Center for BRIGHT BEAMS

2022 Center for Bright Beams Annual Symposium: Compact Light Sources

Friday 3 Jun 2022, 08:00 → 18:00 America/Los_Angeles

Faculty Center - Morrison Room (UCLA)

J. Ritchie Patterson , Joan Curtiss

Paths toward Compact FELs

Zhirong Huang

June 3, 2022

BOLD PEOPLE. VISIONARY SCIENCE. REAL IMPACT.

Outline

- Introduction
- X-ray FEL basics
- Ingredients for compact XFELs
  - Compact accelerators
  - Brighter electron beams
  - Pre-bunching or beam manipulation
  - Shorter period undulators
  - X-ray cavities
- Summary

What is Free Electron Laser

- John Madey—Inventor of the FEL (1971)

JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 5 APRIL 1971

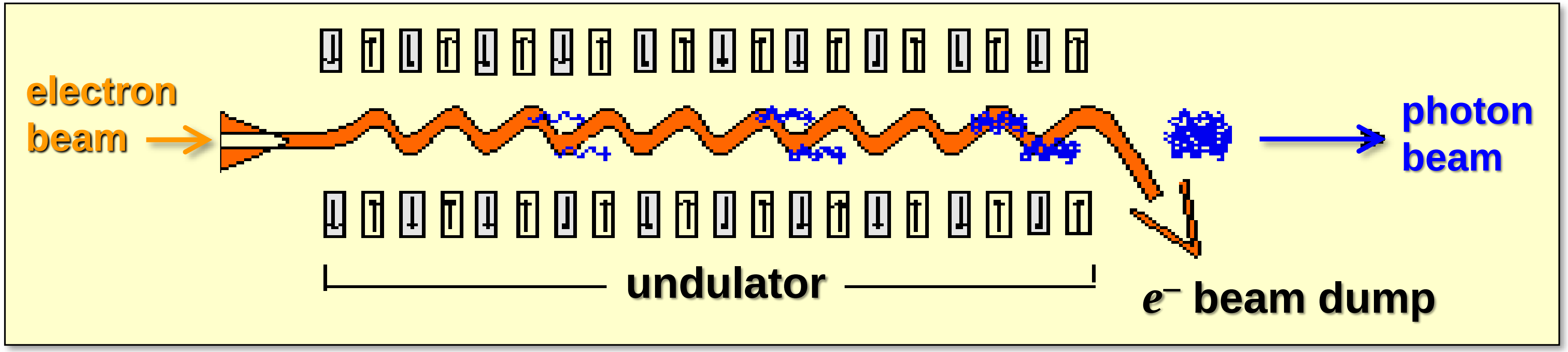
Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field

JOHN M. J. MADEY

Physics Department, Stanford University, Stanford, California 94305

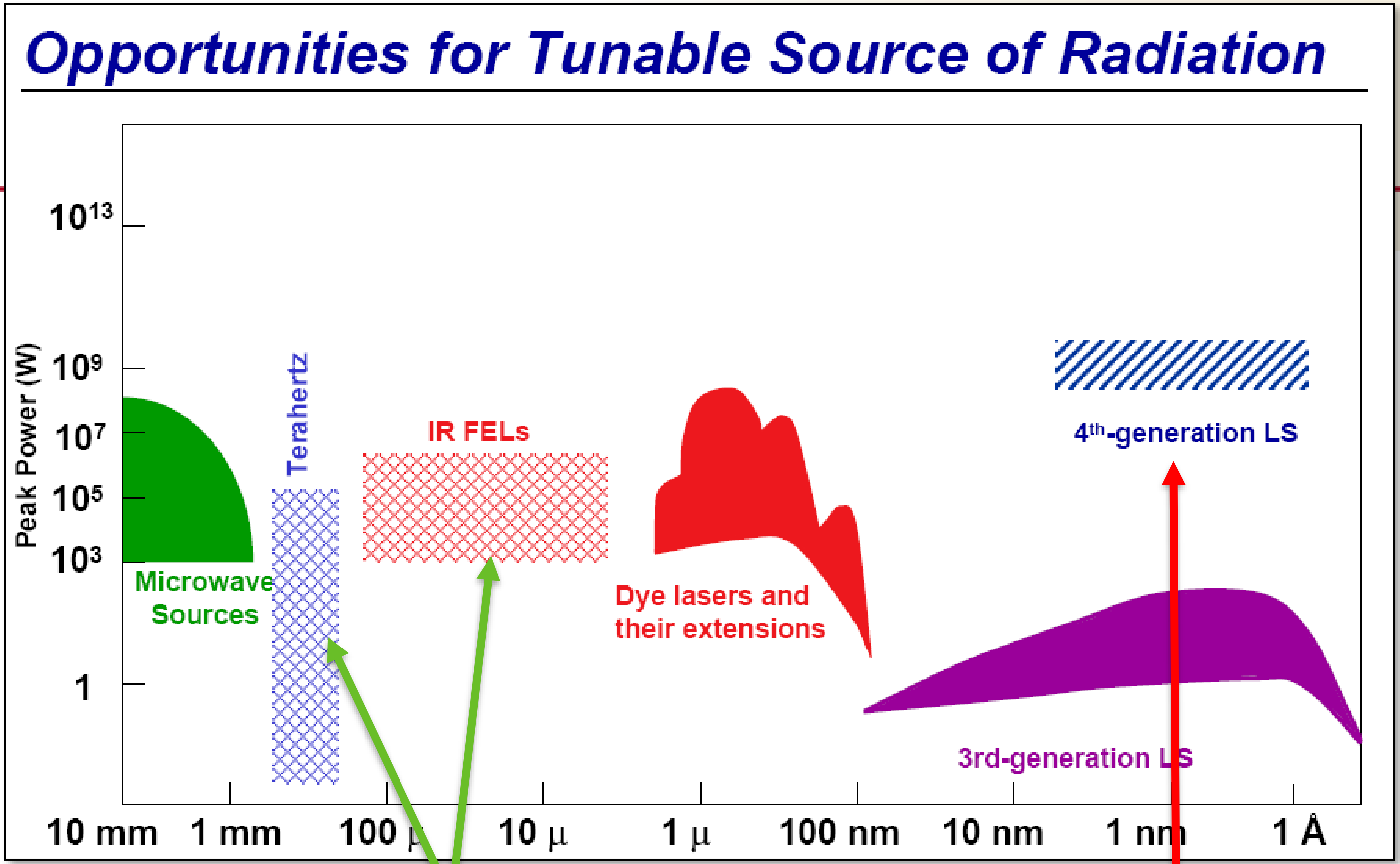
(Received 20 February 1970; in final form 21 August 1970)

- Produced by **resonant interaction** of a relativistic electron beam with EM radiation in an undulator



- **Tunable, Powerful, Coherent radiation sources**
- **Tunable means arbitrary wavelengths!!!**

