11-13/12/2023 CLIC Mini Week - CERN

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

# Progress on the Eupraxia@SPARC_LAB Project: with special focus on X-band

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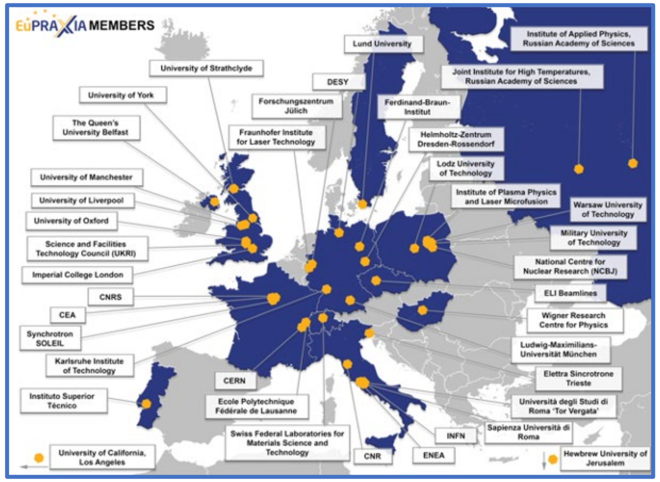
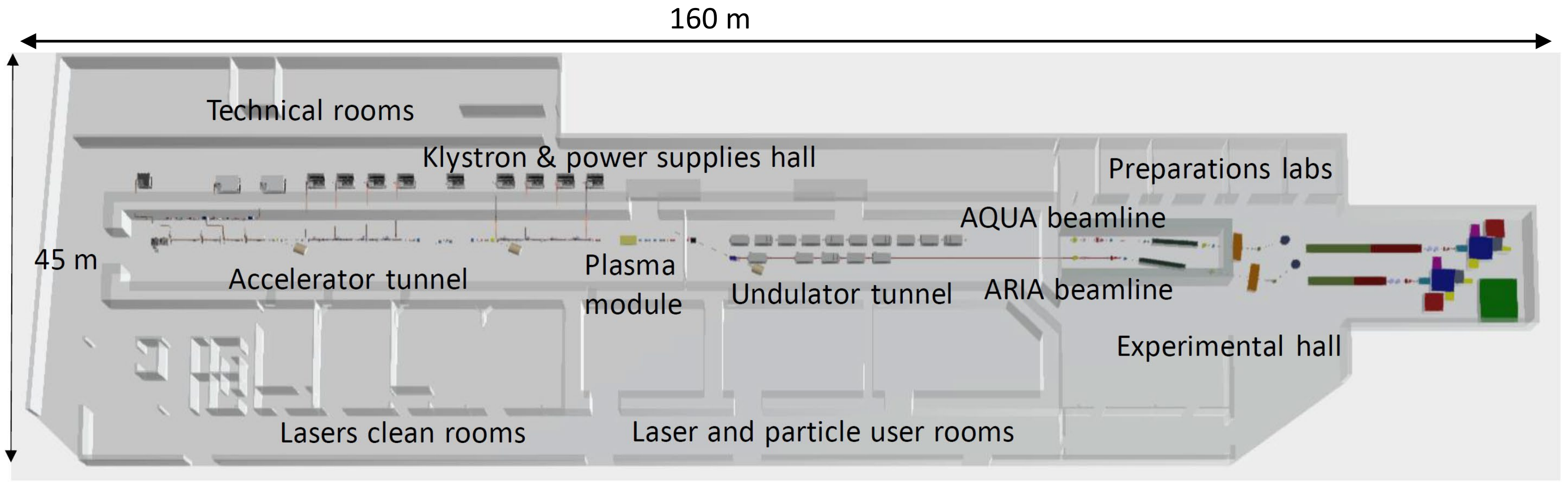
on behalf of the TeX technical team and the EuPRAXIA@SPARC_LAB team

Istituto Nazionale di Fisica Nucleare

# EuPRAXIA@SPARC_LAB Project

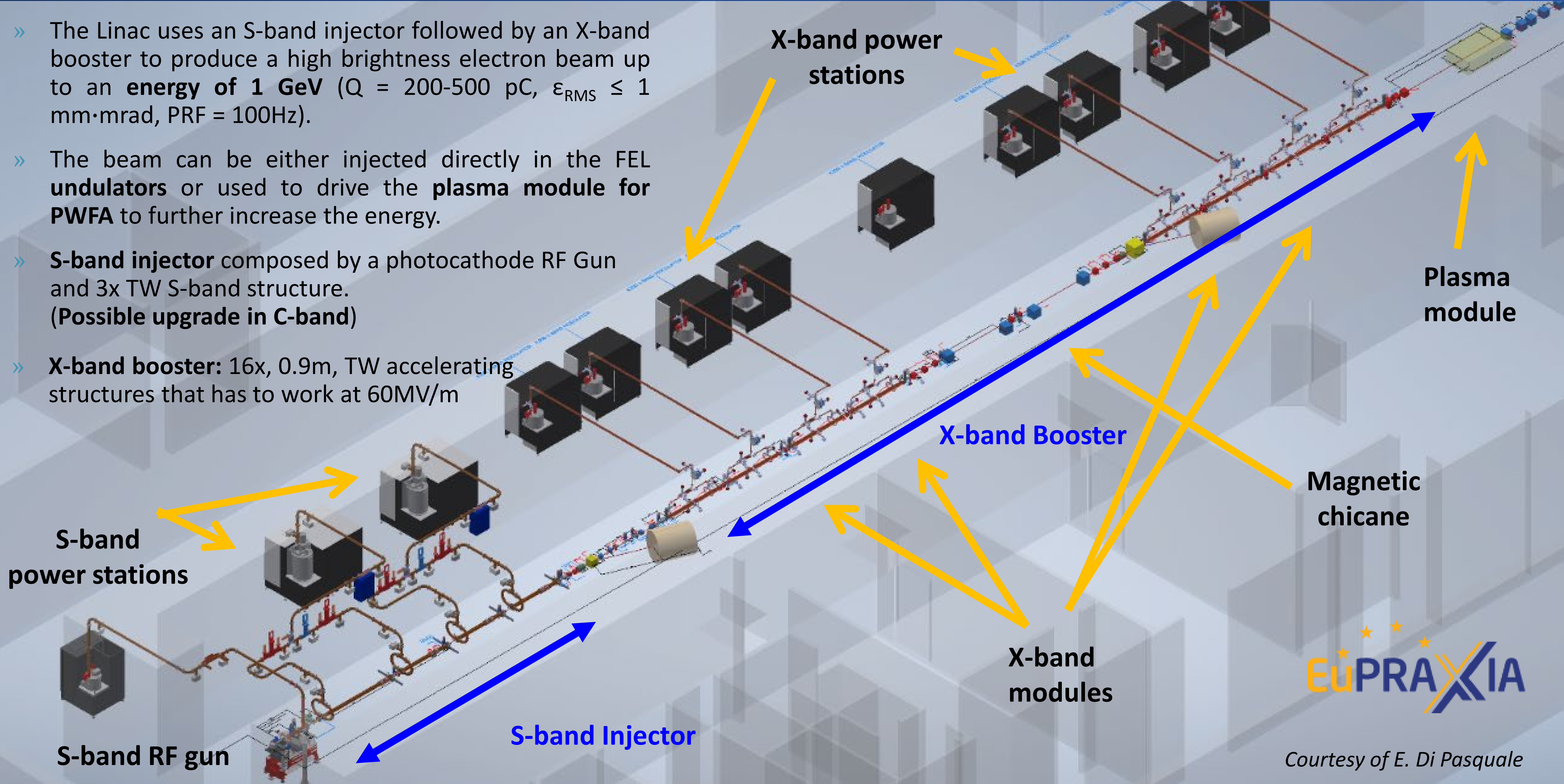
- The project is one of the pillars of the **European Project EUPRAXIA** (http://www.eupraxia-project.eu/) – European Plasma Research Accelerator with excellence in Applications
- EuPRAXIA has **been included in the ESFRI 2021 Roadmap**
- The project EuPRAXIA@SPARC_LAB is the pillar of the EuPRAXIA project based on beam driven plasma wakefield acceleration (PWFA). It aims at constructing a FEL radiation source (two FEL lines $\lambda_{FEL}$=4 nm and 50-180nm) combining by:
  - **1GeV RF X-band Linac with an high brightness injector**
  - **Plasma module for PWFA**.
- The project is currently in the preparatory phase of the Technical Design Report.
- A **new building**, now under executive design phase, will host the new Facility at LNF, the construction should start by the end of 2024.





