INFN LNF Istituto Nazionale di Fisica Nucleare

SLAC NATIONAL ACCELERATOR LABORATORY

KEK

ASTERIX: Development of TIG-Welded Four-Quadrant X-Band RF Accelerating Structures at INFN.

Luigi Faillace

INFN – LNF, Frascati (Rome), Italy

Project Overview

The main goal of ASTERIX is the design, fabrication and high-power RF testing of a **practical meter-long, four-quadrant, "open-type" X-band accelerating structure** made of hard copper, joined and vacuum-sealed by TIG welding — a braze-free technique — targeting gradients above 100 MV/m.

- high **accelerating gradients (>100 MV/m)**
- composed of **four-quadrants** ("open-type")
- made out **hard copper**
- joined and vacuum sealed by using **TIG welding** ("braze-free" technique)

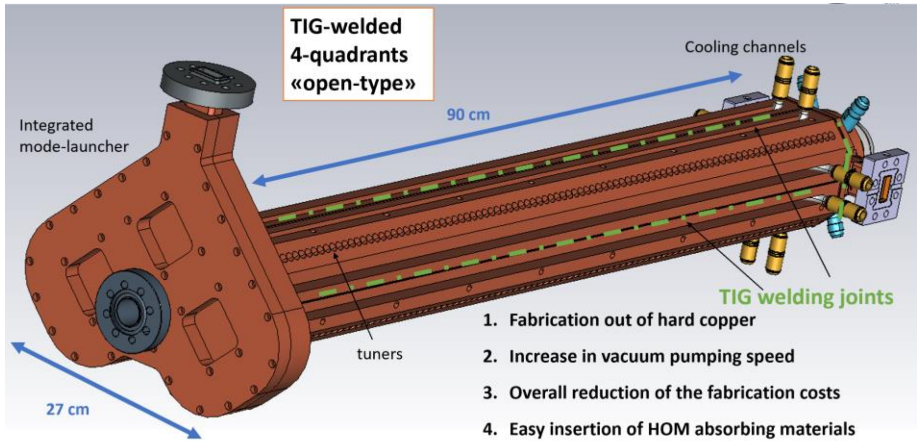
Funded by Scientific Committee 5 of INFN

Collaboration

LNF coordination · mechanical & RF design

LNS RF couplers · multiphysics simulation

Roma1 wakefield & HOM characterisation



90 cm, four-quadrant, TIG-welded "open-type" structure with integrated mode-launcher, cooling channels and tuners.

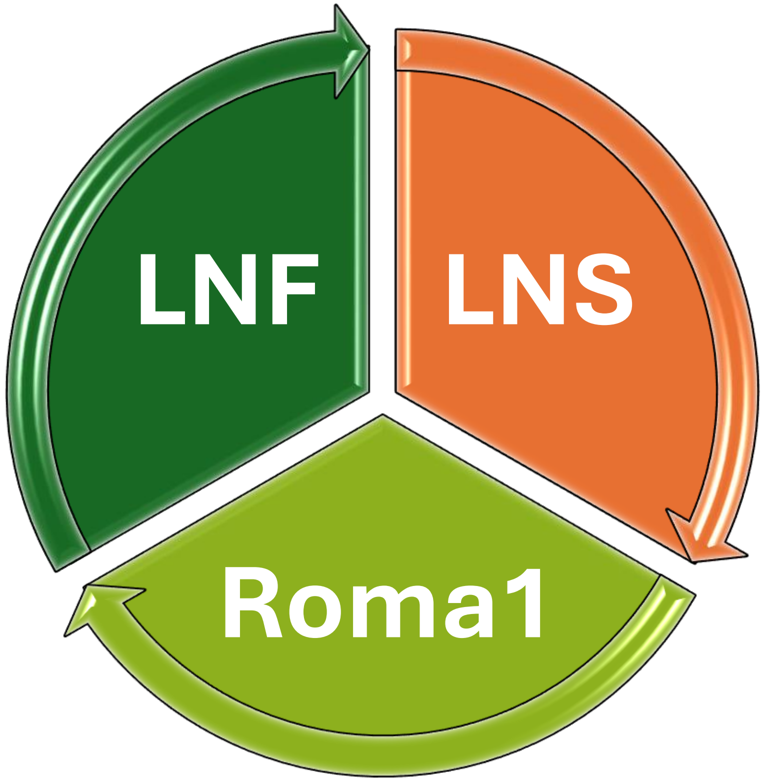
ASTERIX (**A**ccelerating **ST**ructures made of multipl**E** secto**R**s **I**n ***X***-Band)

PI: Luigi Faillace INFN-LNF

3 years (2025-2027)

Total budget = 400 kEuros

ASTERIX INFN- team



LNF	FTE	LNS	FTE	Roma1	FTE
L. Faillace (Resp. Naz.)	0.3	G. Torrisi (RL)	0.1	L. Ficcadenti (RL)	0.3
D. Alesini	0.2	D. Mascali	0.05	M. Petrarca	0.2
M. Bellaveglia	0.05	G. Mauro	0.1	M. Migliorati	0.2
S. Bini	0.2	G. Sorbello	0.2	G. Silvi	0.2
F. Cardelli	0.3	T. Isernia	0.3	L. Palumbo	0.4
M. Carillo	0.2	R. Palmeri	0.3		
E. Chiadroni	0.2	A. Locatelli	0.1		
A. Falone	0.2	C. De Angelis	0.1		
A. Gallo	0.15	L. Vincetti	0.1		
A. Giribono	0.2				
A. Liedl	0.1				
L. Piersanti	0.1				
S. Pioli	0.2				
B. Spataro	0				
C. Vaccarezza	0.2				
Tot./Unit	**2.6**		**1.35**		**1.3**

Contributors

This work is made possible by the efforts :

INFN Laboratori di Frascati, Roma1 (Sapienza University) and Laboratori del Sud (Catania)

SLAC(USA)

External Collaborators: V. Dolgashev (SLAC), Tetsuo Abe (KEK)

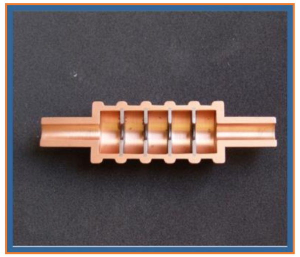
KEK (JAPAN)

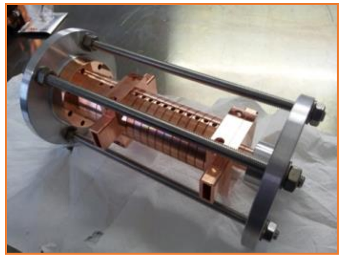
USTC (CHINA) University of Science and Technology of China: Yelong Wei, PhD student Zhicheng Huang in Frascati.

History

- **MOU between SLAC and INFN-LNF** within the world-wide collaboration on studies of RF breakdown physics in RF accelerating structures:

  from **X-band** (11-12 GHz) to other frequencies (S, C, Ka, W) .

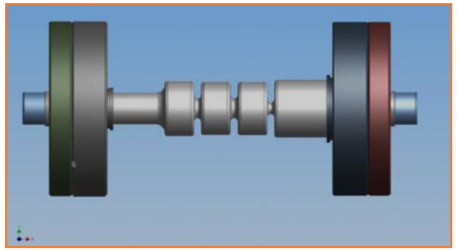
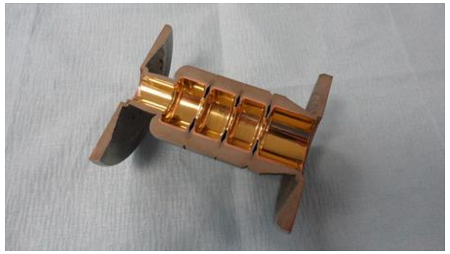





Courtesy of B. Spataro

- **DEMETRA (2016-18)**
- **ARYA (2020-23)**

Funded by CSN5 (V. Bonvicini)

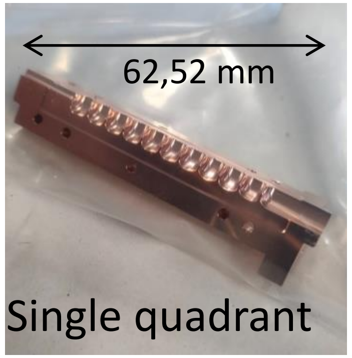




- **MICRON (2022-24)**

  Ka-band structures made of four quadrants

Resp. Loc. L. Faillace - LNF

Funded by CSN5 (A. Quaranta)



Single quadrant

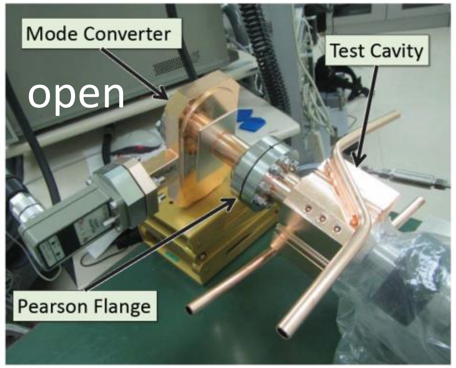
RF power Coupler: 4-port Mode Launcher

ASTERIX

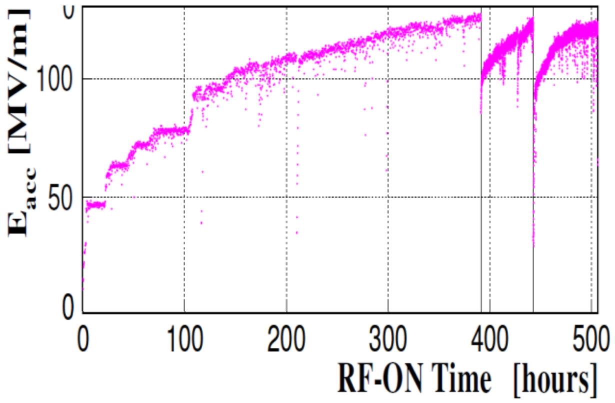
Accelerating **St**ructures made of multipl**E** secto**R**s **I**n ***X***-Band

