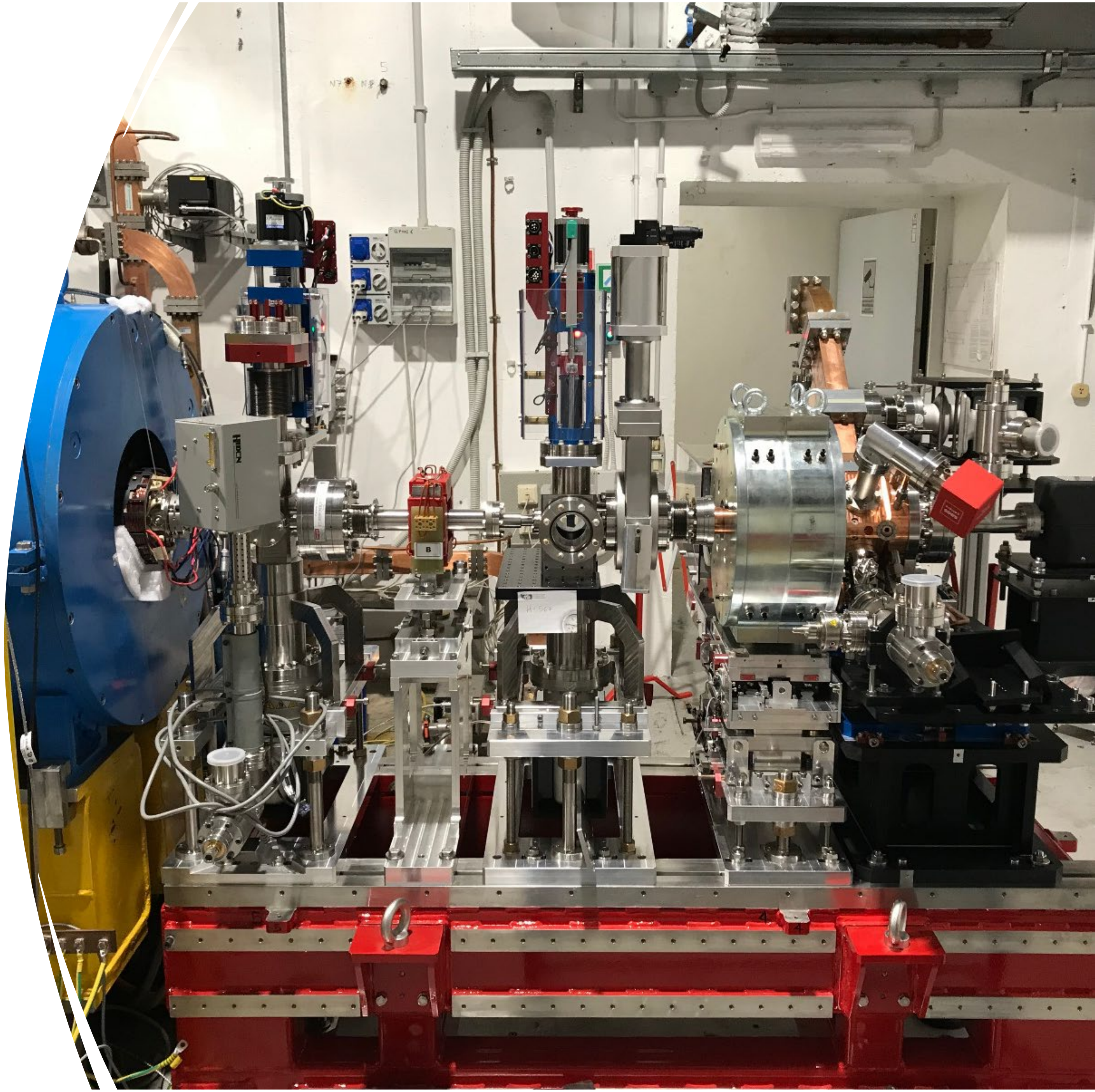
Design, test and commissioning of high gradient structures at LNF

L. Piersanti on behalf of the LNF RF team

Seminari tematici INFN-A 14/04/2023



Outline

- Introduction to standing wave (SW) and travelling wave (TW) accelerating structures
- State of the art of high gradient structure design
- High gradient structures R&D at LNF:

Braze-free SW cavities | **C-band TW structures** | **X-band TW prototype for EuPRAXIA@SPARC_LAB**

- Conclusions and future perspectives

Introduction to accelerating structures: light vs heavy particles

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Light particles (as electrons) are essentially fully relativistic ($\beta \approx 1$, $\gamma >> 1$) at relatively low energy (few MeV).

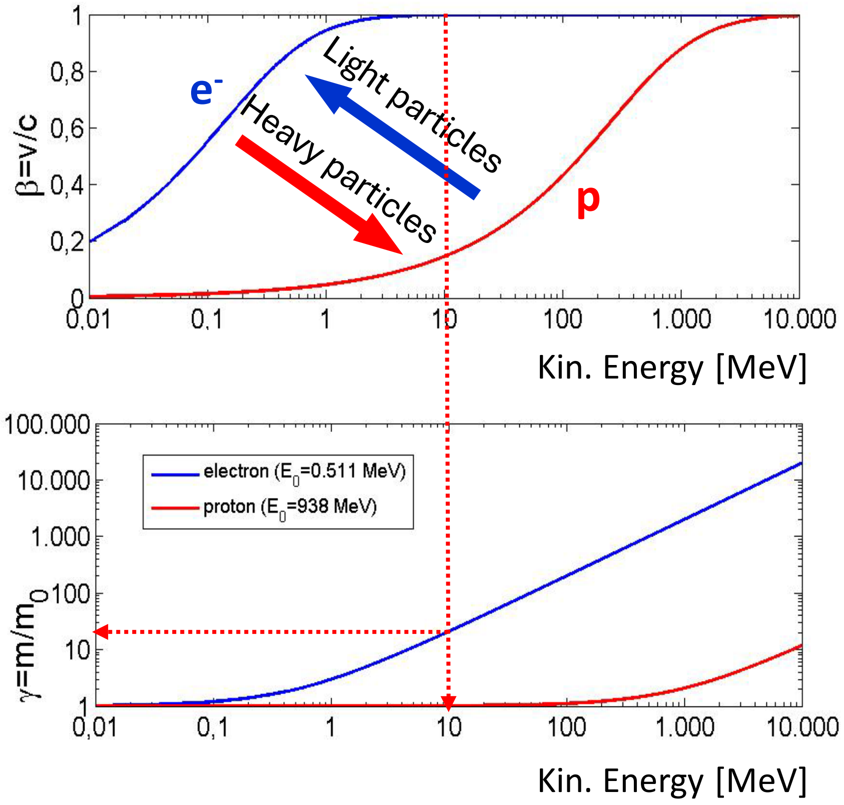
The acceleration process occurs at constant particle velocity

Heavy particles (protons and ions) are typically weakly relativistic and reach a constant velocity only at very high energy.

The velocity remarkably changes during the acceleration process

This implies important differences in the technical features of the accelerating structures and in the beam dynamics for the various particle species.

In the following only **normal conducting accelerating structures for electrons** will be reviewed



Standing wave & travelling wave accelerating structures working principle

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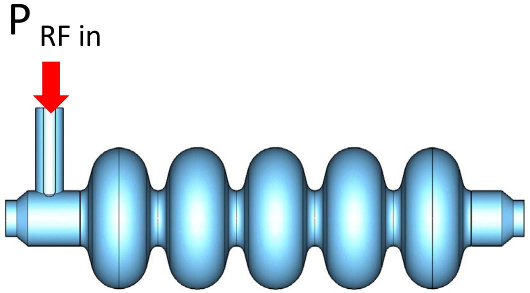
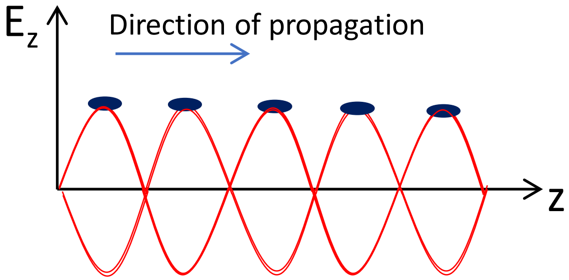
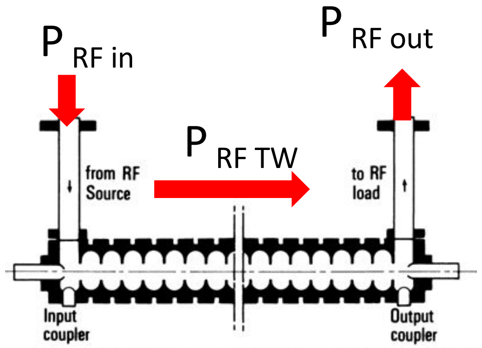
Two kind of accelerating structures are employed for electrons acceleration: standing wave (SW) and travelling wave (TW)

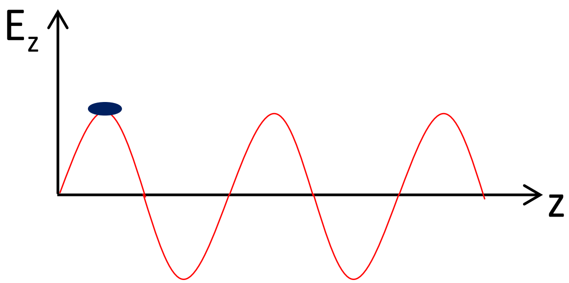
- SW structures are high frequency resonant cavities where the EM fields can only exist in a particular spatial configuration (resonant modes) whose components oscillate at some specific frequency f_{RF} (resonant frequency) typical of the mode.
- Assuming to excite a mode with $E_z \neq 0$, if the phase of the RF field and electrons arrival time are well synchronized, particles experience an accelerating field





- TW structures are special waveguides, periodically loaded by irises, in which EM fields and beam travel together. If the **wave phase velocity** matches **particle velocity**, the beam absorbs energy from the wave and is continuously accelerated.





Typically, these structures **are used only for electrons** because $\mathbf{v_{ph}}$ **can be assumed** equal to **c** all along the structure.
It is difficult to modulate $\mathbf{v_{ph}}$ very quickly for a low β particle that changes its velocity during acceleration.

Standing Wave structures: high beta cavities and main parameters

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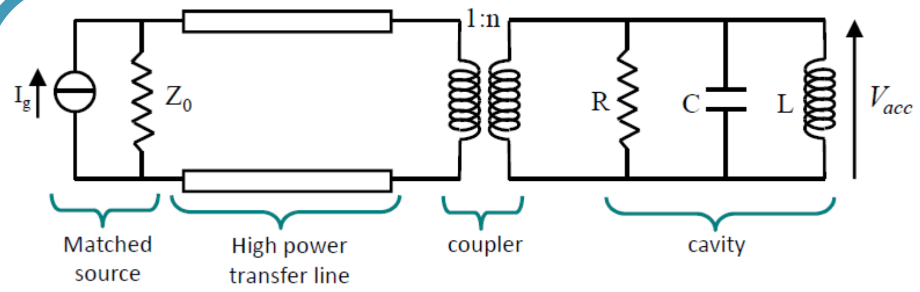
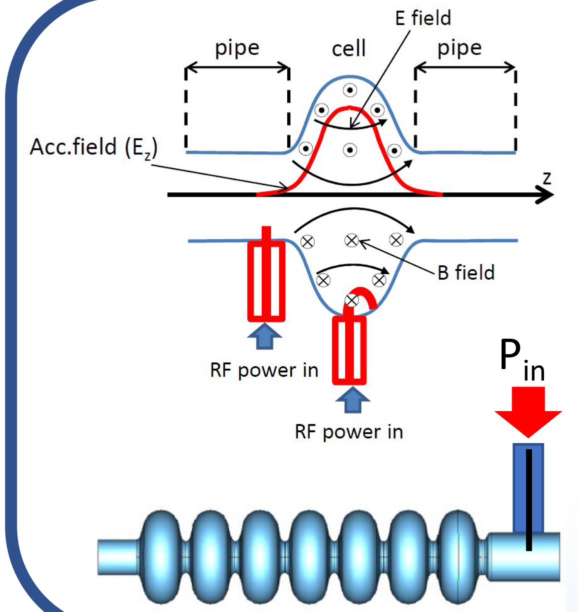


$$R = \frac{\hat{V}_{acc}^2}{P_{diss}} \ [\Omega] \qquad Q = \omega_{RF} \frac{W}{P_{diss}}$$

- Shunt impedance **R** qualifies the **efficiency of an accelerating mode**. The higher its value, the larger is the obtainable accelerating voltage for a given power dissipated on the cavity walls.

- Quality factor **Q** takes into account the ohmic losses in the cavity, i.e. a certain amount of RF power must be provided to keep the accelerating fields at the desired level. If the external excitation is turned off the fields decay exponentially with a time constant $\tau_n = 2Q/\omega_n$



For a **pure cylindrical structure** ("pillbox cavity") the first accelerating mode (i.e. with non-zero longitudinal electric field on axis) is the **TM_{010} mode**. It has a well-known analytical solution from Maxwell equation. **Real cylindrical cavities: TM_{010}-like mode** (because of the shape and presence of beam tubes).

It is also possible to realize a **multi-cell structure** where one RF input coupler feeds many cavities. The adjacent cavities are coupled by means of irises and/or special coupling slots.
Advantages: reduced **number of RF sources**; RF **layout simplification** and **reduction of the costs; R_n=n*R;**
Disadvantages: **higher fabrication complexity.**

TW figures of merit, constant impedance and constant gradient structures

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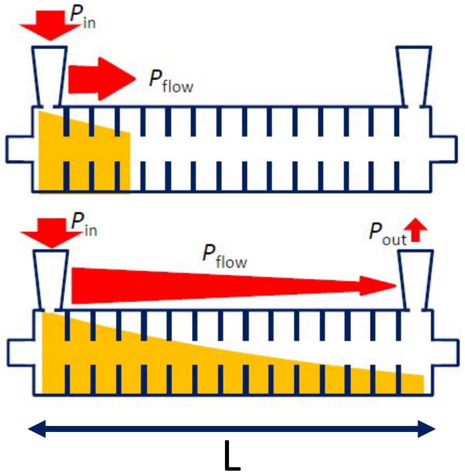
Like for SW cavities it is possible to define some figure of merit for the TW structures:

Shunt impedance per unit length $r[\Omega/m] = \hat{E}_{acc}^2/p_{diss}$

Group velocity $v_g[m/s] = P_{in}/w$: the velocity of the energy flow in the structure

Field attenuation constant $\alpha[1/m] = p_{diss}/2P_{in}$

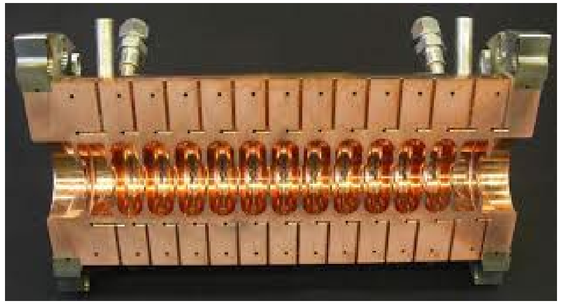
Working mode $\Delta\phi[rad] = kD$ field phase advance over a period D

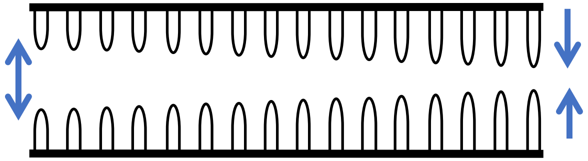


In a purely periodic structure, made by a sequence of **identical cells** (called "**constant impedance - CI**"), the RF power flux and the intensity of the accelerating field decay exponentially along the structure:

$$\tau_F = \frac{L}{v_g} \qquad \hat{E}_{acc}(z) = E_0 e^{-\alpha z} \qquad P(z) = P_{in} e^{-2\alpha z}$$

