EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA
Preparatory Phase

Towards 400Hz RF system for EuPRAXIA@SPARC_LAB

Fabio Cardelli INFN-LNF

fabio.cardelli@lnf.infn.it

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

Outline

1. **Challenges of operating at high repetition rate**
2. **Status of the RF system for the Linac**
   - X-band module layout and components
   - TEX (TEst stand for X-band)
3. **RF Sources status and high rep. rate option**
   - 400Hz X-band test stand at TEX
4. **X-band structure at high rep. rate**
   - EM and Thermomechanical simulations @400Hz
5. **C-band injector at 400Hz**
   - IFAST C-band high repetition, high gradient RF Gun
   - Electromagnetic and Thermo-mechanical analysis
   - Possible RF Scheme for EuPRAXIA and C-band photoinjector test facility at TEX: FRINGE
6. **Conclusions and perspectives**

High Repetition Rate Operation

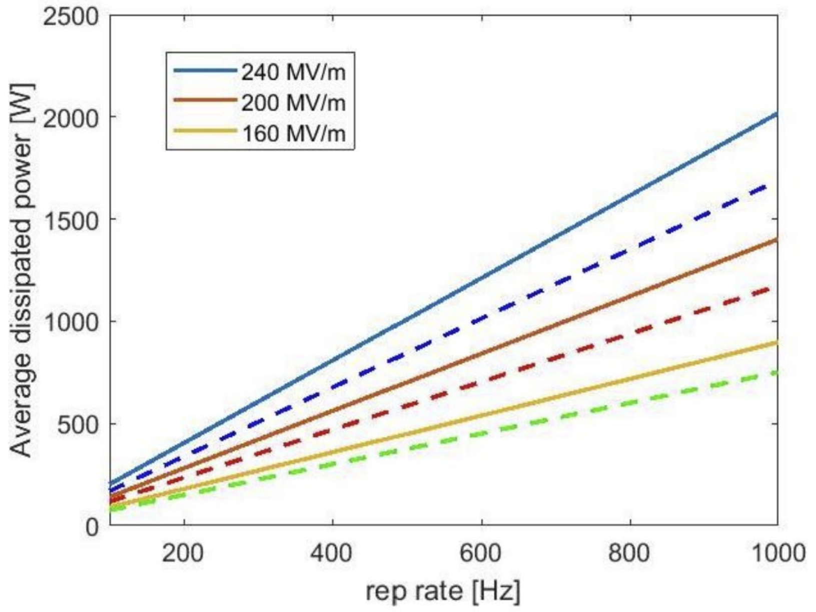
Main challenges:

- **High average dissipated power** in the RF components and structures. It must be managed with a proper cooling system design and specifications to avoid:
  - Structure **detuning** → efficiency loss and reflected power to the sources
  - Higher **outgassing** rate due to increased temperature → vacuum degradation → higher breakdown (BD) probability

- Klystron power available at high repetition rate (limited by the maximum power that can be released and dissipated on the collector). This limits the **availability of commercial Klystrons at high repetition rates** (>100Hz) and high peak power

- High average dissipated power in the RF source (Klystron and Modulator) if not controlled lead to **excessive heating**
  - High **stress on components** → reduced lifetime

- **Fast real-time RF diagnostics and LLRF** are needed to monitor pulse-to-pulse behavior and prevent continuous pulsing in case of an interlock (e.g. discharge)

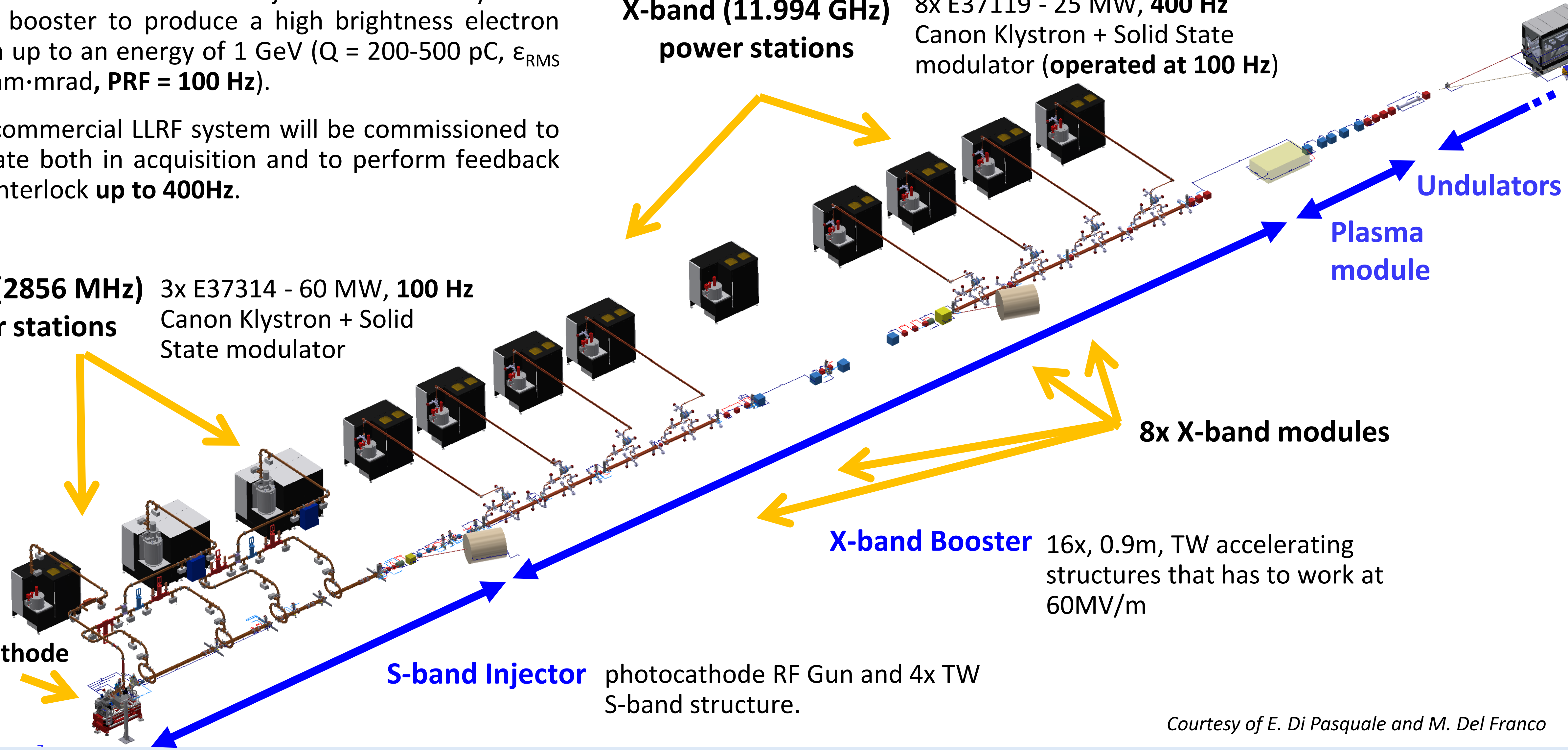


Cont. Line: t_p=200 ns
Dashed Line: t_p=100 ns

Great attention must be paid to the **design and sizing of the cooling circuits** for individual components and devices, as well as the **cooling systems infrastructure** (i.e. dry coolers, chillers, cooling towers etc)

Status of the RF 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 = 100 Hz**).
- The commercial LLRF system will be commissioned to operate both in acquisition and to perform feedback and interlock **up to 400Hz**.