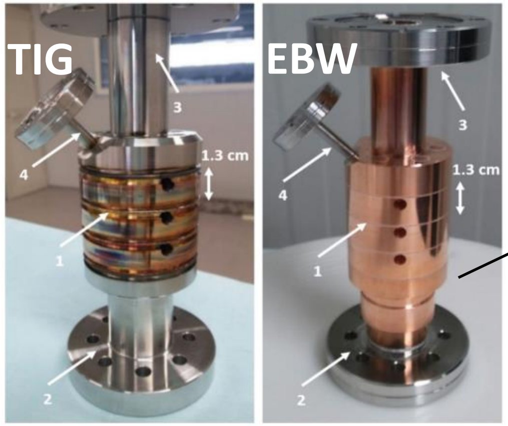
State-of-the-art

1. "Single-cell" cavities (open and closed; disk-type and multi-sector)

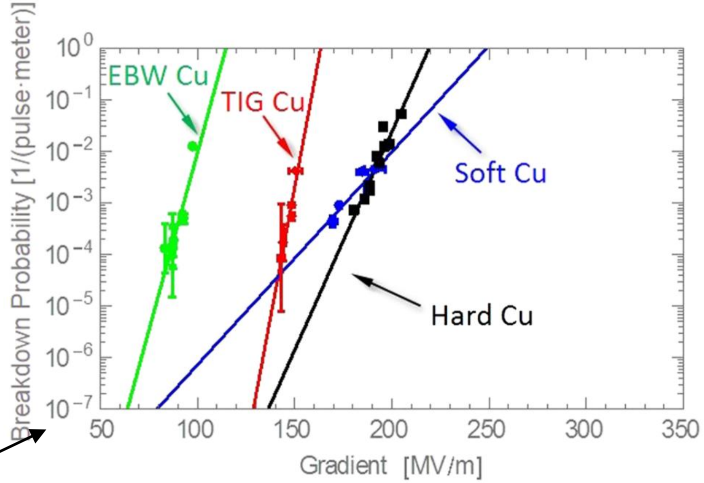


T. Abe, et al., High-gradient test results on a quadrant-type X-Band single-cell structure.



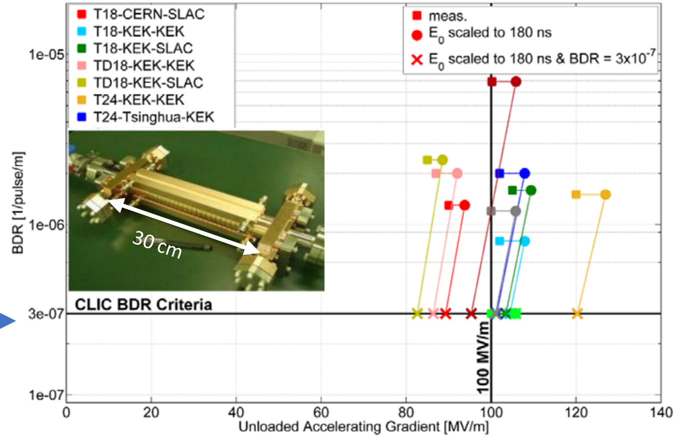


Dolgashev VA, Faillace L, Spataro B, Tantawi S, Bonifazi R. High-gradient rf tests of welded X-band accelerating cavities. Physical Review Accelerators and Beams. 2021 Aug 10;24(8):081002.



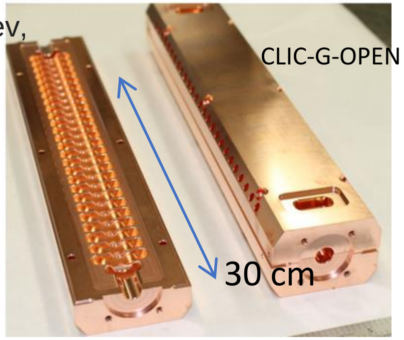
2. TW multi-cell structures (open and closed; disk-type and multi-sector)

3. Open-type multi-sector cavities, typically of small lengths (20-30 cm).



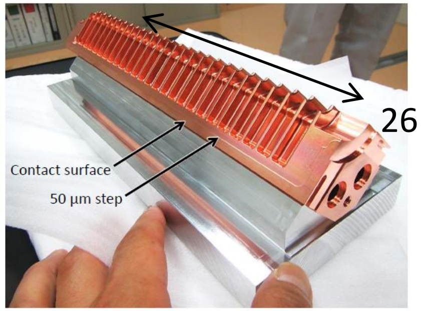
SLAC/CERN 2018 (Grudiev, Wuensch et al)
- X-band
- 2 halves, open structure
- Brazed
- High-power tested:

→ Gradient: 100 MV/m with 200 ns pulse length.



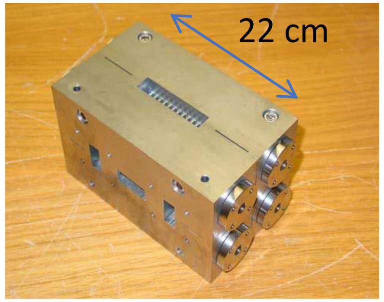
KEK (Tetsuo Abe) 2023
- X-band
- 4 quadrants
- EBW welding
- To be High-power tested.

(T. Abe)



26 cm

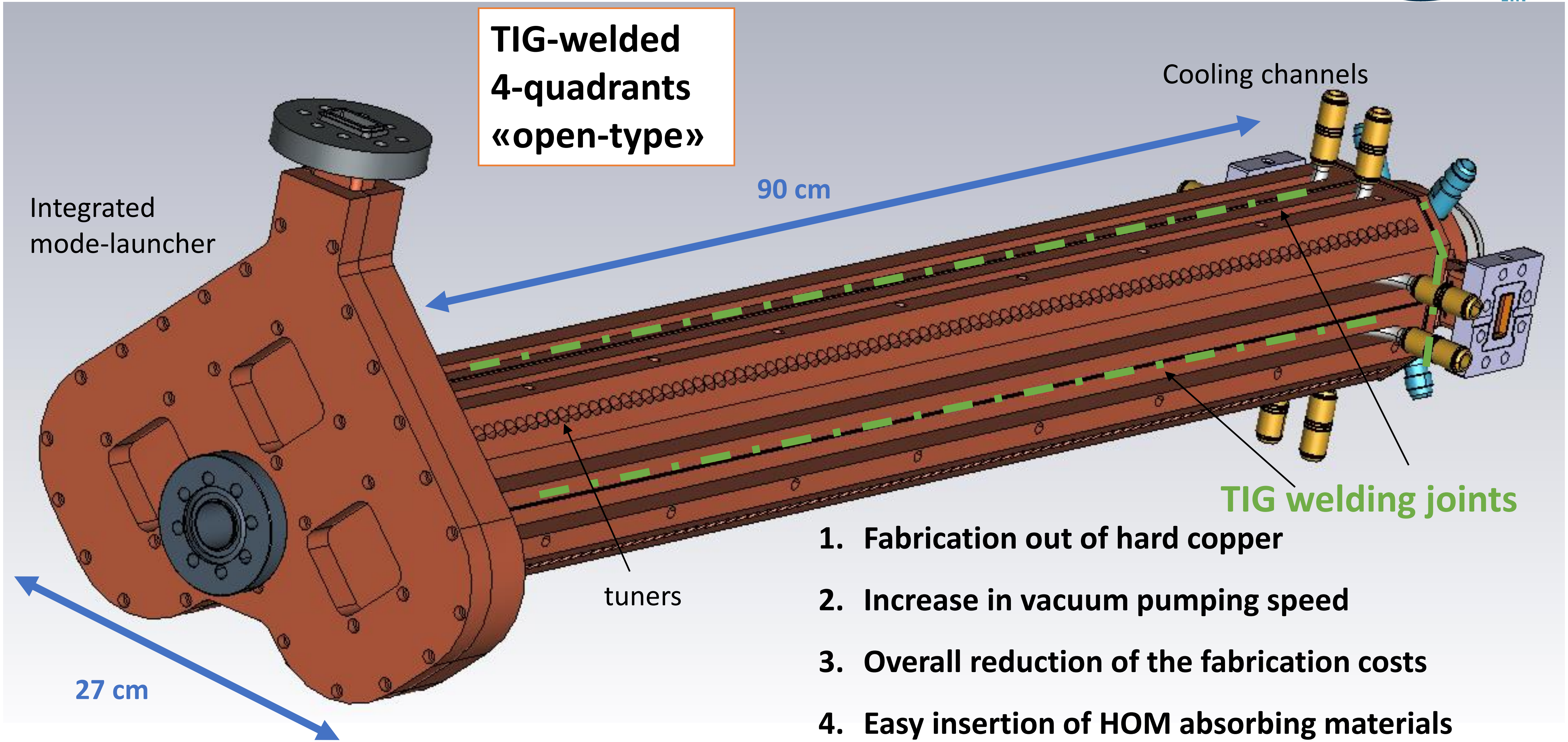
Figure 3: A quadrant fabricated with ultraprecision milling.



