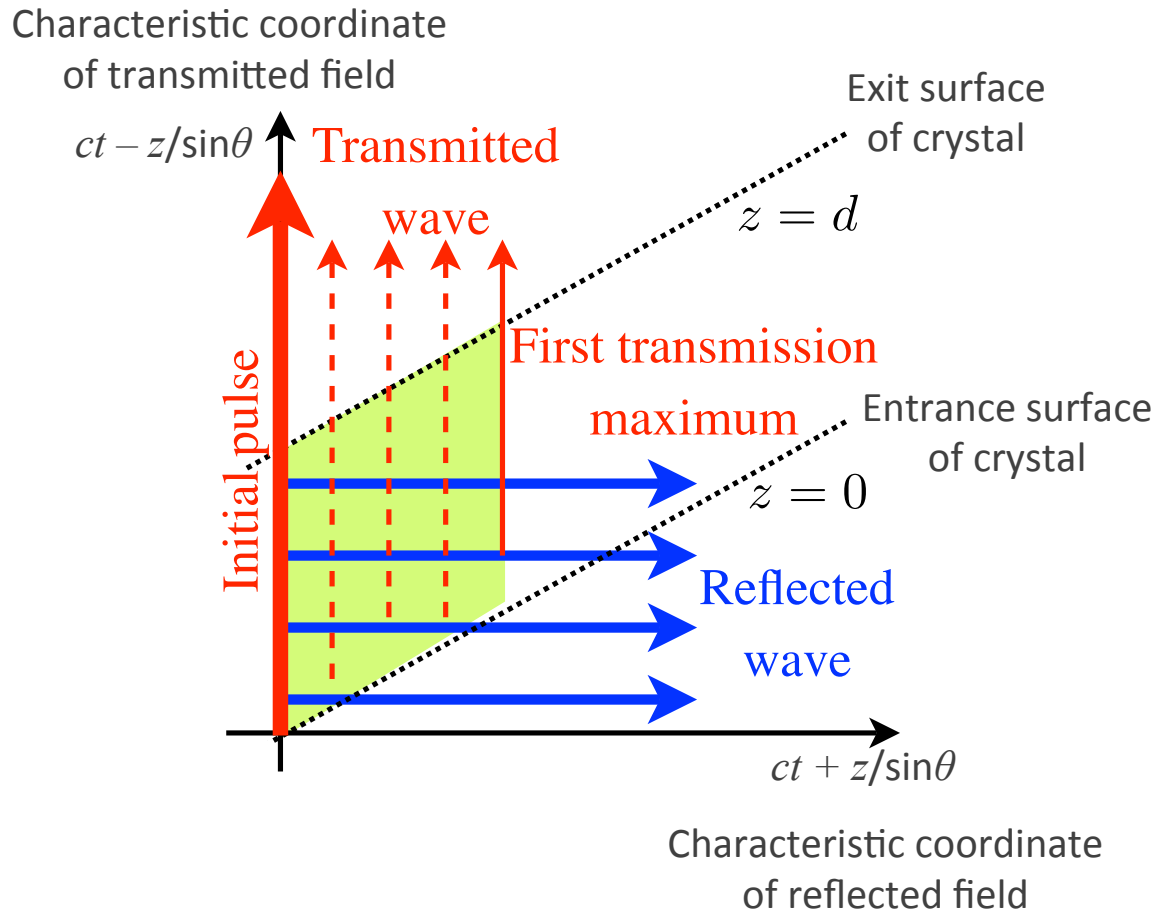
Next step requires experimentally optimizing the predicted benefits of a post-saturation tapering of the undulator strength



Extra Slides



Time domain picture of self-seeding “wake”



Position of first peak
proportional to

Interaction area:

$$\Delta t \, d / \sin\theta = \text{constant}$$

→ time delay scales inversely
with crystal thickness

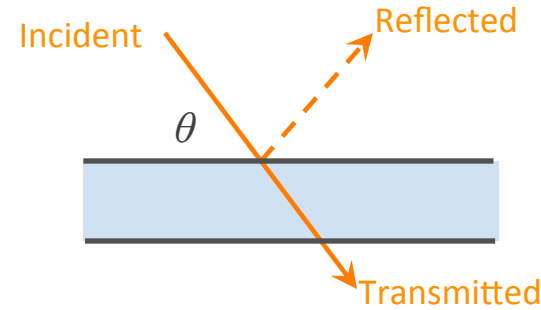
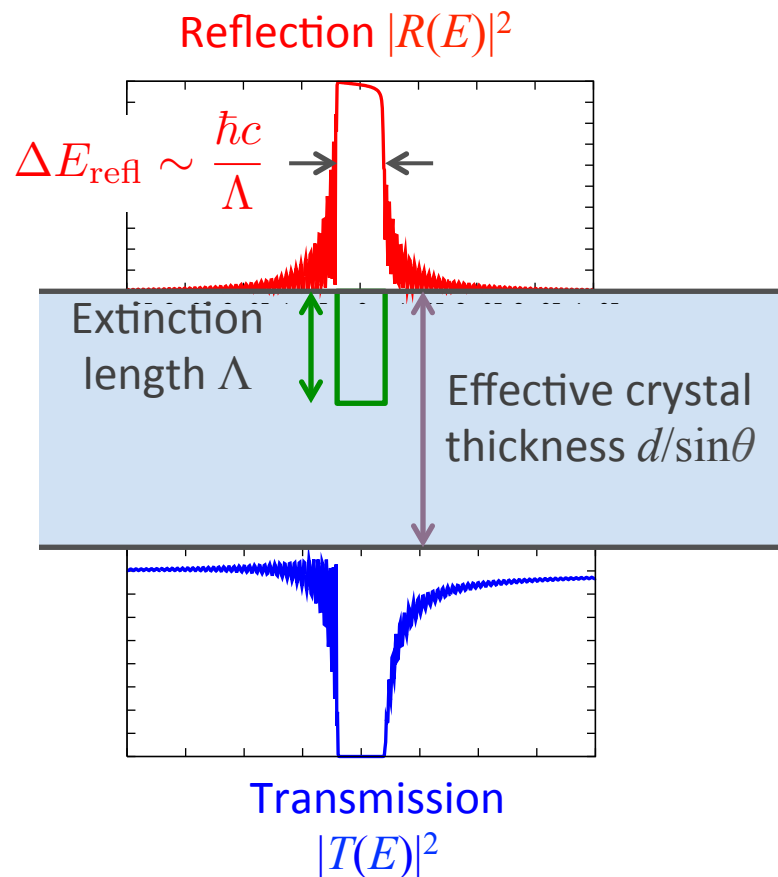
Seed amplitude scales with
Interaction length

