PhD thesis on collaborative studies between:

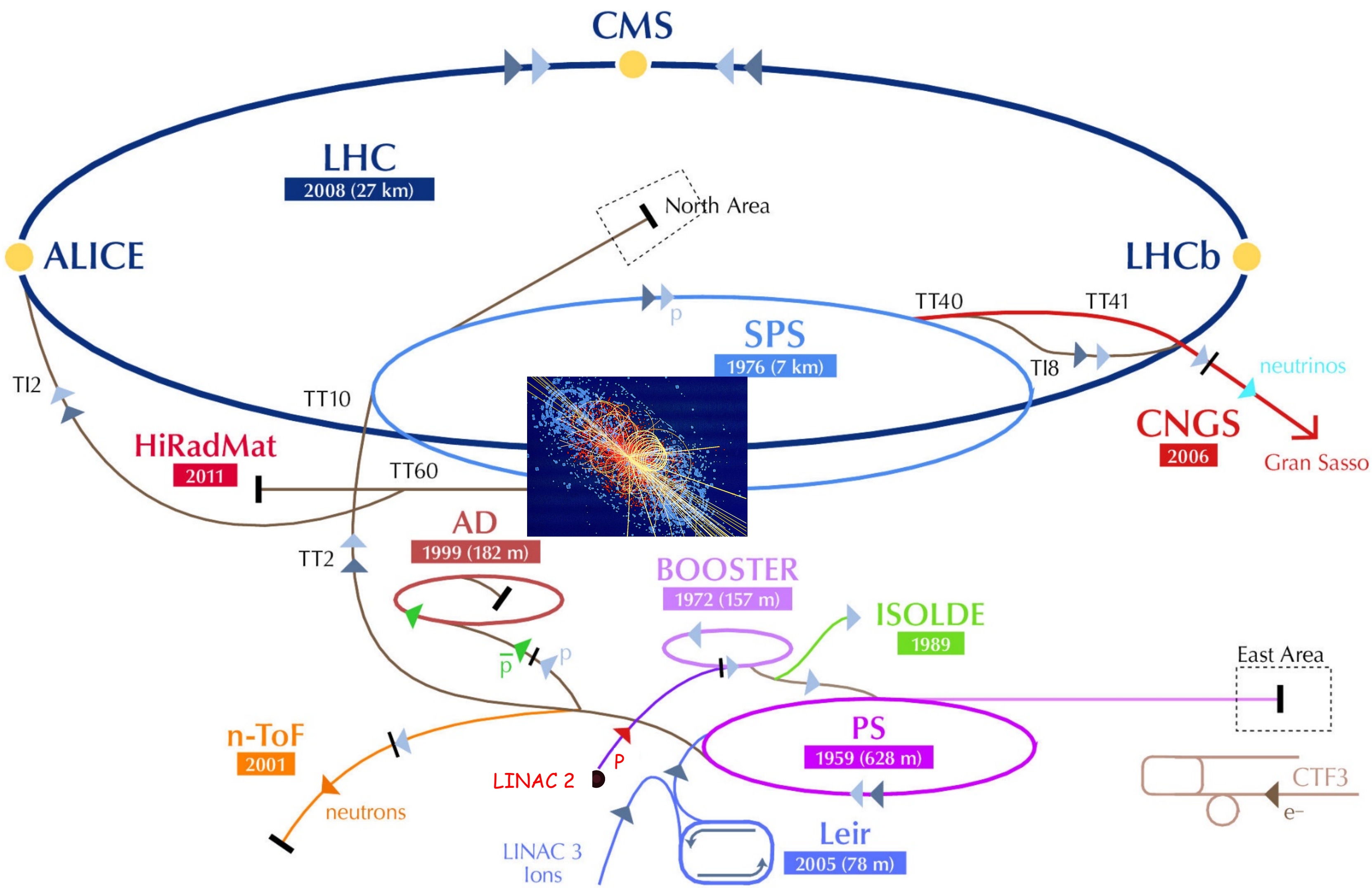
- INFN / Rm1 and CERN
- INFN / Rm1 and ELI
- INFN / Rm1 and SBAI

INFN / Rm1 and Uni Napoli

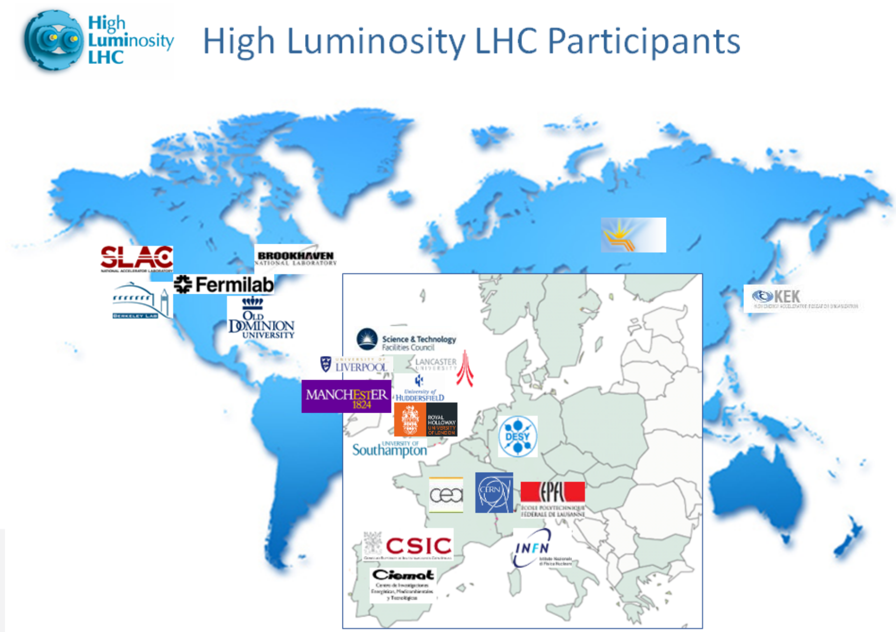
R. Cimino – LNF-INFN

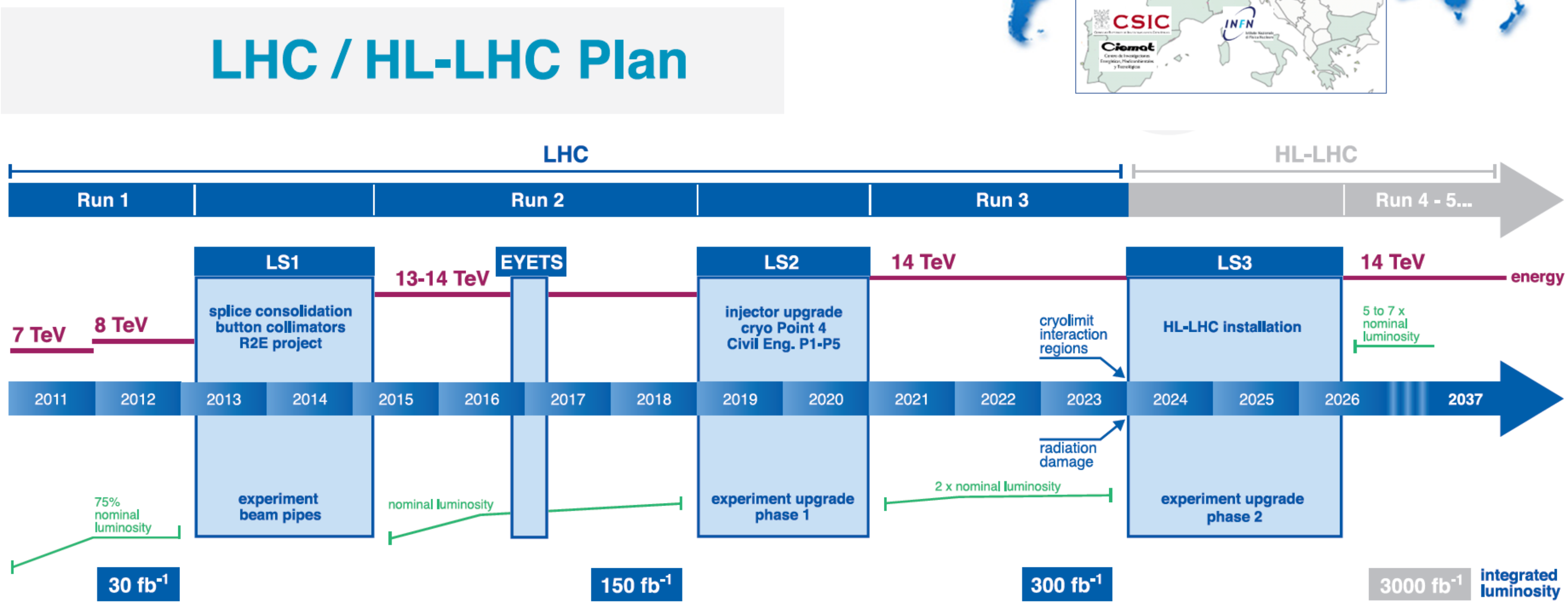
INFN LNF Istituto Nazionale di Fisica Nucleare

CERN Accelerators Complex

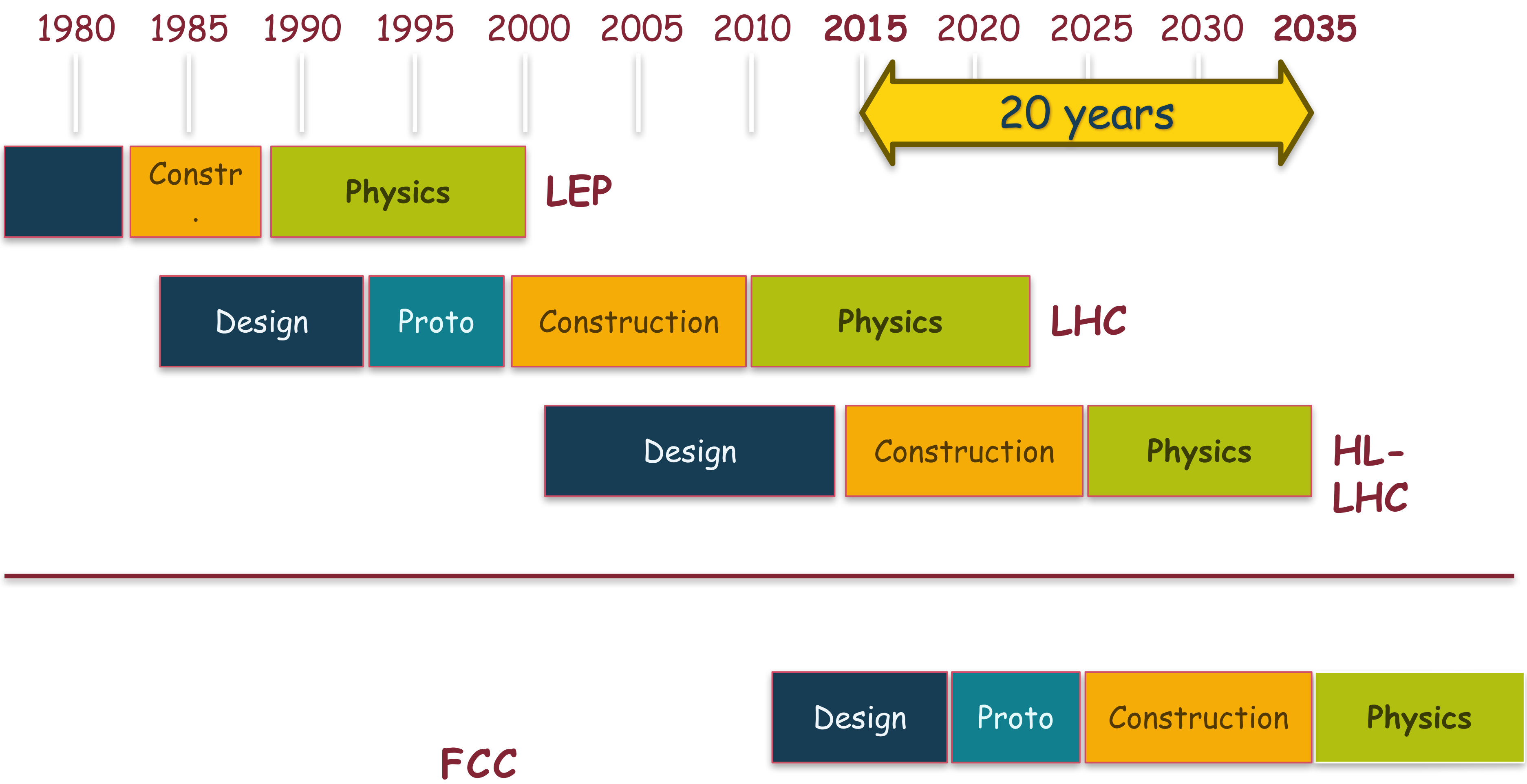


Upgrade of LHC (HL-LHC)





