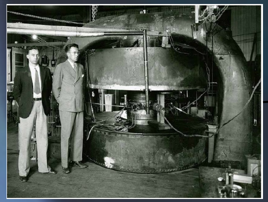
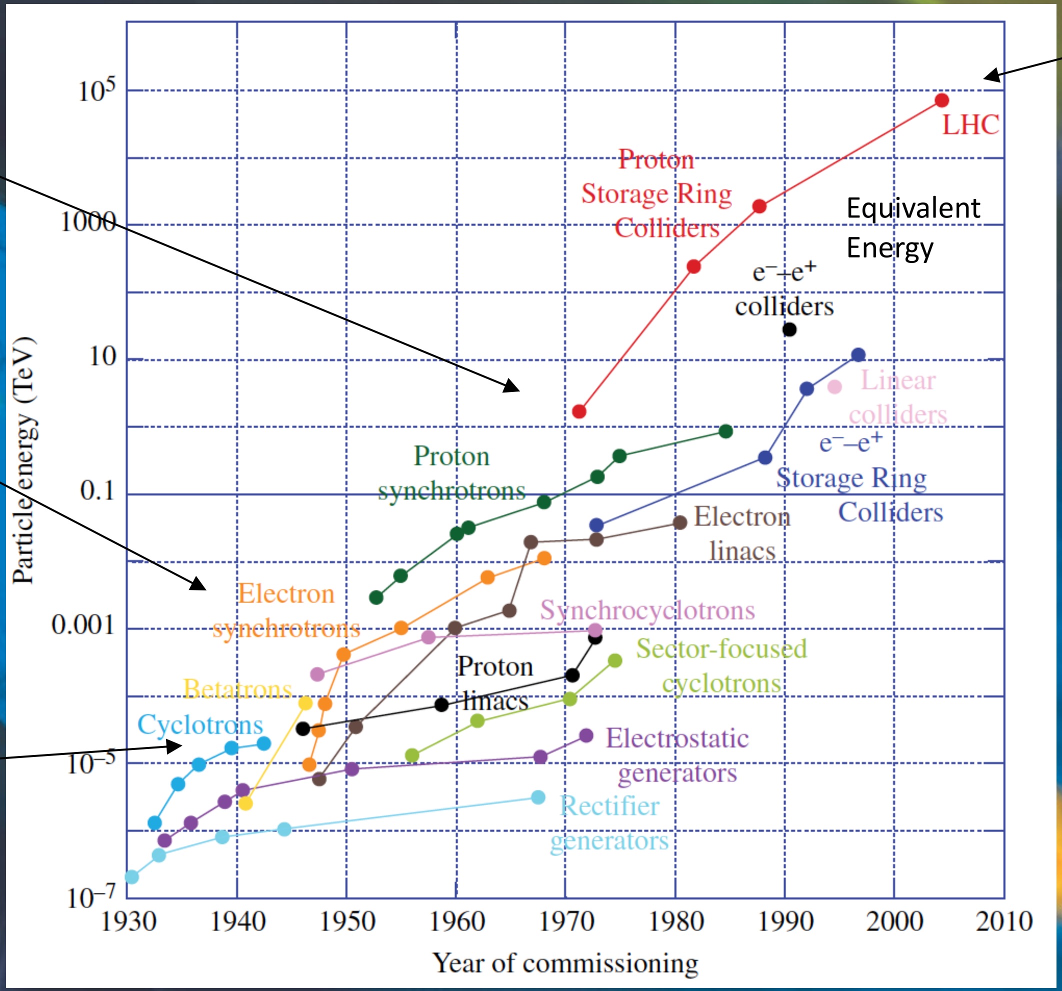
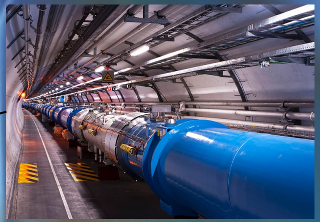
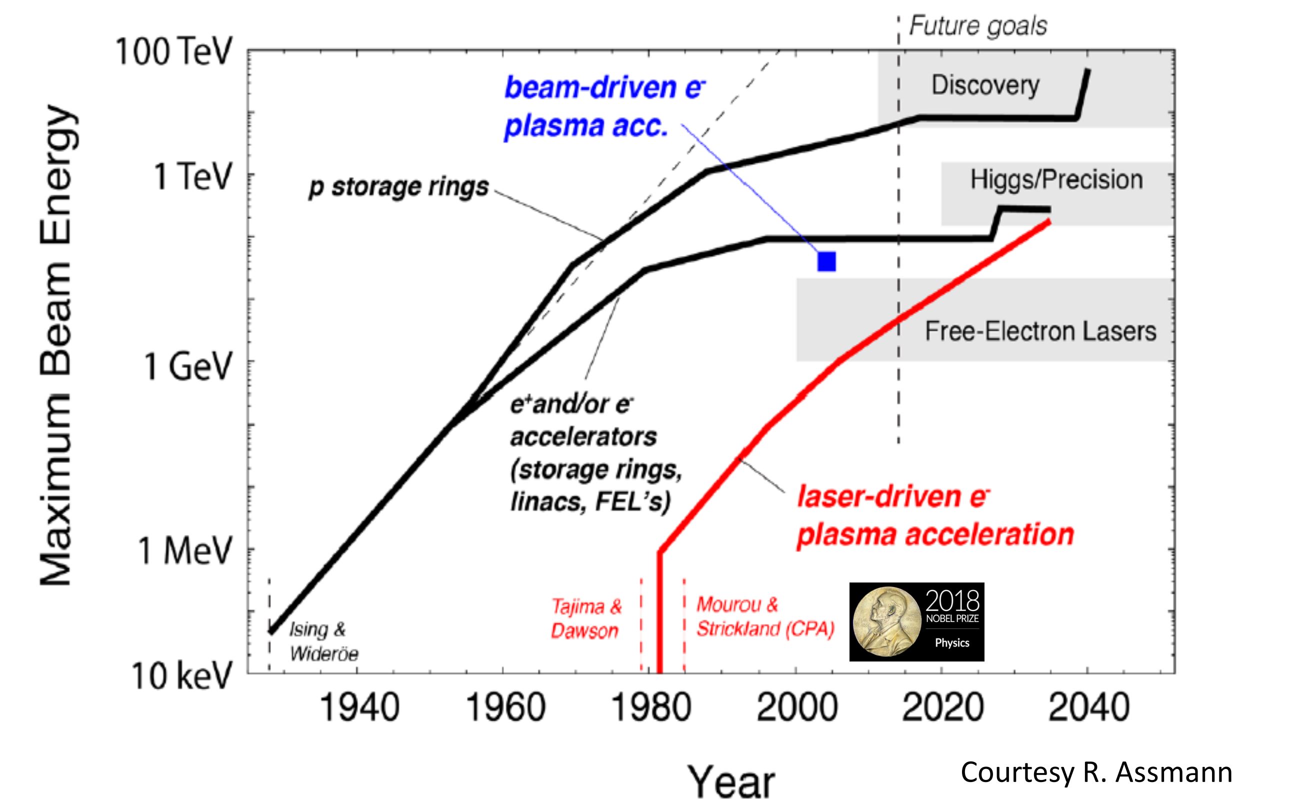
The Livingstone Diagram



