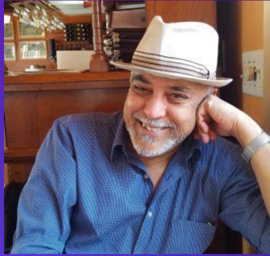
*Particle Accelerators, Lasers, Electromagnetic Cavities and Atomic Beams : Symposium Celebrating Swapan Chattopadhyay's Retirement on his 70th.*



# Amazing Particles and Light

Zhirong Huang (Stanford/SLAC)

April 30, 2021

# Outline

- *Particles, Light, Swapan!*
- *X-ray FEL in a flash!*
- *Wonderful noise!*
- *Final thoughts…*

# Particles, Light, Swapan!

As the founding director of CBB, Swapan had a vision for beam physics especially beam interactions with light!

Under Swapan's vision and leadership, pioneering work at CBB includes

- Ultrafast X-ray generation by Thomson scattering
- Ultrafast X-ray generation by laser slicing
- Transient-time optical stochastic cooling
- Laser plasma accelerators
- Three-dimensional FEL theory
- …

# Particles, Light, Swapan!

PHYSICS OF PLASMAS VOLUME 5, NUMBER 5 MAY 1998

## Alight a beam and beaming light: A theme with variations*

Swapan Chattopadhyay[†,a)]
*Ernest Orlando Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720*

(Received 20 November 1997; accepted 27 January 1998)

The interaction of light (coherent and incoherent) with charged particle beams is explored in various configurations: incoherent scattering of coherent light (laser) from an incoherent particle beam (high temperature), coherent scattering of coherent light (laser) from a ‘‘cold’’ (bunched) beam, femtosecond generation of particle and light beams via ‘‘optical slicing’’ and Thomson/Compton scattering techniques, etc. The domains of ultrashort temporal duration (femtoseconds) as well as ultrashort wavelengths (x rays and shorter), with varying degrees of coherence, are explored. The relevance to a few critical areas of research in the natural sciences, e.g., ultrafast material, chemical and biological processes, protein folding, particle phase space cooling, etc. are touched upon. All the processes discussed involve proper interpretation and understanding of coherent states of matter and radiation, as well as the quality and quantity of information and energy embedded in them. © *1998*

In May 1998, I finished Ph.D. from Stanford

- Had a postdoc offer at LBL but turned it down 😔
- Went to Argonne to work on FEL with Kwang-Je 🙂

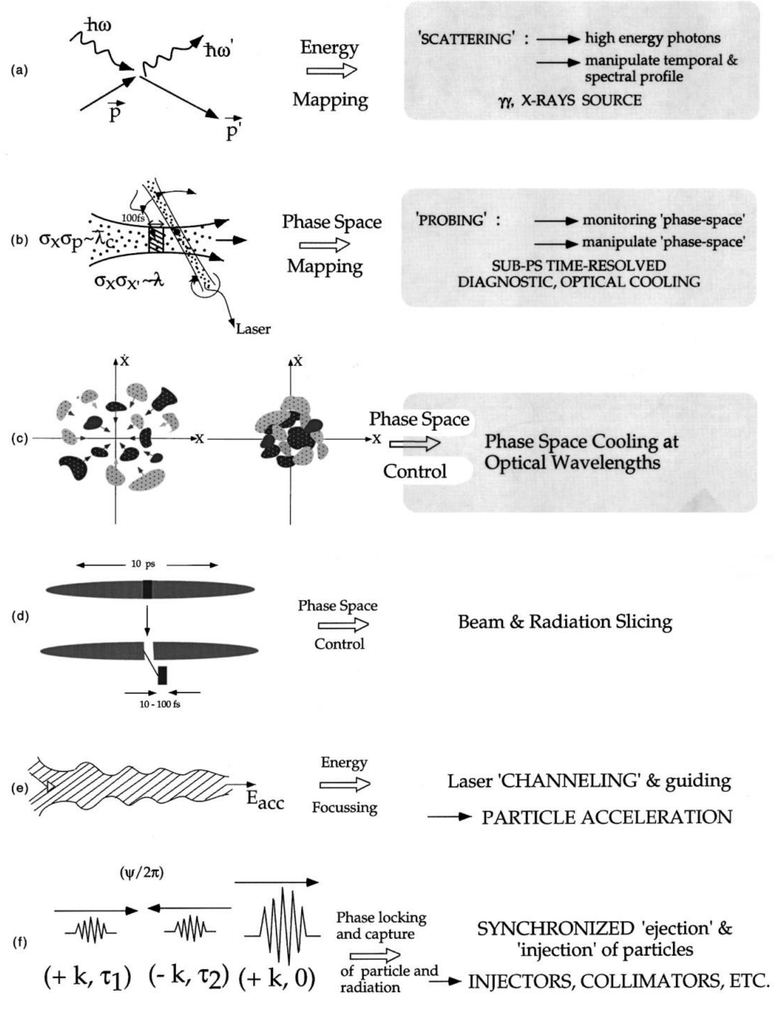
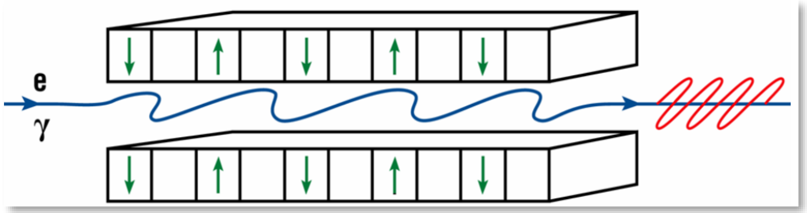
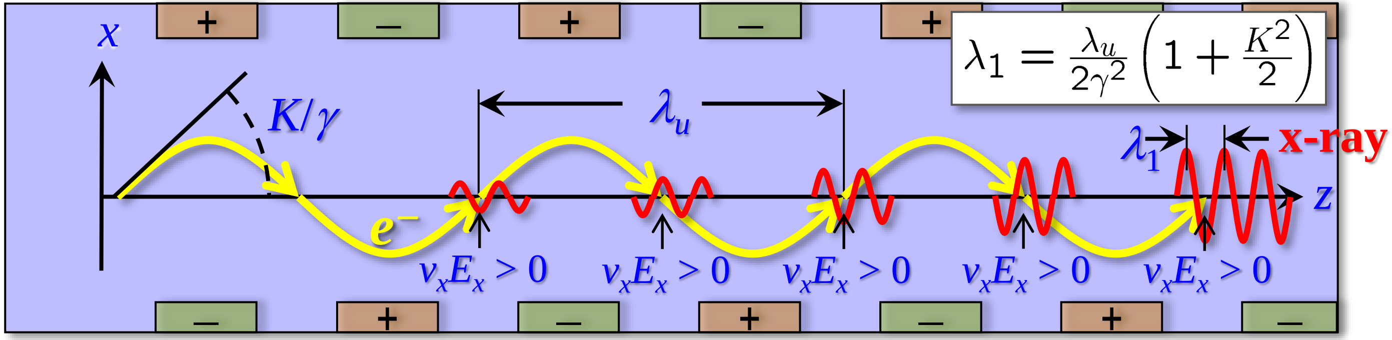