# Overview of the LINAC

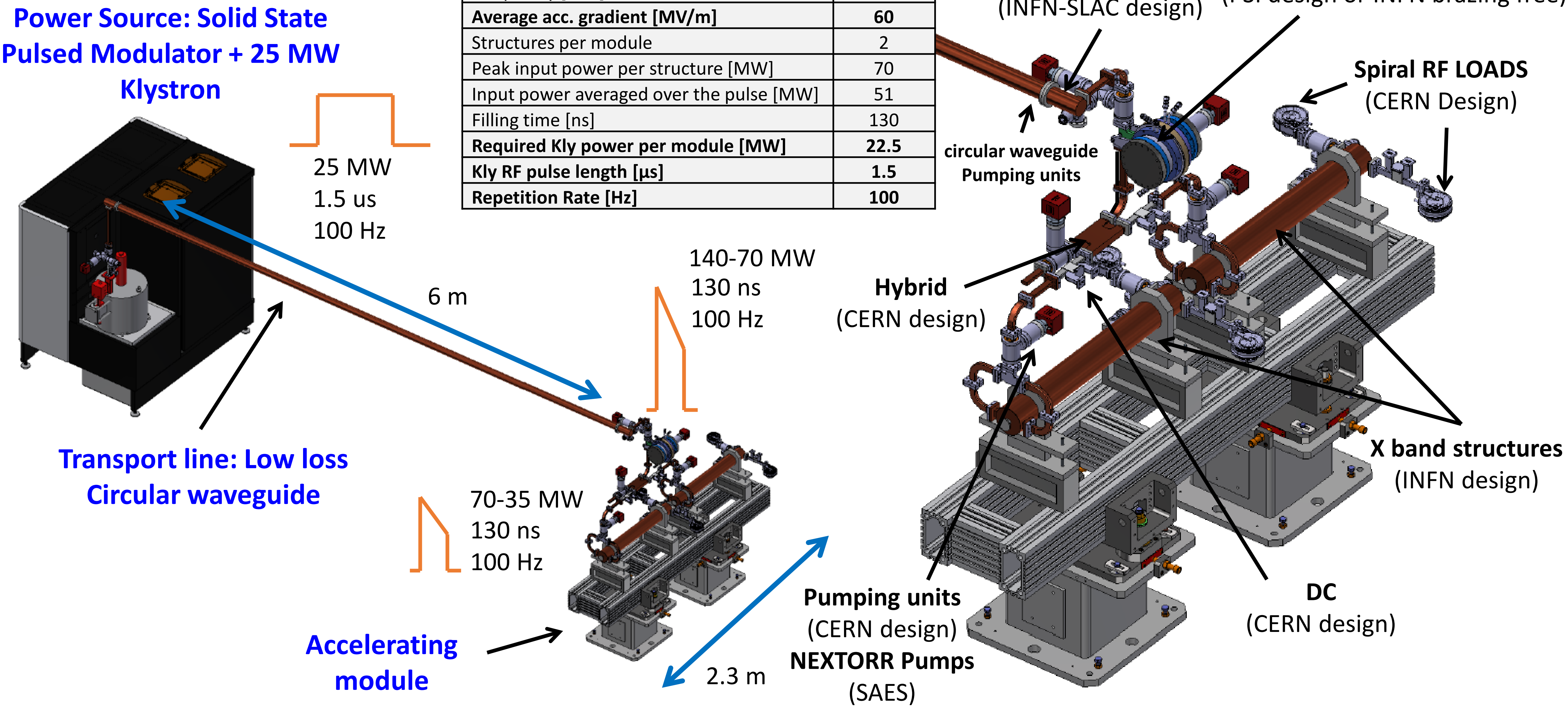
- The Linac uses an S-band injector followed by an X-band booster to produce a high brightness electron beam up to an **energy of 1 GeV** (Q = 200-500 pC, $\varepsilon_{RMS} \leq 1$ mm·mrad, PRF = 100Hz).
- The beam can be either injected directly in the FEL **undulators** or used to drive the **plasma module for PWFA** to further increase the energy.
- **S-band injector** composed by a photocathode RF Gun and 3x TW S-band structure. (**Possible upgrade in C-band**)
- **X-band booster:** 16x, 0.9m, TW accelerating structures that has to work at 60MV/m




*Courtesy of E. Di Pasquale*

# X-band RF Module Layout

| PARAMETER | Value |
|---|---|
| Frequency [GHz] | 11.9942 |
| **Average acc. gradient [MV/m]** | **60** |
| Structures per module | 2 |
| Peak input power per structure [MW] | 70 |
| Input power averaged over the pulse [MW] | 51 |
| Filling time [ns] | 130 |
| **Required Kly power per module [MW]** | **22.5** |
| **Kly RF pulse length [μs]** | **1.5** |
| **Repetition Rate [Hz]** | **100** |



# X-band RF Power Sources

Currently, the test stand is based on **CPI VKX8311A** Klystron on loan from CERN already **commissioned** and **in operation**

Two other X-band klystrons will be tested at TEX:

1. **CANON E37119**
   - Low modulator peak power requirement
   - Very high repetition rate (Interesting for a future upgrade of the machine)
   - 8x power sources for the linac booster

   **Status**:
   - *FAT of the klystron done **@CANON*** 11/2023, 25 MW, 10 Hz, t=1.5us
   - *FAT do be done with modulator @SCANDINOVA spring 2024*

2. **CPI High efficiency VKX8311HE** (collaboration CERN/INFN/CPI).
   - High efficiency
   - Increased klystron lifetime
   - 4x power sources for the linac booster

   **Status**:
   - Realization phase (expected delivery February 2025)

| Parameter | Unit | Canon E37119 | CPI VKX8311HE | CPI VKX8311 |
|---|---|---|---|---|
| Frequency | MHz | 11994 | | |
| Vk beam voltage | kV | 318 | 415 | 430 |
| Ik cathode current | A | 197 | 201 | 330 |
| Peak RF output Power | MW | 25 | 50 | 50 |
| Average RF output power | kW | 15 | 7,5 | 7,5 |
| Modulator Average power | kW | 75,2 | 25 | 43 |
| RF pulse length | µs | 1,5 | | |
| Repetition Rate | Hz | 400 | 100 | 100 |
| Gain | dB | 47 | 50 | 47 |
| Efficiency | % | 40 | 55 | 38 |
| Perveance | µp | 1.16 | 0.75 | 1.15 |

*CANON E37119*

# X-band RF components

» Many of the X-band components needed for the EuPRAXIA module are based on CERN design and have been manufactured, purchased and installed in the TEX layout: **directional couplers, pumping units, splitter, loads** [6]

## *3D printed Ti spiral load*

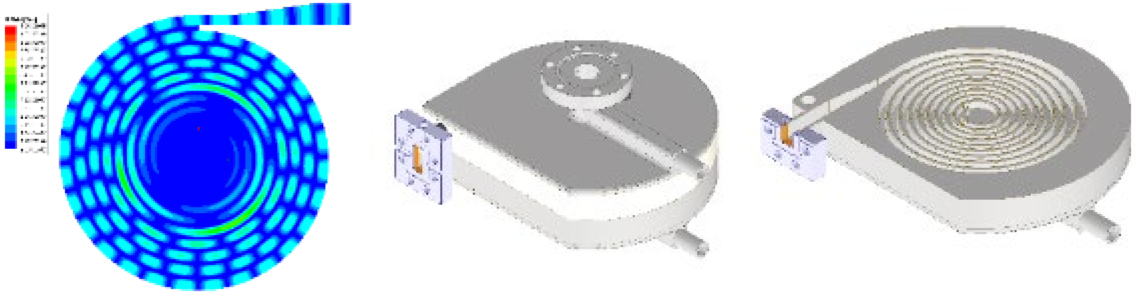
We procured 6 spiral loads 3D printed. Two has been installed and conditioned up to 35 MW with 200 ns pulse length at 50 Hz.

