Free Electron Lasers: Are “New Architectures” Feasible?

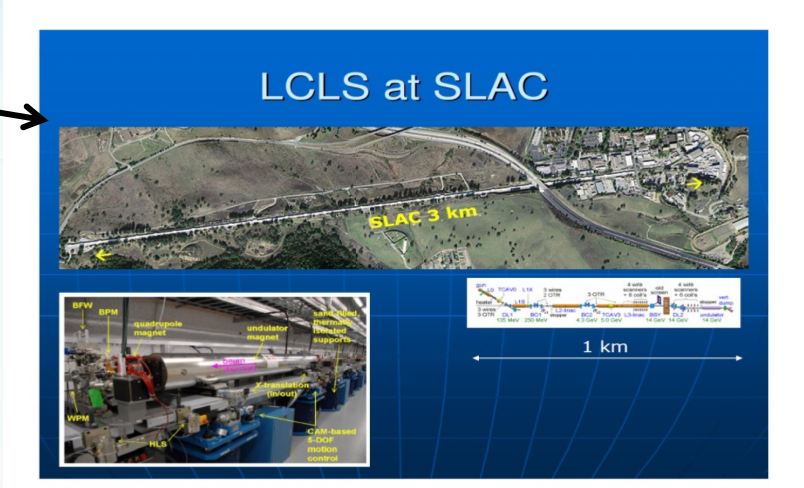
G.Dattoli
C.R.E. ENEA, Frascati, Italy

Common places !!!

- Free Electron Lasers (FELs) are certainly among the most interesting devices, belonging to the realm of coherent radiation sources. These lasers are now widely used all over the world and are the highest performing in terms of brilliance, monochromaticity, coherence, directionality and polarization control.
- Despite their undoubted success and reliability as experimental devices, their wider use is still hampered by their size and cost, which require large laboratories and significant financial efforts.
- It would be therefore desirable to develop more compact and economical FELs with, e.g., higher repetition rates and larger average brightness.

4-th Generation SR Sources
the right choice?

- Size
- Cost



FEL size and cost

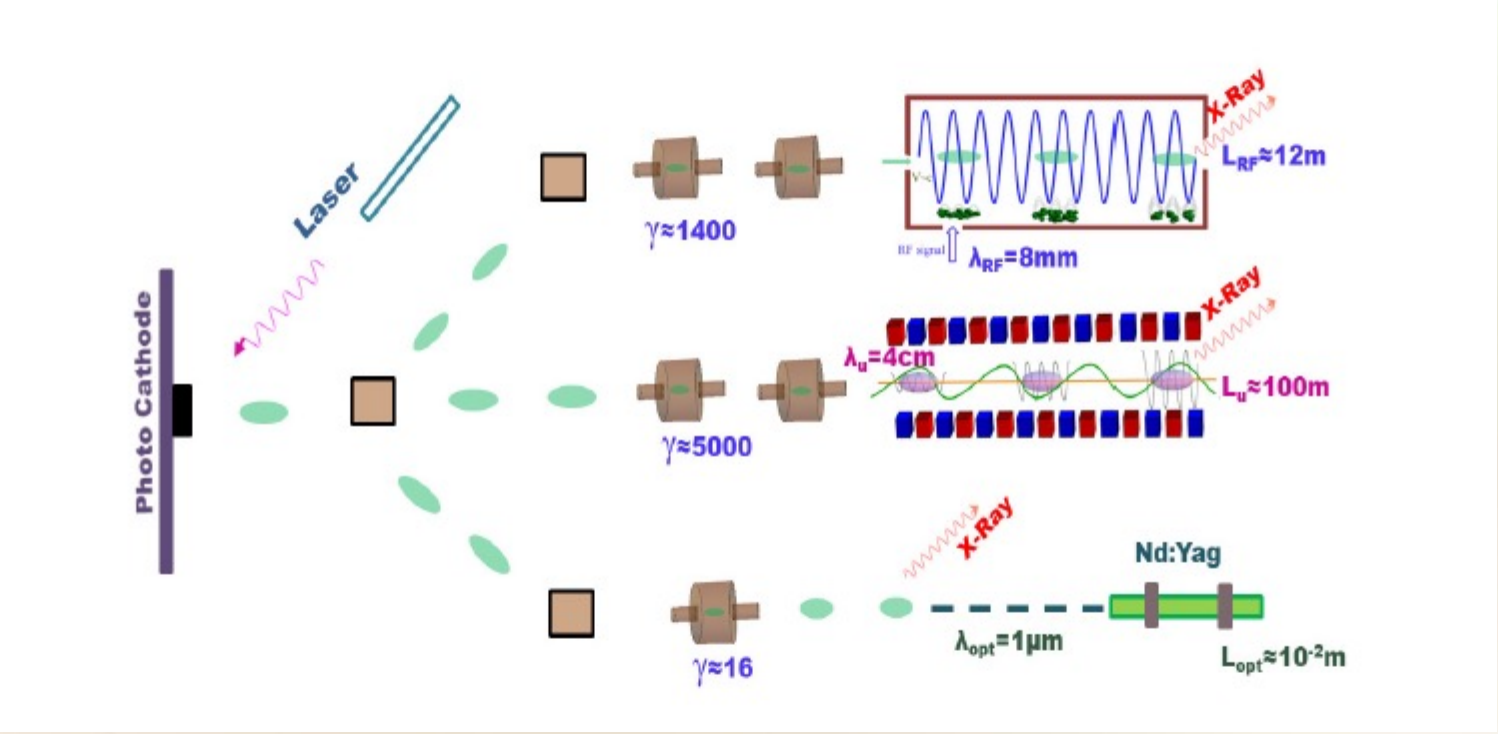
Wavelength	Energy	Size [m]	Cost [M$
IR 2-10 μm	10-40 MeV	3-10	1-5
EUV 13.5 nm	0.5-1 GeV	40	30-50
X 0.15 nm	15 GeV	500-1000	1000

