Collaboration meeting ESRF-INFN 19-20/02/2025

EUPRAXIA@SPARC_LAB S-band injector and X-band LINAC

F. Cardelli, INFN-LNF

fabio.cardelli@lnf.infn.it

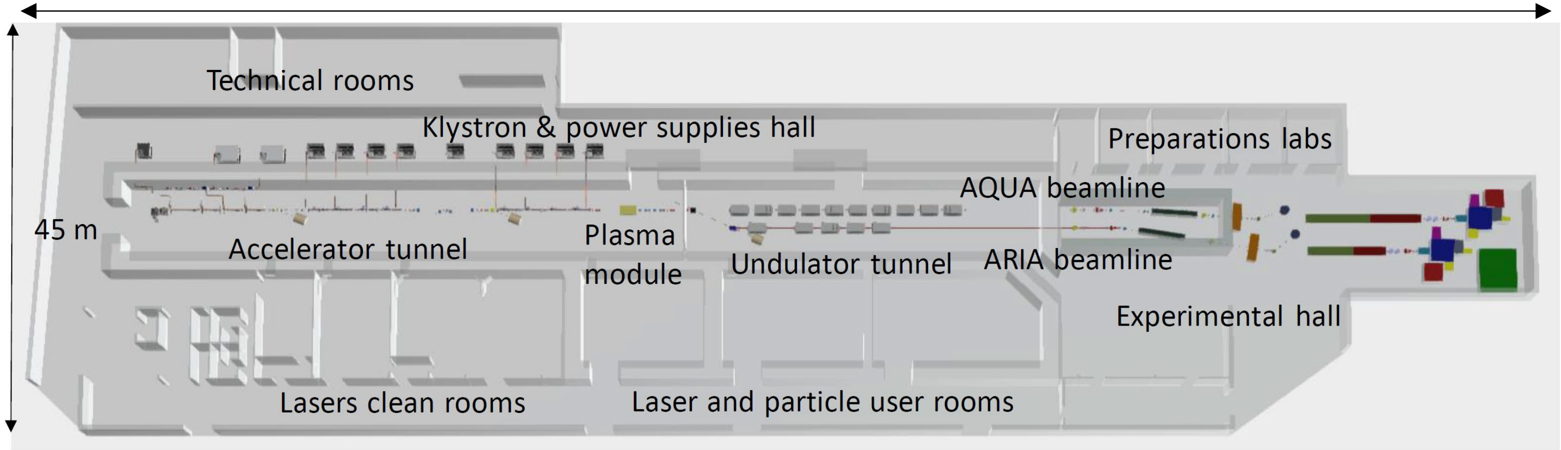
INFN-LNF, Frascati, Italy
19/02/2025

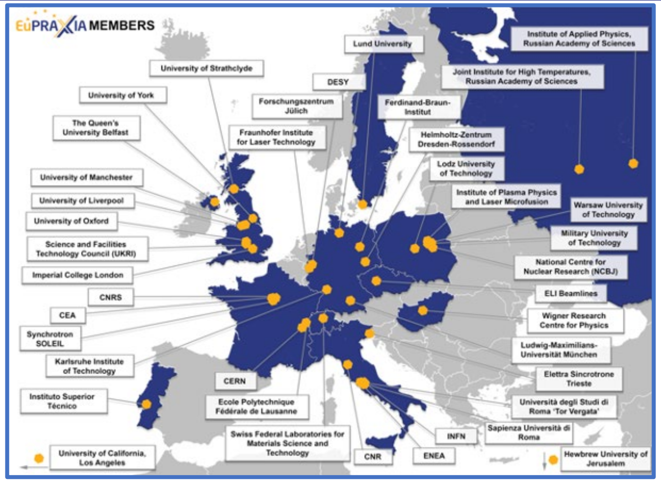
Outline

1. **Overview of the EuPRAXIA@SPARC_LAB Project**
2. **Layout of the Linac**
3. **S-band Injector**
4. **X-band module layout**
5. **RF components designed realized and tested**
6. **TEX Facility and Upgrade**
7. **X-band structure design and first test**

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 λ_{FEL}=4 nm and 50-180nm) combining:
  - **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 in September 2026.

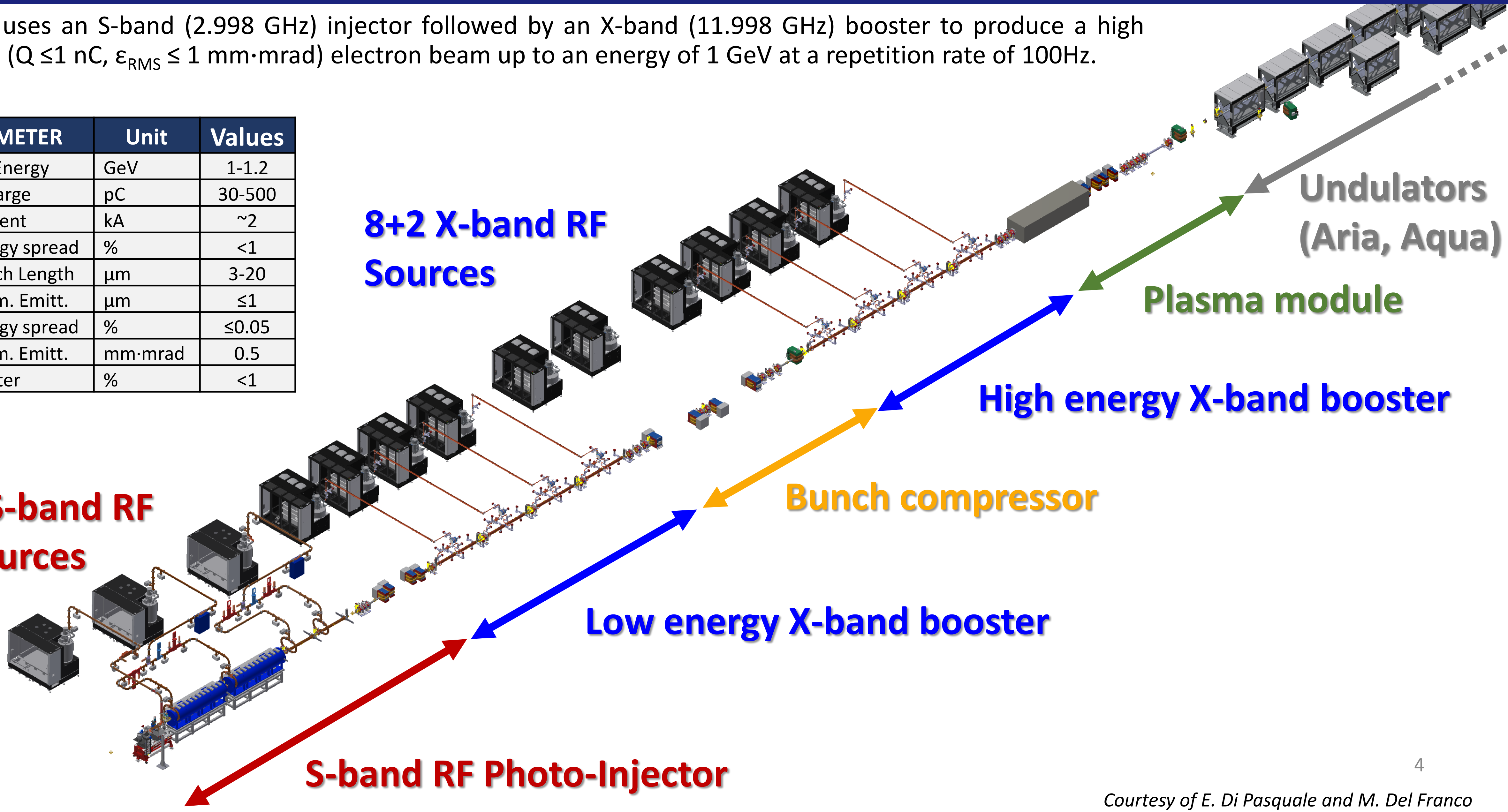




Layout of the EuPRAXIA RF LINAC

The Linac uses an S-band (2.998 GHz) injector followed by an X-band (11.998 GHz) booster to produce a high brightness ($Q \leq 1$ nC, $\varepsilon_{RMS} \leq 1$ mm·mrad) electron beam up to an energy of 1 GeV at a repetition rate of 100Hz.

PARAMETER	Unit	Values
Electron Energy	GeV	1-1.2
Bunch charge	pC	30-500
Peak Current	kA	~2
RMS Energy spread	%	<1
RMS Bunch Length	µm	3-20
RMS Norm. Emitt.	µm	≤1
Slice Energy spread	%	≤0.05
Slice Norm. Emitt.	mm·mrad	0.5
Energy jitter	%	<1



Courtesy of E. Di Pasquale and M. Del Franco

S-band injector

Photo-Gun:
SLAC, BNL, UCLA type
1.6 cell SW RF Gun
Ecath = 120 MV/m

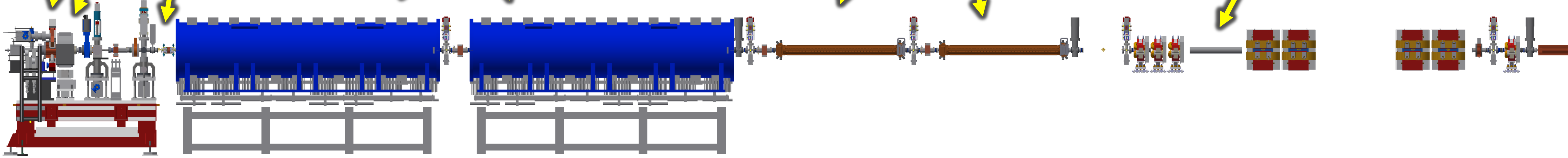
Gun **Solenoid**

X-band linearizer
SW cavity

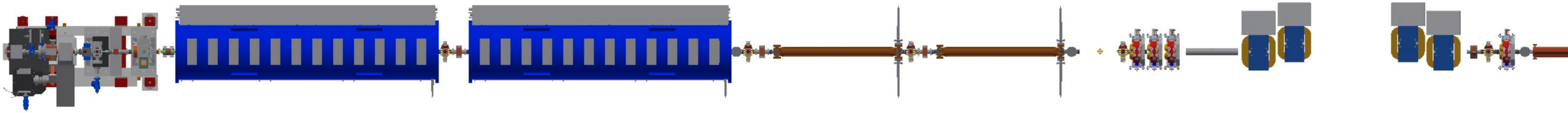
2x **S-band 3 m TW structures**
+ solenoids
Eacc = 21 MV/m

2x **S-band 1.5 m TW structures**
High gradient Eacc = 35 MV/m

PolariX Deflector



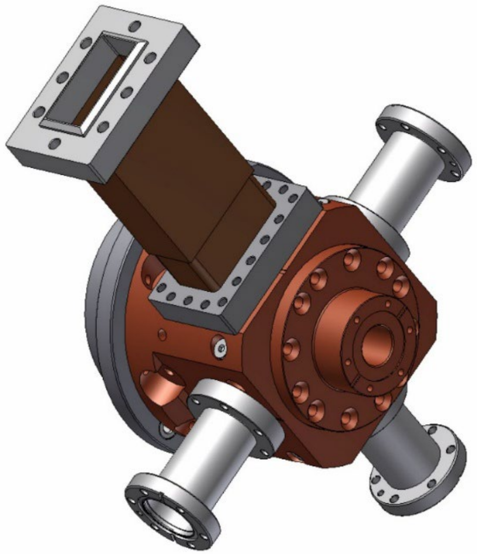
Side view



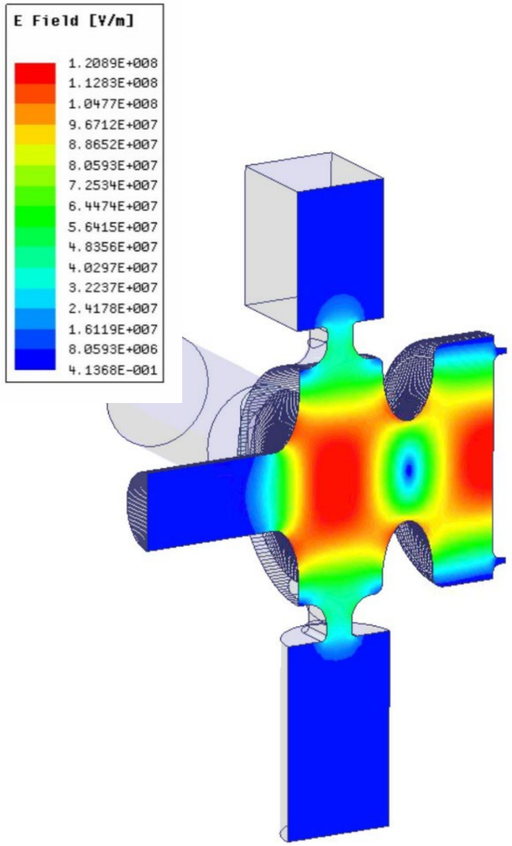
Top view

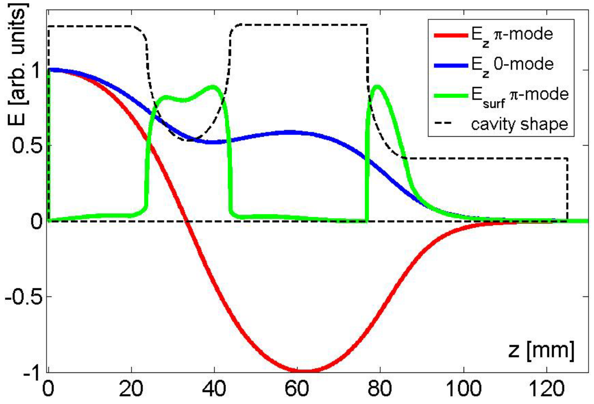
S-band RF Gun

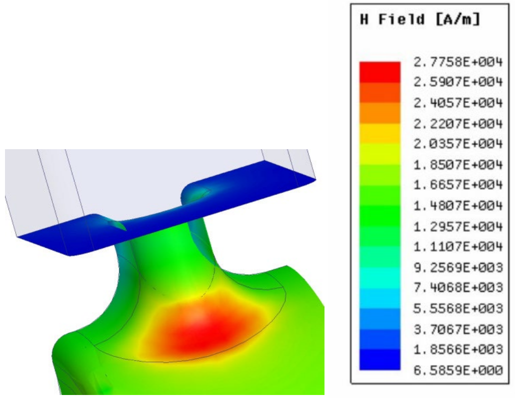
- **elliptical irises** with increased aperture
- **Four symmetric ports**, one connected to the input waveguide and 3 for vacuum pumping. These ports **compensate the dipole and quadrupole magnetic field component** induced by the input coupler.
- The **coupling hole strongly rounded** to reduce the peak surface magnetic field and the **pulsed heating.**
- The gun will be fabricated w/o brazing using **special RF-vacuum gaskets**



