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

Roma – Sala Direzione INFN – 20/11/2023

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

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

Enrica Chiadroni - November 20th, 2023

DIPARTIMENTO DI SCIENZE DI BASE E APPLICATE PER L' INGEGNERIA

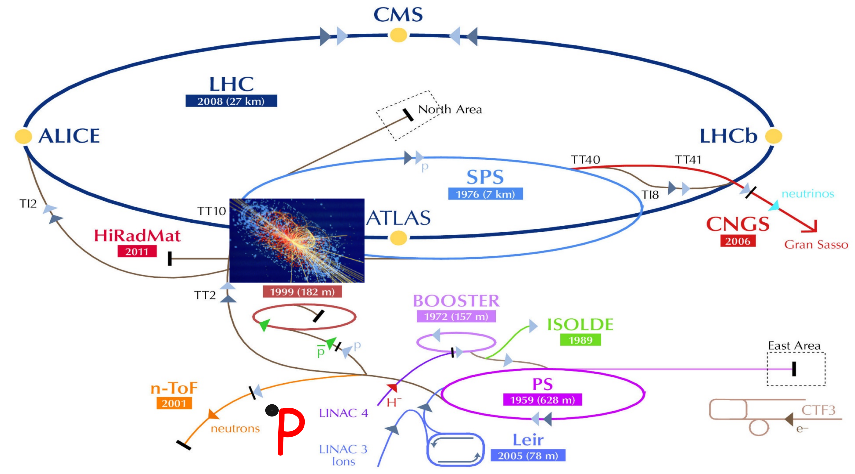
SAPIENZA UNIVERSITÀ DI ROMA

Group Research at SBAI Dept.

- E. Chiadroni (PA), L. Ficcadenti (INFN-Roma1), L. Giuliano (RTDA), M. Migliorati (PA), A. Mostacci (PA), 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.
- We have 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 Laser Laboratory
- We strongly contribute to National and International Project, e.g. EuPRAXIA_PP, EuPRAXIA@SPARC_LAB, FCC, …

Group Research at SBAI Dept.

- **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

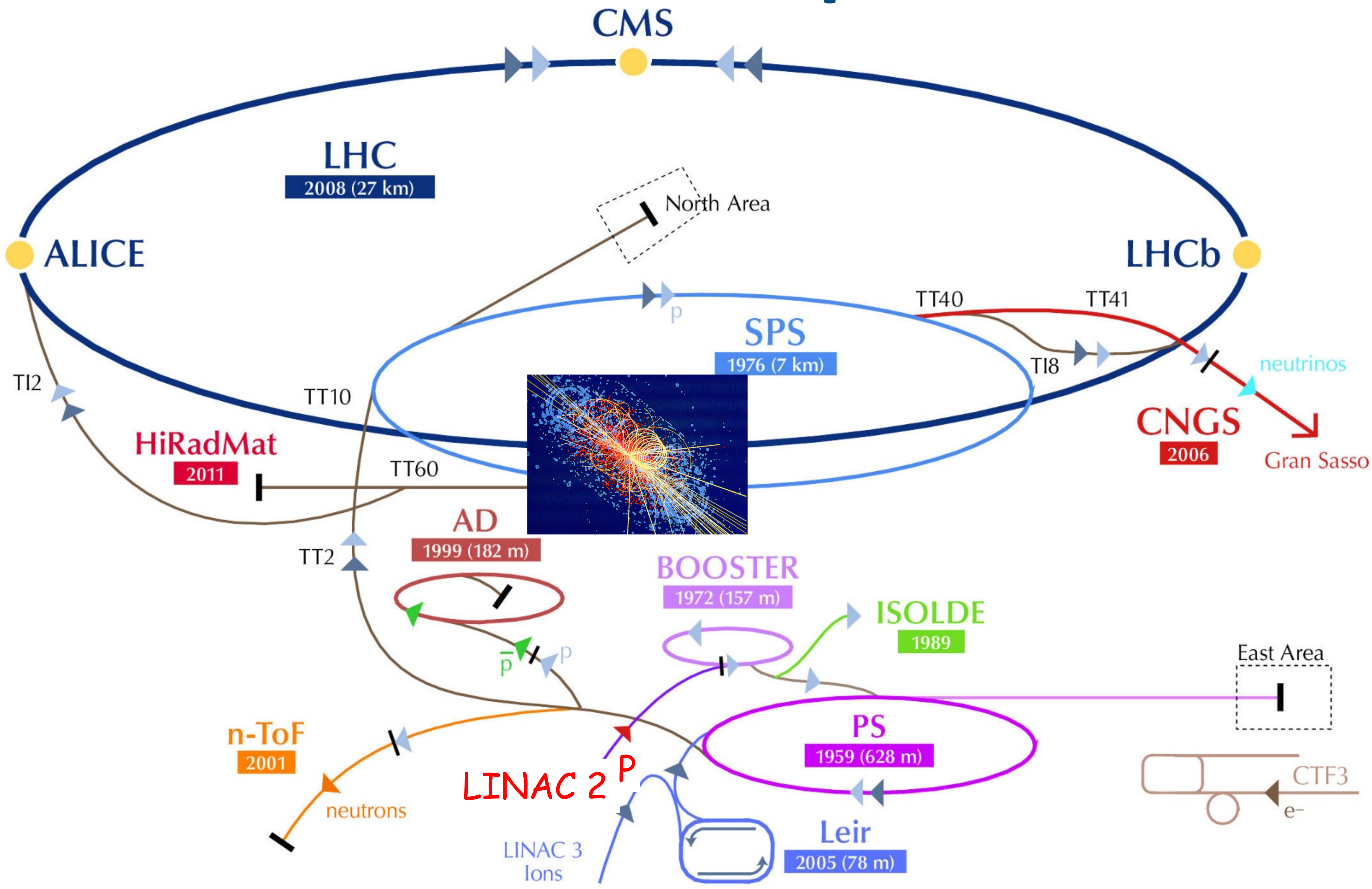
EUROPE TARGETS A USER FACILITY FOR PLASMA ACCELERATION

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.

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

CERN Accelerator Complex

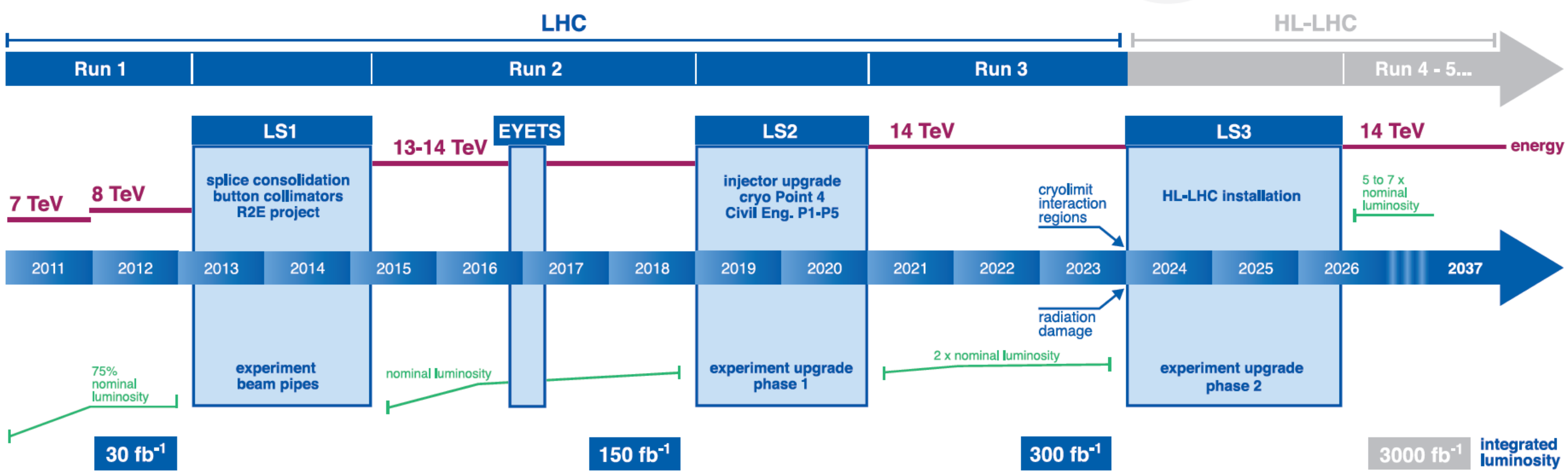


Upgrade of LHC (HL-LHC or Hi Lumi LHC)

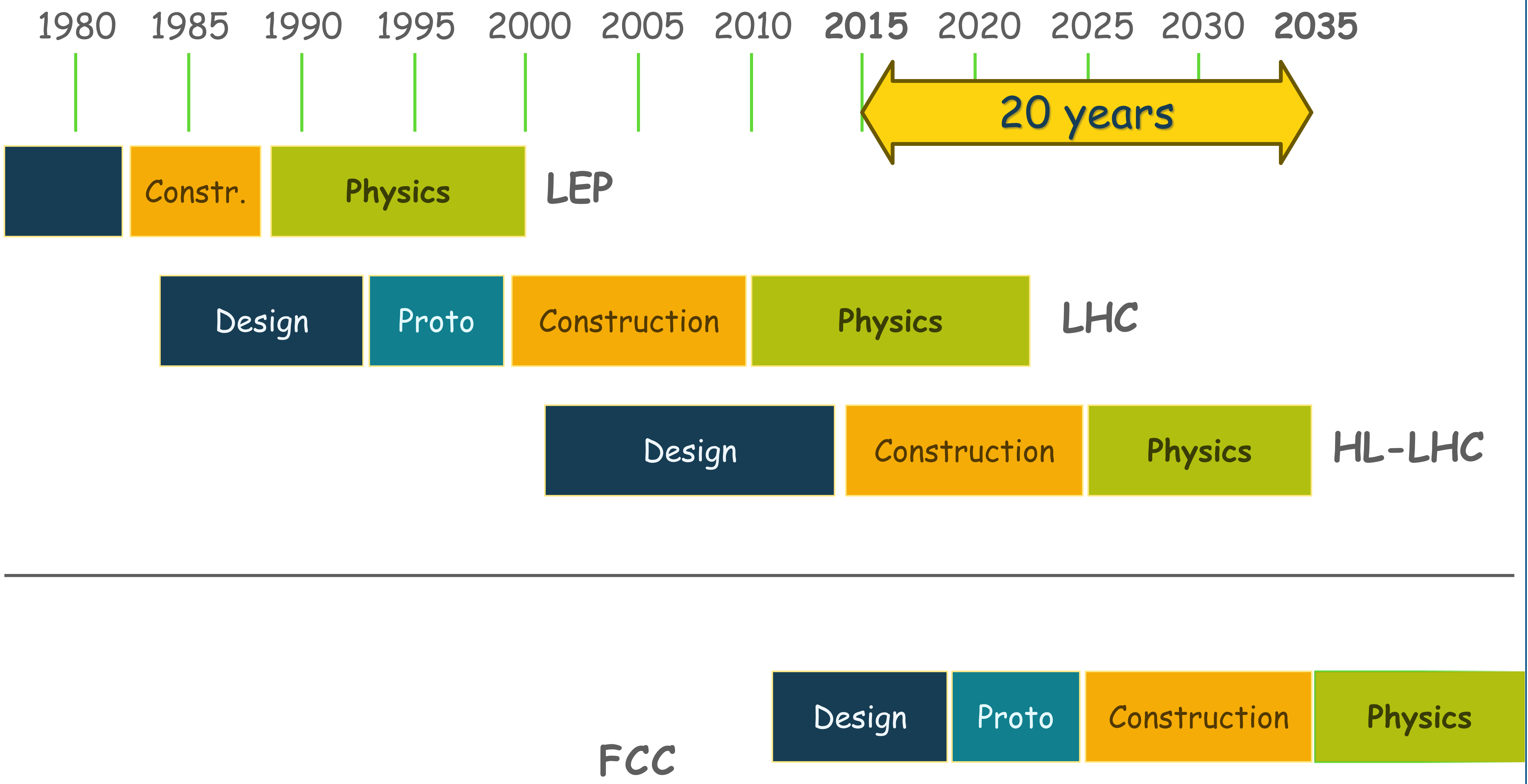
High Luminosity LHC Participants

LHC / HL-LHC Plan

High Luminosity LHC



The Future Circular Collider Project (FCC)



