CURRENT STATUS AND FUTURE PROSPECTS OF BRIGHT X-RAY SOURCES

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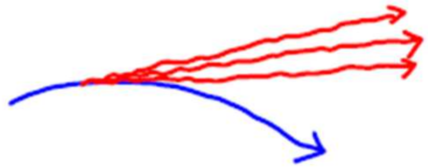
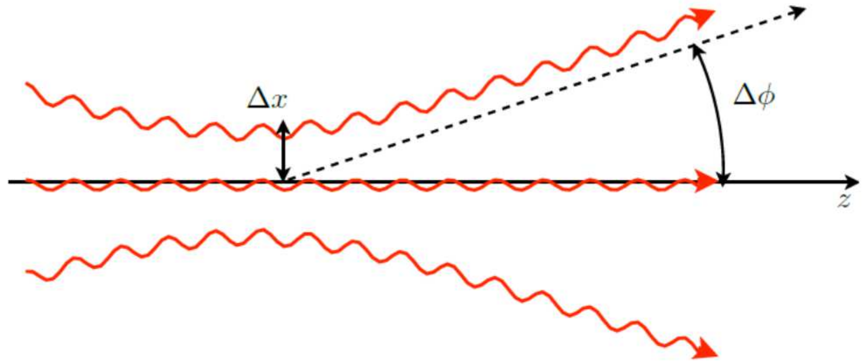
RELATIVISTIC ELECTRONS AND SYNCHROTRON RADIATION

- If an electron with velocity $v \to c$, $\gamma = \frac{1}{\sqrt{1-(v/c)^2}} \to \infty$ makes a curved motion under magnetic field, short wavelength radiation is radiated: $\lambda \sim \rho/\gamma^3$



- # of photons in $\frac{1}{\gamma}$ angle ~$\alpha \simeq 1/137$

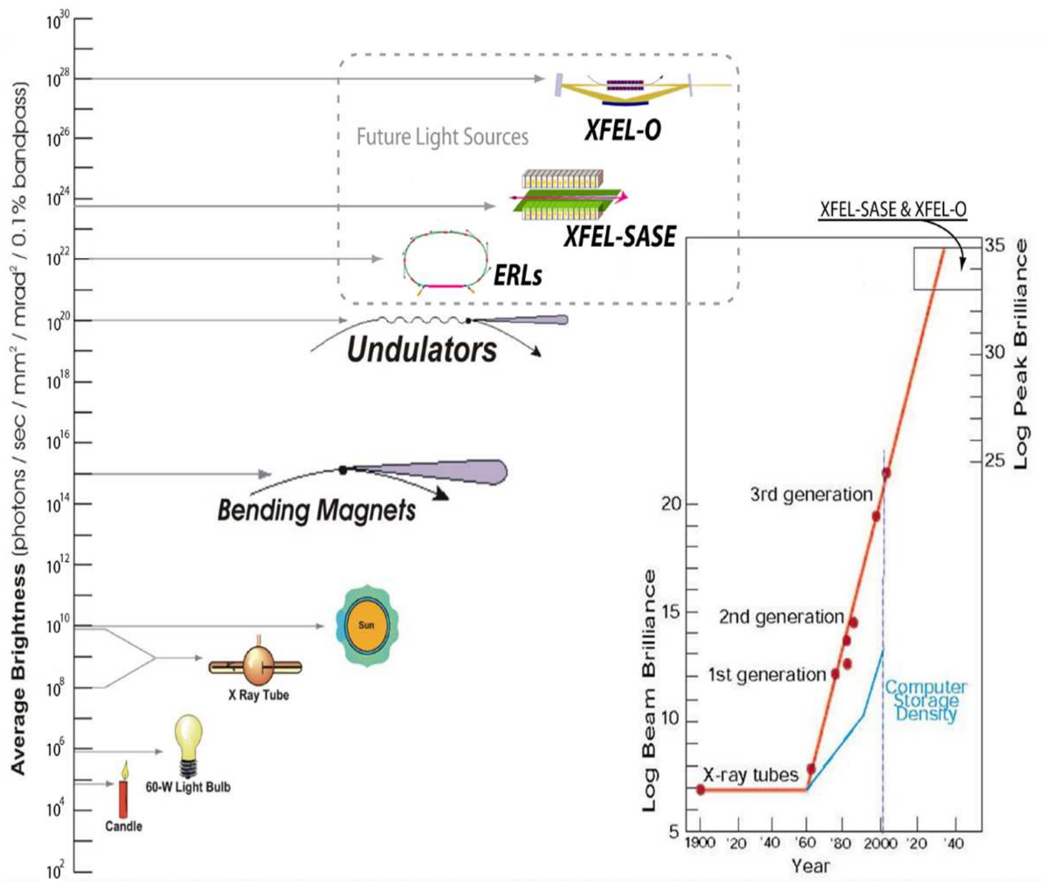
RADIATION (PHOTON) IS USEFUL (BRIGHT) IF THE TRANSVERSE EXTENT IS SMALL & DIRECTIONAL

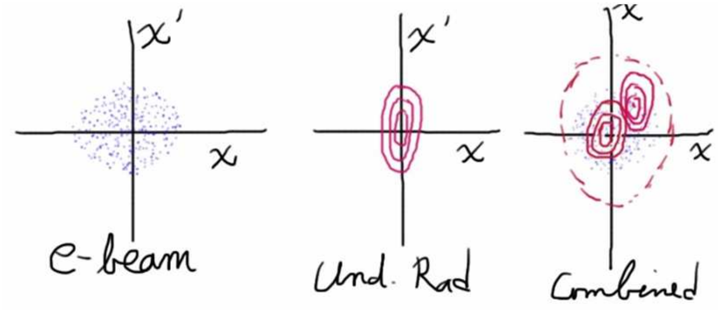


- $\Delta x \cdot \Delta\phi$= phase space area =$\Delta x \cdot \Delta p_x / m\gamma$ *:* Phase space area
- Liouville's theorem in Hamiltonian mechanics: Phase space area is conserved
- Beam physics terminology: $\Delta x \cdot \Delta\theta$ = "emittance" =ε_x
- Brightness= # of photons/$\varepsilon_x \varepsilon_y$. *Real figure of merit since it is conserved*

