Some R&D Toward Brighter X-ray FELs

Zhirong Huang (SLAC)

March 6, 2012

FLS2012 Workshop, Jefferson Lab

SLAC NATIONAL ACCELERATOR LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Introduction
- Seeding for temporal coherence
  - Hard x-rays
  - Soft x-rays
- Push for higher power
  - High peak power
  - High average power
- Control of x-ray properties
  - Temporal shape
  - Polarization
- Summary

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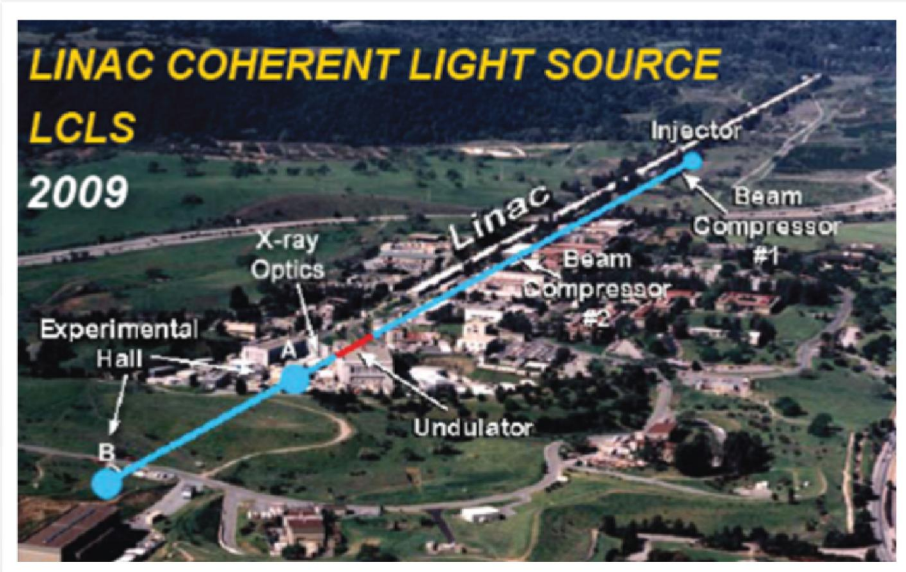
Where are we now (hard x-rays)



- SASE wavelength range: **25 – 1.2** Å
- Photon energy range: **0.5 - 10** keV
- Pulse length (**5 - 100** fs FWHM)
- Pulse energy up to **4** mJ
- **~95**% accelerator availability

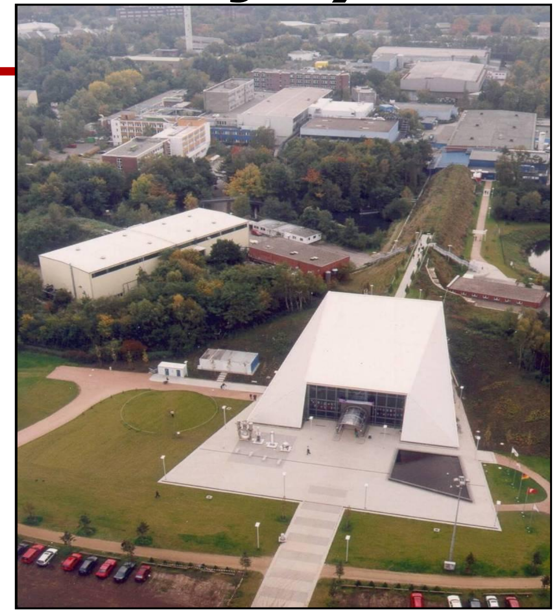
- SASE Wavelength range: **3 – 0.6** Å
- Photon energy range: **4 - 20** keV
- Pulse length (**10** fs FWHM)
- Pulse energy up to **1** mJ

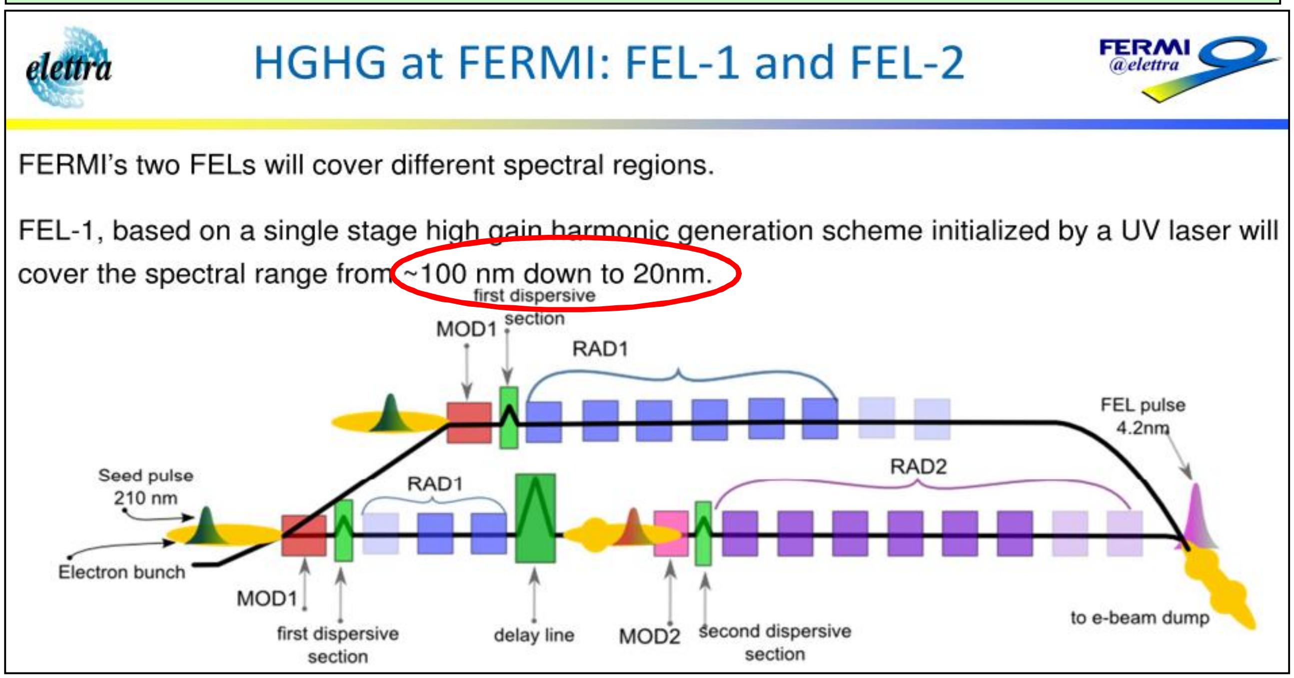
more XFELs to come…

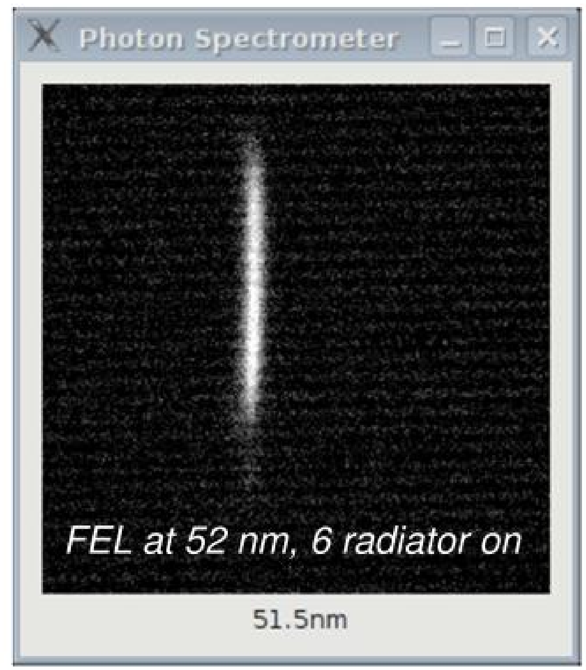
Where are we now (soft x-rays)

FLASH 2011

SASE wavelength range	4.1 – 45 nm
Average single pulse energy	10 – 400 µJ
Pulse duration (FWHM)	50 – 200 fs
Peak power (from av.)	1 – 3 GW
Average power (example for 3000 pulses/sec)	~ 300 mW
Spectral width (FWHM)	~ 0.7 - 2 %
Average Brilliance	$10^{17} – 10^{21}$ *
Peak Brilliance	$10^{29} – 10^{31}$ *







X-ray FEL Parameters – Now and Future

(C. Pellegrini et al)

Parameter	Now	Future
Photon energy, keV	Up to 20	**Up to 100**
Pulse repetition rate, Hz	≤ 120	10^2-**10^6**
Pulse duration, fs	~2-300	**<1-1000**
Coherence, transverse	diffraction limited	diffraction limited
Coherence, longitudinal	not transform limited	**transform limited**
Coherent photons/pulse	2×10^{12}-3×10^{13}	**10^9-10^{14}**
Peak brightness, ph/s mm^2 $mrad^2$ 0.1% bandwidth	10^{33}	10^{30}-**10^{34}**
Average Brightness, ph/s mm^2 $mrad^2$ 0.1% bandwidth	4×10^{22}	10^{18}-**10^{27}**
Polarization	linear	**variable, linear to circular**

red: parameter space to be developed

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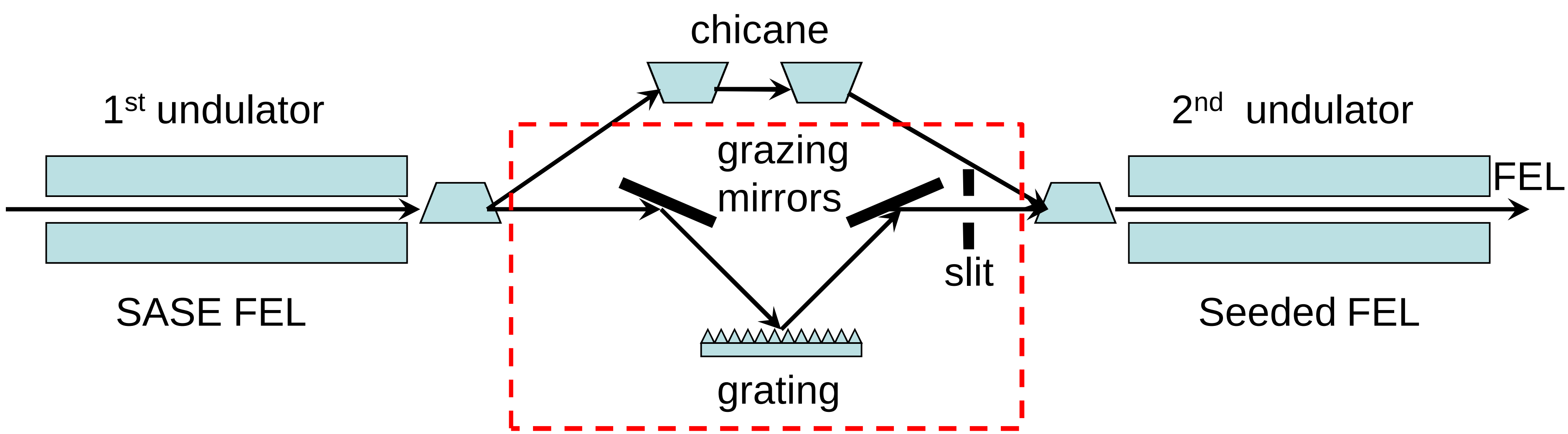
Self-Seeding

