Accelerator R&D for HEP and beyond

Eduardo Martinez-Lopez

On behalf of the accelerators physics and technology team

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Spanish network for future colliders

Accelerator physics and technology team

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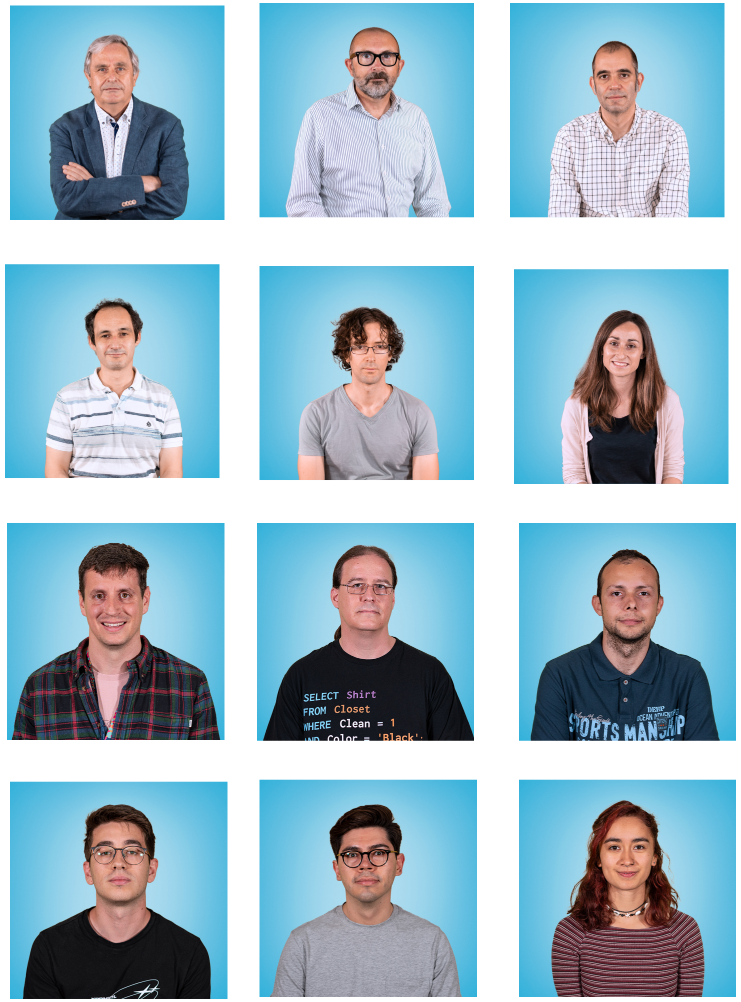


Within the AITANA group:

- https://aitanatop.ific.uv.es/aitanatop/

Accelerator R&D main ongoing activities

❑ R&D on RF technologies

- ✓ The IFIC high-gradient RF laboratory
- ✓ Dielectric Assist Accelerating (DAA) cavities design
- ✓ Design of Normal-Conducting cavities for medical LINACs in Hadron Therapy applications

❑ R&D on novel accelerating technologies

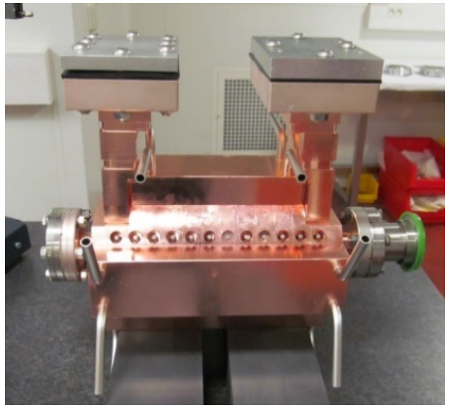
- ✓ Beam-driven wakefield in a carbon nanotube (CNT)

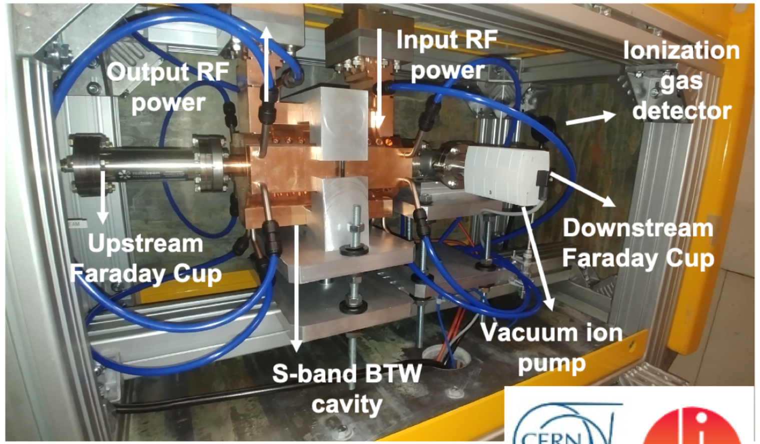
❑ Beam instrumentation

- ✓ Cavity BPMs R&D for the International Linear Collider project

R&D on RF technologies: The IFIC high-gradient RF laboratory

- Currently testing a **novel Backward Travelling Wave high-gradient (50 MV/m) RF accelerating structure** designed and constructed at CERN for **hadron therapy** based on the developed CLIC high-gradient methodology.



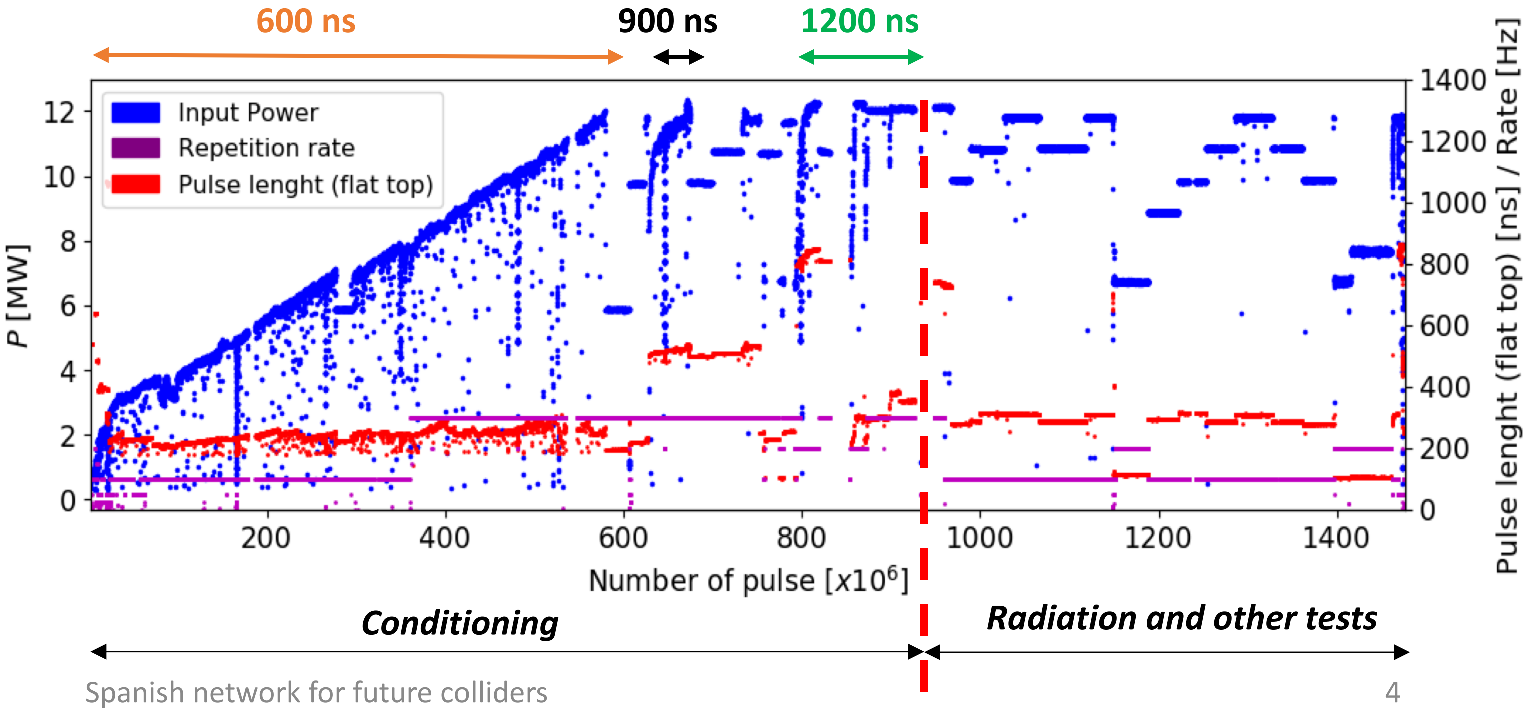


Operation:

- Conditioning of the BTW cavity.
- Maximum power reached of 12MW (~39 MV/m).