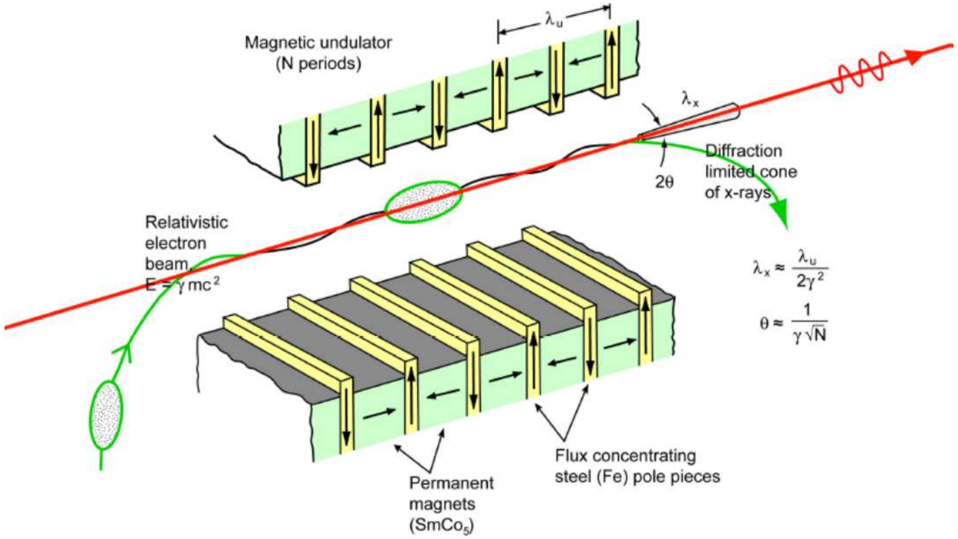
X-RAY BEAM PHASE SPACE IS A CONVOLUTION OF THE RADIATION AND E-BEAM PARTS

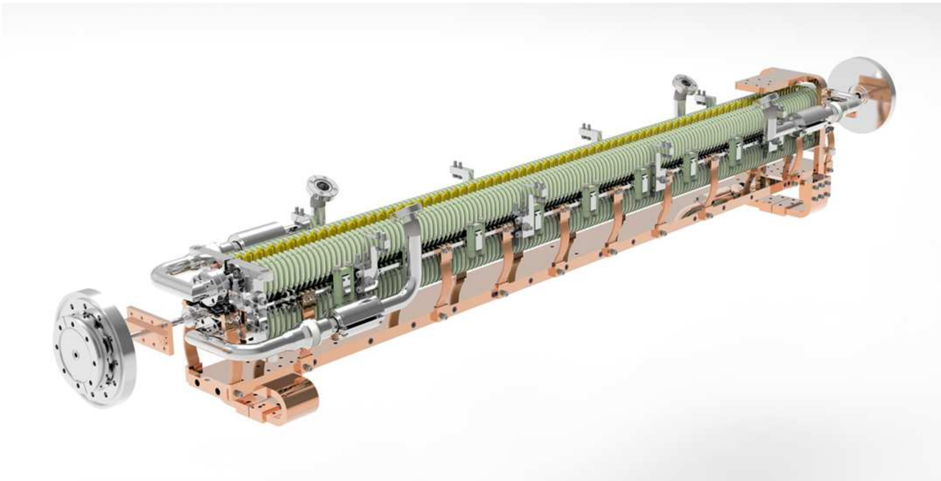
Advance of X-ray beam brightness follows the advance of the electron storage ring performance

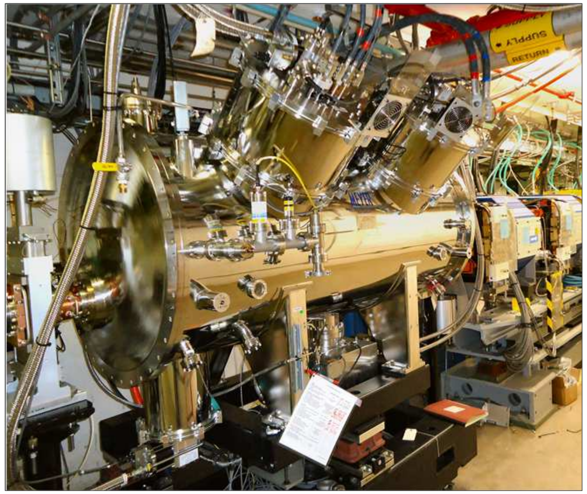




PRODUCING DIRECTED RADIATION (I) UNDULATORS: EM→PM→SC







SCU18-1 in Sector 1 of the APS ring.

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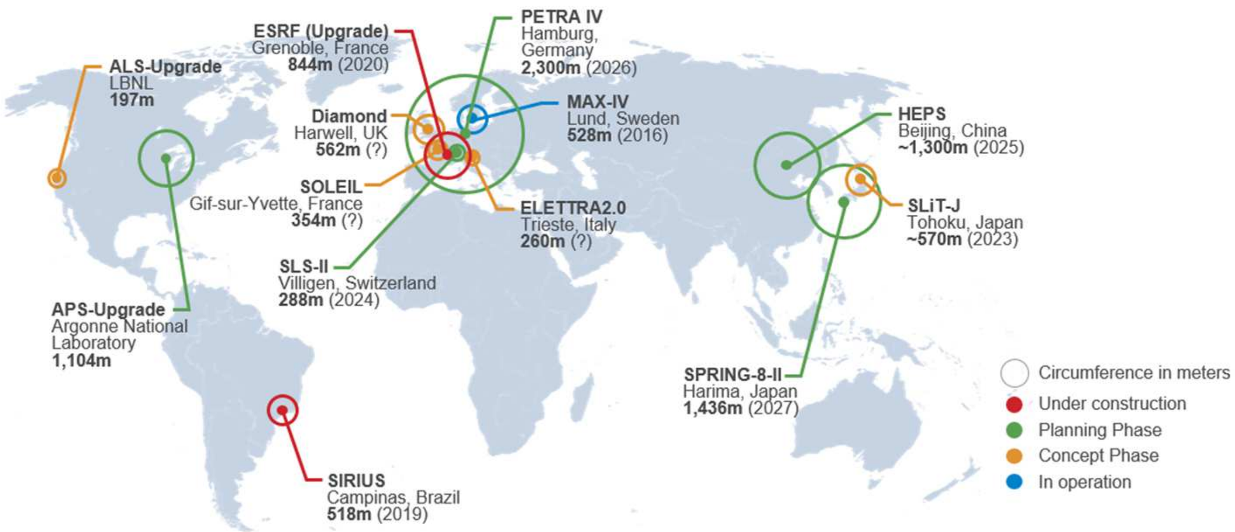
PRODUCING DIRECTED RADIATION (II): REDUCING THE ELECTRON BEAM EMITTANCE

- E-beam emittance is determined from the balance of two effects: damping from the classical nature and diffusion due to the quantum nature (discrete photon effect) of the synchrotron radiation in bending magnets

→ Use a short achromatic bending units

– (N_D = # of dipoles/sector)

- 3rd generation source: N_D = 2,3
- “Diffraction limited storage ring (DLSR)” sources for X-rays: N_D = 7
- Many DLSR projects, new or retrofitting 3rd gen facilities around the world

