Universidade de São Paulo (USP)
Instituto de Física de São Carlos (IFSC - USP)
Eletromagnetismo 1
Prof. Dr. Philippe Wilhelm Courteille

The free-electron laser

Marcelo da Silva Cruz

How the free-electron laser (FEL) works?

Electron Accelerators as Short-Wavelength Light Sources:

Relativistic electrons are accelerated toward the center of the ring and emit synchrotron radiation:

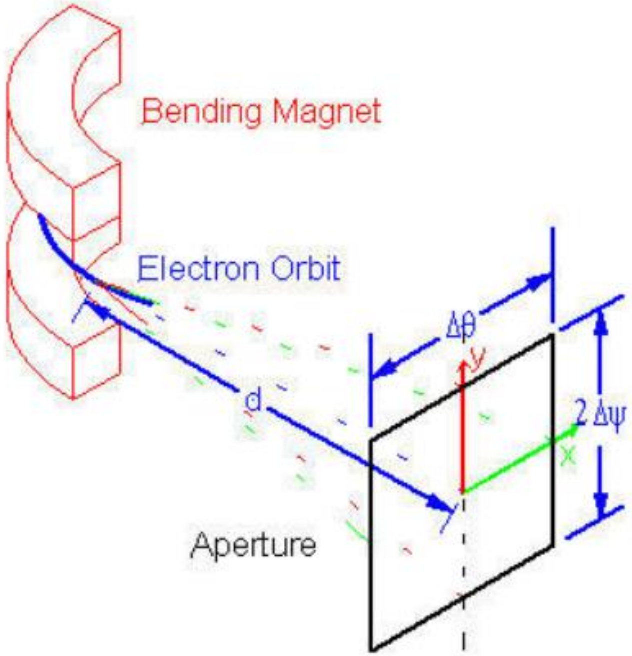


Figure 1: Geometry of synchrotron radiation collection.

The frequency spectrum is continuous and extends from zero to frequencies beyond critical frequency ωc,
R is the Radius of ring and c the velocity of light

$$\omega_c = \frac{3c\gamma^3}{2R} .$$

The Lorentz factor:

$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}} = \frac{W}{m_e c^2} ,$$

W is the total relativistic energy of the electron

The radiated power in a bending magnet of field B:

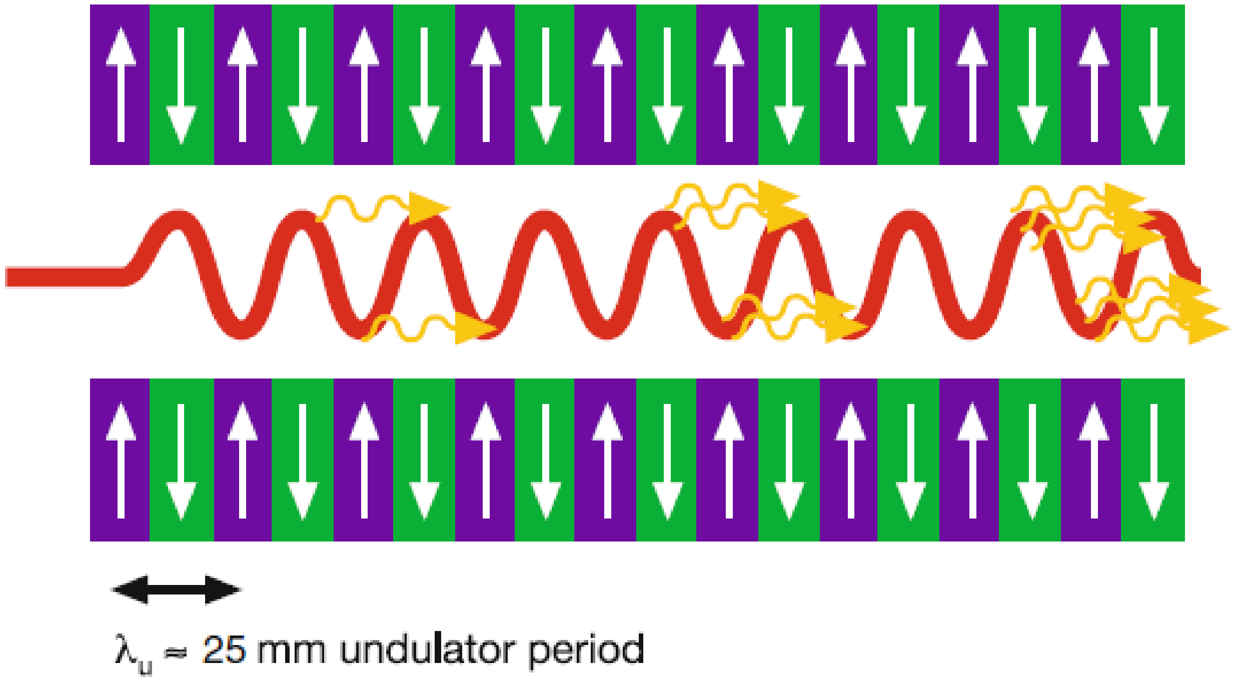
$$P_{\text{syn}} = \frac{e^4 \gamma^2 B^2}{6\pi\varepsilon_0 c\, m_e^2} .$$

Source: Schmüser, Peter, et al. "Free-electron lasers in the ultraviolet and X-ray regime." Springer Tracts in Modern Physics 258 (2014).

The electron motion in a planar undulator and the emission of undulator radiation.

The wiggler or undulator magnets are periodic arrangements of many short dipole magnets of alternating polarity.

The electrons move on a sinusoidal orbit through such a magnet.

