



# *X-ray Free Electron Lasers: seeing the light fantastic*

*J. B. Hastings*  
*SLAC National Accelerator Laboratory*  
*September 15, 2014*



*The challenge:  
Maximize the number of photons/electron/unit time*

## The solution: Free Electron Lasers

### *The LCLS Proposal 1992*

C. Pellegrini, “A 4 to 0.1 nm FEL based on the SLAC linac”, in Workshop on 4th Generation Light Sources, M. Cornacchia and H. Winick, (Eds), pp. 364-375, 1992. SSRL-Report-92/02.

“...one is forced to have high gain, *i.e.* to use electron beams with large peak current, and at the same time small emittance and energy spread. **The road to an X-ray FEL requires the development of electron beams with unprecedented characteristics.”**

# *From Ring to Linac*

## Storage ring



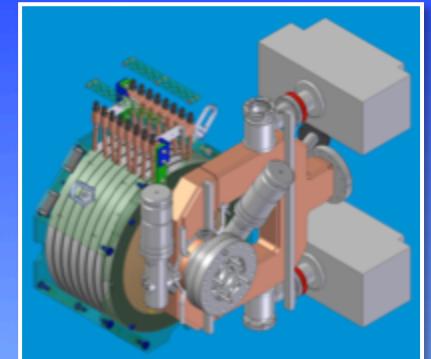
$$\epsilon_x \sim \gamma^2 / C^3$$

( $\gamma$  is e<sup>-</sup> energy, C is circumference)

- Higher energy → higher transverse emittance (overcome by larger circumference)
- Large longitudinal emittance (→ bunch length 10 ps, energy spread 0.1%)

## Linac

+ RF photocathode gun

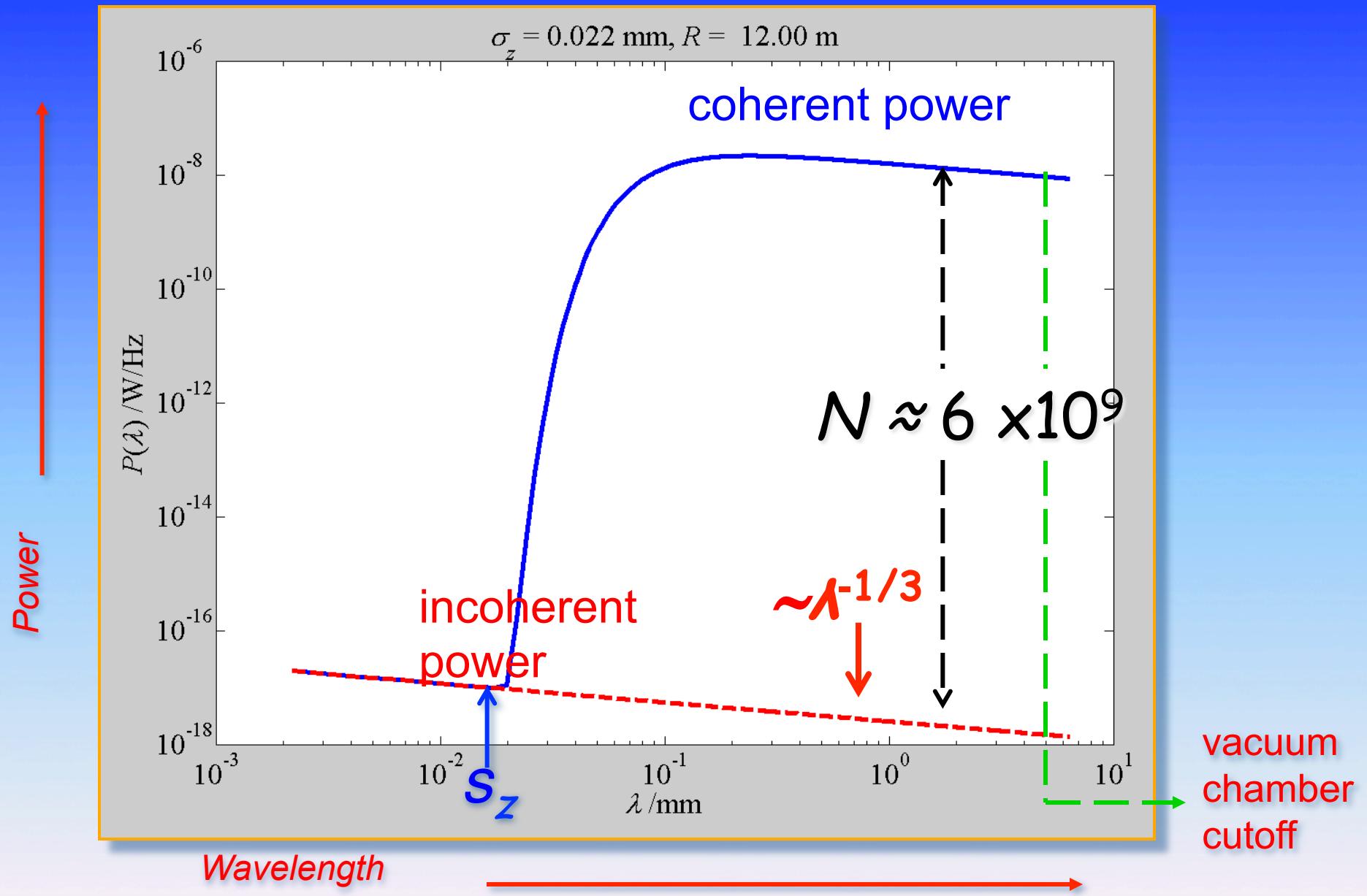


$$\epsilon_x \sim 1/\gamma$$

(R. Sheffield et al., LANL,  
...D. Dowell et al., SLAC)

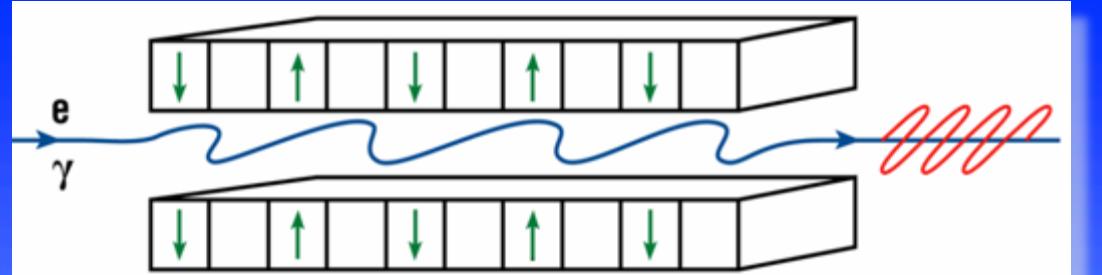
- Emittance **decreases** with increasing energy
- RF guns produce very **low** emittance beams
- **Small** longitudinal emittance (→ **High** peak current, bunch length 100 fs, energy spread 0.01%)

# Coherent Synchrotron Radiation

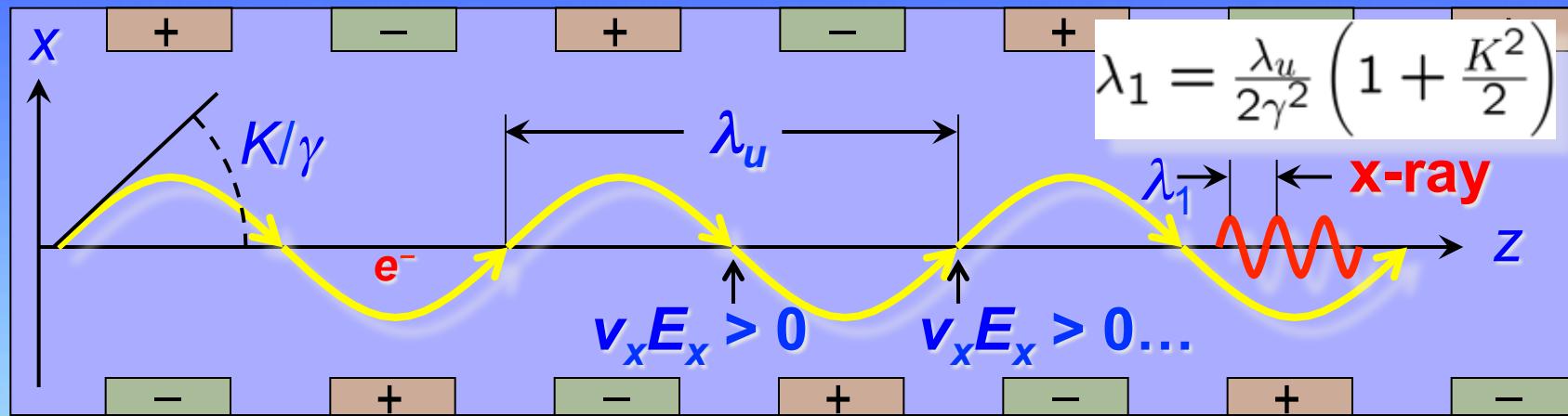


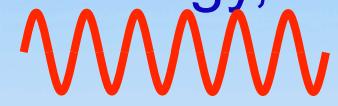
# FEL Principles

Z. Huang



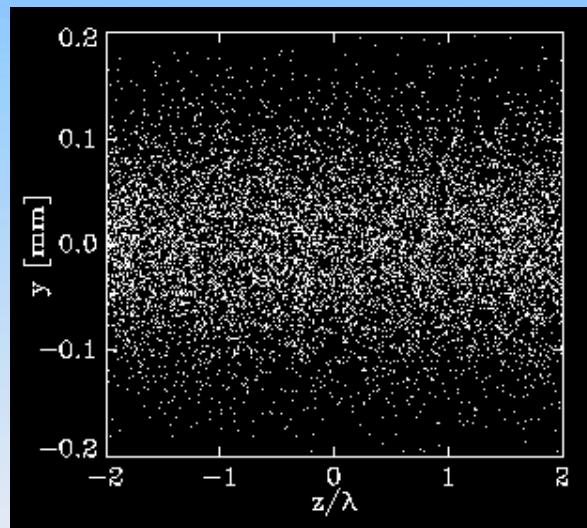
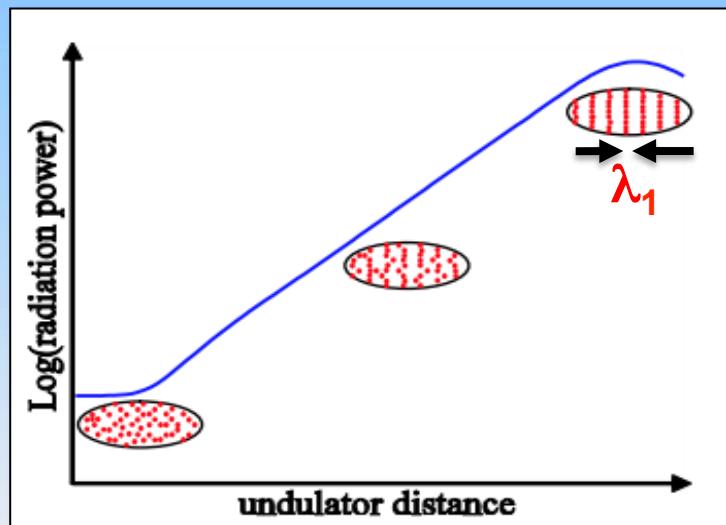
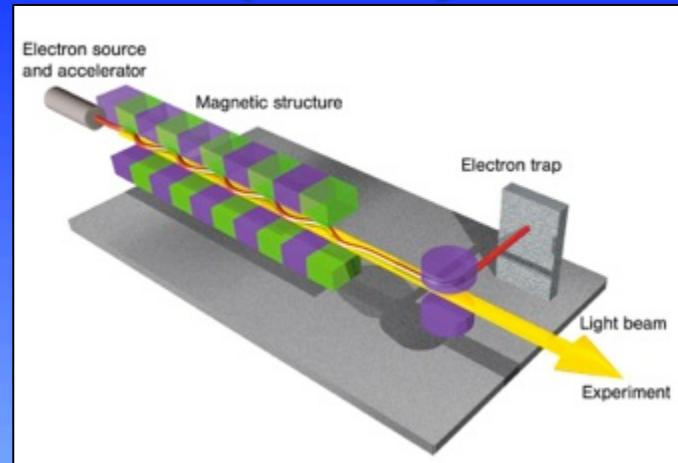
- Electrons **slip** behind EM wave by  $\lambda_1$  per undulator period ( $\lambda_u$ )



- Due to sustained interaction, some electrons lose energy, while others gain → **energy modulation at  $\lambda_1$**  
- $e^-$  losing energy slow down, and  $e^-$  gaining energy catch up → **density modulation at  $\lambda_1$  (microbunching)** 
- Microbunched beam radiates coherently at  $\lambda_1$ , enhancing the process → **exponential growth of radiation power**

# Free Electron Laser (FEL)

- Resonant interaction of electrons with EM radiation in an undulator<sup>^</sup>
- Coherent radiation intensity  $\propto N^2$  due to beam microbunching  
(N: # of  $e^-$  involved  $\sim 10^6$  to  $10^9$ )
- At x-ray wavelengths, use **Self-Amplified Spontaneous Emission\*** (**a wonderful instability!**) to reach high peak power



S. Reiche

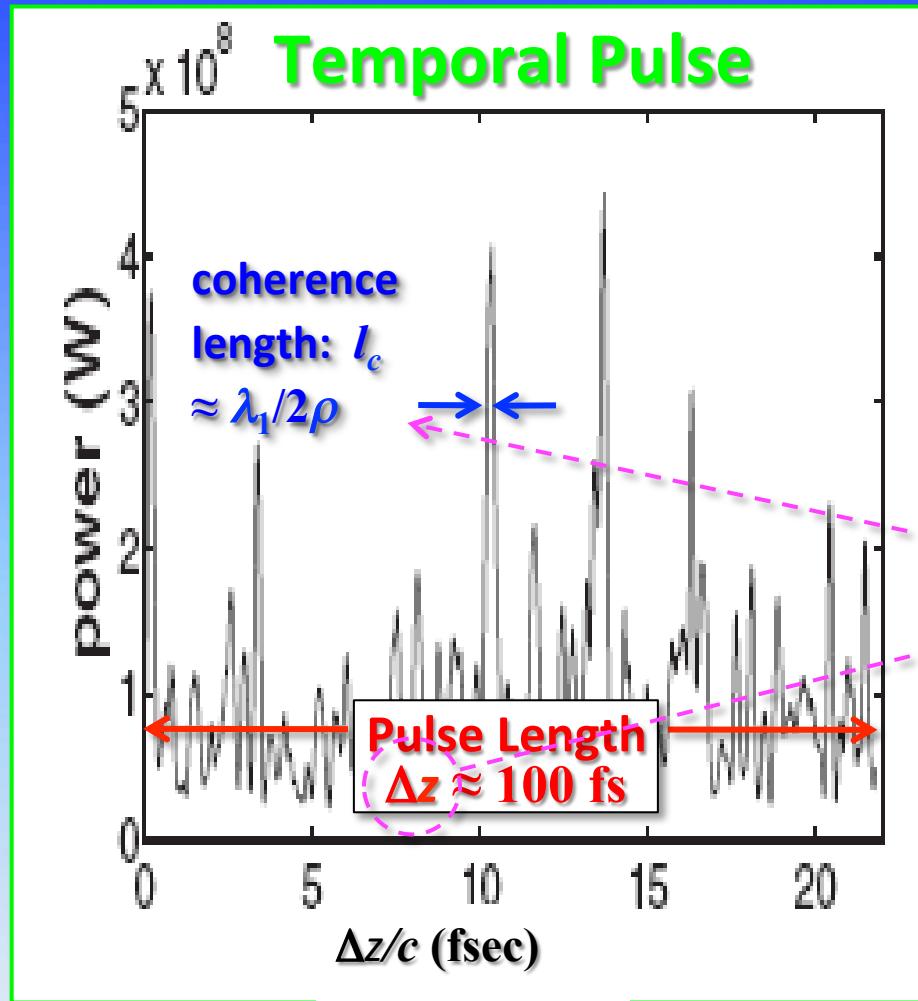
<sup>^</sup> J. Madey, J. Appl. Phys., 1971