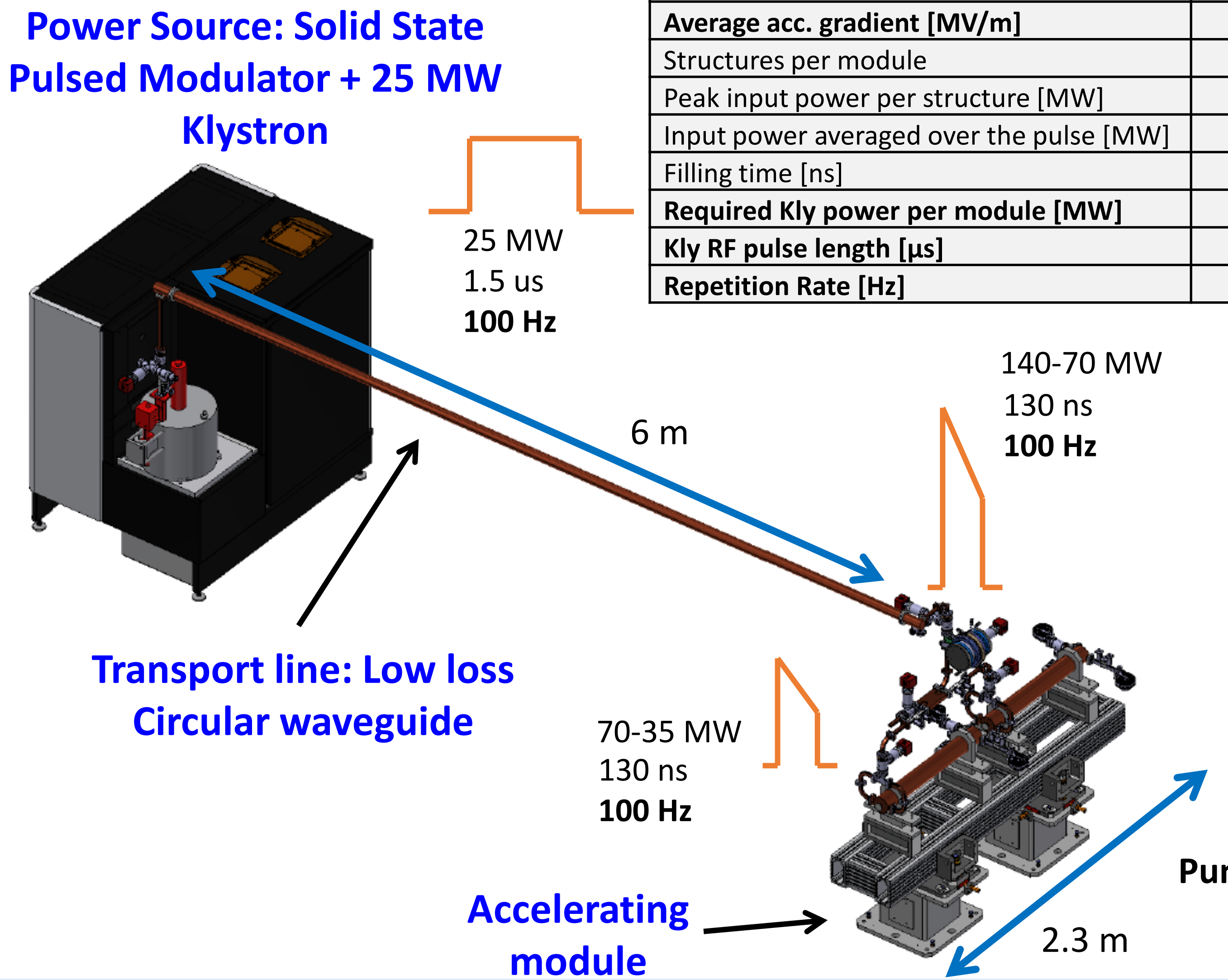


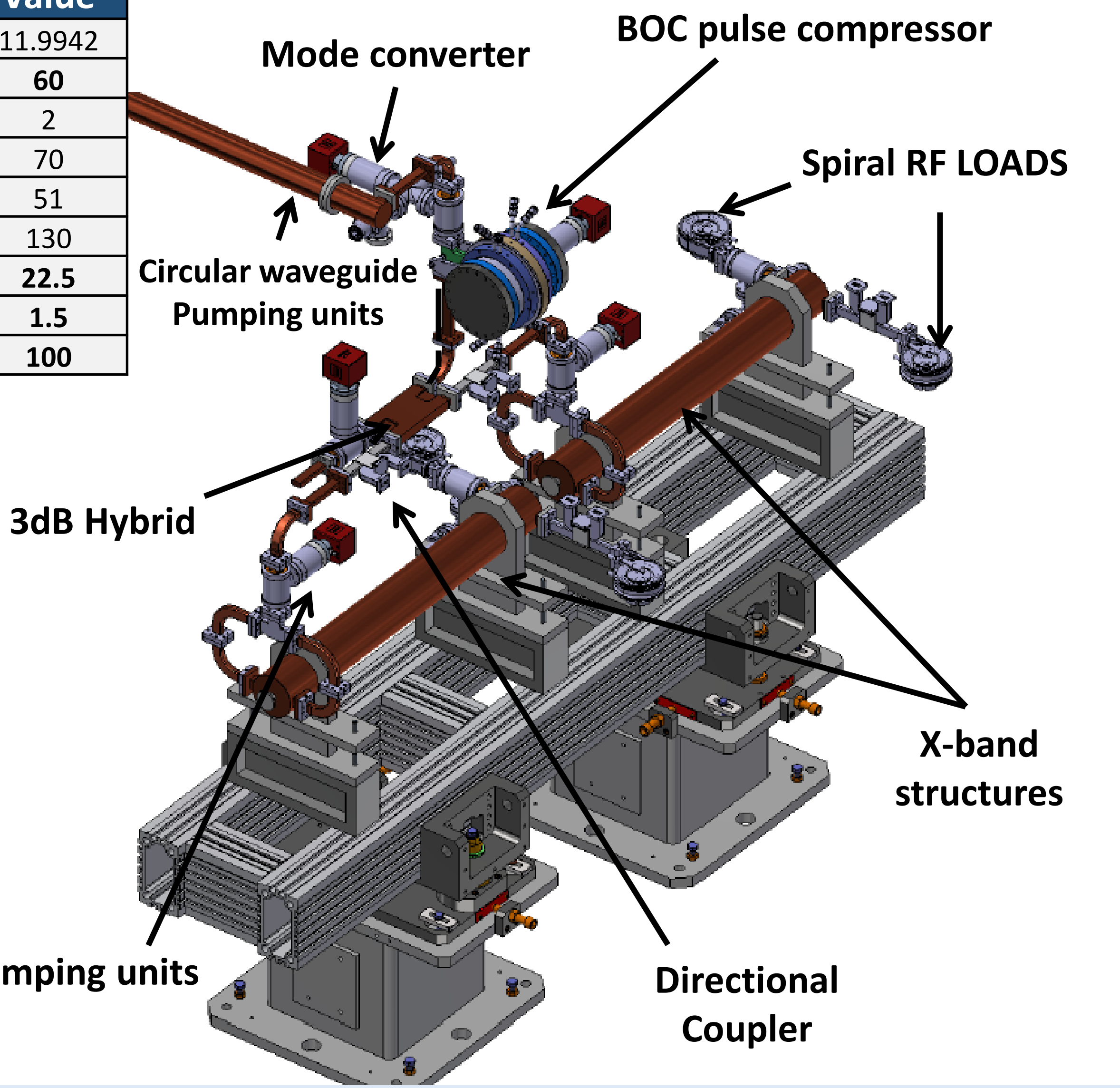
Courtesy of E. Di Pasquale and M. Del Franco

X-band RF Module Layout

Funded by the European Union

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 components

» Some of the X-band components needed for the EuPRAXIA module are based on CERN design (i.e. **directional couplers, pumping units, splitter, 3dB hybrid, RF loads**) Other has been designed at INFN and manufactured by Italian companies (i.e. **rectangular to circular mode converters, T-pumping unit for circular waveguide**). All of them have been manufactured and/or purchased

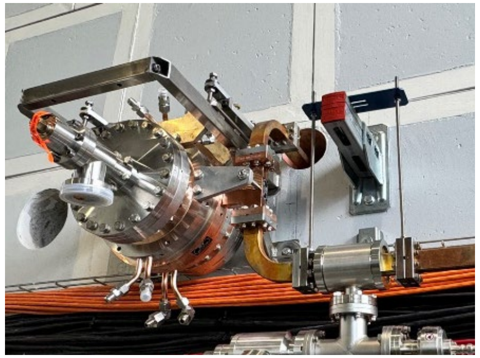
» The **X-band BOC pulse compressor** has been purchased from PSI and integrated in the test facility in July 24

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/INFN	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

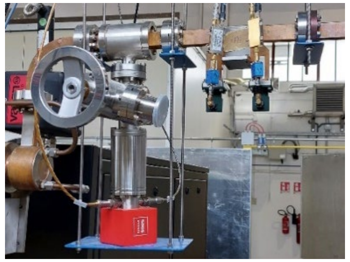
Mode converter and T-pump for circular wg

RF loads

BOC pulse compressor



DC and pumping unit



3dB Hybrid

TEX (Test stand for X-band) 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, Beam Diagnostics, Vacuum system and Control System

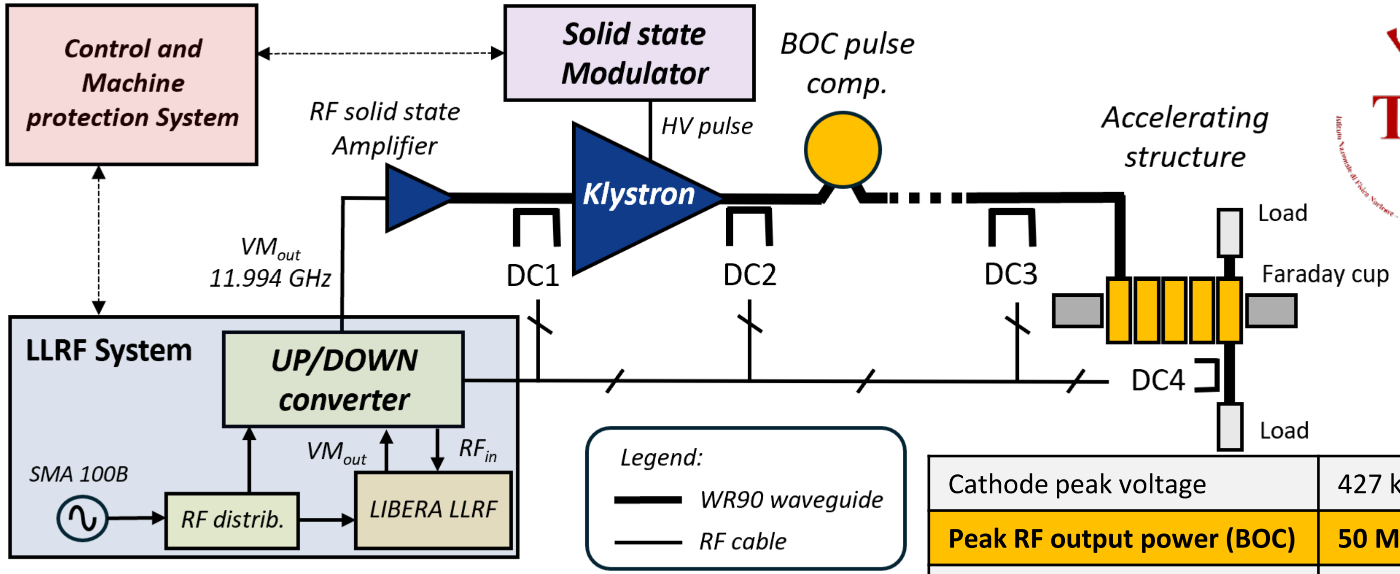
» It has been co-funded by Lazio region in the framework of the **LATINO project** (Laboratory in Advanced Technologies for INnOvation). The setup has been done in **collaboration with CERN** and it will be also used to test **CLIC structures**

» The installation and commissioning of the whole system have been completed by the end of 2022.

