Challenges of 4th Generation Accelerator-Based Light Sources

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Outline

- Motivations to Accelerator-Based Light Sources
- Storage Ring Light Sources
  - The Challenge of Brilliance
- Free-Electron Lasers
  - The Challenge of Coherence
- Outlook & Conclusions

Why do we *need X-rays* ?

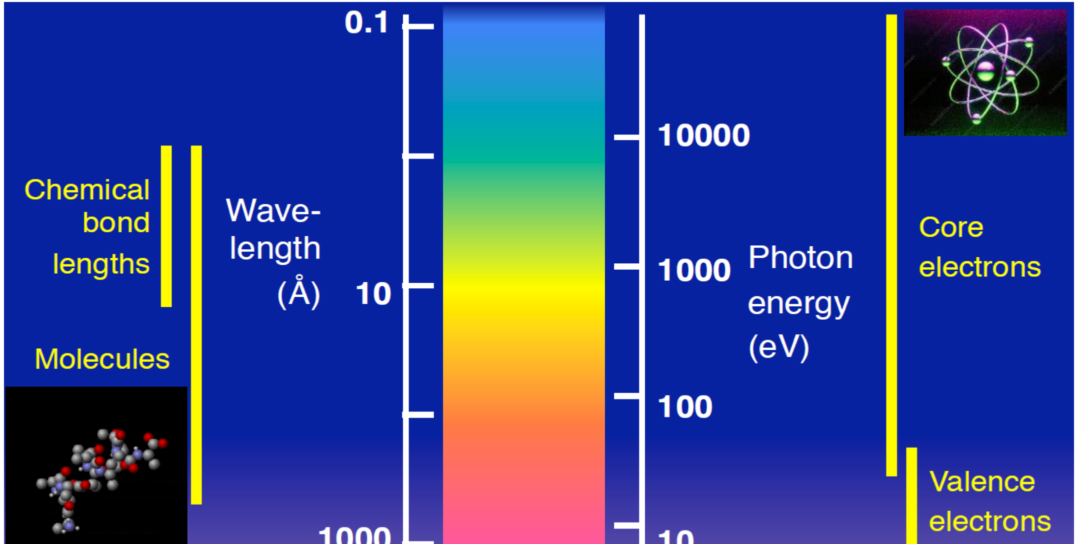
photon energy ~ spatial resolution

$$\begin{cases} \Delta z \cdot \Delta p \geq \frac{h}{2} \\ p = \frac{h}{\lambda} \end{cases}$$

W. Heisenberg

L. De Broglie

$$\lambda \leq \Delta z$$
$$\Delta\lambda/\lambda \ll 1$$



EUV and X-rays are ideal probes of chemical bonds, where most of science is rooted. They can be used to look “through the looking-glass”, i.e., to visualize proteins, molecular dynamics, orbitals…

How do we *generate and use* X-rays ?

$$P_{SR} \propto \frac{\gamma^4}{R^2} \propto \frac{E^2 B_y^2}{m_0^4}$$

- High energy electrons
- Strong magnetic field

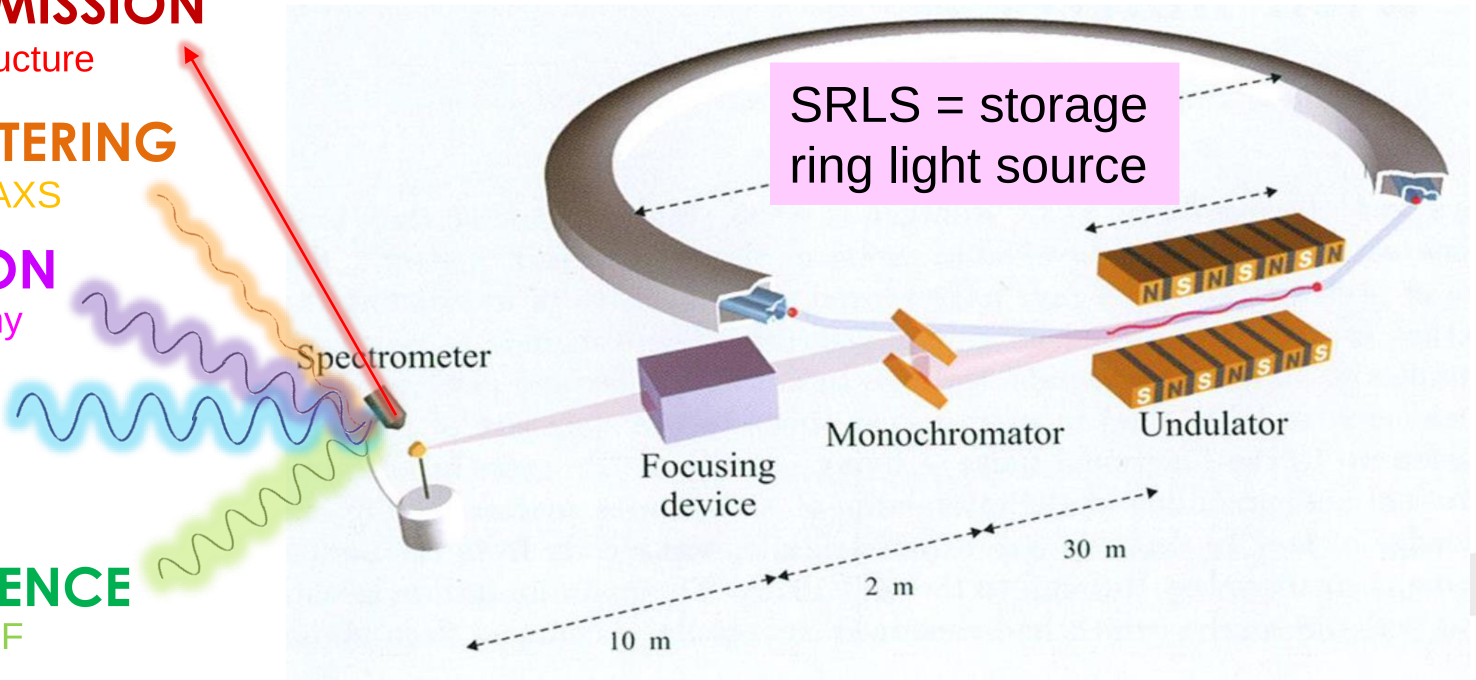
e- PHOTO-EMISSION
electronic structure

SCATTERING
SAXS

DIFFRACTION
Cristallography

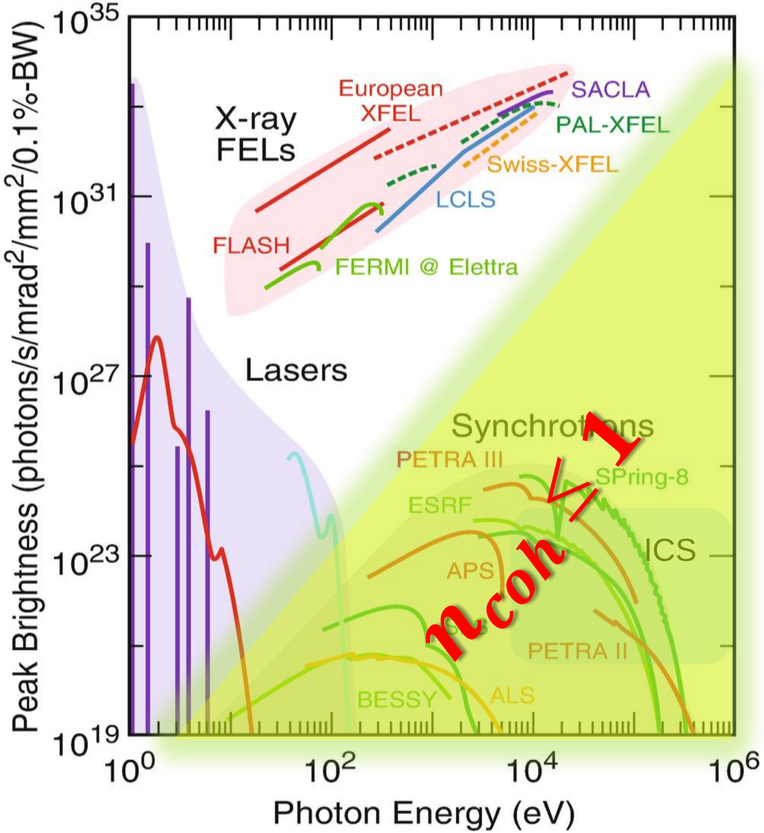
ABSORPTION
Spectroscopy,
EXAFS, XANES

FLUORESCENCE
EXAFS, XRF



SRLS = storage ring light source

Why *accelerator-based* light sources?