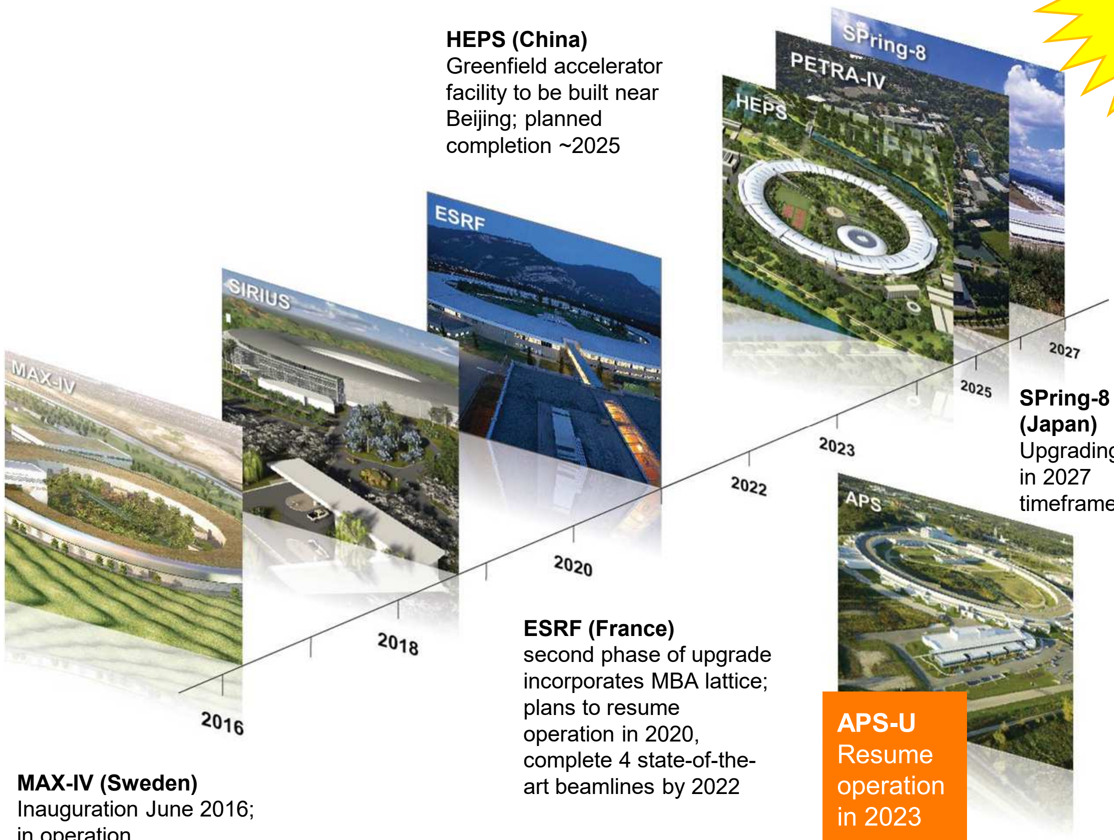


INTERNATIONAL HIGH ENERGY "DIFFRACTION LIMITED (DL) SR DEVELOPMENT

$$\frac{\lambda}{4\pi}$$

Diffraction limited transverse emitance

HEPS (China)
Greenfield accelerator facility to be built near Beijing; planned completion ~2025



SPring-8 (Japan)
Upgrading in 2027 timeframe

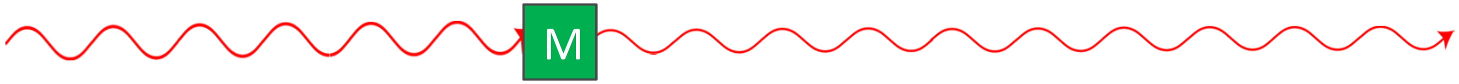
ESRF (France)
second phase of upgrade incorporates MBA lattice; plans to resume operation in 2020, complete 4 state-of-the-art beamlines by 2022

MAX-IV (Sweden)
Inauguration June 2016; in operation

APS-U
Resume operation in 2023

TEMPORAL COHERENCE

- Monochromater improves temporal coherence :$\Delta\omega \rightarrow \Delta\omega_M << \Delta\omega$,

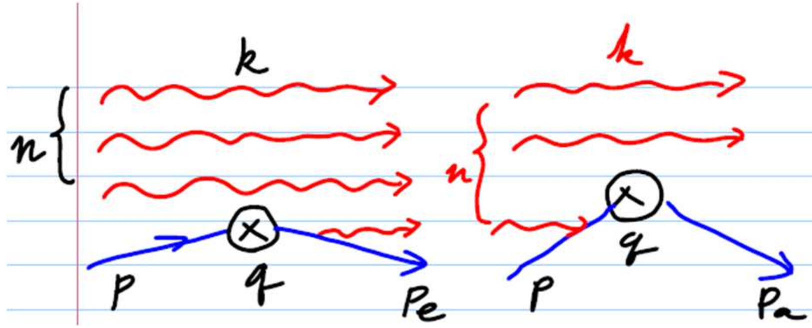


- If e-beam bunch length >> wavelength →the intensity of wave-trains adds incoherently ~N_e

- The amplitudes add in phase if $\Delta z_{el} << \lambda_1$ *or if* electrons are concentrated at positions z =$n\lambda_1$, n=1,2,.. **Intensity~N_e^2**

- This happens in free-electron laser

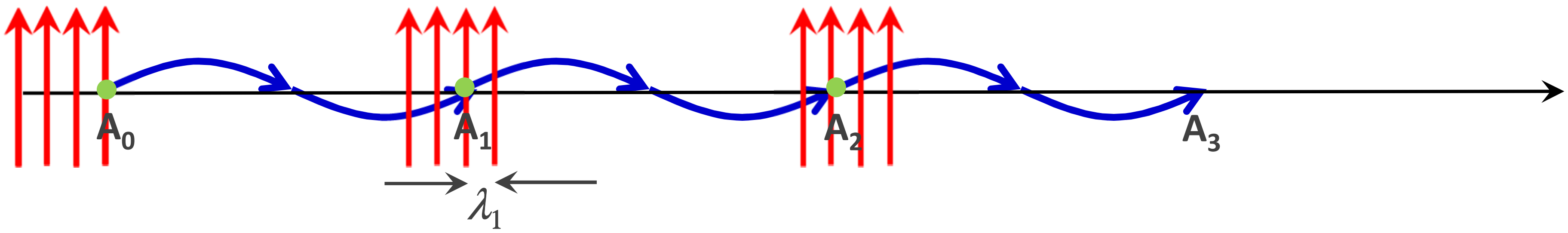
FREE ELECTRON LASER IS A LASER



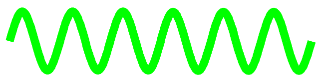
- For every spontaneous process, there exists stimulated emission
- In the presence of *n* coherent modes, the emission probability $\propto n+1$ while absorption probability $\propto n$ → light amplification
  – J. Weber (1951), Maiman, Townes, Shawlow, Basov, Porkhorov,..
- Free electron laser—the emission process involves “free electrons” in an undulator magnetic field rather than bound electrons in atoms or molecules
  – John Madey (1971)
- In the limit of low photon energy, drops out → classical interpretation

Classical View of a Free Electron laser

- When the EM wavelength satisfies the undulator condition, an electron sees the same EM field in the successive period→ sustained energy exchange



