X-band activities at INFN Frascati National Laboratories towards the EuPRAXIA@SPARC_LAB project

GFA Accelerator seminar @ PSI - 2023/08/28

Marco Bellaveglia and Luca Piersanti on behalf of the INFN–LNF RF & LINAC group

Presentation outline

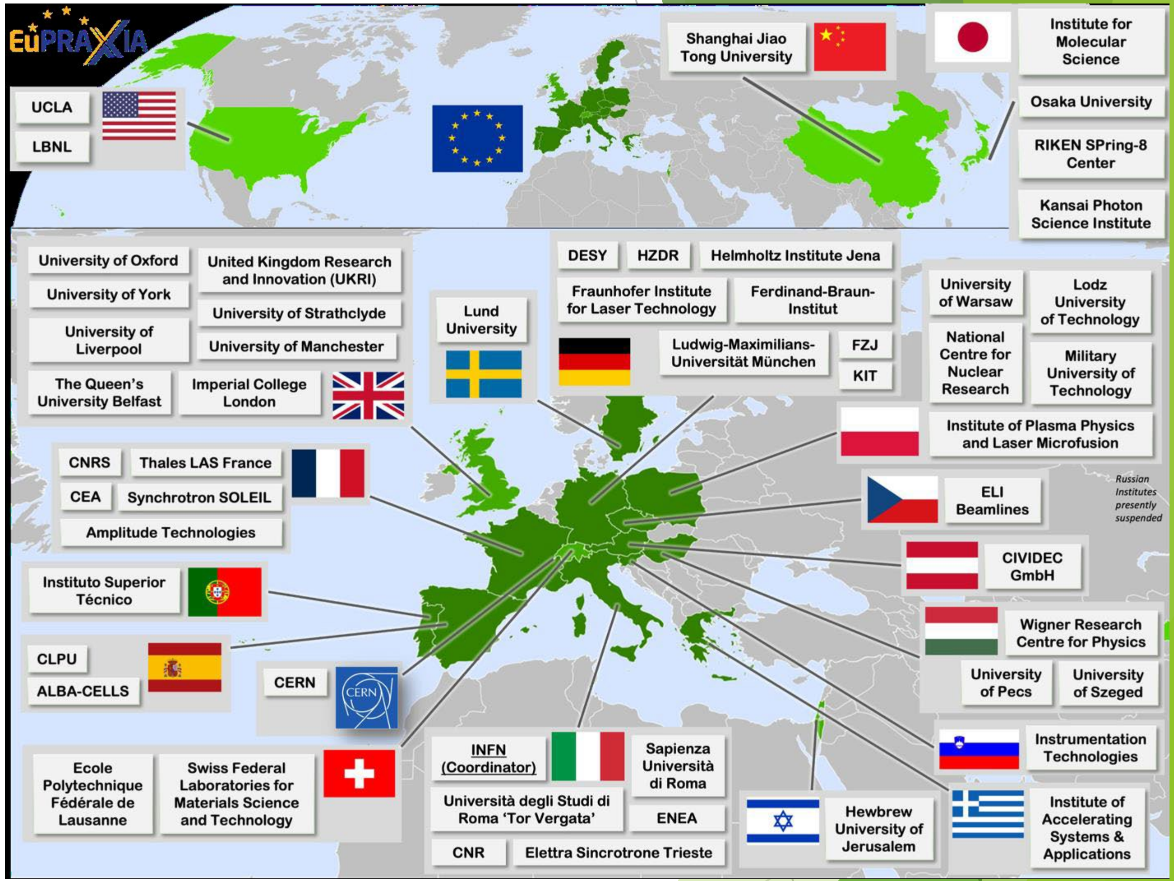
- Introduction to EuPRAXIA
  - Overview of the European project

- X-band activities at LNF
  - EuPRAXIA@SPARC_LAB and relative R&D
    - Waveguide components design
    - Accelerating structure optimization
    - Prototype realization
  - TEst stand for X-band (TEX) facility
    - RF power unit commissioning
    - X-band LLRF implementation and first results

- Conclusions and future developments

Introduction to EuPRAXIA

- The EuPRAXIA project (European Plasma Research Accelerator with eXcellence in Applications) was funded under the **EU Horizon 2020 program** and culminated at the end of 2019 with the publication of the worldwide first **Conceptual Design Report** for a plasma accelerator facility. EuPRAXIA was then **included in 2021 in the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap**, which identifies those research facilities satisfying the long-term needs of the European research communities
- For the Design Study 3 M€ of funding have been awarded to **16 laboratories and universities** from 5 EU member states within the European Union's Horizon 2020 program. They were joined by **25 associated partners** (as of December 2018) that made additional in-kind commitments



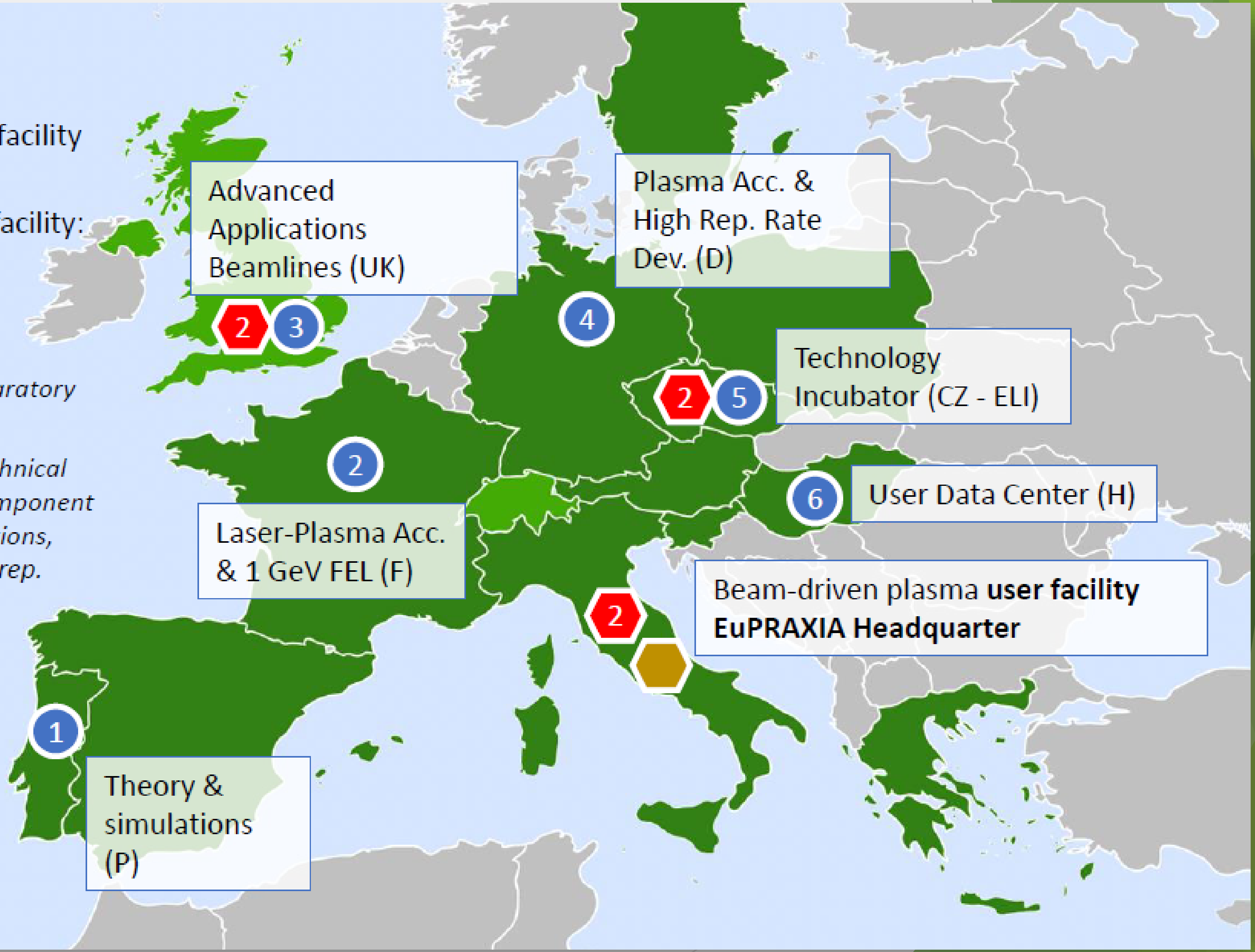
- The goal of this ambitious project was to produce a Conceptual Design Report for the worldwide first high energy **plasma-based compact accelerator (from 1 to 100 GV/m gradient)** that can provide industrial beam quality and user areas
(see more at https://www.eupraxia-project.eu/)

Introduction to EuPRAXIA

- Beam-driven plasma user facility EuPRAXIA Headquarter
- 2 Laser-driven plasma user facility: candidates
- Excellence Center

Second site will be decided in Preparatory Phase project.

Excellence centers (EC) perform technical developments, prototyping and component construction. Number of EC's, locations, roles, responsibilities reviewed in Prep. Phase.



EuPRAXIA

Horizon Europe

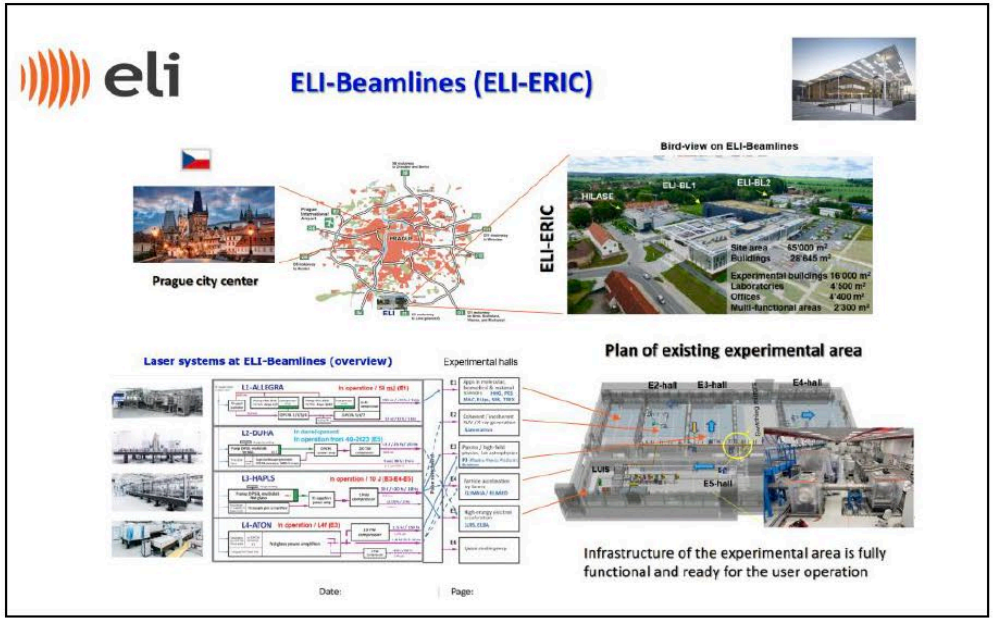
X-band activities at LNF – EuPRAXIA@SPARC_LAB

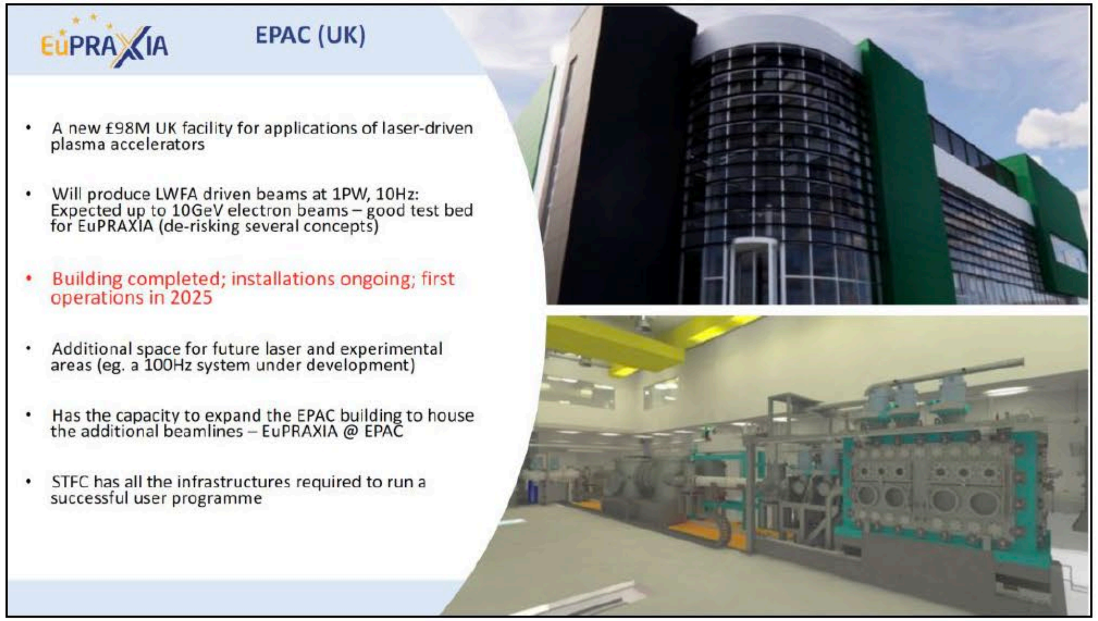
- LNF has been chosen as project headquarter and as **particle driven (PWFA) site (>130 M€ funding)**
- The project EuPRAXIA@SPARC_LAB aims at realizing a **FEL radiation source** (λ_FEL=4 nm) based on **RF linear accelerator combined with a plasma module** [1,2]
- We are currently in a **preparatory phase of the TDR** for this machine
- The executive project of the **new building hosting the facility** has been recently approved by the ministry