\* Kondratenko, Saldin, Part. Accel., 1980

\* Bonifacio, Pellegrini, Narducci, Opt. Com., 1984

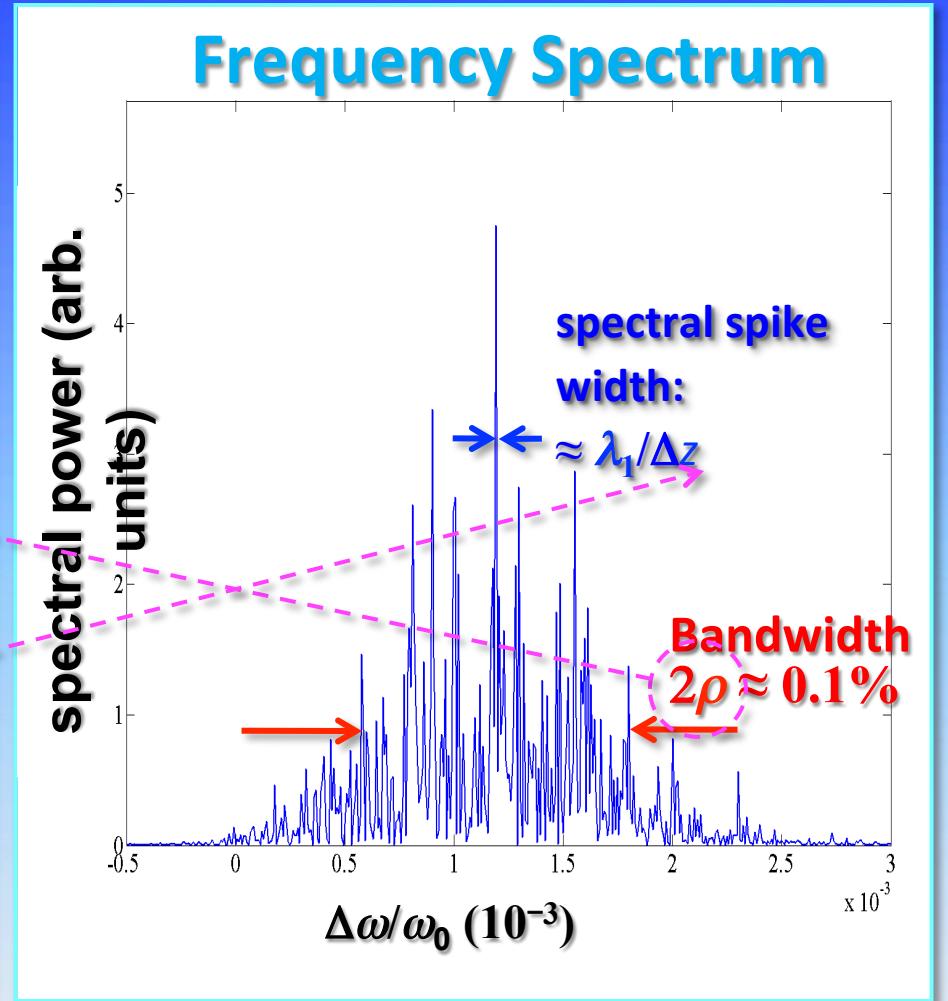
# SASE Temporal and Spectral Pulse

spikes appear in temporal pulse



$$\lambda_1 = 1 \text{ \AA}, \rho \approx 5 \times 10^{-4}, l_c \approx 0.2 \text{ fs}$$

spikes also in spectrum



$$\Delta z = 100 \text{ fs} :$$

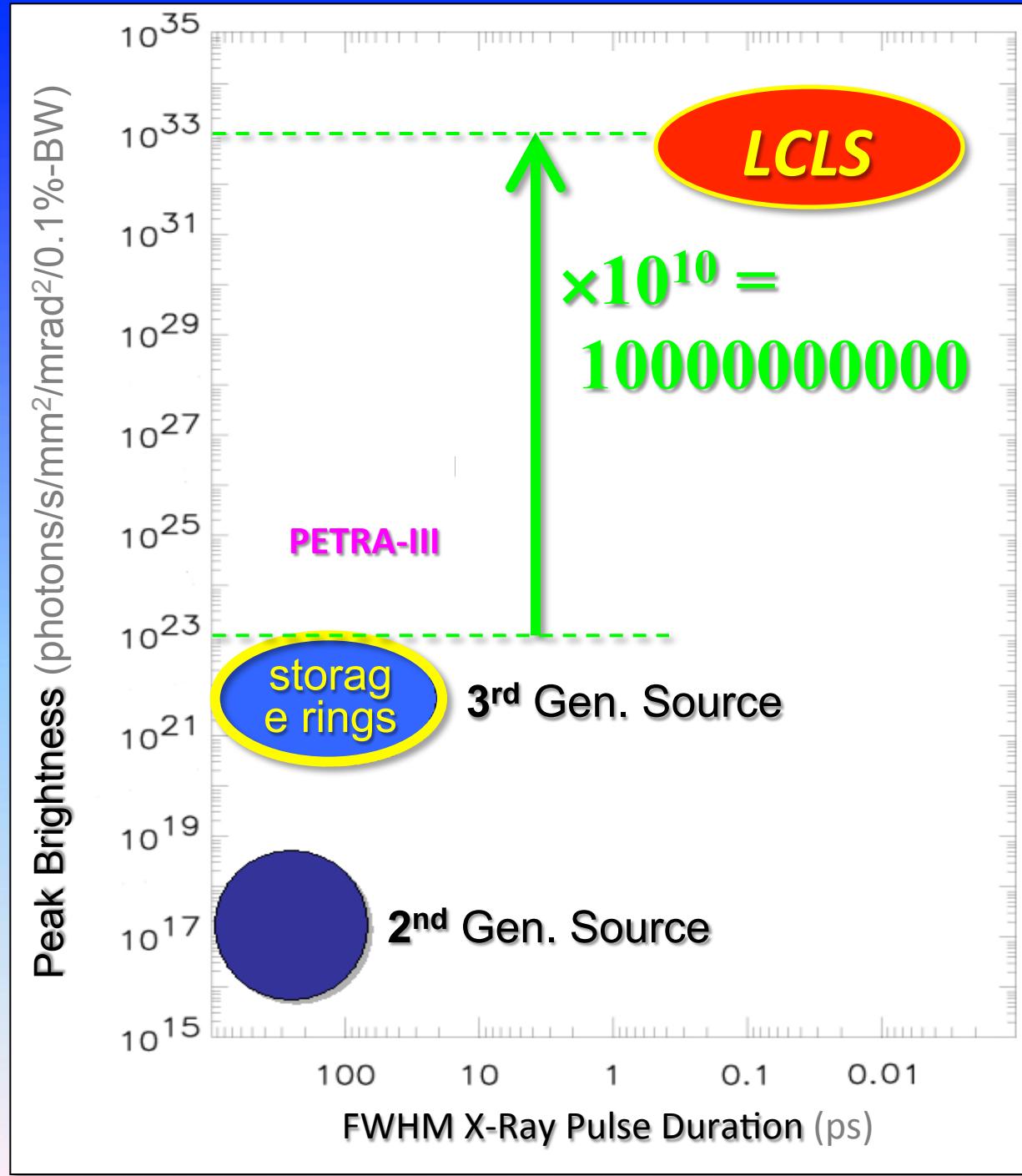
$$\Delta z = 1 \text{ fs} :$$

$$\lambda_1/\Delta z \approx 5 \times 10^{-6}$$

$$\lambda_1/\Delta z \approx 5 \times 10^{-4}$$

# Light Sources at ~1 Å

H.-D. Nuhn,  
H. Winick



Free-Electron Lasers represent a huge technical advance with  $10^{10}$  increase of peak brightness, coherent x-rays, and femtosecond pulses at Angstrom wavelengths

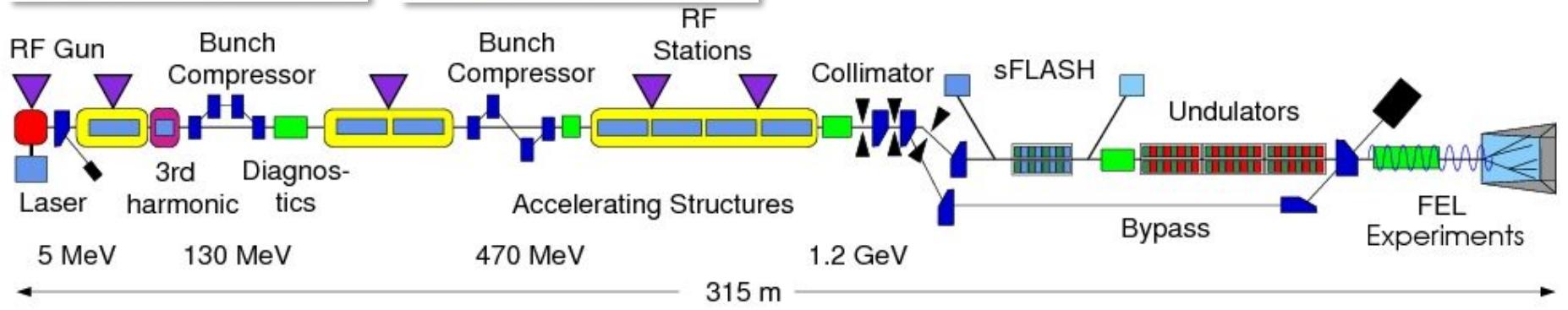
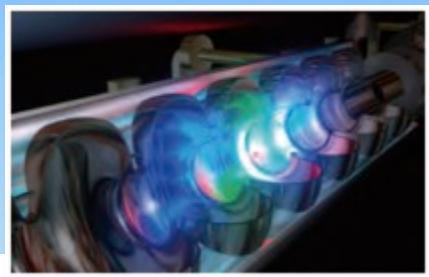
## *Photon beam characteristics*

- Short pulses: fs to as
- ‘Full’ transverse coherence
- High field strengths
- High peak power
- Unmatched peak brilliance

$$P_{sat} \cong \rho E_{GeV} I_{Amp} \sim GWs$$

# The ***FLASH*** FEL at DESY (Hamburg, Germany)

- 10 years of FEL operation (100 - 4 nm)
- Development of FEL science & technology
- Many experienced people now at ***LCLS***



# LCLS: First Hard X-Ray Laser

A 4 to 0.1 nm FEL Based on the SLAC Linac\*.

C. Pellegrini

UCLA Physics Department, 405 Hilgard Avenue, Los Angeles CA 90024

March 2, 1992



Measurements of Gain Larger than  $10^5$  at 12  $\mu\text{m}$  in a Self-Amplified Spontaneous-Emission Free-Electron Laser

M. J. Hogan, C. Pellegrini, J. Rosenzweig, S. Anderson, P. Frigola, and A. Tremaine  
Department of Physics and Astronomy, UCLA, Los Angeles, California 90095

C. Fortgang, D. C. Nguyen, R. L. Sheffield, and J. Kinross-Wright  
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

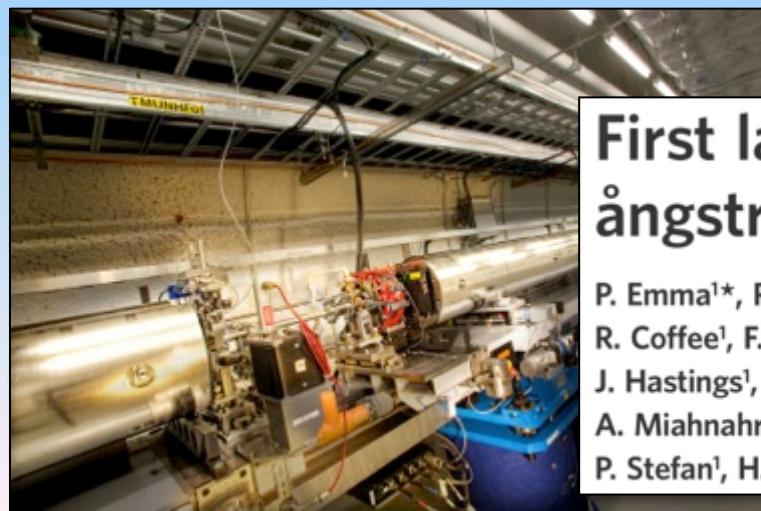
A. Varfolomeev, A. A. Varfolomeev, and S. Tolmachev  
RRC-Kurchatov Institute, Moscow, Russia

Roger Carr  
Stanford Synchrotron Radiation Laboratory, Palo Alto, California 94304

PRL 1998

## Exponential Gain and Saturation of a Self-Amplified Spontaneous Emission Free-Electron Laser

S. V. Milton,<sup>1\*</sup> E. Gluskin,<sup>1</sup> N. D. Arnold,<sup>1</sup> C. Benson,<sup>1</sup> W. Berg,<sup>1</sup> S. G. Biedron,<sup>1,2</sup> M. Borland,<sup>1</sup> Y.-C. Chae,<sup>1</sup> R. J. Dejus,<sup>1</sup> P. K. Den Hartog,<sup>1</sup> B. Deriy,<sup>1</sup> M. Erdmann,<sup>1</sup> Y. I. Eidelman,<sup>1</sup> M. W. Hahne,<sup>1</sup> Z. Huang,<sup>1</sup> K.-J. Kim,<sup>1</sup> J. W. Lewellen,<sup>1</sup> Y. Li,<sup>1</sup> A. H. Lumpkin,<sup>1</sup> O. Makarov,<sup>1</sup> E. R. Moog,<sup>1</sup> A. Nassiri,<sup>1</sup> V. Sajaev,<sup>1</sup> R. Soliday,<sup>1</sup> B. J. Tieman,<sup>1</sup> E. M. Trakhtenberg,<sup>1</sup> G. Travish,<sup>1</sup> I. B. Vasserman,<sup>1</sup> N. A. Vinokurov,<sup>3</sup> X. J. Wang,<sup>1</sup> G. Wiemerslage,<sup>1</sup> B. X. Yang<sup>1</sup>  
*Science 2001*



## First lasing and operation of an *Nature Photon.* 2010 ångstrom-wavelength free-electron laser

P. Emma<sup>1\*</sup>, R. Akre<sup>1</sup>, J. Arthur<sup>1</sup>, R. Bionta<sup>2</sup>, C. Bostedt<sup>1</sup>, J. Bozek<sup>1</sup>, A. Brachmann<sup>1</sup>, P. Bucksbaum<sup>1</sup>, R. Coffee<sup>1</sup>, F.-J. Decker<sup>1</sup>, Y. Ding<sup>1</sup>, D. Dowell<sup>1</sup>, S. Edstrom<sup>1</sup>, A. Fisher<sup>1</sup>, J. Frisch<sup>1</sup>, S. Gilevich<sup>1</sup>, J. Hastings<sup>1</sup>, G. Hays<sup>1</sup>, Ph. Hering<sup>1</sup>, Z. Huang<sup>1</sup>, R. Iverson<sup>1</sup>, H. Loos<sup>1</sup>, M. Messerschmidt<sup>1</sup>, A. Miahnahri<sup>1</sup>, S. Moeller<sup>1</sup>, H.-D. Nuhn<sup>1</sup>, G. Pile<sup>3</sup>, D. Ratner<sup>1</sup>, J. Rzepiela<sup>1</sup>, D. Schultz<sup>1</sup>, T. Smith<sup>1</sup>, P. Stefan<sup>1</sup>, H. Tompkins<sup>1</sup>, J. Turner<sup>1</sup>, J. Welch<sup>1</sup>, W. White<sup>1</sup>, J. Wu<sup>1</sup>, G. Yocky<sup>1</sup> and J. Galayda<sup>1</sup>

# Japanese X-ray FEL facility, SACLA

(Spring-8 Angstrom Compact free electron Laser)

Construction: FY2006~2010

First lasing: June 7, 2011

User Operation: March 2012~

User time: > 3151 h/year (FY2012)