- ☐ Almost all experimental techniques gain from a large ***6-D photon density***, or ***brilliance:*** (brightness)

$$B_{max} \cong \frac{dN_\gamma/dt}{\Delta\omega/\omega}\frac{1}{(\lambda^2/2)}$$

for

Diffraction Limit

$$\sigma_u\sigma_{u'} = \varepsilon_u \le \frac{\lambda}{4\pi}$$

Race to **ultra-low emittance SRLS**

- ☐ The number of ***fully coherent*** photons is smaller at shorter wavelengths:

$$n_{coh} = \left(\frac{dN_\gamma/dt}{\Delta\omega/\omega}\right)_{\perp,coh} \cdot \Delta t_{coh} \cdot \frac{\Delta\omega}{\omega} = \frac{B\lambda^3}{8c}$$

Race to fully coherent **X-ray FELs**

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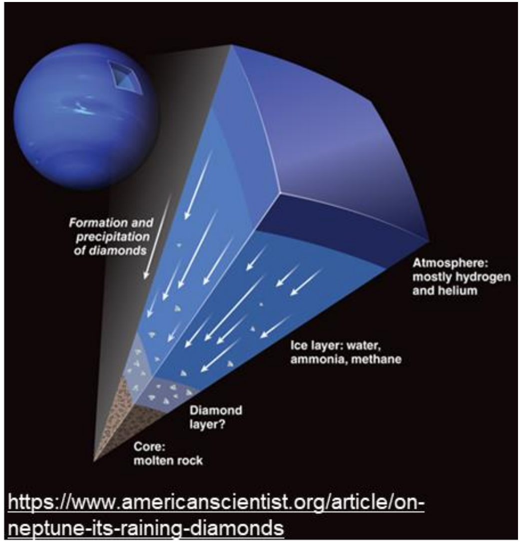
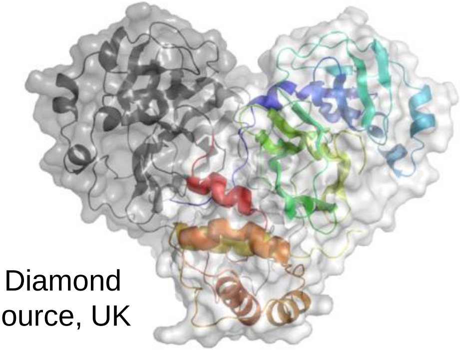
What science at light sources?



https://www.americanscientist.org/article/on-neptune-its-raining-diamonds

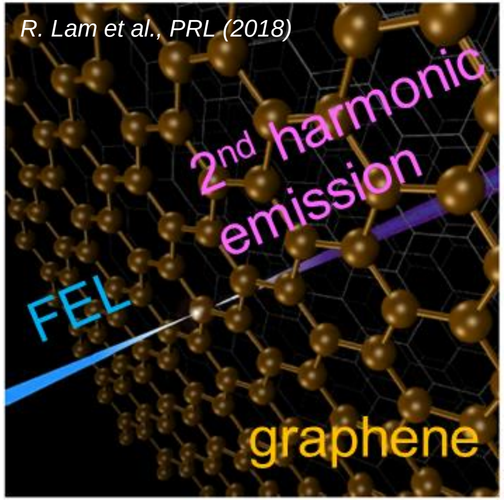
Multi-GW X-FEL pulses compress polystyrene to interior pressure and temperature of **Neptune**. Postulated nano-diamonds sink into core.

Brilliant SRLS pulses led to 3D representation of the main **SARS-CoV-2** protease.



Credit: Diamond Light Source, UK

R. Lam et al., PRL (2018)



Highly coherent, sub-ps FEL pulses stimulate a nonlinear spectroscopic signal from graphene. Open the door to time-resolved interface chemical reactions in **new materials**.

Outline

Motivations to Accelerator-Based Light Sources

Storage Ring Light Sources

- ○ The Challenge of Brilliance

Free-Electron Lasers

- ○ The Challenge of Coherence

Outlook & Conclusions

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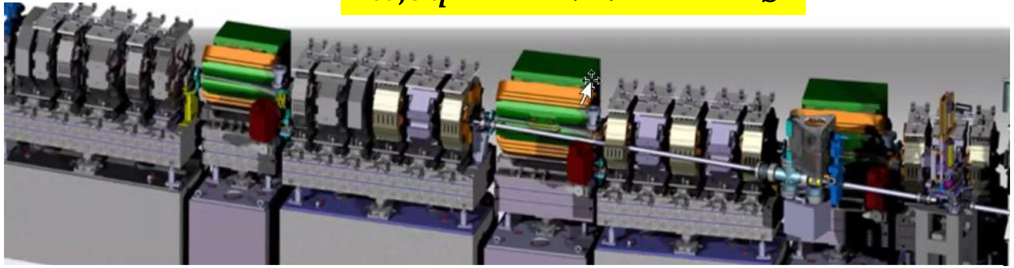
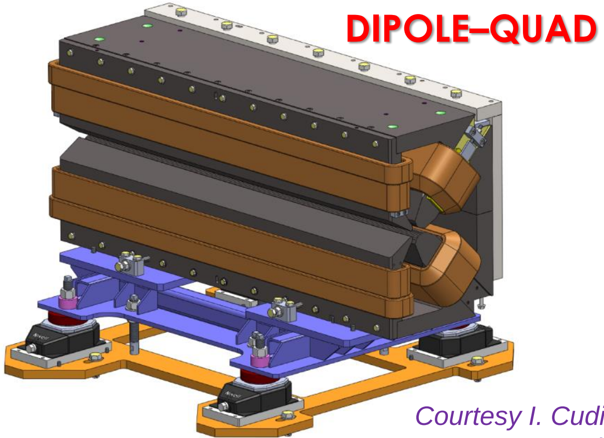
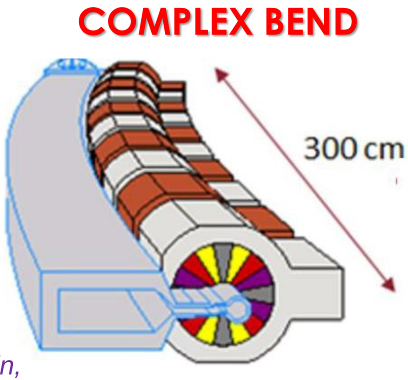
Multi-bend lattices

$$\varepsilon_{x,eq} \propto F(k)\,\gamma^2/N_b^3$$







Courtesy I. Cudin,
G. Le Bec, T. Shaftan

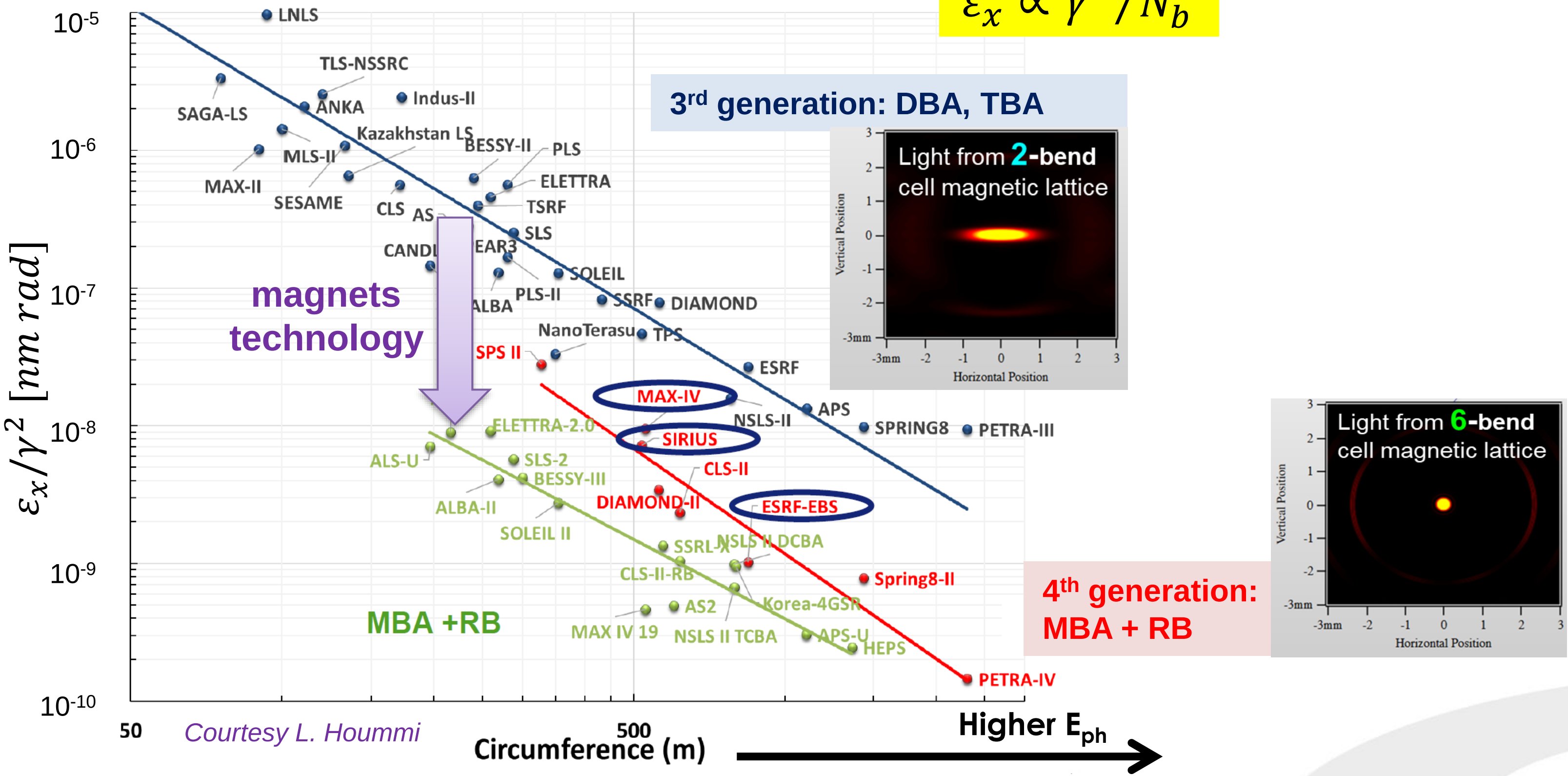
☐ From relatively sparse to **tight, dense, strong focusing lattices**