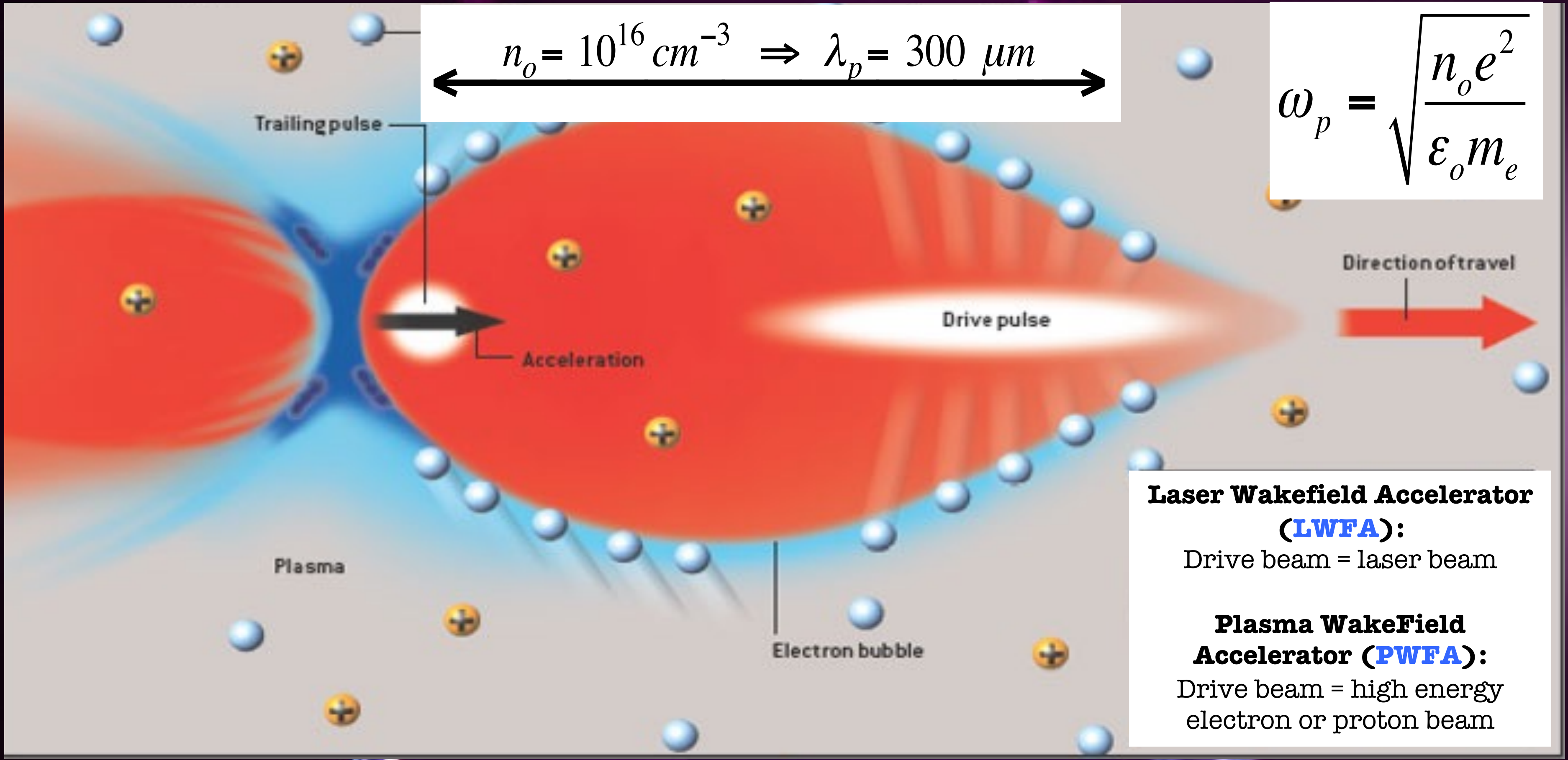




Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.


Future goals
100 TeV
1 TeV
1 GeV
1 MeV
10 keV
Maximum Beam Energy
beam-driven e-
plasma acc.
Discovery
Higgs/Precision
p storage rings
Free-Electron Lasers
e+and/or e-
accelerators
(storage rings,
linacs, FEL's)
laser-driven e-
plasma acceleration
Ising &
Wideröe
Tajima &
Dawson
Mourou &
Strickland (CPA)
2018
NOBEL PRIZE
Physics
1940
1960
1980
2000
2020
2040
Year
Courtesy R. Assmann

Plasma Acceleration



$$n_o = 10^{16}\ cm^{-3} \Rightarrow \lambda_p = 300\ \mu m$$

$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$

Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

Principle of plasma acceleration

Driven by Radiation Pressure

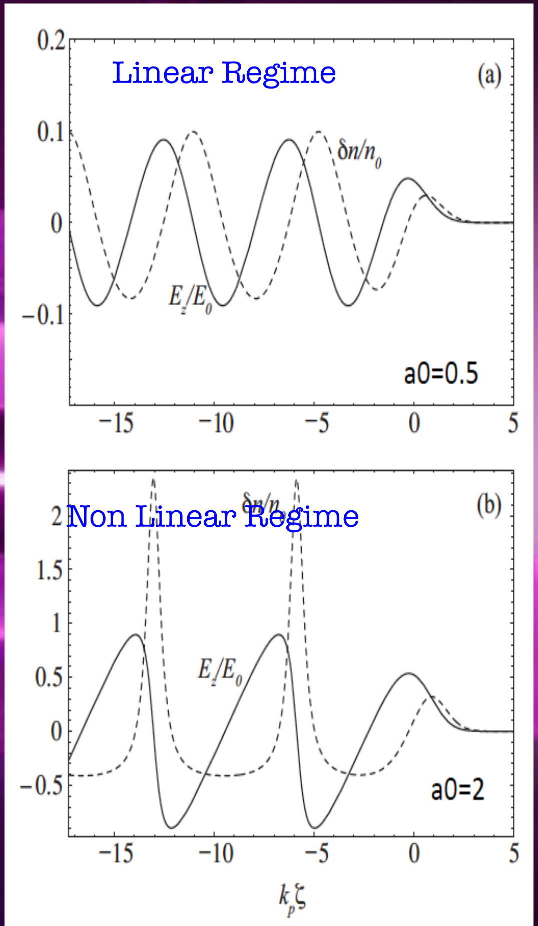
$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=c^2\nabla^2\frac{a^2}{2}$$

$$a=\frac{eA}{mc^2}\propto \lambda J^{1/2}$$

Driven by Space Charge

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{n}{n_o}=-\omega_p^2\frac{n_{beam}}{n_o}$$