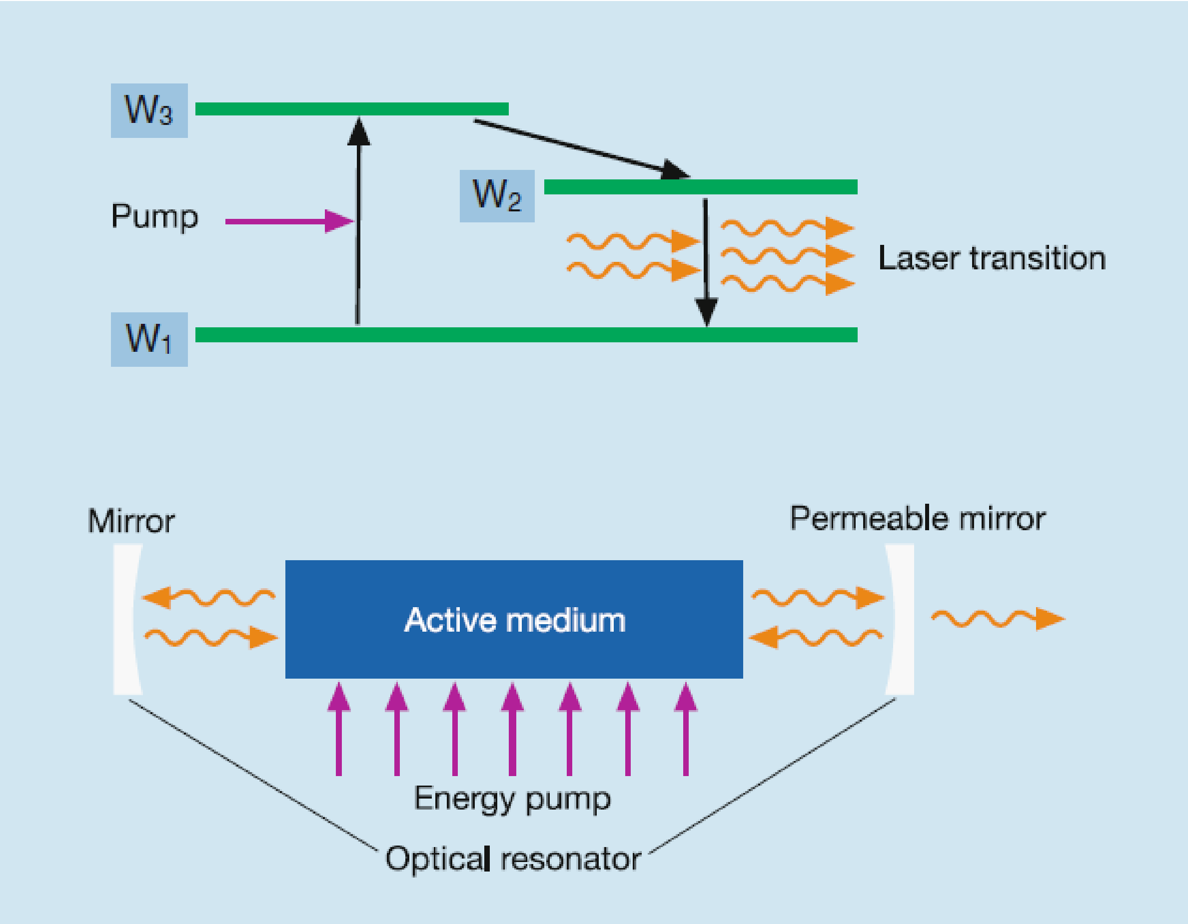


$$\lambda_\ell = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \quad \text{with} \quad K = \frac{e B_0 \lambda_u}{2\pi m_e c} \ .$$

K is the undulator parameter

Source: Schmüser, Peter, et al. "Free-electron lasers in the ultraviolet and X-ray regime." Springer Tracts in Modern Physics 258 (2014).

The Laser mechanism :



- Inversion of population.

- Virtual state and high state of energy.

- Stimulated emission of radiation.

- Amplification.

Fig. 1.2 Principle of a quantum laser where the electrons are bound to atomic, molecular or solid-state energy levels (“bound-electron laser”).

Source: Schmüser, Peter, et al. "Free-electron lasers in the ultraviolet and X-ray regime." Springer Tracts in Modern Physics 258 (2014).

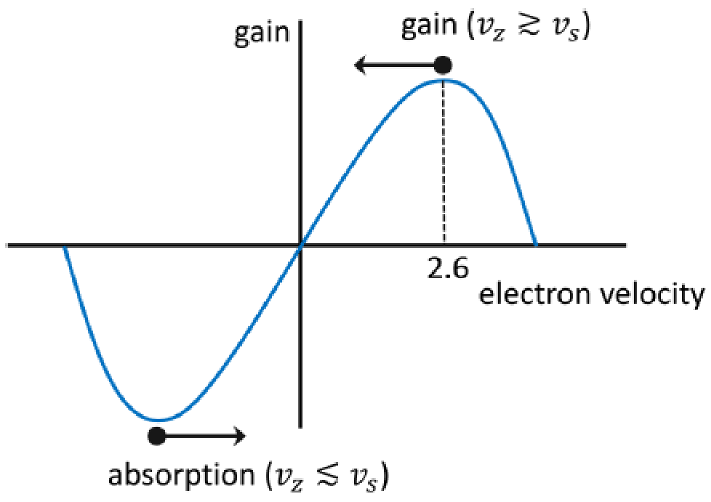
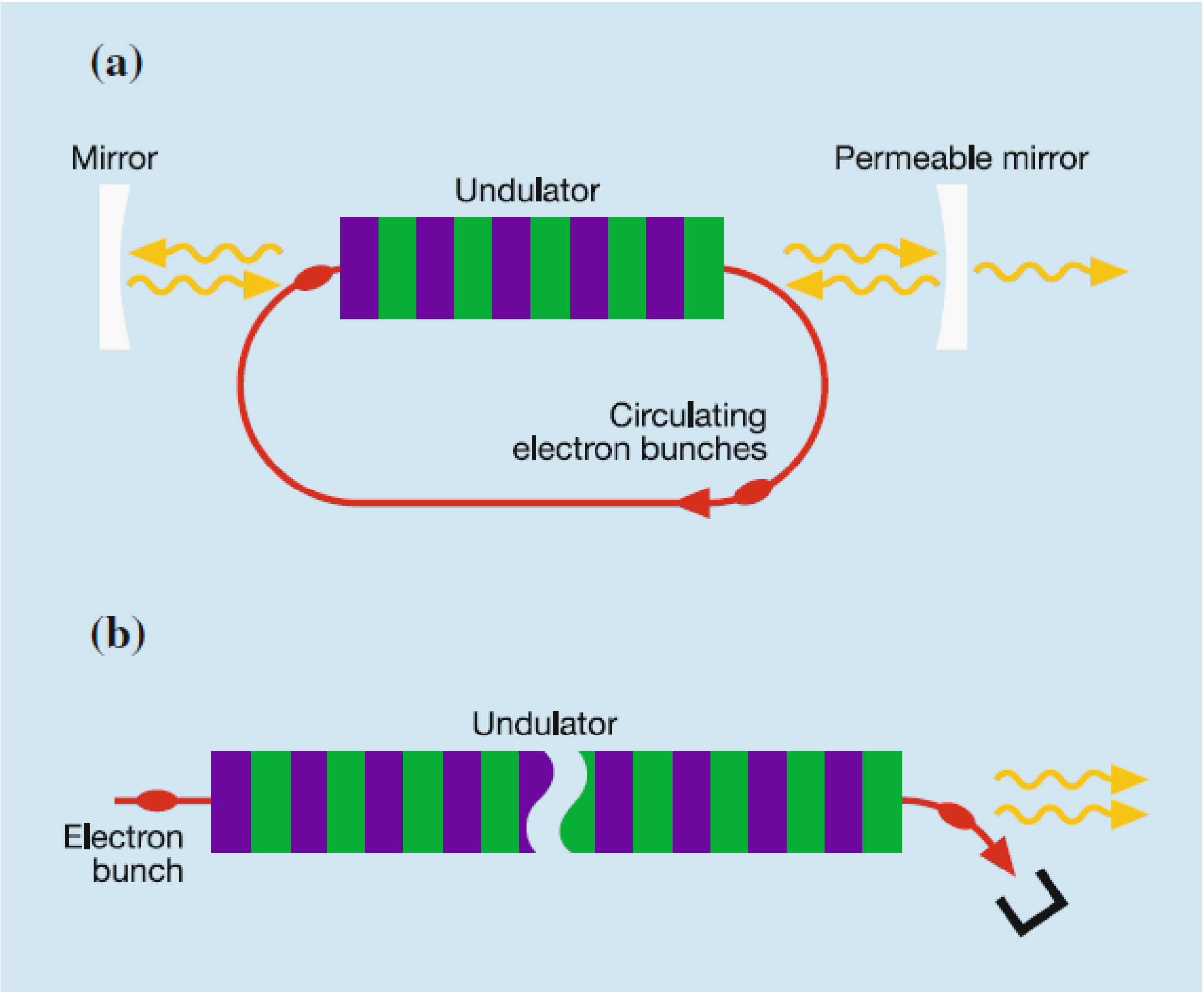


Figure 4. Gain versus electron velocity, that is the 'detuning' parameter $\mu = \Delta\omega\left(\frac{1}{v_s} - \frac{1}{v_z}\right)$.



The principle of SASE allows to realize high-gain FELs at these short wavelengths; seeding by an external coherent source.

The FEL uses a beam of electrons as the lasing medium.

Fig. 1.3 Principle of free-electron laser. For visible or infrared light an optical resonator can be used. A increase in light intensity of a few per cent per passage of a short undulator magnet is sufficient to achieve laser saturation within many round trips. In the ultraviolet and X-ray region one can apply the mechanism of Self-Amplified Spontaneous Emission where a large laser gain is achieved in a single passage through a very long undulator. **a** Low gain FEL. **b** SASE FEL.

Source: Schmüser, Peter, et al. "Free-electron lasers in the ultraviolet and X-ray regime." Springer Tracts in Modern Physics 258 (2014).

Why Does the FEL Need an Undulator?