Opportunities for Tunable Source of Radiation



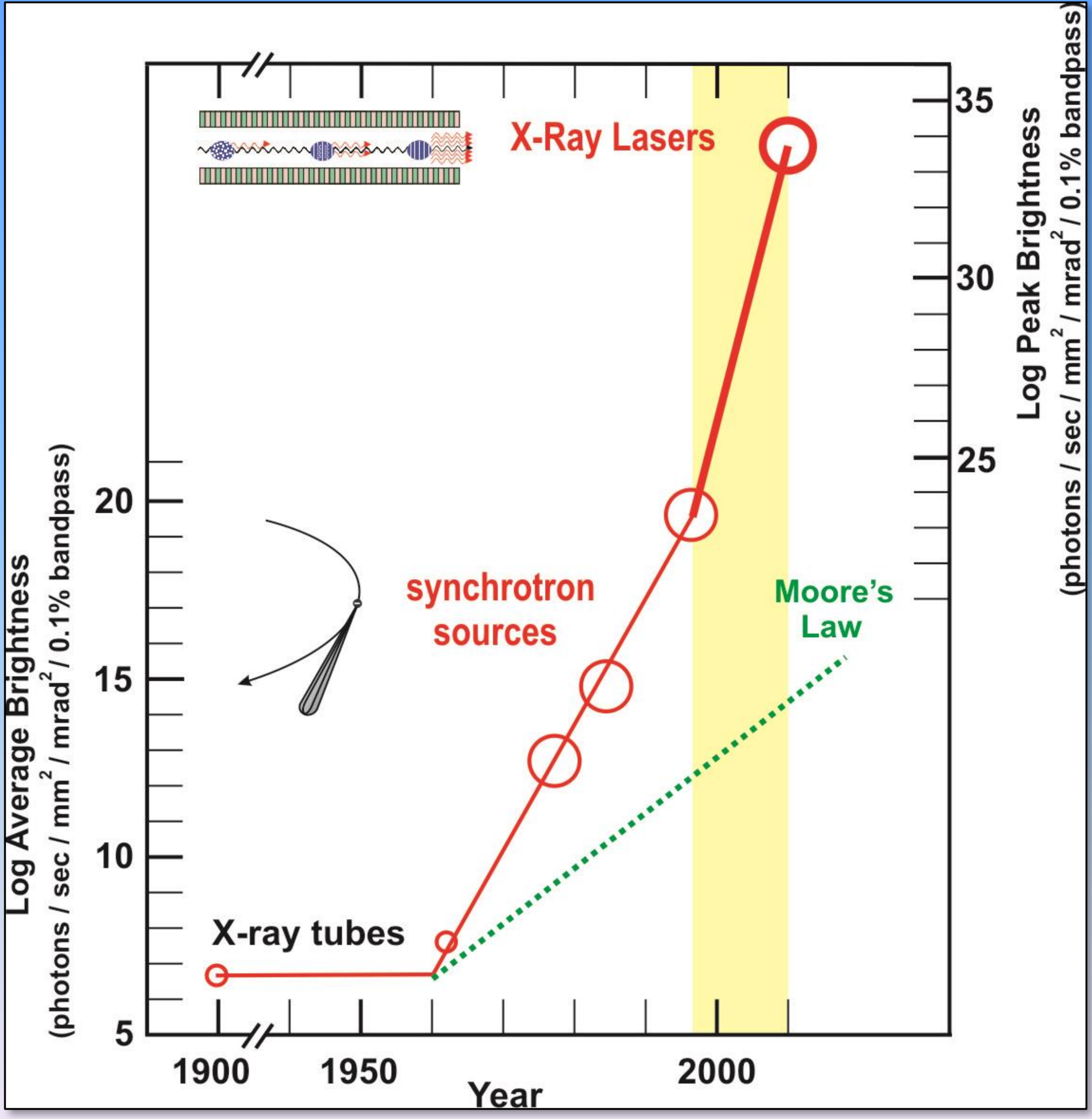
FEL oscillators

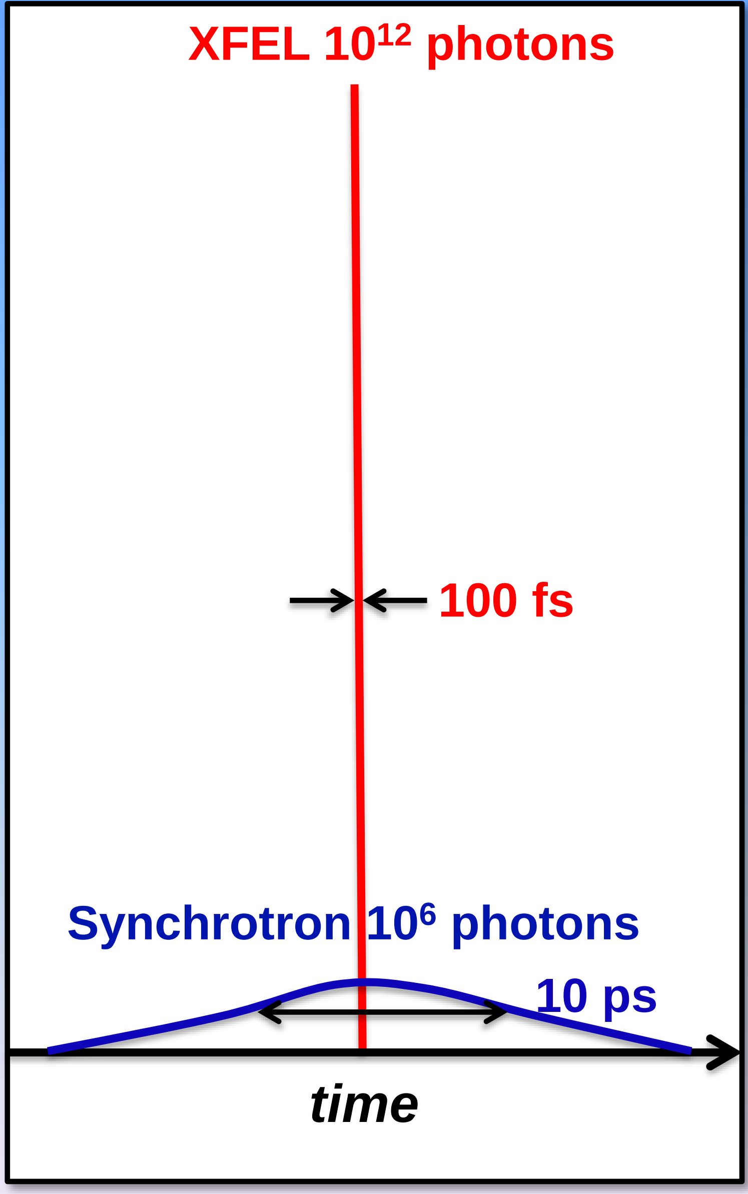
X-ray FELs

FELIX
(Radboud Univ.)

LCLS-I (SLAC)

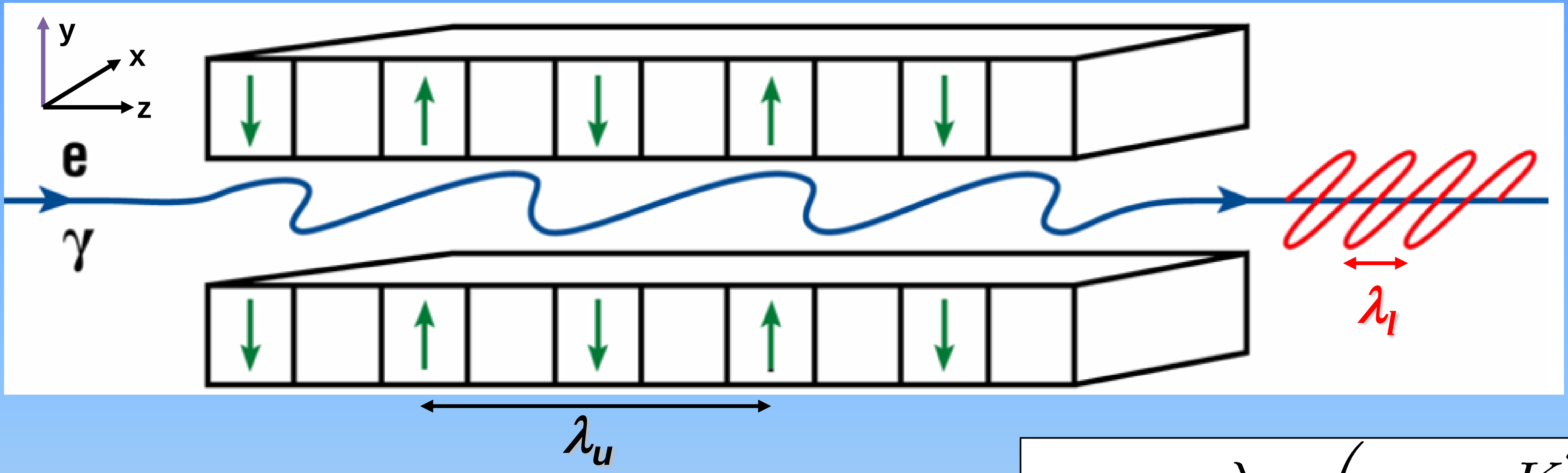
XFELs are Extremely Bright and Ultrafast





Note: High rep. rate and average brightness XFELs are coming

Undulator Radiation



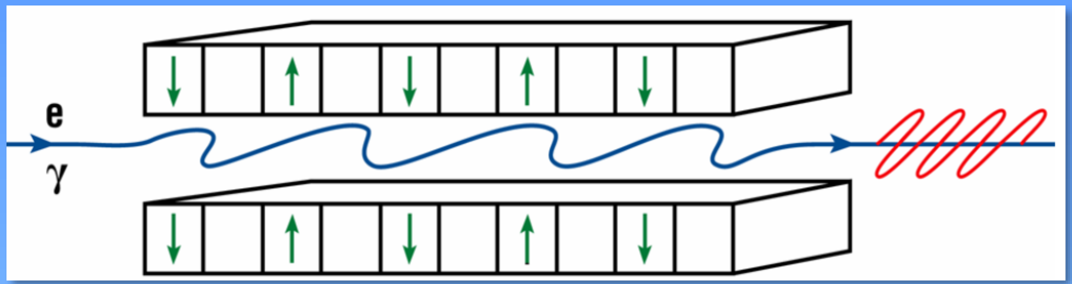
Undulator radiation wavelength (forward direction) $$\boxed{\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)}$$

undulator parameter $K = 0.94\, B$[Tesla] λ_u[cm]

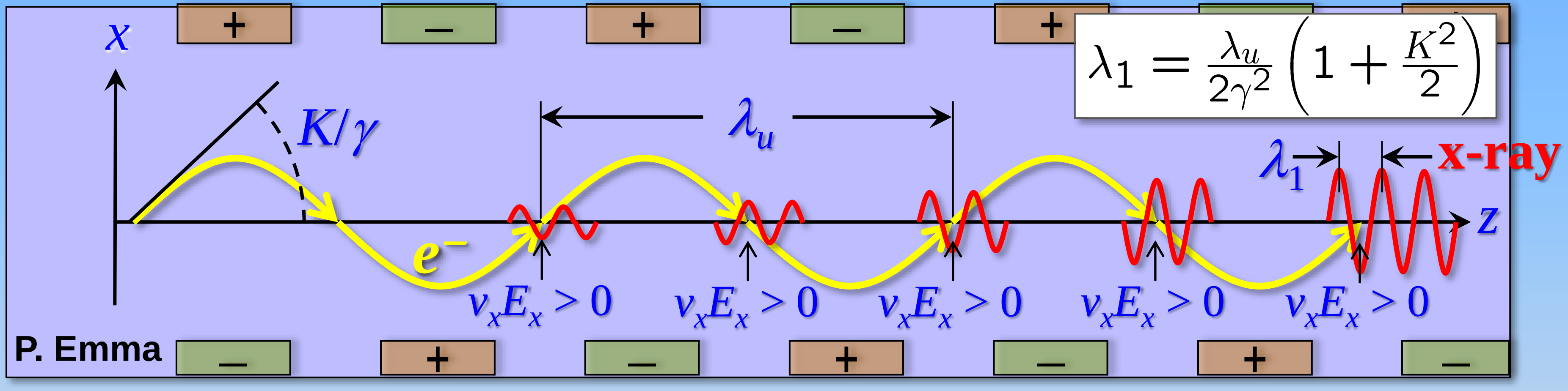
LCLS undulator $K = 3.5$, $\lambda_u = 3$ cm, e-beam energy from 3 GeV to 15 GeV to cover $\lambda_1 = 30$ Å to 1.2 Å

Key question: can energy be exchanged between electrons and co-propagating radiation pulse?

