Sapienza Università di Roma
Istituto Nazionale di Fisica Nucleare
Sezione di Roma
Dipartimento di Scienze di Base e Applicate per l' Ingegneria

Research activity at SBAI (Basic and Applied Sciences for Engineering) – Sapienza and INFN-Roma1, and collaborations with other institutes: beam dynamics and collective effects in linear and circular accelerators

M. Migliorati
(mauro.migliorati@uniroma1.it)

Group at Department of Basic and Applied Sciences for Engineering

- E. Chiadroni (PA), L. Ficcadenti (INFN-Roma1), M. Migliorati (PA), A. Mostacci (PA), L. Palumbo (PO), M. Petrarca (PA) + PhD and master students + INFN-LNF collaborators (L. Faillace, B. Spataro).
- Our group has a long-standing tradition of work 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
  - Laser-plasma acceleration, THz Laser Laboratory
- Here I will focus the presentation essentially on the general experiments in which we are involved rather than on specific topics.

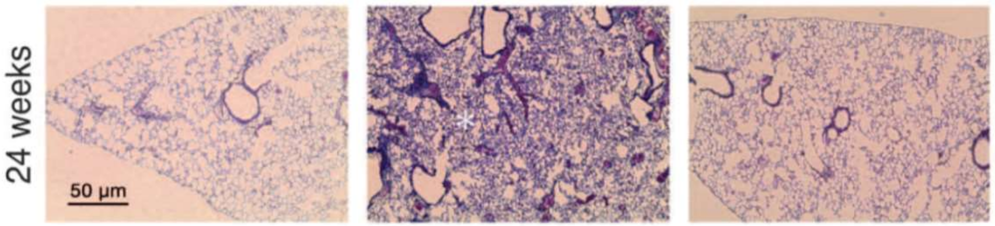
Novel medical linear accelerators for FLASH therapy

FLASH THERAPY is a new method for cancer treatment using Linacs and consisting in delivering very high doses in short time intervals (see presentation on medical physics by Alessio Sarti, here we focus on the Linac design):

- μs pulses of radiation, beam-on time < 100-500ms high dose per pulse → very high dose rate (>100 Gy/s)

FLASH EFFECT is the improvement of the healthy tissue tolerance to the delivered dose.

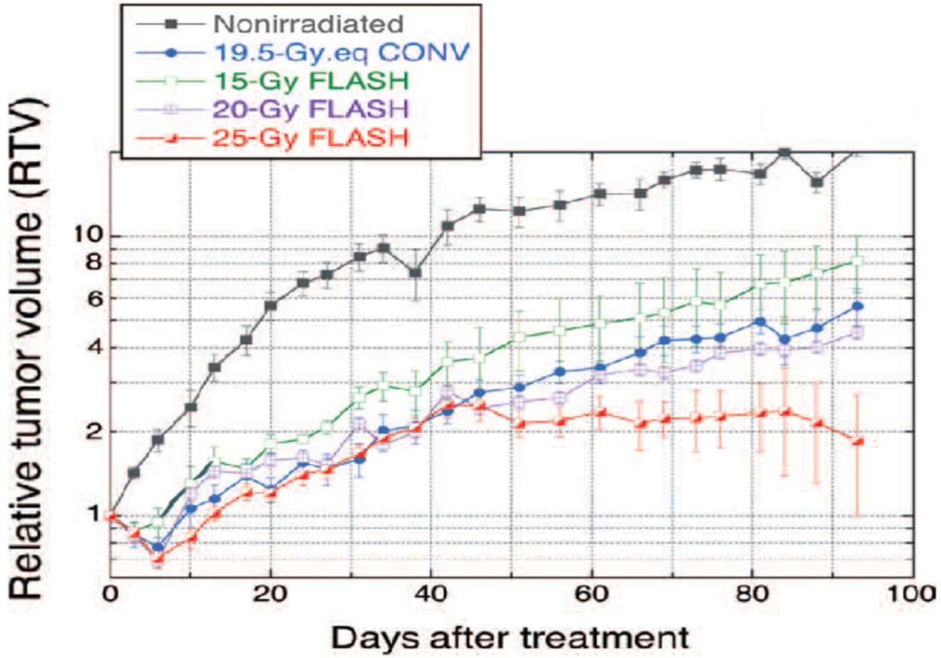
Control 17Gy CONV 17Gy FLASH



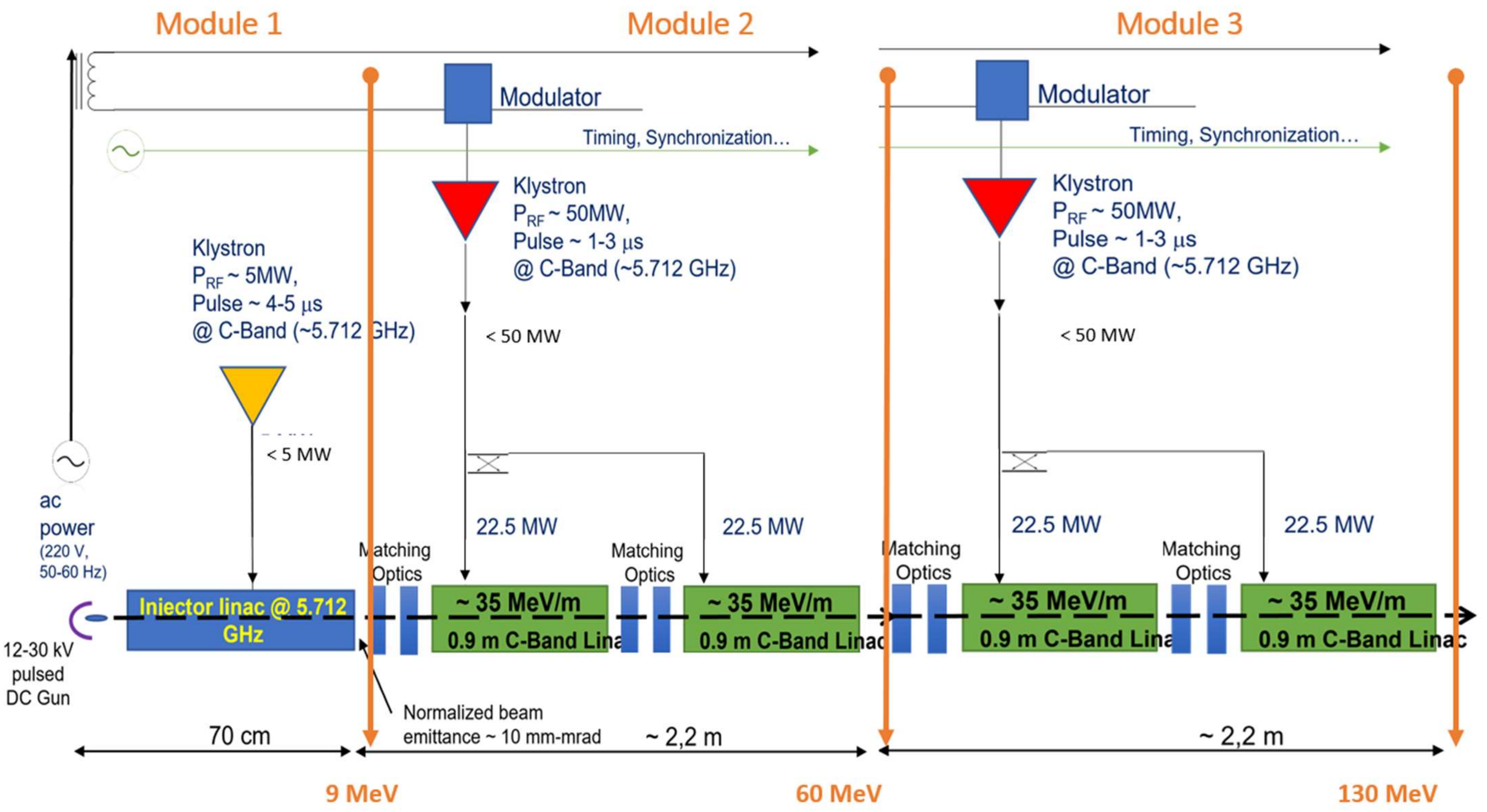
Healthy **Fibrosis** **Healthy**

V. Favaudon et al., "Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumour tissue in mice", *Science Translational Medicine* 6, 2014

The FLASH therapy is **as efficient as Conventional** irradiation in the repression of tumor growth