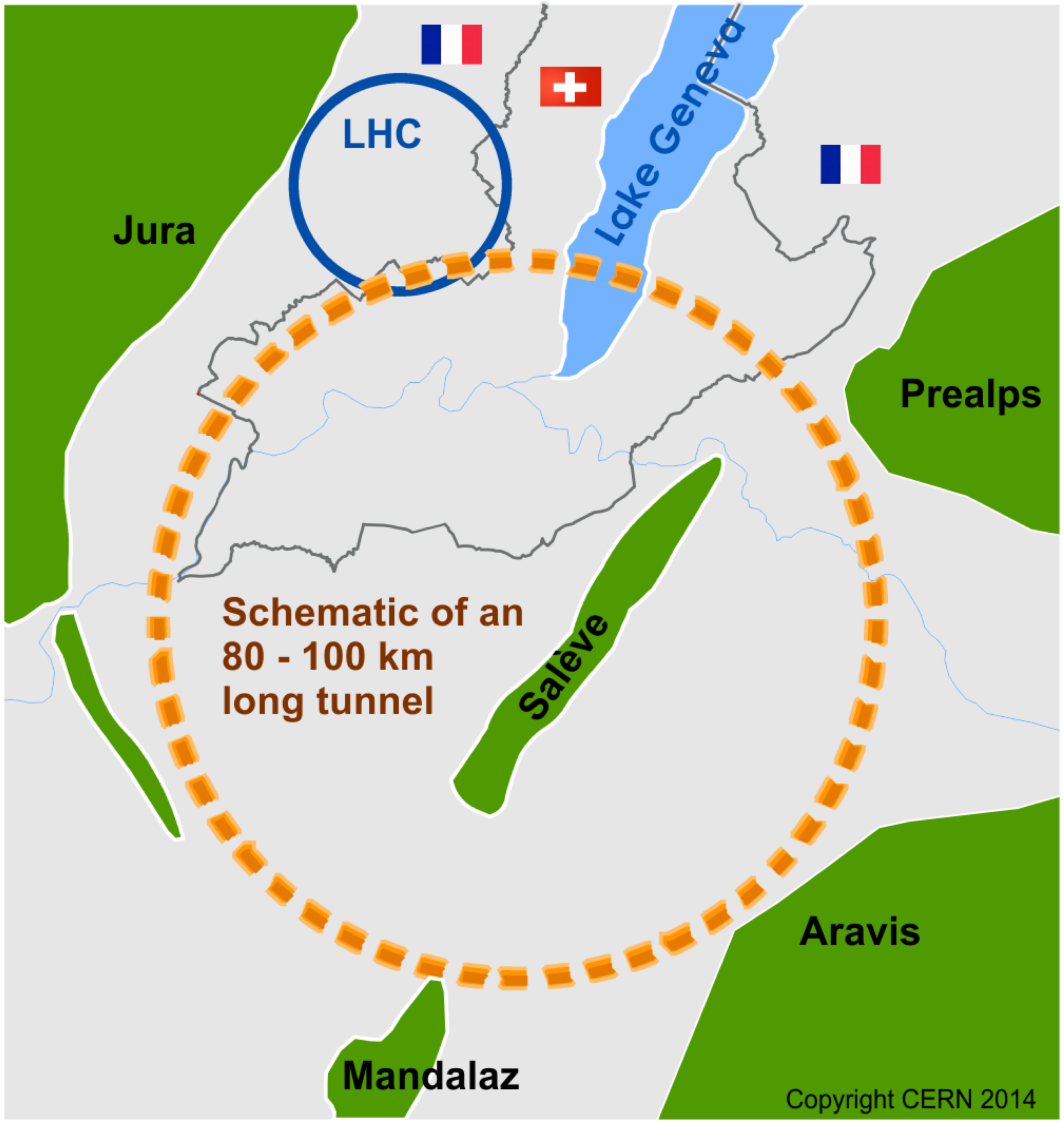
The Future Circular Collider Project (FCC)

International FCC collaboration to study:

- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

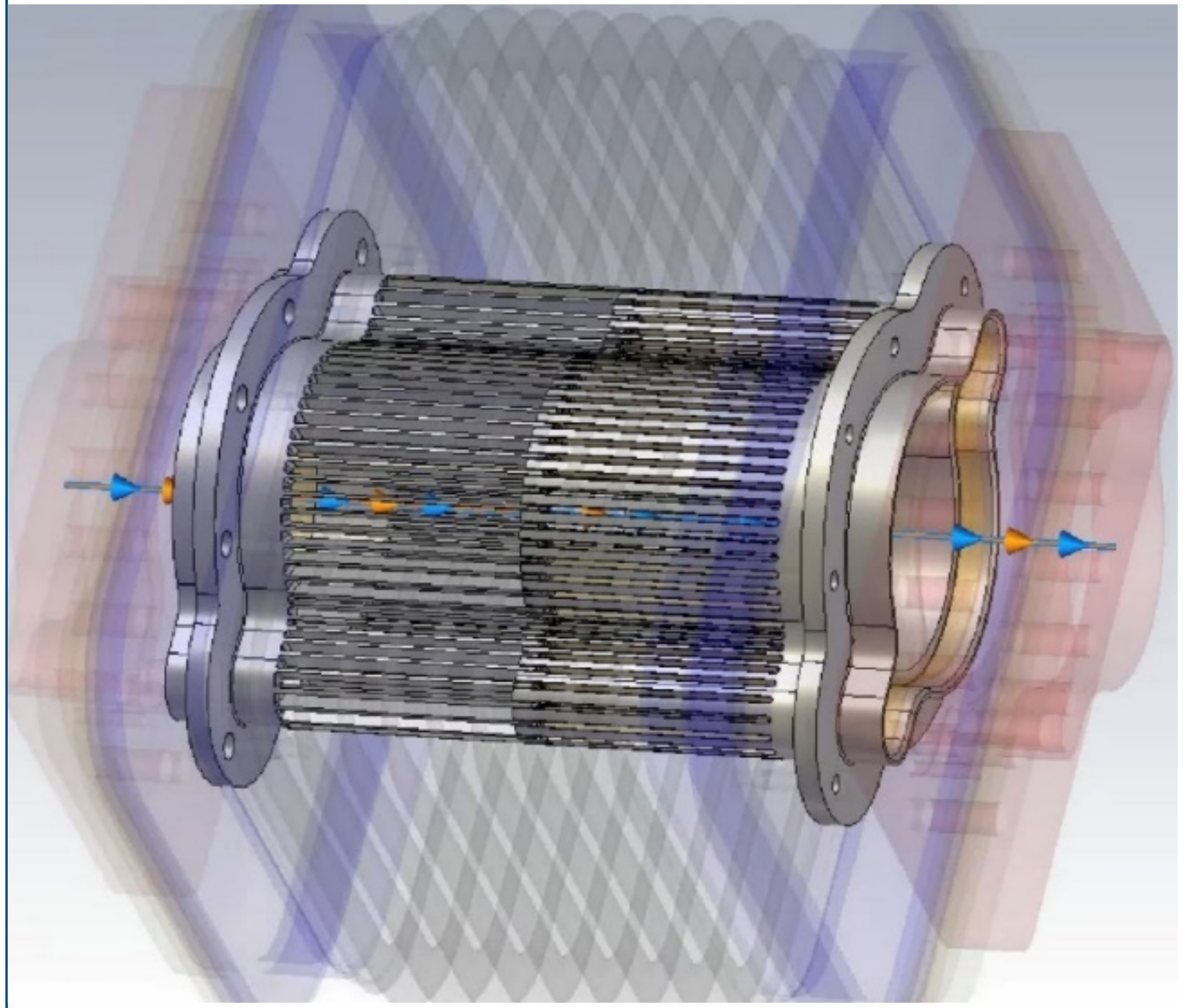
- **80-100 km infrastructure** in Geneva area
- ***e*$^{+}$*e*$^{-}$ collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**



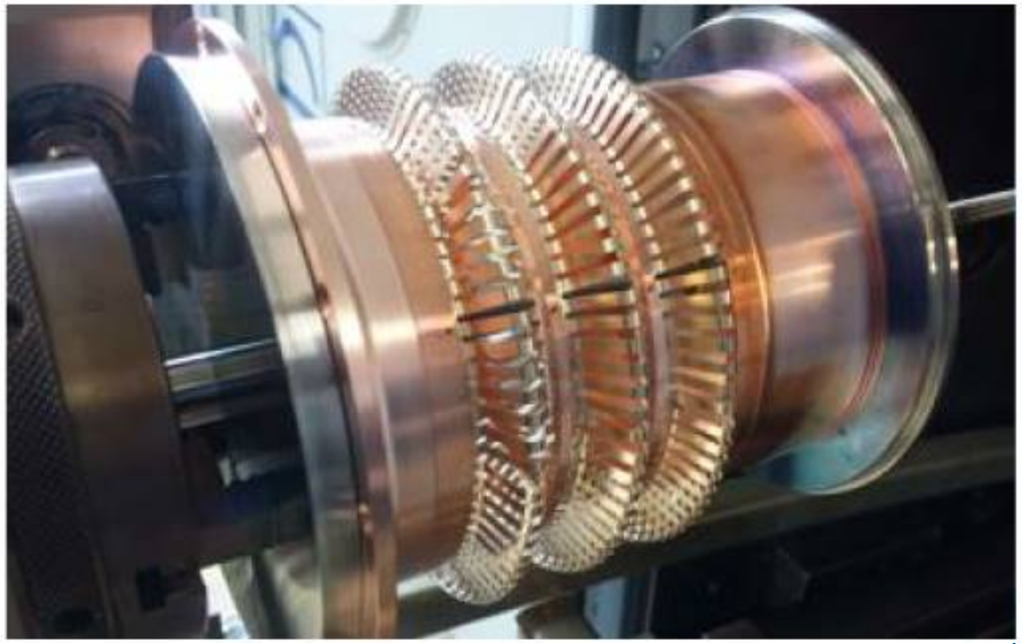
Activity: Collaboration with CERN on Collective Effects and Machine Impedance Model for FCC-ee

