Dottorato in Fisica degli Acceleratori: Incontri con gli studenti del I anno

Plasma Driven Free Electron Lasers

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the SPARC_Lab Collaboration and the EuPRAXIA Consortium

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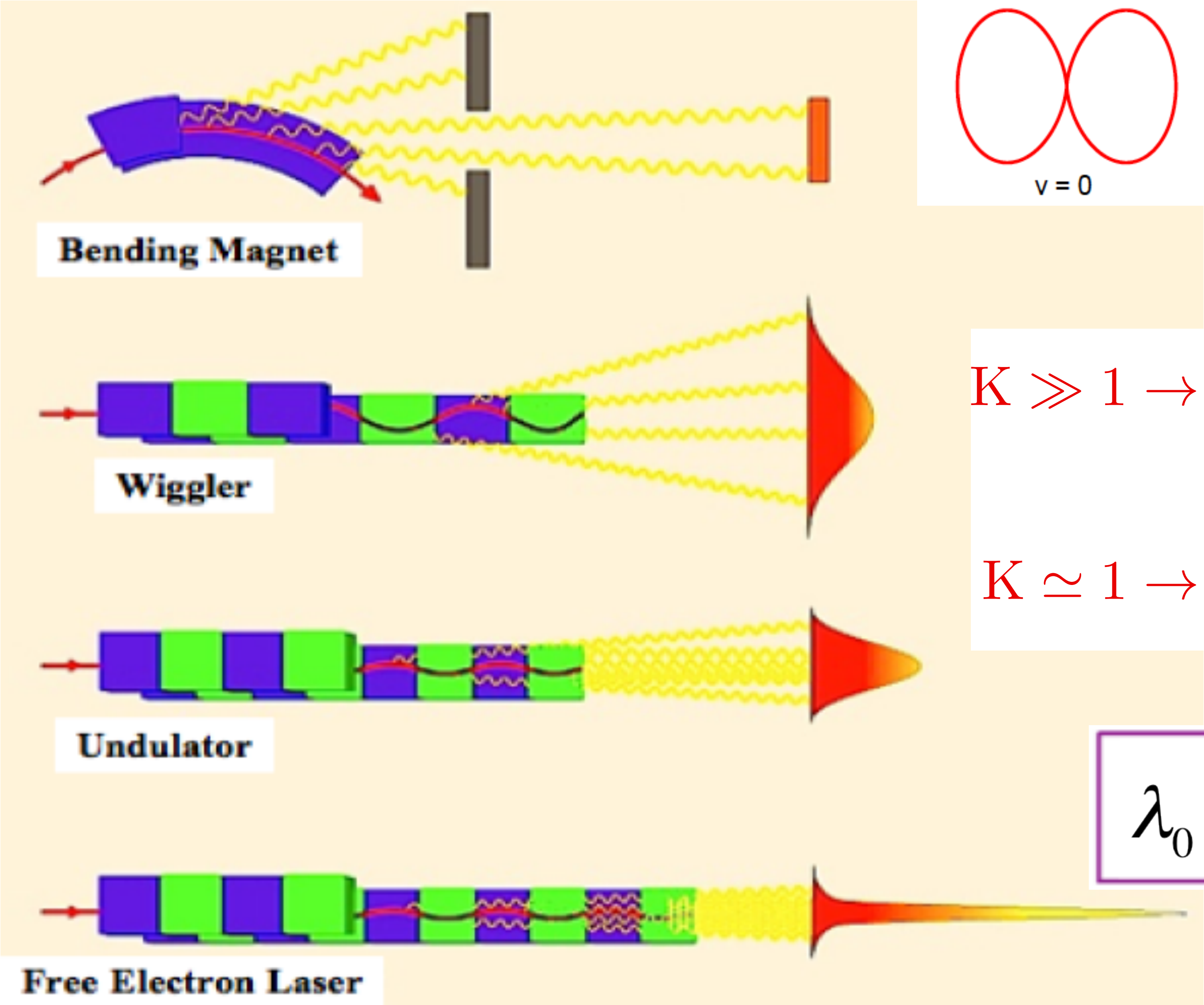
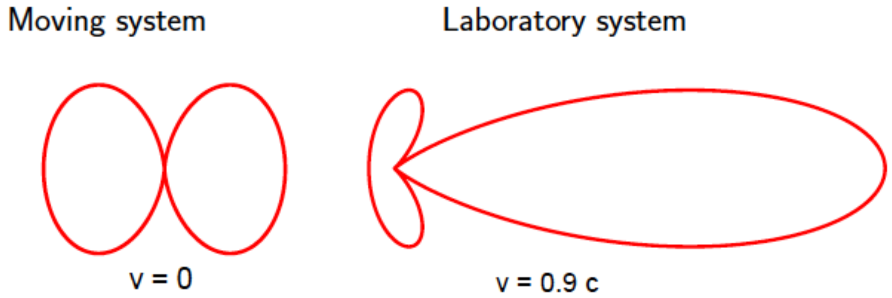
From synchrotron to FEL radiation



