Plasma Driven Free Electron Lasers

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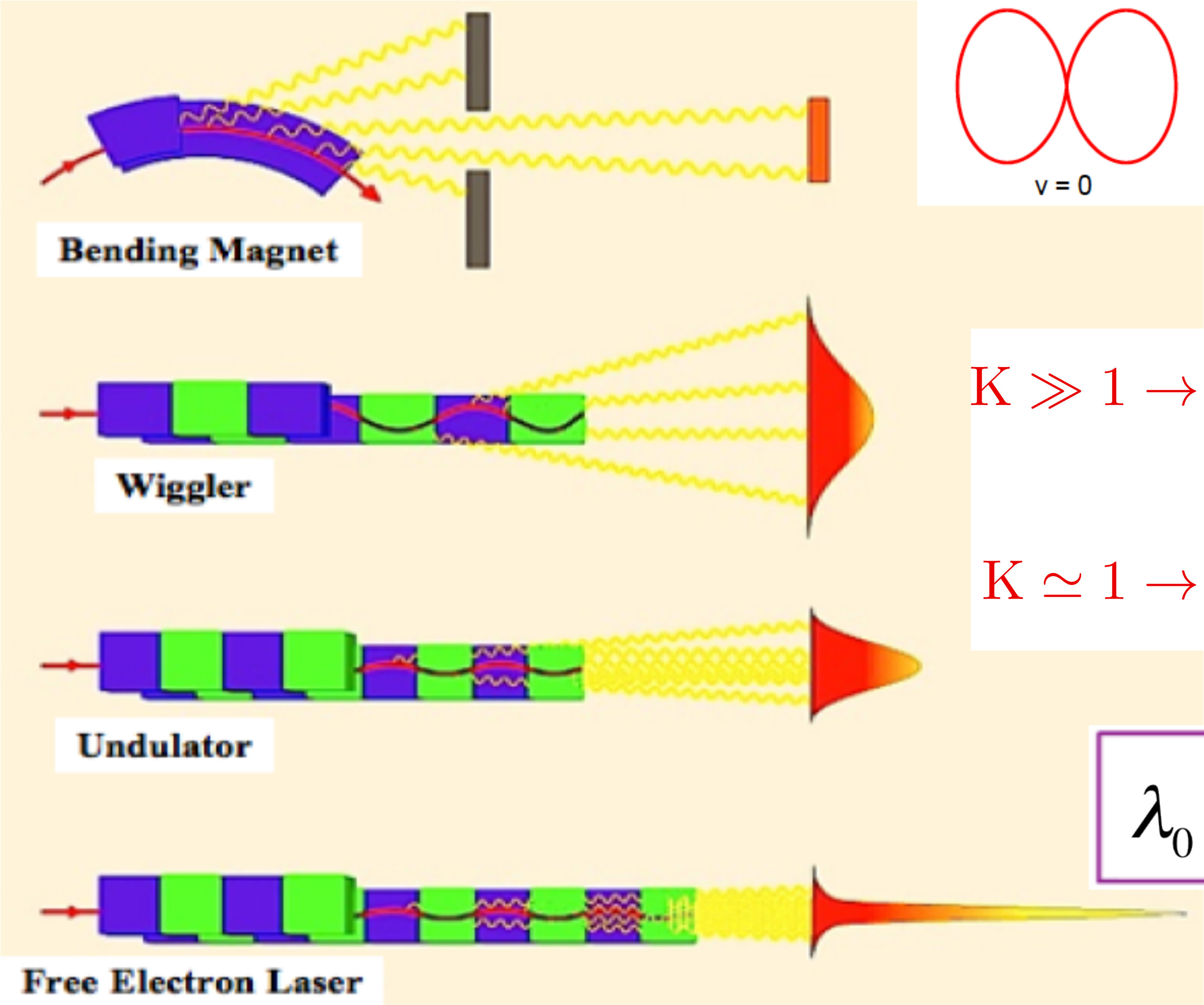
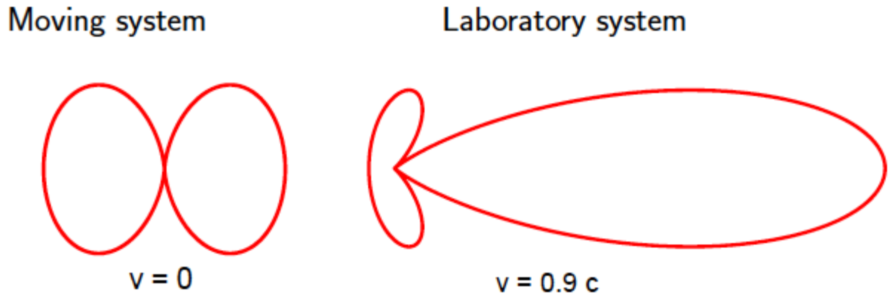
From synchrotron to FEL radiation