The point is what do we need?

- compact accelerators and shorter undulator sections:
- high gradient accelerating devices, capable of providing high-quality electron beams and non-standard undulator lines
- “Alternative” undulator lines (Wave Undulators…)
- Combined architectures: non-linear harmonic generation, seeding, hybrid devices, coupled oscillators amplifier systems…

Undulator options and…

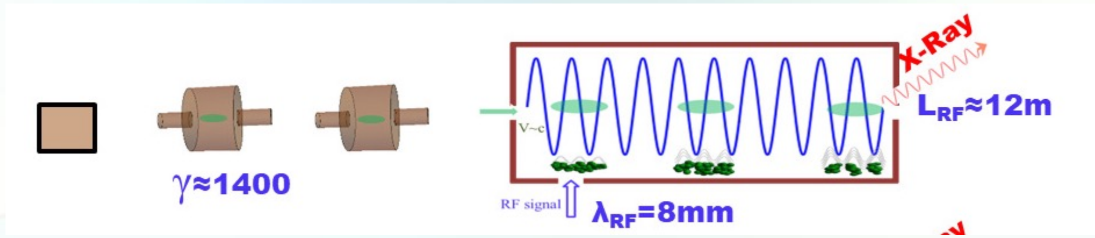
- X-ray operation
- E. Di Palma et al. **Radio-Frequency Undulators, Cyclotron Auto Resonance Maser and Free Electron Lasers MDPI**, (2021)



Are there any Reliable Alternatives?

- ***A. Curcio, G. Dattoli and D. Giulietti***
- **Oscillator-Amplifier Free Electron Lasers an Outlook to Their Feasibility and Performances**
- ***G. Dattoli, E. Di Palma, S. Sabchevski and I. Spassovsky***
- **RF-Based Undulators and High-Gradient Accelerator Fed by High-Frequency Electromagnetic Devices**

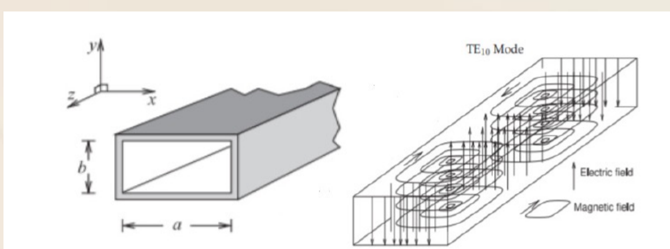
Microwave undulators



- M. Seidel, Parameter Evaluation for Microwave Undulator Schemes; report number DESY-TESLA-FEL-2001-08; DESY: Hamburg, Germany, 2001
- C. Pellegrini, X-band microwave undulators for short wavelength free-electron lasers. AIP Conf. Proc. **2006**, 807, 30–45.
- A. Di Palma et al. Comments on the Physics of Microwave-Undulators, 2022 Science MDPI

$$\lambda_u = \frac{\lambda}{1+\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}},$$

$$B_u = \frac{E_0}{c}\left(1+\sqrt{1-\left(\frac{\omega_c}{\omega}\right)^2}\right),$$



$$E[V/m] \sim \sqrt{3}10^{-3}\omega[Hz]K.$$

$$K_u = \frac{eB_u\lambda_u}{2\pi m_e c} = \frac{e\,E_0\lambda}{2\,\pi\,m_e c^2},$$

Pro's/Con's

- Tunability (field strength controlled very fast)
- Pipe Apertures not Critical
- No Radiation Damage
- Simplicity
- Short Wavelength Possible (14 mm period)

GOOD!!!! BUT

Field Strength: The best performance 0.35 T

Stability: As a dynamical and pulsed device an RF system is less stable than a static magnet

$$E_0 \cong \sqrt{\frac{Z_0 P}{ab}},$$

$$Z_0 = 120\pi\,\Omega \equiv vacuum - impedance.$$

Large inhomogeneous broadening induced by the waveguide machining…

Pellegrini (2006)-Di Palma et al. (2022)