Currently working on the power upgrade of the facility.

Non-linear EM phenomena simulations and measurements (breakdowns, dark current and radiation generation).



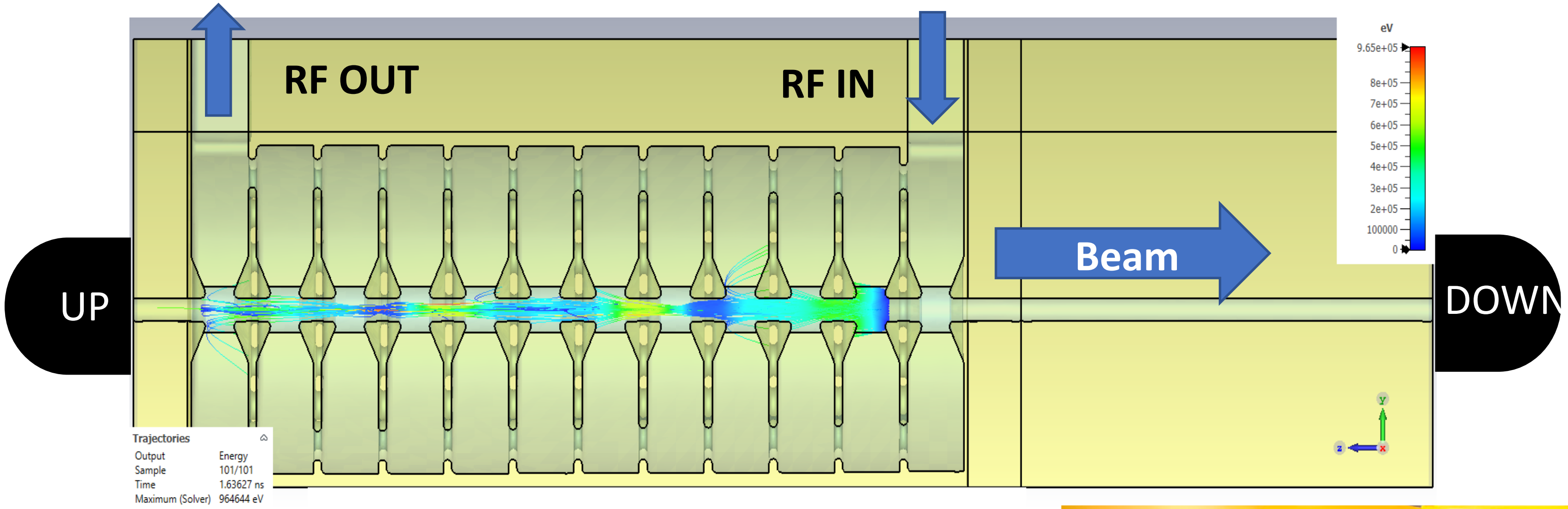
R&D on RF technologies: The IFIC high-gradient RF laboratory

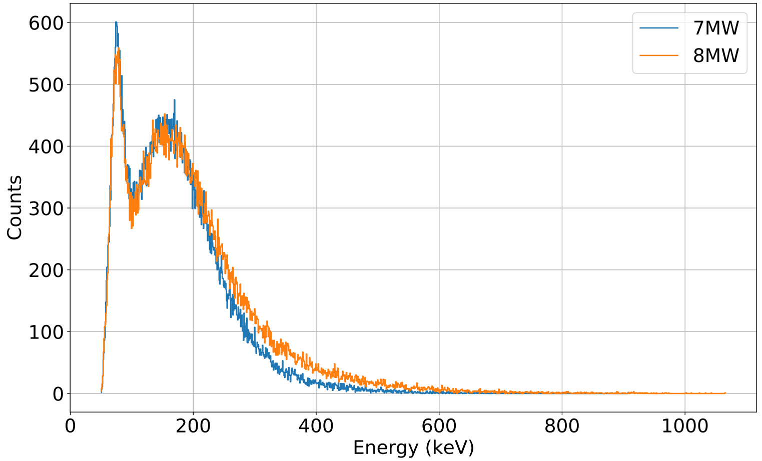
Non-linear EM phenomena studies:
- ❑ Model and characterize the dynamics and impact of the electrons generated by field emission.

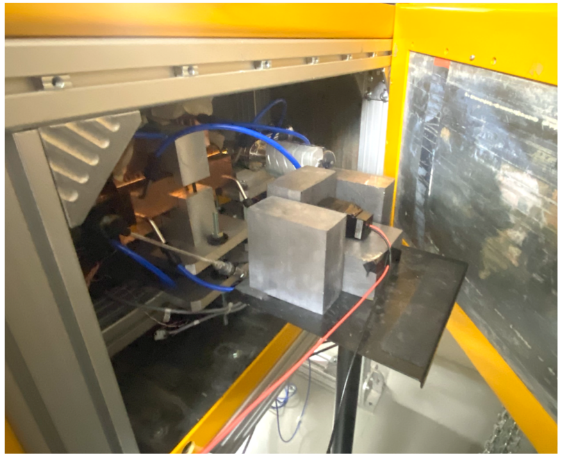
Simulations:
- ❑ Using 3D EM codes (CST PS).

Results:
- ❑ More electrons in the upstream FC w.r.t. beam.
- ❑ Maximum energy of electron impact on the walls is about 700-900 KeV (8-12 MW).

Model validation:
- ❑ Radiation characterization:
  - ❑ Energy spectrum of photons with a CeBr3.
  - ❑ Ionization chamber to measure the dose.
  - ❑ Monte-Carlo simulations.







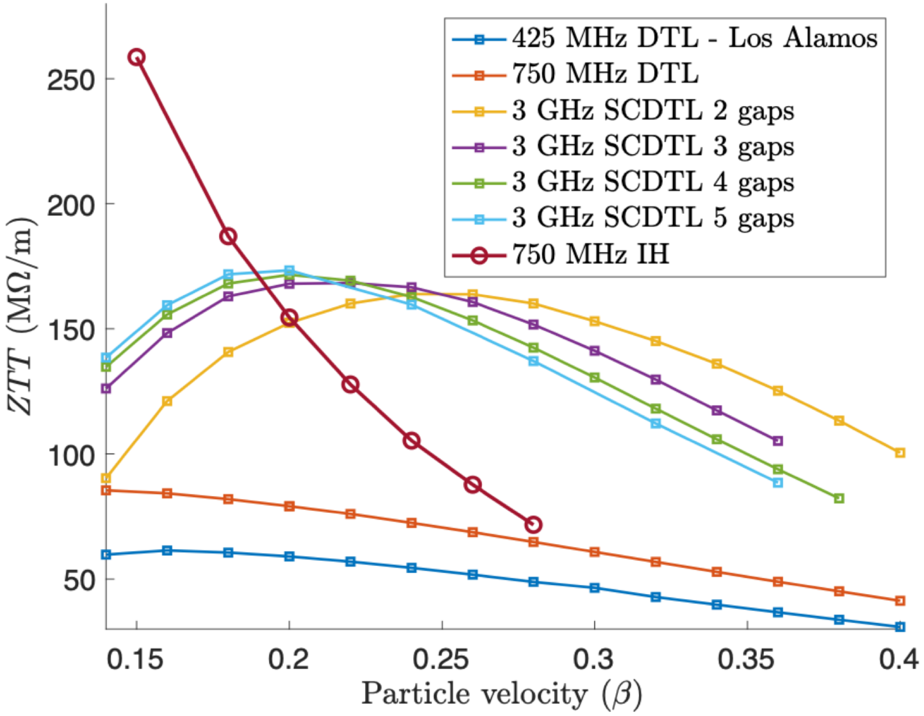
Thanks to E. Nacher and F. Hueso.

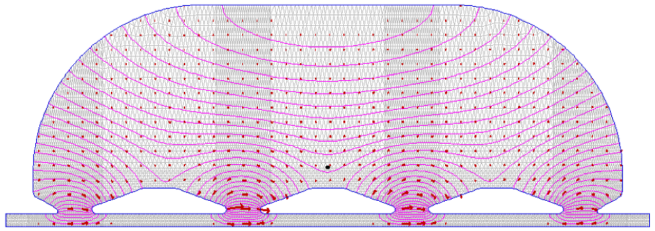
- Linear accelerators provide significant advantages for hadron therapy, including fast energy modulation and reduced activation compared to circular machines.