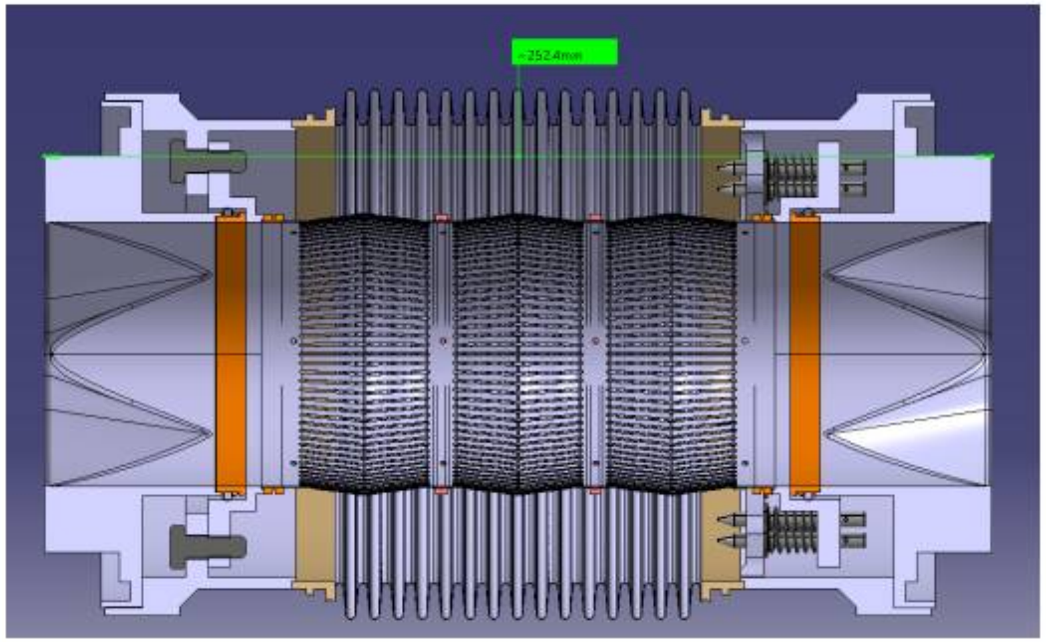
Impedance budget and wakefields: example for the bellows

Current model



Alternative model under study

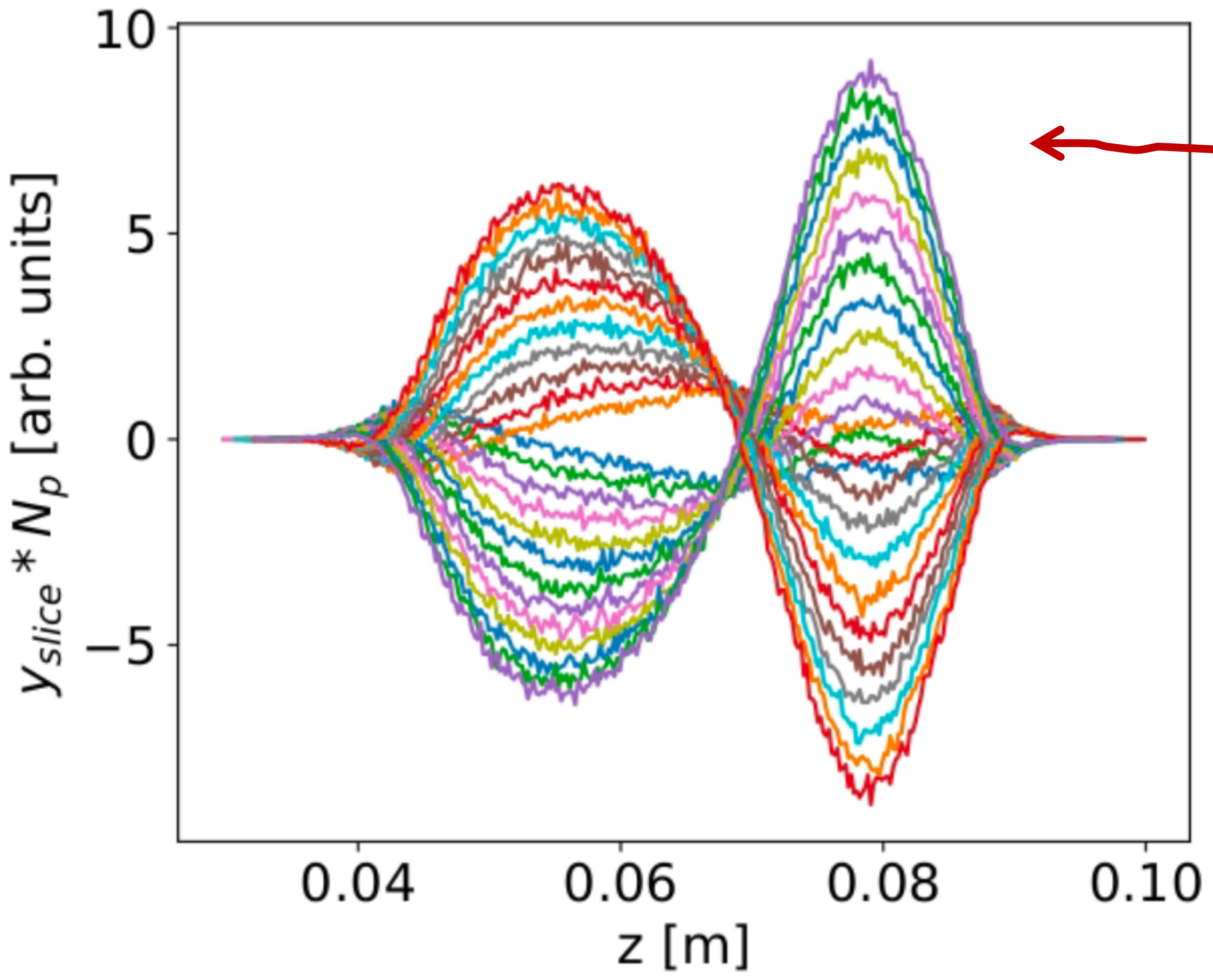


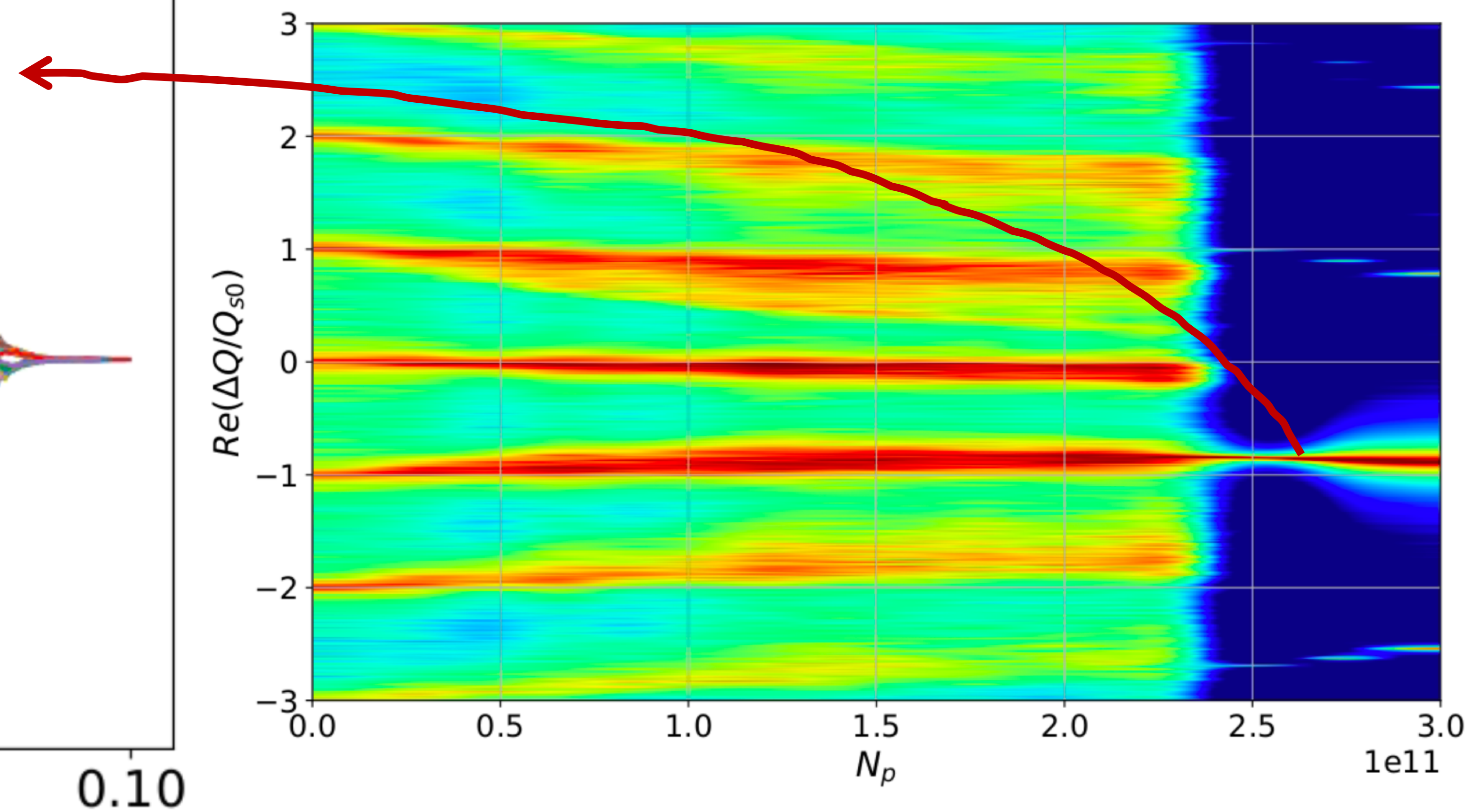


Activity: Collaboration with CERN on Collective Effects and Machine Impedance Model for FCC-ee

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)



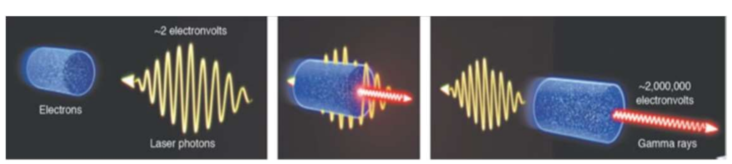


HIGH BRIGHTNESS C-BAND RF PHOTOINJECTORS FOR ELECTRON LINACS

UCLA SAPIENZA UNIVERSITÀ DI ROMA INFN
SLAC NATIONAL ACCELERATOR LABORATORY Los Alamos NATIONAL LABORATORY EST. 1943 RadiaBeam

- **High brightness beams** for advanced radiation sources by a proper combination of radio frequency (RF) **photoinjectors** and linear accelerating (Linacs) sections

Inverse Compton Sources (DARPA-GRIT)