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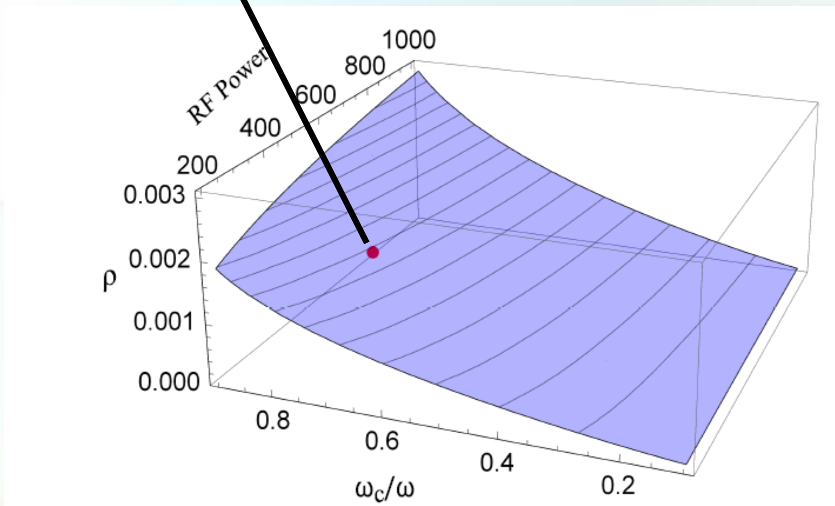
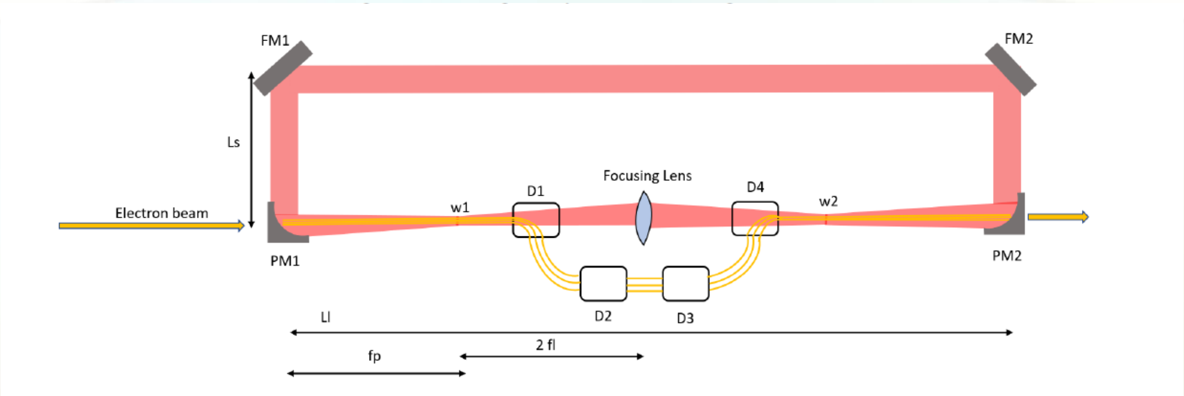


Beam Current [A]	1500
Beam Energy [MeV]	1300
Normalized Beam emittance [mm·mrad]	1
Twiss Parameter β [m]	5
Microwave Power [MW]	200
Equivalent undulator Period length λ_u [cm]	0.77–1.8
Undulator parameter Strength	$K_u = 0.15$–0.35
FEL operating wavelength	$\lambda \cong 2$–5 nm

More advanced conceptions

- **A. Curcio «Recirculated wave undulators for Compact undulators»**



$$\lambda = \frac{\lambda_L}{4\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