It is possible to keep the **accelerating field constant**, but the **iris aperture needs to be reduced along the structure ("constant gradient - CG").**





CI ADVANTAGES:

- Sequence of identical cells: easier fabrication, lower costs

CI DISADVANTAGES:

- In order to reach a target avg. gradient, a much higher gradient will be required in the first cells (increased probability of breakdowns)

CG ADVANTAGES:

- Slightly more efficient acceleration and lower surface fields

CG DISADVANTAGES:

- Each cell is machined separately, irises reduction in the last cells (more difficult vacuum pumping and beam clearance)

State of the art

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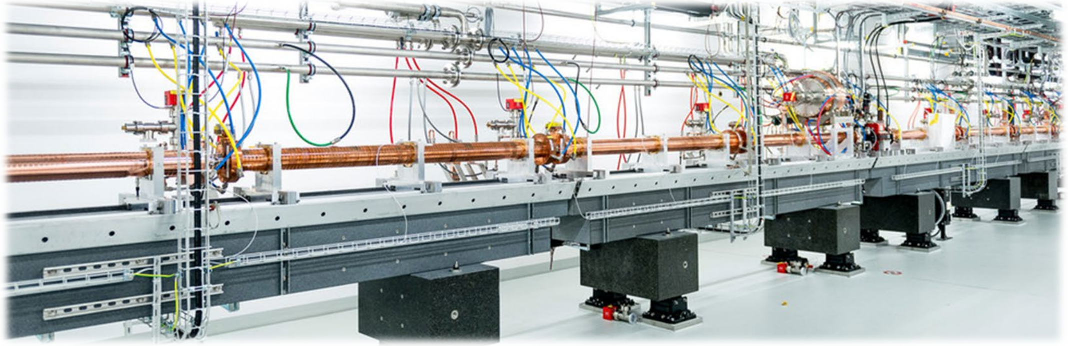
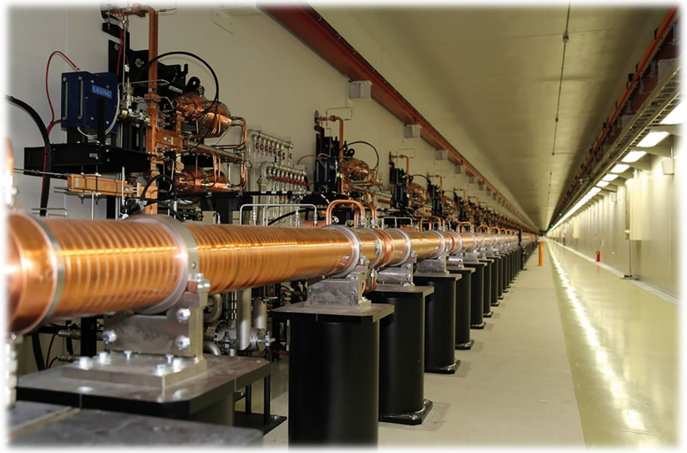
Where it all started…

SLAC – Two mile accelerator
960 structures, S-band (2.856 GHz) 3m, **20 MV/m** (18 MV/m in operation)
Constant Gradient

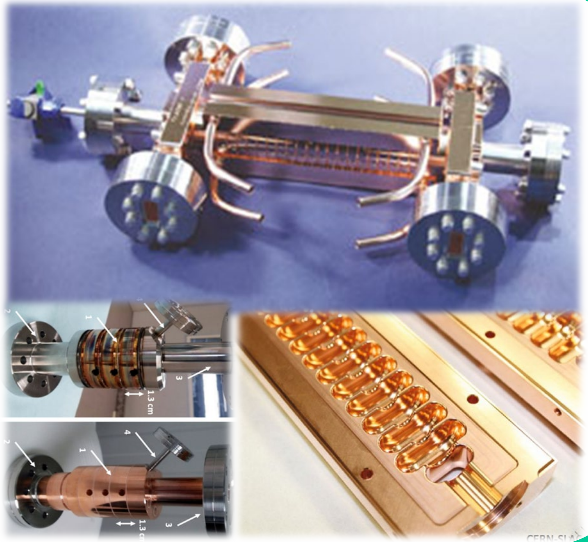
PSI – SWISSFEL
112 Structures, C-band (5.712 GHz), 2m, **28 MV/m**, CG structures



Spring8 – SCSS
16 Structures,
C-band (5.712 GHz)
1.8 m**, >35 MV/m**,
quasi-CG damped structures



CERN – CLIC
X-band (11.994 GHz),
0.3 m, **>100 MV/m**
SLAC-KEK-CERN-LNF
1-3 cells **prototypes** for high gradient studies, f>12 GHz, cryocooled etc. **>150 MV/m**



RF gun introduction

An RF gun is an **electron source** that generates low emittance pulsed beams. Very short laser pulses (ps) hit a metallic cathode and extract electrons by photoelectric effect.

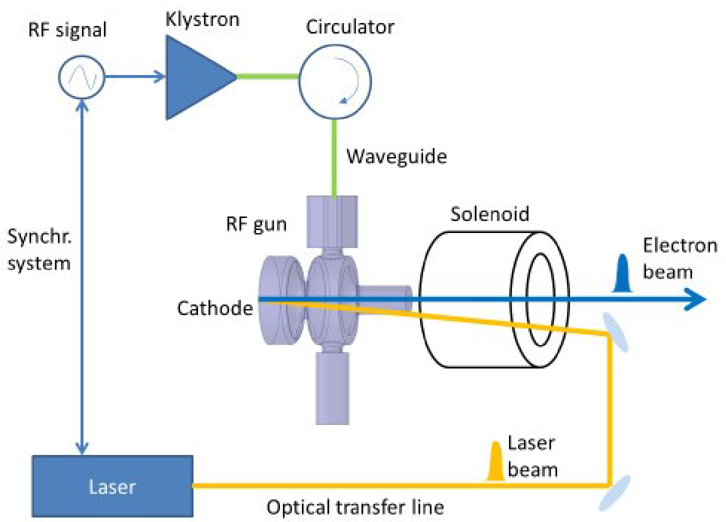
The cathode is embedded in a SW accelerating structure made of typically 2 (or 3) coupled resonant cavities.

The bunches are immediately accelerated by an intense (60-120 MV/m) axial electric field and confined by a solenoidal magnetic field.

The higher the accelerating gradient the better the beam characteristics (low emittance, high brightness). At present S-band RF guns represent the state of the art of high-quality electron sources

Due to the very high EM fields in the structure, the key aspect is to keep under control the breakdown probability. This can be done with an accurate EM and cooling system design:

- Reducing the surface electric and magnetic fields
- Increasing the iris aperture
- Reducing the pulsed heating
- Reducing the RF pulse length



Braze-free SW RF-guns

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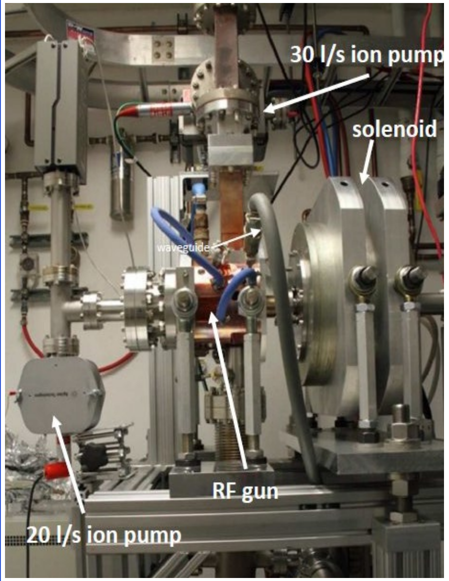
In the last decade several standing wave RF injectors have been designed, realized, tested and commissioned at LNF.

All of them are based on the **new INFN technology with gasket clamping** (without brazing)

SPARC_LAB (v. 1.0)

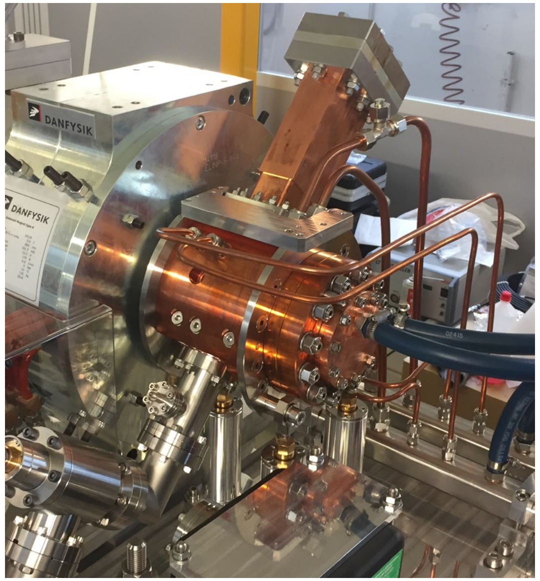


D. Alesini et al., Phys. Rev. ST Accel. Beams 18, 092001 (2015)

10 MW, 1.5 us, 10 Hz, 80-100 MV/m

In operation @UCLA

ELI-NP

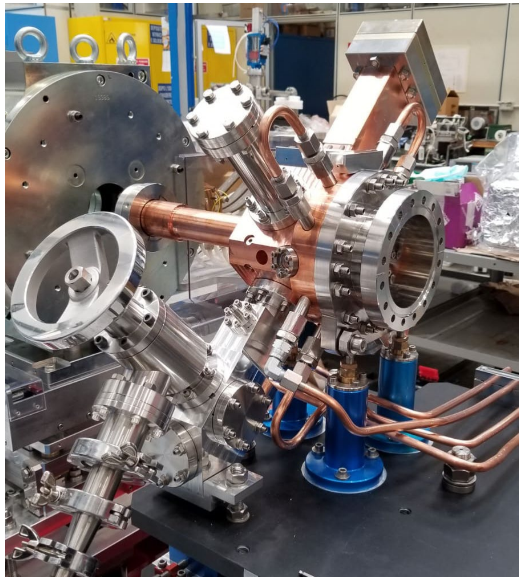


D. Alesini et al., PHYS. REV. ACCEL. BEAMS 21, 112001 (2018)

16 MW, 1.5 us, 100 Hz, 120 MV/m

Tested at high power @ Bonn University

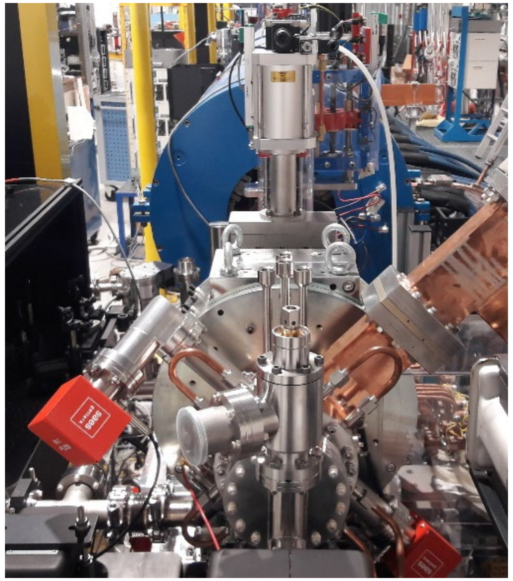
CLEAR (CERN)



13.5 MW, 1 us, 10 Hz, 120 MV/m

Under test @ CERN

SPARC_LAB (v. 2.0)



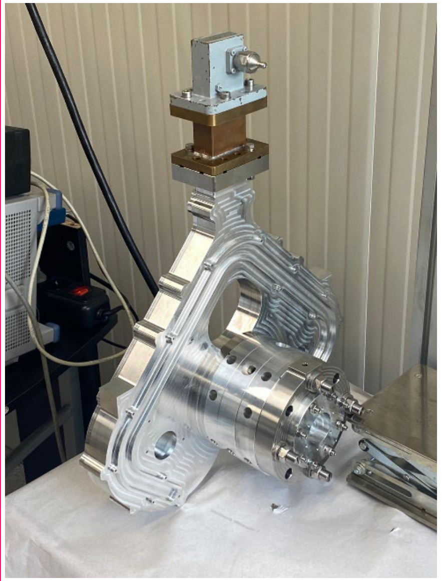
V. Shpakov et al 2022 JINST 17 P12022
D. Alesini et al. Proc. IPAC22 MOPOMS019

13.5 MW, 1 us, 10 Hz, 120 MV/m

In operation @ SPARC_LAB

S-band

I-Fast



18 MW, 0.3 us, <1 kHz, >160 MV/m

Under construction

C-band

Braze-free SW RF-guns: mechanical features

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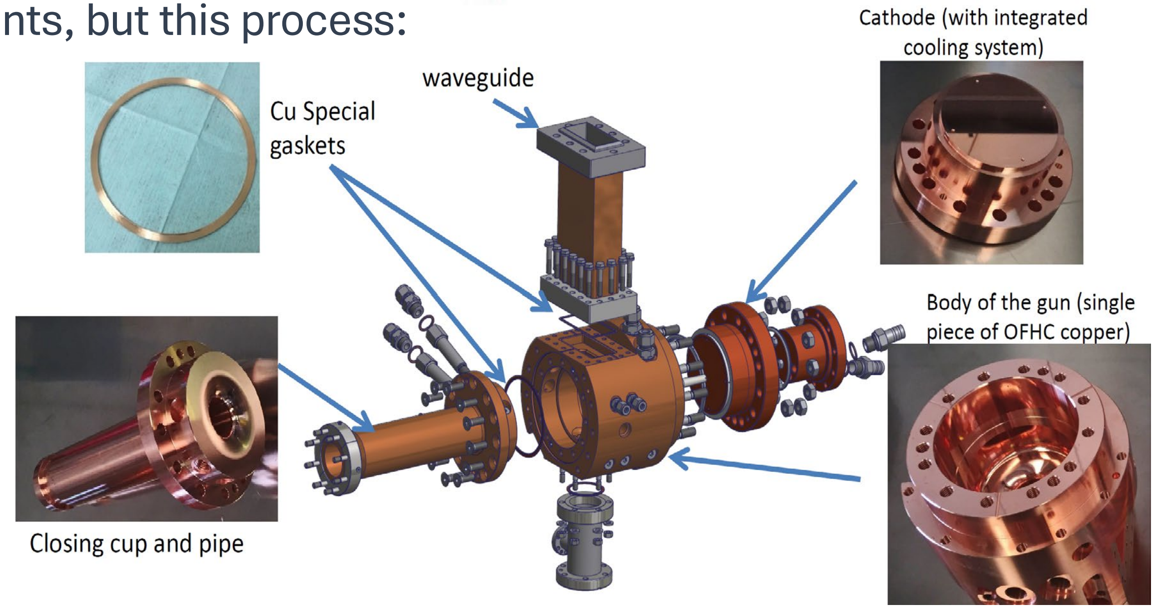
Accelerating structures generally are realized brazing different components, but this process:

- requires large vacuum furnaces;
- is very expensive;
- poses a not negligible risk of failure (e.g. vacuum leaks);
- “softens” the copper (increase of BDR and conditioning time).

