Dottorato in Fisica degli Acceleratori: Incontri con gli studenti del I anno su temi di ricerca

Roma – Sala Direzione INFN – 13/11/2025

Beam Dynamics and Collective Effects in Linear and Circular Accelerators, Plasma Acceleration, Medical Applications, THz Source R&D and Novel Ideas

Research Activity at SBAI (Basic and Applied Sciences for Engineering) - Sapienza Univ. and INFN RM1 and LNF and MI, and collaborations with other Institutes

Enrica Chiadroni (Sapienza Univ.) on behalf of the collaboration

Dipartimento di Scienze di Base e Applicate per l' Ingegneria

Sapienza Università di Roma

Research Teams for the Presented Topics

- **SBAI Dept.**:
  - E. Chiadroni (PA), A. Curcio (RTT), L. Ficcadenti (INFN-Roma1), L. Giuliano (RTDA), M. Migliorati (PO), A. Mostacci (PO), L. Palumbo (PO), M. Petrarca (PA) + PhD and master students + INFN-LNF collaborators
  - Our group has a long-standing tradition in particle accelerators and collective effects. We have close collaborations with UCLA, CERN, INFN and ENEA

- **INFN MI**
  - V. Petrillo, A. R. Rossi, L. Serafini + PhD and master students + collaborators

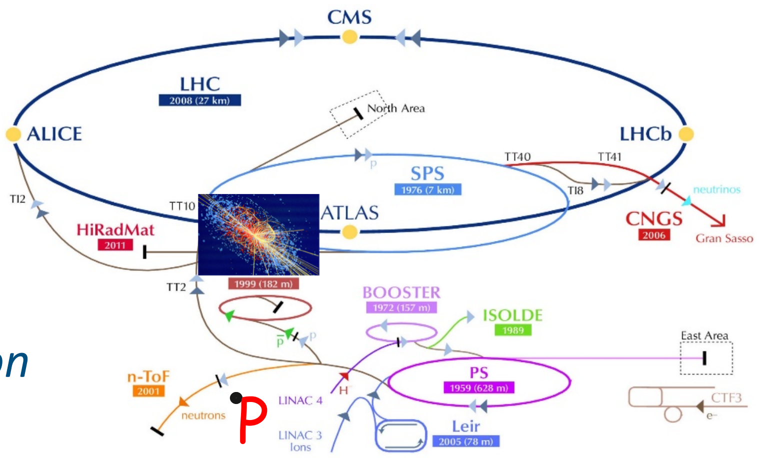
- **INFN LNF**
  - A. Biagioni, M. Ferrario, M. Galletti, R. Pompili, + PhD and master students + collaborators

- **Expertise in**:
  - design of devices for Linacs and circular accelerators
  - beam dynamics and development of simulation codes
  - collective effects and electromagnetic beam-environment interactions
  - RF characterization of accelerator devices
  - Plasma acceleration
  - THz generation and applications

  - Strong contribution to National and International Project, e.g. EuPRAXIA_PP, EuPRAXIA@SPARC_LAB, FCC, …

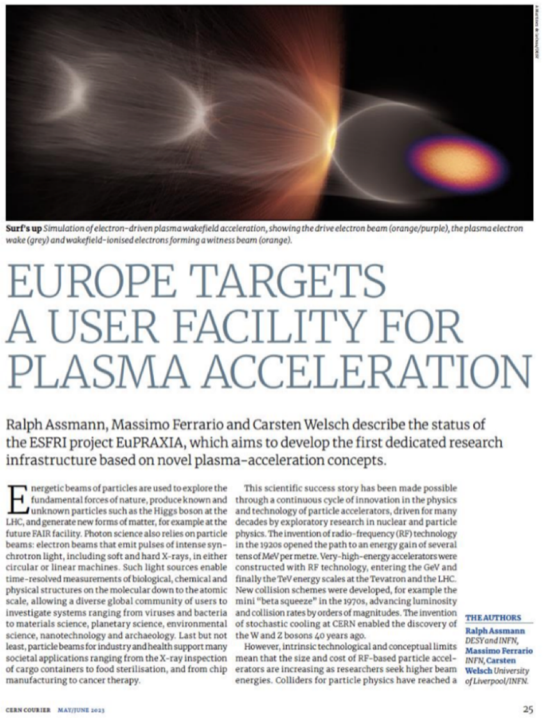
Research Activities

- **Frontiers Accelerators**



  - *Particle colliders (e.g. LHC and its upgrade), Radiation sources (Inverse Compton Scattering, UC-XFEL)*
    - ➢ Beam dynamics studies, optimization and R&D

- **Novel Accelerators**
  - *Plasma Wakefield Accelerators (SPARC_LAB, EuPRAXIA and EuPRAXIA@SPARC_LAB)*
    - ➢ Numerical Studies and Advanced Diagnostics



Surf's up *Simulation of electron-driven plasma wakefield acceleration, showing the drive electron beam (orange/purple), the plasma electron wake (grey) and wakefield-ionised electrons forming a witness beam (orange).*

EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

Ralph Assmann, Massimo Ferrario and Carsten Welsch describe the status of the ESFRI project EuPRAXIA, which aims to develop the first dedicated research infrastructure based on novel plasma-acceleration concepts.

Energetic beams of particles are used to explore the fundamental forces of nature, produce known and unknown particles such as the Higgs boson at the LHC, and generate new forms of matter, for example at the future FAIR facility. Photon science also relies on particle beams: electron beams that emit pulses of intense synchrotron light, including soft and hard X-rays, in either circular or linear machines. Such light sources enable time-resolved measurements of biological, chemical and physical structures on the molecular down to the atomic scale, allowing a diverse global community of users to investigate systems ranging from viruses and bacteria to materials science, planetary science, environmental science, nanotechnology and archaeology. Last but not least, particle beams for industry and health support many societal applications ranging from the X-ray inspection of cargo containers to food sterilisation, and from chip manufacturing to cancer therapy.

This scientific success story has been made possible through a continuous cycle of innovation in the physics and technology of particle accelerators, driven for many decades by exploratory research in nuclear and particle physics. The invention of radio-frequency (RF) technology in the 1920s opened the path to an energy gain of several tens of MeV per metre. Very-high-energy accelerators were constructed with RF technology, entering the GeV and finally the TeV energy scales at the Tevatron and the LHC. New collision schemes were developed, for example the mini "beta squeeze" in the 1970s, advancing luminosity and collision rates by orders of magnitudes. The invention of stochastic cooling at CERN enabled the discovery of the W and Z bosons 40 years ago.

However, intrinsic technological and conceptual limits mean that the size and cost of RF-based particle accelerators are increasing as researchers seek higher beam energies. Colliders for particle physics have reached a

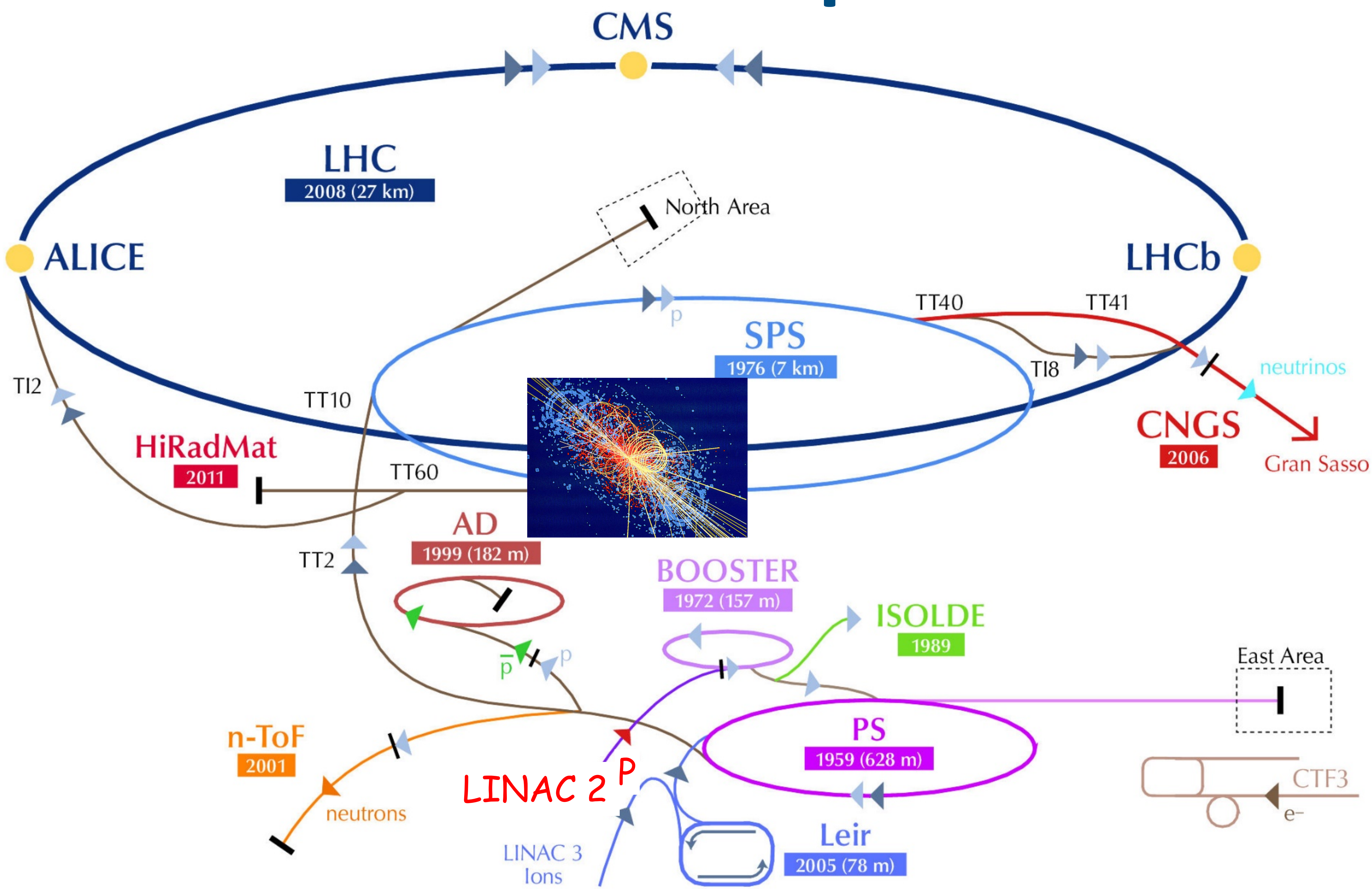
THE AUTHORS
Ralph Assmann *DESY and INFN,* **Massimo Ferrario** *INFN,* **Carsten Welsch** *University of Liverpool/INFN.*

CERN COURIER MAY/JUNE 2023 25

https://cerncourier.com/a/europe-targets-a-user-facility-for-plasma-acceleration/

