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Sincrotrone
Trieste

Introduction to Short Wavelength Coherent Light Sources: Present and Outlook

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ISO 9001
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Certification

Smart-X, Trieste, April 2022

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Outline

- ❑ Coherence of Radiation
  - Transverse and longitudinal coherence length
  - Brilliance, degeneracy parameter
- ❑ Light Sources
  - High Harmonic Generation (in gas)
  - Free-Electron Laser (high gain regime)
- ❑ Overview and Perspectives

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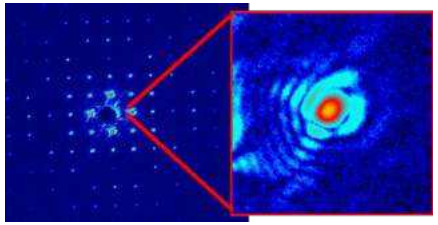
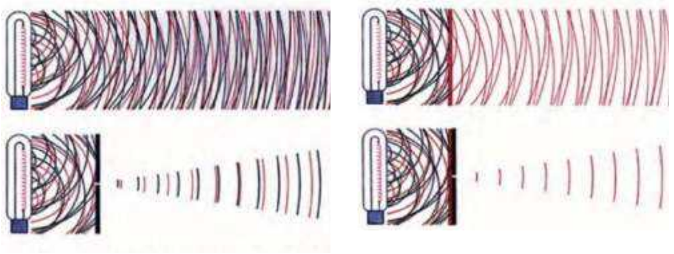
Coherence of Radiation

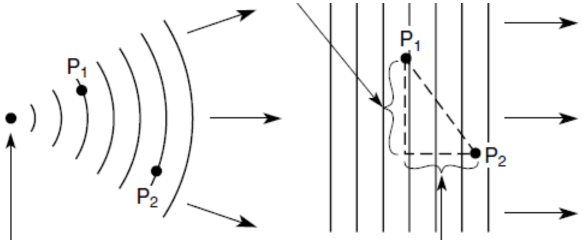
Interference fringes

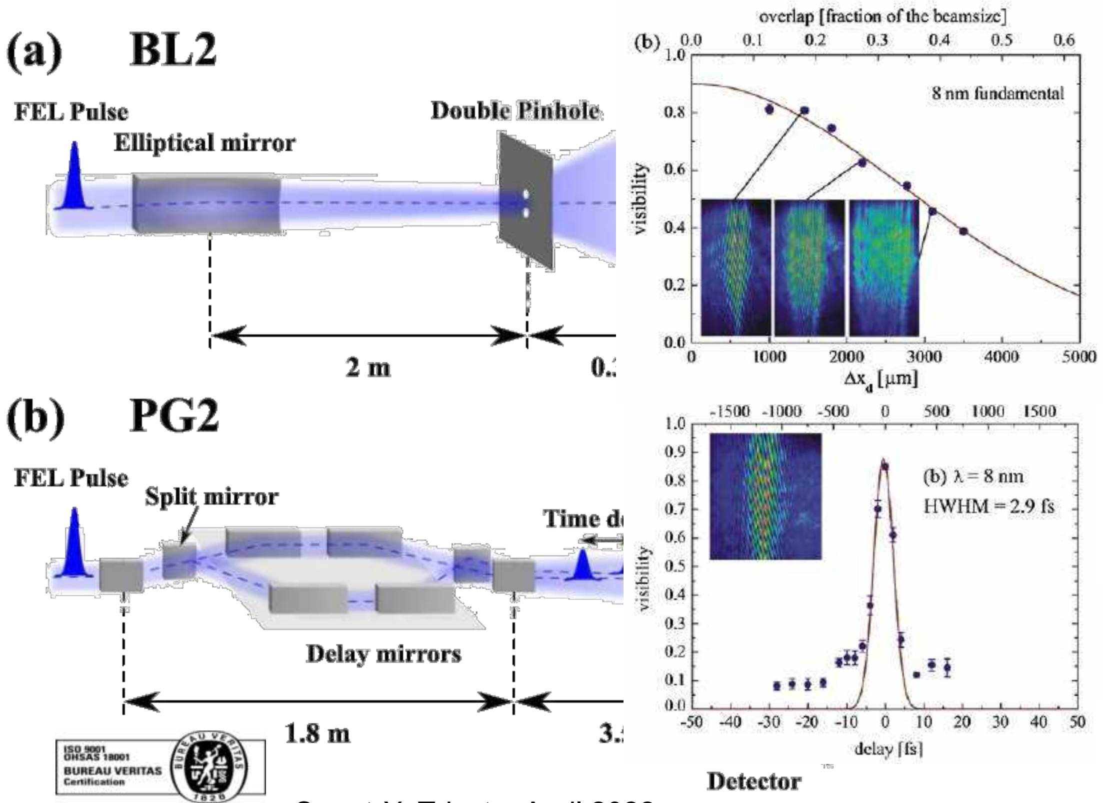


Collimated, monochromatic light



Correlated field (*Glauber's*)





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)

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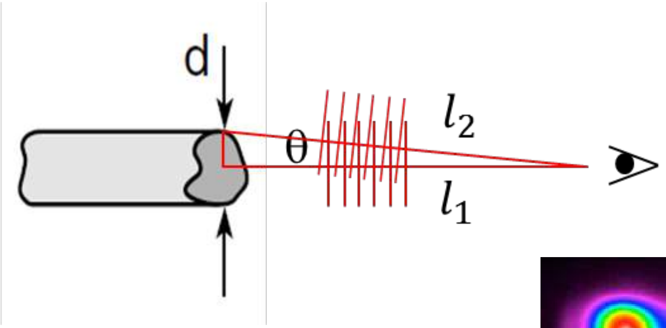
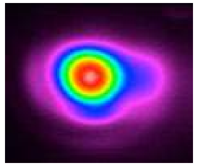
Coherence Lengths

Classical model: path length over which two waves become **out of phase**

Uncertainty Principle: the smallest **phase space area** occupied by the light pulse

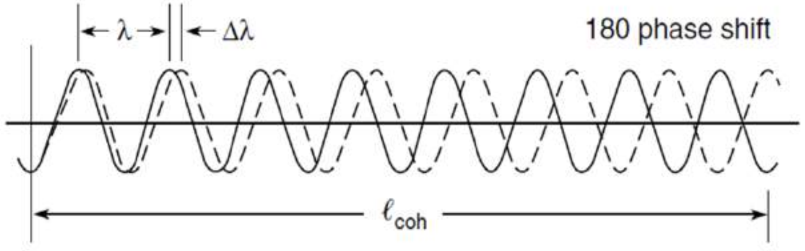


$$\Delta x \Delta p_x \geq \frac{\hbar}{2} \quad and\ \theta = \frac{\Delta p_x}{p_z} \cong \frac{\Delta p_x}{(h/\lambda)} \Rightarrow \frac{d}{2}\theta_c = \frac{\lambda}{4\pi}$$



TEM00

Minimum transverse phase space area (**"emittance"**) of a transversally coherent light pulse



$$\Delta t \Delta E \geq \frac{\hbar}{2} \rightarrow \frac{c\Delta t}{\lambda^2/\Delta\lambda} \geq \frac{1}{4\pi} \Rightarrow L_{c,\parallel} = c\Delta t = \frac{1}{4\pi}\frac{\lambda^2}{\Delta\lambda}$$

Longitudinal coherence shows up $\boldsymbol{\Delta t_{pulse} \leq L_c}$

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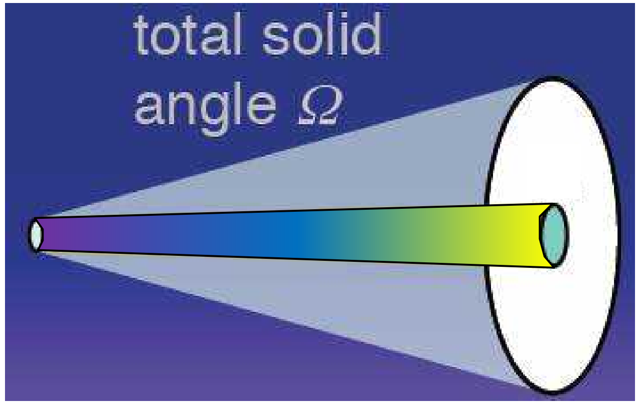
Brilliance

- The **fraction of spectral flux transversally coherent**, emitted in a solid angle $\Sigma_{x'}\Sigma_{y'} = \Omega$ from a source of size $\Sigma_x\Sigma_y = (d/2)^2$, is:

$$\left(\frac{dN_\gamma/dt}{\Delta\omega/\omega}\right)_{\perp,coh} = \left(\frac{dN_\gamma/dt}{\Delta\omega/\omega}\right)\frac{\theta_c^2}{\Omega} = \left(\frac{dN_\gamma/dt}{\Delta\omega/\omega}\right)\frac{\lambda^2}{(4\pi)^2\left(\frac{d}{2}\right)^2\Omega} = \boldsymbol{B}\times\left(\frac{\lambda}{2}\right)^2$$

Full transverse coherence for $\frac{\theta_c^2}{\Omega} = 1$ or $\Sigma_x\Sigma_y\Sigma_{x'}\Sigma_{y'} = \left(\frac{\lambda}{4\pi}\right)^2$,

"diffraction limit"



- The **number of photons** transversally *and* longitudinally **coherent** is:

$$n_{coh} = \left(\frac{dN_\gamma/dt}{\Delta\omega/\omega}\right)_{\perp,coh}\cdot\frac{L_{c,\parallel}}{c}\cdot\frac{\Delta\omega}{\omega} = B\left(\frac{\lambda}{2}\right)^2\frac{\lambda^2}{2c\Delta\lambda}\frac{\Delta\lambda}{\lambda} = \frac{B\lambda^3}{8c}$$

"degeneracy parameter"

- *It is harder to get full coherence at shorter wavelengths*
- *In a real beamline, B (at sample) ∝ B (at source)*

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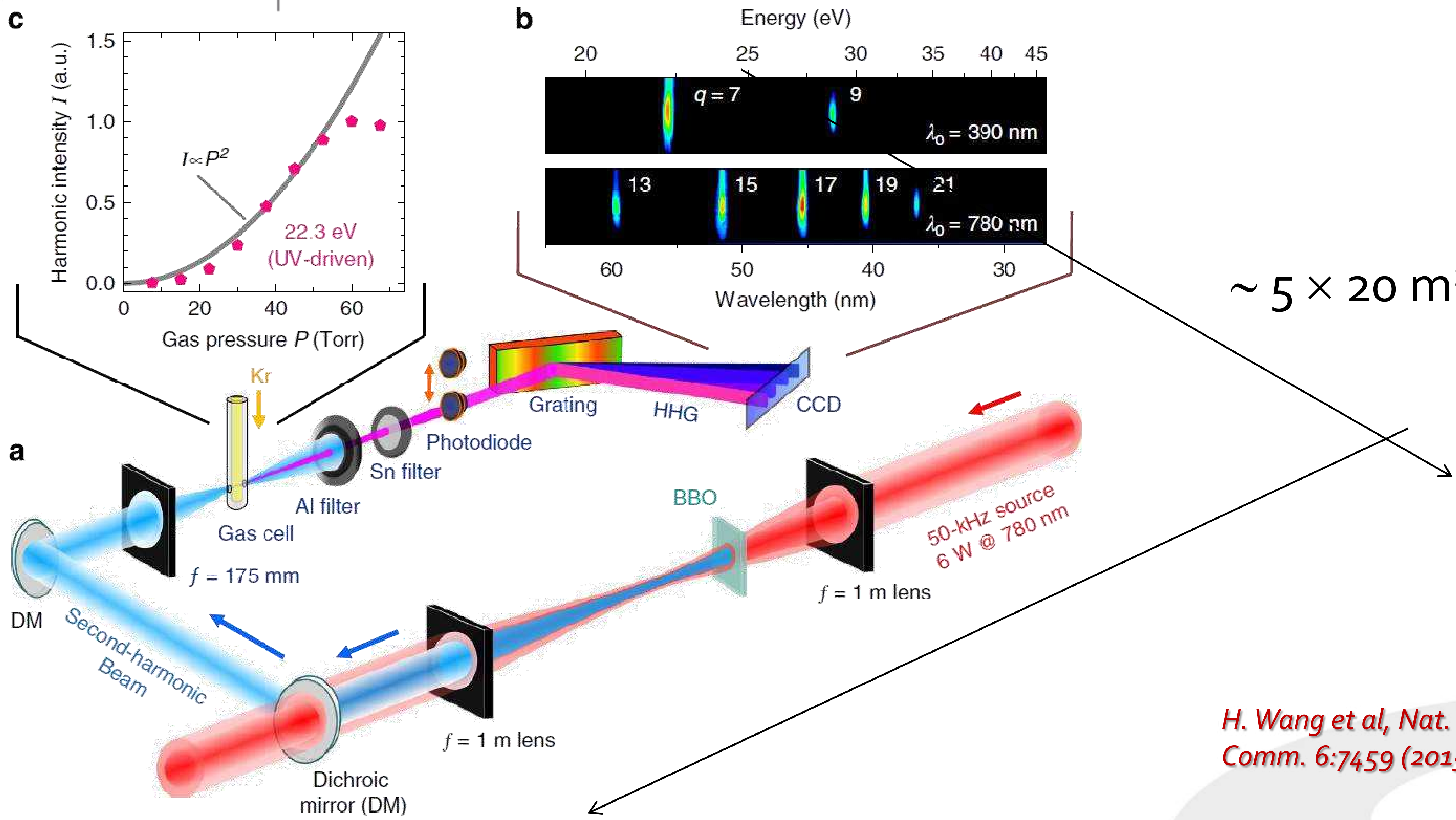
HHG in Gas