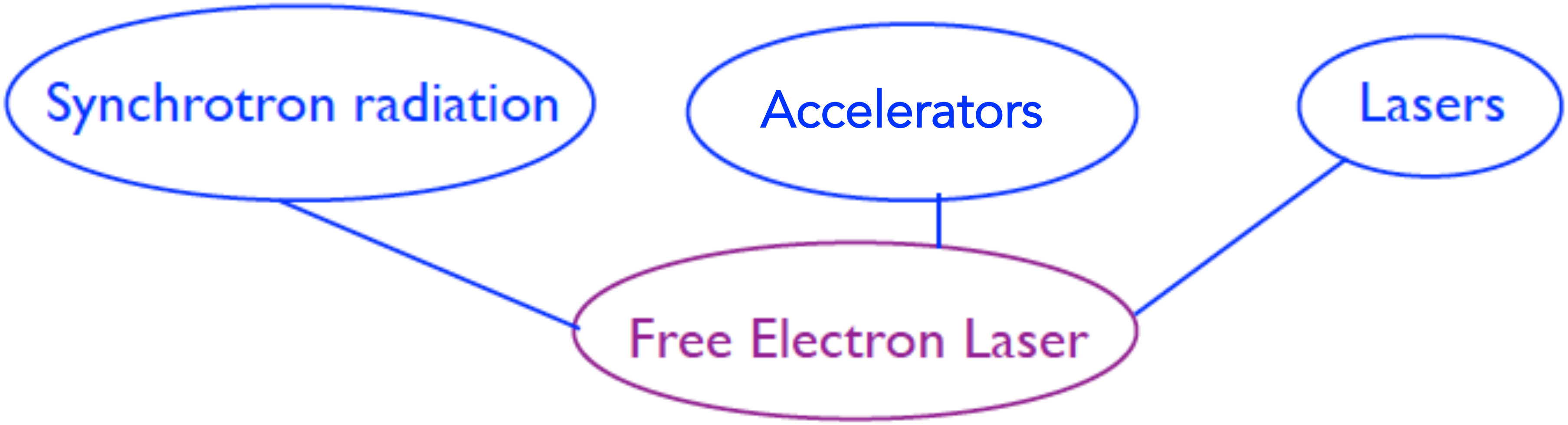


$$K \gg 1 \rightarrow \text{wiggler}: \quad \text{also } \theta \gtrsim \frac{1}{\gamma}$$