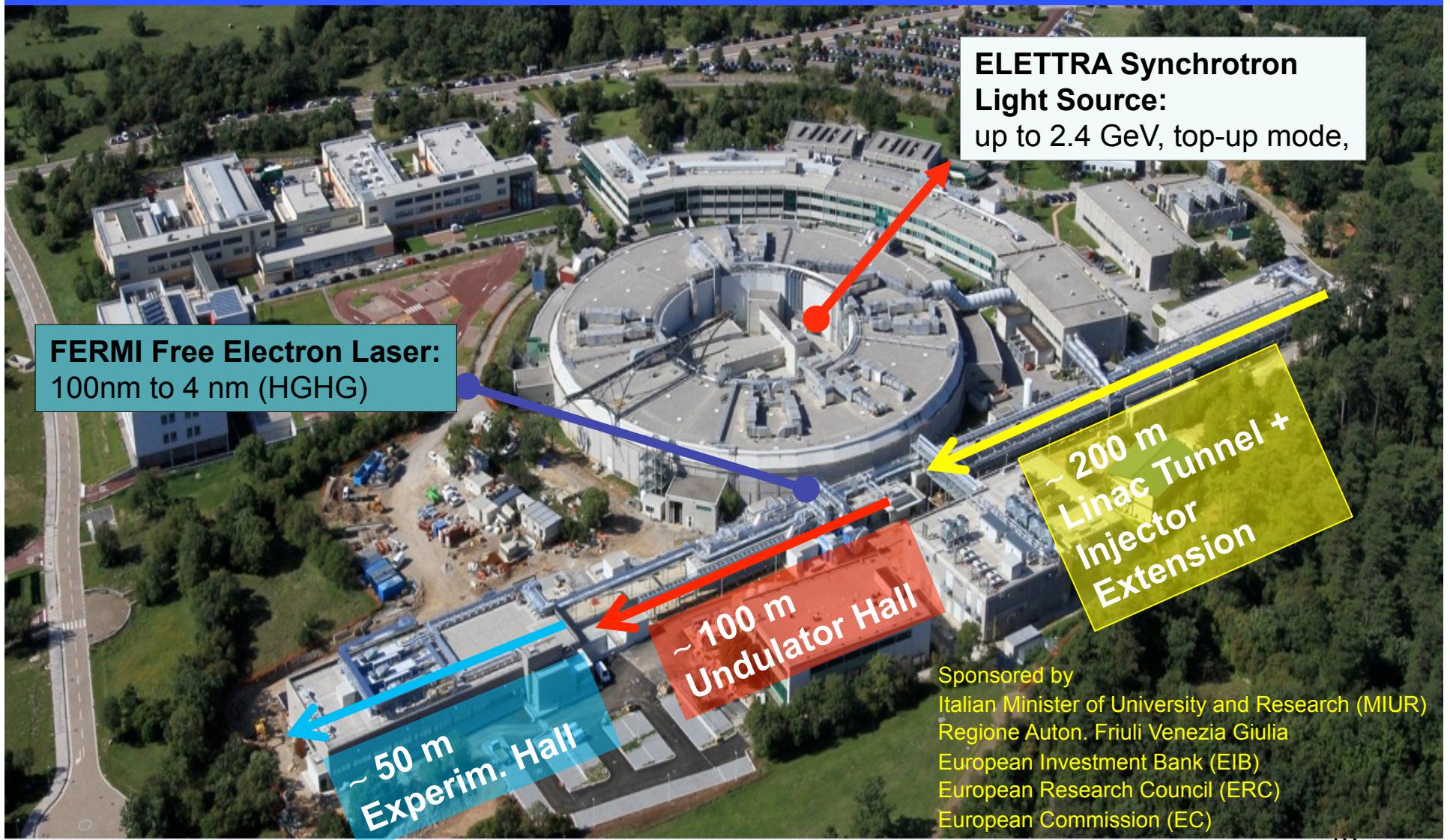
Number of users: 732 (FY2012)

Co-locate with  
SPring-8 SR

Compact XFEL with 700 m length



# *Elettra – Sincrotrone Trieste*

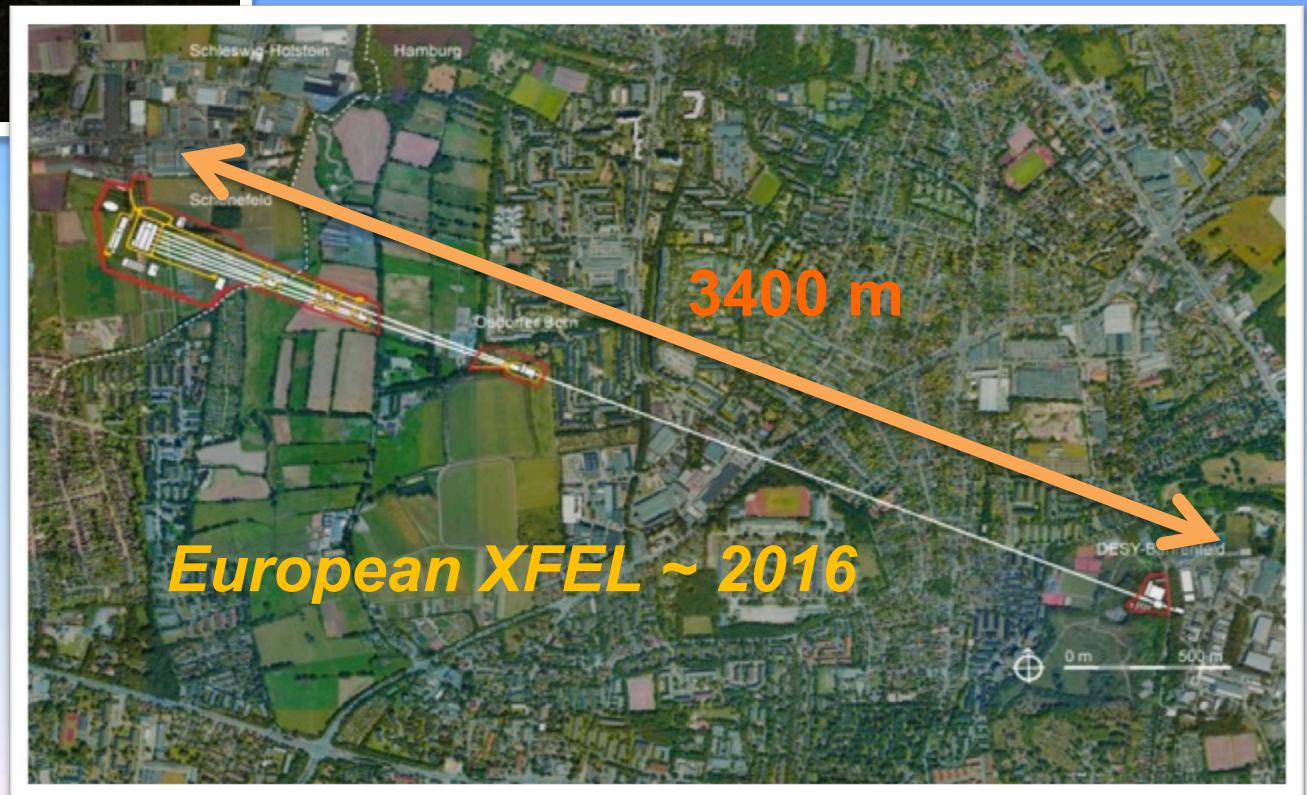


# More X-ray Lasers



*more to come:*  
**PAL-XFEL (2015)**  
**SwissFEL (2016)**  
**LCLS-II (2019)**

...

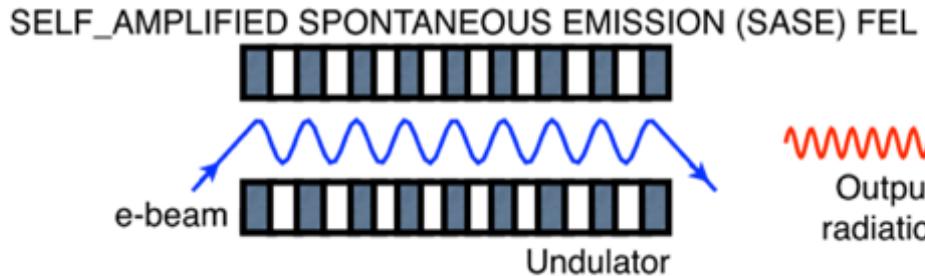


## *R&D for a Bright Future*

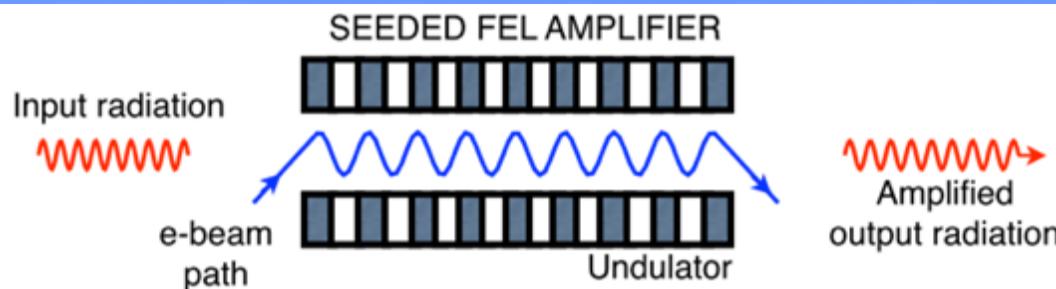
- Seeding (precise color and higher brightness)
- Terawatt FEL (higher intensity)
- Novel undulators for SR and FEL
- Electron Beam generation and manipulation
- X-ray beam sharing and manipulations
- Femtosecond and attosecond x-rays
- Two-color FEL (pump-probe)
- High-rate and continuous wave operation
- X-ray FEL oscillators
- Advanced accelerators for compact XFELs
- ...

# Options for X-Ray Free Electron Lasers

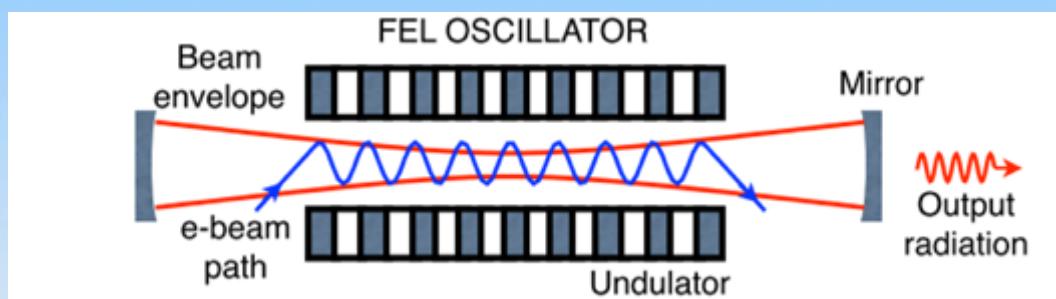
Easy  
↓  
Hard



LCLS USA  
SACLA Japan  
FLASH Germany  
*XFEL* Germany  
SWISSFEL Switzerland  
PAL FEL Korea



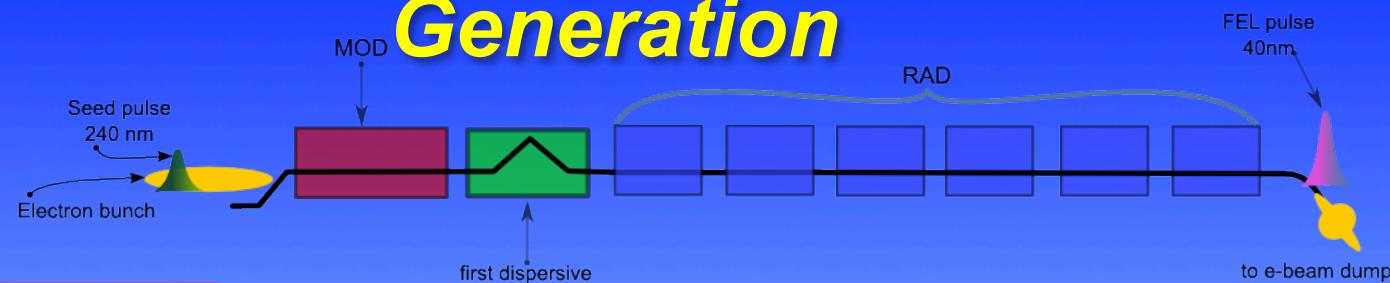
FERMI Italy  
FLASH-II Germany  
HXRSS LCLS



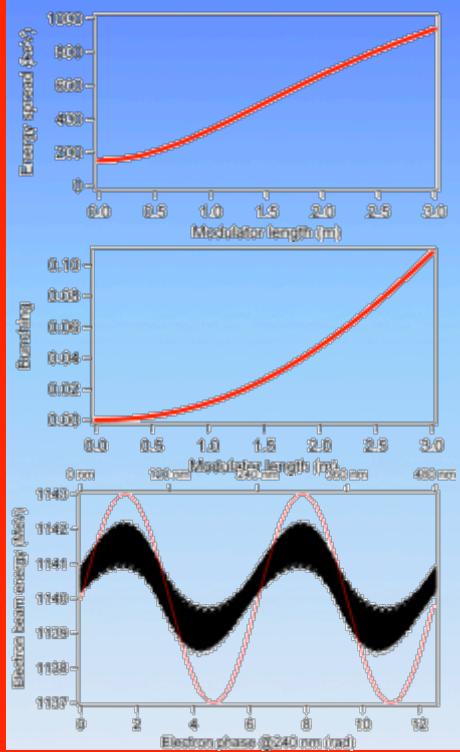
Proposal ANL USA

Introduction to the Physics of Free Electron Lasers Kwang-Je Kim (ANL) and Zhirong Huang (SLAC)

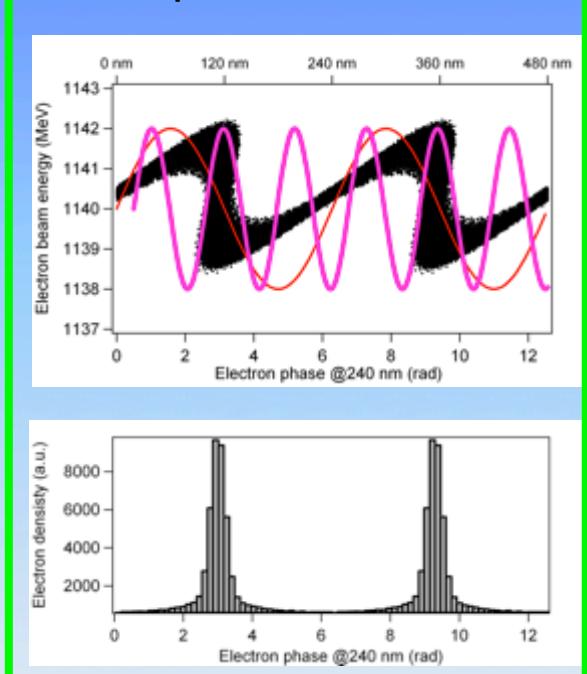
# FEL-1 at Elettra: High Gain Harmonic Generation