~ 5 × 20 m²

H. Wang et al, Nat. Comm. 6:7459 (2015)

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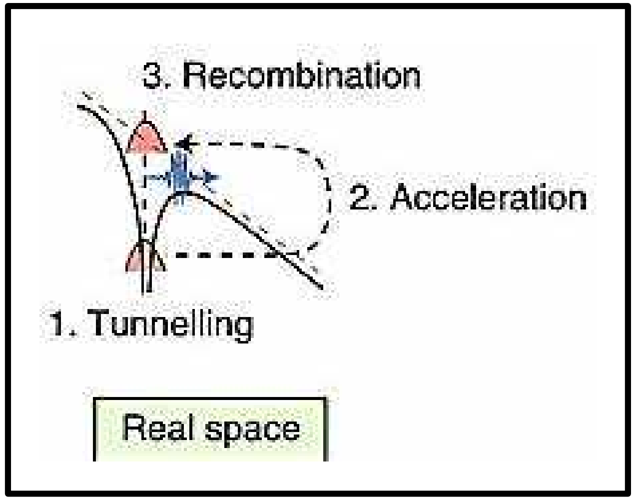
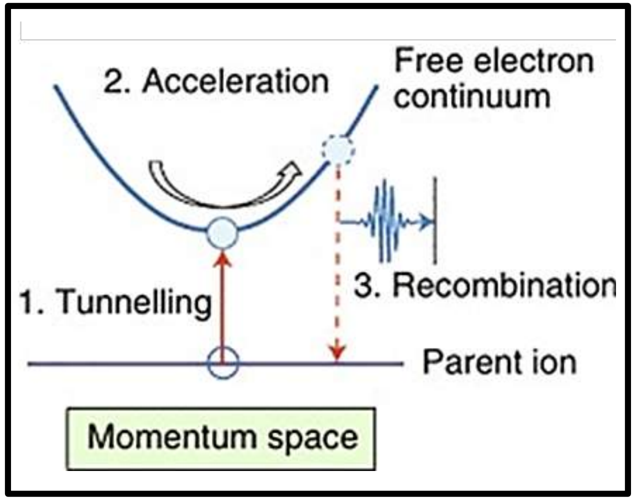
3-Step Model





L. Ortmann A.S. Landsman, Adv. AMO Phys. 70 (2021)

① Electron orbit in “continuum”:

$$v_x \sim \quad v_0 \sin(\omega t) \qquad a = \begin{cases} 0 & \textit{linear} \text{ polarization} \\ \pm 1 & \textit{circular} \text{ polarization} \end{cases}$$
$$v_y \sim a v_0 \cos(\omega t)$$

For circularly polarized field, the e- never returns in vicinity of the ion

Only **linearly polarized** light is emitted after recombination

② Electron orbit is anti-symmetric in the rest frame (“figure-8” electric dipole)

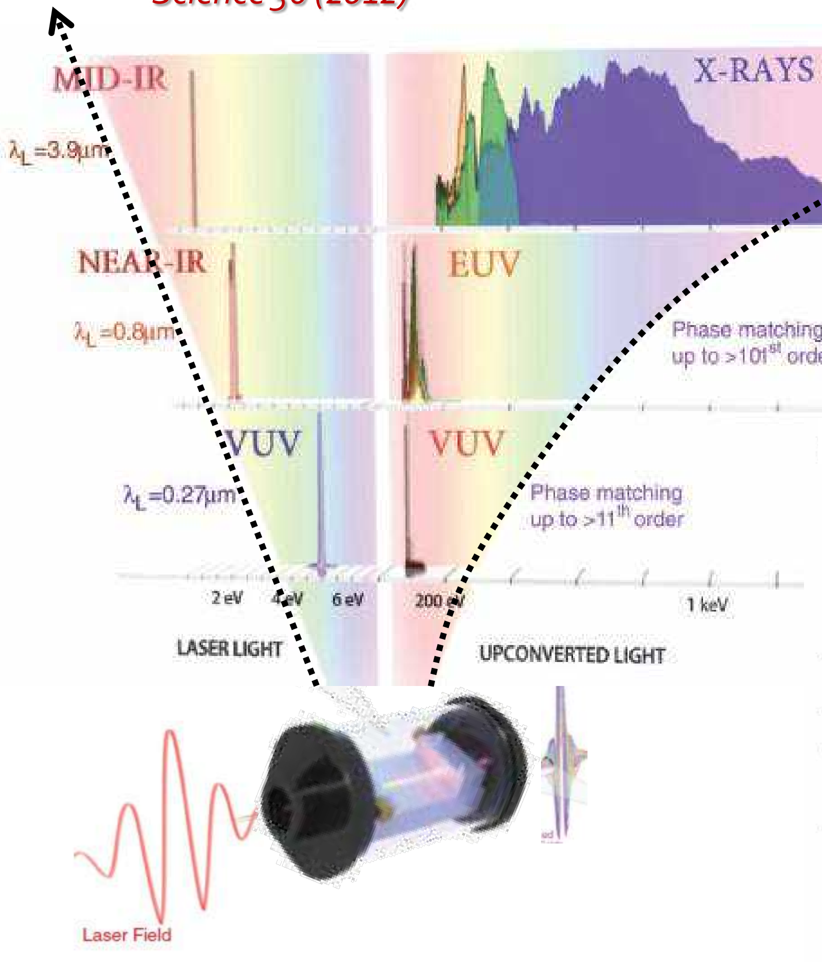
Only **odd harmonics** are allowed

③ Electron recombination happens every half-cycle of the laser field

Harmonics are separated by $2\omega_{laser}$

Photon Energy

T. Popminchev et al.,
Science 36 (2012)



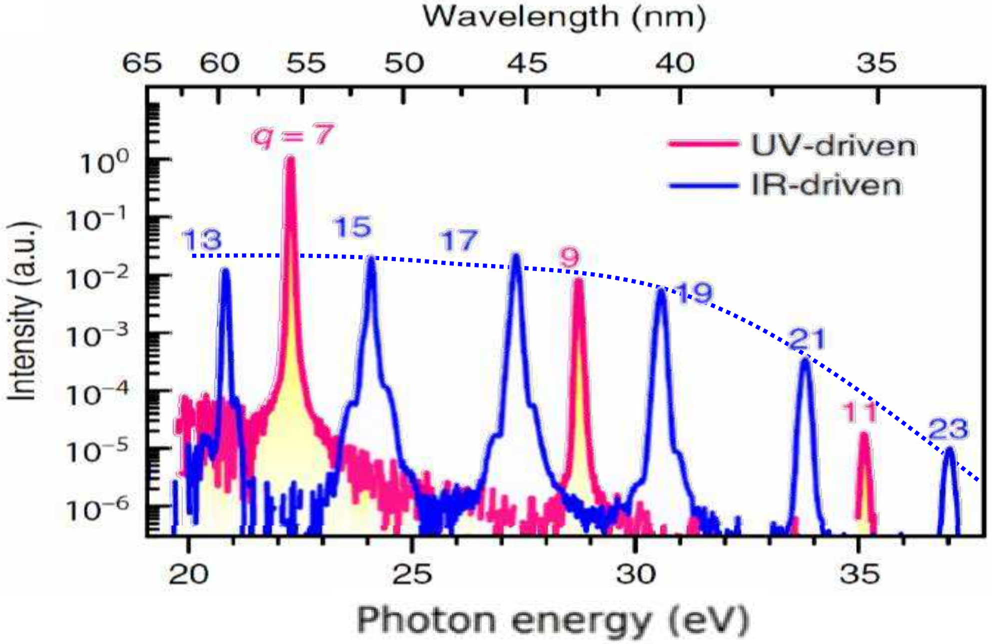
Energy conservation:

$E_\gamma \leq \; E_e$ at impact + ionization potential

$E_\gamma \leq 3.17U_p + I_p$ cut-off

$$U_p = \frac{(eE_0)^2}{4m_e\omega^2}$$ ponderomotive potential energy

Yb, 1030 nm,
~0.5 MV/cm or 10^{13} W/cm^2
I_p (He) = 25 eV
⇒ E_γ < 130 eV



H. Wang et al, Nat. Comm. 6:7459 (2015)

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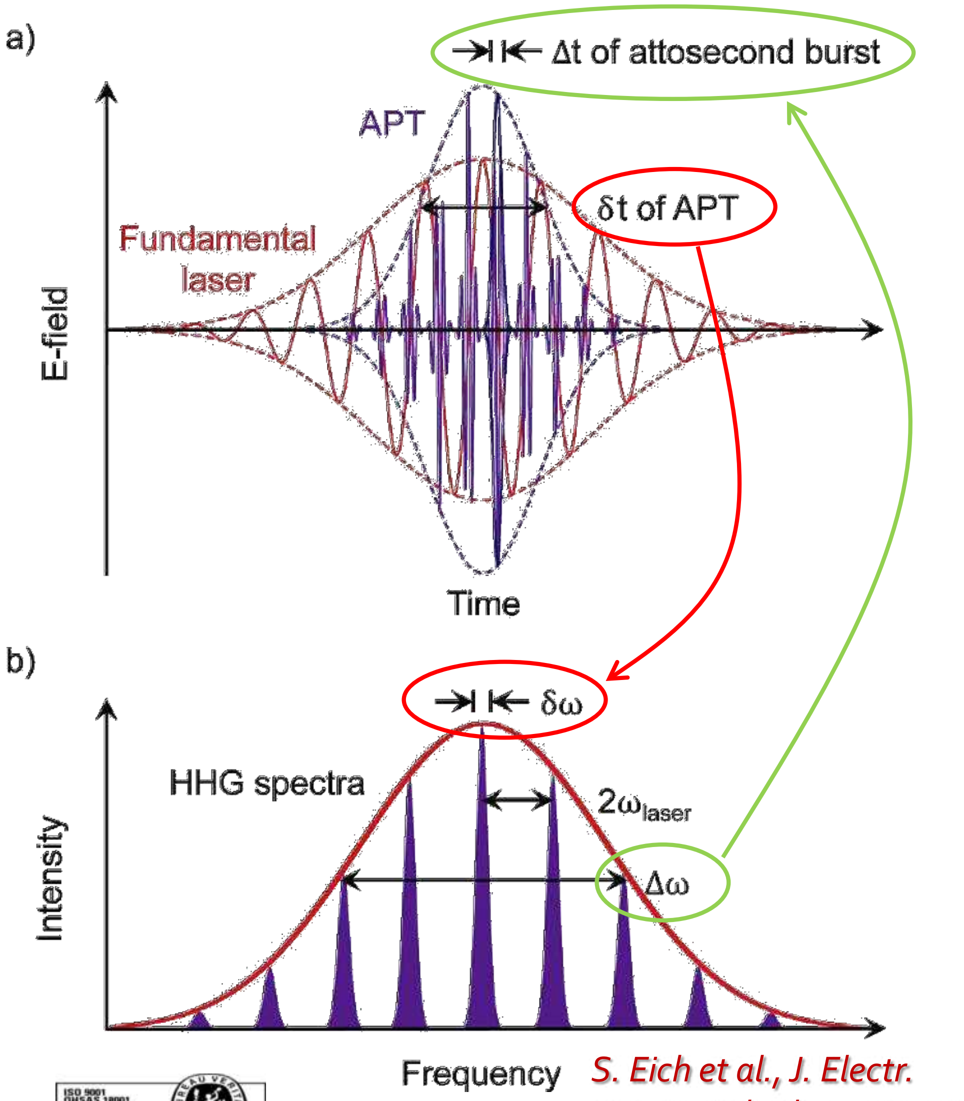
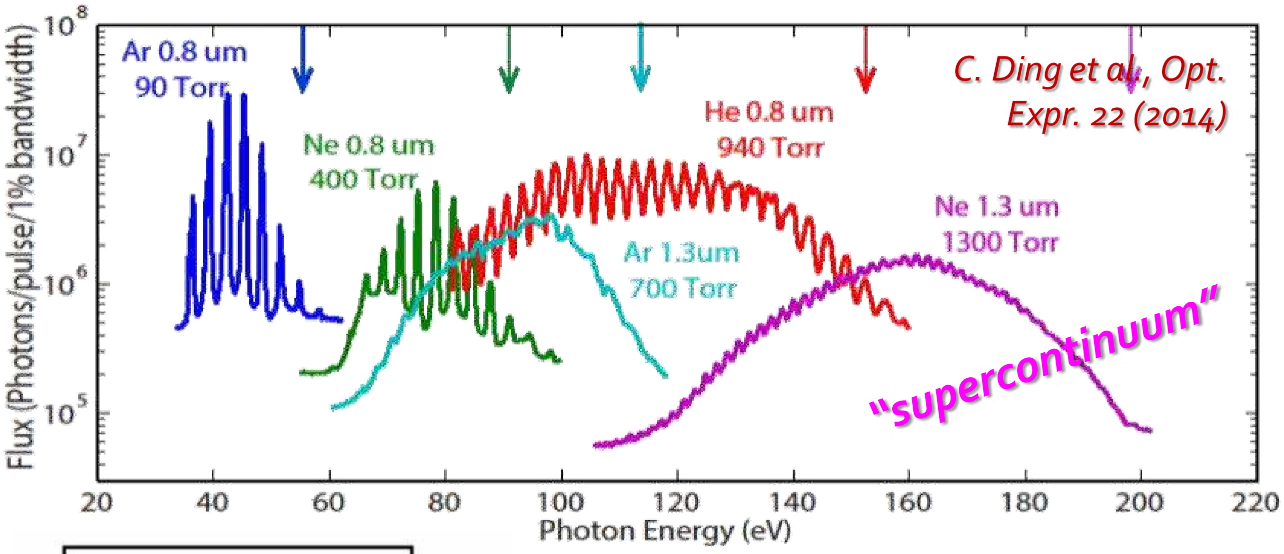
Spectrum