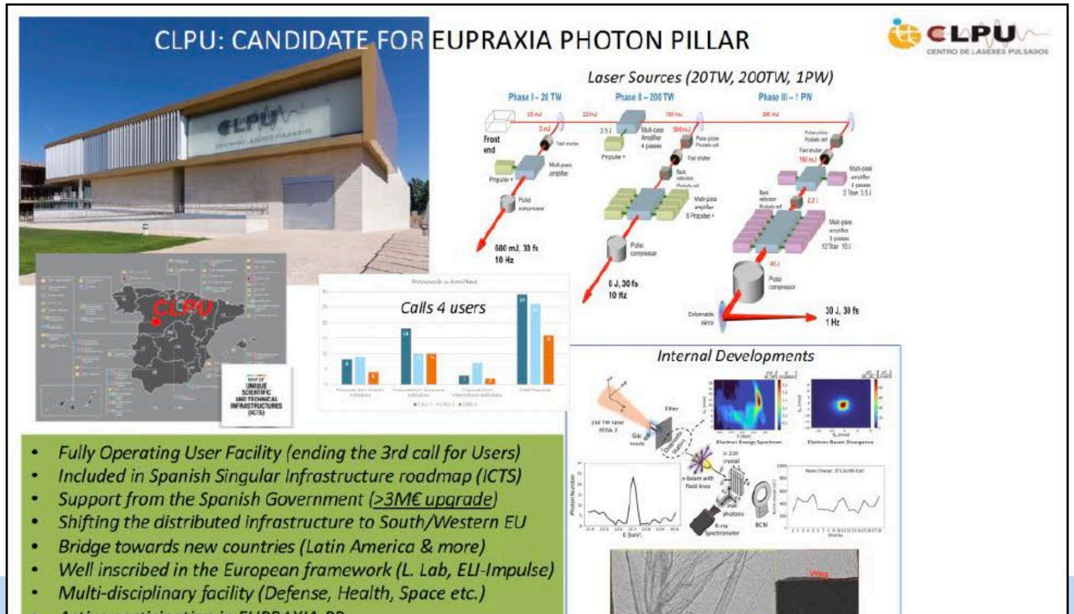
Credit: INFN and Mythos – cosorziostabile s.c.a.r.l.

[1] Ferrario et al., NIM A 909, (2018) pp.134-138
[2] D. Alesini et al., "EuPRAXIA@SPARC_LAB Conceptual Design Report", INFN-18-03/LNF

X-band activities at LNF – EuPRAXIA laser driven candidates



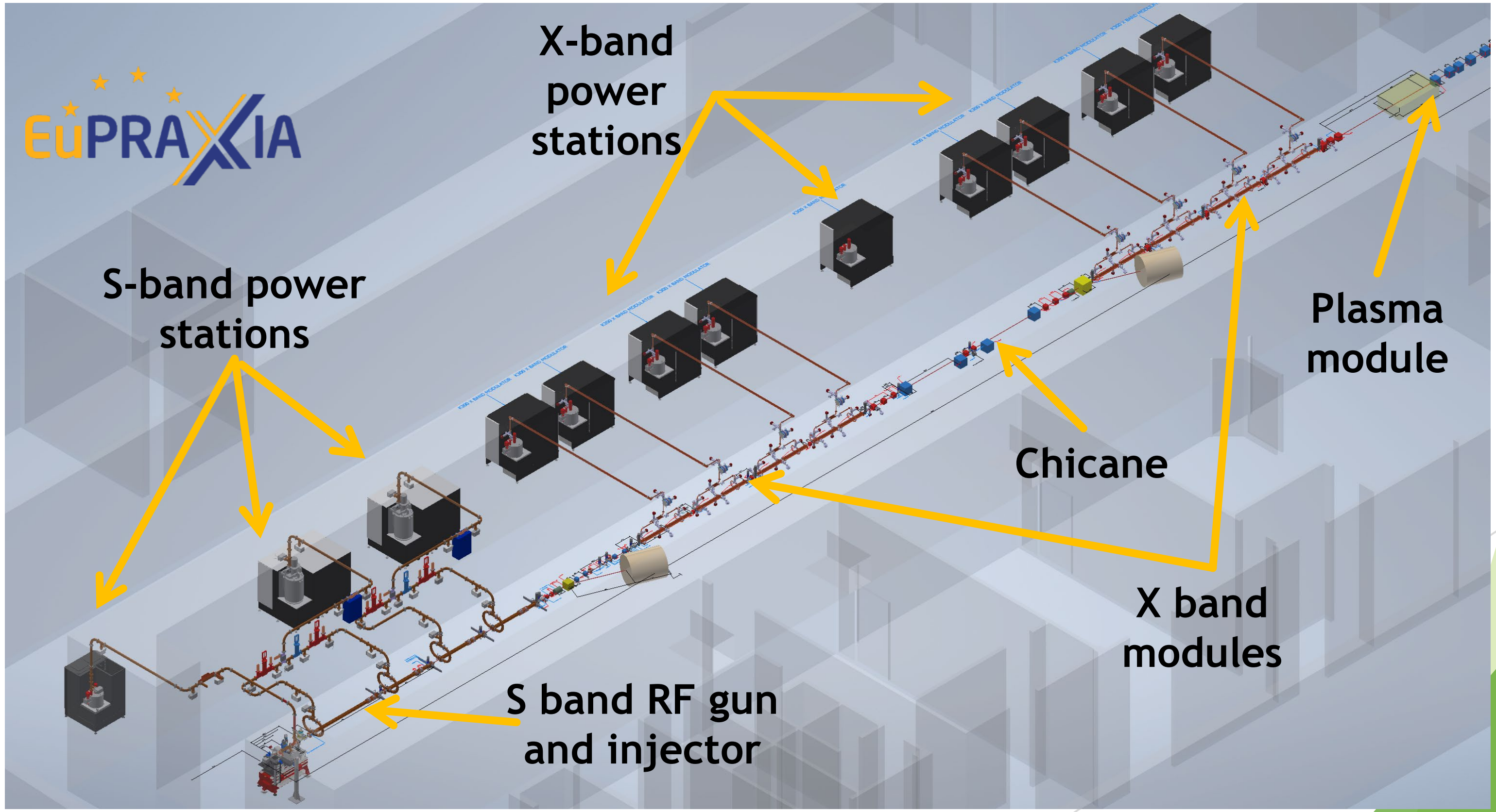




X-band activities at LNF – EuPRAXIA@SPARC_LAB

Overview of the RF LINAC

- The RF baseline of the linac is the X-band technology, it will be used to produce high brightness electron beams up to 1 GeV
- The beam will be either injected in the FEL undulators or used to drive a plasma cell to further boost the energy before the undulators
- S-band (2.856 GHz) injector composed by a photocathode RF Gun and 1x 3m TW S-band and 3x 2m TW S-band structures
- X-band (11.994 GHz) booster composed by 16x TW, 0.9 m accelerating structures with a nominal gradient of 60 MV/m

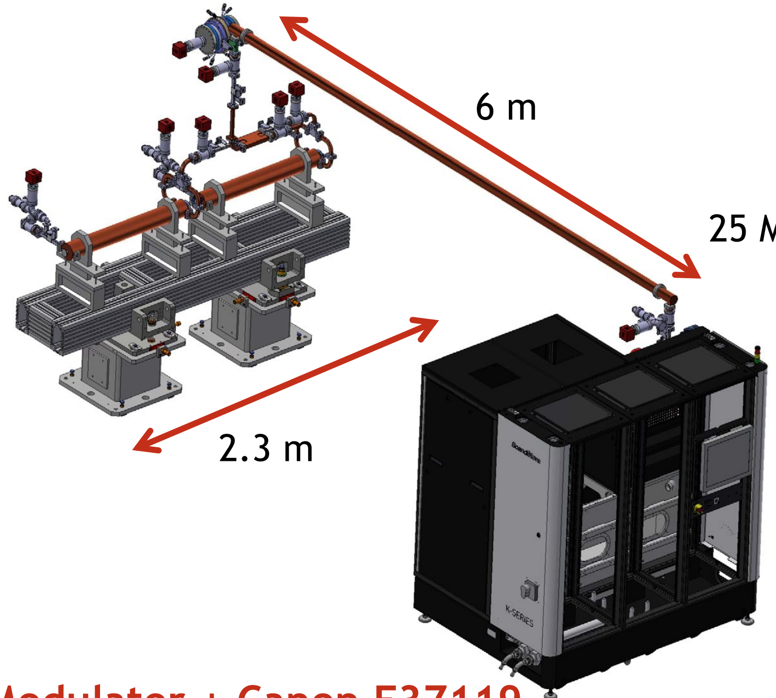


X-band activities at LNF – EuPRAXIA@SPARC_LAB

RF accelerating module options

CANON - BASELINE

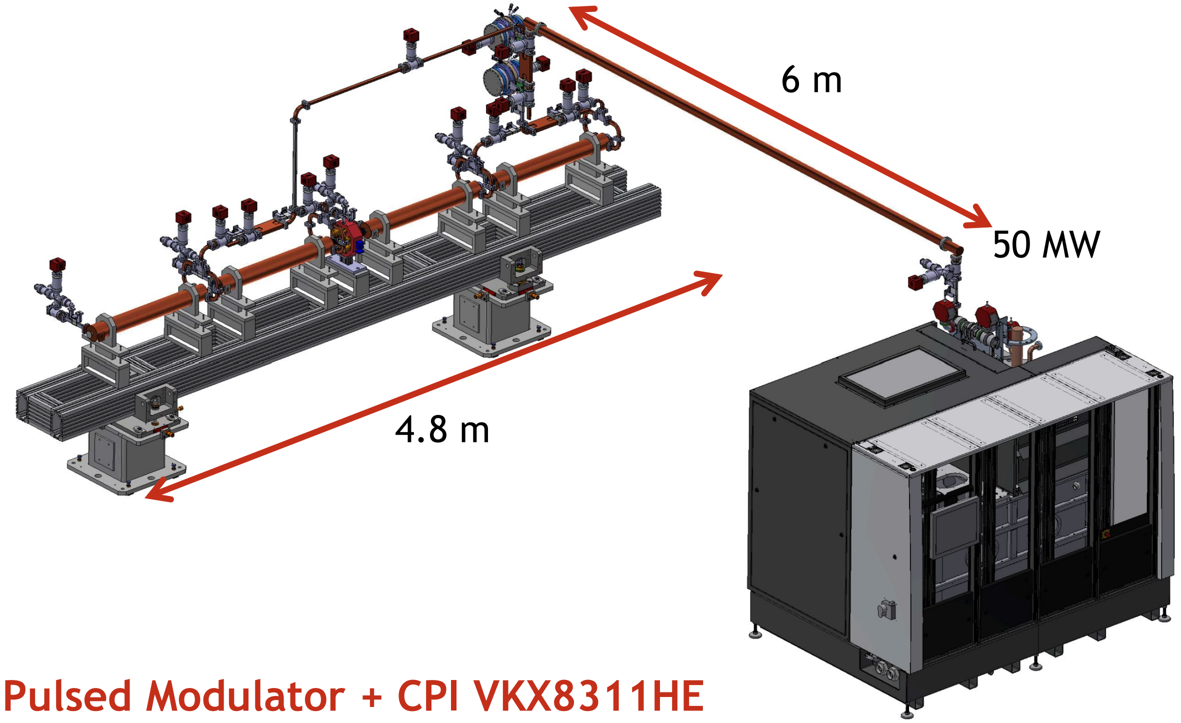
- 1x BOC on one line
- Higher flexibility
- Lower Modulator power requirements
- Possible high rep. rate upgrade of the linac (400 Hz)



Pulsed Modulator + Canon E37119

CPI - OPTION (HIGH EFFICIENCY)

- 2x BOC on one line
- Less flexibility
- Different LE and HE module layout
- Lower power plants number



Pulsed Modulator + CPI VKX8311HE

Curtesy of F. Cardelli

X-band activities at LNF – EuPRAXIA@SPARC_LAB

New klystrons test

Currently we have a klystron test stand based on CPI VKX8311 tube

Two other klystrons will be tested in the next future:

- CANON E37119
  - Low modulator peak power requirement
  - Very high repetition rate achievable (appealing for a future upgrade of the machine)
  - 8x power sources for the Linac booster
- CPI High efficiency VKX8311HE (developed in collaboration with CERN).
  - High efficiency
  - Increased klystron lifetime
  - 4x power sources for the Linac booster
  - Still to be demonstrated, a prototype is being developed

Status:

- Test station based on the VKX8311A klystron already commissioned and in operation at TEX facility
- CANON E37119 klystron with modulator is in procurement phase (expected delivery 03/2024)
- CPI VKX8311HE is in procurement phase (expected delivery 01/2025)

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 drive power	W	500		
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	us	1,5		
Repetition Rate	Hz	400	100	100
Gain	dB	47	50	47
Efficiency	%	40	55	40

CPI Klystron VKX-8311A

Solid State Modulator Scandinova k400

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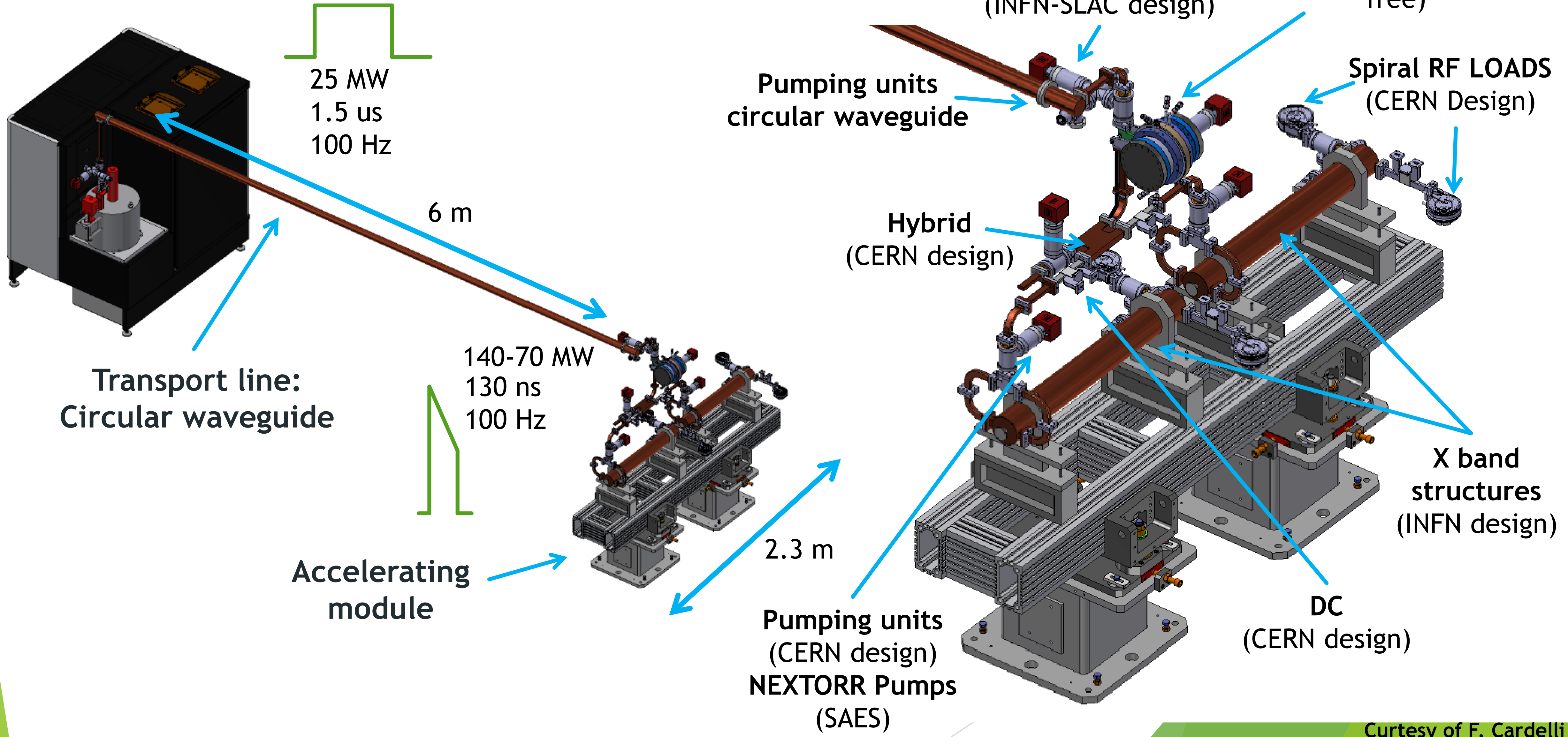
X-band activities at LNF – EuPRAXIA@SPARC_LAB

Current Baseline for the single X-band RF Module



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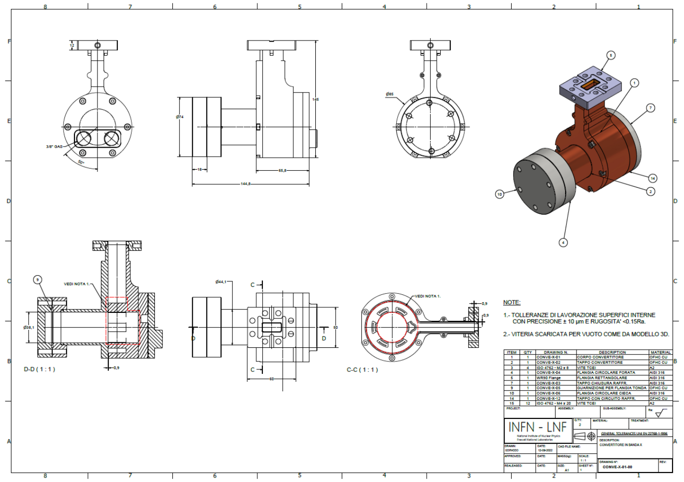
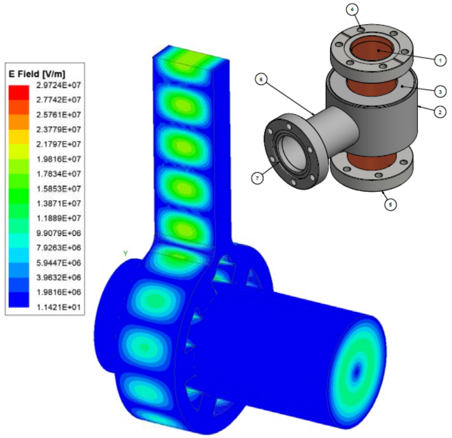
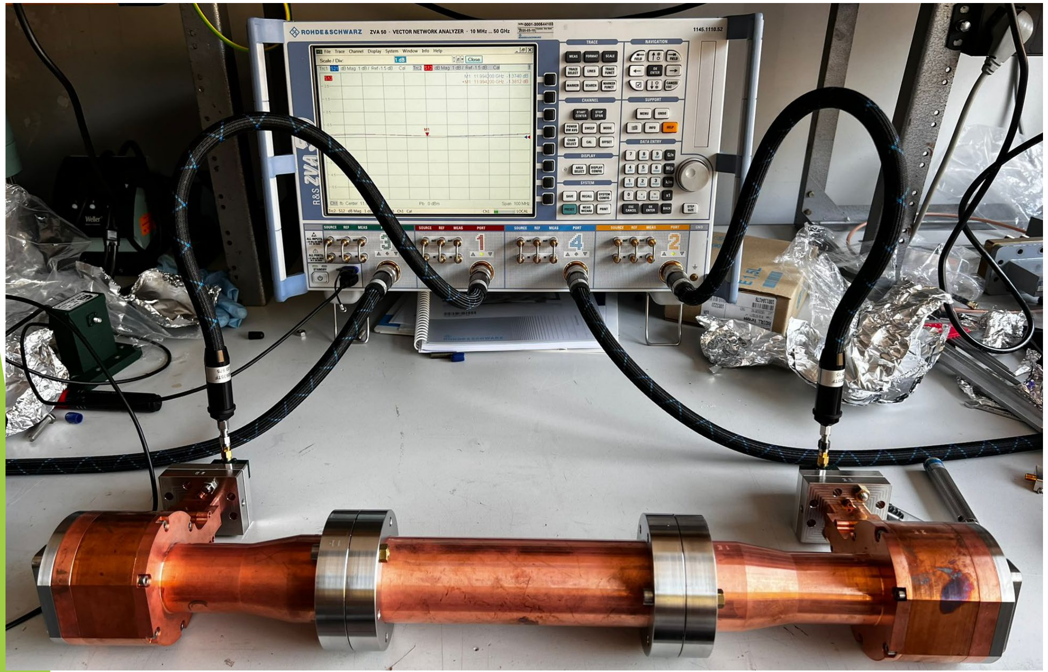
X-band activities at LNF – Waveguide components design

Circular/rectangular mode converter[3] and pumping port



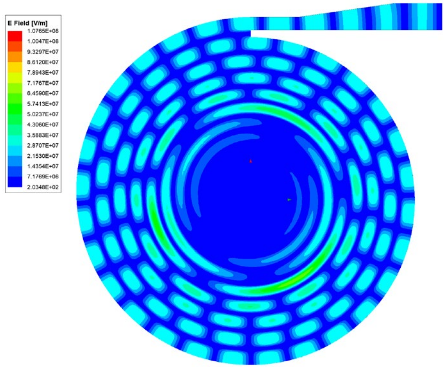


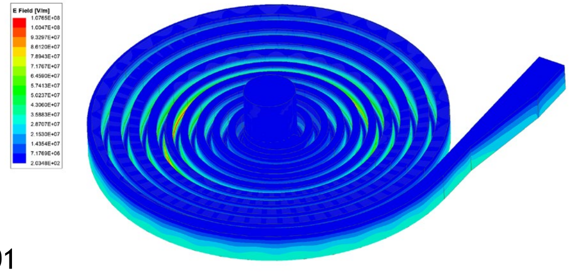


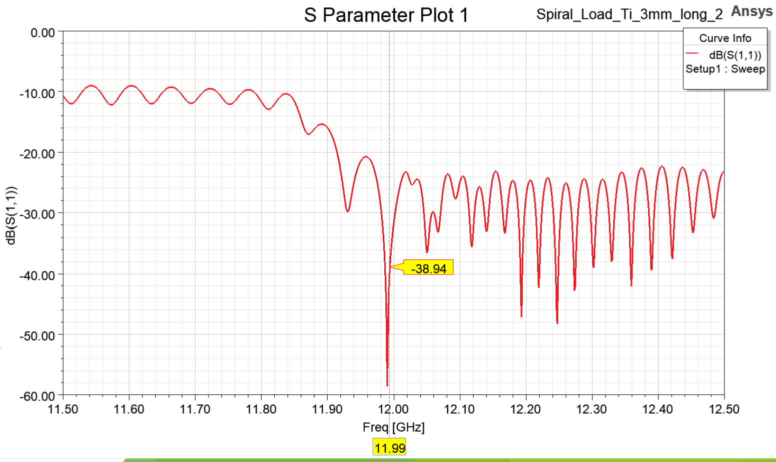
Spiral load 3D printed[4] and milled

Currently, realization is by **additive manufacturing**.
We are developing a design that can be implemented by **milling**:

- **Motivation:** the aim is to allow other companies to be able to realize this type of load even without the use of additive manufacturing
- The idea is to replace the vacuum pumping holes by «cutting» the entire load transversely leaving a 1 mm thick gap along the entire length of the waveguide.
- To do this, the thickness of the waveguide walls has been increased







[3] S. Tantawi, et all. (2000). Reviews of Modern Physics – doi: 10.1103/PhysRevSTAB.3.082001
[4] N. Catalan-Lasheras, et al., 9th Int. Particle Accelerator Conf. (IPAC18), Vancouver, BC, Canada, May 2018, paper WEPMF074.