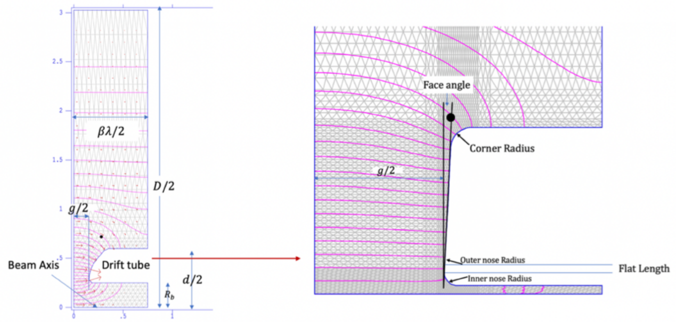
- The design of Normal-Conducting accelerating structures should be primarily guided by the effective shunt impedance ZTT, as it directly determines the energy efficiency of the system:

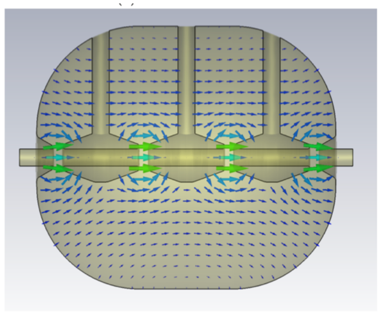
$$\Delta W \propto \sqrt{ZTT \times P_d \times L}$$

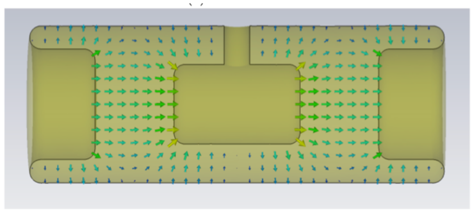
- We study the design and construction of different cavities for linear accelerators dedicated to hadron therapy, operating in TE and TM modes, through electromagnetic simulations





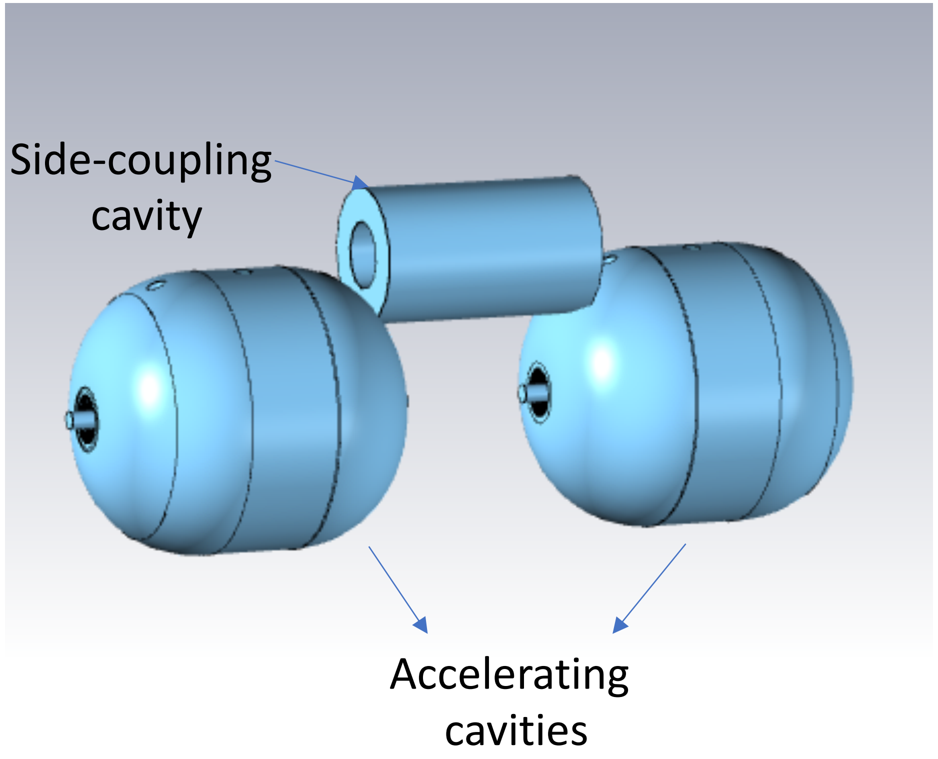


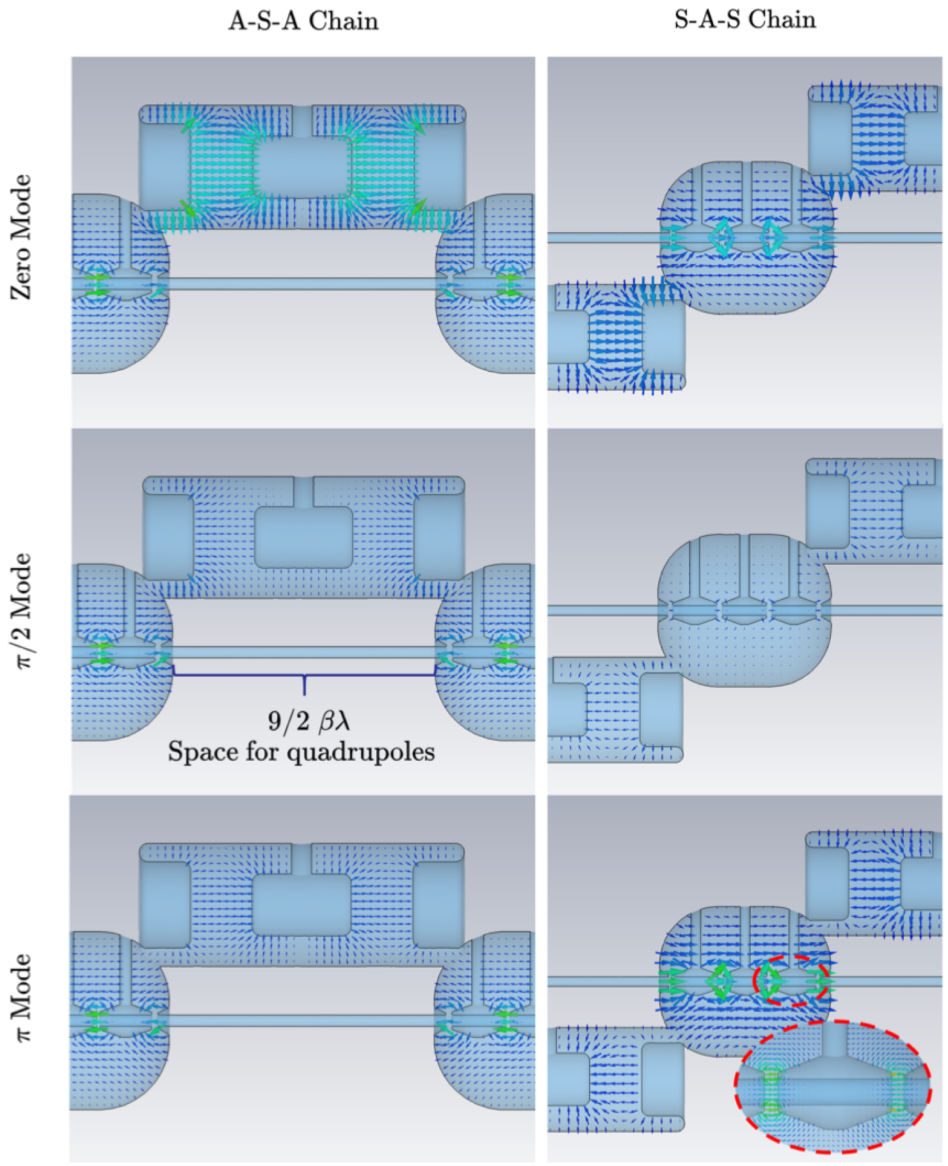




- The 3 GHz Side-Coupled Drift Tube Linac (SCDTL) structure is the most efficient configuration for accelerating hadrons from approximately 10 MeV/u up to about 100 MeV/u.