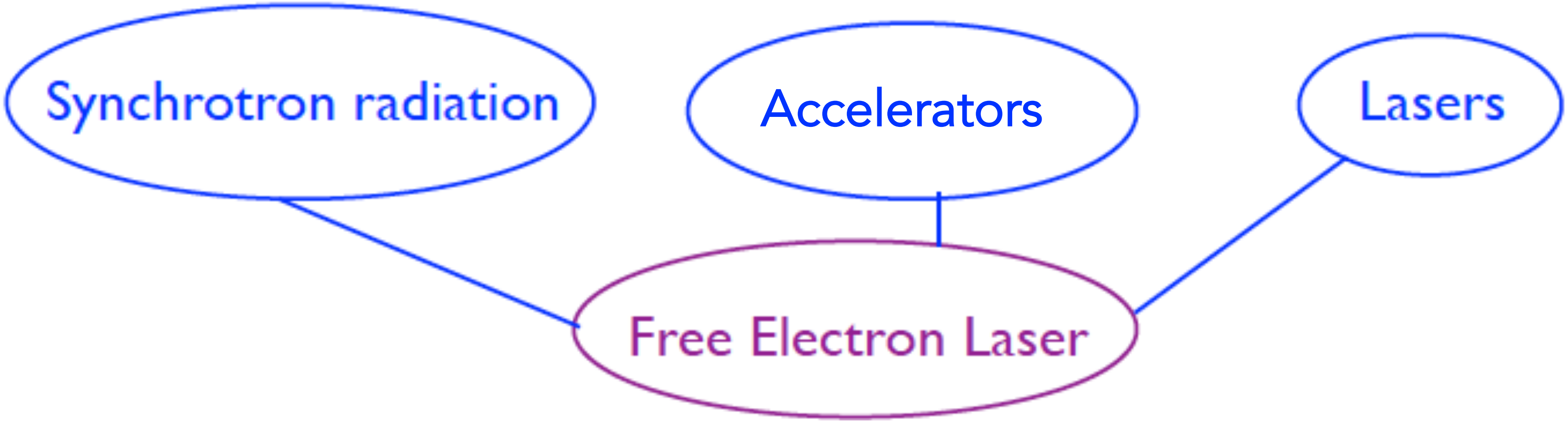


$$K \gg 1 \rightarrow \text{wiggler}: \;\; \text{also } \theta \gtrsim \frac{1}{\gamma}$$

$$K \simeq 1 \rightarrow \text{undulator}: \;\; \theta \ll \frac{1}{\gamma}$$

$$\boxed{\lambda_0 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_u^2}{2} + \gamma^2\theta^2\right)}$$