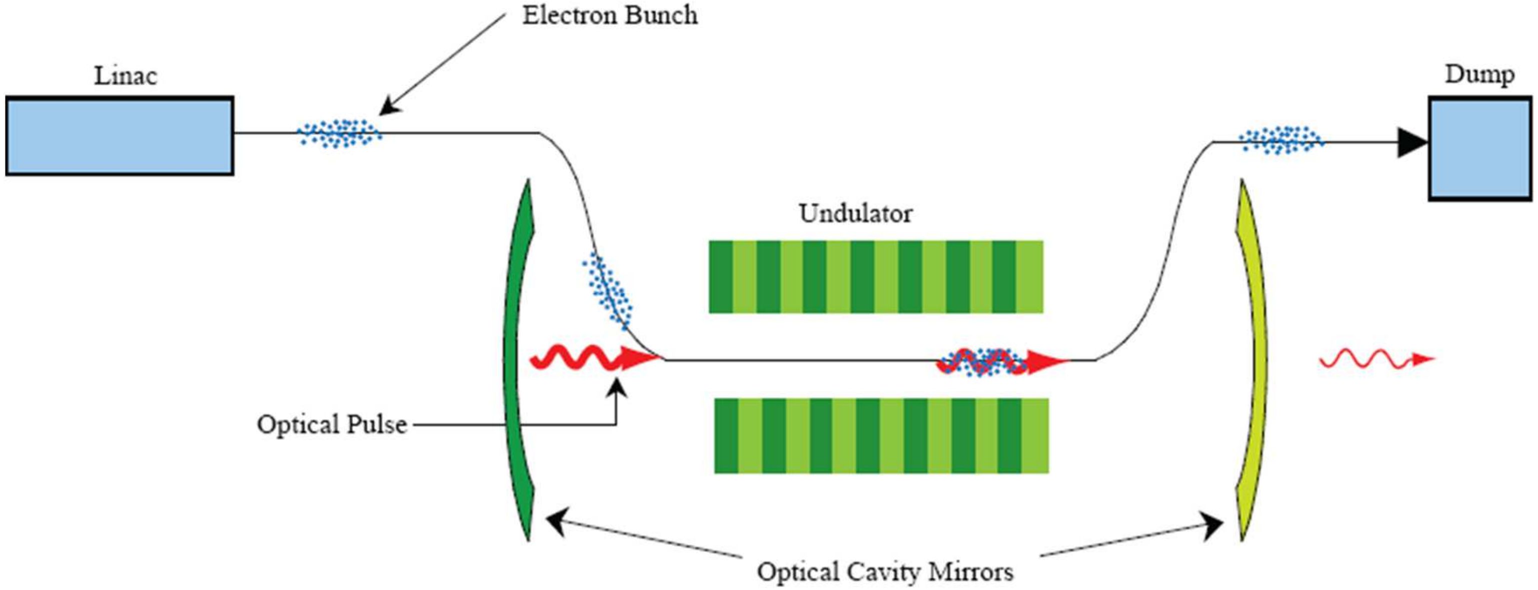
- An e^- arriving at A_0 loses energy to the field (ev E <0). Similarly the e^- at distance $n\lambda_1$, n=1,2,… also loses energy. However, those at $\lambda_1(1/2+n)$ away gain energy.
- The electron beam develops energy modulation (period length λ_1).



- Higher energy electrons are faster → density modulation develops

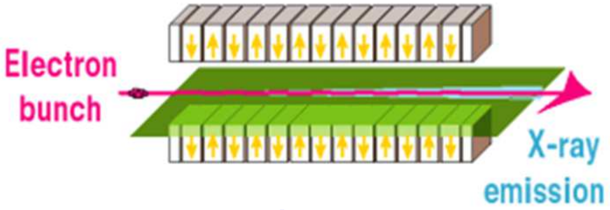
- Coherent EM of wavelength λ_1 is generated→ "Free electron laser"

CHALLENGES FOR X-RAY FELS

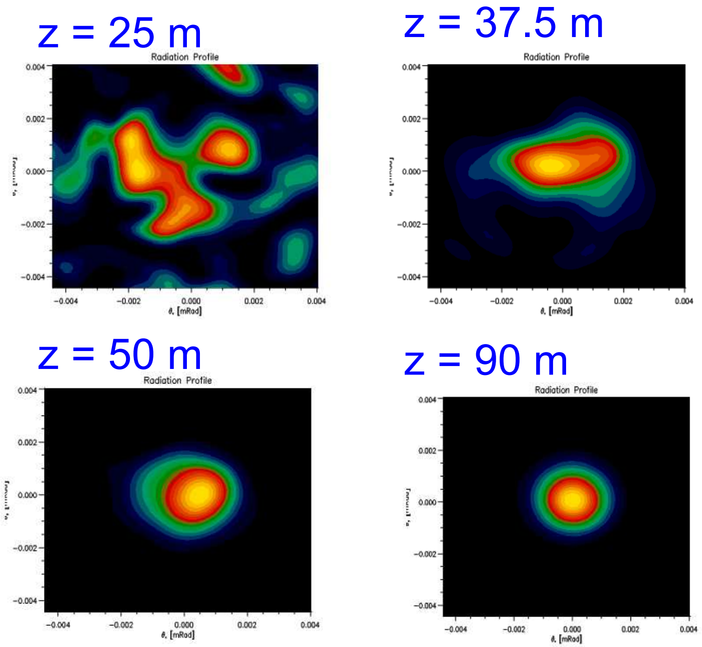


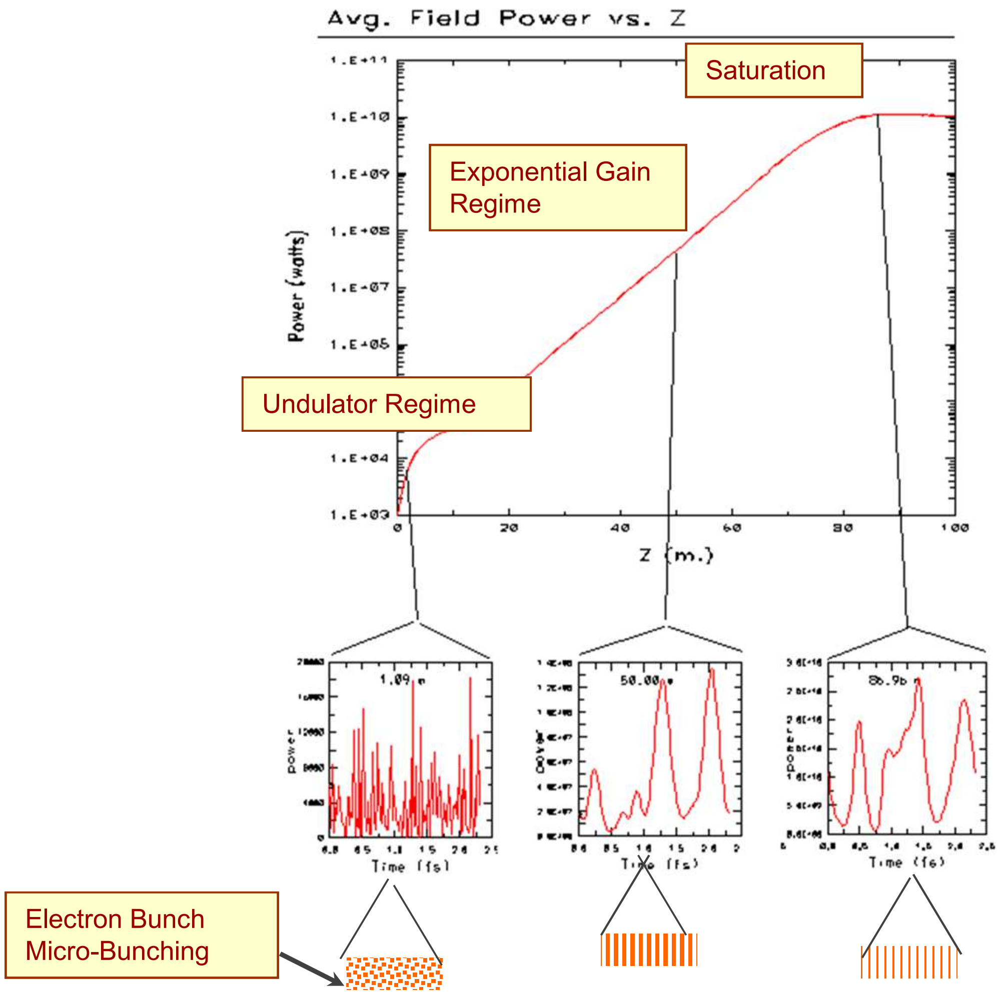
- **X-rays are difficult to reflect→ Low-gain oscillators are difficult**
  - Make a single pass, high-gain ($\sim 10^6$) device for **self-amplified spontaneous emission (SASE)** for intense, **quasi-coherent** X-rays
  - The required e-beam can be produced from an RF photo-cathode gun, compression, and acceleration
- **Use Bragg reflector (diamond)→ XFELO** producing **fully coherent X-rays**