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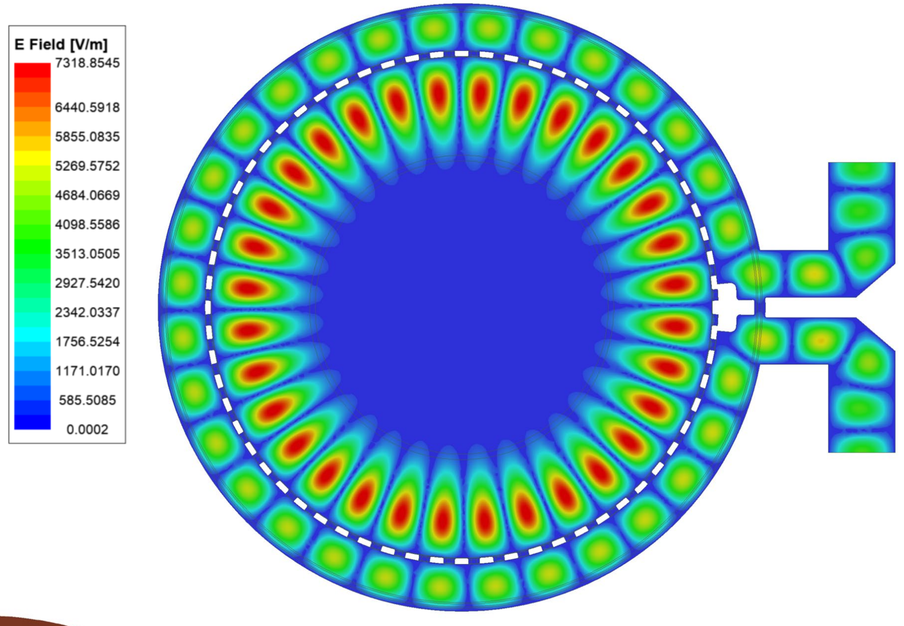
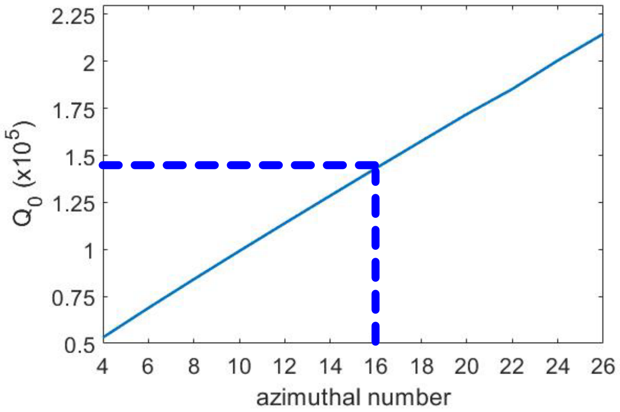
X-band activities at LNF – Waveguide components design

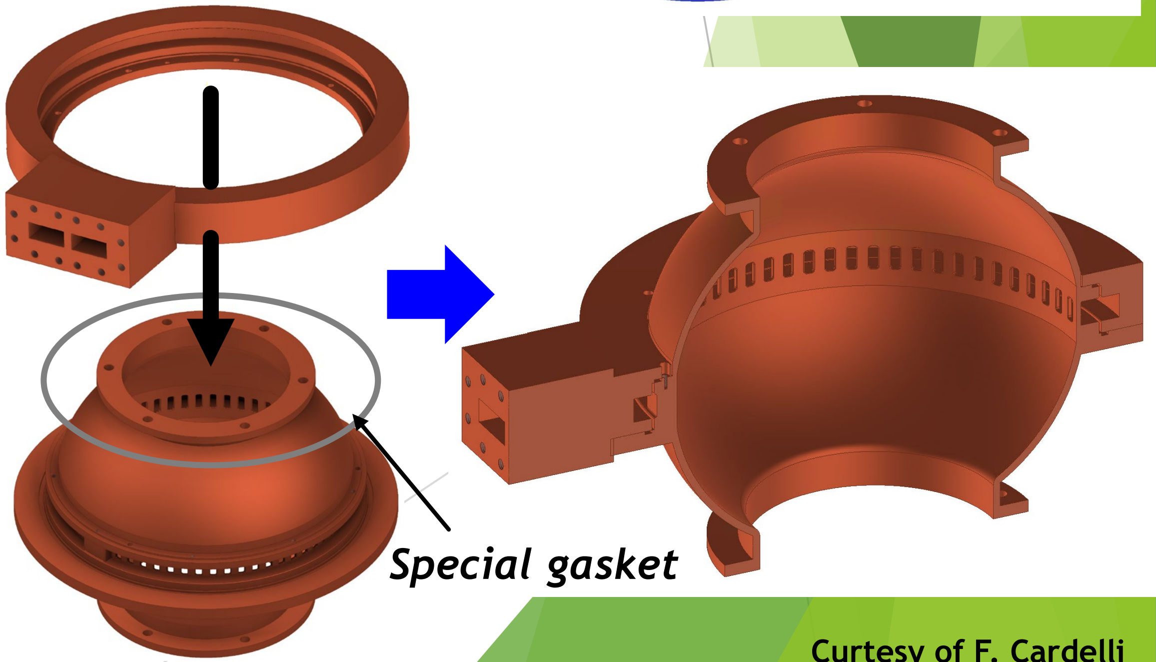
Brazing free BOC type pulse compressor

- We are developing a new design for X-band BOC that implements the **INFN-LNF brazing-free technology**
- The brazing free or "clamping" technology is based on the use of special RF/vacuum gaskets
- The choice of the mode to increase the Q_0 keeping the size of the BOC reasonable. Higher order modes can be also considered to increase the Q-factor
- To allow the use of the gaskets it was necessary to introduce a gap on the edge of the circular waveguide, and a new input splitter design
- EM and mechanical design are being carried out in parallel

Pulse Compressor	Parameter
Type	Barrel Open Cavity
Frequency	11.994 GHz
Resonant Mode	$TM_{16,1,1}$
Diameter	171 mm
Q_0	150000
Coupling factor β	7.8







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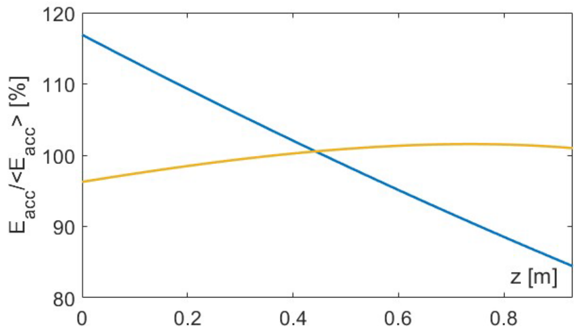
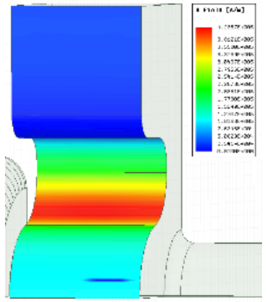
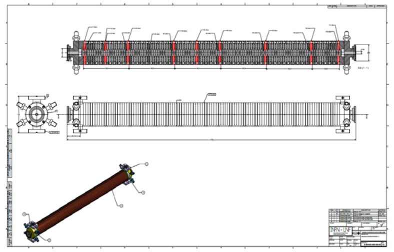
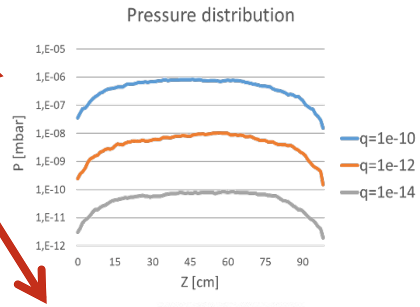
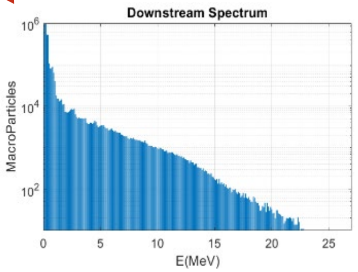
X-band activities at LNF – Accelerating structure design









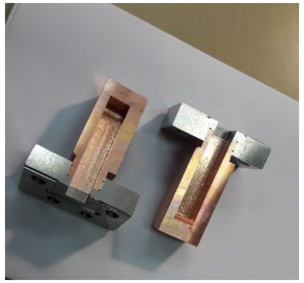


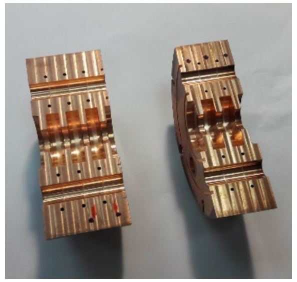
- E.m. design: done
- Thermo-mechanical analysis: done
- Mechanical design: done
- Vacuum calculations: done
- Dark current simulations: done
- Waveguide distribution simulation with attenuation calculations: done

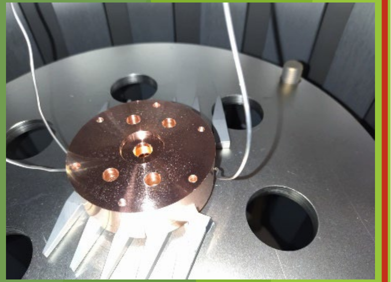
PARAMETER	Value	
	Quasi CG	CI
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85-3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length (flange-to-flange) [m]	**0.94 (1.05)**	
No. of cells	112	
Shunt impedance R [MΩ/m]	93-107	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
Unloaded SLED/BOC Q-factor Q_0	150000	
External SLED/BOC Q-factor Q_E	21000	21000
Required Kly power per module [MW]	**20**	
RF pulse [μs]	**1.5**	
Rep. Rate [Hz]	**100**	

X-band activities at LNF – Accelerating structure prototyping

1. **Pre-prototypes** on few cells and simplified couplers to optimize the brazing procedure (brazing time, type of alloy, temperature…), cells assembly, alignment etc: done



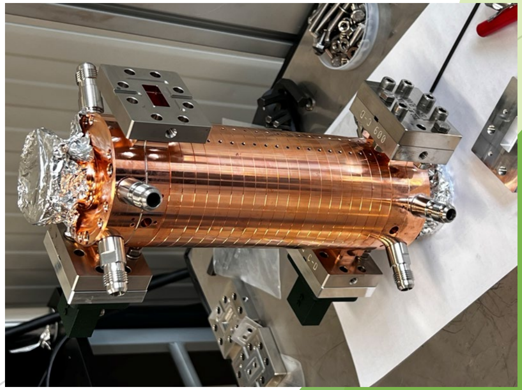


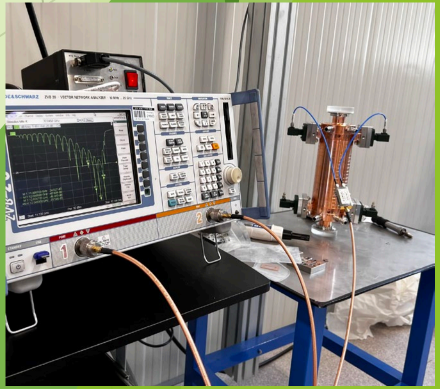


2. **Full scale mechanical prototype**: to test the overall brazing process of the full structure and the cell-to-cell alignment before and after brazing: done

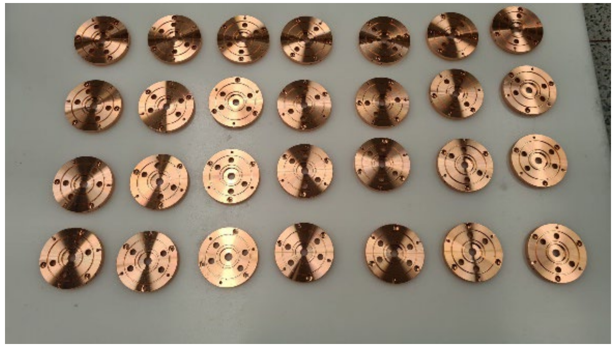
3. **20+2 cells RF prototype for high power test** w/o tuning, constant impedance: realized, low power measurements ongoing.

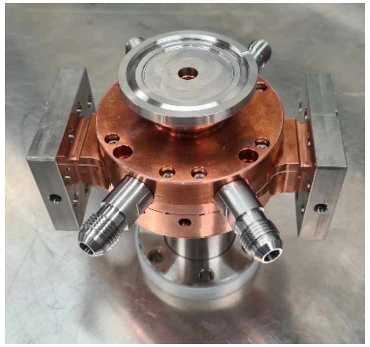
4. **Final full scale structure prototype** constant impedance: *order to be assigned*.



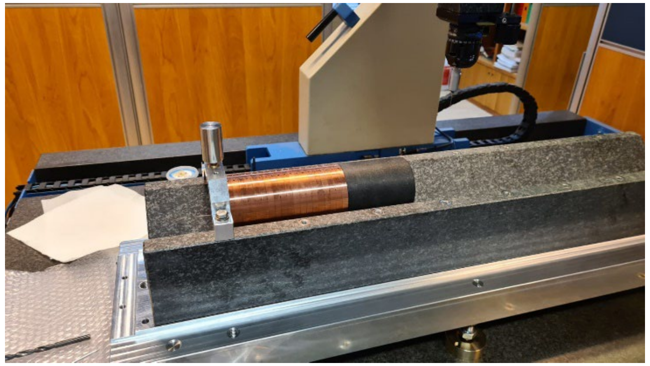


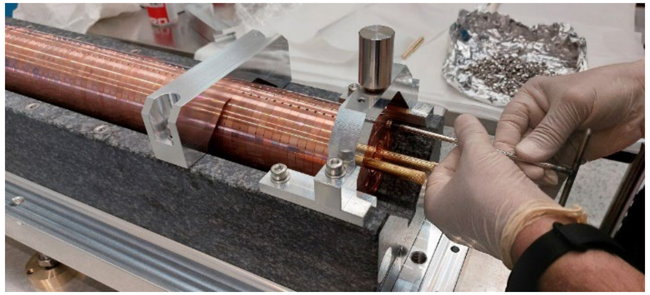
X-band activities at LNF – Mechanical prototype assembly and characterization