- The electric force acting on an electron is always perpendicular to its velocity because electromagnetic waves in vacuum are transverse.

- The Lorentz force exerted by the light wave is almost perfectly balanced by the electric force exerted by the wave.

The forces are:

$$\boldsymbol{F}_{\text{mag}} = -e\,\boldsymbol{v} \times \boldsymbol{B} = +e\,v\,(E/c)\,\boldsymbol{e}_x\,, \quad \boldsymbol{F}_{\text{el}} = -e\,\boldsymbol{E} = -e\,E\,\boldsymbol{e}_x\,.$$

Source: Schmüser, Peter, et al. "Free-electron lasers in the ultraviolet and X-ray regime." Springer Tracts in Modern Physics 258 (2014).

The undulator mechanism:

The potential is:

$$\Phi_{\mathrm{mag}}(x, y, z) = \frac{B_0}{k_u} \sinh(k_u y) \sin(k_u z) .$$

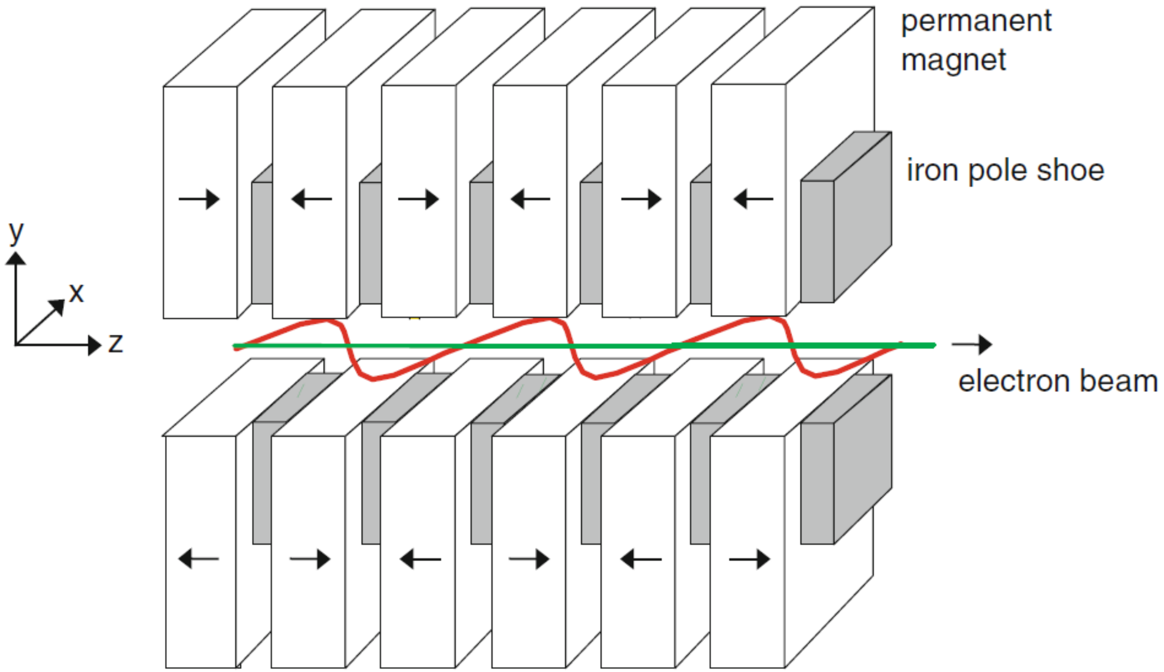


Fig. 2.1 Schematic view of a planar undulator magnet with alternating polarity of the magnetic field and of the sine-like trajectory of the electrons. In the magnet shown here the field is produced by permanent magnets that are placed between iron pole shoes. The distance between two equal poles is called the undulator period λ_u. A typical value is $\lambda_u = 25$ mm.

Source: Schmüser, Peter, et al. "Free-electron lasers in the ultraviolet and X-ray regime." Springer Tracts in Modern Physics 258 (2014).

The low gain mode:

- an electron storage ring or a recirculating linac in which relativistic electron
- bunches carry out many revolutions,
- a short undulator magnet,
- an optical cavity.

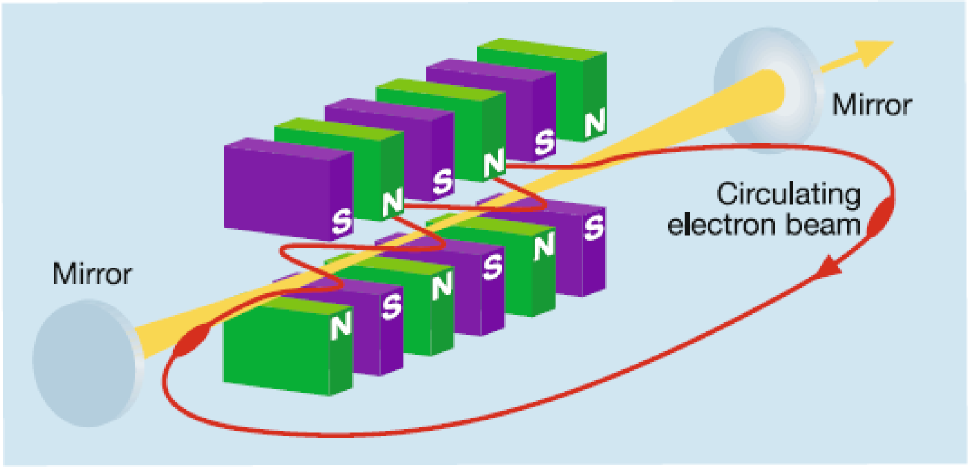


Fig. 3.1 Principle of a low-gain free-electron laser.

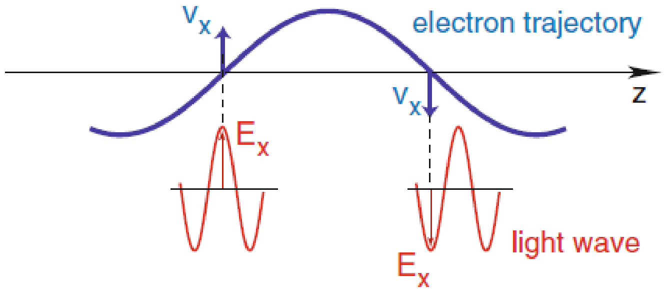


Fig. 3.2 Condition for sustained energy transfer from electron to light wave: the light wave has to advance by $\lambda_\ell/2$ per half period of the electron trajectory.

The plane electromagnetic wave:

$$E_x(z,t) = E_0 \cos(k_\ell z - \omega_\ell t + \psi_0) \quad \text{with} \quad k_\ell = \omega_\ell / c = 2\pi/\lambda_\ell \,.$$

The energy is:

$$\frac{dW}{dt} = \boldsymbol{v} \cdot \boldsymbol{F} = -e v_x(t) E_x(t) \,.$$

Source: Schmüser, Peter, et al. "Free-electron lasers in the ultraviolet and X-ray regime." Springer Tracts in Modern Physics 258 (2014).

The high gain mode:

High-Gain Harmonic Generation (HGHG) process.

The energy of the electron beam is periodically modulated by the interaction with the seed beam.

A magnetic chicane converts the energy modulation into a charge density modulation.