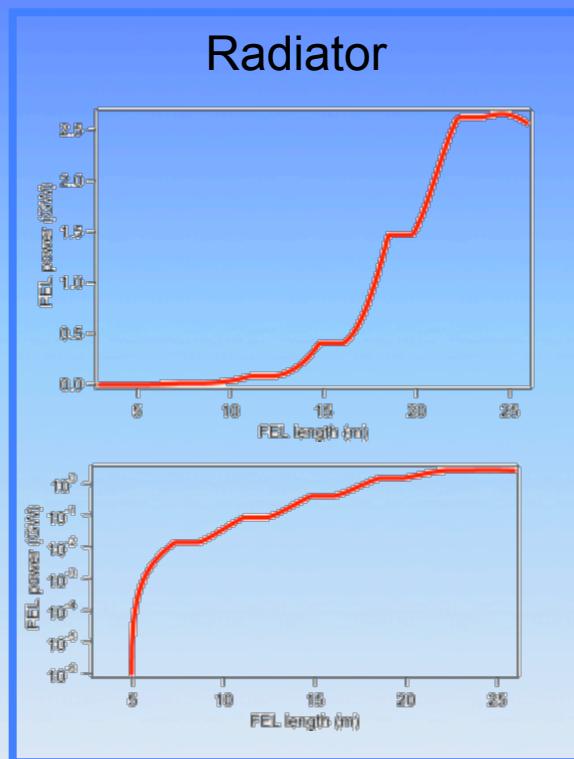
**Modulator**



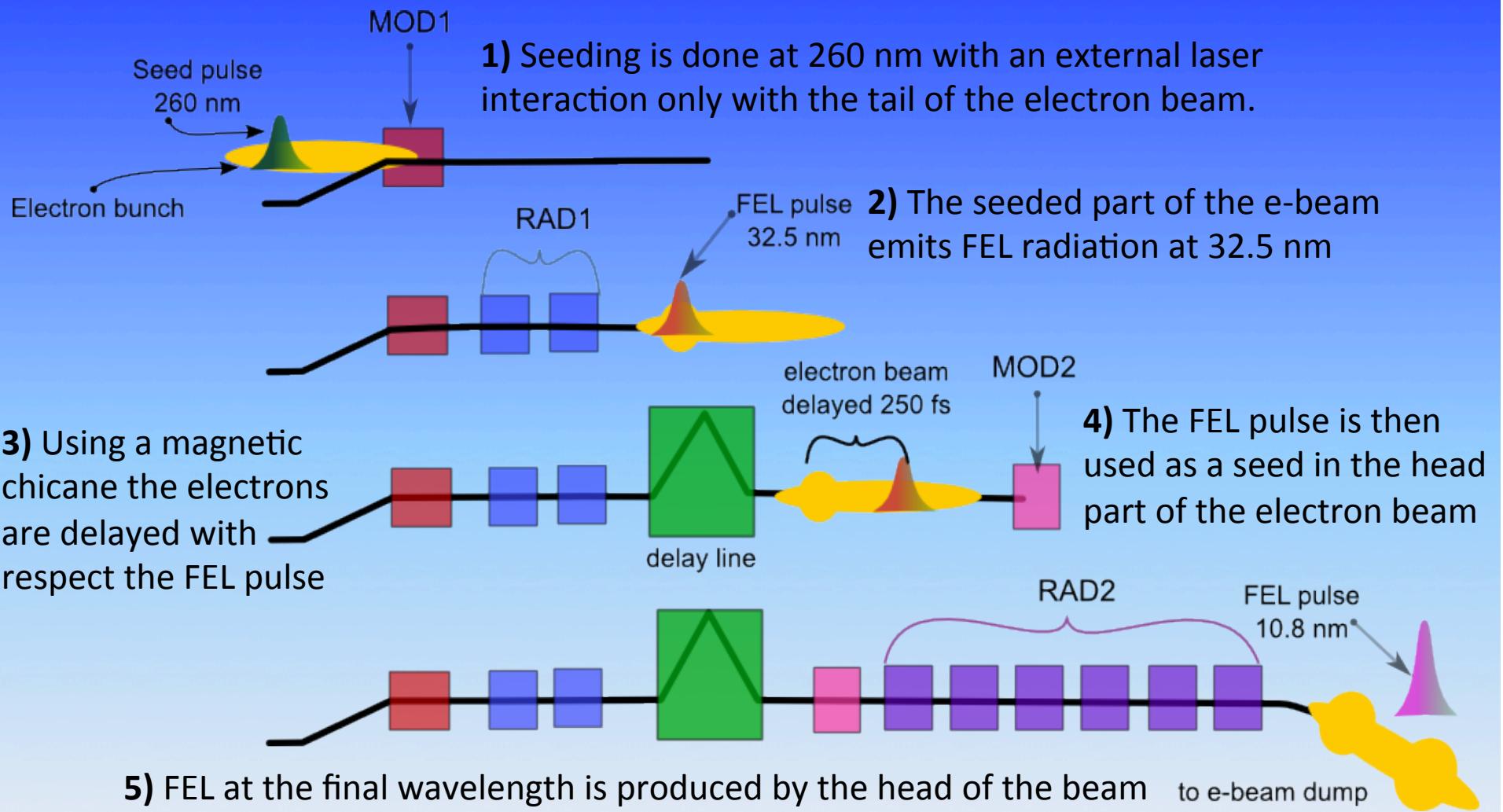
**Dispersive section**



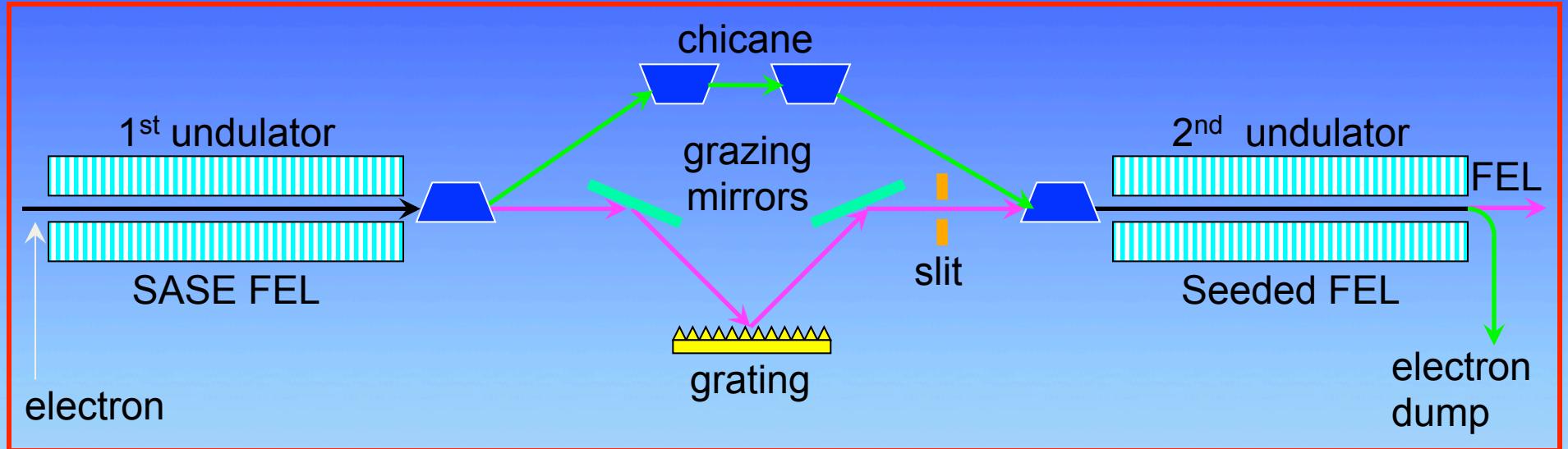
**Radiator**



# FEL-2 at Elettra: fresh bunch double cascade

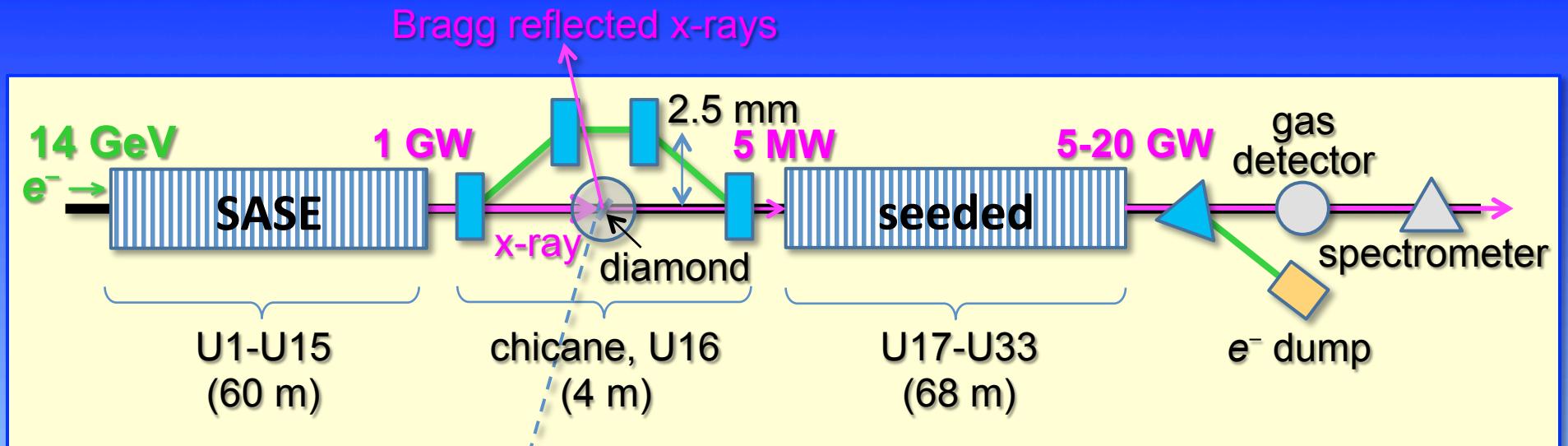


# *Seeded FEL Concept*

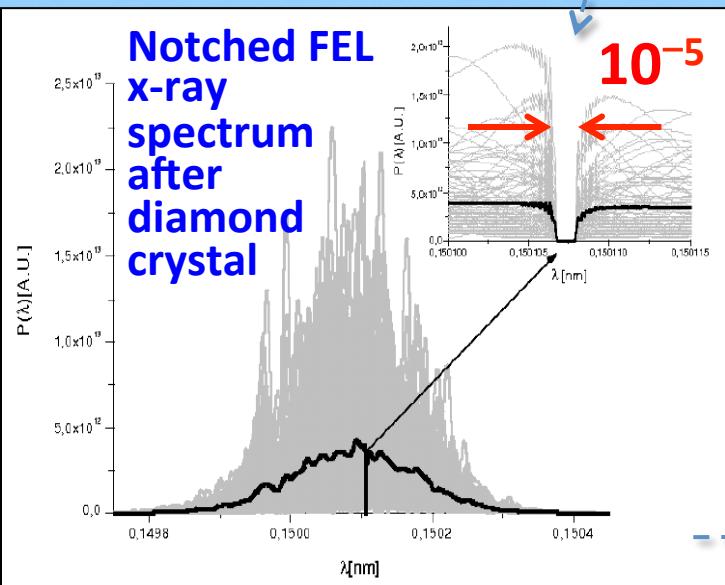


"Seeded FEL Concept Possible application of X-ray optical elements for reducing the spectral bandwidth of an X-ray SASE FEL" J. Feldhaus <sup>a</sup>I, E.L. Saldin <sup>b</sup>, J.R. Schneider <sup>a</sup>, E.A. Schneidmiller <sup>b</sup>, M.V. Yurkov Opt. Comm. 140, 341 (1997)

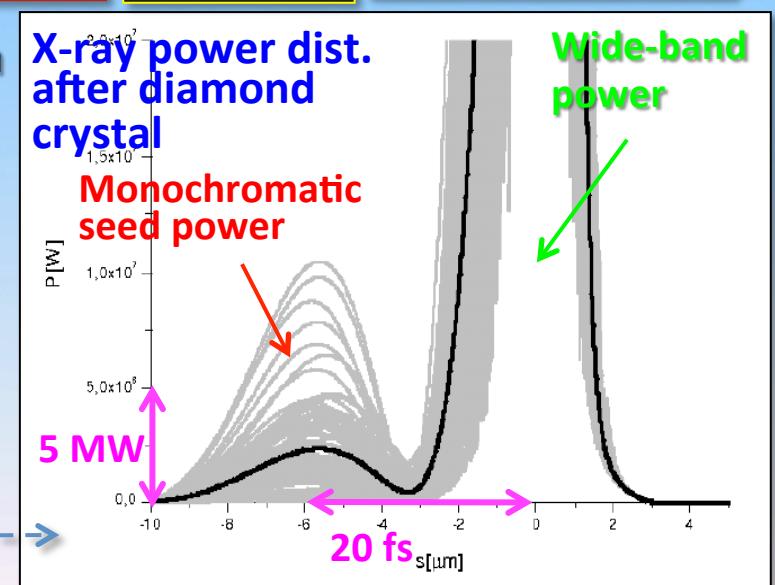
# Self-Seeding Scheme @ LCLS

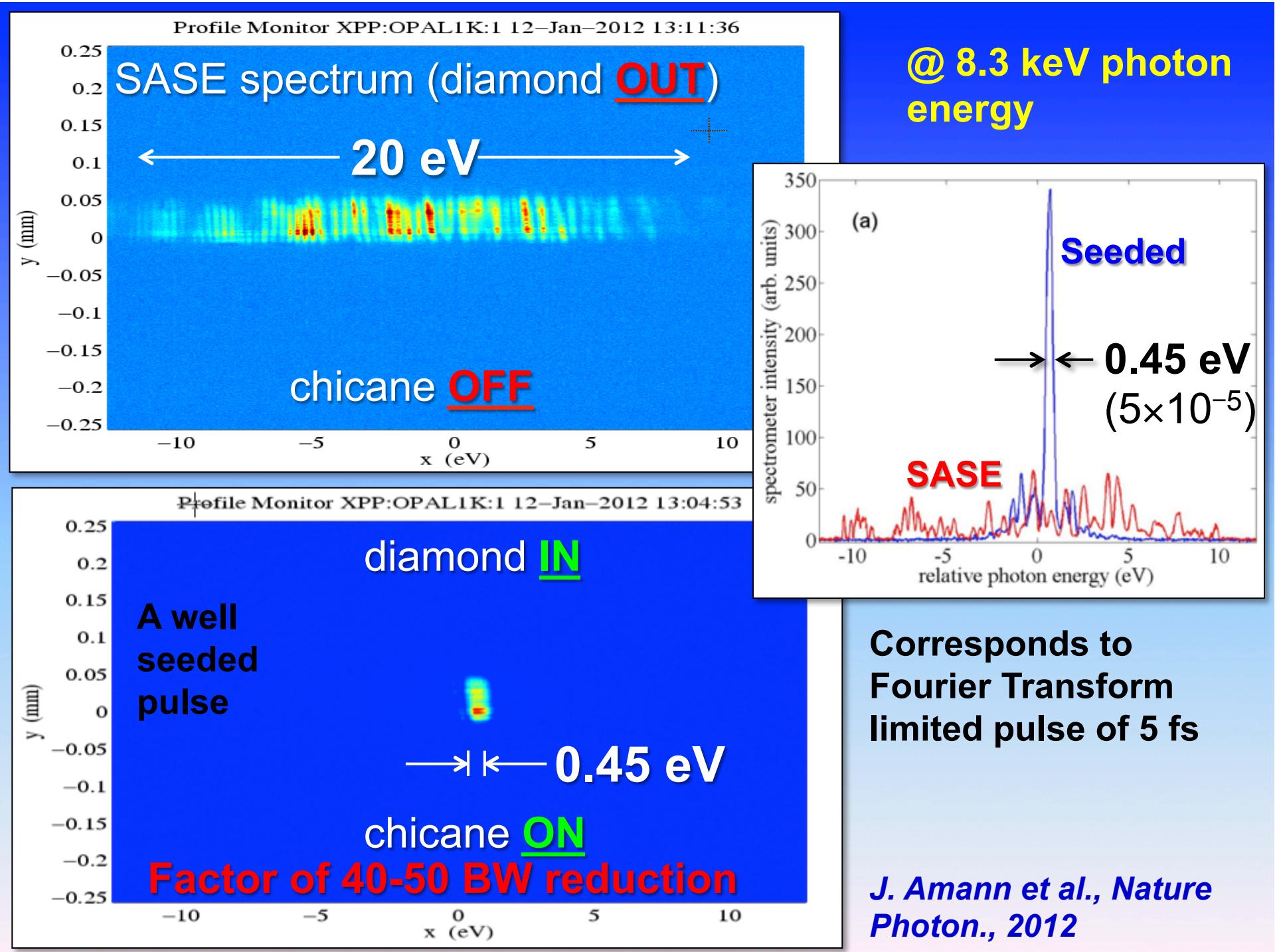


Geloni, Kocharyan,  
Saldin (DESY 10-133)



Use 10-fs bunch (low charge) to self-seed 1.5 Å (20-40 pC)







# Hard X-ray self-seeding set-up and results at SACLA

**T. Inagaki<sup>a</sup>, T. Tanaka<sup>a</sup>, N. Azumi<sup>a</sup>, T. Hara<sup>a</sup>, T. Hasegawa<sup>c</sup>,**  
**Y. Inubushi<sup>b</sup>, T. Kameshima<sup>b</sup>, H. Kimura<sup>b</sup>, R. Kinjo<sup>a</sup>, H. Maesaka<sup>a</sup>,**  
**A. Miura<sup>b</sup>, H. Ohashi<sup>b</sup>, T. Ohata<sup>b</sup>, Y. Otake<sup>a</sup>, S. Tanaka<sup>c</sup>, K. Togawa<sup>a</sup>,**  
**K. Tono<sup>b</sup>, H. Yamazaki<sup>b</sup>, M. Yabashi<sup>a</sup>, S. Goto<sup>b</sup>, H. Tanaka<sup>a</sup>, T. Ishikawa<sup>a</sup>**

