# RF power for Eupraxia@SPARC_LAB

***David Alesini, INFN-LNF, Frascati***

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

2nd Workshop on efficient RF Sources

23-25 September 2024, Toledo, Spain

# OUTLINE

1. **EuPRAXIA@SPARC_LAB Project**
    - X Band LINAC
    - X BAND RF MODULE
2. **TEX FACILITY STATUS AND PERSPECTIVES**
    - TEST OF X BAND ACCELERATING STRUCTURES
    - TEST OF THE RF COMPONENTS
3. **S BAND INJECTOR**

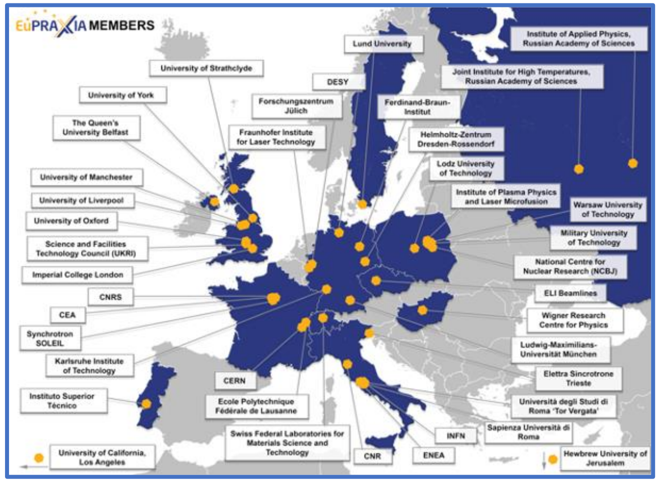
# EuPRAXIA@SPARC_LAB Project

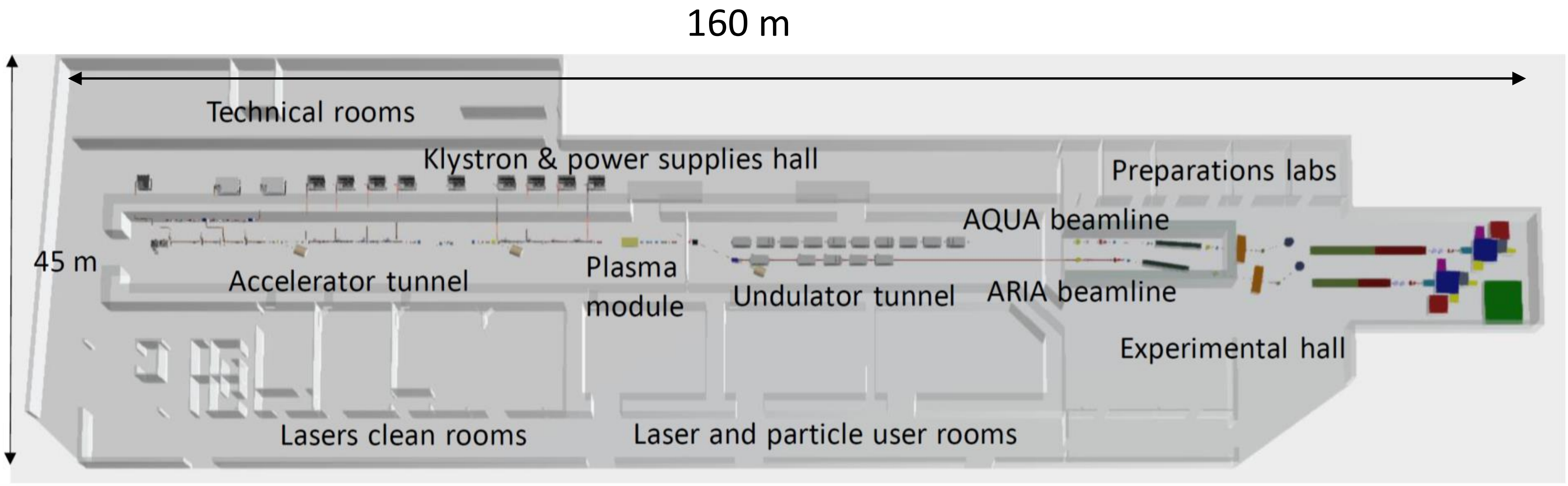
⇒ The project EuPRAXIA@SPARC_LAB is the **pillar** of the **European** Project **EUPRAXIA** (http://www.eupraxia-project.eu/) and is project based on beam driven plasma wakefield acceleration (**PWFA**). It aims at constructing a FEL radiation source ($\lambda_{FEL}$=4 nm) combining:

- **1 GeV RF X-band Linac with an high brightness S band photo-injector**
- **Plasma module for PWFA**.