- *Originally proposed at DESY (J. Feldhaus et al, NIMA, 1997)*
  - *First undulator generates SASE*
  - *X-ray monochromator filters SASE and generates seed*
  - *Second undulator amplifies seed to saturation*



- *Chicane delays electrons and washes out SASE microbunching*
- *Long x-ray path delay (~10 ps) requires large chicane that take space and may degrade beam quality*

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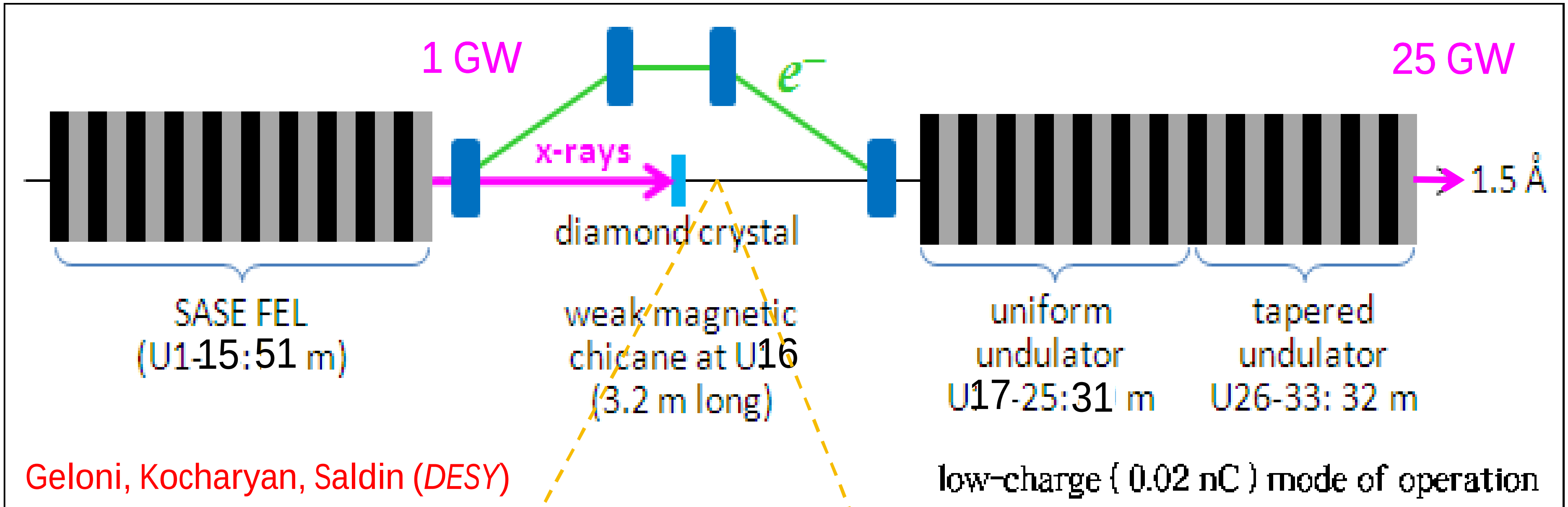
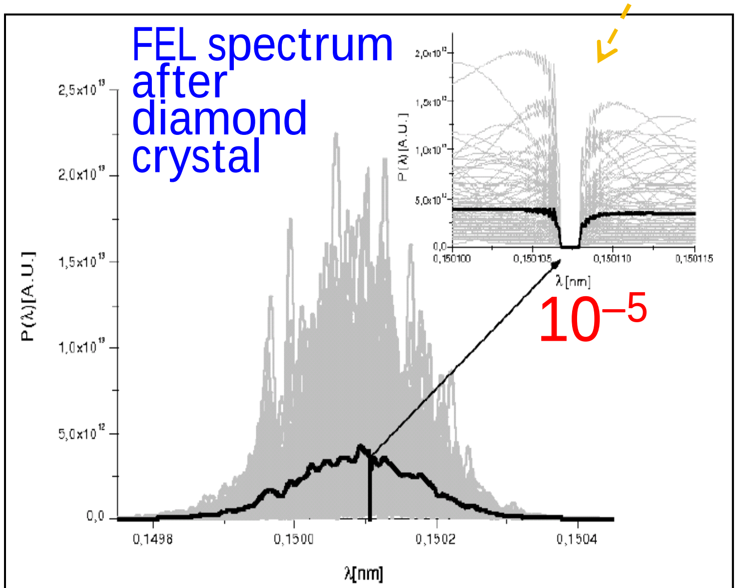
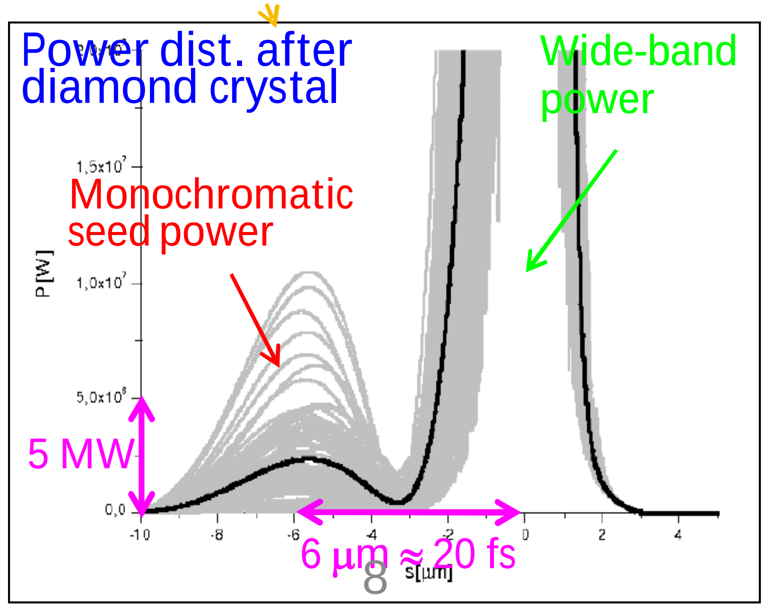
Hard x-ray self-seeding

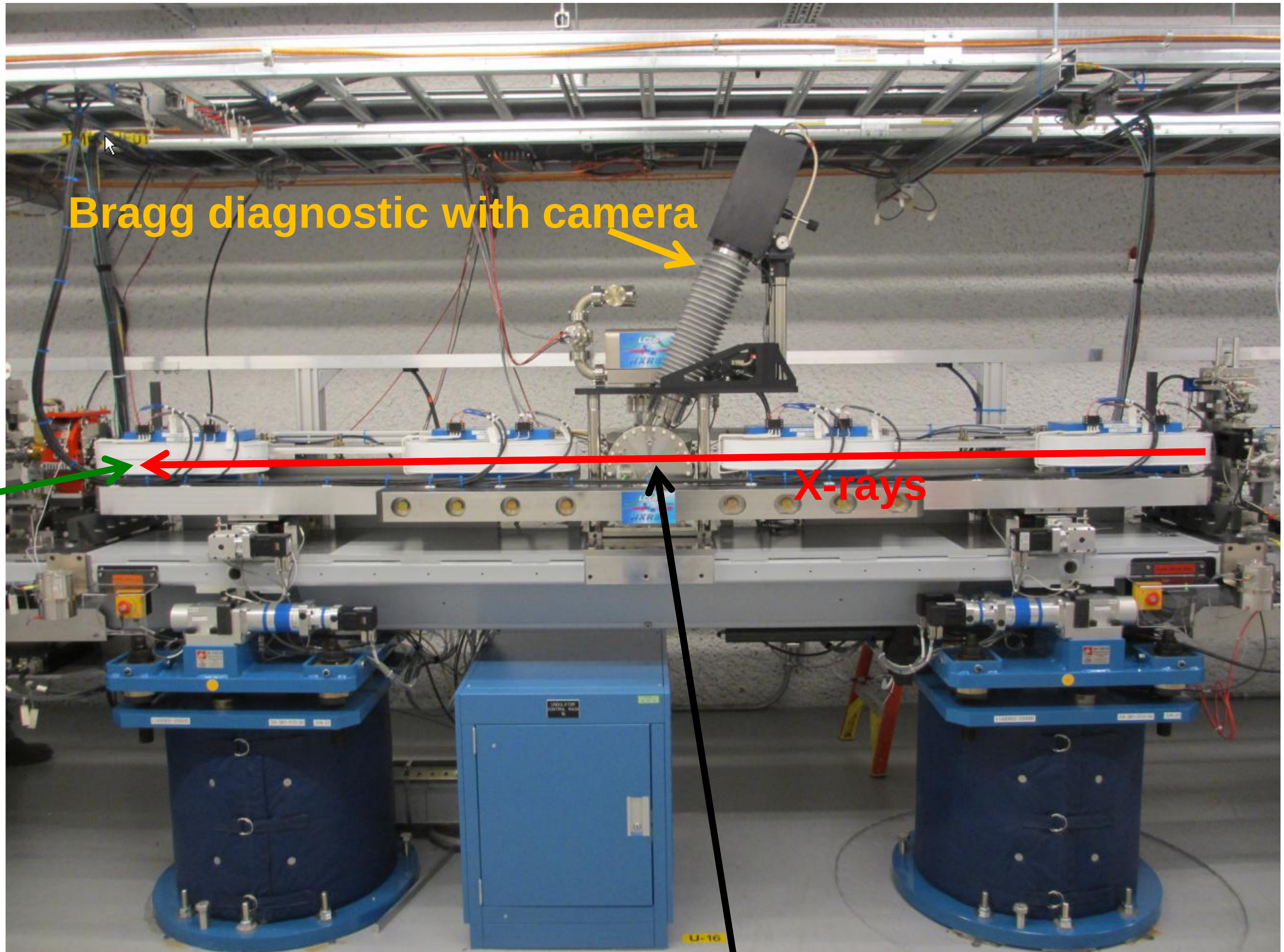






Self-seeding of 1-μm e^- pulse at 1.5 Å yields 10^{-4} BW with low charge mode

HXRSS at LCLS (replacing U16)



P. Emma (SLAC/LBL)
A. Zholents (ANL)

Self-Seeding works!

Single shot SASE and Seeded FEL spectra

Single shot pulse energy from the gas detectors https://sites.google.com/a/lbl.gov/realizing-the-potential-of-seeded-fels-in-the-soft-x-ray-regime-workshop/agenda/home

Realizing the Potential of Seeded FELs in the Soft X-Ray Regime

Workshop Home | Agenda | Maps and Directions | Registered Attendees | Announcements | Registration & Lodging | Talks | Recent Site Activity

113

days since

Discussion Summary Reports Due

Questions?