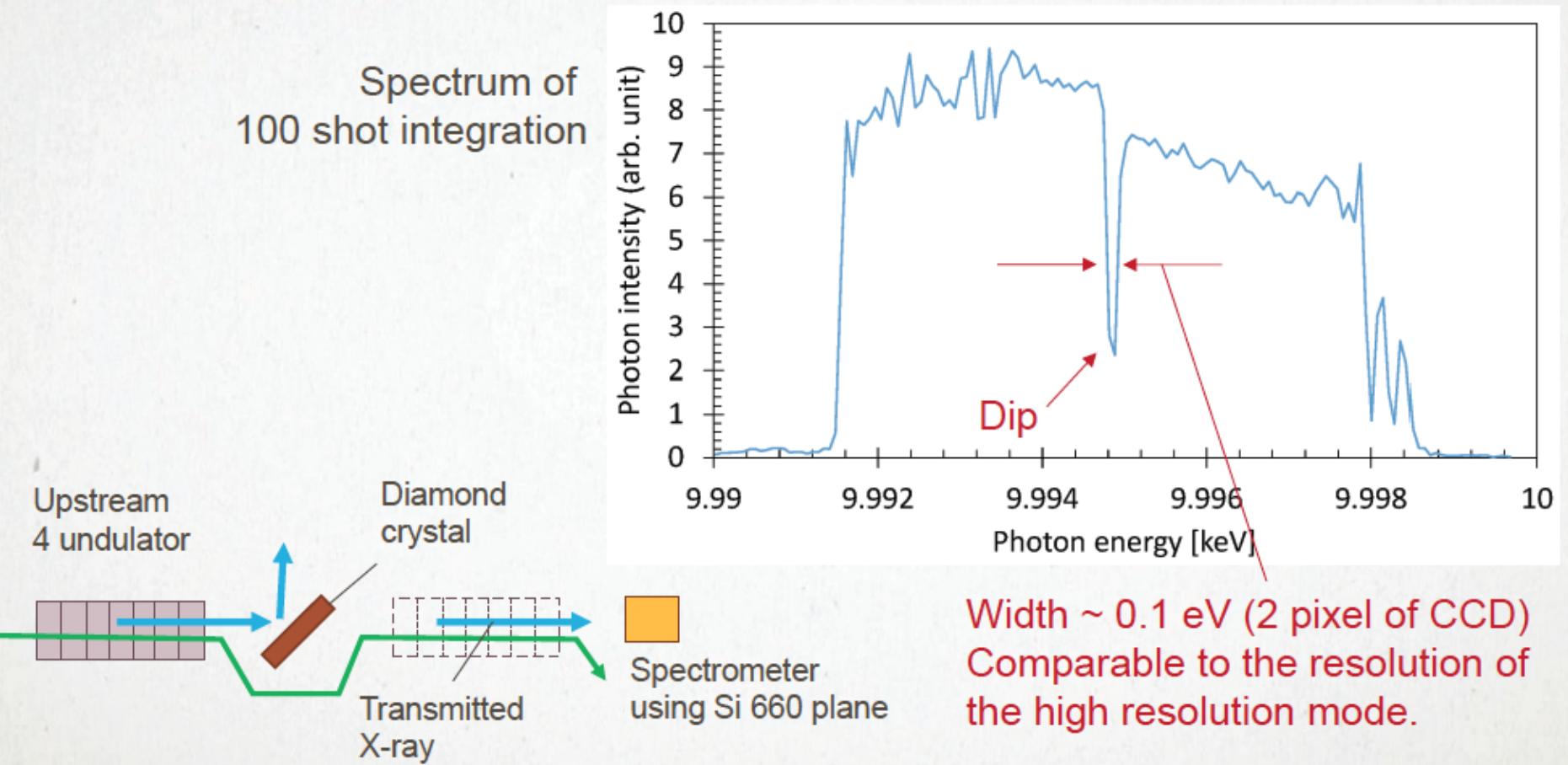
<sup>a</sup> RIKEN SPring-8 center

<sup>b</sup> Japan Synchrotron Radiation Research Institute (JASRI)

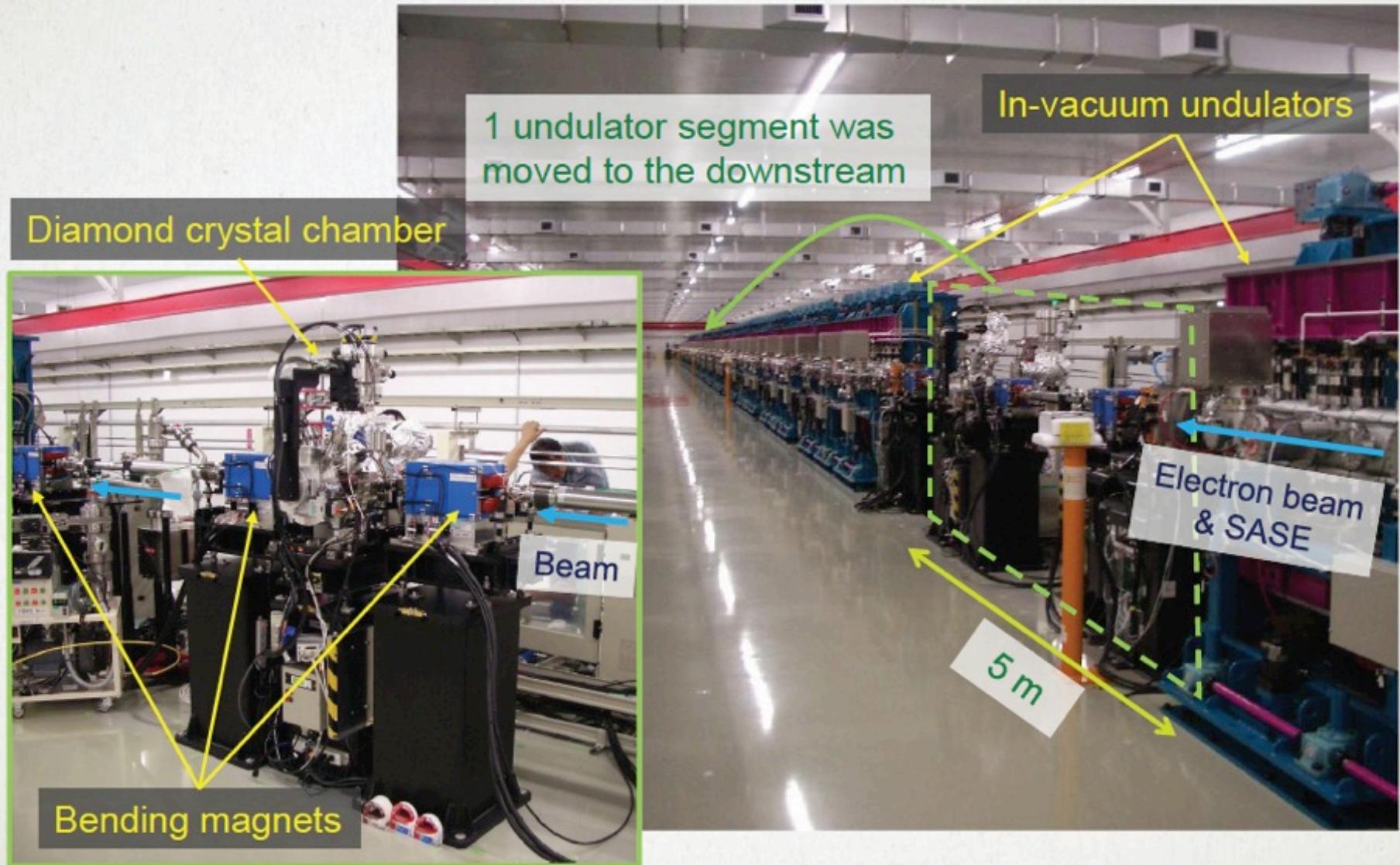
<sup>c</sup> SPring-8 Service Co. Ltd.

# Spectrum of the transmitted SASE radiation

- We observed clear dip due to the Bragg diffraction
- The diamond crystal has a good quality, without degradation

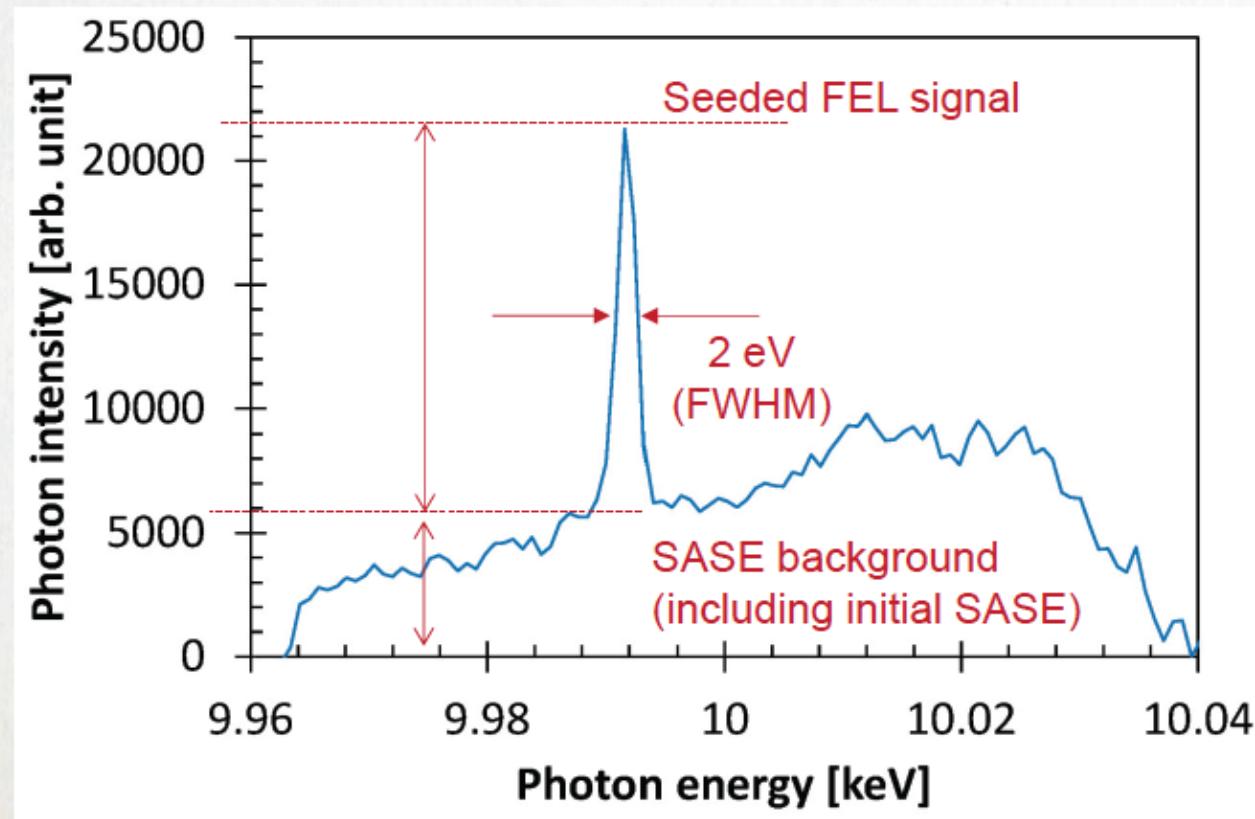


# Magnetic chicane (50 fs max.) in BL3 beamline



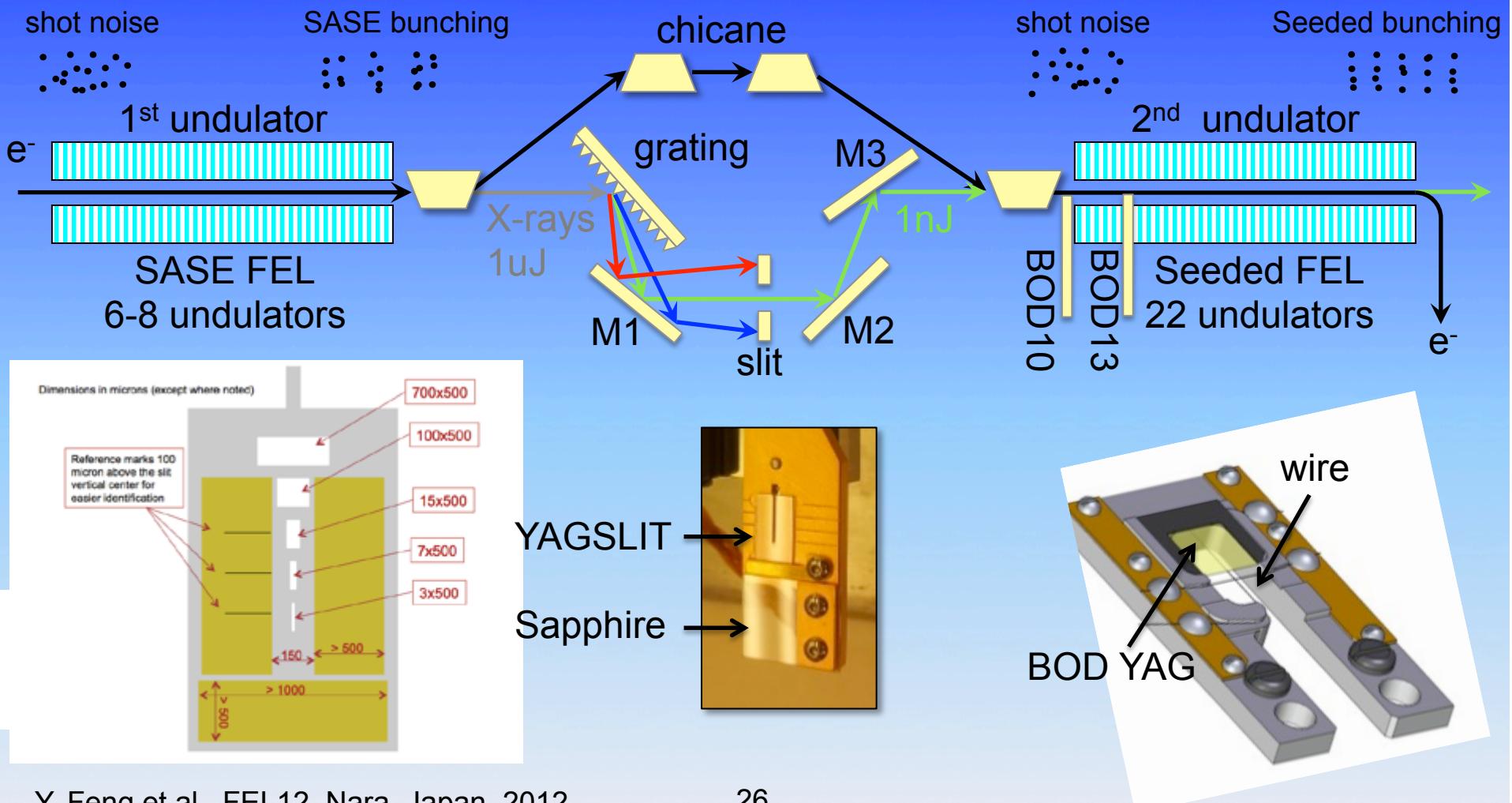
# 100 shot integrated spectrum

- Peak intensity: 4 times higher than SASE background
- Spectral width: 2 eV (FWHM), which is 1/15 of SASE
- Self seeding drastically enhanced the monochromatic photon intensity and spectral narrowing as expected.