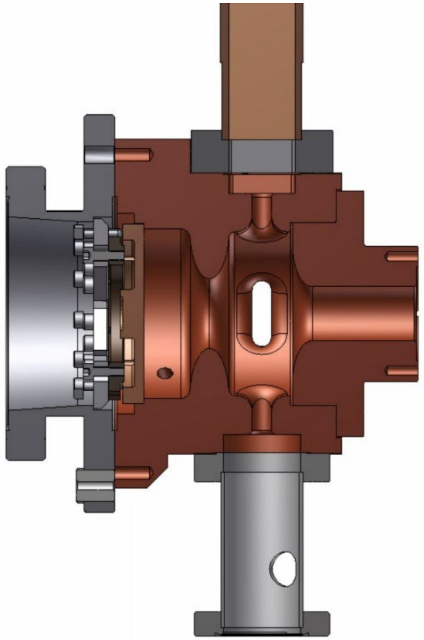
Parameters	SPARC Gun	CLEAR Gun
f_{res} [GHz]	2.856	2.99855
Q_0	13500	13800
Nominal Cath. peak field [MV/m]	120	
$E_{cathode}/\sqrt{(P_{diss})}$ [MV/(mMW$^{0.5}$)]	37.5	
E_{surf}/E_{cath}	0.9	
Δfreq. 0 /π-mode [MHz]	~ 41	~ 44
RF input power [MW]	12-16	
RF pulse length [μs]	1-2	
Coupling β	2	
H_{surf} [kA/m]	< 300	
Pulsed heating	< 30 [°C]	
Repetition rate	10 [Hz]	
Working temp.	30 [°C]	
Fill. Time (τ)	~ 500 ns	



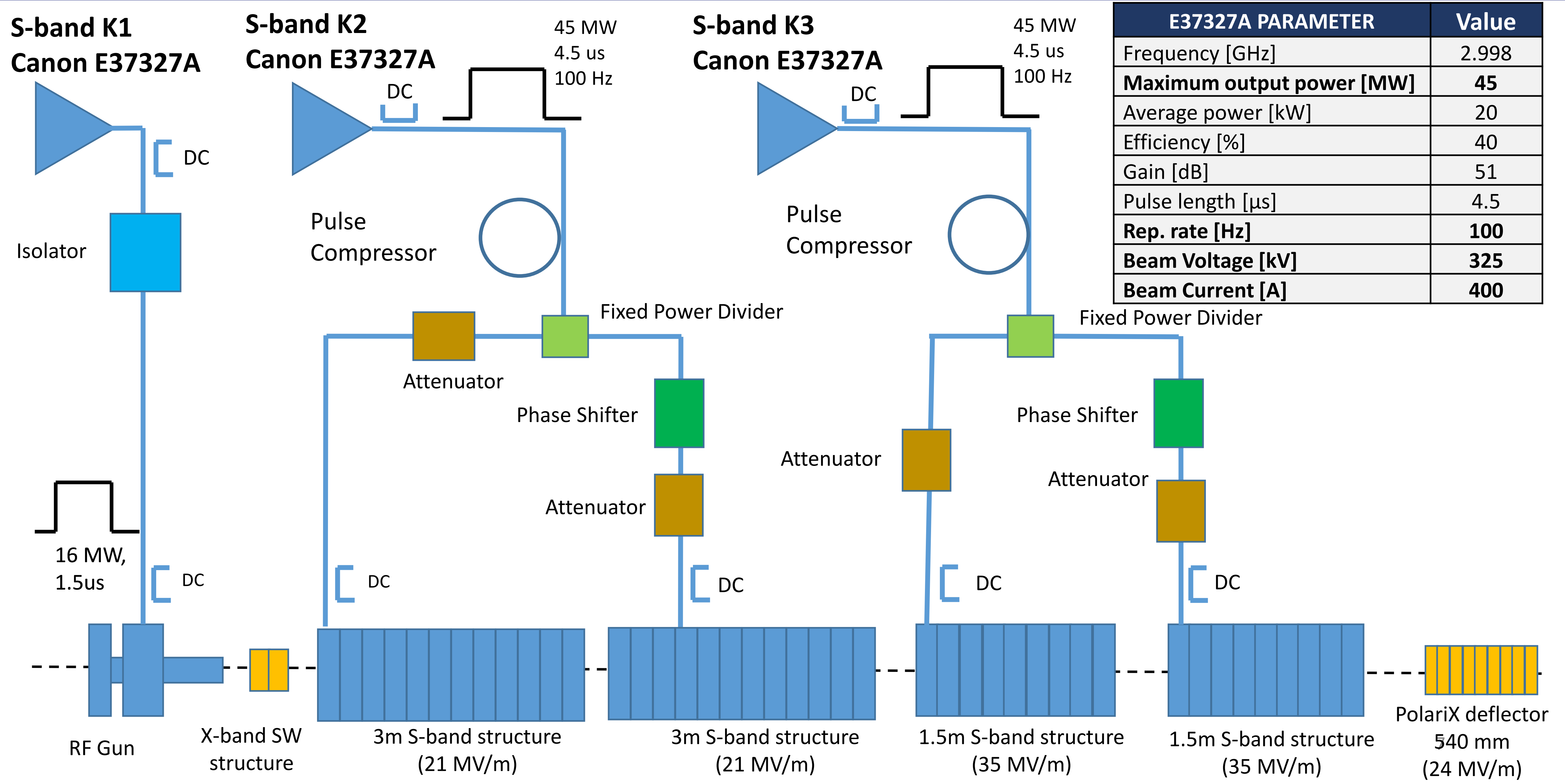




The tuning and simulations have been performed with Poisson Superfish and Ansys HFSS.



S-band injector



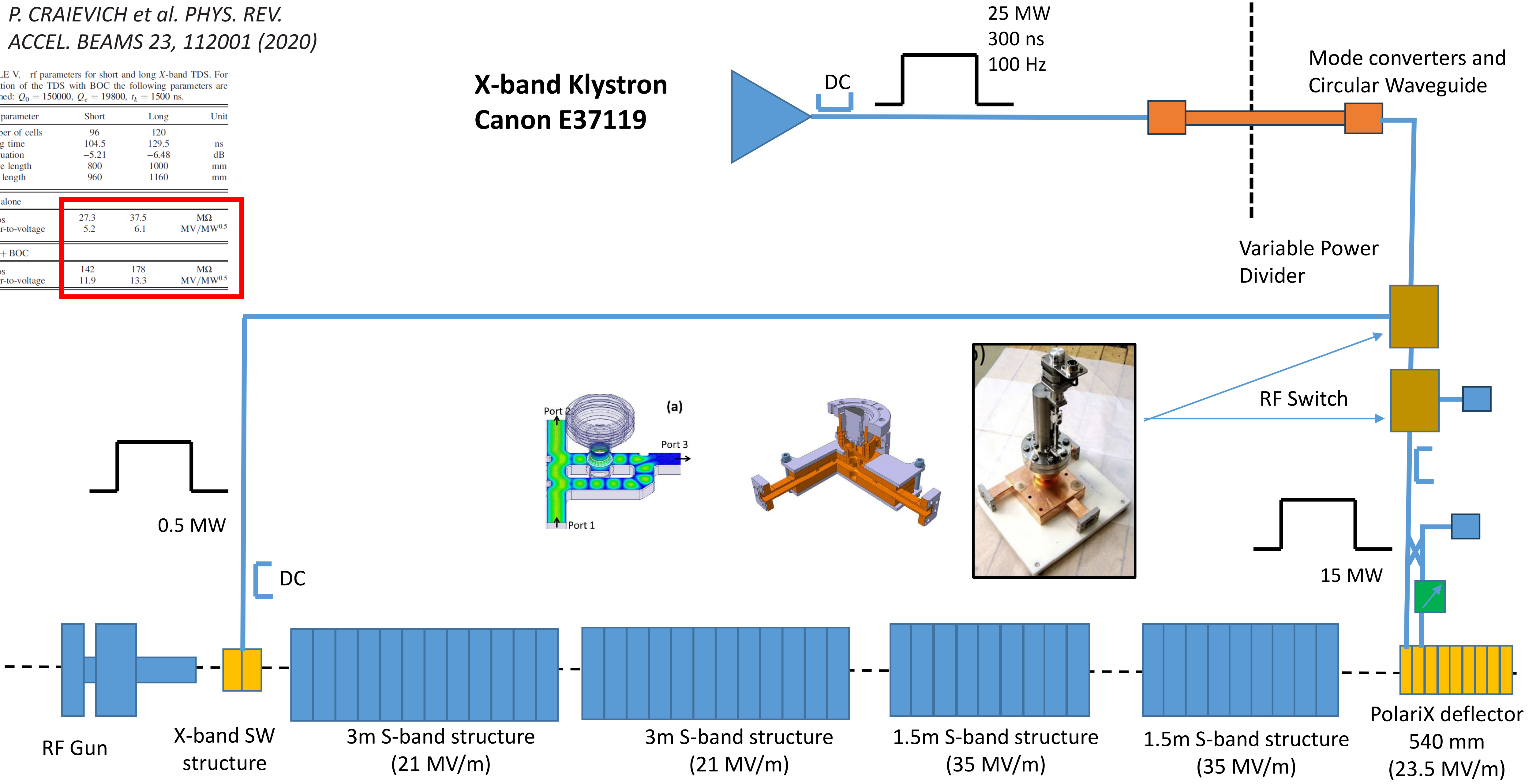
E37327A PARAMETER	Value
Frequency [GHz]	2.998
Maximum output power [MW]	**45**
Average power [kW]	20
Efficiency [%]	40
Gain [dB]	51
Pulse length [μs]	4.5
Rep. rate [Hz]	**100**
Beam Voltage [kV]	**325**
Beam Current [A]	**400**

S-band injector

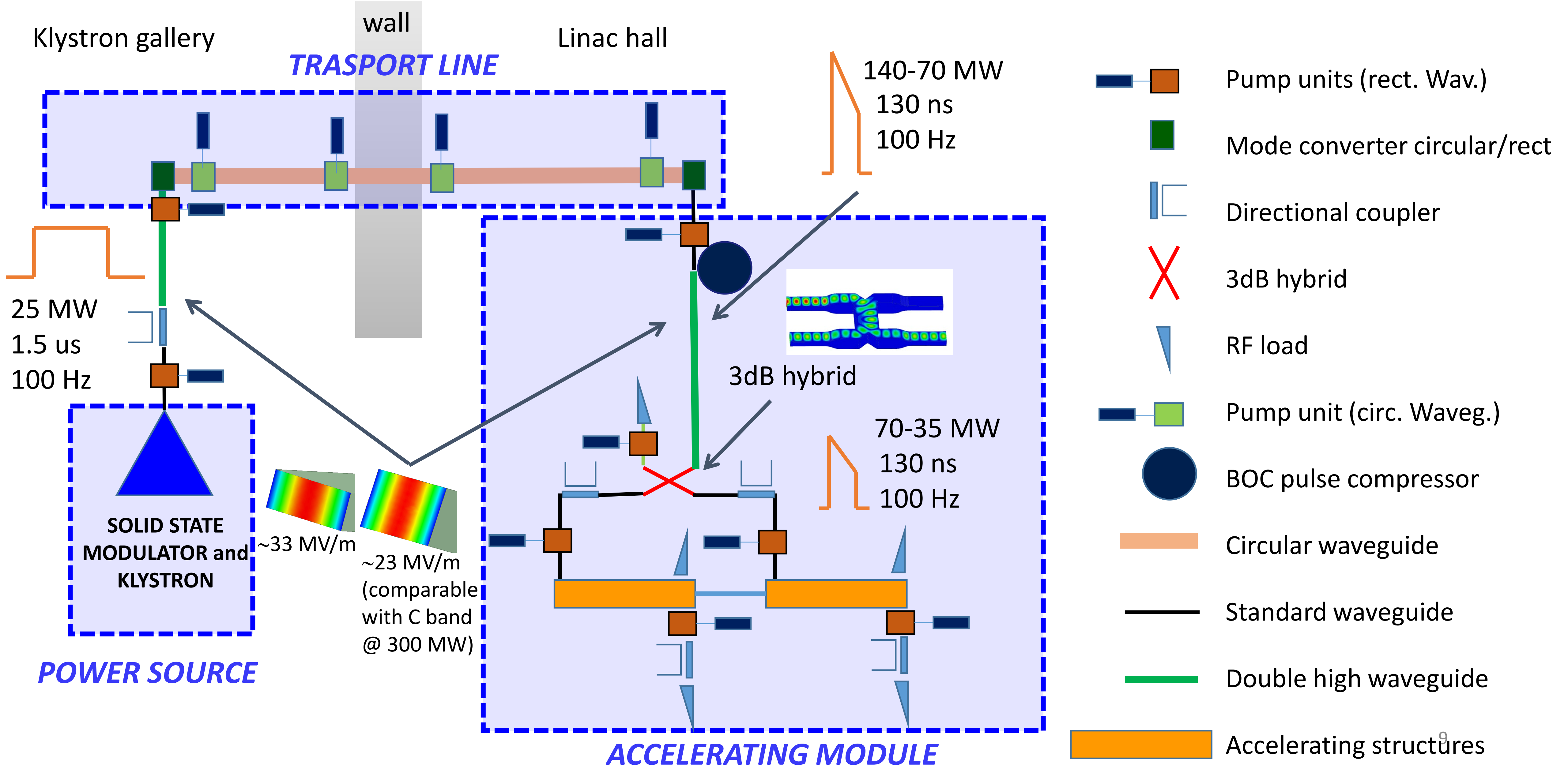
P. CRAIEVICH et al. PHYS. REV. ACCEL. BEAMS 23, 112001 (2020)

TABLE V. rf parameters for short and long X-band TDS. For operation of the TDS with BOC the following parameters are assumed: $Q_0 = 150000$, $Q_e = 19800$, $t_k = 1500$ ns.