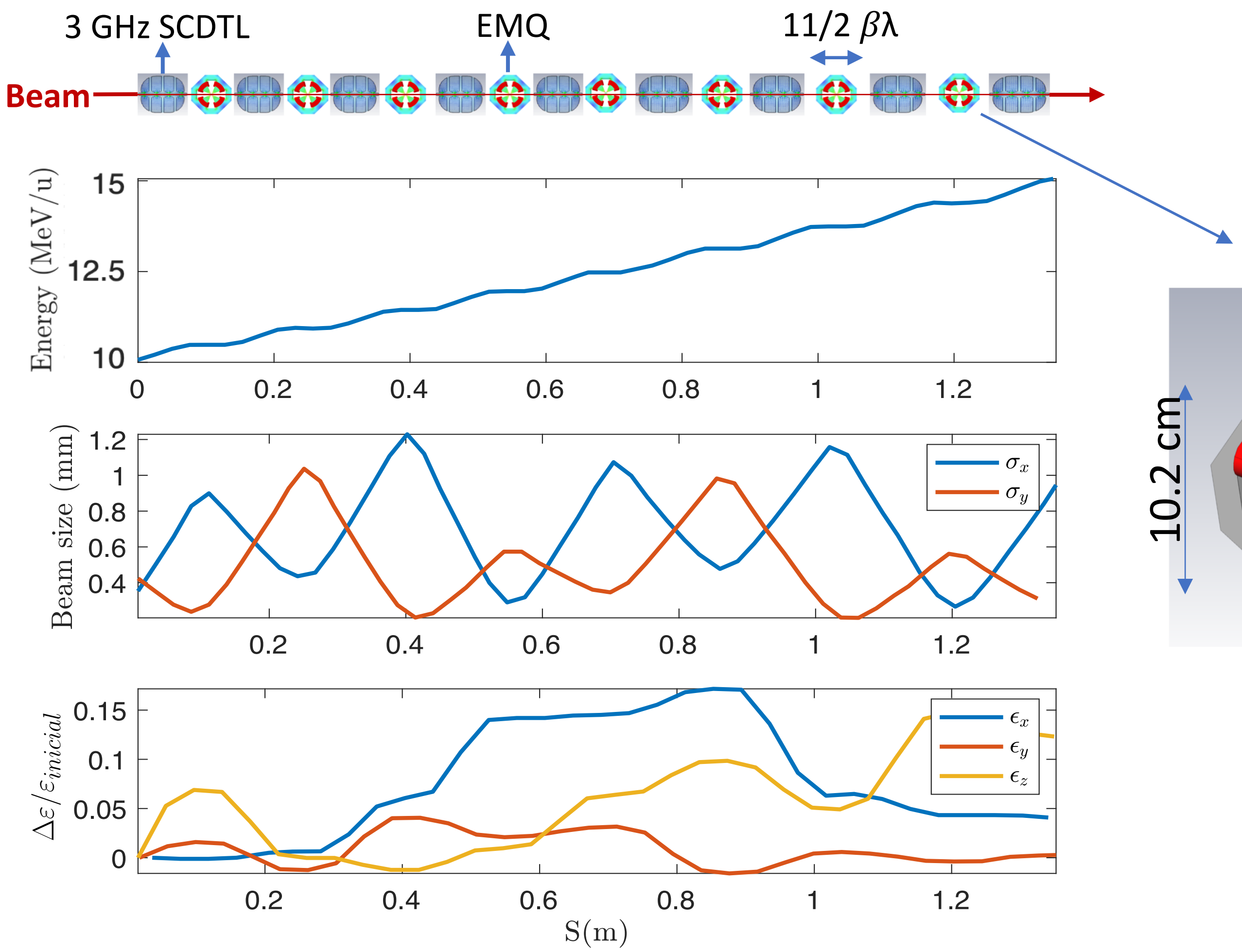
- The SCDTL is composed of a series of short accelerating cavities interconnected by side-coupling cavities (SCCs) via coupling slots

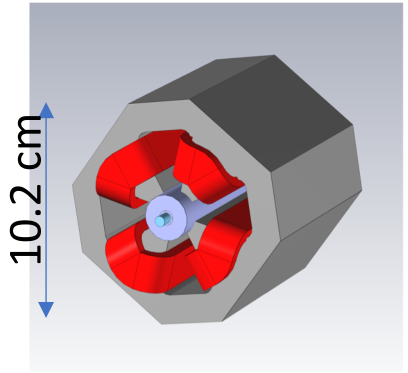




- We design alternative 3 GHz SCDTL configurations that allow the integration of Electromagnetic Quadrupoles (EMQs) for multiparticle acceleration within a single linac.

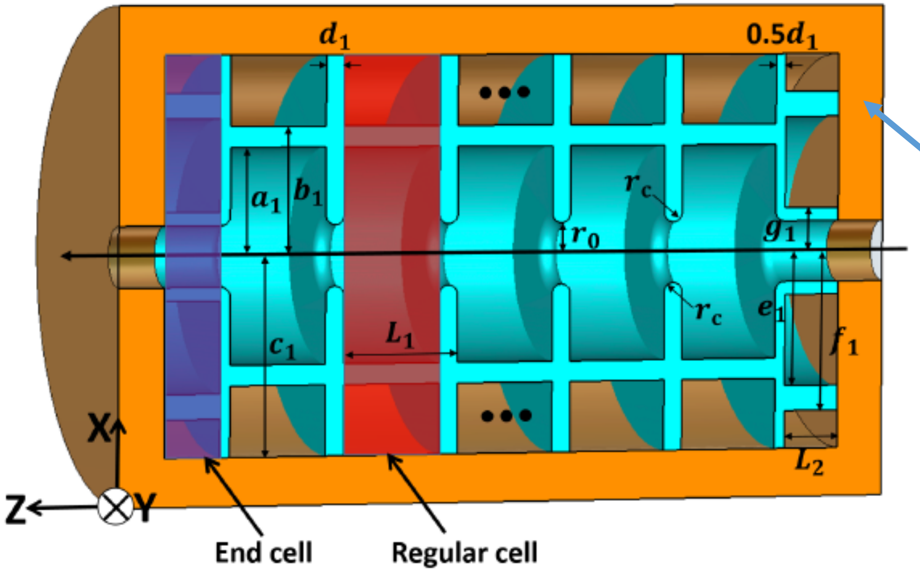
Parameter	Value
W_{IN}	10 MeV/u
W_{OUT}	15 MeV/u
Gaps per tank	5
Total length	1.35 m
Active length	0.69 m
Active length /Total length	0.51
Effective gradient	14.5 MV/m
Gradient	7.4 MV/m
Transmission	100%





R&D on RF technologies: Dielectric Assist Accelerating (DAA) cavities design

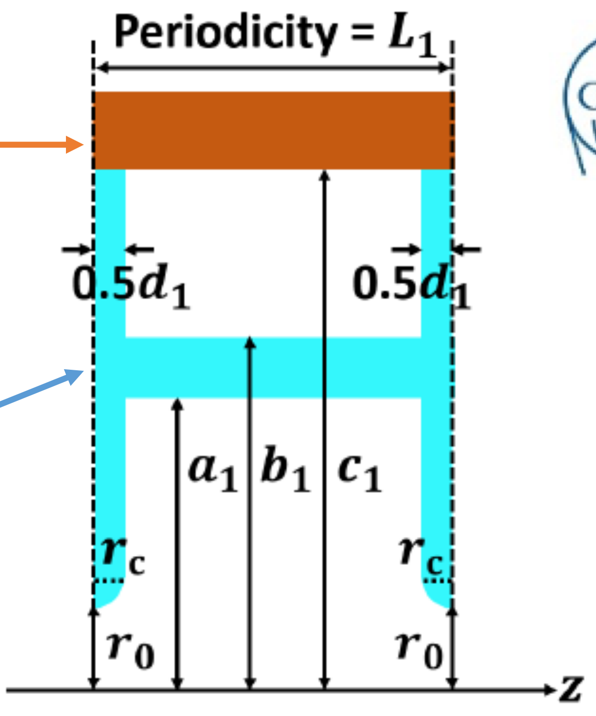
- **Goal:** design more efficient RF accelerating cavities.



Investigations Into *X*-Band Dielectric Assist Accelerating Structures for Future Linear Accelerators. Yelong Wei, Alexej Grudiev

Copper

Dielectric:
- High ϵ_r
- Low tan δ



- Working under $TM_{02-\pi}$ resonant mode:
  - ✓ Dielectric helps to decrease cavity size.
  - ✓ They seem to stand higher electromagnetic fields before breakdown (preliminary experimental data).

- Potential solution for **compact linear accelerators** for **hadron therapy treatments**.