Katherine Schall

510-486-6961

or email

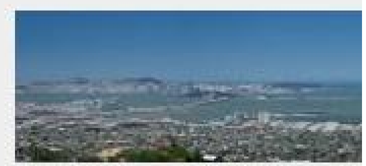
kschall@lbl.gov

Please check back for.....

Agenda >

Workshop Home

A SUMMARY REPORT written by the program committee and discussion session moderators is available at the link in the "Attachments" section *below*



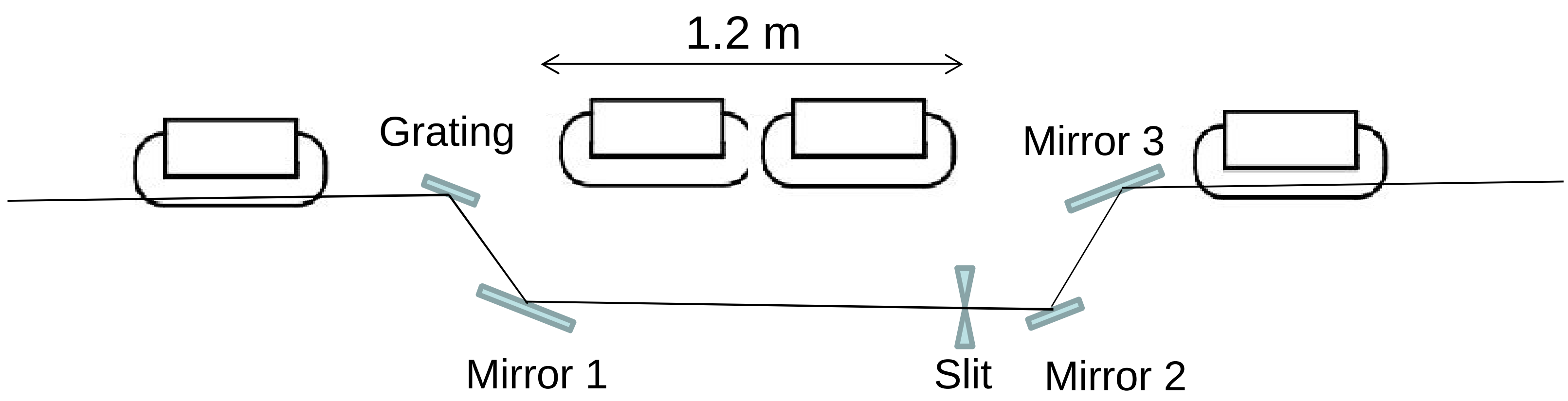
October 26-28, 2011 Lawrence Berkeley National Laboratory

Sponsored by LBNL and SLAC

Co-chairs: John Corlett (LBNL) and Zhirong Huang (SLAC)

Soft X-Ray Self-Seeding

- **LCLS is developing a compact grating monochromator and chicane that is similar to HXRSS unit in size**

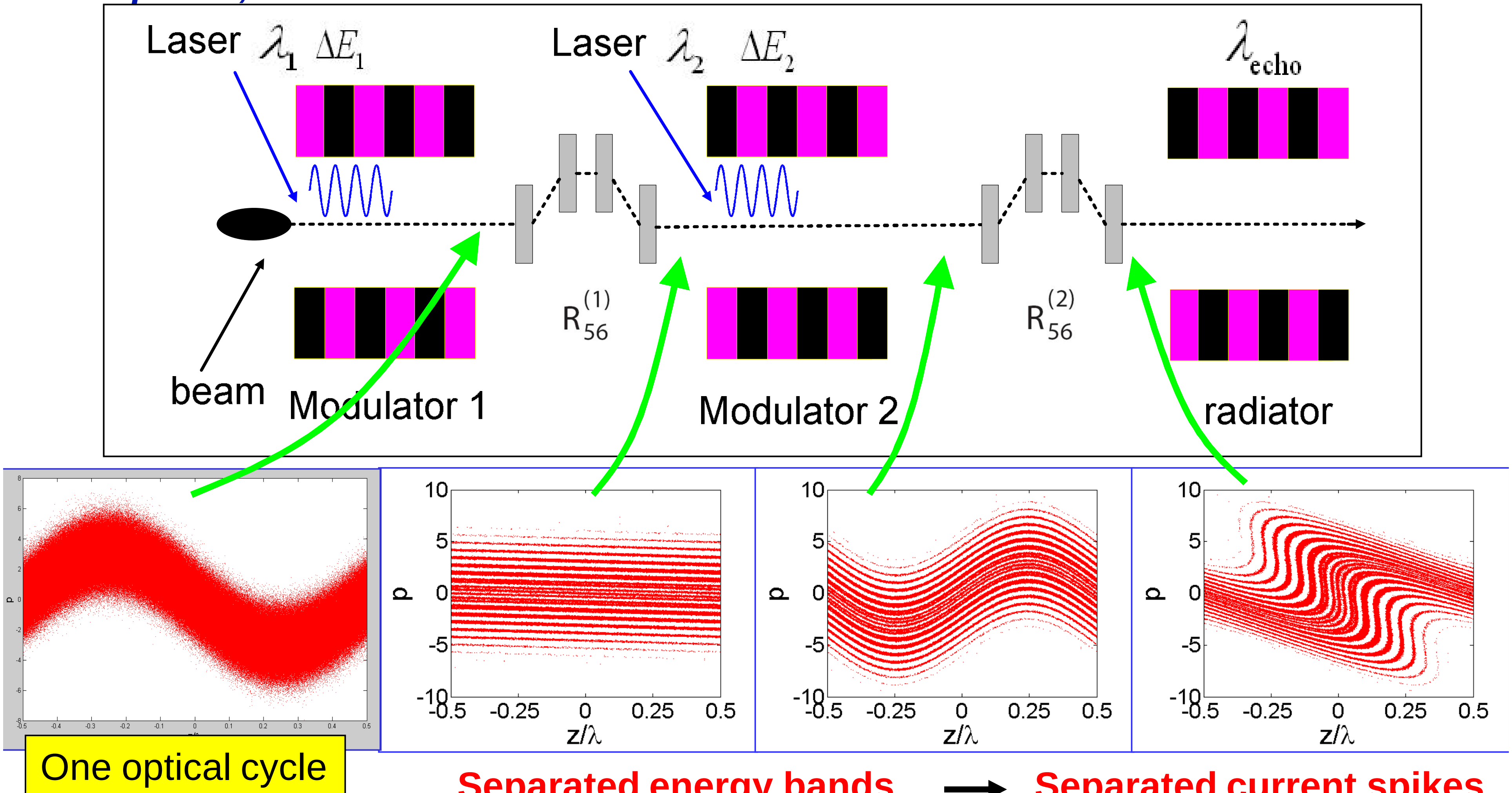


- Fit within the length of one undulator module 4 m.
- Photon energy range 400 - 1000 eV.
- X-ray and electron delay varies from 660 - 850 fs.
- Resolving power from 7800 (400 eV) to 4800 (1000 eV).

P. Heimann's talk at FEL working group

Echo-Enabled Harmonic Generation

G. Stupakov, PRL 2009



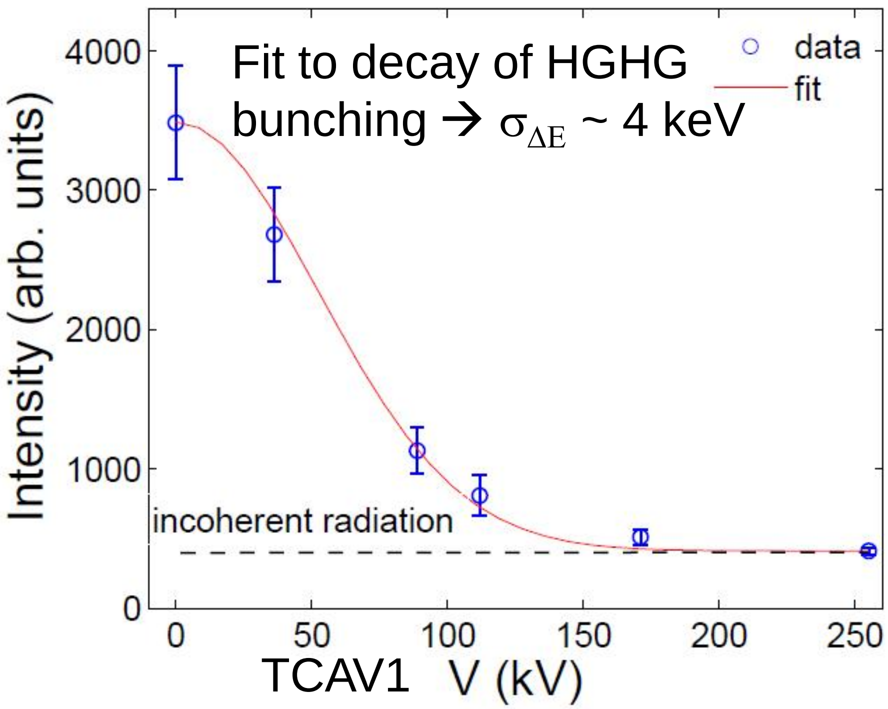
Separated energy bands → Separated current spikes

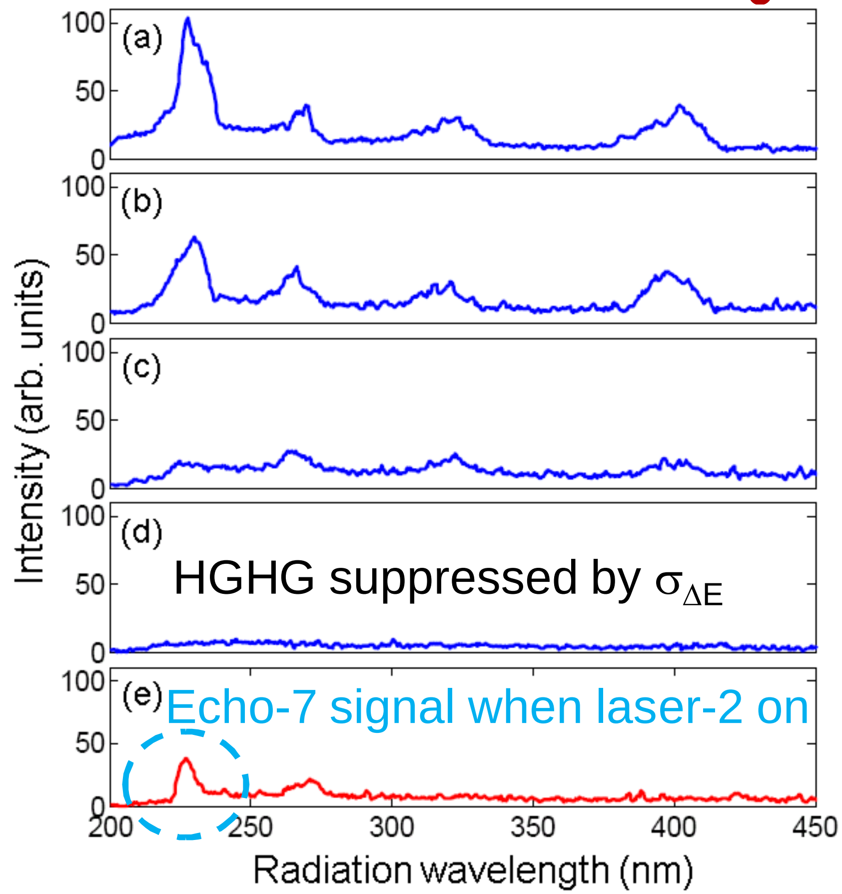
- Very high harmonic bunching may be produced from external laser
- Demonstration experiments at SLAC and SINAP look promising
- High harmonic bunching may seed a soft x-ray FELs (a few nm wavelength)