- **Accelerator Applications**
  - *Medical (FLASH Therapy) and THz Applications*
    - ➢ Beam dynamics studies, Linac Design
    - ➢ THz production for spectroscopic imaging for basic and applied science
  - *Social safety*
    - ➢ ERMES project

CERN Accelerator Complex

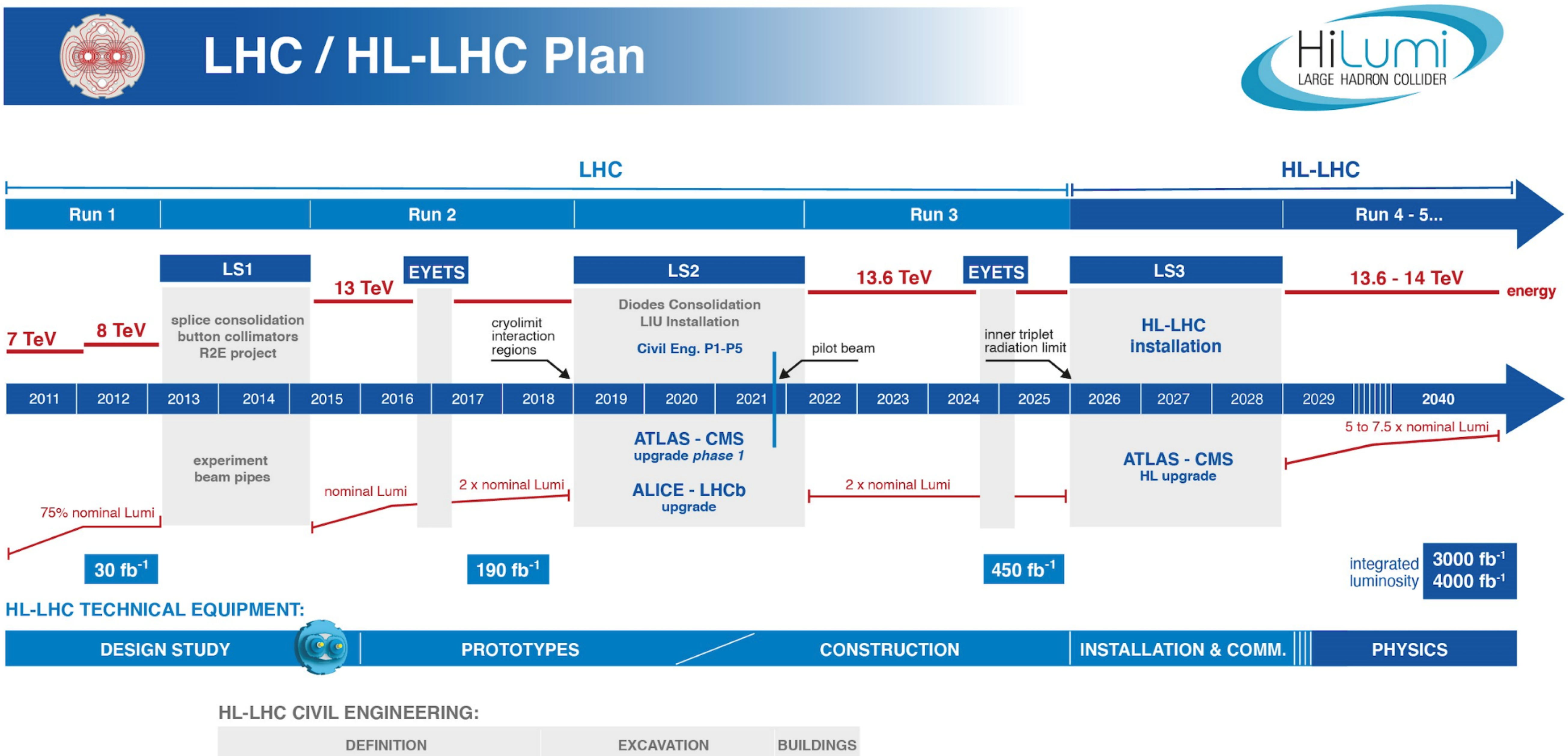


mauro.migliorati@uniroma1.it

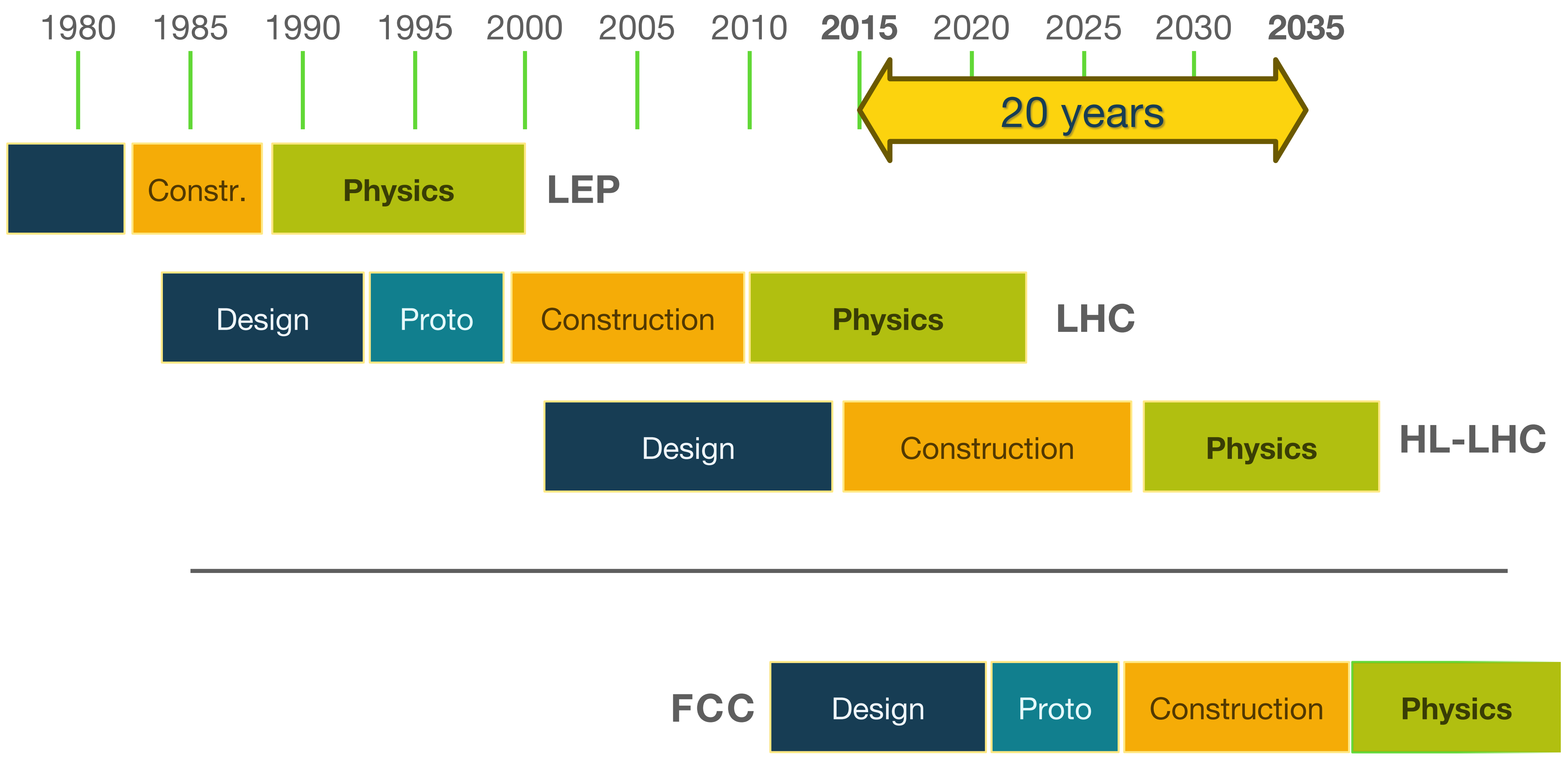
Upgrade of LHC: High Luminiosity LHC project

LHC and its upgrade program

The goal is to reach a luminosity 10 times higher in LHC and double the bunch intensity.



The Future Circular Collider project (FCC)

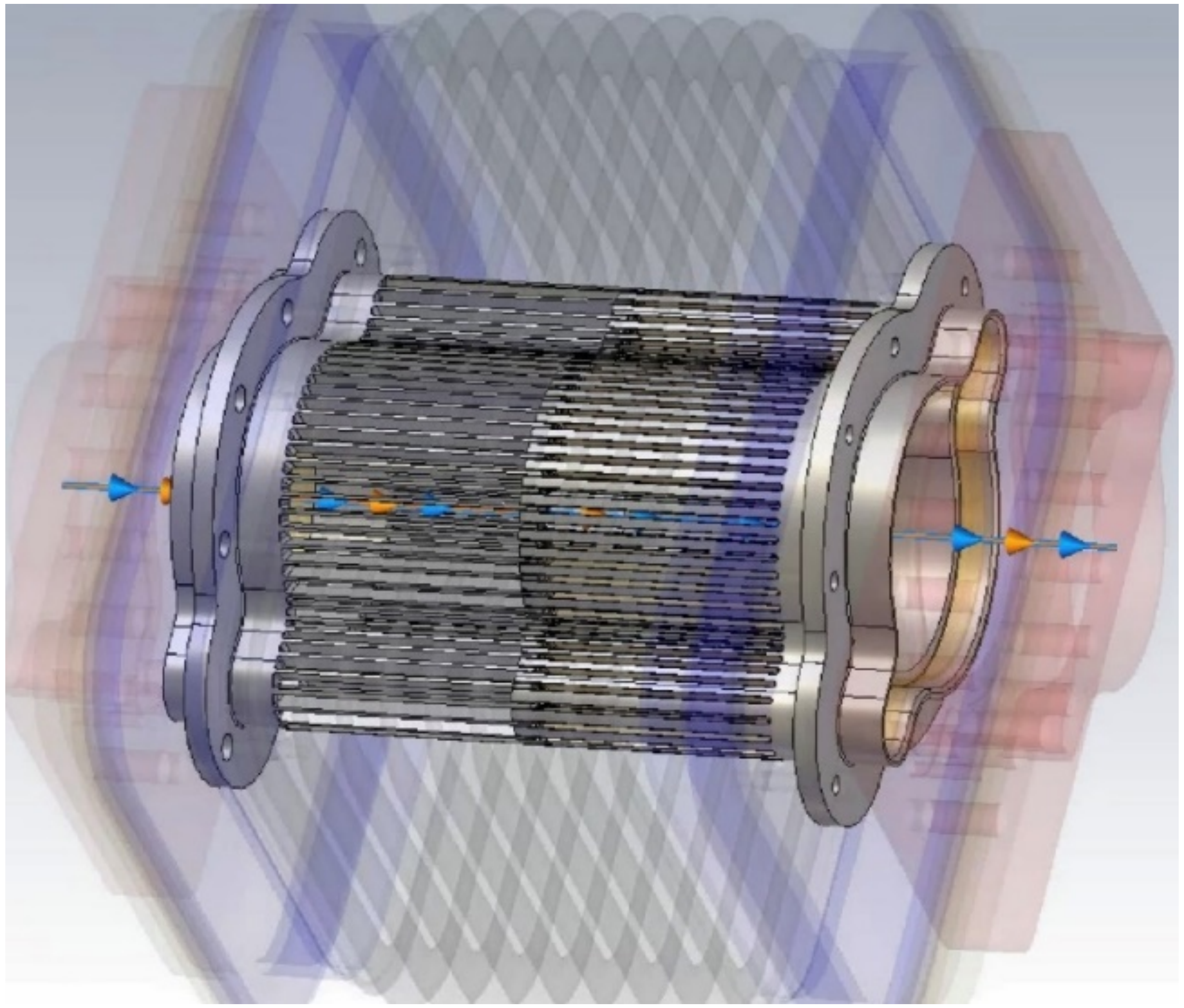


- **1983** first LHC proposal, launch of design study
- **1994 CERN Council: LHC approval**
- **2010 first collisions at 3.5 TeV beam energy**
- **2015 collisions at design energy**