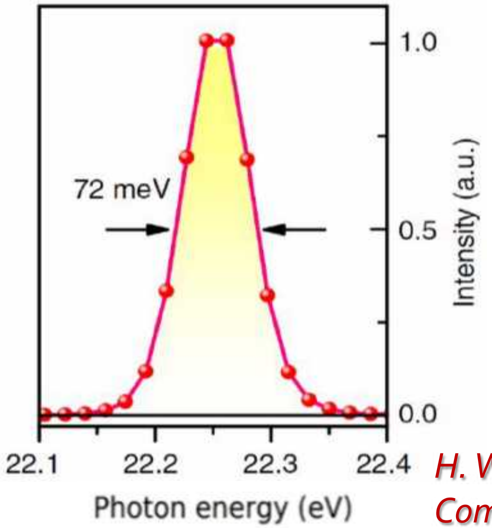


S. Eich et al., J. Electr. Spectr. Rel. Phen. (2014)

$\lambda_L = 0.3 - 1\ \mu m \;\Rightarrow\; 2\omega_L \sim 8 - 2\ eV$



C. Ding et al., Opt. Expr. 22 (2014)



H. Wang et al, Nat. Comm. 6:7459 (2015)

Ti:Sa, 100 fs
$h\nu = 20\ eV$
$\Rightarrow bw \approx 0.2\%$

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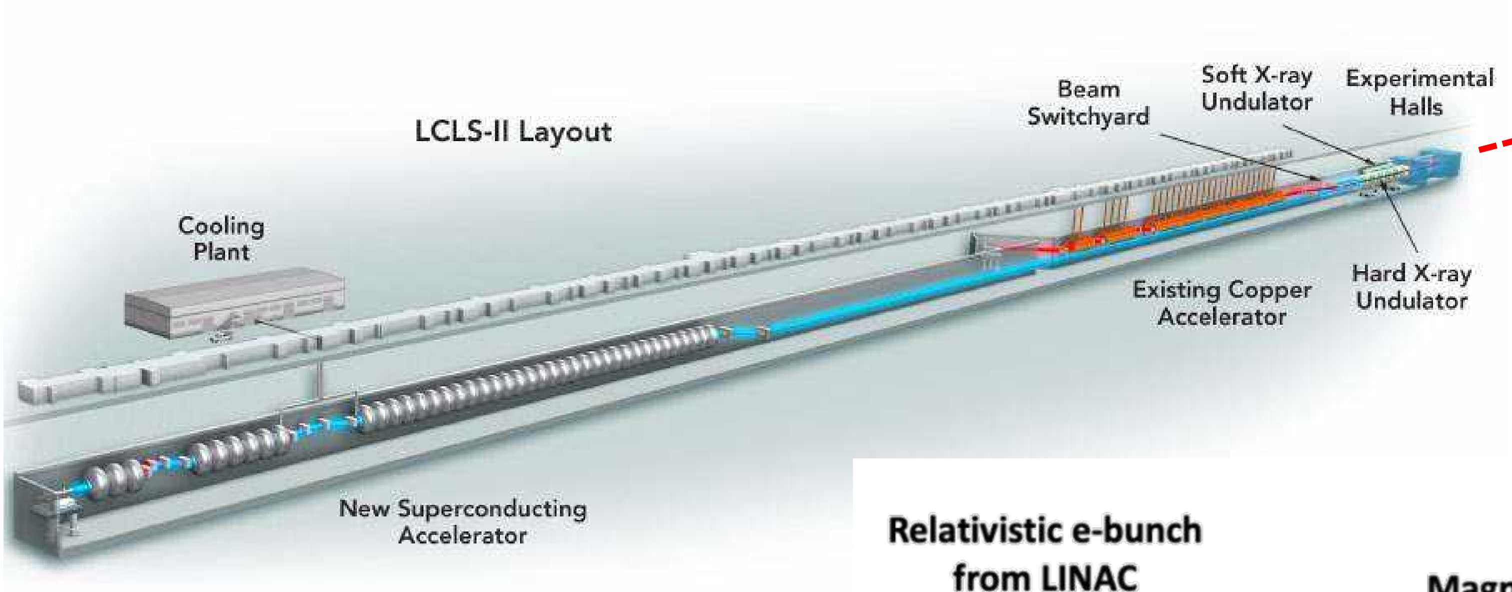
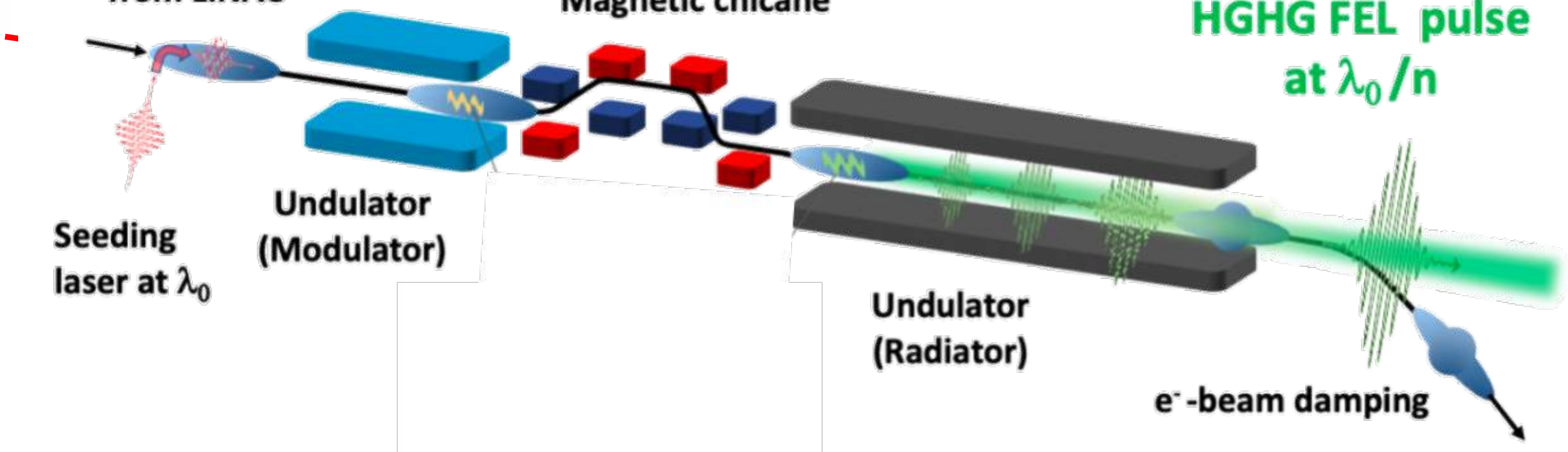
High Gain FEL



~ 5 m × 0.1 - 3 km

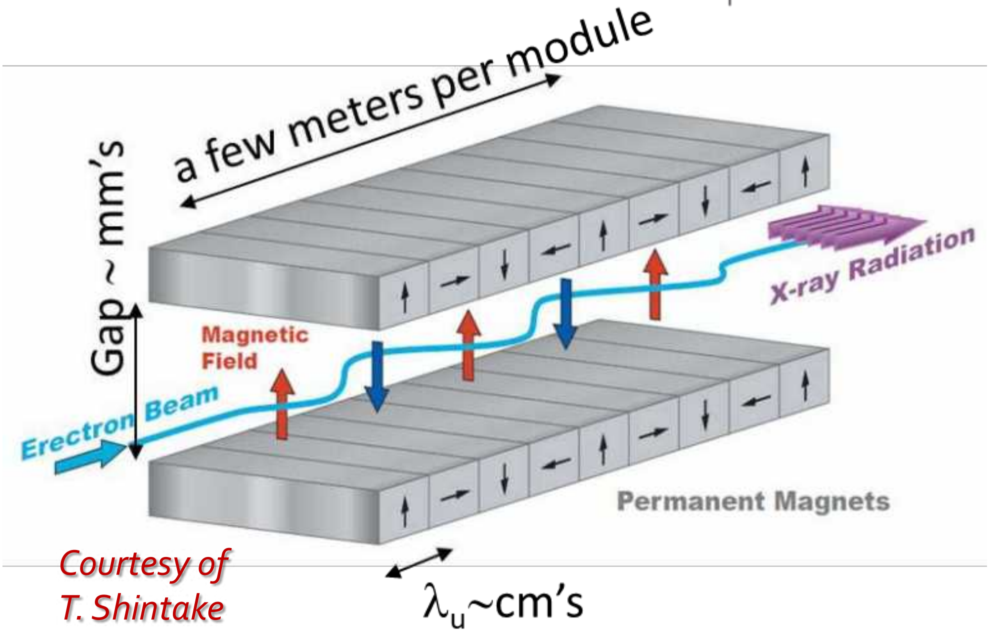
Relativistic e-bunch from LINAC



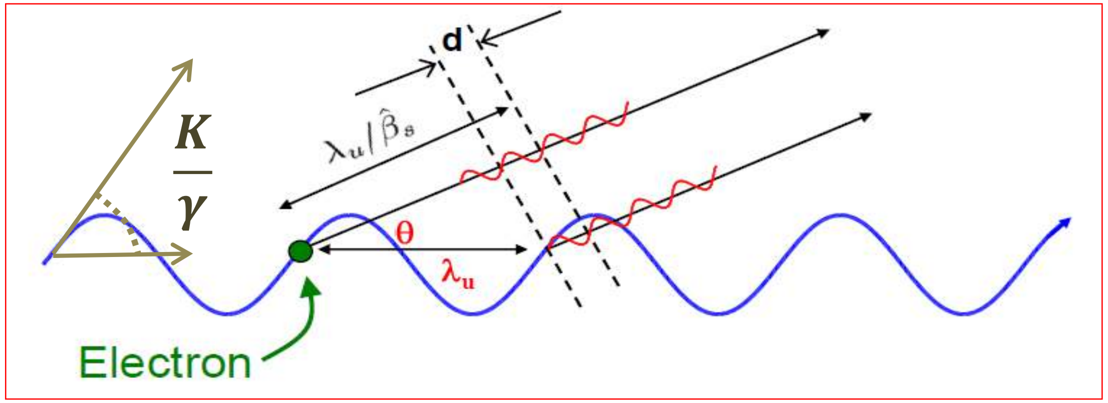
LCLS-II TDR

F. Benatti et al., Opt. Expr. 29, 24 (2021)

Undulator Spontaneous Radiation



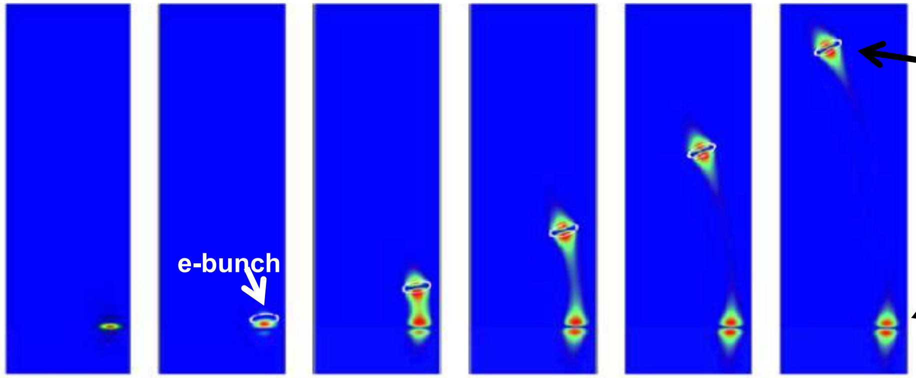
Courtesy of T. Shintake



Undulator parameter

$$K = \frac{eB_y\lambda_u}{2\pi m_0 c}$$

Constructive interference: $\frac{\lambda_u}{v_z} - \frac{\lambda_u cos\theta}{c} = \frac{\lambda}{c} \Rightarrow \lambda = \frac{\lambda_u}{2\gamma^2}\left(\underbrace{1+\frac{K^2}{2}}_{\text{central wavelength}} + \underbrace{\gamma^2\theta^2}_{\text{red-shift off-axis}}\right)$