Echo-7 at NLCTA

(intensity at 227 nm)

Laser modulation ~ 15 keV





- Future Plans (Echo-75): Demonstrate technology for direct laser seeding at 3nm (from 200 nm)

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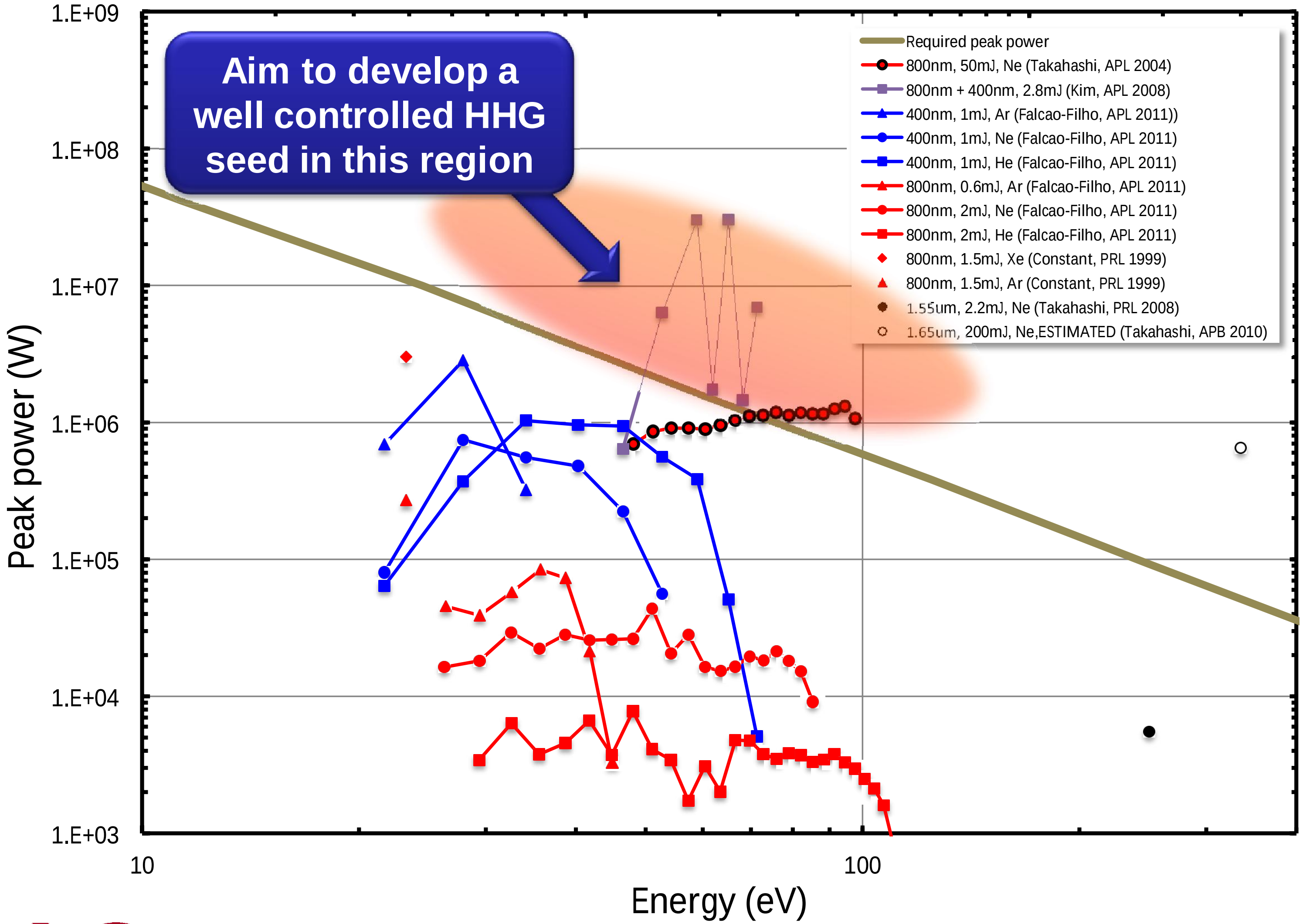
T. Raubenheimer, D. Xiang, et al.,

Another seeding route: short-wavelength HHG



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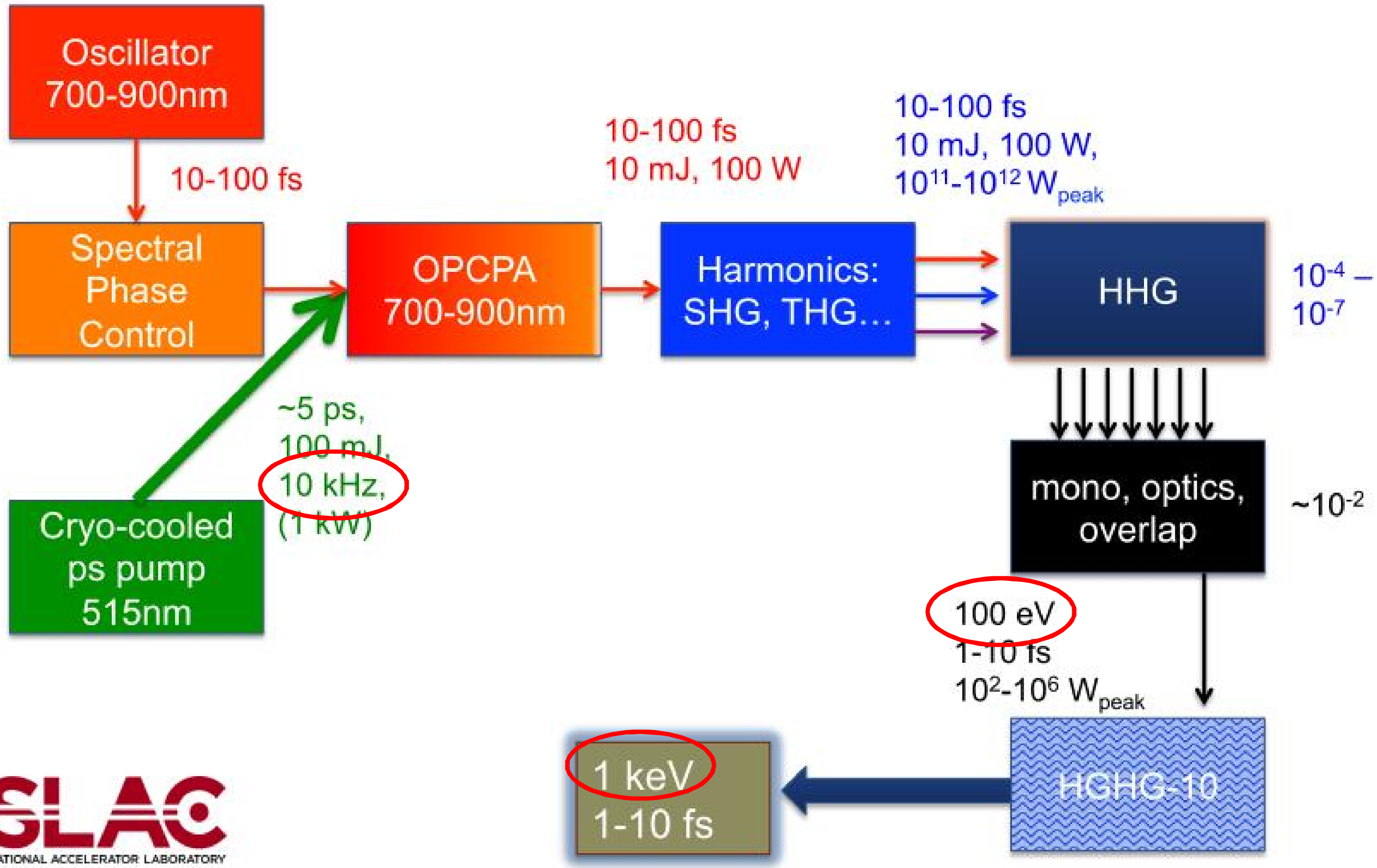
J. Robinson, W. White

Proposed R&D System: Cryo Pumped, Near-IR OPCPA, HHG, HGHG



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A. Fry, LBL seeding workshop