$$K = a_0 = 0.85 \times 10^{-5} \lambda_0[m] \sqrt{I_p(W/m^2)}$$

$\lambda_L \cong 10.6\,\mu m$ $\quad E_e \rightarrow$ reduced by a factor 100

Non Linear Harmonic generation

$$\vec{B}_u \equiv B_0[0, \sin(k_u z), 0].$$

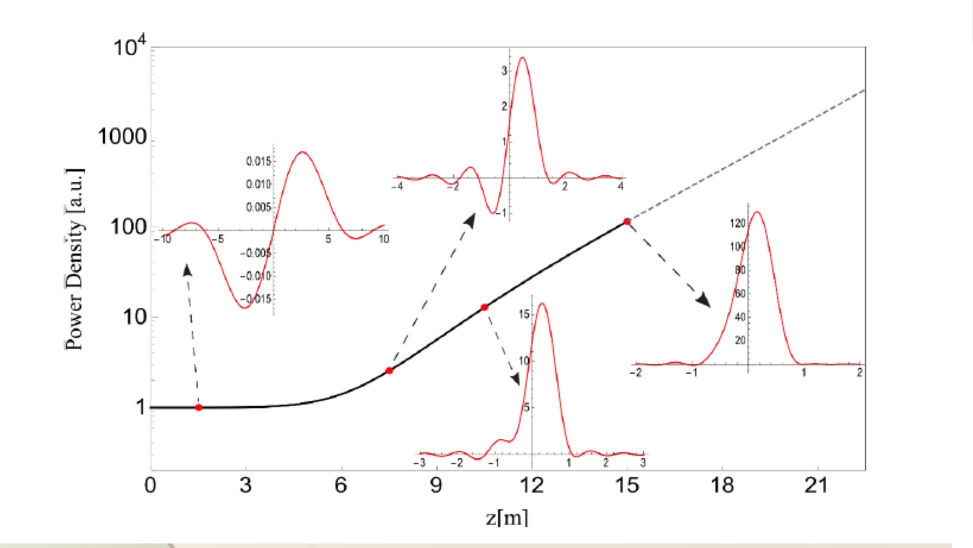
$$|a|^2 = 8\,\pi^2 \frac{I}{I_s},$$

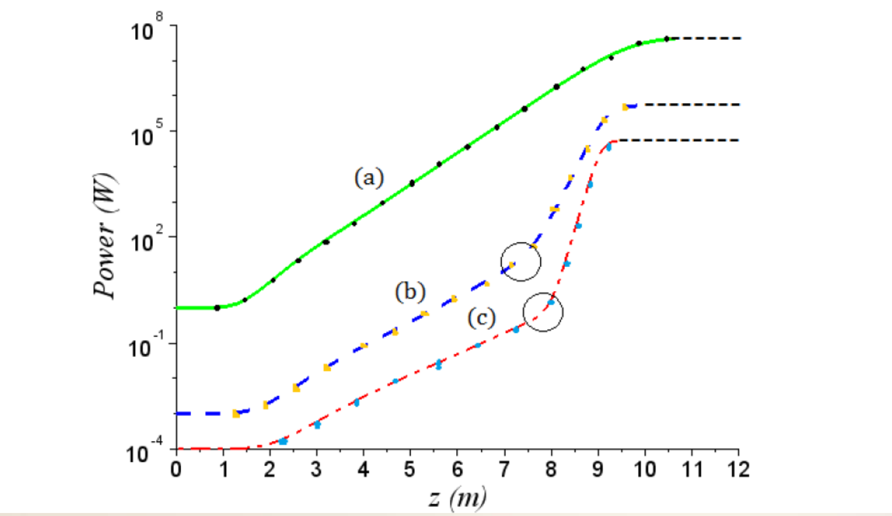
$$I_s = \frac{c}{8\pi}\left(\frac{m_e c^2}{e}\right)^2 \left(\frac{\gamma}{N}\right)^4 \left(\lambda_u \frac{K}{\sqrt{2}} f_b\right)^{-2}$$

$$\frac{d^2}{d\tau^2}\zeta = \sum_{n=0}^{\infty} |a_n| \cos(\psi_n), \quad \psi_n = n\zeta + \phi_n,$$

$$a_n = |a_n| e^{i\,\phi_n},$$

$$\frac{d}{d\tau} a_n = -j_n \langle e^{-in\zeta} \rangle.$$





Bi-Harmonic Undulators (BCU)

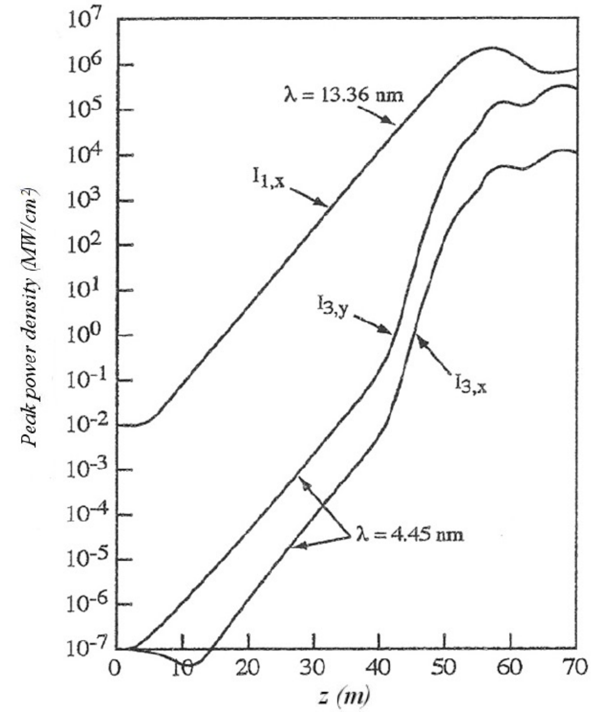
- $$\vec{B}_u \equiv [3\,B_0 \sin(3\,k_u z), B_0 \sin(k_u z), 0],$$

$$\frac{\partial^2 \zeta_{x,1}}{\partial \tau^2} = |a_{x,1}| \cos(\zeta_{x,1} + \varphi_{x,1}),$$

$$\frac{\partial a_{x,3}}{\partial \tau} = -j_{x,3}\langle e^{-i\zeta_{x,3}}\rangle,$$

$$\frac{\partial a_{x,1}}{\partial \tau} = -j_{x,1}\langle e^{-i\zeta_{x,1}}\rangle,$$

$$\frac{\partial a_y}{\partial \tau} = -j_y\left\langle e^{-i\zeta_y}\right\rangle; \quad \zeta_{x,3} = \zeta_y = 3\zeta_{x,1}.$$