TDS parameter	Short	Long	Unit
Number of cells	96	120	
Filling time	104.5	129.5	ns
Attenuation	−5.21	−6.48	dB
Active length	800	1000	mm
Total length	960	1160	mm
TDS alone			
$R_{\perp,\mathrm{TDS}}$	27.3	37.5	MΩ
Power-to-voltage	5.2	6.1	MV/MW$^{0.5}$
TDS + BOC			
$R_{\perp,\mathrm{TDS}}$	142	178	MΩ
Power-to-voltage	11.9	13.3	MV/MW$^{0.5}$

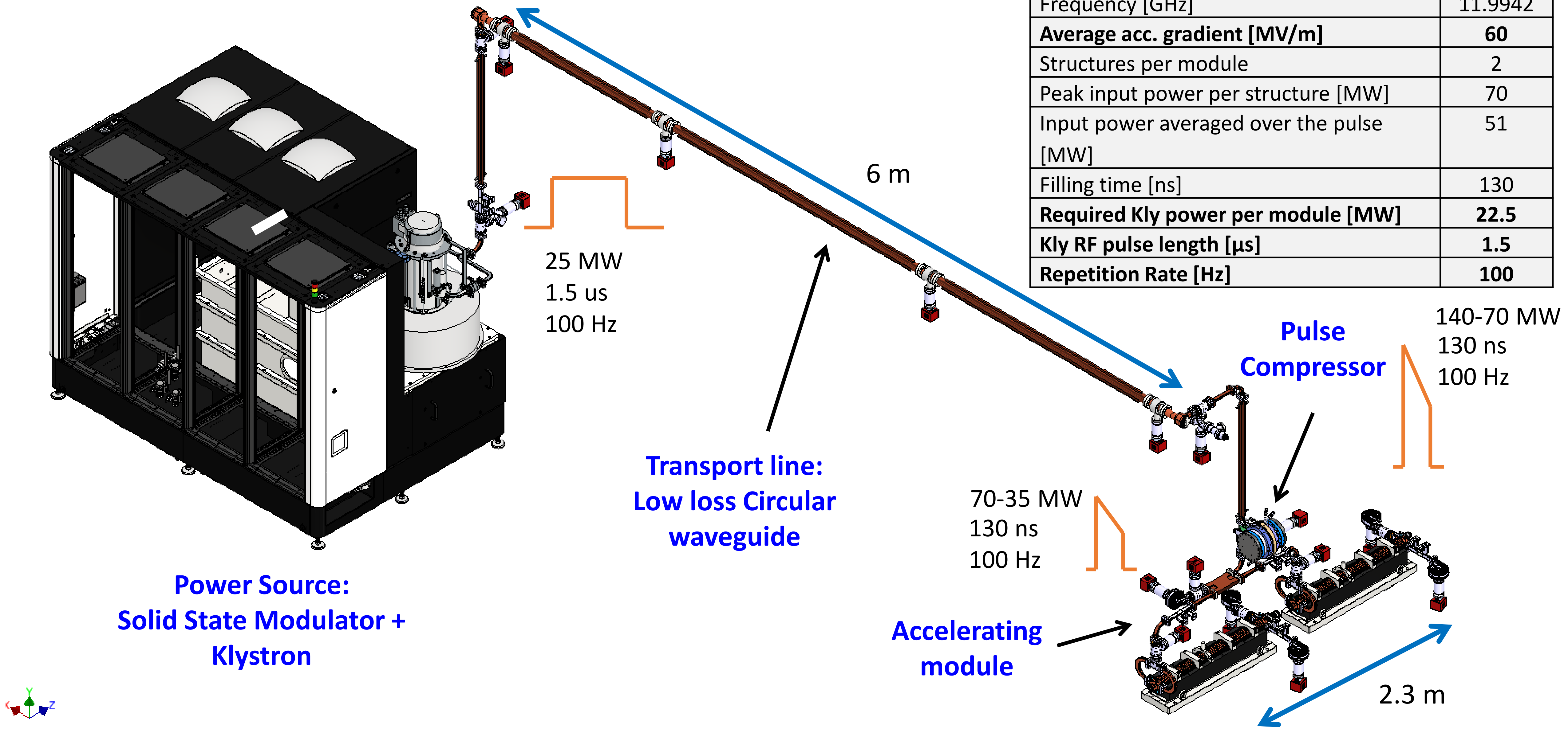


X-band RF Module Layout

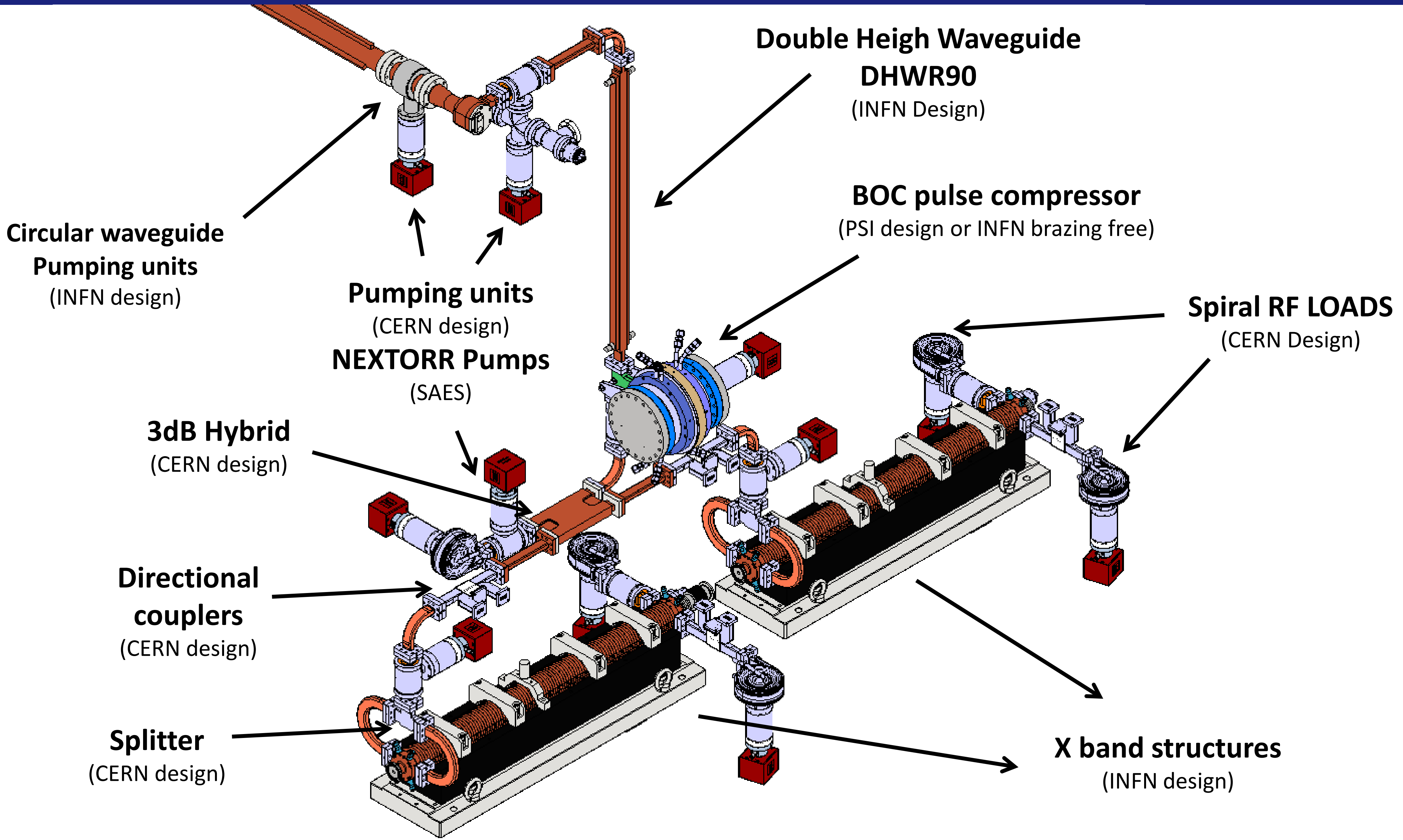


X-band RF Module Layout

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 Module Layout



X-Band Power Sources

Currently we have a test stand based on **CPI VKX8311** Klystron

Two other klystrons will be tested at INFN:

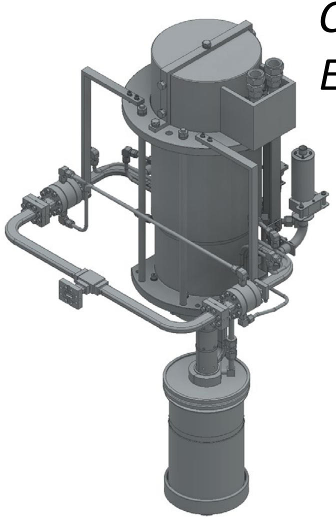
A. **CANON E37119**
   - Low modulator peak power requirement
   - Very high repetition rate (Interesting for a future upgrade of the machine)

B. **CPI High efficiency VKX8311HE** (developed in collaboration with CERN).
   - High efficiency
   - High peak power available

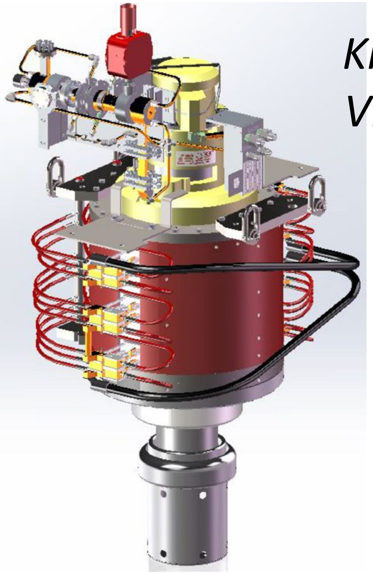
Status:

- Test station based on the VKX8311A klystron already commissioned and **in operation** at TEX facility
- CPI VKX8311HE is **in procurement phase** (expected delivery 08/2025 and test scheduled in Autumn 2025)
- CANON E37119 klystron with modulator
  - FAT of the klystron done @CANON on a PFN modulator 11/2023, 25 MW, 10 Hz, t=1.5us
  - FAT of the RF source @Scandinova 05/2024, full power in diode mode
  - Modulator and klystron positioned at TEX
  - SAT with Scandinova and Canon is scheduled in April

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



CANON E37119



Klystron CPI VKX8311HE

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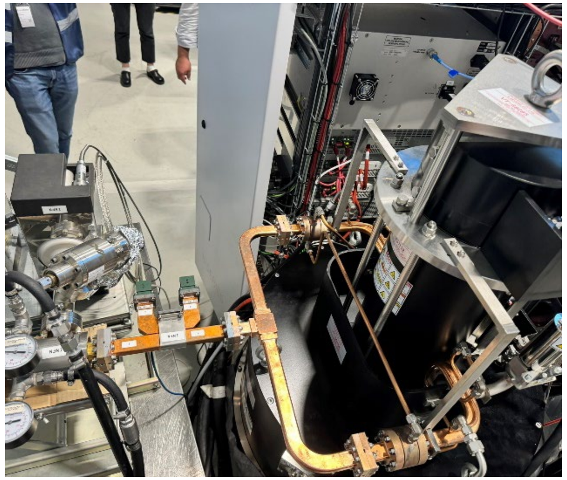
FAT of the RF Source



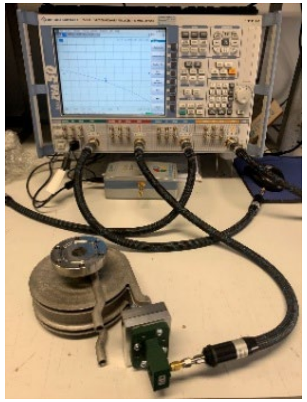
CANON E37119

Installation at TEX

Spiral Loads

- Realization by 3D printing based on CERN design: ***done***
- Low Power RF test: ***done***
- High Power test: ***done***
- Currently used as load for TW structures
- 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.

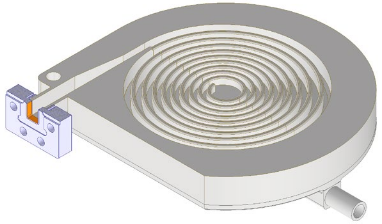
#	Company	S11@f0 [dB]
001	3t am	-31
002	3t am	-30
003	ISC	-37,7
004	ISC	-36,4
005	ISC	-42
006	ISC	-43,9

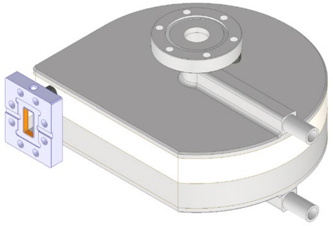


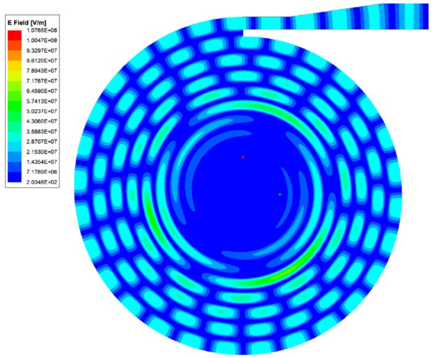
Currently, realization is by **additive manufacturing**. We are developing a design that can be implemented by **milling**:

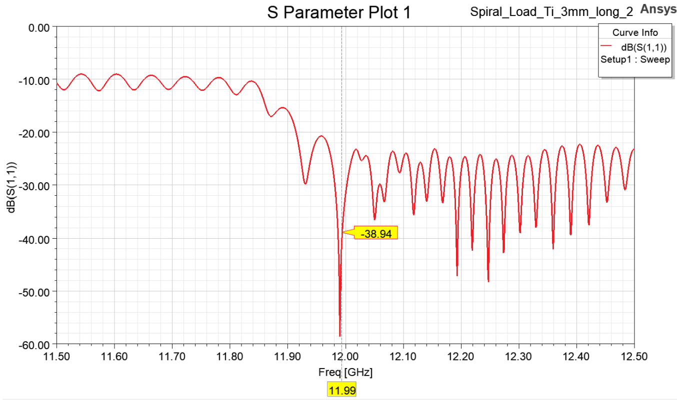
- **Motivation**: the aim is to allow other companies to be able to realize this type of load even without the use of additive manufacturing
- The idea is to replace the vacuum pumping holes by «cutting» the entire load transversely leaving a 1 mm thick gap along the entire length of the waveguide.
- To do this, the thickness of the waveguide walls have been increased from 2 mm to 3 mm to decouple the field between the waveguide windings. The windings of the spiral have been recalculated to keep the overall length of the waveguide as in the original design.