- Complex dipoles with transverse and/or longitudinal gradients
- Combined multipole magnets
- Fringe-field interference

- 3-D “AI”-driven optimization of magnets design

Emittance landscape

$$\varepsilon_x \propto \gamma^2 / N_b^3$$



3rd generation: DBA, TBA

magnets technology

MBA +RB

4th generation: MBA + RB

Courtesy L. Hoummi

Higher E_{ph} →

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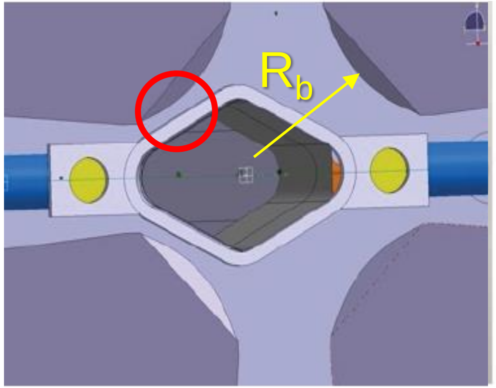
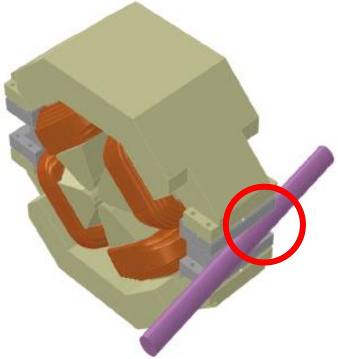
Smaller beams imply stronger instabilities

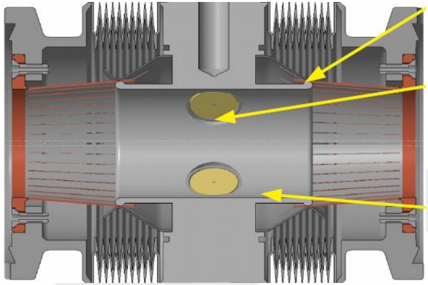
- Smaller beams permit smaller vacuum chambers to maximize the magnetic gradients, $g[T/m] \propto I/R_b^2$





- Stronger impedance from smaller gap of vacuum components

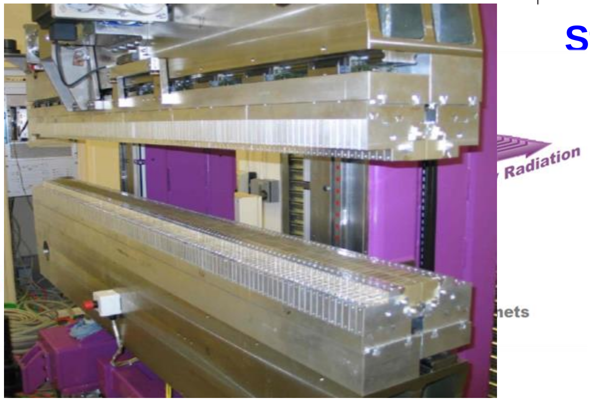
$$Z(\omega) \propto \frac{1}{r^{\alpha}}$$



Courtesy I. Cudin, L. Rumiz, R. Lindberg

- Lower current (thresholds) to avoid single- and multi-bunch instabilities, $I_{th}[A] \propto 1/Z_{\parallel}, 1/Z_{\perp}$

Smaller beams drive undulator technology

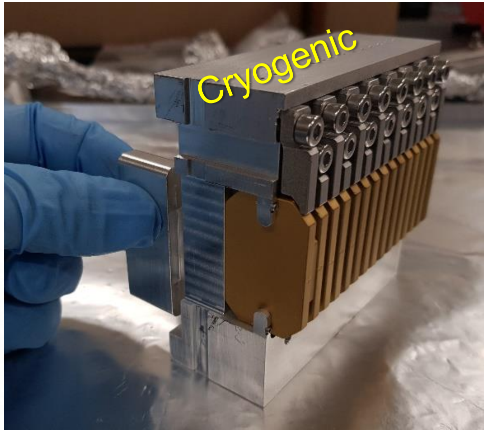


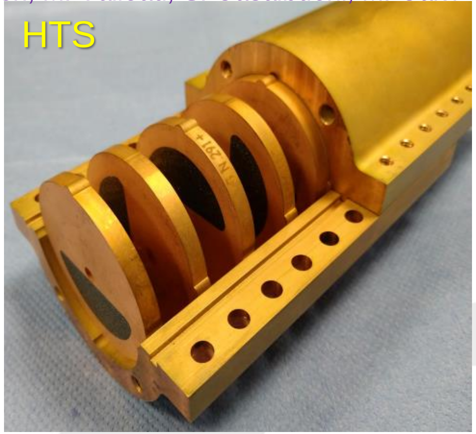
Stronger field by shorter poles → *technological challenge*

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

Shorter poles permit lower beam energies → *energy & cost saving*

Courtesy B. Diviacco, H. Tarawneh, M. Valleau, S. Casalbuoni, M. Calvi





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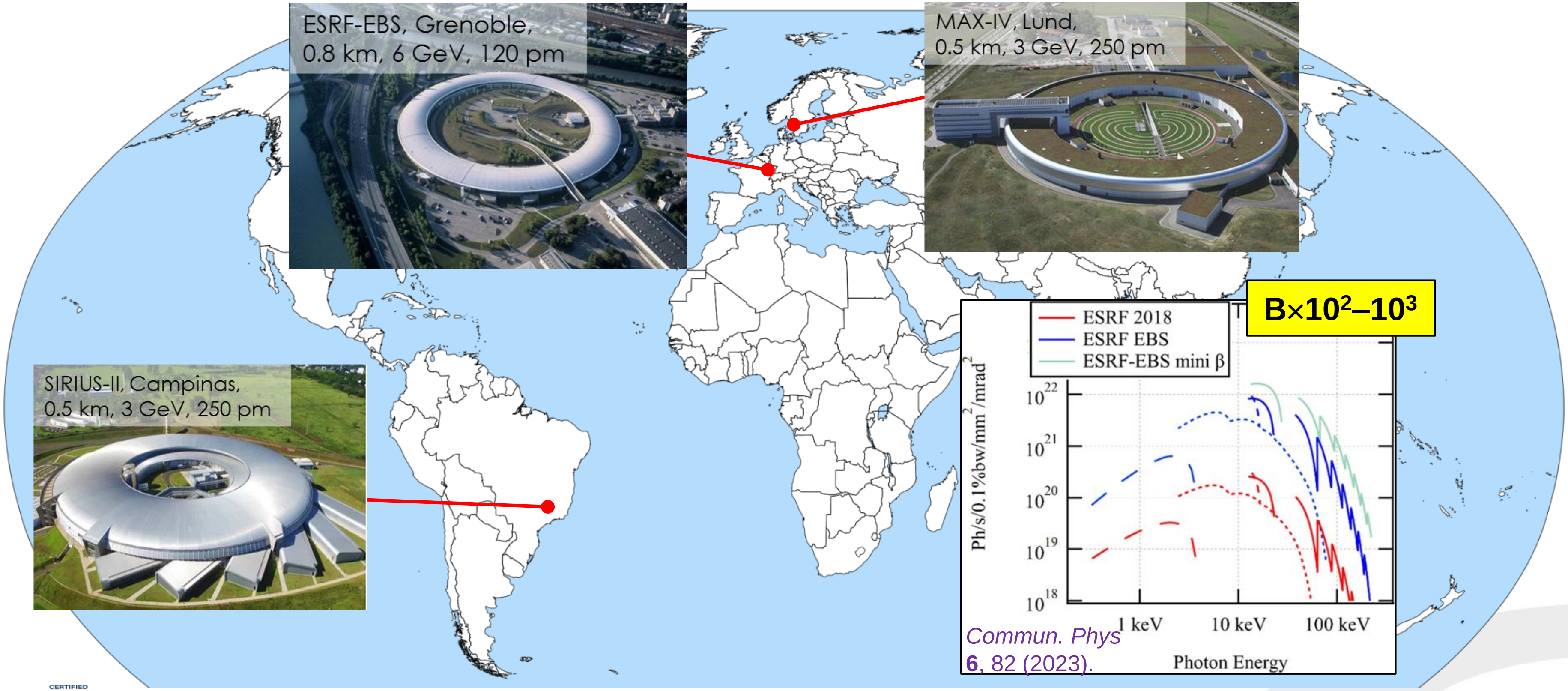
4th generation SRLS are running already



B×10^2–10^3

Commun. Phys **6**, 82 (2023).