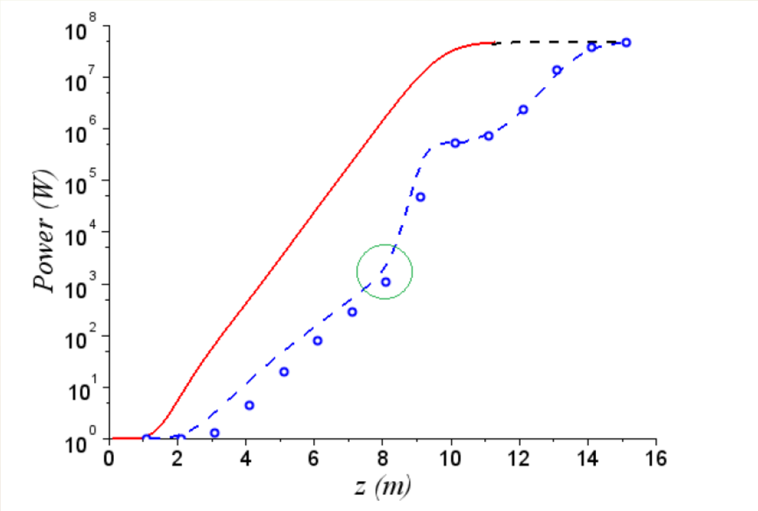


Harmonically coupled beams (HCB) (Mc-Neal, Robb and Poole (2004))

- *HBC scheme foresees 2 e.b. injected in a linearly polarized undulator.*

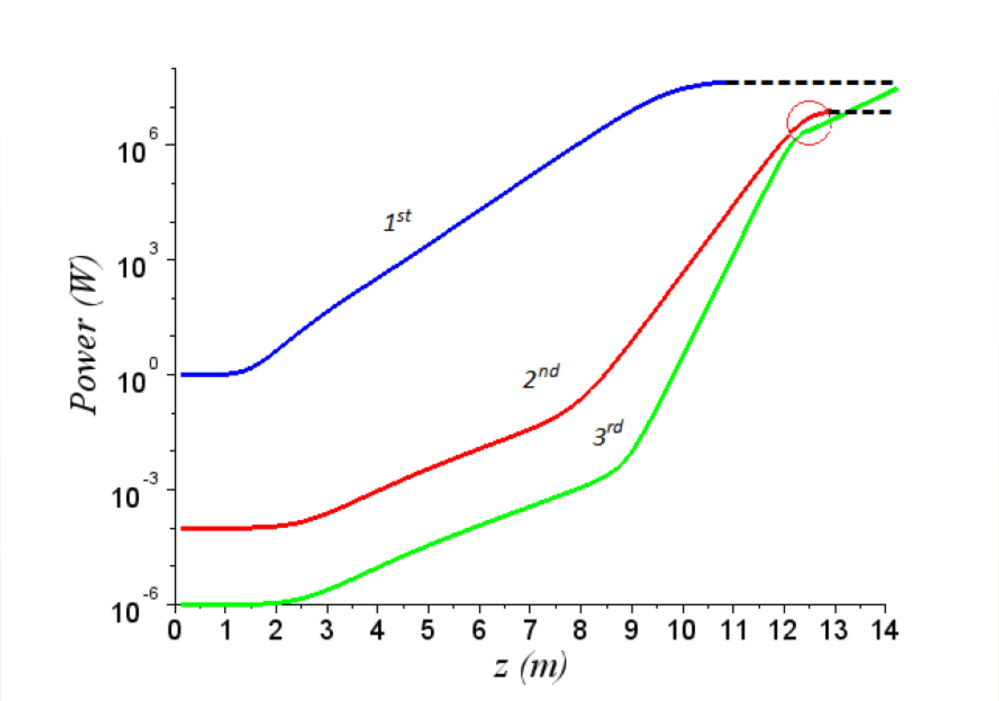
$$\gamma_2 = \sqrt{n\gamma_1} \rightarrow \begin{matrix} \lambda_1 = \frac{\lambda_u}{2\gamma_1^2}\left(1+\frac{K^2}{2}\right) \\ \lambda_2 = \frac{\lambda_u}{2n\gamma_1^2}\left(1+\frac{K^2}{2}\right) \end{matrix}$$

- *1,2 radiate independently, two distinct FEL operate, until the n-th harmonic, of the beam with lower energy, seeds that emitted by the beam with larger energy.*



FEL OPERATING WITH HCB and BHU

- Sabia et al. 2021.