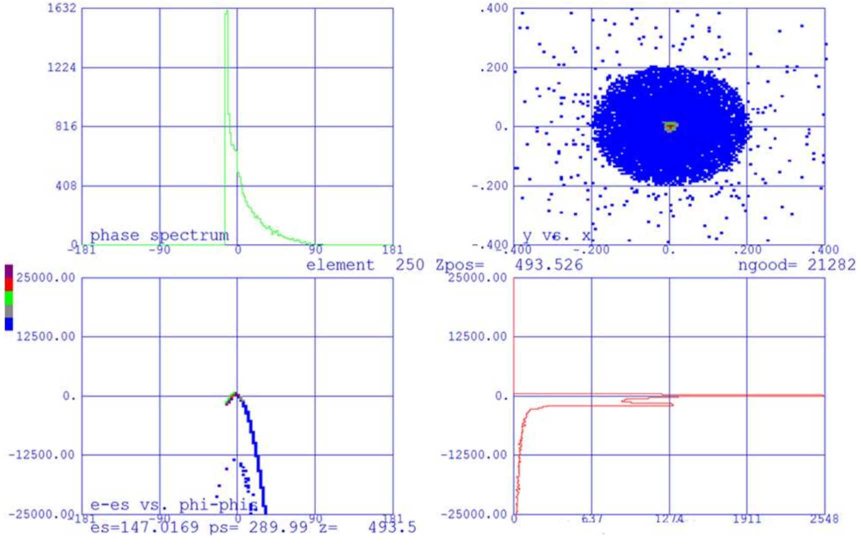


Compact C-band linear accelerator

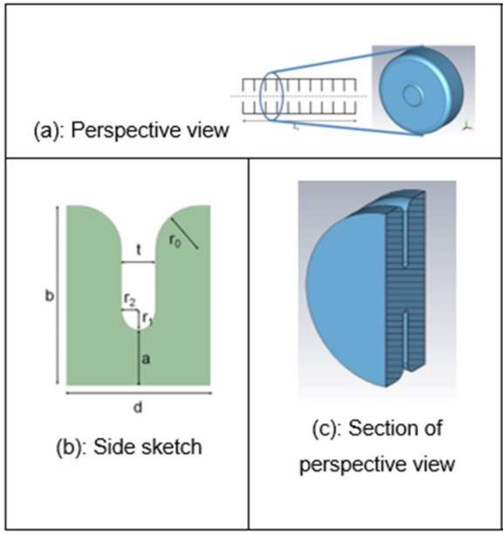


Compact C-band linear accelerator: activity

Beam dynamics

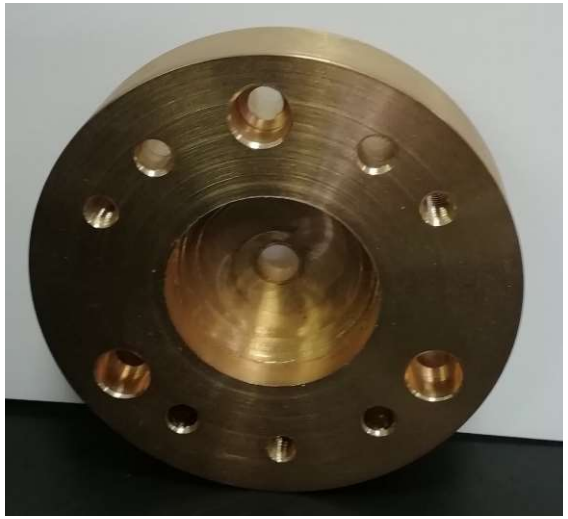


RF design

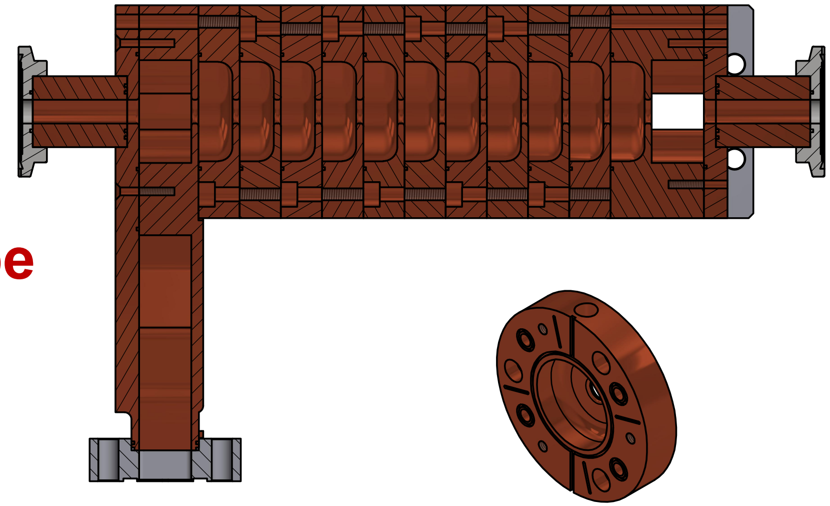


Cell geometric parameter

- a: iris radius ($a \in [3,7] mm$)
- t: iris thickness (2 mm)
- r_1: iris rounding radius (1 mm)
- r_0: edge rounding radius (2.5 mm)
- d: cell length (function of ϕ_0, $d = \frac{c}{\omega}\phi_0 = 17.5\ mm$)
- b: outer radius (function of a and frequency f)
- ϕ_0: phase advance per cell ($\frac{2}{3}\pi$)



Prototype



UCLA, La Sapienza, LNF-INFN, SLAC, LANL

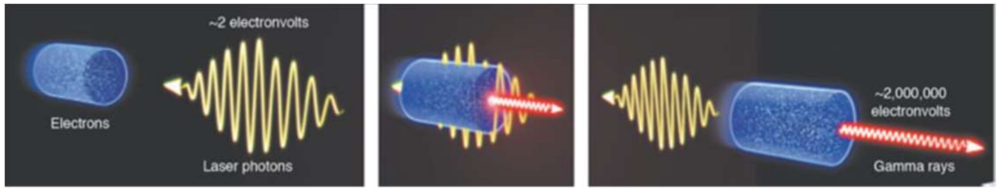
HIGH BRIGHTNESS C-BAND RF PHOTOINJECTORS FOR ELECTRON LINACS

Main Applications and Projects

- High **brightness** (high current, low transverse emittances) electron beams are the key to achieve good performances for advanced radiation sources
- Such beams can be produced by a proper combination of radio frequency (RF) **photoinjectors** and linear accelerators (Linacs) sections

Inverse Compton Sources

- 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 $(5.712\ \text{GHz})$ linac

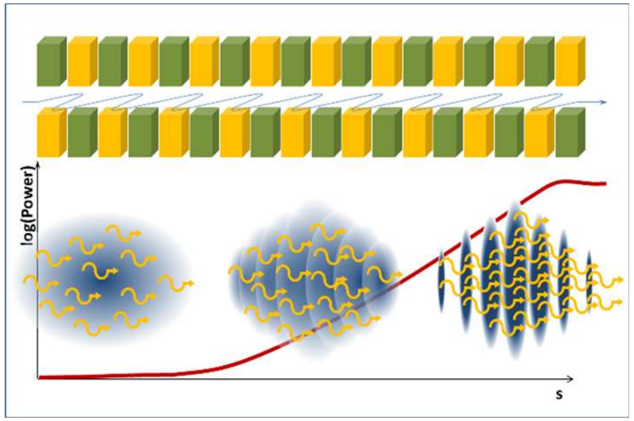


Ultra Compact X-rays Free Electron Laser

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

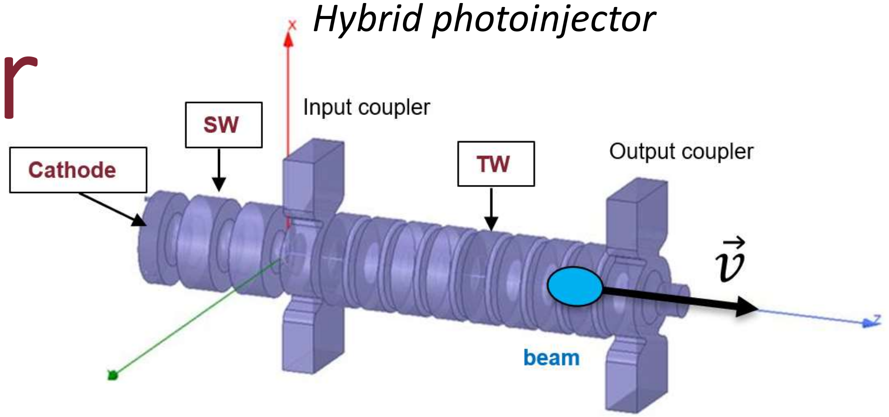
MEMS= Micro-Electro-Mechanical Systems

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



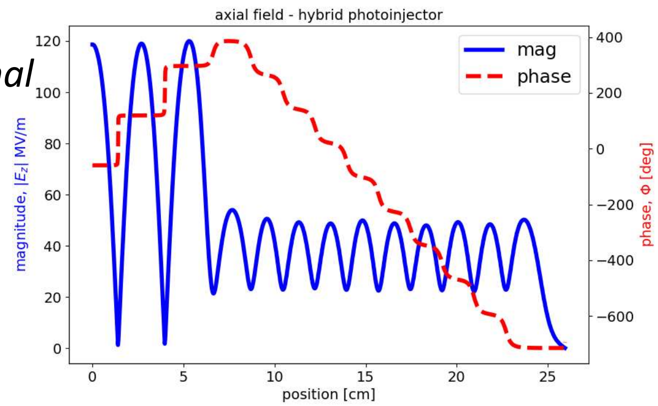
Hybrid RF Photoinjector

Hybrid photoinjector

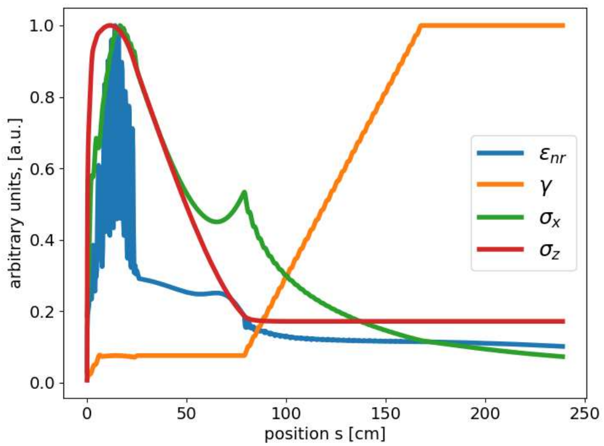


- Multicell RF structure combining a **standing wave** (SW) and a **traveling wave** (TW) section fed from a common coupling cell
- C-band RF design: working frequency is 5.712 GHz
- Electrons are extracted from the **cathode** by an UV laser pulse and are accelerated in the SW region
- The TW structure introduces **velocity bunching** which shortens the beam enhancing the peak current
- A proper combination with solenoid coils and a booster linac allows to achieve **emittance compensation** and velocity bunching together
- The latter results in beams of high **5D brightness** (high current, low emittance)