Bunch self-field

Synchrotron radiation

$$\boxed{P_{SR} \propto \gamma^4 = \frac{E^4}{m_0^4}}$$

Courtesy of A. Novokatsky

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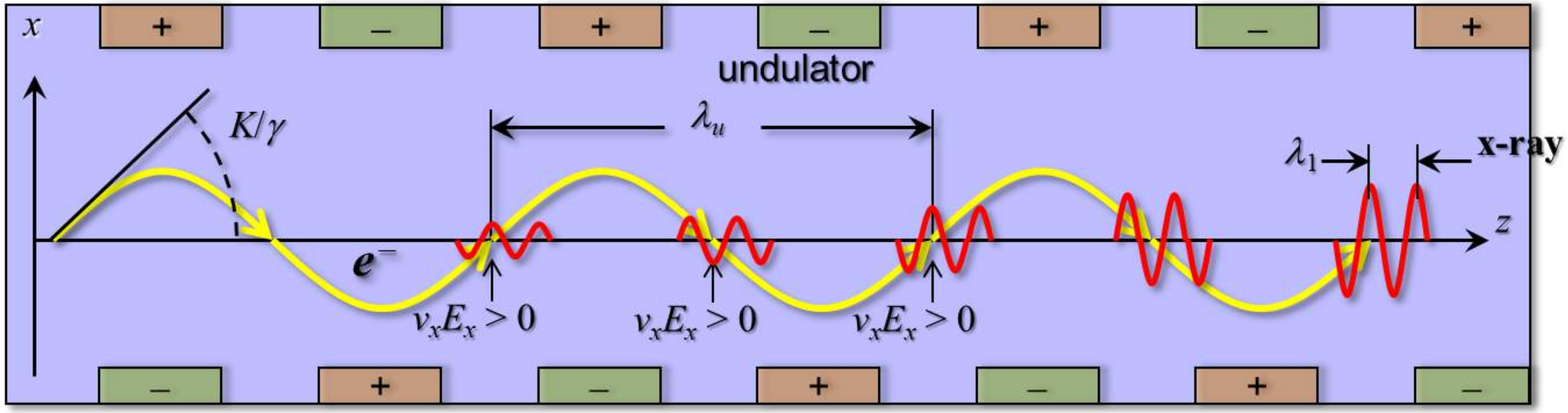
Undulator Stimulated Radiation



Courtesy of P. Emma

Energy exchange:

$$P = q\vec{E} \cdot \vec{v_\perp} > 0$$

Ponderomotive phase:

$$\zeta = (k_u + k)z - \omega t$$

Synchronization:

$$\frac{d\zeta}{dt} \equiv 0 \Rightarrow v_z = \frac{\omega}{k_u + k} = v_p$$

"Resonance" condition:

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

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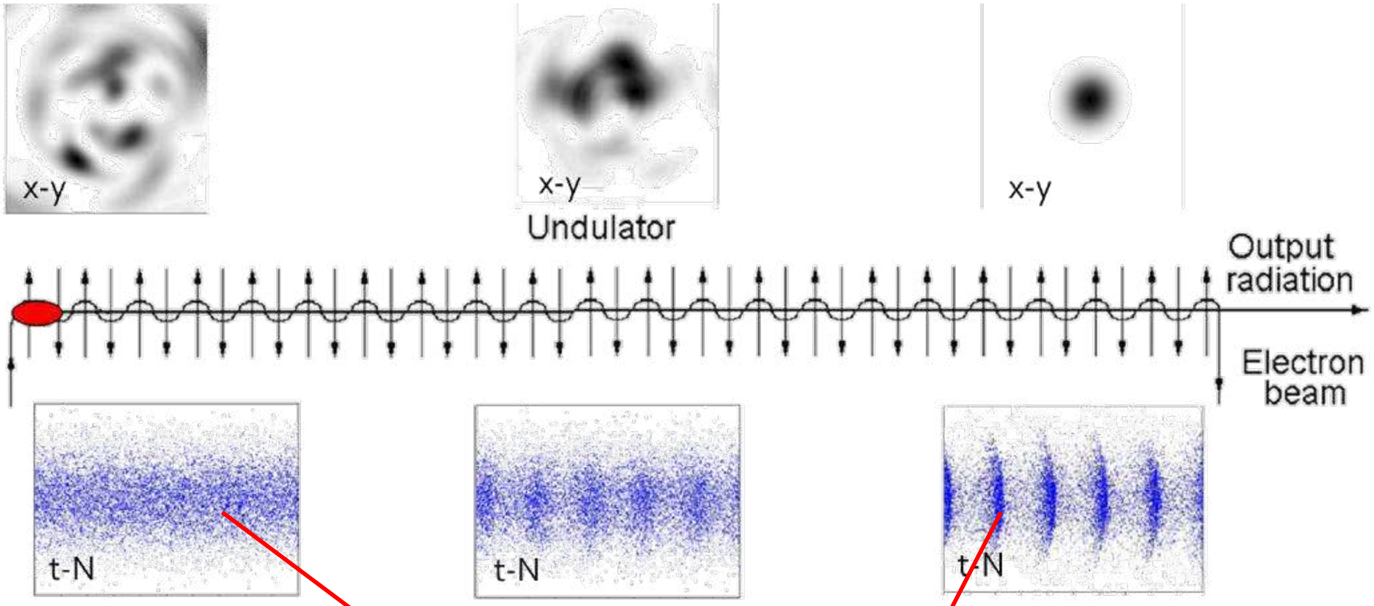
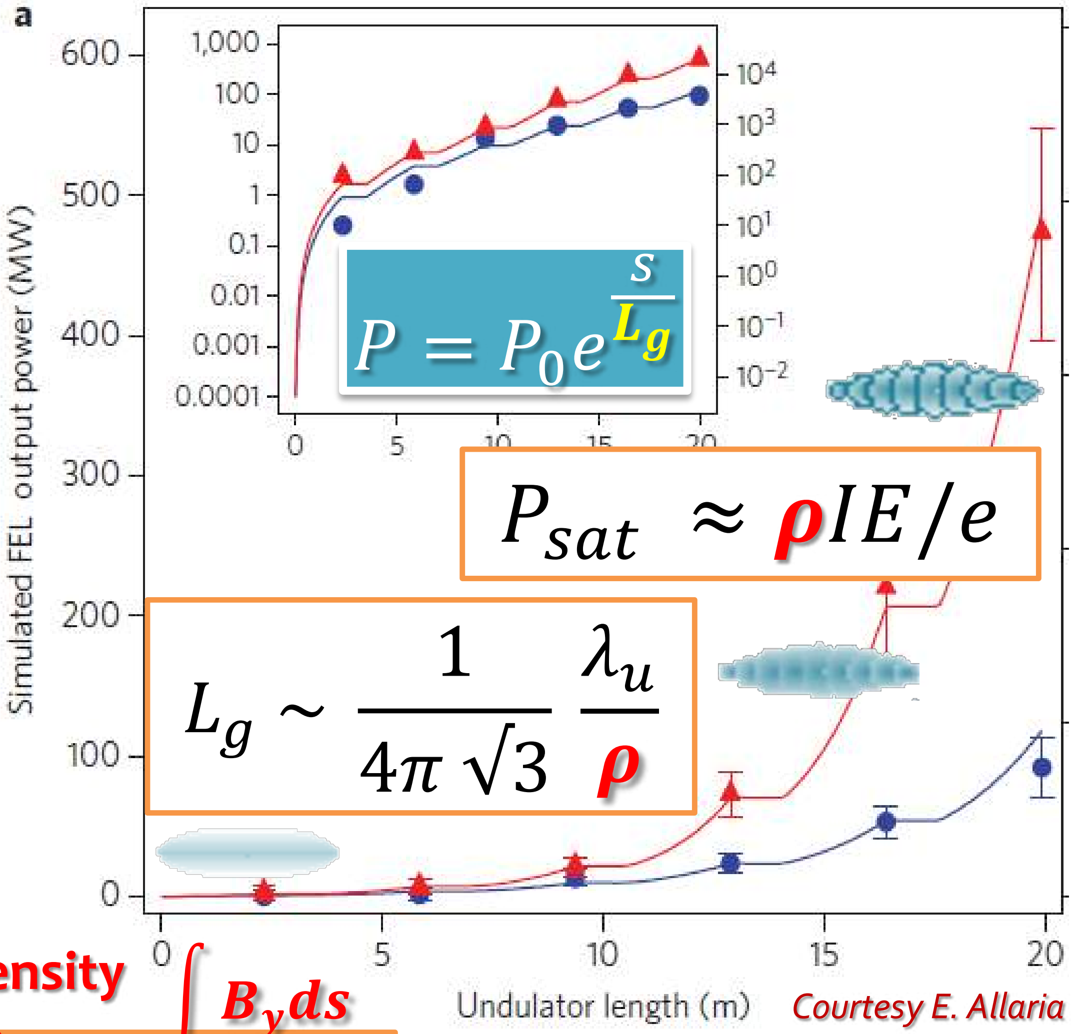
High Gain