EM and mechanical design: ***done***
Manufacturing : ***ongoing***



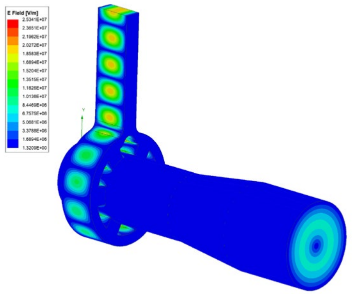
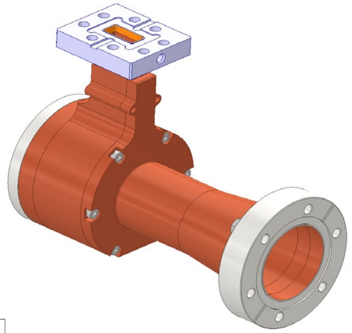
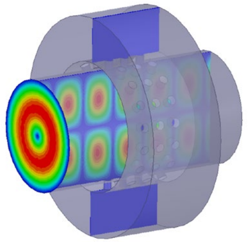
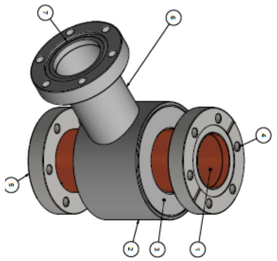
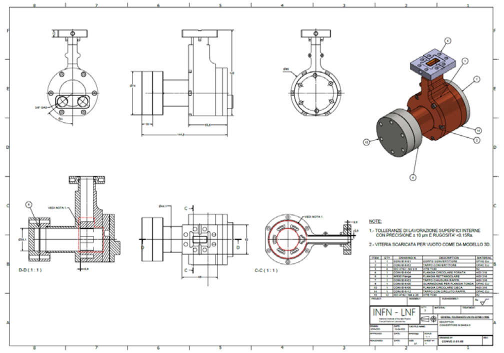


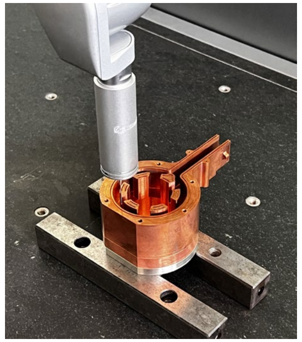
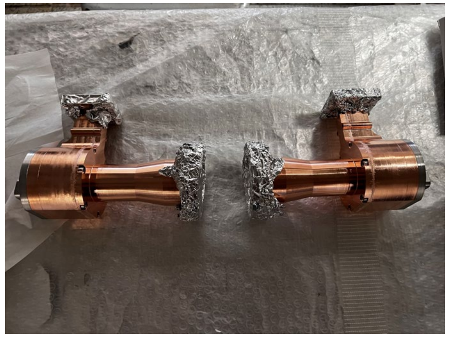
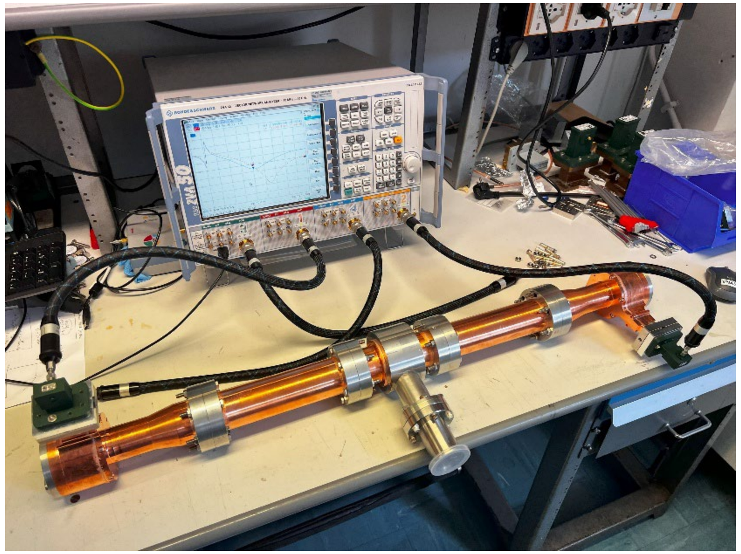


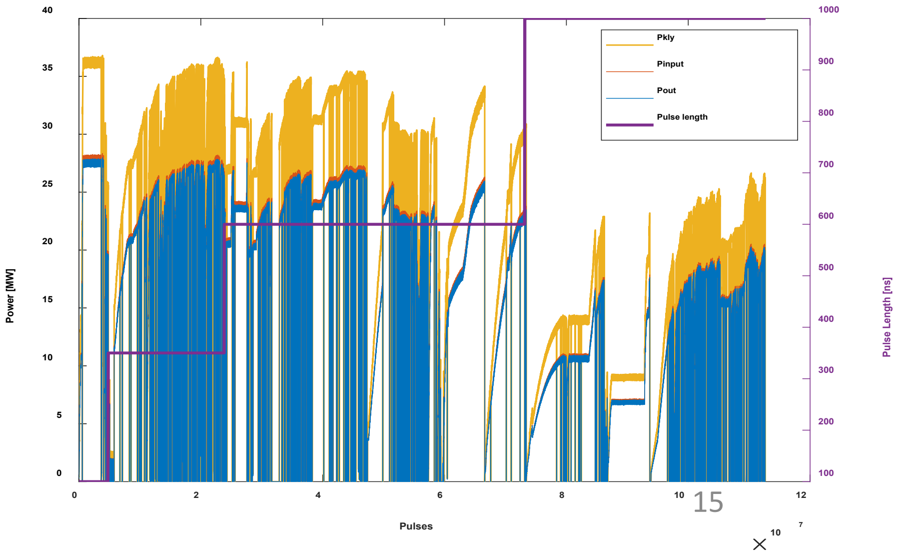


Mode Converter

- Modified version of the “wrap around” mode converter from $TE_{10}^{\square}$ to TE_{01}° developed at SLAC 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: ***done***

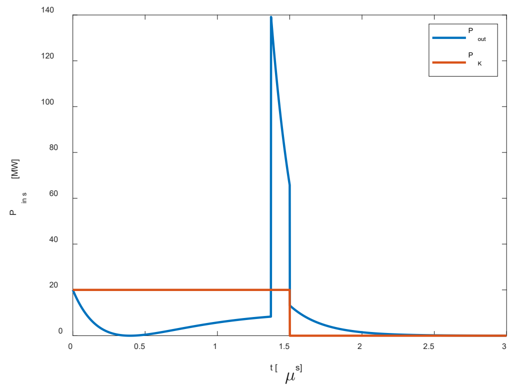


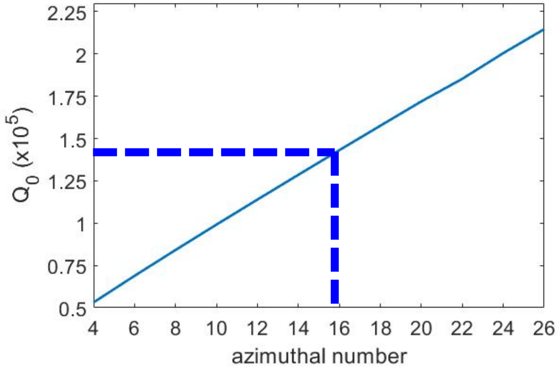
S. Tantawi, et all. (2000). Reviews of Modern Physics – doi: 10.1103/PhysRevSTAB.3.082001

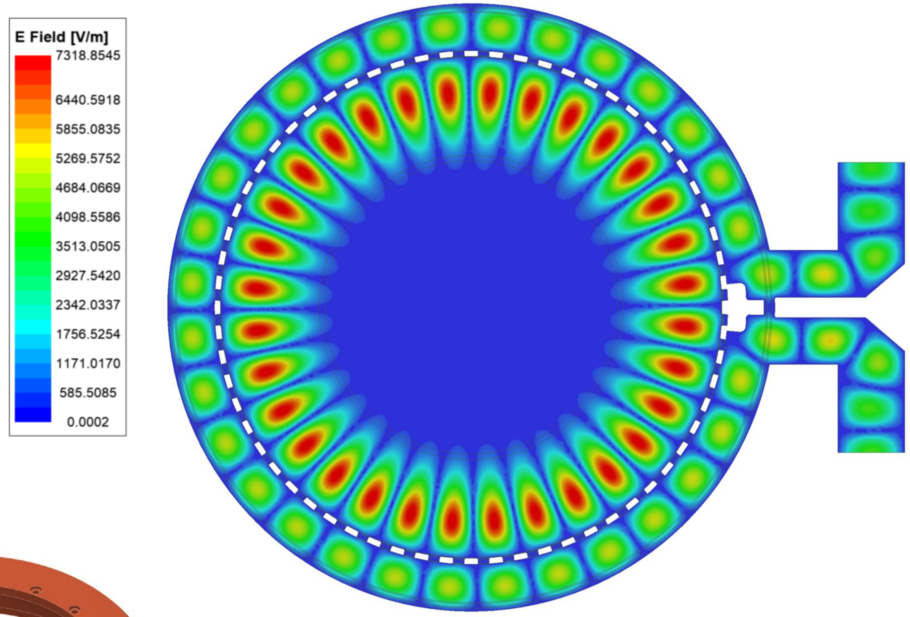
Brazing free BOC Pulse Compressor

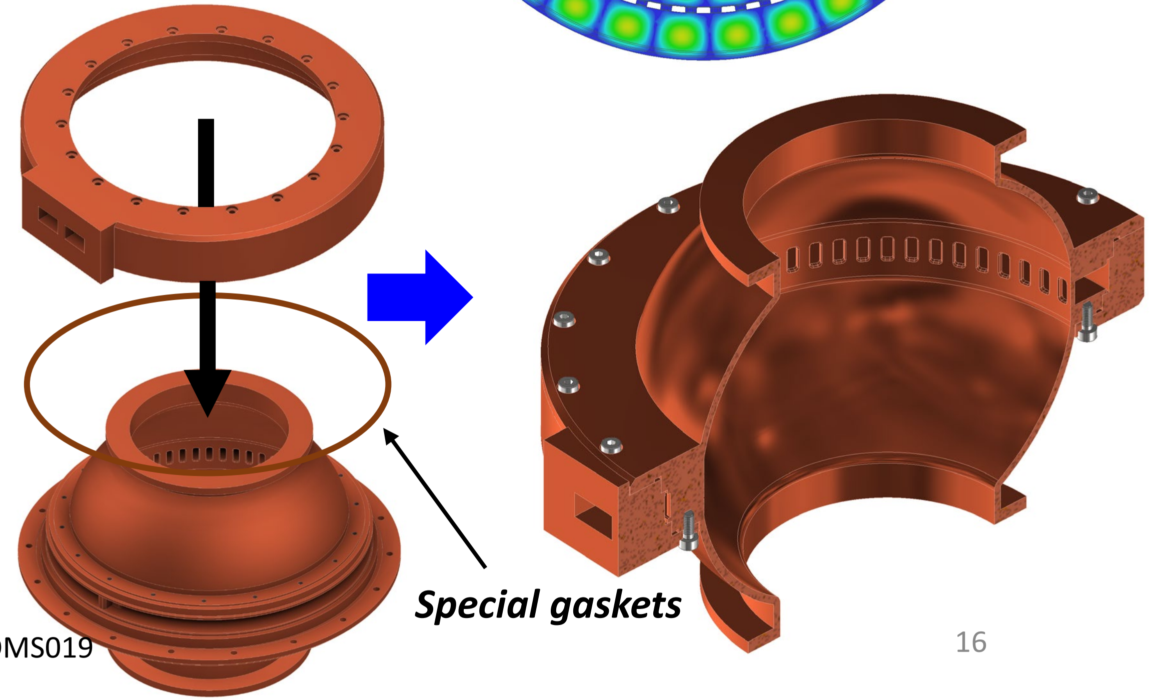
- We are developing a **new design for X-band BOC** that implements the INFN-LNF brazing-free technology
- The **brazing free or "clamping" technology** is based on the use of **special RF/vacuum gaskets** [8,9]
- The choice of the mode to increase the Q_0 keeping the size of the BOC reasonable.
- To use the gaskets has been introduced a gap on the edge of the circular waveguide, with new input splitter design
- EM design: ***done***
- The mechanical design and cooling system design: ***ongoing***
- The development of a high rep. rate brazing free BOC is part of PACRI Project

Pulse Compressor	Parameter
Frequency	11.994 GHz
Resonant Mode	$TM_{16,1,1}$
Diameter	171 mm
Q_0	130000
Coupling factor β	6.5





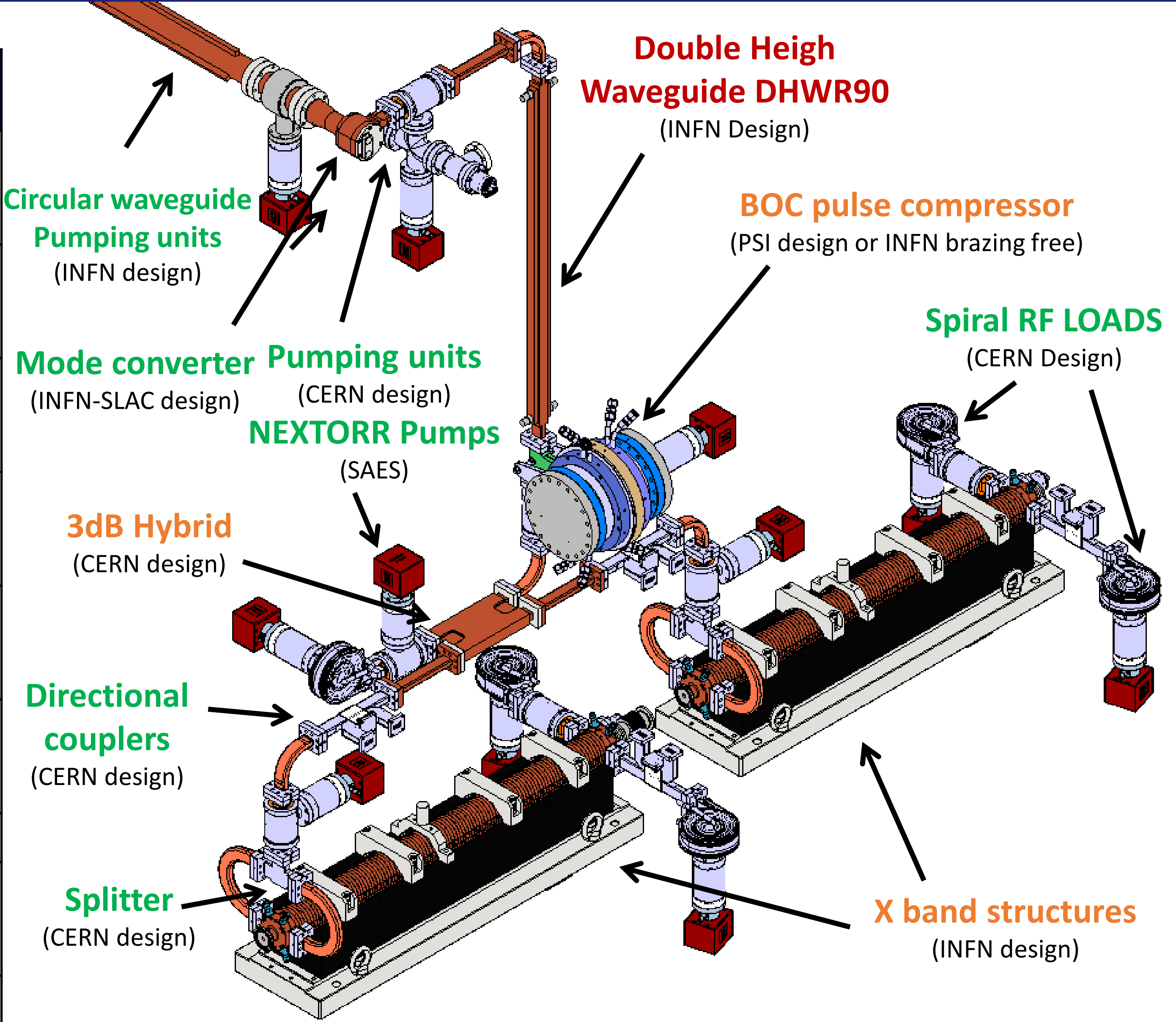




D. Alesini, et al., 13th Int. Particle Accelerator Conf. (IPAC22), Bangkok, Thailand, June 2022, paper MOPOMS019
D. Alesini, et al., 14th Int. Particle Accelerator Conf. (IPAC23), Venice, Italy, May 2023, paper TUPA009