X-ray FEL solution I :Initial noise is amplified to intense, quasi-coherent radiation (SASE)

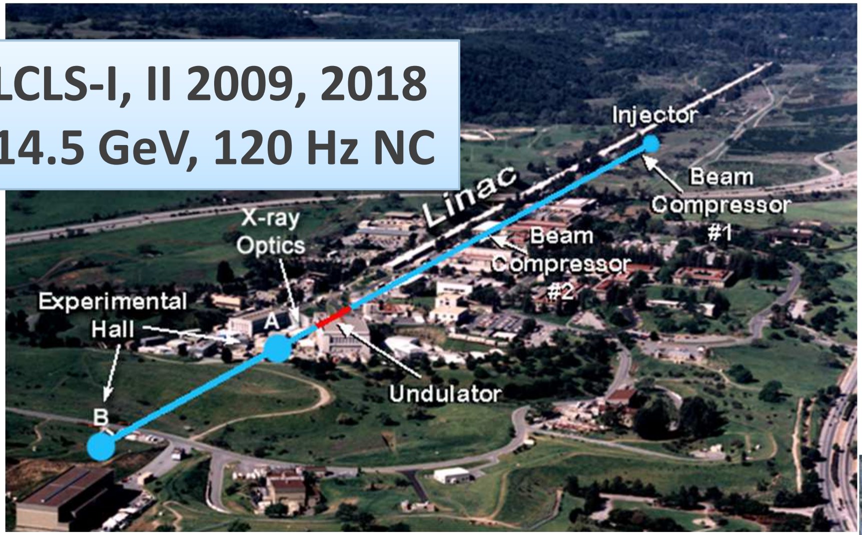


Transverse mode



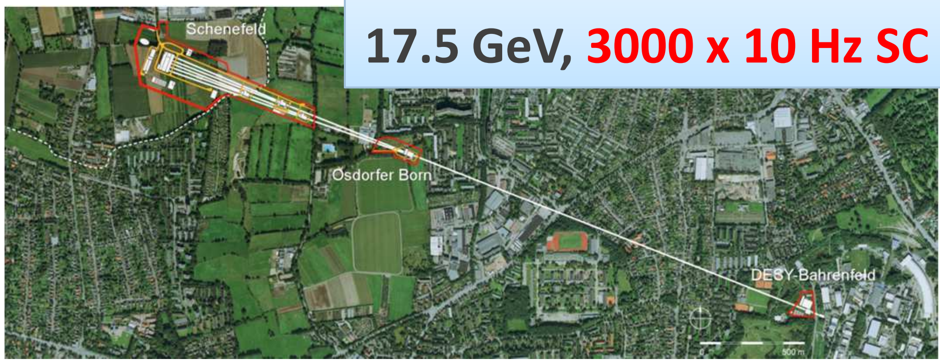


Hard X-Ray FELs Operating in 2017



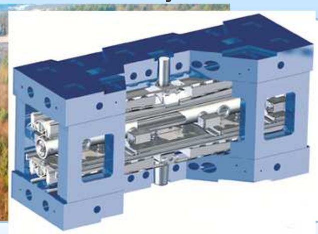
LCLS-I, II 2009, 2018
14.5 GeV, 120 Hz NC

SACLA 2011
8.5 GeV, 60 Hz NC



XFEL 2017
17.5 GeV, 3000 x 10 Hz SC

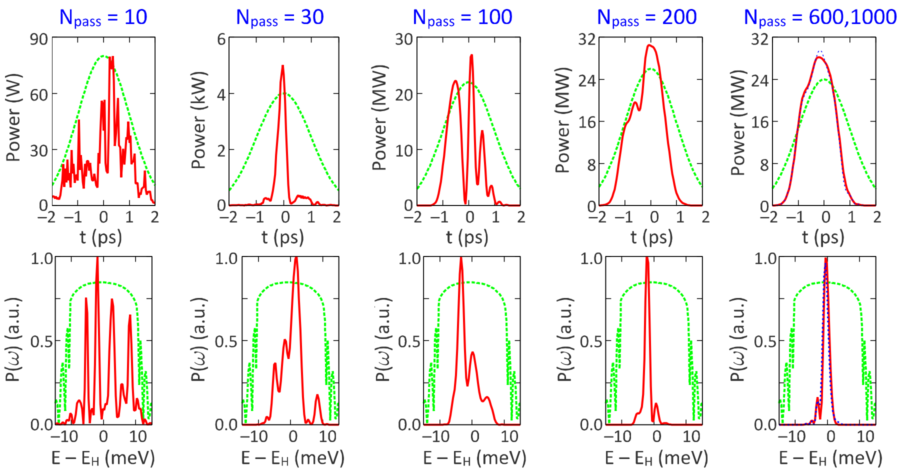
PAL XFEL 2017
10 GeV, 60 Hz NC

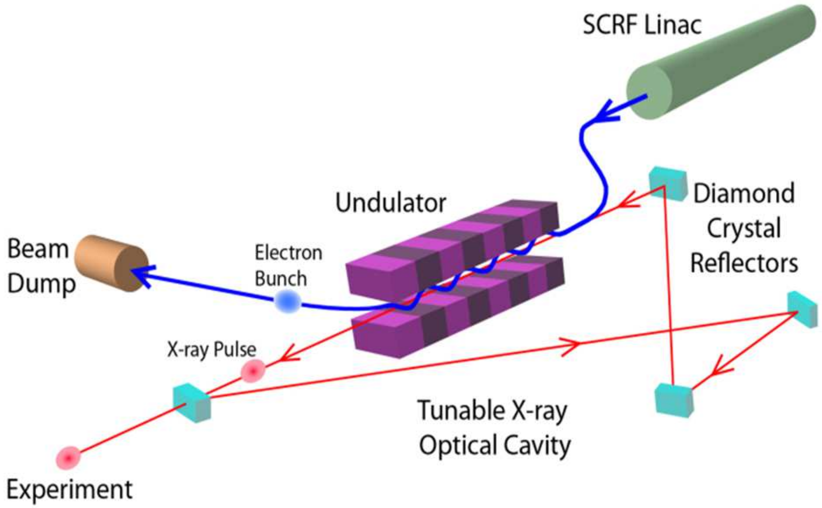


λ_U=15mm
K=1.2
G=4.5 mm

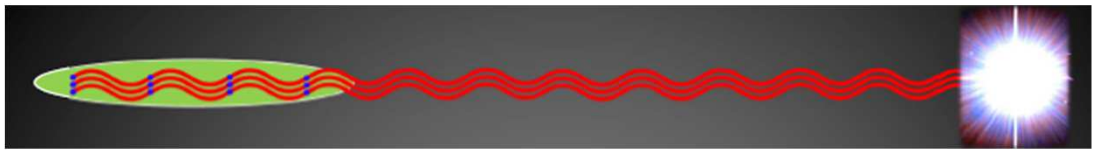
SWISS FEL 2017
5.8 GeV, 100 Hz NC

X-RAY FEL SOLUTION II: FEL OSCILLATOR BY USING BRAGG REFLECTORS





- First proposed by R. Collela and A. Luccio (1983)
- Revived by KJK, Y. Shvyd'ko, S. Reiche (2008) spurred by the ERL development
- Will provide ultra-narrow BW (a few meV) and full coherence
- *Real X-ray laser!!*