Courtesy E. Saldin

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



$$P = P_0 e^{\frac{s}{L_g}}$$

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

$$L_g \sim \frac{1}{4\pi\sqrt{3}}\frac{\lambda_u}{\rho}$$

Courtesy E. Allaria

3-D charge density

$\int B_y ds$

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

beam energy

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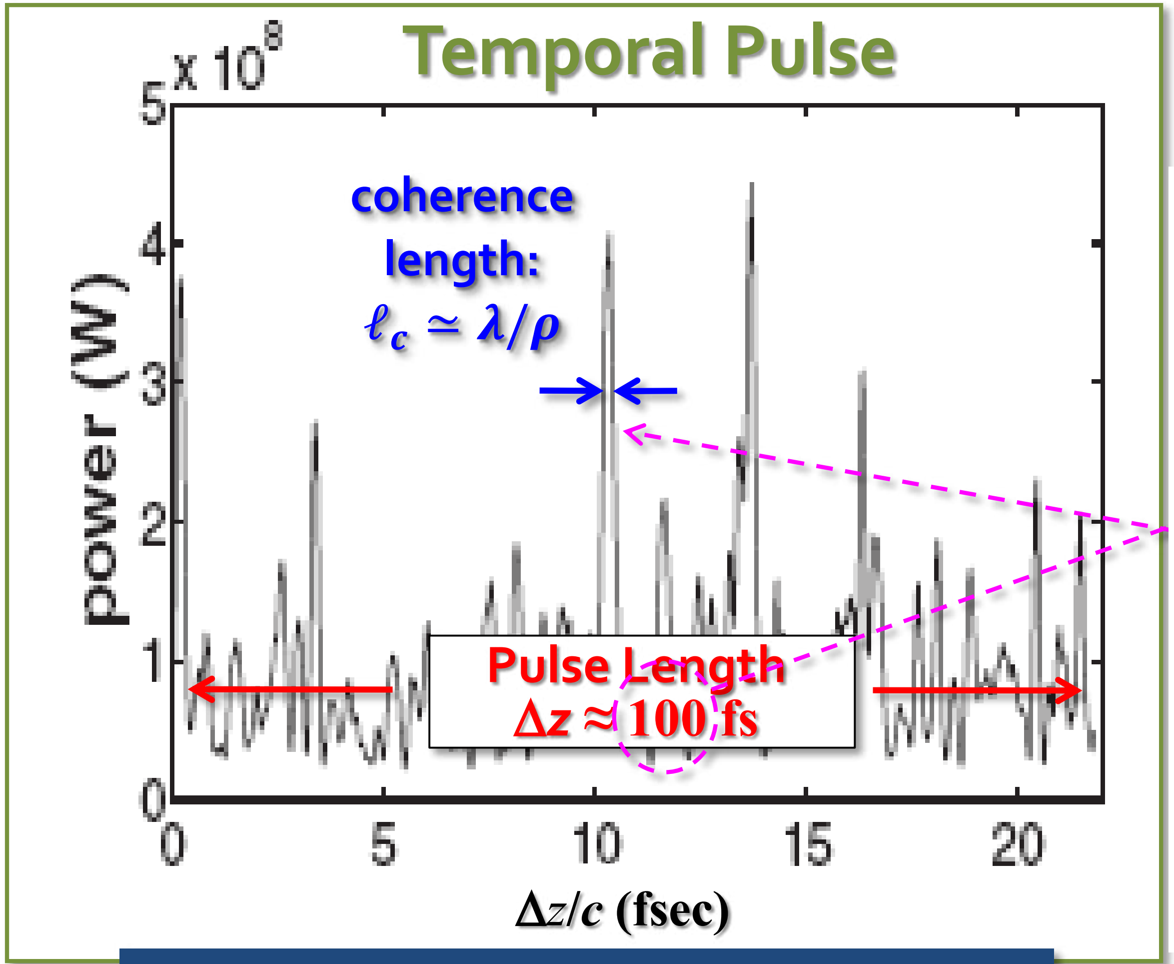
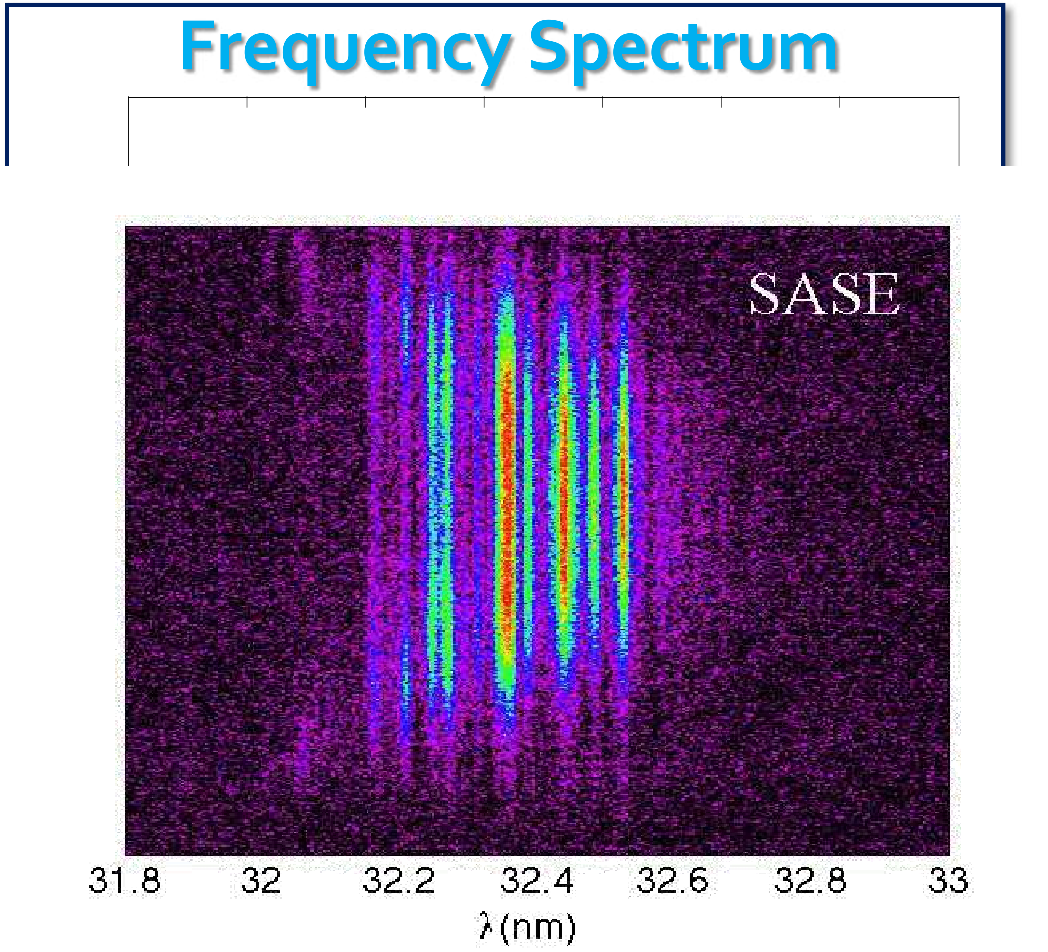
Self-Amplified Spontaneous Emission

spikes appear in temporal pulse

spikes also in spectrum



Temporal Pulse



Frequency Spectrum

$\lambda = 1$ Å, $\rho \approx 1\times10^{-3} \rightarrow \ell_c \approx 0.3$ fs

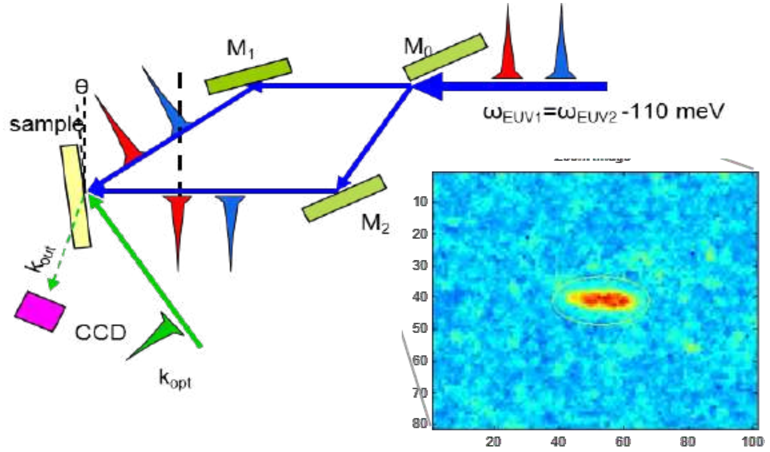
$\Delta z/c = 100$ fs $\rightarrow \lambda/\Delta z \approx 3\times10^{-6}$

Courtesy P. Emma, M. Venturini, L. Giannessi

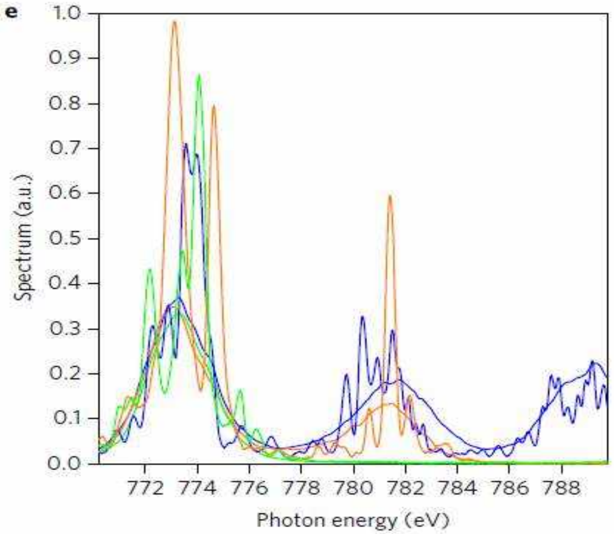
Operating Modes

2/3-color, pump-probe 4-wave mixing

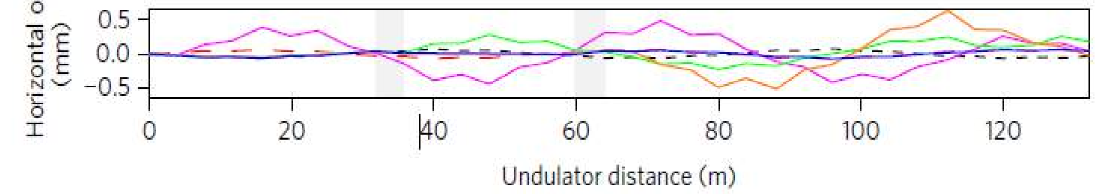
F. Bencivenga et al., Faraday Discuss. 194 (2016)



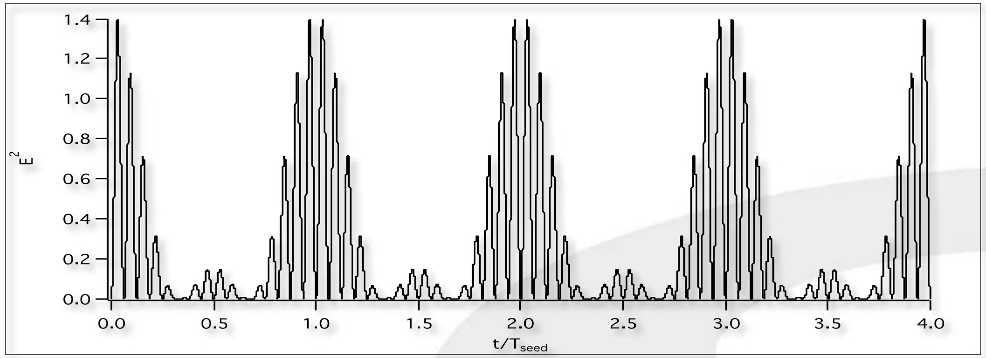
Different colors on different orbits



A. Lutman et al., Nat. Phot. 10 (2016)



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



The superposition of >3 phase-locked FEL harmonics generates a train of attosecond pulses

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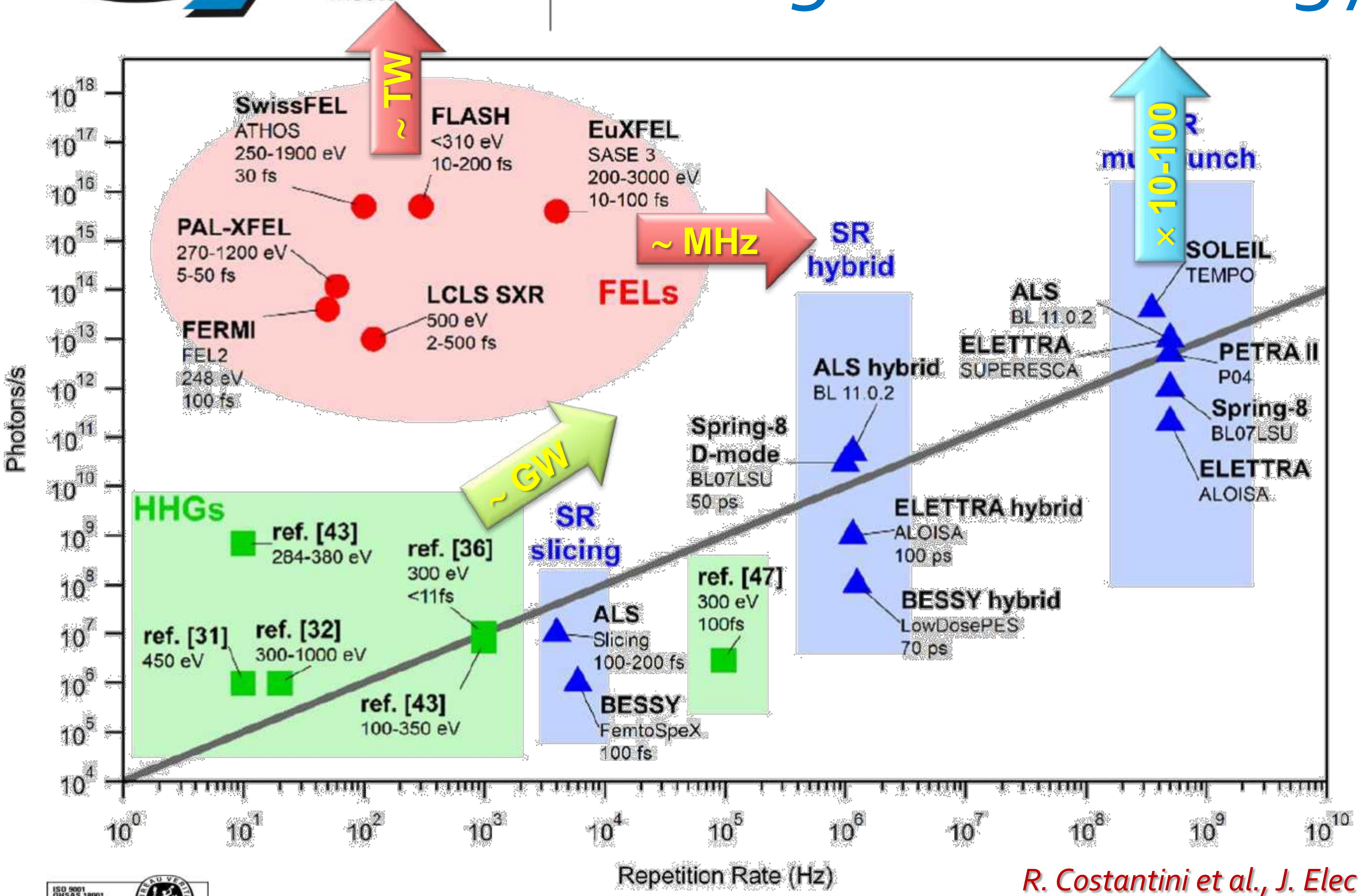
Average Pulse Energy