longitudinal on-axis electric field



Beam distribution moments along a hybrid photoinjector-drift-linac system



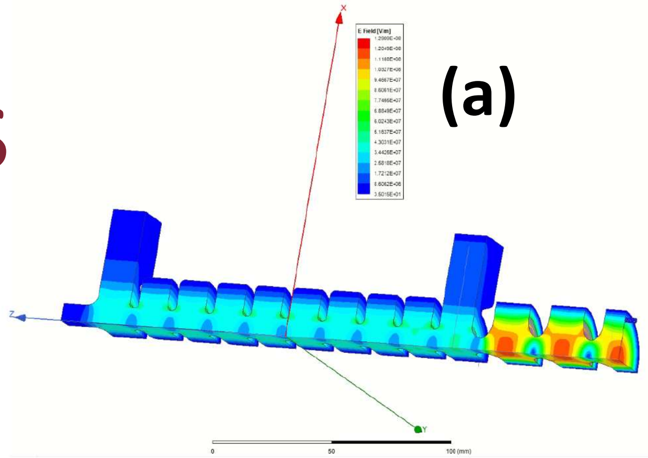
Main Research Activities

Activities concerning the hybrid photoinjector

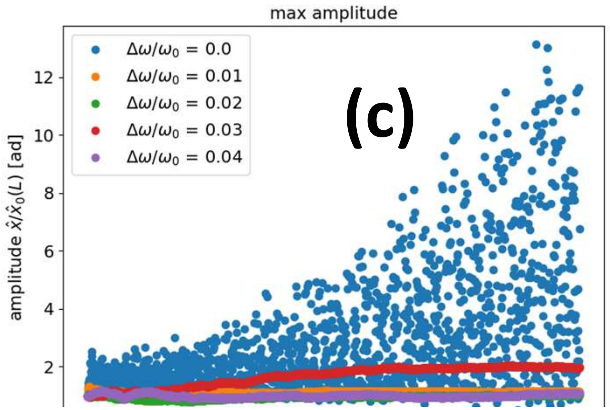
- Design and optimization of the C-band **RF structure (a)**
- Beam **dynamics** studies to achieve the best working point in terms of emittance and peak current **(b)**
- Studies on **instabilities** aimed to keep under control the effects the self-fields generated by the electron beam in the downstream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

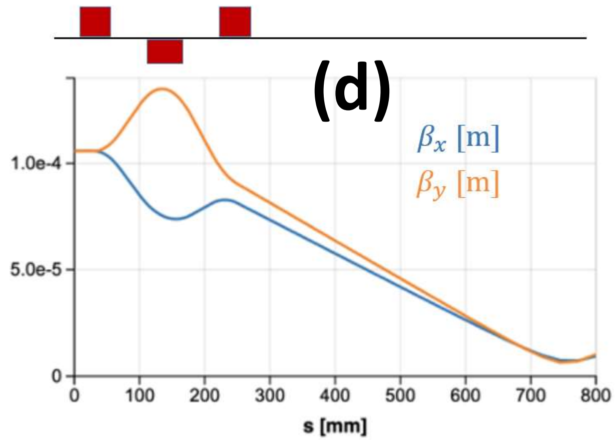
Further applications

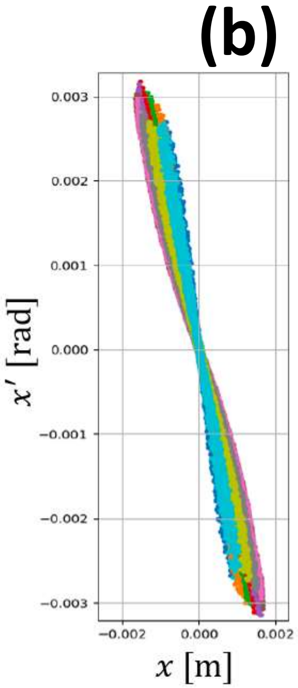
- The good performances shown by hybrid photoinjectors allow to foresee a wide panorama of applications beyond Compton sources
- Hybrid photoinjectors could be employed to drive **FEL radiation** or to fulfill **THz radiation** sources for medical applications



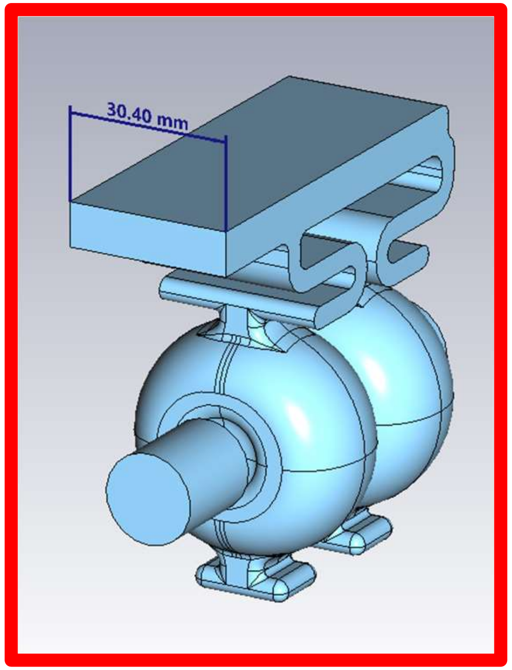
(a) *Electric field*

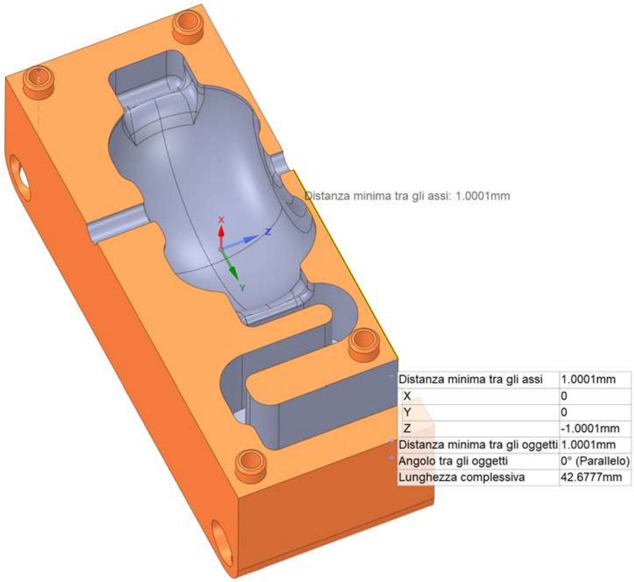






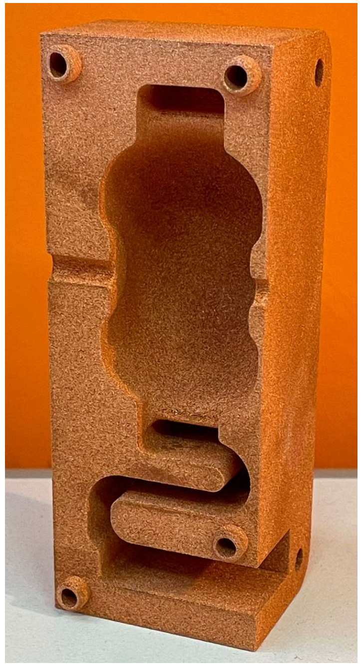
Additive manufacturing for novel RF structures