$$n_{beam}=\frac{N}{\sqrt{(2\pi)^3}\,\sigma_r^2\sigma_z}$$



LWFA limitations: Diffraction, Dephasing, Depletion

PWFA limitations: Head Erosion, Hose Instability

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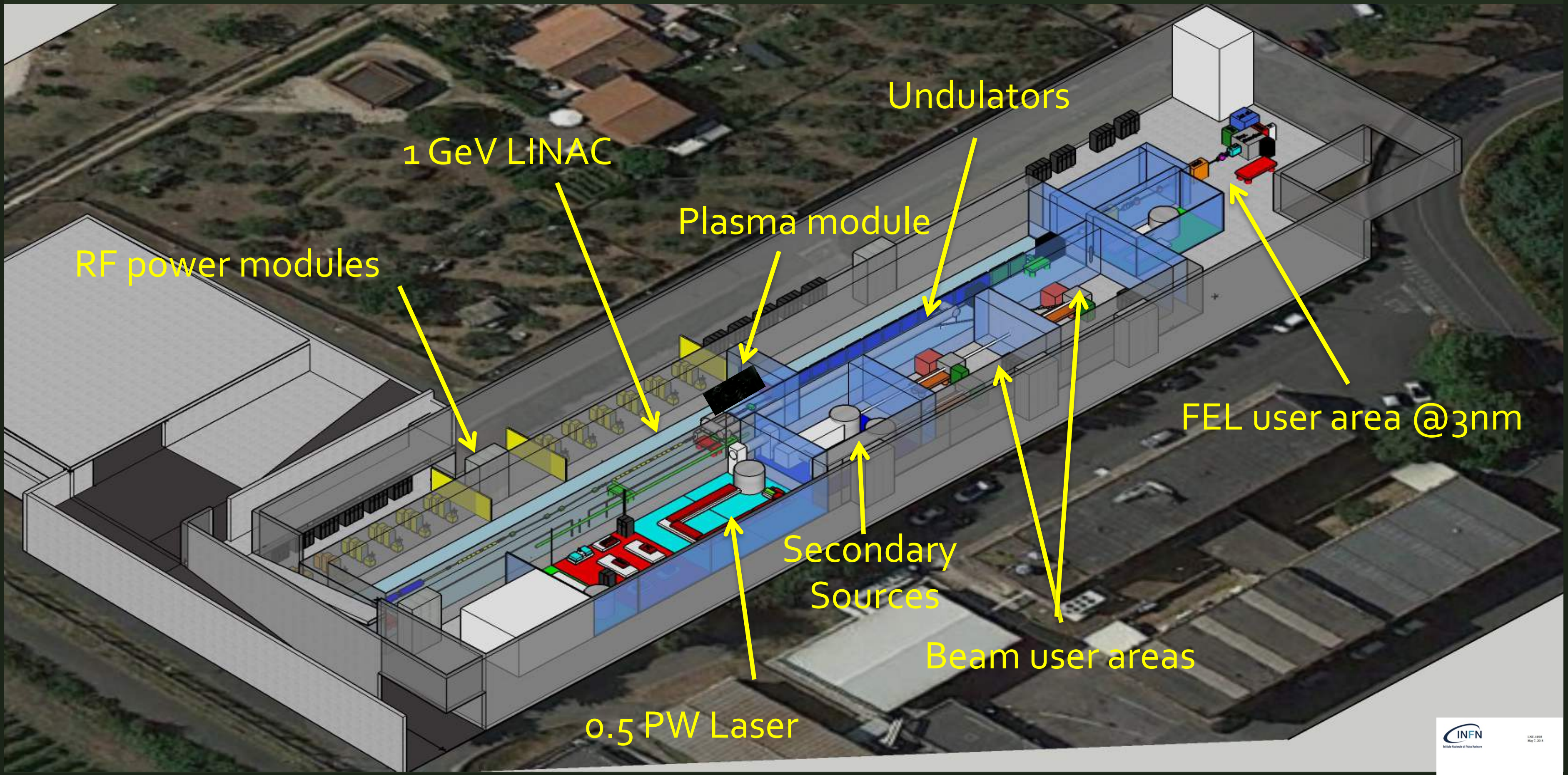
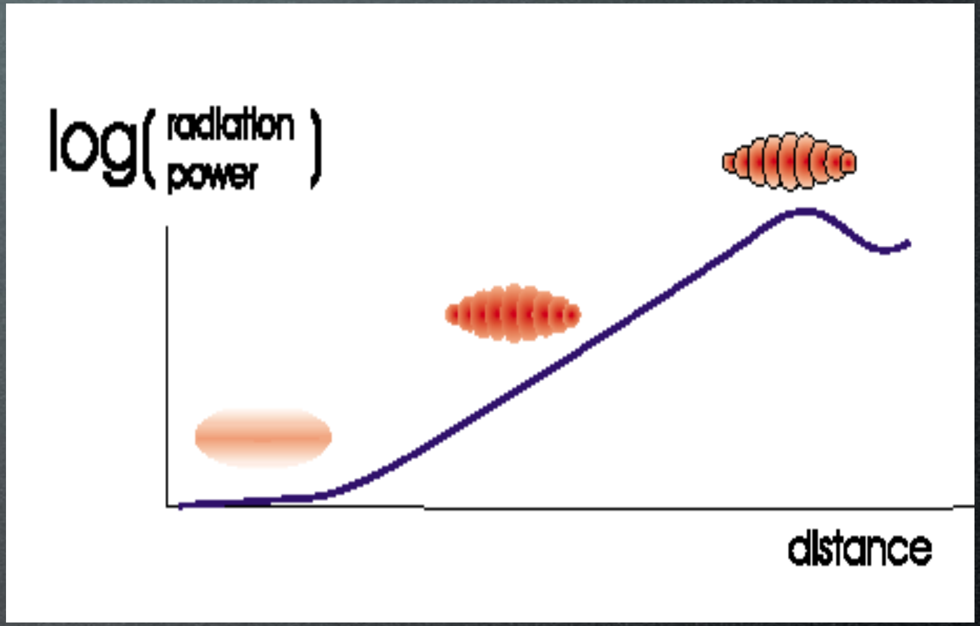


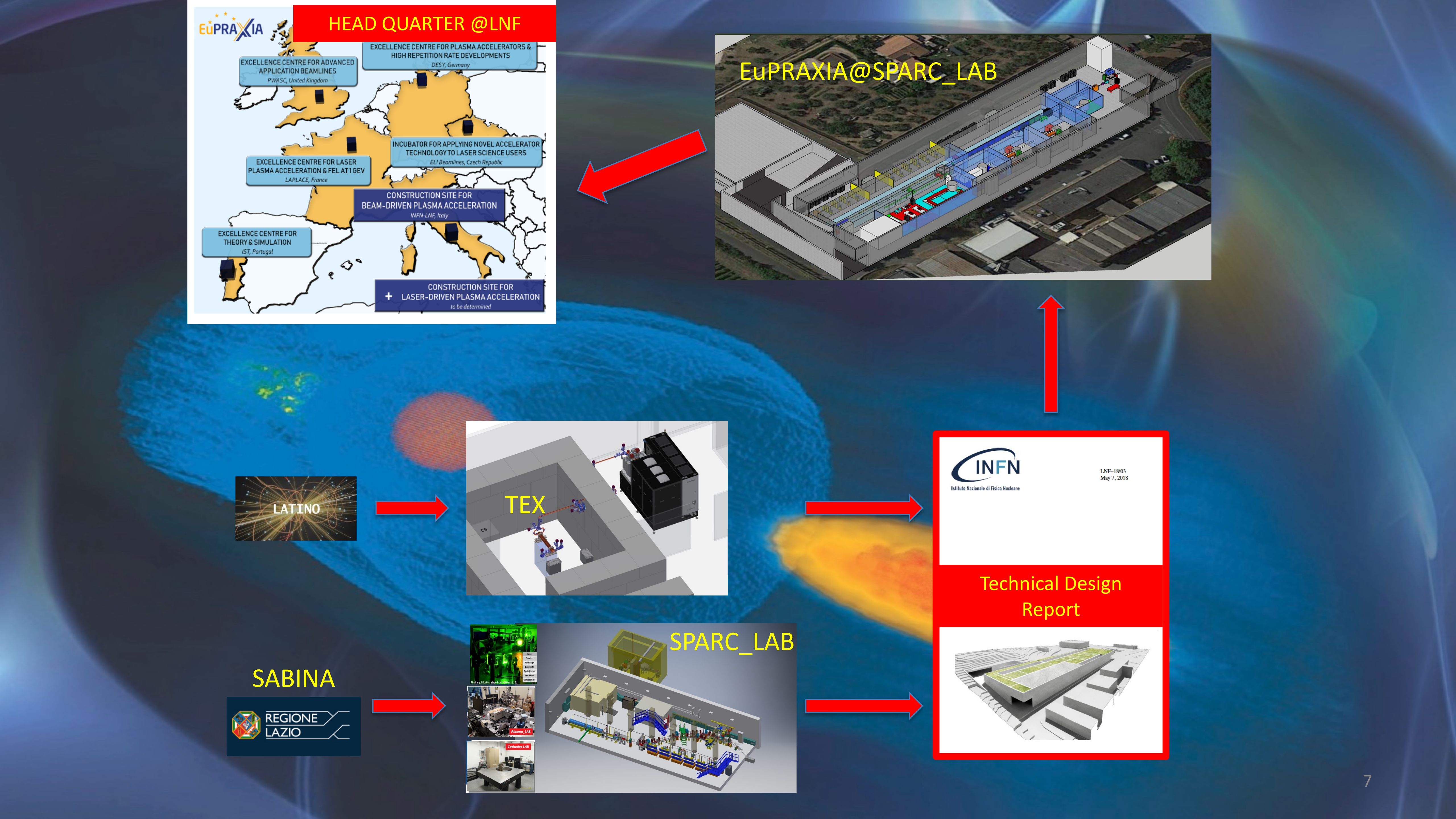
http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

A Free Electron Laser is a device that converts a fraction of the electron kinetic energy into coherent radiation via a collective instability in a long undulator