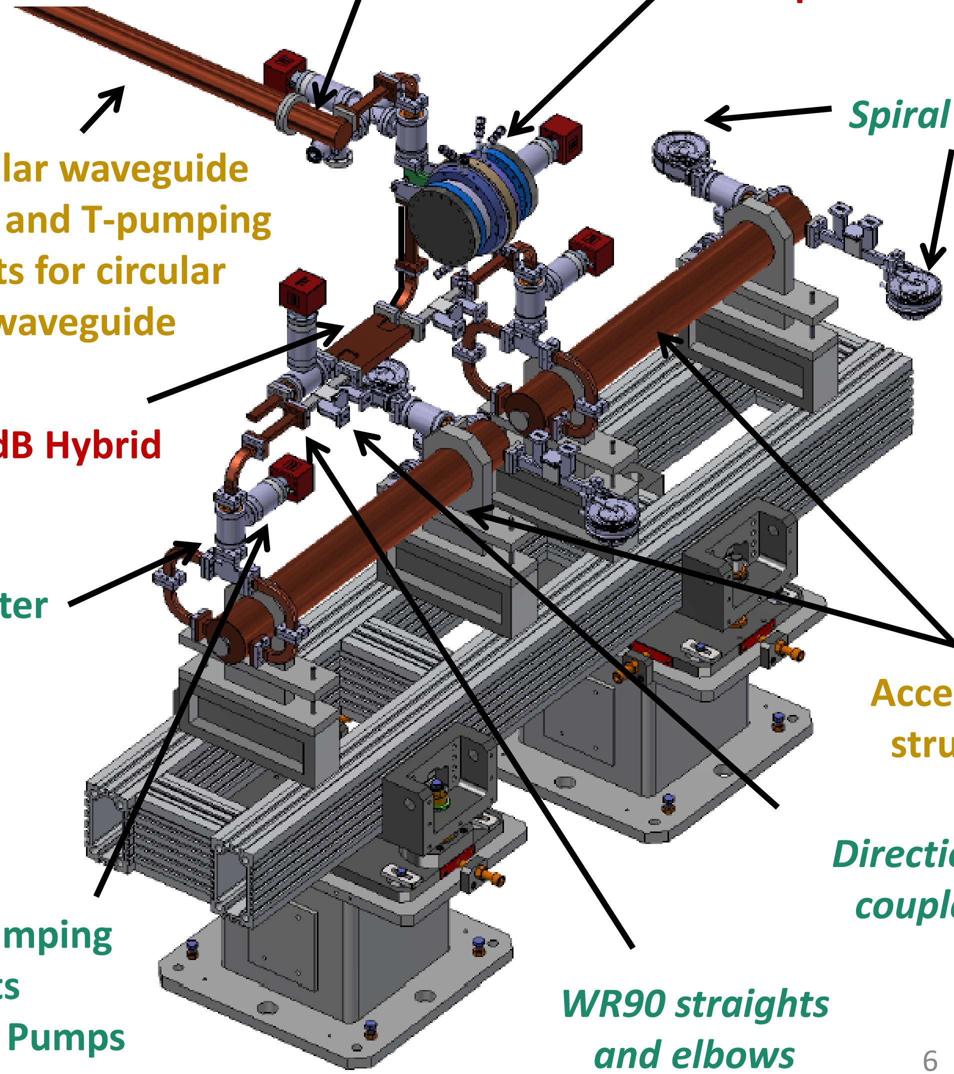
| # | Company | S11@f0 [dB] |
|---|---|---|
| 001 | 3t am | -31 |
| 002 | 3t am | -30 |
| 003 | ISC | -37,7 |
| 004 | ISC | -36,4 |
| 005 | ISC | -42 |
| 006 | ISC | -43,9 |

## *Machined spiral load*

EM and mechanical design: *done*

Manufacturing : *ongoing*



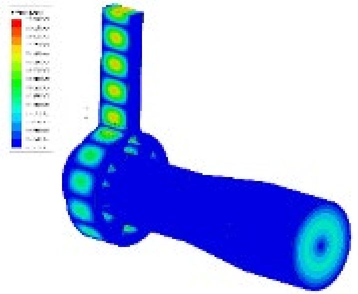
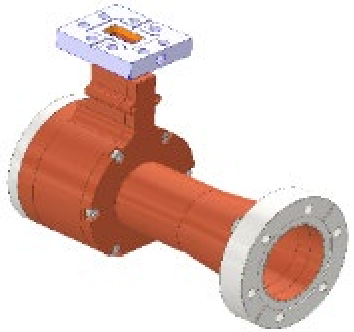
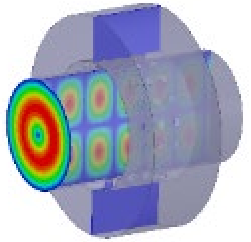
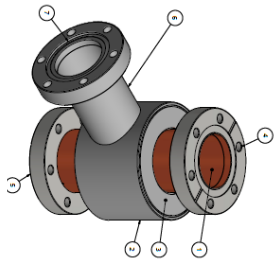
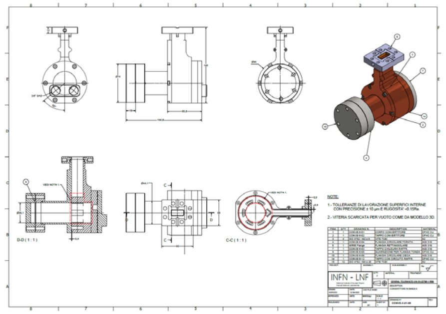


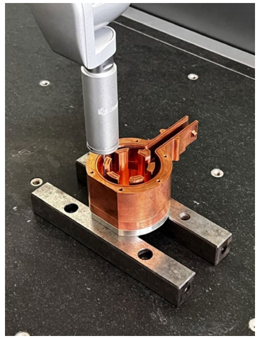


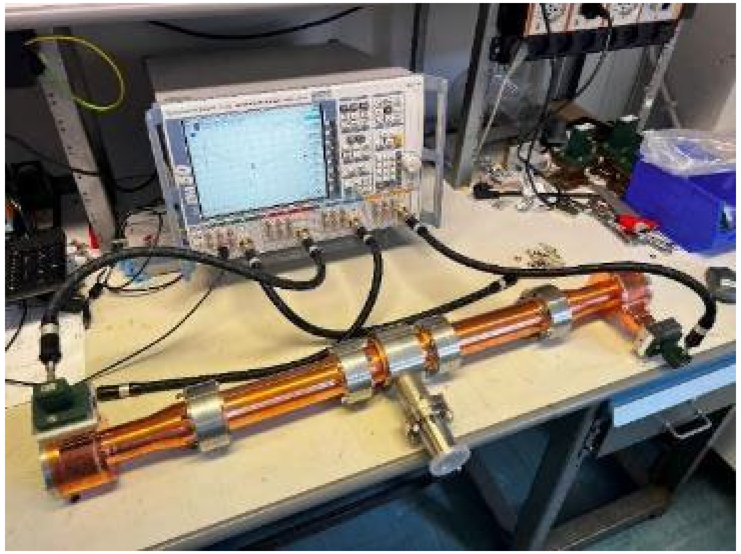
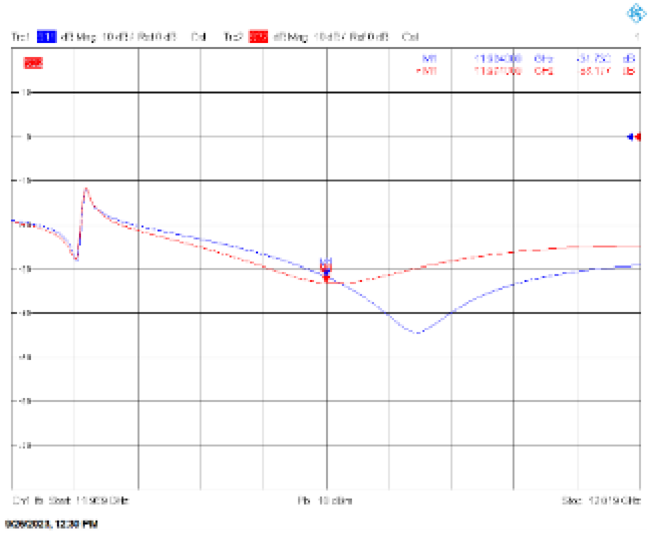

[6] N. Catalan-Lasheras, et al., 9th Int. Particle Accelerator Conf. (IPAC18), Vancouver, BC, Canada, May 2018, paper WEPMF074.

# Mode Converter

- Modified version of the "wrap around" mode converter from $TE_{10}^{\square}$ to $TE_{01}^{\circ}$ developed at SLAC [7] and pumping port for circular waveguide
- EM and mechanical design: ***done***
- Machining by a private company (TSC): ***done***
- Brazing at INFN-LNF: ***done***
- Low Power RF test: ***done***
- High Power test: ***Ongoing***



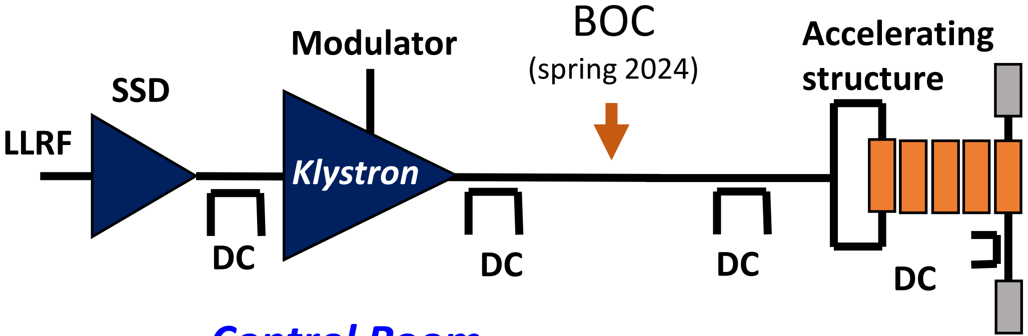




[7] S. Tantawi, et all. (2000). Reviews of Modern Physics – doi: 10.1103/PhysRevSTAB.3.082001