FIG. 5. Energy and Phase Space Mappings and Control attainable in various Laser-Beam Interactions.

# *XFEL in a flash!*




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

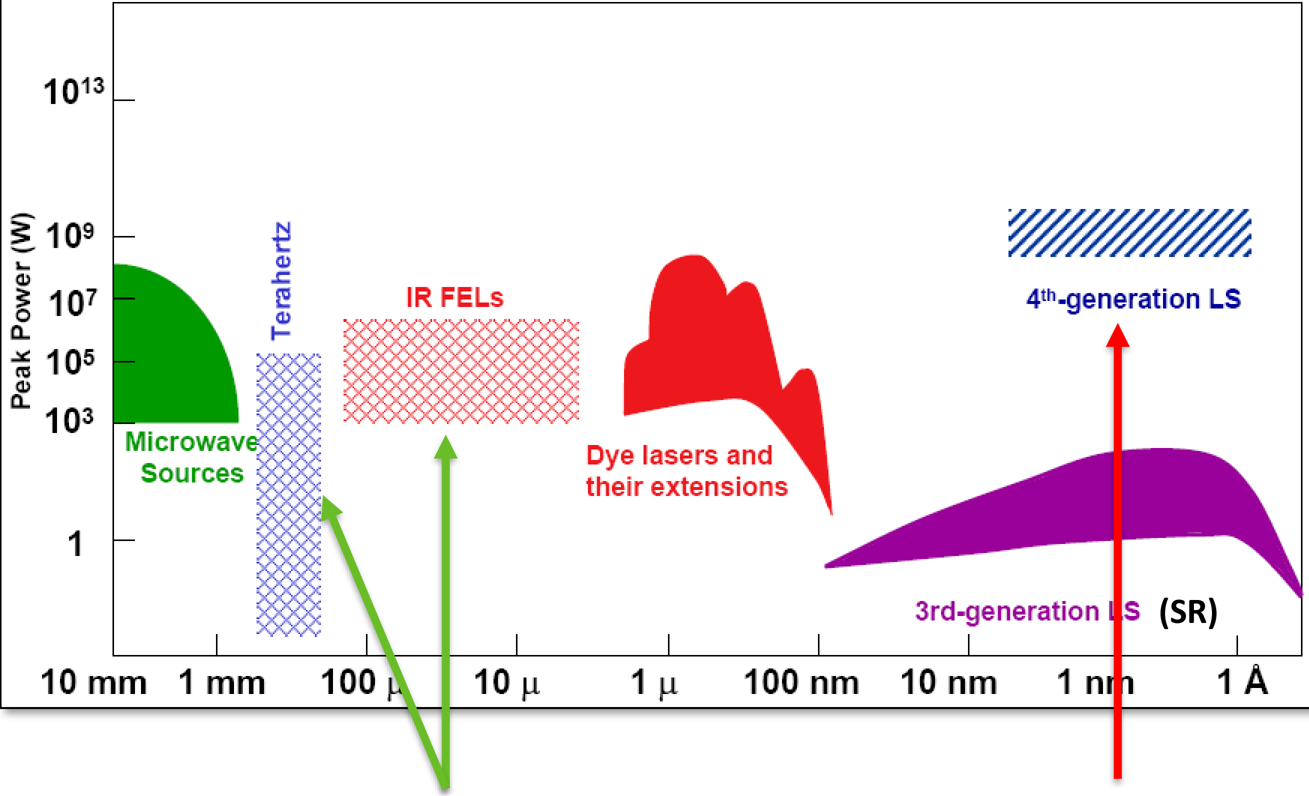



- Due to sustained interaction, some electrons lose energy, while others gain ➔ energy modulation at $\lambda_1$


- $e^-$ losing energy slow down, and $e^-$ gaining energy catch up ➔ density modulation at $\lambda_1$ (microbunching)