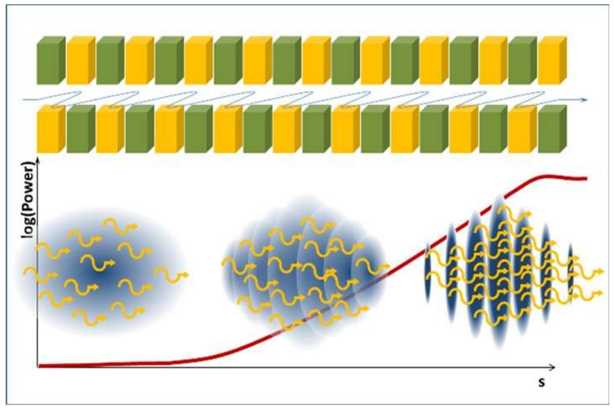
- Small footprint facility aimed to produce X/γ **radiation** from electron-photon scattering
- Design based on a **hybrid photoinjector** electron source and a room temperature C-band (5.713 GHz) linac

Ultra Compact X-rays Free Electron Laser (UC-XFEL)

- Compact $(\sim 40\,m)$ facility generating high brightness **X-rays**
- Design based on a high field ($240\,MeV/m$) standing wave photoinjector, **cryogenic** $(77\,K)$ high gradient RF linacs and **short period** $(3 \div 6.5\,mm)$ MEMS based undulators

MEMS= Micro-Electro-Mechanical Systems

J. B. Rosenzweig, N. Majernik et alia, "An ultra-compact X-ray free-electron laser," 2020.



XFEL for chip metrology

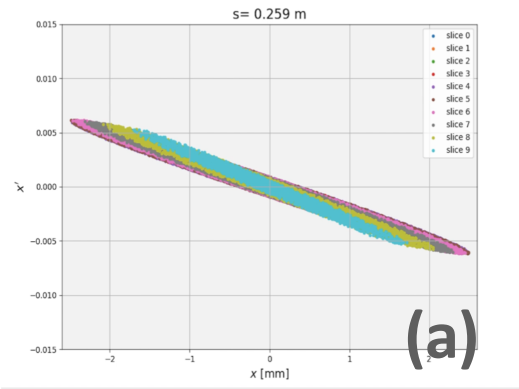
Single XFEL spot

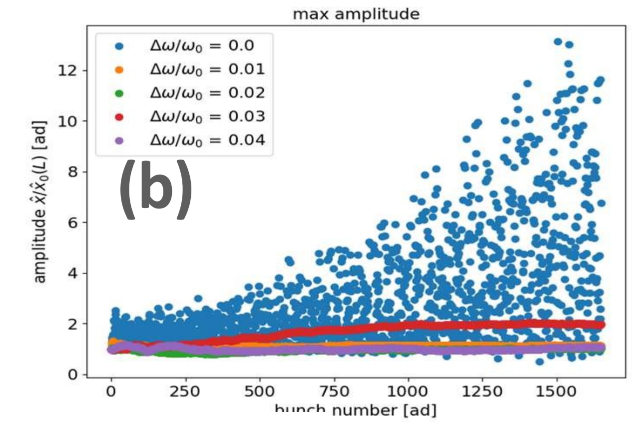
- For semiconductor device imaging **we need 1.5 Å** (resolution, penetration for 3D)
- **Ptychographic laminography** demands *high level of coherence*

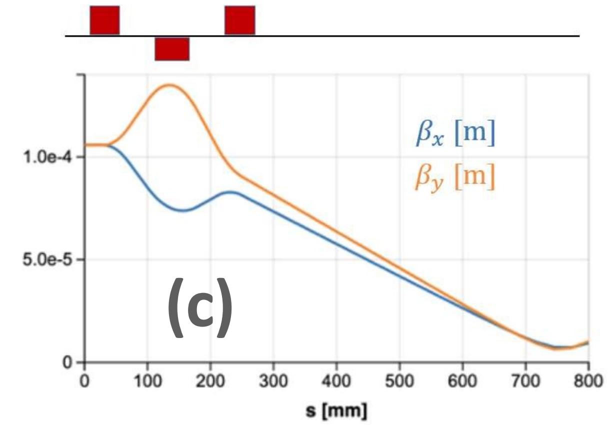
Main Research Activities

Beam Dynamics

- Beam **dynamics** studies for emittance and peak current optimization **(a)**
- Studies on **instabilities** aimed to keep under control the effects of the self-fields generated by the electron beam in the downstream linac sections **(b)**
- Design of the **final focus** optics for the Compton interaction point **(c)**

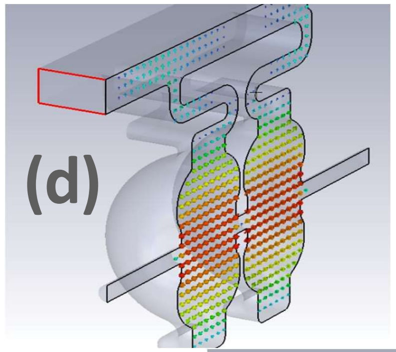


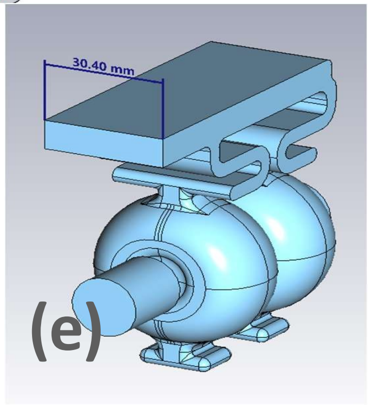




Design

- RF Design of novel RF structures that include:
- **Electromagnetic design**, to optimize the field shape inside cells **(d)**
- **Mechanical design and Manufacturing**: reproduction of the structure in the mechanical design for construction and realization. **(e,f)**

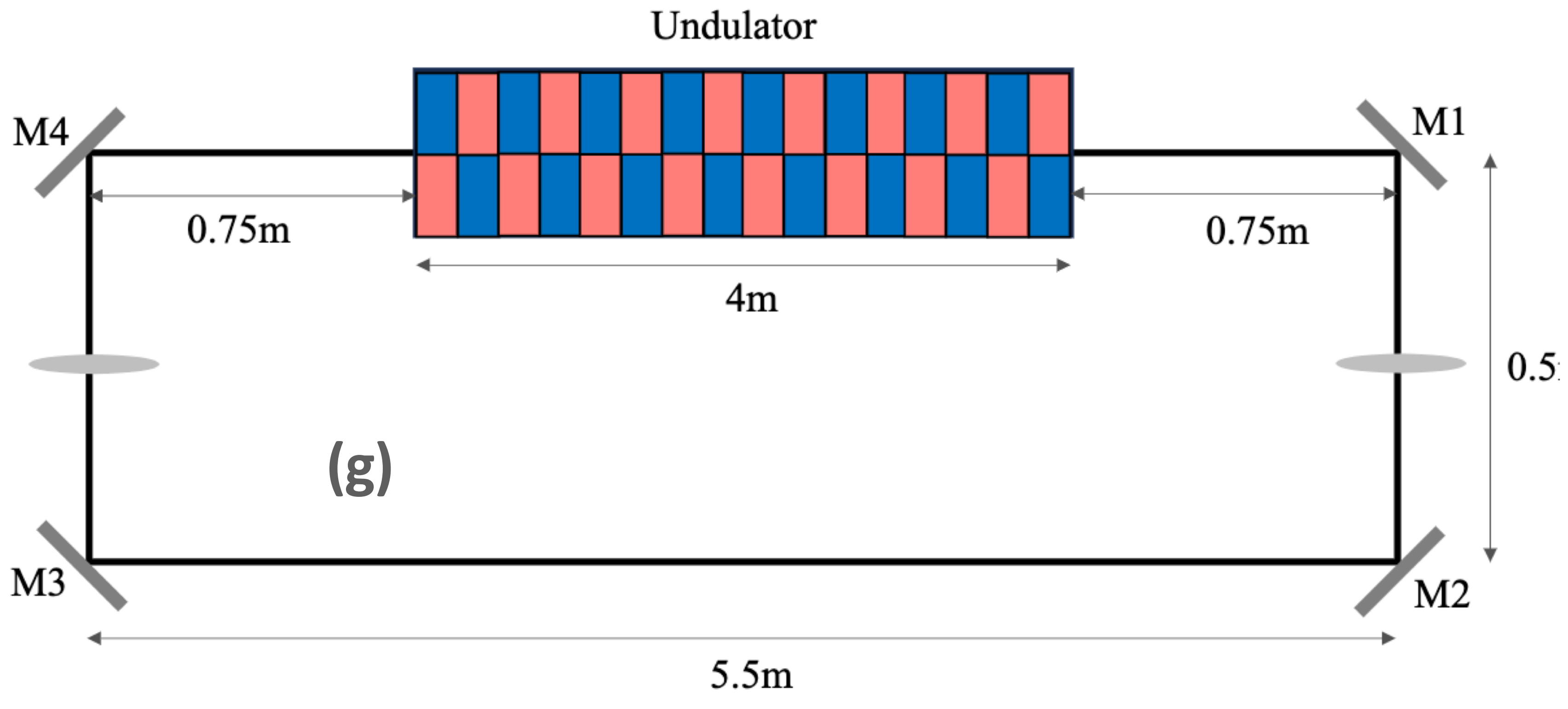




Main Research Activities

Applications

- The good performances shown by hybrid photoinjectors allow to foresee a wide panorama of applications beyond Compton sources
- Hybrid photoinjectors could be employed to drive **FEL radiation** or to fulfil $\boldsymbol{THz}$ **radiation** sources for medical applications
- X-rays in XRAFEL configuration for 8 passes **(g)**