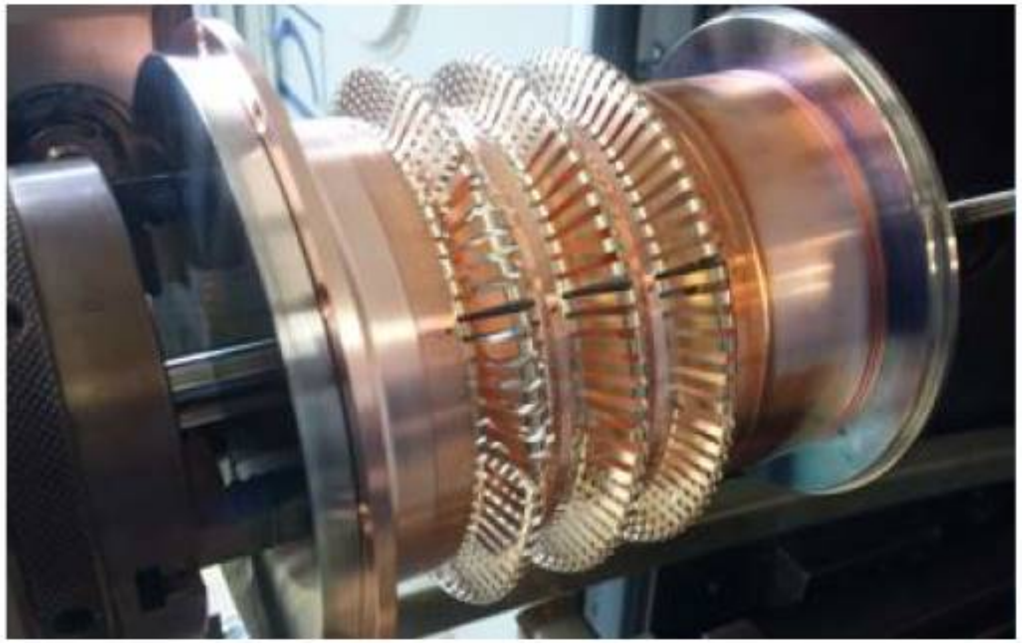
Collaboration with CERN on Collective Effects and Machine Impedance Model for FCC-ee

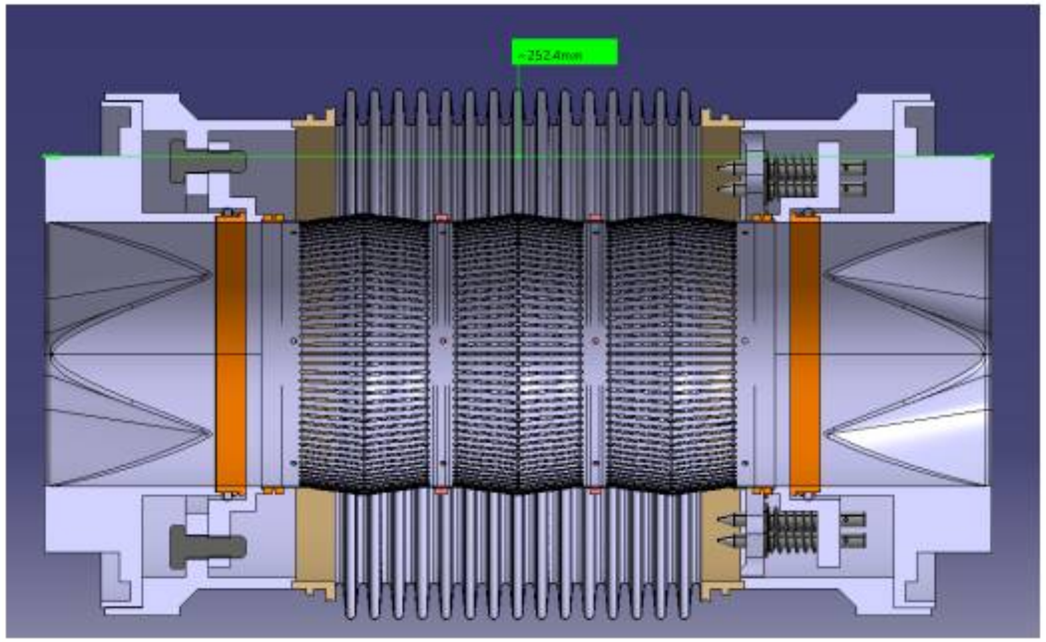
Impedance budget and wakefields: example for the bellows