- Microbunched beam radiates coherently at $\boldsymbol{\lambda_1}$, enhancing the process ➔ **exponential growth of radiation power**

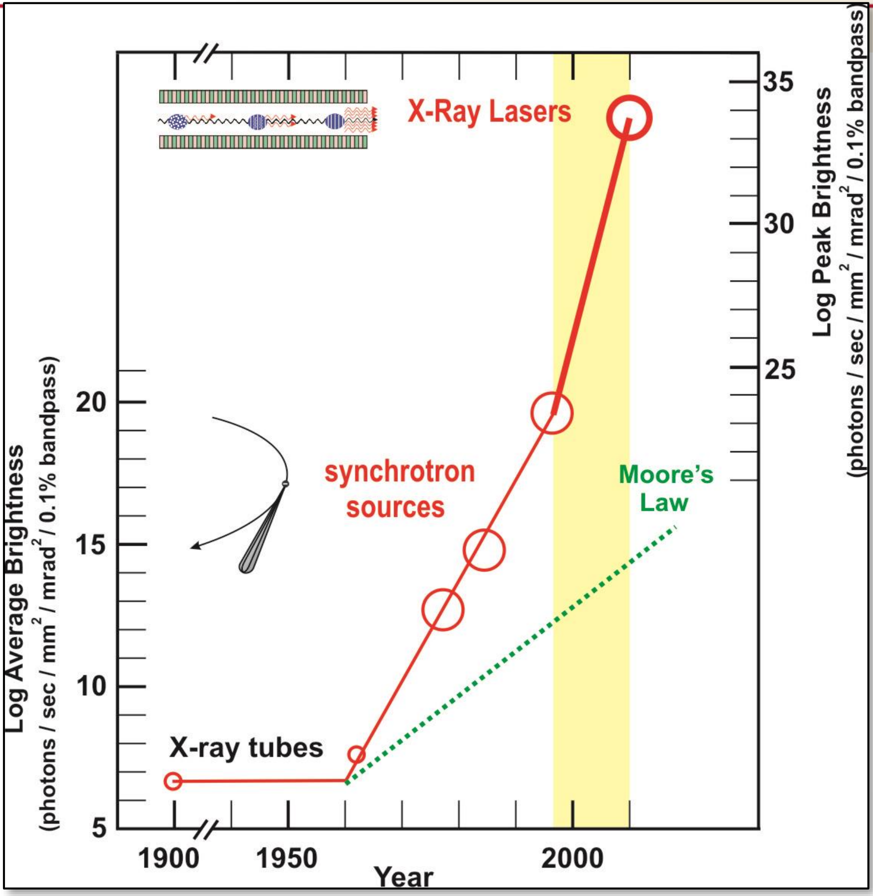
# Opportunities for Tunable Source of Radiation

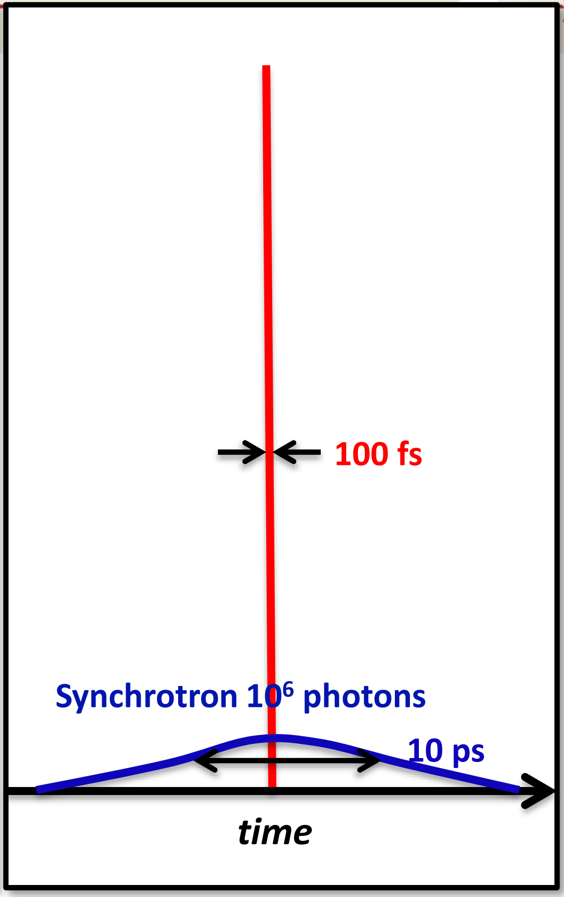



FEL oscillators (High-average power)

X-ray FELs! (High coherence and power)

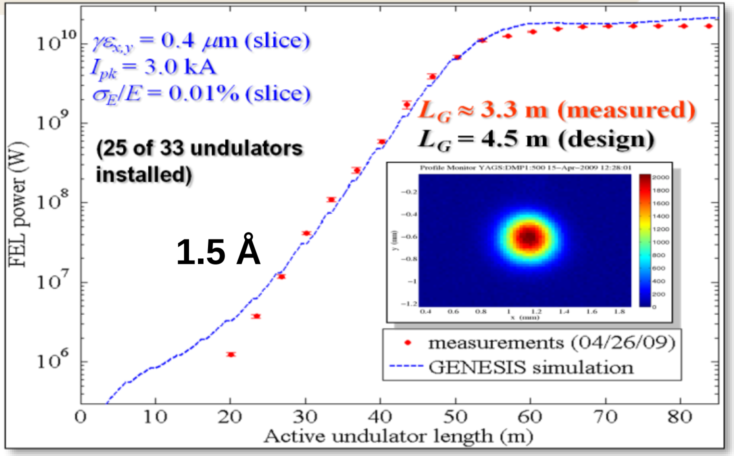
# XFELs are extremely bright and ultrafast