FEL: laser from an e-beam in a magnetic field

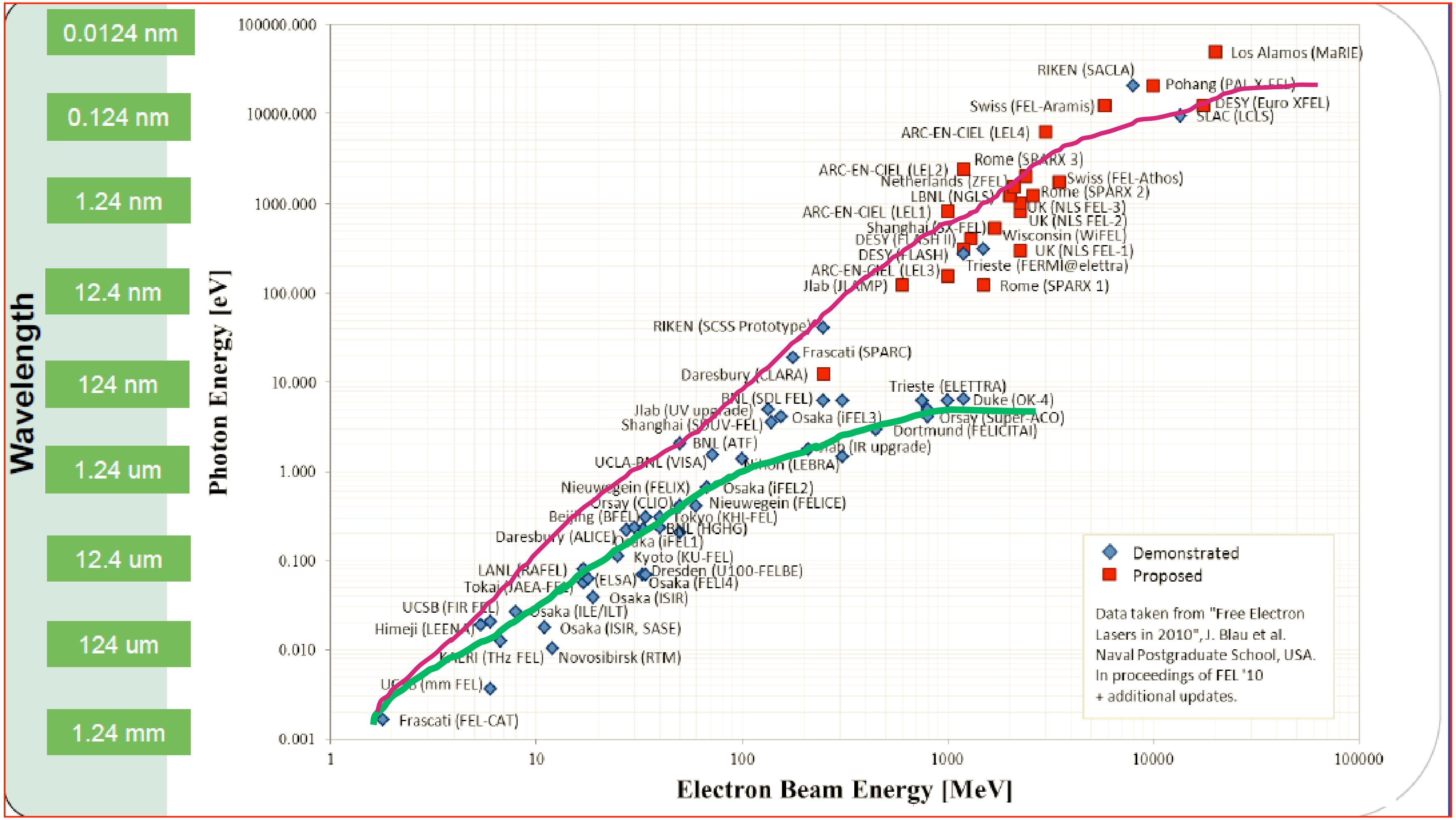


free electrons
bound electrons in atoms and molecules : vibrate at specific frequencies

- broad wavelength tunability (vibration frequency can be adjusted by changing the magnetic field or the speed of the electrons)
- excellent optical beam quality
- high power

$$K_u = \frac{eB_u\lambda_u}{2\pi m_o c}$$

Letardi FEL Chart: beam energy vs. γ wavelength



We observe sort of saturation of photon energy with the *e*-beam energy ➔ novel acceleration technologies (see M.Ferrario)

Reasons to go beyond state of the art

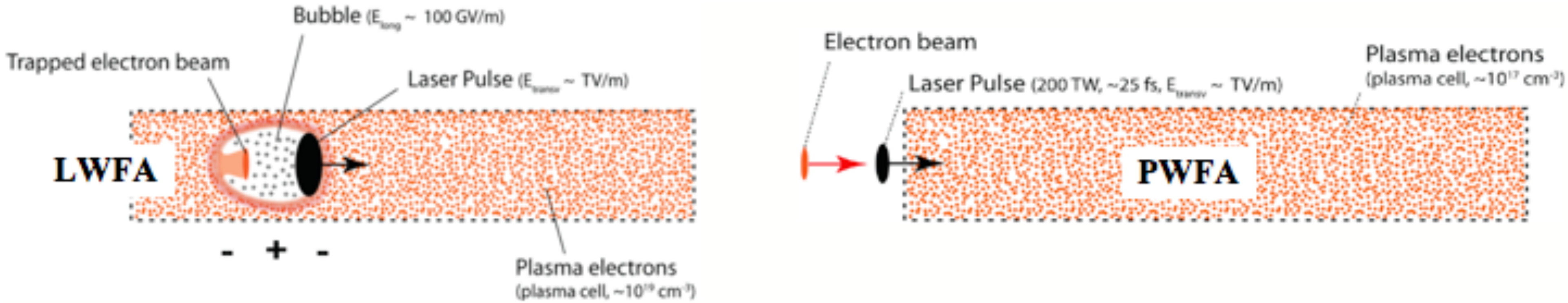
FEL size and cost

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

A) reduce the size of the accelerator using different accelerating schemes (see M.Ferrario) (High gradient, Plasma accelerators,…)

B) reduce the undulator length using novel technologies (Superconducting, Cryogenic Permanent Magnet, R.F. Undulators,….)