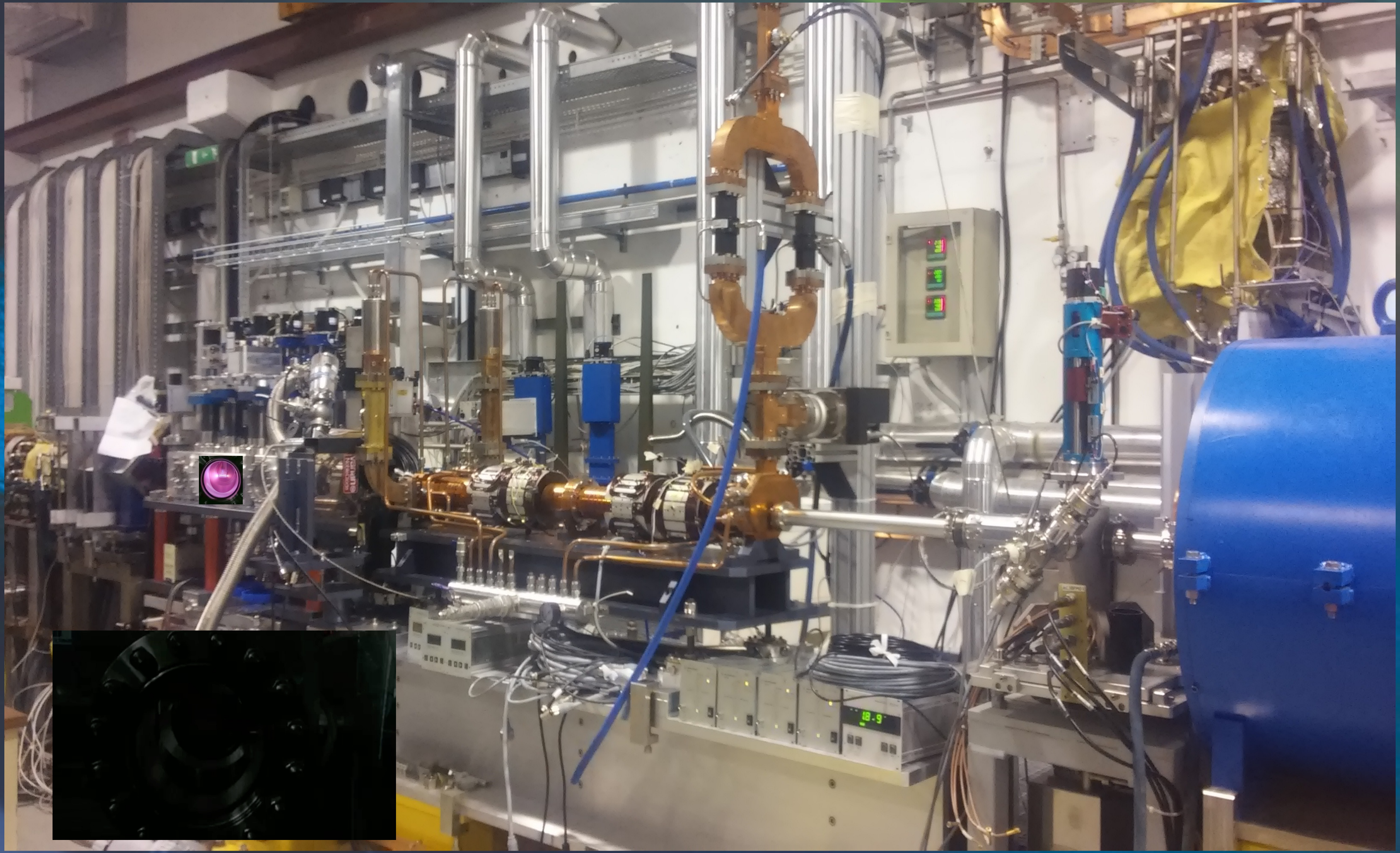
$$\lambda_{rad} \approx \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\vartheta^2\right)$$

(Tunability - Harmonics)


HEAD QUARTER @LNF
EuPRAXIA
EXCELLENCE CENTRE FOR PLASMA ACCELERATORS & HIGH REPETITION RATE DEVELOPMENTS
DESY, Germany
EXCELLENCE CENTRE FOR ADVANCED APPLICATION BEAMLINES
PWASC, United Kingdom
INCUBATOR FOR APPLYING NOVEL ACCELERATOR TECHNOLOGY TO LASER SCIENCE USERS
ELI Beamlines, Czech Republic
EXCELLENCE CENTRE FOR LASER PLASMA ACCELERATION & FEL AT 1 GEV
LAPLACE, France
CONSTRUCTION SITE FOR BEAM-DRIVEN PLASMA ACCELERATION
INFN-LNF, Italy
EXCELLENCE CENTRE FOR THEORY & SIMULATION
IST, Portugal
CONSTRUCTION SITE FOR LASER-DRIVEN PLASMA ACCELERATION
to be determined
EuPRAXIA@SPARC_LAB
LATINO
TEX
SABINA
REGIONE LAZIO
SPARC_LAB
INFN
Istituto Nazionale di Fisica Nucleare
LNF–18/03
May 7, 2018
Technical Design Report

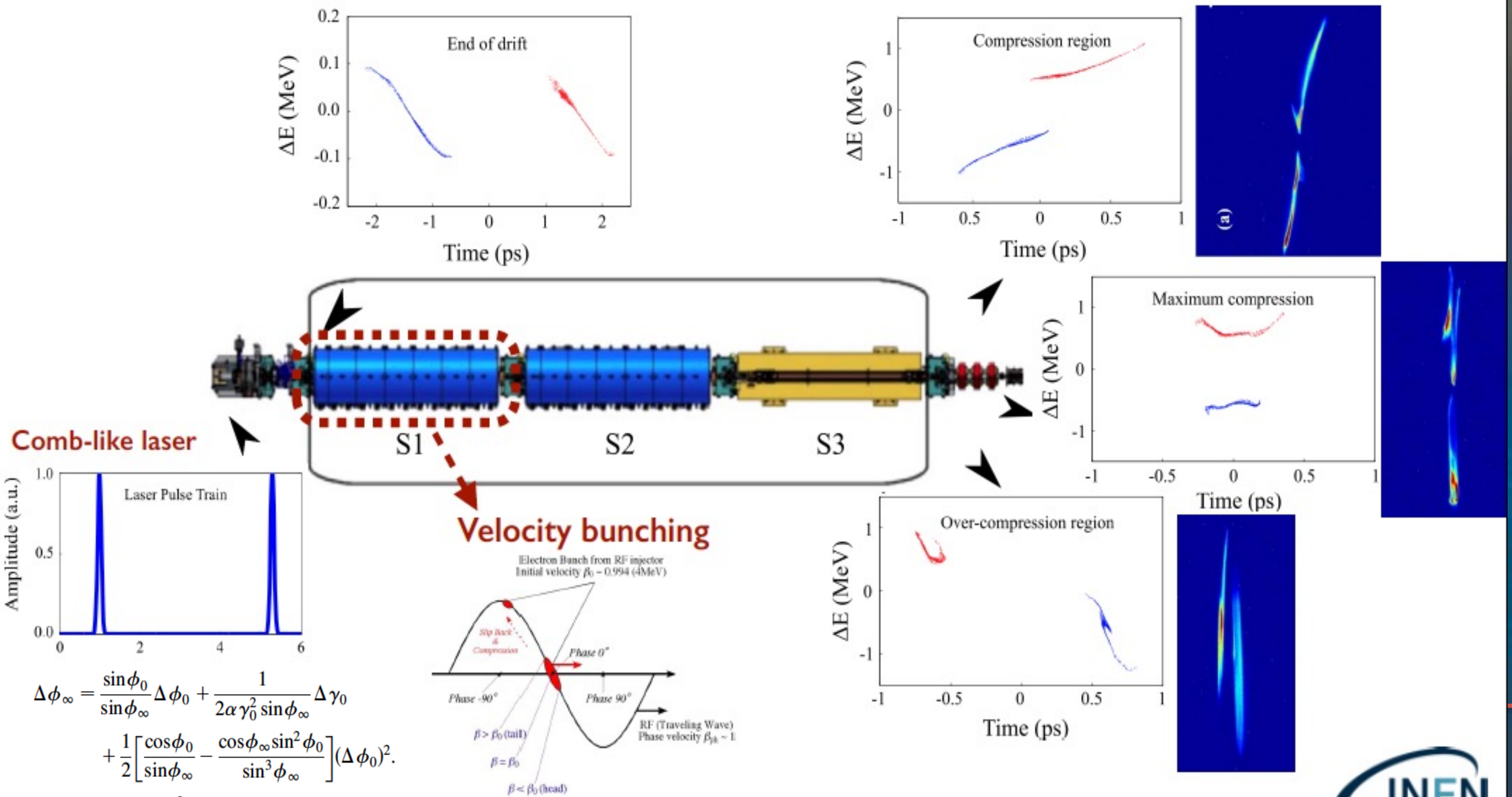
SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)