# TEX Facility Now

- The **TEst-stand for X-band (TEX)** is conceived for R&D and test on high gradient X-band accelerating structures, RF components, LLRF systems, Beam Diagnostics, Vacuum system and Control System
- It has been co-funded by Lazio region 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**
- The civil engineering works in the building has been concluded in August 2021
- The installation and commissioning of the **Modulator and klystron** has been completed in February 2022 [3]. At the same time **LLRF system** [4], **EPICS control system** have been commissioned
- The complete **waveguide network** has been procured and installed

| PARAMETER | MEAS. VALUE |
|---|---|
| Cathode peak voltage | 427 kV |
| **Peak RF output power** | **50 MW** |
| Pulse length | 250 ns (1.5 us) |
| **Repetition Rate** | **50 Hz** |
| RF output amplitude stability | < 0.09 % |
| RF output phase stability | 20.9 fs |




***Control Room***

***LLRF system***

***Concrete Bunker***

***RF Source***

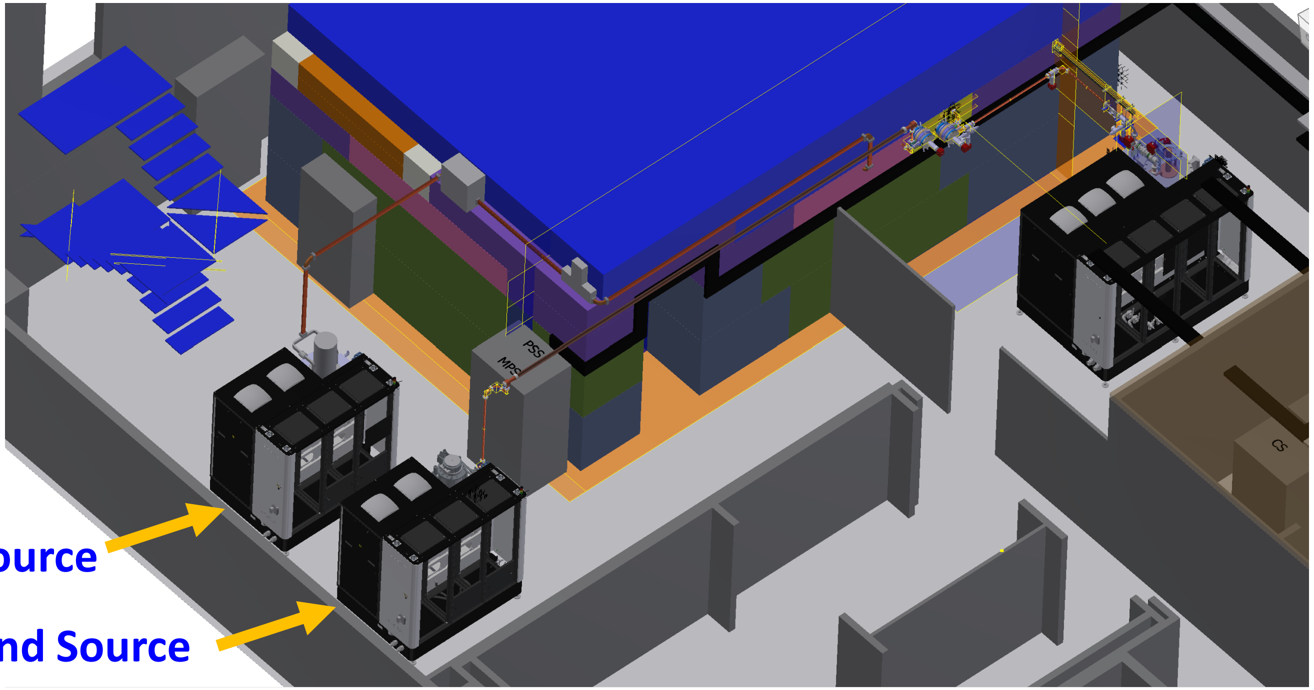
***VKX8311A Klystron***


*[3] F. Cardelli et al., 13th Int. Particle Accelerator Conf. IPAC22, Bangkok, Thailand, Jun. 2022, paper TUPOPT061*

*[4] L. Piersanti et al., 13th Int. Particle Accelerator Conf. IPAC22, Bangkok, Thailand, June 2022, paper TUPOST015*

# TEX Upgrade

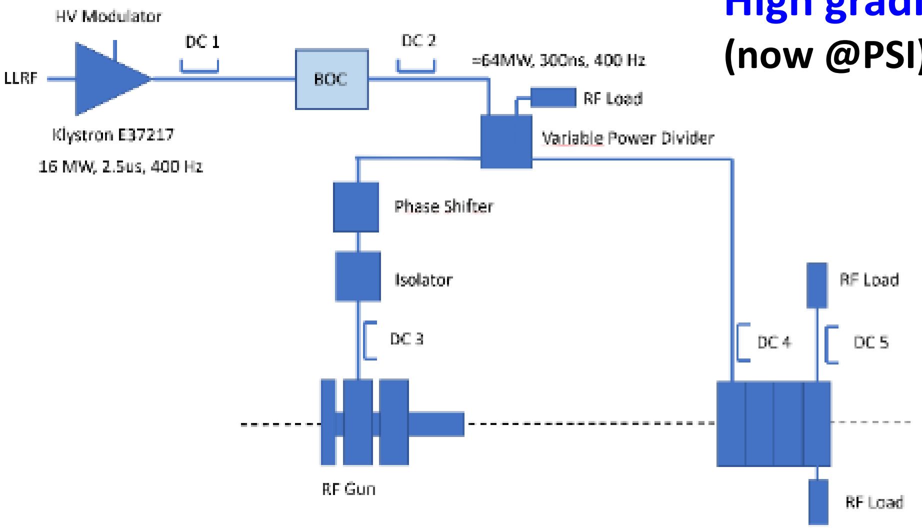
- An X-band **BOC pulse compressor** will be integrated in actual layout in order to increase the available power (ordered to PSI)
- A new **X-band power source** based on **Scandinova k300 modulator** with **Canon E37119 klystron**
- A **C-band power source Scandinova k300 modulator** with **Canon E37217 klystron** with a **BOC pulse compressor** already purchased (FAT of the klystron performed at Canon in November 2023, expected FAT of the complete source in Spring 2024)



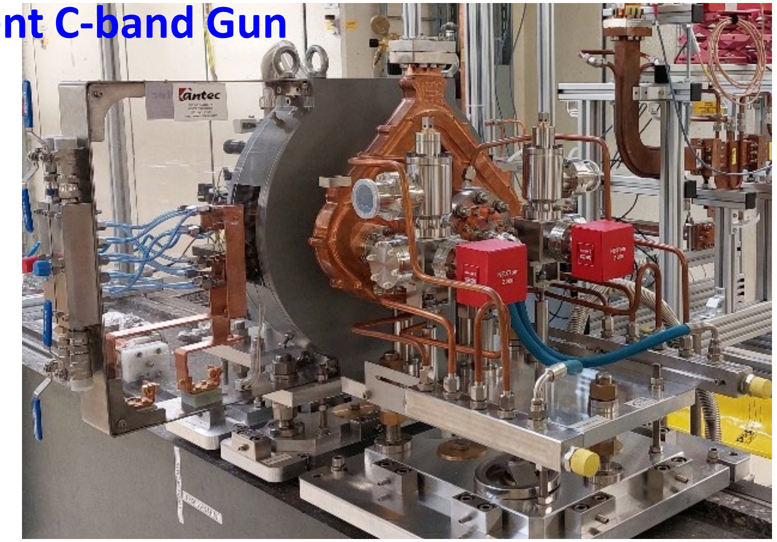

**New C-band Source**

**New X-band Source**

| Parameter | Unit | Canon E37217 |
|---|---|---|
| Frequency | MHz | 5712 |
| Vk beam voltage | kV | 280 |
| Ik cathode current | A | 240 |
| Peak drive power | W | 500 |
| Peak RF output Power | MW | 20 |
| Average RF output power | kW | 21 |
| Modulator Average power | kW | 75,2 |
| RF pulse length | us | 2.5 |
| Repetition Rate | Hz | 400 |
| Gain | dB | 50 |
| Efficiency | % | 40 |