CERN 2007 (Dobert, Grudiev, Wuensch et al)
- X-band
- 4 quadrants
- Clamped, high T-treated
- High-power Tested:

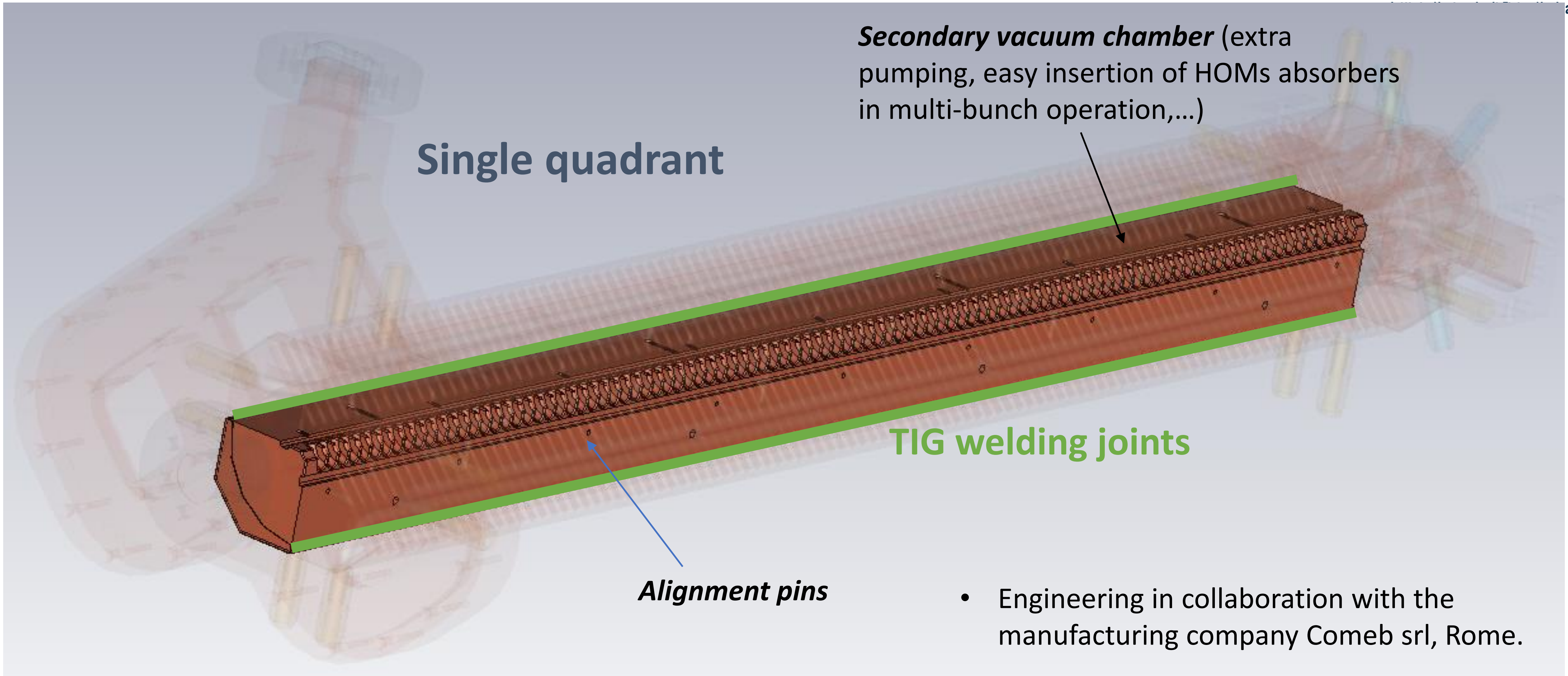
→ Gradient: 80 MV/m with 40 ns pulse length.

Full TW multi-cell X-band structure

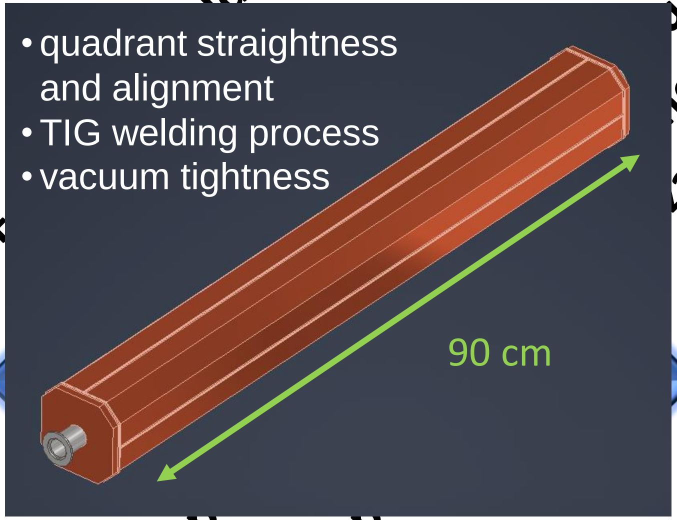


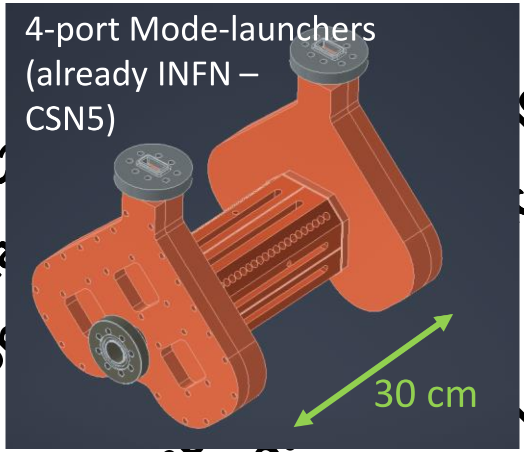
1. **Fabrication out of hard copper**
2. **Increase in vacuum pumping speed**
3. **Overall reduction of the fabrication costs**
4. **Easy insertion of HOM absorbing materials**

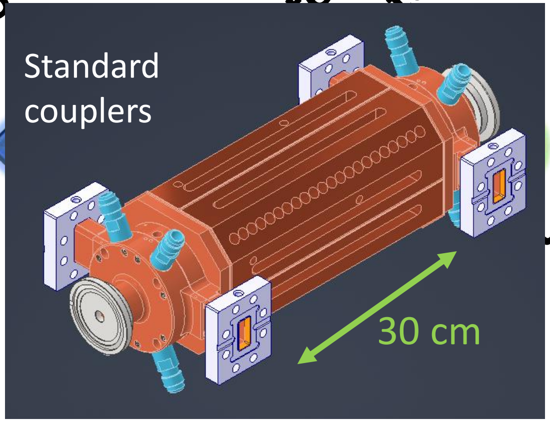
Full TW multi-cell X-band structure

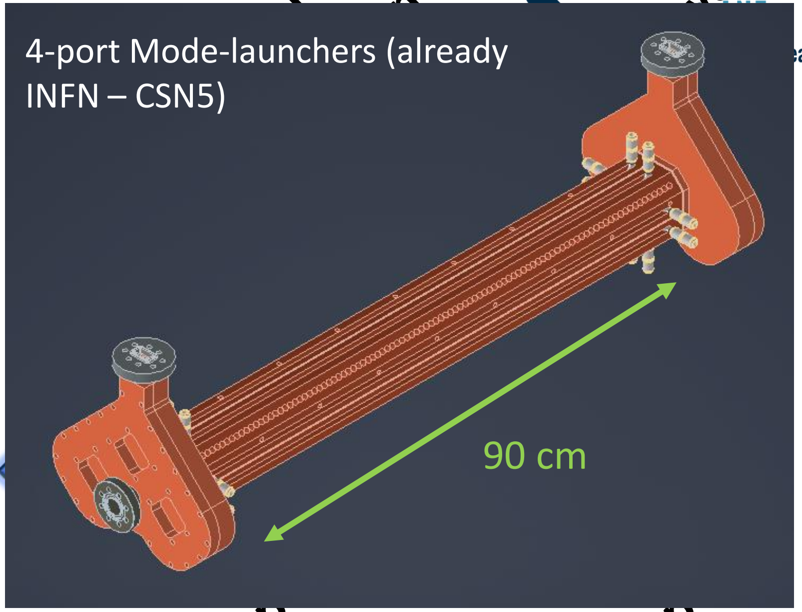


- Engineering in collaboration with the manufacturing company Comeb srl, Rome.