PWFA vacuum chamber at SPARC_LAB



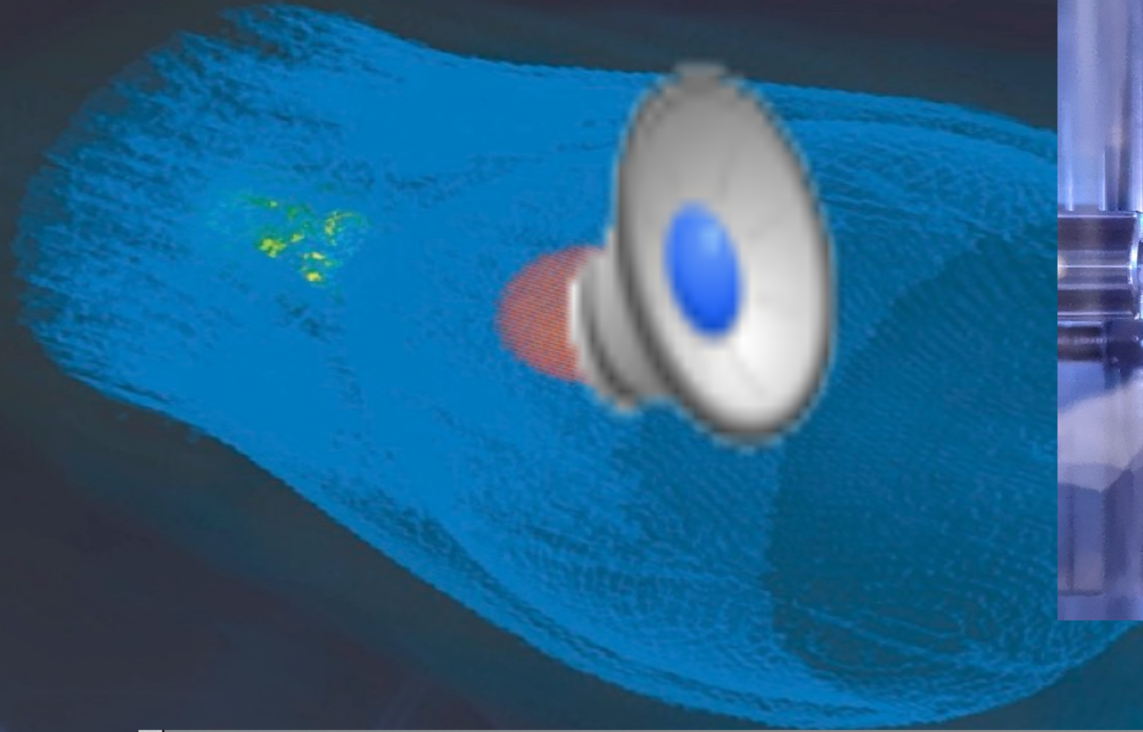
Generation of multi-bunch trains

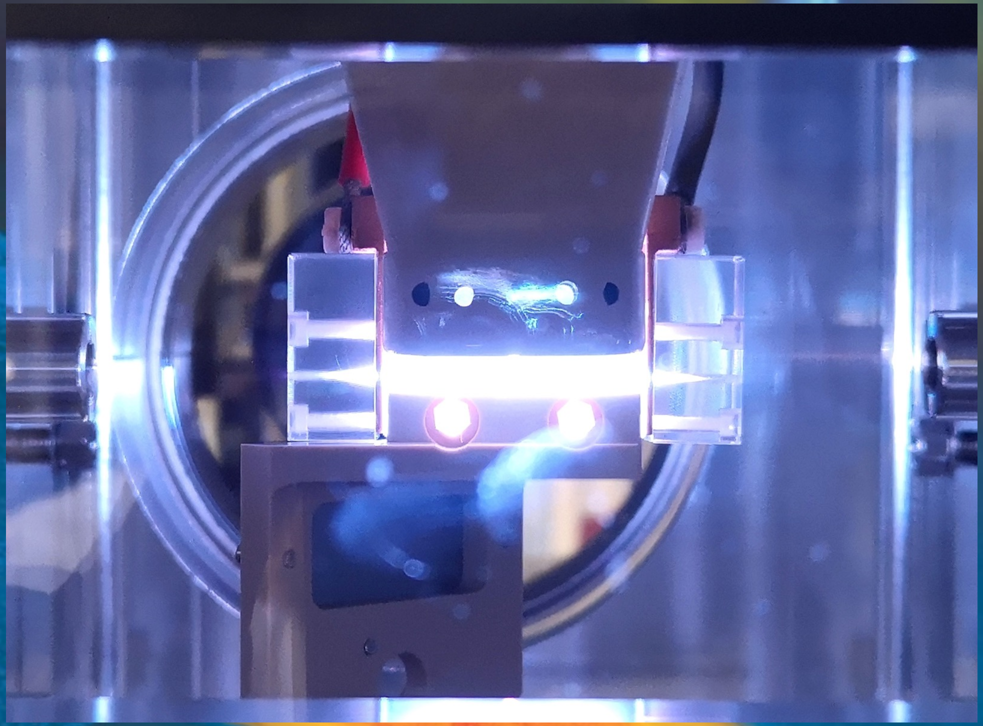
Sub-relativistic electrons ($\beta_c < 1$) injected into a traveling wave cavity at zero crossing move more slowly than the RF wave ($\beta_{RF} \sim 1$). The electron bunch slips back to an accelerating phase and becomes simultaneously accelerated and compressed.



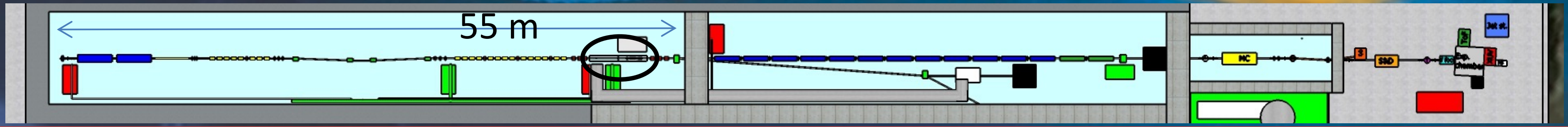
$$\Delta\phi_\infty = \frac{\sin\phi_0}{\sin\phi_\infty}\Delta\phi_0 + \frac{1}{2\alpha\gamma_0^2\sin\phi_\infty}\Delta\gamma_0 + \frac{1}{2}\left[\frac{\cos\phi_0}{\sin\phi_\infty} - \frac{\cos\phi_\infty\sin^2\phi_0}{\sin^3\phi_\infty}\right](\Delta\phi_0)^2.$$