# LCLS (2009): the first hard X-ray FEL!

SLAC




| Parameter | Design | Typical | Unit |
|---|---|---|---|
| Photon energy range | 800–8000 | 270–11 200 | eV |
| Peak x-ray power | 10 | Up to 100 | GW |
| X-ray pulse energy | 2 | 2–4 | mJ |
| Pulse repetition rate | 120 | 120 | Hz |
| SXR[a] bandwidth (FWHM) | 0.1 | 0.2–2 | % |
| SXR pulse duration (FWHM) | 200 | 50–500 | fs |
| SXR pulse energy jitter (rms) | 20 | 3–10 | % |
| SXR wavelength jitter (rms) | 0.2 | 0.15 | % |
| HXR[b] bandwidth (FWHM) | 0.1 | 0.2–0.5 | % |
| HXR pulse duration (FWHM) | 200 | 30–100 | fs |
| HXR pulse energy jitter (rms) | 20 | 5–12 | % |
| HXR wavelength jitter (rms) | 0.2 | 0.05 | % |

nature photonics | ARTICLES | DOI: 10.1038/NPHOTON.2010.176

**~3000 Citation!**

**First lasing and operation of an ångstrom-wavelength free-electron laser**

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

REVIEWS OF MODERN PHYSICS, VOLUME 88, JANUARY–MARCH 2016

**Linac Coherent Light Source: The first five years**

Christoph Bostedt,* Sébastien Boutet, David M. Fritz, Zhirong Huang, Hae Ja Lee, Henrik T. Lemke,† Aymeric Robert, William F. Schlotter, Joshua J. Turner, and Garth J. Williams‡

# A world-wide growth spurt in XFELs

SACLA 2011
8.5 GeV, 60 Hz NC


European XFEL 2017
17.5 GeV, **2800 x 10 Hz SC**

PAL XFEL 2016
10 GeV, 60 Hz NC

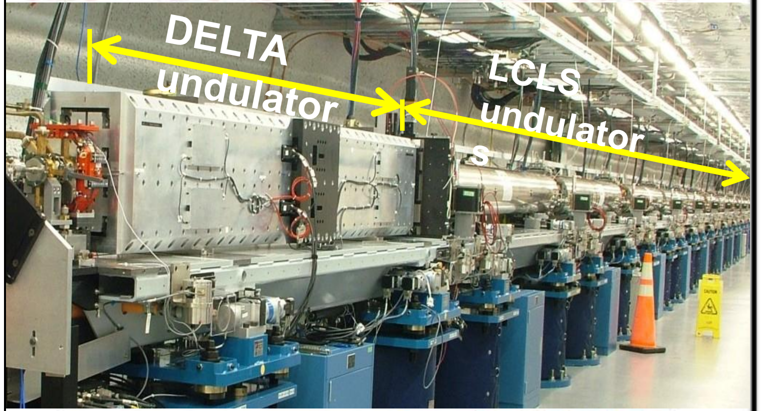
SWISS FEL 2018
5.8 GeV, 100 Hz NC


LCLS-II (HE) 2020(25)
4 (8) GeV, **1 MHz SC**

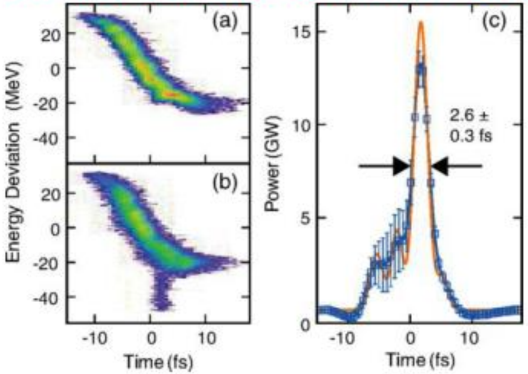

Shanghai SHINE 2025
8 GeV, **1 MHz SC**

# FEL R&D keep improving source properties in the last decade

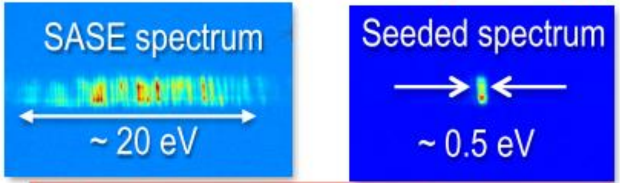
## Expanded photon energy range, 0.25 – 12.8 keV & polarization control