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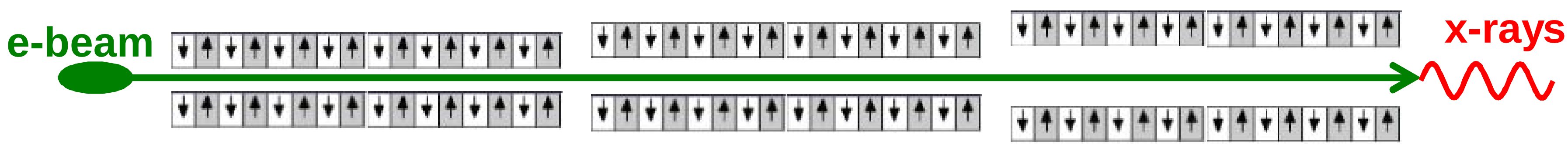
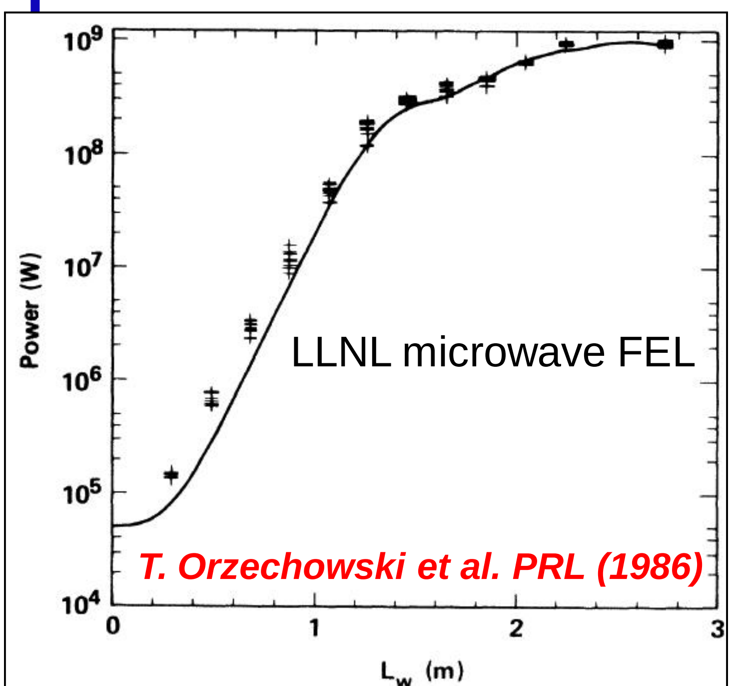
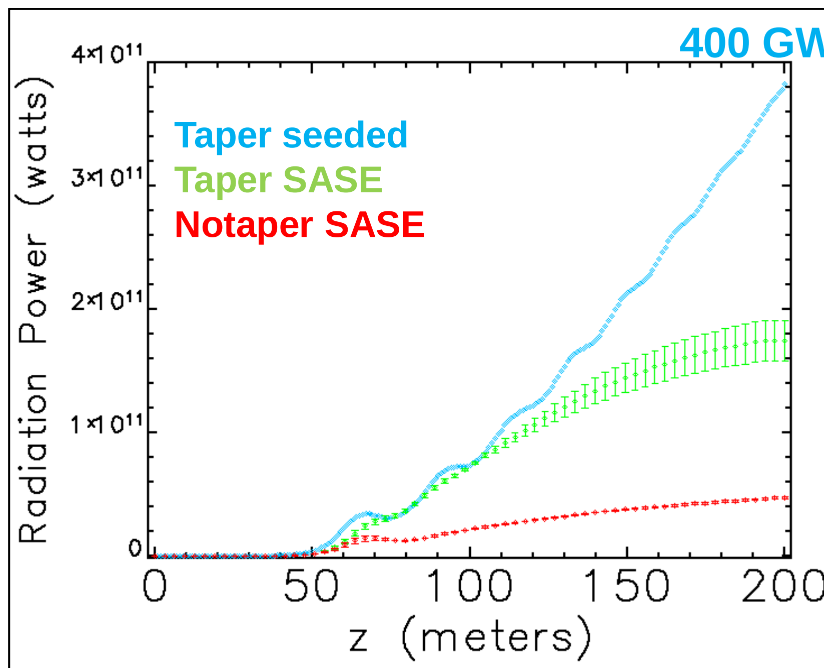
Taper to enhance FEL efficiency

- FEL saturates due to significant E-loss
- Tapered undulator keeps FEL resonance and increase power



- **Taper works much better for a seeded FEL than SASE**





W. Fawley, Z. Huang et al. NIMA (2002)

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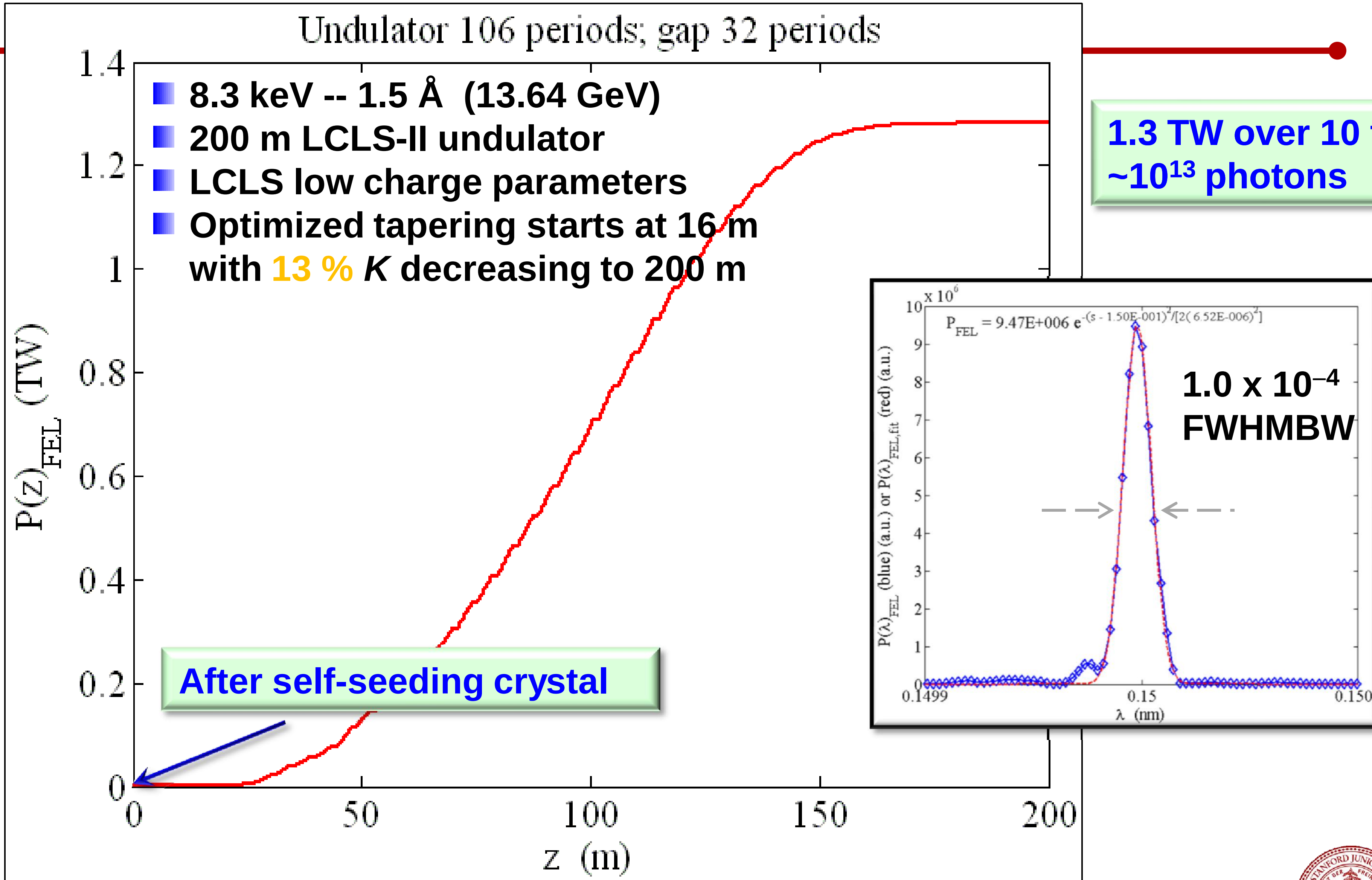
Self-seeding + Tapered undulator ➔ TW FEL

- 8.3 keV -- 1.5 Å (13.64 GeV)
- 200 m LCLS-II undulator
- LCLS low charge parameters
- Optimized tapering starts at 16 m with 13 % *K* decreasing to 200 m