A Touch on Segmented undulators

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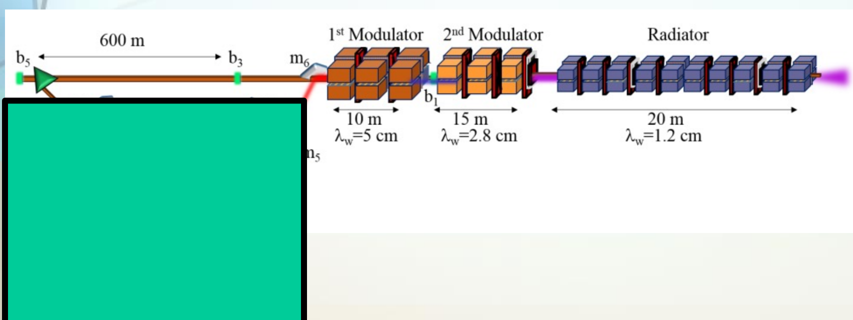
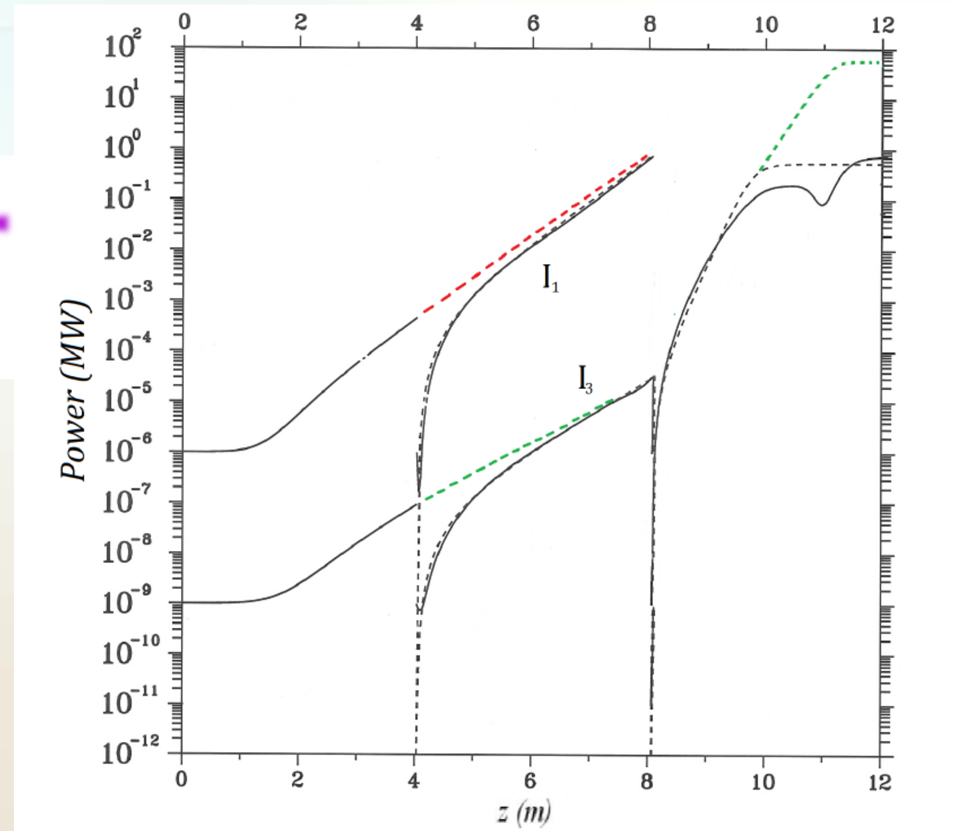
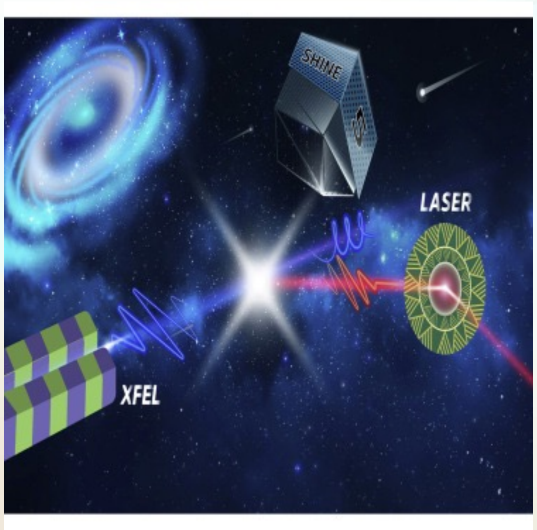
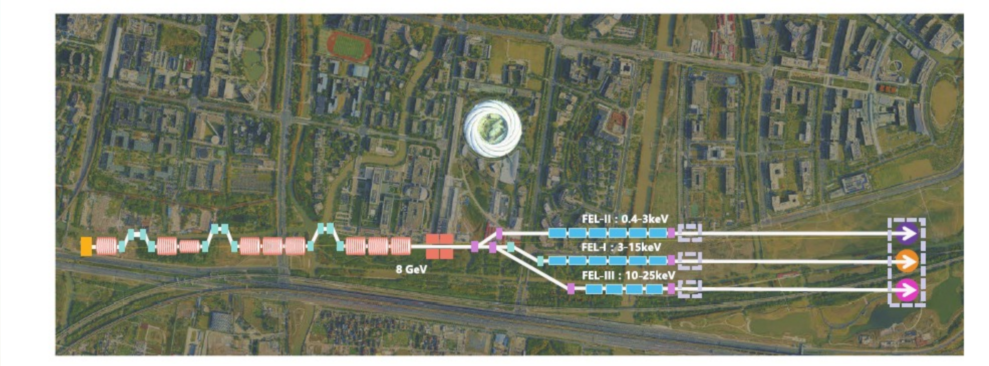