First stage of this Thesis subject



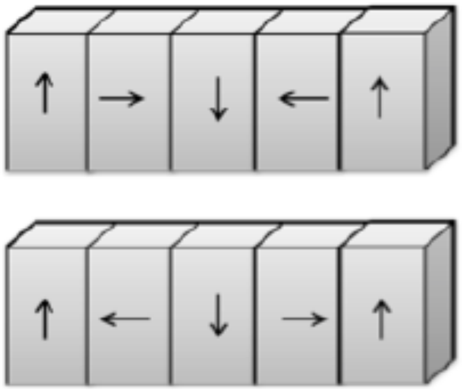
a) Study and define scaling laws describing the qualities of the e-beam accelerated through the plasma sections

b) Matching the beam out of plasma, all the way down to the undulator entrance with high accuracy ➔ control of energy spread $\Delta\gamma/\gamma$ and emittance growth

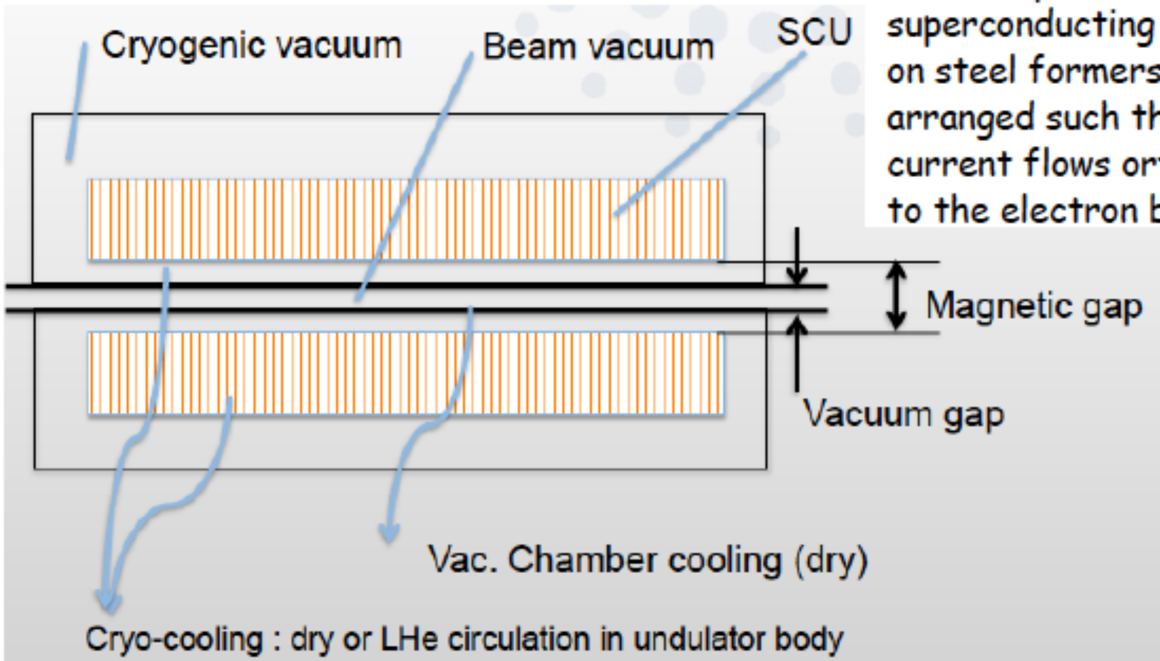
c) Scrutinize (with exp. input) the back-ups for coping with large $\Delta\gamma/\gamma$:

- Magnetic dispersive chicane to reduce the $\Delta\gamma/\gamma$ impact
- 2N-pole (sextupole, etc…) chromatic corrections

Undulator technologies: PPMU, SCU, CPMU



pure permanent magnet in Hallbach configuration



Two independent sets of superconducting windings on steel formers are arranged such that the current flows orthogonal to the electron beam

Cryogenic cooling of permanent magnet arrays:

- ✓ ~ 40-50 % gain in peak field compared with standard PM undulators
- ✓ better vacuum performance because cold, and better radiation damage resistance

➢ Present limitations for SCUs:

1) gap can't be squeezed because of the vacuum chamber
2) very sensitive to synchrotron and wakefield radiations

➢ Cheaper alternative: high temperature SCU?