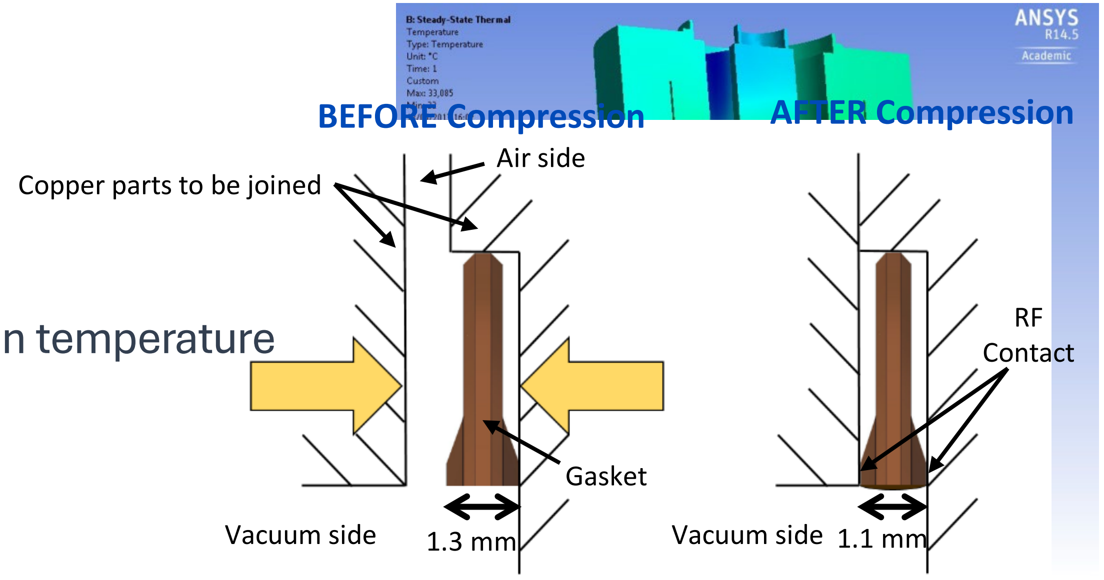
All the RF-guns designed and realized at LNF do not have brazed components, but use **special RF/vacuum gaskets** developed @ LNF (European patent application n. EP20160722364) in order to:

- simplify the fabrication;
- reduce the costs;
- reach higher accelerating field with lower BDR, due to the hard copper not annealed.



Tuning is performed using deformation tuners;

Improved cooling pipes and increased in number to guarantee a better gun temperature uniformity and operation up to 100 Hz.



Braze-free SW RF-guns: RF features

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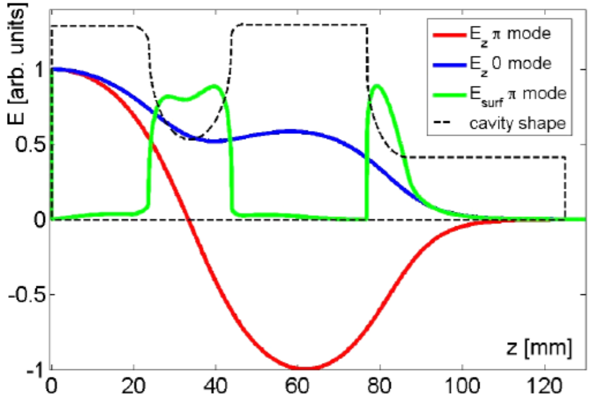
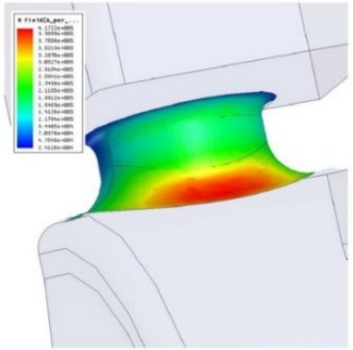
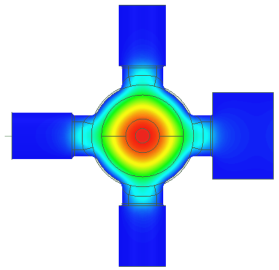
All the S-band RF GUNs are **1.6 cell** of the BNL/SLAC/UCLA type, with several **new mechanical and electromagnetic features:**

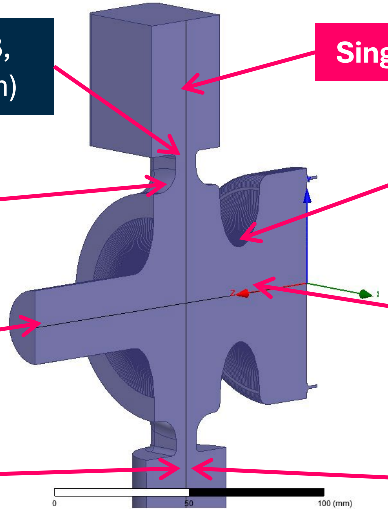
- The iris profile has an elliptical shape and a larger aperture to:
  - **reduce the peak surface electric field**;
  - **increase the frequency separation** between the two RF gun modes (up to 40 MHz) that is necessary to avoid 0-mode excitation when the gun is fed with short RF pulses (<1 us)
  - **increase the pumping speed** on the half-cell;
- The coupling hole has been strongly rounded to reduce the peak surface magnetic field and, therefore, the pulsed heating;
- The coupling coefficient (ß) has been increased to 2-3, to allow operation with short RF pulses (< 1 µs) thus reducing the BDR, the power dissipation and to allow RF gymnastics in case of multi-bunch operation (ELI-NP)



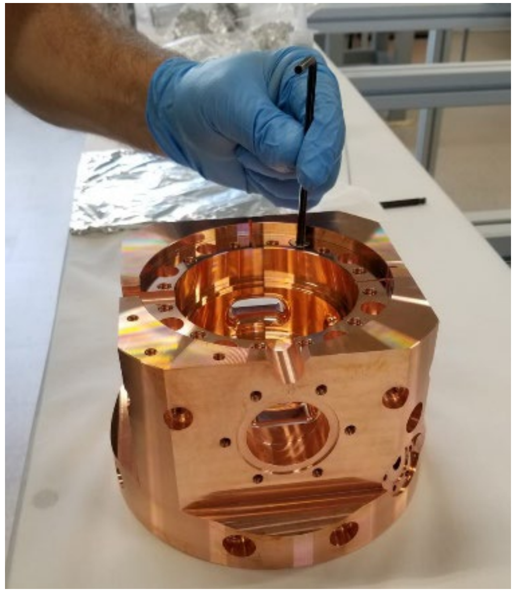
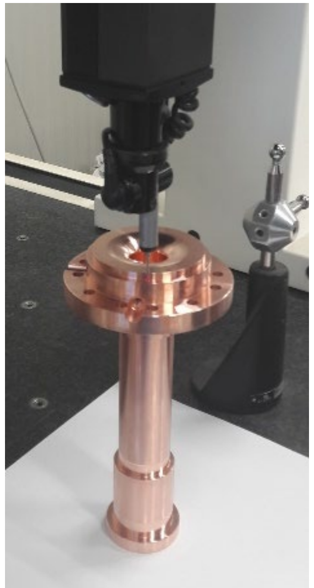
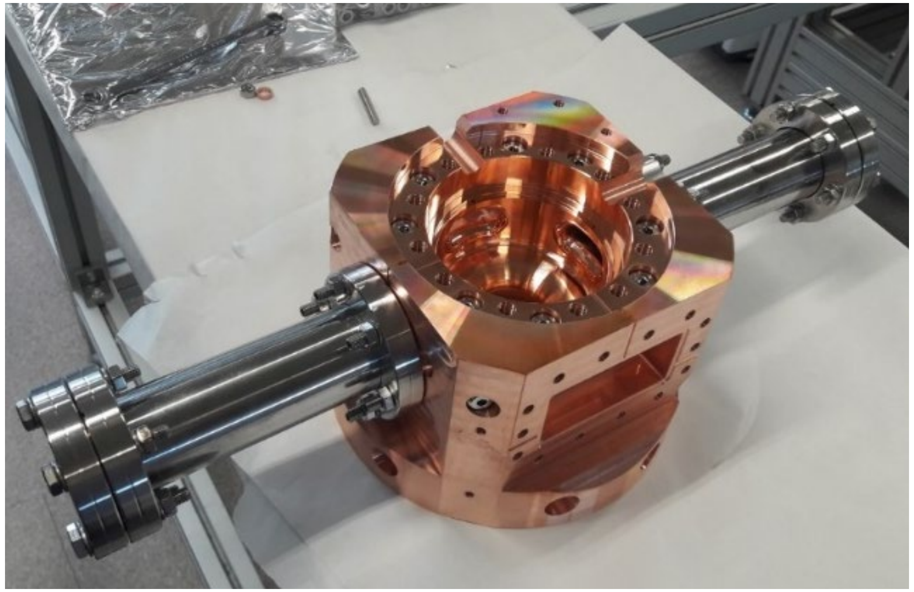
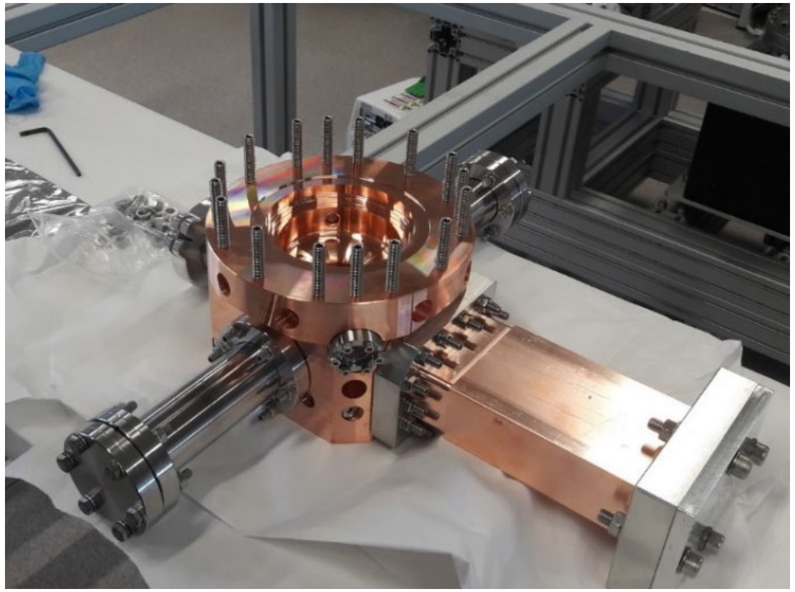
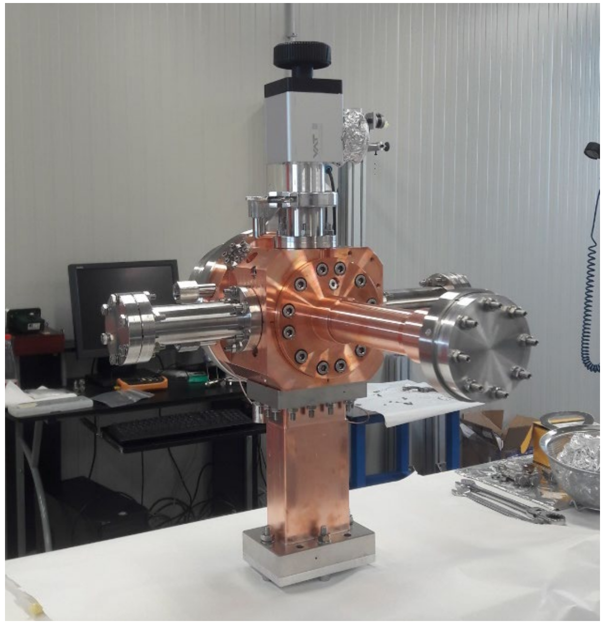
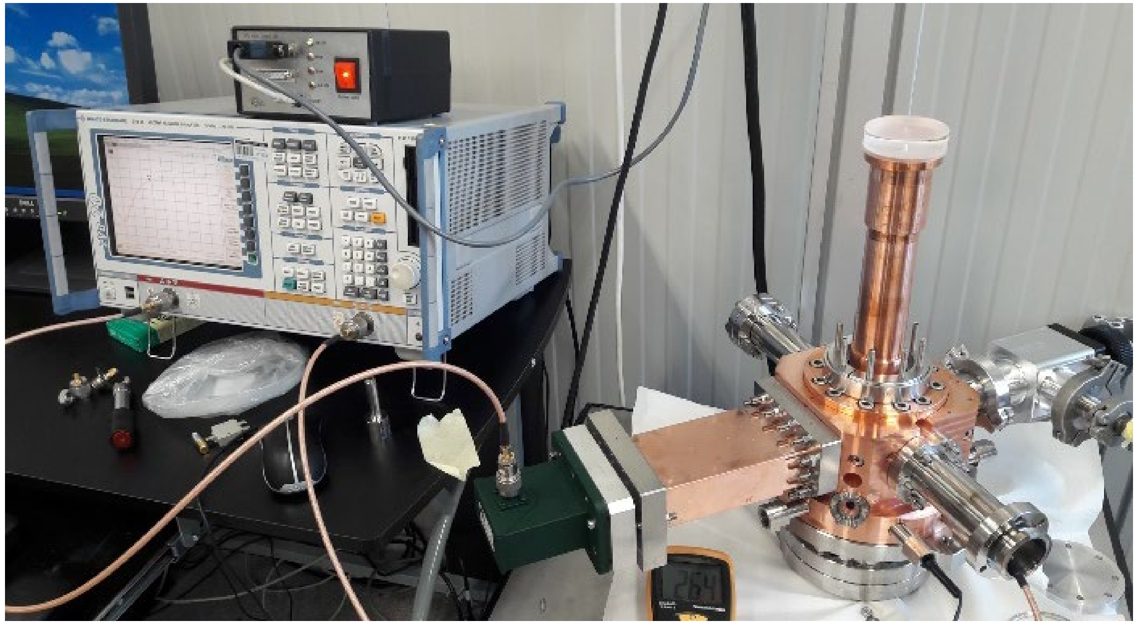
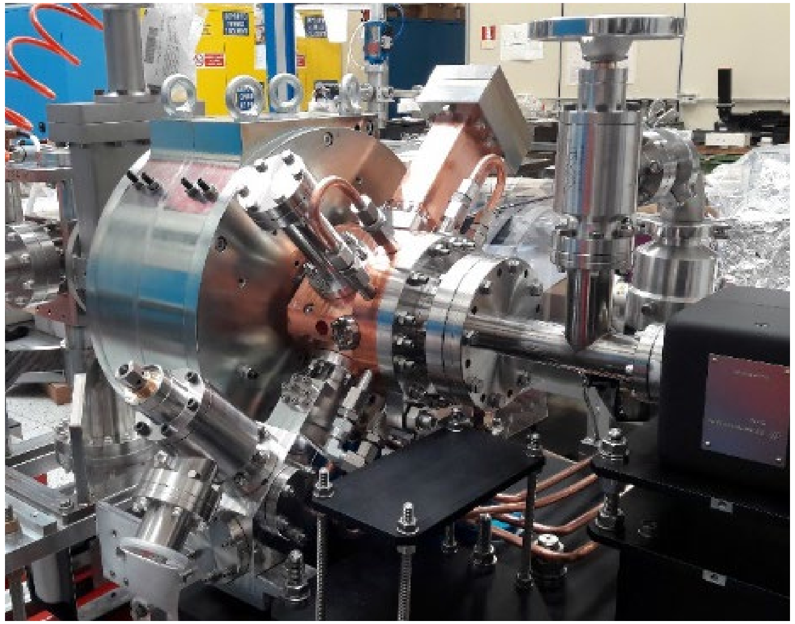


SPARC_LAB (v. 2.0)