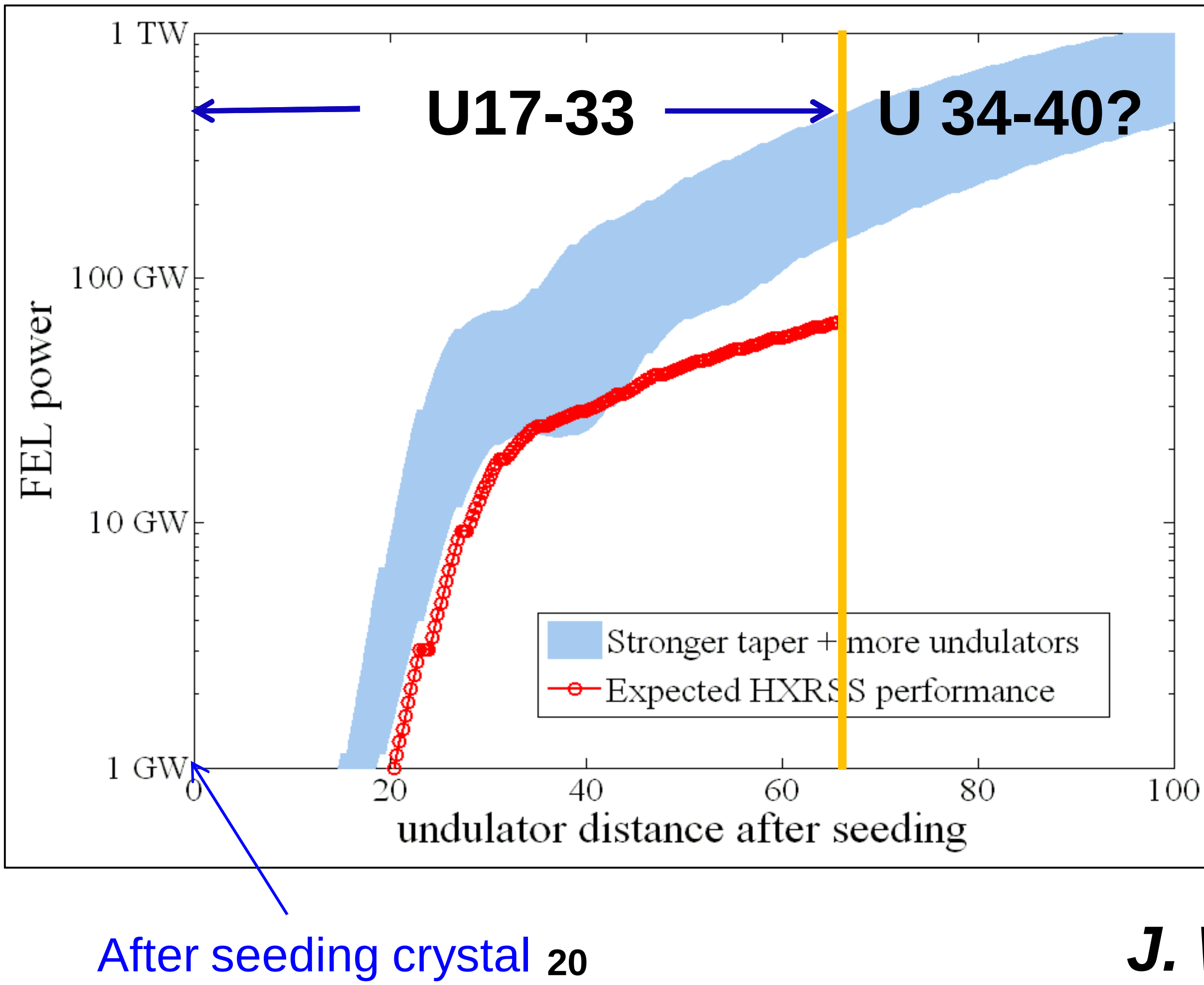


1.3 TW over 10 fs
~10^{13} photons

W. Fawley, J. Frisch, Z. Huang, Y. Jiao, H.-D. Nuhn, C. Pellegrini, S. Reiche, J. Wu (FEL2011)

Similar approach to enhance LCLS power

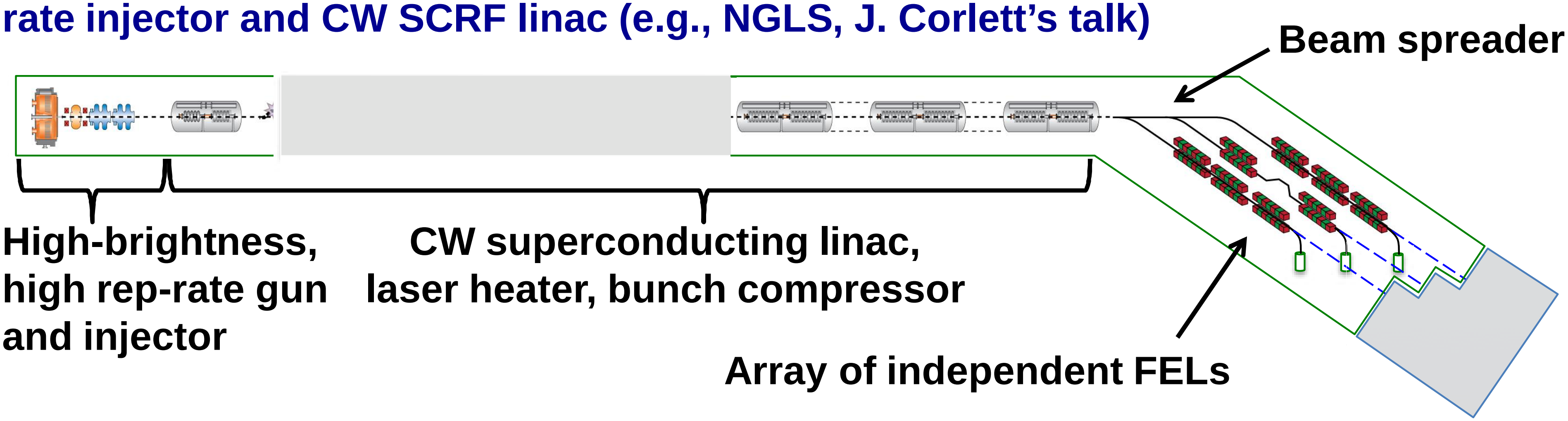
- Enhanced taper + adding 5-7 existing LCLS undulators (20-30 m) can boost the LCLS power by a factor of 10



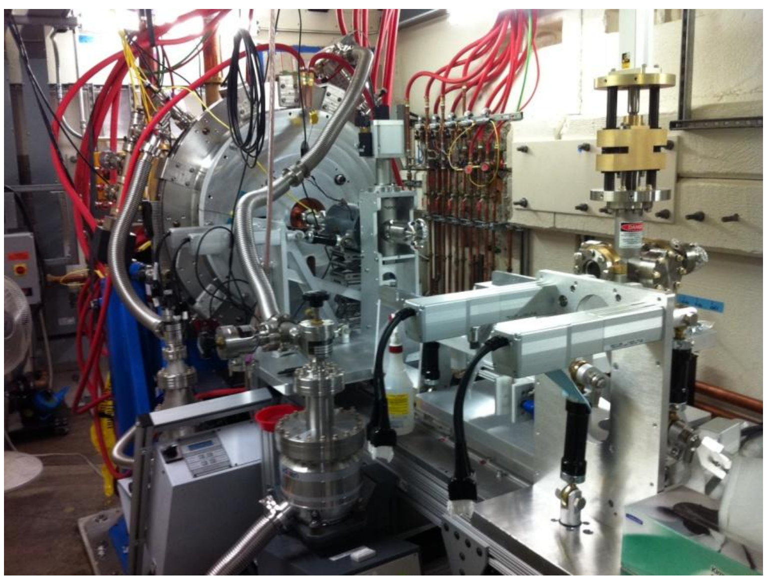
J. Wu

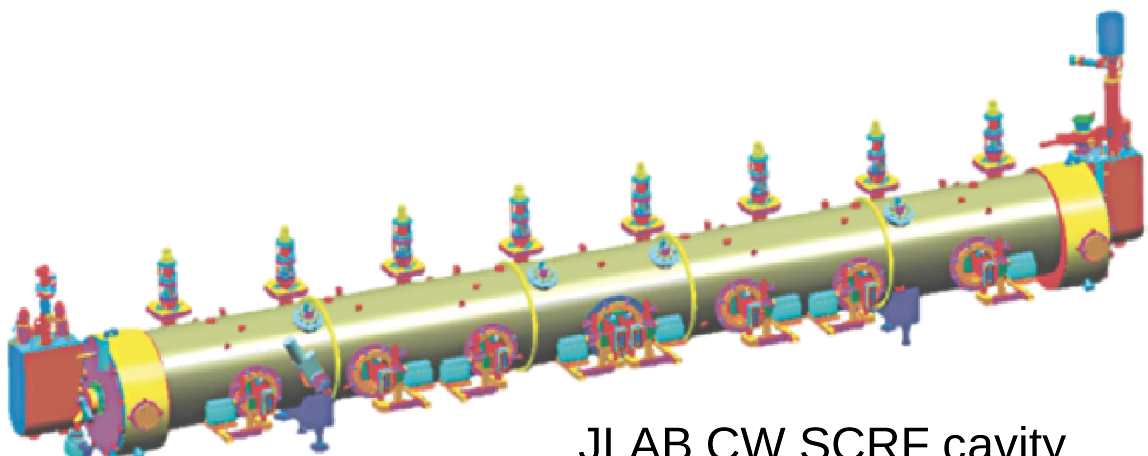
High-average power XFEL

High average power electron beam distributed to an array of FELs from high rep-rate injector and CW SCRF linac (e.g., NGLS, J. Corlett's talk)



LBL APEX gun

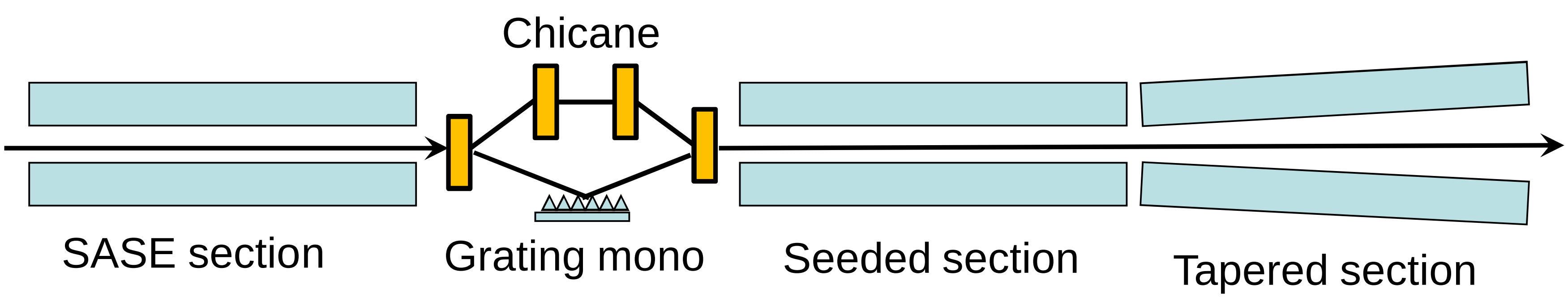




JLAB CW SCRF cavity and cryomodule

Reaching High-average x-ray power

- For a 1-2 GeV linac, FEL saturation power at ~1 GW level, or 100 uJ pulse energy for a 100-fs x-ray pulse
- High-rep. rate (1 MHz) operation yields 100 W average x-ray power
- Combine self-seeding (works at full rate) and tapered undulator ➔ 1 kW average x-ray power



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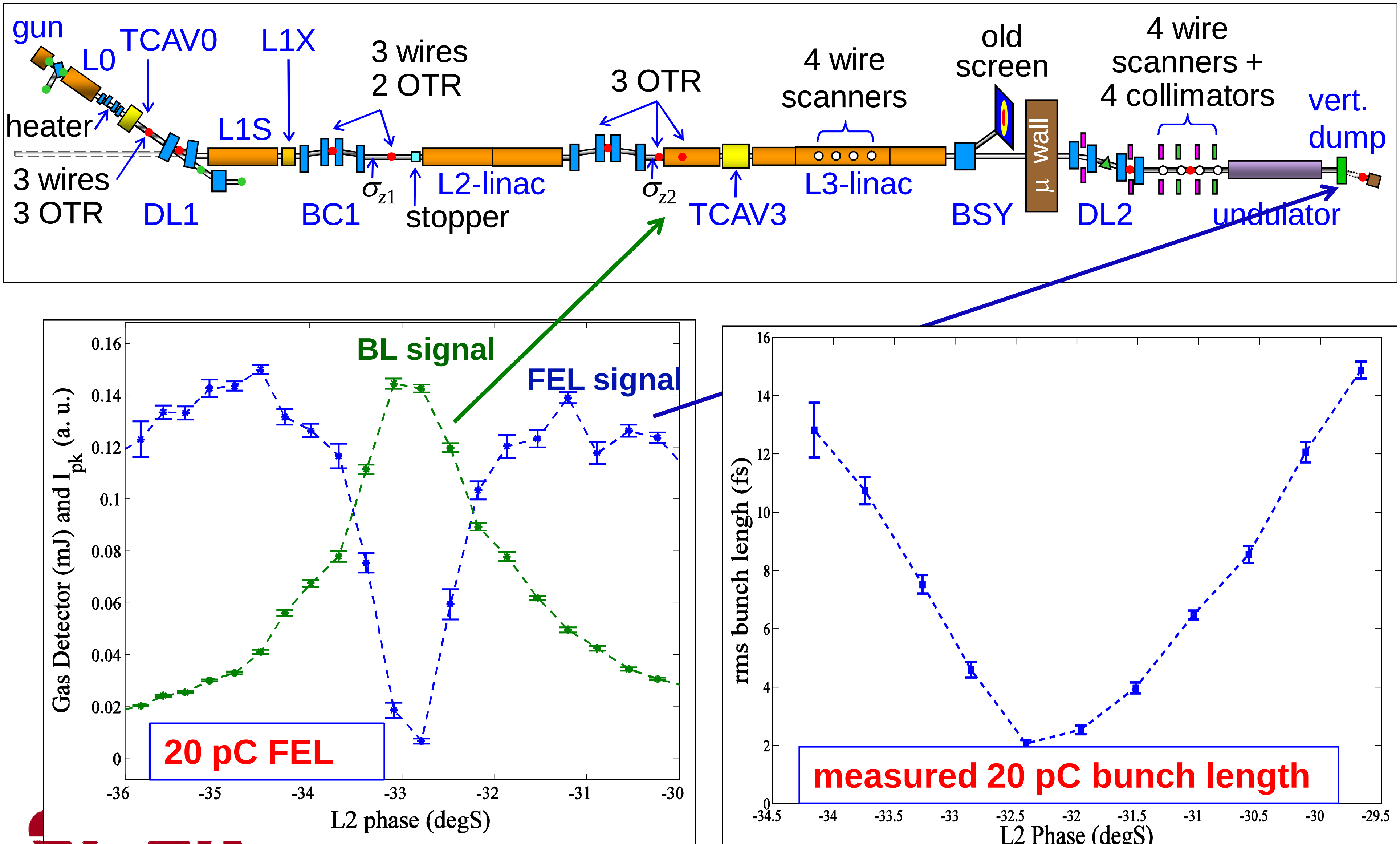
Smaller charge, shorter x-rays