» **Then started the testing activity:**

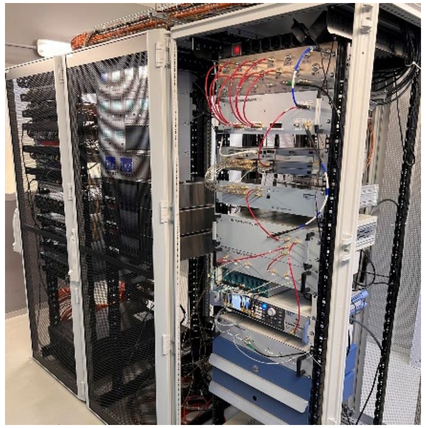
Period	Device tested at high power
Jan. - Feb. 2023	**3D printed Spiral RF loads** and wg
May - Oct. 2023	X-band **T24 CLIC structure (CERN)**
Nov. - Dec. 2023	X-band **Mode converter** and **circular wg**
Jan. - Feb. 2024	X-band RF **waterload (PSI)**
March 2024	**20 cells first EuPRAXIA RF prototype**

F. Cardelli et al., in Proc. IPAC'22, Bangkok, Thailand. (2022) paper TUPOPT061
L. Piersanti et al. Photonics 2024, 11(5), 413.
F. Cardelli et al., in Proc. IPAC'24, Nashville, TN (2024) paper TUPR02



Cathode peak voltage	427 kV
Peak RF output power (BOC)	**50 MW - 200 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

Bunker

CPI Klystron

EuPRAXIA RF Power Sources

Funded by the European Union

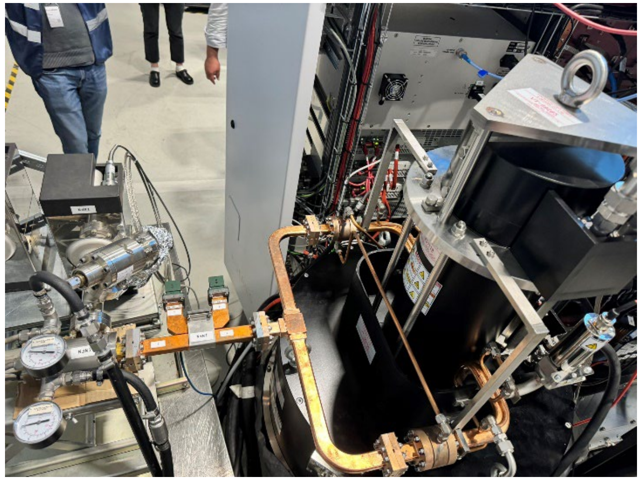
1. **INJECTOR: S-band (2856 MHz) CANON E37314 Klystron**
   - **Installed and tested at ELI facility for SSRIP**
   - High rep. Rate solution: 2.856 GHz CANON E37311 30MW, 3us, 400Hz
   - Facilities with S-band klystron at 400Hz:
     - 2.998 GHz CPI 7.5 MW, 5us, 400Hz @IFIMED (Valencia)
     - 2.998 GHz THALES 10 MW, 5us 400Hz @CLARA (UK)

CANON E37314

Parameter	Unit	Canon E37314	Canon E37119
Frequency	MHz	2856	11994
Vk beam voltage	kV	370	312
Ik cathode current	A	450	199
Peak RF output Power	MW	60	25
Average RF output power	kW	27	15
Modulator Average power	kW	75	80
RF pulse length	µs	4,5	1,5
Repetition Rate	Hz	**100**	**400**
Gain	dB	53	47
Efficiency	%	41	40
Perveance	µp	2	1.2

2. **BOOSTER: X-band (11994 MHz) CANON E37119 Klystron**
   - CPI has a klystron at 25 MW, 1.5 us, 400 Hz
   - 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 at the beginning of 2025** depending on the dry cooler commissioning

FAT of the RF Source



CANON E37119

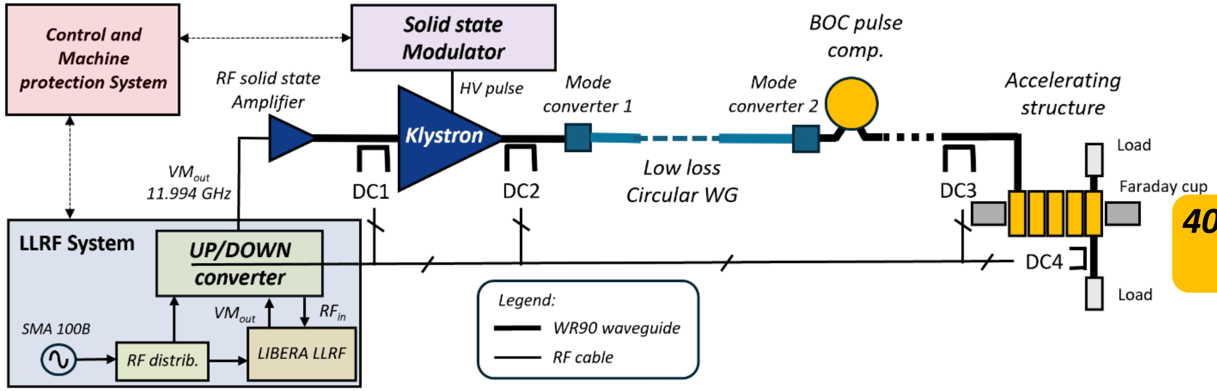
Installation at TEX

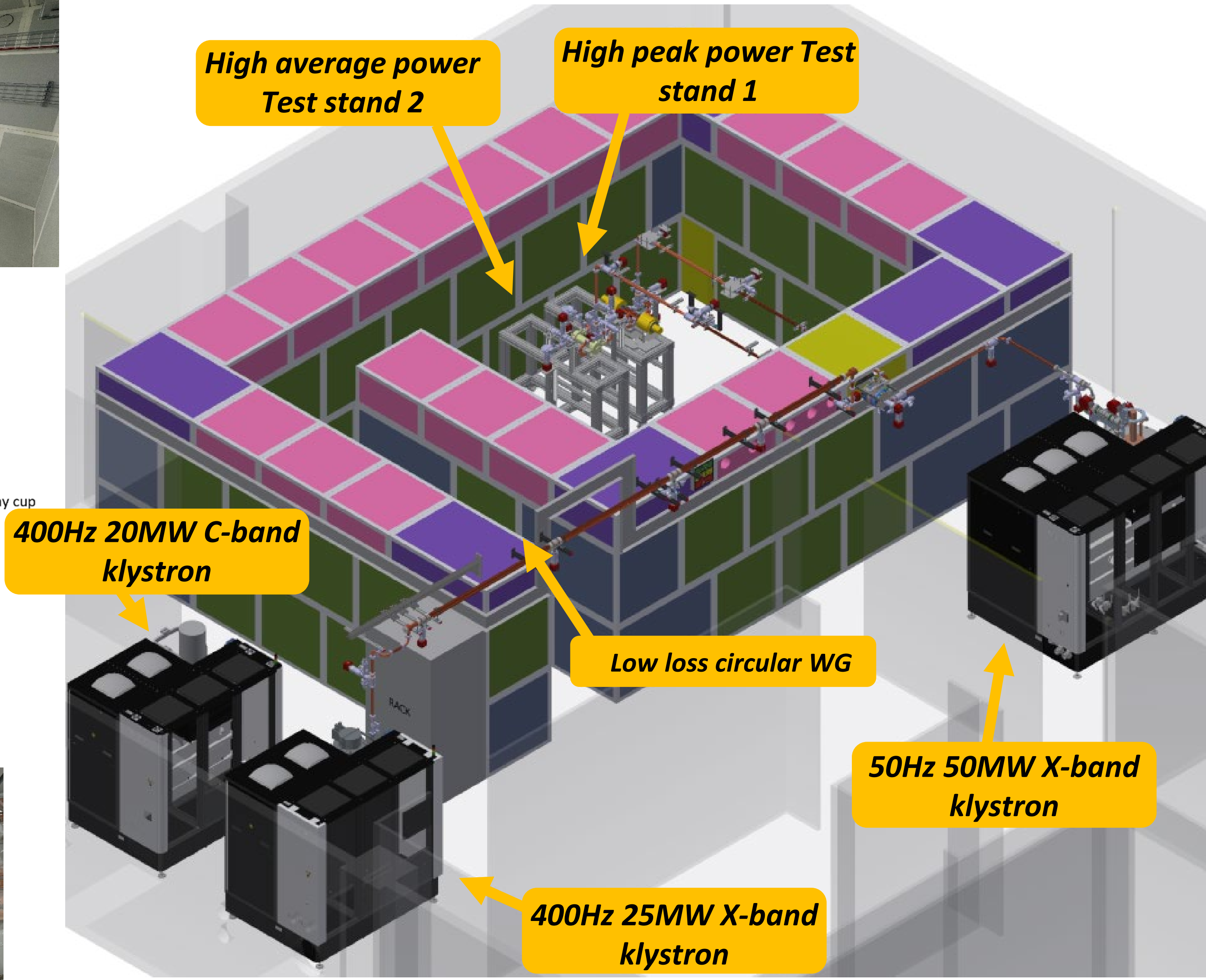
400Hz X-band Test stand at TEX

» This two test stand will **double the TEX testing capabilities**

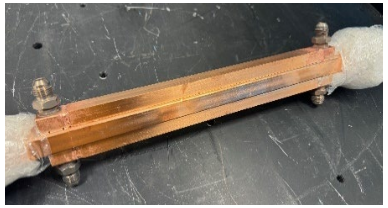
» The 1st test bench has been moved and the waveguide network modified

» **All the waveguide system has been already designed and procured** and will be installed in October-November 2024





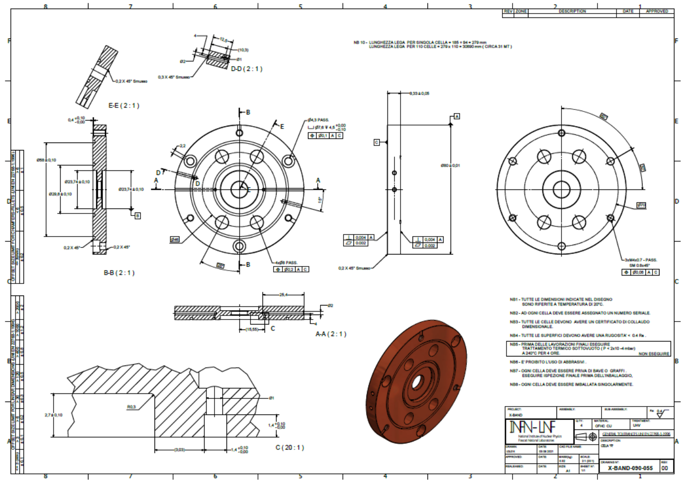
X-band WR90 and Circular waveguide with integrated cooling