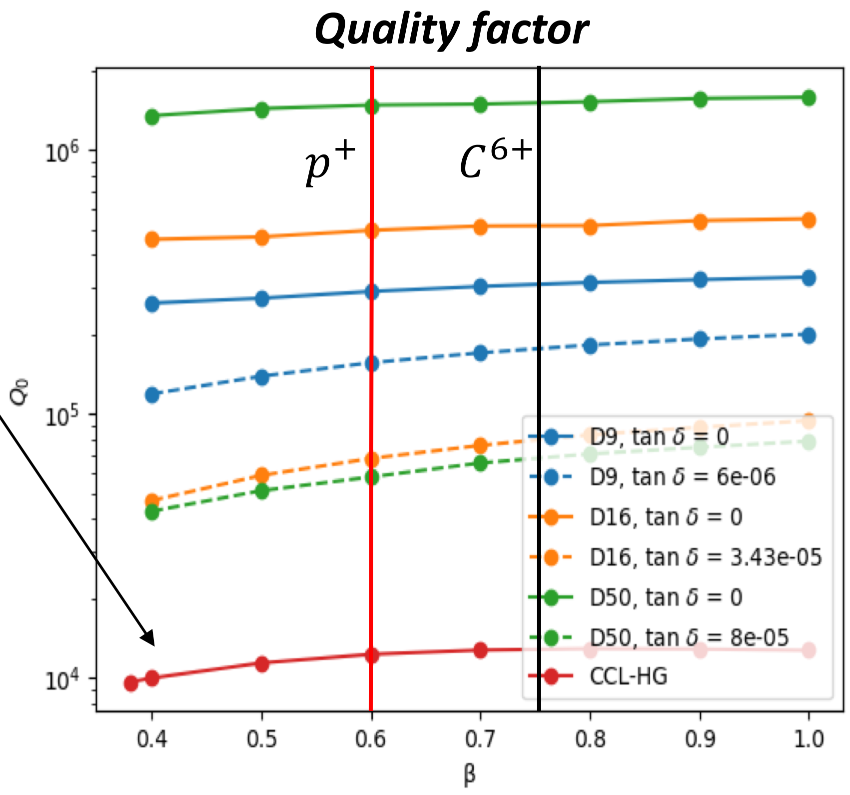
Efficiency optimization

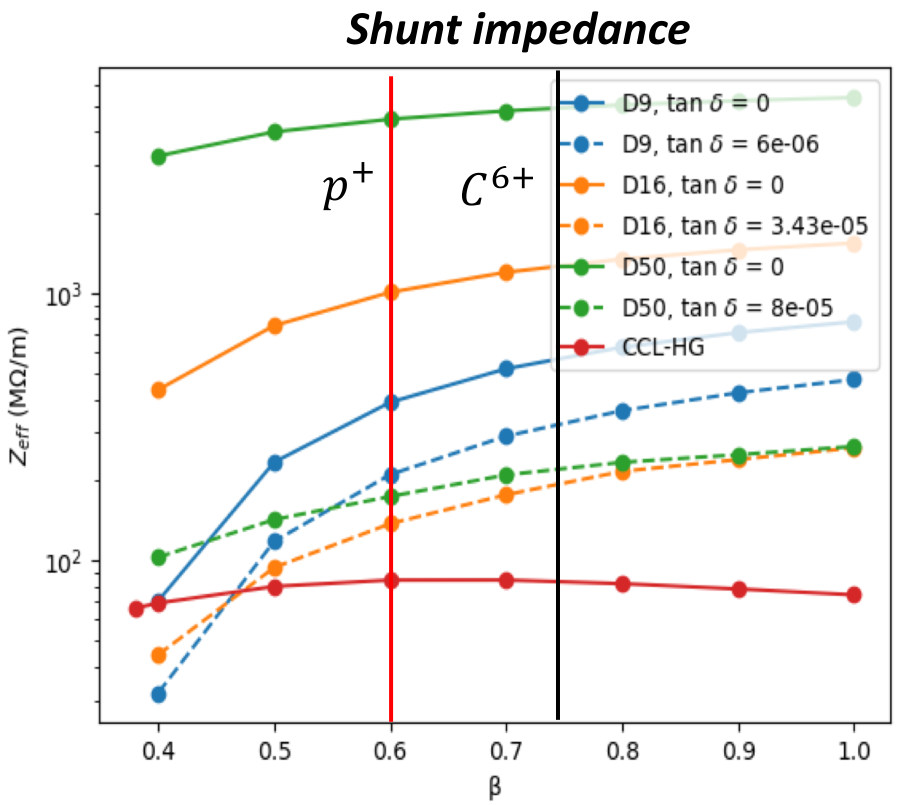
Shunt impedance: $r_e = \frac{G_{\rm eff}^2}{p_{\rm diss}}\ [\Omega/\mathrm{m}]$

Quality factor: $Q = \omega_{\rm RF}\frac{w}{p_{\rm diss}}$

R&D on RF technologies: Dielectric Assist Accelerating (DAA) cavities design

- ❑ Design compared with a **normal cooper cavity** for proton therapy (red).
- ❑ Factor 1.5 to 100 improvement depending on the material and characteristics.





Challenges

- ❑ Finding the right material (high ϵ_r and small $\tan\delta$).
- ❑ Mechanize the geometry within the tolerances required.
- ❑ Mitigation of non-linear EM phenomena such as multipactor.
- ❑ Field singularities at triple point junctions.

Material	ϵ_r	$\tan\delta$
MgO: D-9	9.64	6×10^{-6}
MgTiO3: D-16	16.66	3.43×10^{-5}
BaTiOX: D-50	50.14	8×10^{-5}

Future directions: materials testing and prototyping.

R&D on novel accelerating technologies: Beam-driven wakefield in carbon nanostructures

- The current state-of-the-art of the RF techniques for particle acceleration is limited to gradients on the order of 100 MV/m.

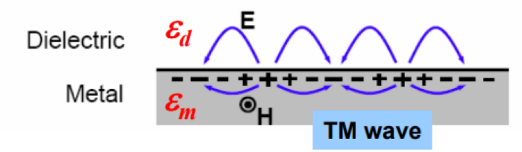
- To obtain higher energies, we can increase the length of the accelerators or use new techniques of acceleration with higher gradients.

- **Beam-driven wakefield in carbon nanostructures**: a charged particle beam can excite surface plasmonic modes (collective motion of wall electrons acting like a structured plasma).

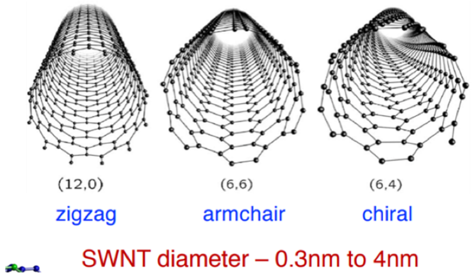
NOVAS group

ICMUV
INSTITUT DE CIÈNCIA DELS MATERIALS de la Universitat de València

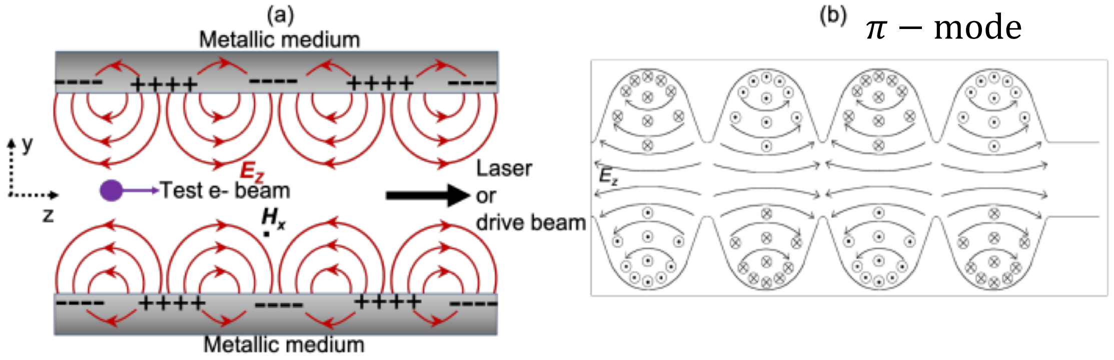
2D plasmon



single-walled nanotubes (SWNT)



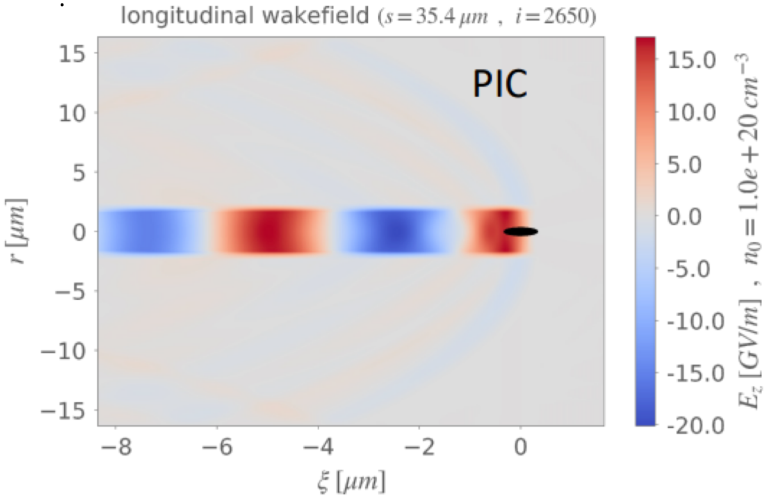
	Plasmonic acceleration	RF cavities
Aperture size	$\sim\mu$m	$\sim$mm-cm
Length	$\sim$mm	$\sim$cm – m
Gradient	$\sim$100 GV/m	$\sim$100 MV/m
Operation	Travelling wave (TW)	Standing Wave (SW) or TW