The Future Circular Collider project (FCC)



The Future Circular Collider project (FCC)

international FCC collaboration to study:

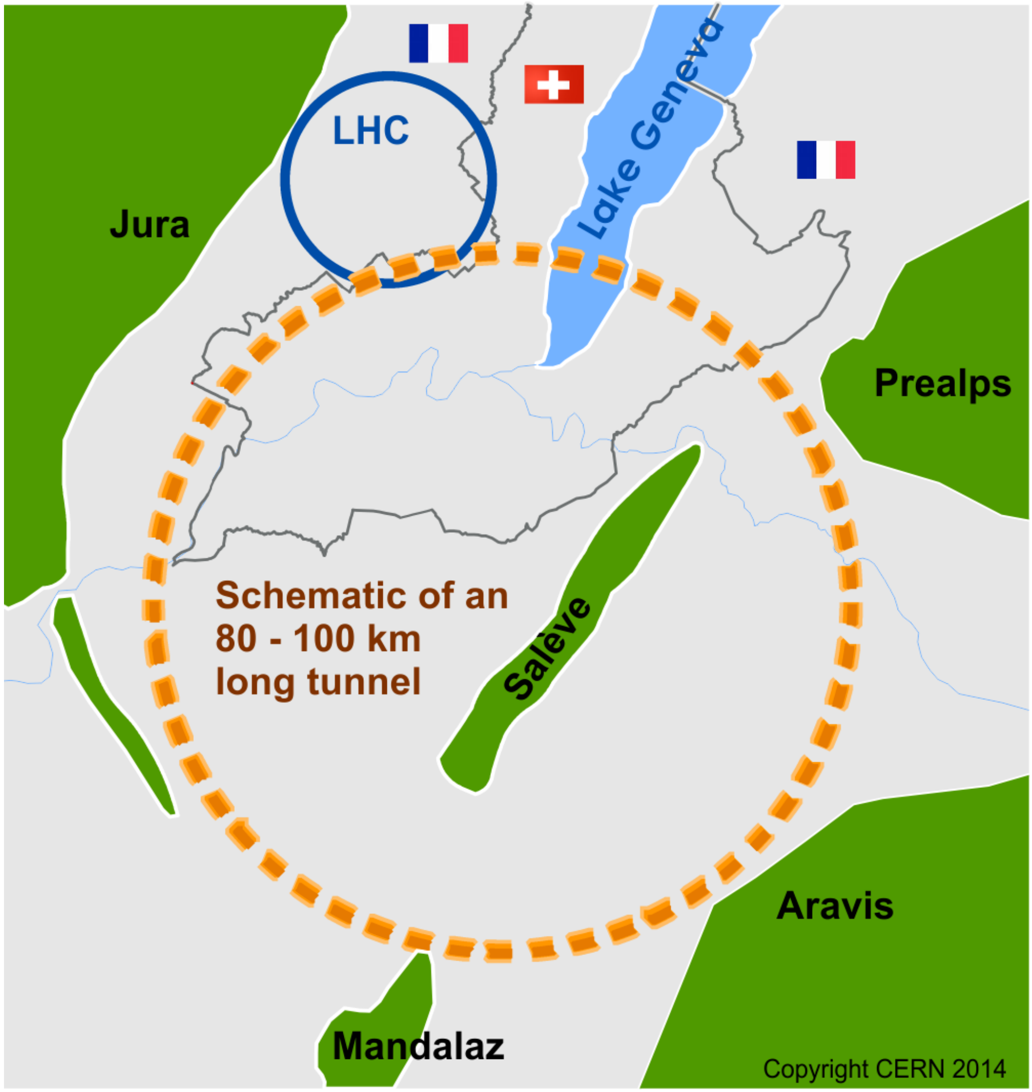
- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements

- **80-100 km infrastructure** in

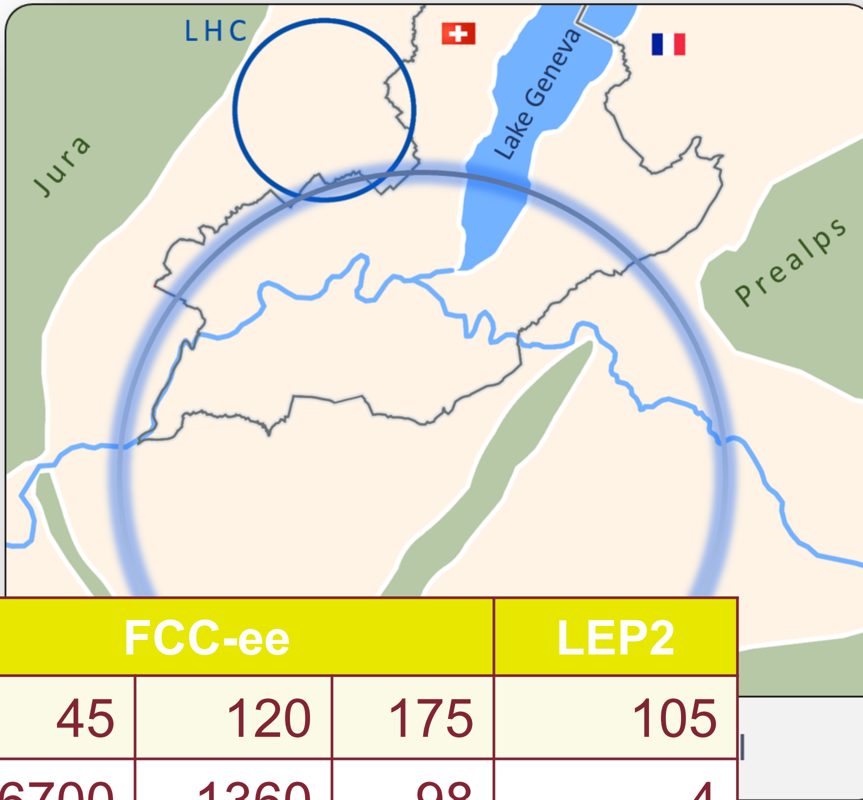
~16 T ⇒ 100 TeV *pp* in 100 km

- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step

- ***p-e* (*FCC-he*) option**

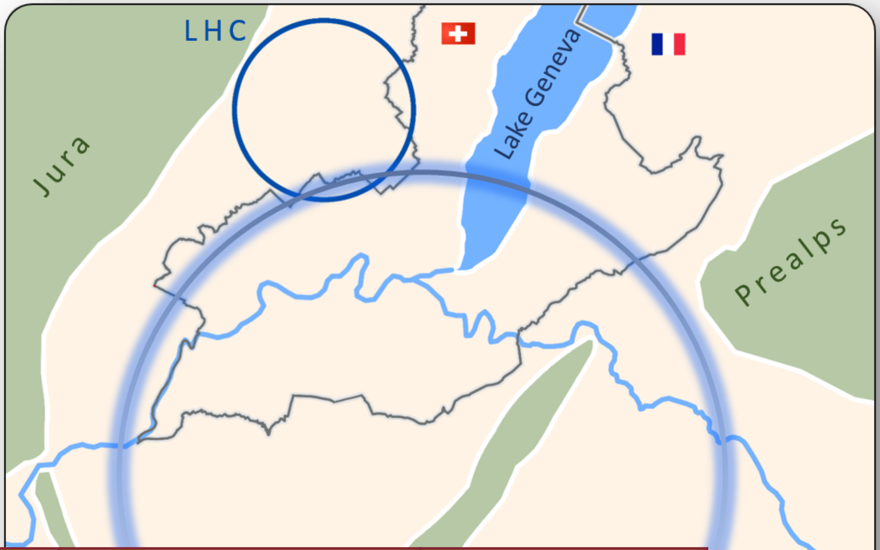


FCC-ee
Key Parameters



Parameter	FCC-ee			LEP2
Energy/beam [GeV]	45	120	175	105
Bunches/beam	16700	1360	98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	28	6	1.8	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchr. Power [MW]	100			22
RF Voltage [GV]	2.5	5.5	11	3.5

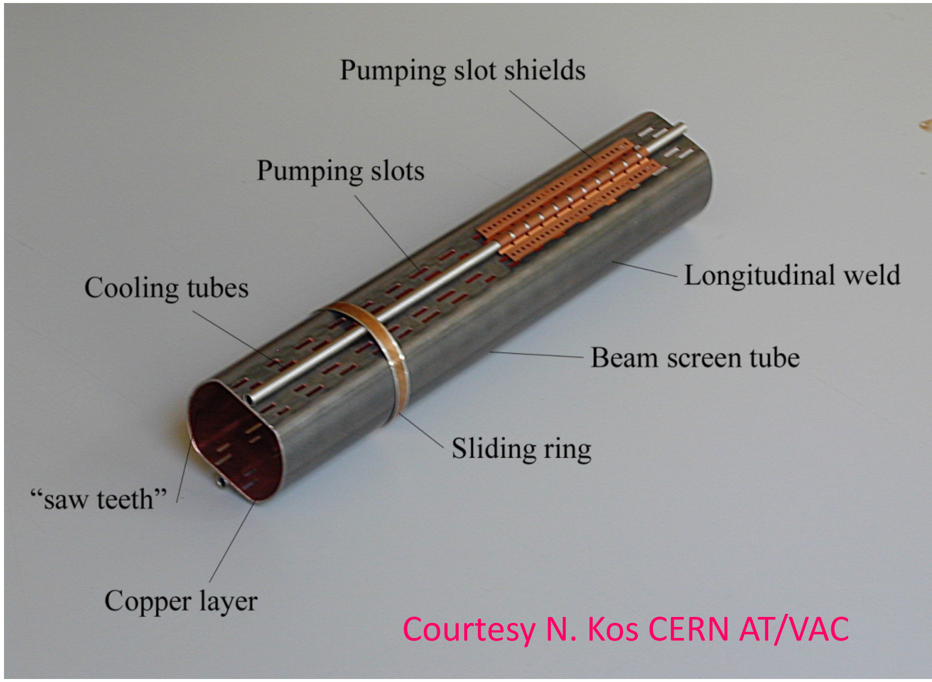
FCC-hh
Key Parameters



Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5-10 x 10^{34}	1 x 10^{34}
Energy/beam [GJ]	8.4	0.39
Synchr. rad. [W/m/apert.]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