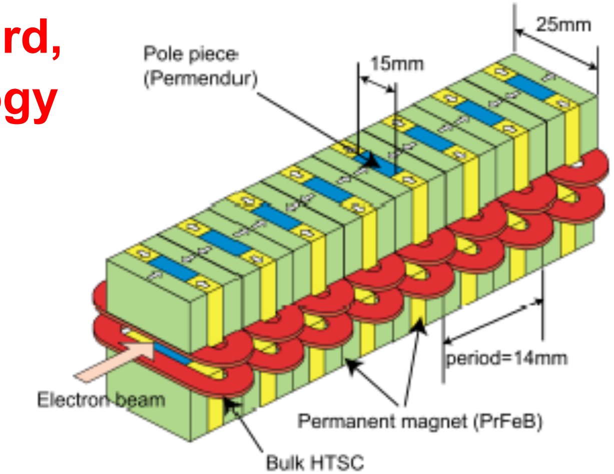
High temperature Superconducting undulators

High Temperature Superconductors

Courtesy of Axel Bernhard, Karlsruhe Institute of Technology

Status

- HTS-PMU structures: concept & proof-of-principle experiments
- HTS staggered array: concept & proof-of-principle experiments
- HTS tape wound coils: short prototypes

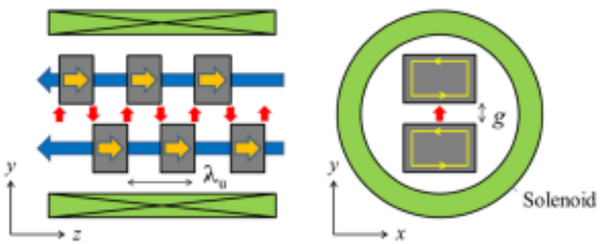


Tanaka et al., PRSTAB **7** (2004), Hybrid HTS permanent magnet undulator

XLS developments/challenges

- explore potential in terms of magnetic design parameters
- develop enabling technologies
- \+ LTS challenges

Magnet technology also of interest for CERN, INFN & PSI



Kinjo et al., PRSTAB **17** (2014), HTS Staggered array undulator

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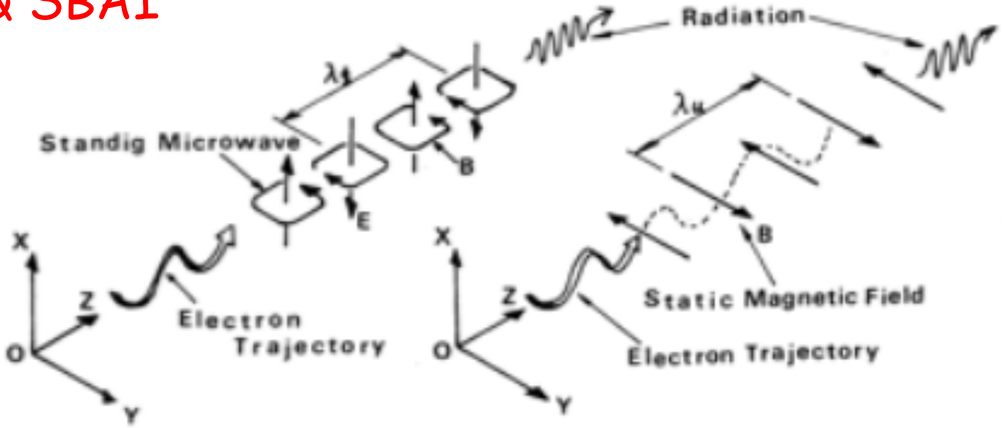
Novel undulators: length reduction

Activity also of interest for SLAC & SBAI Department, Univ. “La Sapienza”



(a) Microwave Undulator (b) Magnetic Undulator

Drawbacks of Static Undulators

1. Cannot control the polarization
2. Cannot change the undulator period
3. Vulnerable to X-ray radiation
4. High cost

Advantages of RF undulators

1. Easy polarization control
2. Short undulator periods and large gaps.
3. Cheap in comparison with the Permanent Magnet Undulators