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

SRLS:

✓ easyness of access
✗ lack (sub-)ps pulses

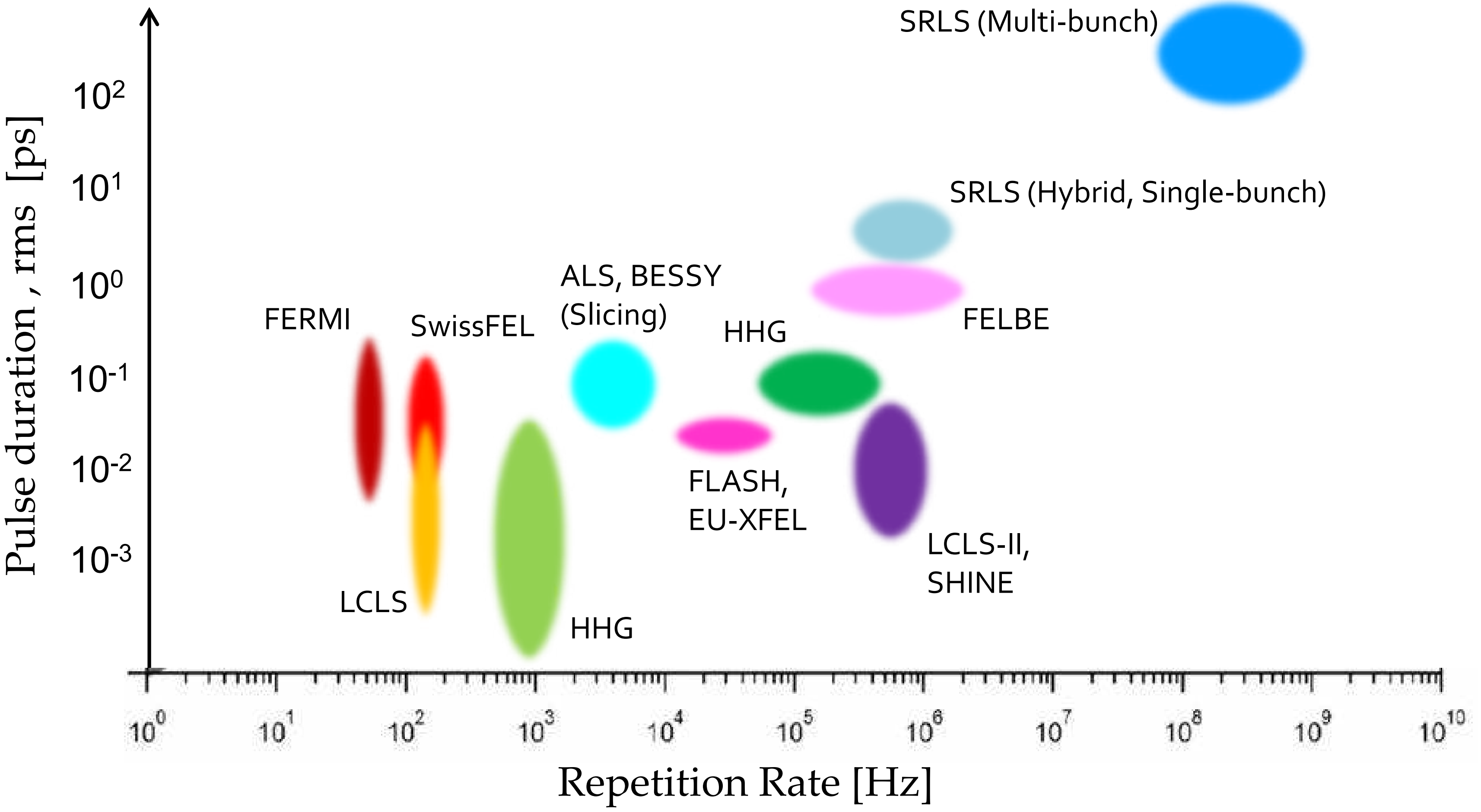
HHG:

✓ lab-scale size
✗ lack pulse energy

FEL:

✓ large peak power
✗ limited access

Pulse Duration



SRLS:

new generation (multi-bend) tends to produce **longer bunches**

HHG:

pushing **<fs** pulses towards **MHz** repetition rate

FEL:

super-conducting linacs target **as** pulses at **MHz** repetition rate

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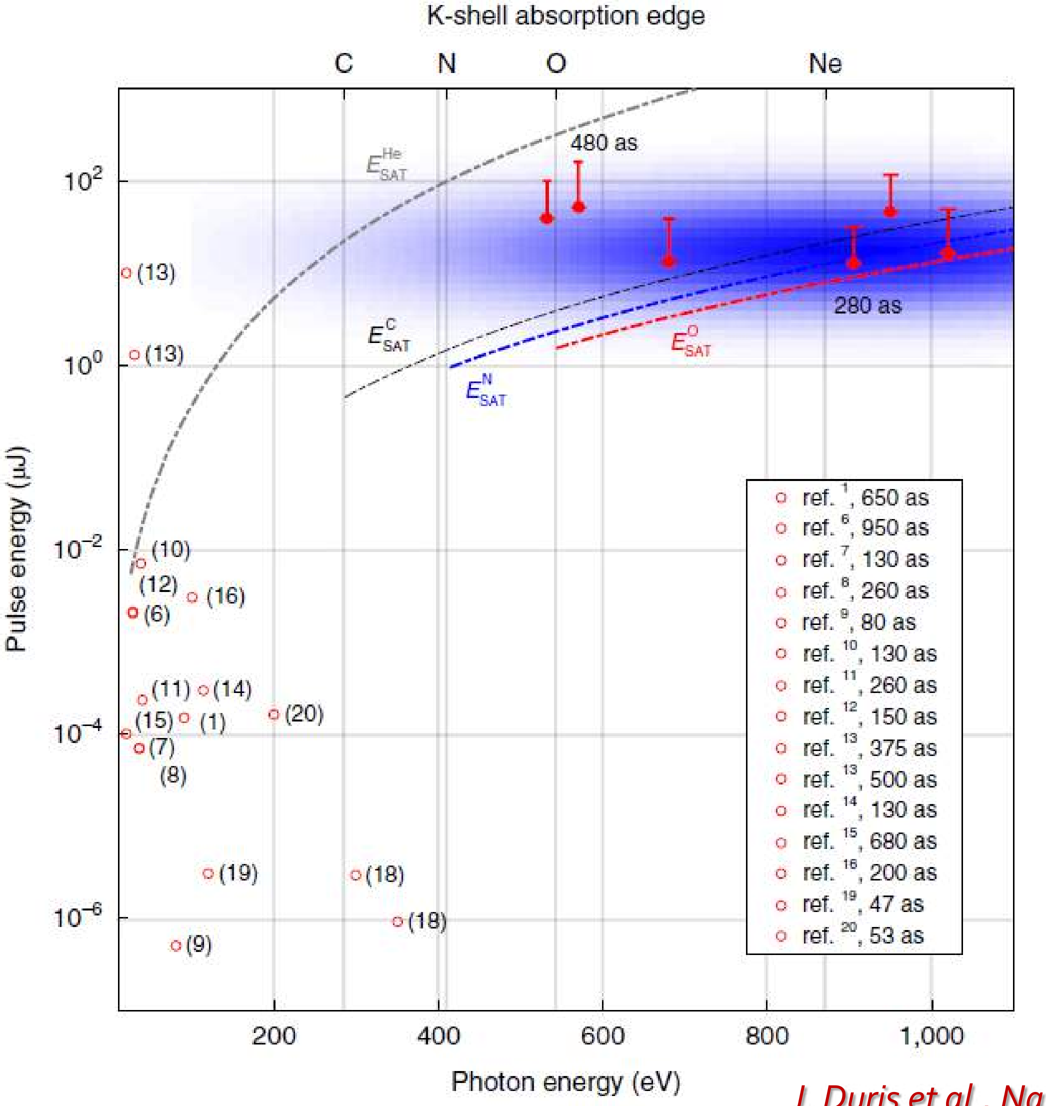
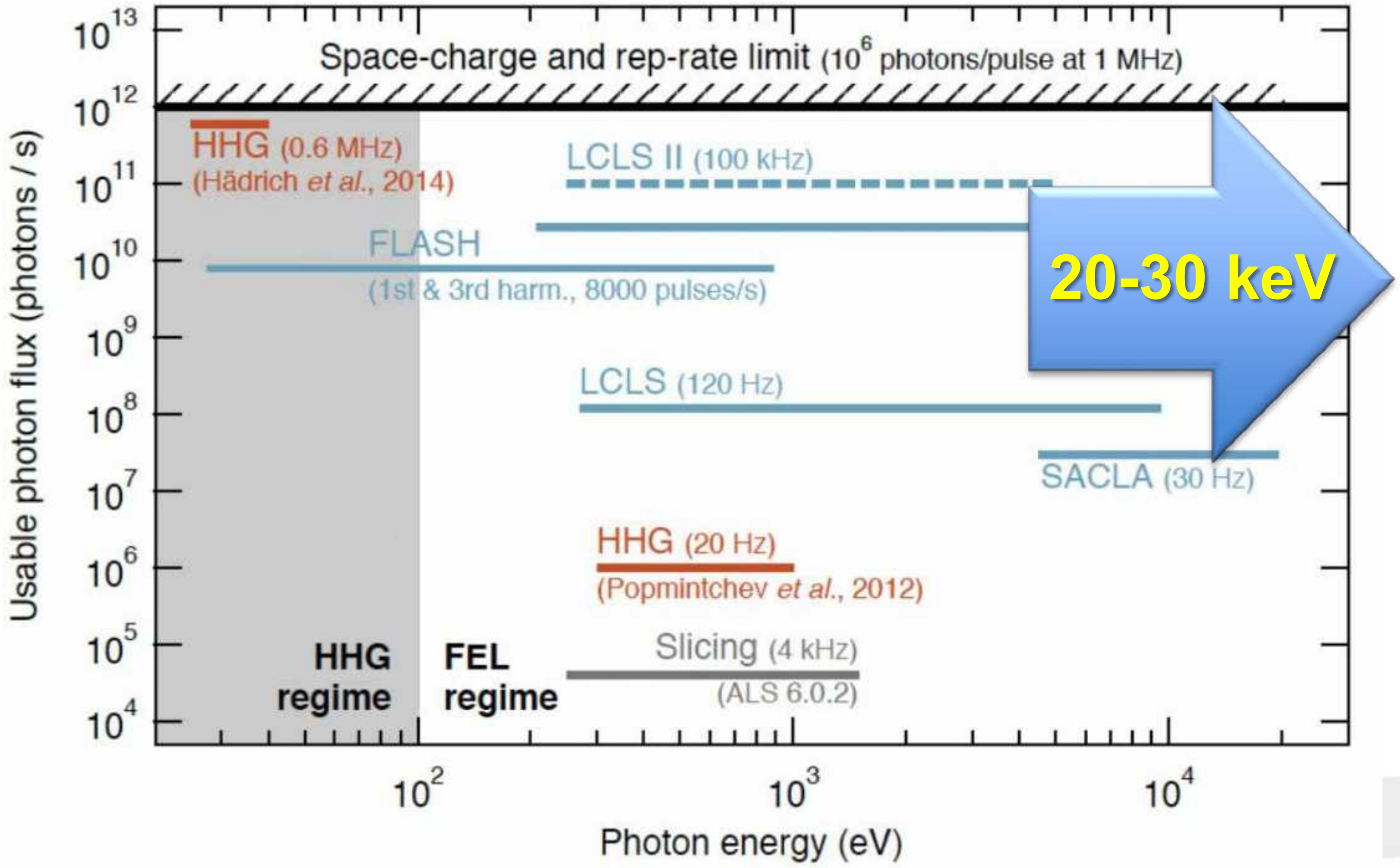
Peak Pulse Energy