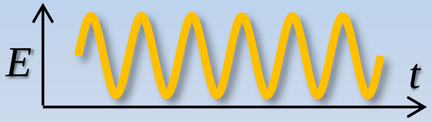
Resonant Interaction of Field with Electrons



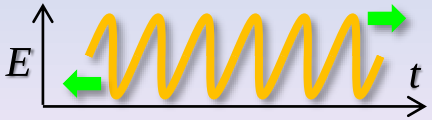
- Electrons **slip** behind EM wave by λ_1 per undulator period (λ_u)



- Due to sustained interaction, some electrons lose energy, while others gain ➔ energy modulation at λ_1

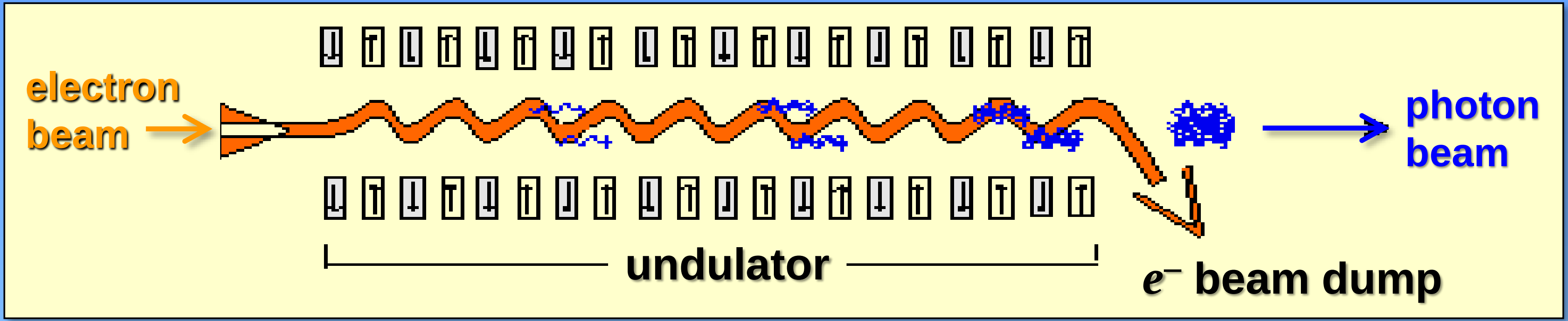


- e^- losing energy slow down, and e^- gaining energy catch up ➔ density modulation at λ_1 (microbunching)

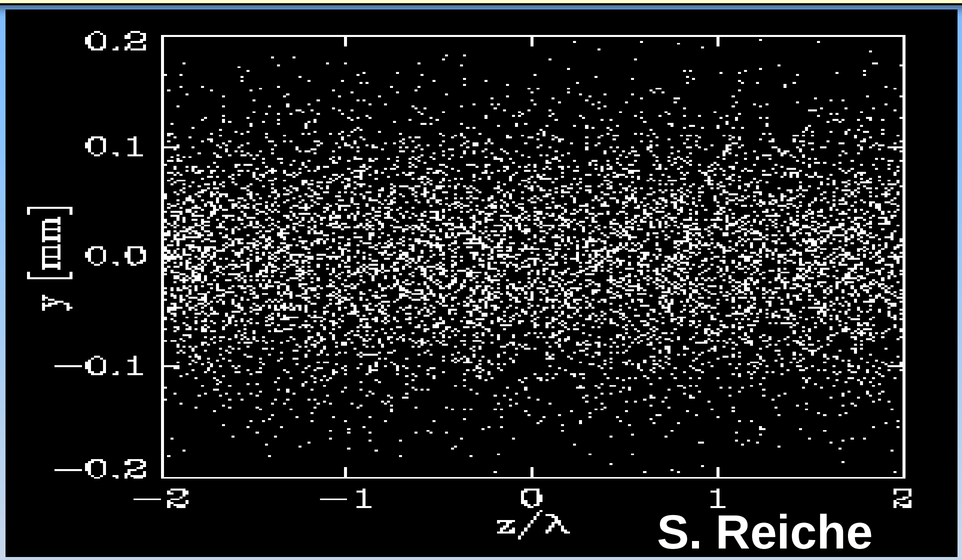


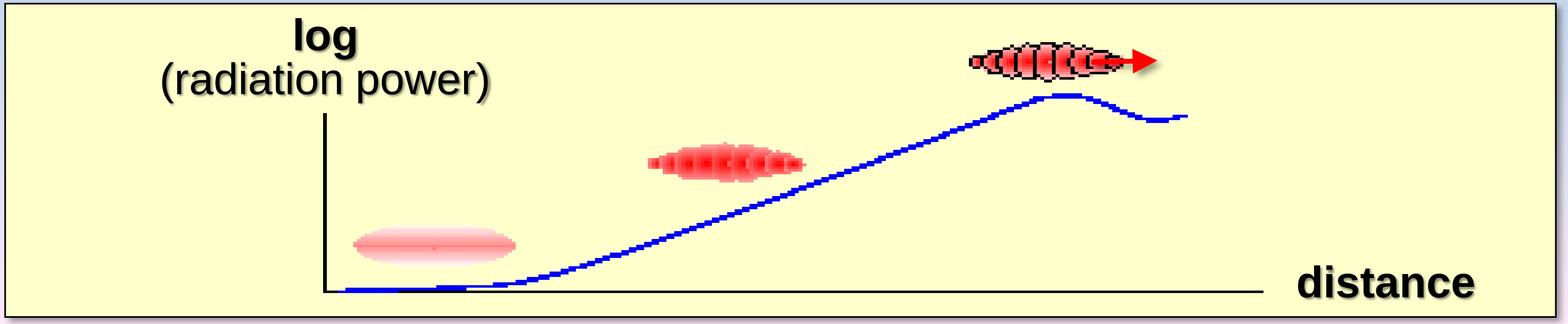
- Microbunched beam radiates coherently at λ_1, enhancing the process ➔ **exponential growth of radiation power**

FEL Micro-Bunching Along Undulator



$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



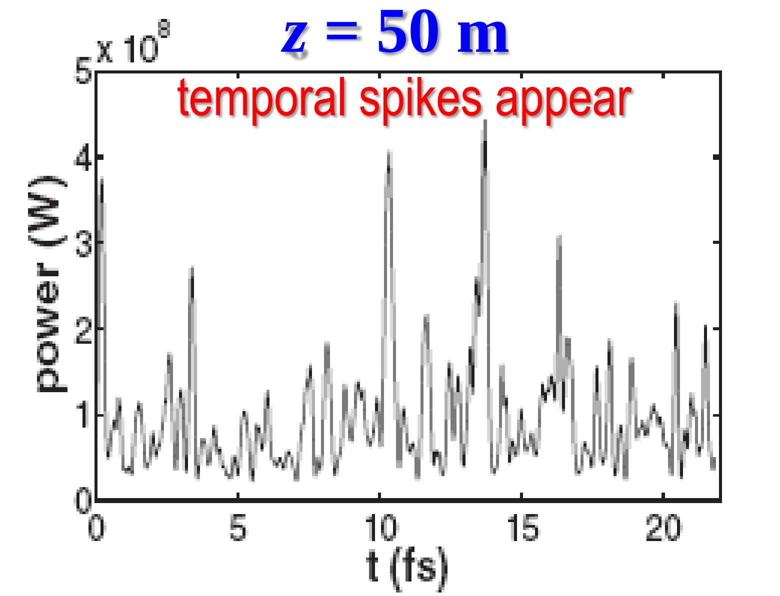


Statistical fluctuation of Self-Amplified Spontaneous Emission (SASE)

- Due to noise start-up, SASE is chaotic light with M_L coherent modes (*i.e.*, spikes in intensity profile):

$$\boxed{M_L \approx \frac{\text{bunch length}}{\text{coherence length}} = \frac{\Delta z}{l_c}}$$

l_c coherence length



← 50 % of X-Ray Pulse Length →

- Longitudinal phase space is M_L larger than Fourier Transform limit
- SASE energy fluctuation is…

$$\boxed{\frac{\Delta W}{W} = \frac{1}{\sqrt{M_L}}}$$

- M_L is **not** constant – reduced by increased coherence during exponential growth, and increased with reduced coherence after saturation
- ***LCLS*** near saturation (~50 fs): $M_L \approx 200$ ➔ $\Delta W/W \approx 7\ \%$

SASE FEL Electron Beam Requirements

$$\varepsilon_N < \gamma \frac{\lambda_r}{4\pi}$$

radiation wavelength (*e.g.*, 1 Å)

transverse emittance: ε_N < 0.5 μm at 1 Å, 15 GeV for LCLS

peak current

$$\sigma_\delta < \rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I_{pk}}{I_A}\frac{\lambda_u^2}{\beta\varepsilon_N}\left(\frac{K}{\gamma}\right)^2\right)^{1/3}$$

relative energy spread:

<0.04% at I_{pk} = 3 kA,

$K \approx 3$, $\lambda_u \approx 3$ cm, …

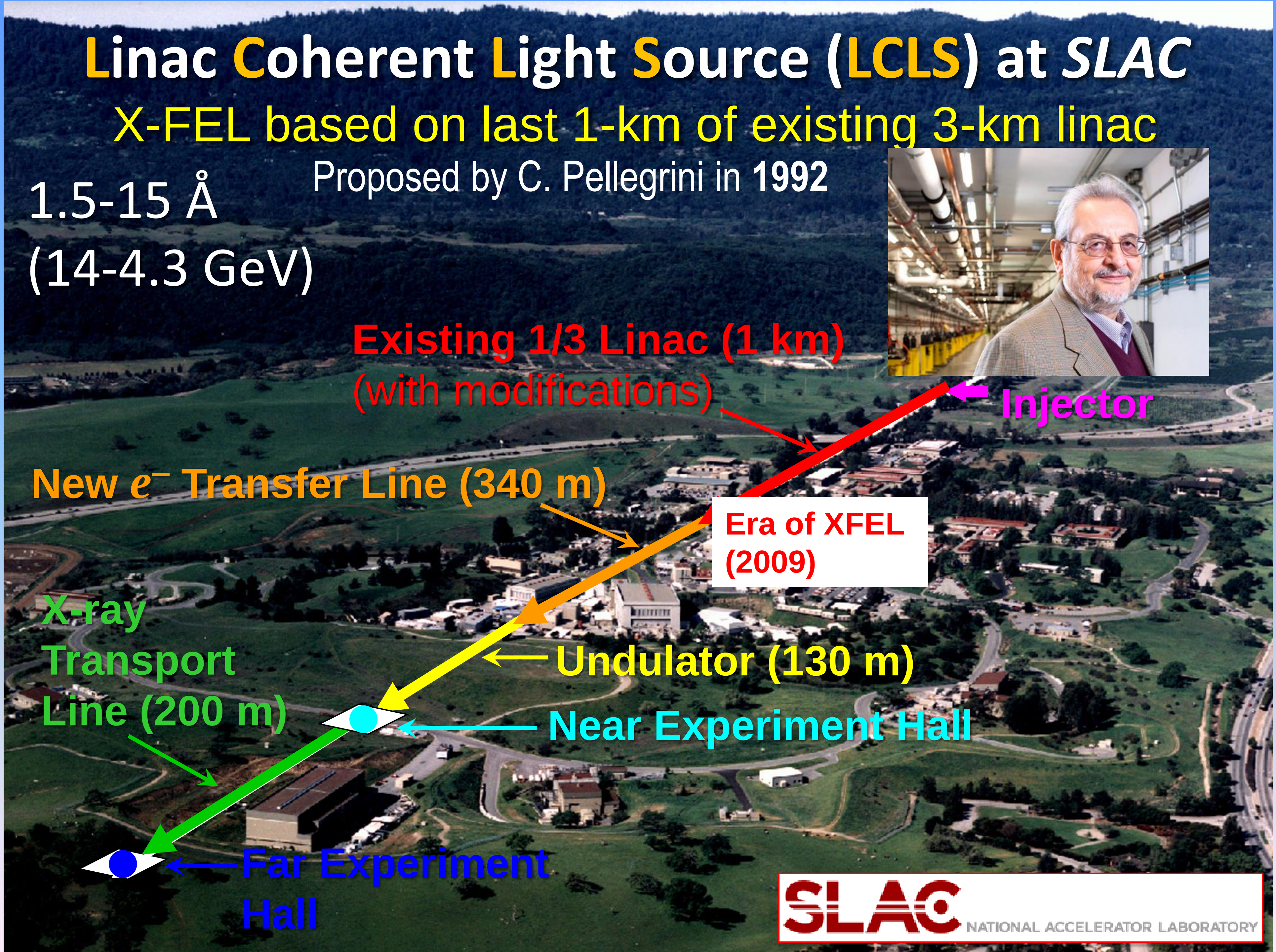
beta function

undulator 'field' = $0.93 \cdot B\lambda_u$

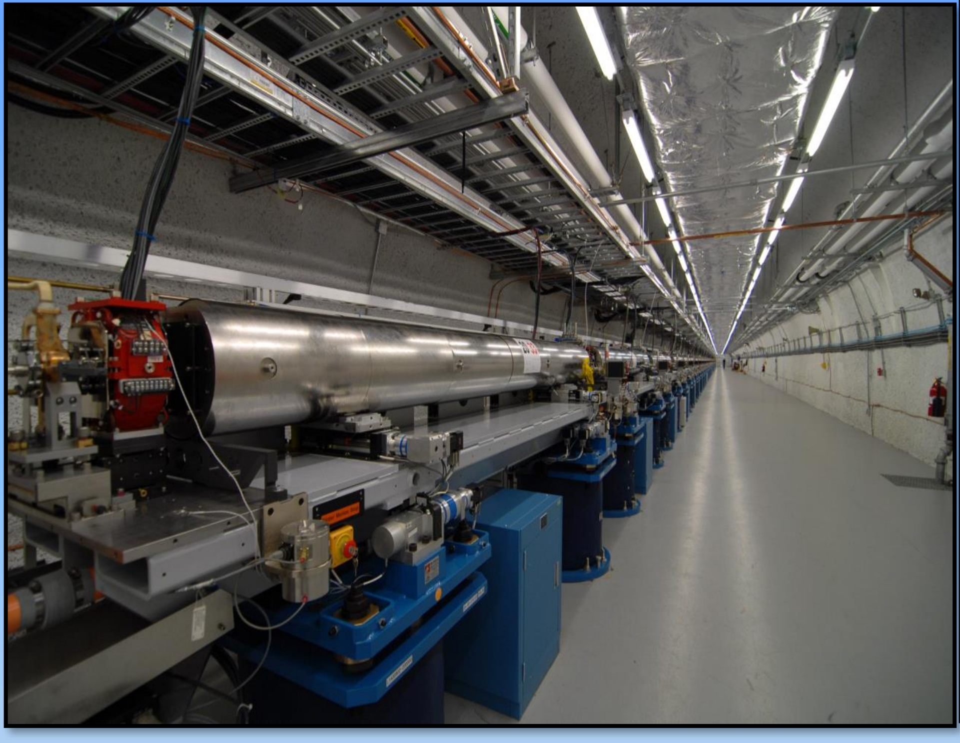
$$L_g \approx \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

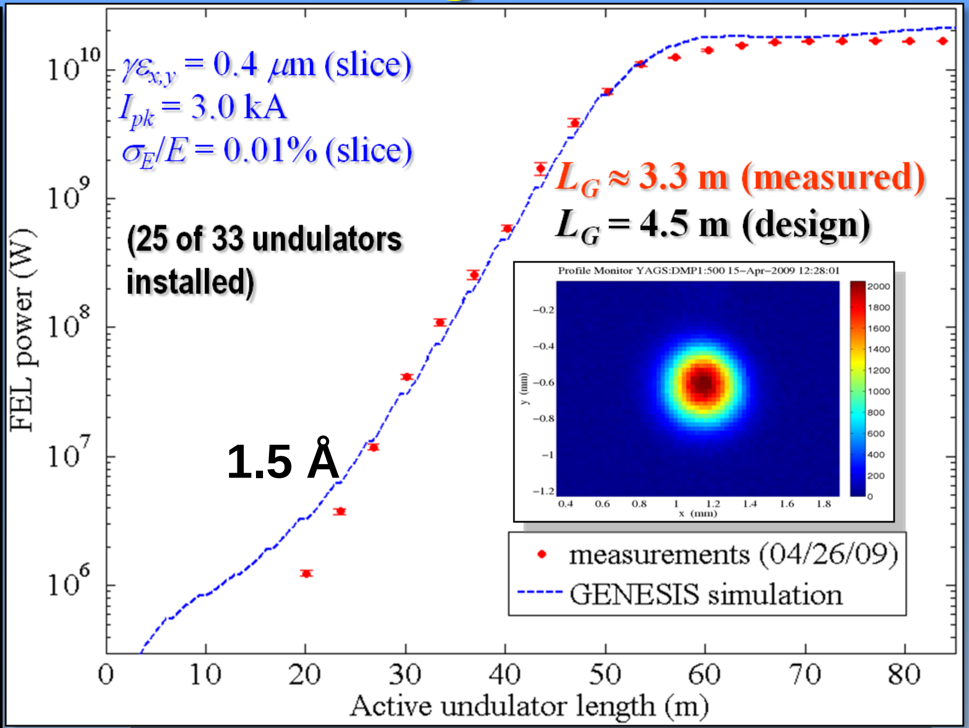
FEL gain length: $18L_G \approx$ 60 m for $\varepsilon_N \approx$ 0.4 μm

- We must increase peak current, preserve emittance, and maintain small energy spread so that power grows exponentially with undulator distance, z, $P(z) = P_0 \cdot \exp(z/L_G)$
- FEL power reaches *saturation* at $\sim 18L_G$
- SASE depends *exponentially* on e^- beam quality (to be exploited)


Linac Coherent Light Source (LCLS) at *SLAC*
X-FEL based on last 1-km of existing 3-km linac
Proposed by C. Pellegrini in **1992**
1.5-15 Å
(14-4.3 GeV)
Existing 1/3 Linac (1 km)
(with modifications)
Injector
New e^- Transfer Line (340 m)
Era of XFEL
(2009)
X-ray
Transport
Line (200 m)
Undulator (130 m)
Near Experiment Hall
Far Experiment
Hall
SLAC NATIONAL ACCELERATOR LABORATORY