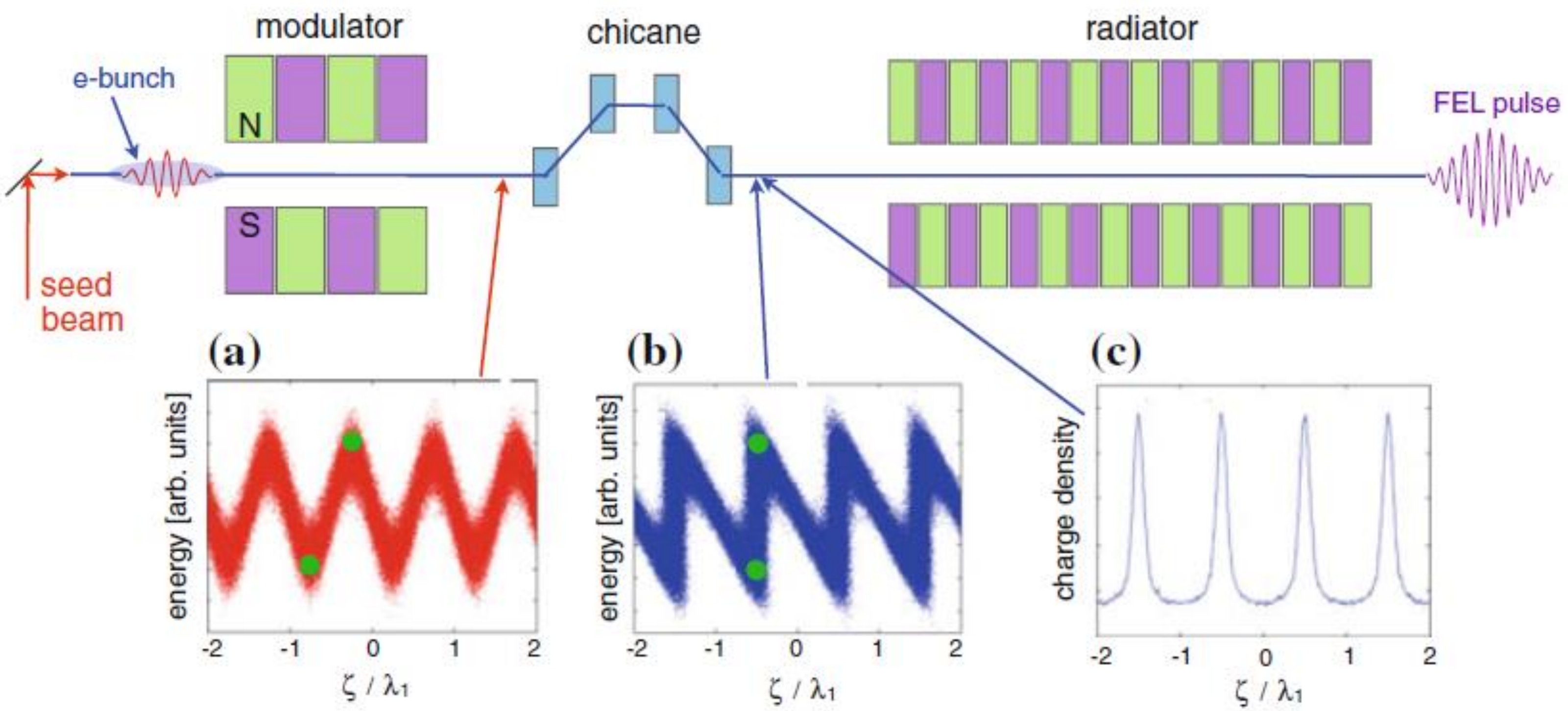


Fig. 7.19 Principle of the high-gain harmonic generation process. The *top graph* shows the experimental setup. The longitudinal phase space distributions (courtesy of D. Xiang) are displayed in *the bottom graphs*. The energy distribution in the bunch is plotted as a function of ζ/λ_1. **a** Downstream of the modulator, **b** downstream of the magnetic chicane. Graph **c** shows the microbunching: charge density as a function of ζ/λ_1.

High energy and brillhance:

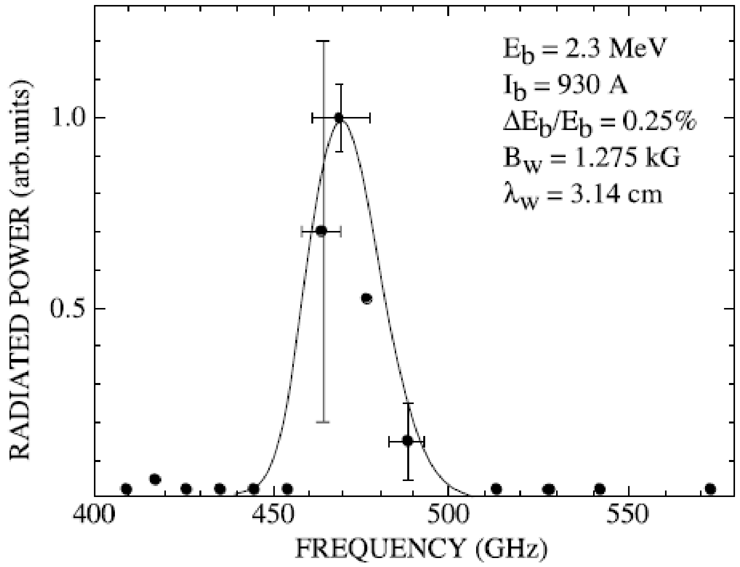


Fig. 4. The output spectrum from the 600-μm SASE FEL at MIT (*19*). The dots represent measurements; the curve is the result of simulation. The shot-to-shot fluctuations are reflected in the error bars.

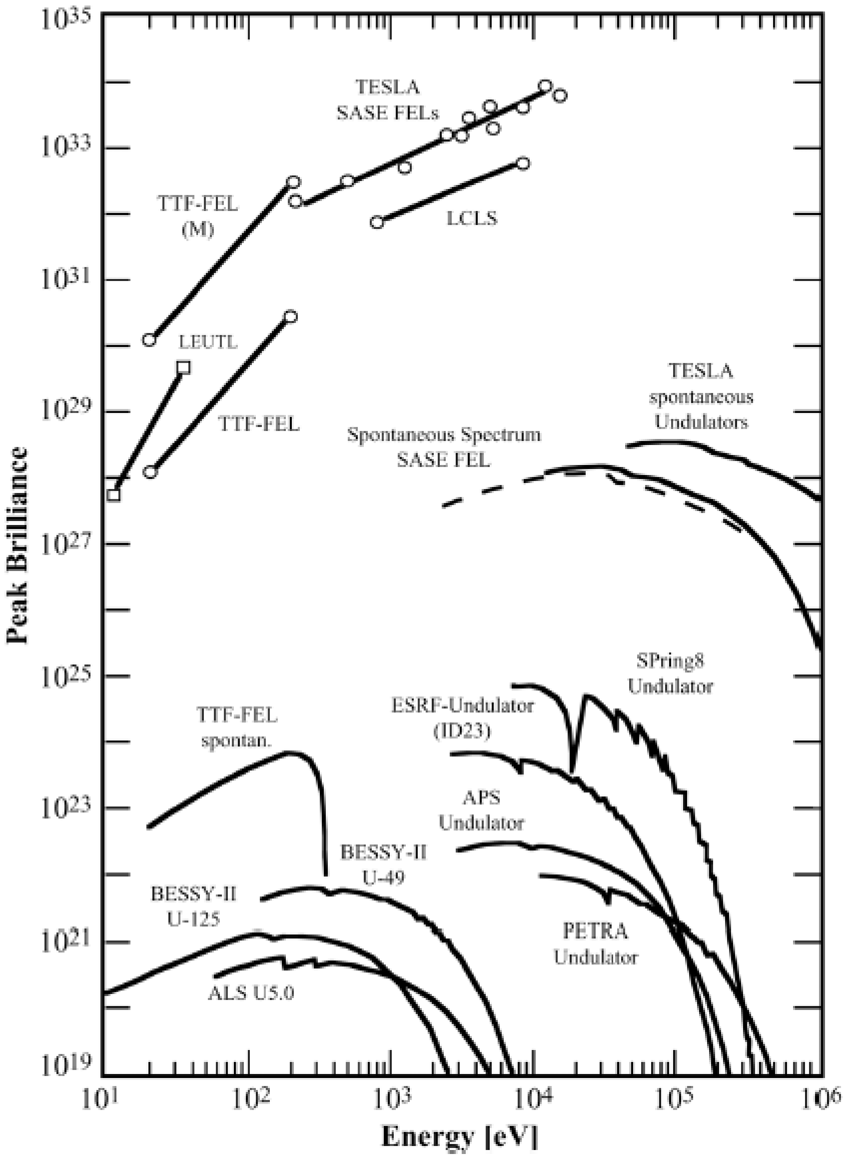


Fig. 3. Peak brilliance of x-ray FELs and undulators for spontaneous radiation at the TESLA Test Facility, in comparison with synchrotron radiation sources. Brilliance is expressed as photons s^{-1} $mrad^{-2}$ mm^{-2} per 0.1% bandwidth. For comparison, the spontaneous spectrum of x-ray FEL undulators is also shown. The label TTF-FEL indicates design values for the FEL at the TESLA Test Facility, with (M) for the planned seeded version (*28*).