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

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

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



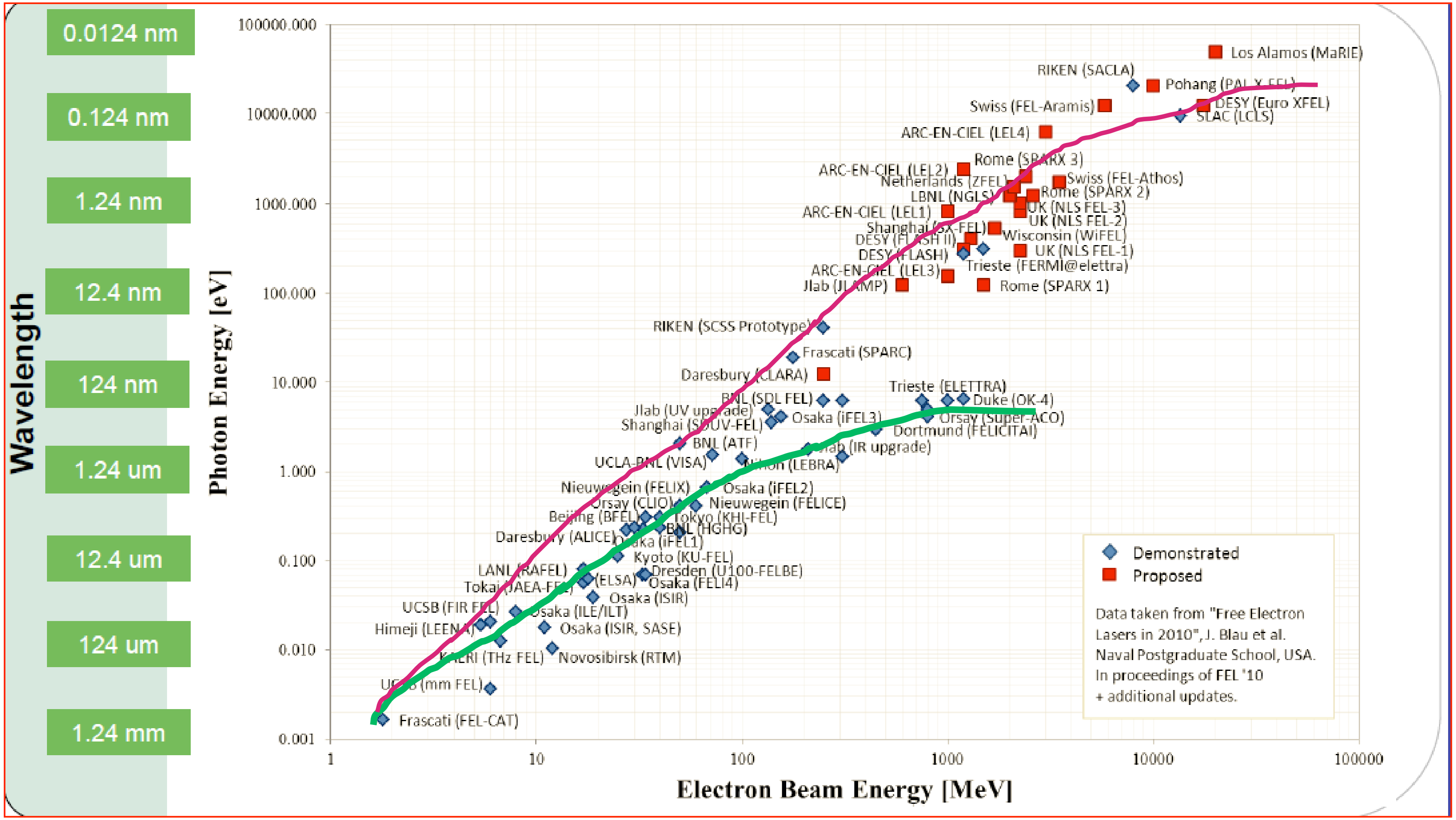
free electrons

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)

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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 innovative devices
(Laser Wave undulators, R.F. Undulators,….)