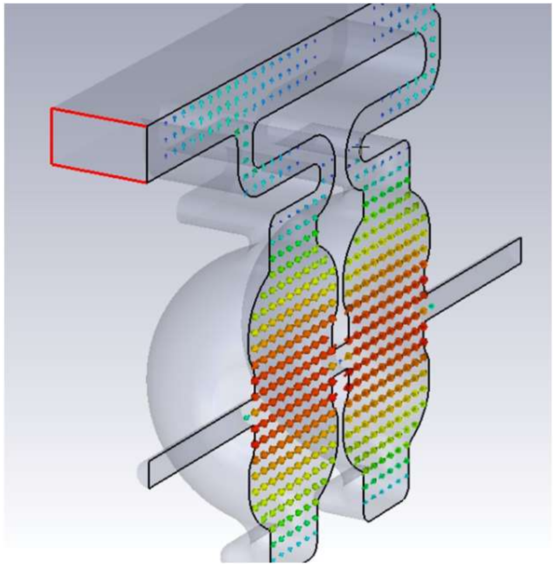


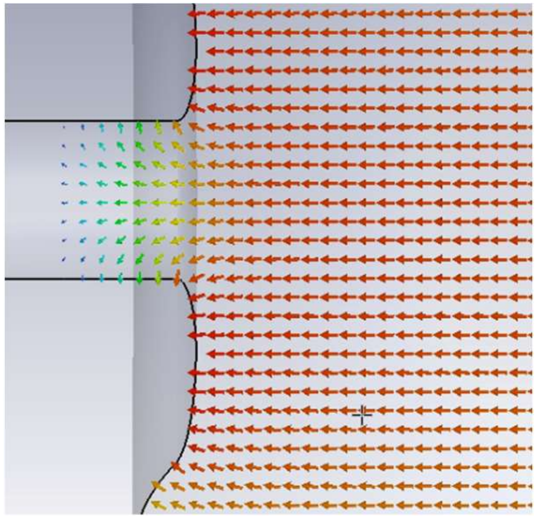


INFN
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

HAMMER



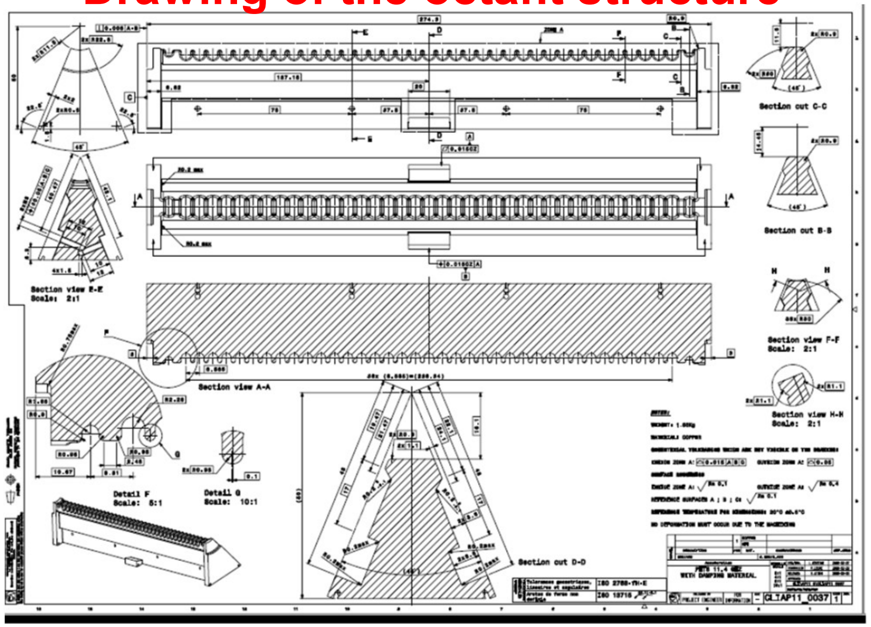


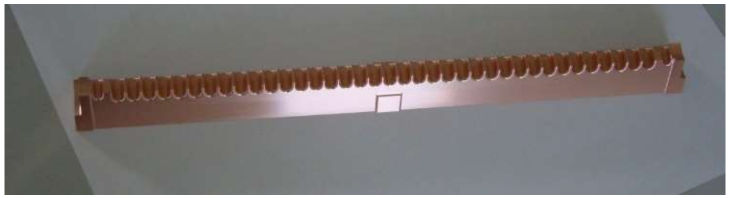


RF technology for ultra-compact, high gradient Linacs

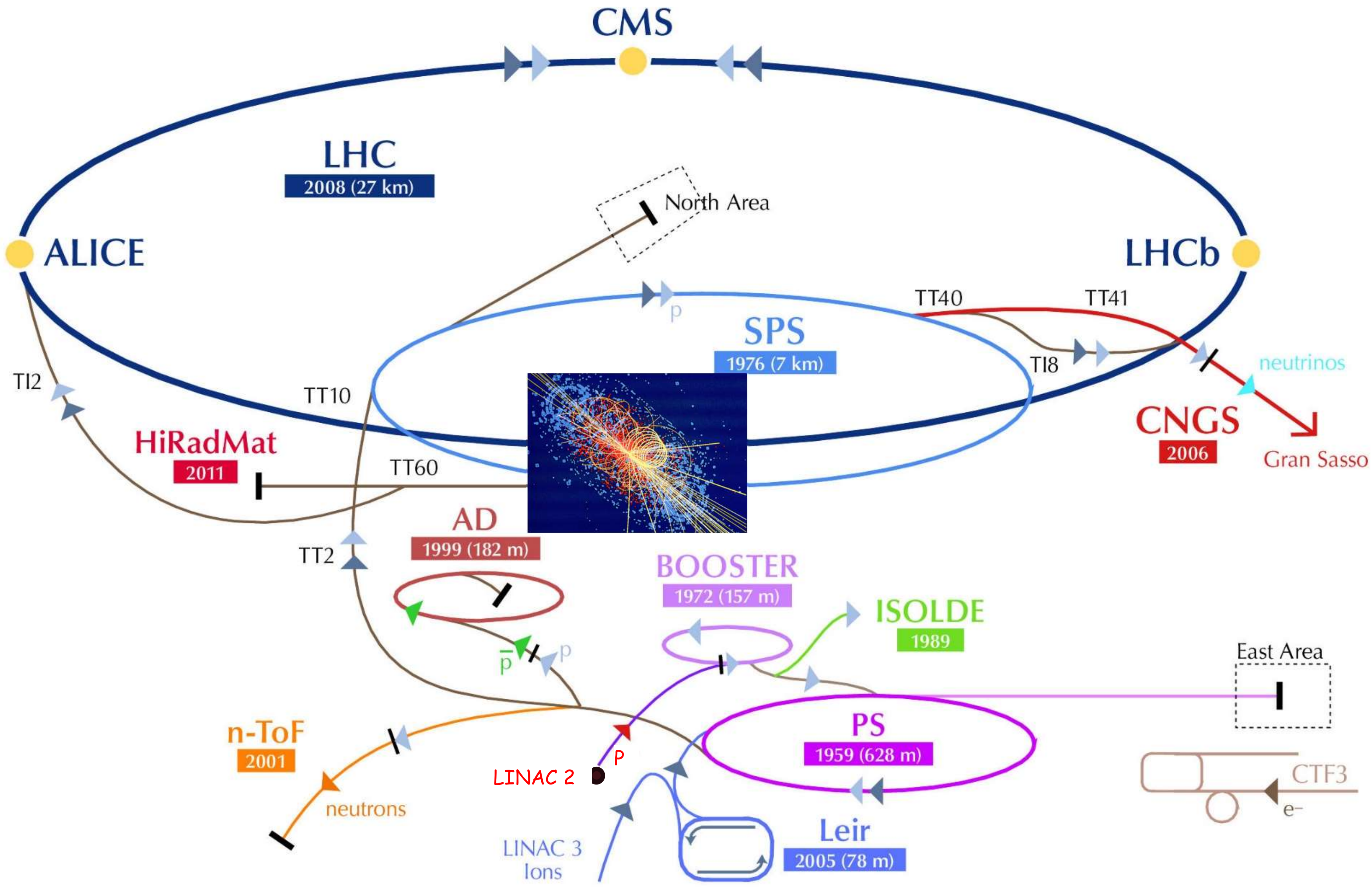
- **Realization of an X-band accelerating structure at high gradient using the jointless 'open structure' technique**

Drawing of the octant structure

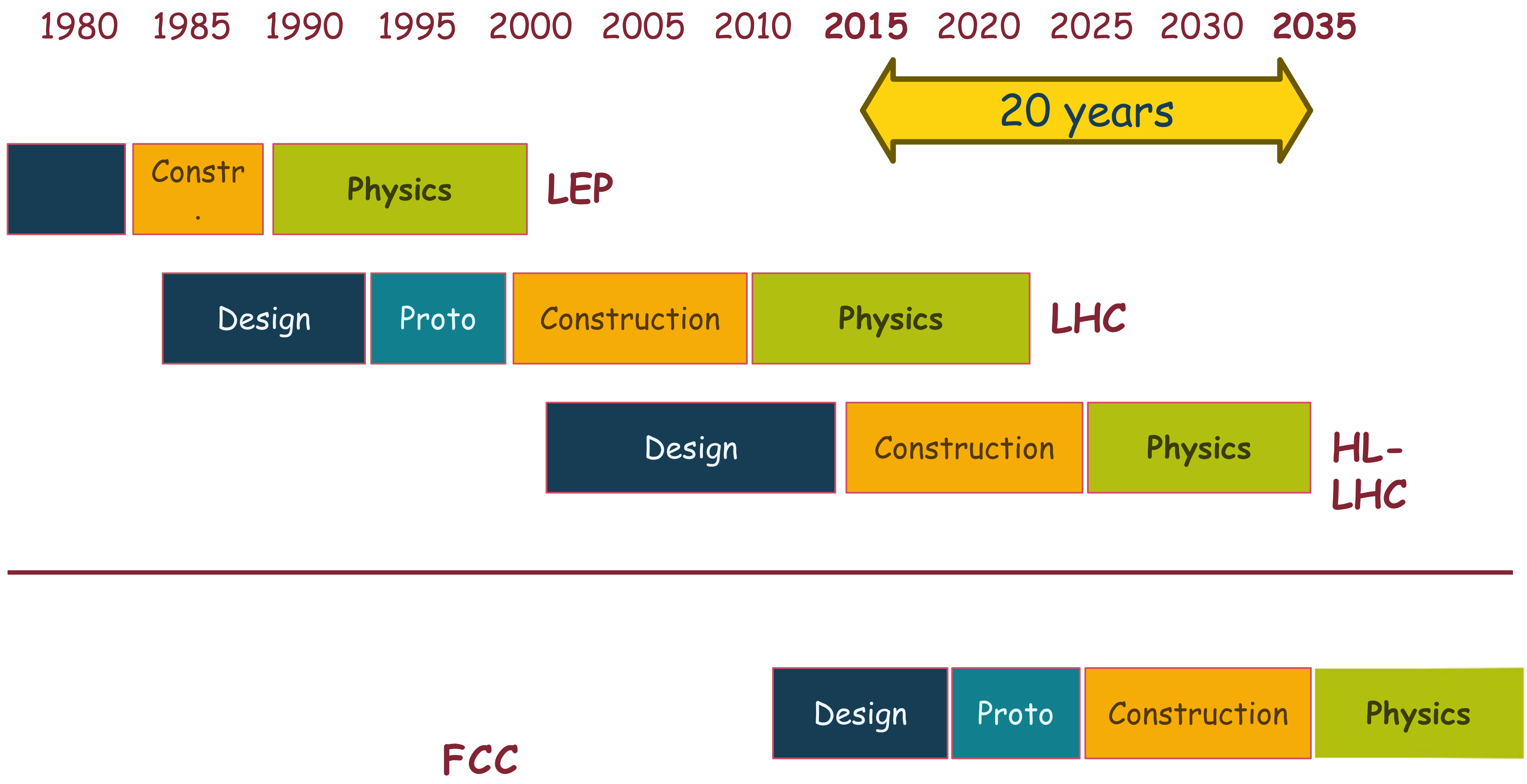




CERN Accelerators Complex



The Future Circular Collider project (FCC)