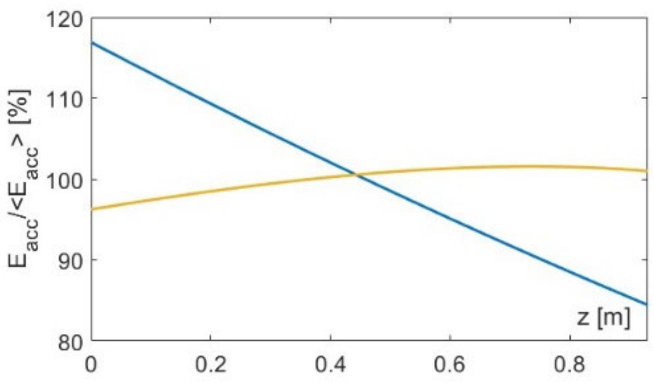


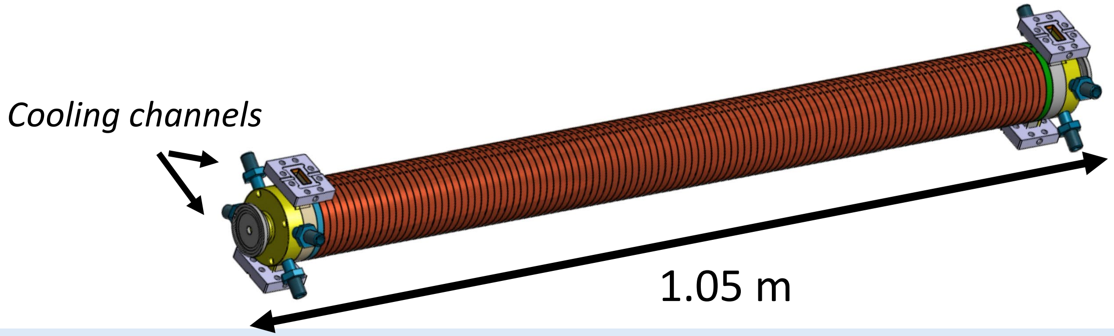
X-band Accelerating Structure

Funded by the European Union

- The **accelerating structure has been completely designed**: **1.05 m flange to flange long** structure with **3.5 mm average iris radius** with an average acceleration gradient of **60 MV/m.**
- A **first 20 cells RF prototype** has been realized and preliminary tested up to 74MV/m. The test will continue on the test stand 1 in October 2024.
- **A full scale 1m RF prototype will be ready by the end of 2024.**







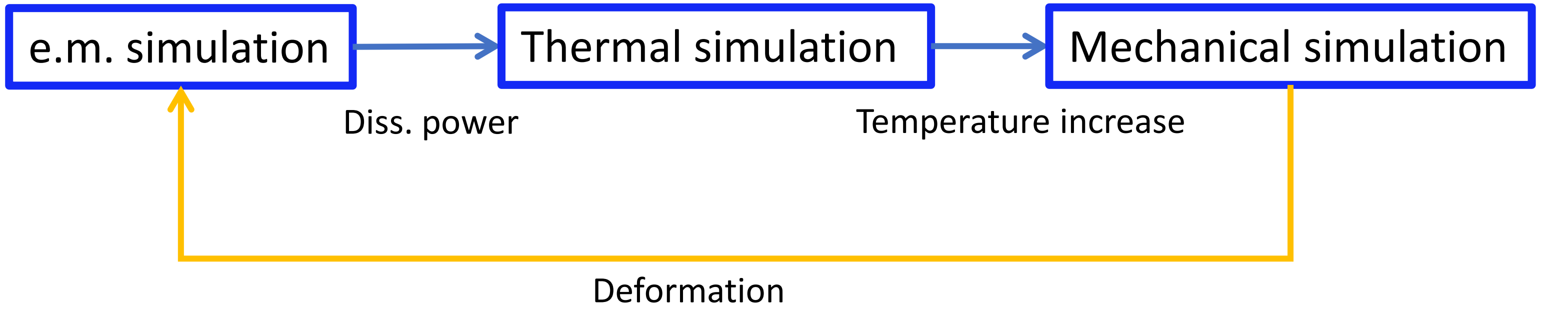
PARAMETER	Value	
	Quasi-Constant Gradient	Constant Impedance
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85 - 3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length [m]	**1.05**	
No. of cells	112	
Shunt impedance R [MΩ/m]	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 (400)**	

EM / Thermo-mechanical analysis

Funded by the European Union

- The integrated cooling circuit was designed to operate at 100Hz and consists of 4 cooling channels with 4 mm radius.
- Working temperature = 25 °C (with RF at 100 Hz)
- When we switch to 400 Hz the thermal load on the structure increases, leading to higher power dissipation and a consequent **rise in temperature**.
- This results in a **deformation of the cell geometry** (particularly the diameter) and thus to a **detuning of the structure** (phase advance per cell variation) and a **loss of efficiency** (lower accelerating gradient).

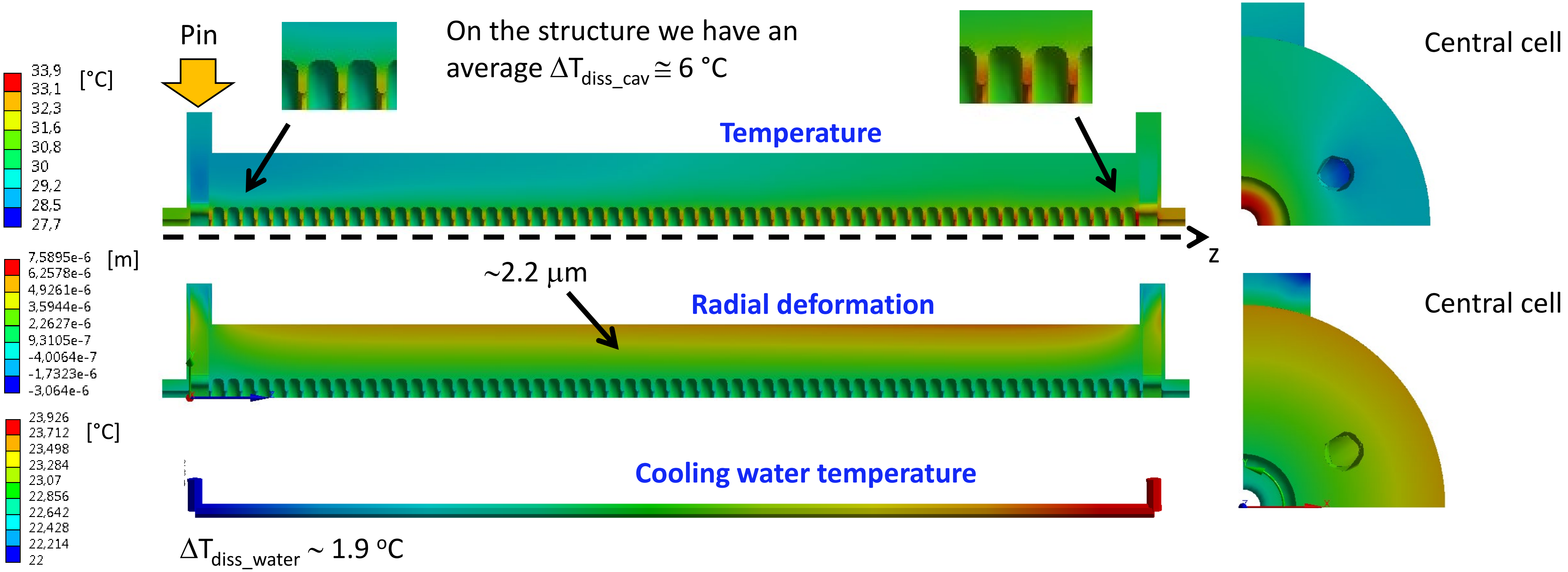
Rep. rate	Average Dissipated Power in the structure	Average Dissipated Power in RF loads
100 Hz	1 kW	0.3 kW
400 Hz	4 W	1.2 kW



- We perform both **analytical calculation and numerical simulations with Ansys**.
- Thanks to these, we assess the impact of the increased power dissipation on the deformation of the structure and thus on the detuning, and whether the cooling circuit can handle the rise in temperature and prevent the loss of efficiency.
- We can calculate **how much we have to reduce the temperature of the water in input** to have an average temperature of the cavity at regime equal to that in the case w/o RF.

Thermo-mechanical analysis (1)

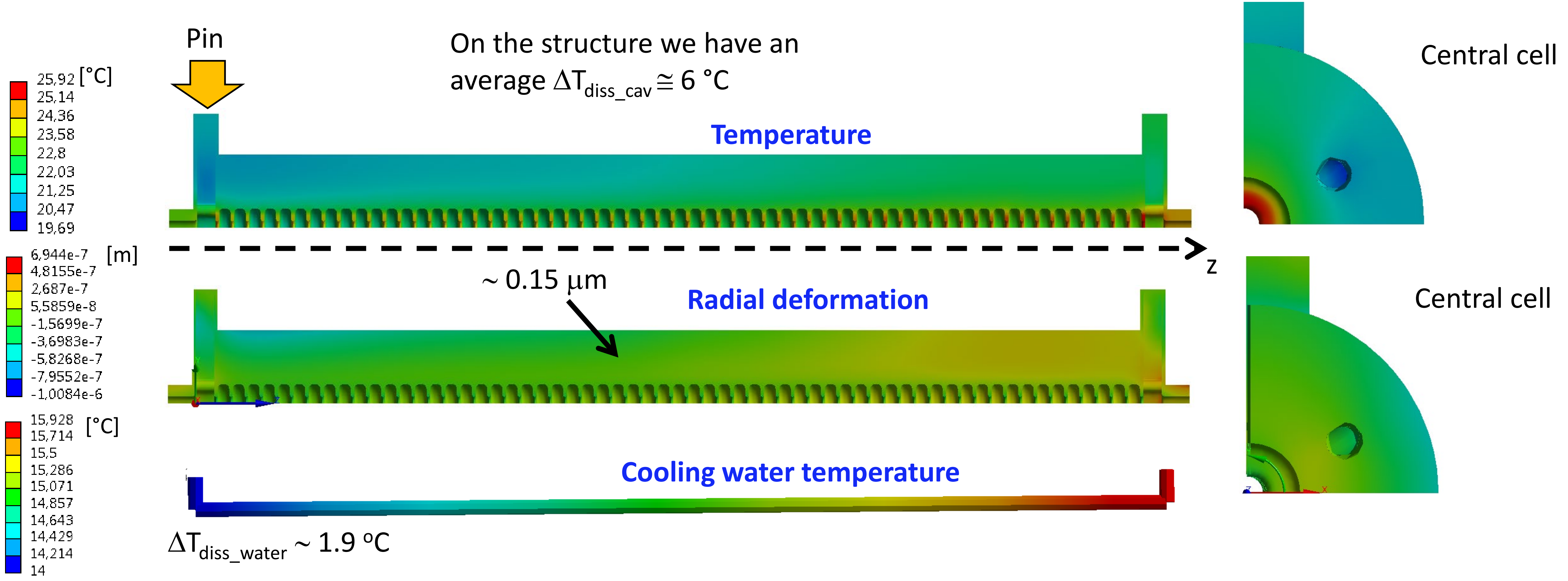
- Uniform dissipated power along the structure at 400Hz
- 60 cells structure
- **16 l/min total flux**
- **T_{water_in}= 22°C = cavity temperature without RF**