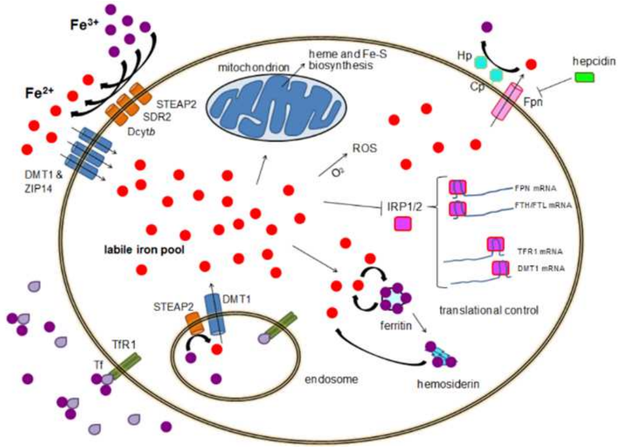


A SHORT LESSON IN KOREAN AND CHINESE

- Je (제, 齊)– ordered, coherent
- Kwang (광, 光)--light
- Kwang-Je → *Coherent Radiation*

According to Yuan T. Lee

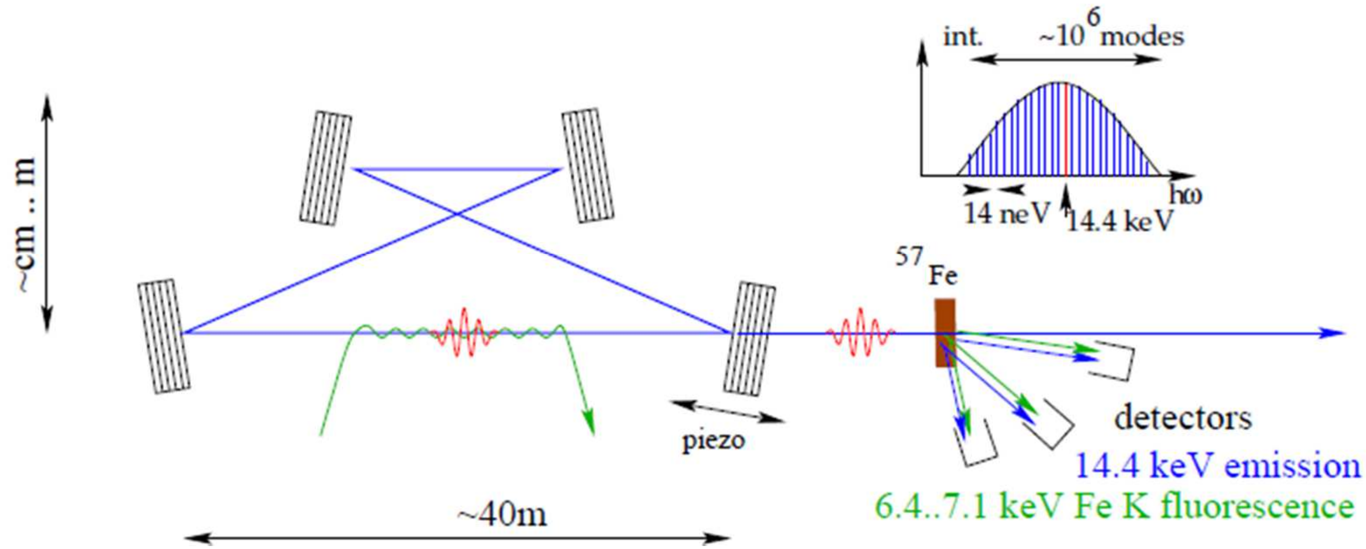
SCIENCES WITH XFELO



- **Enhanced application of techniques developed at 3GSR sources**
  - IXS, XPCS, NRS→ higher resolution, smaller volume,.
  - Deep-earth core material, strongly correlated system,..
- **Techniques in infancy at current sources**
  - Coherent control with X-rays, X-ray NLO,..
  - Practical applications of NRS, such as study of red cells without enriching the excited states of Fe
- **Emergence of new areas**
  - Nuclear quantum optics, entangled state
  - X-ray spectral comb→ 10 orders of magnitude improvement in precision atomic spectroscopy (QED test), quantum optics of nuclear states

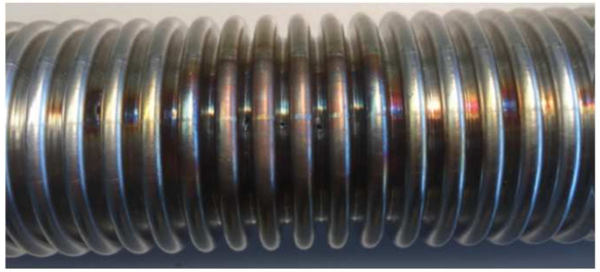
Nuclear-resonance-stabilized XFELO(B.W. Adams and K.-J. Kim, 2015, PRSTAB)

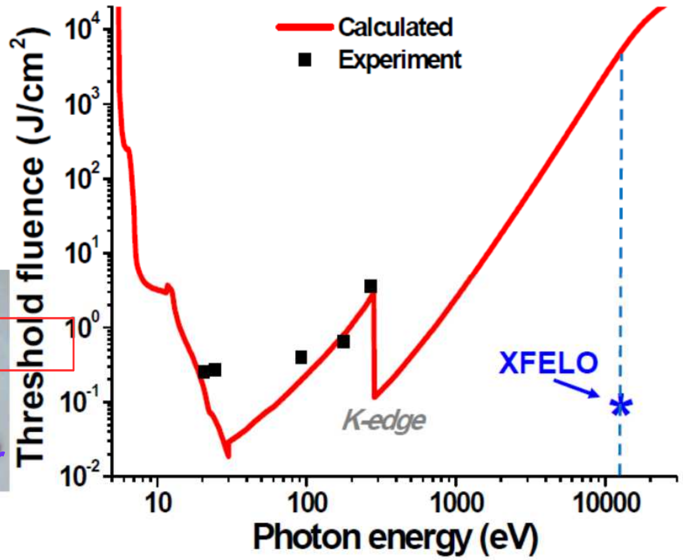
- **The XFEL-O output pulses are copies of the same circulating intra-cavity pulse → By stabilizing cavity length to a fraction of λ, the spectrum of XFELO output becomes a comb**
- **The extreme-stabilized XFEL-O will**
  - **establish an x-ray-based length standard**
  - **Revolutionize the quantum optics of nuclear states**
  - **have applications in fundamental physics such as x-ray Ramsey interf**