Current model



Alternative model under study

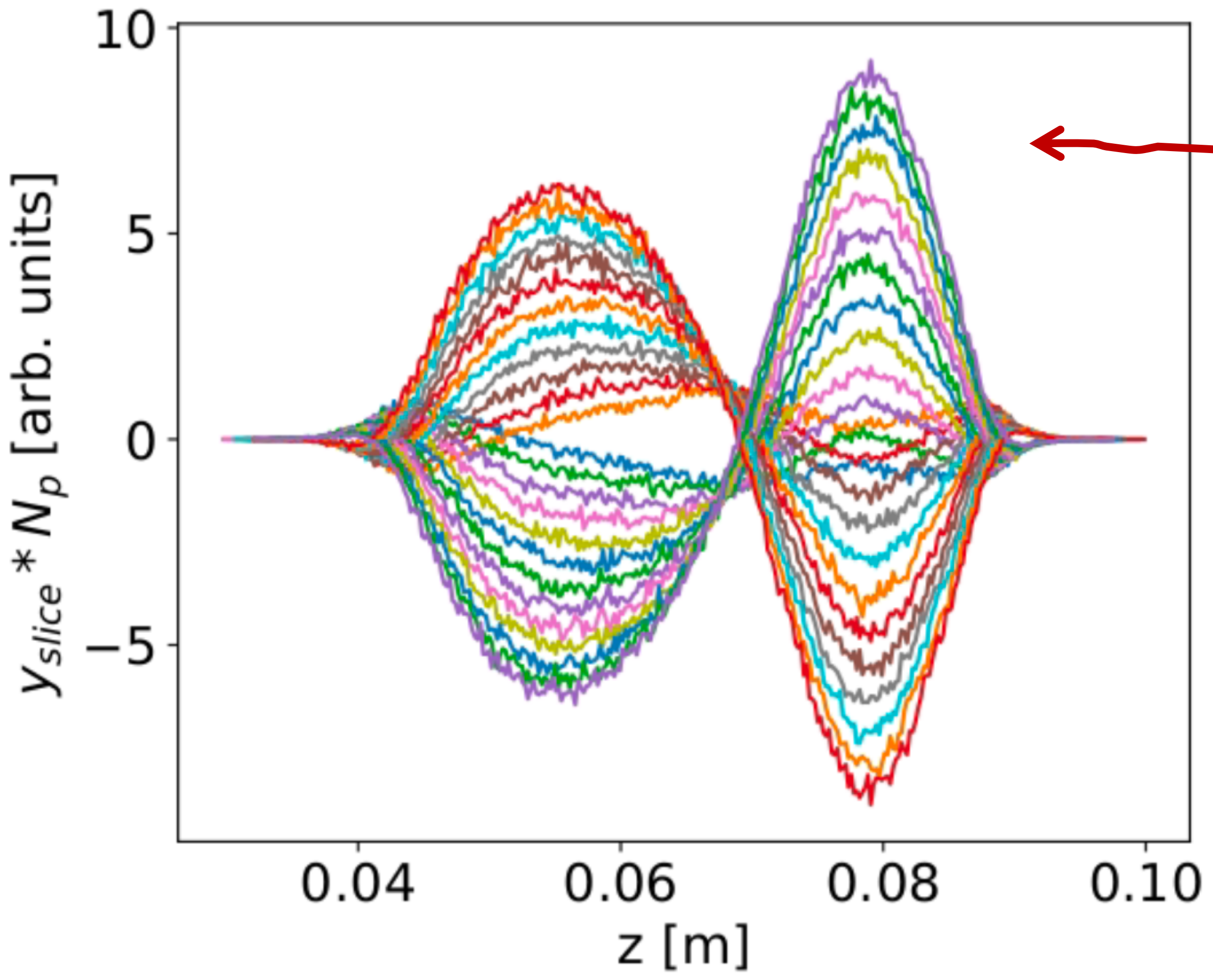


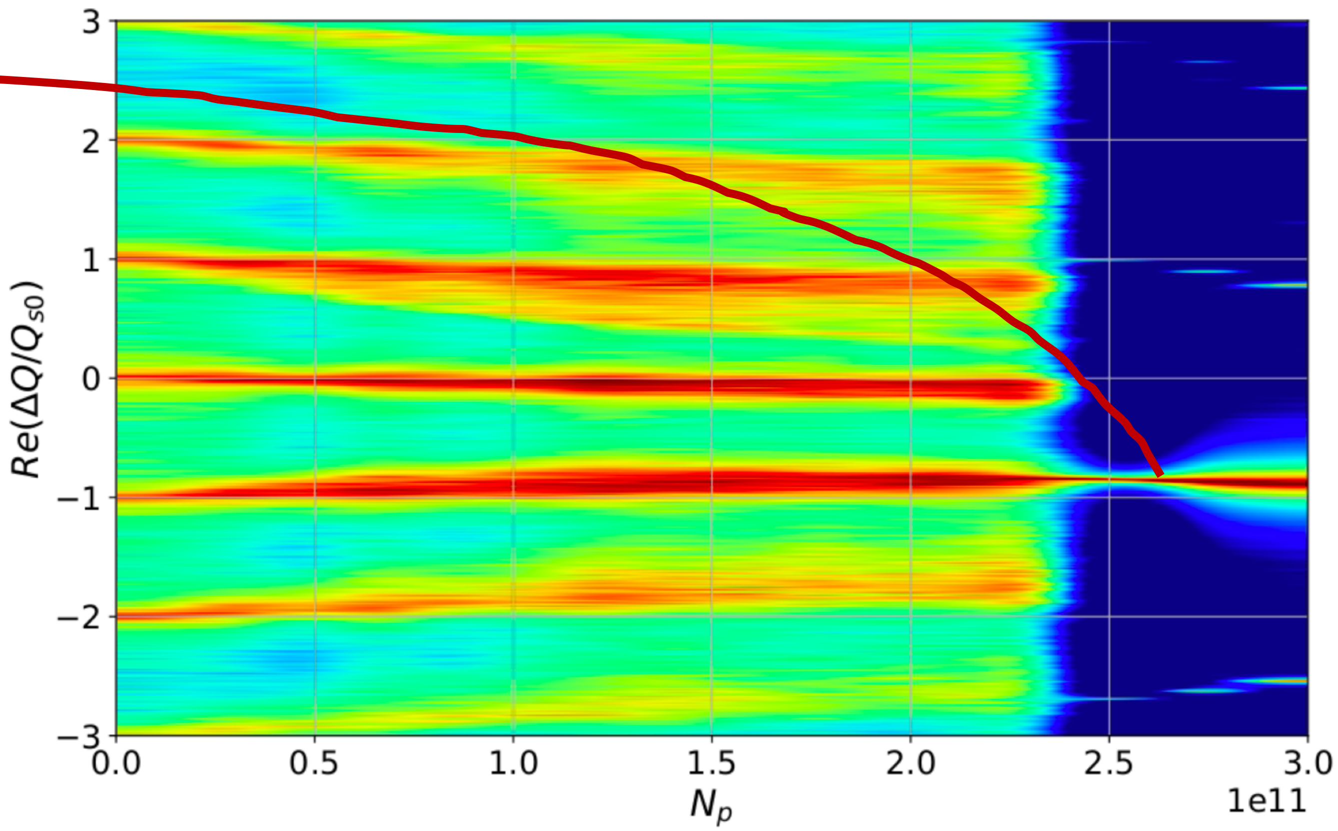


Collaboration with CERN on Collective Effects and Machine Impedance Model for FCC-ee

Beam dynamics and collective effects (using analytical tools and simulation codes)

The PhD activity is performed in collaboration mainly with CERN, but also with IHEP (China) and SuperKEKB (Japan)





FLASH Effect in Radiotherapy

FLASH THERAPY is a new way to deliver the dose:

- ms pulses of radiation,
- beam-on time < 100-200ms
- high dose per pulse (>1 Gy)
- high mean dose rate (>40-100Gy/s)

	Conventional	FLASH
Facility	γ−rays: ^{137}Cs	**e-** LINAC
Nominal energy (MeV)	0,66	4,5
Pulse vs continuous	Continuous	Pulsed
Pulse repetition frequency (Hz)	-	150 Hz
Dose (Gy)	17	17
Mean Dose rate (Gy/s)	0,03	60
Temporal width of pulse	few ms	1 ms

Favaudon et al., Science Translational Medicine 6, 2014

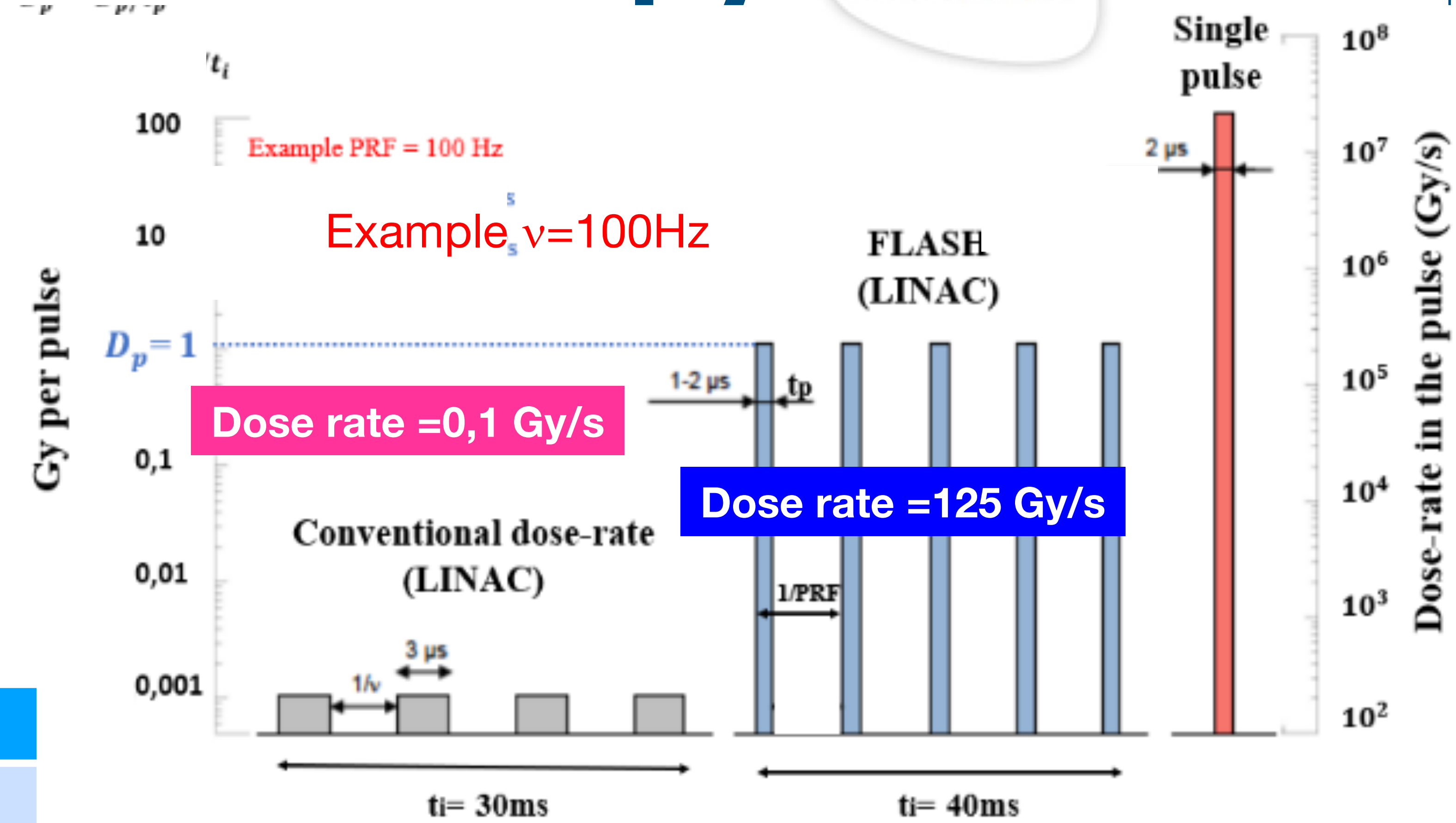
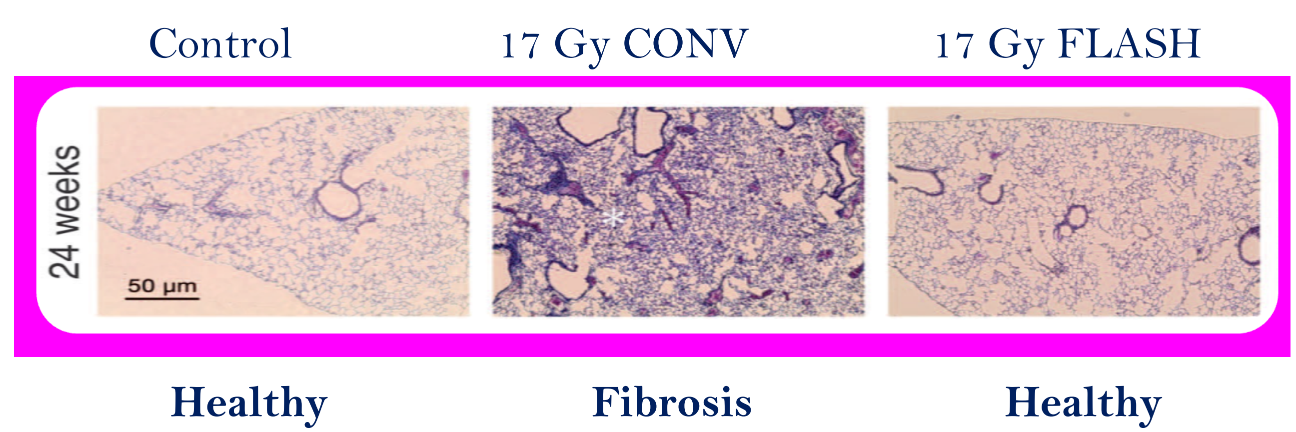