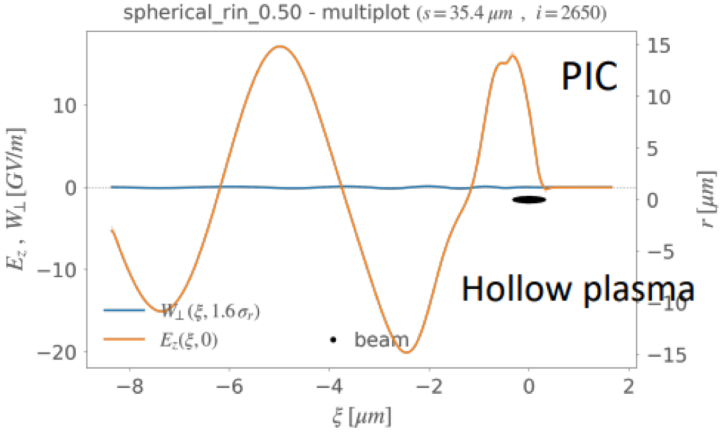


R&D on novel accelerating technologies: Beam-driven wakefield in a carbon nanotube (CNT)

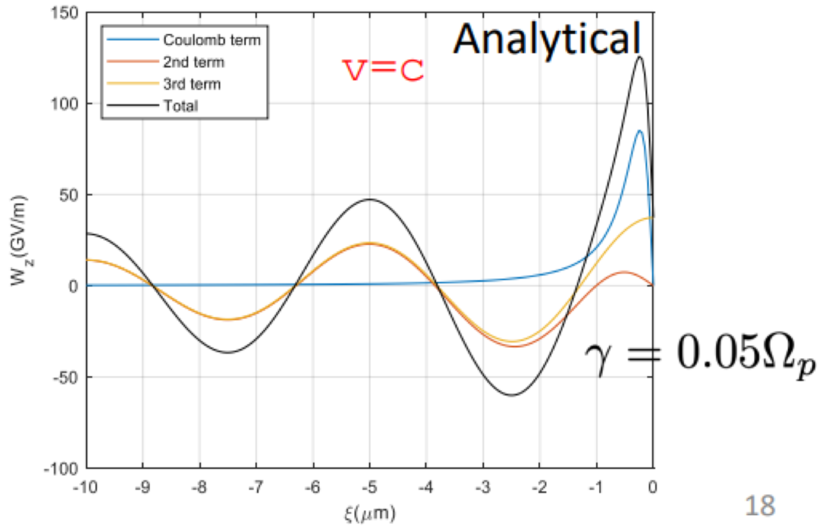
- **Development of a hydrodynamic model for particle beam-driven wakefield in a carbon nanotube (CNT)*** [1] [2].

[1] P. Martín-Luna et al., New J. Phys. **25**, 123029, 2023
[2] P. Martín-Luna et al., Plasmonic Excitations in Carbon Nanotubes: PIC simulations vs Hydrodynamic Model. IntechOpen, 2024.





Hydrodynamic model



Fourier-Bessel PIC code (FBPIC). R. Lehe, et al., "A spectral, quasi-cylindrical and dispersion-free Particle-In-Cell algorithm", Computer Physics Communications, 203, 66–82 (2016).

- The hydrodynamic model predicts results that qualitatively agree with PIC EM codes.
- This model allows to obtain rapidly predictions in the optimum parameters (radius a and surface density of the CNT n_0) according to the velocity v of the charged particles that we want to accelerate.

$$a_{opt}[\text{nm}] \approx 156.55 \frac{(v/c)^2}{n_0[10^{20}\ \text{m}^{-2}]}$$

***Ongoing work: design the proof-of-concept experiment.**

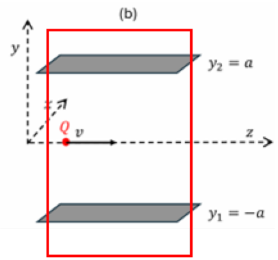
R&D on novel accelerating technologies: Beam-driven wakefield in graphene layers

- **Development of a hydrodynamic model for particle beam-driven wakefield in graphene layers*** [1].

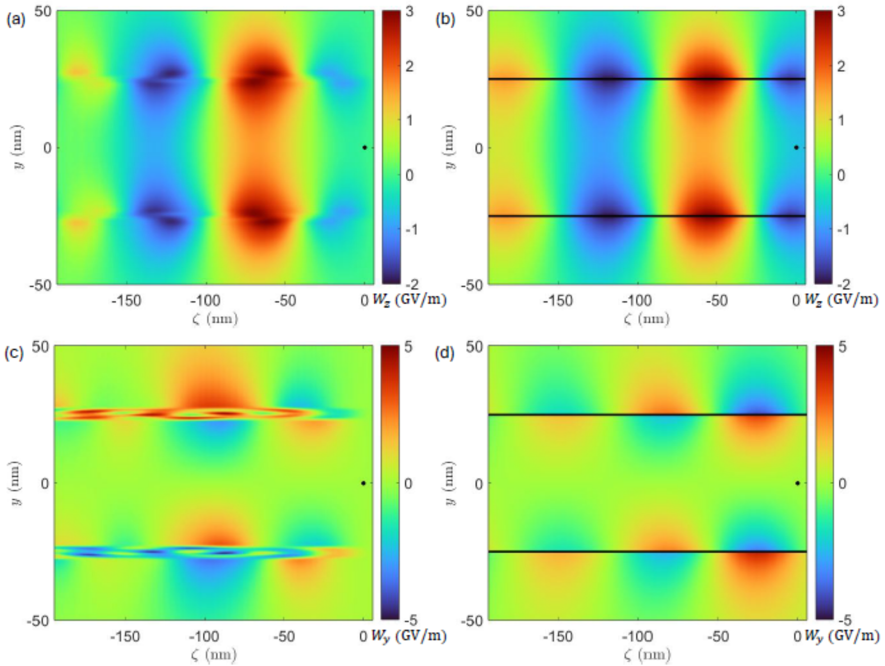
[1] P. Martín-Luna et al., Chin. J. Phys. **97**, 607-624, 2025

PIC: WarpX | Hydrodynamic model

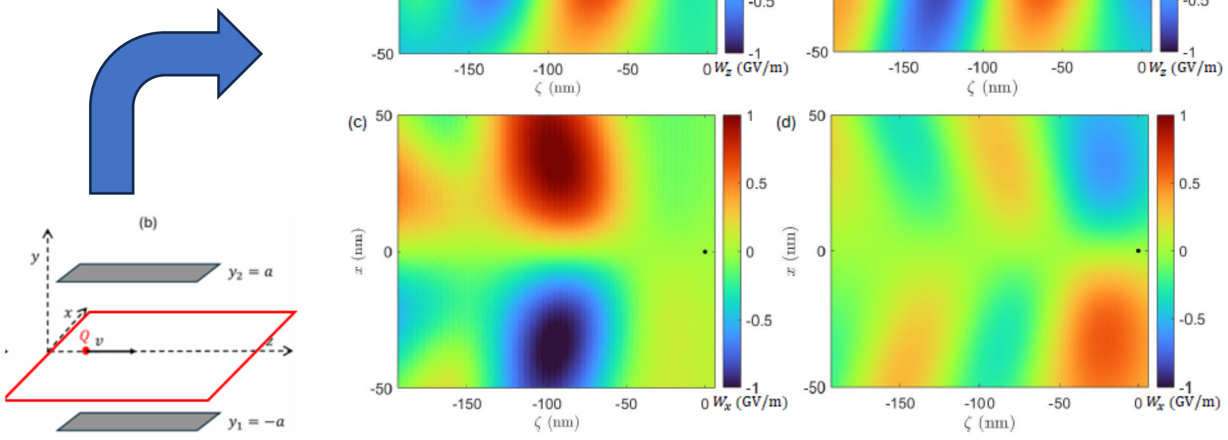
Longitudinal wakefield



Transverse wakefield



PIC: WarpX | Hydrodynamic model



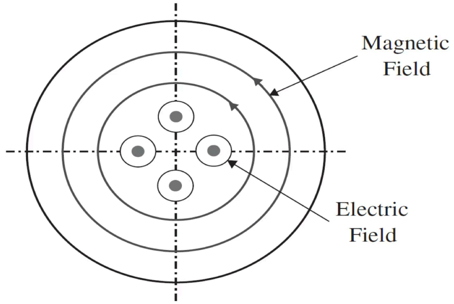
- The hydrodynamic model predicts results that agree with PIC EM codes.