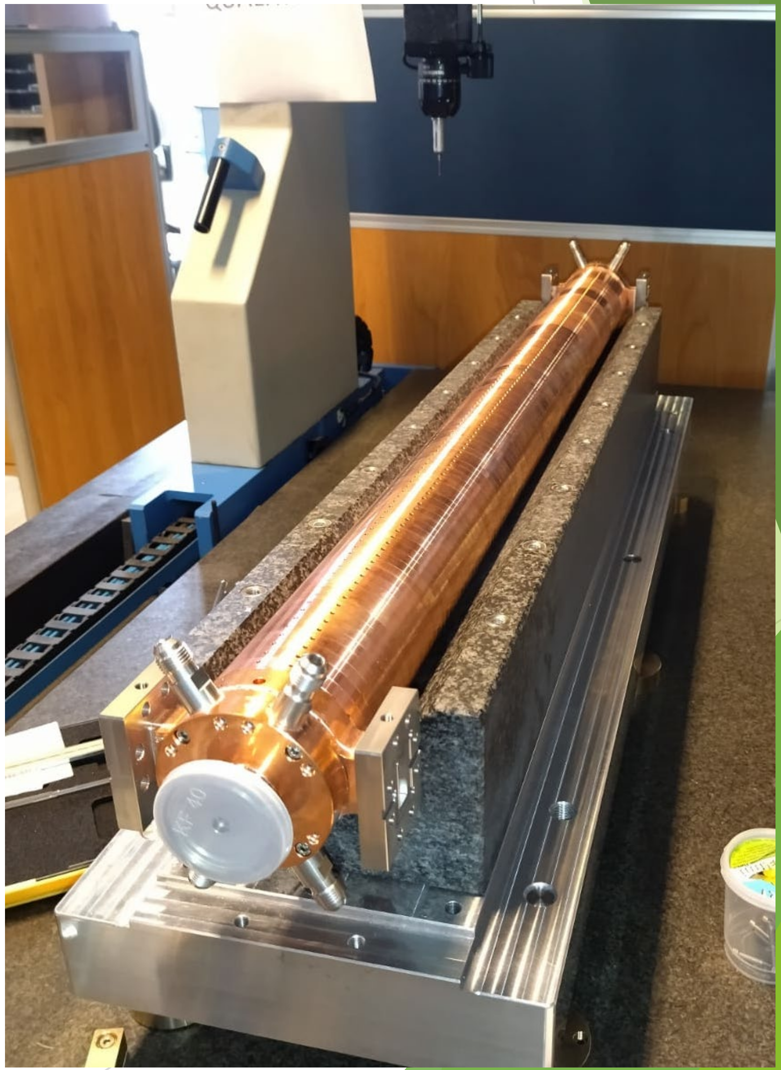


Assembly procedure and dimensional characterization





Complete structure
(straightness ±15 μm before brazing,
±30 μm acceptable by BD simulations)



X-band activities at LNF – Mechanical prototype brazing

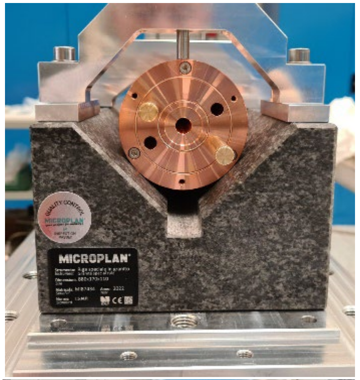
Brazing took place at LNF in the new vacuum furnace (Ø 400 mm, L = 1300 mm) acquired with a regional project LATINO

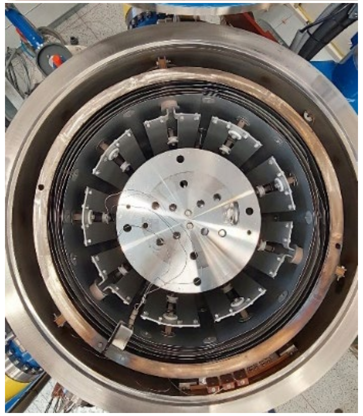
Results:

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

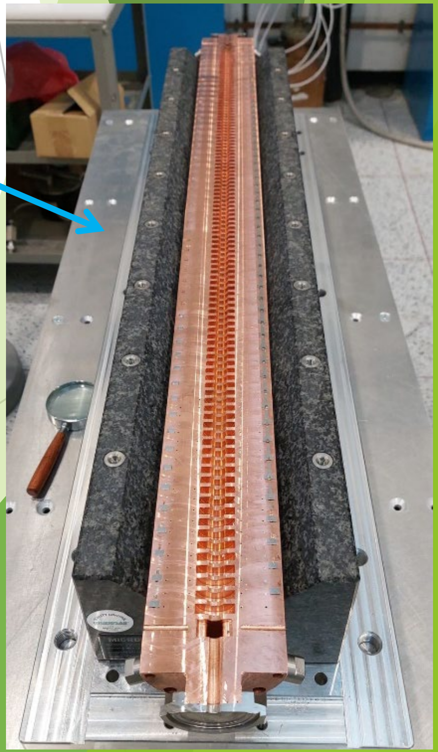
Next steps:

- 22 cells RF prototype for high power test (w/o tuning, constant impedance): currently ongoing
- FINAL structure: expected by December 2023





Brazing alloy distribution check with cut structure



Prototype during leak test at LNF

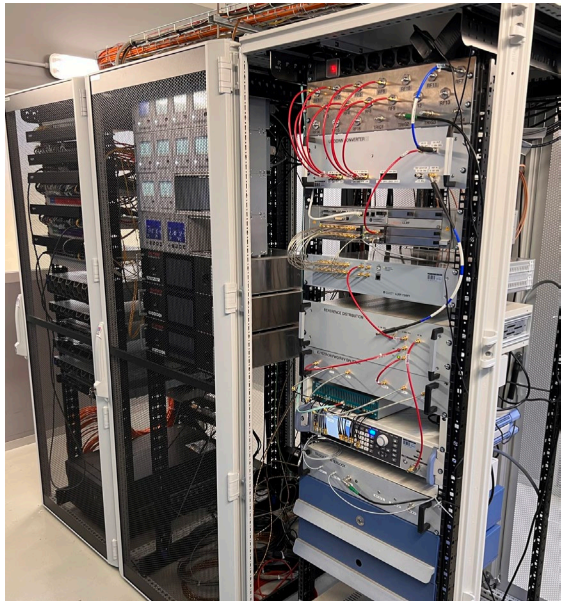
X-band activities at LNF – TEX facility

- The TEst-stand for X-band (TEX) facility at LNF 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 in view of the EuPRAXIA@SPARC_LAB project
- 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
- An entire building has been completely refurbished in order to host this new facility, with the construction of a new concrete bunker, control room, 3 laboratories and one meeting room

Concrete Bunker

Control Room

LLRF system

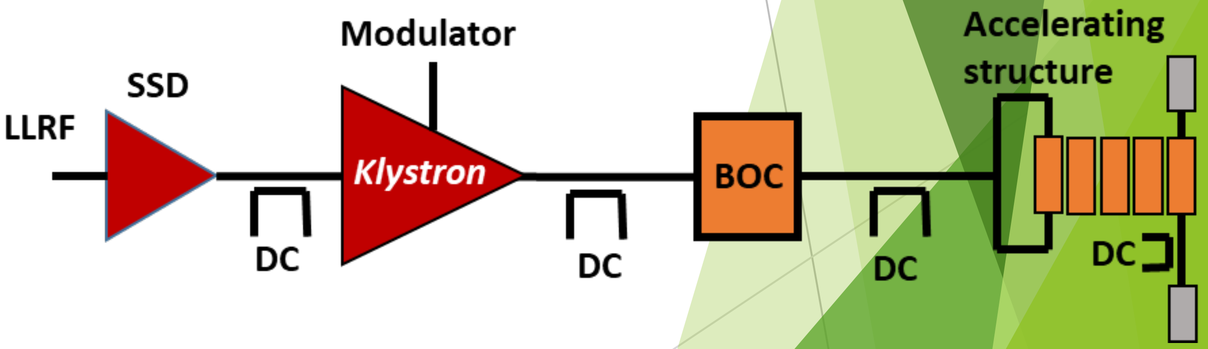


RF Source (Scandinova K400 + CPI klystron VKX-8311A

X-band activities at LNF – TEX facility timeline

- The civil engineering works in the building have been completed in August 2021
- The installation and commissioning of the modulator and klystron has been completed in February 2022 [5]. At the same time LLRF system [6-7], EPICS control system have been commissioned
- The complete waveguide network has been procured and installed (terminated on two spiral RF loads)
- A BOC pulse compressor will be integrated in the layout in the next future, in order to increase the available RF power
- The authorization from radioprotection authority required many months but from December 2022 we are in operation!

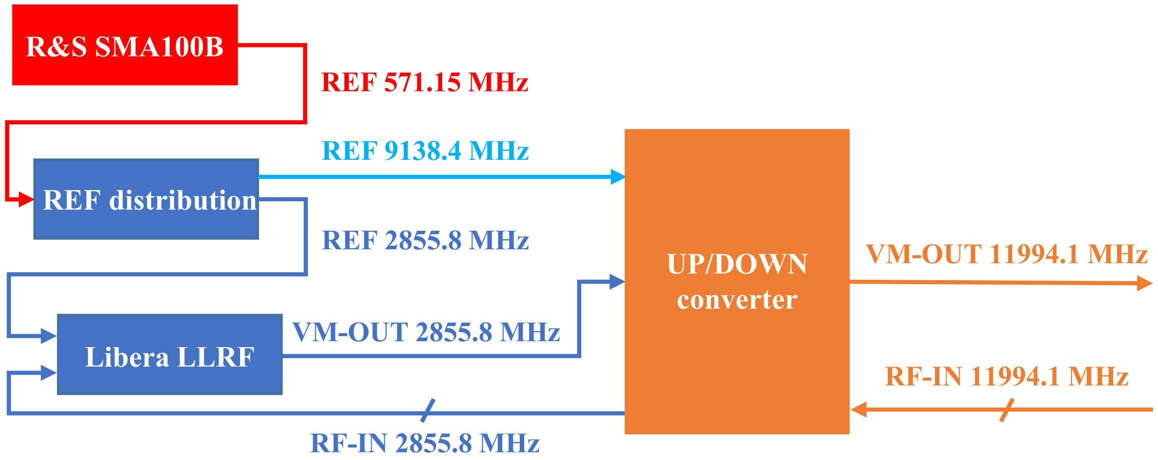
Parameter	Value
Cathode peak voltage	427 kV
Peak RF output power	50 MW
Pulse length	250 ns (1.5 us)
Repetition Rate	50 Hz
Measured RF output amplitude stability	< 0.09 %
Measured RF output phase stability	20.9 fs

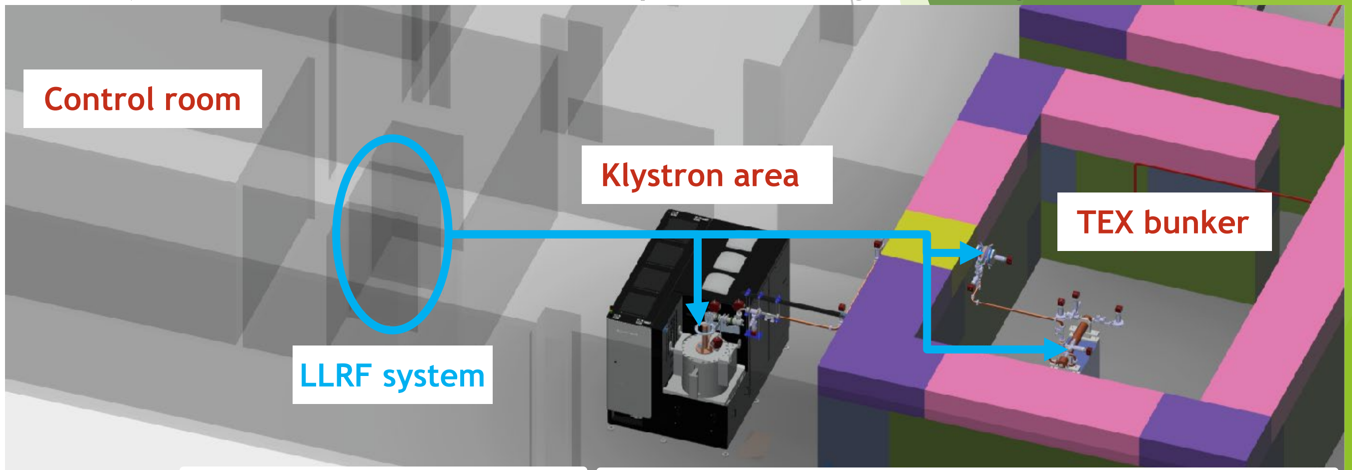


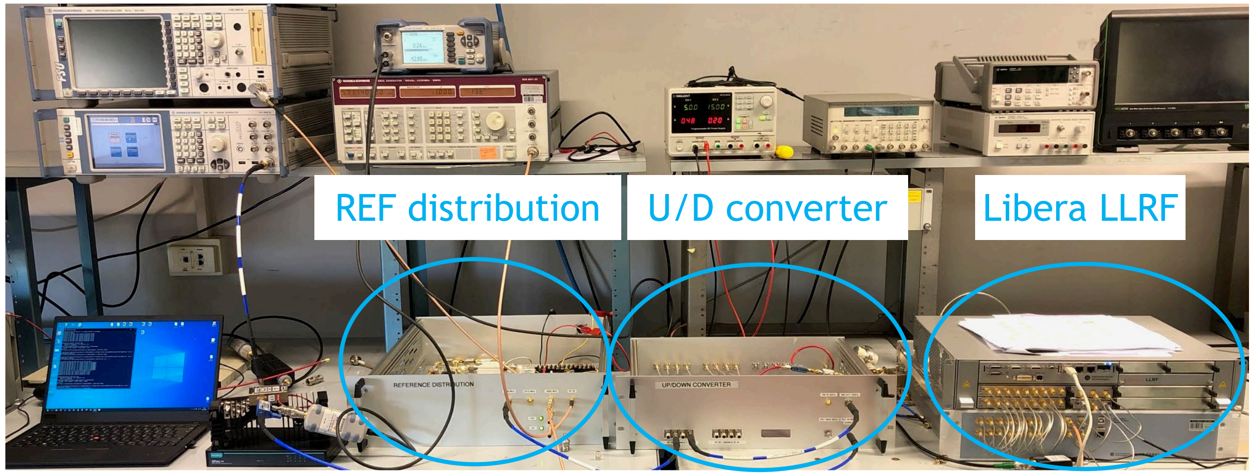
[5] F. Cardelli et al., 13th Int. Particle Accelerator Conf. IPAC22, Bangkok, Thailand, Jun. 2022, paper TUPOPT061
[6] L. Piersanti et al., 12th Int. Particle Accelerator Conf. IPAC21, Campinas, Brazil, May 2021, paper WEPAB301
[7] L. Piersanti et al., 13th Int. Particle Accelerator Conf. IPAC22, Bangkok, Thailand, June 2022, paper TUPOST015