Drawbacks of RF Undulators

1. Realization of High-Power RF Sources with stable amplitude and phase
2. Complicate design and fabrication

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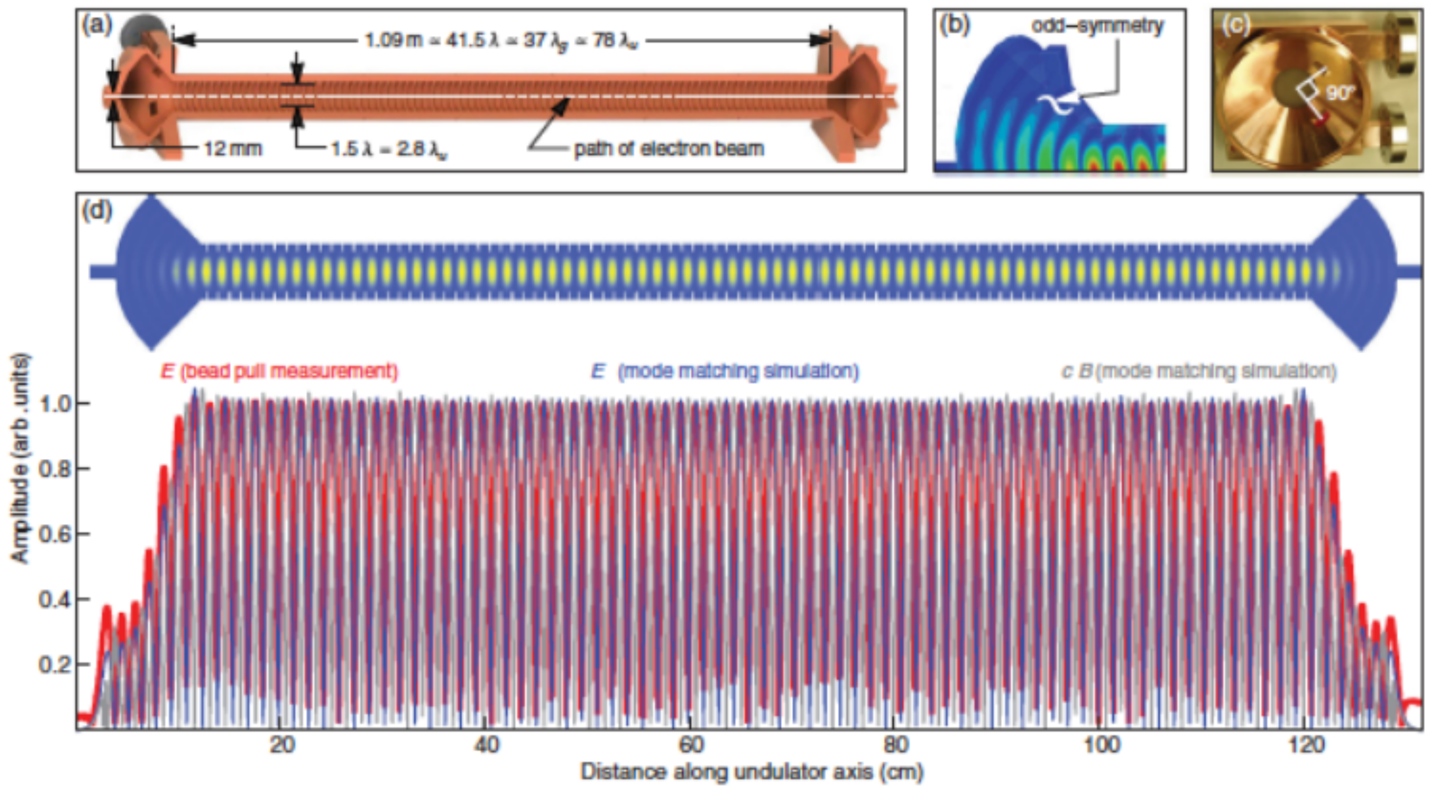
RF undulators @ SLAC

Experimental Demonstration of a Tunable Microwave Undulator

S. Tantawi et al. PRL 112, 164802 (2014)



We wish to address this technology

Further stages of this Thesis subject

a) Undulator choice to be deployed as a FEL driven by Plasma acceleration stages, a systematic comparison study among:
- Conventional undulators
- Superconducting undulators
- Cryogenic permanent magnet undulators

b) Research and development on innovative technologies such as R.F. microwave and Laser undulators

c) Making use of a broad tools range: from exact analytical and semi-analytical scaling laws through start-to-end simulations including the full transport chain and also realistic (higher order…) corrections

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Pledged under full endorsement of:

EuPRAXIA – Research & Innovation Action H2020-INFRADEV-2014-1
Project n. 653782
ENEA is *FEL Pilot Experiments* WP deputy coordinator

XLS-CompactLight – Research & Innovation Action H2020-INFRADEV-2017-1
Project n. 777431
ENEA is *Undulators and Light Production* WP coordinator