Braze-free SW RF-guns: typical assembly procedure

Conditioning procedure and measurements at SPARC_LAB

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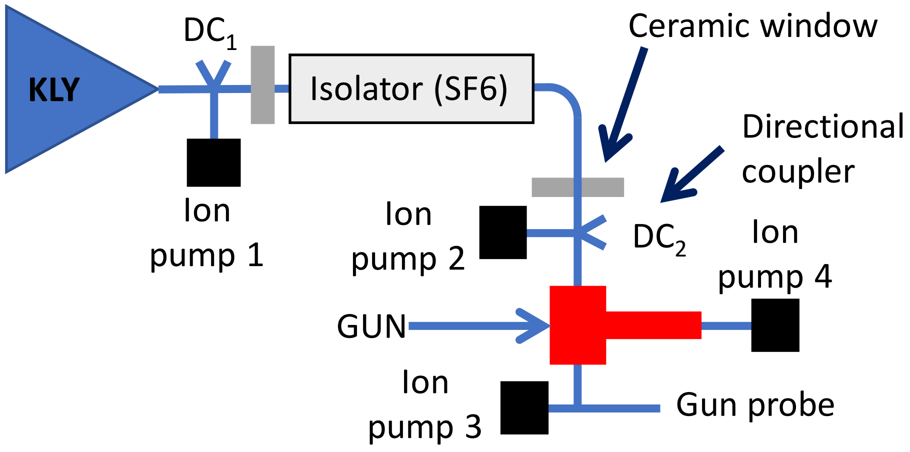
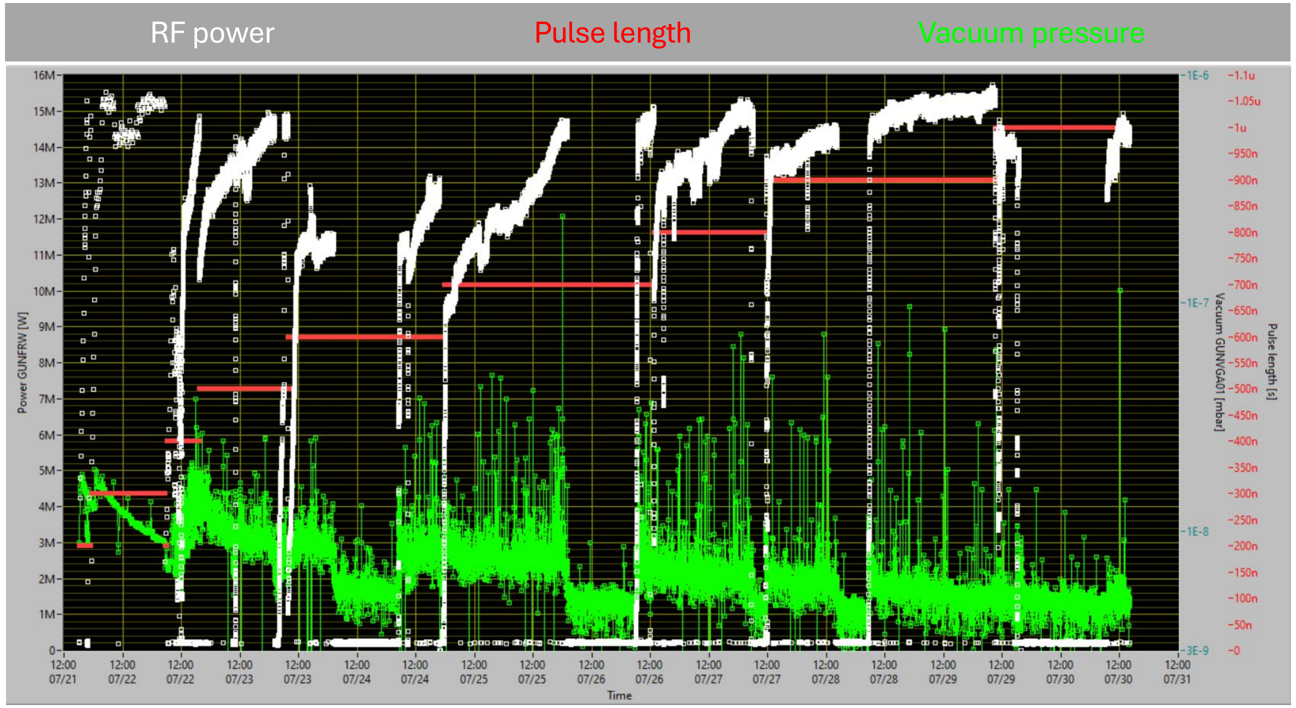
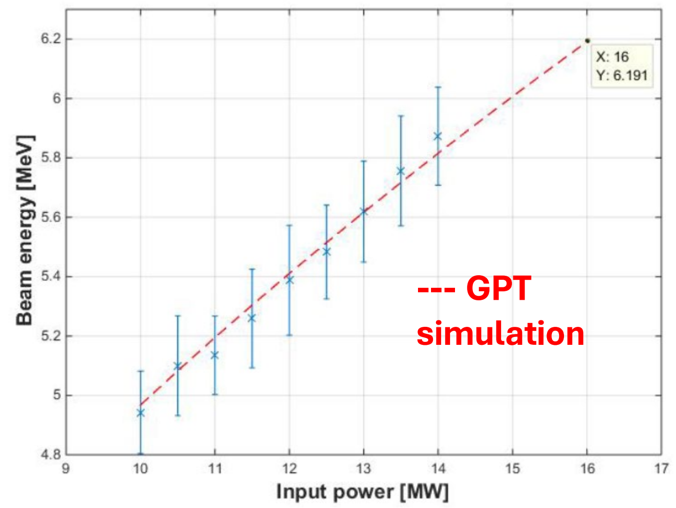
- The SPARC_LAB 2.0 injector has been tested at high power, reaching the final performances in an incredible short time (<10 days, 10 Hz, $5x10^6$ pulses, < 10^3 cumulative arcs)
- The conditioning has been done in a semi-automatic way looking both at vacuum pressure and RF pulse shape
- In case of discharge the system automatically stops the RF power waiting until vacuum recovery and starts again with a reduced power (-0.1 dB)
- Similar results have been obtained for the ELI-NP RF-gun (160 hours, BDR<10-5, 14 MW, 1.5 us, 100 Hz)

Typical RF conditioning setup







Measured **beam energy** at the exit from the gun as a function of the RF input power

Courtesy of V. Shpakov

Braze-free SW RF-guns: Next step → C-band gun

The future path for RF guns in terms of **gradient** (**160-180 MV/m**), beam parameters, compactness and **very high repetition rates** (up to 1 kHz);

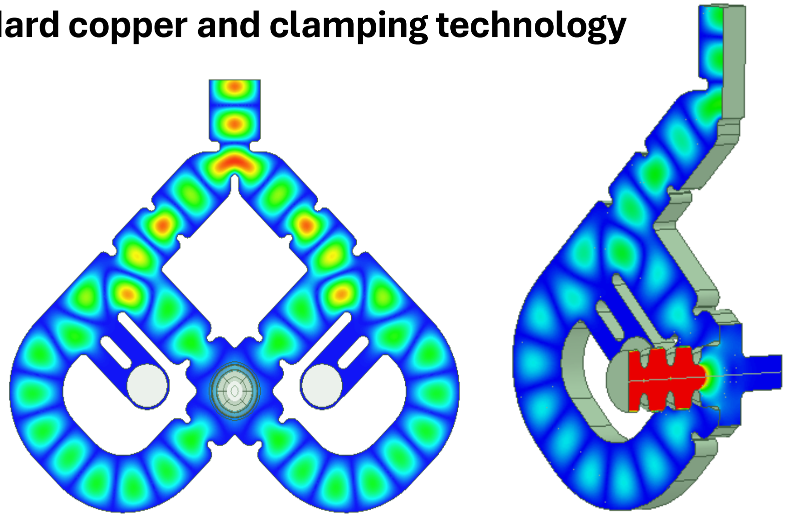
R&D program started few years ago, funded by the **IFAST (Horizon 2020)** and **TUAREG (INFN commission V)** projects;

The availability of a new state-of-the-art, electron injector would bring benefits to a large accelerator user community, (FEL radiation sources, Thomson/Compton photon sources and plasma-based accelerators)

This system is also the **basic injector of the Compact light EU project** and could be studied as a future upgrade of **EuPRAXIA@SPARC_LAB** injector.

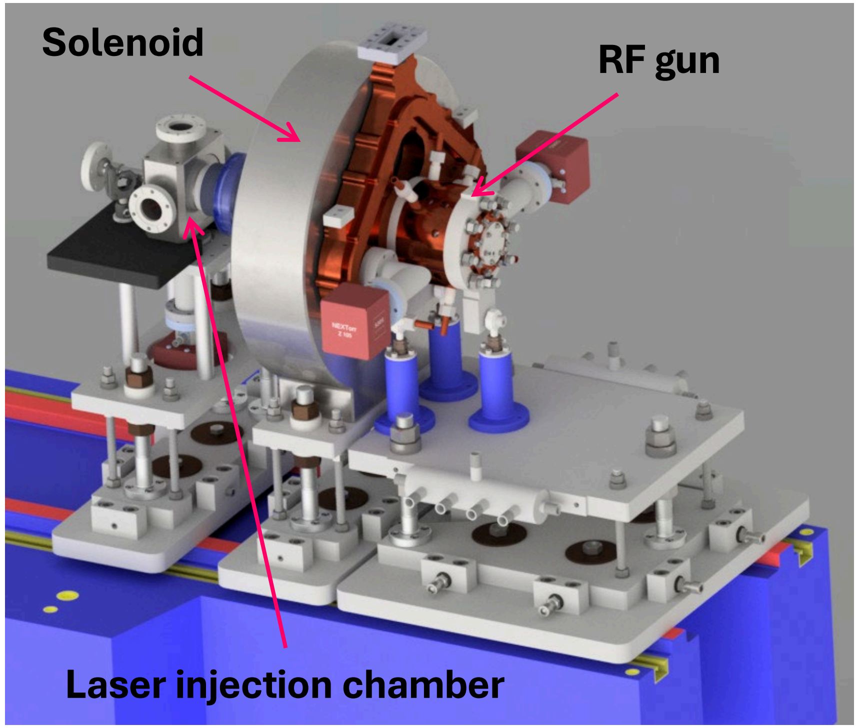
DESIGN AND REALIZATION STRATEGY

- **Very short RF pulses (~300 ns) to reduce BDR**
- **4-port mode launcher** for quadrupole compensation and low pulsed heating
- **Hard copper and clamping technology**



Mode-launcher design based on G. Castorina et al 2018 J. Phys.: Conf. Ser. 1067 082025

Parameter	value
Frequency [GHz]	5.712
Number of cells	2.5
$E_{cath}/\sqrt{P_{diss}}$ [MV/(m·MW$^{0.5}$)]	51.4
Peak input power [MW]	18
Cathode field [MV/m]	160
Cathode type	copper
Rep. rate [Hz]	100 Hz
Quality factor	11900
Filling time [ns]	166
Coupling coefficient	3
RF pulse length [ns]	300
E_{surf}/E_{cath}	0.96
Mod. Poy. Vect. [W/μm^2]	2.5
Pulsed heating [°C]	<16
Av.diss. Power [W]	300



C-band gun layout, final assembly and tests

iFAST
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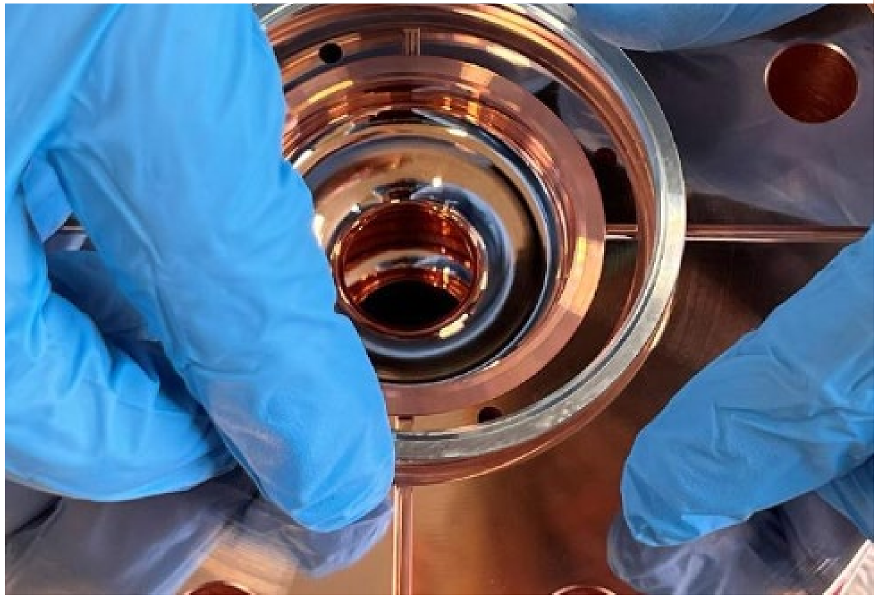
NEWS: The cells have been clamped and finally the cathode is mounted. The assembly is then vacuum tested and low power RF measurement have been conducted