The Future Circular Collider project (FCC)

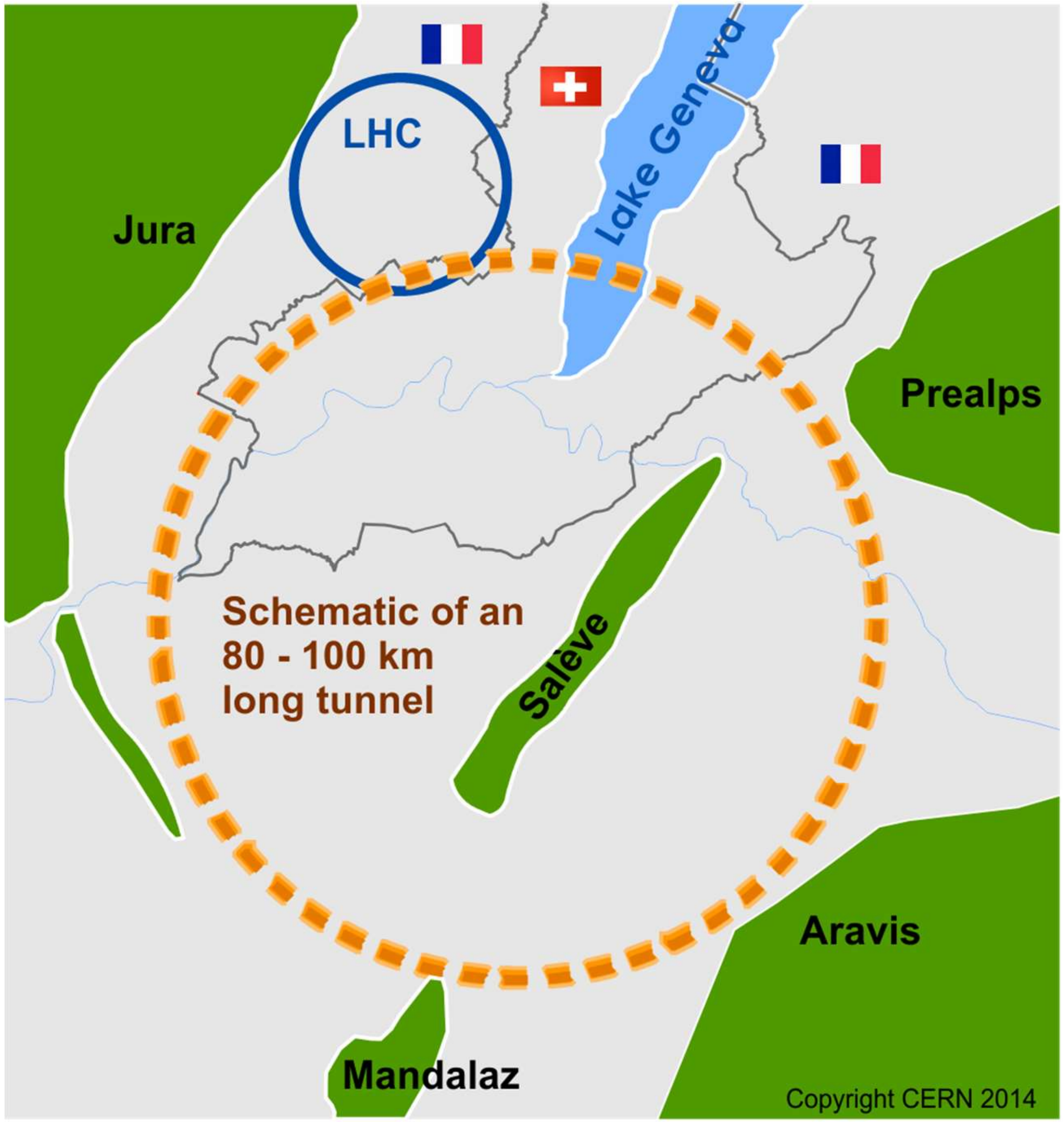
international FCC collaboration to study:

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

- **80-100 km infrastructure** in

~16 T ⇒ 100 TeV *pp* in 100 km

- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**

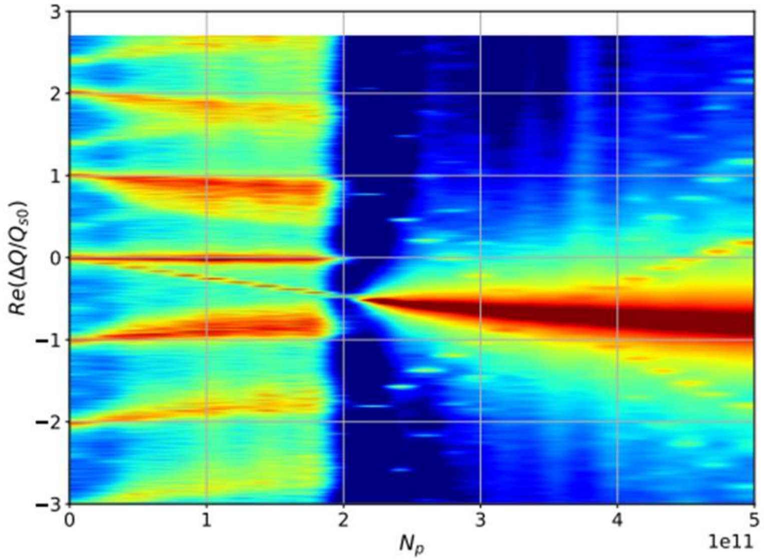


Activity: collaborations with CERN on collective effects and machine impedance model for FCC-ee

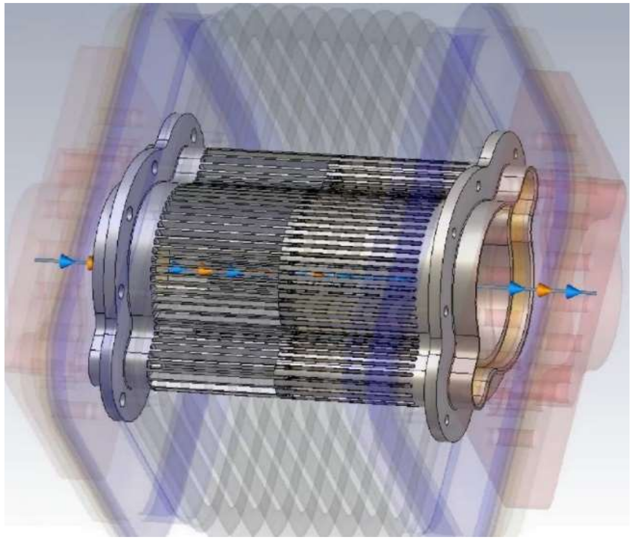
impedance budget

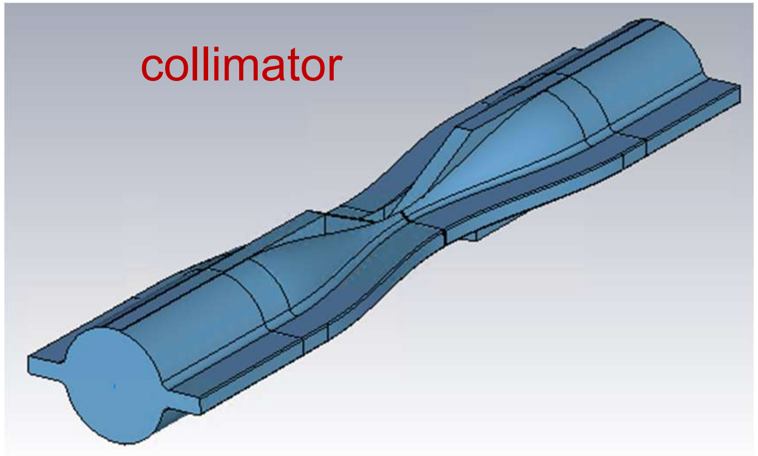
Component	Number	k_{loss} 3.5 mm (V/pC)	k_{loss} 12.1 mm (V/pC)
Resistive wall	97.75 km	214.9	33.1
Bellows	20000	129.3	0.94
BPMs	4000	40.1	4.81
RF cavities	52	17.0	8.76
RF double tapers	13	25.4	2.33
total		426.7	49.94

Beam dynamics and collective effects



bellow





Background Processes Affecting the Machine-Detector Interface at FCC-ee

The proposed activity for this PhD thesis is to study the FCC-ee machine backgrounds processes, their impact on the luminosity and the solutions to control and minimize this effect on detectors.

Simulation studies for the e+e- circular collider FCC-ee will be performed together with complementary studies on SuperKEKB, the e+e- collider in Japan. Experimental data could be used as benchmark for the simulation tools.