Thermo-mechanical analysis (2)

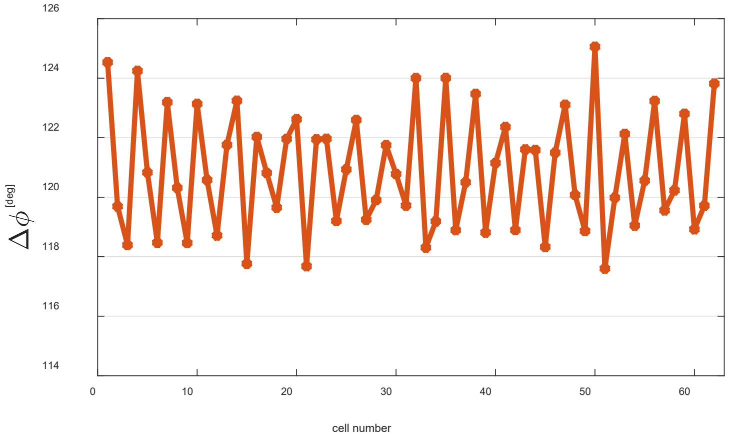
Funded by the European Union

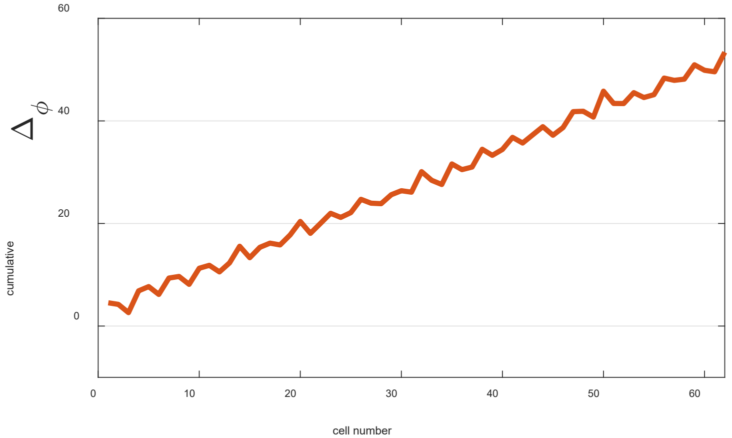
- Uniform dissipated power along the structure at 400Hz
- 60 cell structure
- **16 l/min total flux**
- **T_{water_in}= 22°C - 8°C = 14° C during pulsing**



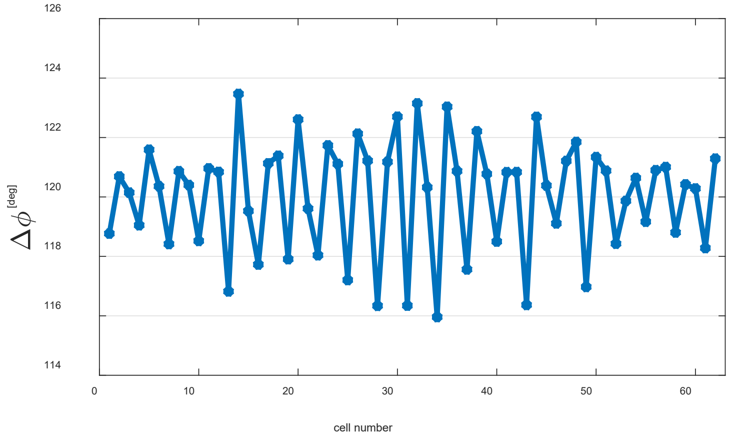
Detuning compensation at 400 Hz

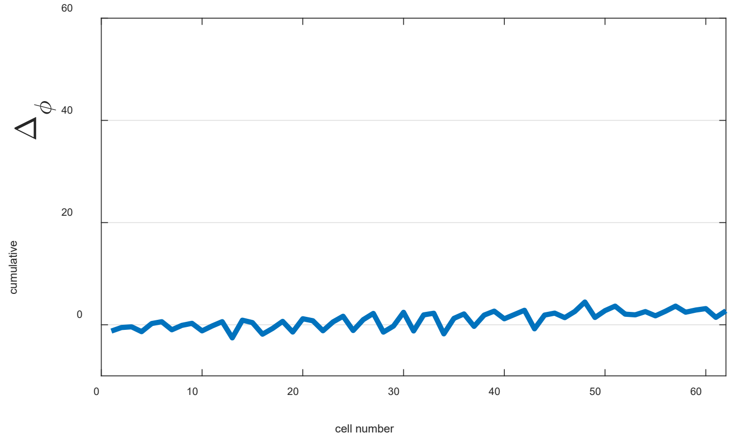
RF on, 400Hz



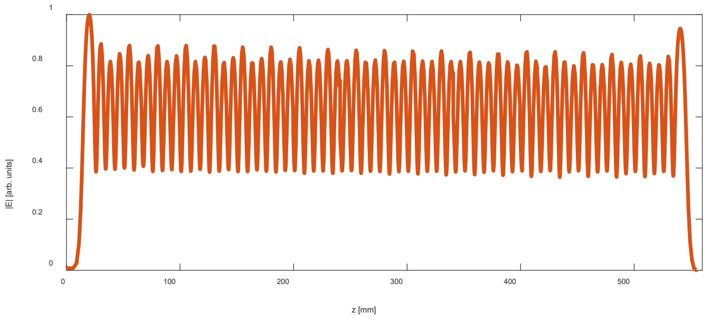


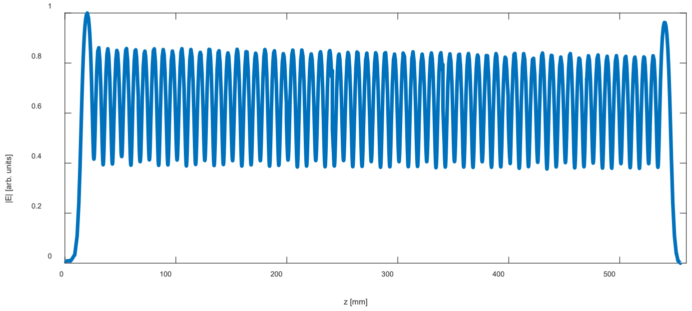
RF on, 400Hz (-8°C)





	100 Hz	400 Hz
Average dissipated power [kW]	1	4
Flow rate [l/min]	16	16
Temperature stability [°C]	≤±0.1	≤±0.1
ΔT water temperature IN-OUT rf on [°C]	1	4
Water temperature (27° with RF off) [°C]	25	19
Pressure drop [bar]	<0.5	<0.5



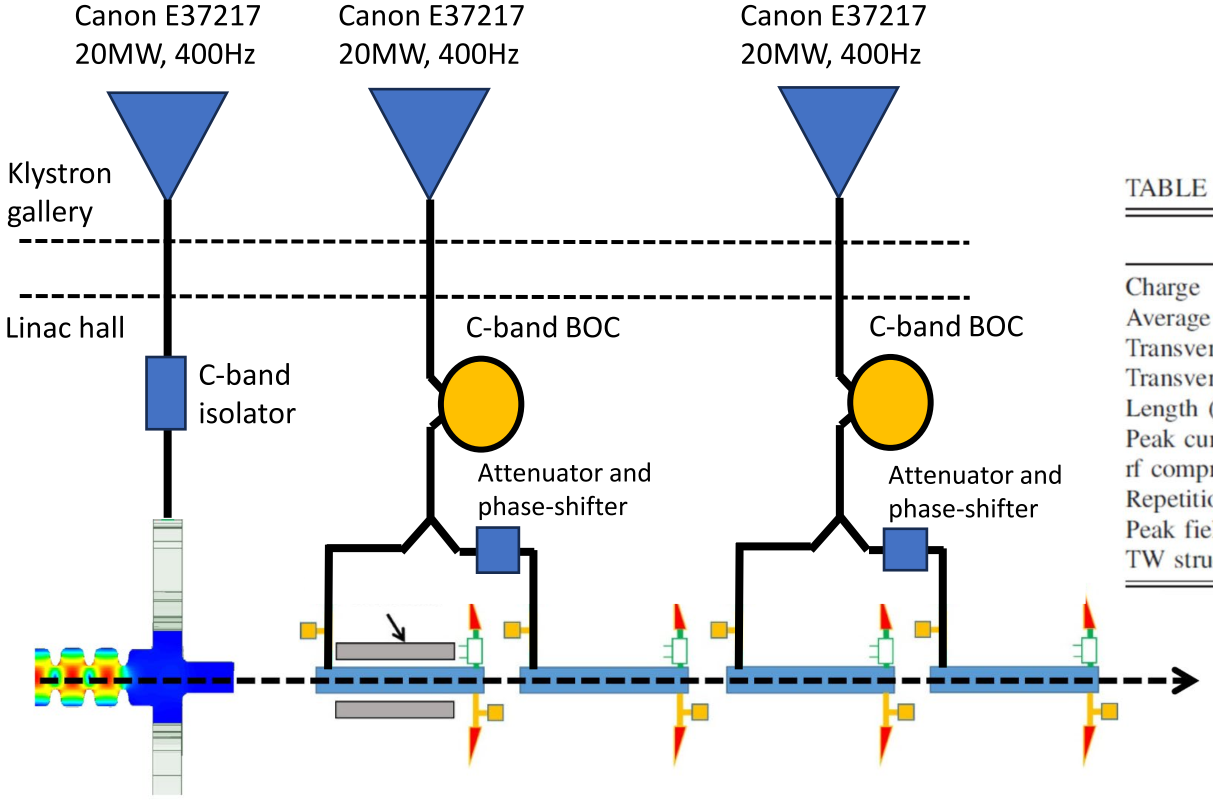


$$\Delta\phi_{cell} = \alpha\Delta T \sum_i \left.\frac{d\phi}{dx}\right|_i x_i \underset{\Delta T=2^\circ C}{\Rightarrow} \Delta\phi_{cell} \cong 0.72\,\mathrm{deg} \Rightarrow \Delta_\phi = \sum_{60} \Delta\phi_{cell} \cong 43\,\mathrm{deg}$$

C-band injector for EuPRAXIA@SPARC_LAB

C-band technology represents a good solution for the development of a high repetition rate, high-performance photoinjector also for the EuPRAXIA@SPARC_LAB project. This is due not only to its achievable **beam parameters** but also to its **potential for operation at high repetition rates**.