LCLS: the first hard X-ray FEL





- SASE wavelength range: **40 – 1** Å
- Photon energy range: **0.3 - 12** keV
- Pulse length FWHM **5 – 100** fs
- Pulse energy up to **5** mJ
- Tremendous science output!

nature photonics ARTICLES
PUBLISHED ONLINE: 1 AUGUST 2010 | DOI: 10.1038/NPHOTON.2010.176

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‡

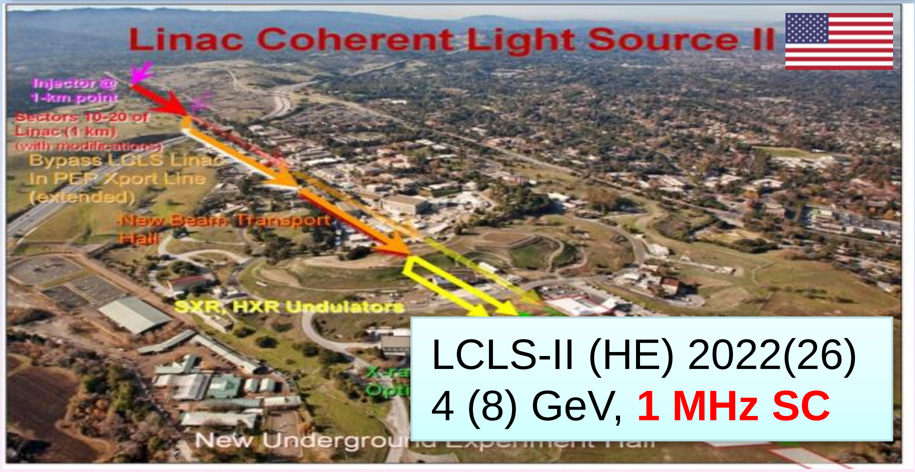
A world-wide growth spurt in XFELs

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) 2022(26)
4 (8) GeV, **1 MHz SC**

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

And soft X-rays:

Fermi FEL (Italy)
FLASH (Germany)
SXFEL (China)
…

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  - Compact accelerators
  - Brighter electron beams
  - Pre-bunching or beam manipulation
  - Shorter period undulators
  - X-ray cavities
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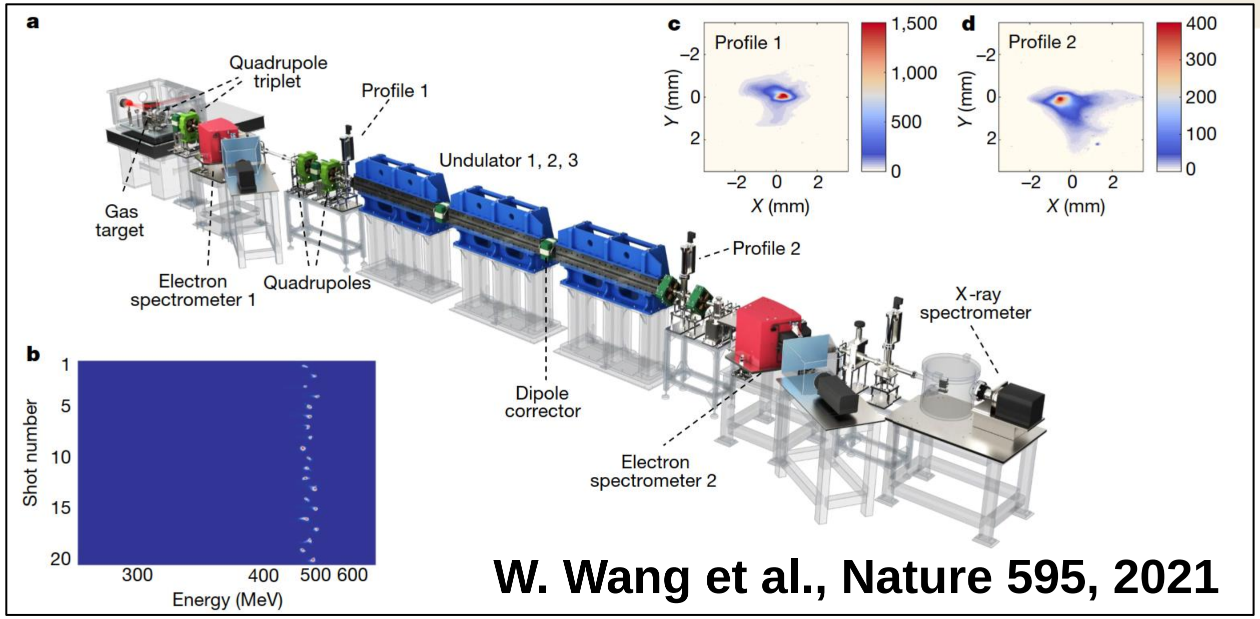
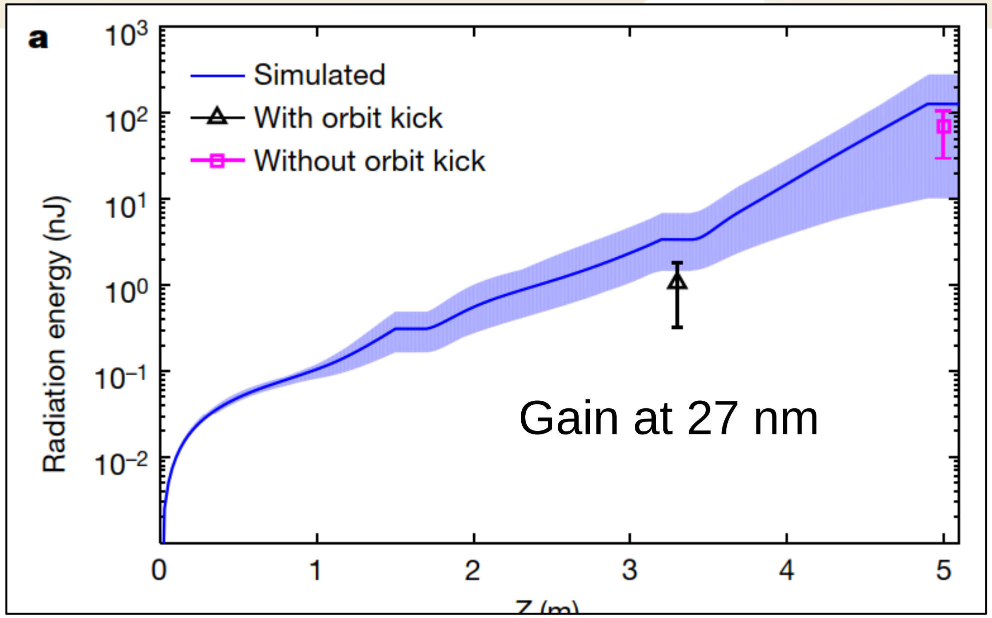
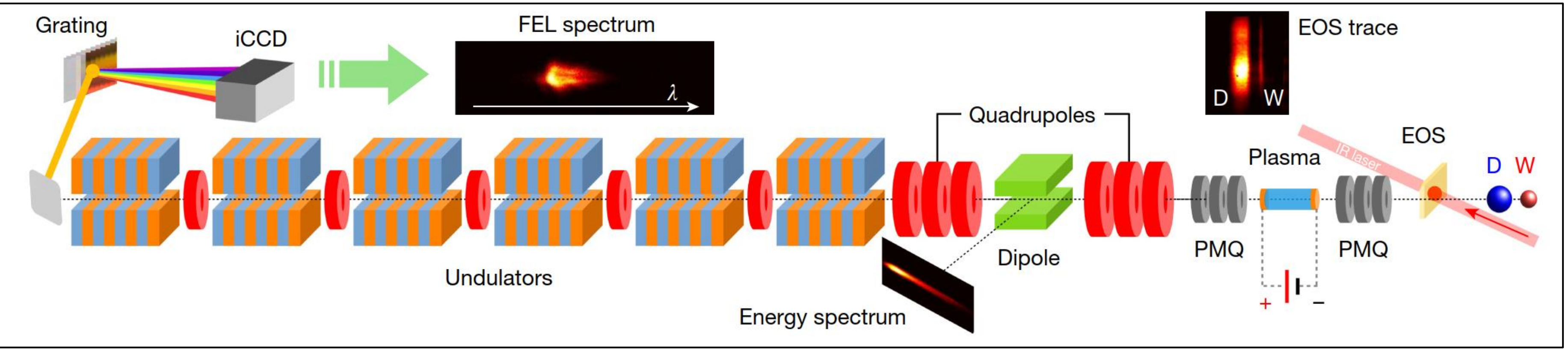
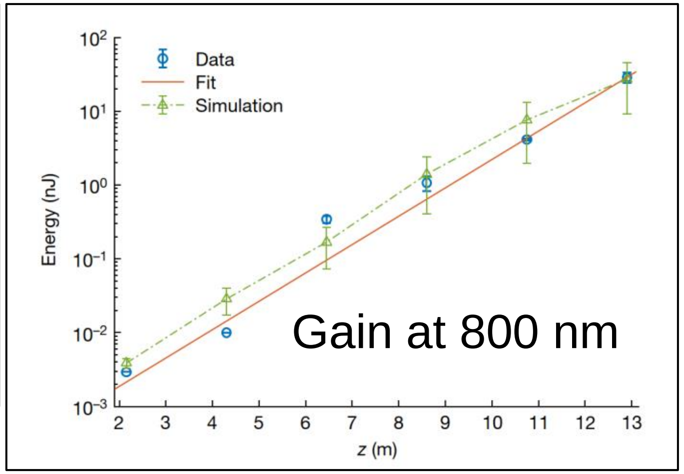
Compact accelerators: Plasma-Accelerator-Based FELs