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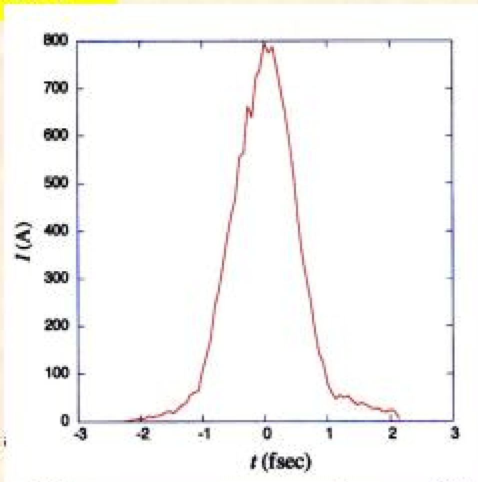
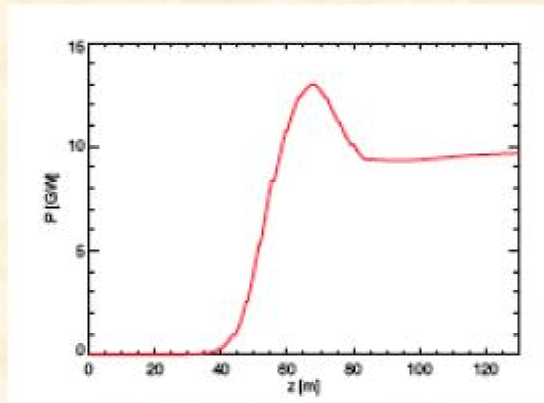
Ultra-low charge for attosecond pulses

UCLA

LCLS 1pC example: attosecond pulses.



Beam current profile



Peak power vs. z

$$\lambda = 0.15nm,$$
$$\sigma_E = 10^{-4},$$
$$\sigma_L = 160nm(530as).$$

Single spike at saturation, with 10^{10} photons.

Beam brightness~ $4\text{x}10^{17}$ A/m^2 rad^2 compared to $6\text{x}10^{15}$ A/m^2 rad^2 for the 1 nC design case.

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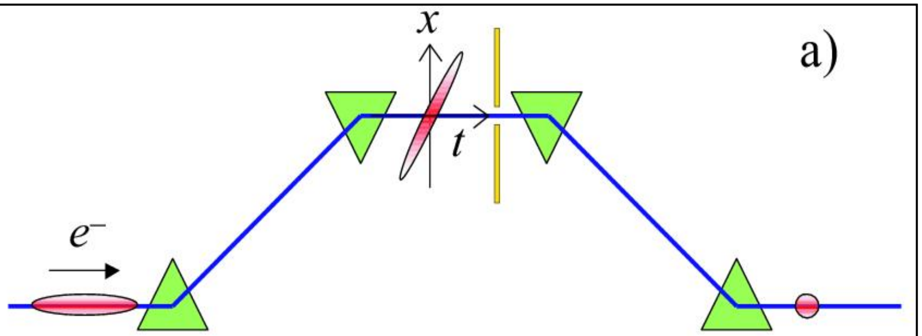
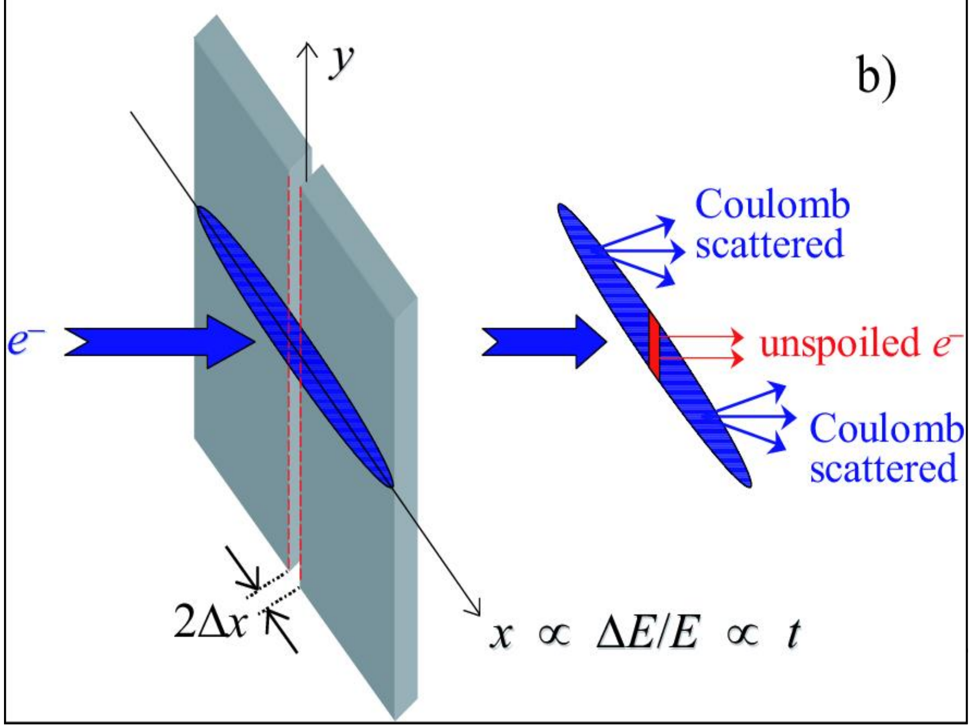
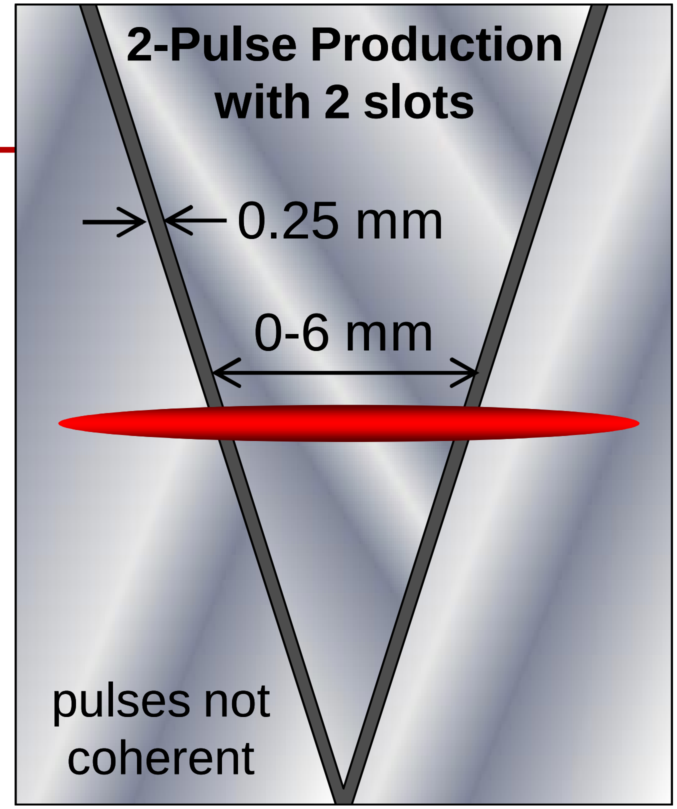
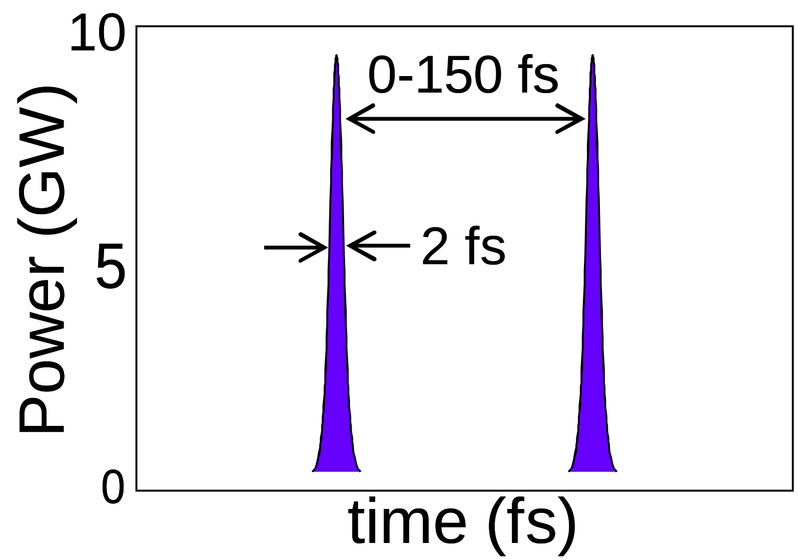
Slotted foil for x-ray pulse length control