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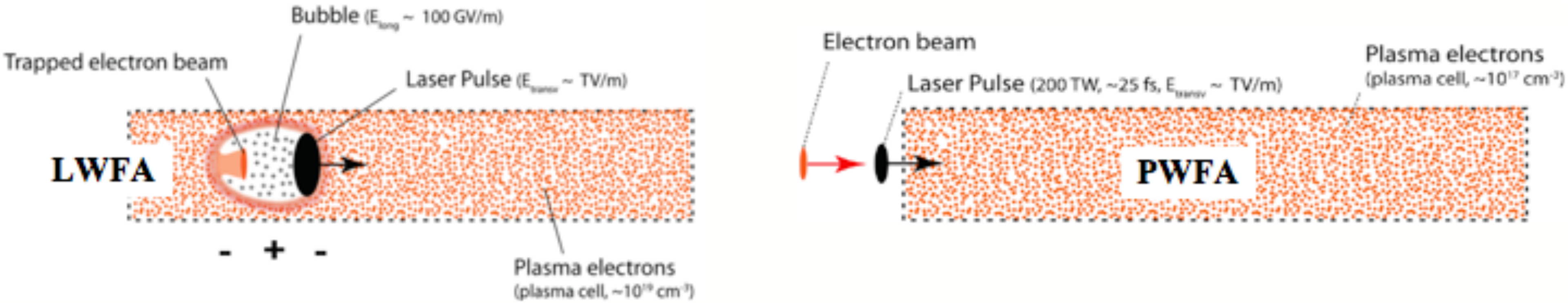
First stage of this Thesis subject



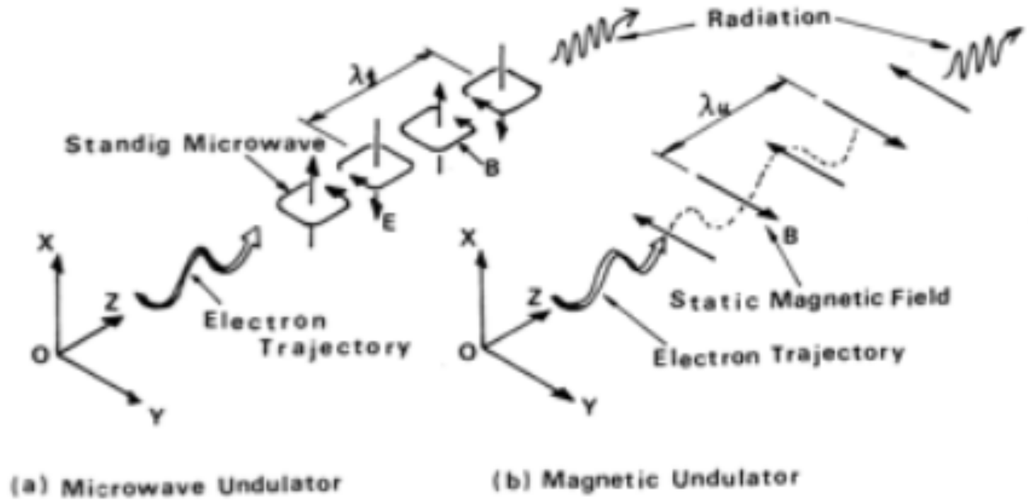
a) Matching out of plasma with beam size ~ 1 μm ➔ it requires offsets between driver & *e*-beam known with 1 μm accuracy ➔ control of energy spread and emittance growth

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

- Lengthening the outcoming bunch over the slice that lases, to reduce $\Delta\gamma/\gamma$
- Transverse gradient undulators with a dispersive chicane