W. Wang et al., Nature 595, 2021







R. Pompili et al., Nature 2022 (https://doi.org/10.1038/s41586-022-04589-1)

See Maria-Emmanuelle's talk later

Brighter electron beams

- A key requirement for XFEL is high-brightness e-beam.
- Typically, the relative slice e-beam energy spread is much less than the FEL parameter. In this case, the 3D gain length depends critically on transverse brightness defined as

$$B_\perp = \frac{I_e}{4\pi^2 \varepsilon_n^2}$$

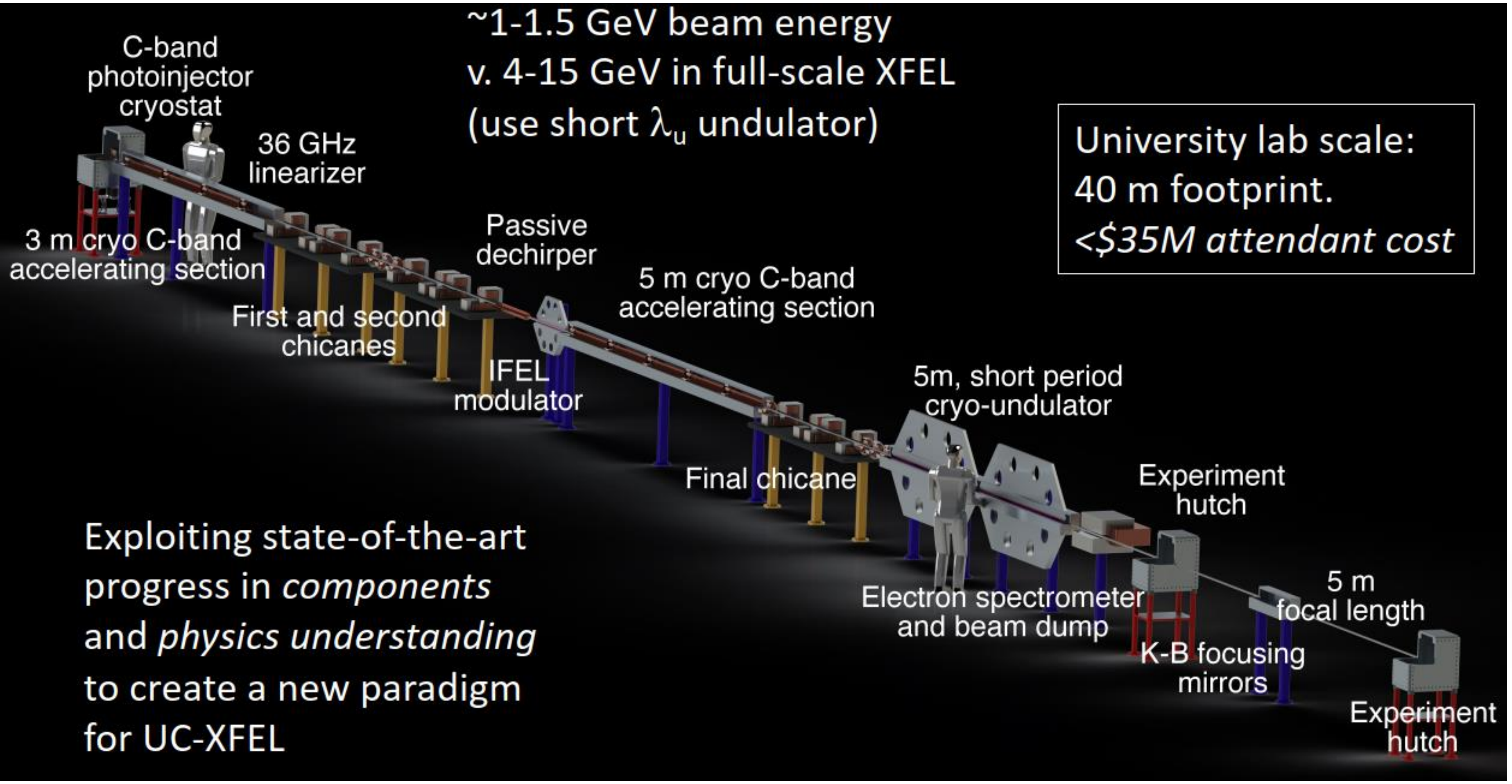
$$L_G = 1.2\left(\frac{I_A}{I}\right)^{1/2} \frac{\varepsilon_n^{5/6}\lambda_u^{5/6}}{\lambda_r^{2/3}} \frac{(1+K_0^2/2)^{1/3}}{K_0[\mathrm{JJ}]} \propto B_\perp^{-1/2}\varepsilon_n^{-1/6}.$$

E. Saldin, Opt. Commun. 235, 415 (2004).
Z. Huang, K.-J. Kim, PRSTAB 10, 034801 (2007)

- Significant payoff to reduce transverse emittance and increase peak current (a big focus of CBB research)

UCXFEL: brighter e-beam source + high-gradient linac

SLAC



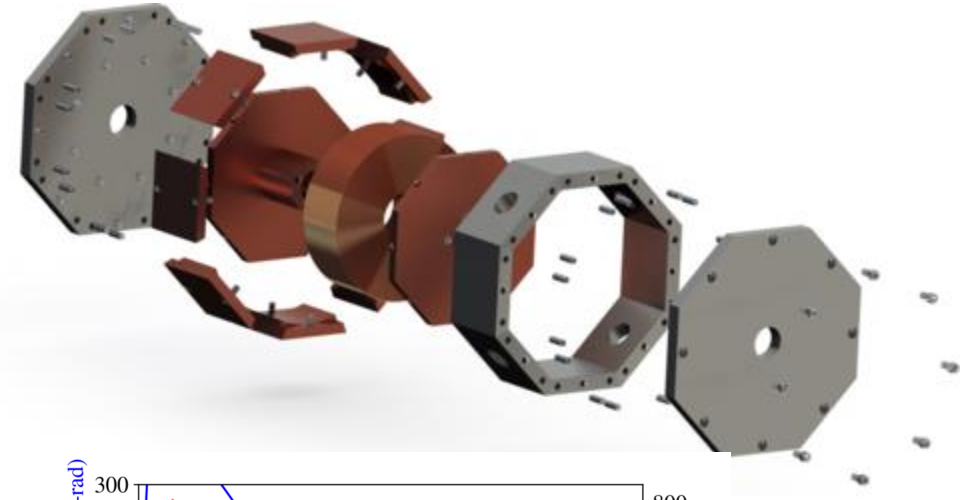
J. Rosenzweig et al., NJP 22, 2020

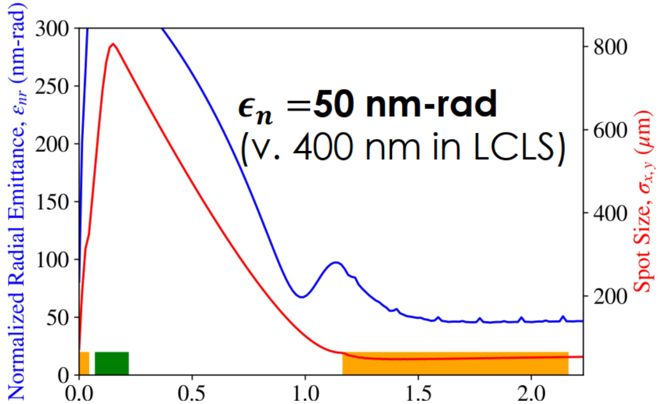
PHYSICAL REVIEW ACCELERATORS AND BEAMS **24**, 063401 (2021)

Versatile, high brightness, cryogenic photoinjector electron source

River R. Robles[*,†], Obed Camacho, Atsushi Fukasawa, Nathan Majernik, and James B. Rosenzweig

Department of Physics and Astronomy, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, California 90095, USA