Source: Patrick G. O'Shea, Henry P. Freund; Free-Electron Lasers: Status and Applications. Sci-ence 292, 1853-1858 (2001)

The Stanford experiment:

- Superconducting helix having a period of 3.2 cm over 5.2 m.

- Infrared light from a transverse-excitation-atmospheric 3.3 mm beamwaist CO2 laser excited the mode of copper tube of 10.2 mm.

- The gain was measured at optical powers from 100 to 1.4 10^5 W cm^-2.

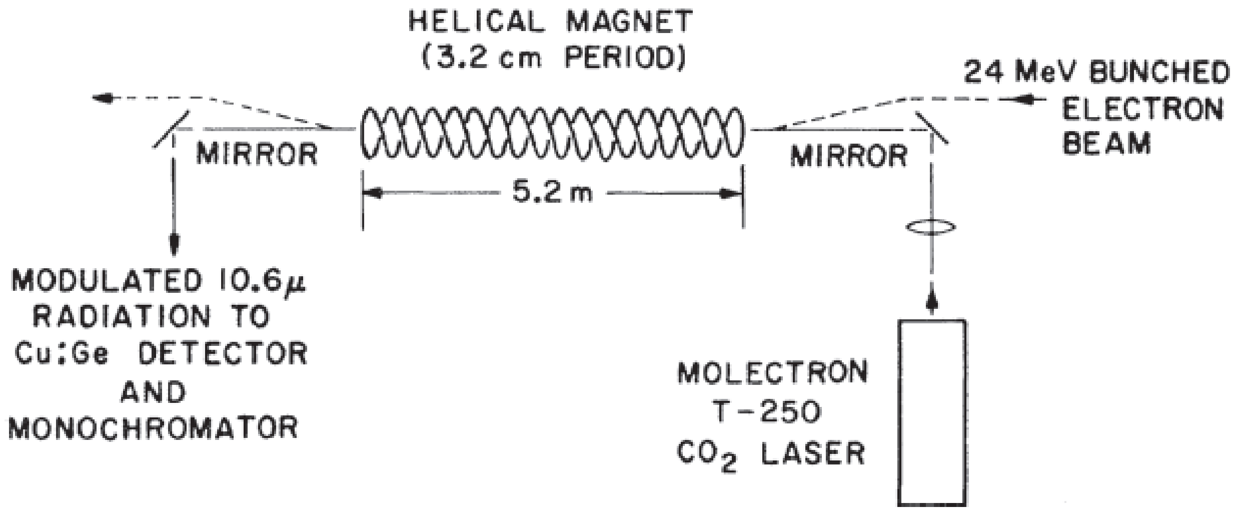
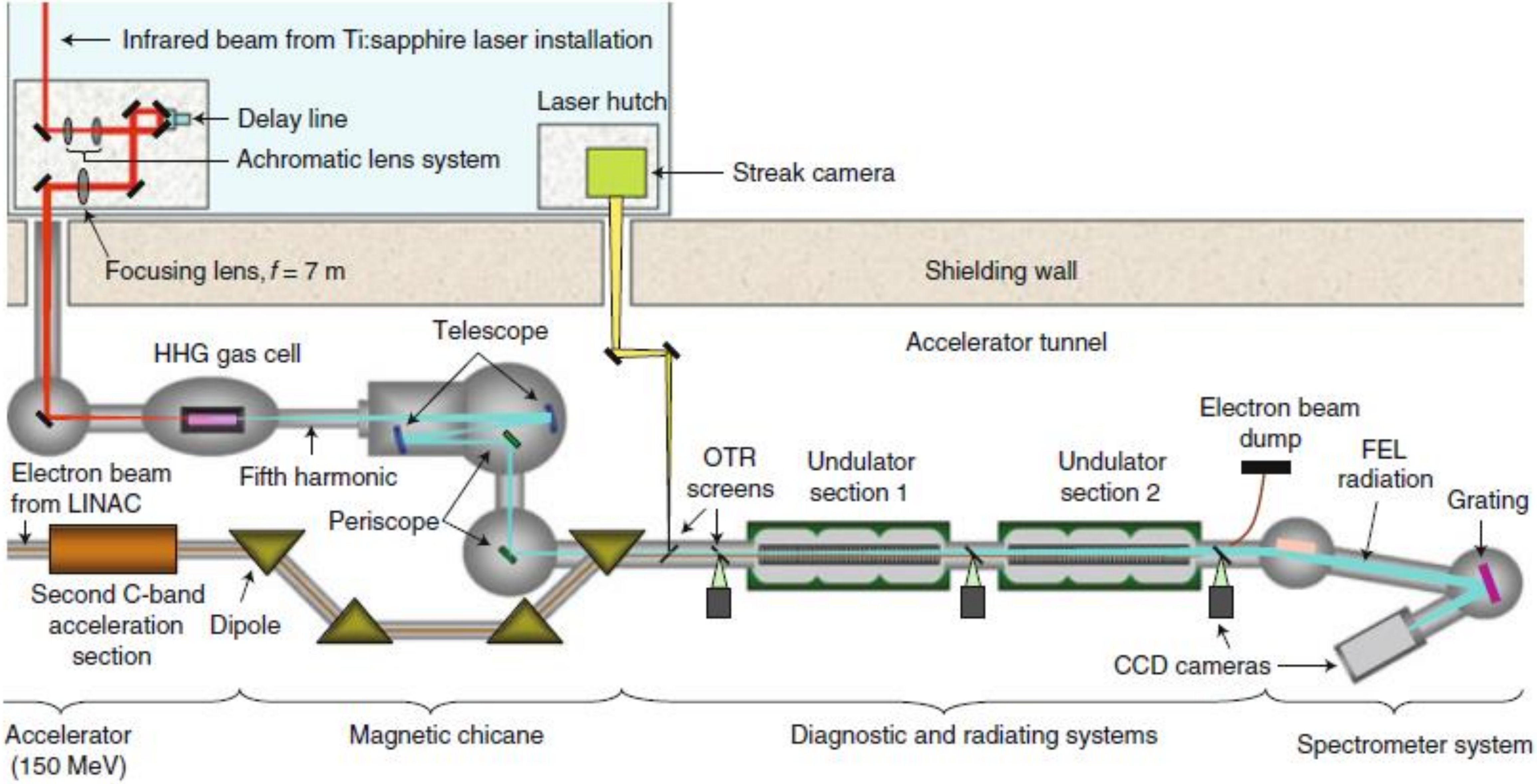


Figure 6. Experimental setup. The electron beam was magnetically deflected around the optical components on the axis of the helical magnet. (Adapted with permission from [11]. Copyrighted by the American Physical Society 1976.)