Possible RF layout



PHYSICAL REVIEW ACCELERATORS AND BEAMS **26,** 083402 (2023)

Dynamics studies of high brightness electron beams in a normal conducting, high repetition rate *C*-band injector

A. Giribono,[1,*] D. Alesini,[1] F. Cardelli,[1] G. Di Raddo,[1] L. Faillace,[1] M. Ferrario,[1] A. Gallo,[1] A. Gizzi,[1] S. Lauciani,[1] A. Liedl,[1] L. Pellegrino,[1] L. Piersanti,[1] C. Vaccarezza,[1] A. Vannozzi,[1] J. Scifo,[1,2] L. Ficcadenti,[3] G. Castorina,[4] G. Pedrocchi,[5] G. J. Silvi,[5] and T. G. Lucas[6]

TABLE I. List of the working points described in this paper.

	Low charge		Medium charge			High charge		Units
Charge	75	75	200	200	200	500	500	pC
Average energy	125	105	125	250	200	200	125	MeV
Transverse normalized emittance (100%—rms)	0.15	0.18	0.25	0.25	0.37–0.69	1.3	0.65	mm mrad
Transverse normalized emittance (95%—rms)	0.11	0.13	0.18	0.16	0.25–0.45	0.80	0.44	mm mrad
Length (rms)	380	100	500	500	280–55	55	720	μm
Peak current	20	85	40	40	70–500	1000	70	Ampere
rf compression	off	on	off	off	on	on	off	
Repetition Rate	high	high	high	low	low	low	high	
Peak field @cathode	160	160	160	180	180	180	160	MV/m
TW structure accelerating field	15	15	15	31	31	31	15	MV/m

Next talk: High repetition rate C-band Photoinjector (G. Silvi)

IFAST high rep. rate C-band Gun

Funded by the European Union

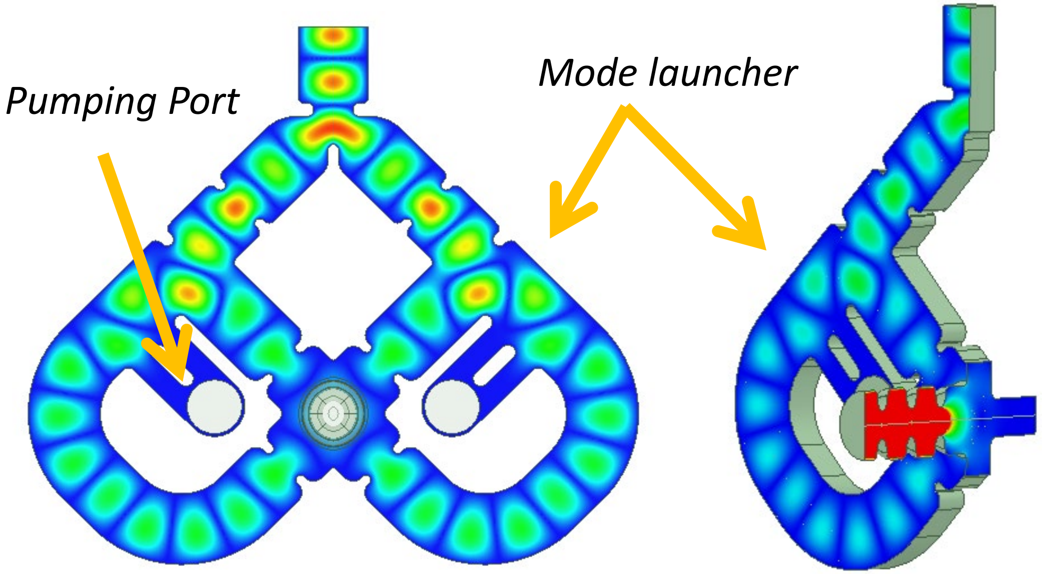
C-band (6 GHz) RF Gun enables higher achievable cathode peak fields (>120MV/m) and due to its increased efficiency, is also suitable for high repetition rates operation (1 KHz)

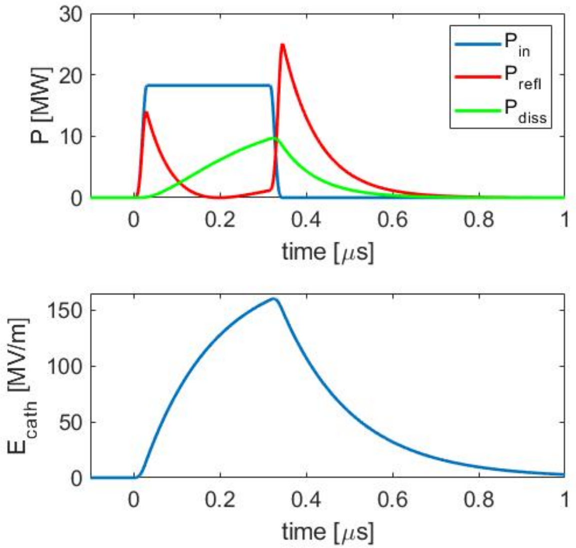
C-Band RF gun design and realization has been funded by the **European I.FAST project and INFN Commission V**

CSN5 Ricerca Tecnologica

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)

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





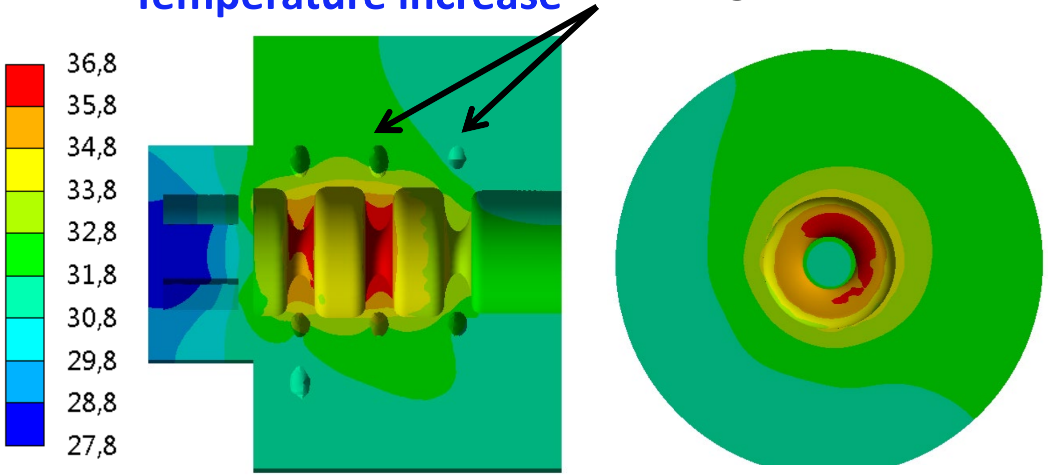
D. Alesini et al., MOPOMS021, IPAC2022, Bangkok, Thailand, p. 679, 2022
D. Alesini et al., TUPA009, IPAC2023, Venezia, Italy, p. 1356, 2023
F. Cardelli et al., MOPOMS020, IPAC2022, Bangkok, Thailand, p. 675, 2022
F. Cardelli, Nuovo Cimento issue 5 (2024)

EM / Thermo-mechanical analysis

Funded by the European Union

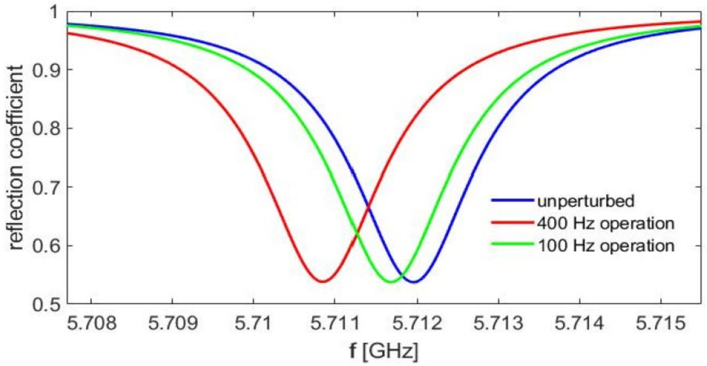
Temperature increase

Cooling channels

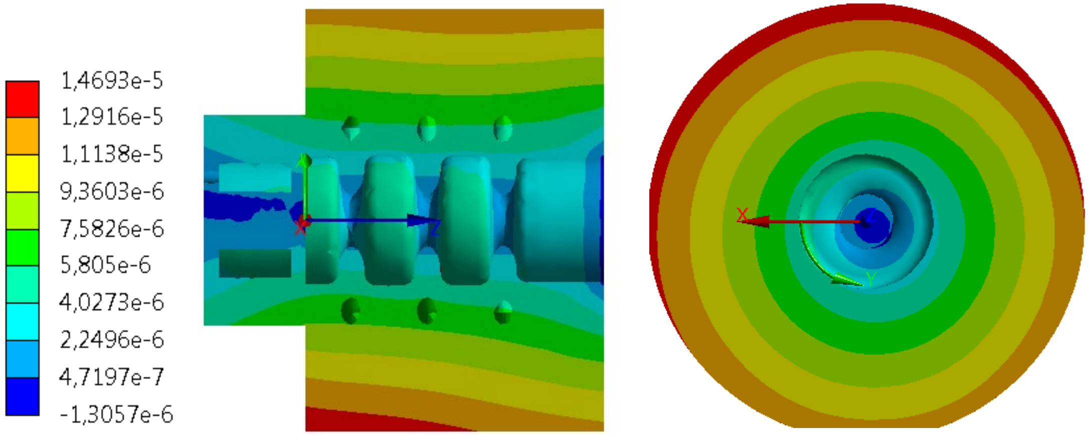


The gun integrates a system of **4 cooling channels**: 3 for the cells and 1 for the cathode. A thermo-mechanical analysis in ANSYS workbench has been done to simulate the deformations and detuning of the gun at a maximum rep. rate of 400 Hz.