## Generation of few-fs x-ray pulses & measurements with XTCAV

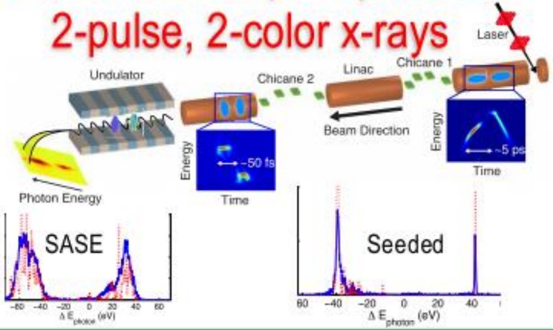



## From SASE fluctuations to controlled pulse width & spectrum (seeding)




**40x Increase in Temporal Coherence!**

## Creation of multiple options for 2-pulse, 2-color x-rays



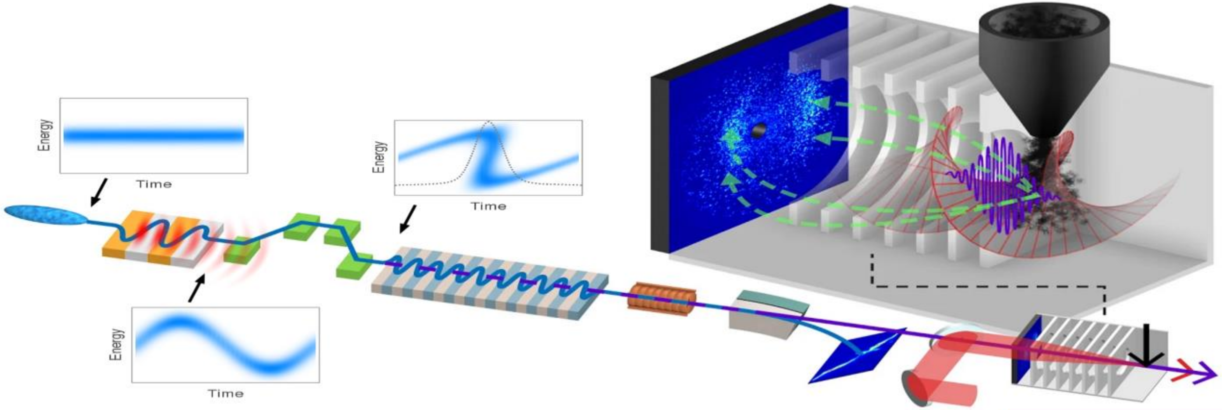
# Attosecond X-ray pulses with XLEAP

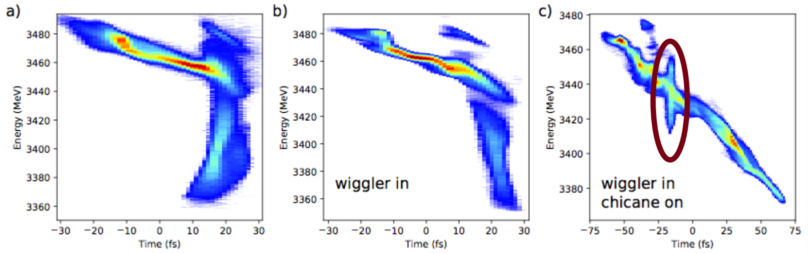
- Current-Enhanced SASE with a modulated electron beam
- Instead of laser modulation, use coherent undulator radiation to create modulation

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 040701 (2005)

**Method of an enhanced self-amplified spontaneous emission for x-ray free electron lasers**

Alexander A. Zholents




ARTICLES
https://doi.org/10.1038/s41566-019-0549-5
nature photonics

**Tunable isolated attosecond X-ray pulses with gigawatt peak power from a free-electron laser**

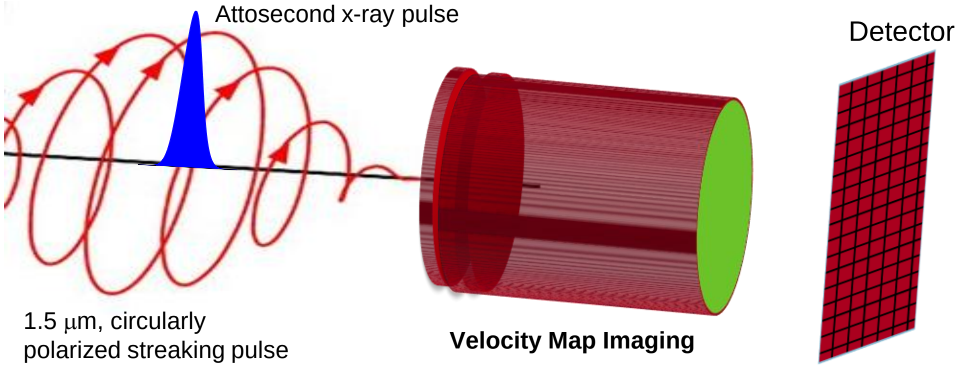
Joseph Duris[1,12], Siqi Li[1,2,12], Taran Driver[1,3,4], Elio G. Champenois[3], James P. MacArthur[1,2], Alberto A. Lutman[1], Zhen Zhang[1], Philipp Rosenberger[1,3,5,6], Jeff W. Aldrich[1], Ryan Coffee[1], Giacomo Coslovich[1], Franz-Josef Decker[1], James M. Glownia[1], Gregor Hartmann[7], Wolfram Helml[6,8,9], Andrei Kamalov[2,3], Jonas Knurr[3], Jacek Krzywinski[1], Ming-Fu Lin[1], Jon P. Marangos[4], Megan Nantel[1,2], Adi Natan[3], Jordan T. O'Neal[2,3], Niranjan Shivaram[1], Peter Walter[1], Anna Li Wang[3,10], James J. Welch[1], Thomas J. A. Wolf[3], Joseph Z. Xu[11], Matthias F. Kling[1,3,5,6], Philip H. Bucksbaum[1,2,3,10], Alexander Zholents[11], Zhirong Huang[1,10], James P. Cryan[1,3*] and Agostino Marinelli[1*]