With  
Upstream 4 undulators  
Downstream 13 undulators  
20 fs delay at chicane

# Soft X-ray Self-Seeded (SXRSS) Concept

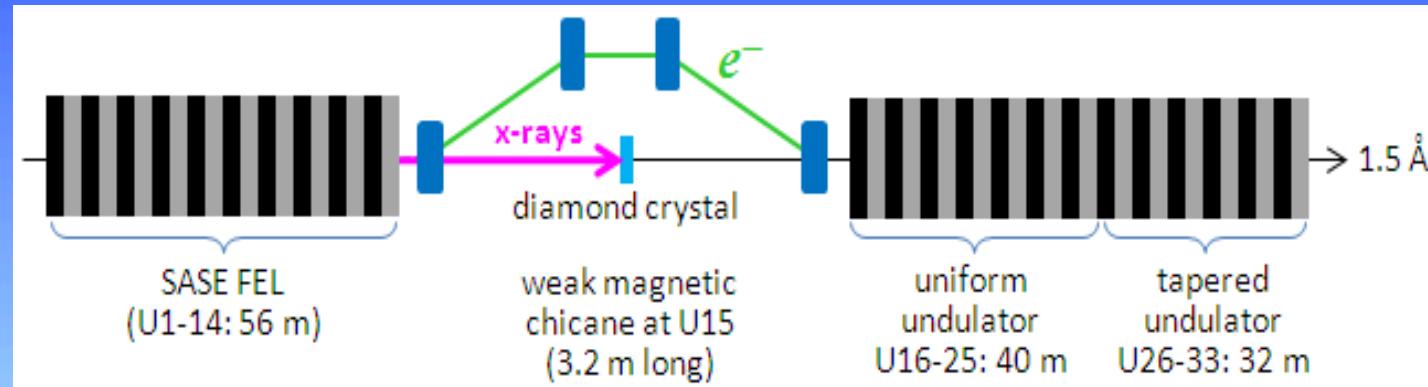


Y. Feng et al., FEL12, Nara, Japan, 2012.  
D. Cocco et al., Proc. SPIE, 2013.

# SXRSS Commissioning

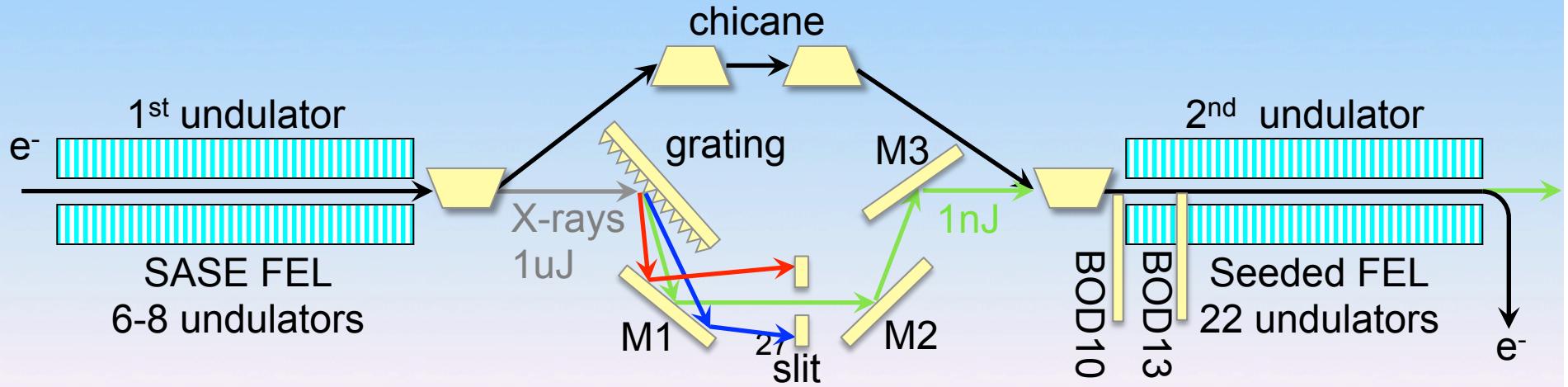
HXRSS

1 optical component



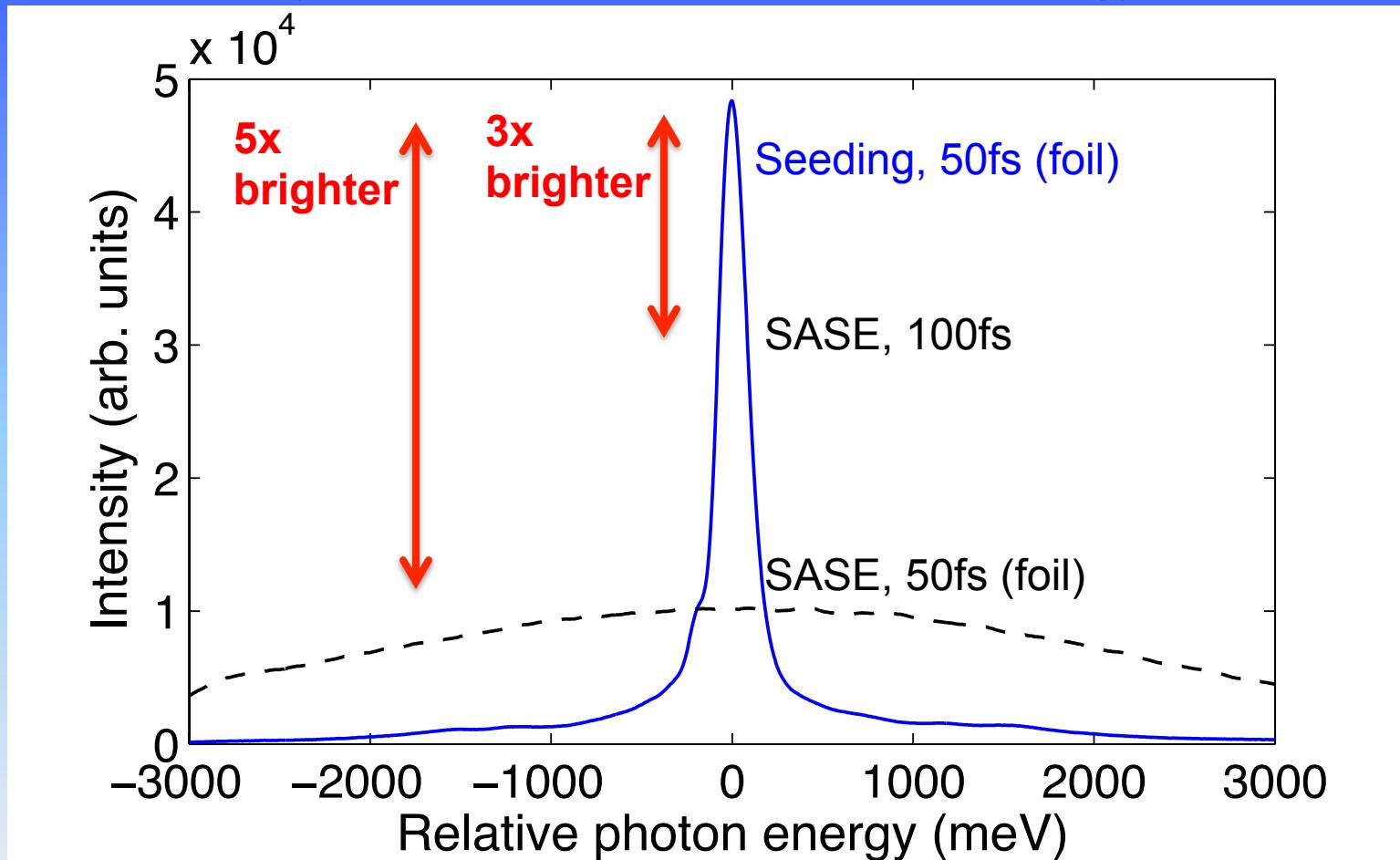
SXRSS

5 optical components and 2 diagnostics



# SXRSS at LCLS: 29-July-2014

(Undulators 10-25 inserted for seeding)

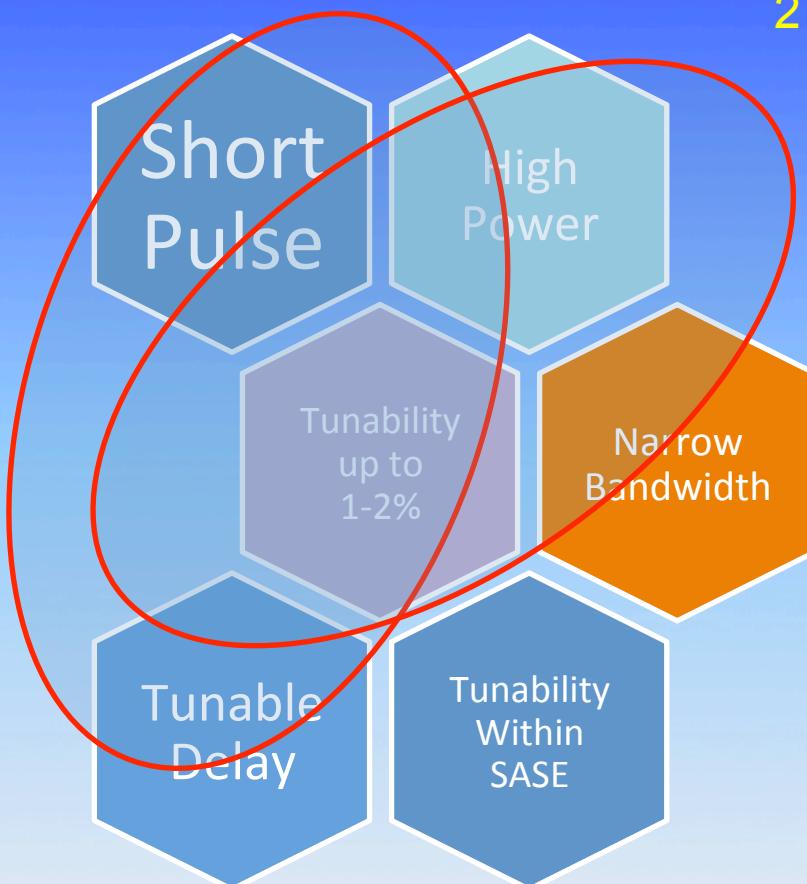


$$E=930 \text{ eV}$$

# **2-bunch Users' wish list**

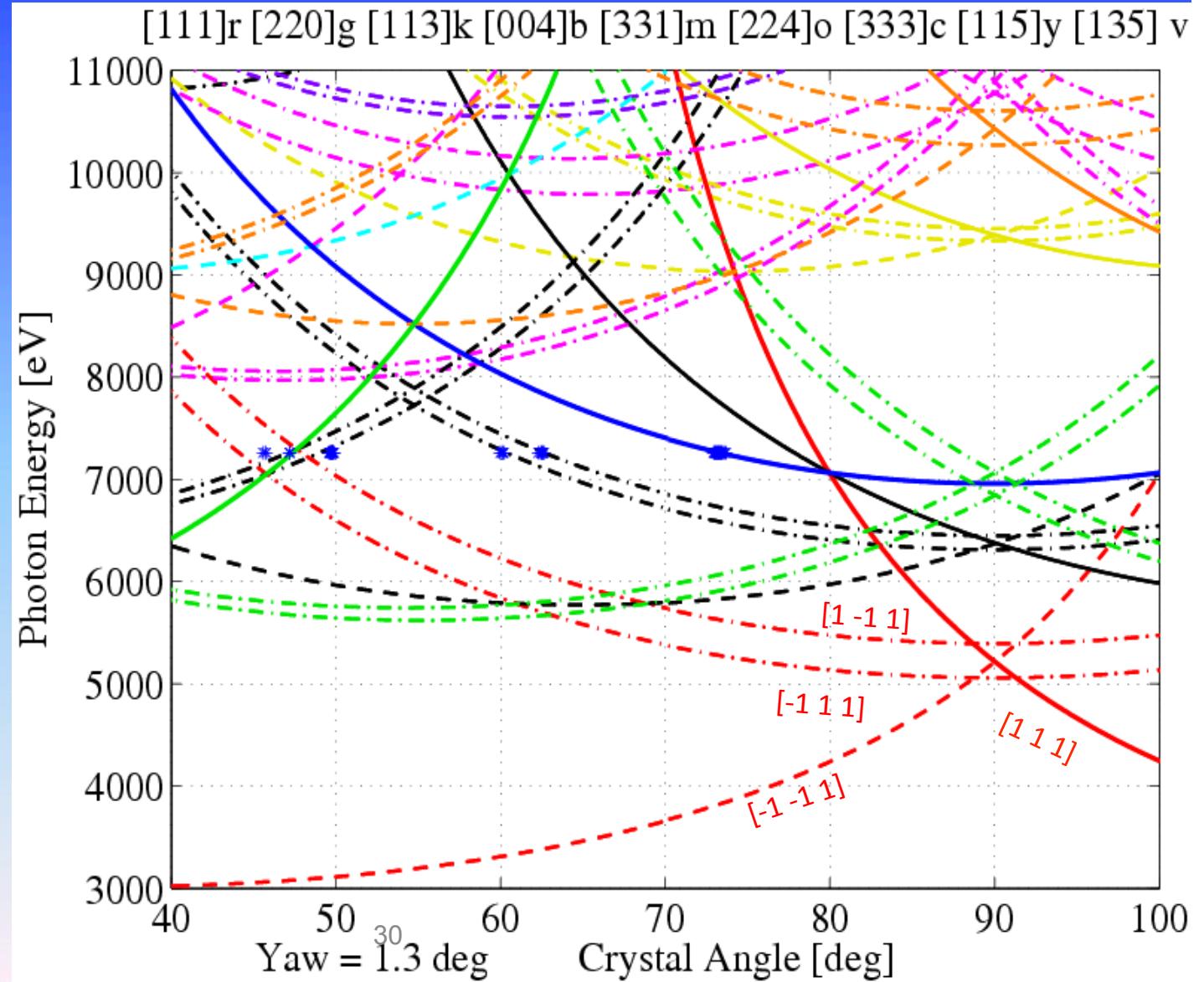
2 bunch SASE

2 bunch Self-Seeding

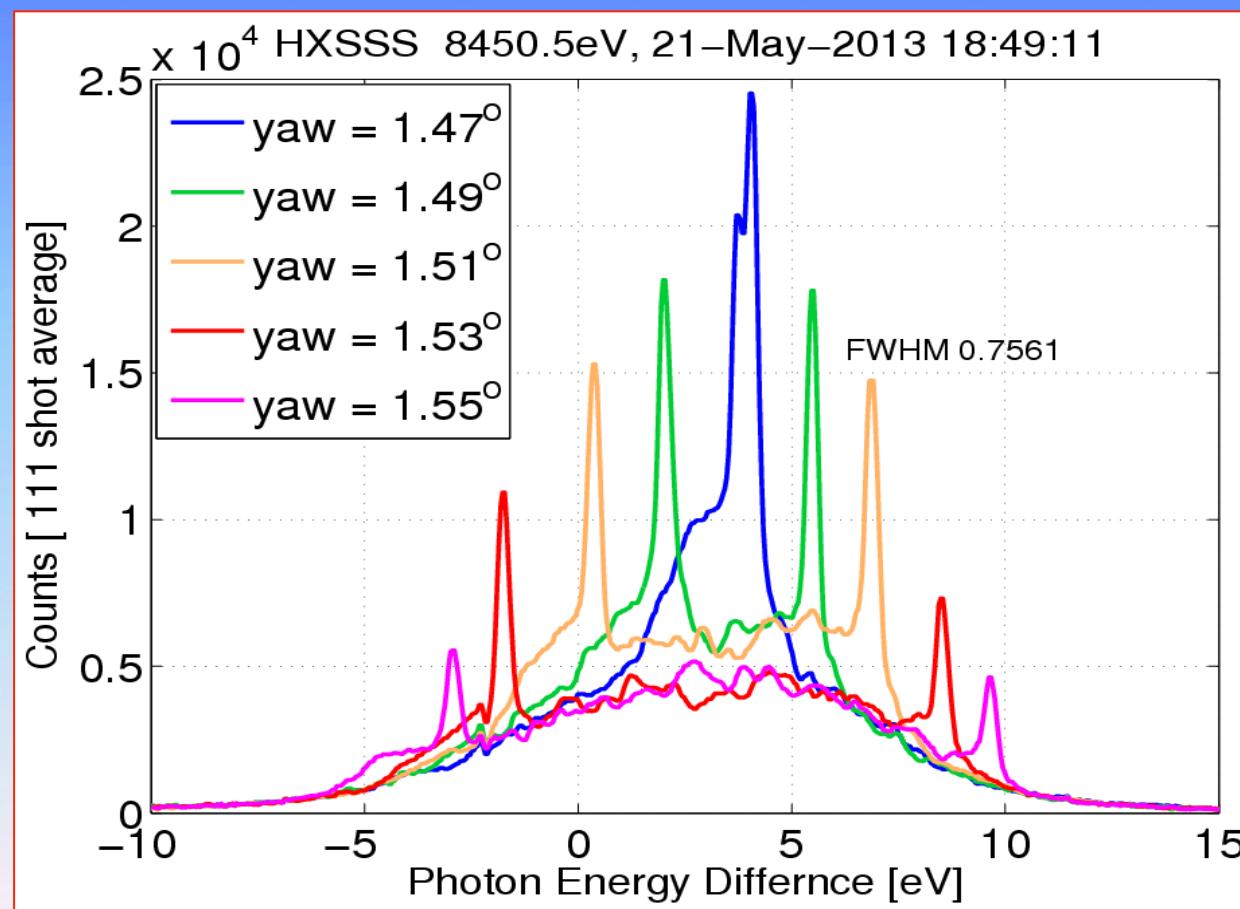
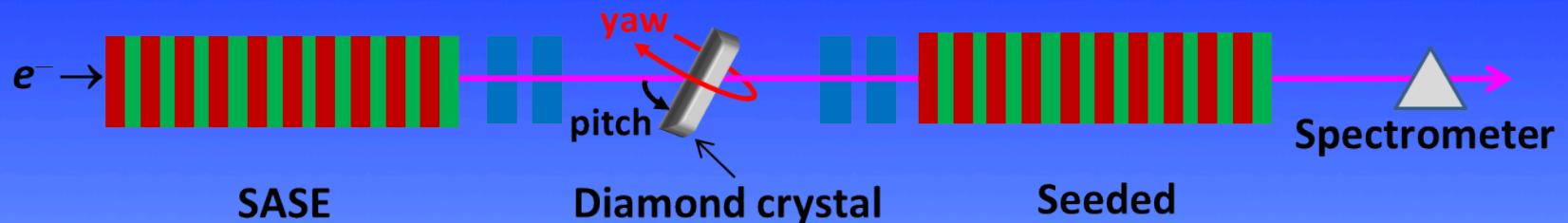


# **Yaw Angle gives Two-Color Hard X-ray Seeding at Any Energy**

- Rules:
  - All odd or even
  - If even, sum =  $n \cdot 4$
- Colors:
  - indices family
- Line styles:
  - In-plane:
    - positive:  $[a a b]$
    - negative:  $[-a -a b]$
  - Out-of-plane:
    - . - [a b c] with  $a \neq b$