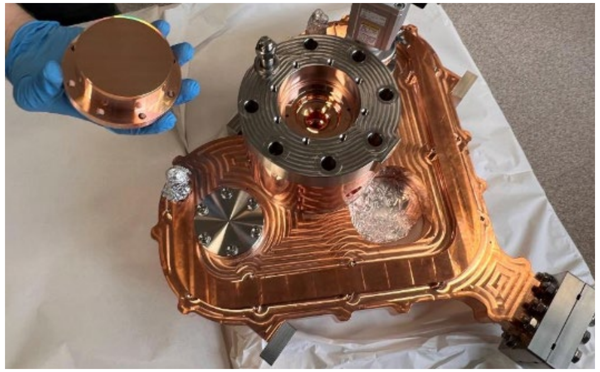
Accelerating cells detail



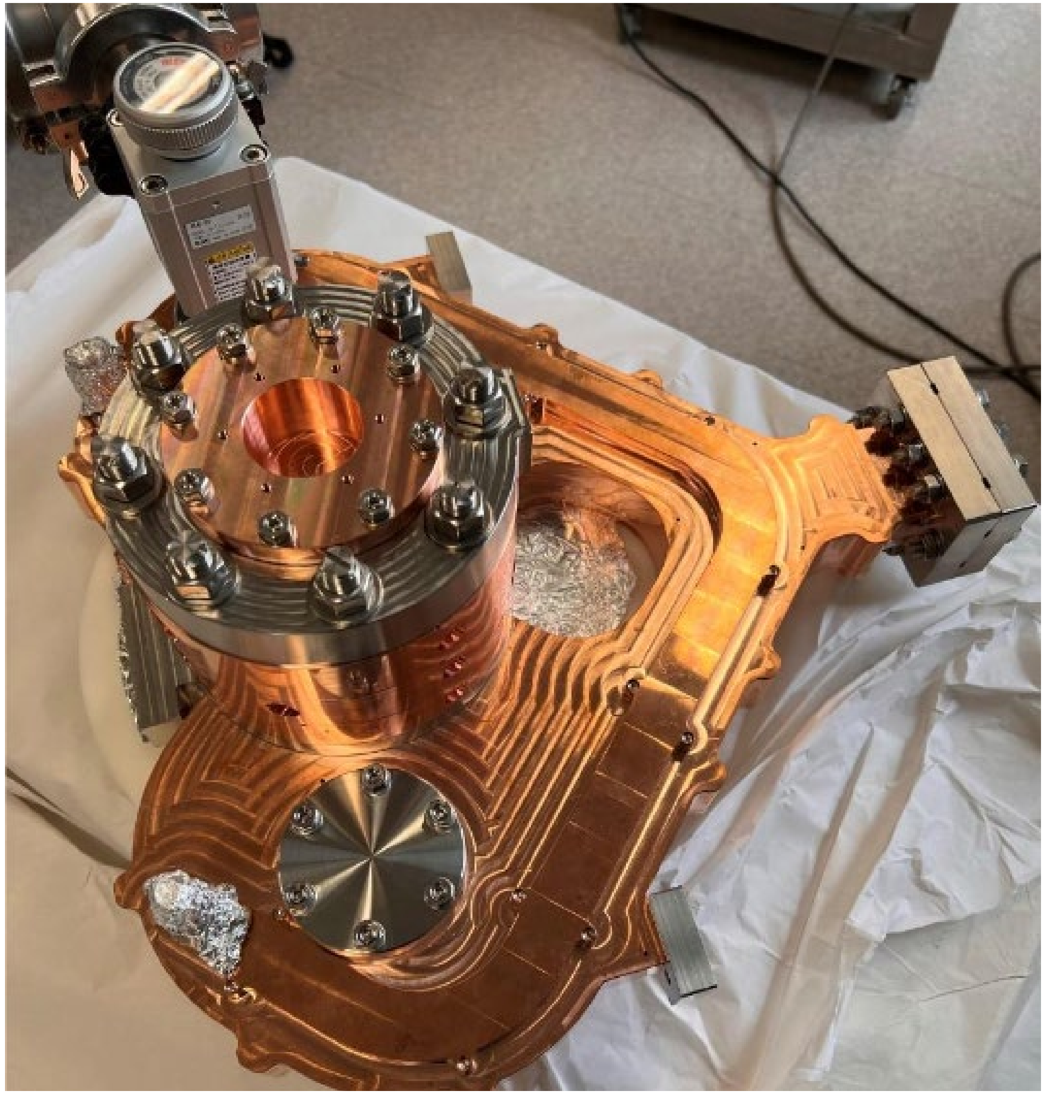
Special gasket assembly

Mode launcher before brazing

Cathode assembly



Full RF gun assembled, ready for vacuum tests

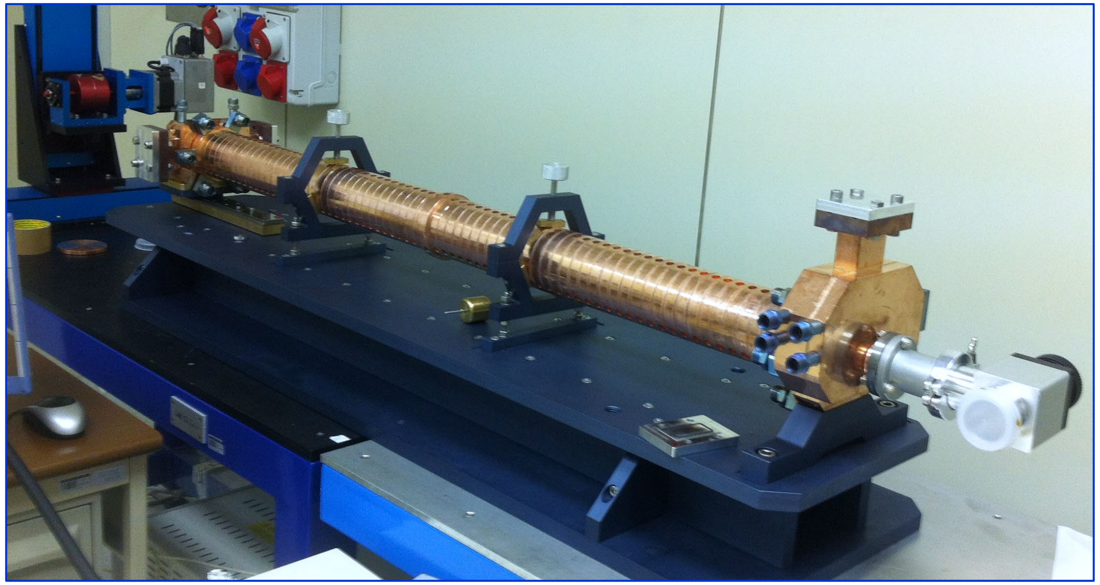


C-band TW structures

Two main projects have driven C-band TW structures design at LNF

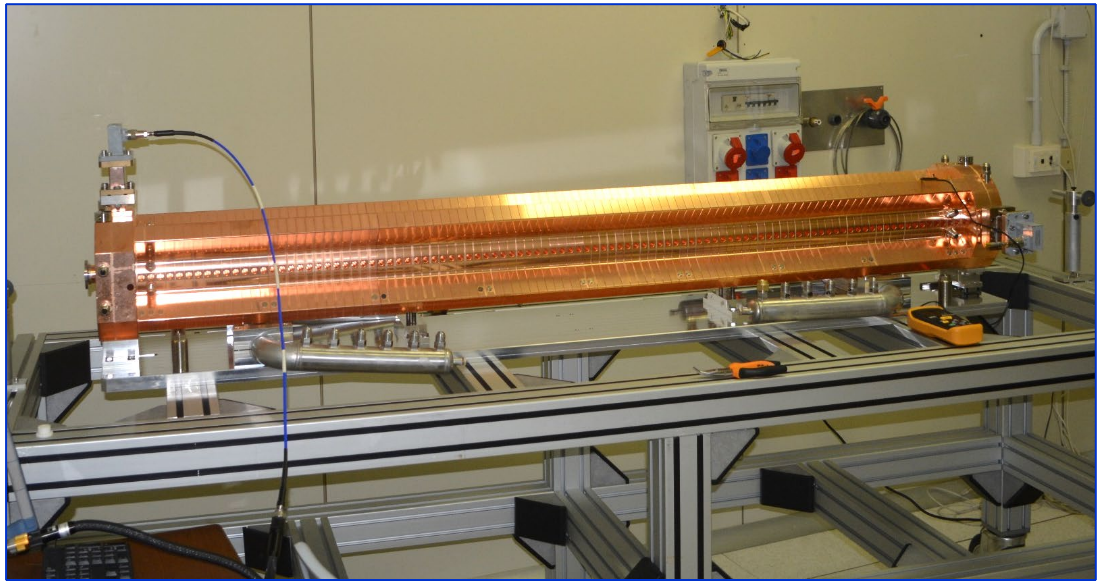
SPARC_LAB energy upgrade

2x Constant Impedance structures
35 MV/m, 10 Hz, 1 µs, single bunch



ELI-NP-GBS

12x Quasi-constant Gradient structures
33 MV/m, 100 Hz, 1.5 us, 32 bunches 16 ns separation



C-band TW structures for SPARC_LAB energy upgrade

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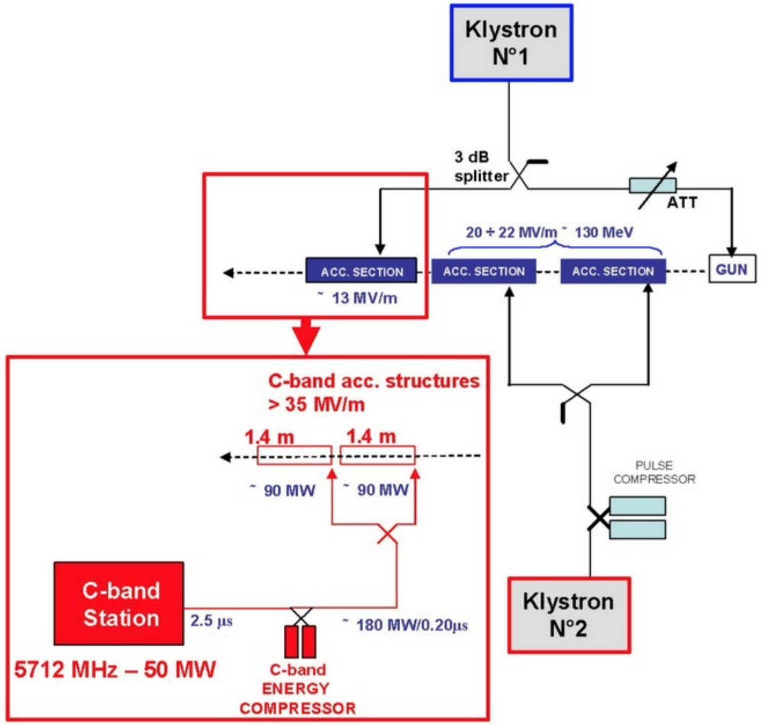
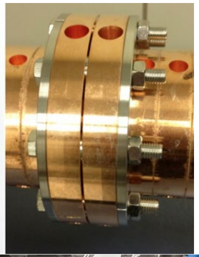
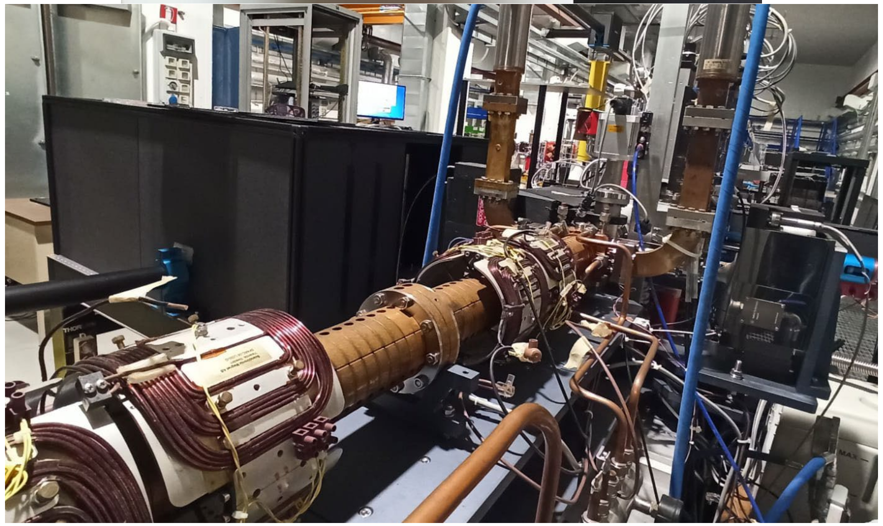
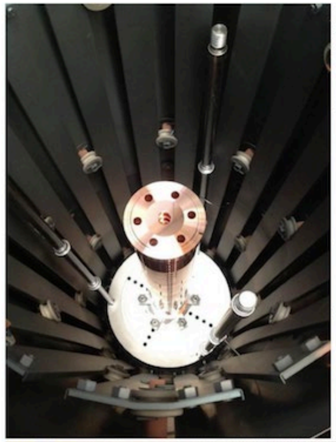
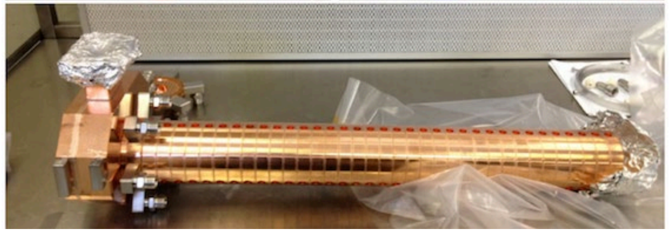
- Design aimed at reaching >200 MeV electron energy at SPARC_LAB (2x 1.4 m sections, >35 MV/m gradient)
- **First C-band structure to reach 50 MV/m** during prototype high power test at KEK in 2010 *(D. Alesini, et al., JINST 8 (05) (2013) P05004)*
- Constant Impedance (reduced cost, easier fabrication), optimized for pulse compressor operation (large irises: limit surface fields, higher pumping speed, lower filling time)
- Symmetric coupling based on the “low pulsed heating” X-band couplers developed at SLAC







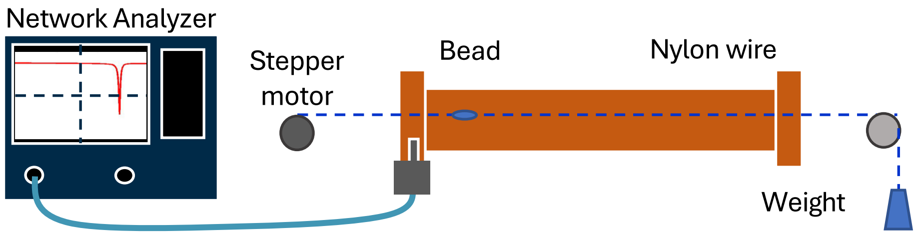




Parameter	Value
Frequency	5.712 GHz
Phase advance per cell	$2\pi/3$ rad
Number of accelerating cells (N)	71
Structure length including couplers (L)	1.4 m
Cell length (d)	17.495 mm
Iris radius (a)	7 mm
Outer radius (b)	21.13 mm
Normalized group velocity (v_g)	0.02831/c
Field attenuation (α)	0.2061/m
Series impedance	34.1 MΩ
Shunt impedance	82.8 MΩ/m
Filling time (t_F)	150 ns
Minimum average accelerating gradient (V_{acc}^{avg})	>35 MV/m
Max. peak surf. electric field*	80 MV/m
Max. peak surf. magnetic field*	92 kA/m
Max. modified Poynting vector*	0.88 $\sqrt{\mathrm{MW/mm^2}}$
Output power	$0.6P_{in}$
Average dissipated power**	59.6 W
Pulsed heating**	<1 °C

Low and high-power RF tests at LNF

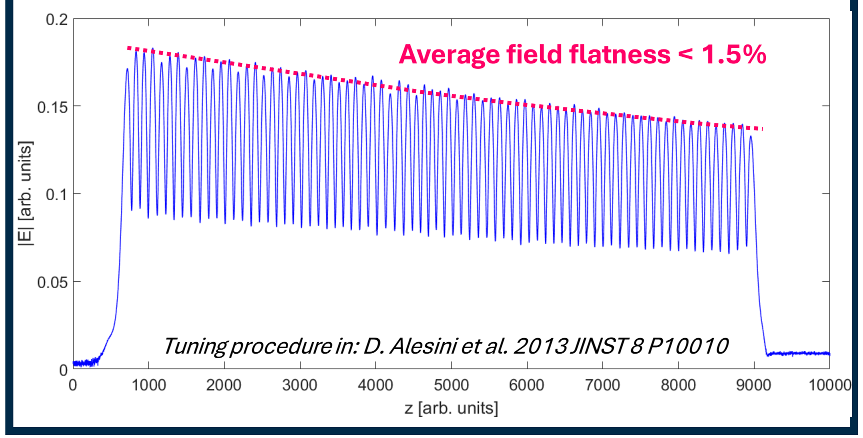
Bead pull measurement *(C. Steele, IEEE T. Microw. Theory 14 (1966) 70)*



$$2P_{in}(S_{11\,p} - S_{11\,u}) = -j\omega k E_{acc}^2$$

Structure n.1 during low power tests at LNF

Measured electric field on axis AFTER tuning



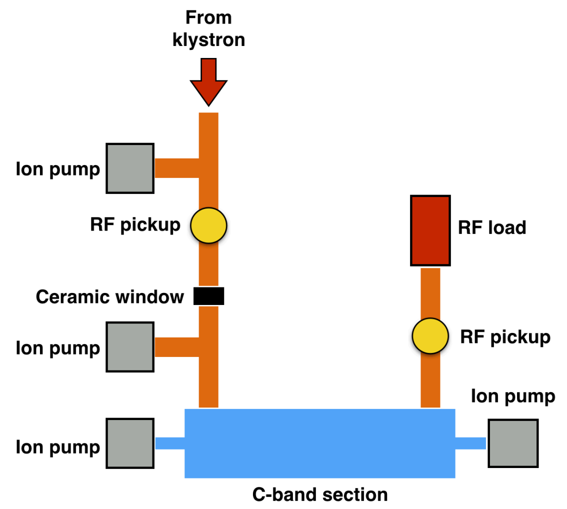
High power test of the 1st structure in late 2013, 10 Hz, 165 ns pulse length, 155 hours ≈ **5.5 x10^6 pulses** delivered. 2nd structure followed with the same setup and comparable results.