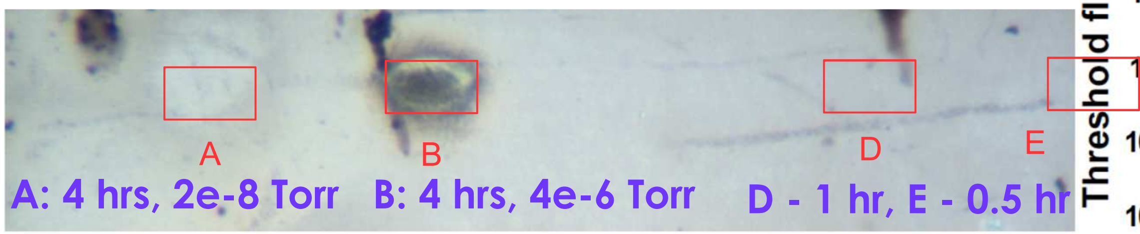


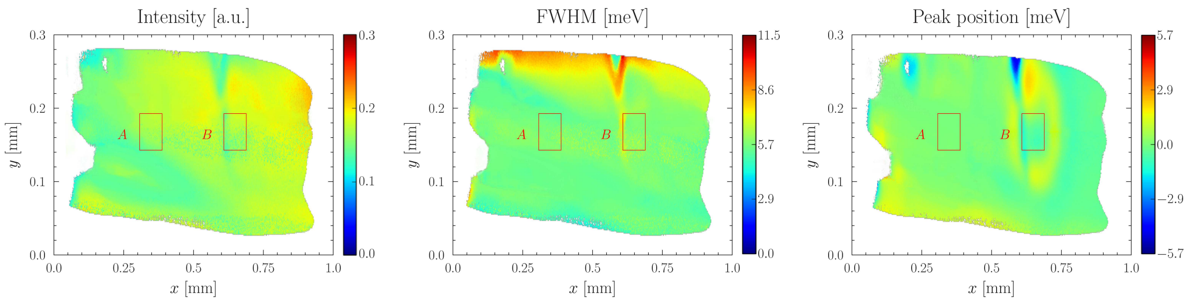
TEST FOR DIAMOND ENDURANCE @ X-RAY POWER DENSITY 10-20 KW/MM^2 T. KOLODZIEJ, ET AL (JSR 2018)

- Steel will melt in < mili-seconds
- Irradiation up to 4 hours at APS
  - **9 kW/mm^2** in 30x120 μm^2 spots (K-B mirror focusing) under medium vacuum
  - **12.5 kW/mm^2** in 30x40 μm^2 spots (Be-CRL focusing) under UHV (~10^{-8})