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

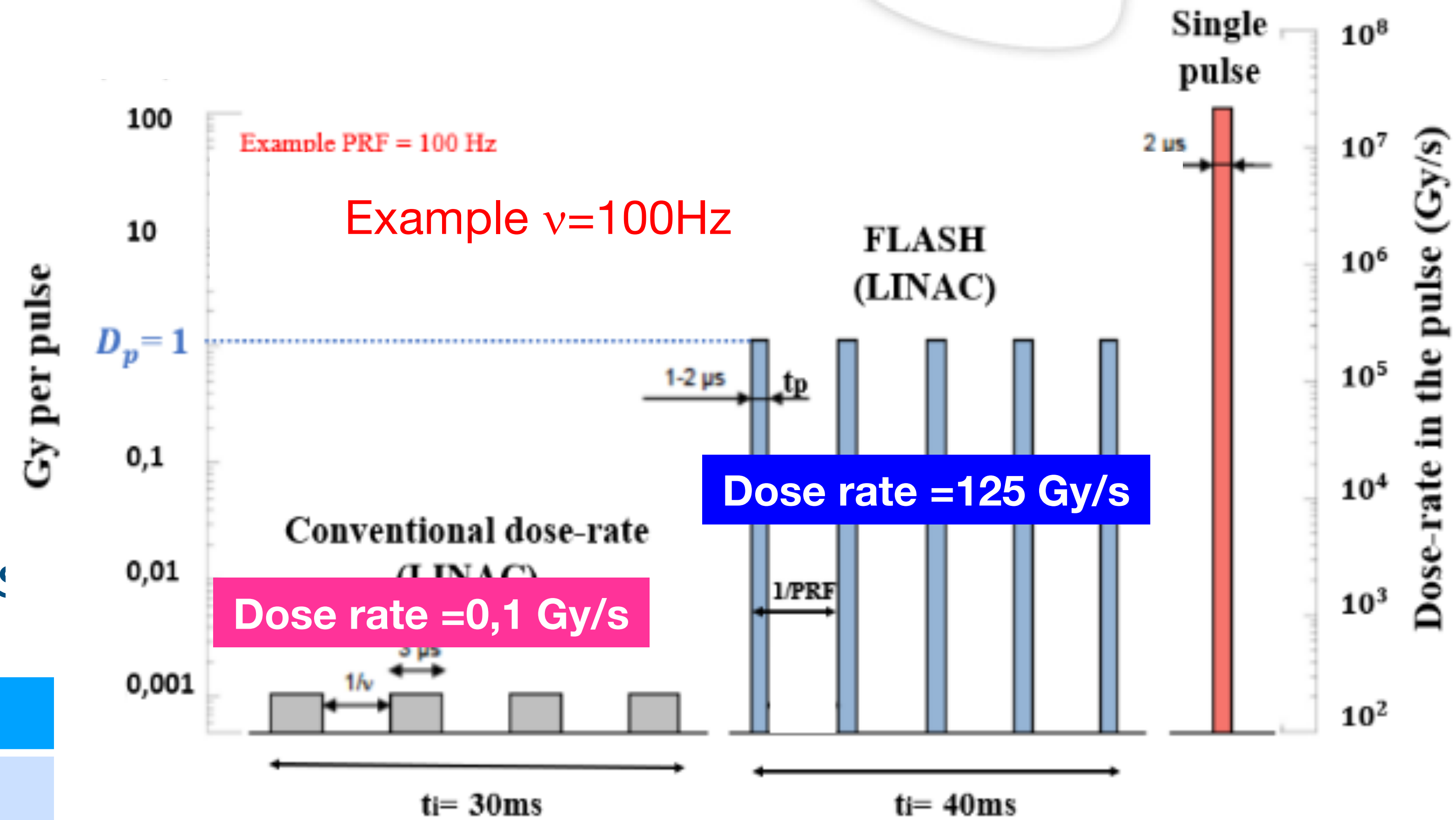
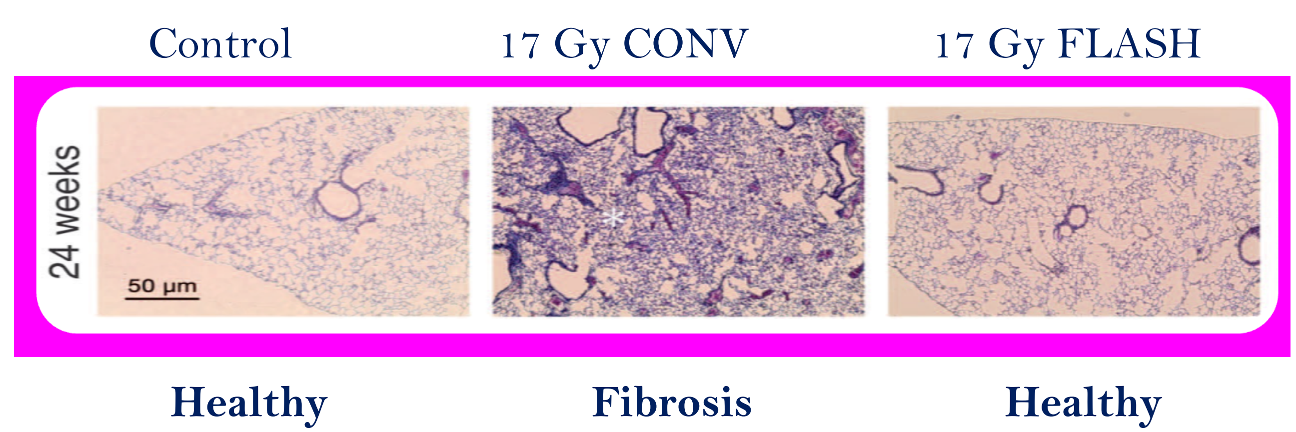


Fig. Courtesy of Vincent Favaudon - Curie Institute



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

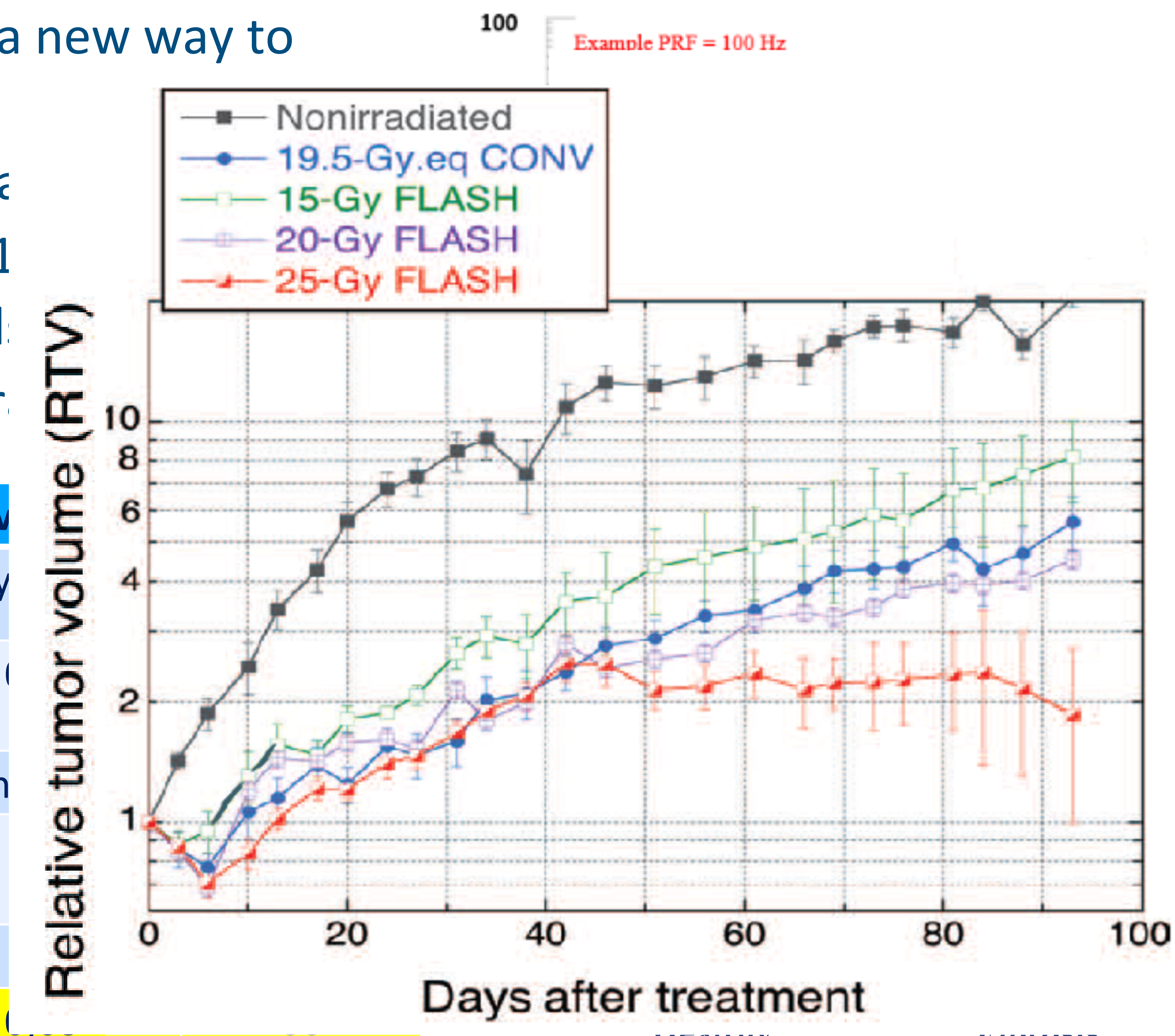
FLASH Effect in Radiotherapy

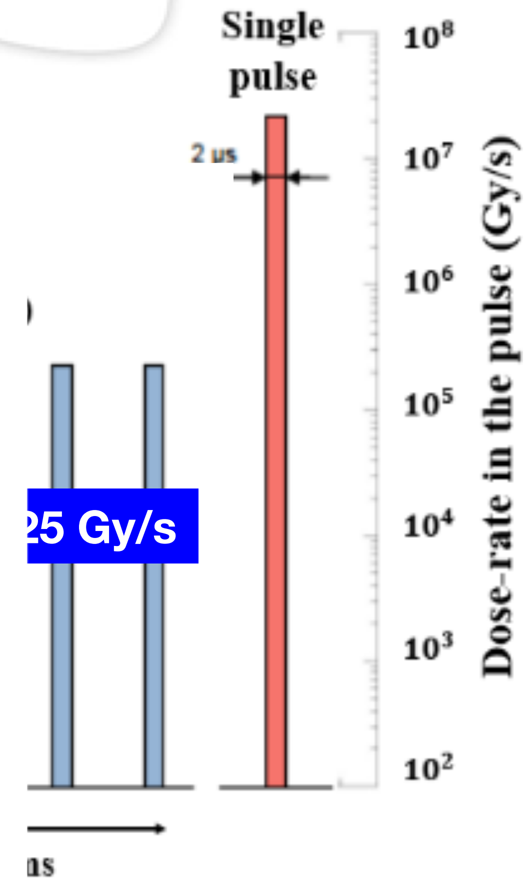
institutCurie

FLASH THERAPY is a new way to deliver the dose:

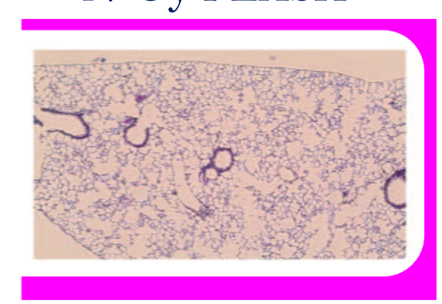
- ms pulses of radi…
- beam-on time < 1…
- high dose per pul…
- high mean dose r…

	Conv…	
Facility	γ−ray…	
Nominal energy (MeV)	[illegible]	
Pulse vs continuous	Con…	
Pulse repetition frequency (Hz)		
Dose (Gy)		
Mean Dose rate (Gy/s)	[illegible]	[illegible]
Temporal width of pulse	few ms	1 ms