Report 3

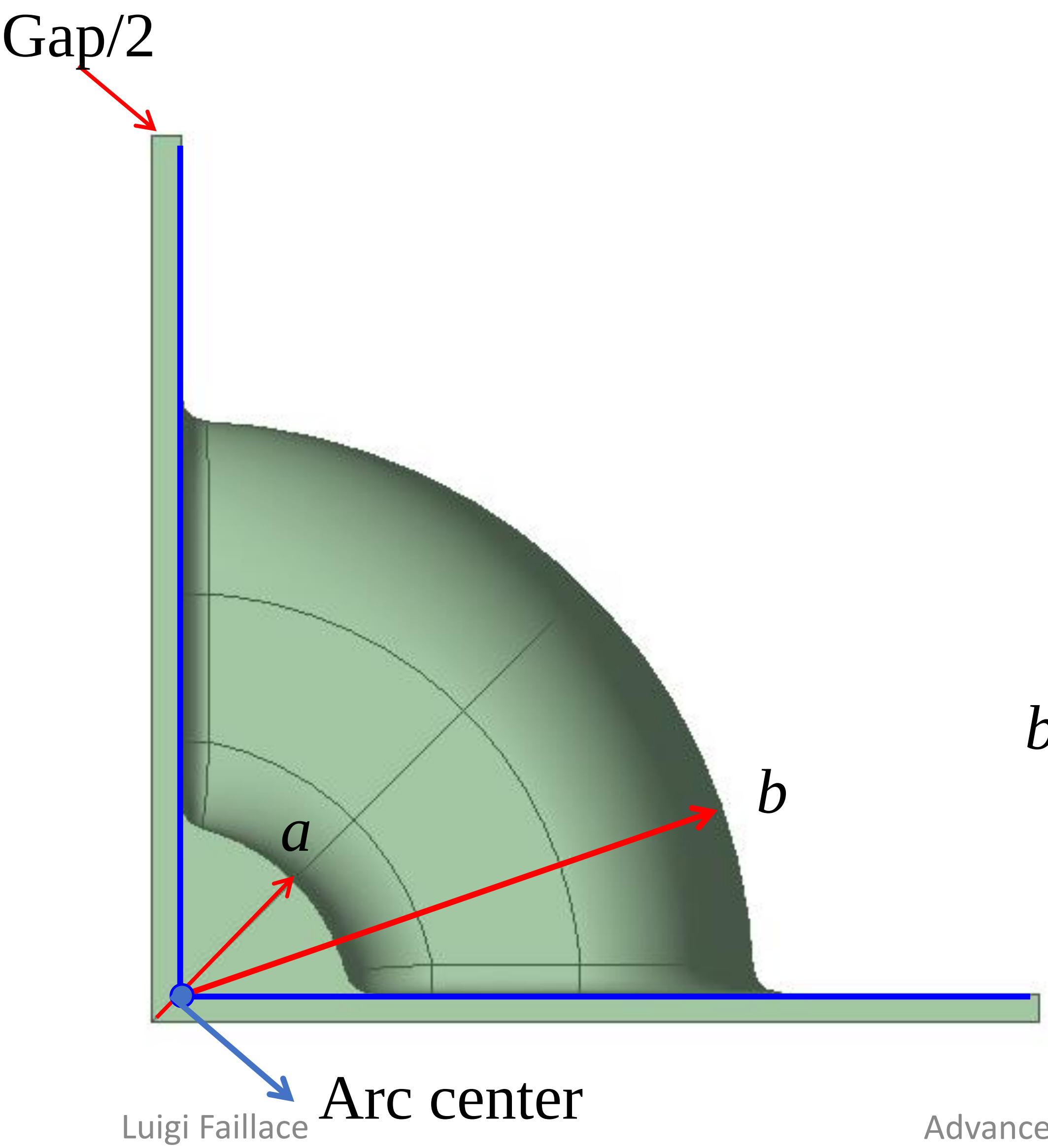
Start 2025	Feasibility Study	End 2025	Prototyping Activity	End 2026	Final full-structure Tests	End 2027

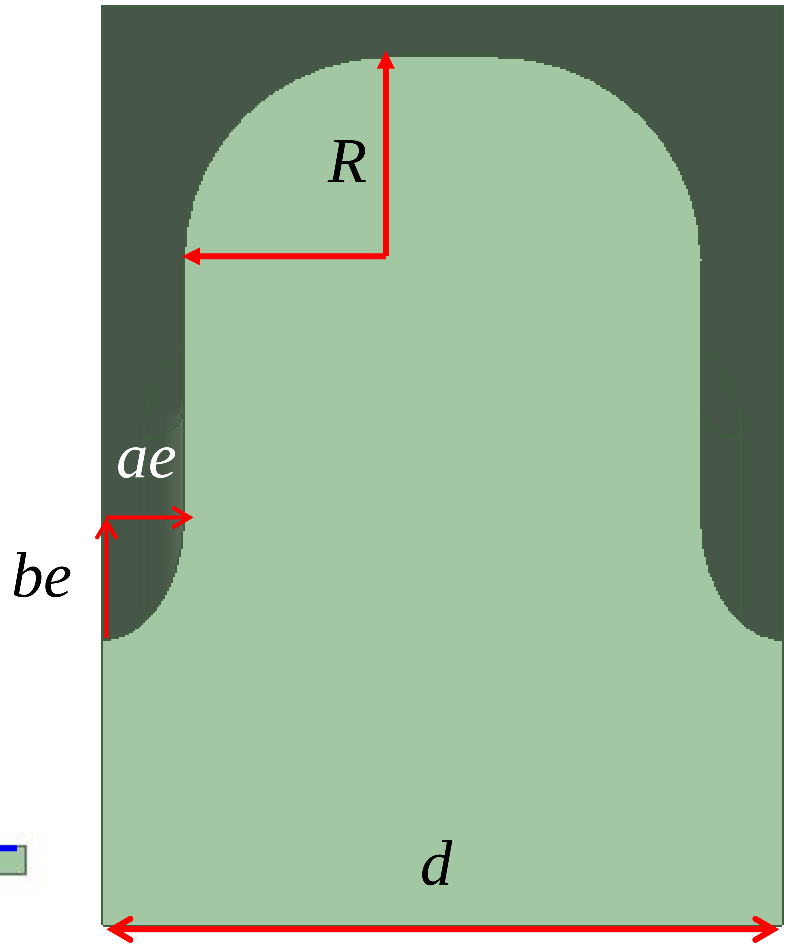
7 Milestones

6 Deliverables

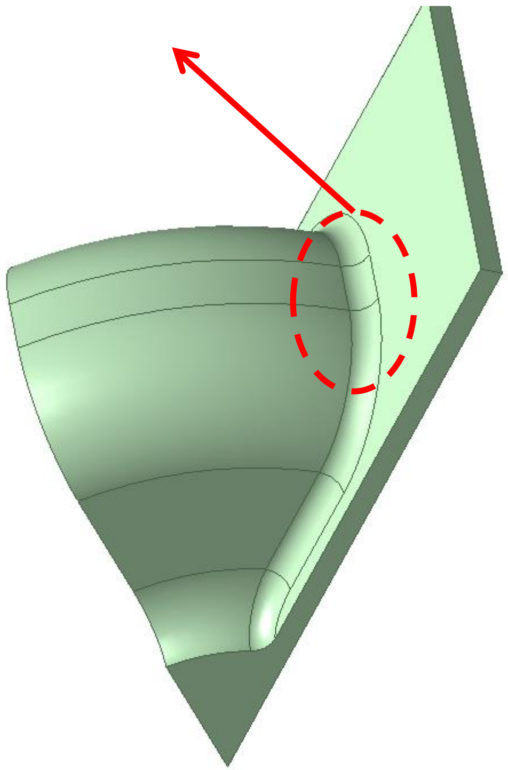
1. Report of the Feasibility Study (RF and Wakefields/HOMs);
2. Report of the Mechanical Engineering of the low-precision prototype with standard RF couplers for Mechanical, TIG welding and vacuum testing;
3. Report of the Mechanical Engineering of the small-scale structures with ad-hoc integrated RF Mode Launcher couplers;
4. Report of the low/high RF power testing of the small-scale structures;
5. Report of the Mechanical Engineering of the Full Structure with with ad-hoc integrated RF Mode Launcher couplers;
6. Final Report of low and High RF power testing of final full-scale structure.