Plasma WakeField Acceleration

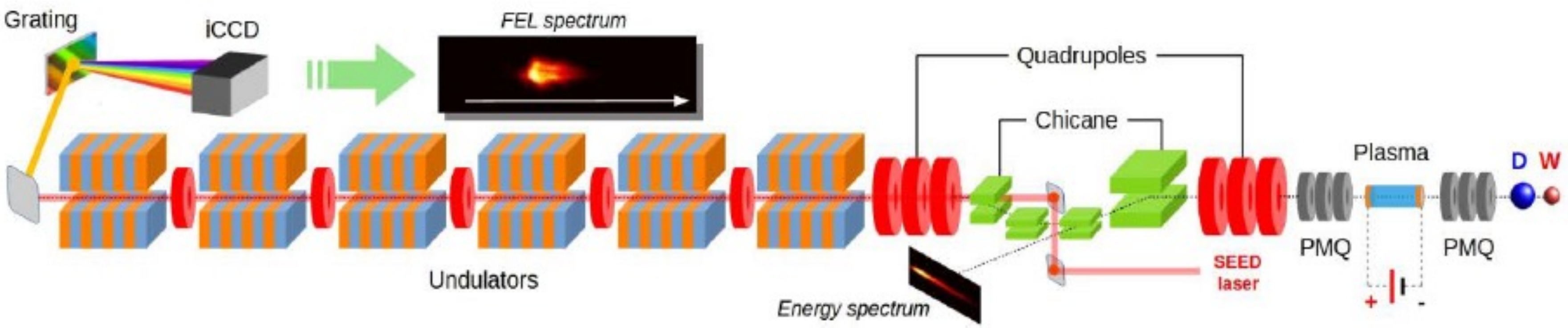




Capillary discharge at SPARC_LAB

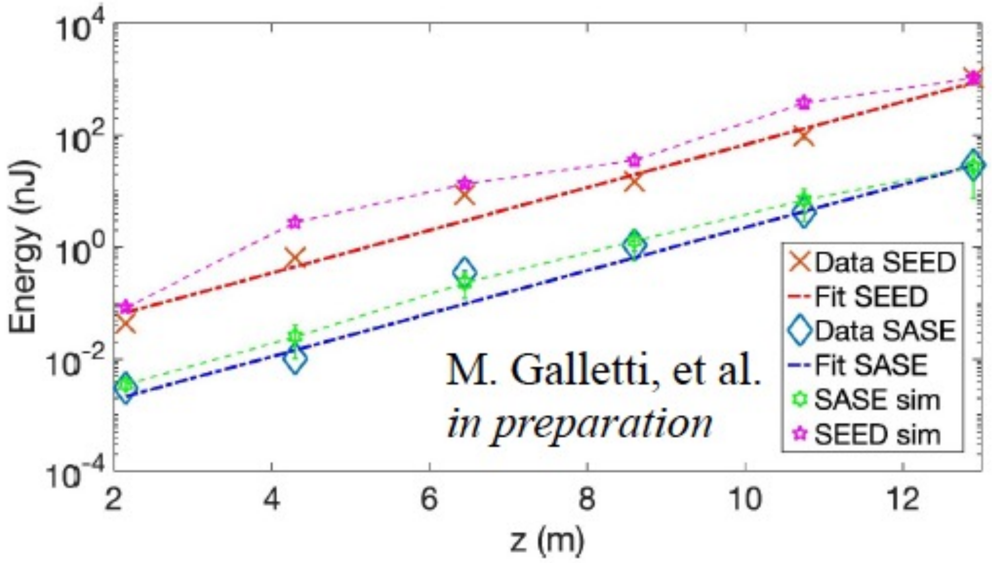


First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)

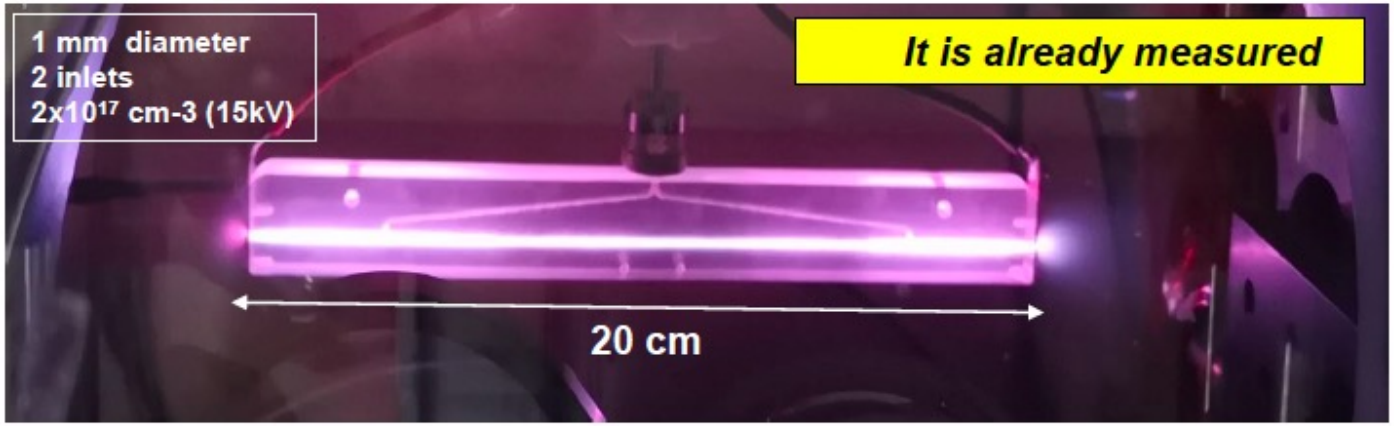


Seeded FEL radiation:

- part of the EOS laser was used as a seed;
- seed laser 795 nm, FEL peak still at 827 nm;
- pulse energy increase from ~30 nJ up to ~ 1 μJ;
- increased stability of radiation.