J. Duris et al., Nat. Phot. 14 (2020)

Courtesy S.L. Molodtsov, School on SR & FEL Methods (2018)



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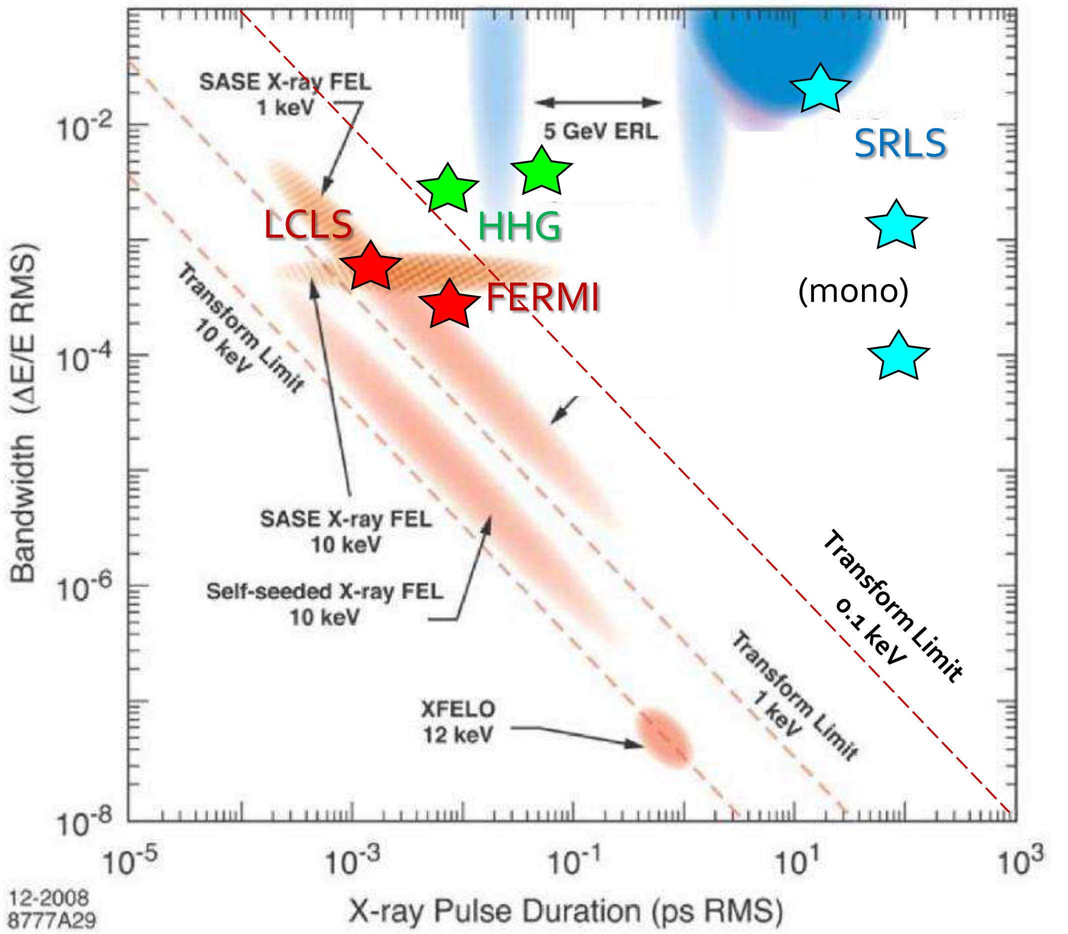
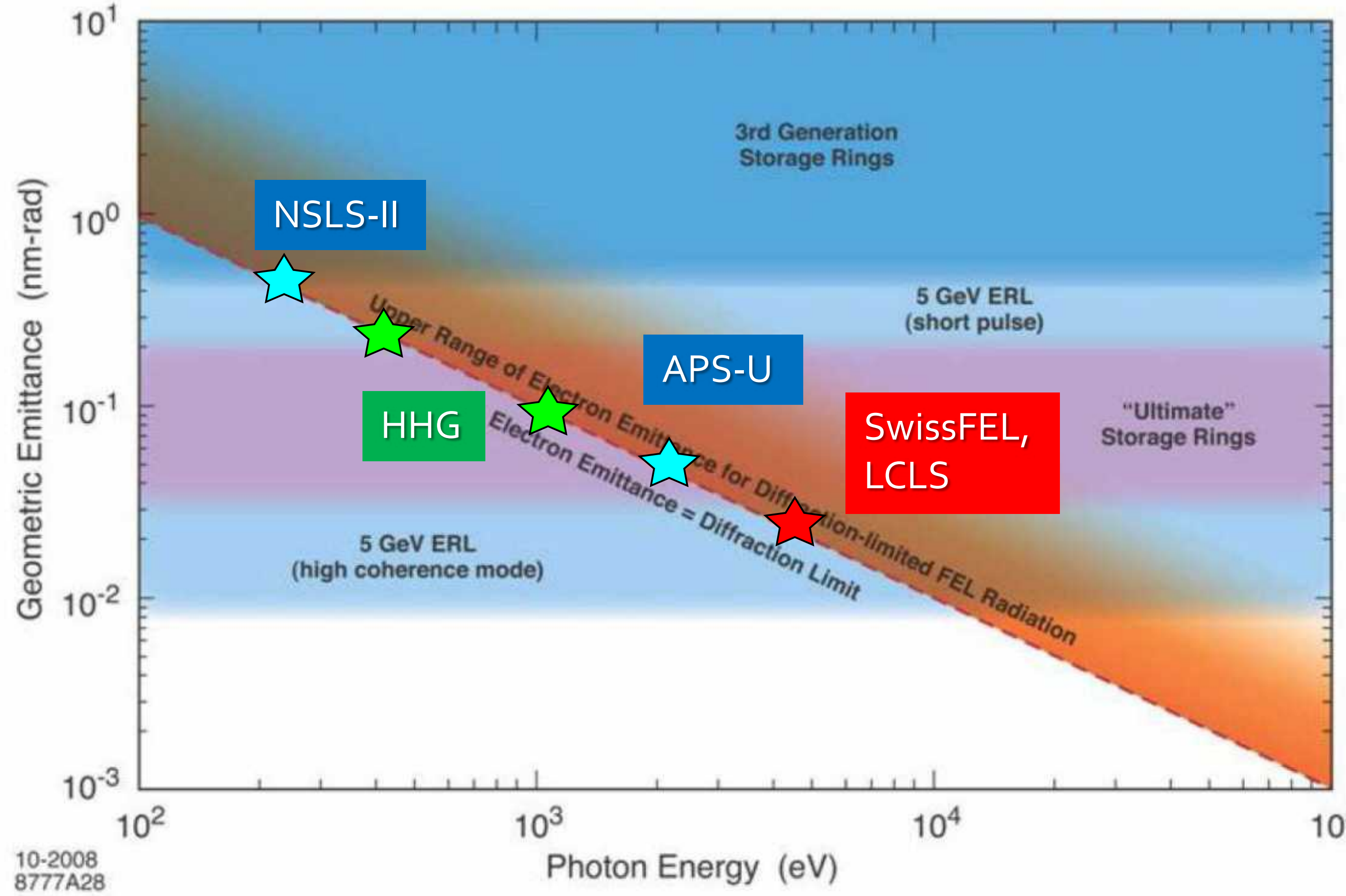
Coherence

Fourier Transform Limit, $\sigma_\nu \sigma_t = \frac{1}{4\pi}$ **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).

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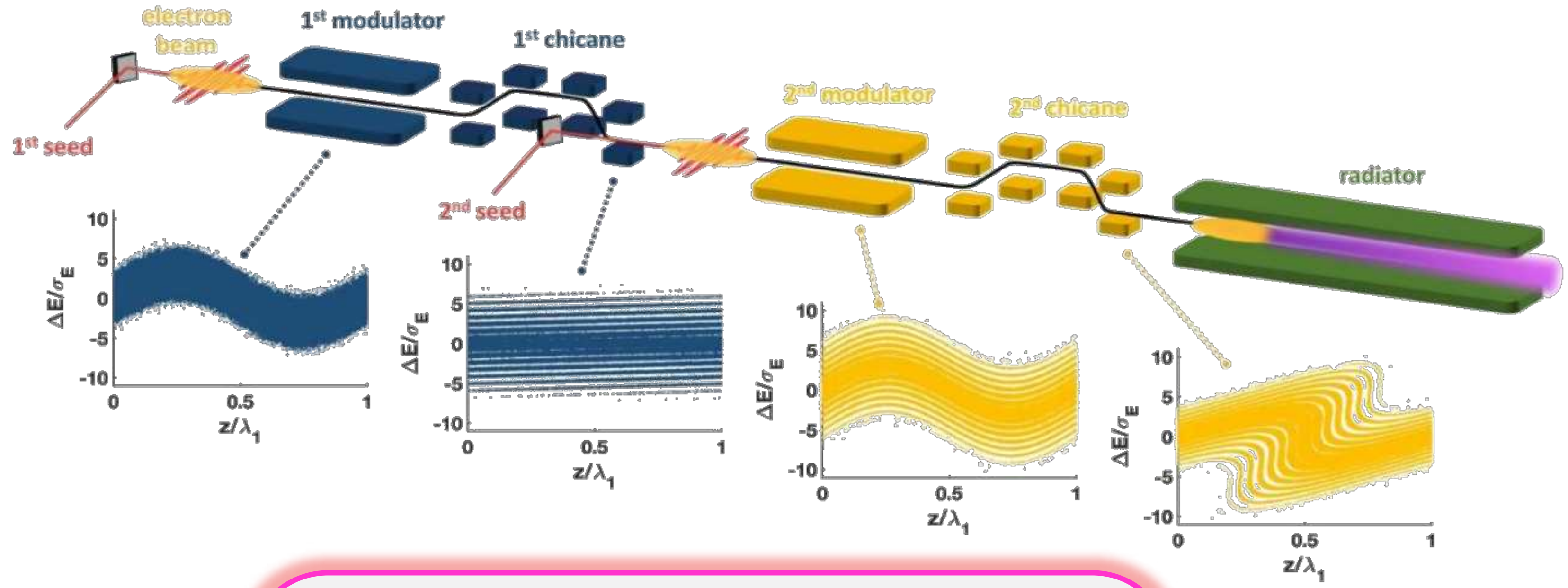
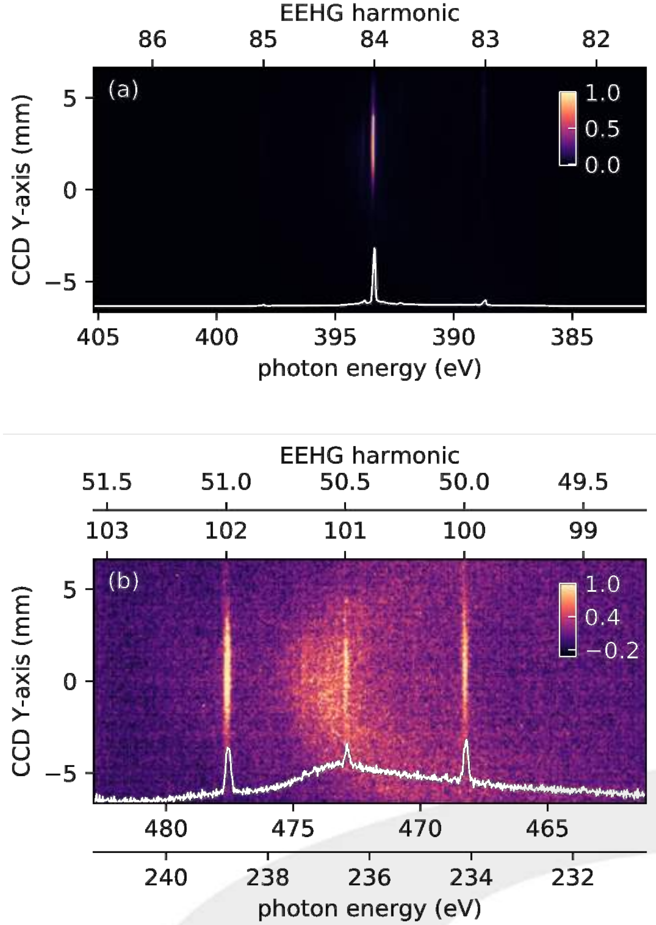
EEHG FEL