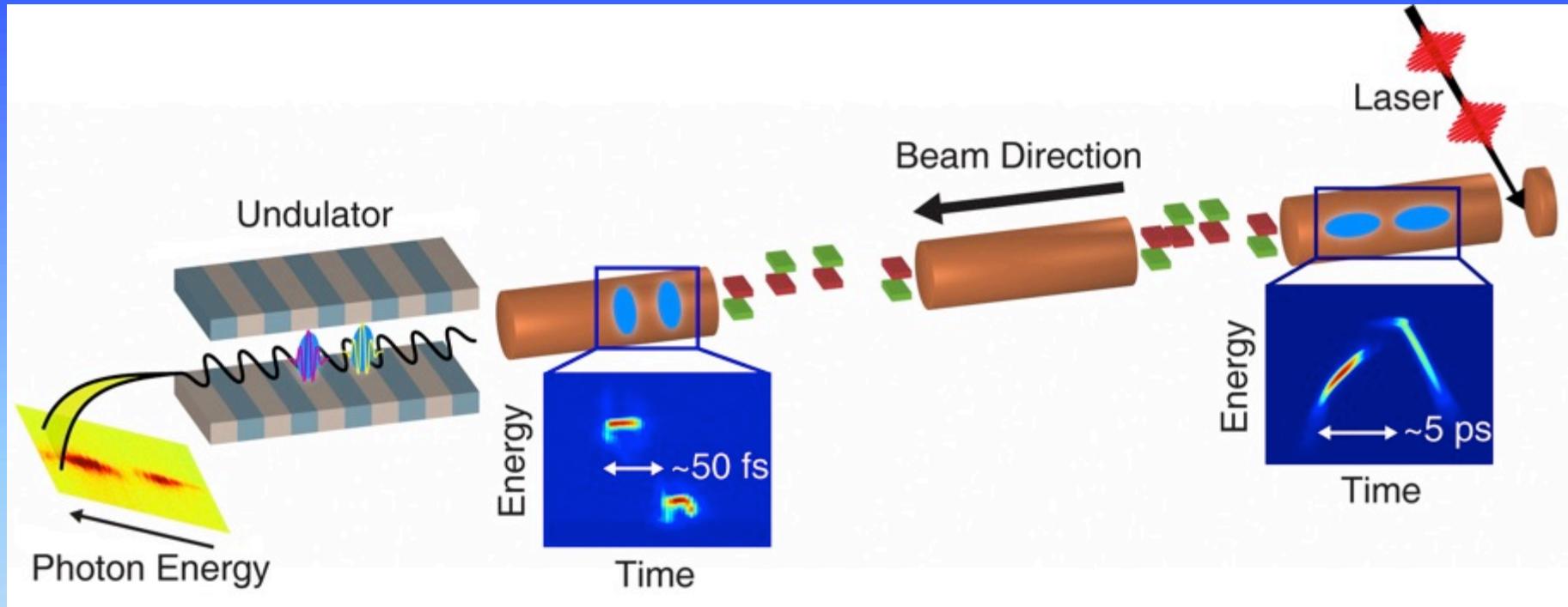


# Seeding Chicane Side View



Reflection pair:  
[-3 -1 1], [-1 -3 1]  
pitch angle:  $60.5^\circ$

# *Double Bunch Scheme*

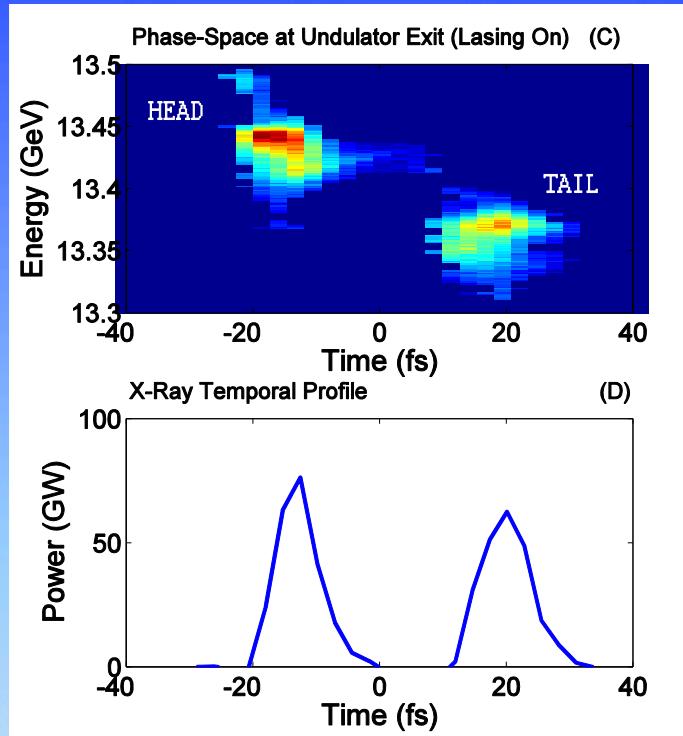


- Generate 2 bunches @ cathode
- Accelerate and compress
- 2 color lasing in undulator

Advantages:

- FULL SATURATION POWER
- SELF-SEEDING
- TEMPORAL DIAGNOSTIC WITH XTCAV

# *Experimental Results at 8.4 keV*



Measured Phase-Space

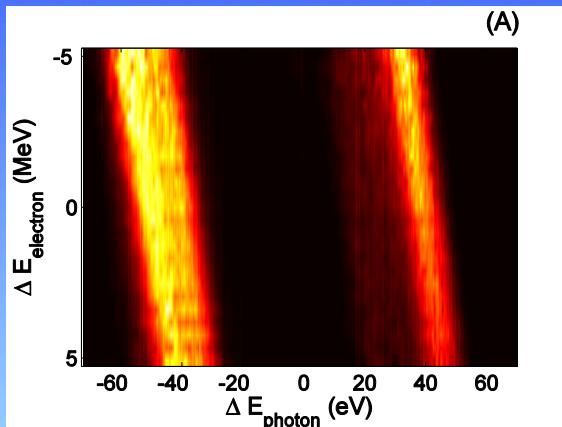
Reconstructed x-ray temporal profile  
(high comes first...)

Time delay variable up to  
~100 fs

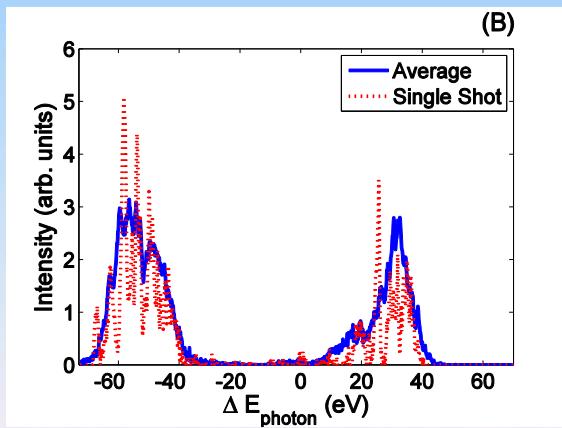
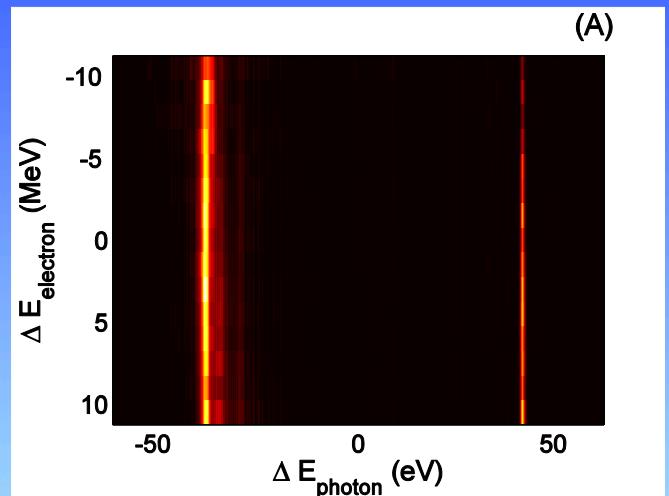
(independently of energy separation and individual pulse duration!)

~50 GW peak power  
1.2 mJ pulse energy

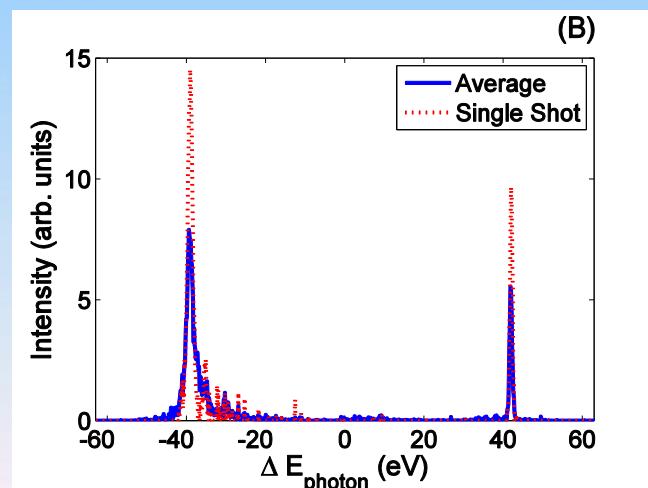
# *SASE and Seeded at 8.4 keV*



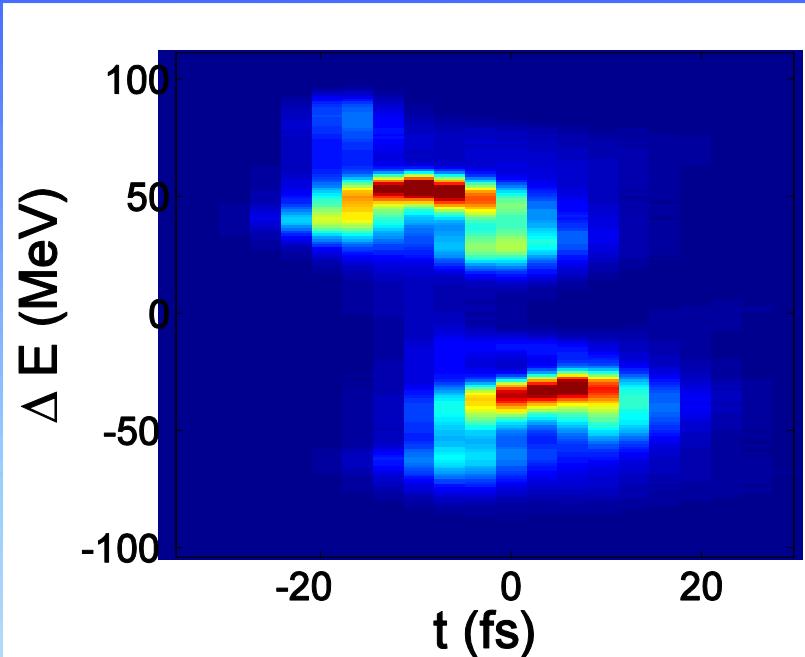
Max energy separation  
~ 1.5 % at HXR  
~ 3-4 % at SXR



Seeded pulse energy  
~ 130 uJ  
(but double the spectral  
brightness...).



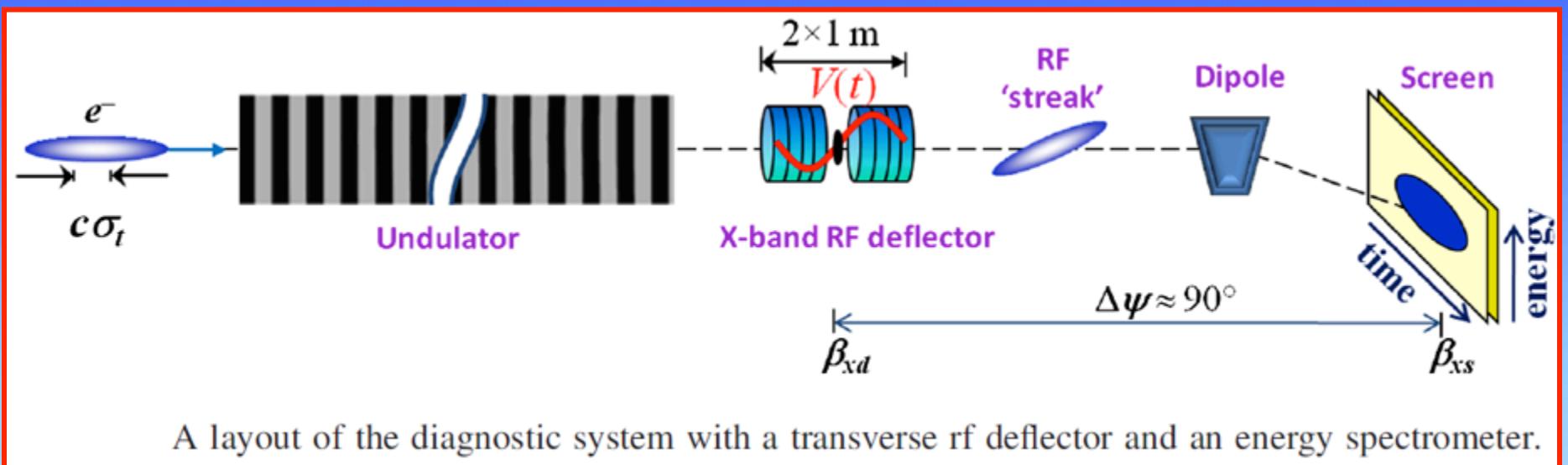
## *Small Delay Setup*



Time delay is typically variable independently of energy separation AND pulse duration.

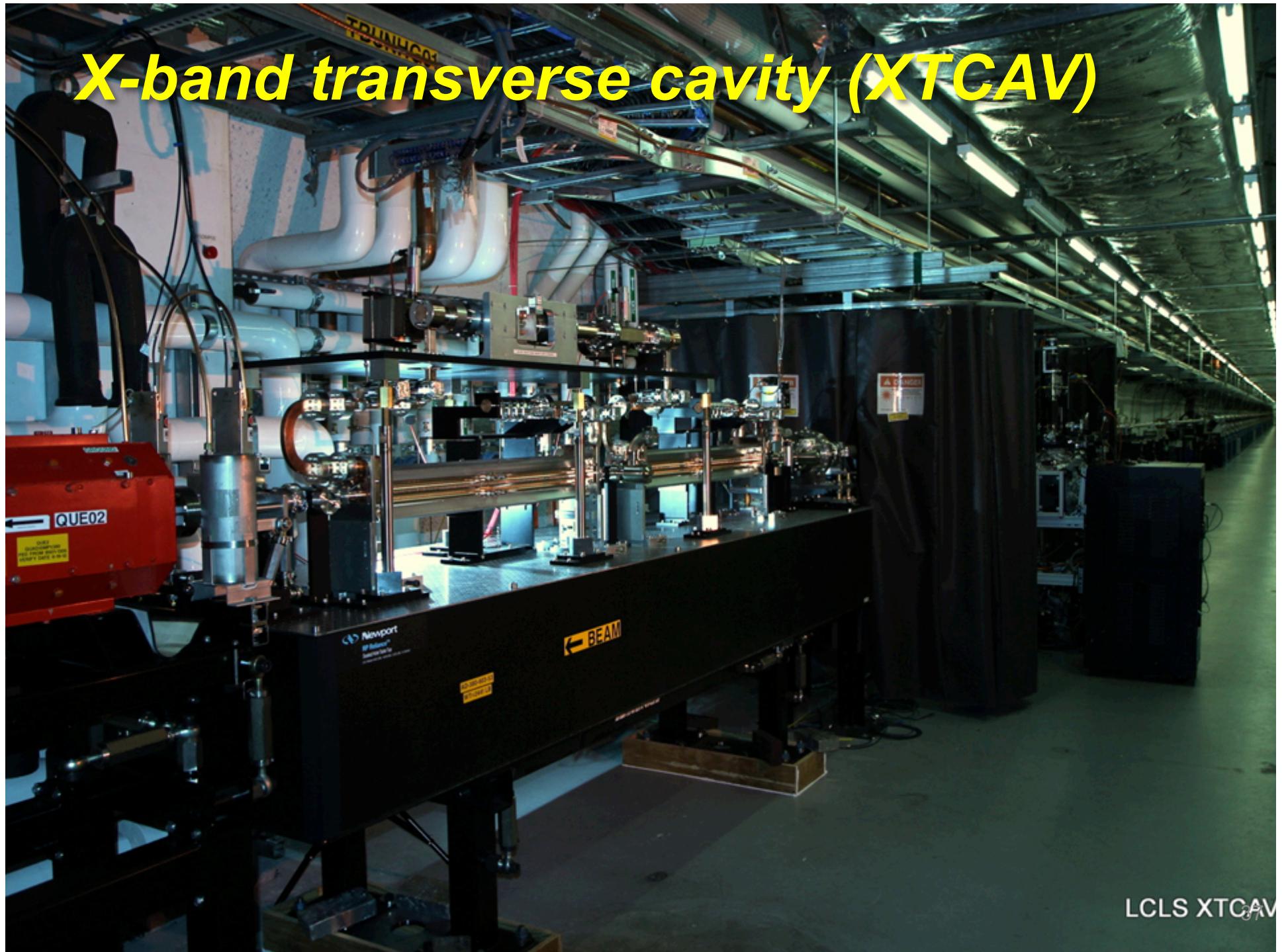
Image shows a phase-space for a MAD experiment, where small time delay is a crucial feature...