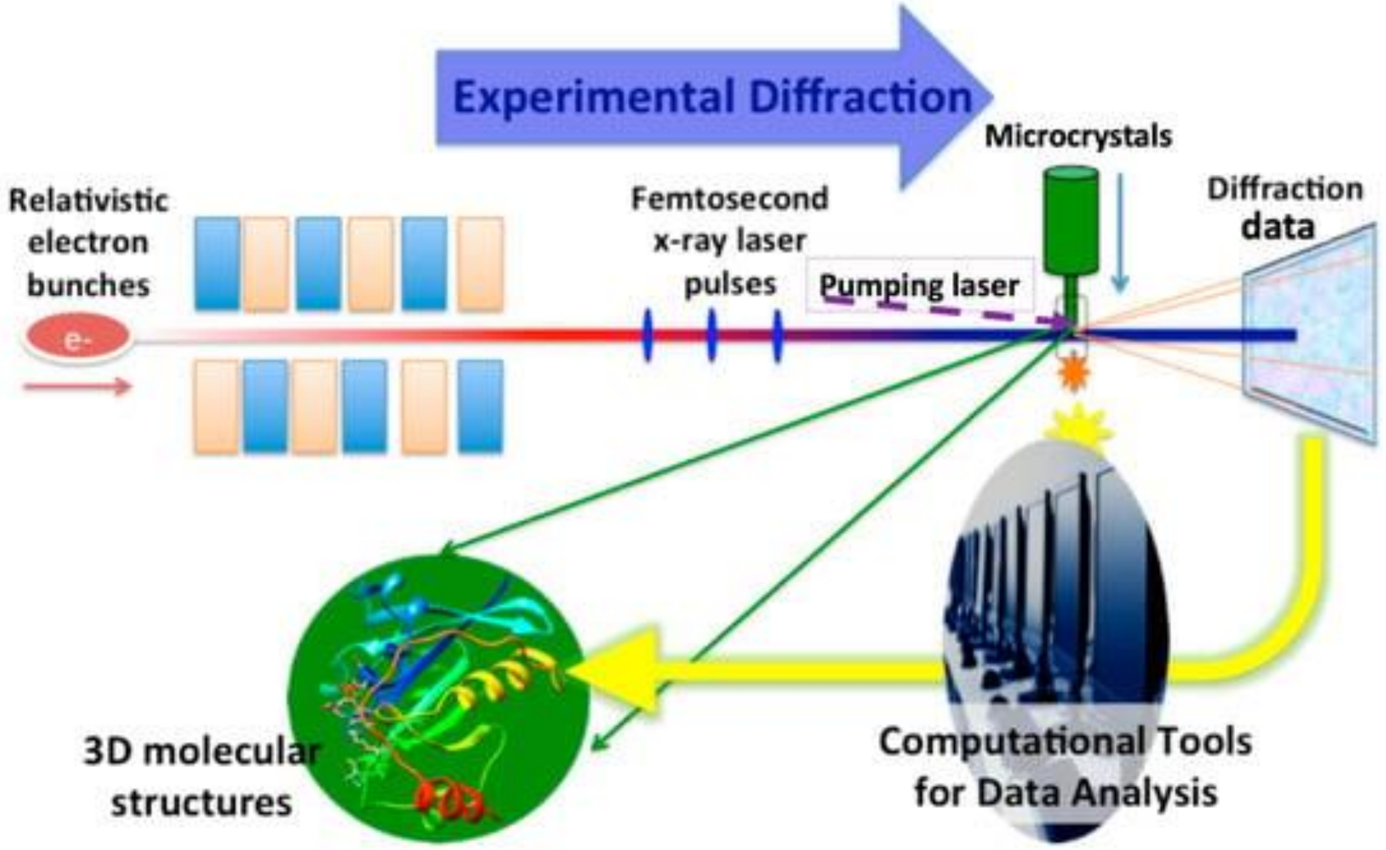
Seeding by Higher Harmonics of an Infrared Laser:

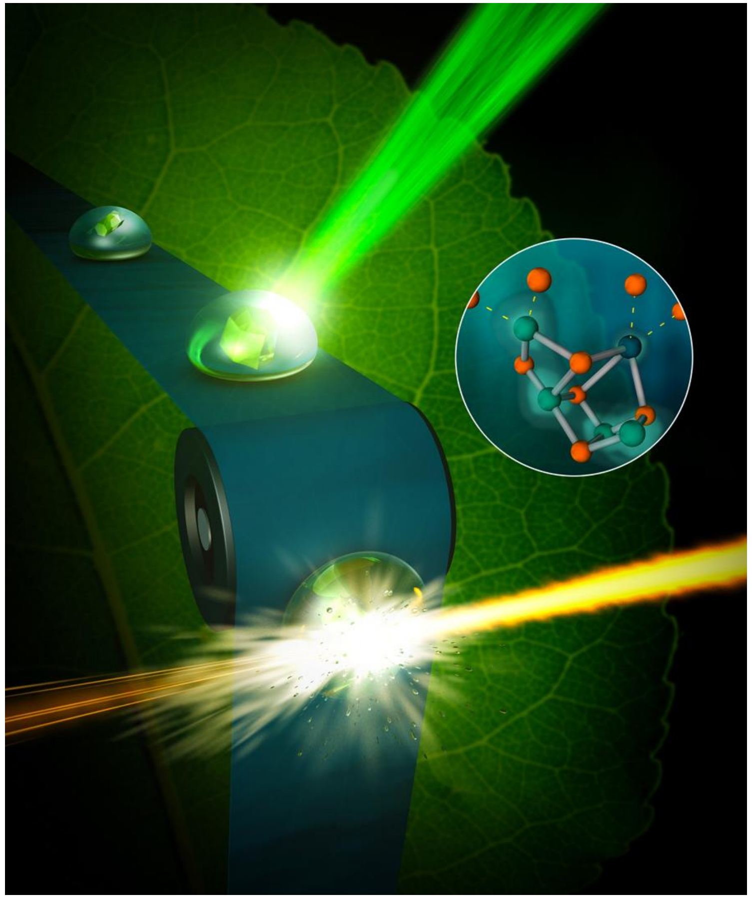


Source: Schmüser, Peter, et al. "Free-electron lasers in the ultraviolet and X-ray regime." Springer Tracts in Modern Physics 258 (2014).

Applications:

- MOLECULAR DYNAMICS, STRUCTURAL BIOLOGY AND BIO-MEDICAL APPLICATIONS



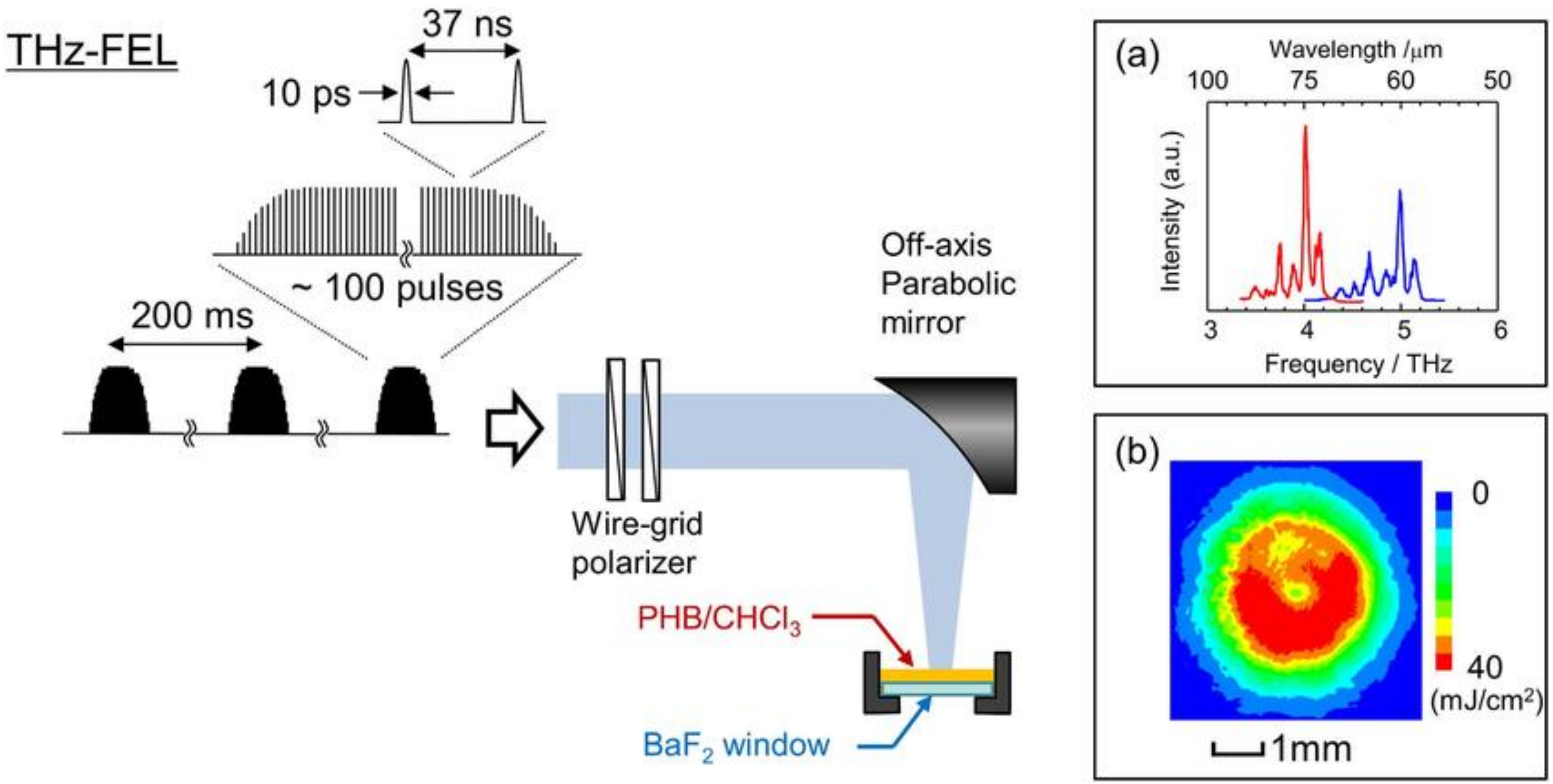


Source: Liu H, Lee W. The XFEL Protein Crystallography: Developments and Perspectives. *International Journal of Molecular Sciences*. 2019; 20(14):3421. https://doi.org/10.3390/ijms20143421 and https://researchoutreach.org/articles/free-electron-lasers-biggest-brightest-light-sources/

Applications：

TeraHertz（THz） free-electron laser setup：

THz-free electron laser (FEL) output 5-Hz macropulses composed of 100 micropulses with 10-ps duration. The THz-FEL output was attenuated by a pair of wire-grid polarizers and focused by an off-axis parabolic mirror (effective focal length (EFL) = 102 mm). The sample was dropped on the BaF 2 window, which was placed at a 25-mm offset from the focal point. Insets: (a) Typical spectral profile measured at λ = 60 and 75 μ m; (b) Typical beam pattern at sample position, measured at λ = 70 μ m.



Source: Hoshina, Hiromichi & Suzuki, Hal & Otani, Chiko & Nagai, Masaya & Kawase, Keigo & Irizawa, Akinori & Isoyama, Goro. (2016). Polymer Morphological Change Induced by Terahertz Irradiation. Scientific Reports. 6. 27180. 10.1038/srep27180.

Applications:

Interplay of wavelength, fluence and spot-size in free-electron laser ablation of cornea

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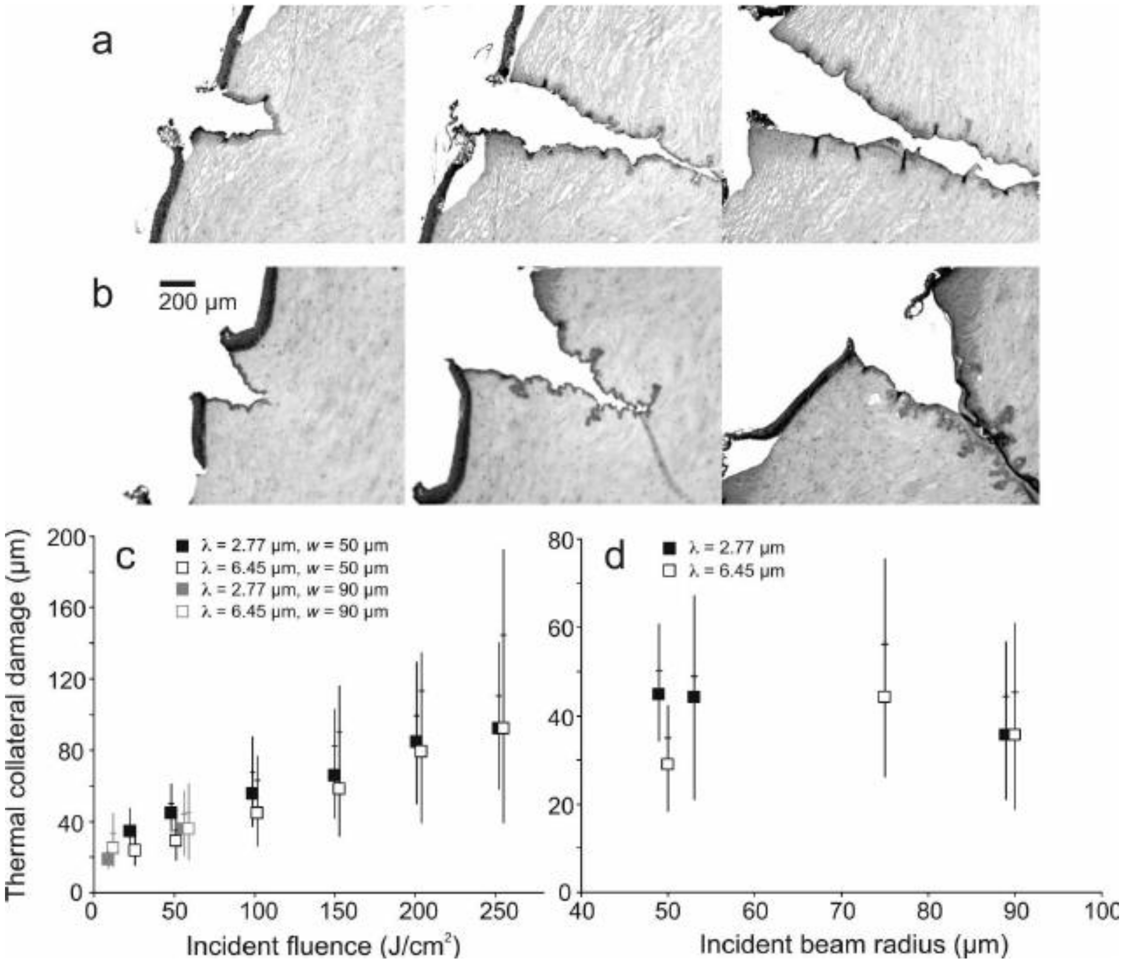
Abstract: Infrared free-electron lasers ablate tissue with high efficiency and low collateral damage when tuned to the 6-μm range. This wavelength-dependence has been hypothesized to arise from a multi-step process following differential absorption by tissue water and proteins. Here, we test this hypothesis at wavelengths for which cornea has matching overall absorption, but drastically different differential absorption. We measure etch depth, collateral damage and plume images and find that the hypothesis is not confirmed. We do find larger etch depths for larger spot sizes – an effect that can lead to an apparent wavelength dependence. Plume imaging at several wavelengths and spot sizes suggests that this effect is due to increased post-pulse ablation at larger spots.

OCIS codes: (140.2600) Free-electron lasers (FELs); (170.1020) Ablation of tissue



FELIX stands for: **F**ree-**E**lectron **L**asers for **I**nfrared e**X**periments.