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…and more are coming!

SLS 2.0, Villigen,
0.3 km, 2.7 GeV, 140 pm

HEPS, Beijing area
1.3 km, 6 GeV, 60 pm

Upgrade plans also in UK, Germany, France, and Spain

ALS-U, Berkeley,
0.2 km, 2 GeV, 70 pm

APS-U, Chicago area,
1.1 km, 6 GeV, 50 pm

ELETTRA 2.0, Trieste,
0.26 km, 2.4 GeV, 230 pm

Korea-4GSR, Ochang,
0.4 km, 4 GeV, 60 pm

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- **Free-Electron Lasers**
  - ○ **The Challenge of Coherence**
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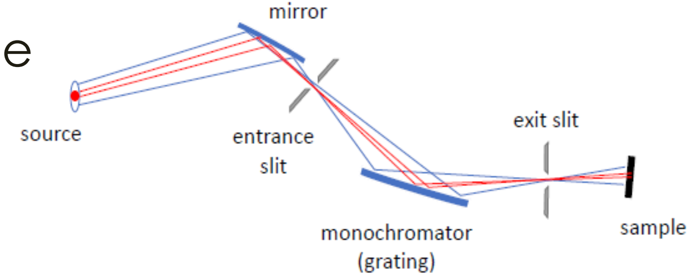
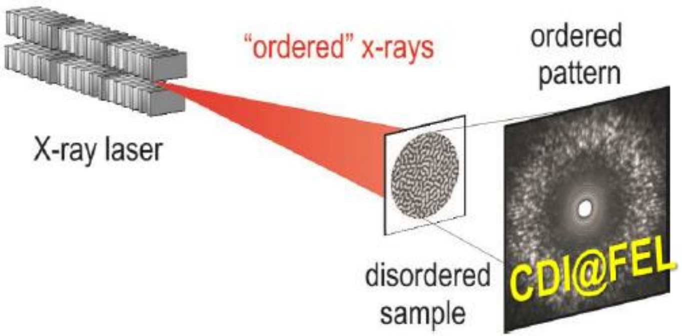
From the source to the sample

Brilliance is a conserved quantity in a perfect optical system. *However…*

☹ Larger light spots sample **geometric defeats** of optical elements.
→ *Brilliance is reduced*



☹ Coherence can be retrieved through **physical cut** of the light pulse.
→ *Flux is reduced*



☺

The more brilliant and coherent the light is at the **source**, the more it will be at the **sample!**

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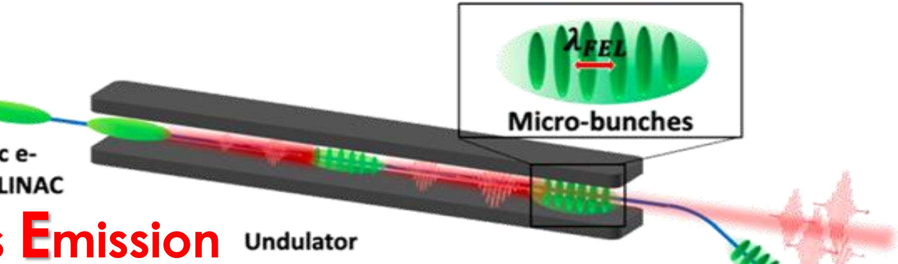
High gain free-electron lasers

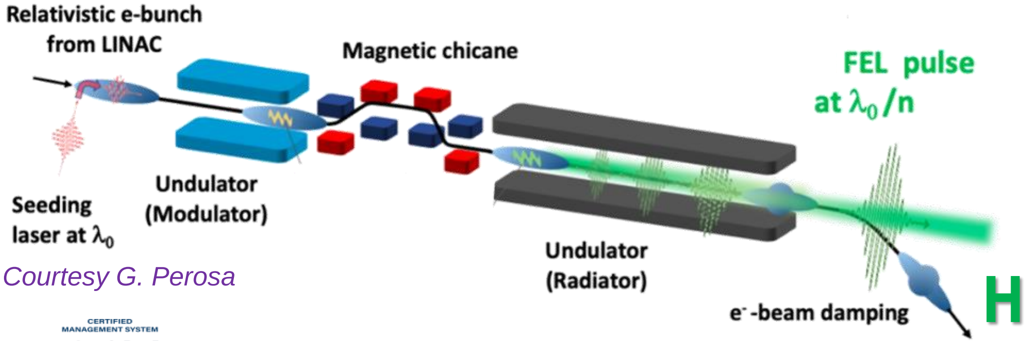
Up to 10^9-fold increase of brilliance by bunching beam at radiation wavelength. Radiation adds coherently and is almost monochromatic.

Each bunch is anew!