→ Peak power scales
quadratically with
crystal thickness

† R.R. Lindberg and Yu. Shvyd'ko, *Phys. Rev. ST-Accel. Beams* **15**, 050706 (2012)

Bragg crystals in transmission for “wake” self-seeding

Bragg's law defines central energy of reflection $\lambda = \lambda_B \sin\theta$

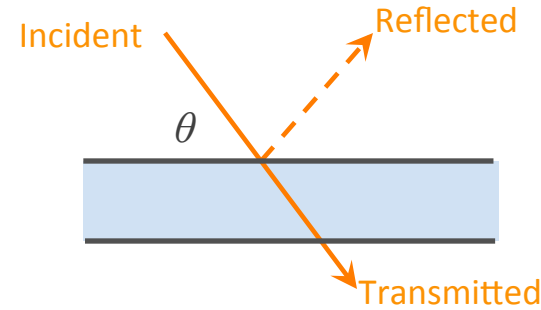
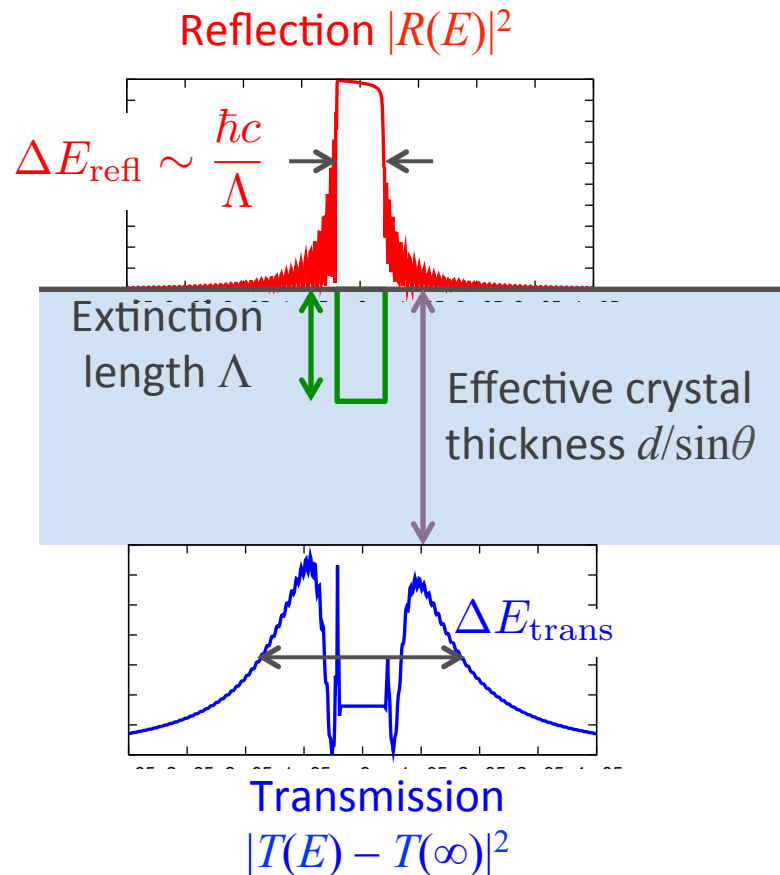


- Radiation has $\hbar/T_{\text{rad}} \gg \Delta E_{\text{refl}}$
 → Large Region of T contributes
- Seeding “wake” is determined by the difference $T(E) - T(\infty)$

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- Radiation has $\hbar/T_{\text{rad}} \gg \Delta E_{\text{refl}}$
 → Large Region of T contributes
- Seeding “wake” is determined by the difference $T(E) - T(\infty)$
- Relevant spectral components interact over entire crystal thickness

$$\Delta E_{\text{trans}} \sim \frac{d}{\Lambda \sin \theta} \Delta E_{\text{refl}}$$

$$\Delta t_{\text{trans}} \sim \frac{\Lambda^2 \sin \theta}{cd}$$

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