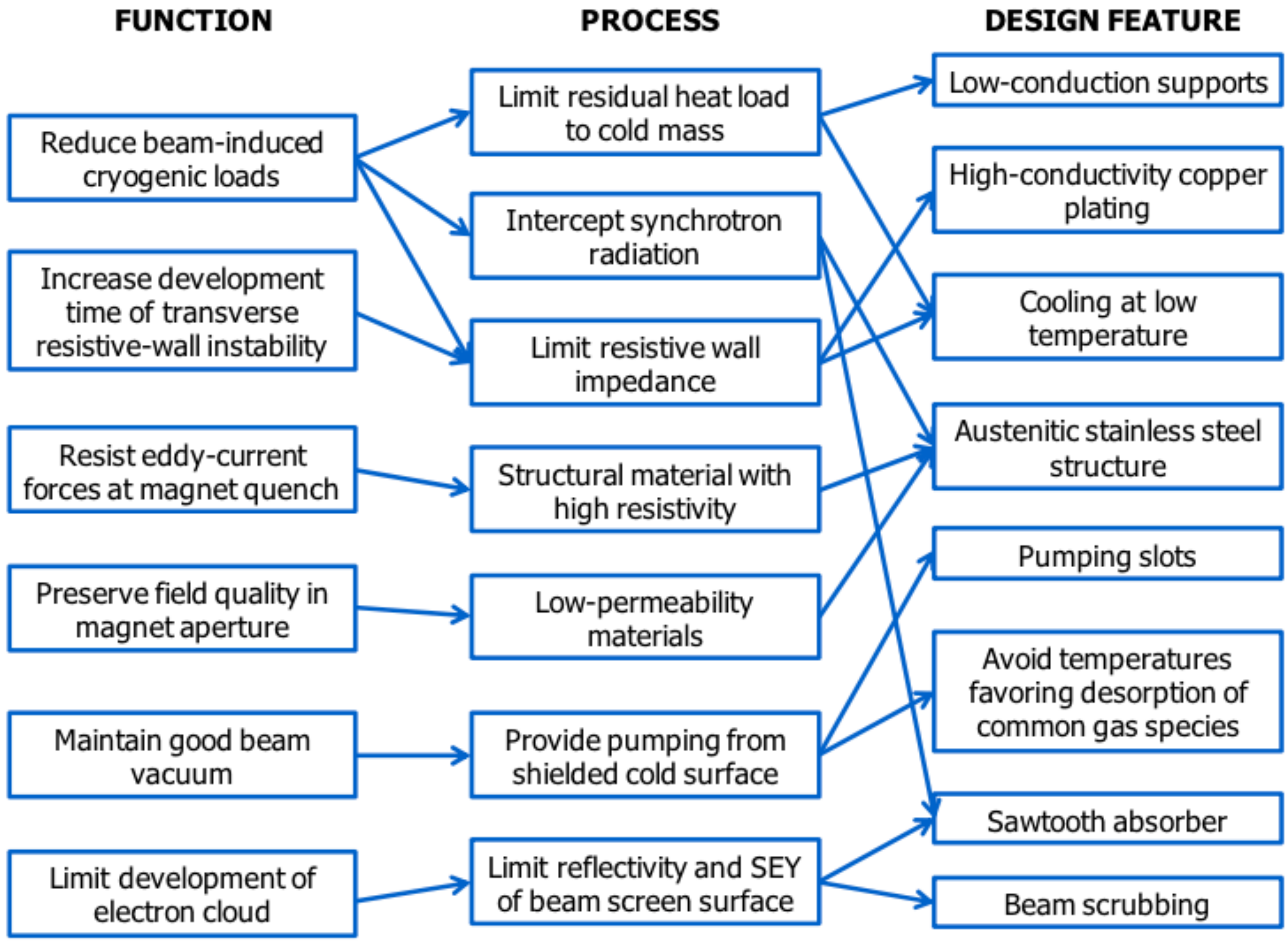
LHC Beam Screens Functionalities

- Intercept the heat load induced by the circulating beam (impedance, synchrotron radiation, electron cloud)
- Operate between 5 and 20 K
- Non-magnetic stainless steel substrate to withstand quench forces (few tons) and to ensure a good field quality
- Copper colamination onto non-magnetic stainless steel to reduce impedance



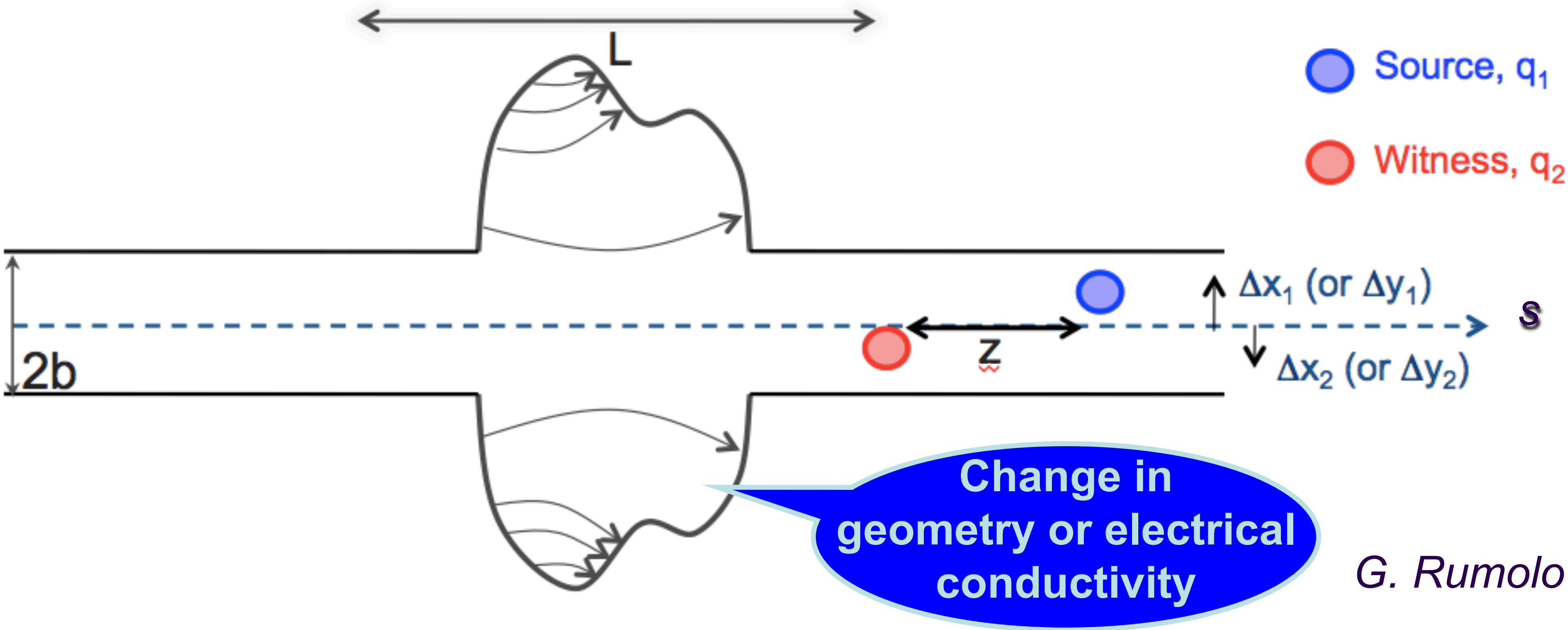
- **Pumping holes to control the gas density**
- **Rounded pumping slots to reduce electromagnetic leakage towards the cold bore held at 1.9 K or 4.5 K**
- **Electron shield to protect the cold bore from the heat loads induced by the electron cloud**
- **Saw teeth to reduce photoelectron yield and forward reflectivity of photons to decrease the seed of electrons**

Any adopted solution for the Beam screen has to compel with many other requirements and boundary conditions.



Functional design map of beam screen

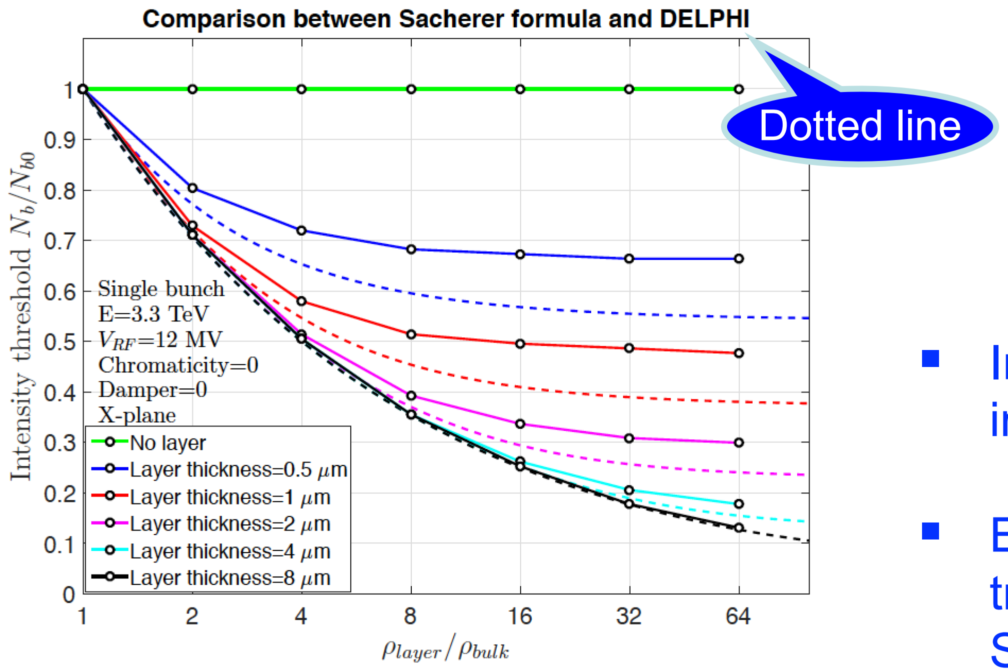
IMPEDANCE



- Wake field = Electromagnetic field generated by the beam interacting with its surroundings (vacuum pipe, etc.)
  - Power loss
  - Beam instabilities
- Impedance = Fourier transform of the wake field (wake function)

THE IMPEDANCE

- The impedance is a complex function of frequency and at least 5 contributions are needed to correctly characterized an equipment
  - Longitudinal impedance
  - Horizontal dipolar/driving impedance
  - Vertical dipolar/driving impedance
  - Horizontal quadrupolar/detuning impedance
  - Vertical quadrupolar/detuning impedance



An example:

COATING (e.g. a-C) OR SURFACE TREATMENT (e.g. LESS) TO FIGHT AGAINST E-CLOUD

- Increase of imaginary part of transverse impedance at high frequency
- Example case of FCC-hh, where laser treatment was proposed as baseline for SEY reduction

Electron cloud formation in a vacuum pipe

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

- **Residual gas ionization**
- **Photoelectrons from synchrotron radiation**
- **Desorption from the losses on the wall**

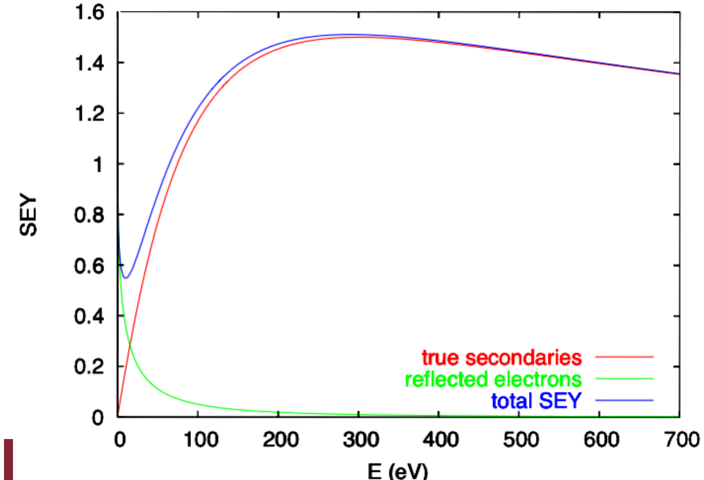
An accelerator Vacuum pipe contains low energy electrons that can induce Electron cloud effects

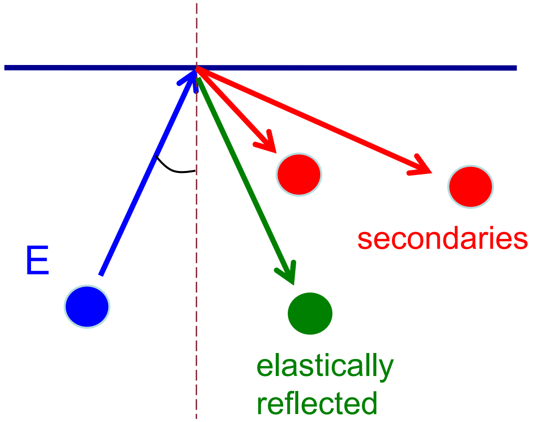
Thanks to G. Rumolo: workshop "Beam Dynamics meets Vacuum, Collimations, and Surfaces" 8-10 March 2017 Karlsruhe.