ASTERIX cell geometry for single-bunch mode





Rounding: 0.5mm



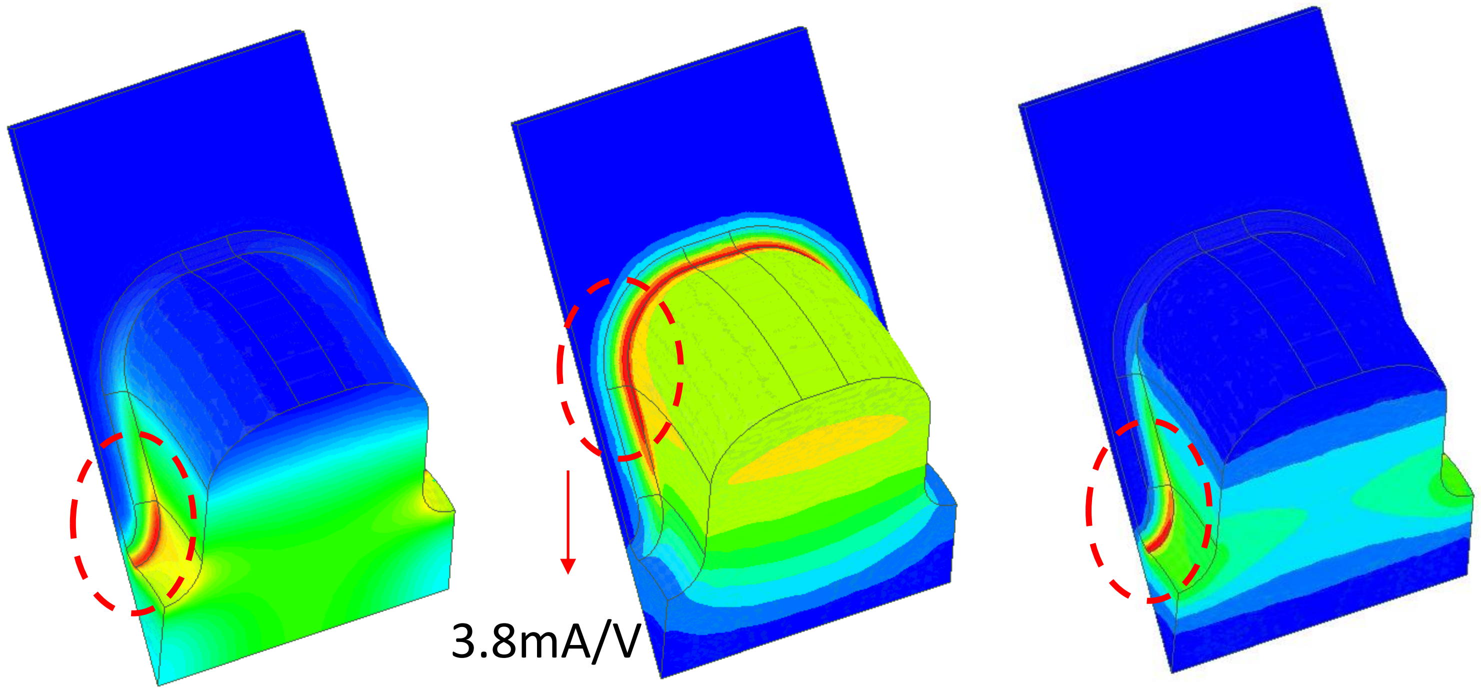
Cell Optimization

Optimization Target:
Low peak electric field ***Ep***, magnetic field ***Hp***, modified Poynting vector ***Sc***
High shunt impedance ***Rsh*** and ***Q***

Elliptical ratio → Ep, Sc
Rounding top → Hp

Iris radius fixed at a = 3.5mm

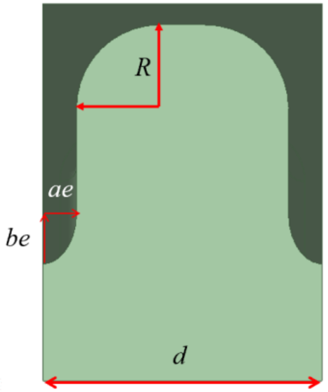
Conventional disk-loaded structure:
Ep/Eacc ≈ 2.1
Hp/Eacc ≈ 2.6 mA/V
Sc/Eacc^2 ≈ 0.6 mA/V
Q = 6800-7500 (different rounding)
Rsh = 105MΩ/m