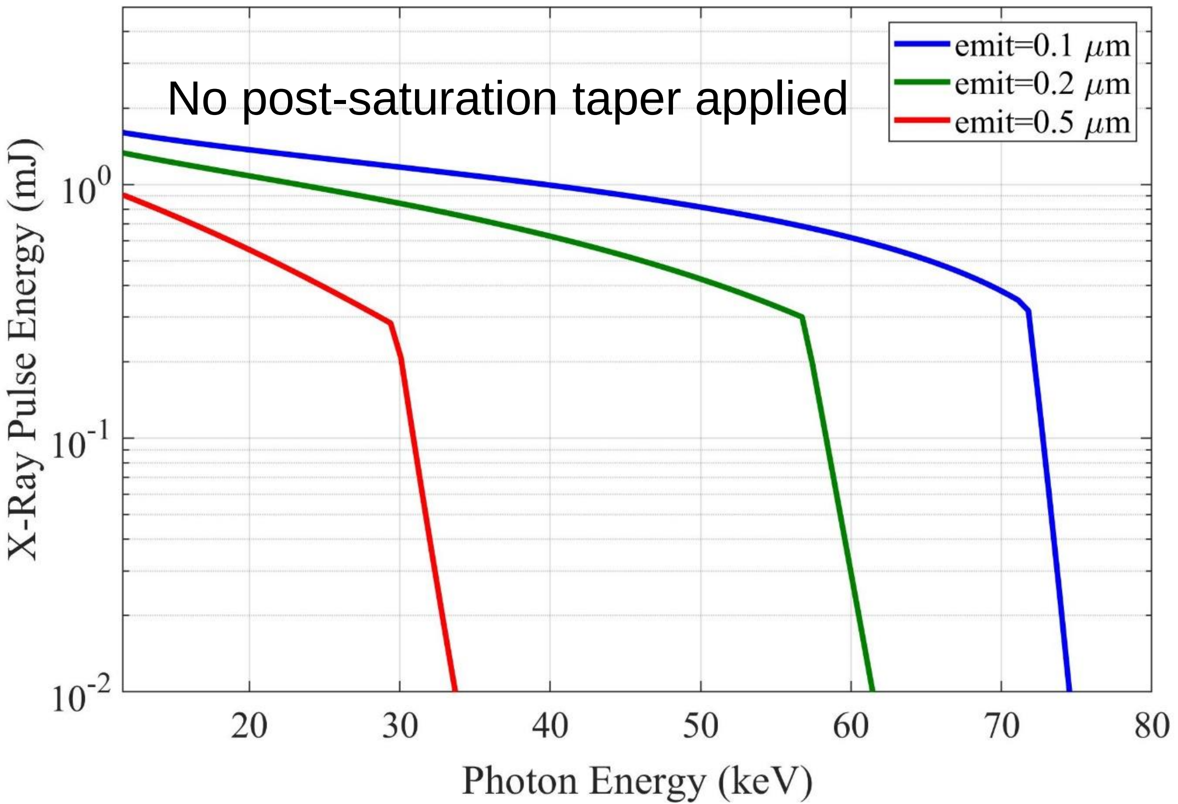


Lower emittance injector + ESASE for current enhancement (see Nathan’s talk later)

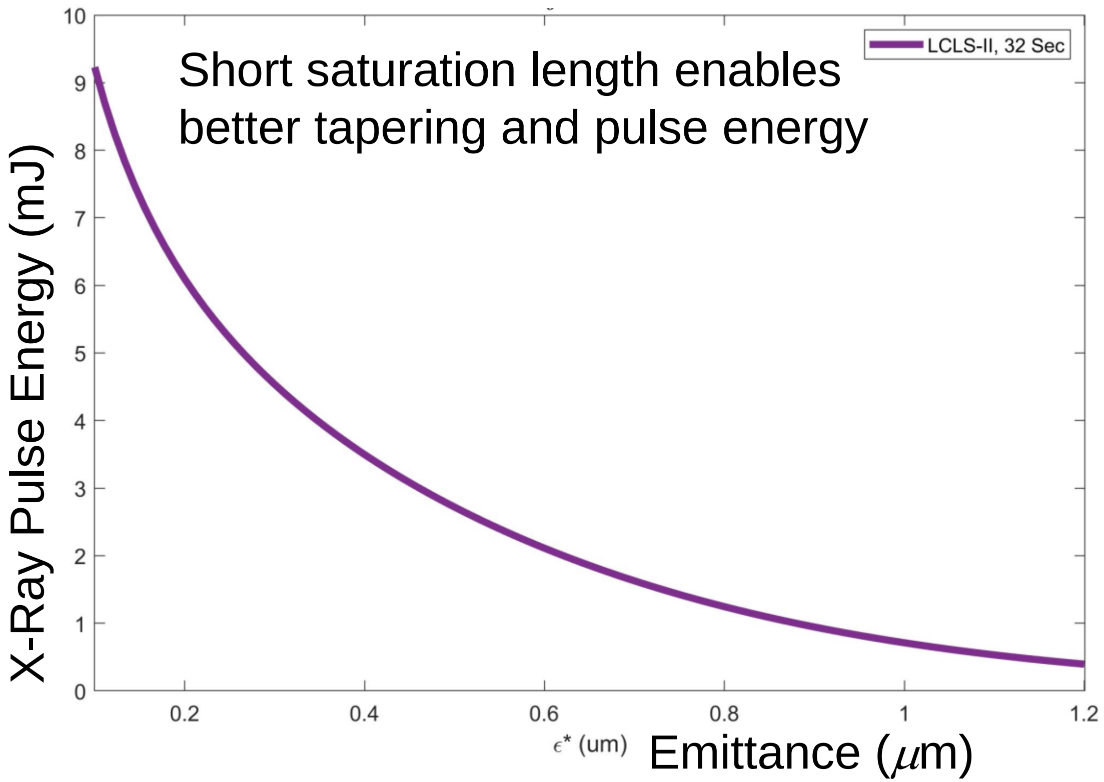
Brighter beam impact on LCLS-II HXR performance

- Assume small emittance can be preserved in LCLS Cu-linac at 0.1 um level
- Such bright beams can expand HXR to >70 keV photons, and/or reduce the gain length sufficiently for strong undulator tapering to increase HXR power

LCLS-II HXR (Cu-linac) (E=15 GeV)

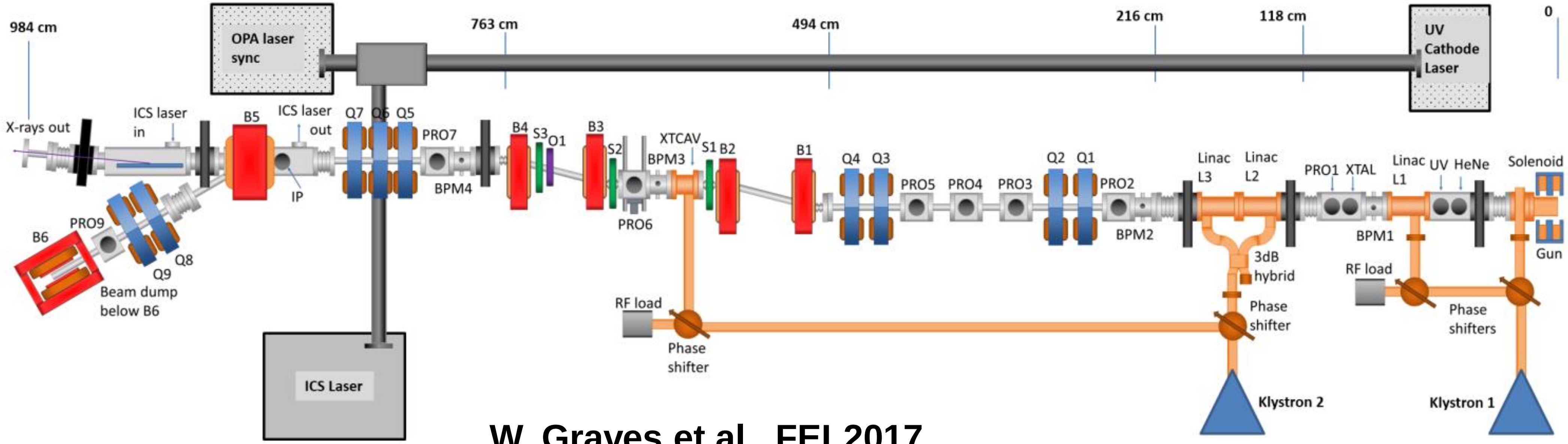


LCLS-II HXR 9 keV (Cu-linac)



Prebunching or beam manipulation: ASU CXFEL

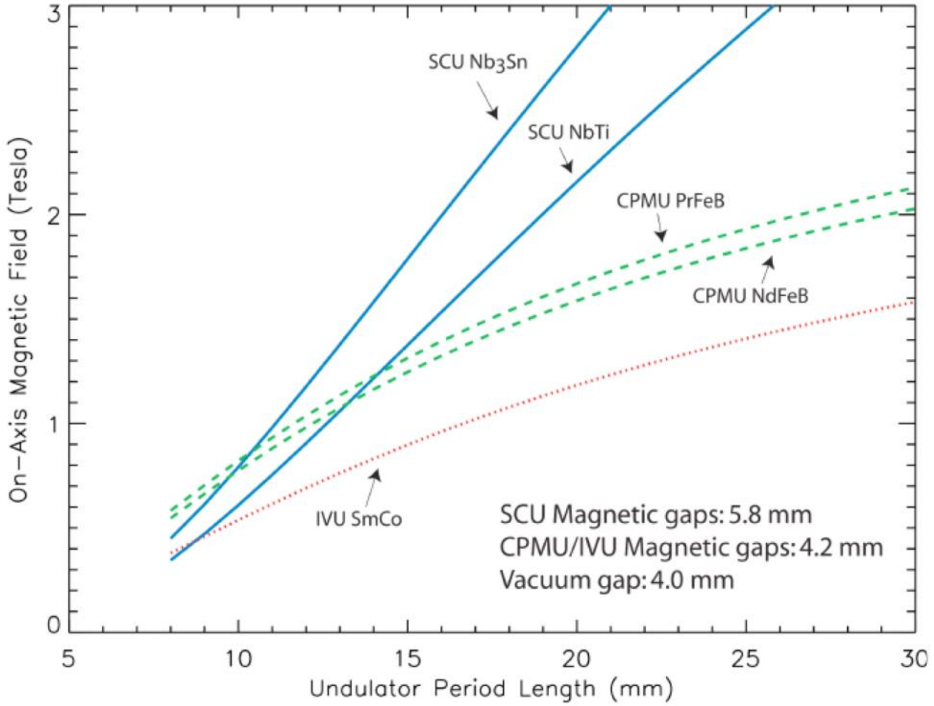
- Prebunching or beam-manipulation: to prepare microbunching in the X-ray or sub-harmonic wavelengths so FEL doesn't start from noise.
- Less undulators necessary and better spectral properties.
- Classical example: HGHG or EEHG (see Luca's talk later)
- A novel example: ASU CXFEL (transverse modulation+EE+ICS)