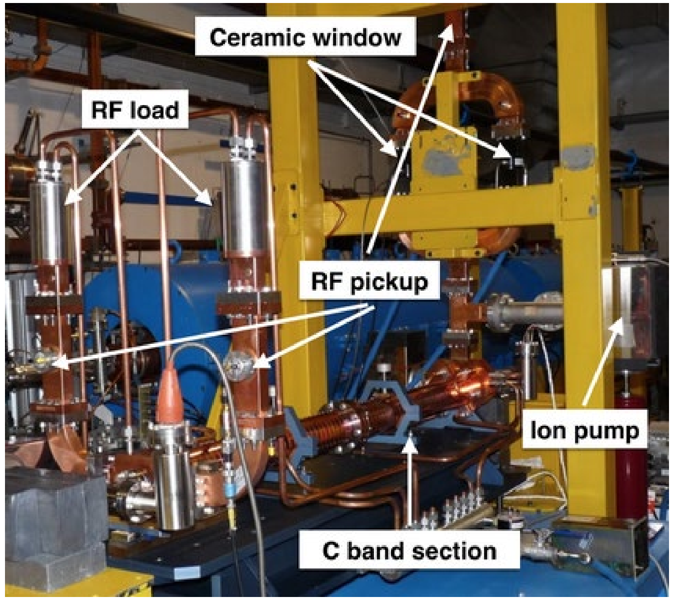
Semi-automatic conditioning procedure. The modulator HV could be interlocked in three cases:

- Exceeding the threshold of any ion pump (corresponding to a vacuum pressure of 10^7 mbar);
- Automatically by klystron interlocks (tube vacuum, modulator interlocks).

With 38 MW input power in the structure (44 MW from the klystron) a **peak gradient of 38 MV/m** has been obtained (32 MV/m avg.)

High power test setup @ SPARC



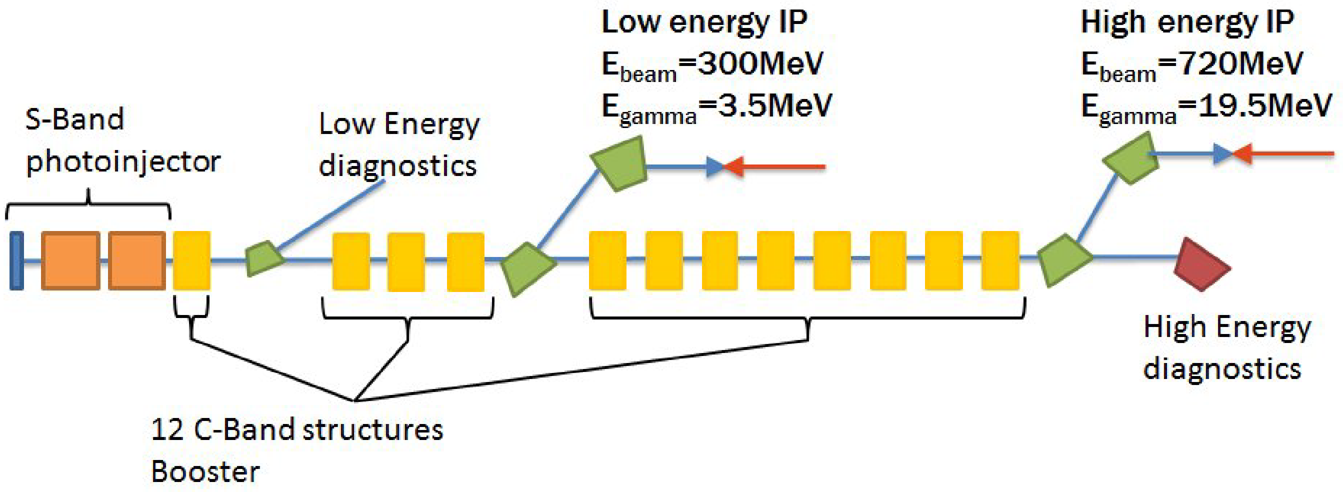


C-band TW HOM damped structures for ELI-NP-GBS

- Advanced source of γ-rays built in Bucharest (Romania) in the framework of ELI infrastructure by the EuroGammaS consortium
- γ-rays generated by Compton back-scattering in the collision between a high quality e- beam and a high power laser (10 PW);
- Booster linac made of **12 quasi-CG damped structures**, 1.8 m long, 2/3π phase advance per cell, **33 MV/m** avg. gradient
- Main RF challenges in the ELI-NP project:
  - To increase the γ flux the number of collisions per second must be increased → **100 Hz rep. rate** + **32 bunches with 16 ns separation** in a single RF pulse

    Damping of HOMs in RF structures to avoid Beam Break Up (BBU) + beam loading compensation + accurate thermal design (high avg. dissipated power)
  - Compact accelerator (to reduce overall dimensions) → **high gradient** + **high frequency**

    C-band booster combined with S-band injector + individual RF power sources + accurate RF design and mechanical realization



Single cell optimization and HOM damping

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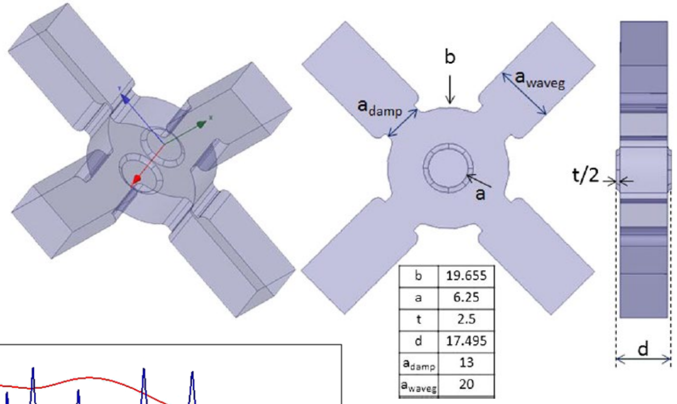
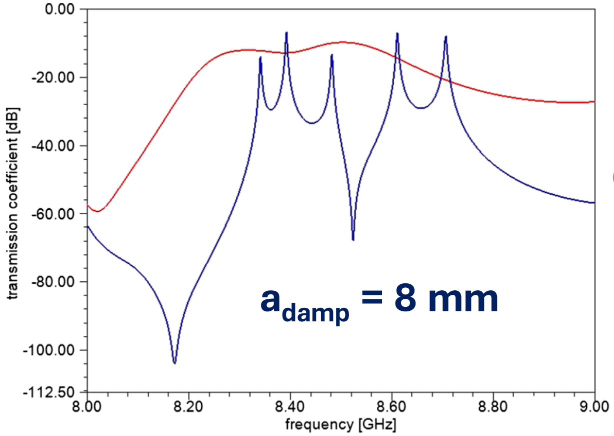
- **Quasi-Constant Gradient approach** has been chosen with respect to Constant Impedance or Constant Gradient, in order not to:
  - deal with a **very high accelerating gradient** (≅ 45 MV/m) **in the first cells** (and thus increase the breakdown probability) → **CI**
  - **strongly reduce the iris dimension in the last cells** (increasing dipole mode R/Q, reducing the pumping speed and beam clearance) → **CG**
- Due to multi-bunch operation, structures are designed with an effective damping of the HOM dipole modes to avoid BBU instabilities
- The solution employs a waveguide damping system (similar to CLIC X-band structures, but simplified) that allows the HOM to propagate and dissipate into SiC RF absorbers

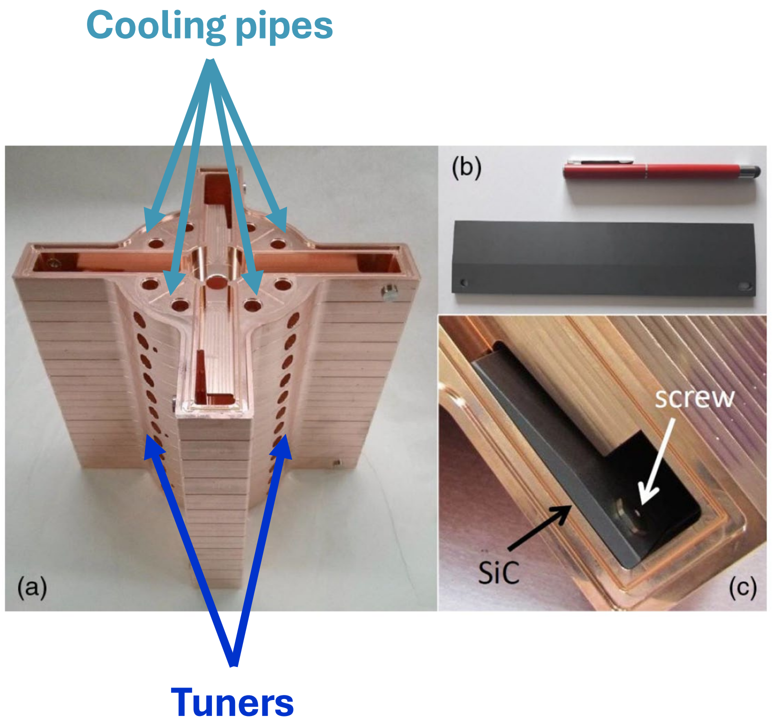
Parameter	Value
Working frequency (f_{rf})	5.712 GHz
Cell phase advance	$2\pi/3$
Number of cells	102
Structure length	1.8 m
Iris aperture radius	6.8–5.78 mm
Repetition rate	100 Hz
Average quality factor	8850
Average accelerating field	33 MV/m
Shunt impedance	67–74 MΩ/m
Group velocity (v_g/c)	0.025–0.015
Filling time	313 ns
rf input power (P_{in})	40 MW
Output power (P_{out})	$0.29P_{\mathrm{in}}$
Pulse duration for beam (τ_{beam})	<512 ns
Pulsed heating (input coupler)	<21 °C
Average wall-loss power	2.3 kW
Working temperature	30 °C





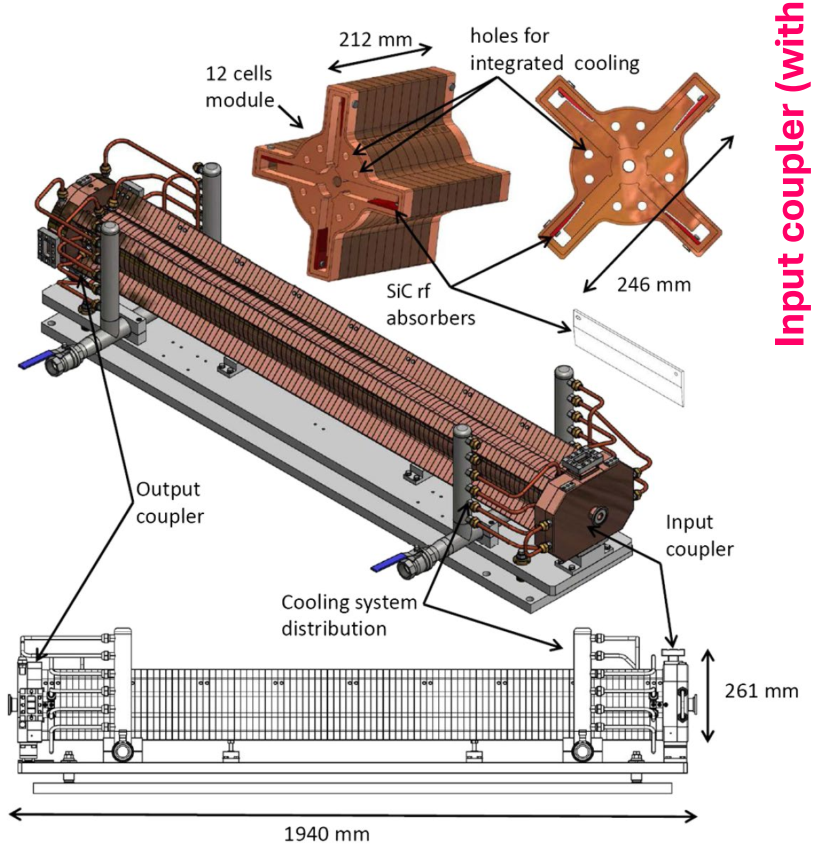
a_{damp} = 13 mm

Q of each dipole mode < 100

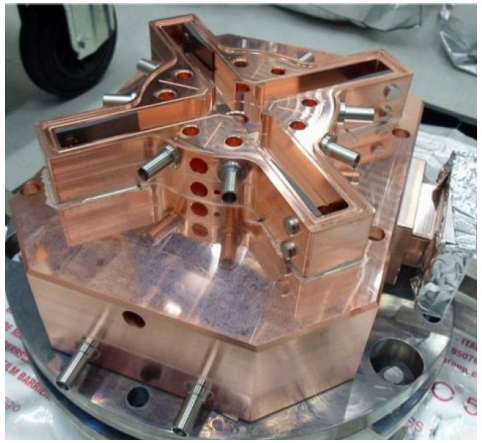


Structure realization and brazing

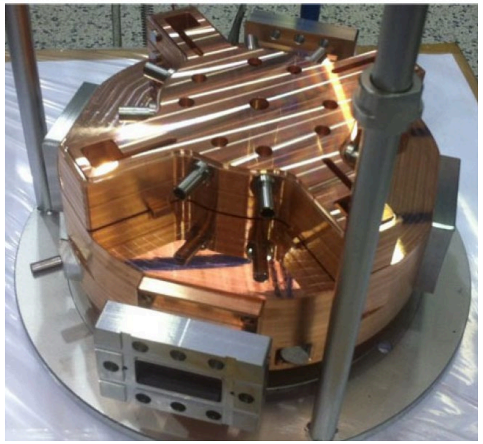
- Each structure is made of 10 modules: the input and output coupler (with their adjacent cells) and 8x 12-cell modules. This **module-based assembly** allowed a **better control of the brazing process** ;
- Input and output couplers designed with a **symmetric feeding** and rounded edges to avoid dipole field components and to reduce the pulsed heating
- Each module once assembled and brazed, is then equipped with HOM dampers and vacuum tested before the final 2 brazing steps
- **Last 2 brazing steps have been done at LNL vacuum furnace**, that can host up to 1.5 m structures. In order to fit the 1.8 m ELI-NP one an extension without heating resistors has been inserted



Input coupler (with integrated splitter)



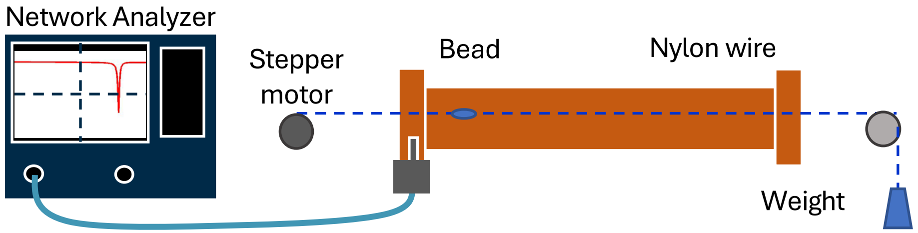
Output coupler

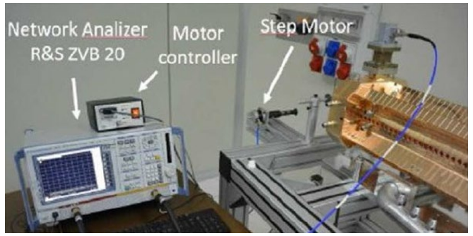


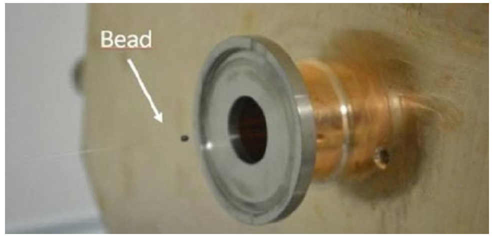
Last 2 brazing steps in LNL vacuum furnace