Fig. Courtesy of Vincent Favaudon - Curie Institute



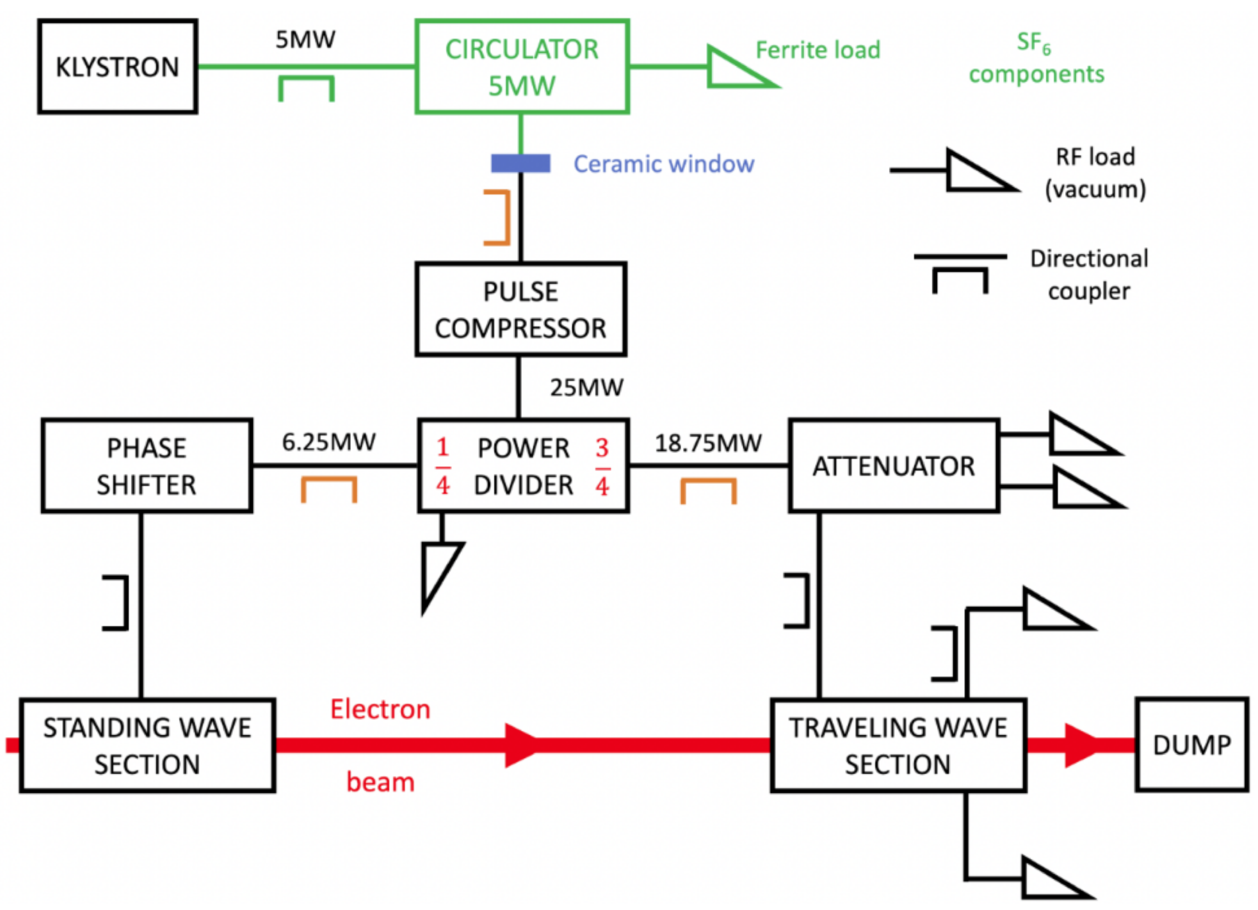
FLASH irradiation protects healthy tissues from damage and remains as ***efficient as*** **CONV** irradiation in the repression of tumor growth

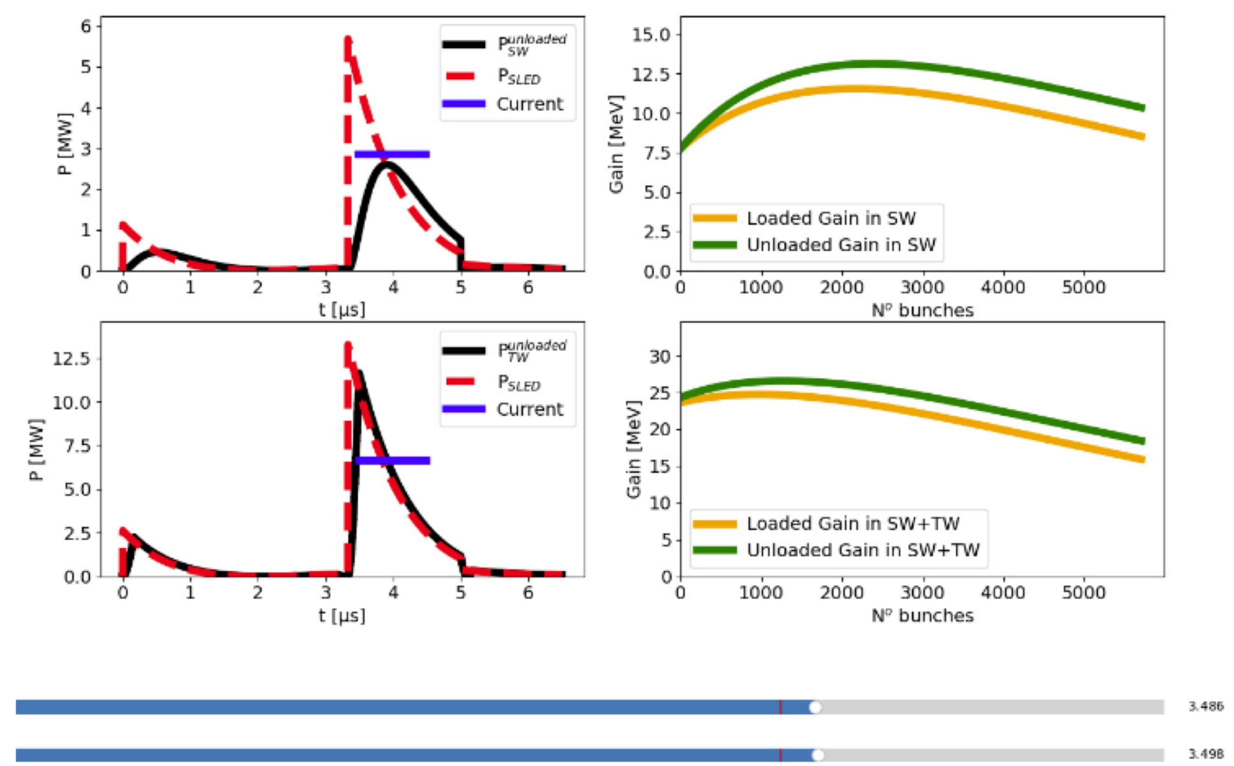
Activity at Sapienza

First Step

Machine for pre-clinical studies of FLASH has been funded with 1.6 ME

Machine Layout





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FLASH Radiotherapy with high Dose-rate particle beAms

INFN Istituto Nazionale di Fisica Nucleare

HEAL ITALIA

Finanziato dall'Unione europea NextGenerationEU

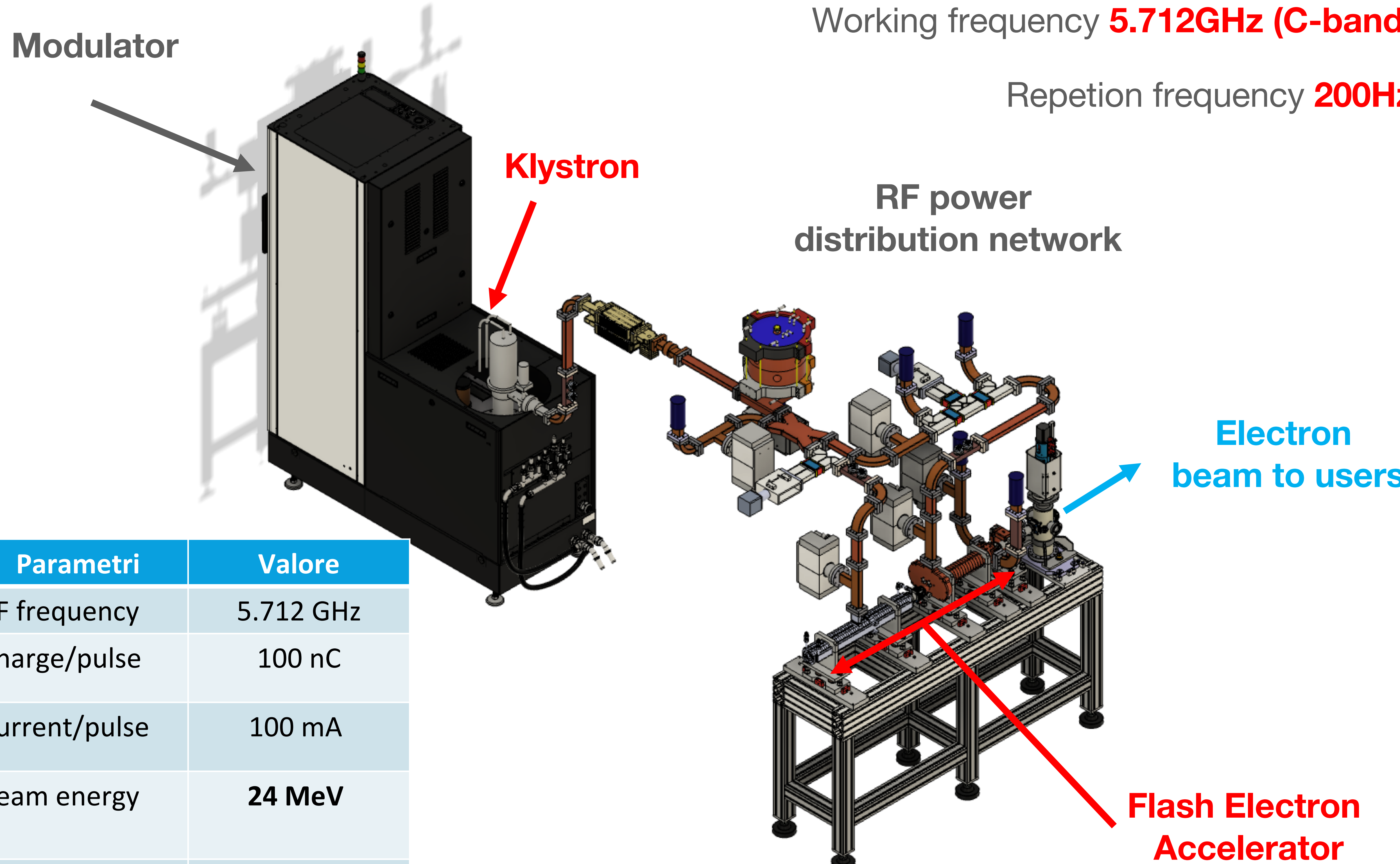
MUR

Italiadomani

TECHNICAL DESIGN

Working frequency **5.712GHz (C-band)**

Repetion frequency **200Hz**



Parametri	Valore
RF frequency	5.712 GHz
Charge/pulse	100 nC
Current/pulse	100 mA
Beam energy	**24 MeV**
Repetition rate	<200 Hz
LINAC length	1.5 m

SAPIENZA UNIVERSITÀ DI ROMA — HEAL ITALIA FOUNDATION — INFN Istituto Nazionale di Fisica Nucleare — SIT Sordina IORT Technologies

Prototyping Phase

1. **Pre-prototypes** on 5-cells **without couplers** to test the brazing procedure, vacuum sealing and the **in-house** mechanical design.

2. **Prototype of 12 cells** with couplers has been **brazed** to perform low-power RF tests.