# X-band Transverse Cavity (XTCAV)



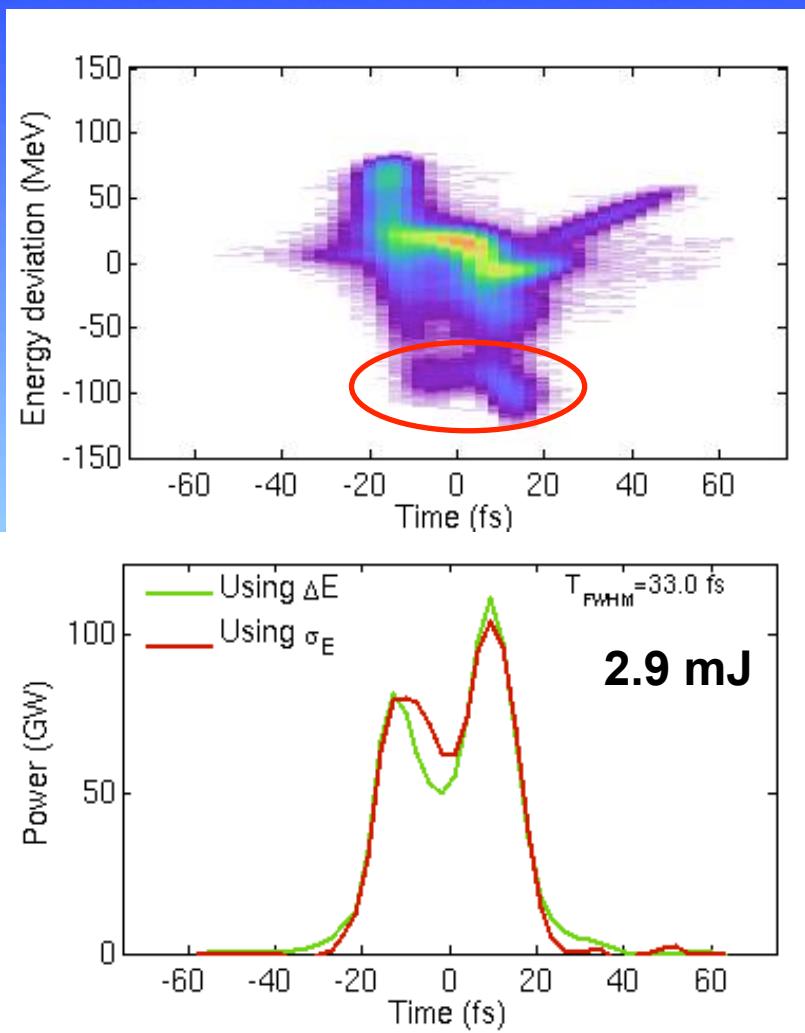
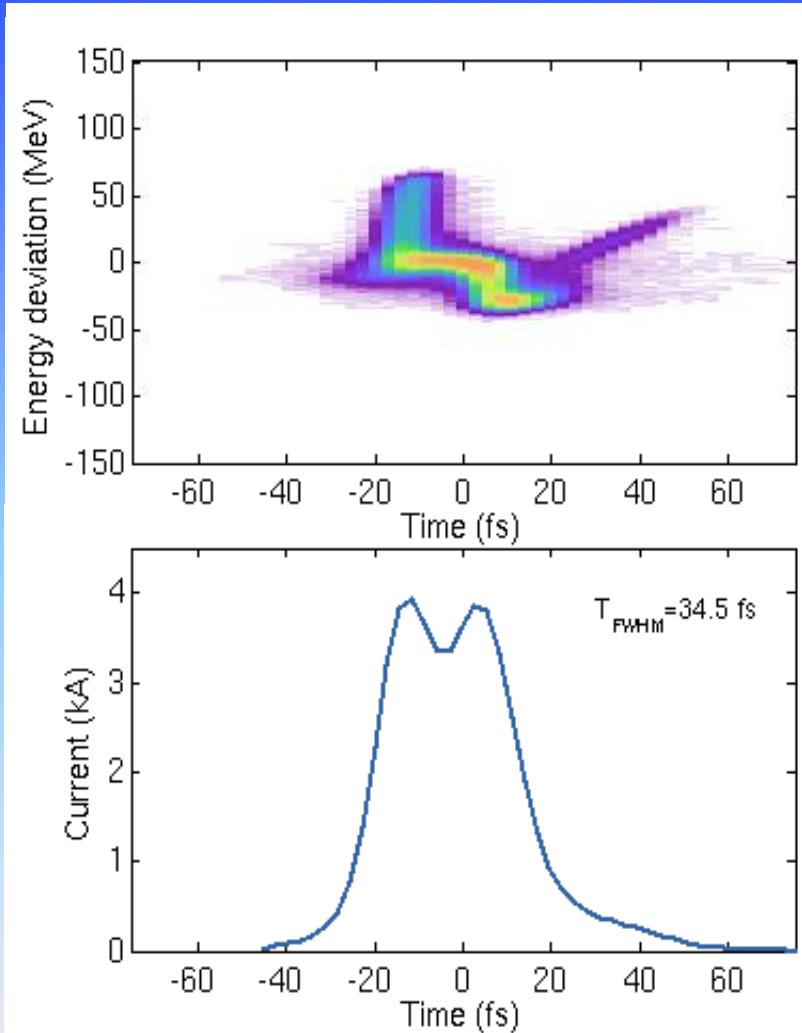
Y. Ding et al., PRSTAB, 14, 120701 (2011)

# *X-band transverse cavity (XTCAV)*

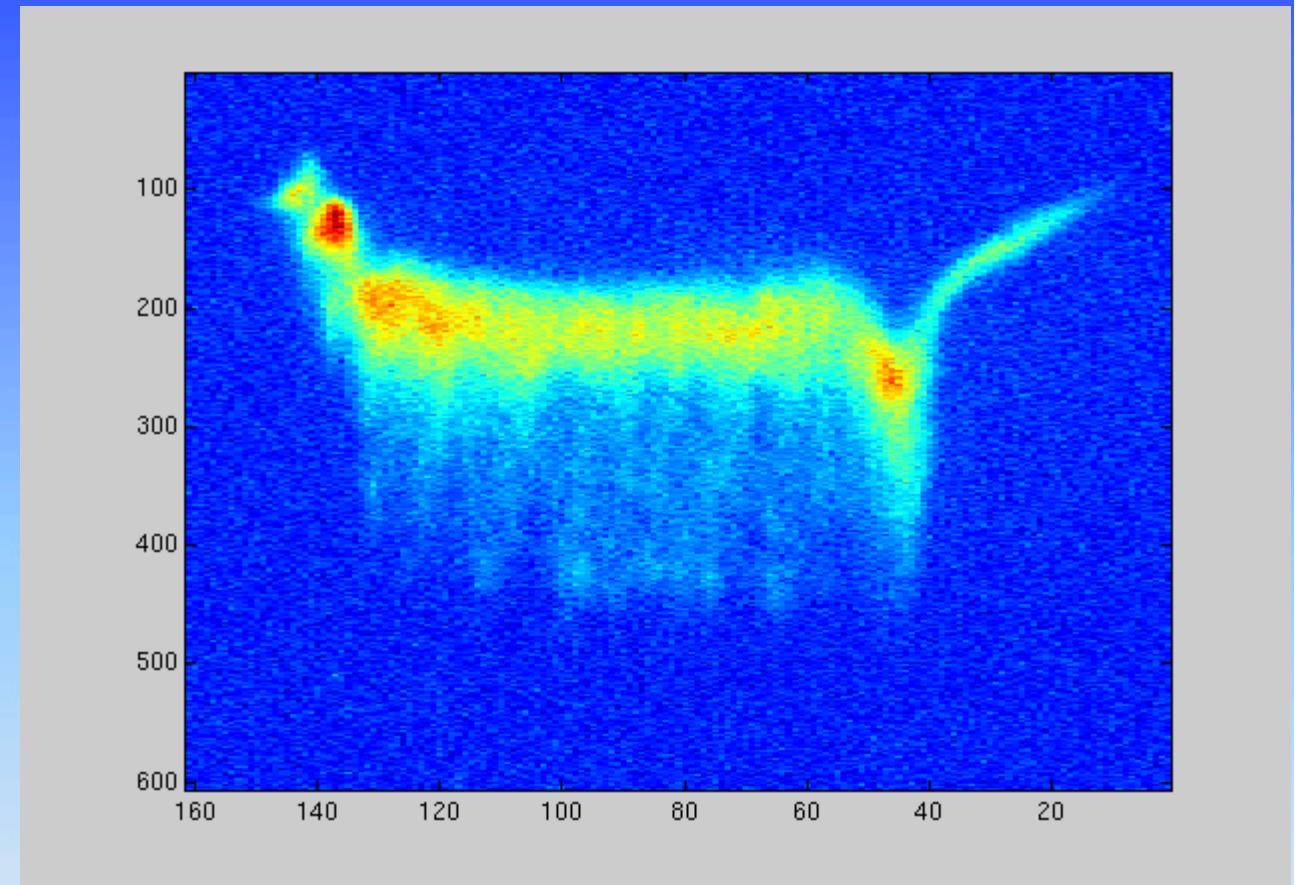
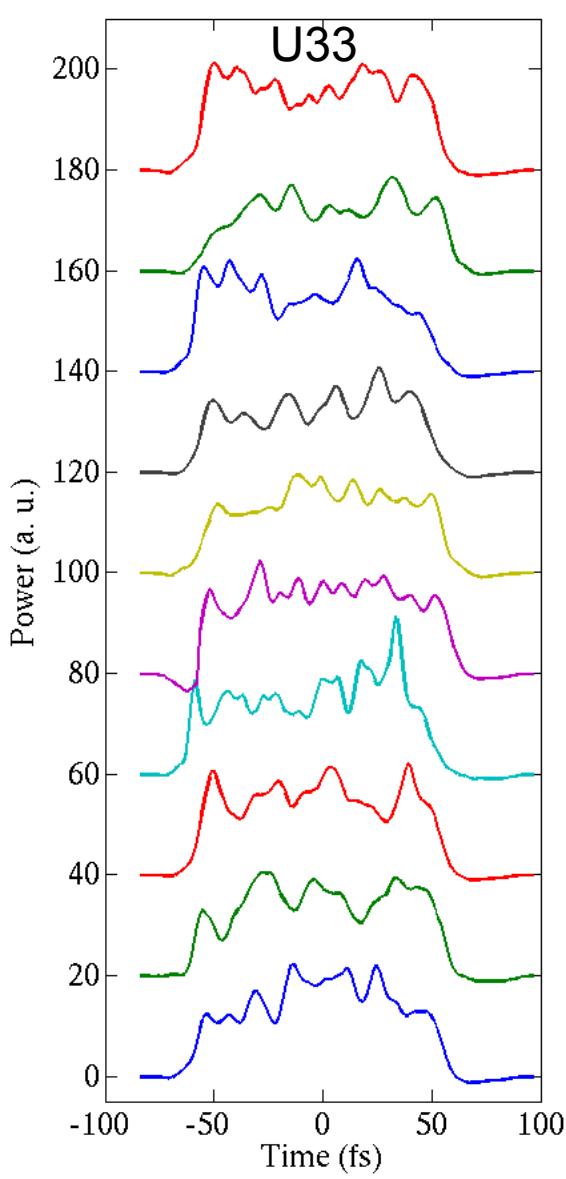


LCLS XTCAV

# *HXR examples: 150pC 9.6keV*

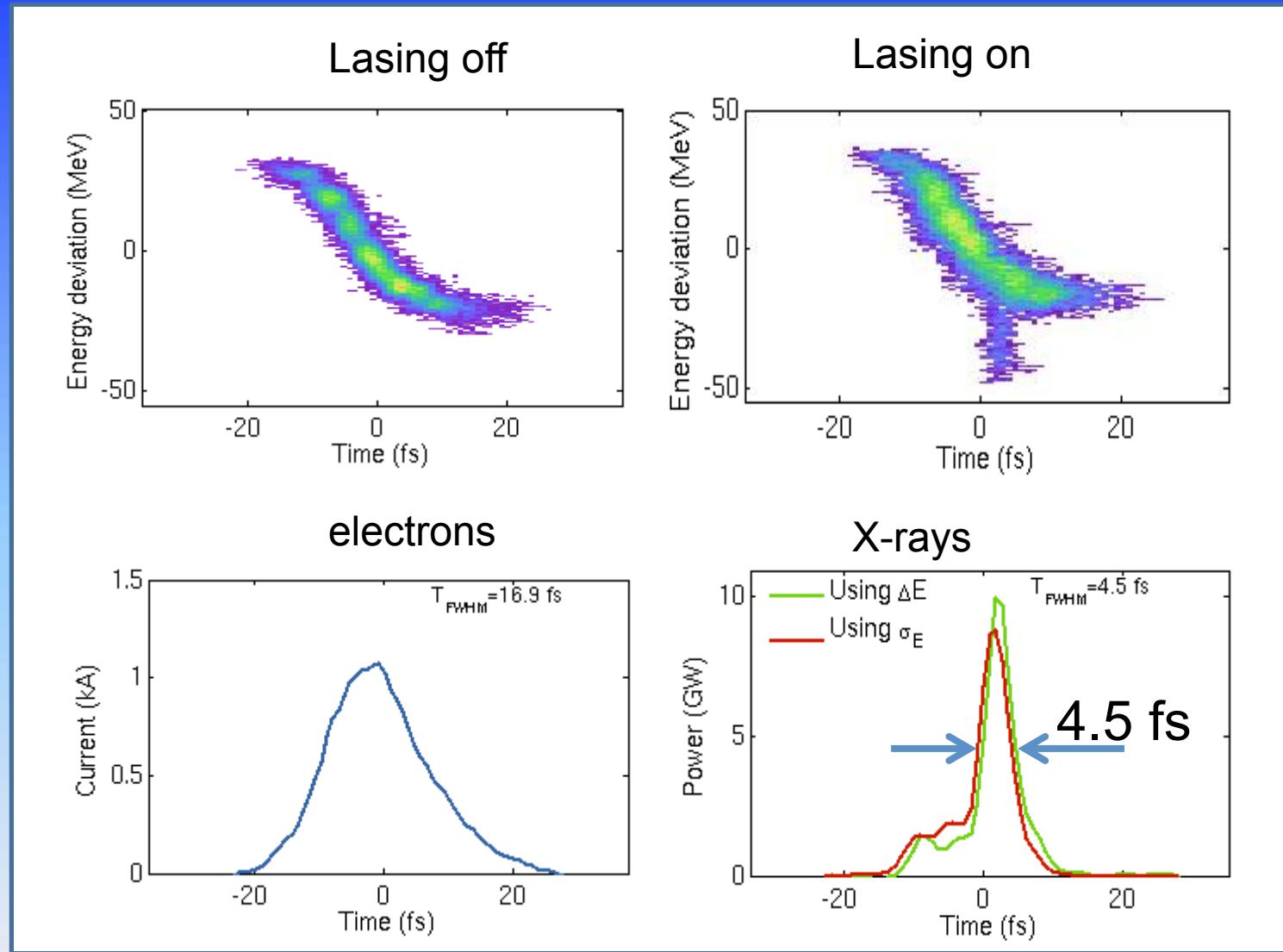


# *10 consecutive shots (1keV, 150pC)*



It is important to analyze every shot at 120 Hz.

# *20pC, 1keV examples*



Correcting for resolution yields 2.6 fs FWHM

## *R&D for a Bright Future*

- Seeding (precise color and higher brightness)
- Terawatt FEL (higher intensity)
- Novel undulators for SR and FEL (polarization control FERMI a Elettra)
- Electron Beam generation and manipulation
- X-ray beam sharing and manipulations
- Femtosecond and attosecond x-rays
- Two-color FEL (pump-probe)
- High-rate and continuous wave operation
- X-ray FEL oscillators
- Advanced accelerators for compact XFELs
- ...

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Pellegrini, Daniel Ratner, LCLS team, SACLA  
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