P. R. Ribic et al.,
Nat. Phot. 13 (2019)



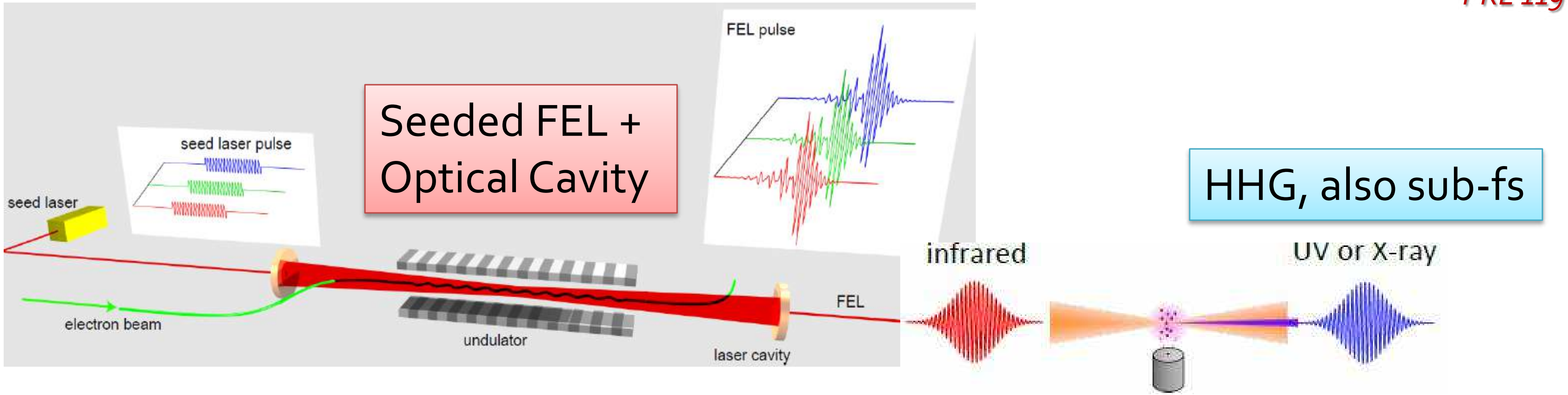


Echo-Enabled Harmonic Generation:

- stable, intense, fully coherent pulses at ~ 1 keV
- *but rep. rate < 1 kHz*

CEP-FEL HHG

R. Hajima, R. Nagai
PRL 119 (2017)



Seeded FEL + Optical Cavity

HHG, also sub-fs

FEL–HHG:

- stable, fully coherent pulses at ~ 1–10 keV, (sub-)fs, < 1 MHz
- 20 x 50 m^2 size
- *but < 10's μJ pulse energy*

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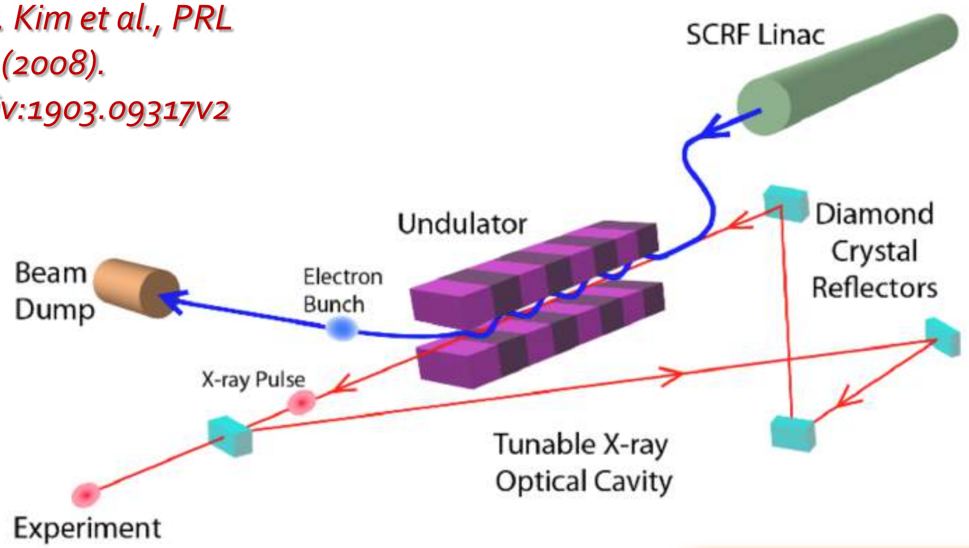
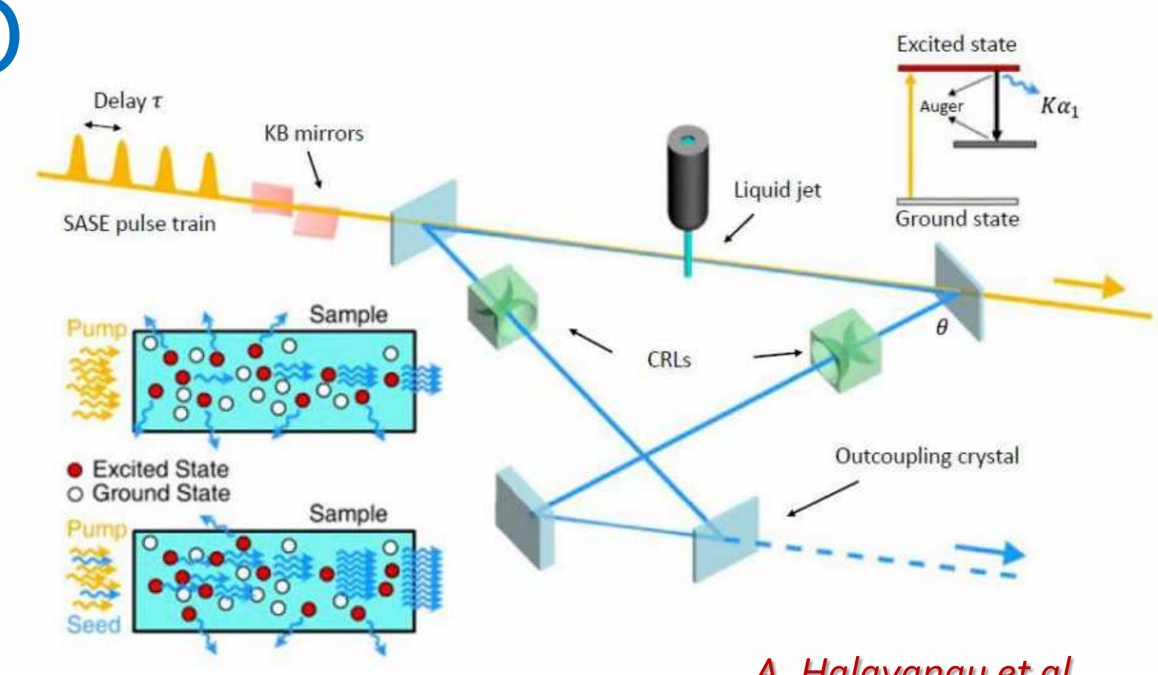
XFELO, XLO

K.-J. Kim et al., PRL 100 (2008).
arXiv:1903.09317v2





A. Halavanau et al., PNAS 117, 27 (2020)

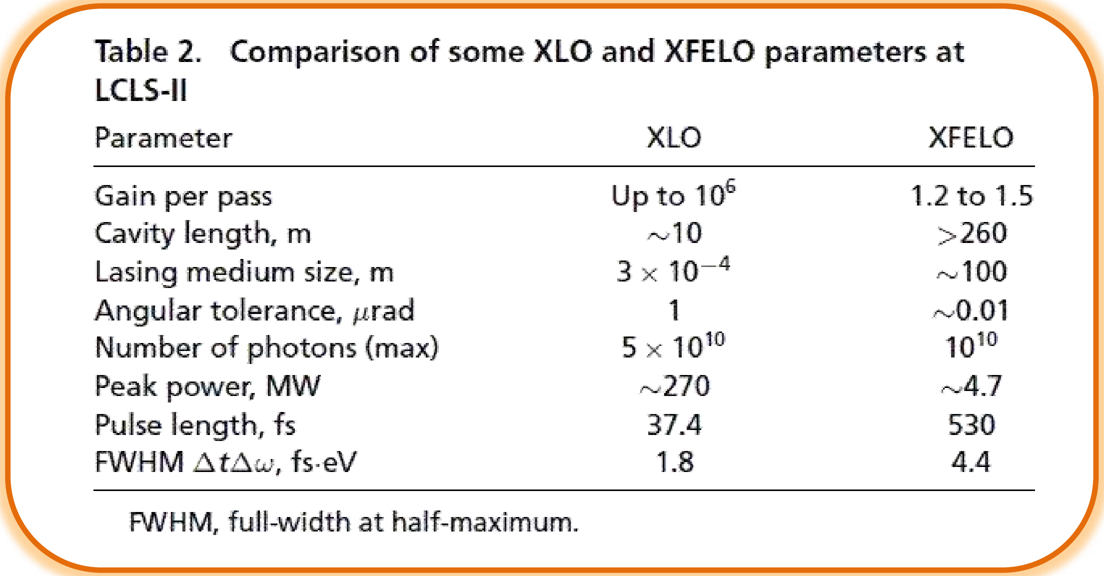


Table 2. Comparison of some XLO and XFELO parameters at LCLS-II

Parameter	XLO	XFELO
Gain per pass	Up to 10^6	1.2 to 1.5
Cavity length, m	$\sim$10	$>$260
Lasing medium size, m	3×10^{-4}	$\sim$100
Angular tolerance, μrad	1	$\sim$0.01
Number of photons (max)	5×10^{10}	10^{10}
Peak power, MW	$\sim$270	$\sim$4.7
Pulse length, fs	37.4	530
FWHM $\Delta t \Delta \omega$, fs·eV	1.8	4.4

FWHM, full-width at half-maximum.

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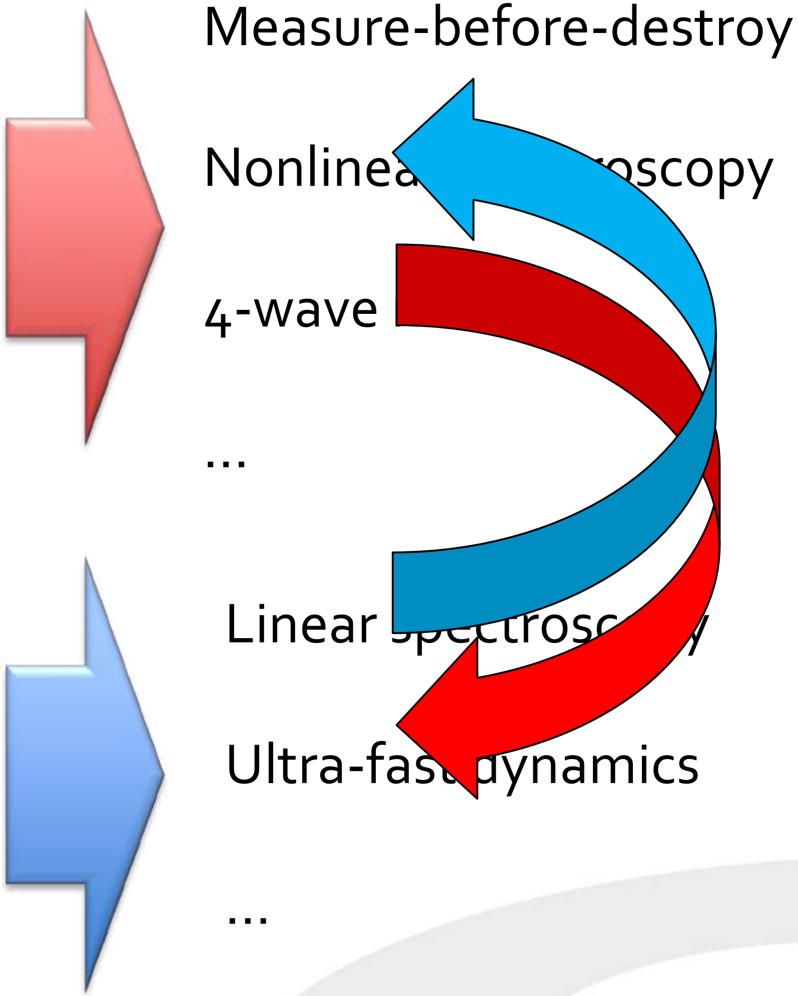
Final Remarks

Present XUV FELs:

- Large size, > 100 – 1000 M€ -scale, limited access
- Low/burst repetition rate
- ~100% transversally coherent, high power density light pulses
- ~100% longitudinally coherent pulses in UV or hard x-ray
- Multi-color, 2-pulse, continuous λ & polarization control

Present HHGs:

- Small size, 1 – 10 M€ -scale, easy access
- High, tuneable repetition rate
- Fully coherent light pulses at moderate power density over entire XUV range
- Limited λ & polarization control



Measure-before-destroy

Nonlinea[illegible]oscopy

4-wave

…

Linear spectroscopy

Ultra-fast dynamics

…

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Thank you for your kind attention

Questions and comments are welcome!

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