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**

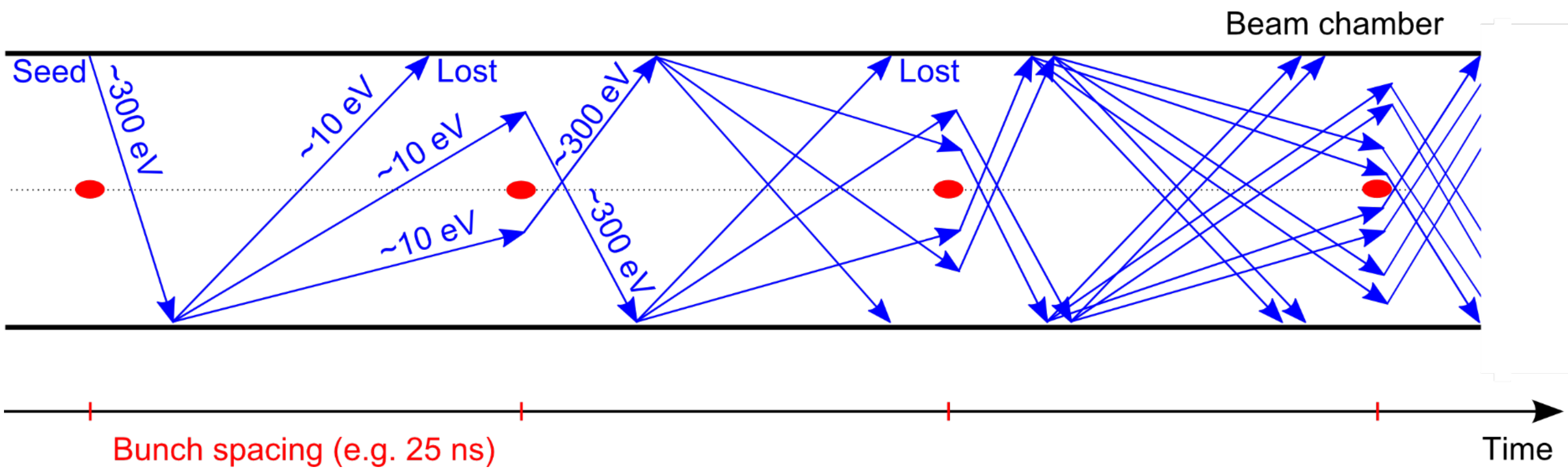




Electron cloud formation in a vacuum pipe

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**



Electron cloud formation in a vacuum pipe

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

↓

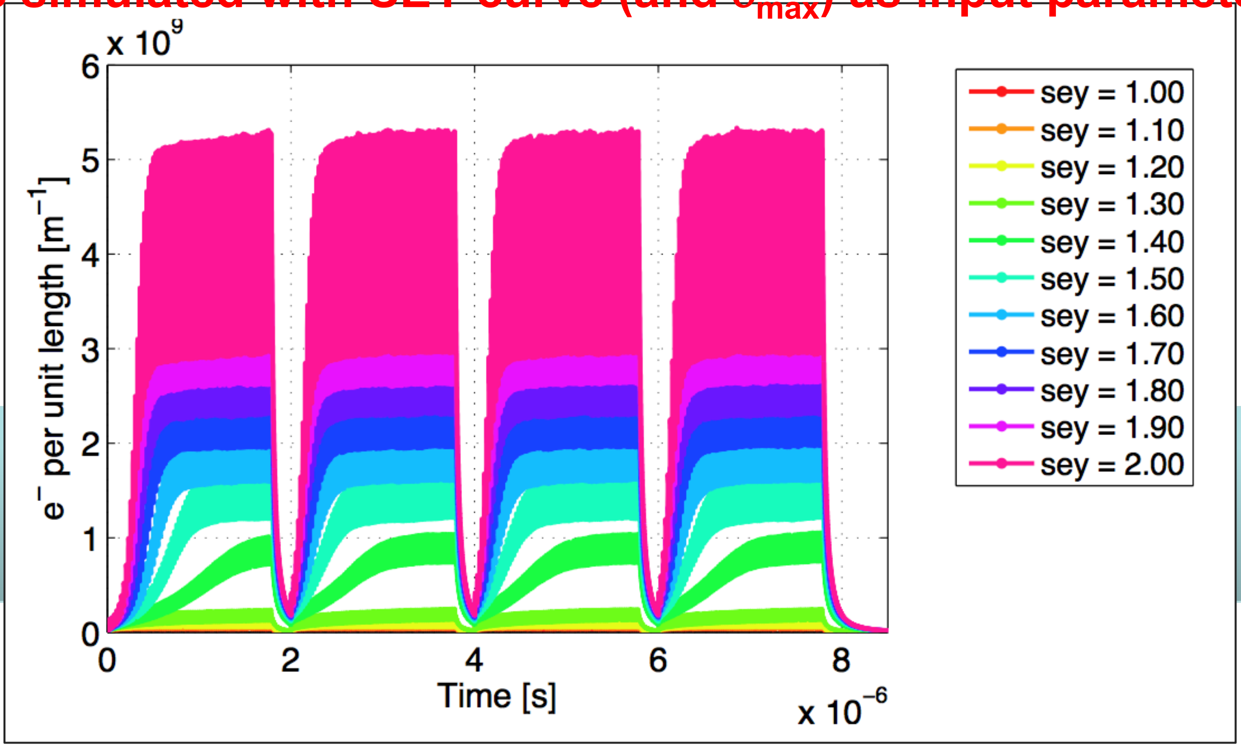
- Acceleration of primary electrons in the beam field
- Secondary electron production when hitting the wall
- Avalanche electron multiplication

↓

After the passage of several bunches, the electron distribution inside the chamber reaches a stationary state
(electron cloud)

Electron cloud formation in a vacuum pipe

Could be simulated with SEY curve (and δ_{max}) as input parameter



After the passage of several bunches, the electron distribution inside the chamber reaches a stationary state (electron cloud)
→ Several effects associated

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 :

Beam dynamics and collective effects for the upgrade program of LHC and FCCee
(contact: mauro.migliorati@uniroma1.it)

- **HiLumi LHC**, is the major funded upgrade to increase LHC luminosity by a factor of 10 beyond its design value. The project is co-funded by the EU and implies significant upgrades not only for LHC but for all the machines in the injection chain (LIU project).

- **FCC (Future Circular Collider)**: is a global effort (lead by CERN) to study a post-LHC particle accelerator in a worldwide context. The project is co-funded by the EU and it is exploring the potential of hadron and lepton circular colliders, considering the technology R&D programs that would be required to build them.

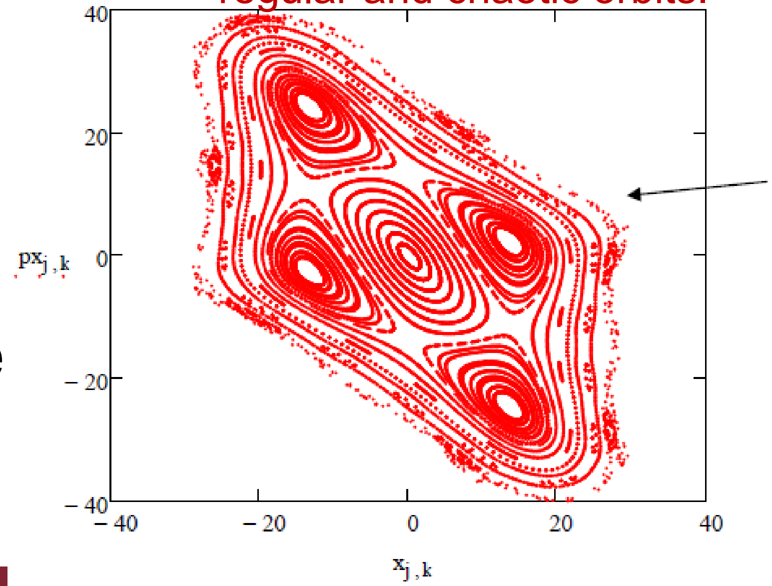
The goal of the PhD work is to predict the behaviour of these future accelerators in terms of beam stability due to the increase of beam intensity that could lead to undesirable collective effects, triggered by self-induced em fields, which may play an important role in the machine performance.

The thesis activity is based at the Department of Basic and Applied Science for Engineering of La Sapienza, but some periods at CERN for beam based measurements during some Machine Development sessions and for discussions are foreseen.

Use of non-linear beam dynamics for beam extraction at CERN PS

- Why non-linear dynamics should be useful?
  - Richer dynamical behaviour, e.g., existence of stable islands (see later).
  - The non-linear motion introduces a dependence of the particle frequency in phase space on amplitude. The frequency spread cures collective instabilities (Landau damping).
  - A non-linear system might be more robust than a linear one (stable under perturbation).
- Integrability of the motion is an added value as it ensures stable motion

Typical non-linear motion with regular and chaotic orbits.



Novel multi-turn extraction with fourth-order resonance

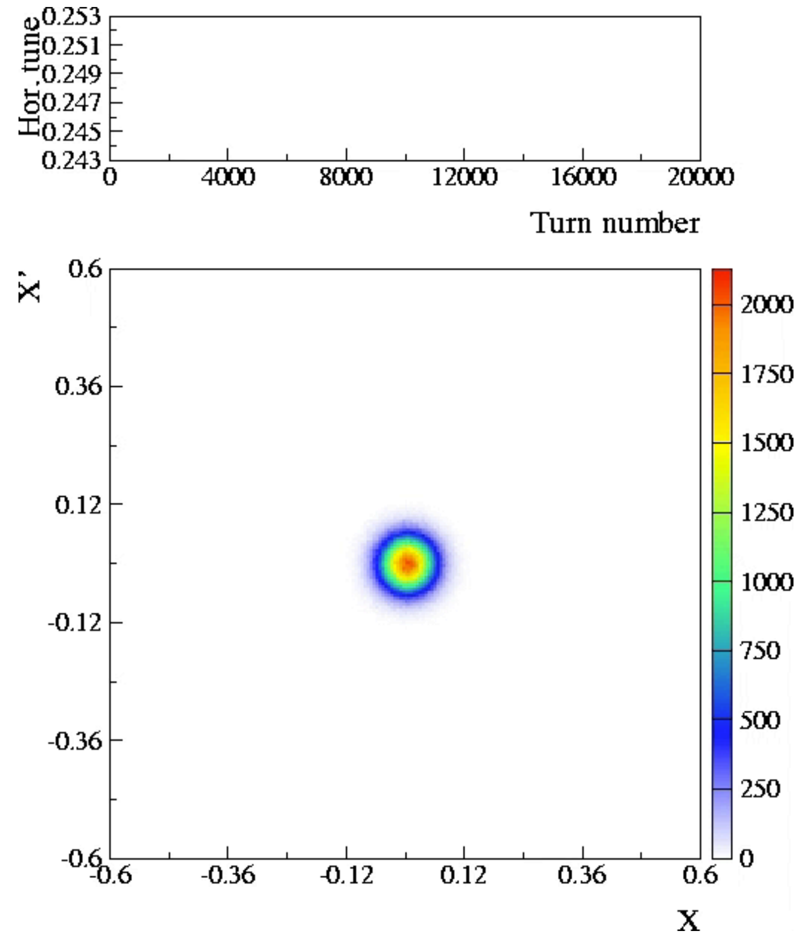
CERN PS Multi Turn Extraction

- Standard approach: nonlinear elements represented as a single kick at the same location in the ring (Hénon-like polynomial maps).
- Vertical motion neglected.
- Normalised (adimensional co-ordinates).