Goals of the research program include:
study and optimization of the FCC-ee interaction region including basic constraints from the detector
study of the shiedings and absorbers for the experimental environment
Simulations to assess detector backgrounds levels and tolerability, e.g. GEANT4
Particle tracking and beam optic simulation tools (e.g. MAD-X, X-suite), and simulation of background generation processes
benchmark with existing machines like SuperKEKB

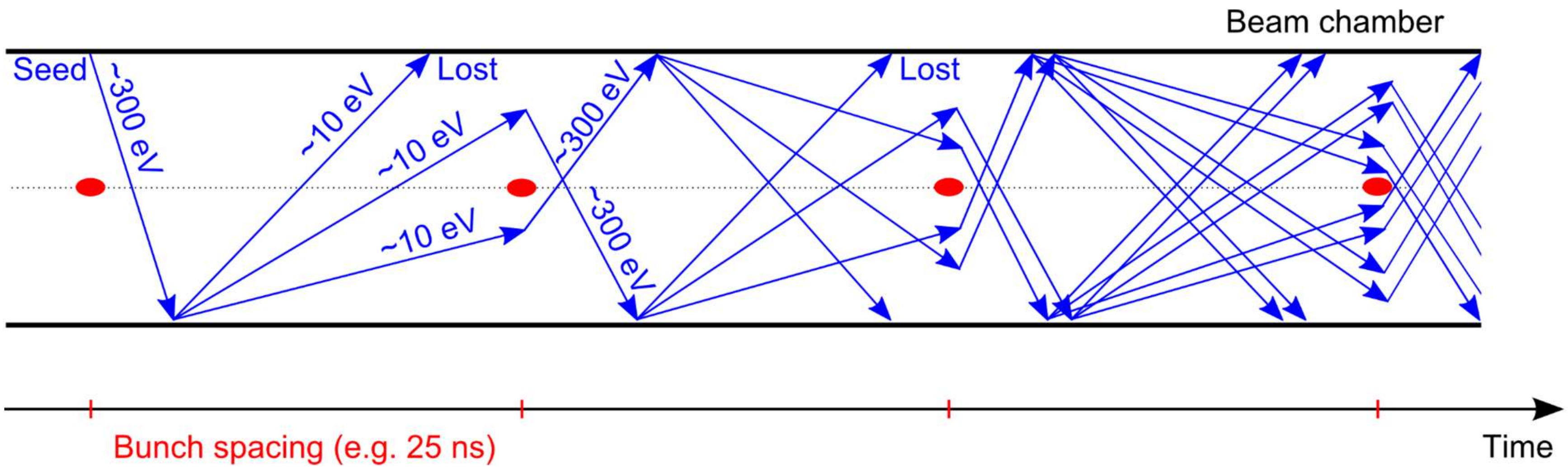
Activity based at the INFN Frascati National Laboratories in collaboration with CERN

Contact: Manuela Boscolo
Manuela.boscolo@lnf.infn.it

Electron cloud formation in a vacuum pipe

Generation of electrons inside the vacuum chamber
(primary, or seed, electrons)

- Acceleration of primary electrons in the beam field
- Secondary electron production when hitting the wall
- Avalanche electron multiplication



Effects of the electron cloud

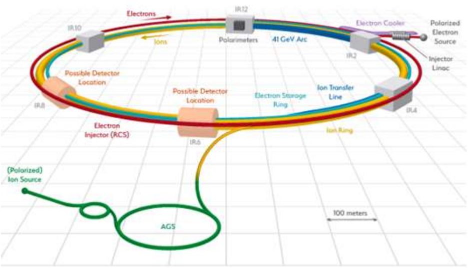
The presence of an e-cloud inside an accelerator ring is revealed by several **typical signatures**

- ✓ Fast pressure rise, outgassing
- ✓ Additional heat load (LHC has cold Dipoles)
- ✓ Baseline shift of the pick-up electrode signal
- ✓ Tune shift along the bunch train
- ✓ Coherent instability
  - Single bunch effect affecting the last bunches of a train
  - Coupled bunch effect
- ✓ Beam size blow-up and emittance growth
- ✓ Luminosity loss in colliders
- ✓ Energy loss measured through the synchronous phase shift
- ✓ Active monitoring: signal on dedicated electron detectors (e.g. strip monitors) and retarding field analysers

} Machine observables (first three items)

} Beam observables (remaining items)

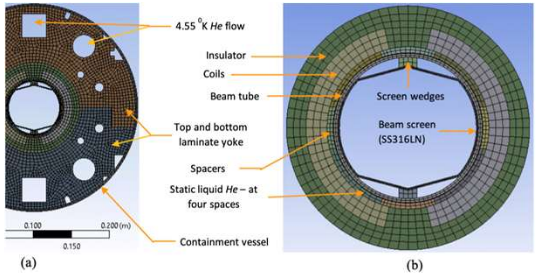
PhD thesis in collaboration with CERN and EIC on the study of coatings for electron cloud mitigation



Surface studies for the EIC hadron ring vacuum chamber

Focus

Definition of the surface properties of the hadron ring vacuum chamber for the future Electron Ion Collider (EIC)



Motivations

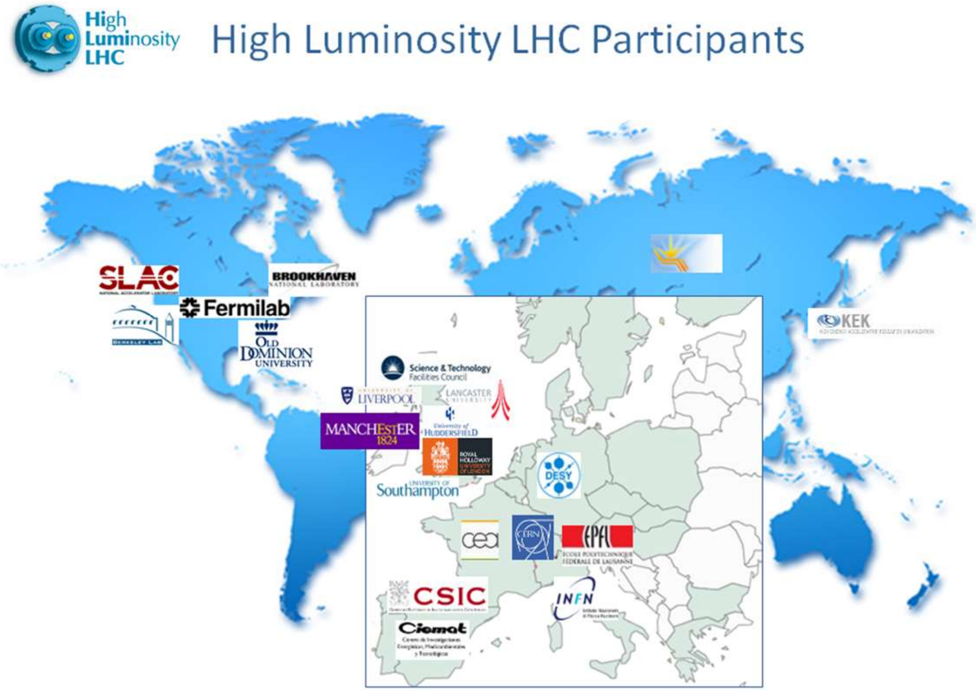
Detrimental collective effects in accelerators (like electron cloud, impedance and dynamic vacuum instabilities) are all driven by the surface properties of the vacuum system, also at cryogenic temperature and under electron, and ion bombardment. All these aspects must to be tackled and solved simultaneously in order to qualify the EIC hadron ring vacuum chamber and grant a fully operational accelerator.

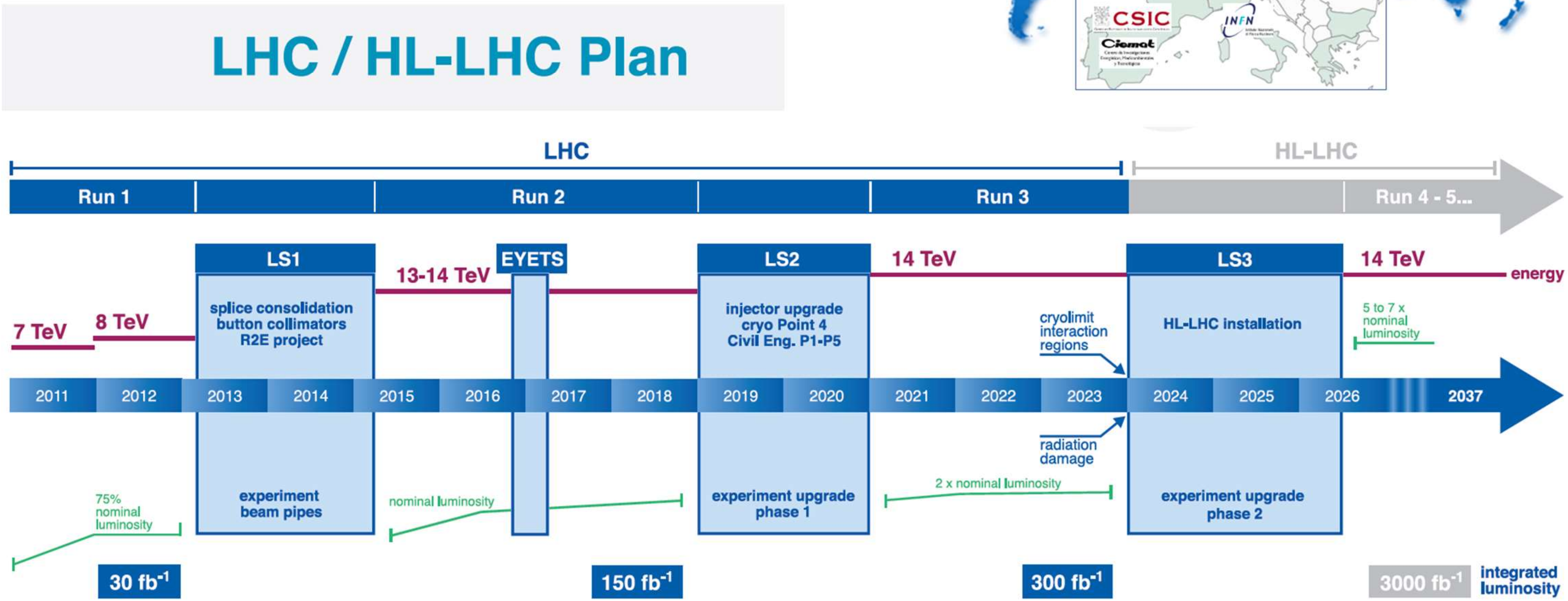
Activity

The experimental activity will consist in testing and validating various material surfaces proposed to be used in the EIC hadron ring vacuum chamber. The work will be done in close collaboration with Brookhaven National Laboratory (BNL). The candidate will access the Material Surface Science Laboratory at LNF-INFN, equipped with all the technology and instrumentation to carry out the proposed research topic.