X-Band RF Components

COMPONENT	DESIGN BY	STATUS	HIGH POWER TEST
Pump unit (rect. wav.)	CERN	Fabricated and installed @ TEX	45 MW, 1 μs, 50 Hz, P_{avg} = 2.25 kW
Directional coupler	CERN	Fabricated and installed @ TEX	45 MW, 1 μs, 50 Hz, P_{avg} = 2.25 kW
Splitter	CERN	Fabricated and installed @ TEX	35 MW, 0.6 μs, 50 Hz, P_{avg} = 1 kW
RF load	CERN	Fabricated and installed @ TEX	17 MW, 0.6 μs, 50 Hz, P_{avg} = 0.5 kW
Mode converter circular/rectangular	INFN/SLAC	Fabricated and Installed @ TEX	35 MW, 1 μs, 50 Hz, P_{avg} = 1.75 kW
Pump unit (circ. waveg.)	INFN/SLAC	Fabricated and Installed @ TEX	35 MW, 1 μs, 50 Hz, P_{avg} = 1.75 kW
3dB hybrid	CERN	Delivered	To be tested
BOC pulse compressor	PSI	Delivered and installed @ TEX	To be tested
Double height waveguide	INFN/CERN	To be realized	To be tested



TEX Facility

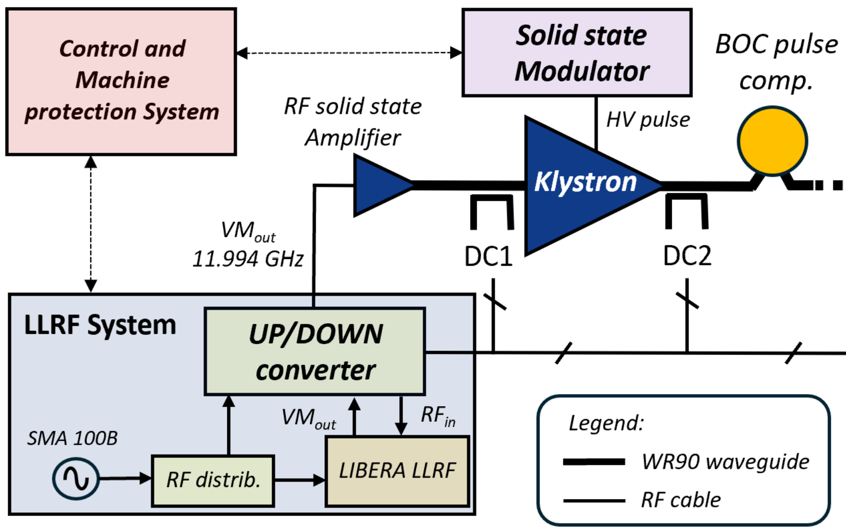
» The **TEst-stand for X-band (TEX)** is conceived for **R&D and test on high gradient X-band accelerating structures, RF components, LLRF systems, Vacuum system and Control System**

» 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 installation and commissioning of the whole system (Source and RF network, LLRF, vacuum and EPICS control system) have been completed by the end of 2022 [3,4,5].

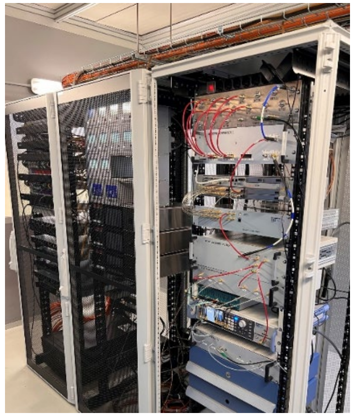
» Then started the **testing activity:**

Period	Device tested at high power
Jan. - Feb. 2023	3D printed Spiral RF loads and wg system
May - Oct. 2023	X-band **T24 CLIC structure**
Nov. - Dec. 2023	X-band Mode converter and circular wg
Jan. - Feb. 2024	X-band RF waterload **from PSI**
March 2024	20 cells **first EuPRAXIA RF prototype**
April 2024 - Now	**Upgrade of the facility**



Cathode peak voltage	427 kV
Peak RF output power	**50 MW**
Pulse length	100 ns - 1.5 us
Repetition Rate	**50 Hz**
RF output amplitude stability	< 0.09 %
RF output phase stability	20.9 fs

LLRF system



50 MW RF Source

VKX8311A Klystron

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

L. Piersanti et al. "RF power station stabilization techniques and measurements at LNF" In Proc. IPAC24 - TUPR01.

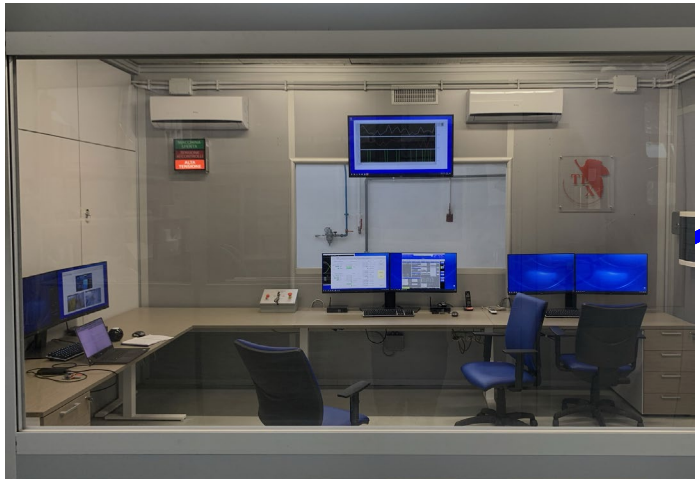
L. Piersanti et al. "Design and test of a klystron intra-pulse phase feedback system for electron linear accelerators" Photonics 2024, 11(5), 413.

F. Cardelli et al., in Proc. IPAC'24, Nashville, TN (2024) paper TUPR02

TEX facility (2)

TEX is located at the building 7 of INFN-LNF that has been completely refurbished to host this facility.

Rack Room



Control Room

Bunker

Experimental hall

TEX Upgrade

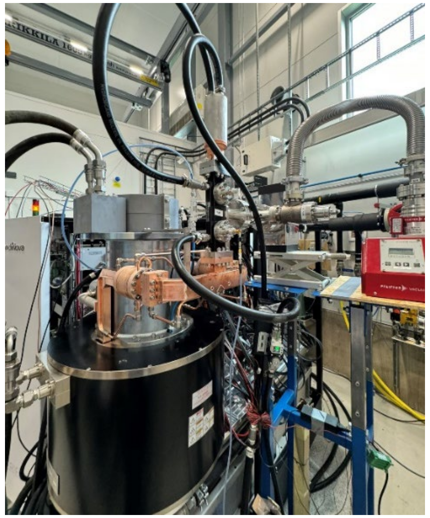
» Thanks to **PNRR Rome Technopole project**, €3M have been allocated for the **upgrade of the TEX facility and Latino project.**

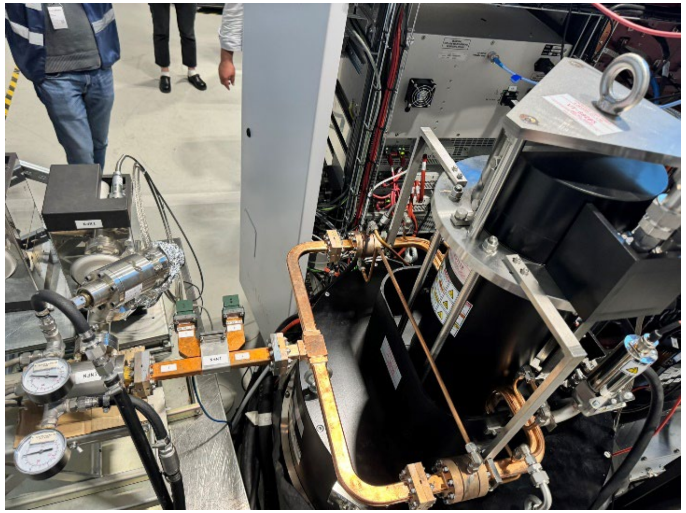
» Procurement, installation and test of **two new RF sources** and waveguide system:

1. **X-band (11994 MHz) 25MW, 400Hz Power Source**
2. **C-band (5712 MHz) 20MW, 400Hz Power Source**
    - FAT of the klystron done @CANON on a PFN modulator 11/2023
    - FAT of the RF source @Scandinova 05/2024, full power in diode mode
    - Modulator and klystron positioned at TEX
    - SAT with Scandinova and Canon is **scheduled at the beginning of 2025** depending on the dry cooler commissioning

Parameter	Unit	Canon E37119	Canon E37217
Frequency	MHz	11994	5712
Vk beam voltage	kV	312	254
Ik cathode current	A	199	196
Peak RF output Power	MW	**25**	**20**
Average RF output power	kW	15	21
Modulator Average power	kW	80	80
RF pulse length	µs	**1.5**	**2.5**
Repetition Rate	Hz	**400**	**400**
Gain	dB	47	50
Efficiency	%	40	40