***Ongoing work: design the proof-of-concept experiment.**

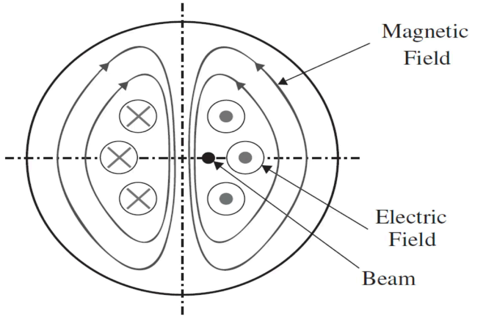
Beam instrumentation for HEP accelerators: Cavity BPMs R&D for the International Linear Collider project

Cavity BPMs are **resonant systems** crossed by the beam pipe.
EM modes are induced on the cavity by the beam and position is calculated by means of measuring their **amplitude and phase**

Reference signal:



Position signal:



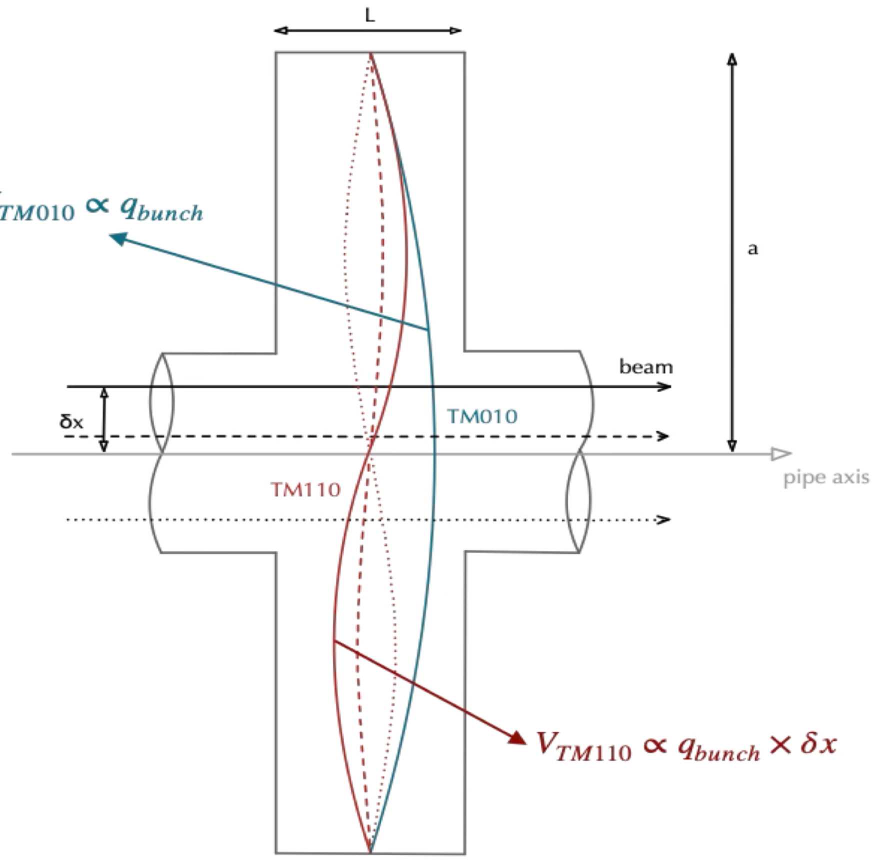


Figure: Representation of the E-fields induced in the cavity

Development of a re-entrant cBPM for the ILC Main Linac with resolution < 1 µm
Project in collaboration with KEK and CIEMAT: development of the cryostat for a BPM and a super-conducting quadrupole

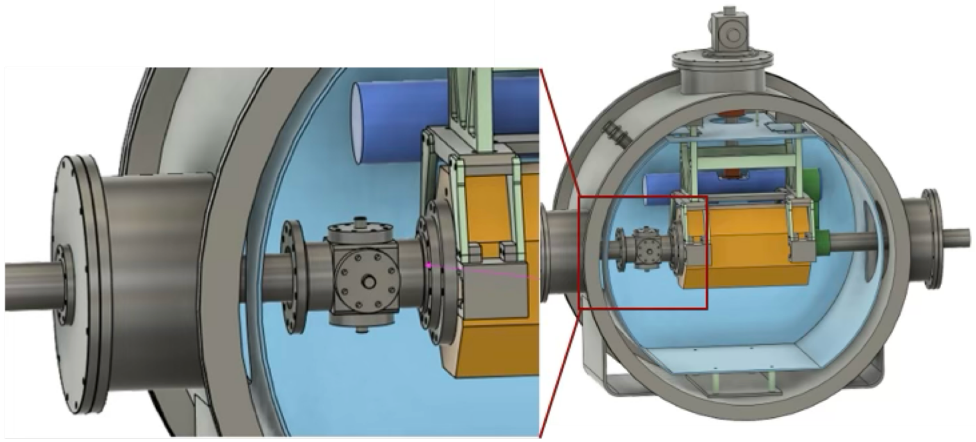


Figure: Cryostat accommodating BPM and SC quadrupole

Objective of the project:
Based on a model developed by CEA Saclay, **improve the performance and resolution** of the BPM by:
- developing a DAQ system to process modes information accurately and consistently
- work on a new cBPM design to increase the sensitivity and resolution of the cBPM form the EM point of view.

Funded by Valencian Government (end of 2022), Next Generation EU.
Tecnologías de RF para monitores de haz en aceleradores y para detectores de axiones de materia oscura", planes complementarios de I+D+I, ASFAE/2022/013.

Beam instrumentation for HEP accelerators: Cavity BPMs R&D for the International Linear Collider project

Testing a DAQ System for a cBPM from CEA SACLAY at ATF (KEK): improving the resolution from electronics point of view

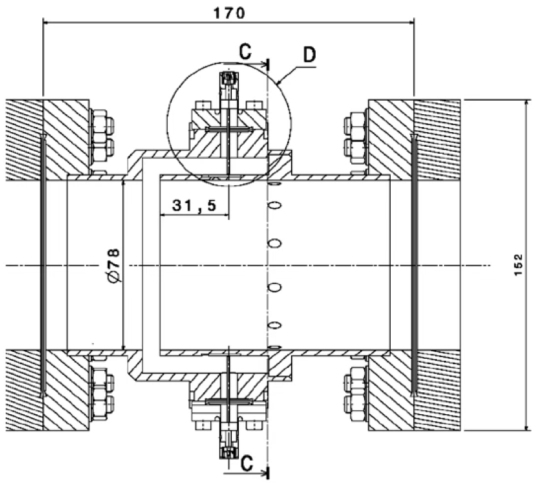
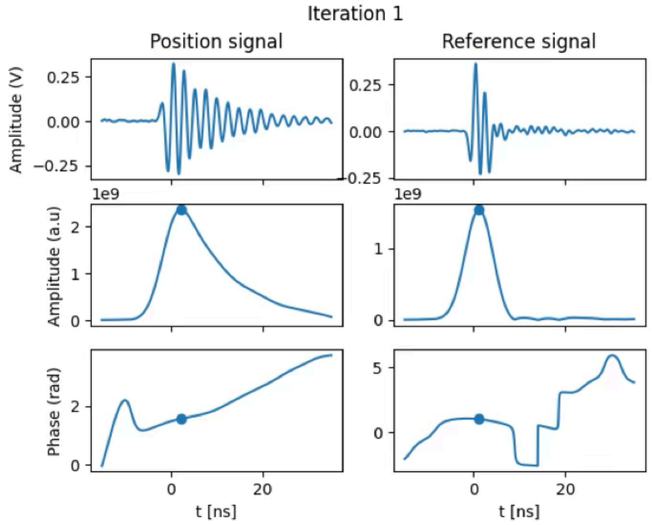