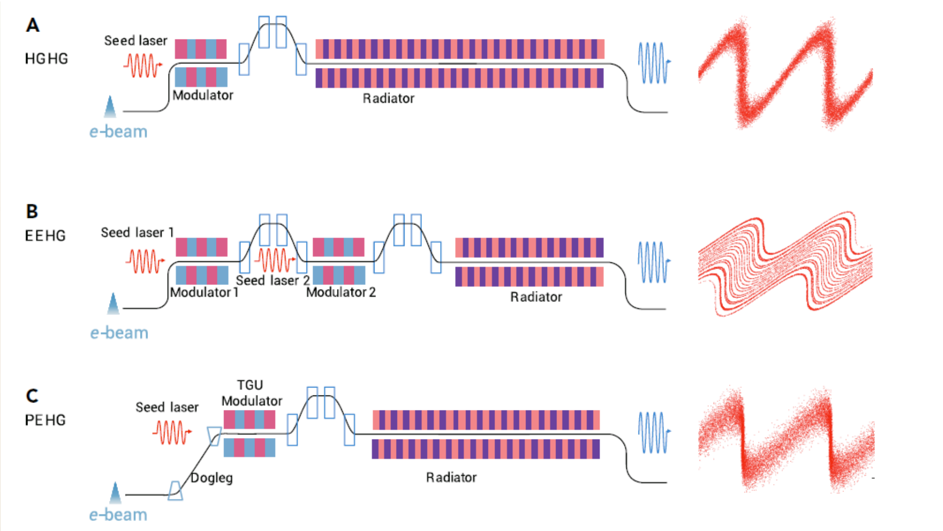


Nanshun Huang et al. The Innovation (2021)

Features and futures of X-ray free-electron lasers







Ottaviani et al. (1999)
Design Considerations for X-ray FELs

- Hybrid scheme (Oscillator-Amplifier)

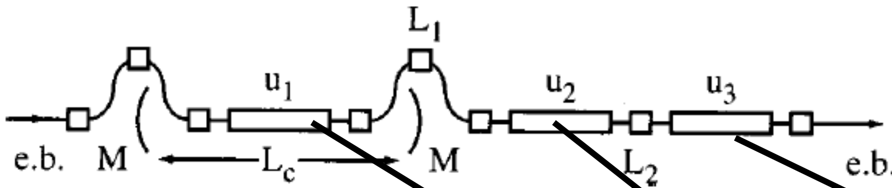


FIG. 1. Layout of the *x*-FEL device: e.b.≡electron beam; *M*≡mirrors; L_c≡cavity length; U_α≡undulator (α=1,2,3); L_{u_α}≡undulator length; L_1≡length of the dispersive section between first and second undulator; L_2≡length of the dispersive section between second and third undulator.

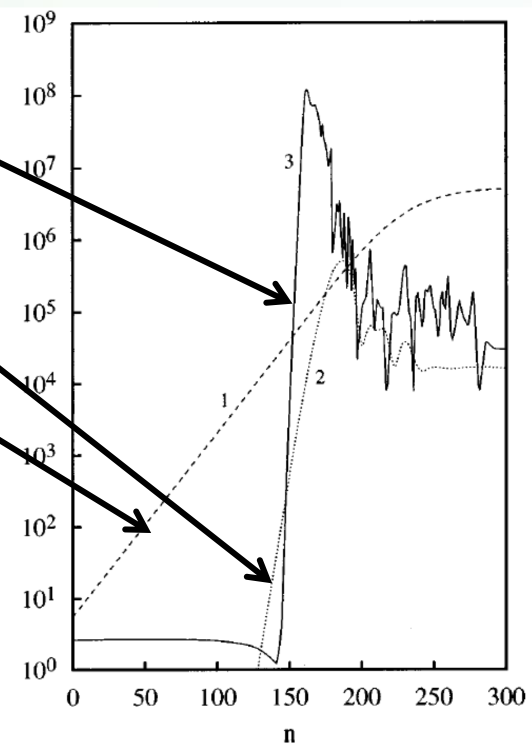


FIG. 4. Evolution vs the cavity round-trip numbers of (1) intracavity oscillator power at 155 nm; (2) second undulator out put power at λ_2=31 nm; (3) third undulator output power at λ_3=6.2 nm. The total losses of the oscillator have been fixed around 6%.