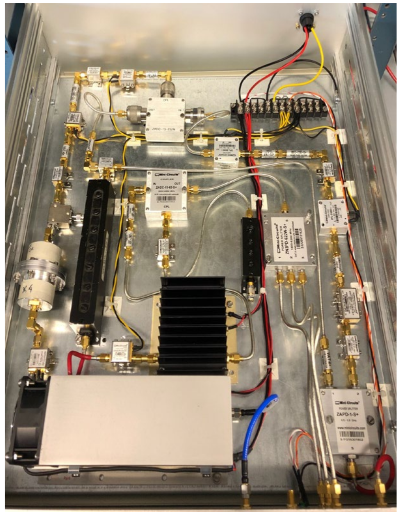
X-band activities at LNF – TEX LLRF system

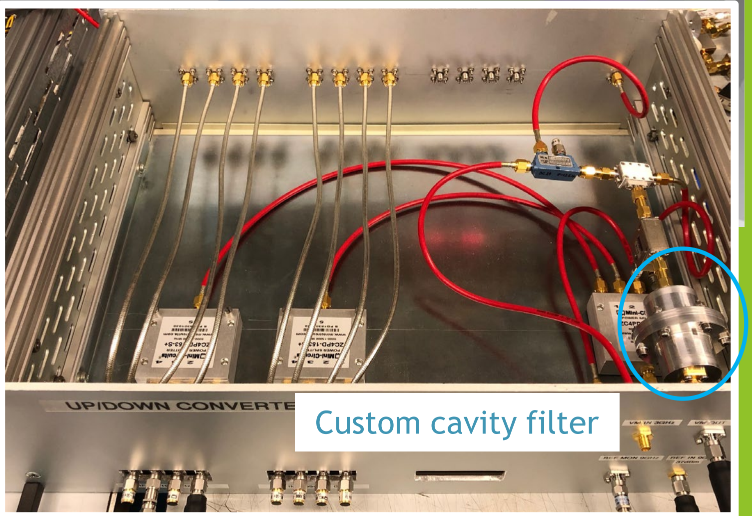
- Given project very short deadline and the test facility nature of TEX, a commercial S-band LLRF system (ITech) has been adapted to work at 11.994 GHz developing at LNF:
  - up/down converter (8 up to 12 channels front-end, 1 ch. back-end)
  - reference generation and distribution system -> coherent source for S-band (2.856 GHz) and X-band (11.994 GHz)
  - custom cavity band-pass filters (9.138 GHz and 11.994 GHz) for reference and VM output filtering after up-conversion







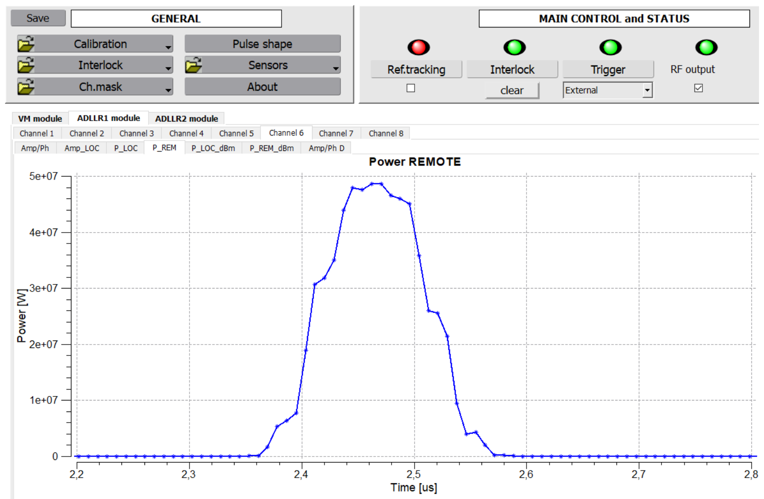




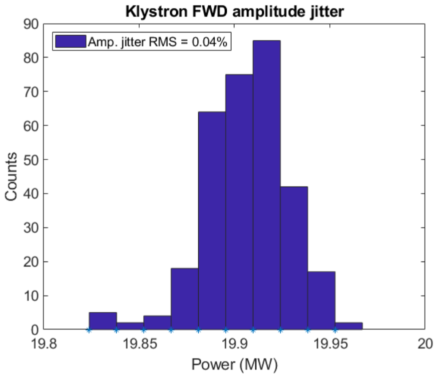
X-band activities at LNF – TEX LLRF system commissioning

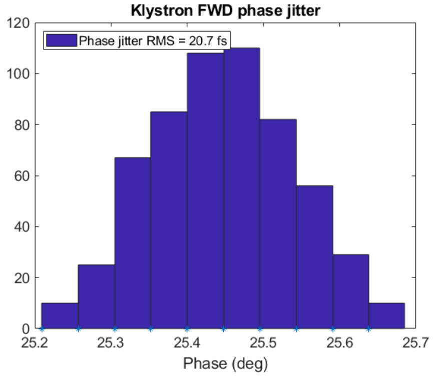
LLRF rack installed

Demodulated RF pulse from Libera LLRF



RF stability first meas. (300 ns pulses at 50 Hz)





Signal	Meas. ampl. jitter (%)	Meas. phase added jitter (deg)
VM output S-band	0.014	0.013
VM output X-band	0.016	0.014
KLY FWD X-band	0.04	0.089 (20.7 fs)

System performance

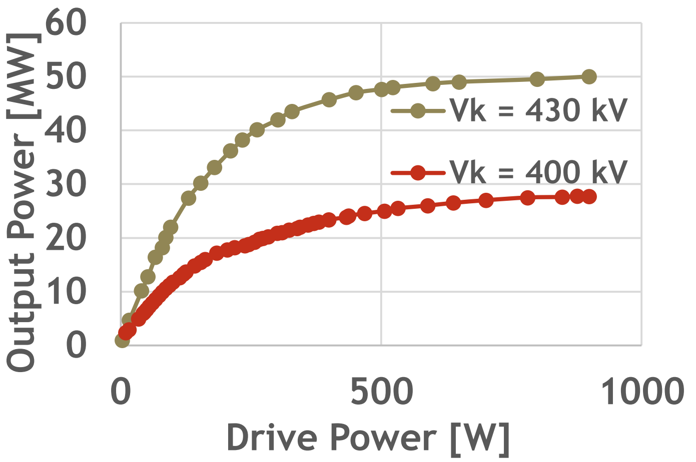
- During the modulator SAT the whole LLRF system has been successfully commissioned
- Measurements done with 300 ns pulses at 20 MW showed an amplitude and phase stability of the klystron FWD power of **0.04 %** and **20.7 fs** respectively

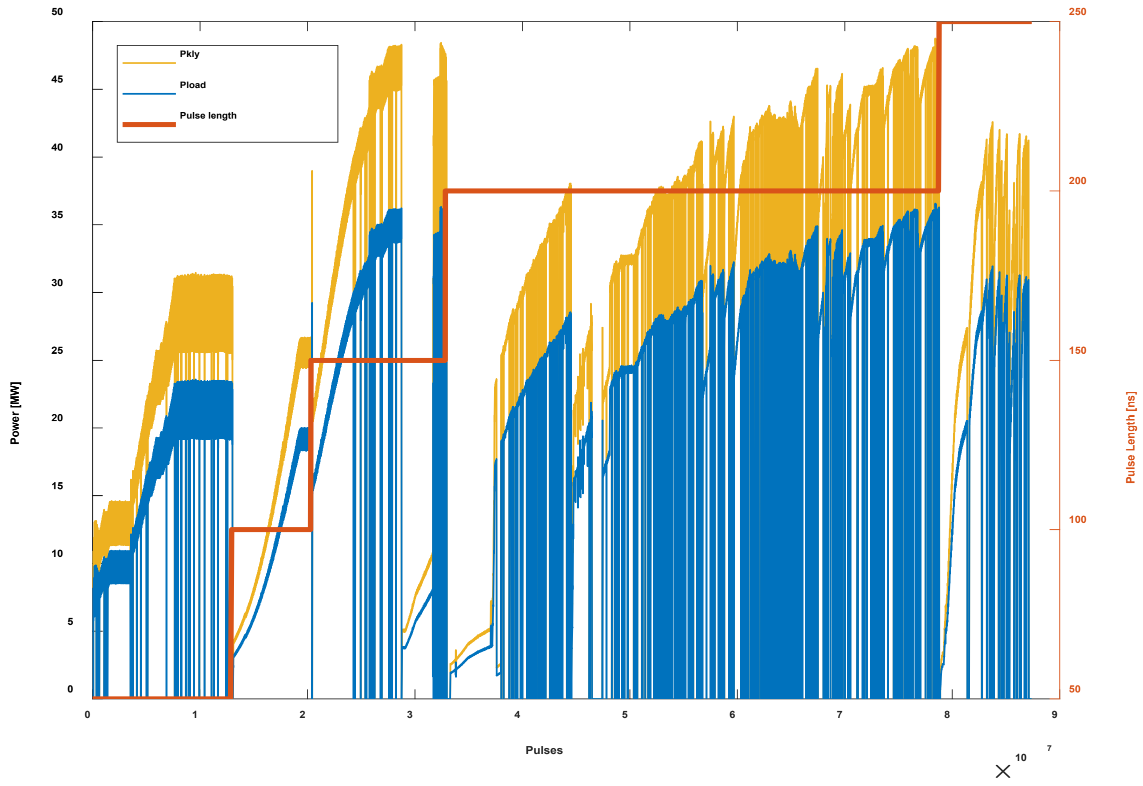
System open points:

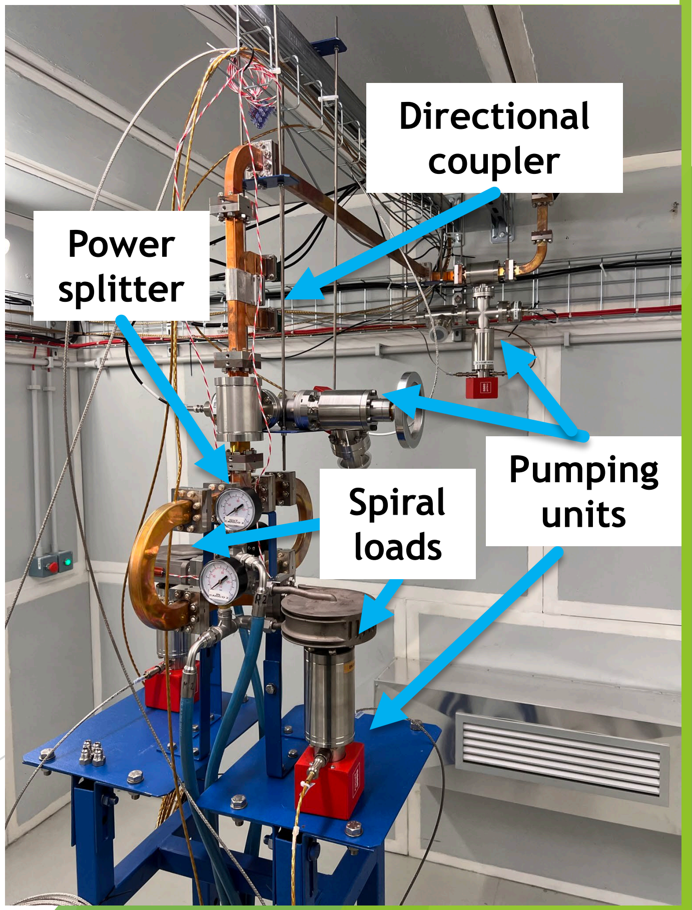
- U/D stage high conversion loss (≅14 dB) limits dynamic range of the LLRF front-end
- 119 MHz ADC sampling rate might be a limitation for the operation with short pulses (100-200 ns)
- Front-end BW 5 MHz, Back-end BW 16 MHz possible bottlenecks for fast and complex modulations
- Comprehensive measurement campaign scheduled for system full characterization