The linear tune is time-dependent

$$\begin{pmatrix}\hat{X}\\ \hat{X}'\end{pmatrix}_{n+1} = \mathbf{R}(\omega)\begin{pmatrix}\hat{X}\\ \hat{X}'+\hat{X}^2+\kappa\hat{X}^3\end{pmatrix}_n \qquad \kappa = \frac{2}{3}\frac{K_3}{K_2^2\beta_x}$$

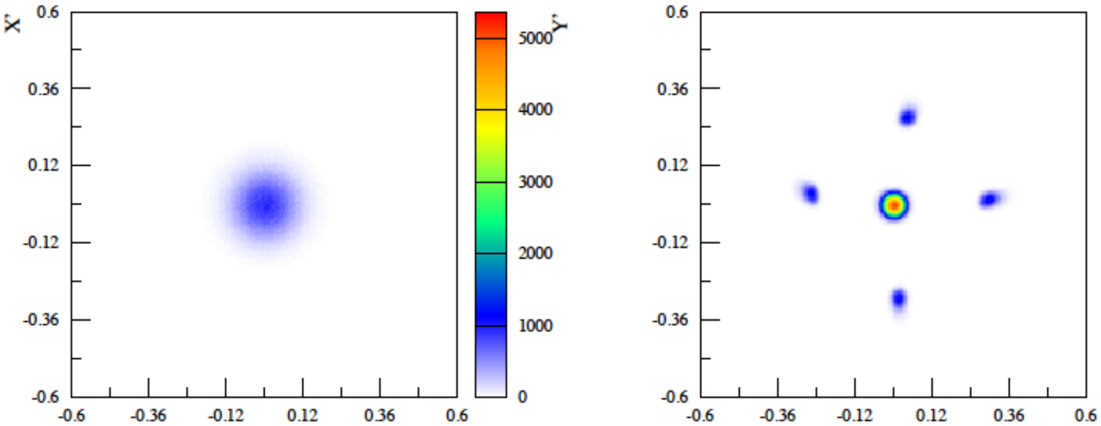
Quadrupoles Sextupole Octupole



Novel applications (for this project)

(contact: mauro.migliorati@uniroma1.it)

- By using skew sextupoles and normal octupoles it is possible to split the beam in the vertical phase space by crossing a vertical resonance.

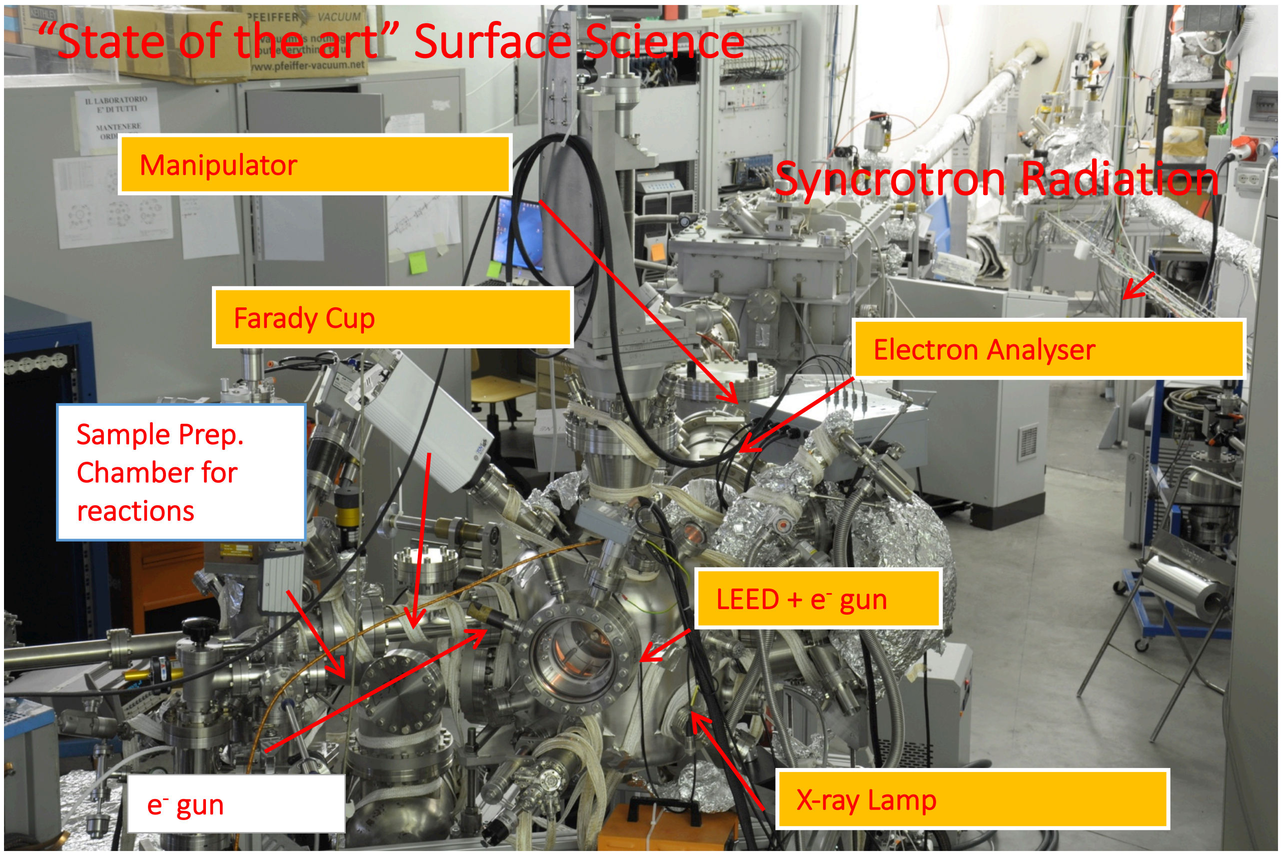


- Pursue the study of beam splitting in the vertical plane
- Study the possibility of optimising the slow extraction using stable islands (essential for high-intensity beams)
- Possibly study stable islands for lepton rings

This PhD activity is based at CERN

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

- Surface properties of Carbon and Cu Surfaces for HL-LHC (INFN project)
- Vacuum stability at FCC-hh (EU / INFN Project)
- Synchrotron radiation material 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.

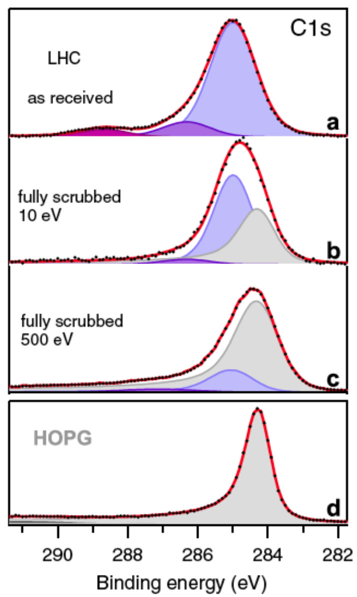
Tesi da svolgere presso il Laboratori Nazionali di Frascati dell’INFN
Contact person: R. Cimino (roberto.cimino@lnf.infn.it)

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

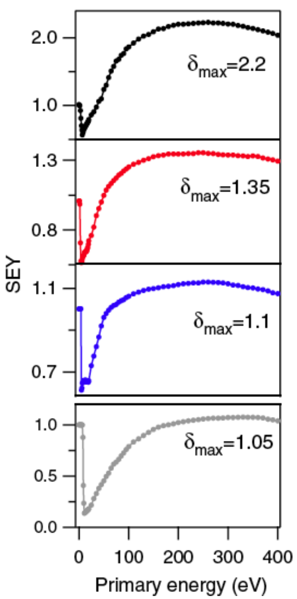
The Surface Science properties of relevance:

- Chemical structure;
- Secondary Electron Yield;
- Photon Reflectivity;
- Photoelectric Yield;
- Photo/ electron stimulated Desorption;
- Low temperature studies

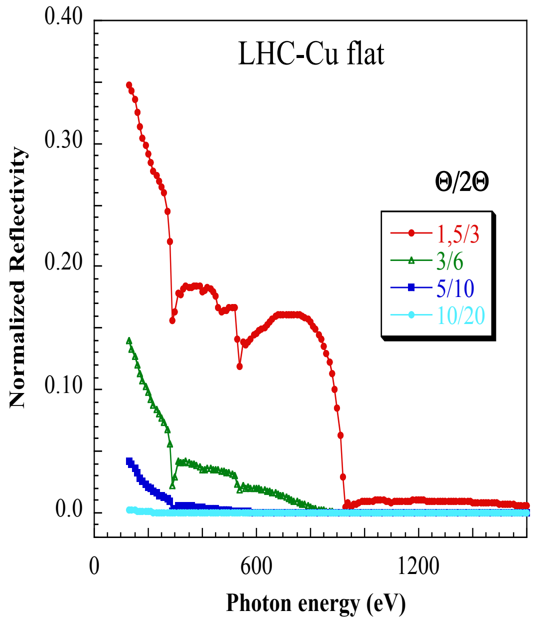
XPS



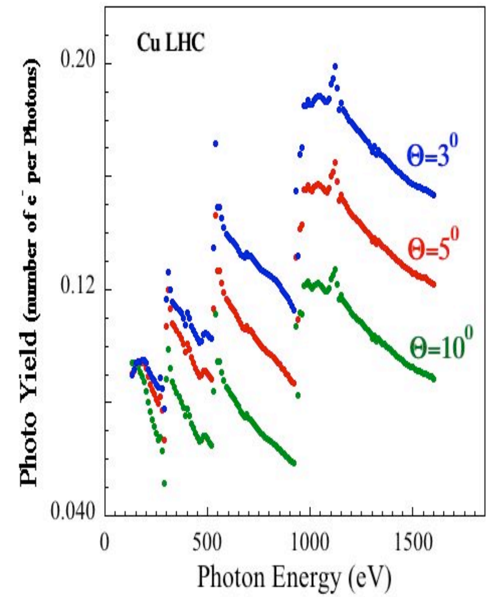
SEY



R



PY



R. Cimino and T. Demma "Electron cloud in Accelerators" Int. J. Mod. Phys. A 29 (2014) 1430023 (pag. 65).

Tesi da svolgere presso il Laboratori Nazionali di Frascati dell'INFN

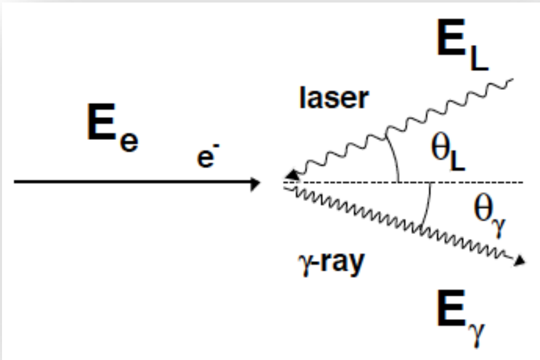
Contact person: R. Cimino (roberto.cimino@lnf.infn.it)