17 Gy FLASH



Healthy

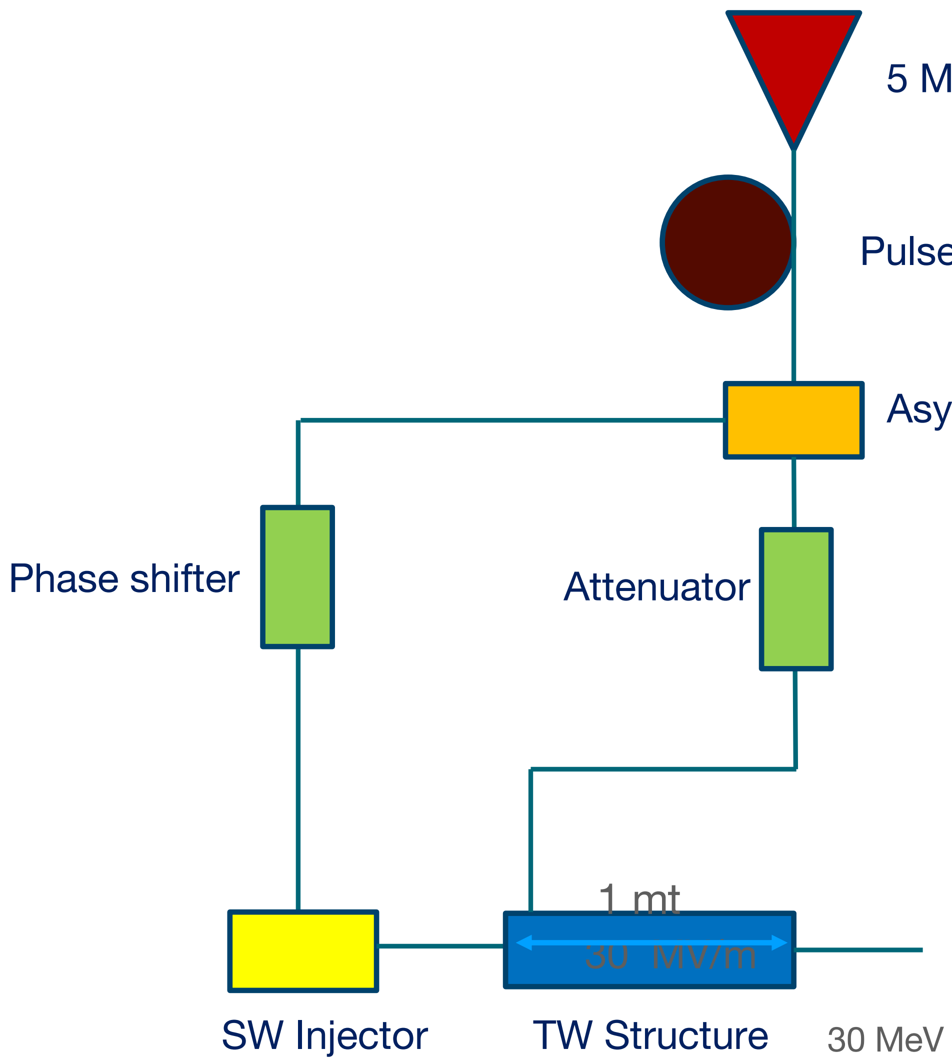
FLASH irradiation protects healthy tissues from damage and remains as ***efficient as*** **CONV** irradiation in the repression of tumor growth

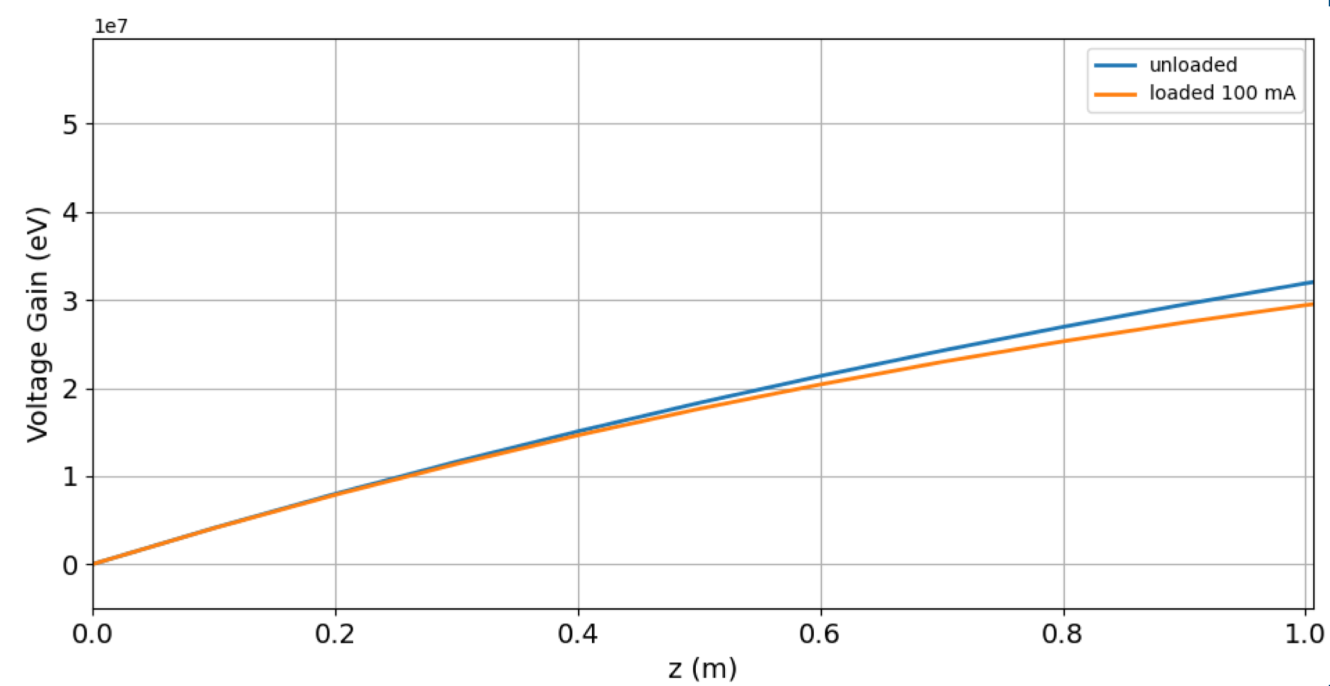
Favaudon et al., Science Translational Medicine 6, 2014

Activity at Sapienza

First Step

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





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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Sezione di Roma

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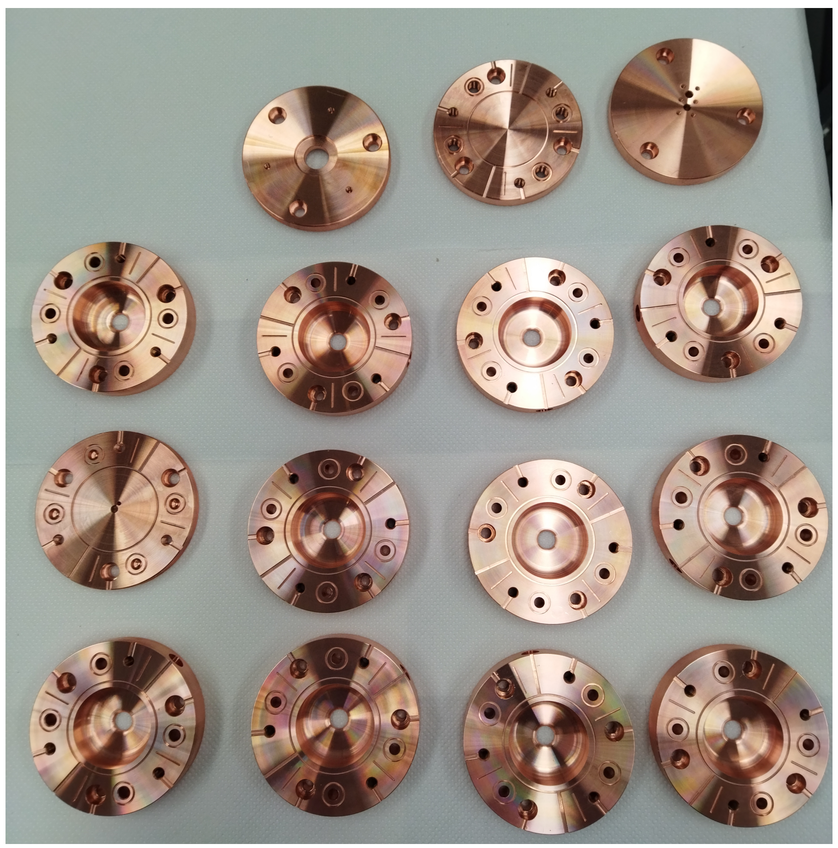
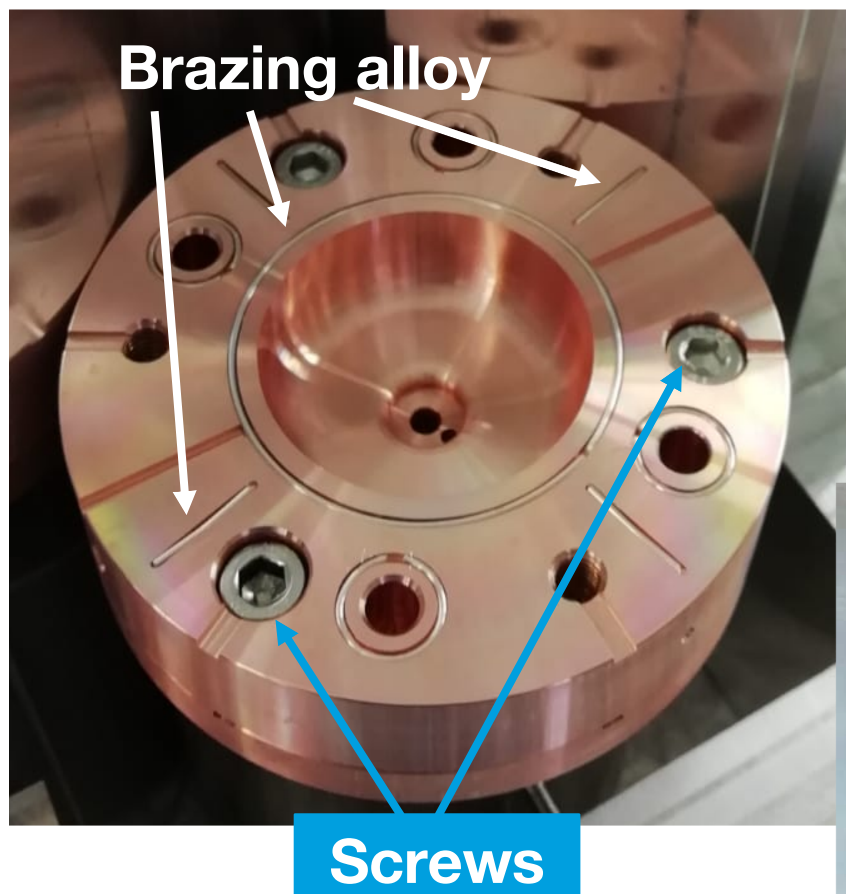
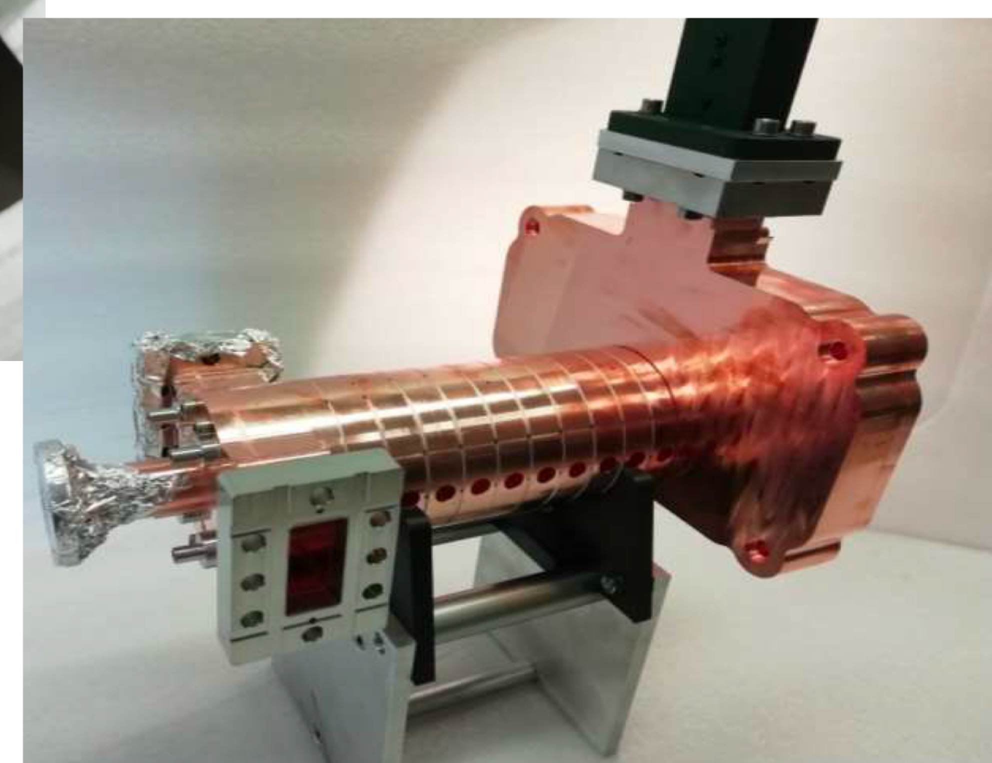