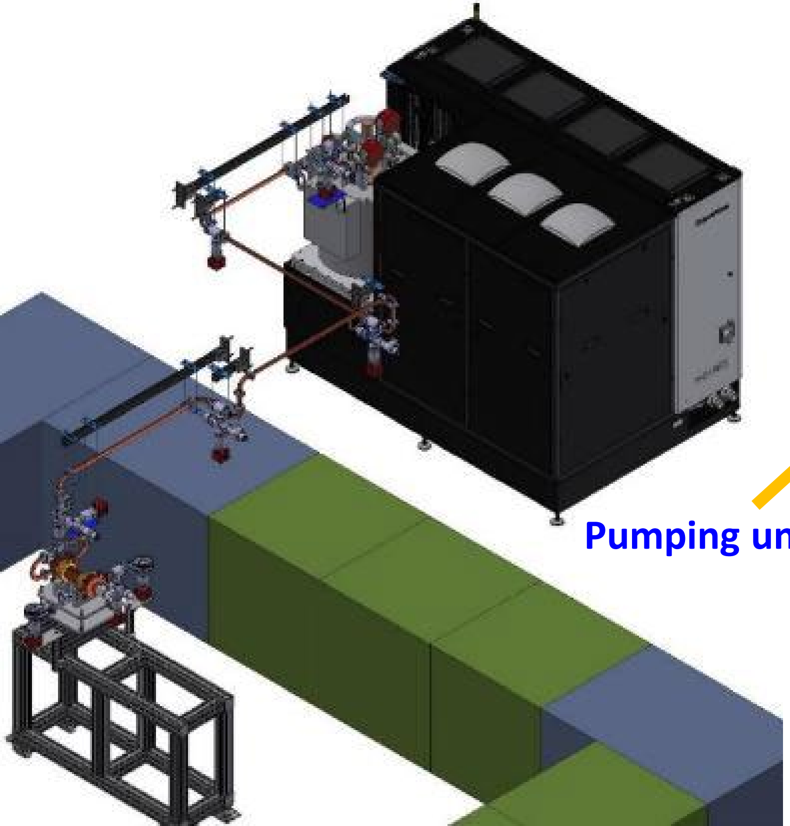


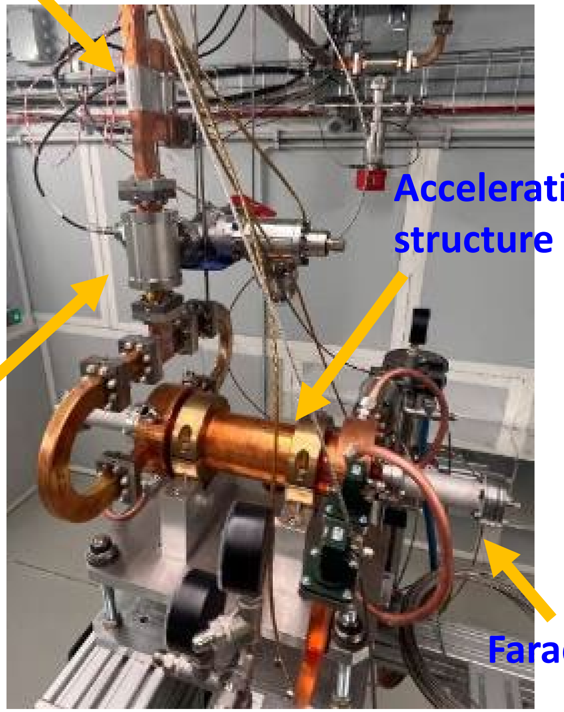

**High gradient C-band Gun**
**(now @PSI)**



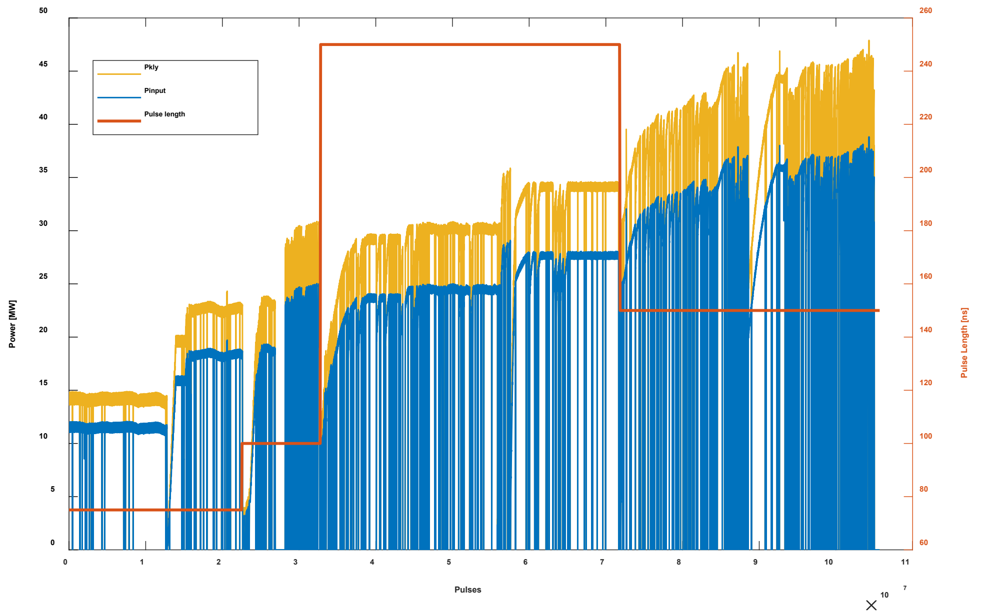
# Conditioning of T24 structure

- In April 2023 we installed, inside the bunker, a CERN accelerating section of the **T24 CLIC** type realized by PSI. The RF test started in May and lasts nearly 40 days reaching 38 MW power at the structure input with 150 ns pulse length at 50 Hz.
- This test has been preparatory to the conditioning of the **first EuPRAXIA accelerating structure prototype**, which will take place by November 2023.
- The test has been performed with an automatic conditioning routine.



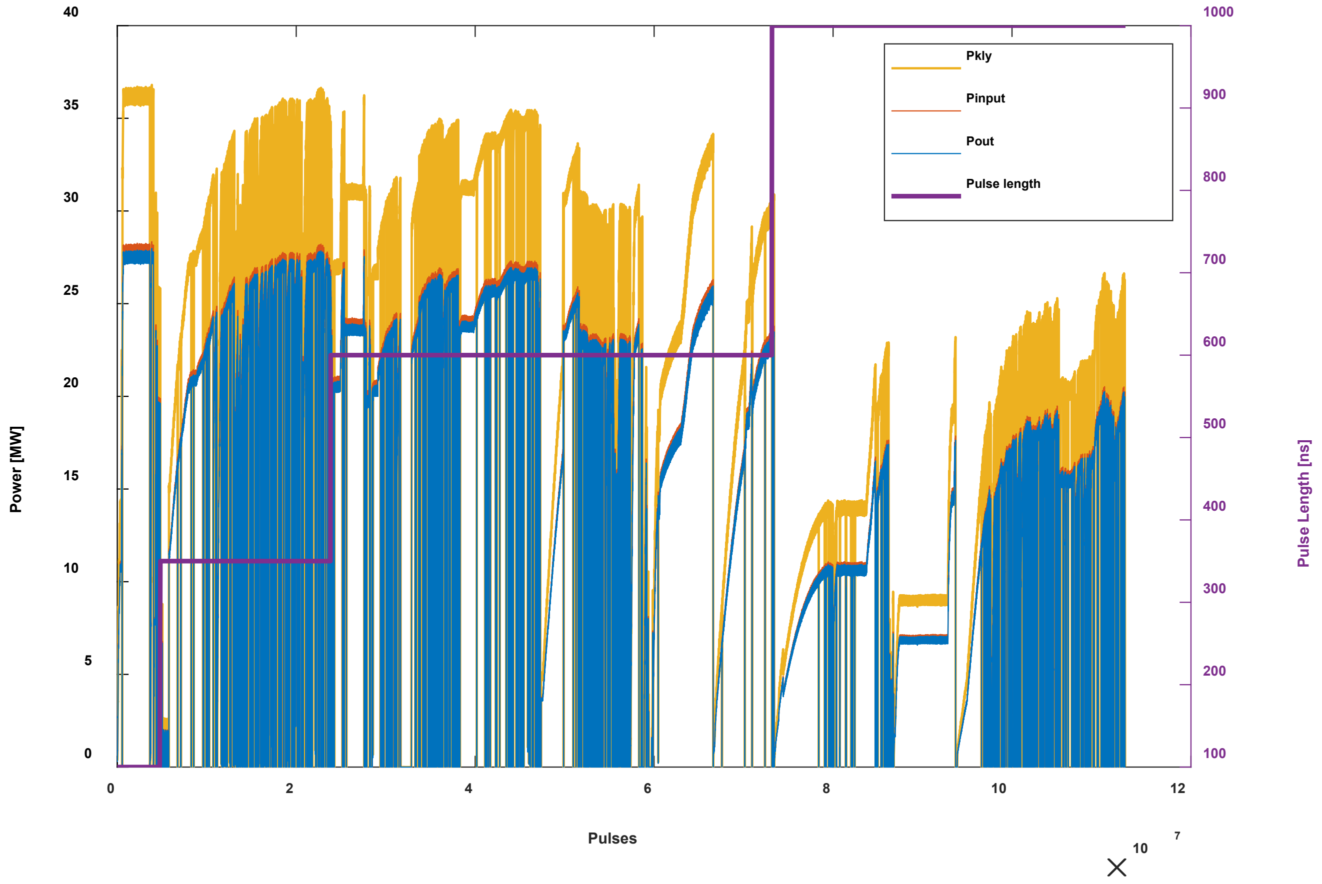



**Conditioning story**



# Mode Converter high power test

- Modified version of the "wrap around" mode converter from $TE_{10}^{\square}$ to $TE_{01}^{\circ}$ developed at SLAC [7] and pumping port for circular waveguide
- EM and mechanical design: ***done***
- Machining by a private company (TSC): ***done***
- Brazing at INFN-LNF: ***done***
- Low Power RF test: ***done***
- High Power test: ***Ongoing***