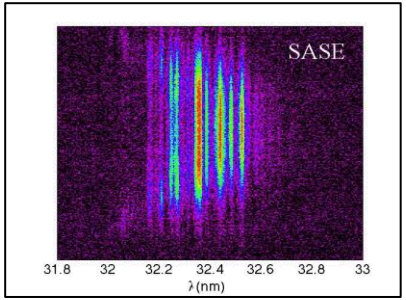
Courtesy SLAC



Self–Amplified Spontaneous Emission

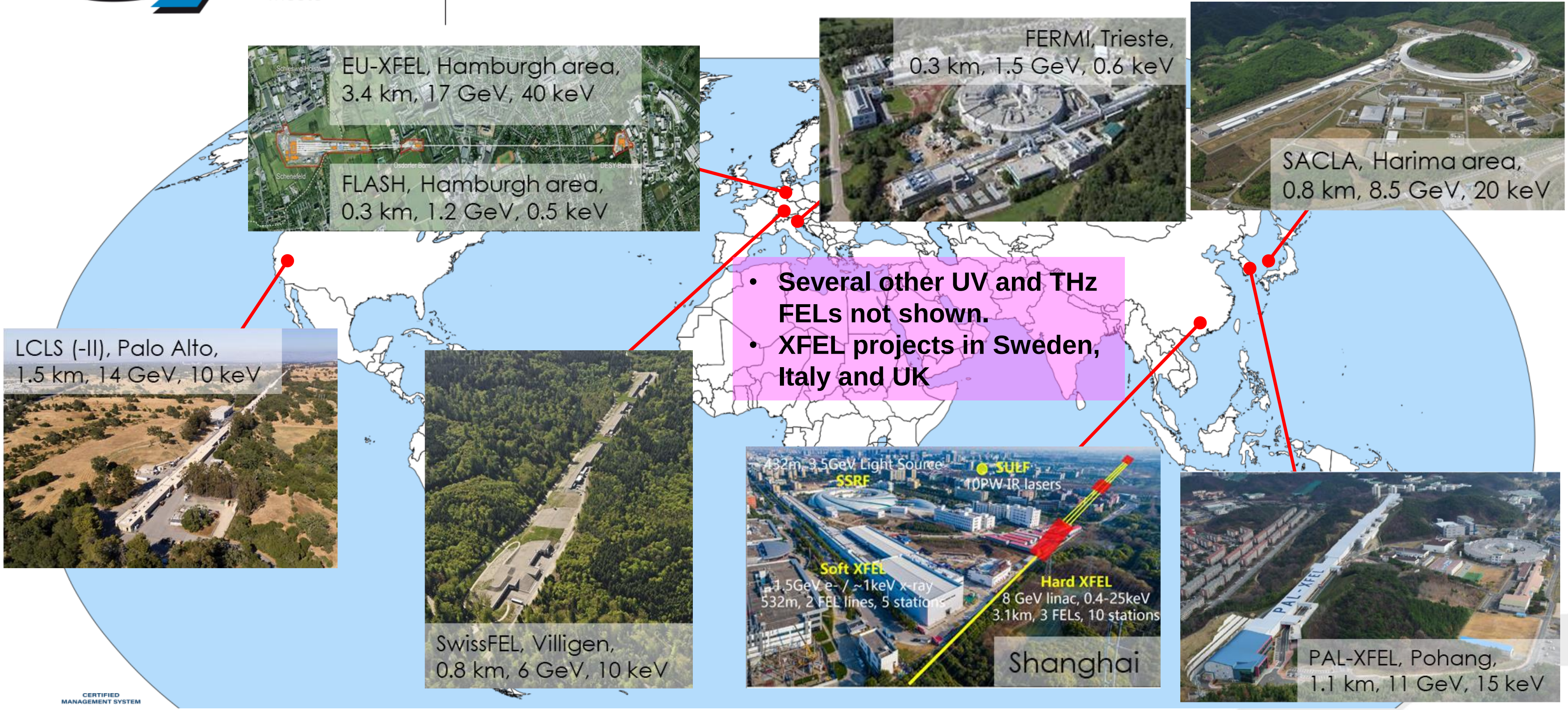


Courtesy G. Perosa



High Gain Harmonic Generation

X-FELs are continuously upgrading



EU-XFEL, Hamburgh area,
3.4 km, 17 GeV, 40 keV

FLASH, Hamburgh area,
0.3 km, 1.2 GeV, 0.5 keV

FERMI, Trieste,
0.3 km, 1.5 GeV, 0.6 keV

SACLA, Harima area,
0.8 km, 8.5 GeV, 20 keV

LCLS (-II), Palo Alto,
1.5 km, 14 GeV, 10 keV

SwissFEL, Villigen,
0.8 km, 6 GeV, 10 keV

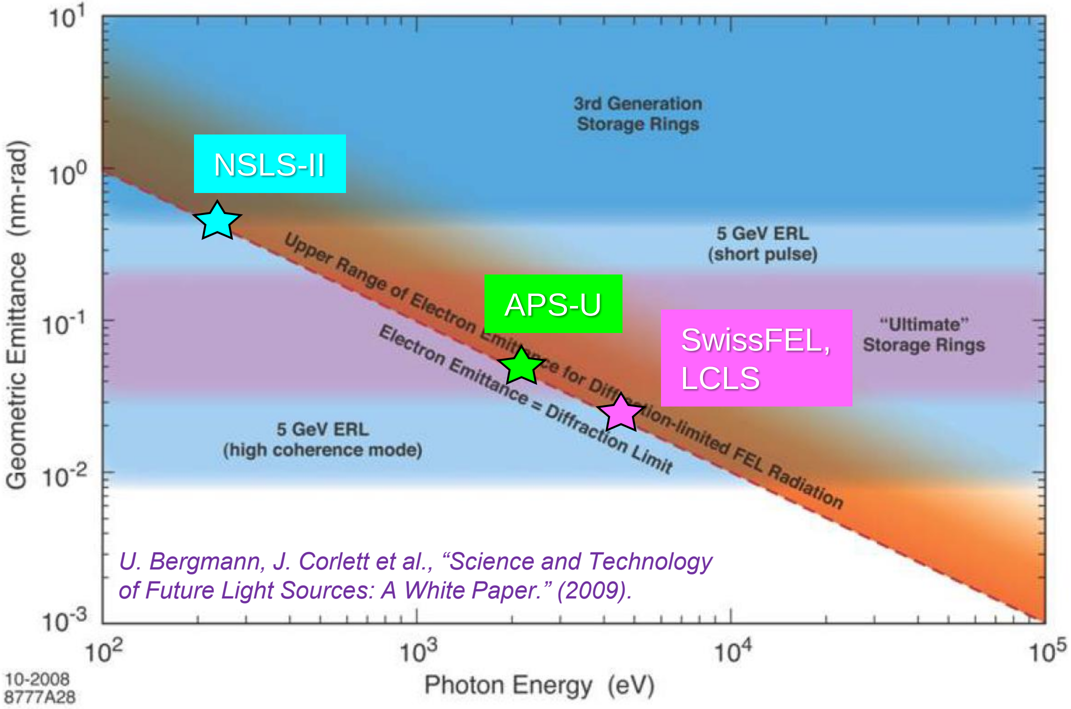
Shanghai

PAL-XFEL, Pohang,
1.1 km, 11 GeV, 15 keV

- **Several other UV and THz FELs not shown.**
- **XFEL projects in Sweden, Italy and UK**

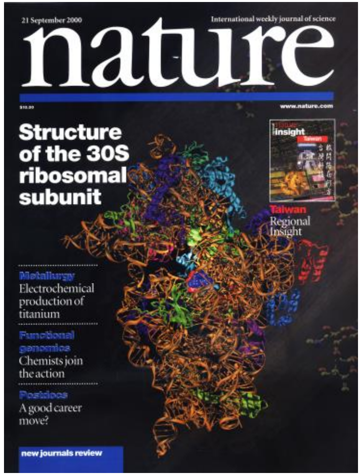
Transverse coherence enables μm-spot sizes

Diffraction Limit, $\varepsilon_{x,y} = \frac{\lambda}{4\pi}$



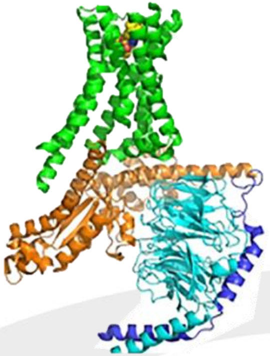
U. Bergmann, J. Corlett et al., "Science and Technology of Future Light Sources: A White Paper." (2009).

The protein is grown in a crystalline structure, bombarded with hard X-rays to map out the protein structure.



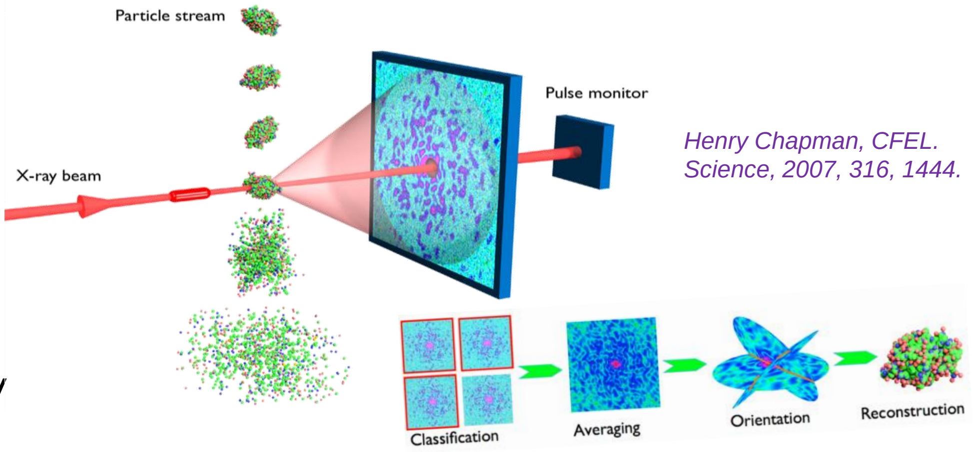
Nobel prize in 2009 for mapping of a ribosomal subunit. Important target for antibiotics.

Nobel prize in 2012 for revealing the 3D structure of a protein complex on the surface of human cells, which affect how the body responds to drugs.



Challenge: coherence at high intensity

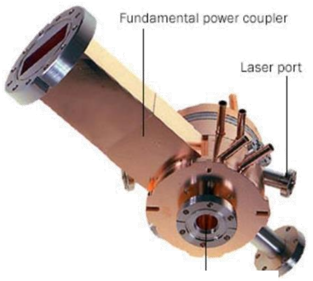
☹ Single shot reconstruction of molecules at X-FELs is a promise yet. Essential for non-crystallized proteins.



Henry Chapman, CFEL. Science, 2007, 316, 1444.

☺ RF photo-injectors produce low emittance to meet the diffraction limit, essential to initiate the FEL process.