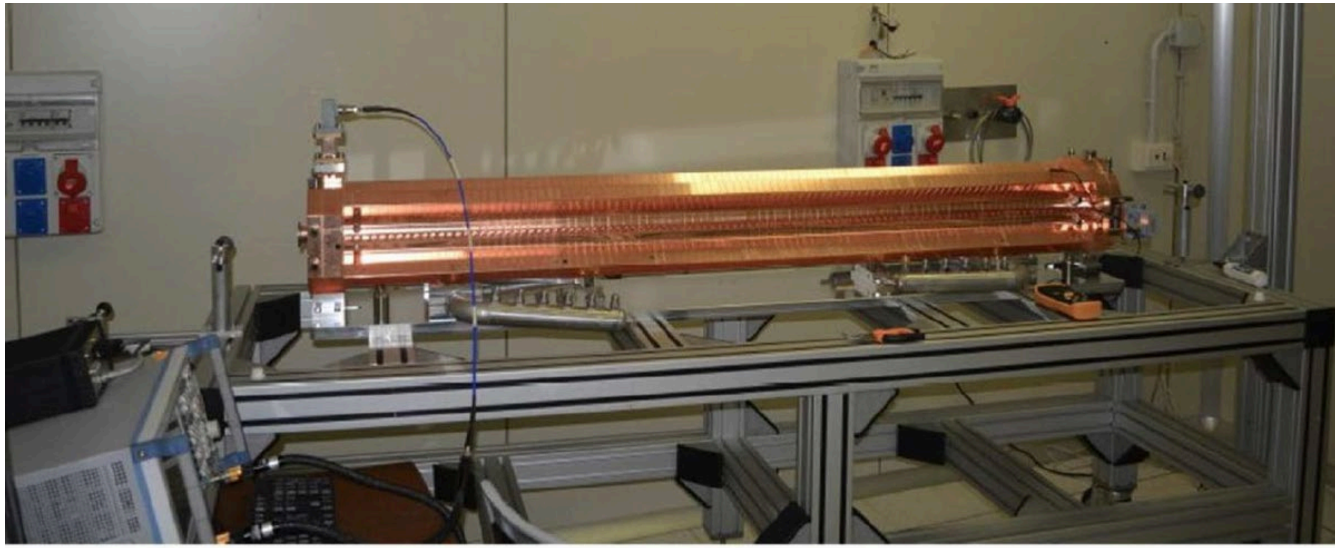
Low power RF tests at LNF

All the 12 structures have been low power tested at LNF with automatic bead-pull measurement setup

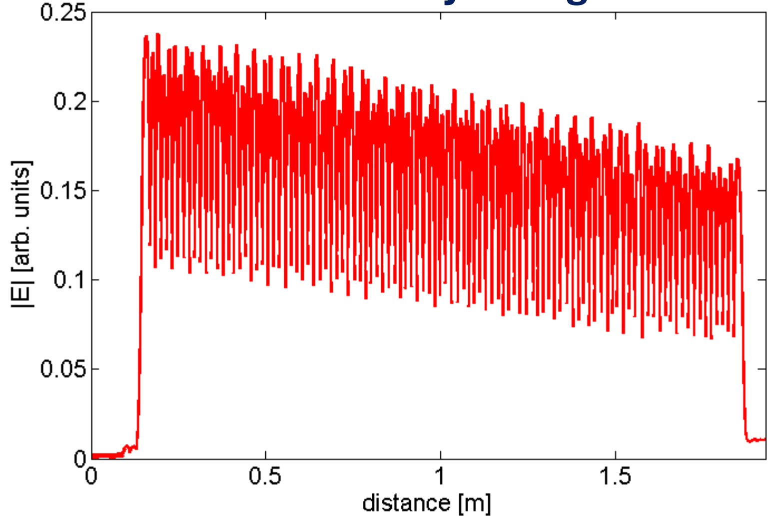


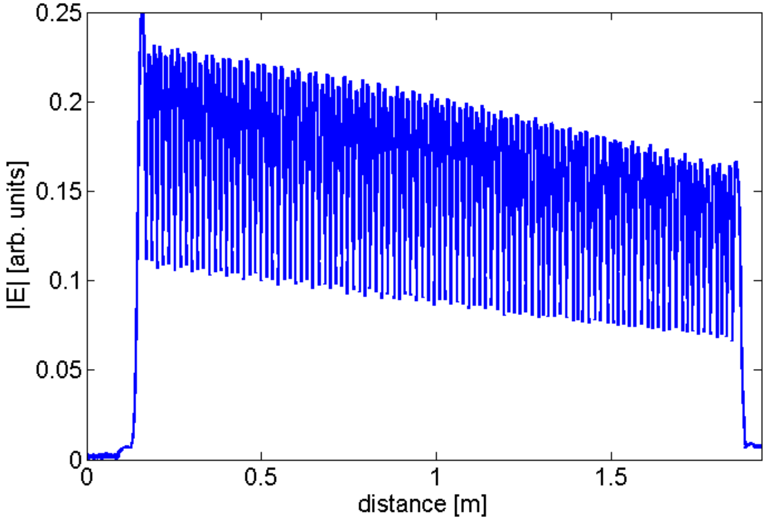






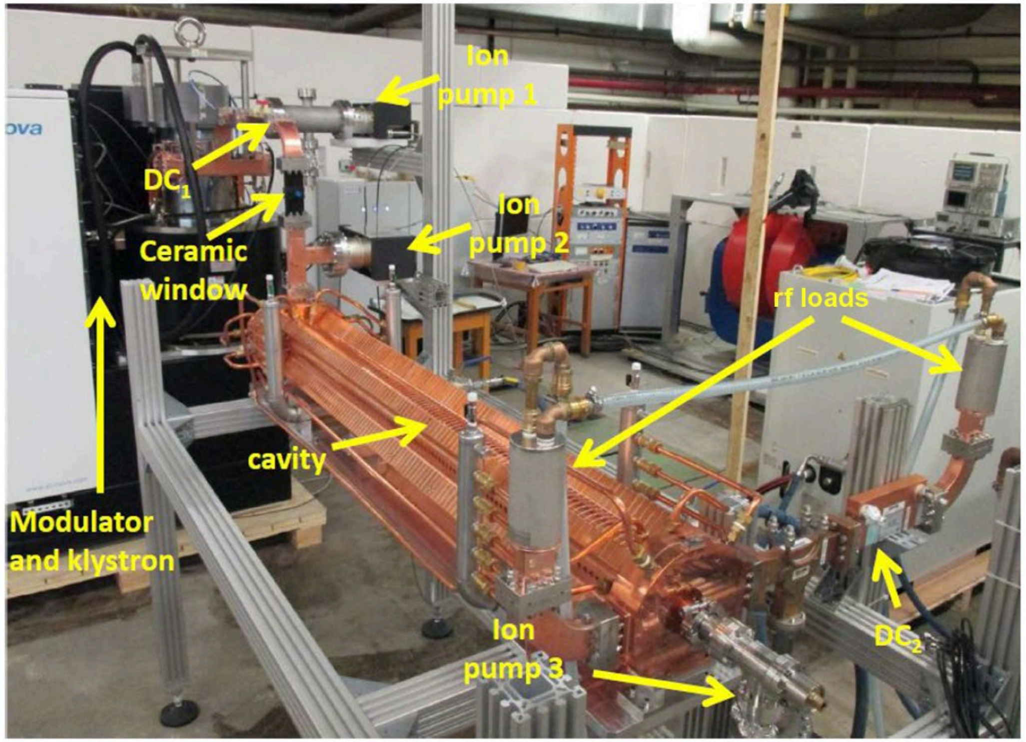
Electric field on axis measured before and after cavity tuning

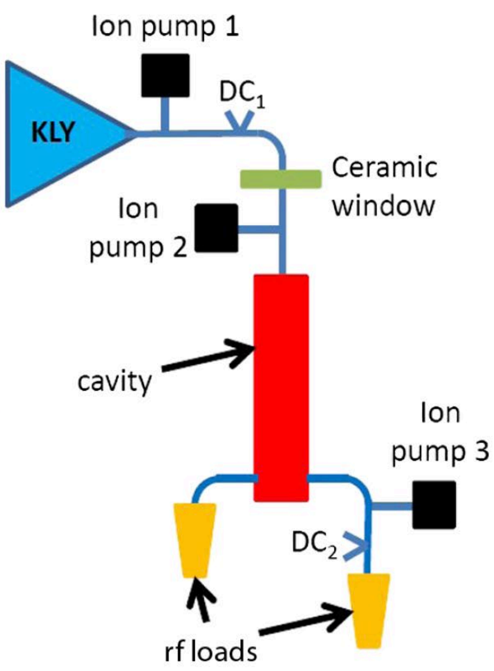




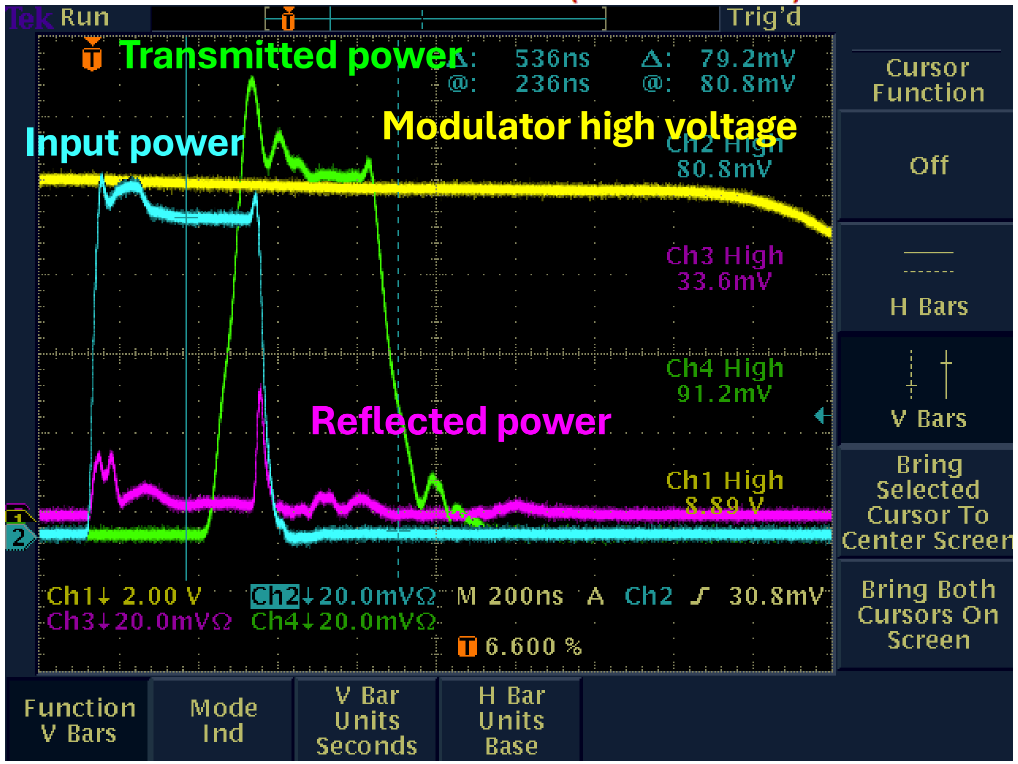
High power RF tests at Bonn University

- High power tests on the first structure prototype have been carried out in Bonn University between March-April 2015
- **AIM**: reach the nominal working parameters (input power **40 MW**, repetition rate **100 Hz**, pulse length **820 ns**)
- RF signals (FWD and REF power at the input and output coupler) measured with calibrated peak detectors read-out by 12-bit oscilloscope
- Conditioning lasted **190 hours**. Started with 100 ns pulse at 50 Hz, then rep. rate increased to 100 Hz, then pulse length progressively
- Reached **BDR of 2÷3 x10^{-6} bpp/m**, due to structure delivery time constraint. BDR much lower is expected with fully conditioned structure





Home: TDS 3034C TEK (131.220.164.218)



X-band TW structures for EuPRAXIA@SPARC_LAB

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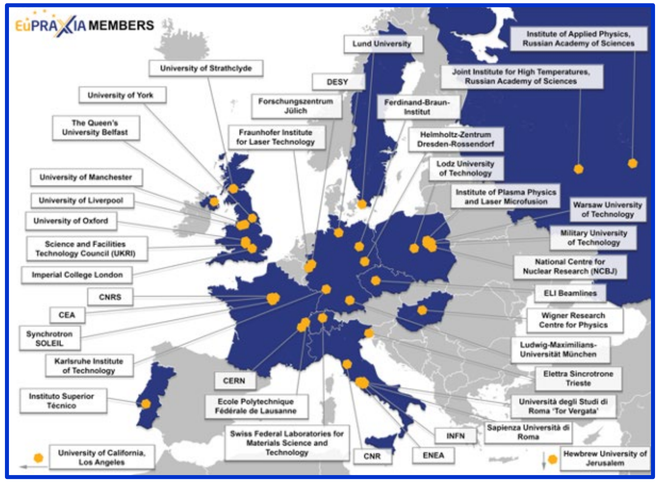
- The EuPRAXIA@SPARC_LAB project aims at building a FEL source (λ_{FEL}=4 nm) for users. The accelerator is based on a **1 GeV RF X-band Linac** with Plasma Acceleration Stage (beam driven)
- The project is currently in the preparatory phase of the Technical Design Report

TDR

- The project is one of the pillar of the **European Project EUPRAXIA** (http://www.eupraxia-project.eu/) – European Plasma Research Accelerator with excellence in Applications
- After a long and challenging evaluation process, EuPRAXIA has **been included in the ESFRI 2021 Roadmap**
- A **new building**, now under executive design phase, will host the new Facility at LNF.
- Main R&D Challenges:
  - **1 GeV RF Linac, S-band injector + X-band booster (16x structures)**
  - Plasma acceleration Stage