FAT of the two Sources



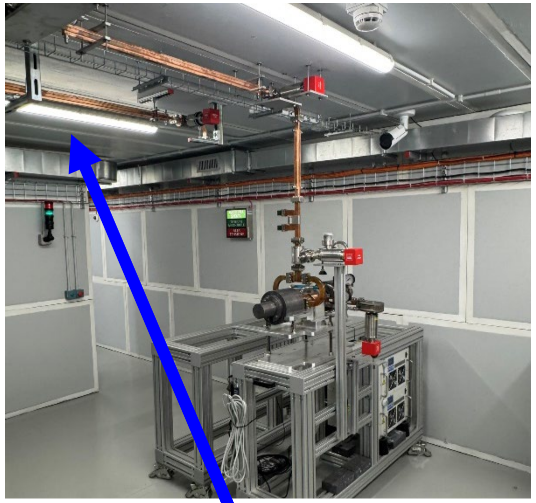


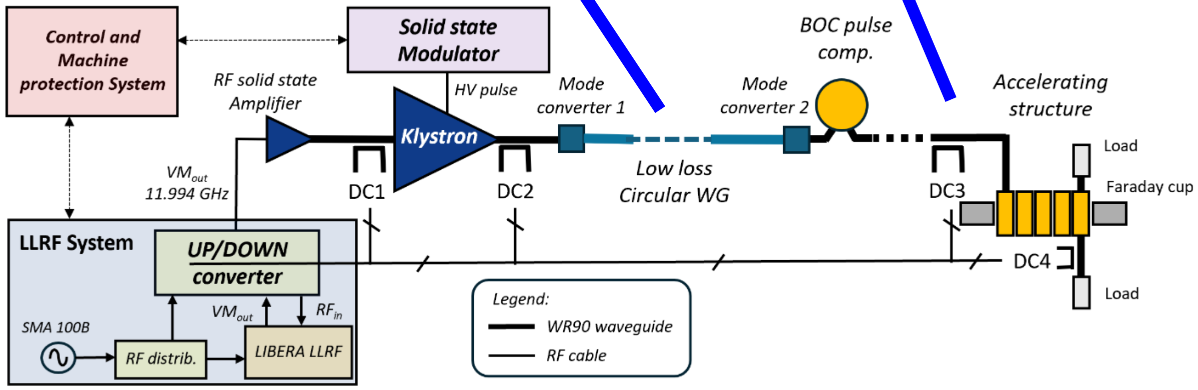
CANON E37119

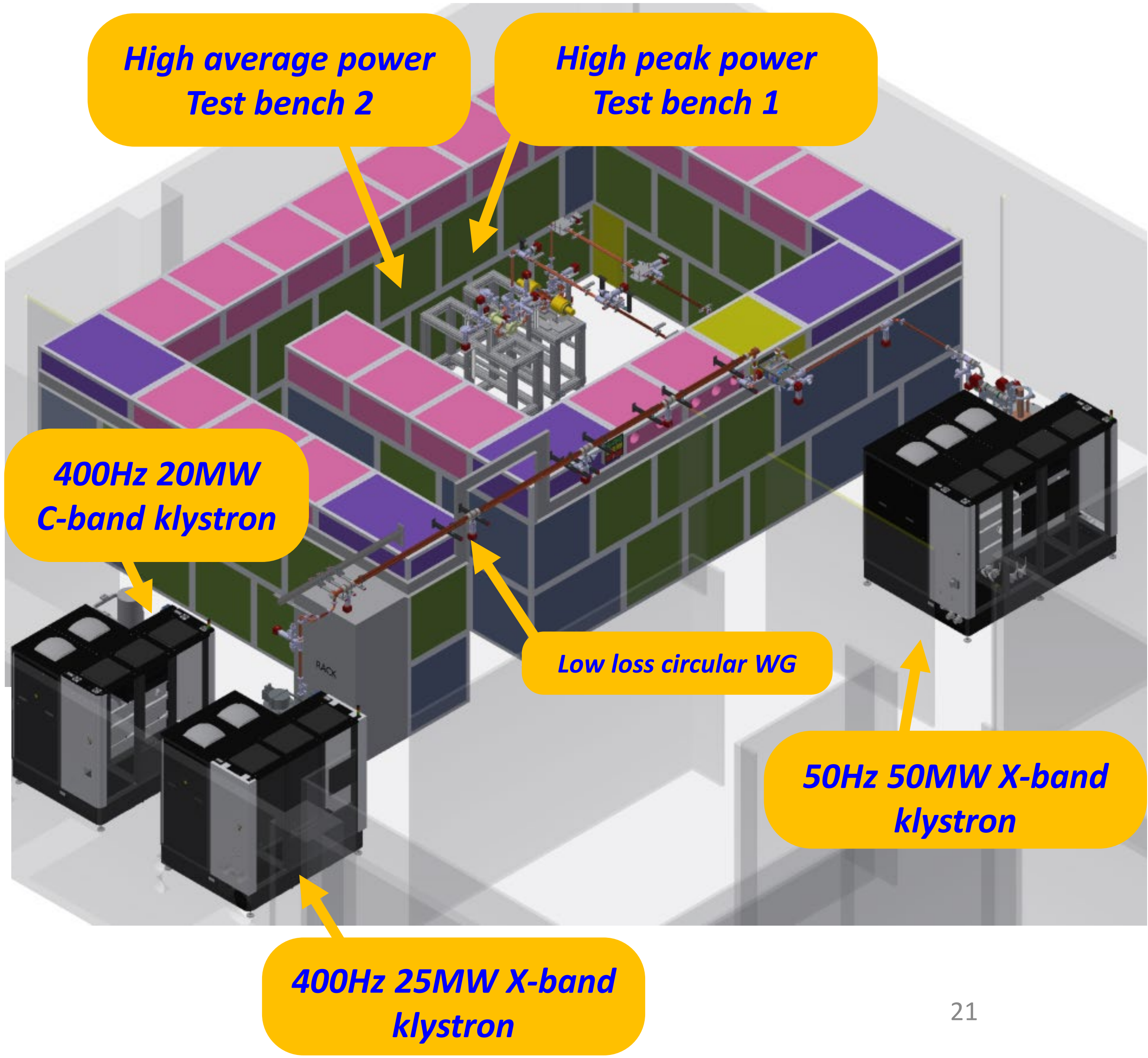
Installation at TEX

TEX Upgrade (2)

- The 2nd **test bench will double the TEX X-band testing capabilities** and will allow for high average power test of X-band components.
- The 1st test bench has been moved and the waveguide network modified.
- **All the waveguide system has been already designed and procured and his installation is ongoing**:



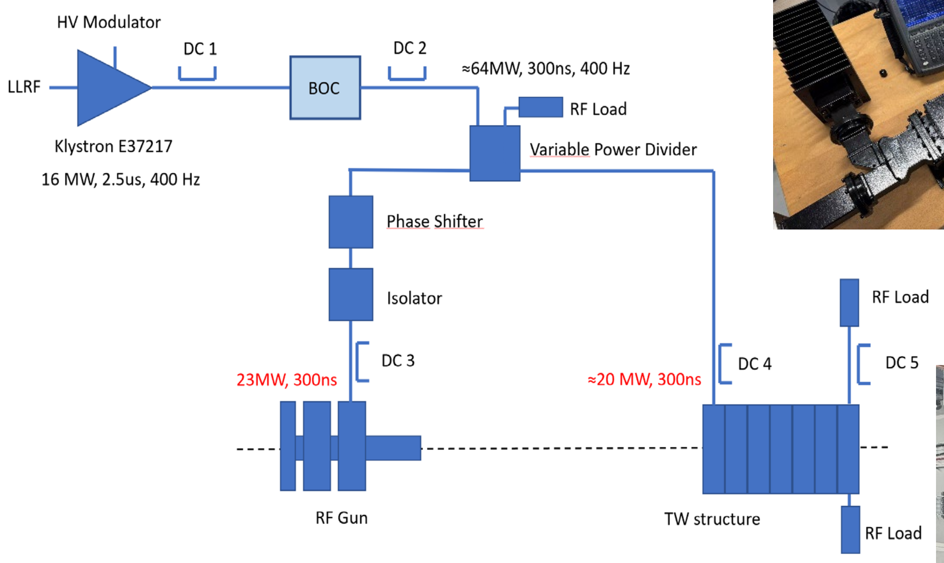


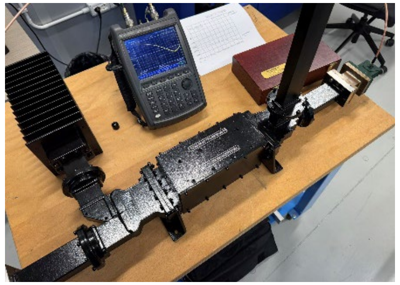


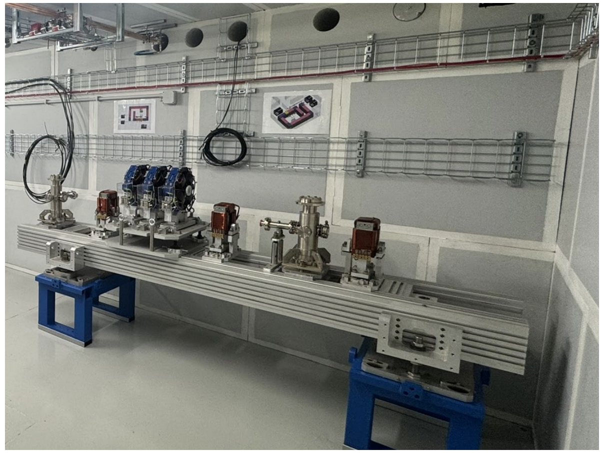
C-band Gun and FRINGE photoinjector

- The **C-band source** will be used to **power and test at high repetition rate a C-band RF photogun** realized in the framework of the IFAST project.
- In a second phase it will be integrated with a traveling wave (TW) structure to form a **compact photoinjector** and will be used for the generation of **high brightness beam and experimental studies**.
- This will be a **first test facility for a full C-band injector** operating at 400Hz for the EuPRAXIA@SPARC_LAB project.

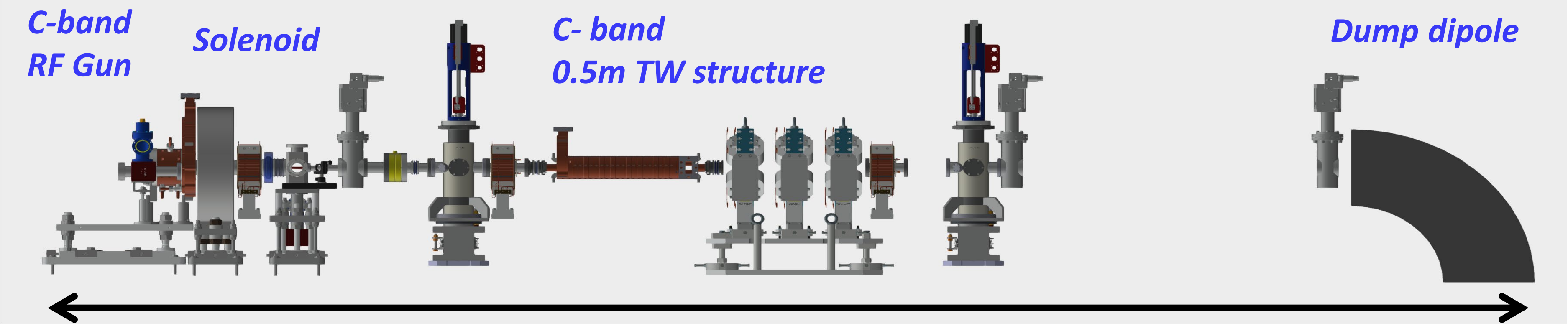
RF wg layout







Photoinjector Preliminary Layout



< 5 m

Preliminary working ponts:
- Laser pulse length 100 fs
- Bunch charge 750/250/50 pC
- Bunch length 300 um rms
- Emittance 3.5/0.5/0.3 mm-mrad

Courtesy of E. Di Pasquale, L. Faillace, S. Pioli, A. Giribono, G. Costa and L. Spallino.

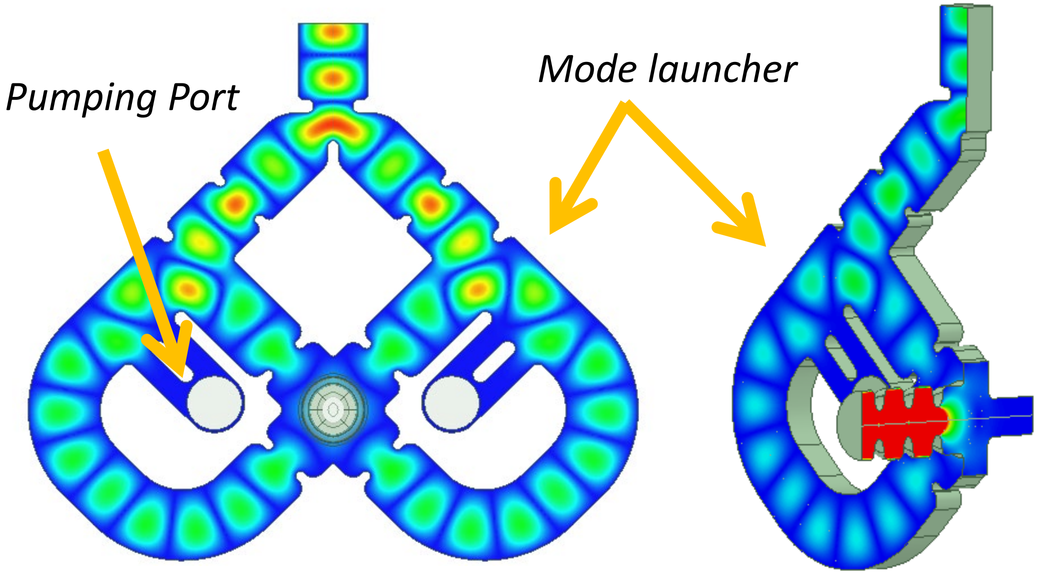
IFAST high gradient C-band Gun

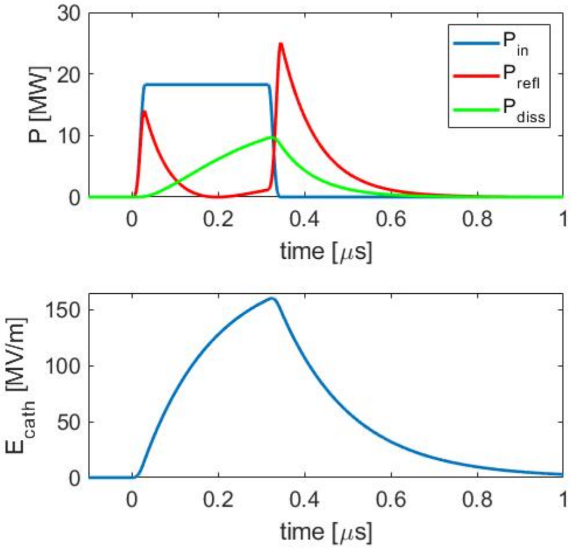
C-band (6 GHz) RF Gun enables **higher achievable cathode peak fields** (>120MV/m) and due to its **increased efficiency**, is also suitable for high repetition rates operation (1 KHz). This should lead to **better quality of the generated beam**.

C-Band RF gun design and realization has been funded by the **European I.FAST project and INFN Commission V**

- The **electromagnetic design** has been guided to minimize surface peak fields, Modified Poynting vector and Pulsed heating
- **Mechanical realization** with Hard copper and clamping technology: Reduced costs and risks of failure, Low BDR, Low conditioning time

Parameter	Unit	Value
Frequency	MHz	5712
Peak input power	MW	23 (19)
Cathode peak field	MV/m	180 (160)
Rep. Rate	Hz	100 (400)
Quality factor		11900
Filling time	ns	166
Coupling coefficient		3
Rf pulse length	ns	300
E_{surf}/E_{cath}		0,96
Mod. Poy. vector	W/um^2	3.2 (2.5)
Pulsed heating	°C	20 (16)
Average diss. Power	W	320 (1000)





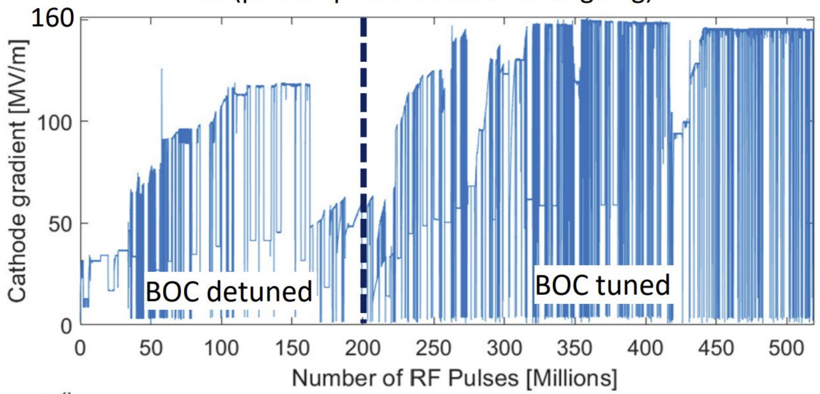
D. Alesini et al., MOPOMS021, IPAC2022, Bangkok, Thailand, p. 679, 2022
D. Alesini et al., TUPA009, IPAC2023, Venezia, Italy, p. 1356, 2023
A. Giribono et al., PRAB 26, 083402, 2023
F. Cardelli, Nuovo Cimento issue 5 (2024)