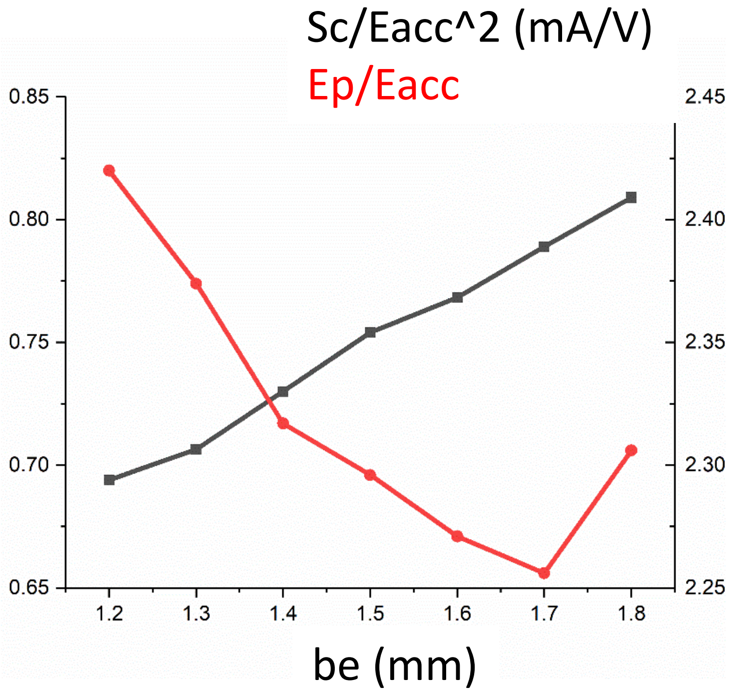
Ep/Eacc Hp/Eacc Sc/Eacc^2

The value will be shown later

Modified Poynting Vector and Peak E field

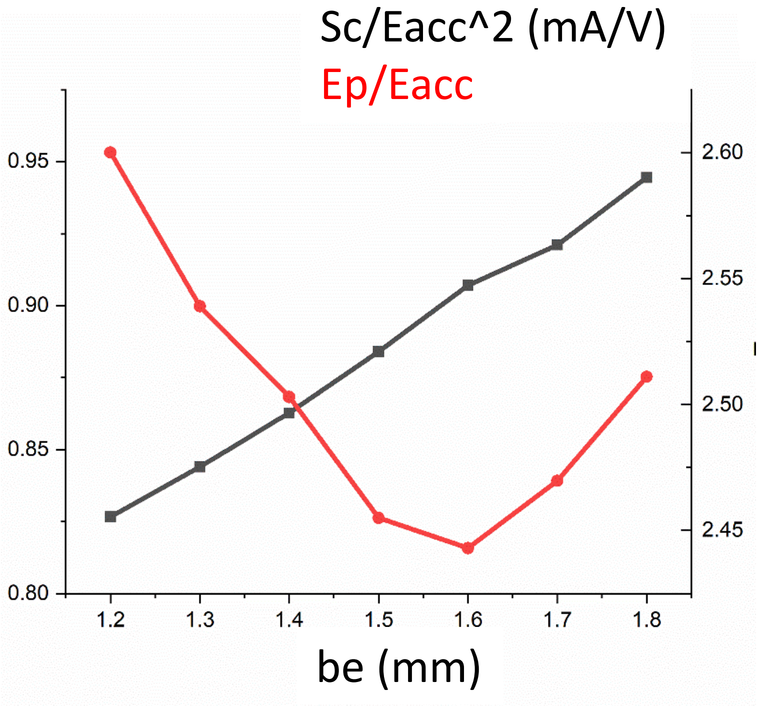


INFN LNF
Istituto Nazionale di Fisica Nucleare



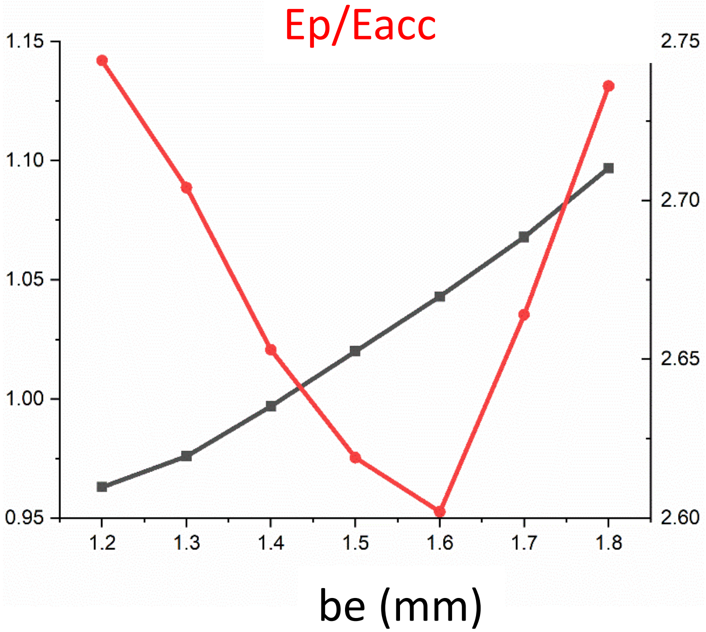
t=2ae=2mm, **gap = 0.5mm**

Optimal value: Sc/Eacc^2 = 0.694
Ep = 2.26
Desired point: be = 1.7mm



t=2ae=2mm, **gap = 1mm**

Optimal value: Sc/Eacc^2 = 0.827
Ep = 2.44
Desired point: be = 1.5-1.6mm

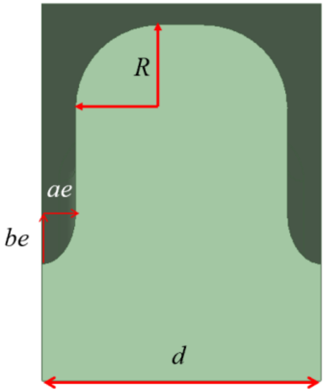


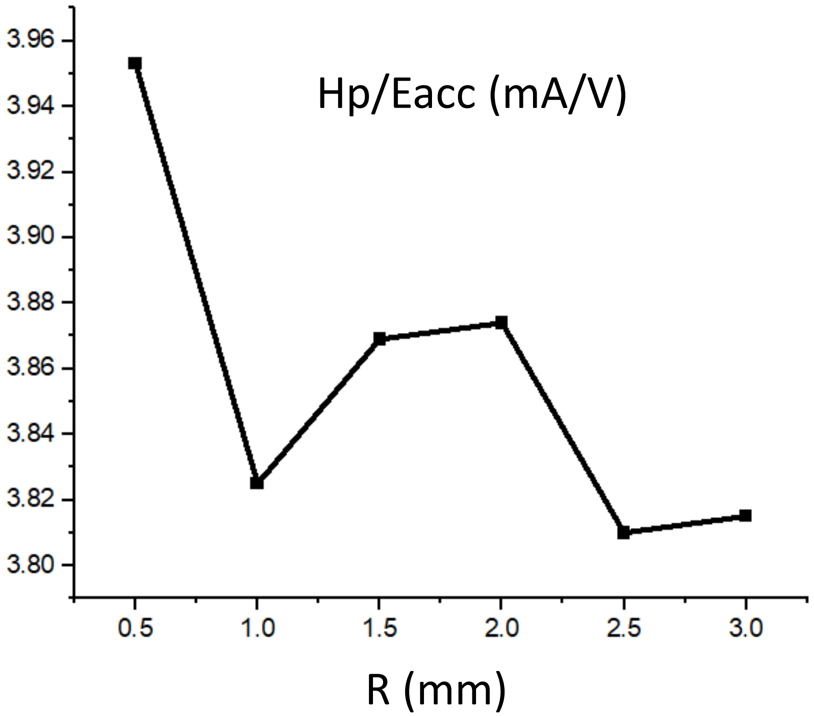
t=2ae=2mm, **gap = 1.5mm**

Optimal value: Sc/Eacc^2 = 0.963
Ep = 2.60
Desired point: be = 1.6mm

Hp, Rsh and Q for gap=1mm

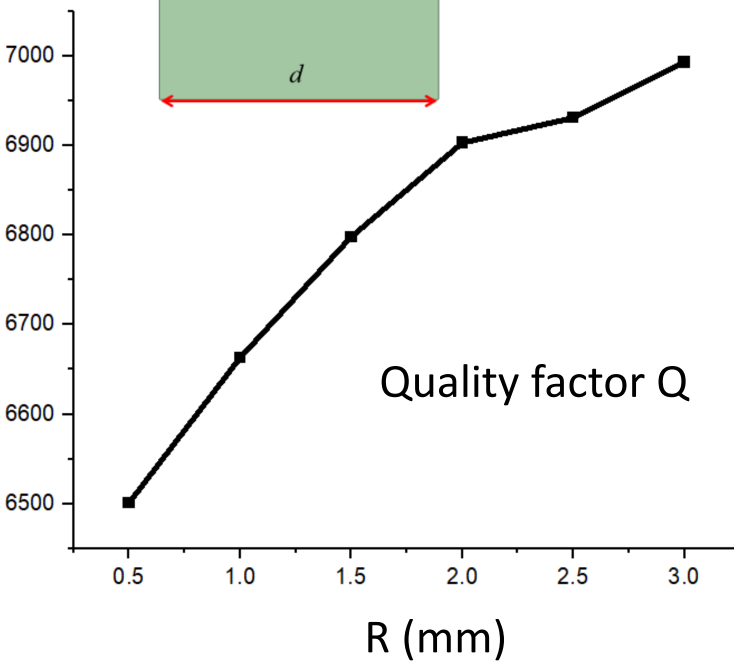
INFN LNF
Istituto Nazionale di Fisica Nucleare





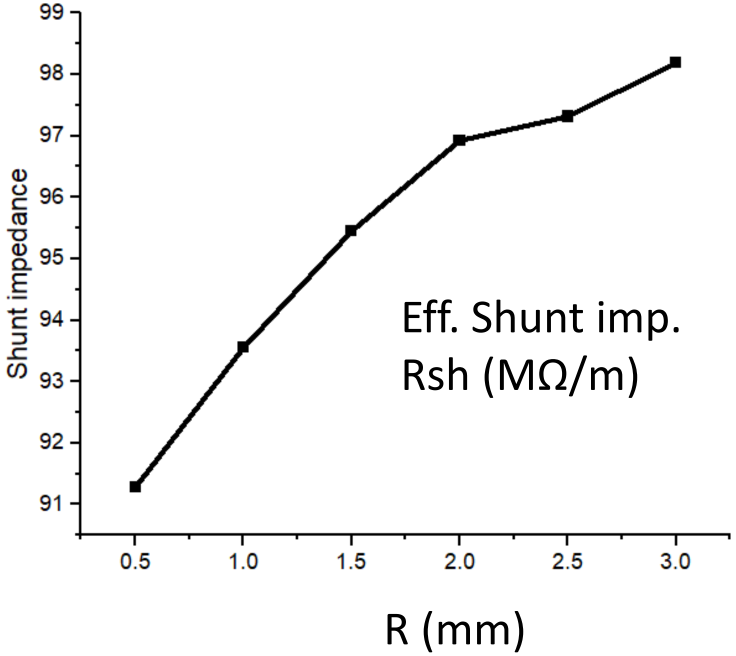
t=2mm, **gap = 1mm**

No significant influence



t=2mm, **gap = 1mm**

Optimal Q :7000

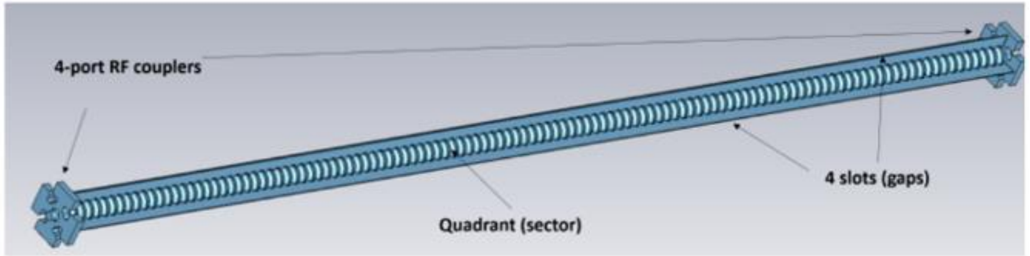


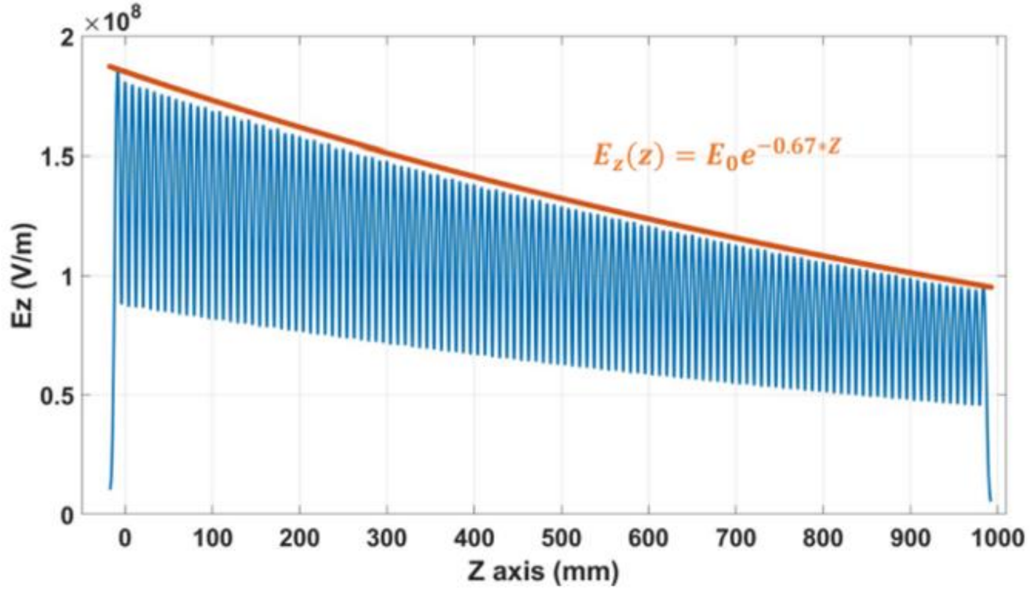
t=2mm, **gap = 1mm**

Optimal impedance: 98.21MΩ/m

Hp is hard to be reduced !!

RF design of the full-scale structure





Top: full 1-metre-long, four-quadrant structure model. Bottom: on-axis electric-field profile.