» Power **loss in the circular waveguide ≤ 100 kW**

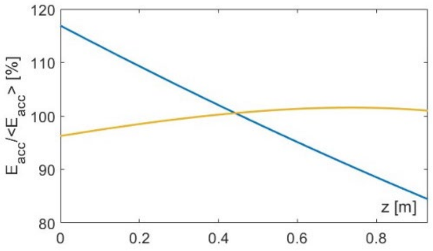
» Power reached on the single Spiral load:

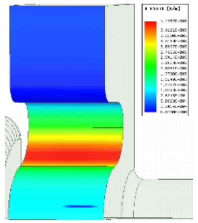
- **$P_{peak}$ = 10 MW, $t_{pulse}$ = 1µs, PRF = 50 Hz**

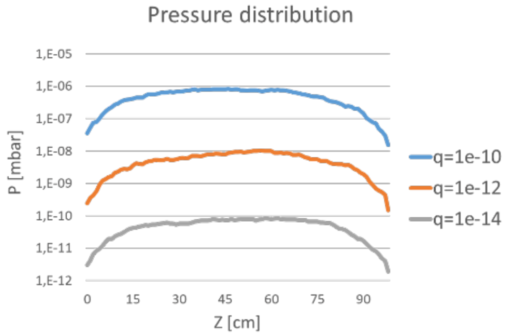
*[7] S. Tantawi, et all. (2000). Reviews of Modern Physics – doi: 10.1103/PhysRevSTAB.3.082001*

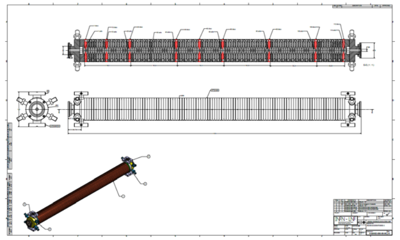
# X-band Accelerating structures design

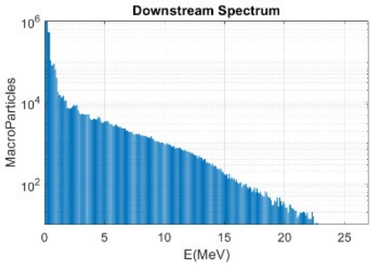
- The **EM design of the structure is completed**: **0.9 m long** structures with **3.5 mm average iris radius** design to work with an average acceleration gradient of **60 MV/m.** The single cell and RF structure optimization has been completed developing a semi-analytical code to consider also the power gain from the BOC pulse compressor [10]: ***done***
- **Thermo-mechanical simulations** to demonstrate the correct sizing of the cooling system (at 100 Hz and 400 Hz): ***done***
- **Dark current simulations** (CST Particle in cell) have been performed to evaluate the background radiation together with **vacuum calculation** to verify the pression distribution along the structure: ***done***
- The final **mechanical design** of the final X-band structure has been under constant review, related to the result of the **pre-prototyping activity**: brazing test, cell to cell alignment, etc: ***done***






| PARAMETER | Value | |
|---|---|---|
| | Quasi-Constant Gradient | Constant Impedance |
| Frequency [GHz] | 11.9942 | |
| **Average acc. gradient [MV/m]** | **60** | |
| Structures per module | 2 | |
| **Iris radius a [mm]** | **3.85 - 3.15** | **3.5** |
| Tapering angle [deg] | 0.04 | 0 |
| **Struct. length $L_s$ act. Length [m]** | **0.94** | |
| No. of cells | 112 | |
| Shunt impedance R [MΩ/m] | 93-107 | 100 |
| Effective shunt Imp. $R_{sh\_eff}$ [MΩ/m] | 350 | 347 |
| Peak input power per structure [MW] | 70 | |
| Input power averaged over the pulse [MW] | 51 | |
| Average dissipated power [kW] | 1 | |
| $P_{out}/P_{in}$ [%] | 25 | |
| Filling time [ns] | 130 | |
| Peak Modified Poynting Vector [W/μm$^2$] | 3.6 | 4.3 |
| Peak surface electric field [MV/m] | 160 | 190 |
| **Required Kly power per module [MW]** | **22.5** | |
| **Kly RF pulse length [μs]** | **1.5** | |
| **Repetition Rate [Hz]** | **100 (400)** | |



*[10] M. Diomede et al. NIM A 909 (2018) 243–246*

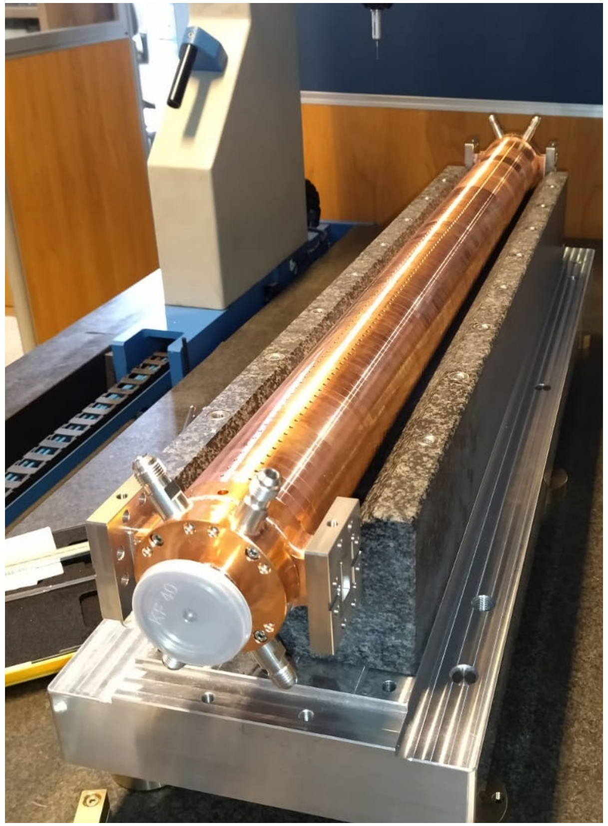
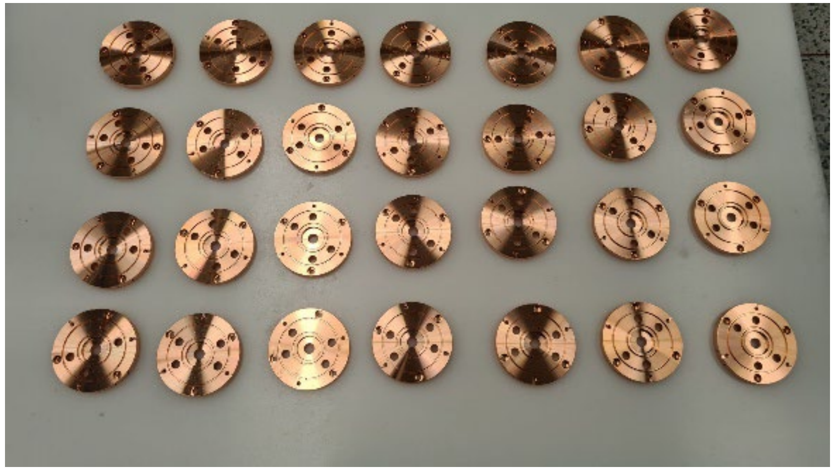
# Structure Prototyping Activity

Four main steps of prototyping:

1. **Pre-prototypes** on 3-cells and simplified couplers to test and optimize the brazing procedure, cells assembly, alignment etc: ***done***
2. **Full scale mechanical prototype**: 0.9 m prototype to test the overall brazing process of the full structure and the cell-to-cell alignment before and after brazing: ***done***
3. **20 (+2) cells RF prototype for high power test** w/o tuning, constant impedance: ***realized (to be tested at high power)***
4. **Final full scale EuPRAXIA@SPARC_LAB structure prototype** 0.9 m constant impedance: ***to do***