c) Optimize conventional transport/tracking software codes

Novel undulators: cost reduction



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

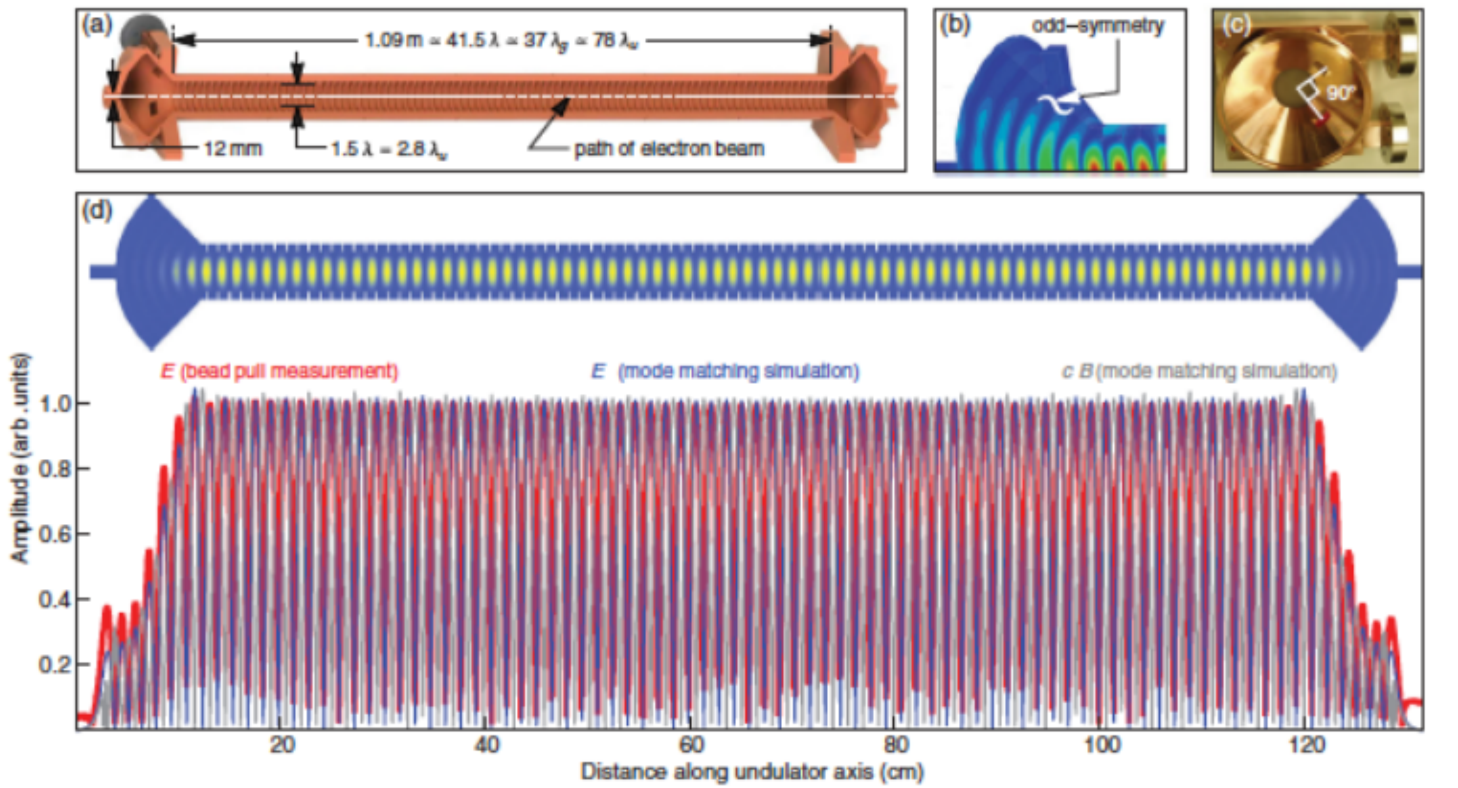
Drawbacks of RF Undulators

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

RF undulators

Experimental Demonstration of a Tunable Microwave Undulator

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



We wish to address this technology

Novel undulators: size reduction

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Pathway to a Compact SASE FEL Device

G. Dattoli, E. Di Palma, V. Petrillo, J. V. Rau, E. Sabia, I. Spassovsky, S. G. Biedron, J. Einstein, S. V. Milton

(Submitted on 29 May 2015)

Newly developed high peak power lasers have opened the possibilities of driving coherent light sources operating with laser plasma accelerated beams and wave undulators. We speculate on the combination of these two concepts and show that the merging of the underlying technologies could lead to new and interesting possibilities to achieve truly compact, coherent radiator devices.