Thesis in collaboration with: ELI Nuclear Physics (Romania)

Laser-Induced Photonuclear Physics

nuclear physics methods to study laser-target interactions, new nuclear spectroscopy, new photonuclear physics

Compton effect: the best energy booster

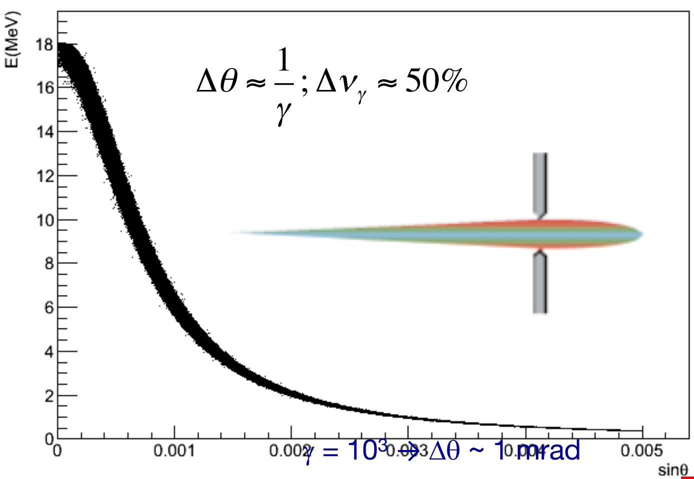


Photon electron collision ($\gamma \gg 1$)

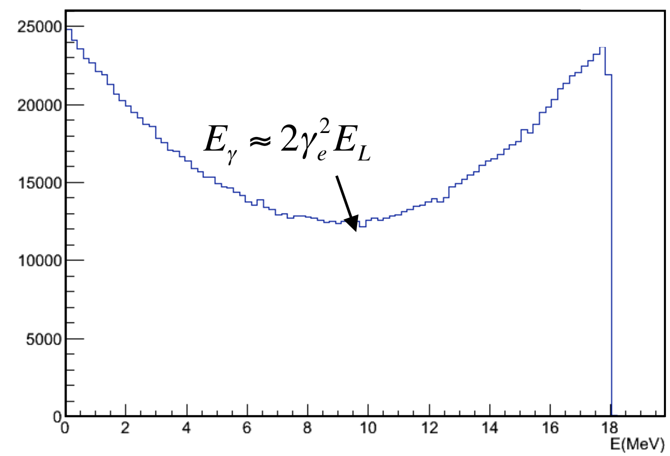
2 boosts, the most efficient energy amplifier

$$E_\gamma = 2\gamma_e^2 \cdot \frac{1+\cos\theta_L}{1+\left(\gamma_e\theta_\gamma\right)^2 + a_0^2 + \frac{4\gamma_e E_L}{mc^2}} \cdot E_L$$

Relativistic antenna effect, forward boost



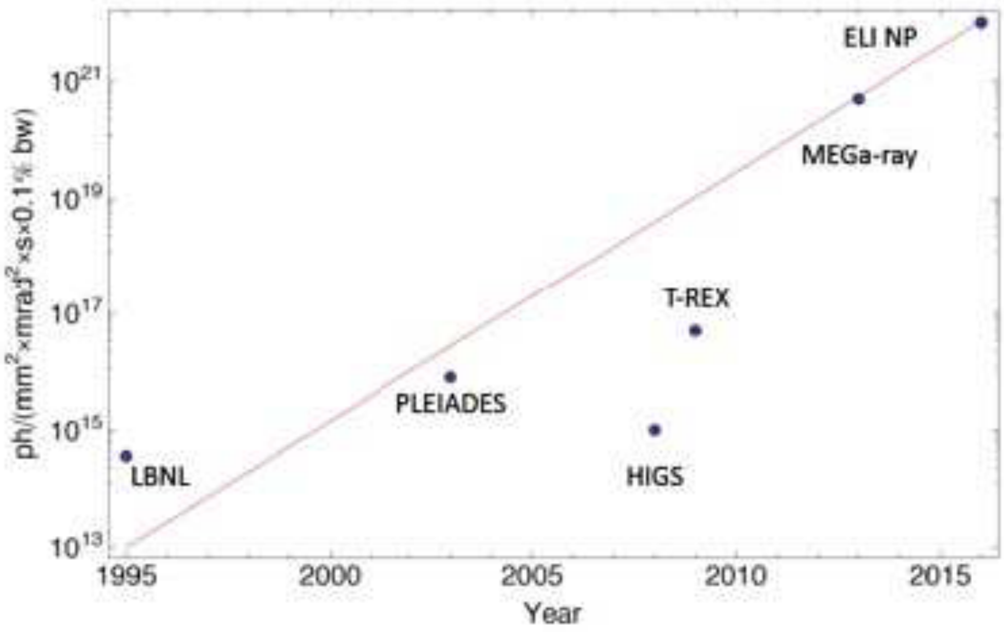
$$\theta_\gamma = 0 \quad E_\gamma \approx 4\gamma_e^2 E_L$$

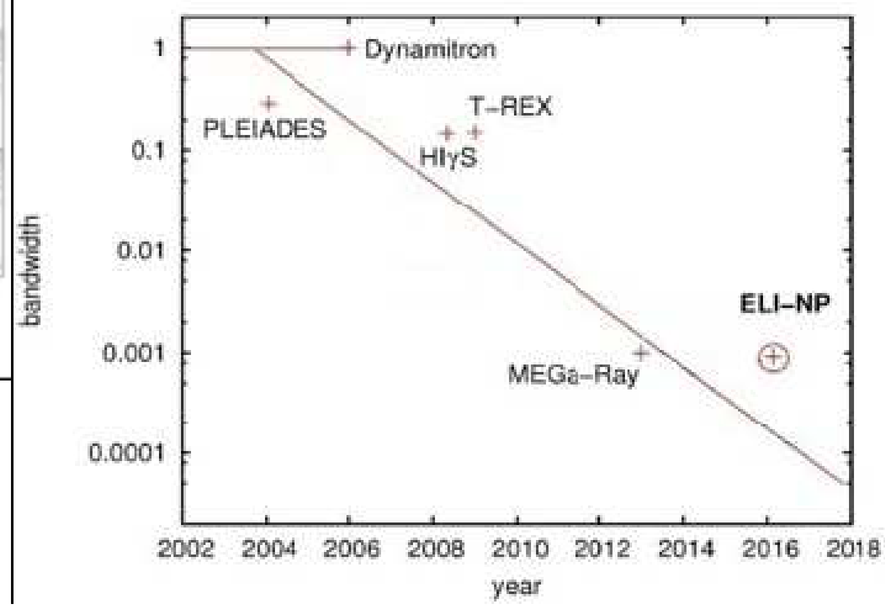


It is a kinematical effect: angle – energy correlation, bw and tunability (polarization)

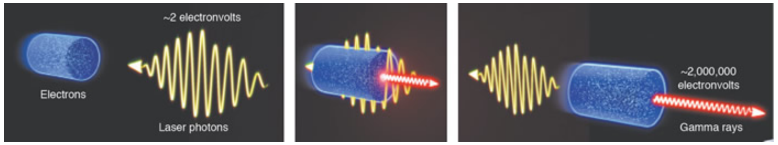
… but cross section ~ 10^{-25} cm^2 -> small for a light source

ELI-NP γ beam: the quest for higher flux and narrow bandwidths





2 order of magnitude in flux and 2 in bandwidth !!!!!!!!



$$Gamma-ray\ Energy: 1-20\ MeV$$

$$rms\ Bandwidth:\ 0.5\%$$

$$Spectral\ Density:\ 5.10^3\ \ photons/s\cdot eV$$

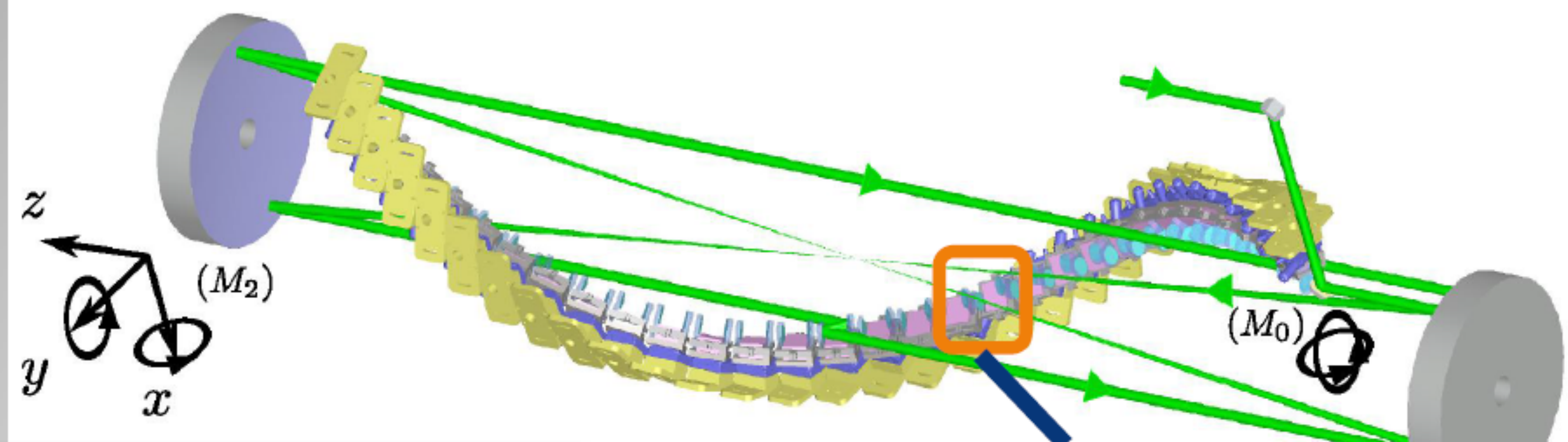
Outstanding electron beam @ 720 MeV with high phase space density (all values are projected, not slice!)

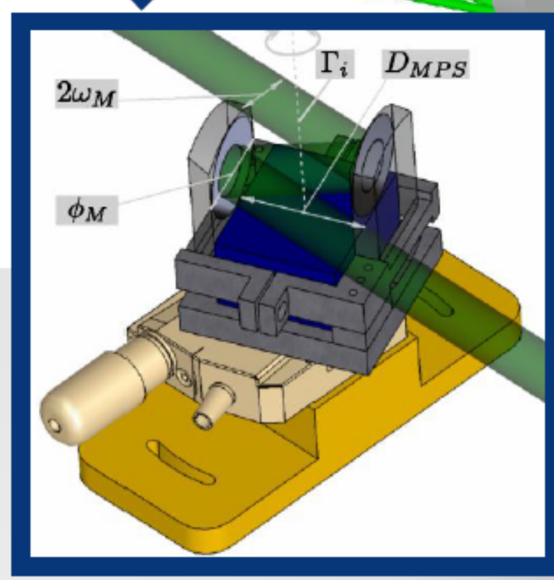
$$Q=250\,pC\ \ ;\ \ \varepsilon_n=0.4\ \ mm\cdot mrad\ \ ;\ \ \frac{\Delta\gamma}{\gamma}=8\cdot 10^{-4}$$

Scattering off a high quality J-class psec laser pulse

$$U_L=400\ \ mJ\ \ ;\ \ M^2=1.2\ \ ;\ \ \frac{\Delta\nu}{\nu}=5\cdot 10^{-4}$$

Advance technology: the *dragon shape* circulator





2 parabolic reflectors M1 & M2

- M1 fixed
- M2: 5 degrees of freedom
- M0: 2 tilts for injection

Mirror-pair system

- For interaction plane switch
- Rotation for synchronization

→ **Alignment issues**

Proposed thesis within the activity @ ELI NP

Experimental activity at ELI-NP GBS gamma source for the commissioning/optimization of the high brightness photo-injector and RF linac towards the tuning of the Compton Interaction for the Gamma source