Figure: Drawing of the CEA Saclay cBPM

Figure: CEA Saclay cBPM installed at ATF

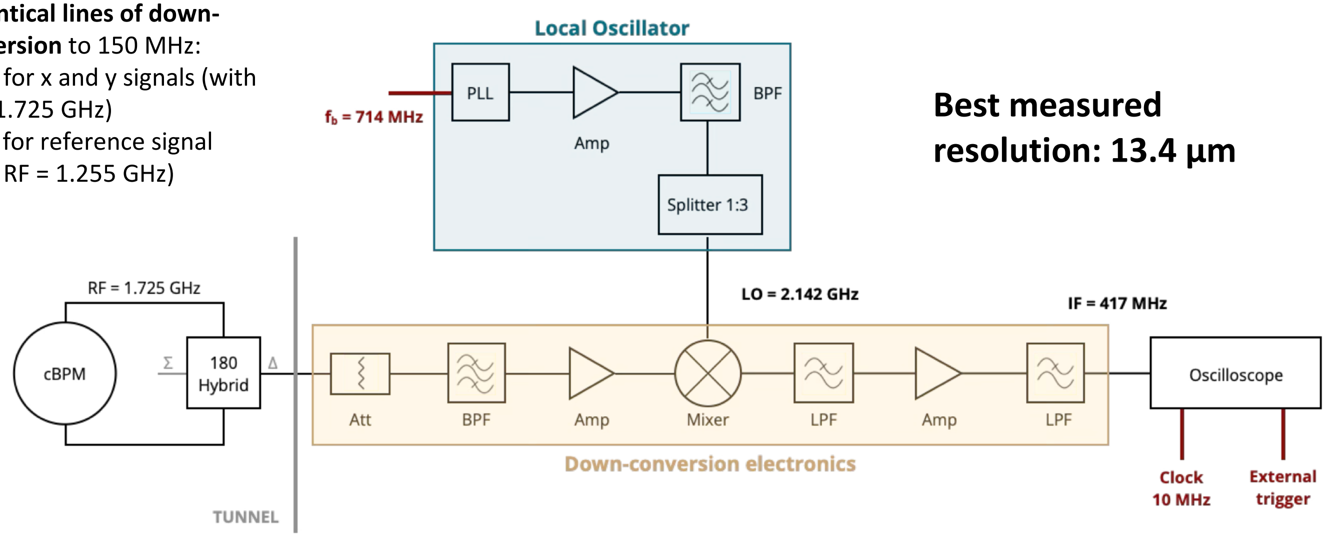
Measurements on May-June 2025 for testing DAQ system of the CEA cBPM:

- Performing the a down-conversion with analog electronics read-out chain
- Implementing DDC algorithm to extract amplitude and phase of both modes
- Perform calibration of the cBPM
- Calculation of the resolution of the system using stripline BPMs from ATF

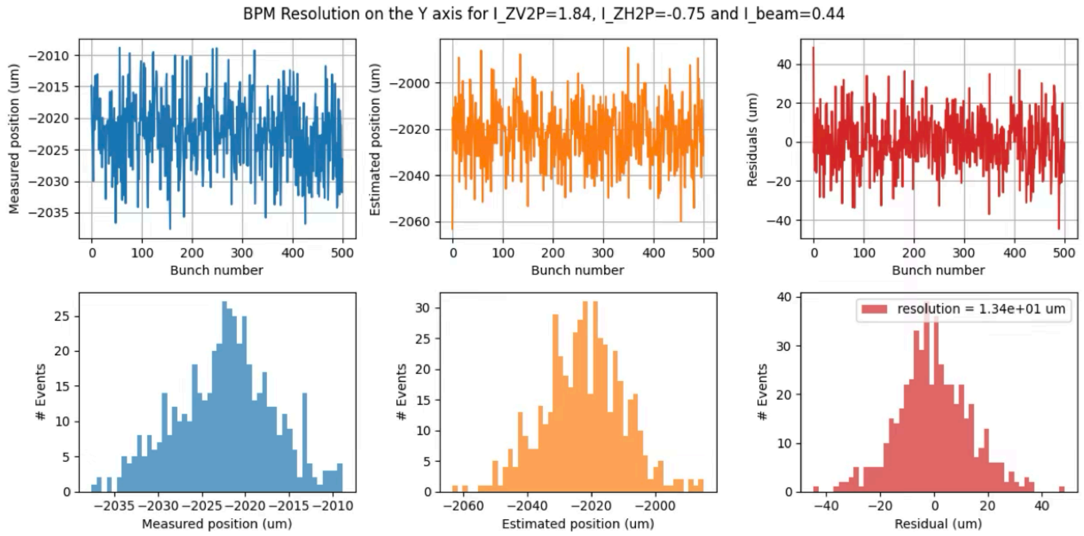


3 identical lines of down-conversion to 150 MHz:

- two for x and y signals (with RF = 1.725 GHz)
- one for reference signal (with RF = 1.255 GHz)



Best measured resolution: 13.4 µm



Beam instrumentation for HEP accelerators: Cavity BPMs R&D for the International Linear Collider project

Electromagnetic design of a new high resolution cBPM for the ILC Main Linac

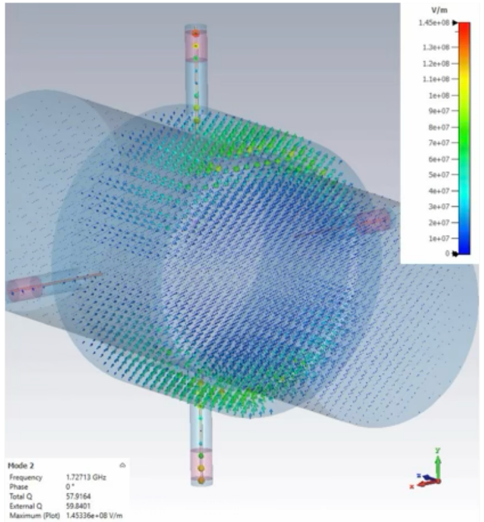
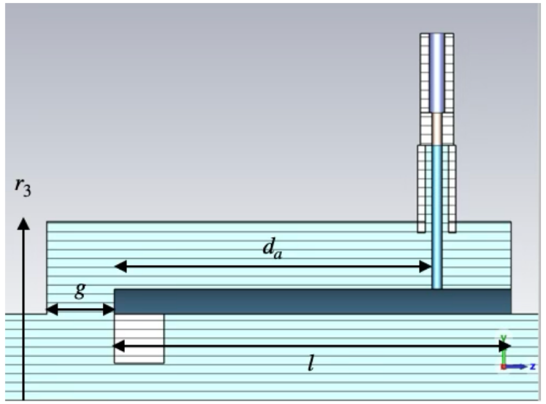


Figure: CST simulations of the CEA Saclay cBPM

CST and **HFSS** eigenmode and frequency domain simulations to evaluate the performance of the cBPM based on the RF parameters.
CEA Saclay is used as baseline prototype and **parametric studies** allowed us to converge to an optimized model:



Parameters of optimization:

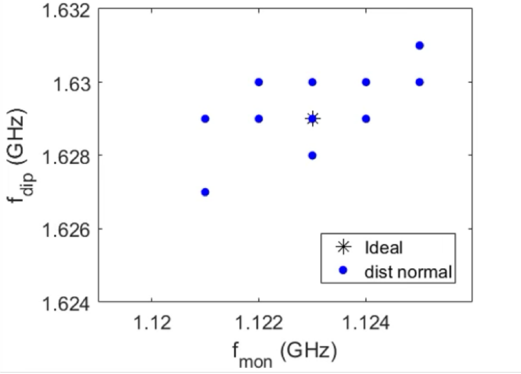
Uses a commercial feedthrough

Modification of parameters g = 10.25 mm, l = 53.3 mm, $r3$ = 51.75 mm and da = 45 mm to obtain desired performance

Mode	Monopole					Dipole (on x)				
	Freq (GHz)	Q_L	R/Q (Ω) @ 5 mm	S_{11} (dB)	S_{12} (dB)	Freq (GHz)	Q_L	R/Q (Ω) @ 5 mm	S_{11} (dB)	S_{12} (dB)
SACLAY	1.255	23.8	12.9	-5.7	-6.5	1.724	59	0.27	-25.0	-33
Our Optimization	1.120	37.65	14.47	-5.4	-6.6	1.626	72.30	0.357	-16.3	-30.6

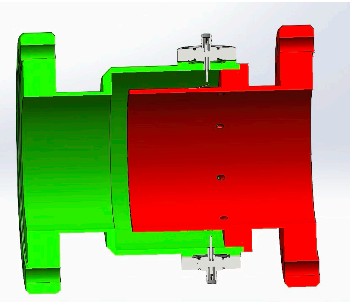
Increases signal length — Proper frequency for ATF — Increases sensitivity — Avoids cross-talk

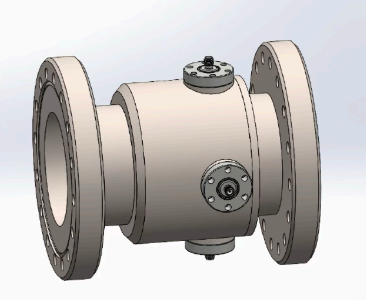
Tolerance studies:
manufacture tolerance with σ = 50 µm



Tolerance studies include: eccentricity of the cavity, misalignment when welding parts, effect of crooked feedthroughs, among others.

We are working with Neptury Technologies for the construction of the new cBPM.





Thank you for your attention!

Questions?

Contact : https://aitanatop.ific.uv.es/aitanatop/accelerator-physics/