W. Graves et al., FEL2017

Shorter period undulators

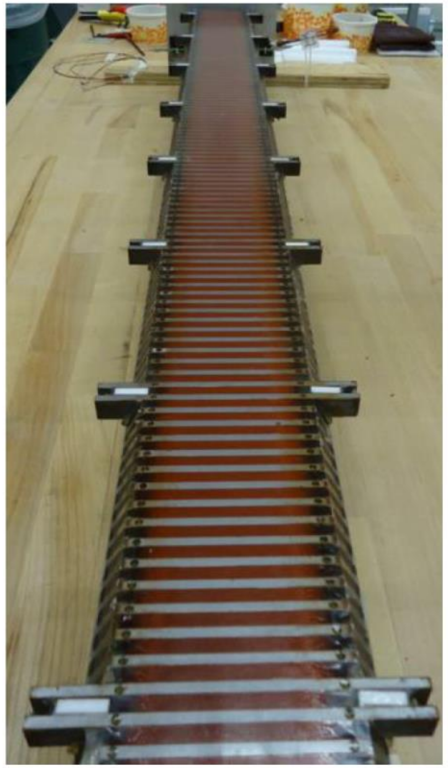
- Lasing at shorter wavelengths (with modest e-beam energy) requires shorter-period undulators



Calculated on-axis magnetic fields of two cryogenic permanent magnet undulators (CPMUs), two superconducting undulators (SCUs) and on in-vacuum undulator (IVU) for a vacuum gap of 4.0 mm for period length from 8 mm to 30 mm.

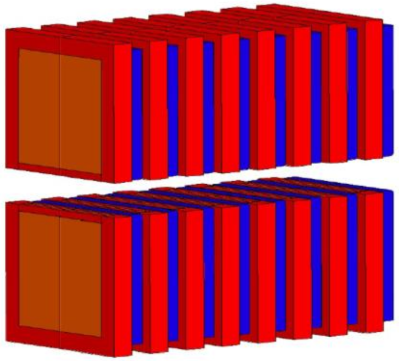
E. Moog, R. Dejus, and S. Sasaki, "Comparison of Achievable Magnetic Fields with Superconducting and Cryogenic Permanent Magnet Undulators – A Comprehensive Study of Computed and Measured Values", ANL/APS/LS-348, 2017.

LCLS prototype SCU

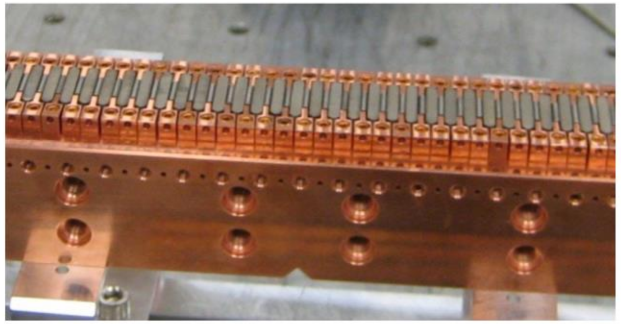


Beam side of magnet core.

Y. Ivanyushenkov et al. (APS)



Hybrid cryo-undulator: Pr-based, SmCo sheath; λ=9 mm up to 2.2 T

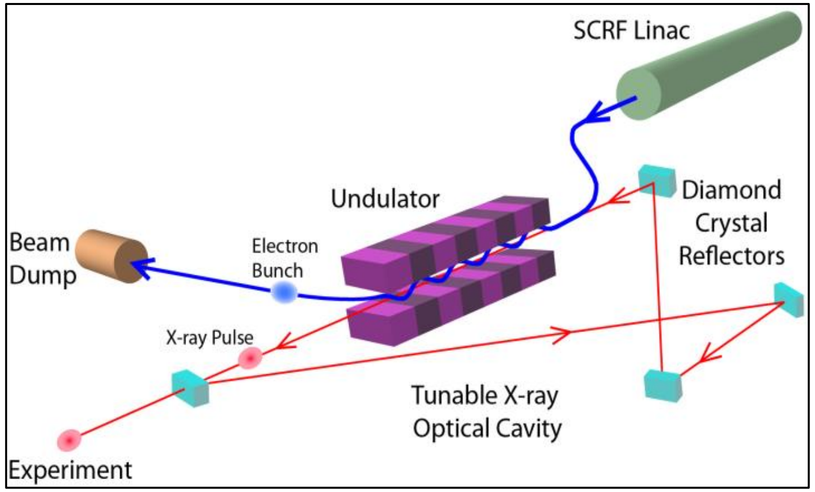


F.H. O'Shea et al, PRSTAB 13, 070702 (2010)

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.
- This Cavity-Based XFEL has the potential to produce highly stable, fully coherent X-ray pulses at a high repetition rate, and hence achieve
  - ➢ 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).



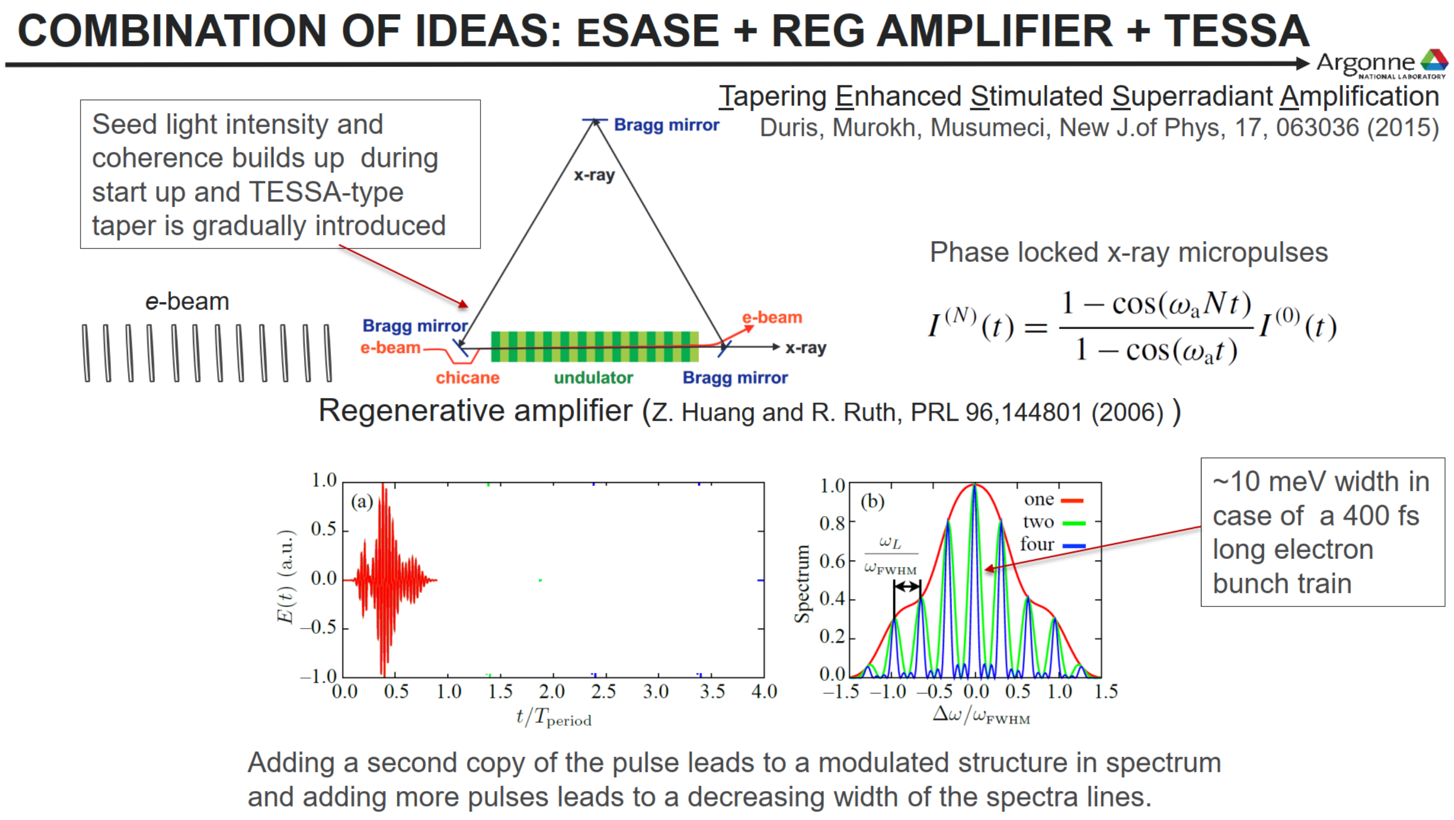
- ANL-SLAC are developing CBXFEL in a phased approach using the LCLS infrastructure.

G. Marcus et al., FEL2019 and IPAC2022

XRAFEL can be used for UCXFEL with multiple bunches

- Single-pass saturation for UCXFEL at Hard X-rays is very challenging.
- With multiple bunches (~10) and a high-gain cavity (XRAFEL), one can have a compact cavity-based XFEL that reaches saturation in 10 passes.

A. Zholents 2019 UCXFEL workshop



Summary

- Large scale XFELs have been very successful, and they will continue to be the brightest femtosecond X-ray sources in the world.
- Compact XFELs have both strong scientific needs and intellectual appeals, and technologies are at our doorsteps.
- Many FEL R&Ds are synergetic for both compact and large XFELs (beam brightness and manipulations, seeding or pre-bunching, shorter-period undulators, Cavity-Based etc…).
- No one-size-fits-all approach, let the thousand flowers bloom!

Thanks all for your attention!