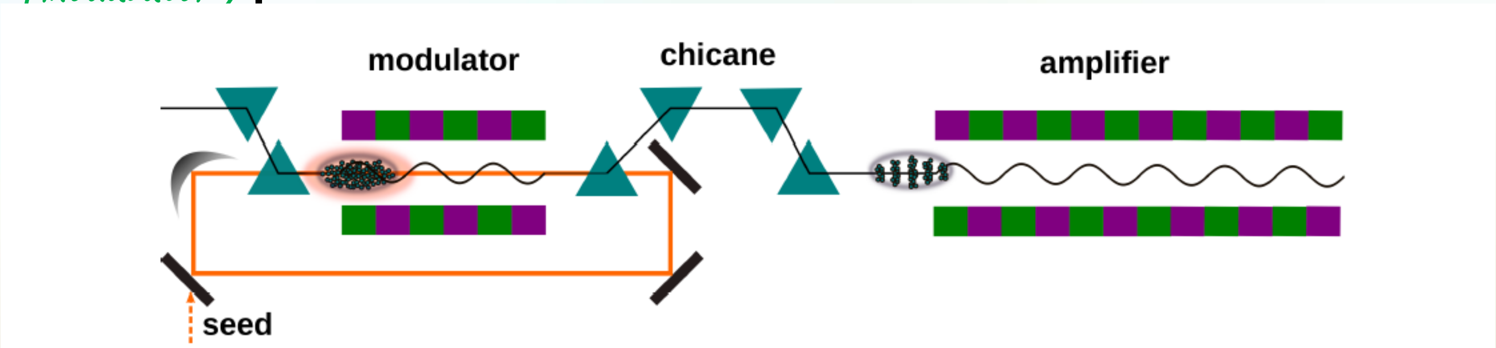
Advanced Scheme to Generate MHz, Fully Coherent FEL Pulses at nm Wavelength

- G. Paraskaki; S. Ackermann, B. Faatz, G. Geloni; T. Lang, F. Pannek, L. Schaper and J. Zemella

- …techniques to resolve electronic structure, require full coherence and high statistics, which can only be fulfilled with fully coherent radiation at high repetition rate…
- …Currently,superconducting accelerators are capable of providing thousands of bunches per second at MHz repetition rate…
- The solution:
- Seeding at «**high repetition rate**»

Going beyond the ordinary seeding…

In ordinary seeding an external seed laser is used to modulate the energy of the electron beam as a result of their interaction along an undulator (modulator).

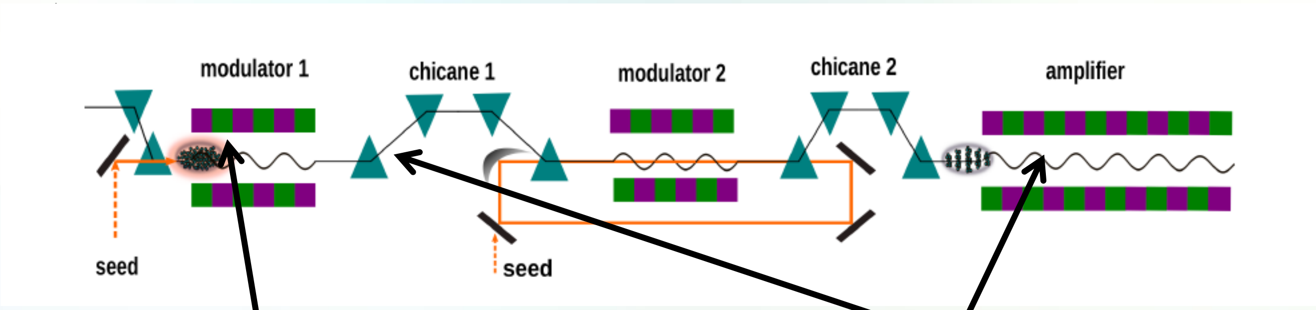


- *An external seed laser initiates the modulation of the first electron bunch and the bunch amplifies the seed pulse to compensate for the power losses in the cavity. The optical cavity feeds back the seed pulse which is used to modulate the following bunches.*

Merging different advanced schemes…seeding, HGHG, Echo.enabled…

- HGHG mechanism is limited by the induced energy spread (Typical Max n = 15). The EEHG scheme overcomes this problem
- Two seed lasers, two modulators, two dispersive sections, and one radiator.

Oscillator Eco Enabled Harmonic Generation

- 

- In the first block an energy modulation is induced, the first dispersive section (with large longitudinal dispersion), shreds the longitudinal phase space of the e.b. creating thin energy bands with lower energy spread
- lower energy modulation is required in the second part of the device to produce higher harmonics in the radiator

Conclusions

- A) There is still space to test new schemes in FEL devices
- B) Wave undulator solutions are promising but require technological improvements
- C) non standard undulators and «tricky» harmonic generation mechanisms may offer significant help in terms of output light performances
- D) Technological improvements like Oscillaor-assisted seed schemes are highly recommended and will determine significant improvements for the short wavelength FELs performances.

PS

- We have ignored solutions regarding the design of high gradient devices.
- It is difficult to comment on plasma accelerating schemes, which are still at a doubtful stage.
- A more «modest» solution in agreement with the discussion developed so far

CARM FED Acc.Cavities
Di Palma et al.

- **Radio-Frequency Undulators, Cyclotron Auto Resonance Maser and Free Electron Lasers.**
- (2022)