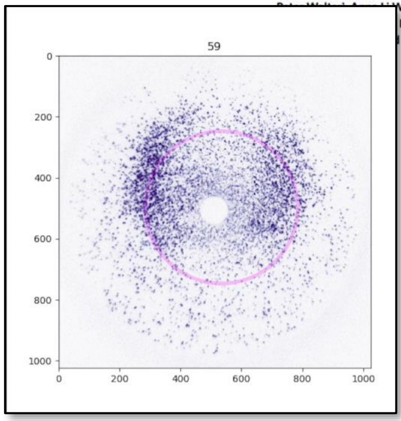
# Attosecond X-ray measurements

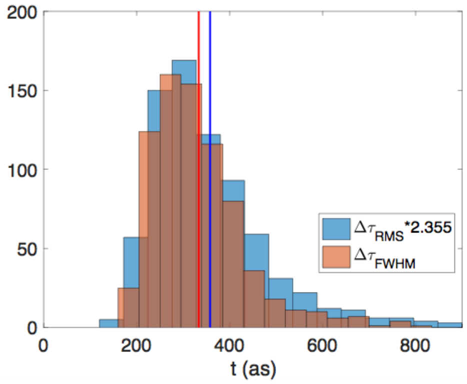
ARTICLES
https://doi.org/10.1038/s41566-019-0549-5
nature photonics

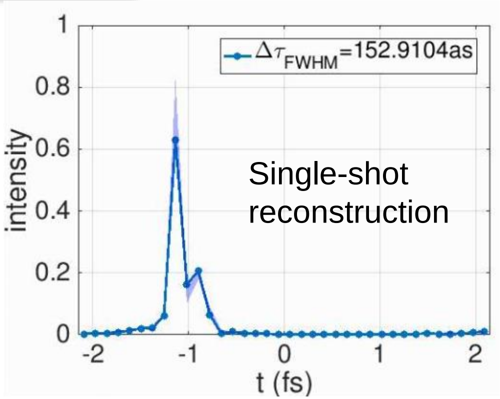
**Tunable isolated attosecond X-ray pulses with gigawatt peak power from a free-electron laser**

Joseph Duris[1,12], Siqi Li[1,2,12], Taran Driver[1,3,4], Elio G. Champenois[3], James P. MacArthur[1,2], Alberto A. Lutman[1], Zhen Zhang[1], Philipp Rosenberger[1,3,5,6], Jeff W. Aldrich[1], Ryan Coffee[1], Giacomo Coslovich[1], Franz-Josef Decker[1], James M. Glownia[1], Gregor Hartmann[7], Wolfram Helml[6,8,9], Andrei Kamalov[2,3], Jonas Knurr[3], Jacek Krzywinski[1], Ming-Fu Lin[1], Jon P. Marangos[4], Megan Nantel[1,2], Adi Natan[3], Jordan T. O'Neal[2,3], Niranjan Shivaram[1], …Wang[3,10], James J. Welch[1], Thomas J. A. Wolf[3], Joseph Z. Xu[11], … Philip H. Bucksbaum[1,2,3,10], Alexander Zholents[11], Zhirong Huang[1,10], … Agostino Marinelli[1*]



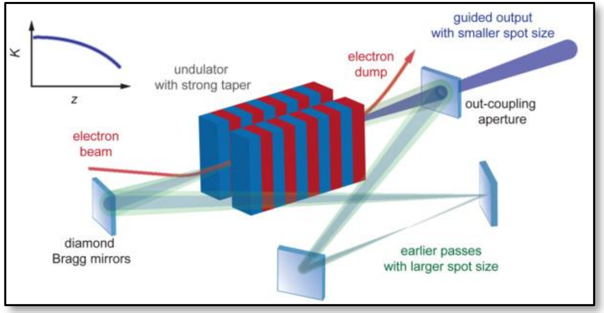



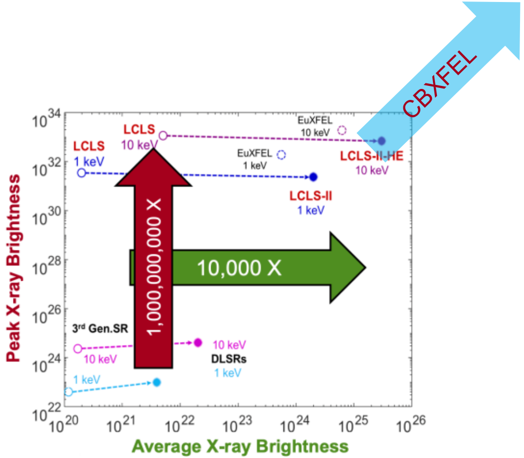

- **350 as** pulses, tens of uJ pulse energy
- **6 orders of magnitude** higher peak brightness compared to HHG sources

# Cavity-Based XFEL (CBXFEL)

- XFELs are based on single-pass SASE: very flexible (fs-as pulses, self-seeding, two-color, …), but not stable and not longitudinally coherent.
- For LCLS-II and other high-rep. rate XFELs, we want to take advantage of extremely high rate to build an X-ray optical cavity to filter and return X-ray pulses for repetitive interactions with e-beams.



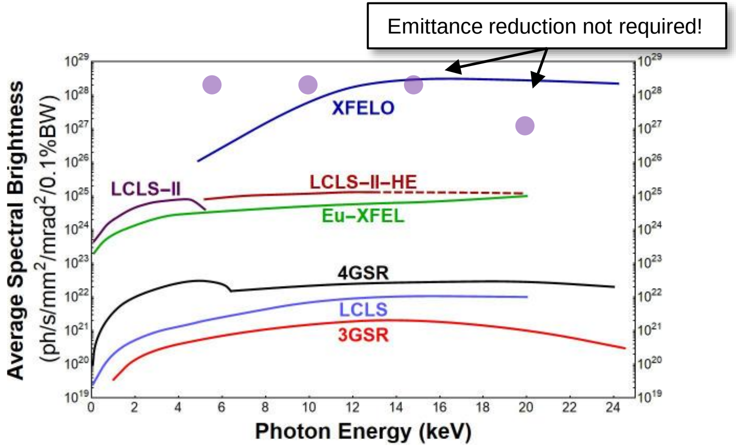

- CBXFEL can produce highly stable, fully coherent X-rays with
  - ➢ Higher average brightness (XFELO and XRAFEL),
  - ➢ High peak brightness (XRAFEL),
  - ➢ Ultrafine spectral capabilities (XFELO).