X-band activities at LNF – TEX WG conditioning

- A conditioning run of the waveguide distribution line terminated on two 3D printed Titanium spiral loads has been completed in February 2022
- A final peak power of **42 MW** with **250 ns** pulse length at **50 Hz** has been reached in **3 weeks**. The test has been interrupted to perform some civil engineering works in the building
- The FWD Klystron power has been gradually increased with an automatic conditioning routine integrated in the control and machine protection system [6]







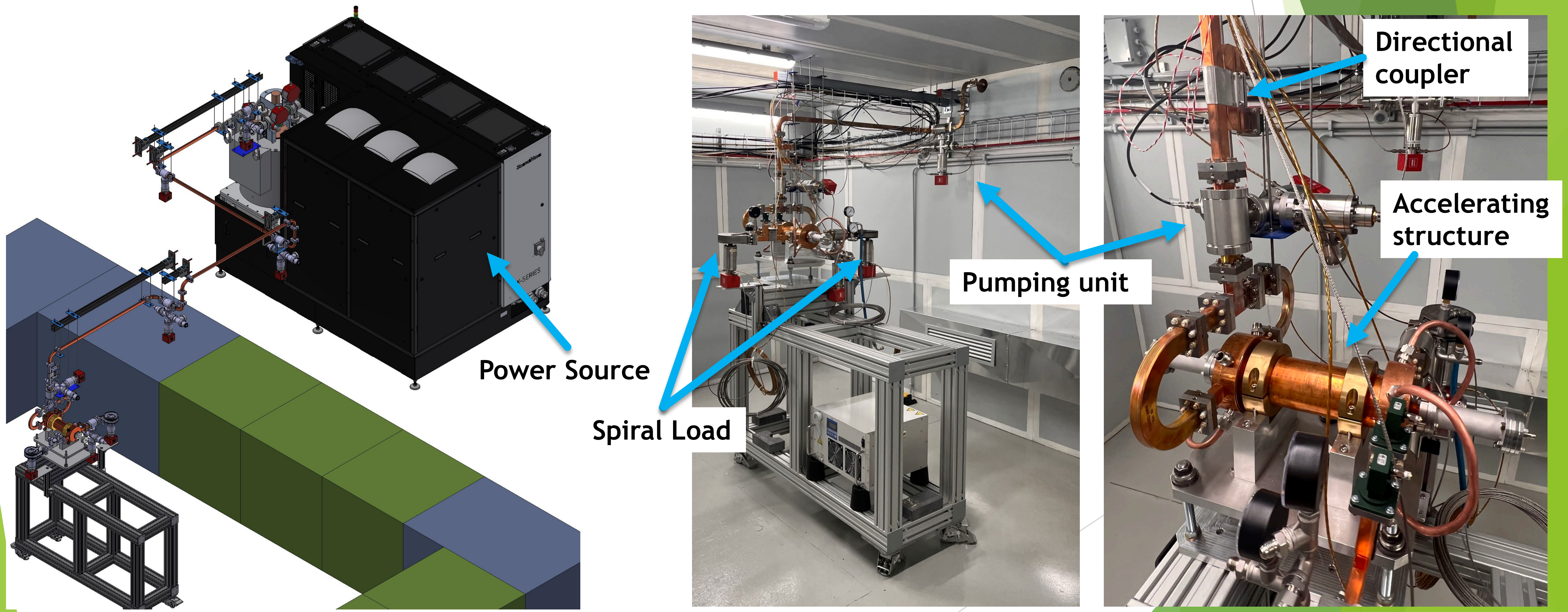
[6] *S. Pioli, et al., 13th Int. Particle Accelerator Conf. (IPAC22), Bangkok, Thailand, June 2022, paper MOPOMS047.*

X-band activities at LNF – TEX automatic conditioning algorithm

- All the conditioning procedure is completely automatic by means of an integrated algorithm in the middle-layer of the control system. Such tool is mainly capable of:
  - Increase the RF feedback set level following a sigmoid curve
  - Detect generic modulator interlocks
  - Handle breakdown events from:
    - Modulator RF digitizer;
    - LLRF;
    - Vacuum gauges;
    - ML-based vacuum anomaly detection;
    - ML-based breakdown real-time detection from RF signals
  - Handle average vacuum level rising trends
  - After a breakdown, seps down RF power and waits until vacuum recovery before switching RF back on
  - Identify and handle breakdown clusters

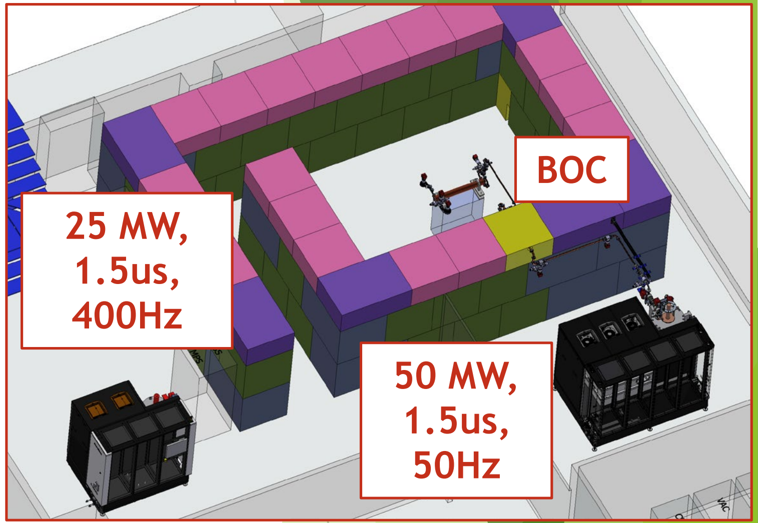
X-band activities at LNF – TEX

- In April 2023 we installed inside the bunker a CERN accelerating section of the T24 CLIC type. The complete setup has been tested at high power reaching **>30 MW** input power with an estimated accelerating gradient of **95 MV/m**, 150 ns pulse length, 50 Hz rep. rate
- This test will be preparatory to the one of the first EuPRAXIA accelerating structure prototype, which will take place by the end of September 2023

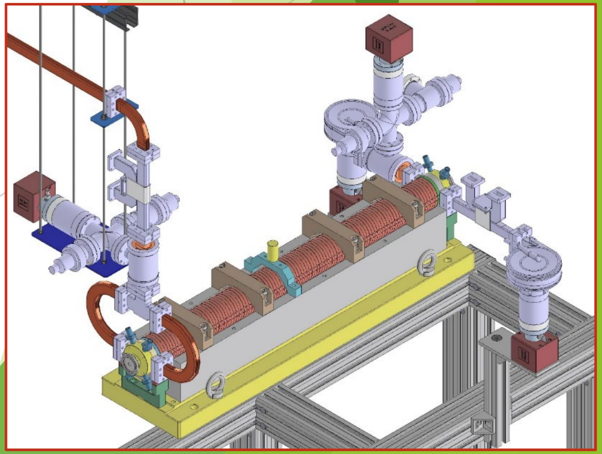


Conclusions and acknowledgments

- EuPRAXIA@SPARC_LAB is the next INFN-LNF project. It is one pillar of the European project EUPRAXIA, that has been included in the ESFRI 2021 Roadmap
- TEX (Frascati Test stand for X-band): new facility fundamental to test all RF components and X band prototypes at the nominal power/gradient. It has been completely commissioned. A **T24 CLIC structure has been tested** in the past months
  - A new X-band RF source based on the **Canon 25 MW, 400 Hz E37119 klystron** will be commissioned starting from February 2024
  - A **high efficiency klystron** version of the **50 MW VKX8311** developed by CPI/CERN should be available from the beginning of 2025
  - Many X-band RF components of the EuPRAXIA RF module have been purchased and will be tested
  - A **brazing free BOC** design is ongoing



- X-band structures prototyping activity continues steadily:
  - An intensive prototyping activity is ongoing exploiting the new vacuum furnace at LNF
  - The brazing tests on the mechanical prototype have been concluded with optimal results in terms of straightness and vacuum seal
  - The **22 cells CI RF prototype has been realized**. One of the couplers is being re-machined, and will be tested with high power at TEX by the end of the year
  - A **full-scale 0.9 m RF prototype will be ready by the end of 2023**



Acknowledgements:

***INFN-LNF**: D. Alesini, S. Bini, B. Buonomo, S. Cantarella, R. Clementi, A. Gallo, C. Di Giulio, E. Di Pasquale, G. Di Raddo, A. Liedl, V. Lollo, S. Pioli, R. Ricci, A. Vannozzi on behalf of the TEX and EuPRAXIA technical team, INFN-LNF Accelerator Division and Technical Division*

***CERN**: W. Wuensh, N. Catalan-Lasheras, A. Grudiev, G. McMonagle on behalf of the CLIC and XBOX group*

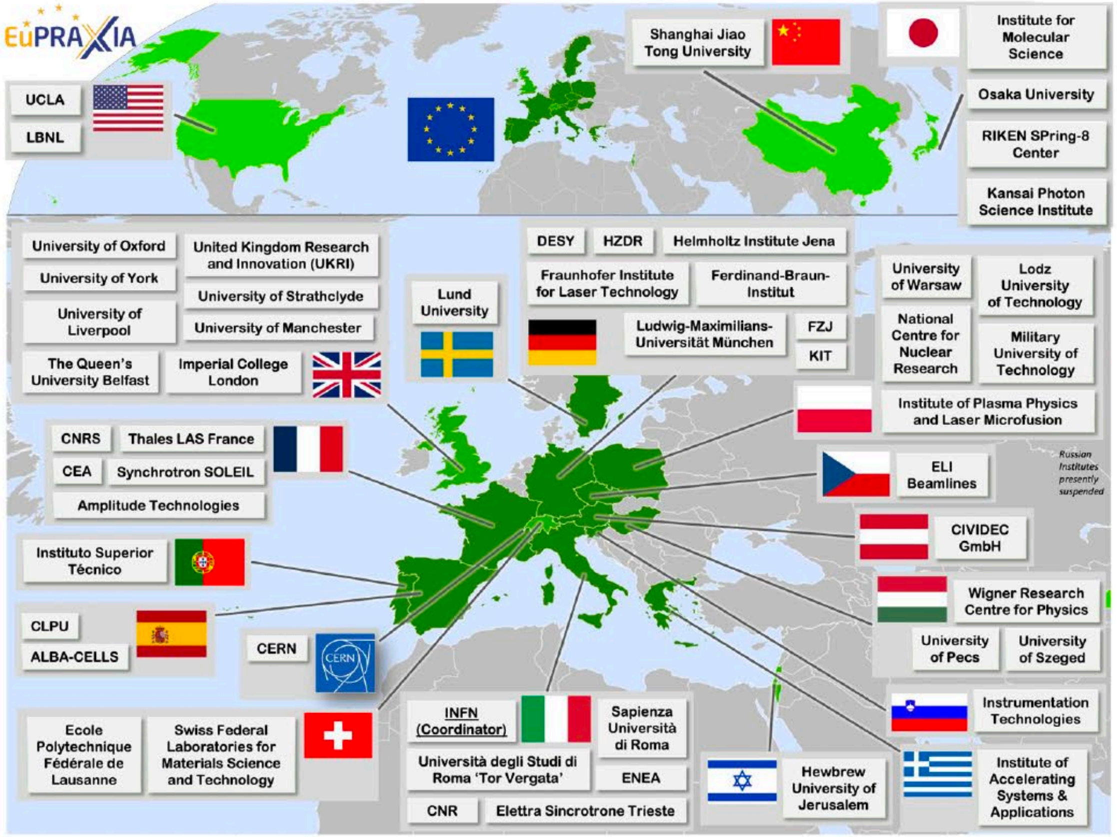
Thank you for the attention

Spares

Wide International Collaboration

Funded by the European Union

- The EuPRAXIA Consortium today: **54 institutes** from **18 countries** plus CERN
- Included in the **ESFRI** Road Map
- Efficient fund raising:
  - –**Preparatory Phase** consortium (funding EU, UK, Switzerland, in-kind)
  - –**Doctoral Network** (funding EU, UK, in-kind)
  - –**EuPRAXIA@SPARC_LAB** (Italy, in-kind)
  - –**EuAPS Project** (Next Generation EU)



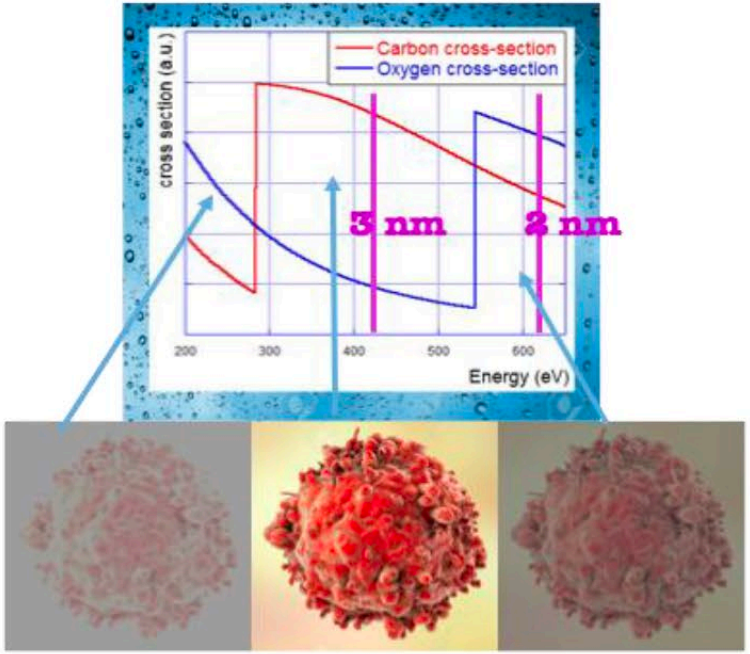
Expected SASE FEL performances

Funded by the European Union

Radiation Parameter	Unit	PWFA	Full X-band
Radiation Wavelength	nm	**3-4**	4
Photons per Pulse	$\times 10^{12}$	**0.1-0.25**	1
Photon Bandwith	%	**0.1**	0.5
Undulator Area Length	m	30	
ρ(1D/3D)	$\times 10^{-3}$	**2**	2
Photon Brilliance per shot	$mm^2 mrad\ bw(0.1\%)$	$\mathbf{1-2\times 10^{28}}$	1×10^{27}