Contact persons:
Roberto Cimino (roberto.cimino@lnf.infn.it); Marco Angelucci (marco.angelucci@lnf.infn.it); Luisa Spallino (luisa.spallino@lnf.infn.it)

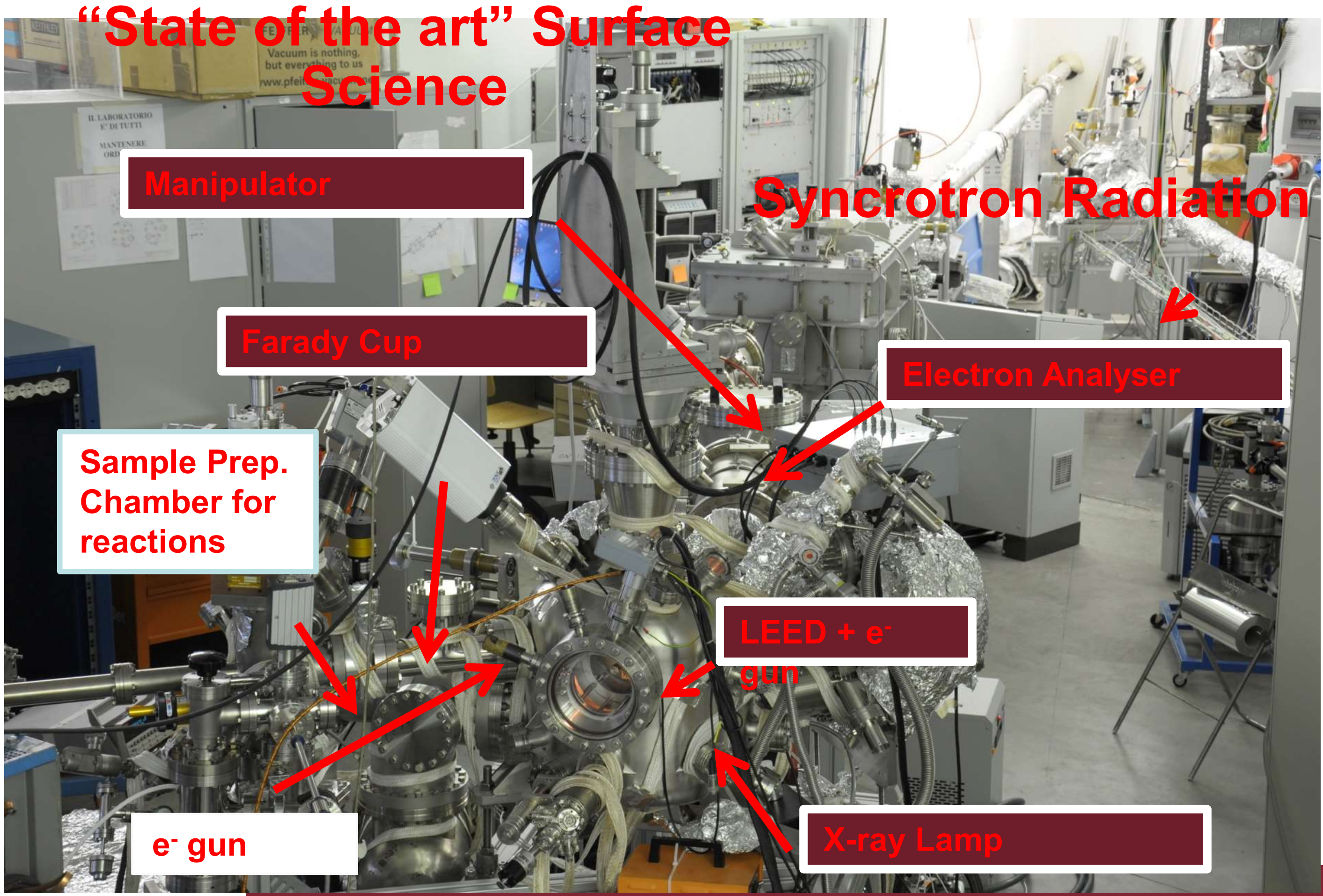
Upgrade of LHC (HL-LHC or Hi Lumi LHC)





Experimental investigation on relevant material properties for FCC & Hi Lumi LHC

- **Surface properties of Carbon and Cu Surfaces for HL-LHC (INFN project)**
- **electron induced Desorption (possibly an EU / INFN Project)**
- **photo desorption: Synchrotron radiation studies (MoU with CERN/ INFN)**



These PhD thesis foreseen experimental studies (with SR and Surface Science techniques) on material properties of interest to the accelerator community.

The interested candidate will work in an international contest, within various international collaborations and will be mainly performing experiments in Frascati National Lab but also in various Facilities around Europe.

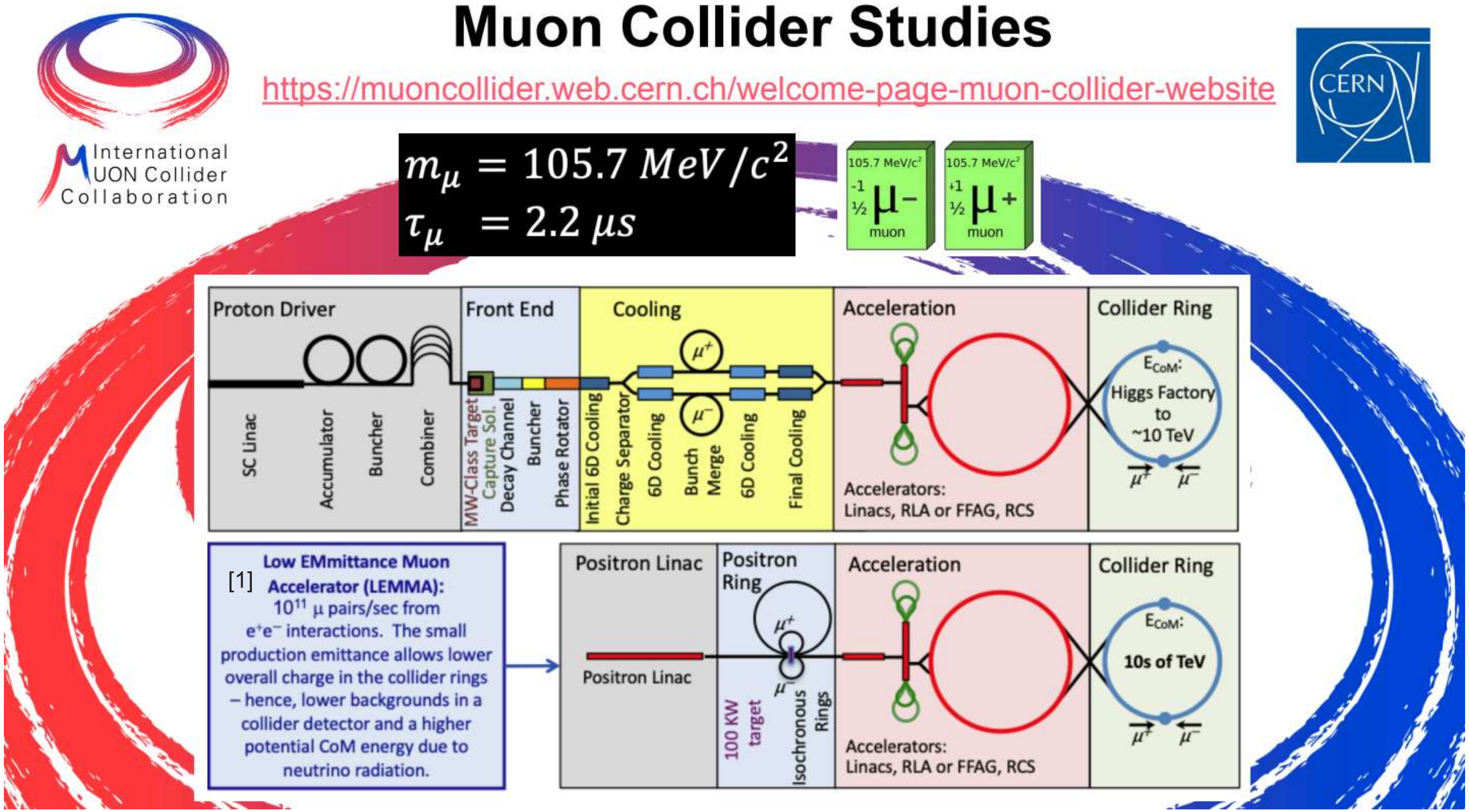
Activity based at Laboratori Nazionali di Frascati dell'INFN
Contact person: R. Cimino (roberto.cimino@lnf.infn.it)

Search of passivating coatings for ultimate performances Vacuum chambers

This thesis work will use the laboratory facilities to study surface preparation/modification apt to produce a vacuum chamber with minimal desorption properties, especially during photon or electron irradiation. The laboratory is equipped with all the technologies and instruments to study thermal, electron and photon stimulated desorption, and some facilities to produce specially designed surfaces and coatings.
Surface morphology modifications, thin film Carbon films, up to Graphene-like coatings, and NEG coatings will be studied to define, at least in principle the way to produce as inert as possible surfaces for Ultra high vacuum applications.