- ➢ *R&D to generate lower emittances at higher charges, also at high rep rate.*

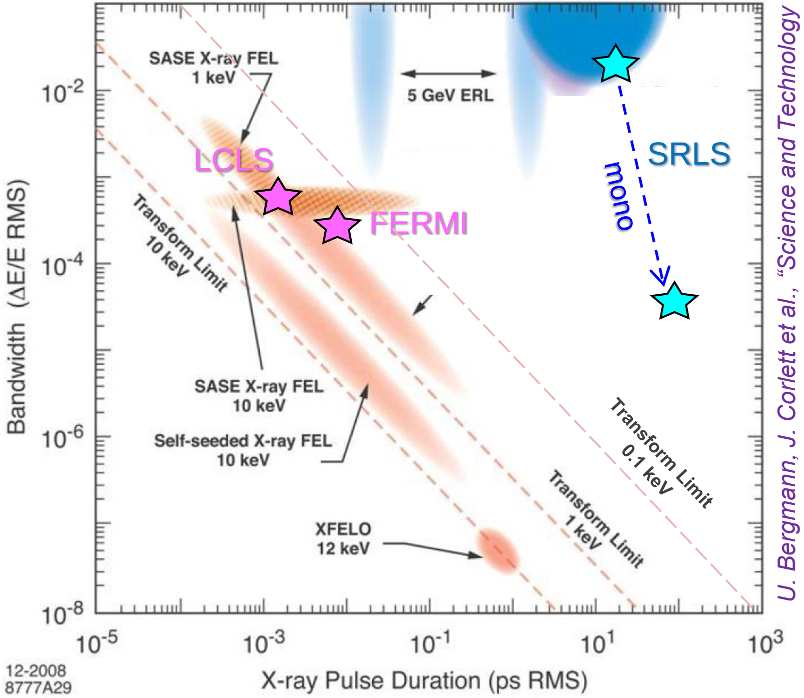


BNL/SLAC/UCLA gun

SwissFEL Gun

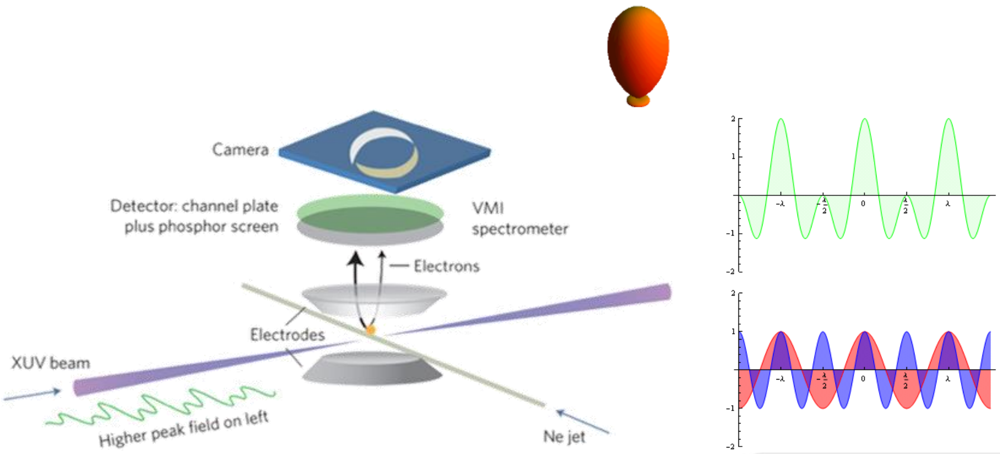
Longitudinal coherence enables phase control

Fourier Limit, $\sigma_\omega \sigma_t = \frac{1}{2}$



U. Bergmann, J. Corlett et al., "Science and Technology of Future Light Sources: A White Paper." (2009).

Lobes represent photo-electron emission from Ne. Asymmetry results from interference of 2-photons and 1-photon emission of electrons from excited state to fundamental. Process is controlled through phase-locked FEL harmonics.



G. Sansone, C. Callegari et al., Nature 578, 386 (2020)

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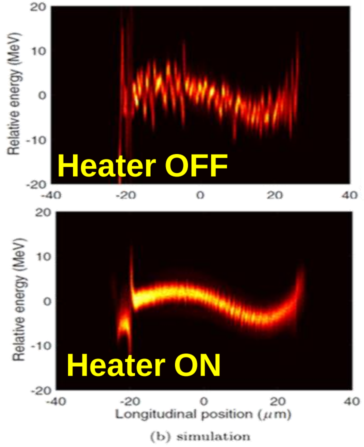
Challenge: longitudinal coherence in X-rays

☹ **Microbunching instability** is still a show-stopper to full coherence in X-rays.

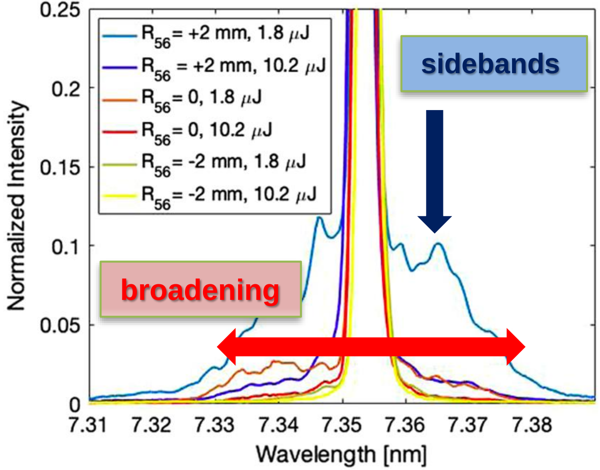
☺ **Laser heater** increases the energy spread of electrons to prevent instability. Not always a solution.

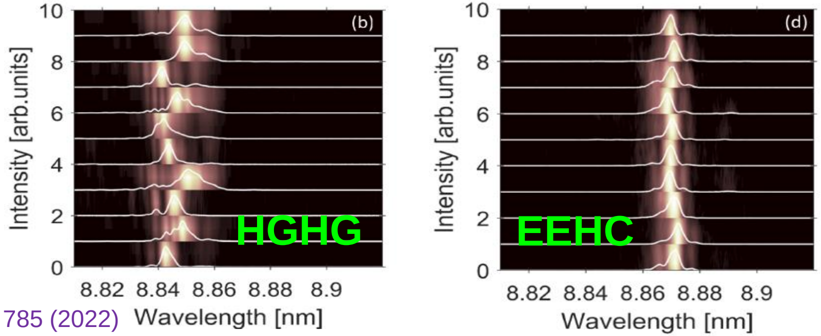
- ➢ *R&D in multi-stage (seeded) FELs for high harmonic jumps, but less prone to the instability.*

J. Qiang et al., PRAB 20, 054402 (2017)



G. Perosa et al., PRAB 23, 110703 (2020)





C. Feng et al., Optica 785 (2022)

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Outline

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Motivations to Accelerator-Based Light Sources

Storage Ring Light Sources

- The Challenge of Brilliance

Free-Electron Lasers

- The Challenge of Coherence

Outlook & Conclusions

CERTIFIED MANAGEMENT SYSTEM
CQY CERTIQUALITY
UNI EN ISO 9001:2015
UNI ISO 45001:2018

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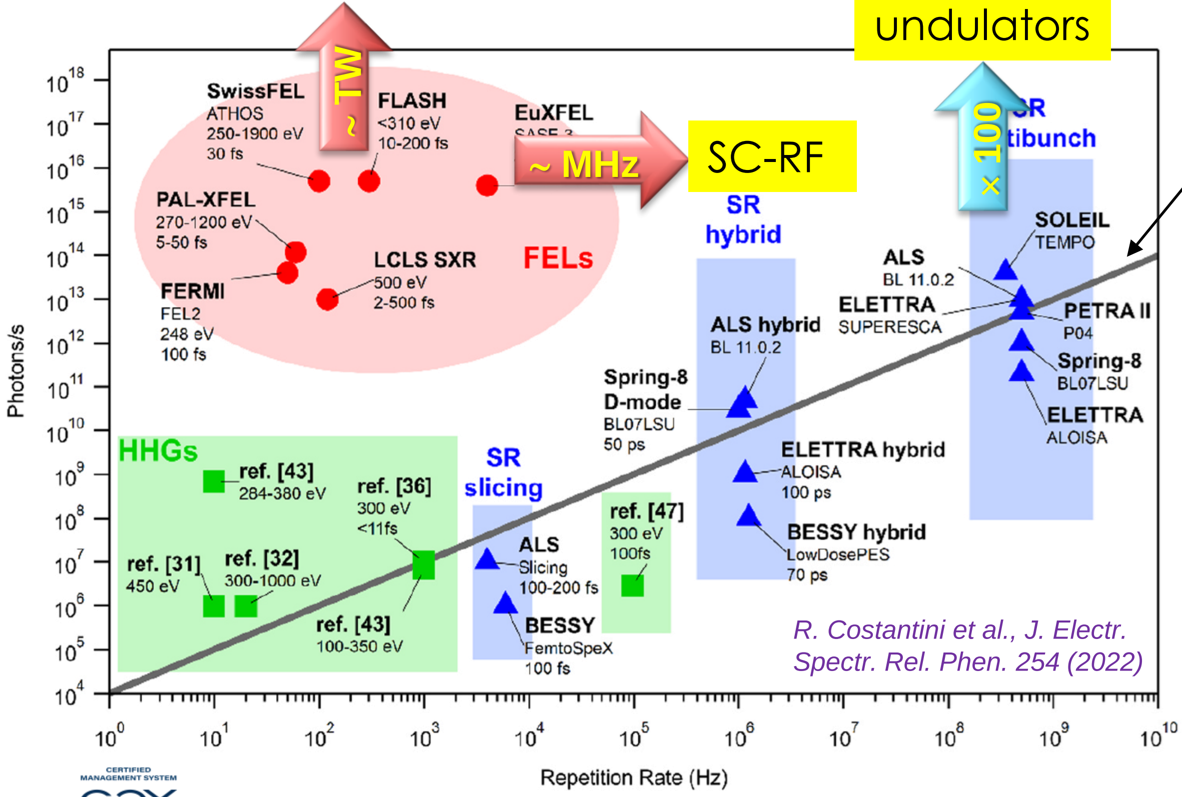
Repetition rate matters