Radboud Universiteit
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An upcoming compact THz radiation and electron beam facility at IUAC

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Inter-University
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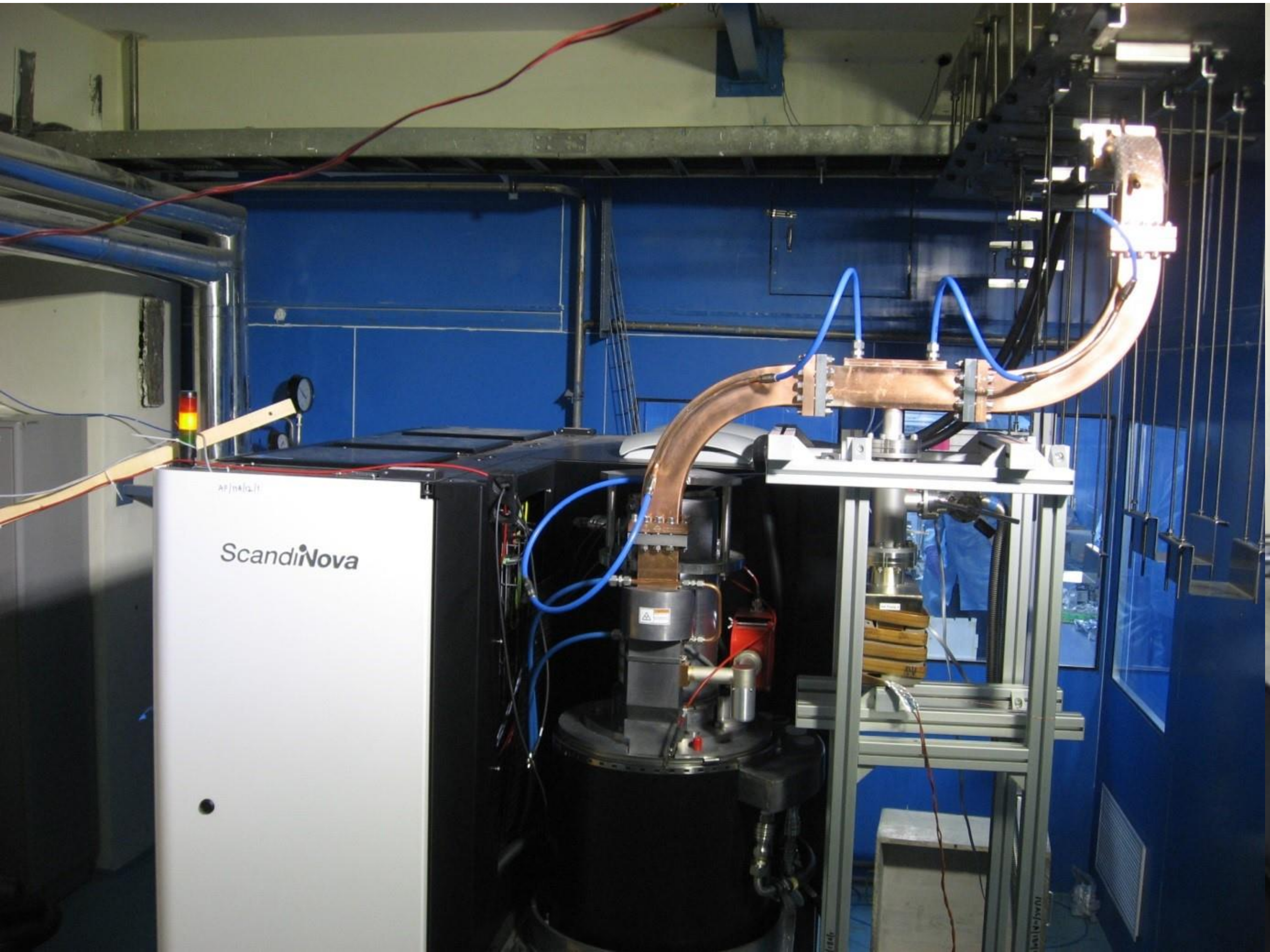

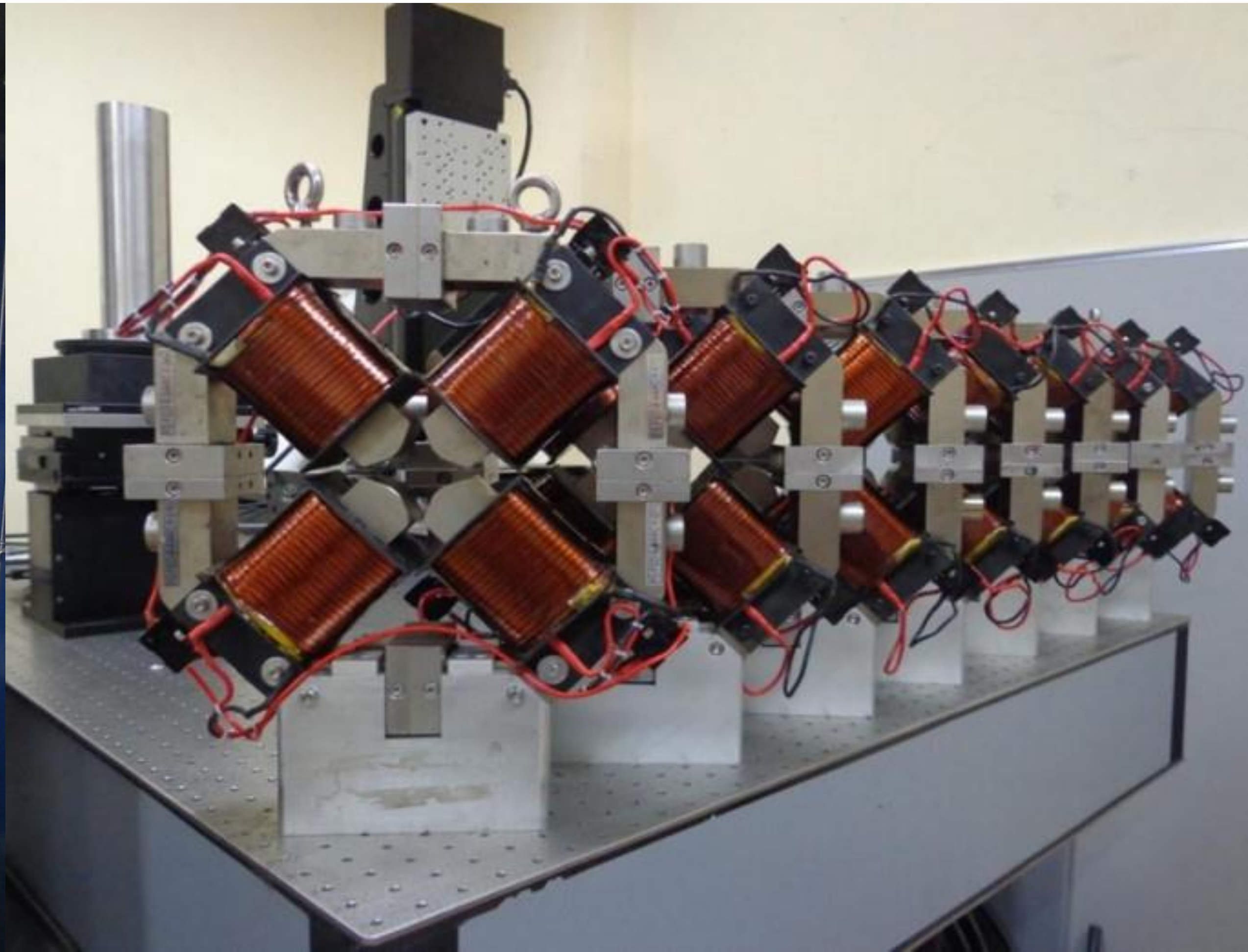

Conclusion:

- Produces high energy intensity and power.
- Important applications in Biology, Chemistry and Physics.
- Light source in UV up to IR, and X-Ray.
- TeraHertz applications
- The cost is very considerable, proper installation is required and there will be a high cost in the production of the undulators.

Thats all folks! Thanks.

Questions? Send me a e-mail: marcelocruz@ifsc.usp.br