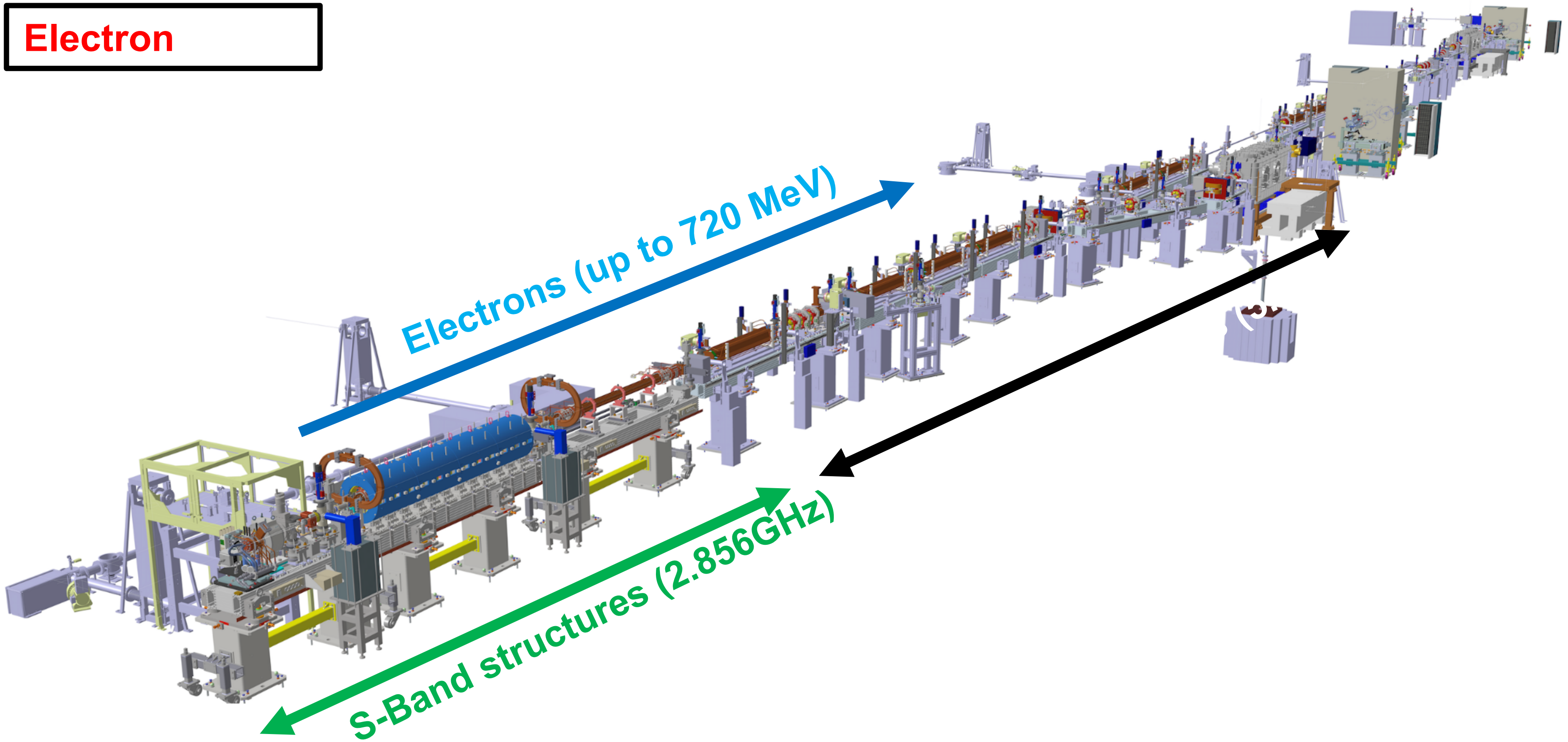
- The Eurogammas international collaboration is meant to produce a gamma source, based on the Compton back-scattering of high quality electron beams and high-power laser pulses, with unprecedented quality in terms of small bandwidth (0.5 %), very high spectral density (> 10^4 photons/sec/eV) in the wide energy range 0.2 - 19.5 MeV.
- Here the scientific advanced potentials will be explored of a high intensity laser system (up to 10^{24} W/cm^2) joined with a high brilliance Gamma ray Beam System, in the field of Nuclear Physics and Nuclear Photonics for users, not yet addressable nowadays.
- The gamma source represents a step forward in the available technologies in comparison to the present state of the art, with an expected step-up of the various beam performances by at least two orders of magnitude.
- Beside the ultra-high quality of the electron beams, the upgrade comes from the operation at 100 Hz repetition rate for the RF in the multi-bunch configuration and the circulation of the laser pulse as many times as possible at the IP that allow to increase the number of collision per second, and so the gamma flux.
- **The PhD thesis will focus on the experimental activity translating, also thanks to the development of novel and advanced high-level applications, electron beam dynamics studies produced so far, into commissioning strategies for the high-brightness photo-injector, high-current high-gradient C-band lilac, transfer lines and Compton interaction region.**

TAKE PART IN **COMMISSIONING AN INNOVATIVE MACHINE!**

Supervisors: A. Variola, C. Vaccarezza

Advanced Diagnostics for bunch by bunch measurements in ELI-NP GBS

Electron



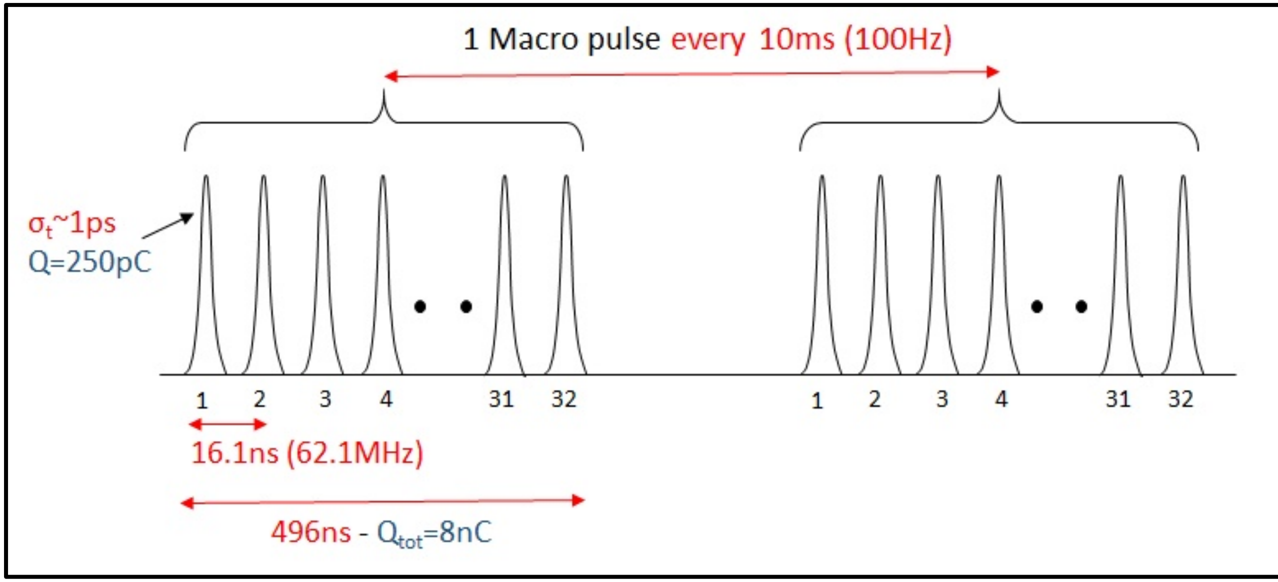
- **Studies on advanced beam diagnostic techniques and devices are required in order to perform bunch by bunch and single-shot measurements on the electron beam with challenging requirements.**
- **The main focus will be to perform studies on bunch by bunch beam imaging diagnostic systems.**

will be held at INFN-LNF.

- **There will be the possibility to join the developer team during the LINAC commissioning and to test the diagnostic techniques by first hand.**

Advanced Diagnostics for bunch by bunch measurements in ELI-NP GBS

Electron Beam



- **Imaging diagnostics will be based on Optical T Transition Radiation (OTR) beam screens and fast digital camera, coupled with gated image intensifier.**
- **Bunch by bunch imaging diagnostics is required to measure:**
  - **position and size**
  - **energy and energy spread**
  - **emittance and Twiss parameters**
  - **bunch length**

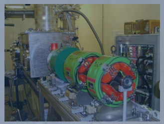
…for every bunch within the beam pulse.

Electron Beam Specifications

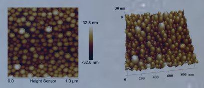
Parameter	Value
Max. Energy at IP [MeV]	280 – 720
Macro Pulse rep. Rate [Hz]	100
Number of bunches	up to 32
Bunch spacing [ns]	16.1
Bunch length [ps]	0.91
Bunch charge [pC]	25-250
Bunch Energy Spread	< 0.1%

Proposed Ph.D. Thesis (P. Antici, INFN-RM1)

- Laser-driven proton (LDP) acceleration and applications PhD. Topics:
  - Development and characterization of a laser-driven proton beamline (collaboration with INRS (Canada) and ELI-ALPS (Hungary)

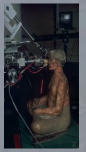


  - Generation of nanoparticles obtained by laser-driven proton acceleration for early cancer detection (collaboration with SLOAN Kettering Memorial Cancer Center, New York, INRS Canada)



  - Development of a material stress testing platform using laser-accelerated protons (collaboration with INRS Canada, LLNL USA and UniCal Calabria)

  - Development of a novel diagnostics for Cultural Heritage based on laser-accelerated protons (coll. With Ministero Beni Culturali, INRS Canada)



  - Improved laser-driven proton acceleration using nanostructured targets (collaboration with INRS (Canada) and ELI-ALPS (Hungary)

  - Characterization of ElectroMagnetic Pollution produced in high-power laser-matter interaction experiments (coll. ELI-ALPS)
- Laser-driven electron (LDE) acceleration and applications
  - Beamhanding of low-energy LDE for electron diffraction applications (coll INRS Canada and FORTH Crete)

iPAT-LAB
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Lasers • Applications • Beamlines
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eli attosecond

Proposed thesis within SBAI

X band mode launcher (contact: bruno.spataro@lnf.infn.it)

- Recent studies of RF breakdown in cryogenic copper structure have shown a strong increase in the operating gradient and the surface electric field that can be attained.
- The RF photoinjector of future generation will use this increase in surface electric field to create an ultra-high brightness cryogenic normal conducting photo-injector. The brightness is expected to increase by over one order of magnitude.
- This RF photoinjector is fed by a dedicated mode launcher with no multipolar components in order to avoid an undesirable emittance growth in the electron beam launched from the RF photoinjector.
- The goal of this work, is to design and fabricate a compact X band mode launcher in order to remove the multipolar RF components.
- The thesis activity is based at the Department of Basic and Applied Science for Engineering of La Sapienza.

Open Split Structure (contact: bruno.spataro@lnf.infn.it)

- Accelerating structures are usually manufactured by precision turning of individual cells, and combined with precision milling for complex parts such as RF power couplers.

- These multiple parts are brazed into a complete structure. An alternative approach is the use of precision milling to cut cells into metal blocks that comprise either halves or quarters of the complete structure.

- One of the main motivations for this work is to study the high gradient performance of accelerating structures made with novel manufacturing methods (or milled out of two halves and brazed together) in order to reduce the fabrication cost.
- The thesis activity is based at the Department of Basic and Applied Science for Engineering of La Sapienza.