In house building of the accelerating cavities

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

Beam dynamics studies

To realize the Medical accelerator

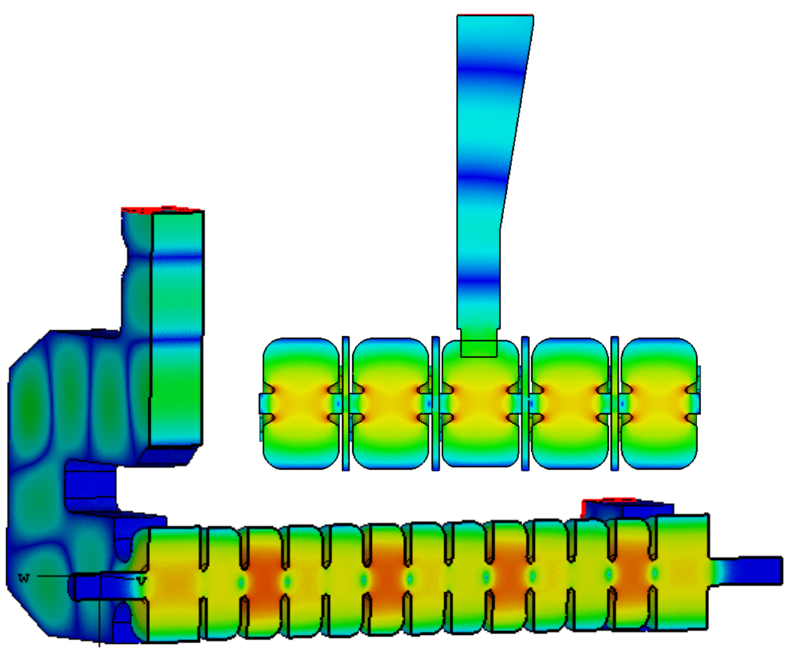
Cell optimization & EM design

Copper prototype

RF measurement

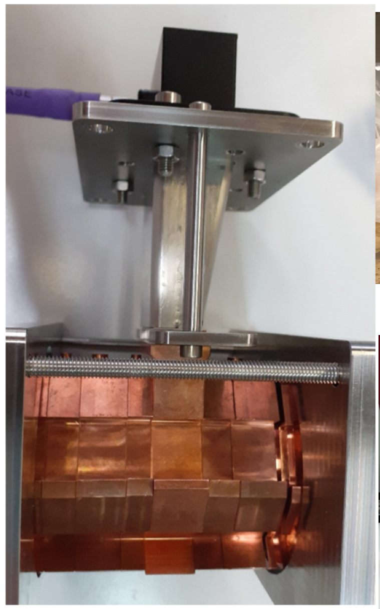
Standing Wave cavity

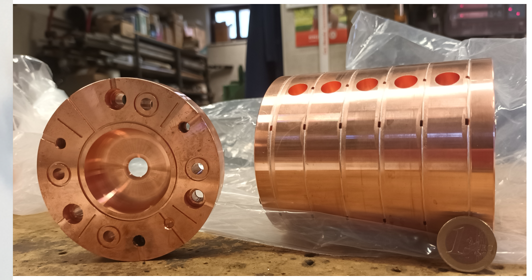
Traveling Wave structure

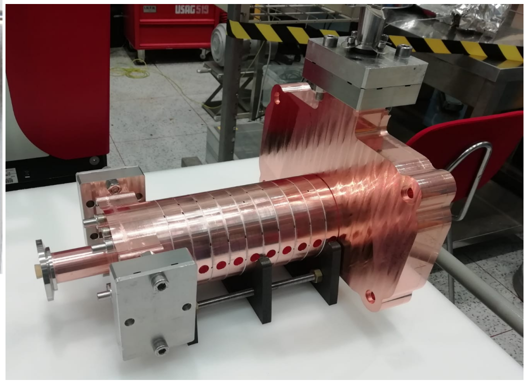


Standing Wave cavity

Traveling Wave structure

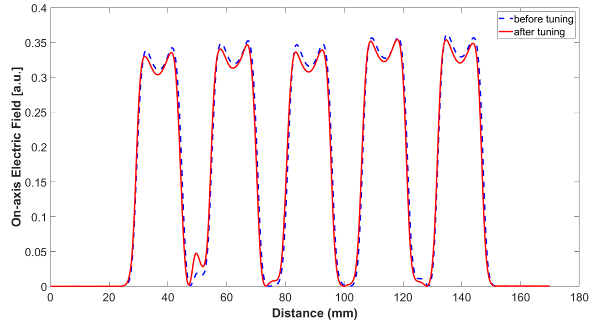


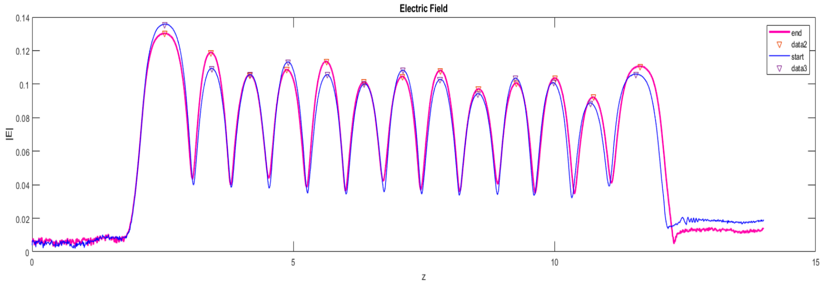




Standing Wave cavity

Traveling wave structure





Plasma Acceleration Activity

EuPRAXIA and EuPRAXIA@SPARC_LAB Collaboration

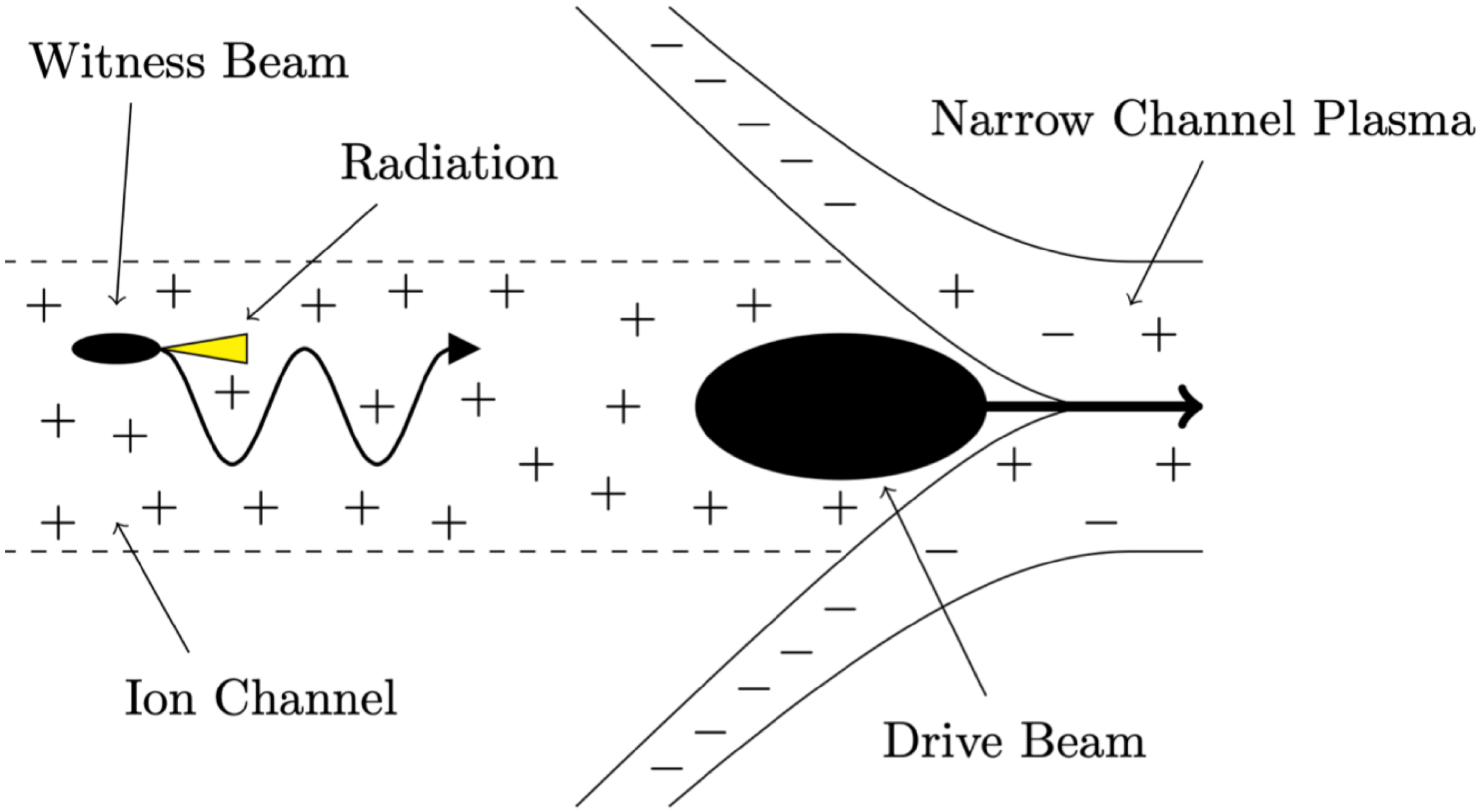
- The EuPRAXIA@SPARC_LAB project focuses to realize a compact plasma-based Free-Electron Laser user facility
  - Plasma acceleration module
  - Ancillary components
- Conventional undulators are still too long => not compact and expensive
  - betatron motion of electrons in an ion-channel to emulate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