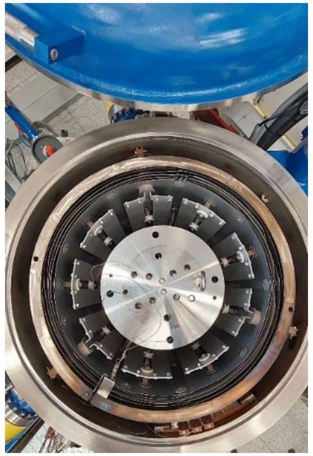


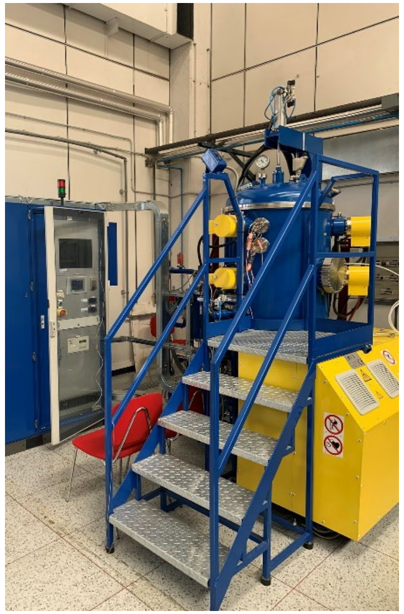



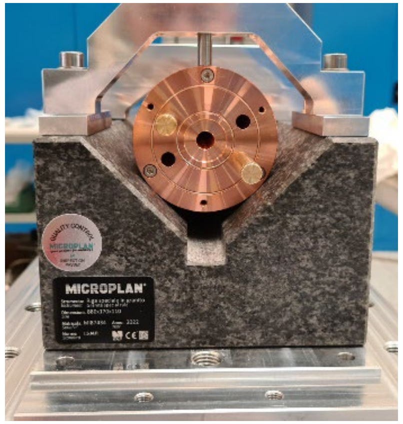

# Full-Scale Mechanical Prototype Brazing

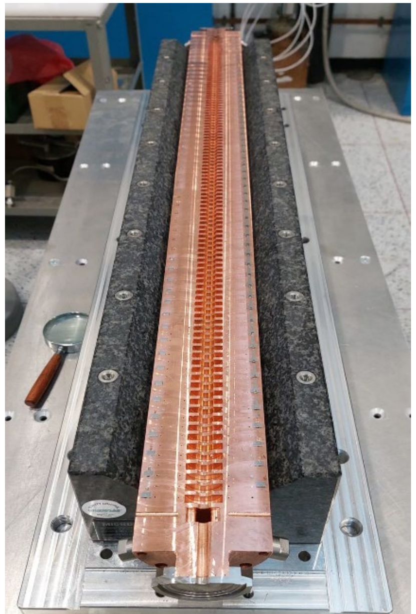
## Full scale mechanical prototype brazing

To maintain the alignment and cell to cell straightness during and after the brazing process, **each cell is fixed to the next one by means of screws** and mounted on a very precise **granite support**. This ease also the cells assembly







## Results on the brazed structure

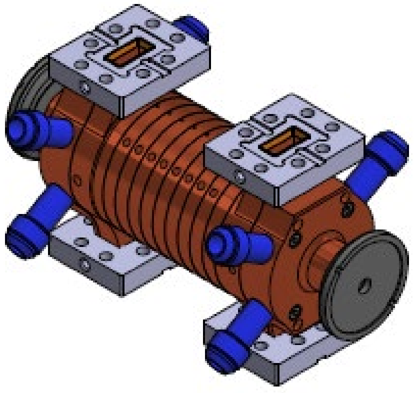
- **Vacuum test OK** (except one coupler for a miss-positioning of the brazing alloy)
- **Straightness ±15 μm** obtained after brazing (±30 μm required by BD)

Another full-scale mechanical prototype has been realized and brazed in order to further optimize the brazing procedure.

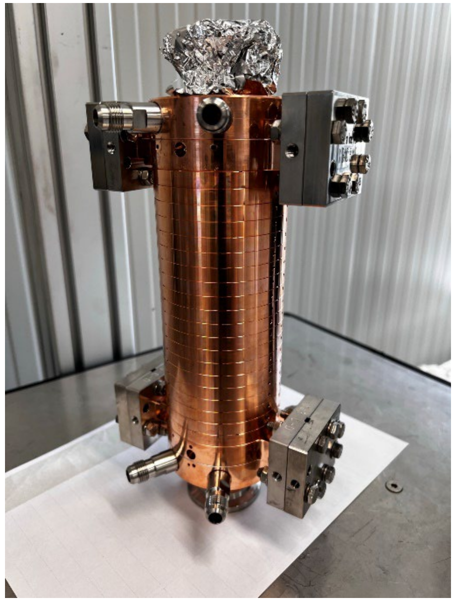
# First RF Prototype

***X-band, 20 (+2) cells, CI, travelling wave structure prototype***

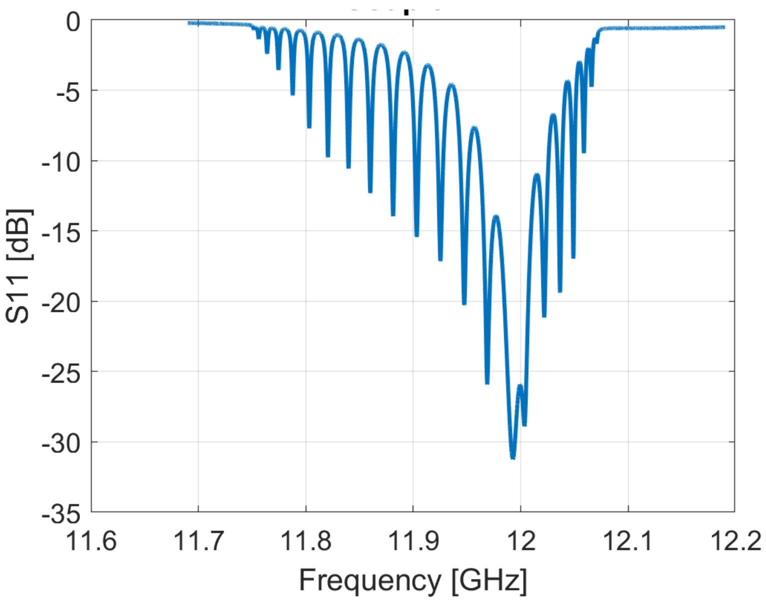
- The structure has been realized **without tuners on the cells**, there are **2 tuners on each coupler**.
- We perform the low power measurement before cells brazing, after the brazing and then we perform the tuning of the couplers.
- During the measurements and the tuning procedures the structure has been continuosly fluxed with nitrogen.