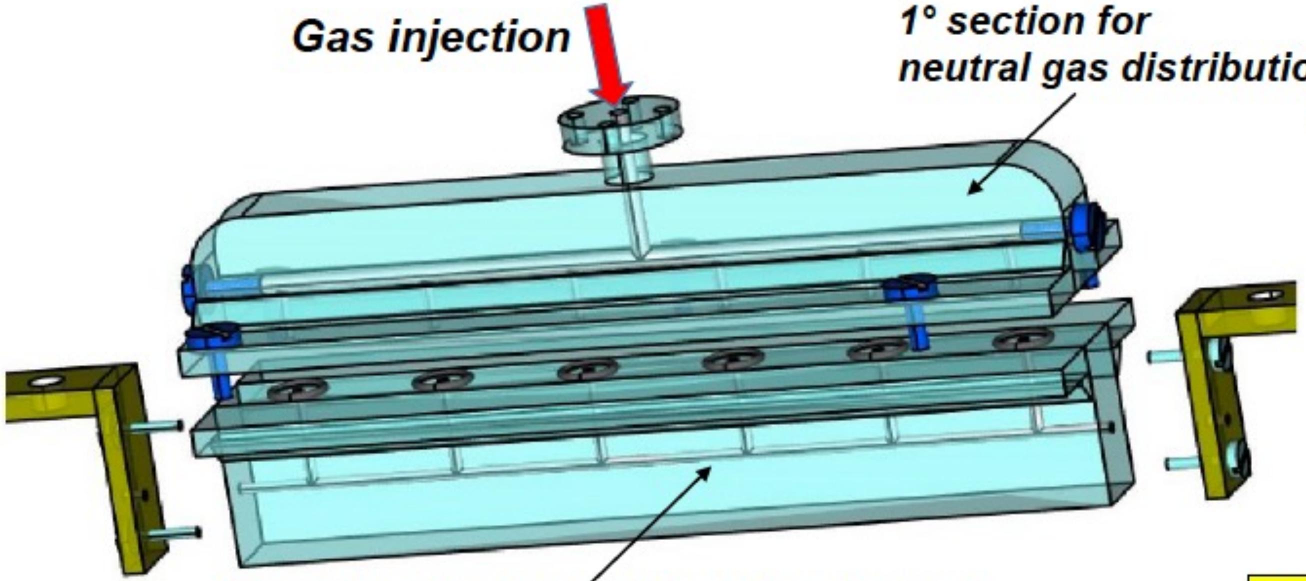


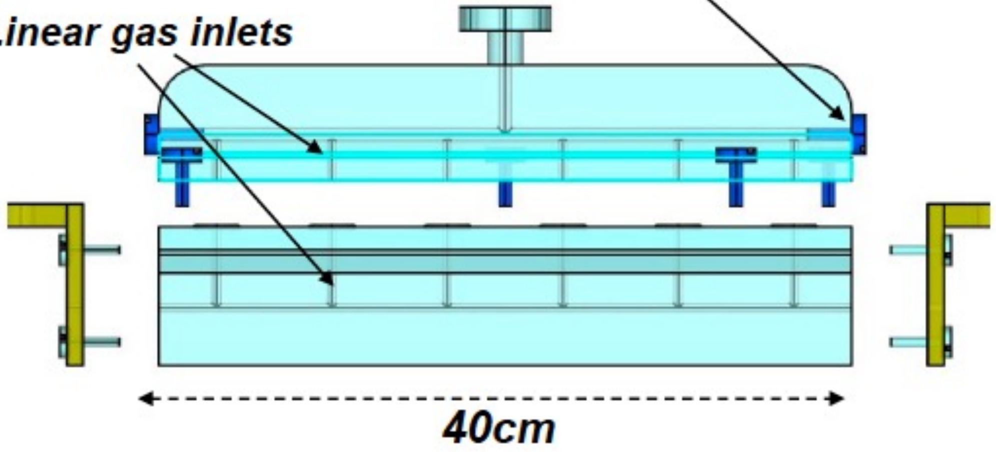
40 cm-long Gas-filled discharge-capillary



Paschen curves (50 mbar)

Length	*Density*	*Vb*
3 cm	4×10^{16} cm-3	3 kV
10 cm	4×10^{16} cm-3	8 kV
20 cm	4×10^{16} cm-3	14 kV
40 cm	4×10^{16} cm-3	23 kV





Linear channel/inlets allow us to clean them from printing residuals

Betatron Radiation Source

$K_u<1$

$K_u>1$

$K_u>>1$

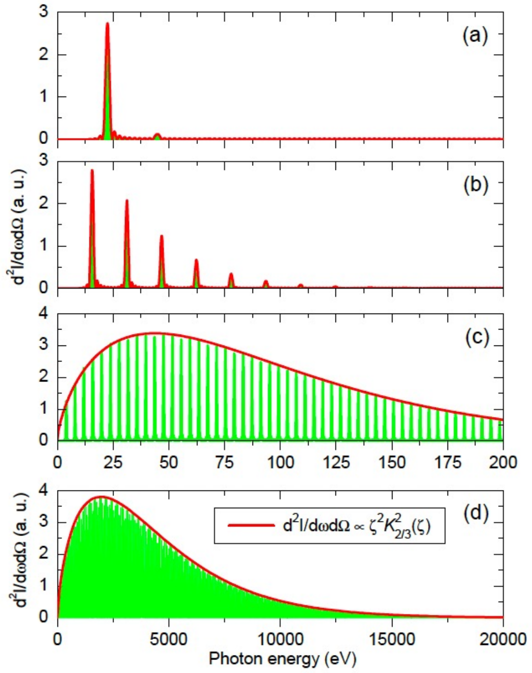


Figure 3.3: *Calculated betatron radiation spectra in a plasma column with density of 7×10^{18} cm^{-3}. The electron energy is 15 MeV, and oscillation amplitudes are (a) 0.1 μm, (b) 0.5 μm, and (c) 1.6 μm. (d) shows the case of a 100 MeV electron with an oscillation amplitude of 1.6 μm.*

$$\omega_c = 3K_u\gamma^2\omega_\beta$$

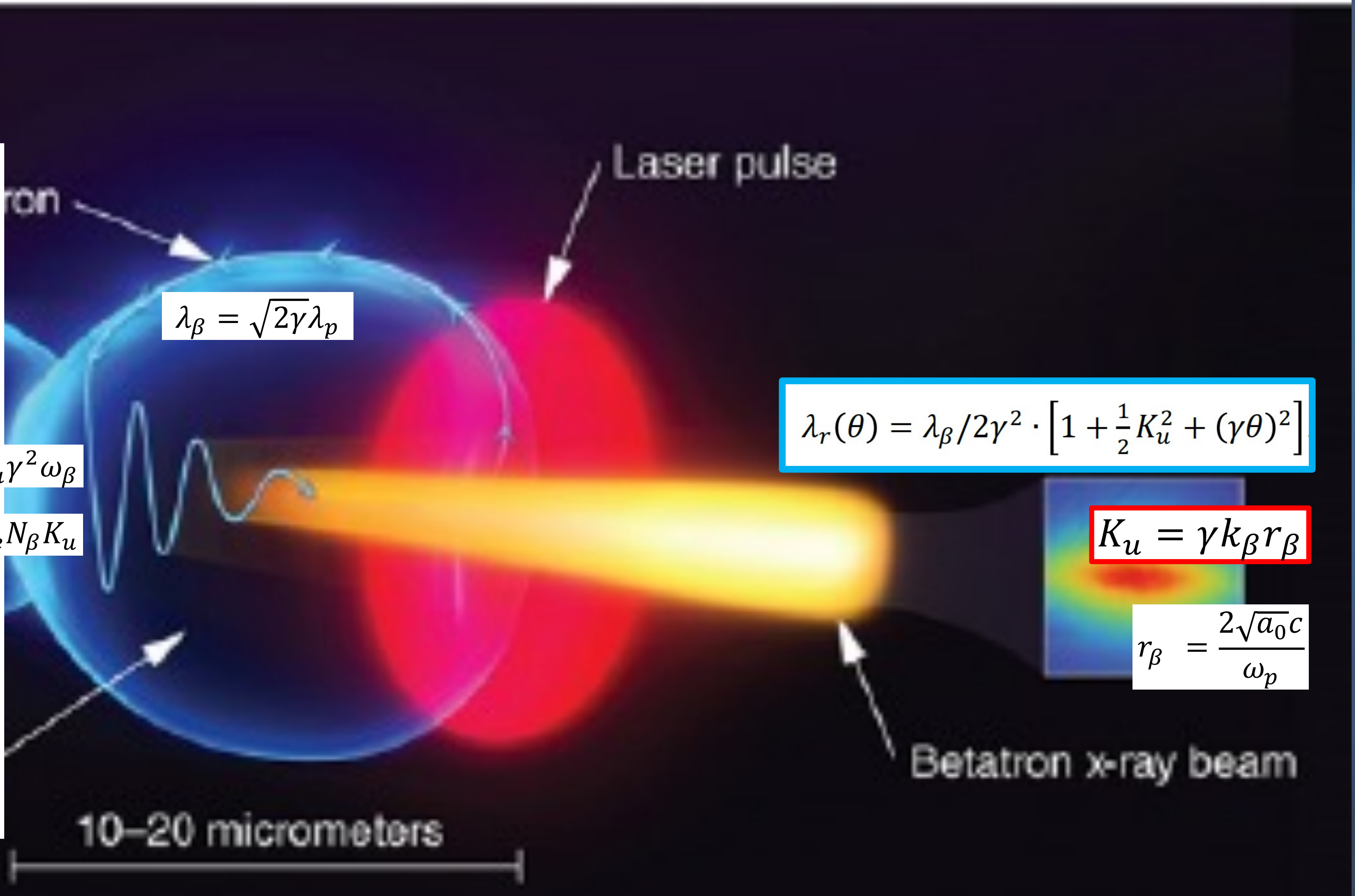
$$N_{ph} \propto N_e N_\beta K_u$$

$$\lambda_\beta = \sqrt{2\gamma}\lambda_p$$

$$\lambda_r(\theta) = \lambda_\beta/2\gamma^2 \cdot \left[1+\frac{1}{2}K_u^2+(\gamma\theta)^2\right]$$