Ion Channel Concept

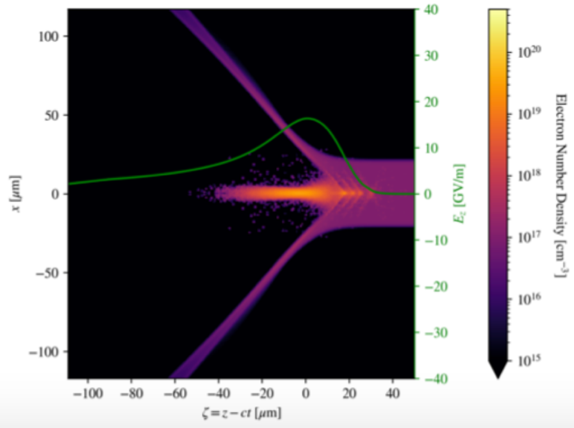
- Replaces magnetic undulator with strong focusing ion channel
- **Linear focusing force** produces periodic betatron oscillations

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

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



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



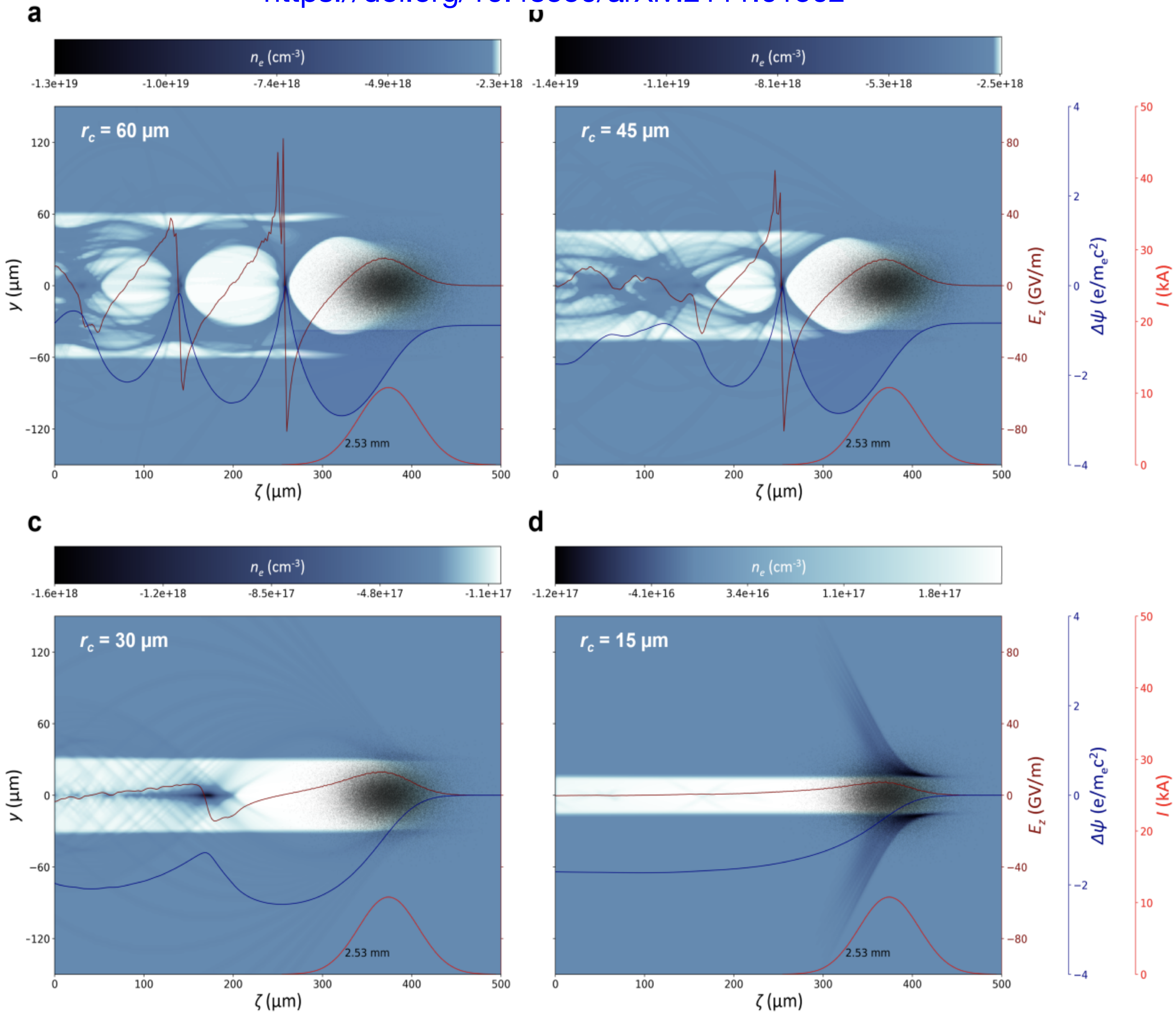
QuickPIC simulation of ion channel formation

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

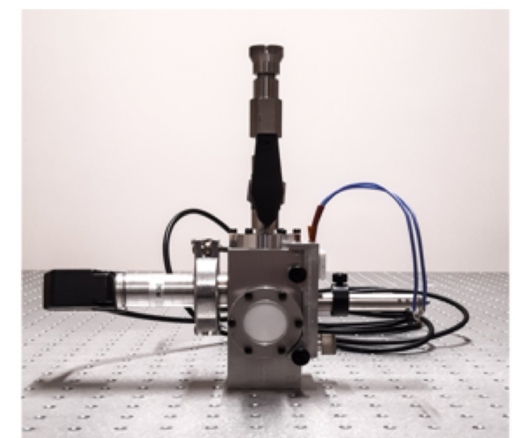


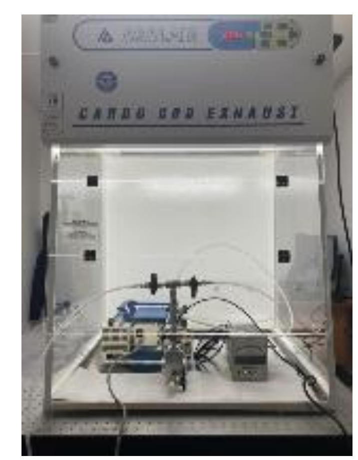
$$K_{u,\beta} = 1.33 \cdot 10^{-10} \sqrt{\gamma / n_0[cm^{-3}]}\, r_\beta[\mu m] \qquad \lambda_{u,\beta}[\mu m] = 4.72 \cdot 10^{10} \sqrt{\gamma / n_0[cm^{-3}]}$$

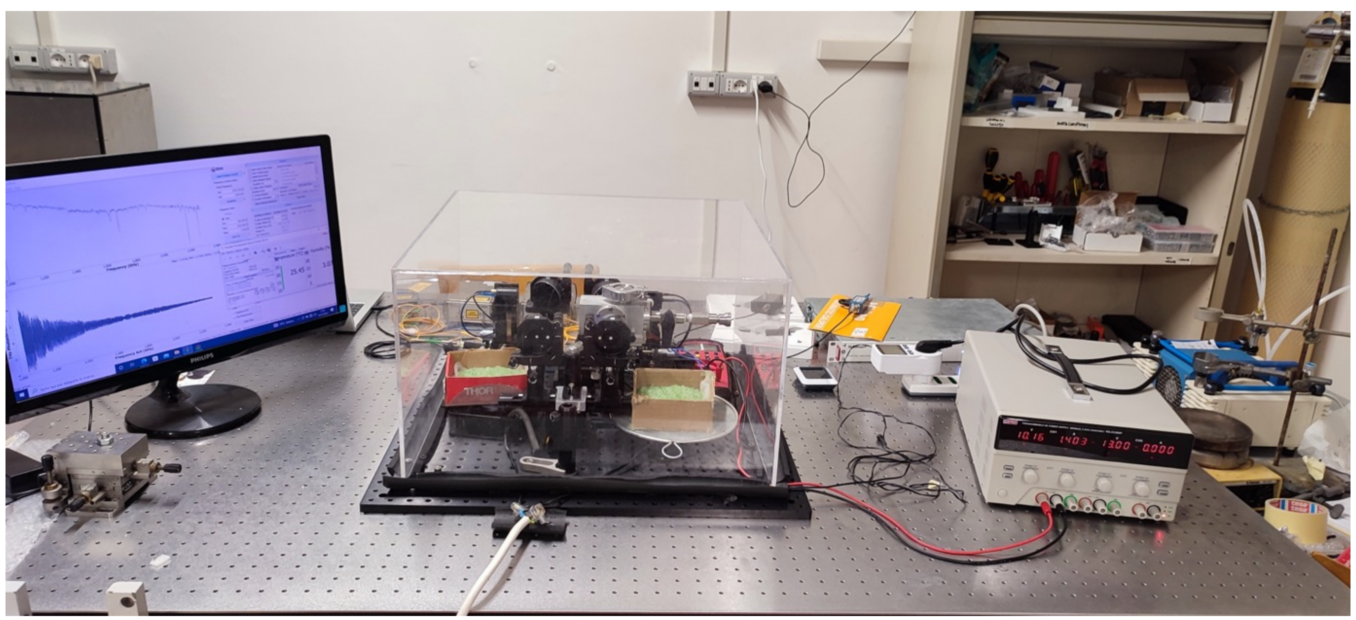
THz Generation

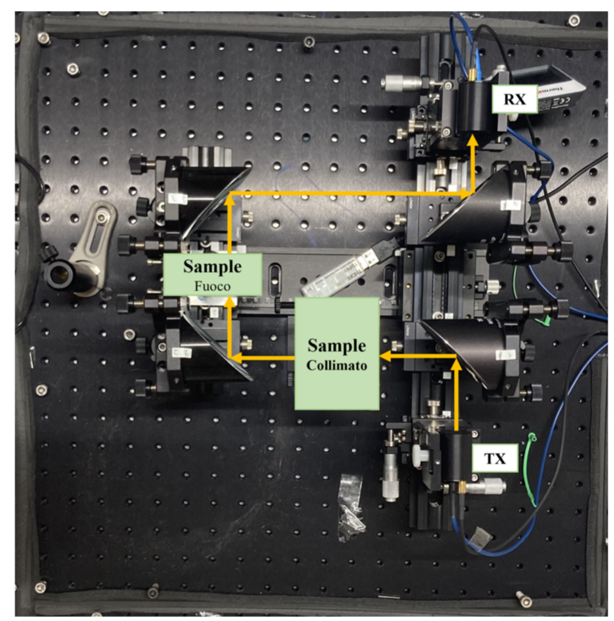
THz-CW source in operation

Gas cell for spectroscopic
measurement on gas samples









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