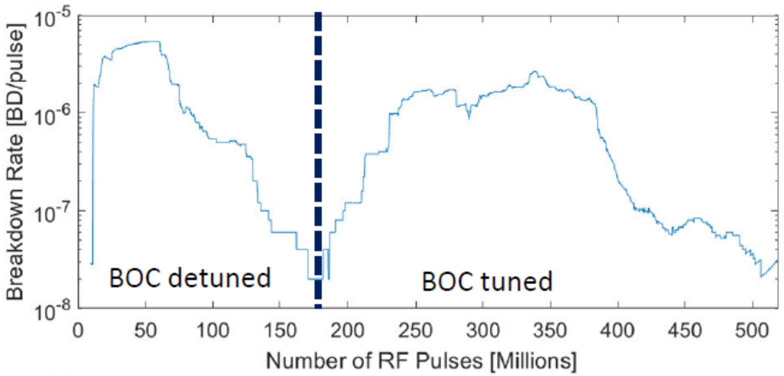
C-band gun high Power test at PSI

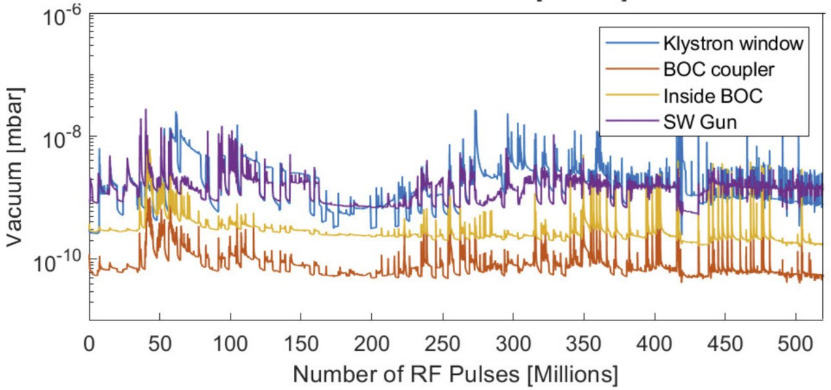
The whole system has then been transported to **PSI and installed in the High Power Test Stand.** RF conditioning began in **February 2024**. The conditioning was done in a semi-automatic way at a repetition rate of **100 Hz.** Conditioning dominated by the vacuum activity in the **waveguide.** Final maximum input power limited by a vacuum **activity in the ceramic of the Klystron.** The cathode peak field reached is about **160 MV/m.**

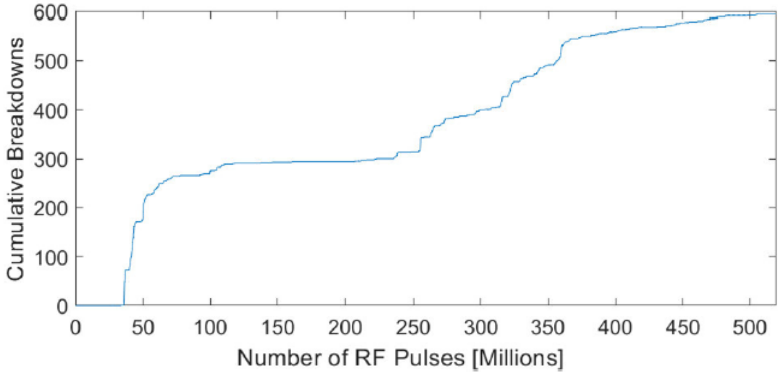
In **January 2025** the Gun will be shipped back to LNF and installed in the TEX bunker. Once the C-band RF source will be commissioned the conditioning of the Gun will continue increasing the cathode peak field up to 180 MV/m.

± 5% (precise power calibration ongoing)

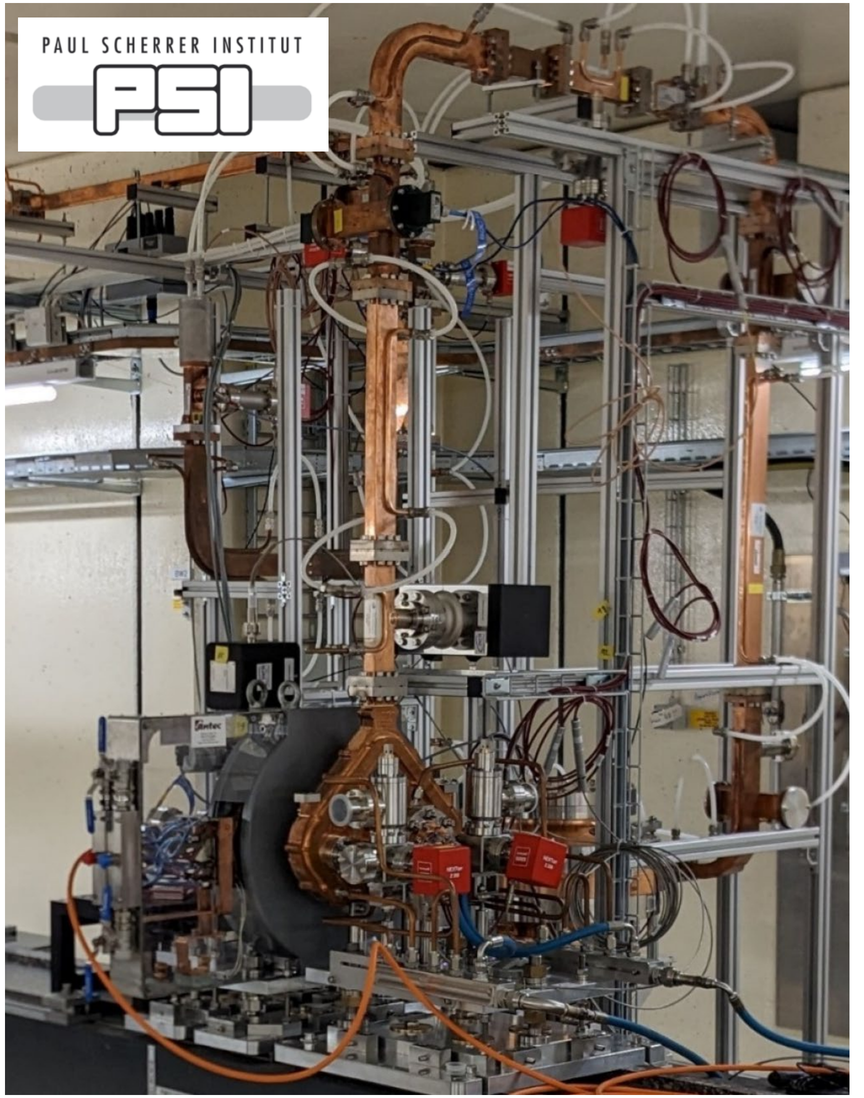






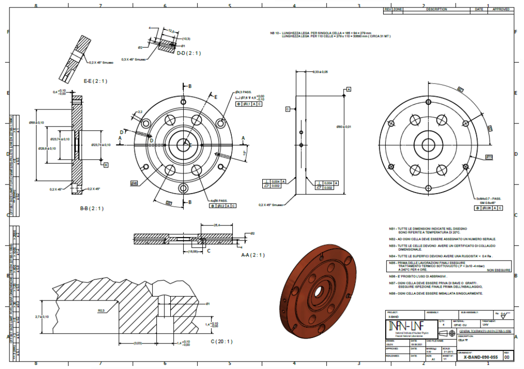


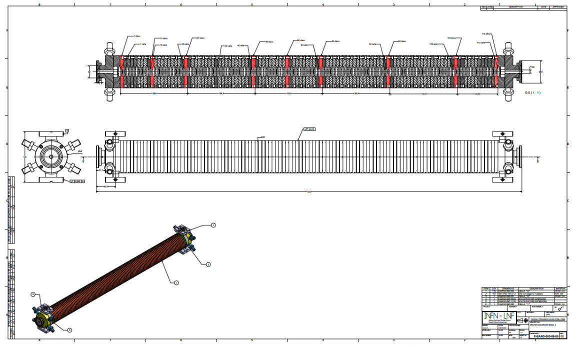
RF Gun Installed @PSI (Switzerland)

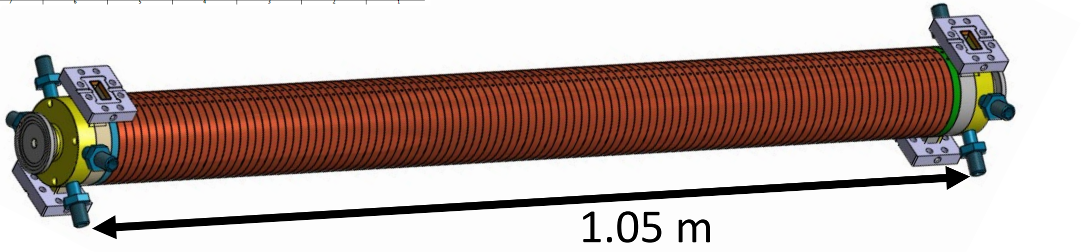


X-band Accelerating structures design

- The **EM design of the structure is completed**: **1.05 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: ***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***







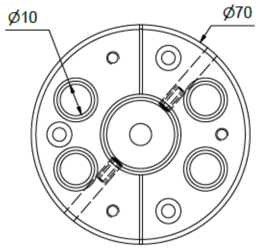
PARAMETER	Value: Quasi-Constant Gradient	Value: Constant Impedance
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85 - 3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length [m]	**1.05**	
No. of cells	112	
Shunt impedance 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 aver. 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**	

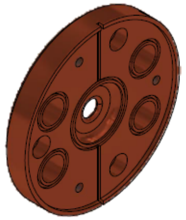
M. Diomede et al. NIM A 909 (2018) 243–246

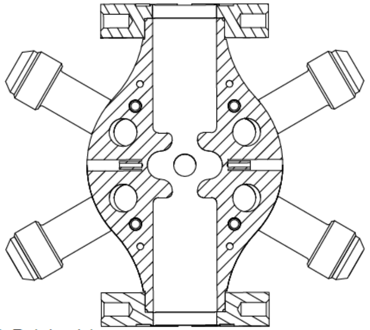
Structure Prototyping

Four main steps of prototyping:

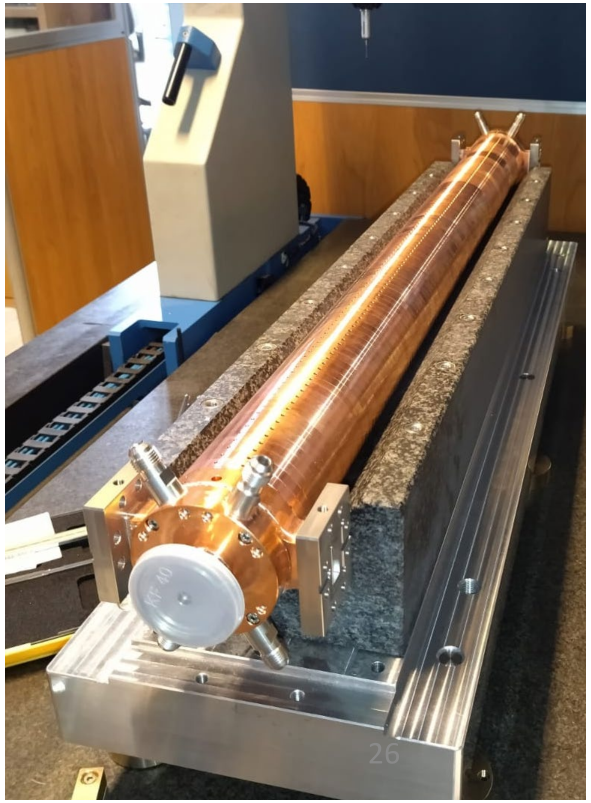
- **Pre-prototypes** on 3-cells and simplified couplers to test and optimize the brazing procedure, cells assembly, alignment etc: ***done***
- **Full scale mechanical prototype**: 1.05 m prototype to test the overall brazing process of the full structure and the cell-to-cell alignment before and after brazing: ***done***
- **20 (+2) cells RF prototype for high power test** w/o tuning, constant impedance: ***realized, high power test is ongoing***
- **Final full scale EuPRAXIA@SPARC_LAB structure prototype 1.05** m constant impedance: ***ongoing***

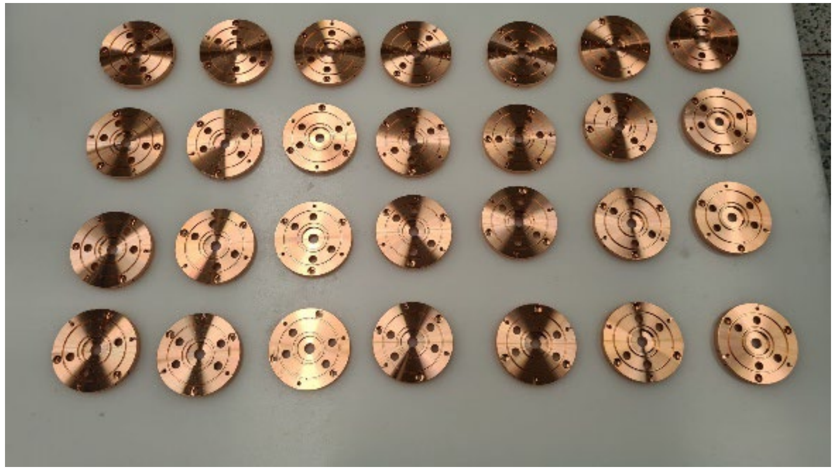


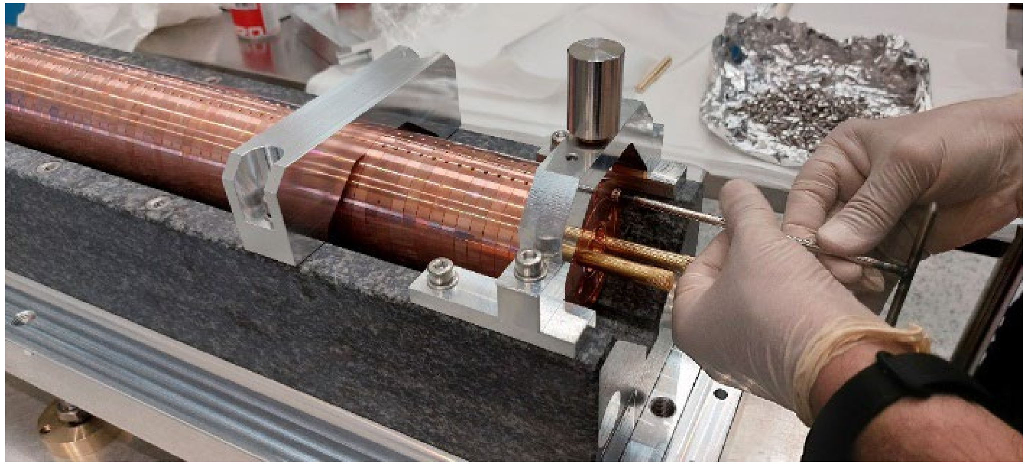




B-B (1 : 1)