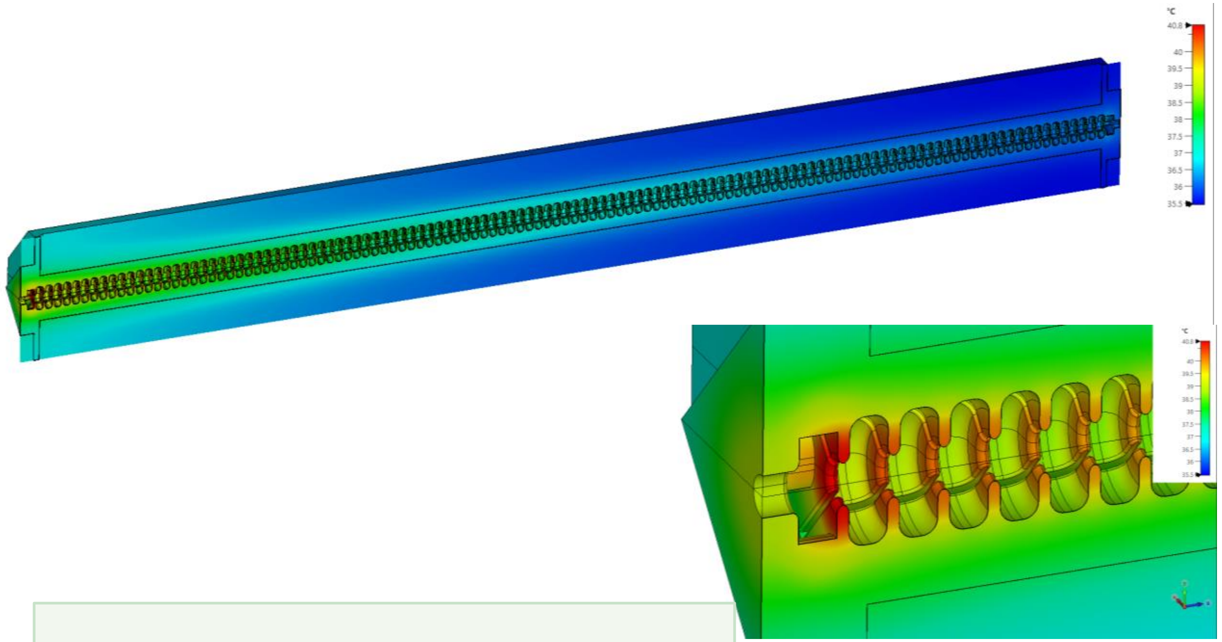
Parameter	Value
Frequency	11.994 GHz
Accelerating gradient	100 MV/m
Input power	77 MW
Operating mode	2π/3
Number of cells	120
Full structure length	1 m
Quality factor	6931
Shunt impedance	97.3 MΩ/m
Peak surface field, Ep	245 MV/m

INFN LNF
Istituto Nazionale di Fisica Nucleare

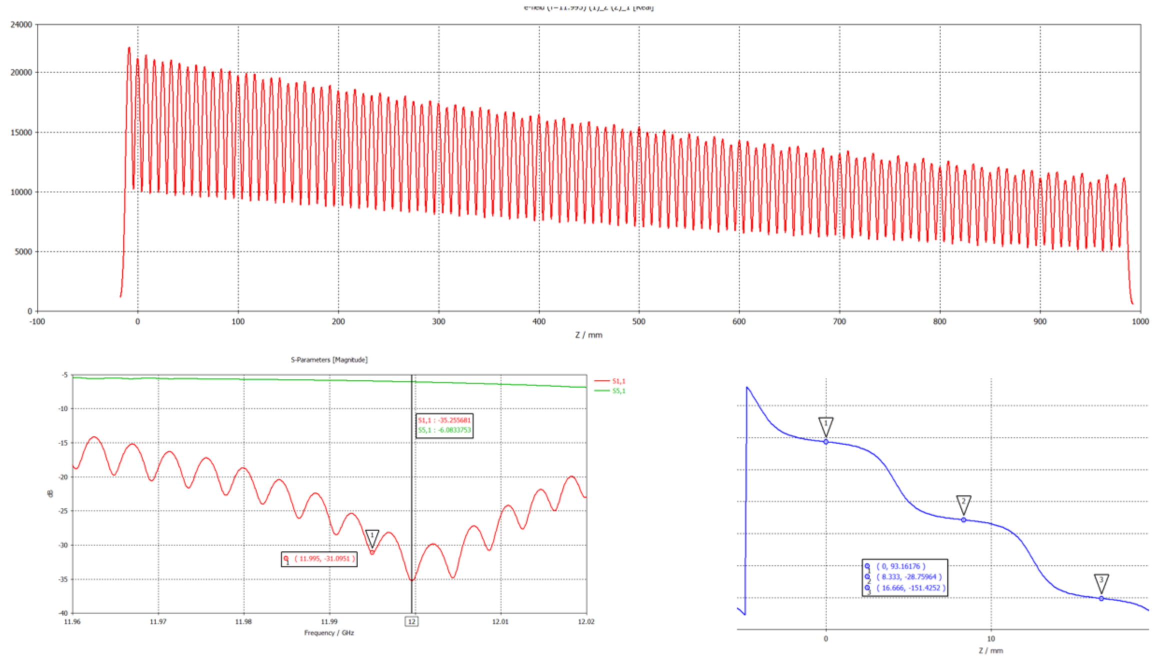
RF–thermal–mechanical multiphysics

Closing the loop between RF losses, cooling, deformation and RF detuning

1 RF baseline field profile phase advance → **2 Thermal wall losses temperature map** → **3 Mechanical thermal expansion deformation** → **4 RF feedback S-parameters field profile**



CST/COMSOL cross-check: temperature distributions agree within about 1 °C.

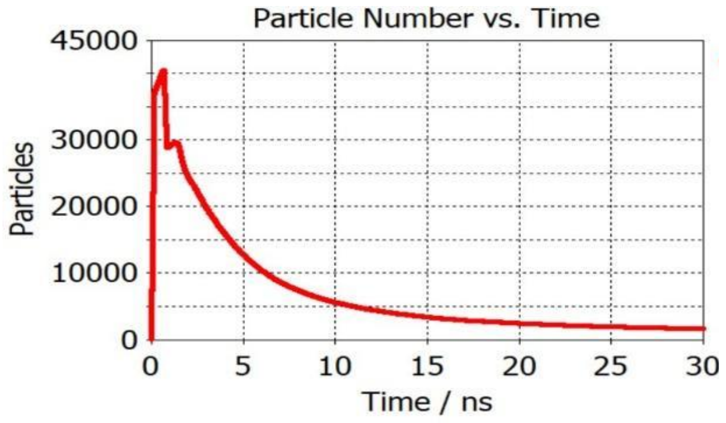


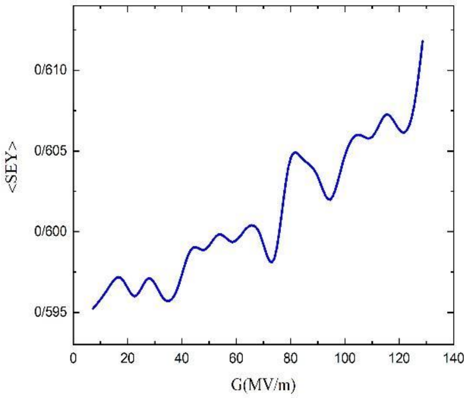
Frequency and field profile/Phase show negligible variation due to temperature gradient distribution along structure

Multipacting, wakefields and HOM studies

Risk reduction before high-power operation

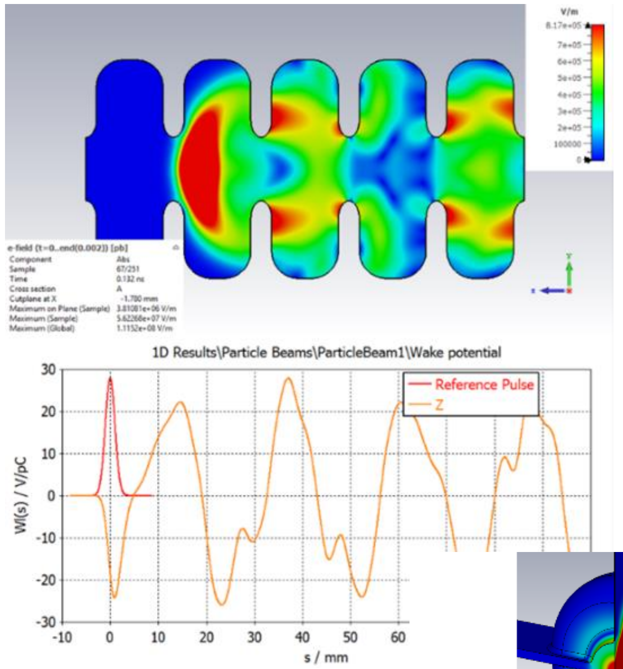
Multipacting analysis





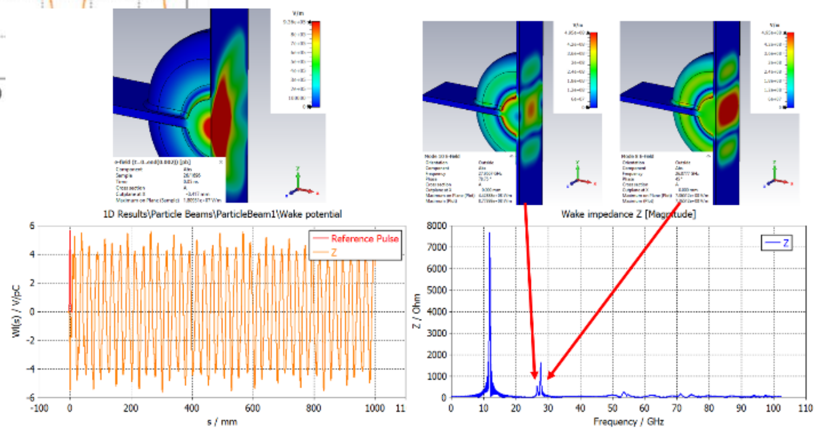
- gradient scan on full quarter-cell model
- gap-size study in internal technical report
- electron population decays in simulations (no MP)
- no critical multipactor observed in investigated range 0.1 mm – 1mm gap (the average SEY remains below unity across the explored gradient range, and the mean collision energy stays below the SEY-unity threshold)

Wakefields / HOM optimization



- single- and multi-bunch operation considered
- HOM mitigation compatible with open-sector concept

- single-bunch case, a Gaussian beam with 1 mm rms bunch length and 200 pC of charge → 1keV energy spread