TW Accelerating Structures with RF power flow outside of accelerating cavities (contact: bruno.spataro@lnf.infn.it)

- An accelerating structure is a critical component of particle accelerators for medical, security, industrial and scientific applications. Standing-wave side-coupled accelerating structures are used when available rf power is available and average current and average power lost in the structure are large.
- These structures are expensive to manufacture and typically require a circulator; a device that diverts reflected power away from rf source, klystron or magnetron. Physics and technology of rf accelerating structures is a mature field with variety of existing geometries and methods.
- The goal of the this activity is to design a new type of traveling wave accelerating structure, which combines the high shunt impedance of the side-coupled standing wave structures with the advantages of traveling wave structures, such as simpler tuning and manufacturing. In addition, the traveling wave structure is matched to the rf source so no circulator is needed.
- The thesis activity is based at the Department of Basic and Applied Science for Engineering of La Sapienza.

Study high gradient accelerating structures in X and W band (contact: bruno.spataro@lnf.infn.it)

- Building more compact accelerators to deliver high brightness electron beams for the generation of high flux, highly coherent radiation is a priority for the photon science community. A relatively straightforward reduction in footprint can be achieved by using high-gradient accelerating structures. RF breakdown is one of the major factors limiting the operating accelerating gradient in rf particle accelerators.
- The breakdown rate could be linked to the movements of crystal defects induced by periodic mechanical stress. Pulsed surface heating possibly creates a major part of this stress.
- The goal of the this activity is to study some material properties in order to design high-gradient accelerating structures in X and W band.

- The thesis activity is based at the Department of Basic and Applied Science for Engineering of La Sapienza in collaboration with INFN-LNF.

USE OF METAMATERIALS FOR THE REDUCTION OF LHC COLLIMATOR COUPLING IMPEDANCE: study, simulations and measurements

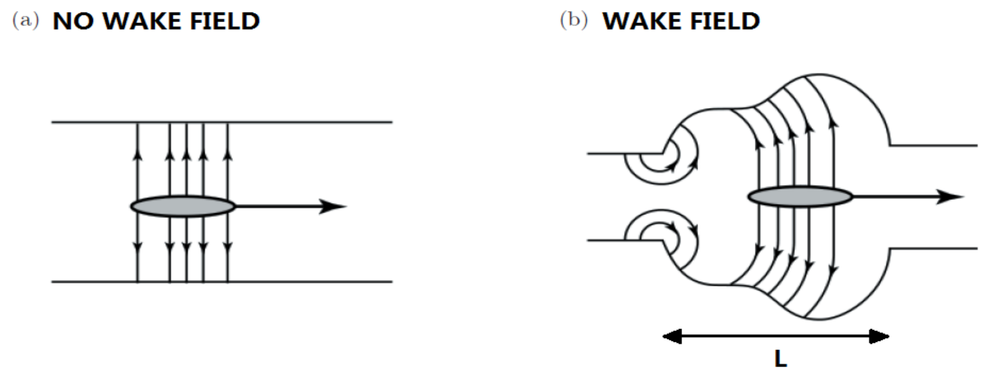
Doctoral thesis at INFN Naples site and Federico II University of Napoli in collaboration with CERN

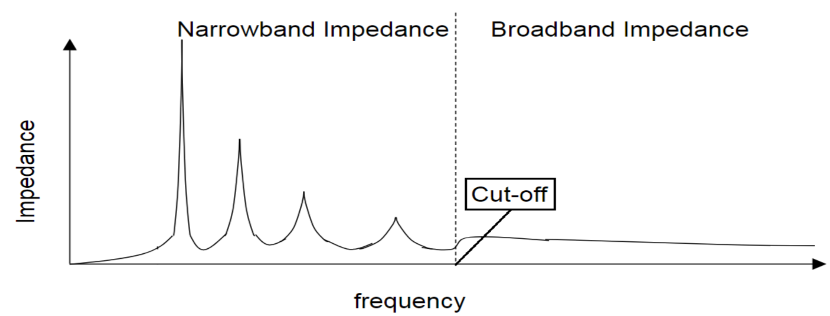
Reference people : Maria Rosaria Masullo –masullo@na.infn.it
Antonello Andreone –andreone@unina.it

In an accelerator the electromagnetic interaction between the beam and the surrounding equipment can be the source of instability problems. In order to study and characterize the interaction process it is possible to use two different parameters:

- Wakefield in the time domain
- Coupling impedance in the frequency domain

Due to this interaction, EM fields are produced. Under some conditions, they can remain in the vacuum chamber perturbing the original field distribution which has to guide the beam.
The coupling impedance function connects the new fields to the perturbed charge and current densities.
This function has to be kept under a well defined threshold in order to reduce the perturbation and instability phenomena. This point is crucial if we want to improve the beam intensity.





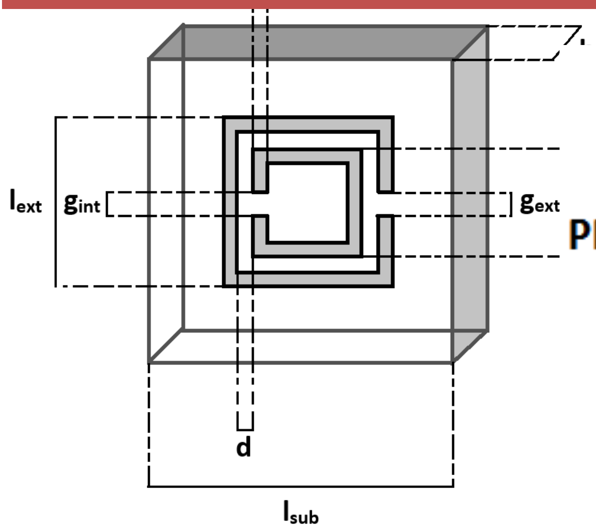
A typical behaviour of the impedance in two frequency regions. The resonances must be “reduced” lowering their quality coefficient, Q.

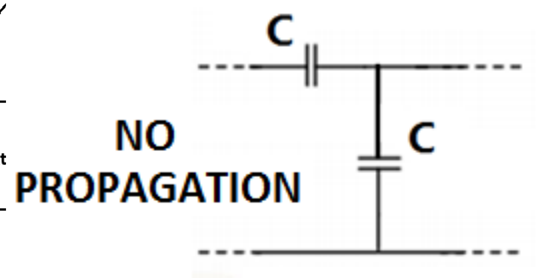
A.W. Chao. *“Physics of Collective Beam Instabilities in High Energy Accelerators”,* Wiley (1993)

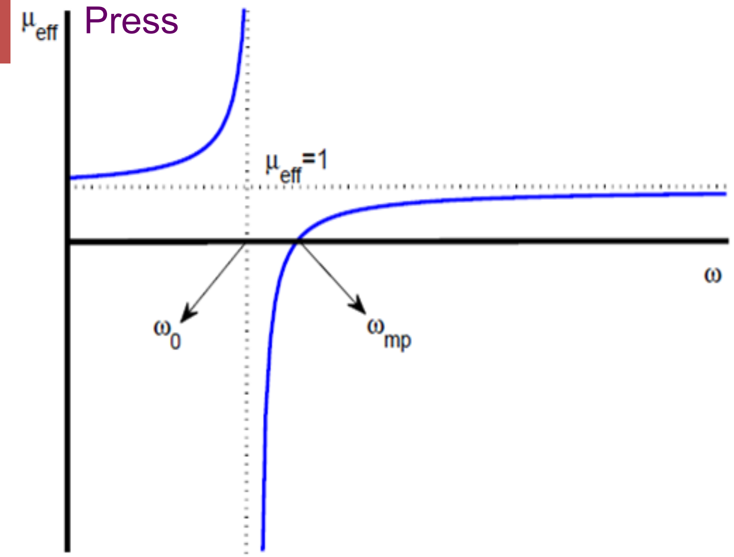
Metamaterials are structures and composite materials that either mimic known material responses or qualitatively have new, physically realizable response functions that do not occur or may not be readily available in nature, as negative μ and ε

Engheta & Richard W. Ziolkowsk "Metamaterials: Physics, Engineering and Explorations" IEEE & Wiley Interscience Press

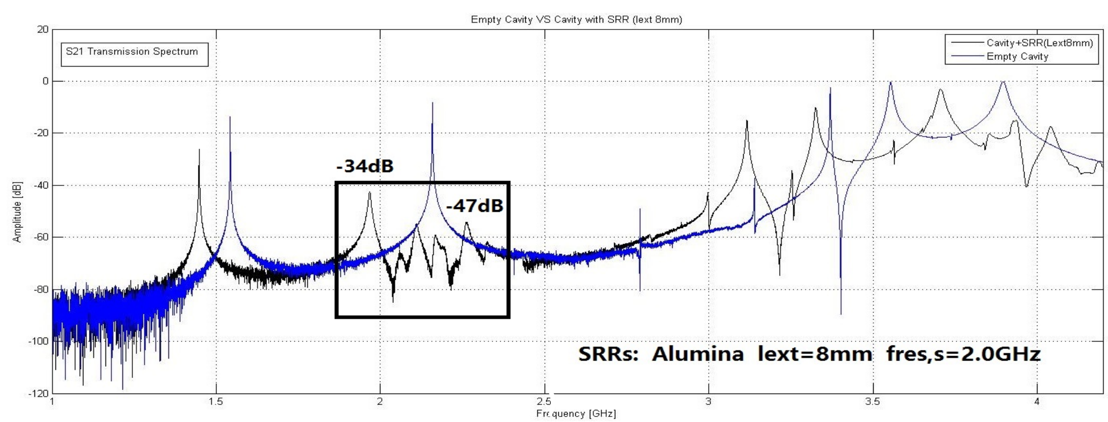
MNG Material(μ<0)





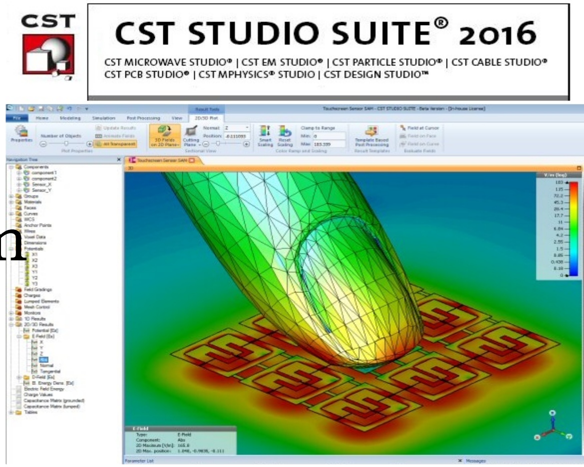


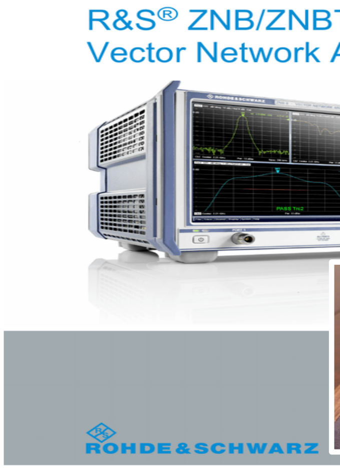
Suitably dimensioned and excited they can be used as absorbers and/or modify the EM response of the region in which they are allocated



What can you learn

- Issues related to the coupling mechanism between beam and accelerator
- Metamaterial application
- How to use simulation EM code (CST)
- EM characterization measurements with network analyzer





Which knowledge is required

Electromagnetism

A previous knowledge of any em simulation code would be helpful

Conclusion

- Phd Thesis is a very important transition from students to researchers
- One of the important skills you are supposed to have and develop is: choosing on what and with whom you want to work!
- So: read carefully, study, look on google scholar publication lists, check for grants available and capabilities of thesis proposers, talk to people, visit labs ... (Supervisors, ex-students, etc.)
- You need to choose where and with whom to spend your next 3 years.
- Take your time!