Electron Beam Parameter	Unit	PWFA	Full X-band
Electron Energy	GeV	**1-*1.2***	1
Bunch Charge	pC	**30-50**	200-*500*
Peak Current	kA	**1-2**	1-2
RMS Energy Spread	%	**0.1**	0.1
RMS Bunch Length	μm	**6-3**	24-20
RMS norm. Emittance	μm	**1**	1
Slice Energy Spread	%	**≤0.05**	≤0.05
Slice norm Emittance	mm-mrad	**0.5**	0.5

In the energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation while nitrogen and carbon are absorbing (and scattering)



Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10 ^{11} photons/pulse needed

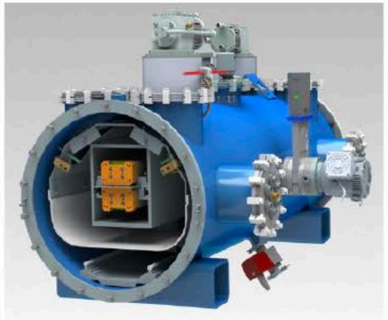
Courtesy C. Vaccarezza

Courtesy F. Stellato (UniTov)

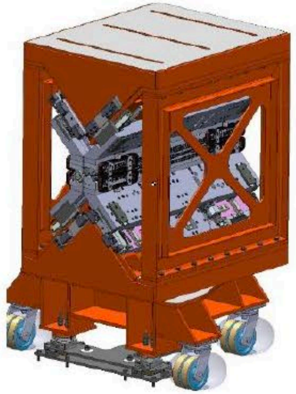
Radiation Generation: FEL

Two FEL lines:

1) *AQUA*: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)

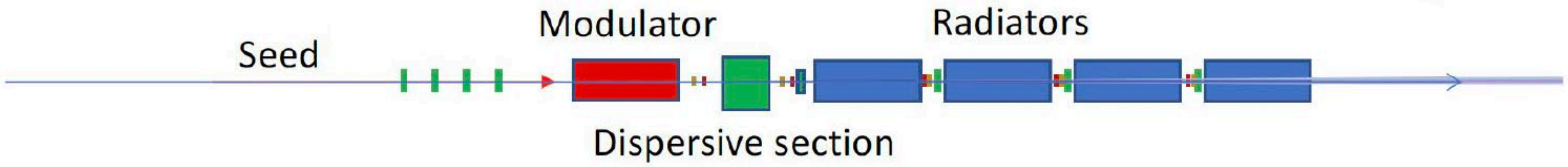


SASE FEL: 10 UM Modules, 2 m each – 60 cm intraundulator sections.
Two technologies under study: Apple-X PMU (baseline) and planar SCU.
Prototyping in progress



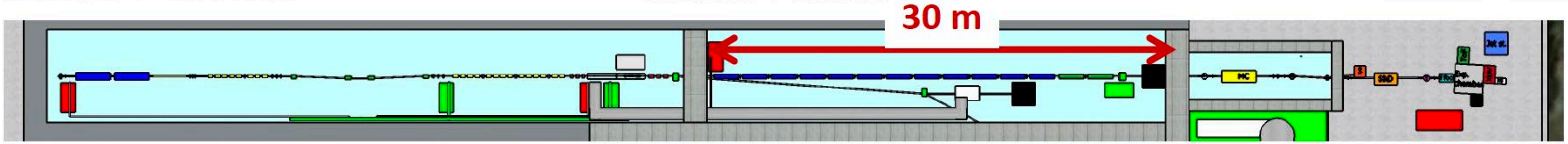
First ***SABINA*** undulator in FRASCATI March 29, 2023

2) *ARIA*: VUV seeded HGHG FEL beamline for gas phase



SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 290 – 430 nm (see former presentation to the committee and *Villa et al. ARIA—A VUV Beamline for EuPRAXIA@SPARC_LAB. Condens. Matter 2022, 7, 11.*) – Undulator based on consolidated technology.

Frascati 06/05/23 – EUPRAXIA TDR



EuPRAXIA Advanced Photon Sources (EuAPS)

- Supported by PNRR funding
- Collaboration among INFN, CNR, University of Tor Vergata
- EuPRAXIA → *laser-driven betatron radiation source @SPARC_LAB*
  → development of high power (up to 1 PW at LNS) and high repetition rate (up to 100 Hz at CNR Pisa) laser
  → pre-cursor for user-facility

1) **Ultrafast** - laser pulse duration tens of fs useful for **time resolved experiments** (XFEL tens of fs, synchrotron tens to 100 ps).
2) **Broad energy spectrum** - important for **X-ray spectroscopy**.
3) **High brightness** - small source size and high photon flux for **fast processes**
4) **Large market** - 50 synchrotron light sources worldwide, 6 hard XFEL's and 3 soft-ray ones (many accelerators operational and some under construction).

Electron beam Energy [MeV]	50-800
Plasma Density [cm^{-3}]	10^{17} - 10^{19}
Photon Critical Energy [keV]	1 - 10
Nuber of Photons/pulse	10^6 – 10^9

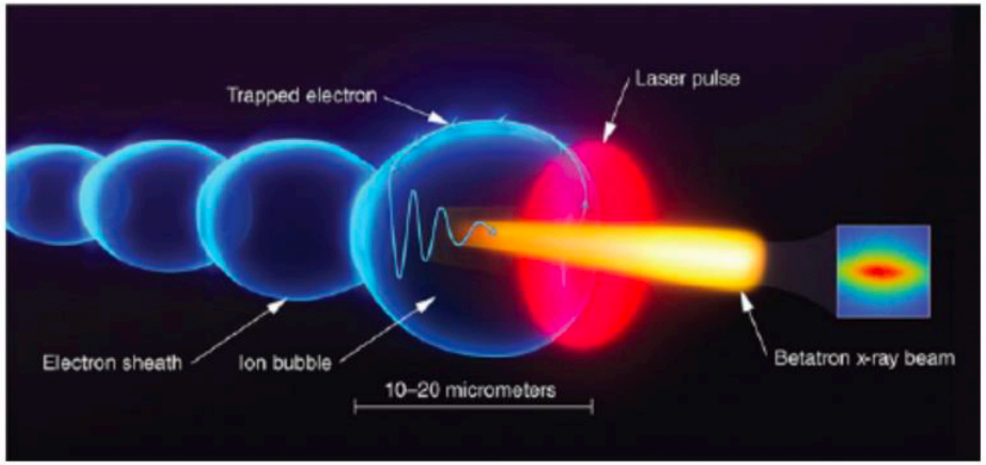


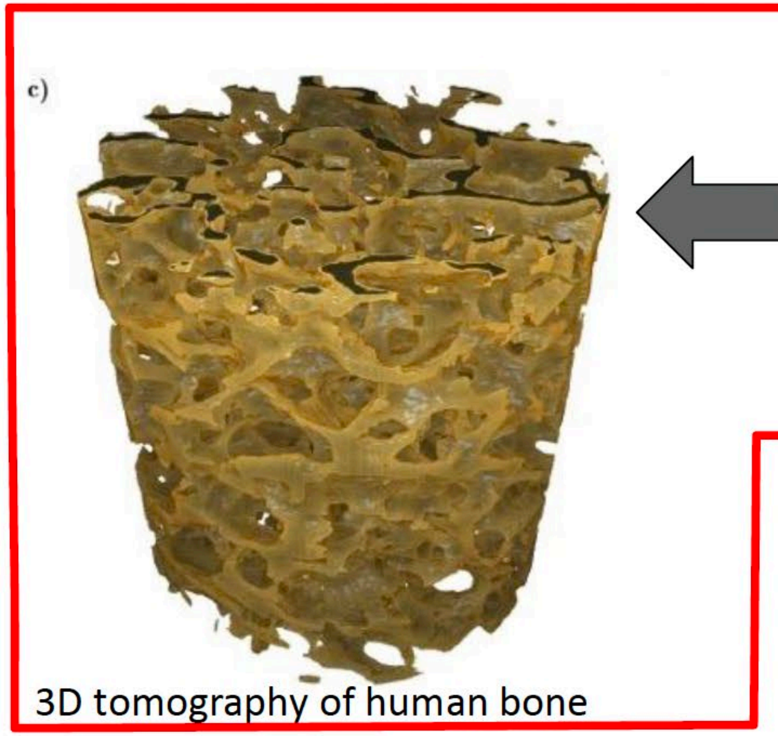
Figure 3: Principle of betatron X-ray emission from a LWFA. Electrons trapped at the back of the wakefield are subject to transverse and longitudinal electrical forces; subsequentlythey are accelerated and wiggled to produce broadband, synchrotron-like radiation in keV energy range [6].

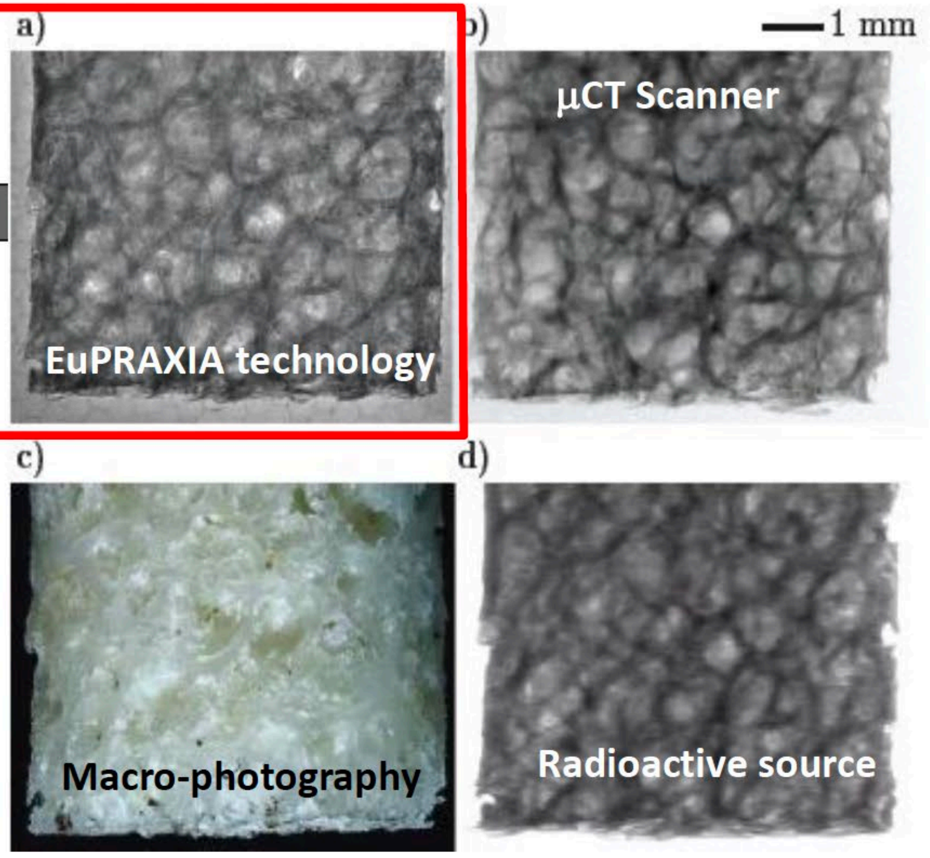
Next Step: 'plasma-based compact undulators'

'EuPRAXIA Advanced Photon Sources PNRR_EuAPS Project', M. Ferrario et al. INFN-23-12-LNF (2023)

Betatron X-Rays: Compact Medical Imaging

J.M. Cole et al, "Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone". Nature Scientific Reports 5, 13244 (2015)





- EuPRAXIA laser advance (industry) will push rate from 1/min to 100 Hz.
- Ultra-compact source of hard X rays → exposing from various directions simultaneously is possible in upgrades

Physics & Technology Background:

- **Quasi-pointlike** emission of X rays.
- High spatial coherence and resolution
- **Sharper image from base optical principle.**
- Quality demonstrated and published, but takes a few hours for one image.
- Advancing flux rate with EuPRAXIA laser by factor > 1,000!

Added value

- Sharper images with outstanding **contrast**
- **Identify smaller features** (e.g. early detection of cancer at micron-scale – calcification)
- Laser advance in EuPRAXIA → **fast imaging** (e.g. following moving organs during surgery)