attoseconds

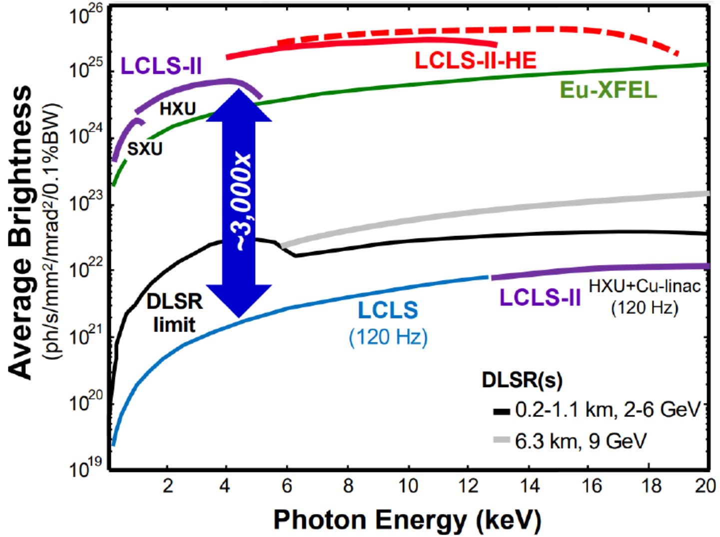
High field undulators

space charge onset for photoemission measurements of 10^4 photons per pulse



R. Costantini et al., J. Electr. Spectr. Rel. Phen. 254 (2022)

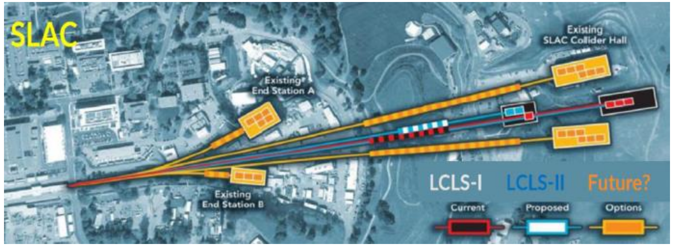
Courtesy M. Dunne

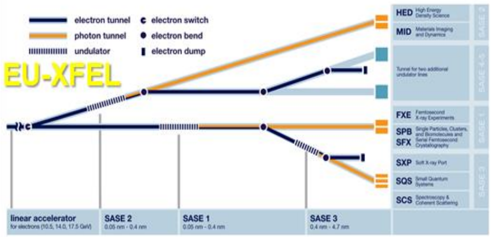


Users access matters as well

- ❑ Rate of over-subscription at most light sources is > 3.
- ❑ Next km-scale SC FELs aim at > 3 simultaneous experiments (vs. 7–50 at SRLS).
- ❑ Worldwide spread of compact & cheaper X-ray sources at UNIV-scale could alleviate the need of research at relatively low intensity.

Inverse Compton Scattering generates **X- to γ-rays** from 10's-100's MeV e-beam incident on a UV laser. Incoherent emission but quasi-monochromatic on–axis. Footprint is **10's m scale**. *Let's hear more from L. Serafini today!*





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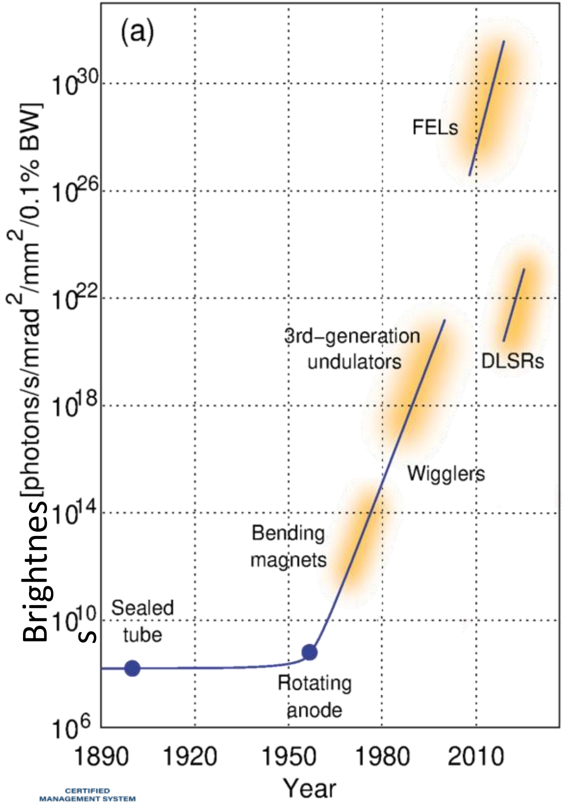
Take-home messages



1. Accelerator-based light sources are the most brilliant sources on Earth, largely coherent.
2. Other strong points are polarization, 6-D pulse shaping at FELs, repetition rate and diversified radiation sources at SRLS.
3. Light sources drive technology: RF, magnets, ultra-vacuum mechanics, lasers.
4. Light sources are multi-purpose science drivers. No one ideal source: pick the one most suited to your experiment!

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What does the future look like?

Credits

For providing pictures and inspiration:

Sarah Cousineau (ORNL)
Giorgio Margaritondo (EPFL)
David Attwood (Univ. of California)
Riccardo Bartolini (DESY)
Dong Wang (CAS)
ELETTRA and FERMI Team

Thank You for Your attention

On the shelf:

- *Free-Electron Lasers in the Ultraviolet and X-Ray Regime*, P. Schmuser, M. Dohlus, J. Rossbach, C. Behrens, Springer (2014).
- *Synchrotron Radiation and Free-Electron Lasers. Principles of Coherent X-ray Generation*, K.-J. Kim, Z. Huang, R. Lindberg, Cambridge University Press (2017).
- *Fundamentals of Particle Accelerator Physics*, S. Di Mitri, Springer (2022).

Back-up Slides

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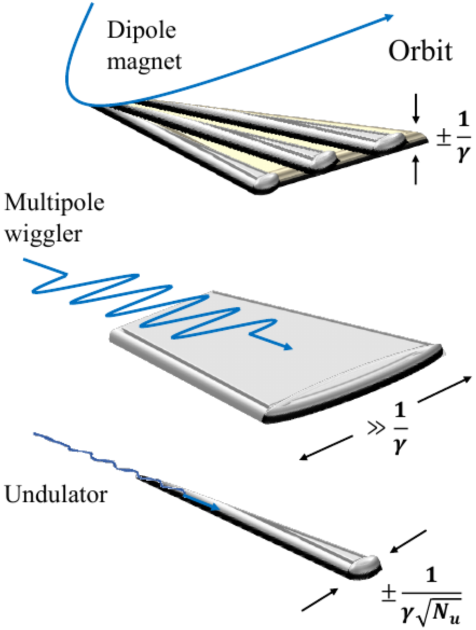
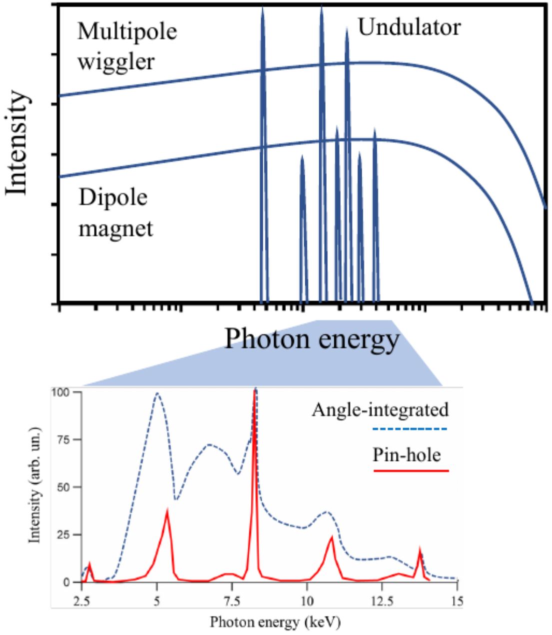
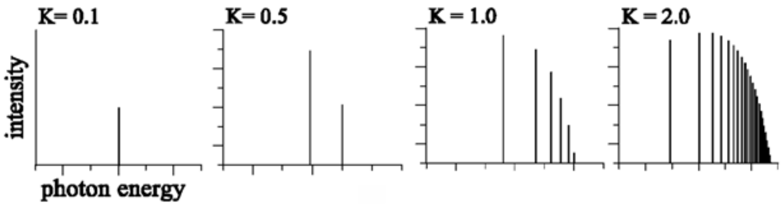
Light Shaping