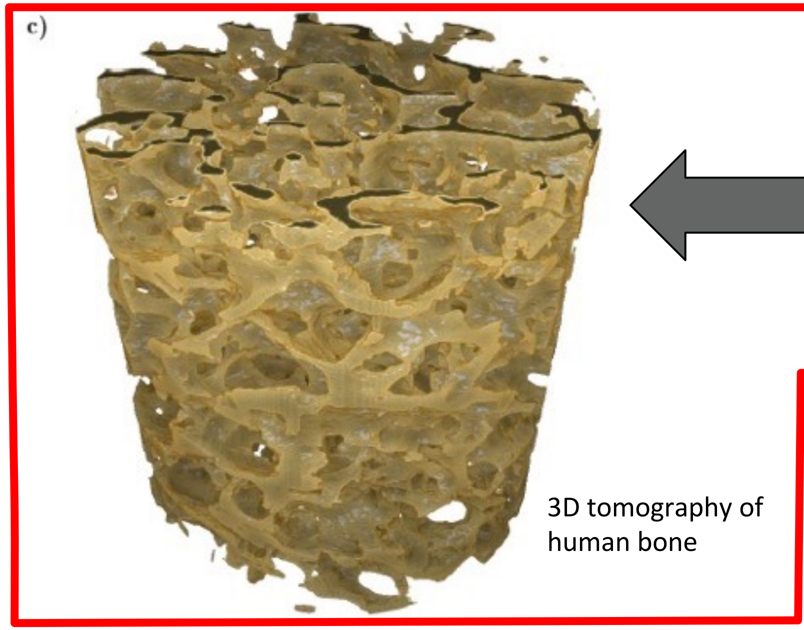
$$K_u = \gamma k_\beta r_\beta$$

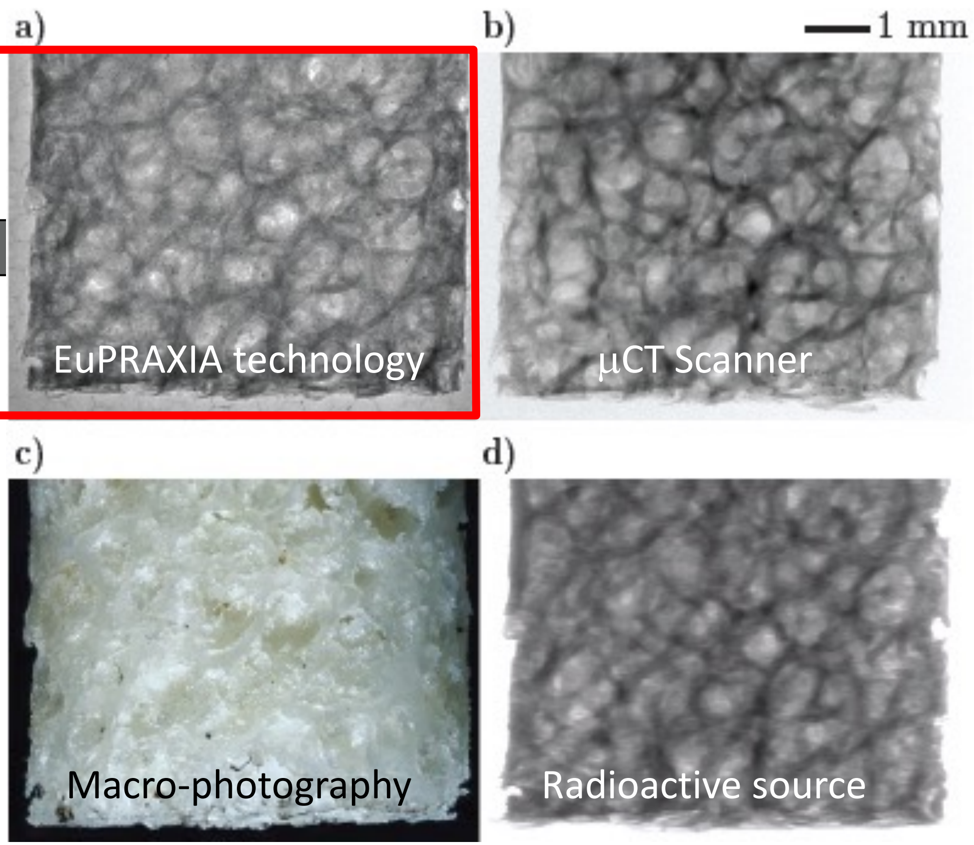
$$r_\beta = \frac{2\sqrt{a_0}c}{\omega_p}$$



Betatron X Rays: Compact Medical Imaging

J.M. Cole et al, "Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone". Nature Scientific Reports 5, 13244 (2015)





- **EuPRAXIA laser advance (industry) will push rate from 1/min to 100 Hz.**
- **Ultra-compact source of hard X rays → exposing from various directions simultaneously is possible in upgrades**

Physics & Technology Background:

- Small EuPRAXIA accelerator → small emission volume for betatron X rays.
- **Quasi-pointlike** emission of X rays.
- **Sharper image from base optical principle.**
- Quality demonstrated and published, but takes a few hours for one image.
- Advancing flux rate with EuPRAXIA laser by factor > 1,000!

Added value

Sharper images with outstanding **contrast**

Identify smaller features (e.g. early detection of cancer at micron-scale – calcification)

Laser advance in EuPRAXIA → **fast imaging** (e.g. following moving organs during surgery)

1. Biagioni - Theoretical and experimental studies of plasma formation in capillary discharge waveguides for plasma-based accelerator
2. Del Dotto - Multi-objective bayesian plasma acceleration
3. Romeo - Positron acceleration in a linear plasma wakefield at EuPRAXIA
4. Costa - External injection and staging studies and tests for plasma wake field acceleration experiments at SPARC LAB
5. Bellaveglia - Theoretical and technological studies on a femtosecond synchronization system towards an efficient Plasma Wakefield Acceleration
6. Vaccarezza: “Analysis and optimization of the EuPRAXIA RF Linac for train generation of ultra-short electron bunch able to drive beam driven plasma wakefield acceleration of high quality electron beam for FEL applications”
7. Mostacci - Beam dynamics issues for the optimisation of beam measurements in Eupraxia plasma accelerator

INJECTOR

- Transverse and longitudinal shaping of laser pulses for high-brightness photo-injectors (R.P.)

RF LINAC

- Design, Realization and High Power radiofrequency tests of X-band structures for the EuPRAXIA@SPARC_LAB project (D.A.)
- Design, Realization and High power radiofrequency test of a C-band photo-gun for high brightness electron LINACs (D.A.)
- Active quasioptical Ka-band rf pulse compressor switched by a diffraction grating (B.S.)
- Beam dynamics of Ka-Band Klystron amplifier including RF drive cavities and ouput cavities design (B.S.)
- 36 GHZ MW MAGNICON Ka-Band Device (B.S.)

DIAGNOSTICS

- Extending electro-optical sampling based diagnostics to femtosecond resolution (R.P.)

PLASMA MODULE

- Theoretical studies of plasma discharges in capillary discharge waveguides. (A.B.)
- Study of pinch effects and heat transfer in capillary-discharge wave-guides (R.P.)
- Optimization of active-plasma lens devices for ultra-high focusing gradients (R.P.)
- Deflection of particle beams with curved active-plasma lens geometries (R.P.)
- Plasma source study and design for particle acceleration

FEL

- Studio e caratterizzazione di un canale di trasporto basato su dispositivi a plasma per l’iniezione nel FEL a EuPRAXIA@SPARC_LAB (E.C.)
- Generation of short pulses in Free Electron Laser Amplifiers (L.G.)
- Free electron laser driven by a laser plasma accelerator.
- Design, construction and application of a innovative THz source for applications
- **Design and R&D for EUPRAXIA@Sparc-Lab XUV and UV beamlines : Devices for Optics and Vacuum Systems**

FLAME

- Femtosecond laser synchronization for external injection of electron bunches in a laser driven plasma wave. (A.G.)
-
- “Study of a compact and high efficiency laser removal technique for EUPRAXIA@SPARC_LAB” (M.P.A.)
-
- Laser plasma acceleration for production of betatron radiation for multi-purpose applications in EuPRAXIA

  Laser plasma acceleration for production of charged and neutral particles for EuPRAXIA. (positrons included)

BEAM DYNAMICS

- Numerical PIC studies for plasma-based acceleration (A.D)

- Studies on beam dynamics of charged particles injected in plasma ramps

  Analysis towards the preservation of plasma resonant regime in multi-bunch driving structure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