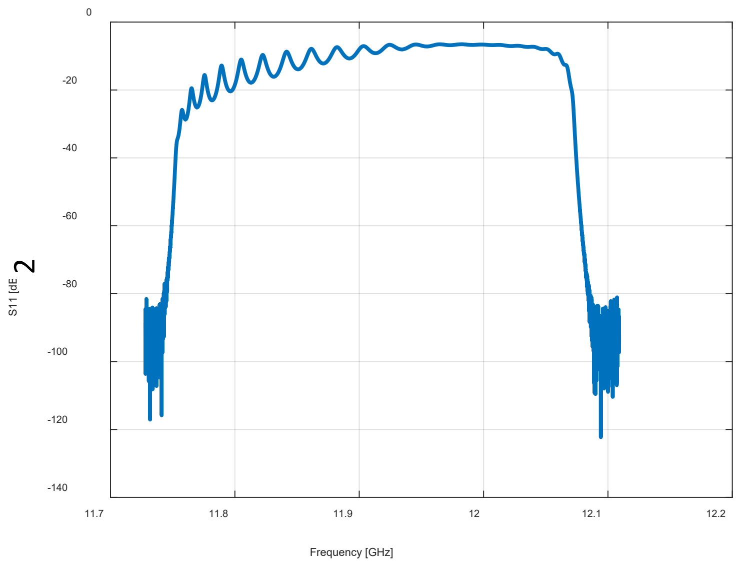


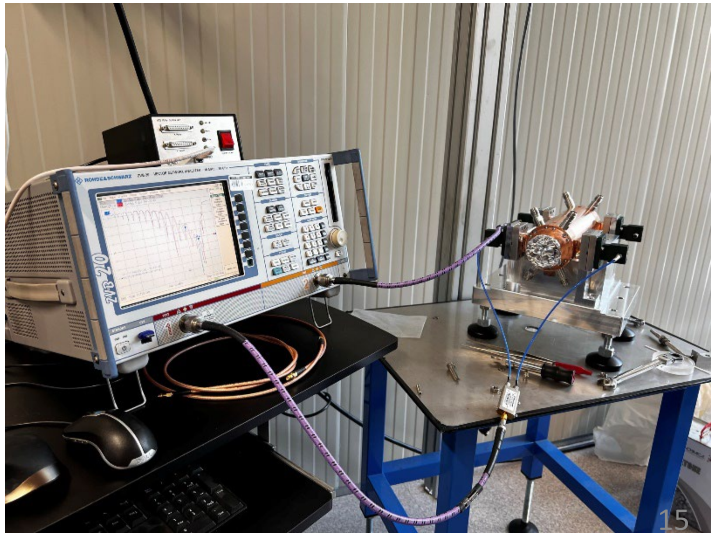
***Before brazing***



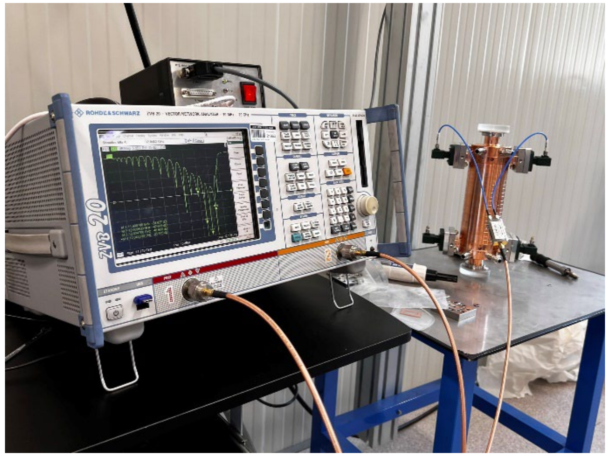
***After brazing***

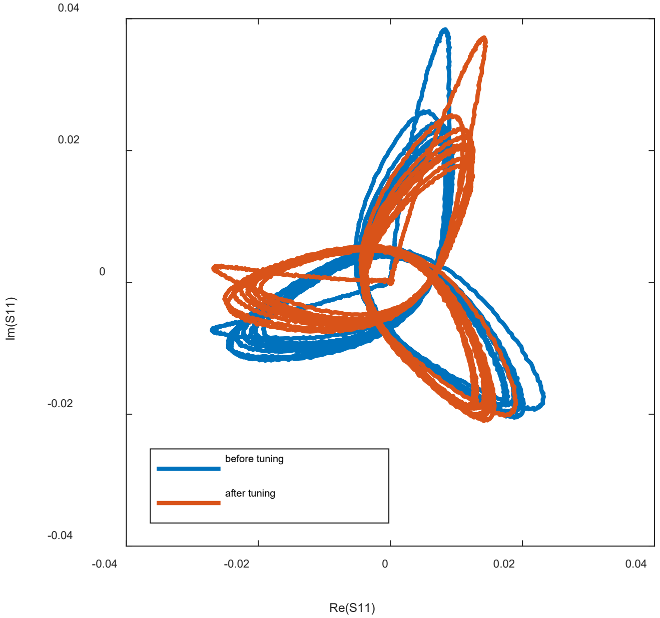


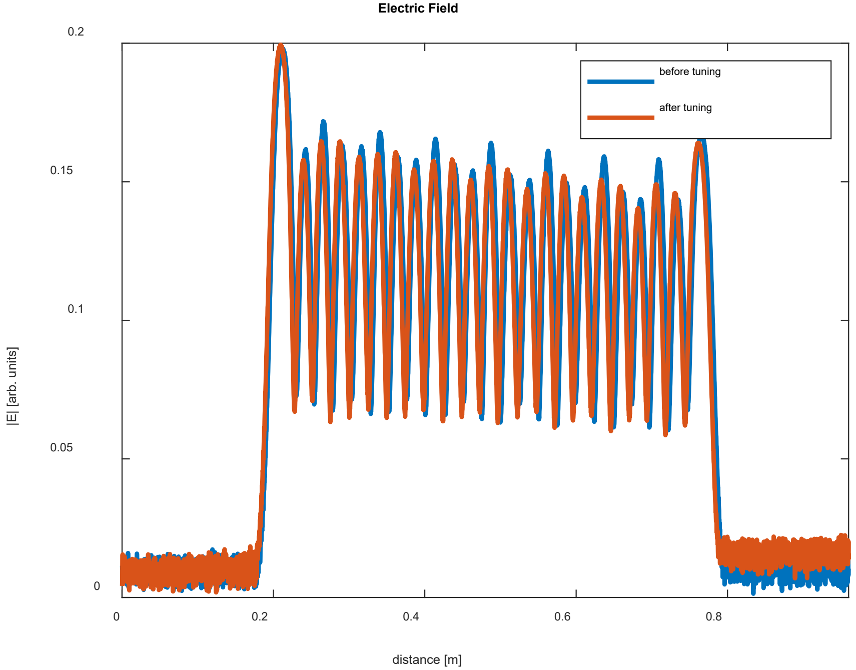



# BeadPull measurements



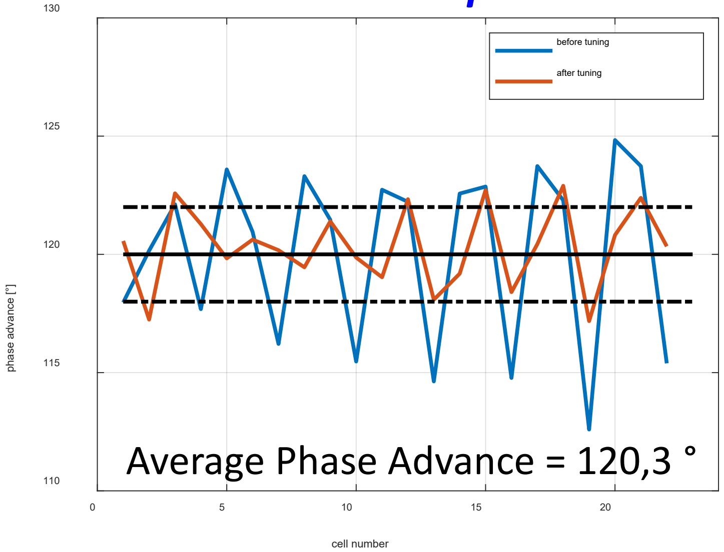


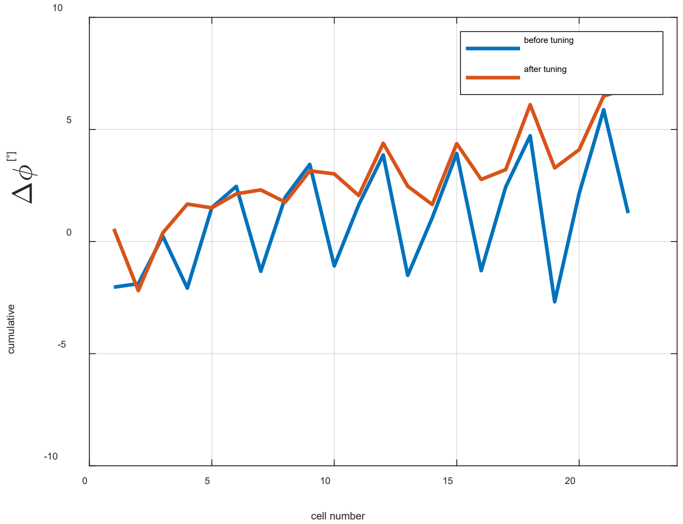

The bead drop measurement has been performed before and after the tuning of the couplers

All the cells sems to be smaller (2-3 um on the diameter) to compensate to obtain the best response from the cells we will need to increase the working temperature → **$T_{cav}$ = 30 – 35 °C**

***Phase advance per cell***




***Cumulative Phase advance***



# Conclusions and future activities

- **EuPRAXIA@SPARC_LAB** is the next INFN-LNF facility. It is the beam driven pillar of the EuPRAXIA project, included in the ESFRI 2021 Roadmap
- **TEX (Frascati Test stand for X-band)**: has been completely commissioned and used to test some components
  - A new X-band RF source based on the **25 MW, 400Hz E37119 klystron** has been tested at CANON and will be commissioned at TEX starting in Spring 2024. Also a C-band source will be installed at TEX in the same period.
  - A **high efficiency klystron 50 MW VKX8311HE** developed by CPI/CERN should be commissioned at the beginning of 2025.
- Many **X-band RF components** of the EuPRAXIA RF module have been purchased and tested at nominal power other will be tested soon:
  - A **brazing free BOC** design is ongoing, a standard BOC is in procurement from PSI.
  - The test of the **mode converters** and **circular waveguide components** is ongoing.
- **X-band structures**: An intensive prototyping activity is ongoing exploiting the new vacuum furnace at LNF.
  1. The **full-scale mechanical prototype** brazing test gives optimum results in term of straightness and vacuum tightness (another prototype has been realized).
  2. The **20 cells CI RF prototype** has been realized and tested at low power
     - Low power RF measurements showed that the cells are all the same but smaller by approx ±2 µm
     - The 20 cells structure **high power test will start in January**.
  3. A **full-scale 0.9m RF prototype is in production.**

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