X-band RF module layout

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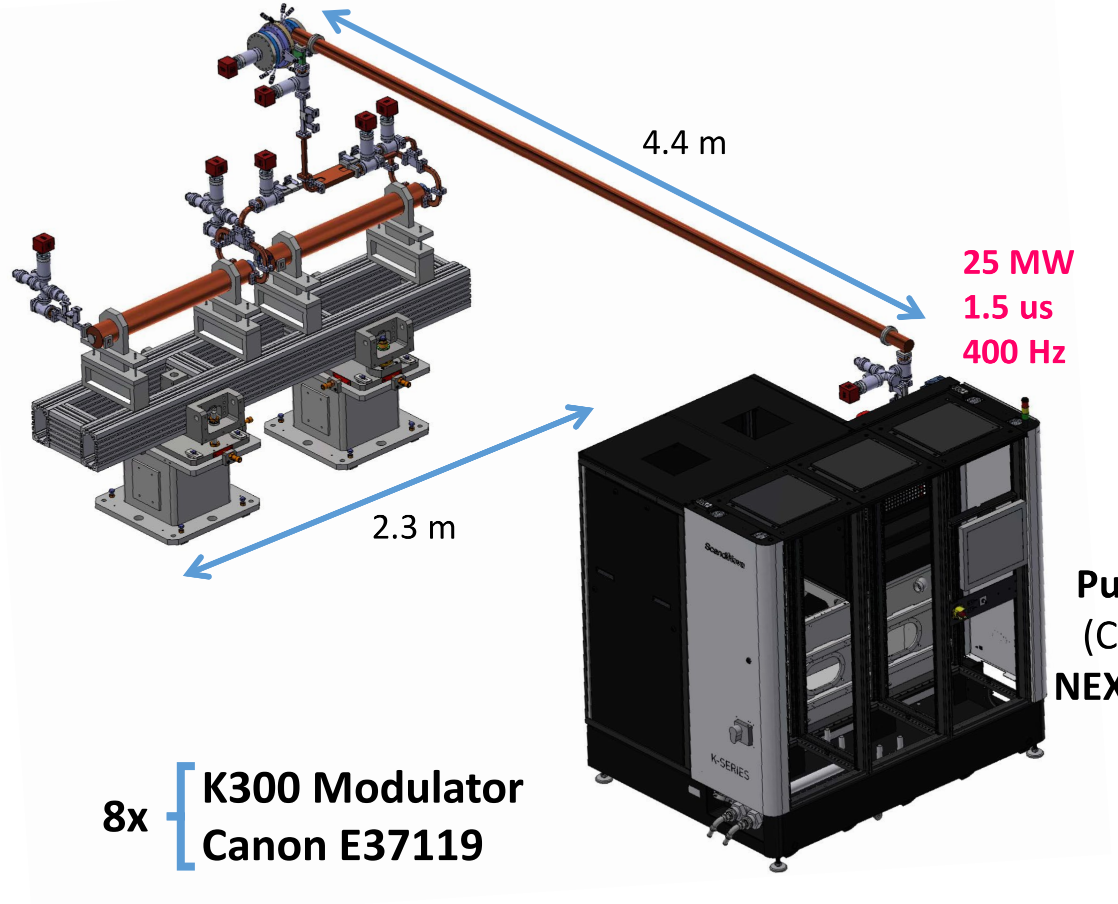
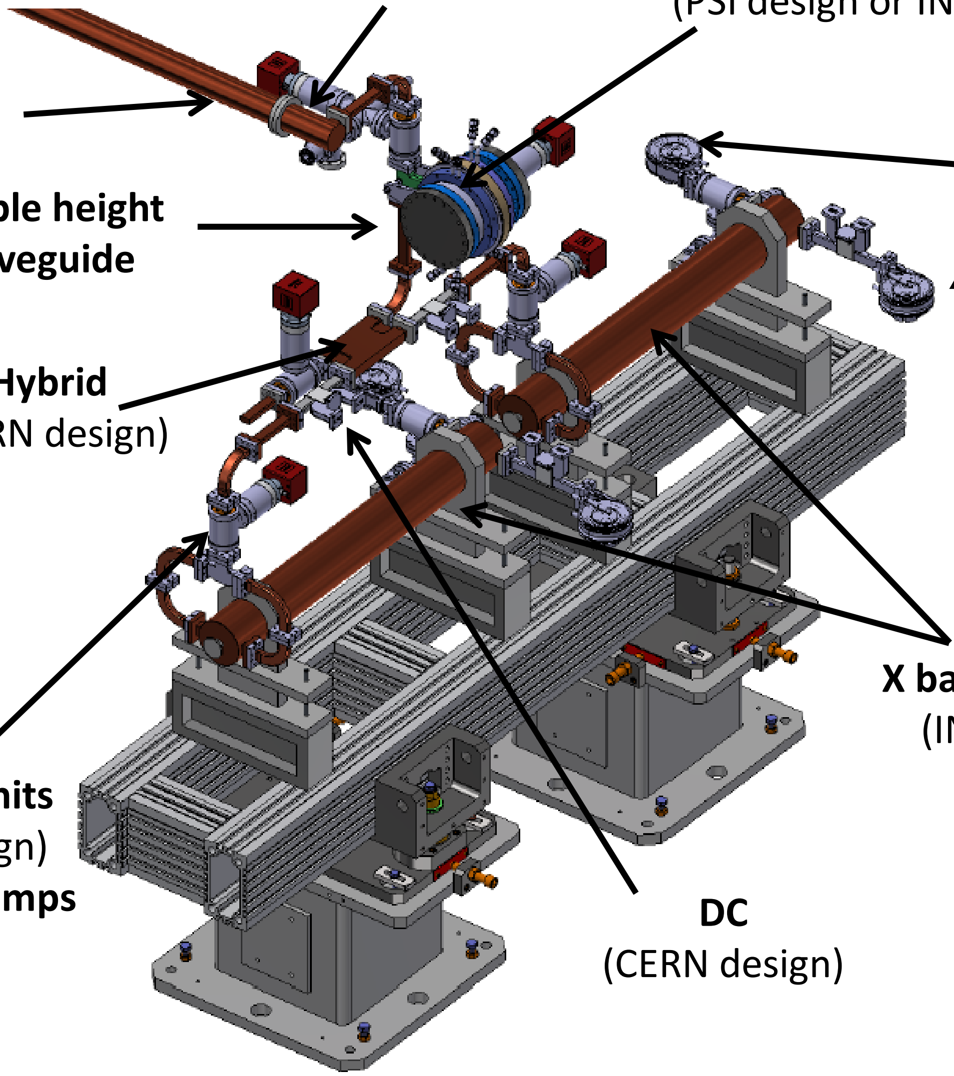
RF module baseline

- High flexibility
- Lower modulator power requirements
- Possible upgrade at high rep. rate of the Linac (very interesting for FEL users)
- Number of RF sources doubled





X-band structure design status

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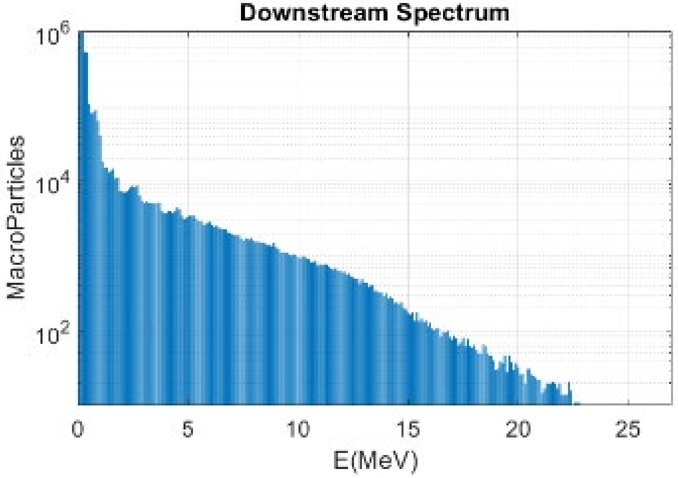
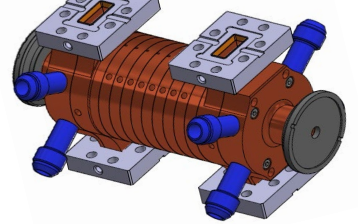
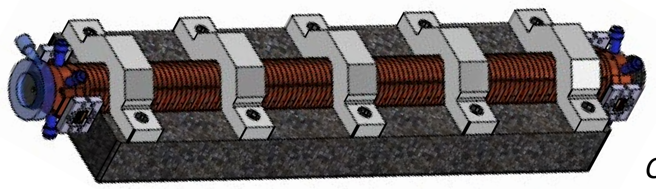
- The single cell and RF structure optimization has been completed developing a semi-analytical code to take into account also the power gain from a pulse compressor (*M. Diomede et al. NIM A 909 (2018) 243–246*)
- The EM design of the structure is completed: **0.9 m long** structures with **3.5 mm average iris radius** design to work with an average acceleration gradient of **60 MV/m**.
- **Thermo-mechanical simulations** of the structure have been completed to demonstrate the correct sizing of the cooling system.
- The **mechanical drawing** of the final X band structure is under constant review and is related to the result of the **prototyping activity**: brazing test, cell to cell alignment, etc.
- Dark current simulations (CST) + waveguide distribution design and attenuation calculation: done
- Three main steps of prototyping:

1. **Full scale mechanical prototype**: to test the brazing process of the full structure, the achievable cell-to-cell alignment and the vacuum seal *(done)*
2. **10-15 cells RF prototype for high power test**: 10-15 cell prototype with input/output coupler to be tested at low and high power *(currently ongoing)*
3. **Final full scale structure prototype** (after positive tests of the RF prototype open tender).

Parameter	Value
Frequency [GHz]	11.994
Average acc. gradient [MV/m]	**60**
Structures per module	**4**
Iris radius (linear tapering <a>=3.5) [mm]	3.8-3.2
Tapering angle [deg]	0.04
Structure length L_s [m]	**0.9**
No. of cells	**108**
Shunt impedance R [MΩ/m]	94-107
Average dissipated power [kW]	1
Filling time [ns]	126
Effective shunt Imp. R_s [MΩ/m]	350
Peak Mod. Poynting Vector [W/μm^2]	3.5
RF pulse [μs]	**1.5**
Rep. Rate [Hz]	**100**




10 cells prototype


Full scale «mechanical prototype»

Courtesy of D. Alesini, V. Lollo, R. Di Raddo

X-band structure preparatory activities and prototype assembly

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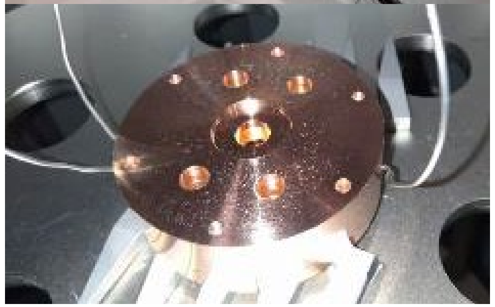
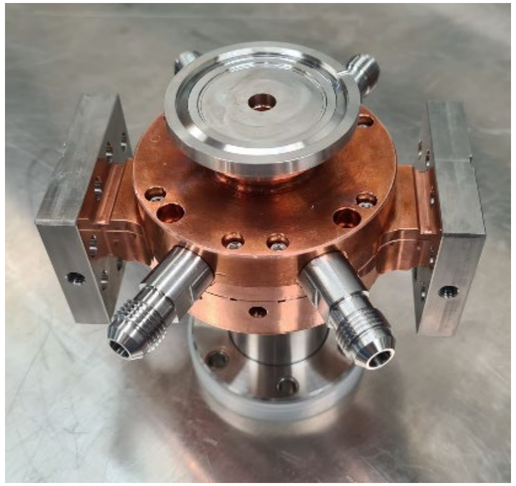
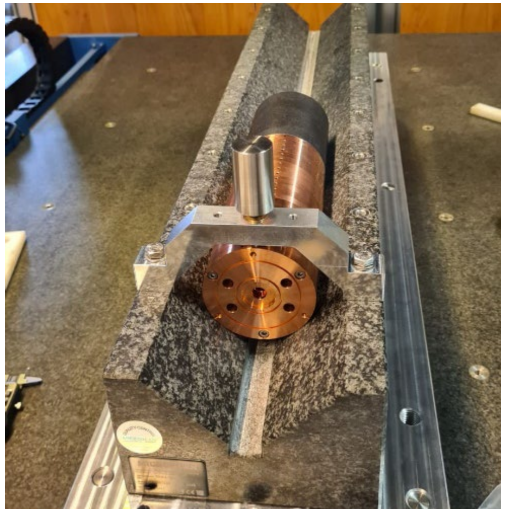


- **New vacuum furnace** model (TAV TUVH 40-130) commissioned at INFN-LNF in the framework of the LATINO Project, that allows for in-house brazing of components.
- Several 3-cells prototypes have been realized to optimize the brazing procedure.
- 0.9 m prototype made up of 36x three-cells module to test the brazing uniformity on the entire structure.
- All these activities are also preparatory to train the technical staff in the use of the furnace and brazing.

Pictures courtesy of D. Alesini, F. Cardelli, A. Liedl, V. Lollo and R. Di Raddo

Final structure **straightness ±15 μm**, before brazing
straightness ±30 μm, after brazing



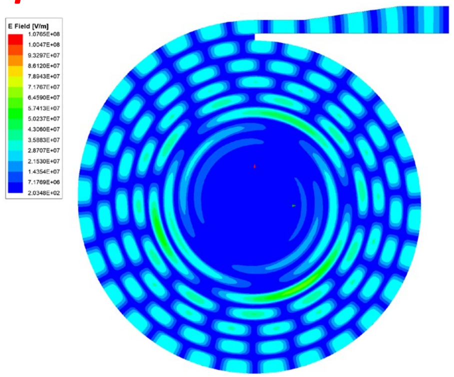


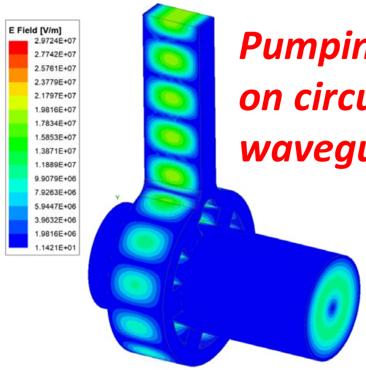
TEX facility – TEst-stand for X-band at Frascati

- The ***TEst-stand for X-band*** (**TEX**) is a facility conceived for R&D on high gradient X-band accelerating structures and waveguide components in view of Eupraxia@SPARC_LAB project. TEX is located in bld. 7 of LNF, fully refurbished and upgraded to host the RF source and bunker.
- It has been co-funded by Lazio regional government in the framework of the **LATINO project** (*Laboratory in Advanced Technologies for INnOvation*). The setup has been done in **collaboration with CERN** and it will be also used to test CLIC structures.
- Not only a facility for accelerator structures but also R&D for: **high power tests on new RF components**, **LLRF systems**, **Beam Diagnostics**, **Vacuum and Control System**

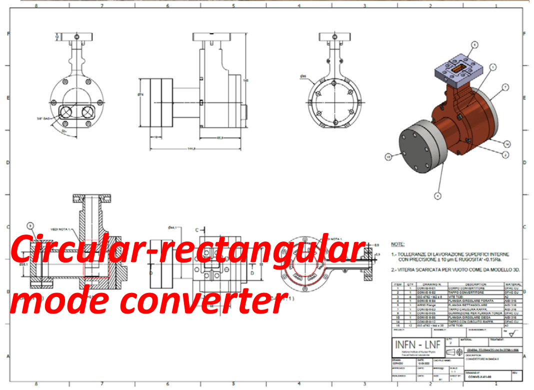
Concrete Bunker and Modulator Cage with the RF Source

Spiral load with additive manufacturing (CERN design)





Pumping port on circular waveguide



Circular-rectangular mode converter

Conclusions and future perspectives

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- In the last decade, a very intense design, prototyping and test activity on high gradient accelerating structures has been carried out at LNF
- The main focus has been on:
  - New paradigm **SW braze-free RF guns**
    - 4x S-band 1.6 cell already realized/in operation, working at **120 MV/m peak field on cathode**
    - 1x C-band 2.5 cell to be high power tested in 2023 at PSI, working at **160 MV/m peak field on cathode**
  - **C-band TW structures**
    - CI structures for SPARC_LAB energy upgrade (**up to 50 MV/m** reached on short prototype)
    - Quasi-CG damped structures for ELI-NP (**33 MV/m average gradient**, **100 Hz**, **multi-bunch**)
  - **X-band TW structures** prototyping and realization for EuPRAXIA@SPARC_LAB project (**60 MV/m average gradient**, **100 Hz**)

- Next steps:
  - X-band prototyping finalization, new RF components and structure high power tests at TEX;
  - high power tests at PSI of the C-band RF gun in the framework of I-Fast collaboration;
  - the development of a full C-band injector, with its appealing beam and EM properties, could be very interesting.

Thank you for your attention