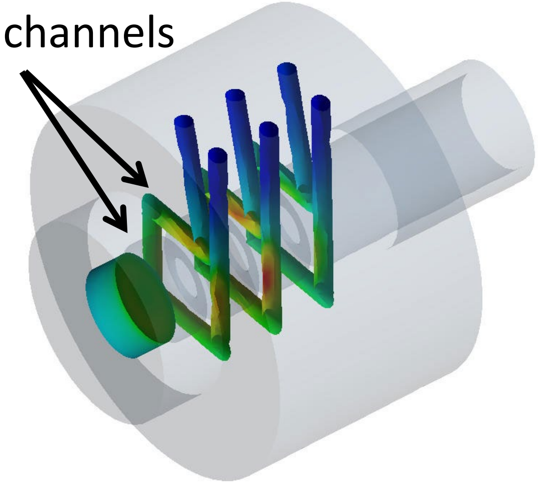
Parameter	value	
Peak input power [MW]	18	
Cathode field [MV/m]	160	
Rep. rate [Hz]	100	400
RF pulse length [ns]	300	
Av. diss. Power [W]	25	1000

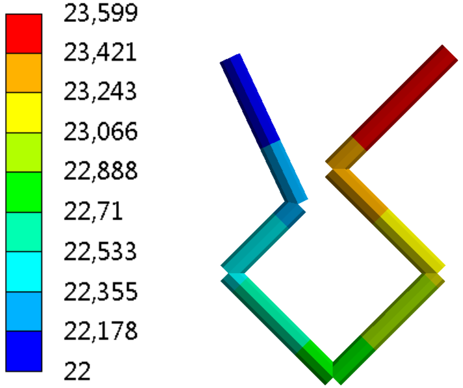


Deformations



Cooling channels





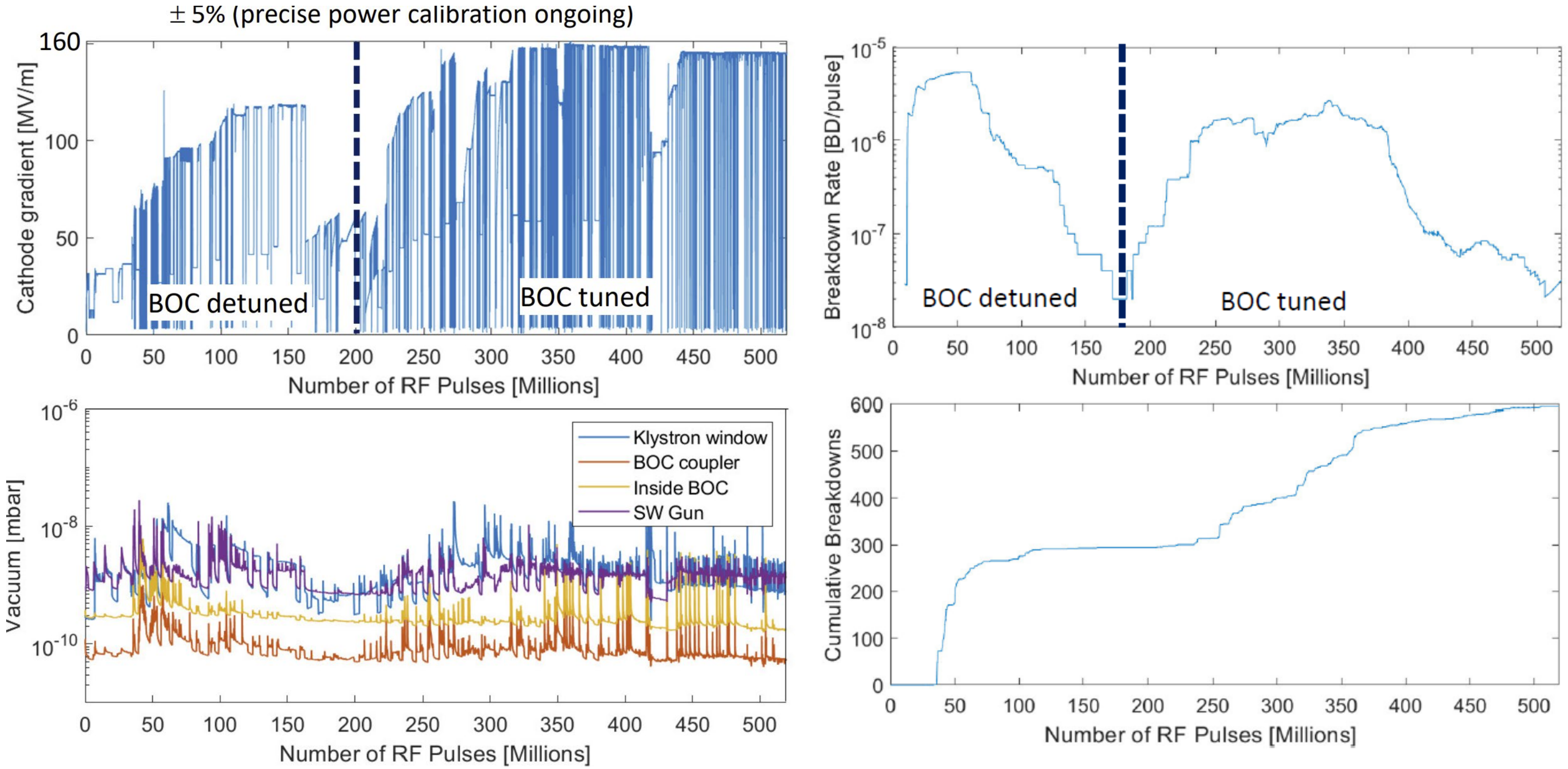
Courtesy of S. Lauciani, L. Pellegrino

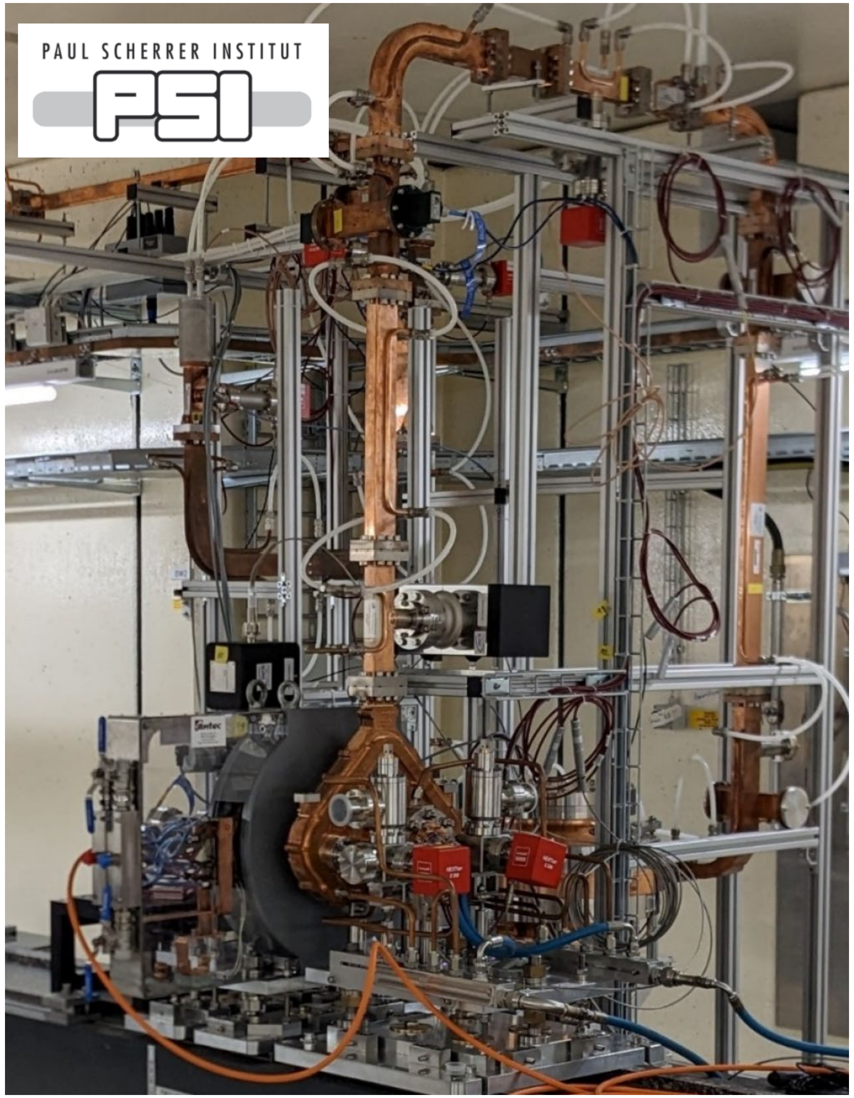
High Power test at PSI

Funded by the European Union

RF Gun Installed @PSI (Switzerland)

The entire system has been transported **to PSI** and **installed in the High Power Test Stand**. The power feeding scheme utilizes power dividers and a BOC-type pulse compressor. RF conditioning began in February 2024 and was performed semi-automatically **at a repetition rate of 100 Hz**. The conditioning process was mainly influenced by vacuum activity in the waveguide. The maximum input power achieved was limited by vacuum activity in the klystron's ceramic. **The peak cathode field reached so far is approximately 160 MV/m.**





FRINGE Linac

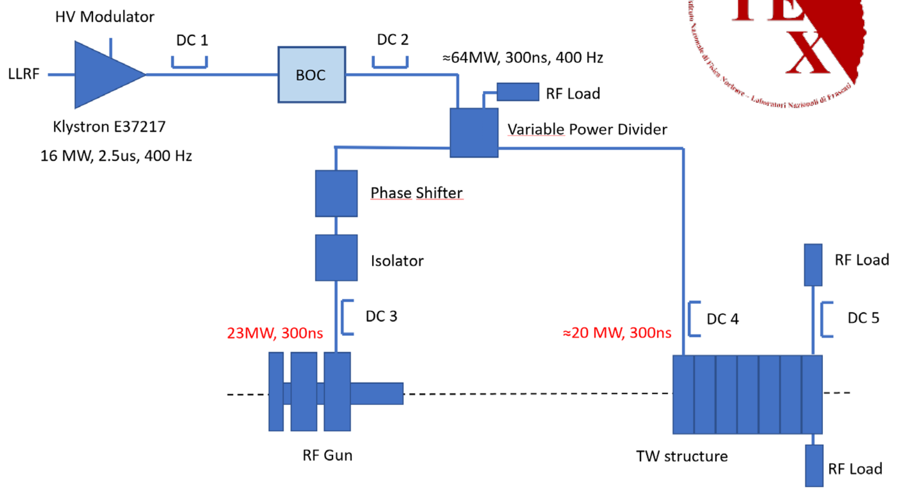
The C-band gun will be installed at the **TEX facility**, which is being equipped with a **high repetition rate C-band source**. It will be integrated with a traveling wave (TW) structure to form a **compact photoinjector** and will be used for high beam quality generation and experimental studies.