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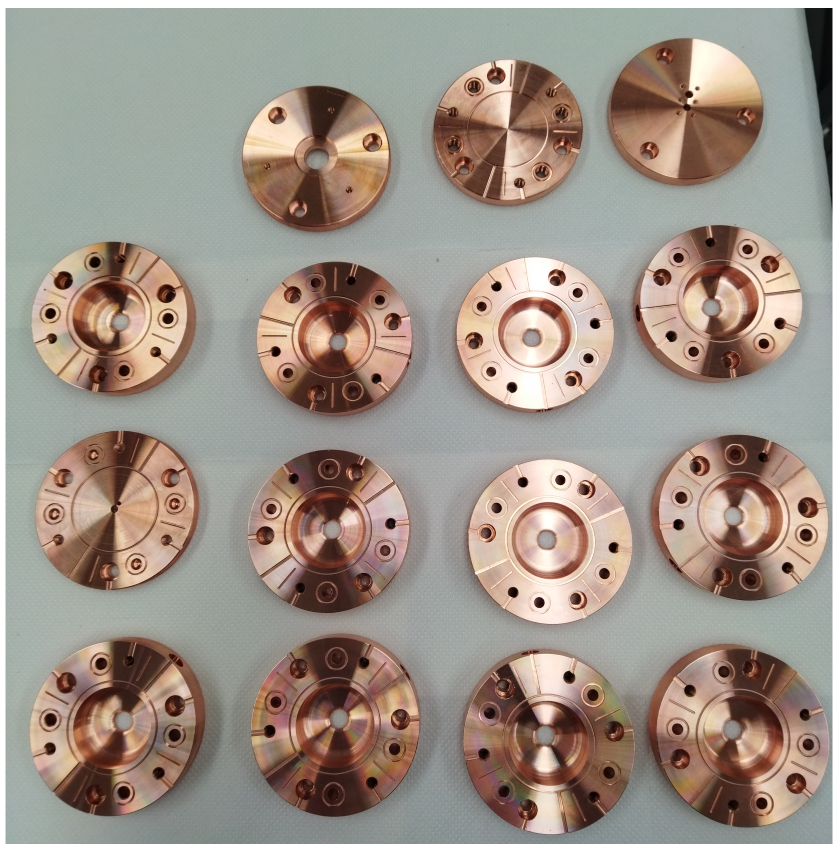
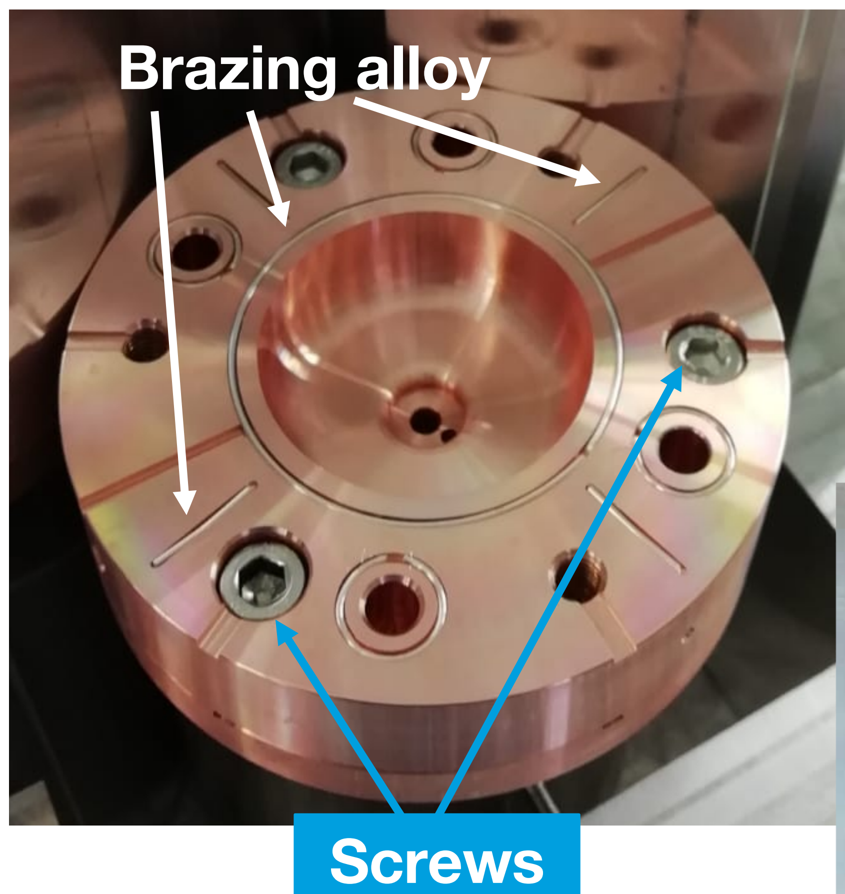
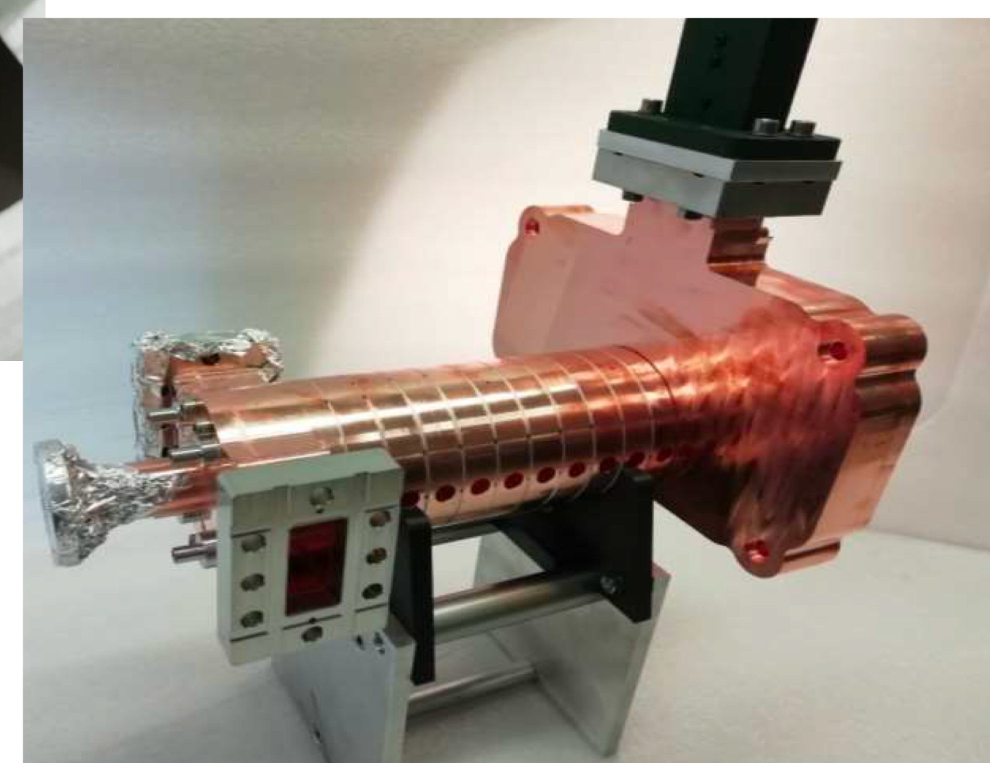






In house building of the accelerating cavities

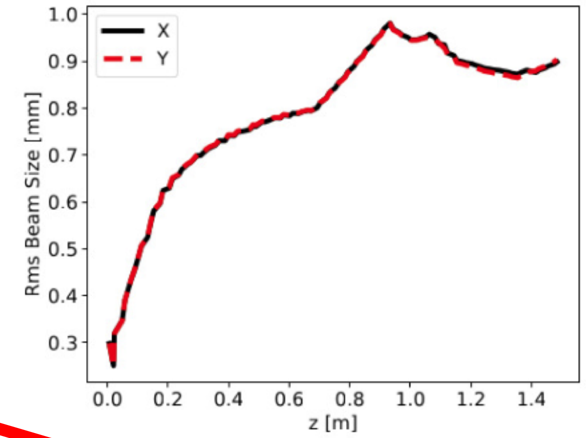
Screws: **prevent external clamping** and ensure alignment and easier assembly

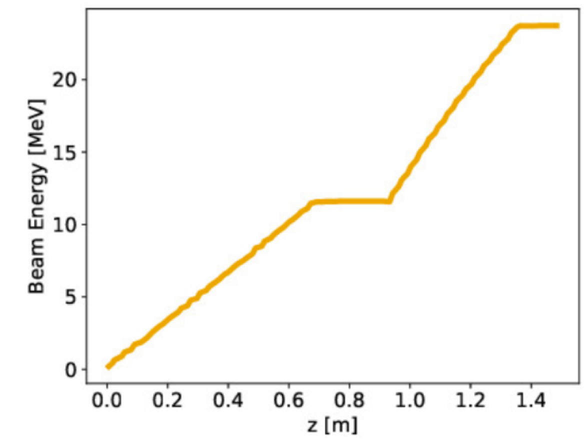
Main contributors: D. Alesini, **R. Di Raddo**, L. Faillace, L. Giuliano, **M. Magi**, M. Migliorati