Subjects: **Accelerator Physics (physics.acc-ph)**
DOI: 10.1016/j.nima.2015.07.031

- 1971 Madey, proposal of Free Electron laser and use of the WW approximation to treat the undulator magnetic field as a wave field
- 1983 Dobsiach, Meystre, Scully, Use of wave undulator in FEL
- 1985 Ciocci, Dattoli, Walsh, Analysis of the Feasibility of a FEL oscillator using a wave undulator
- 1987 J. Gea Banacloche, G. T. Moore, R. R. Schlicher, M. O. Scully, H. Walther
- 1993 Cha Mei Tang, B. Hafizi, S. K. Ride…
- 1999 Dattoli, T. Letardi, L.R. Vazquez, FEL SASE WAVE undulators
- 2006 Bacci, Ferrario, Maroli, Petrillo, Serafini
- 2012 Dattoli, Petrillo, Rau Feasibility of wave SASE FEL undulators

Laser wave undulators

* Wave undulators: Use a laser instead of a magnetic device

The State of the art: ATF experiment

M. N. Polyanskiy, I. V. Pogorelsky and V. Yakimenko
Optics Express 7717, Vol. 19, April 11 (2011)
V. Yakimenko, CO_2 Laser Based undulator for a compact SASE FEL
Talk delivered at "Laser and Plasma Accelerators Workshop 2011"
Brookhaven (New Jork) June 20-21 (2011)

Electron beam	
E[Mev]	**77.3**
I[A]	$1.5 \cdot 10^3$
$\frac{E}{E_X}\rho,$ $E_X[keV] = \hbar\omega_s$	**8.6** **10**
Laser Energy [J]	**30**
Laser duration [ps]	**30**

Further stage of this Thesis subject

a) Research and development on novel undulator technologies to be deployed as a FEL driven by Plasma acceleration stages

b) We aim at a systematic design study of:

- Laser EM wave undulators
- Radiofrequency undulatos

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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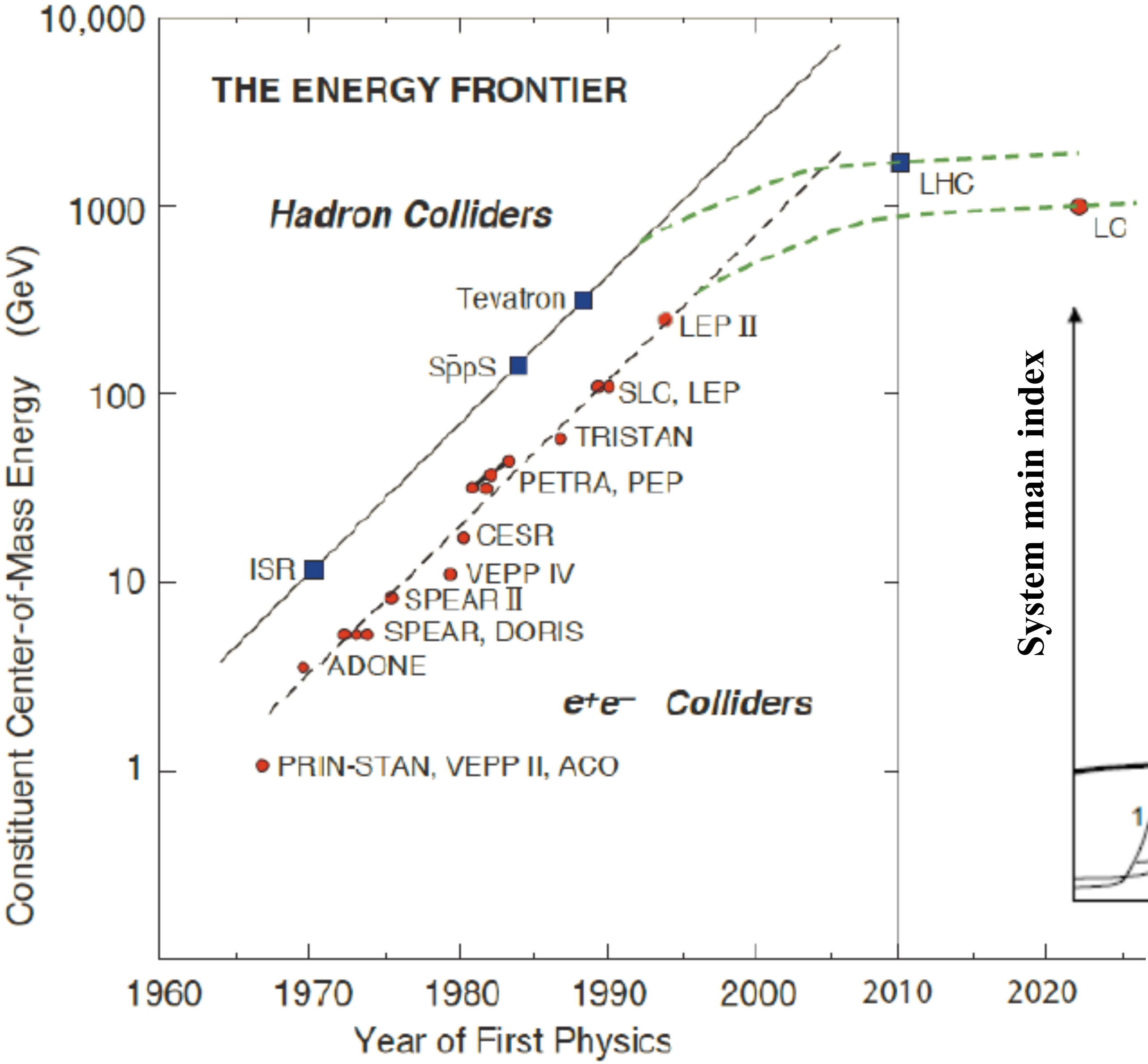
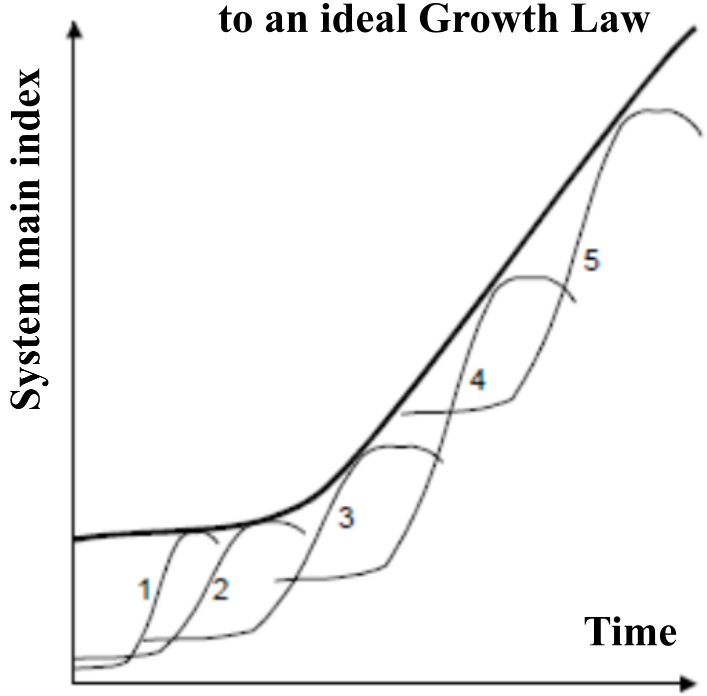
Livingston Chart: new technologies' need