X-ray RAFEL: Z. Huang and R.D. Ruth, Phys. Rev. Lett. 96, 144801 (2006).
X-ray Oscillator: K.-J. Kim, Y. Shvyd'ko, and Sven Reiche, Phys. Rev. Lett. 100, 244802 (2008).

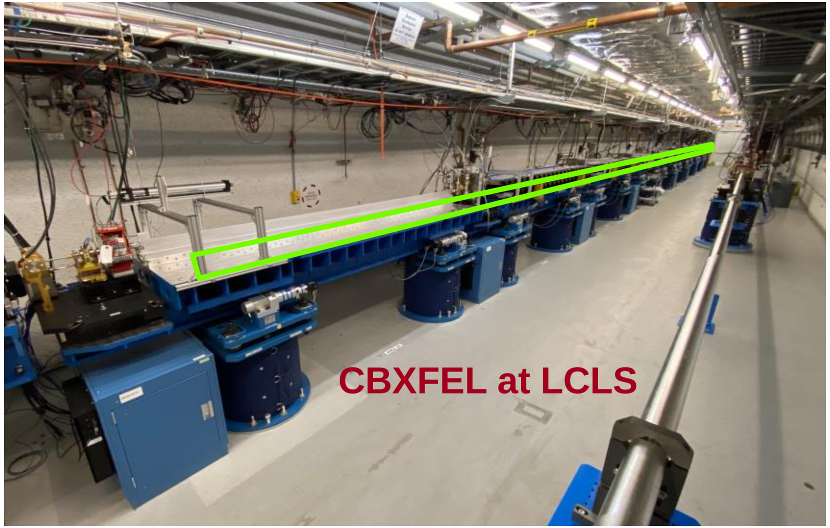
# CBXFEL: Now and Future




- XFELO assumed brighter e-beam from SCRF gun and shorter period (2cm) higher field SCU undulators
- XRAFEL assumed LCLS-II-HE baseline injector and undulator

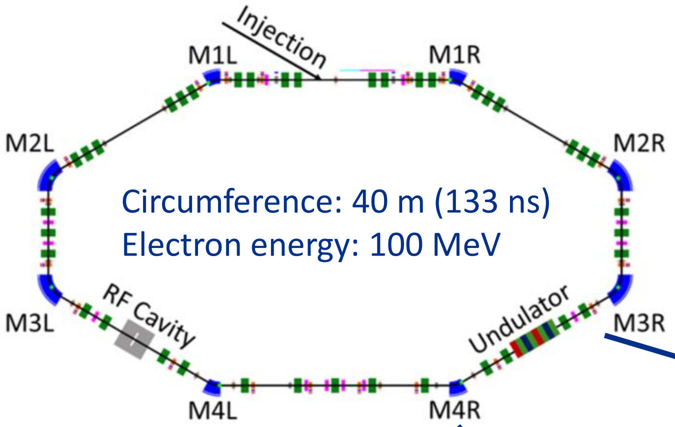
*R. Lindberg et al., PRAB 14, 010701 (2011)*
*W. Qin et al., in proc. FEL17, 2017*
*G. Marcus et al., PRL 125, 254801, 2020*

- **Peak and average brightness 2-3 orders of magnitude greater than single pass SASE amplifiers**
  - **Very stable output**
- All kinds of games to play and tricks to discover by playing with BW and pulse length tradeoffs near the FT limit
  - **A true x-ray laser**



# *Wonderful noise!*

## Measuring turn-to-turn fluctuations in the undulator radiation in IOTA



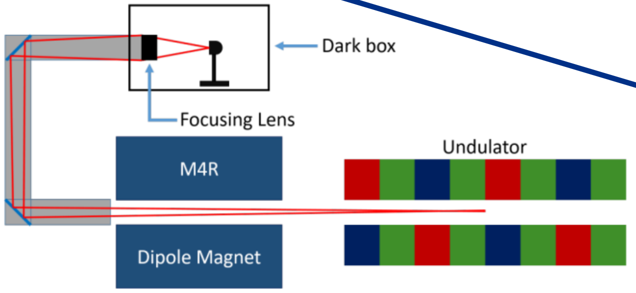

Format of collected data:

| Revolution number | Number of photocounts, N |
|---|---|
| 0 | 9994352 |
| 1 | 9997379 |
| 2 | 10002465 |
| 3 | 9999482 |
| 4 | 9996153 |
| ... | ... |
| 11273 (1.5 ms ) | 10000362 |

$$\mathrm{var}(\mathcal{N}) = \langle \mathcal{N}^2 \rangle - \langle \mathcal{N} \rangle^2$$

Undulator: SLAC

- Number of periods: $N_\mathrm{u} = 10.5$
- Undulator period length: $\lambda_\mathrm{u} = 55\ \mathrm{mm}$
- Undulator parameter (peak): $K_\mathrm{u} = 1$
- Fundamental of radiation: 1.1 um
- Second harmonic: visible light




Detector: InGaAs PIN photodiode
(mostly sensitive to the fundamental)