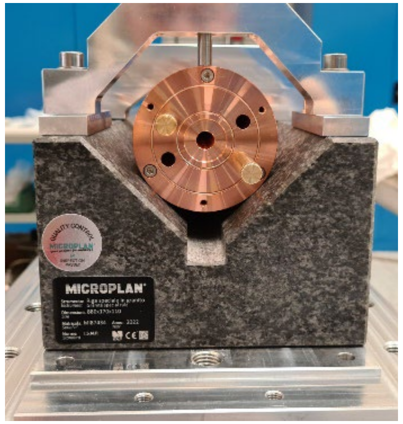




Mechanical Prototype brazing

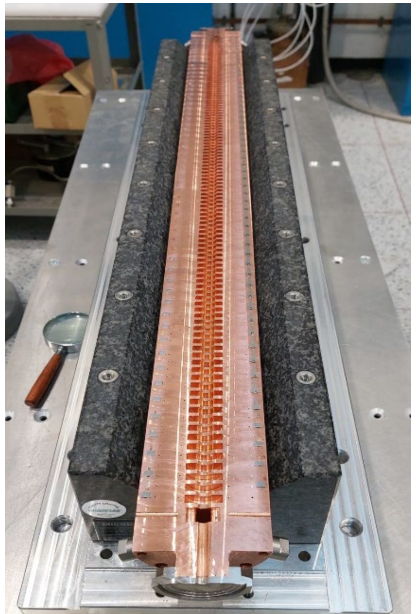
2x Full scale mechanical prototype for brazing optimization and test

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

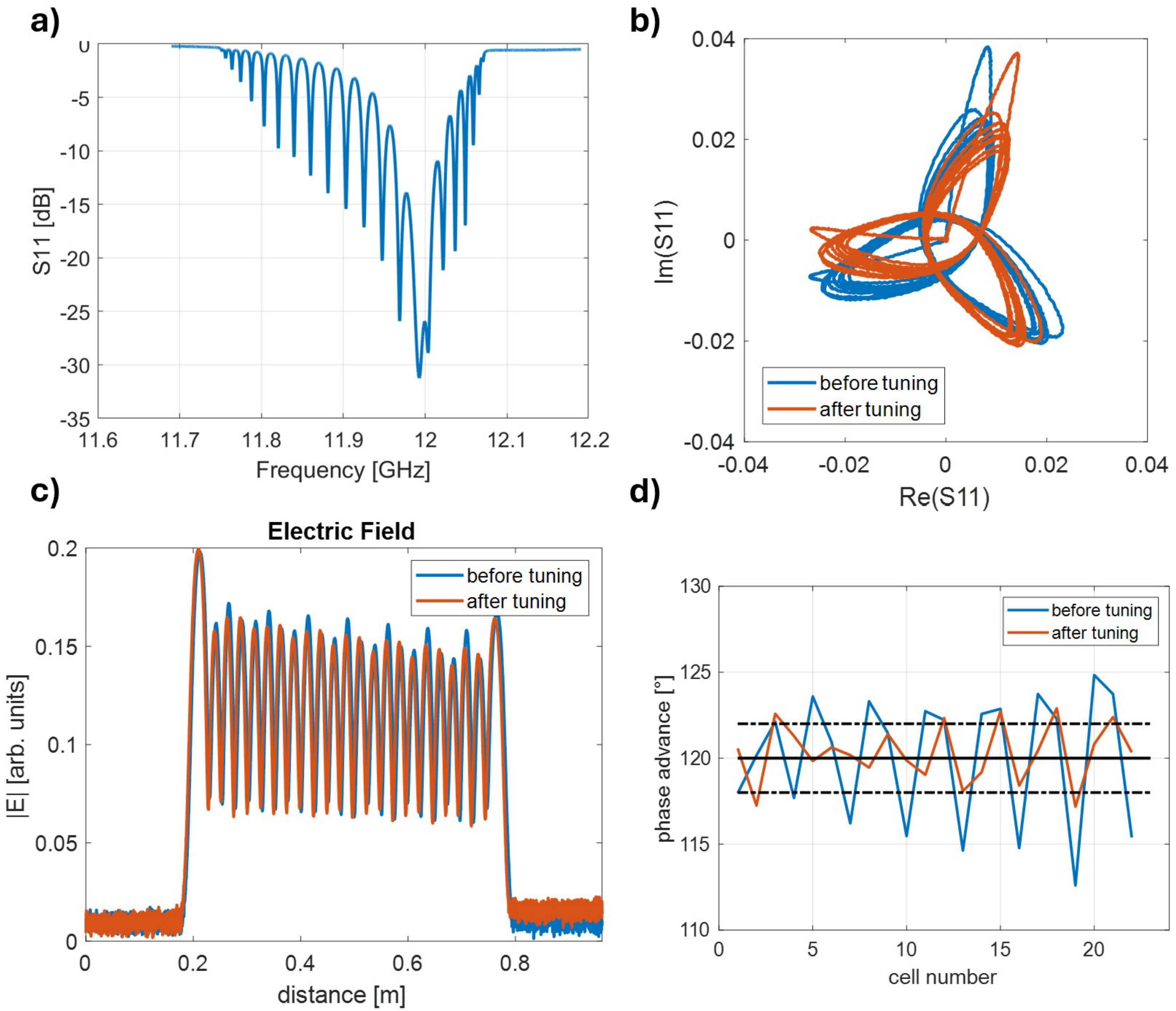
- **Vacuum test OK** (except one coupler for a miss-positioning of the brazing alloy)
- **Straightness <±15 μm** obtained after brazing on both the prototypes (±30 μm required by BD)

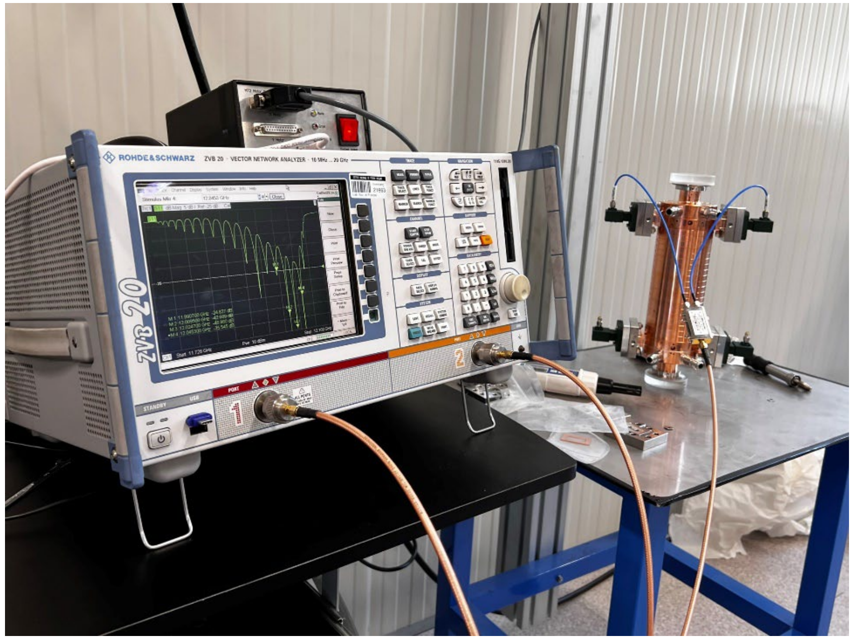


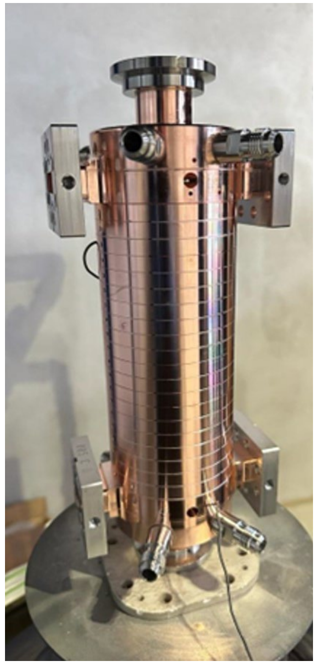
RF prototype

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

- It has been realized without tuners on the cells, we just have a couple of tuners on the two couplers
- We perform low power measurements before cells brazing (thank to the screws), after the brazing and then aftert the tuning of the couplers.
- During the measurements and the tuning procedures the structure has been continuosly fluxed with nitrogen.
- All the cells seems to be smaller (2-3 um on the diameter) to obtain the best response from the cells we will increase the working temperature → **T_{cav} = 30 – 35 °C**



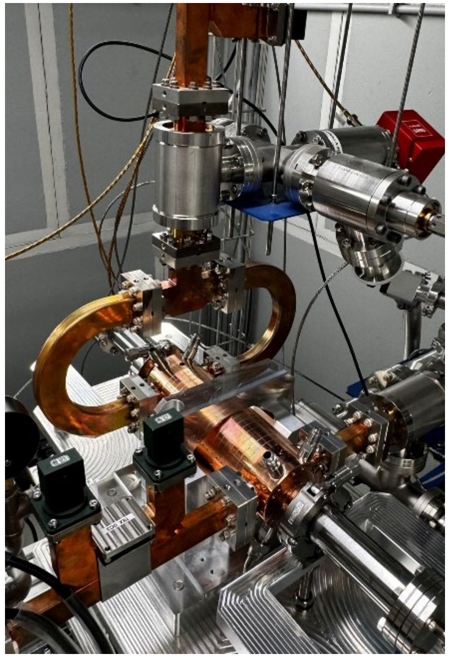


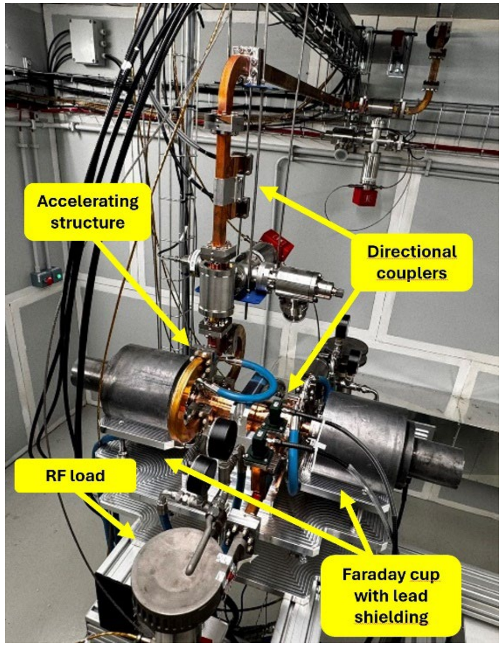


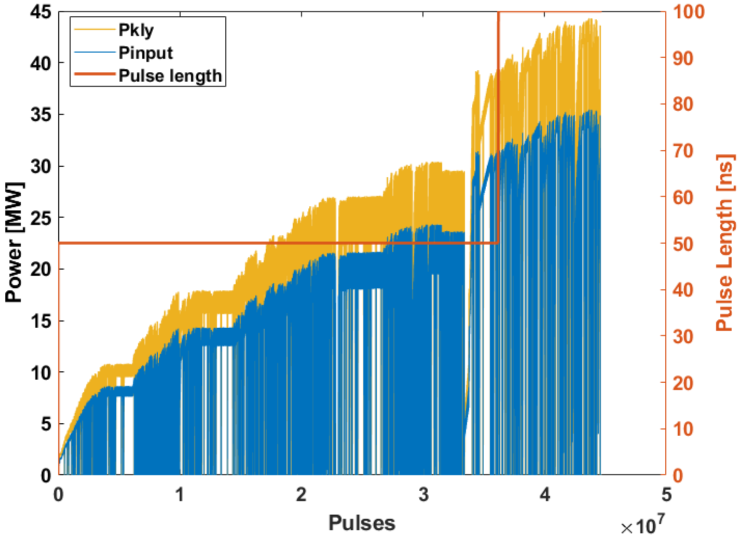
RF prototype high power test

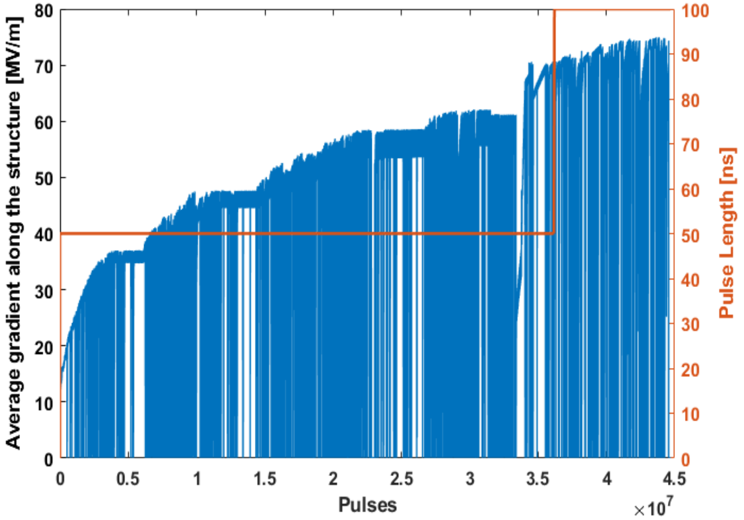
- In March 2024 we perform the **high-power test of the first EuPRAXIA@SPARC_LAB X-band structure prototype**.
- 20 cells, constant impedance, RF prototype (the real structure will be 1 m long).
- In 10 days we reach an input pulse of **35 MW, 100 ns length at 50 Hz repetition rate**, that correspond to an **average gradient** along the structure equal to **74 MV/m** and a peak gradient at the structure input of 80 MV/m with a BDR nearly 1e-5.
- **The test will continue, after the TEX upgrade**, with the BOC pulse compressor installed on the line.
- **The realization of a full-scale RF prototype is ongoing**.

DESIGN PARAMETER	Value
Frequency [GHz]	11.9942
Average acc. gradient [MV/m]	**60**
Structures per module	2
Iris radius a [mm]	**3.5**
Struct. length L_s act. Length [m]	**0.2**
No. of cells	20
Shunt impedance R [MΩ/m]	100
Effective shunt Imp. R_{sh_eff} [MΩ/m]	347
Filling time [ns]	30
Repetition Rate [Hz]	**100**









THANK YOU FOR YOUR ATTENTION

Aknowledgements:

INFN: *D. Alesini, M. Bellaveglia, S. Bini, B. Buonomo, S. Cantarella, G. Catuscelli, P. Chimenti, R. Clementi, G. Costa, A. Falone, L. Faillace, M. Ferrario, A. Gallo, A. Giribono, C. Di Giulio, E. Di Pasquale, G. Di Raddo, G. Latini, A. Liedl, V. Lollo, L. Piersanti, S. Pioli, L. Sabatini, B. Serenellini, L. Spallino, C. Vaccarezza, A. Vannozzi, on behalf of the INFN-LNF Accelerator Division and Technical Division*

CERN: *N. Catalan Lasheras, A. Grudiev, P. M. Sanchez, I. Syratchev.*