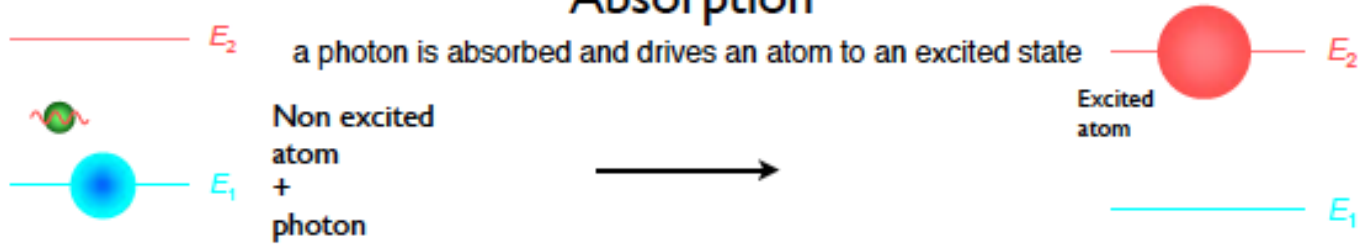


Subsequent replacements of old for new systems according to an ideal Growth Law

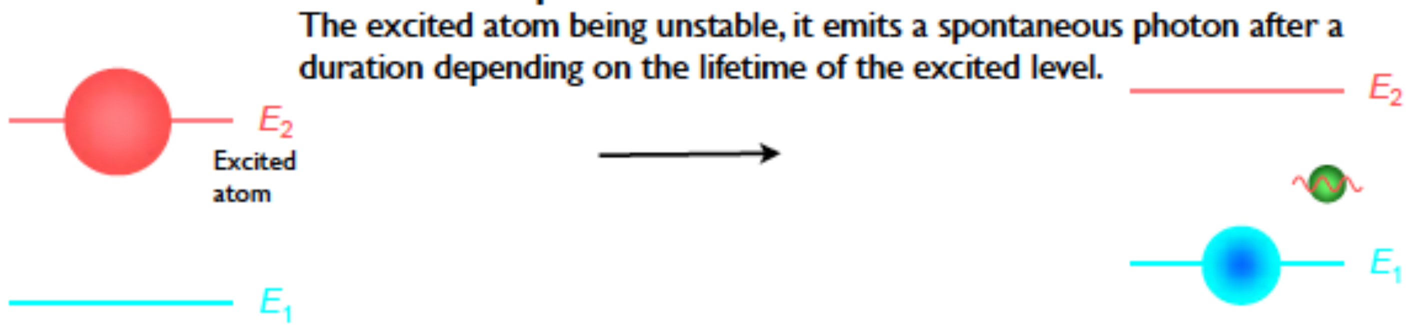


One step behind: lasers principle

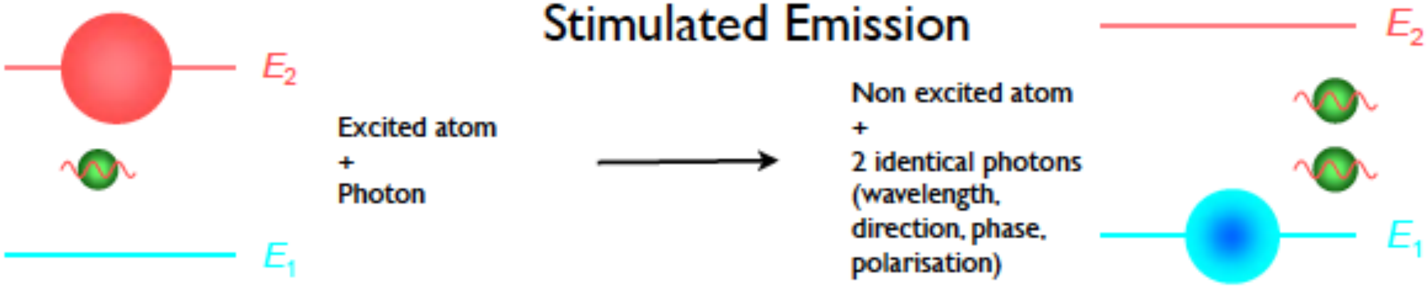
Absorption



Spontaneous Emission



Stimulated Emission



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.

Conclusions

- ✓ Needs to go beyond the state of the art in both accelerators and FELs: plasma acceleration is an opportunity
- ✓ Eupraxia Programme will set the baseline for developments
- ✓ The pathway towards compact and cheap (and performant, of course) is deeply under study, but still a major challenge
- ✓ As WP6 within Eupraxia, we wish to study the design, model and simulation of a FEL driven by plasma acceleration: novel undulator technologies and efficient "manipulation" with the plasma electron beam parameters