# Theoretical prediction for the fluctuations

$$\mathrm{var}(\mathcal{N}_{\mathrm{ph}}) = \langle\mathcal{N}_{\mathrm{ph}}\rangle + \frac{1}{M}\langle\mathcal{N}_{\mathrm{ph}}\rangle^2$$

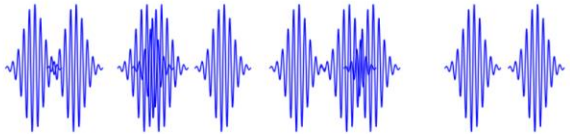
Discrete quantum nature of light

Turn-to-turn variations in relative electron positions and directions of motion

## Origin of the second term:

Explanation for on-axis radiation:

Pulses emitted by the electrons:



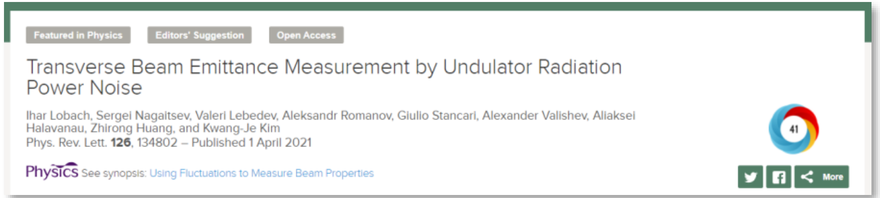
$$W \propto \int dt \left|\sum_{i=1}^{n_e} E(t - t_i)\right|^2$$

The set of arrival times of the electrons $\{t_i\}$ is different during every revolution in the ring. Hence, the radiated energy $W$ fluctuates from turn to turn.

In general, the parameter $M$ will also be a function of the transverse emittances of the electron bunch

*Phys. Rev. Accel. Beams*, 24, 040701 (2021) and *Phys. Rev. Accel. Beams*, 23, 090703 (2020) by Lobach, I., Nagaitsev, S., Lebedev, V., Romanov, A., Stancari, G., Valishev, A., Halavanau, A., Huang, Z., & Kim, K.-J.

# Reconstruction of transverse emittances from the measured magnitude of turn-to-turn intensity fluctuations


Featured in Physics Editors' Suggestion Open Access

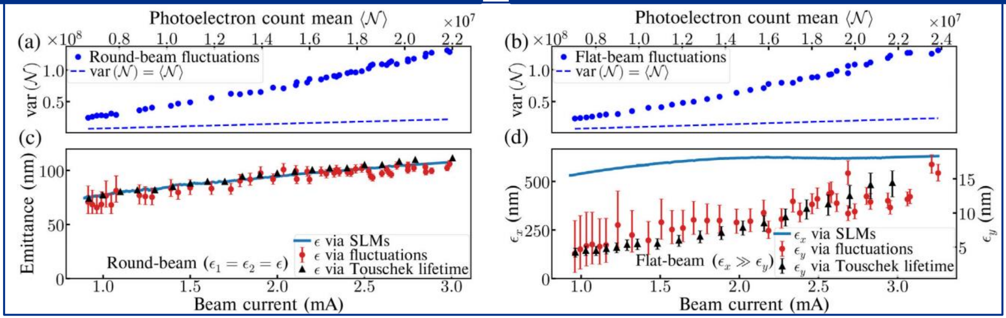
Transverse Beam Emittance Measurement by Undulator Radiation Power Noise

Ihar Lobach, Sergei Nagaitsev, Valeri Lebedev, Aleksandr Romanov, Giulio Stancari, Alexander Valishev, Aliaksei Halavanau, Zhirong Huang, and Kwang-Je Kim
Phys. Rev. Lett. **126**, 134802 – Published 1 April 2021

Physics See synopsis: Using Fluctuations to Measure Beam Properties

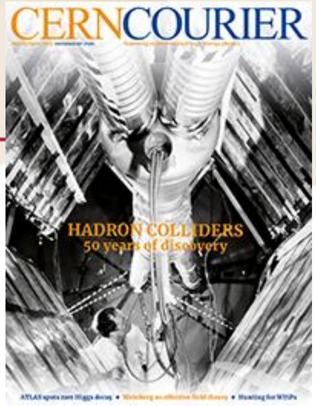
We verified our method with a "round" beam, whose emittances could be independently measured by synchrotron radiation monitors, (a) and (c):

Then, we used our fluctuations to measure the unknown small vertical emittance of a "flat" beam, (b) and (d):




The sensitivity of this technique improves with shorter wavelength. Therefore, this technique may be particularly beneficial for existing state-of-the-art and next-generation low-emittance high-brightness ultraviolet and x-ray synchrotron light sources. For instance, this technique can measure $\epsilon_x \approx \epsilon_y \approx 30$ pm in the Advanced Photon Source Upgrade at Argonne.

# Final thoughts…




VIEWPOINT

## Amazing particles and light

**Swapan Chattopadhyay** reflects on the extraordinary fundamental value of accelerators.

- The vision is one of discovering the secrets of the hidden energy and matter in the universe's evolution; of understanding the protein as the molecular engine of life through studying its energetics and structural folding; of innovating new eco- and bio-friendly materials for human use; and of eliminating radioactive waste and dependence on fossil fuels. **Extraordinarily clever particle accelerators drive this at all scales from "small" to "mezzo" to "grand".**
- Is this just a dream? Inspired by US poet Carl Sandburg, I respond: "**Nothing happens, unless first a dream**."

# Happy retirement (and keep dreaming)!

SLAC

**Look forward to dreaming together in Bay area and SLAC!**