This can be a first test facility for a **full C band injector for EuPRAXIA@SPARC_LAB** operating at 400Hz.

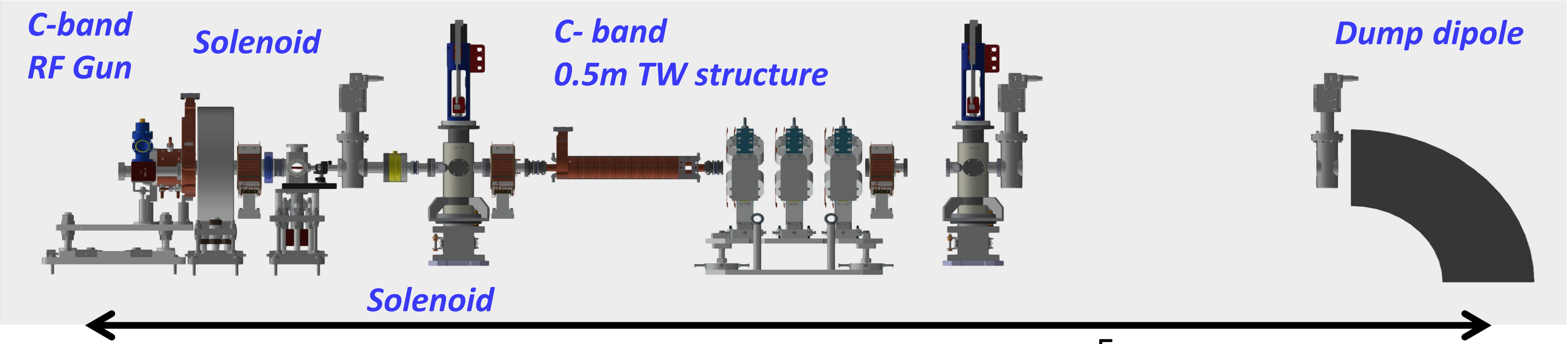
RF Source parameters

Parameter	Unit	Canon E37217
Frequency	MHz	**5712**
Peak RF output Power	MW	**20**
Average RF output power	kW	21
Modulator Average power	kW	80
RF pulse length	us	**2.5**
Repetition Rate	Hz	**400**
Gain	dB	50
Efficiency	%	40

RF wg layout



Photoinjector Preliminary Layout



Preliminary working ponts:

- Laser pulse length 200 fs
- Bunch charge 750/250/50 pC
- Bunch length 300 um rms
- Emittance 1.5/0.5/0.3 mm-mrad

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

Conclusions and Perspectives

- The prospects of operating the RF system of the EuPRAXIA@SPARC_LAB Linac at 400Hz were presented, along with the challenges and necessary upgrades. All of this underscores the **importance of properly designing and sizing the cooling systems**.
- A **new X-band RF source at high repetition rate** will be commissioned at TEX in the next months, together to the waveguide power distribution system. This represent the first test of such a source at this high repetition rate and will **allow testing of components and structures up to 400 Hz repetition rate**.
- A **full scale 1m X-band RF accelerating structure prototype will be realized** by the end of the year and could be tested at a repetition rate up to 400Hz
- **C-band technology represents a good solution for the development of a high repetition rate, high-performance photoinjector**
- **We developed a new C band RF photo-gun** with the brazing free technology that represents the frontier of this type of electron sources in term of cathode peak field (≥160 MV/m) and repetition rate (up to kHz)
- A new C-band RF source at high repetition rate will be commissioned at TEX in the next months. It will be used to **test the C-band IFAST RF Gun up to 400Hz** and to implement a **compact photoinjector**. This represents a preliminary test for the implementation of a potential C-band photoinjector for EuPRAXIA@SPRC_LAB.

THANK YOU FOR YOUR ATTENTION!

Aknowledgements:

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

EuPRAXIA-PP Consortium

Funded by the European Union

Coordinator

INFN
Istituto Nazionale di Fisica Nucleare

Consiglio Nazionale delle Ricerche

Elettra Sincrotrone Trieste

ENEA
Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

SAPIENZA Università di Roma

Università di Roma Tor Vergata

Imperial College London

Queen's University Belfast

UK Research and Innovation

University of Liverpool

University of Oxford

University of Strathclyde Glasgow

CERN

DESY.

Leibniz Ferdinand Braun Institut

Fraunhofer ILT

GSI

hhu Heinrich Heine Universität Düsseldorf

HZDR Helmholtz Zentrum Dresden Rossendorf

Jülich Forschungszentrum

LMU Ludwig-Maximilians-Universität München

Amplitude

cea

cnrs

THALES

eli

Técnico Lisboa

ALBA

CLPU Centro de Láseres Pulsados

Empa Materials Science and Technology

EPFL

Paul Scherrer Institut PSI

The Hebrew University of Jerusalem

IASA

Pécsi Tudományegyetem University of Pécs

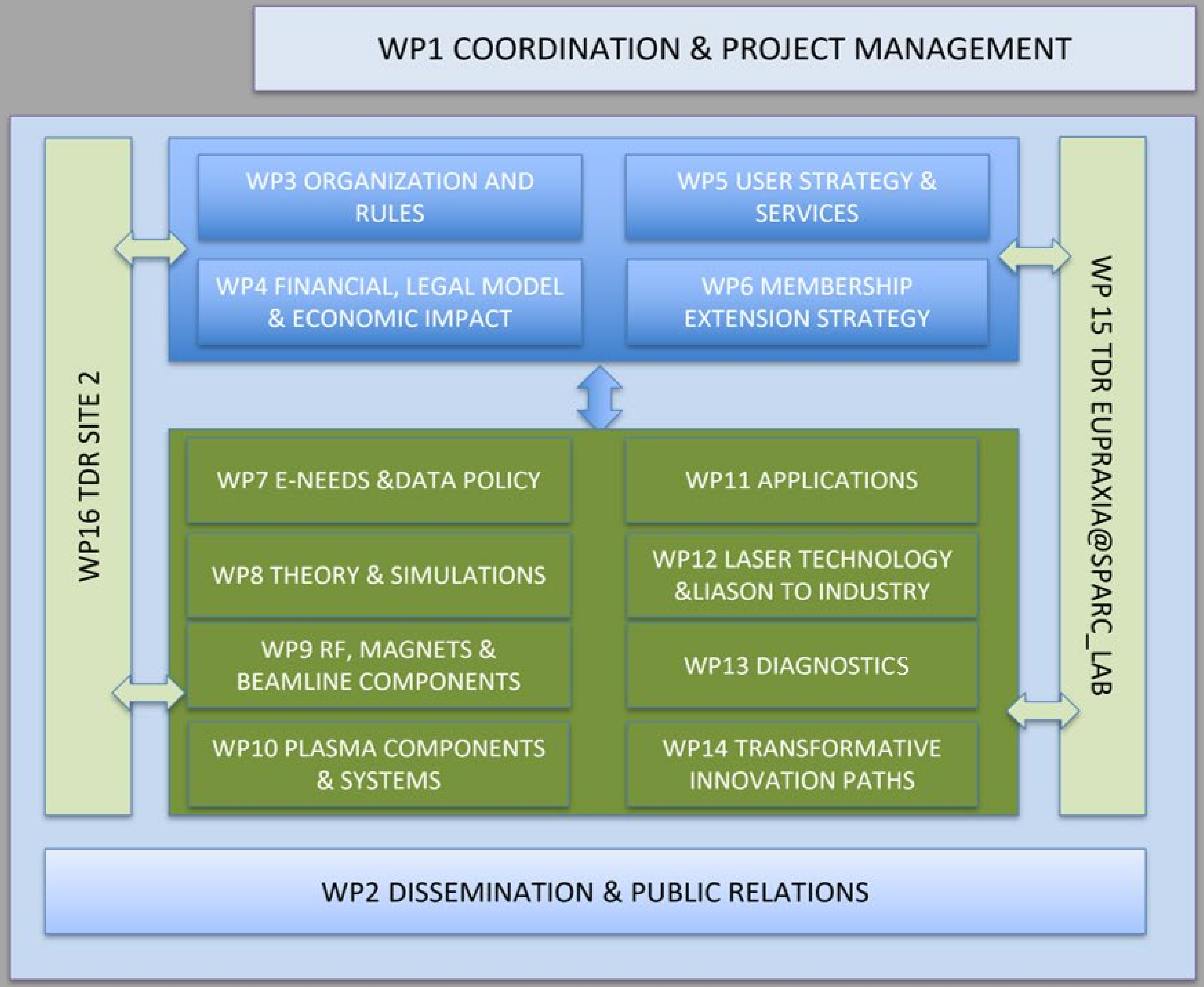
SZTE University of Szeged

Wigner

The University of California UCLA

EuPRAXIA-PP Structure

Funded by the European Union



Selected Committees and Boards

GOVERNING BOARD (decision-making body, 1 representative per institute)

Steering Committee (coordinator plus WP leaders plus experts)

Scientific/Technical Advisory Board (external experts in user services, RI implement-tation, ESFRI aspects and technical themes)

Board of Financial Sponsors (connection to decision makers and funding authorities)

Acknowledgements

Funded by the European Union

- EuPRAXIA Preparatory Phase

This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101079773. It is supported by in-kind contributions by its partners and by additional funding from UK and Switzerland.

- EuPRAXIA Doctoral Network

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement no. 101073480 and the UKRI guarantee funds.

- EuAPS

This publication has been made with the co-funding of European Union Next Generation EU.