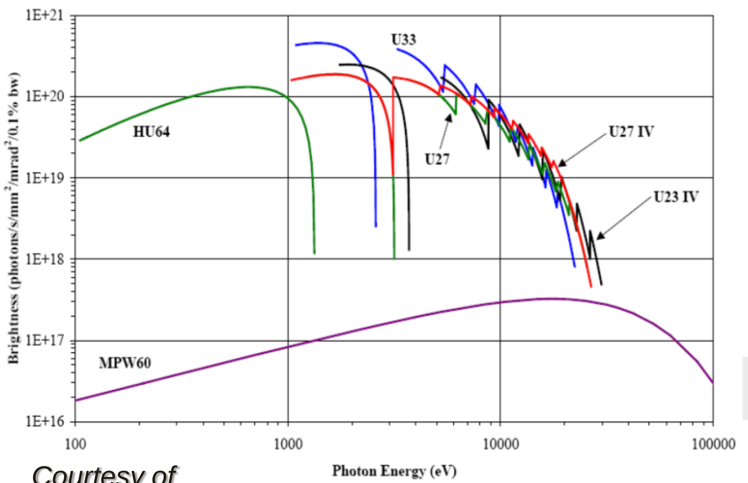
dipole, wiggler, undulator





wiggler vs. undulator

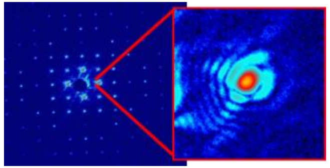




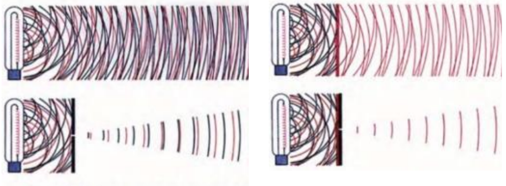
Courtesy of R. Bartolini

What is Coherence?

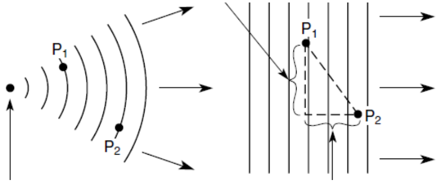
Interference fringes

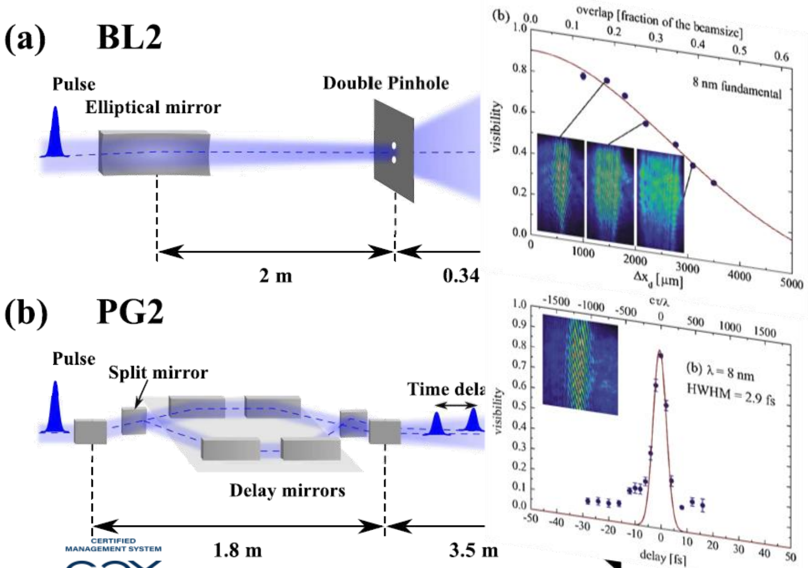


Collimated, monochromatic light



Correlated field (*Glauber*)





Degree of transverse coherence:

$$\xi_c = \frac{\iint |g_1(\vec{r}_1,\vec{r}_2)|^2 \langle I(\vec{r}_1)\rangle \langle I(\vec{r}_2)\rangle d\vec{r}_1 d\vec{r}_2}{\left[\int \langle I(\vec{r}_1)\rangle d\vec{r}_1\right]^2}$$

Longitudinal coherence length:

$$\tau_{c,rms} = \int_{-\infty}^{\infty} |g_1(\tau)|^2 d\tau$$

1st order correlation function:

$$g_1(\vec{r}_1,t_1;\vec{r}_2,t_2) = \frac{\langle E^*(\vec{r}_1,t_1)E(\vec{r}_2,t_2)\rangle}{\sqrt{\langle |E(\vec{r}_1,t_1)|^2\rangle \langle |E(\vec{r}_2,t_2)|^2\rangle}}$$

Visibility of fringe pattern:

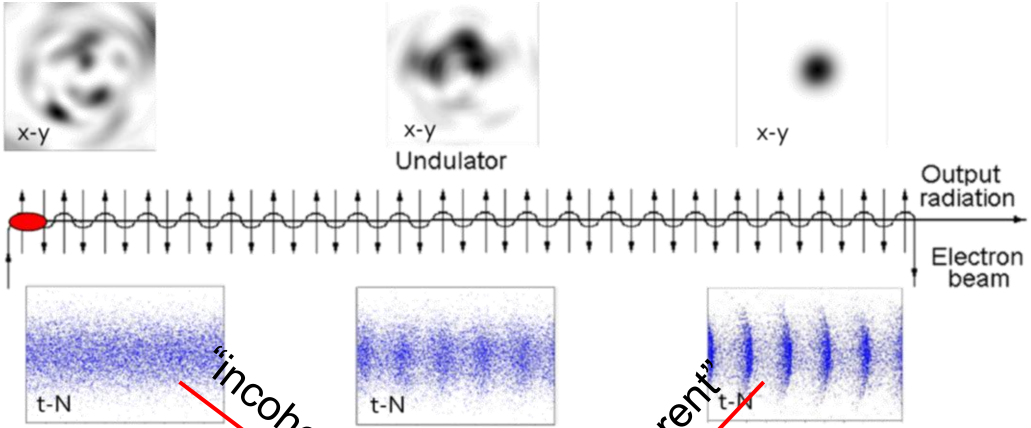
$$v(\lambda) = \frac{I_{max}-I_{min}}{I_{max}+I_{min}} = \frac{2\sqrt{I_1 I_2}}{I_1+I_2}|g_1(\vec{r}_1,t_1;\vec{r}_2,t_2)|$$

D. Attwood and A. Sakdinawat, X-rays and Extreme Ultraviolet Radiation, Cambridge Univ. Press (2016).

A. Singer et al., arXiv:1206.1091v1 (2012)

S. Roling et al., PRST-AB 14 (2011)

High Gain SASE FEL

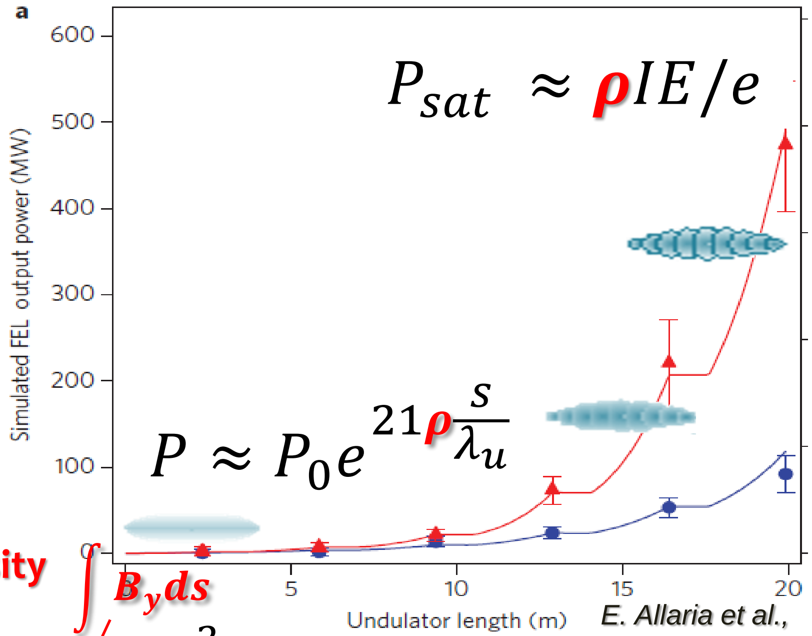


E. Saldin et al., NJP (2008)

“incoherent”

“coherent”

$$N_{ph} \sim \pi\alpha(N_e + N_e^2)$$



$$P_{sat} \approx \rho IE/e$$

$$P \approx P_0 e^{21\rho\frac{s}{\lambda_u}}$$

E. Allaria et al., Nat. Phot. (2010)

3-D charge density

$\int B_y ds$

$$L_g = \frac{1}{4\pi\sqrt{3}}\frac{\lambda_u}{\rho} \qquad \rho = \frac{1}{\gamma_r}\left[\frac{\omega_p\lambda_u a_K}{8\pi c}\right]^{\frac{2}{3}}$$

beam energy