order…) corrections

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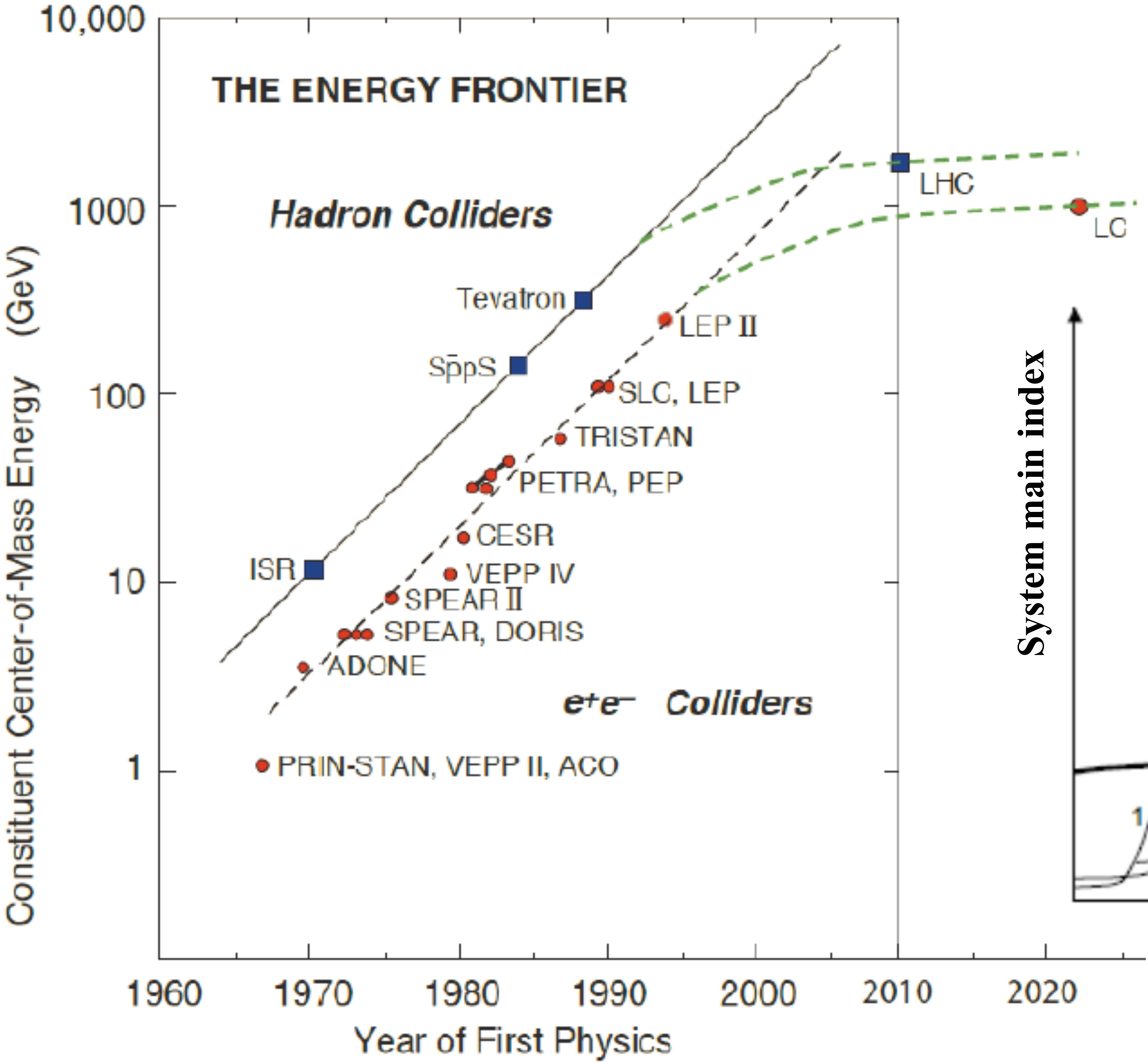
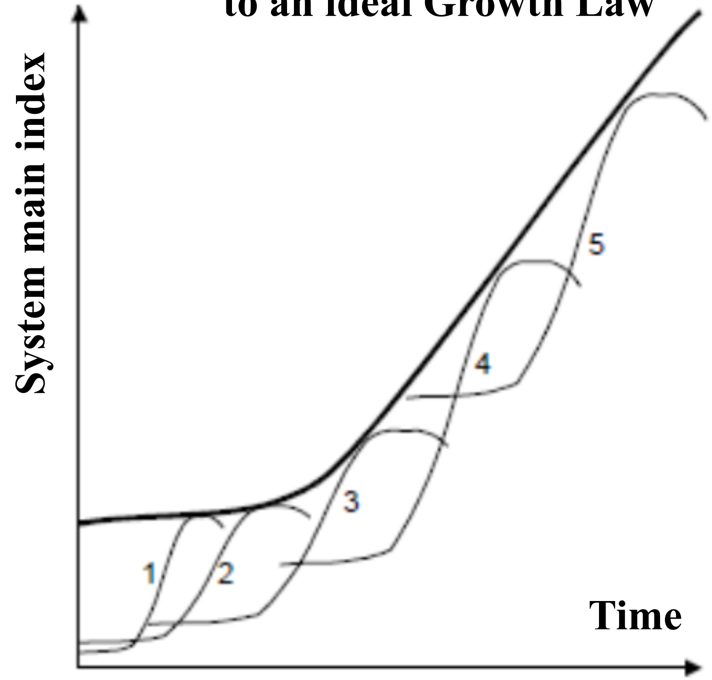
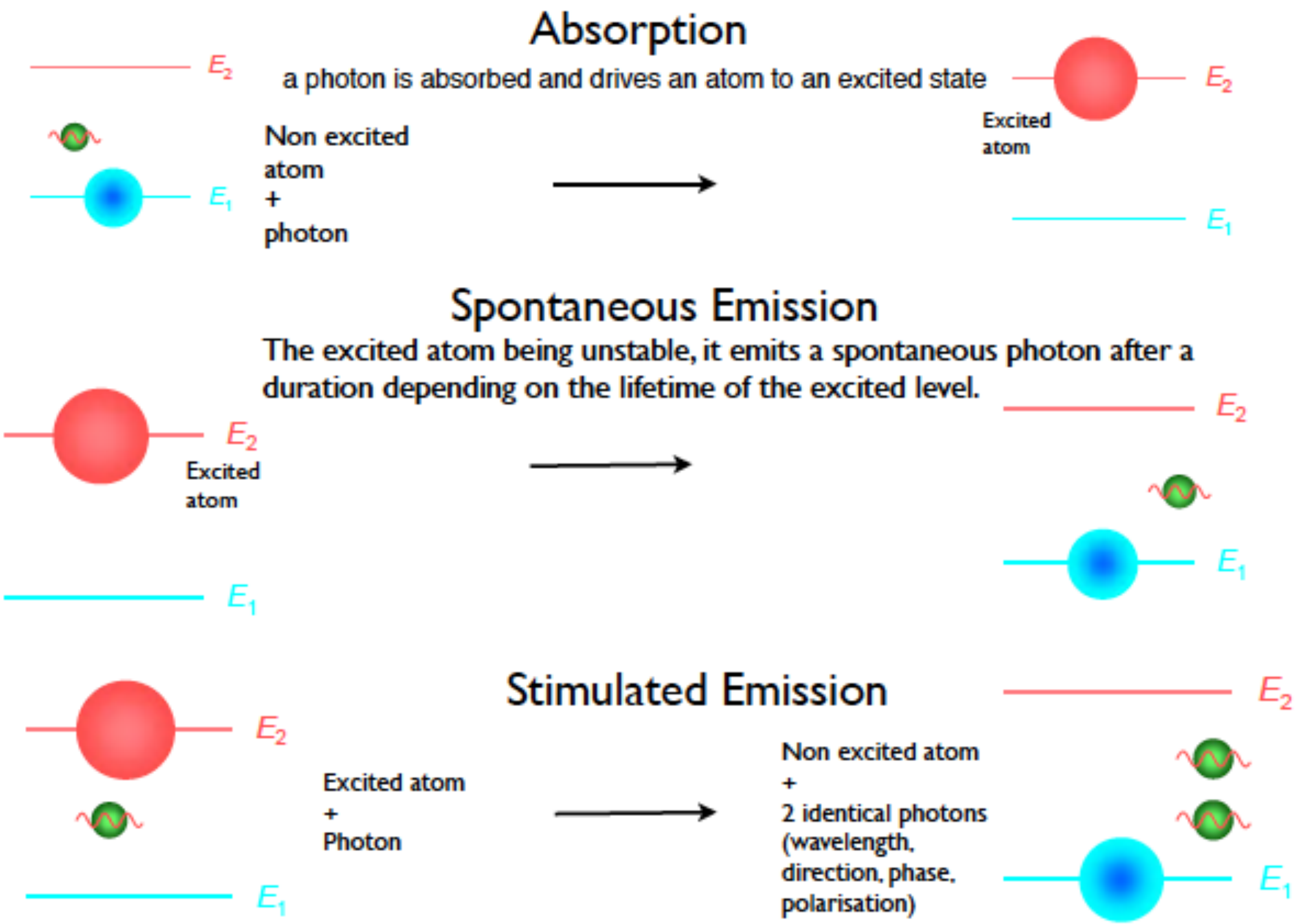
Livingston Chart: new technologies' need



Subsequent replacements of old for new systems according to an ideal Growth Law



One step behind: lasers principle



A photon is absorbed by an excited atom, which results in the emission of two photons with identical wavelength, direction, phase, polarisation, while the atom returns to its fundamental state.