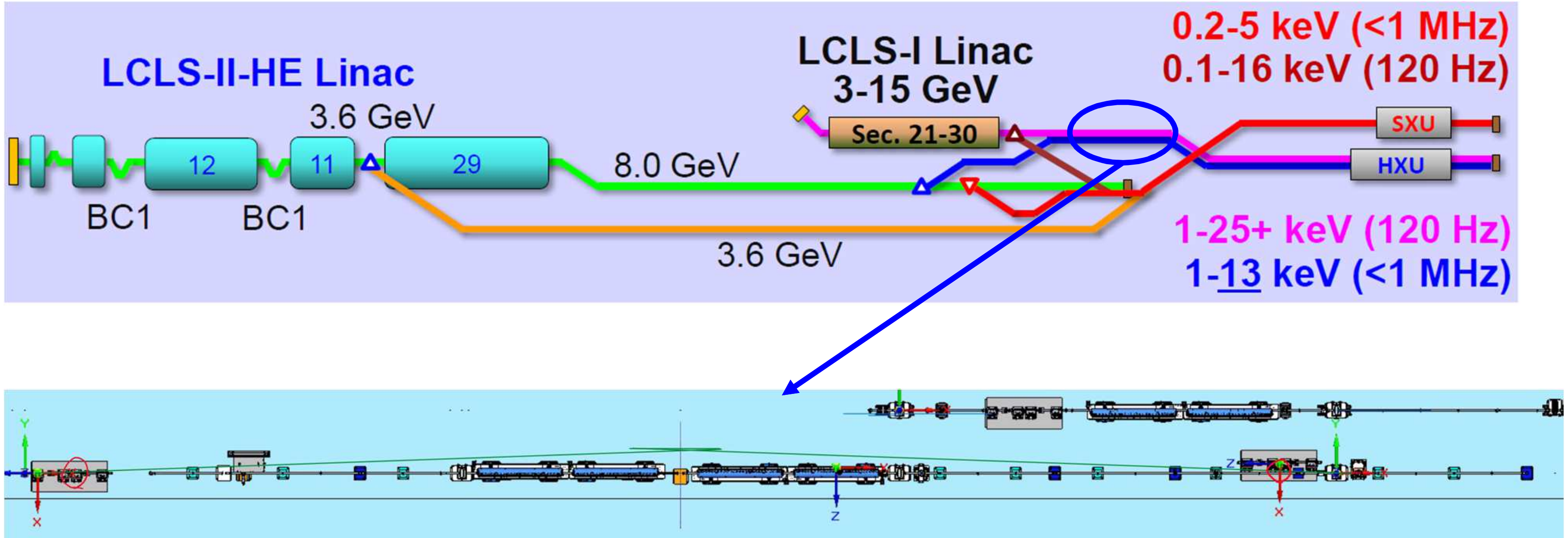






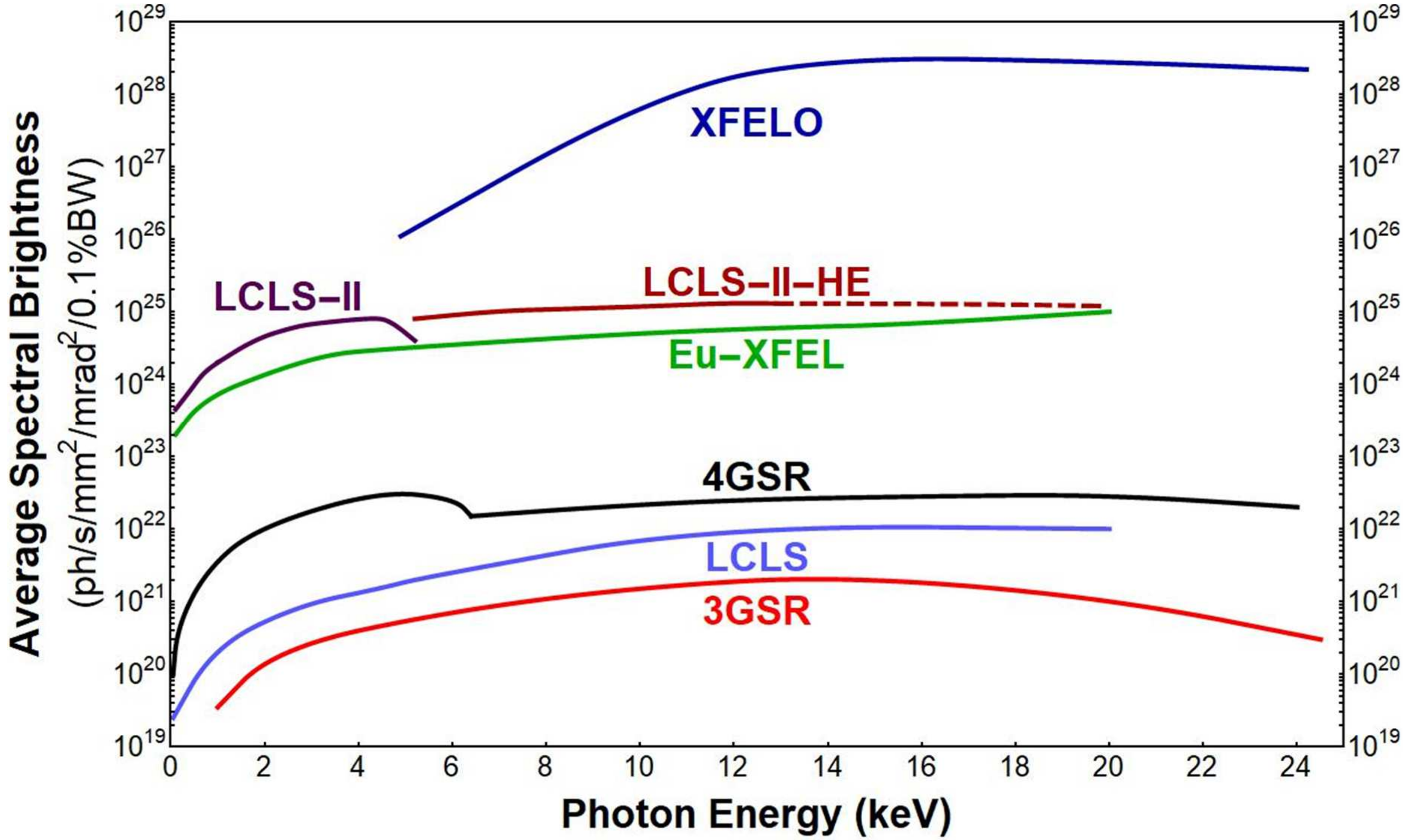


XFELO TEST EXPERIMENT AT LTU, LCLS BEING PLANED FOR 2019-21



- Use four LCLS undulator units (4x3.4 m)
- Begin with the 120 Hz LCLS linac, but produce a pair of bunches separated by the X-ray cavity round trip time
- The first bunch produce X-ray pulse, and the second pulse amplify
- When the LCLS II SCRF linac available, attempt a steady state operation

AVERAGE BRIGHTNESS OF VARIOUS SOURCES



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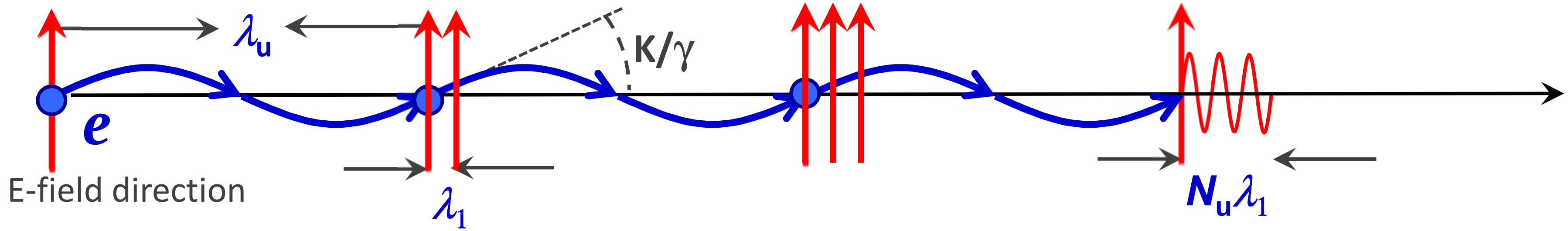
SUMMARY

- **We have reviewed the development of high-brightness X-ray generation techniques:**
- **Storage ring-based:**
  - **2^{nd} and 3^{rd} generation SR sources**
  - **DLSR in near future**
- **Linac-based high-gain FELs producing quasi-coherent, femto-second SASE pulses**
  - **Mostly low rep rate XFELs using pulsed linac in the past and current**
  - **High rep rate, even CW MHz, current and future**
  - **Femto-/ atto- second dynamics**
- **X-ray FEL oscillator producing fully coherent X-rays in the future**
  - **Ultra-narrow BW applications**

BACK UP SLIDES

Radiation by one electron in N_u period undulator

- The e^- emits EM wave in the forward direction due to its x-acceleration. Consider the wave fronts from successive undulator periods:

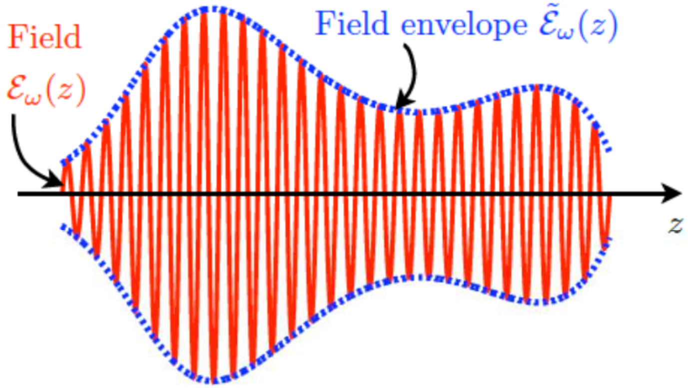


- The e^- is slower since (1) $c > v$ c(1-1/2γ^2), and (2) its trajectory is curved. Thus, the EM wave slips ahead of the e^- in one undulator period by a distance λ_1=wavelength:

  $\lambda_1=\lambda_u(1+K^2/2)/2\gamma^2$, ε_1[keV]=12.4/λ_1[Å]

- N_u periods of the undulator → N_u cycle wave-train

MINIMUM RADIATION EMITTANCE



$$\mathcal{E}_\omega(\boldsymbol{\phi}; z) = \frac{1}{\lambda^2} \int d\boldsymbol{x}\, e^{-ik\boldsymbol{\phi}\cdot\boldsymbol{x}} E_\omega(\boldsymbol{x}; z)$$

$$E_\omega(\boldsymbol{x}; z) = \int d\boldsymbol{\phi}\, e^{ik\boldsymbol{\phi}\cdot\boldsymbol{x}} \mathcal{E}_\omega(\boldsymbol{\phi}; z).$$

$$E(x;0) = E_0 \exp\left(-\frac{x^2}{4\sigma_r^2}\right) \qquad \mathcal{E}(\phi;0) = \mathcal{E}_0 \exp\left(-\frac{\phi^2}{4\sigma_{r'}^2}\right)$$

$$\sigma_r^2(z) = \langle \boldsymbol{x}^2 \rangle = \frac{\int d\boldsymbol{x}\, \boldsymbol{x}^2 \,|E_\omega(\boldsymbol{x};z)|^2}{\int d\boldsymbol{x}\, |E_\omega(\boldsymbol{x};z)|^2} \qquad \sigma_{r'}^2(z) = \langle \boldsymbol{\phi}^2 \rangle = \frac{\int d\boldsymbol{\phi}\, \boldsymbol{\phi}^2 \,|\mathcal{E}_\omega(\boldsymbol{\phi};z)|^2}{\int d\boldsymbol{\phi}\, |\mathcal{E}_\omega(\boldsymbol{\phi};z)|^2}$$

Minimum emittance Radiation emittance for Gaussian amplitude profile

$$\sigma_r \sigma_{r'} = \frac{\lambda}{4\pi} \equiv \varepsilon_r.$$