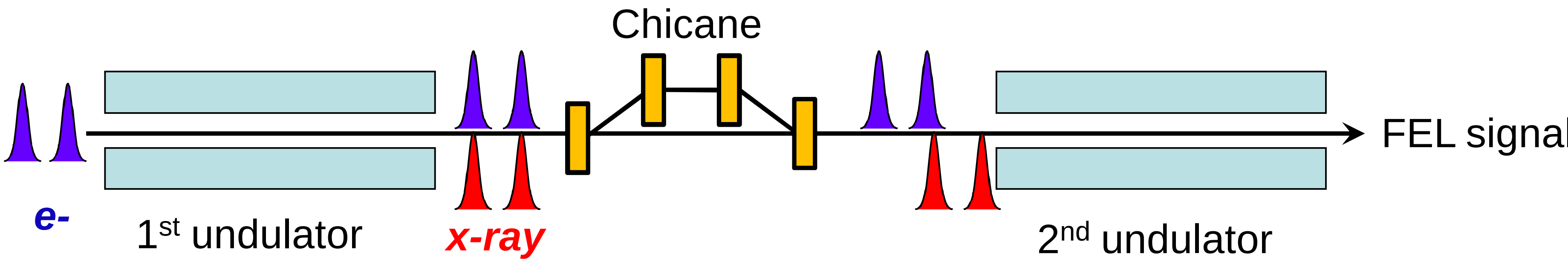
P. Emma et al., PRL 2004

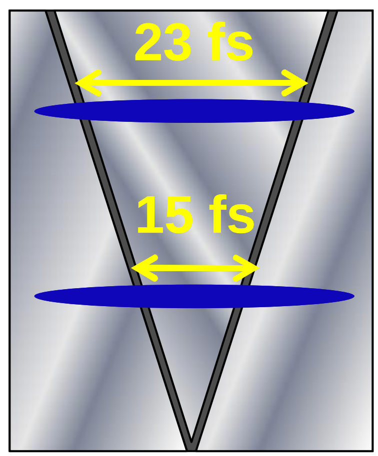






Cross-correlation with e^- and x-ray pulses





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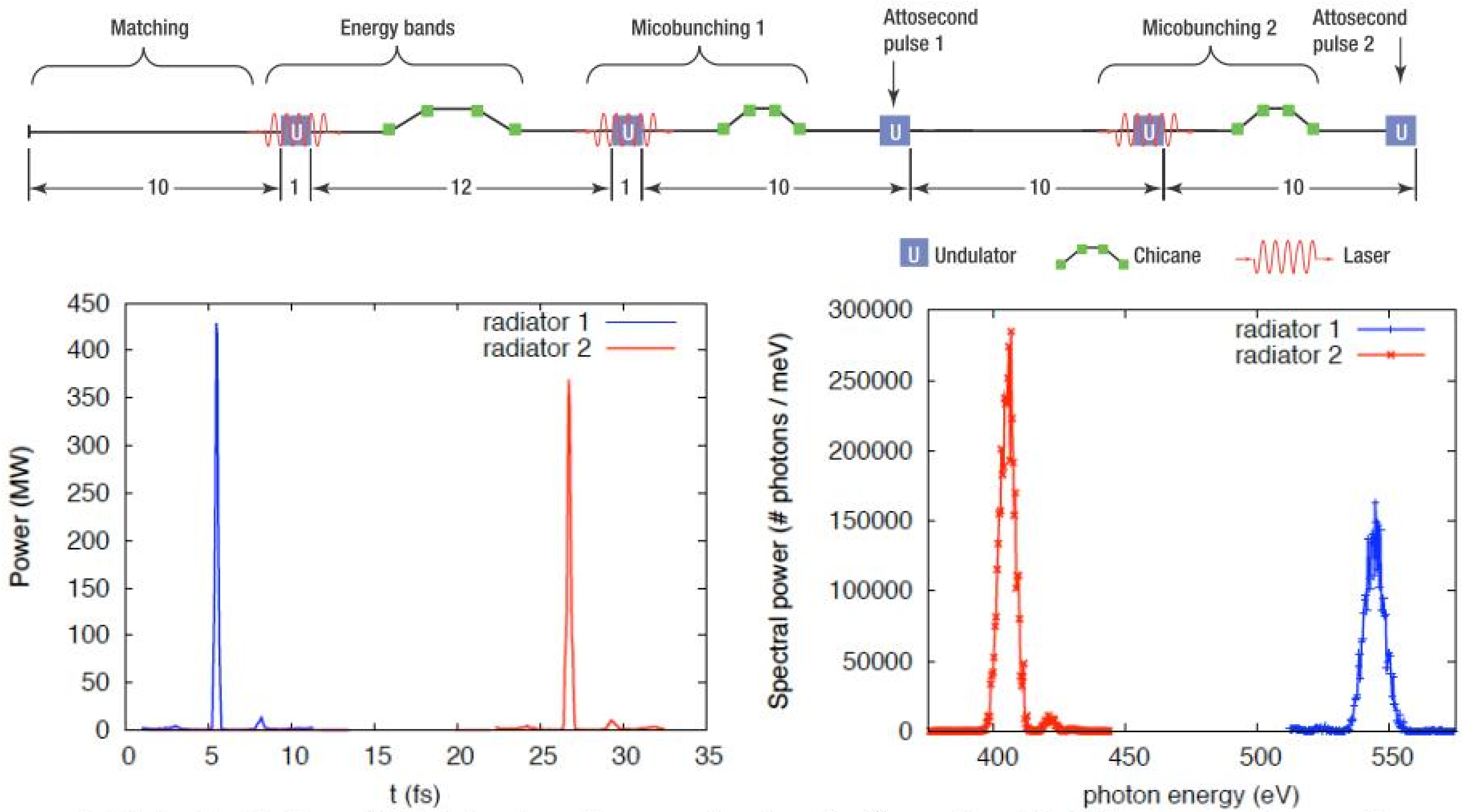
Cross-correlation technique suggested
By Geloni, Kachayan, Saldin

Y. Ding, P. Emma

Two-color, two attosecond pulse generation

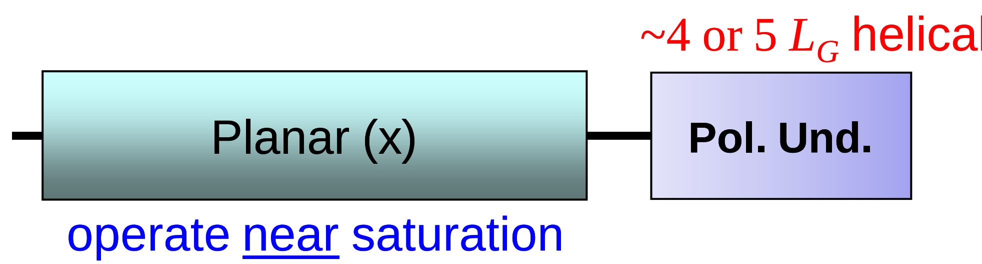


A. Zholents, G. Penn, "Obtaining two attosecond pulses for X-ray stimulated Raman spectroscopy", NIM–A, **612**, 2, (January 2010)

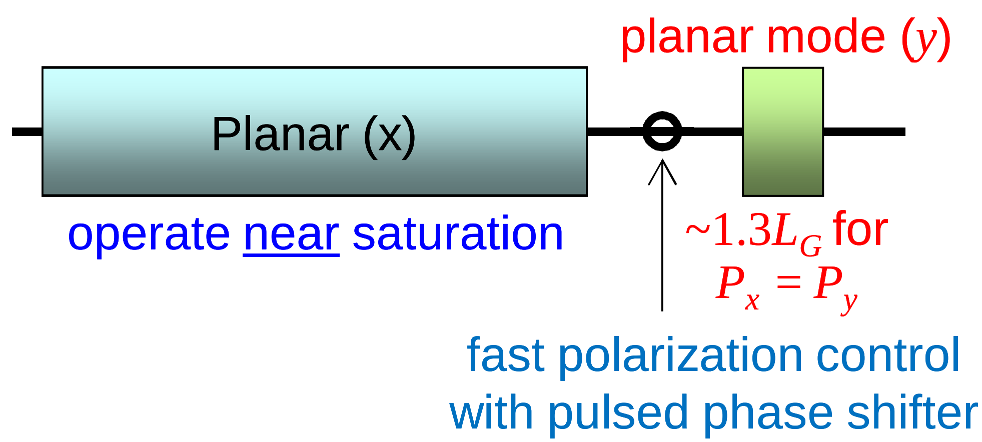
Polarization control

- Key technology is undulator with switchable polarization
- Cost and tolerance for long FEL undulator line lead to considerations of polarization afterburner

- **Planar + Helical**
  - Stable
  - >90% polarization
  - Slow switching

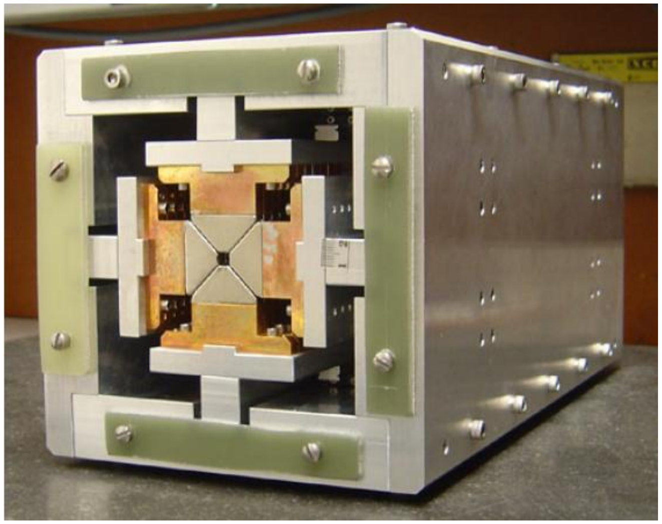


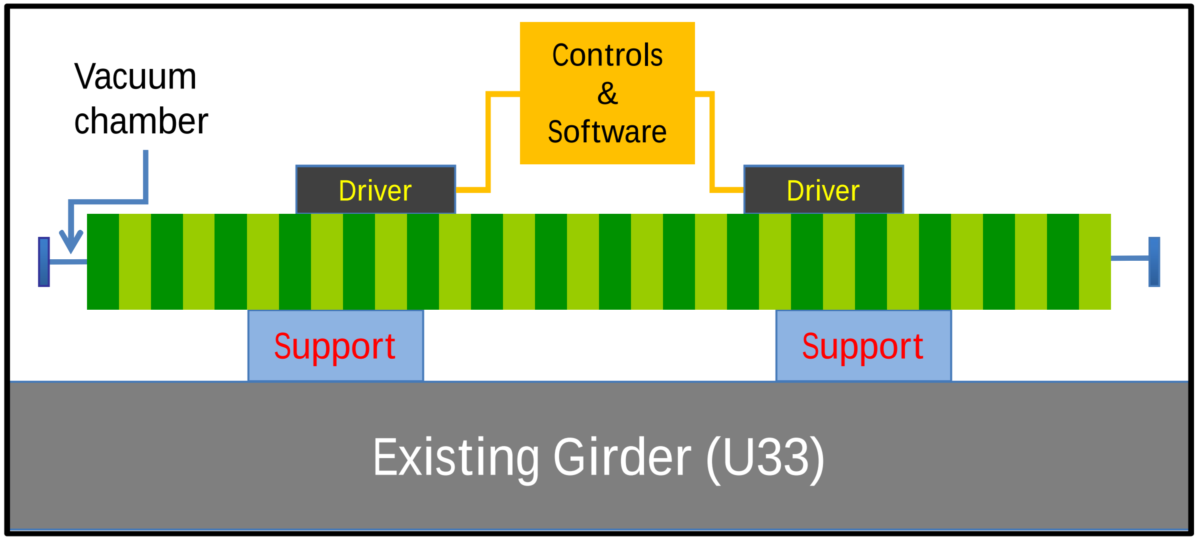
- **Planar + Crossed Planar**
  - ~80% polarization
  - May have fluctuations
  - Fast switching



DELTA undulator

- Delta undulator is a novel, compact design that fits to existing LCLS girder
- LCLS plans to build and test a 3.2-m Delta @ U33 in two years
- Degree of circular polarization for 1 DELTA ~70% at soft x-rays.
- Adding 1 or 2 more DELTA in future provides >90% polarization





Cornell Delta undulator (A. Temnykh)

H.-D. Nuhn, E. Kraft

Summary

- XFELs represent a revolution in light source development.
- Seeding will bring radial improvements to such revolutionary machines.
- Tapered undulator after a seeded FEL has the potential of generating very high FEL power.
- Techniques to control x-ray pulse shapes and polarization states should be fully developed.