Main Activities

To realize the Medical accelerator

Beam dynamics studies





Cell optimization & EM design

Copper prototype

RF measurement

Standing Wave cavity

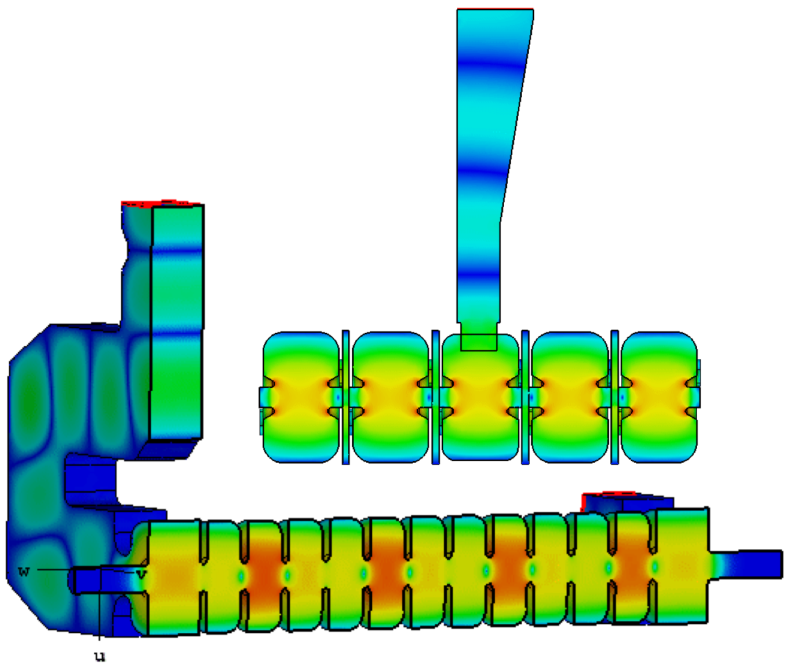
Traveling Wave structure

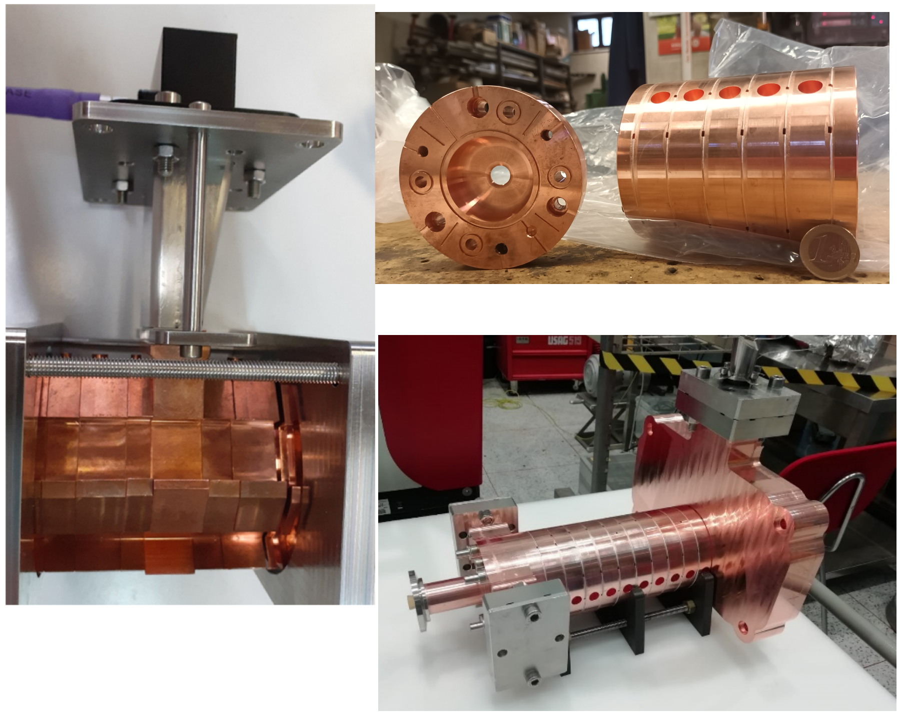
Standing Wave cavity

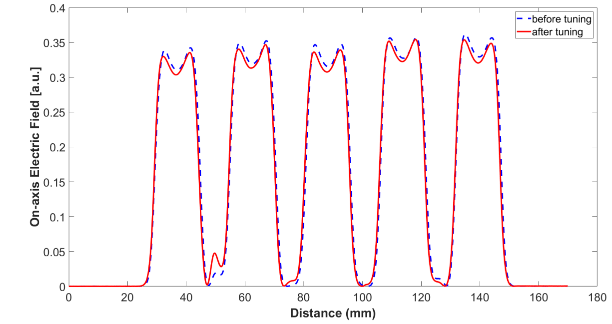
Traveling Wave structure

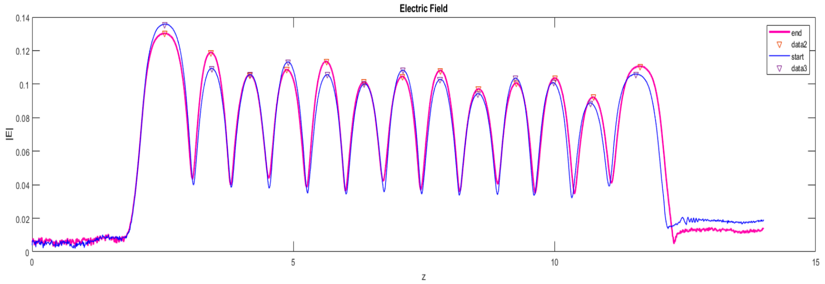
Standing Wave cavity

Traveling wave structure









Plasma Acceleration Activity

EuPRAXIA and EuPRAXIA@SPARC_LAB Collaboration

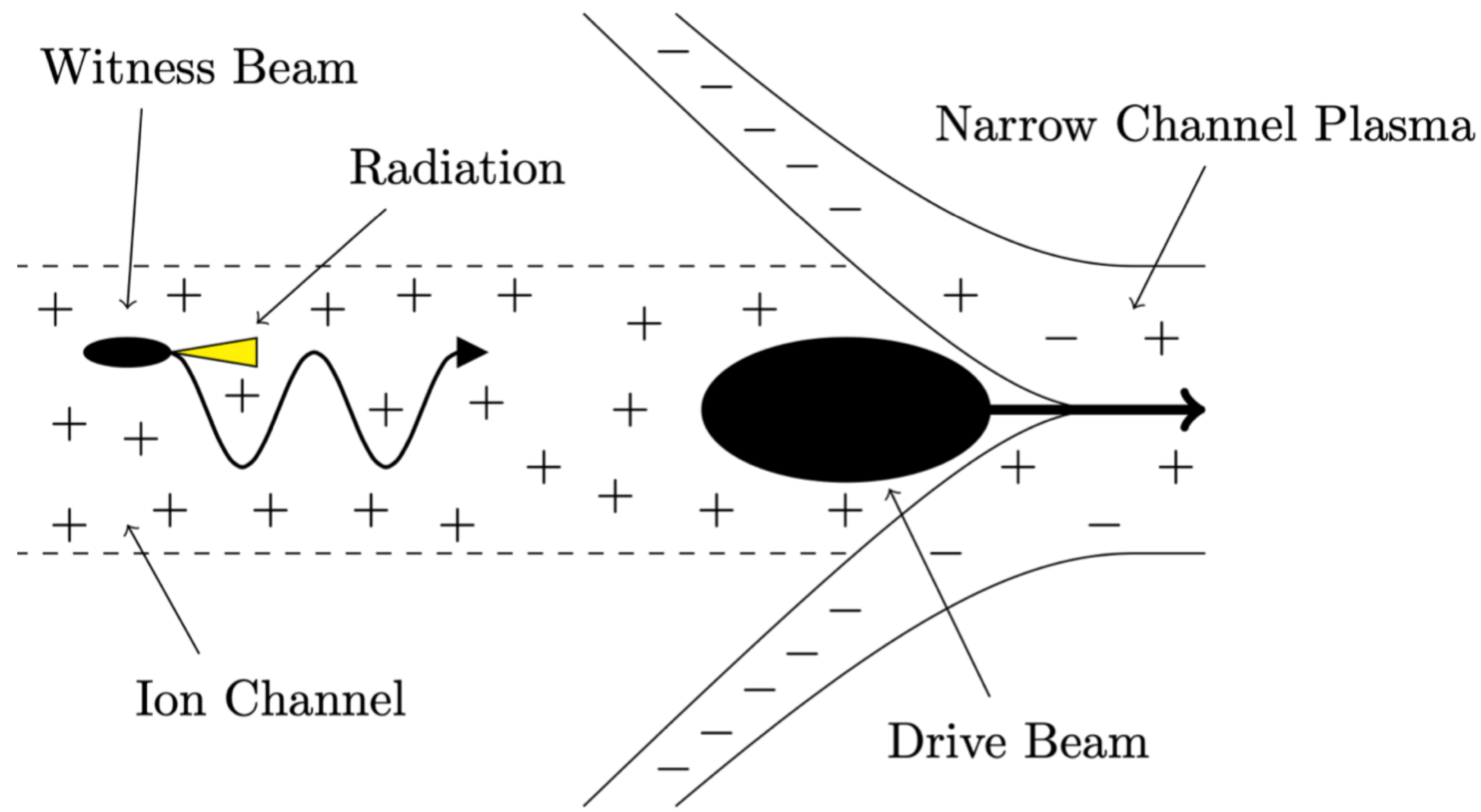
- The EuPRAXIA@SPARC_LAB project focuses to realize a compact plasma-based Free-Electron Laser user facility
  - Plasma acceleration module
  - Ancillary components
- Conventional undulators are still too long => not compact and expensive
  - betatron motion of electrons in an ion-channel to emulate an undulator
    - very compact device
      - ➢ **Experiment funded by CSN5 of INFN (2024-2027)**

Ion Channel Concept

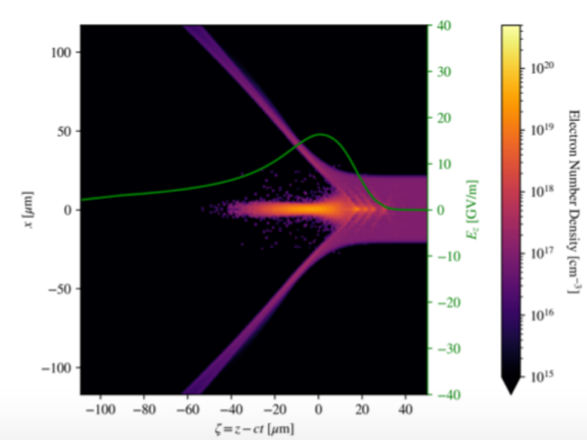
- Replaces magnetic undulator with strong focusing ion channel
- **Linear focusing force** produces periodic betatron oscillations

$$F_r = -\frac{en_0}{2\epsilon_0} r$$

$$r(z) = r_m \cos(k_\beta z + \phi)$$



Key to experimental realization:
Narrow plasma channel + strong drive beam to create "wakeless" ion channel



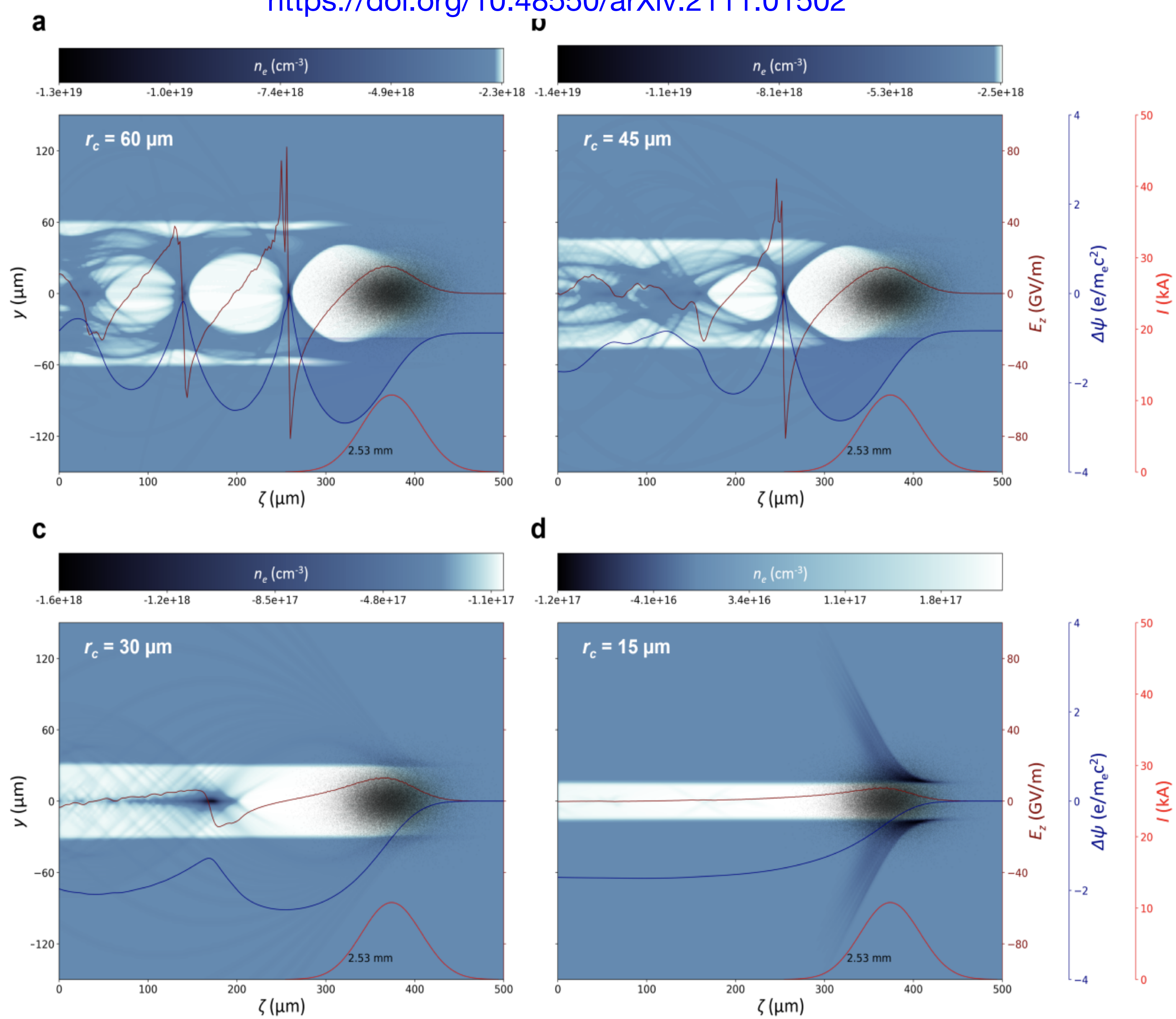
QuickPIC simulation of ion channel formation