Mechanical design & prototype fabrication

During the first project year, LNF completed the mechanical drawings and engineering of the full-scale structure (without RF couplers), fabricated to validate:

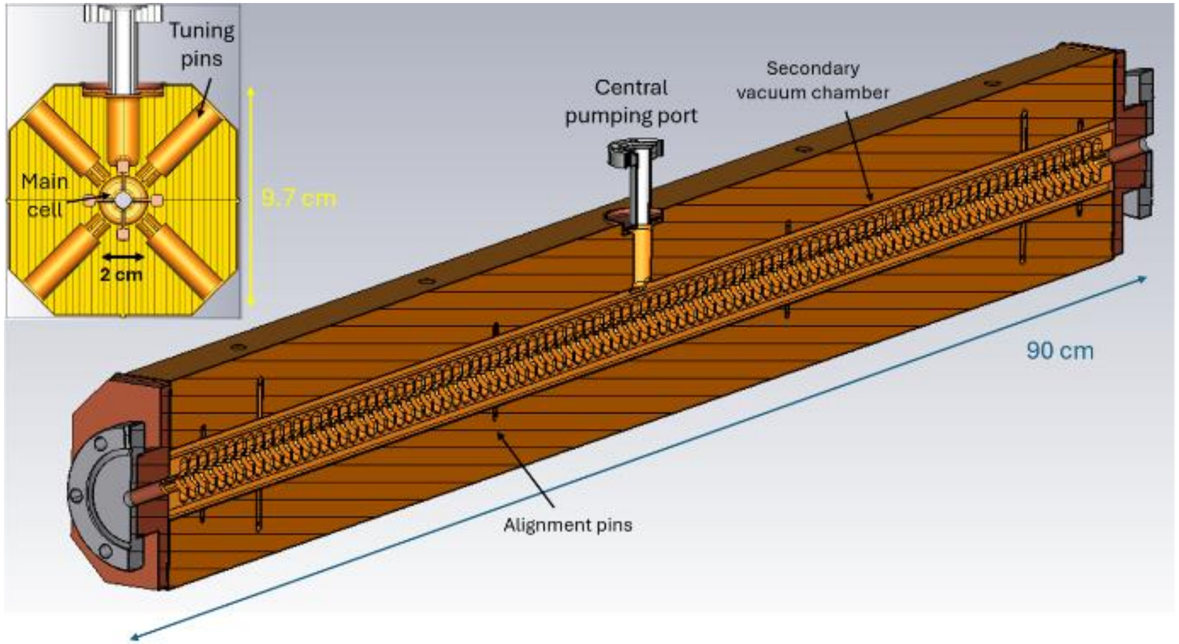
- TIG-welding process
- Structure straightness & quadrant alignment
- Vacuum performance

Machining — complete

Machine: Doosan DNM 750L CNC

Roughness: **Ra** < 1 um

All four quadrants machined on a single CNC capable of hosting the full-length parts.



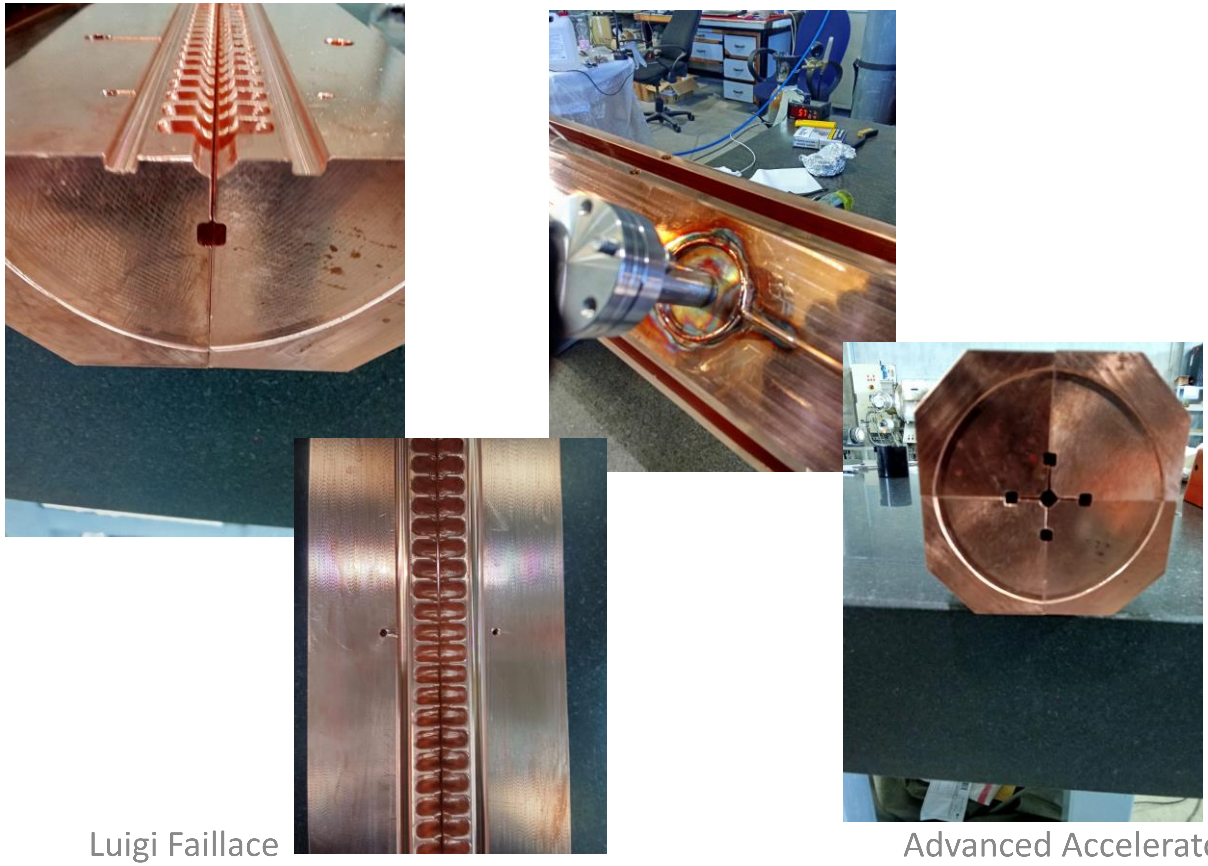
Final CAD model — tuning pins, alignment pins, welding teeth, central pumping port and secondary vacuum chambers.



One quadrant on the inspection table (left); close-up showing individual machined cells (right).

Joining and welding

The quadrants were joined by **TIG welding**, with inert gas flushed during the process to protect the weld and preserve the internal vacuum surfaces — the “braze-free” approach central to ASTERIX.



Left: ASTERIX prototype being TIG welded. Right: TIG-welded prototype on the CMM table for mechanical characterization.

Qualification status

A comparison of the dimensional measurements acquired before and after the welding process indicates only minor deviations at the inspected locations:

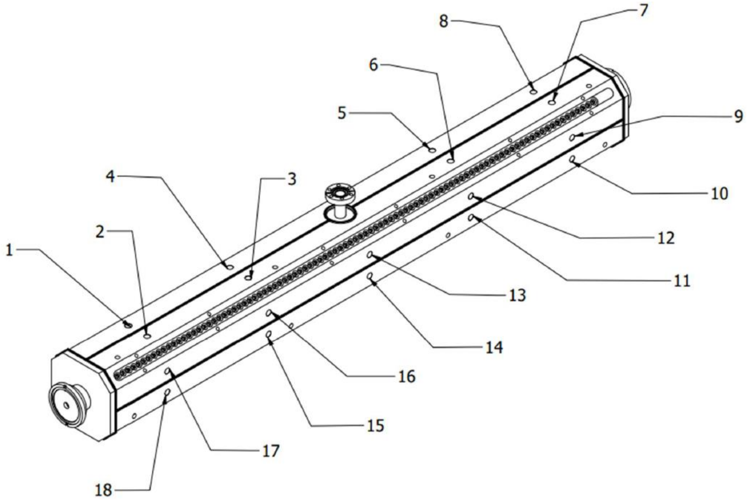
→ straightness **max error 20 um, over 1 m.**

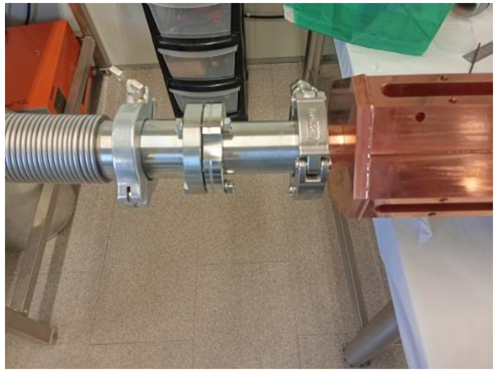
The observed dimensional variations are minimal and within the expected process capability

→ the welding operation preserved the dimensional integrity of the component and was successfully completed without introducing significant deformation.

Result: Positive

Mechanical and vacuum tests on the welded prototype were performed and produced a positive outcome.





Vacuum Leak Check

Conclusions and Future Work

INFN LNF
Istituto Nazionale di Fisica Nucleare

- Two small-scale prototypes, in single-bunch geometry, to be LOW and HIGH power tested in 2026.
- Low RF power measurements are performed at the INFN LATINO Lab.
- **Full length structure (single-bunch mode) to be machined and high RF powered tested at TEX Facility in Frascati by the end of 2027.**