Activity based at Laboratori Nazionali di Frascati dell'INFN
Contact person: R. Cimino (roberto.cimino@lnf.infn.it)

Collaborations with CERN on beam dynamics and collective effects



[1] M. Boscolo, J. P. Delahaye, and M. Palmer, The future prospects of muon colliders and neutrino factories, Rev. Accel. Sci. Techol. 10, 189 (2019).

Collaborations with CERN on beam dynamics and collective effects

International MUON Collider Collaboration

Muon colliders have a great potential for high-energy physics. They can offer **collisions of point-like particles** at very high energies, since muons can be accelerated in a ring **without limitation from synchrotron radiation**

Video on the CERN YouTube on muon collider:
https://www.youtube.com/watch?v=s_px84ukX9Q

Idea

Protons → target

→ pions

→ muons

→ μ- μ+ collider

Challenges (of decaying particles)

– Muon production
– Fast muon cooling
– Fast acceleration
– Neutrino radiation

Activities on laser-interaction with matter
Collaboration with ENEA - Frascati

•Interaction of high intensity laser with targets is a powerful and effective methods to accelerate electrons and ions and important technique for inertial confinement fusion.

•Potential applications are: medicine, material science studies, inertial confinement nuclear fusion, astrophysics.

•This has generated a large interest and impulse in the last years due to the increasing laser performances, promising large particle fluxes and energies. Structures such as **ELI L4** (1 kJ laser pulses, ~100 fs pulse duration and 10 PW power) and **Apollon** (75 laser pulses, ~15 fs pulse duration and 5 PW power) are the most advanced laser facilities, that will reach full performances very soon.

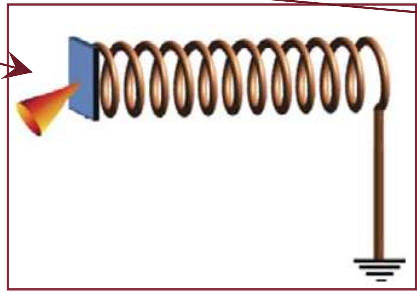
•Laser-matter interaction produces also electromagnetic radiation from radiofrequencies-microwaves to gammas.

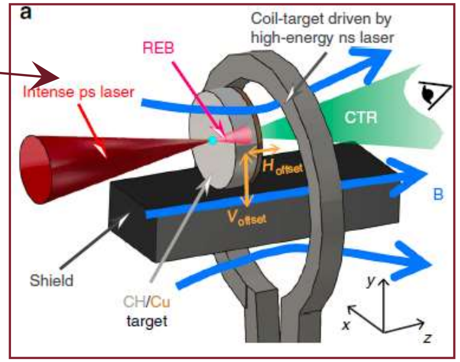
•Fields of research at ENEA-Centro Ricerche Frascati:

- **Electromagnetic pulses**
- **Diagnostics for accelerated particles**
- **Micro and nano materials for targets in laser experiments.**

Electromagnetic Pulses

- Electromagnetic fields up to MV/m order have been observed in intense laser-matter experiments. They are of primary importance for both laser-plasma particle accelerators and inertial confinement fusion [1]
- Their intensity can be a problem for electronics but also used for a lot of significant applications.
  - Transient magnetic fields of the kilo Tesla order [2],
  - Traveling wave electromagnetic fields [3].

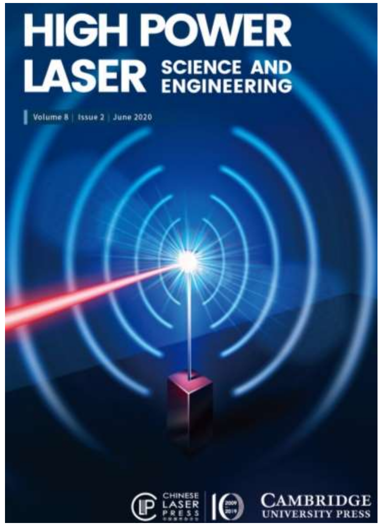




- It is of primary importance to describe the source mechanisms of these fields, improve their diagnostics, the techniques for minimizing them and for use them for applications

- Applications of these fields: acceleration and conditioning (bunching, chopping, focusing) [1-3].

[1] F. Consoli, et al, High Power Laser Science and Engineering Vol. 8, e22, (2020). [2] M. Bailly-Grandvaux et al, Nature Communications (2018) 9, 102; [3] S. Kar, et al, Nature Communications (2018) 7, 10792



- Research fields:
  - source mechanisms of these Electromagnetic Pulses (EMPs)
  - Diagnostic methodologies
  - Methods for tuning them
  - Advanced schemes of application, with particular emphasis to beam dynamics management.

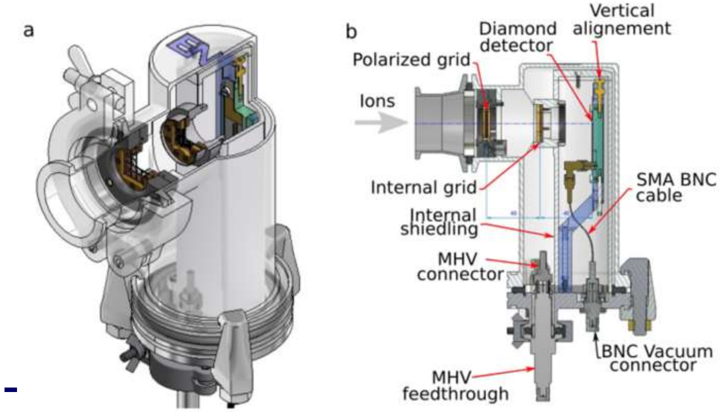
- ENEA-Centro Ricerche Frascati has a recognized world leadership on this activities, coordinating also the Laserlab-Europe AISBL group on laser generated electromagnetic pulses

Diagnostics for accelerated particles

- Typically, two types of diagnostics for laser accelerate particles are used
    - Time-of-flight methodologies
    - Electrostatic-magnetostatic spectrometers.
- ENEA-Centro Ricerche Frascati has recognized experience on both the two approaches, and produced several advanced detectors of this type.

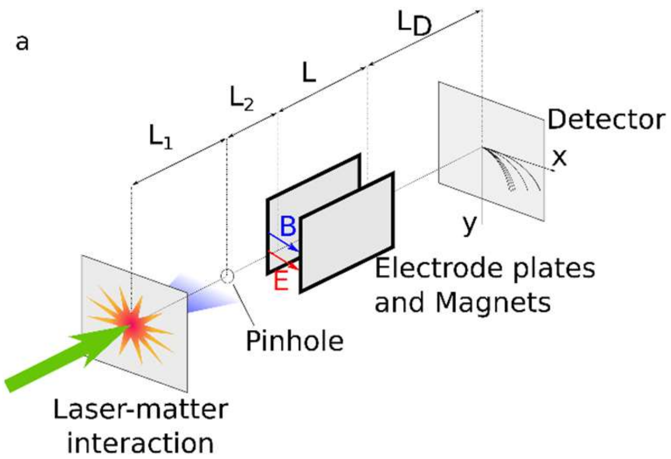
- Several prototypes are under study. In particular
    - Magnetostatic electron spectrometers
    - Calibrated diamond time-of flight ion diagnostics for real-time features
    - Ion Thomson spectrometers of high sensitivity, with high radiation hardness

High sensitivity Time-of-Flight diamonds

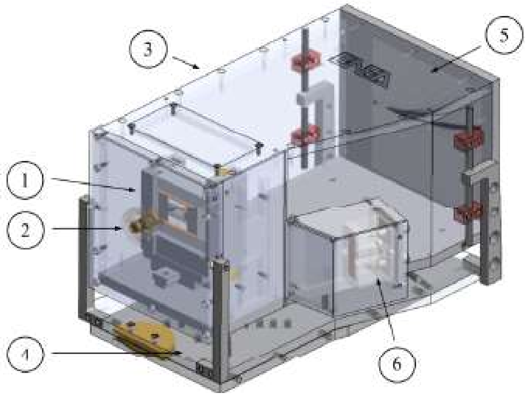


Thomson Spectrometers

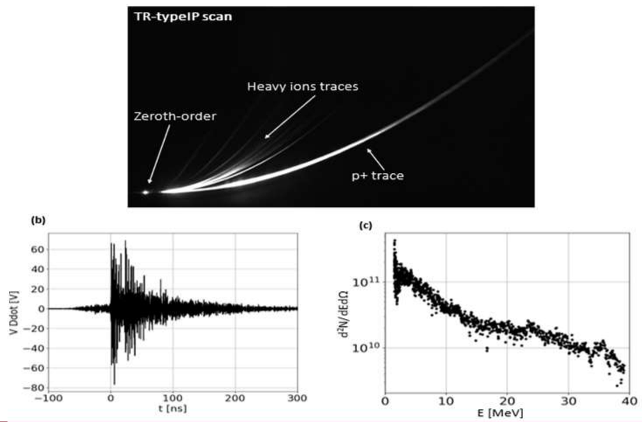
Scheme



Typical prototypes



Experimental results Phelix (GSI) - Thomson



Micro and nano materials for targets in laser experiments

- Micro- and nano-structured materials share a common feature: laser absorption is enhanced by the non-trivial internal structure.

- Nano-structured materials exhibit structures of the order of nanometers and various morphologies. They can help to enhance the efficiency of **laser-plasma acceleration** with short laser pulses, when placed in front of a solid substrate, and of **hard X-rays generation**.

- Micro-structured materials have a micrometric internal structure with solid filaments or membranes and large voids. They can be employed for enhancing **electron acceleration** and **gamma-rays production**, for increasing the **conversion** efficiency **of the laser energy into X-rays** and for optimizing the compression efficiency and irradiation homogeneity for **Inertial Confinement Fusion applications**.

- ENEA-Centro Ricerche Frascati leads the European Expert groups on micro and nano structured materials for laser matter interactions at Laserlab-Europe AISBL association