Credits from M. Litos, EAAC23

Ion Column Formation

A.F. Habib et al.,
https://doi.org/10.48550/arXiv.2111.01502

- Neutral plasma creation through ionization laser
- Blowout of the plasma electrons through the driver beam
  - **plasma electrons are expelled from the plasma region toward the neutral gas region**
    - **negligible restoring force** outside column
    - **negligible accelerating force** inside column
    - **linear restoring force** inside column



$$K_{u,\beta} = 1.33 \cdot 10^{-10} \sqrt{\gamma / n_0[cm^{-3}]}\, r_\beta[\mu m] \qquad \lambda_{u,\beta}[\mu m] = 4.72 \cdot 10^{10} \sqrt{\gamma / n_0[cm^{-3}]}$$

Plasma based Acceleration: modeling and theory

Plasma based acceleration simulations require **huge computational power**, so **reduced models**, catching only the relevant physics for acceleration, allow to scale hardware requirements to tabletop resources.

At present, we are pursuing two distinct strategies:

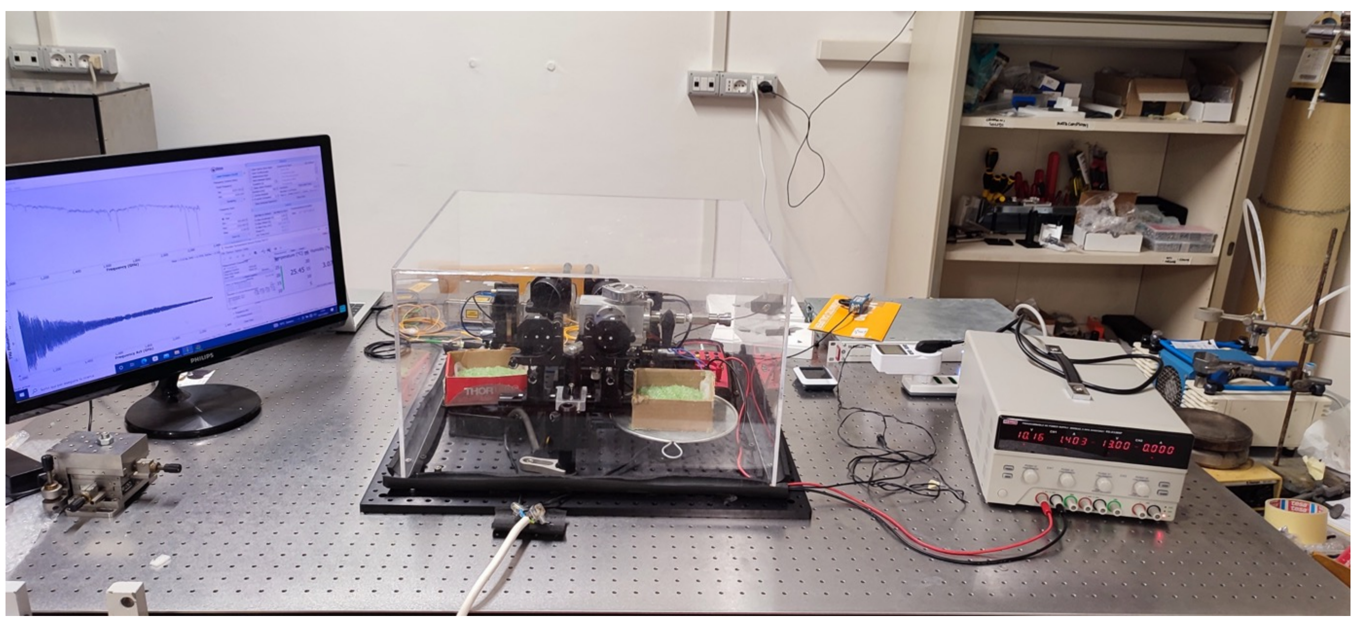
- Moment equations for beam dynamics: $\partial_t < \Phi > = < p_x/\gamma \partial_x \Phi > + < F_x \partial_{p_x} \Phi > + < F_z \partial_\gamma \Phi >$
- Transverse expansion for plasma physics: $\Pi_0'(\zeta) - \frac{1}{\Pi_0^2(\zeta)} + \frac{1}{2} - \alpha S_0 g(\zeta) - \frac{2\Pi_2(\zeta)}{\Pi_0^2(\zeta)} - \frac{2}{1+\Pi_2(\zeta)}\left[\Pi_0'(\zeta)\Pi_2'(\zeta) - \frac{3\Pi_0(\zeta)\Pi_2'^2(\zeta)}{1+2\Pi_2(\zeta)} + \Pi_0(\zeta)\Pi_2''(\zeta)\right] = 0$

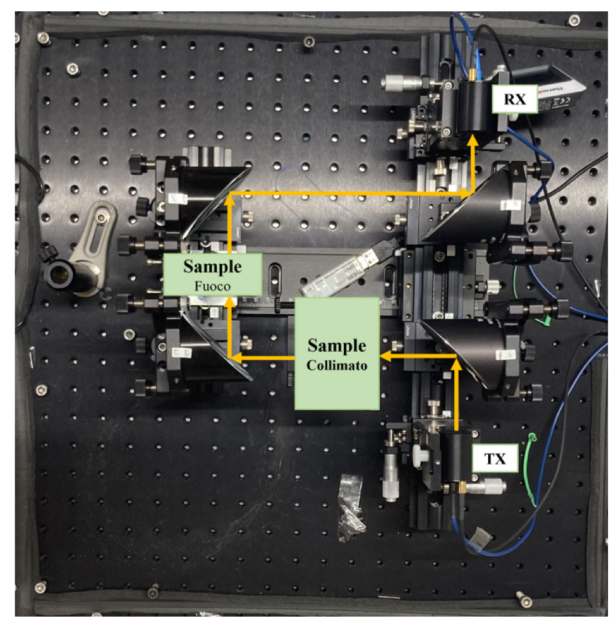
Courtesy of A. R. Rossi (INFN – MI)

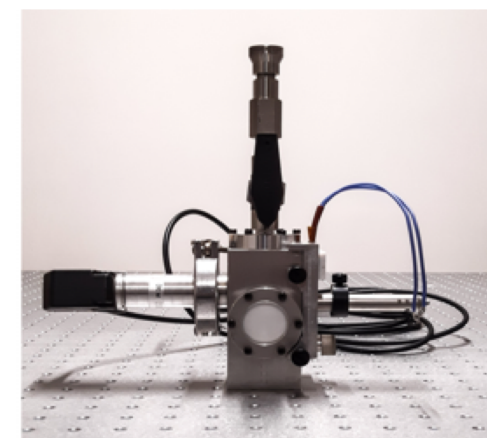
THz Generation for applications

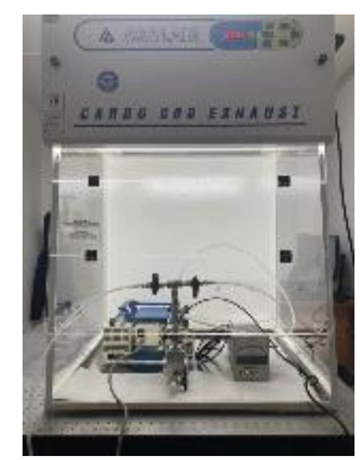
THz-CW source in operation

Gas cell for spectroscopic
measurement on gas samples









Available average power: 10μW @1THz and nW @3THz

Courtesy of Prof. M. Petrarca

ERMES

Earthquake Reconnaissance with Muon beam Evolution in Silicon dioxide

PHYSICAL REVIEW RESEARCH **00**, 003000 (2025)

Remote-sensing of tectonic-induced stress across faults using high energy muon beams

L. Serafini, A. Bacci, F. Broggi, M. Rossetti Conti,* A. R. Rossi, and S. Samsam
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arXiv:2506.12196v1 [physics.acc-ph] 13 Jun 2025

- **Active interrogation of the piezoelectric state in granitic rocks** by propagating high-energy muon beams (with large emittance, 1 m·rad, and low flux, 10^6 s^{-1}) through the planes of active seismic faults

- **The random-walk process** experienced by the muons due to the piezoelectric field **carries** to the detector **information about the tectonic stress** acting in the fault zone, which is responsible for destructive seismic events

  - a high-energy particle beam (500 GeV) can be used for applications of great human impact — namely, to help predict devastating seismic events and potentially save human lives

Courtesy of L. Serafini, V. Petrillo, A.R. Rossi

To get more information

- FCC-ee activities ➔ mauro.migliorati@uniroma1.it
- FLASH application and prototype activities at SBAI ➔ andrea.mostacci@uniroma1.it
- Plasma-based undulator studies ➔ enrica.chiadroni@uniroma1.it
- THz source generation and applications ➔ massimo.petrarca@uniroma1.it
- ERMES project ➔ vittoria.petrillo@mi.infn.it, andrea.rossi@mi.infn.it, luca.serafini@mi.infn.it

THANKS FOR THE ATTENTION