⇒ The project is currently in the preparatory phase of the **Technical Design Report** (end 2025).

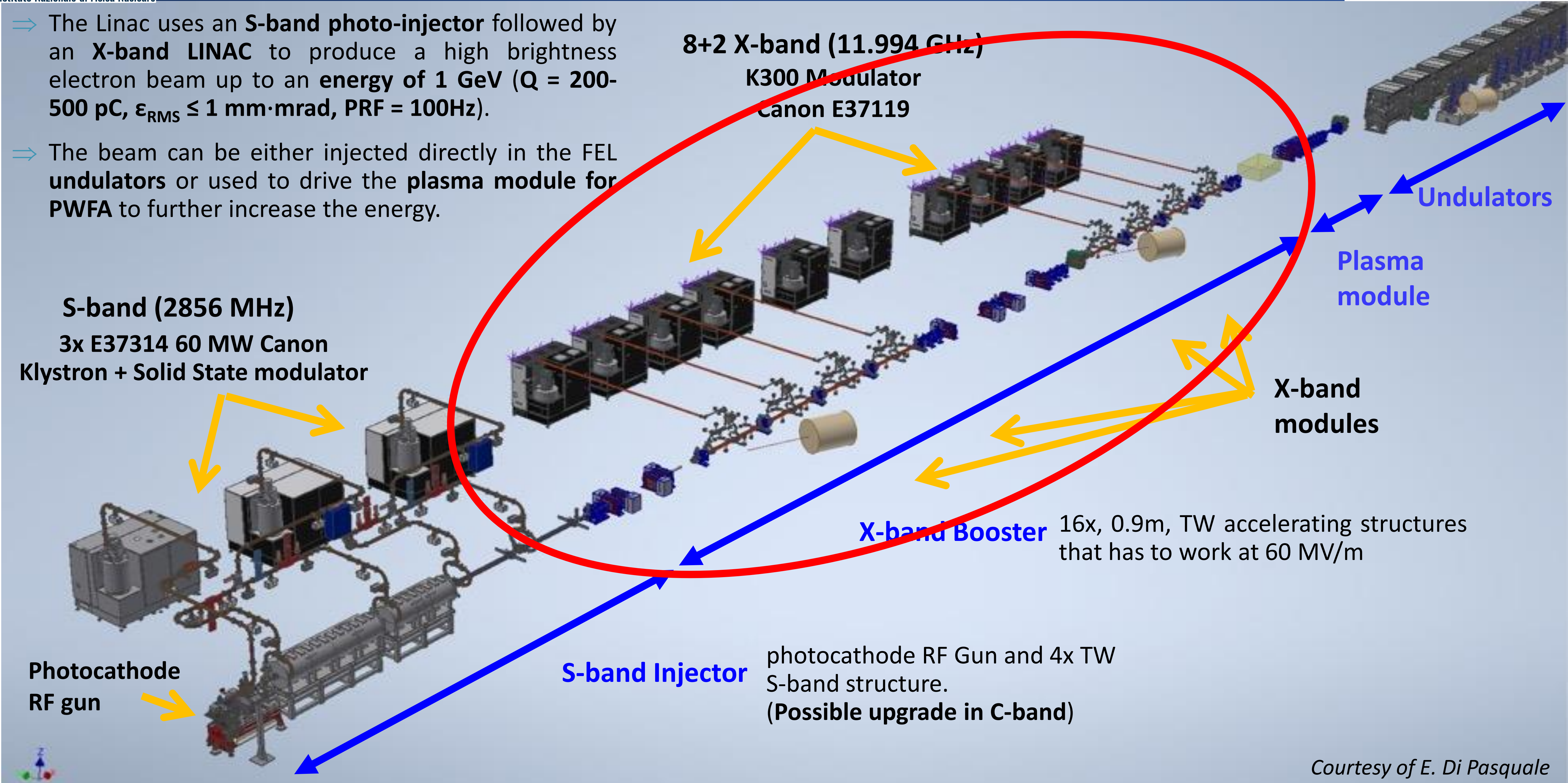
⇒ A **new building**, now under executive design phase, will host the new Facility at LNF, the construction should start in September 2026.



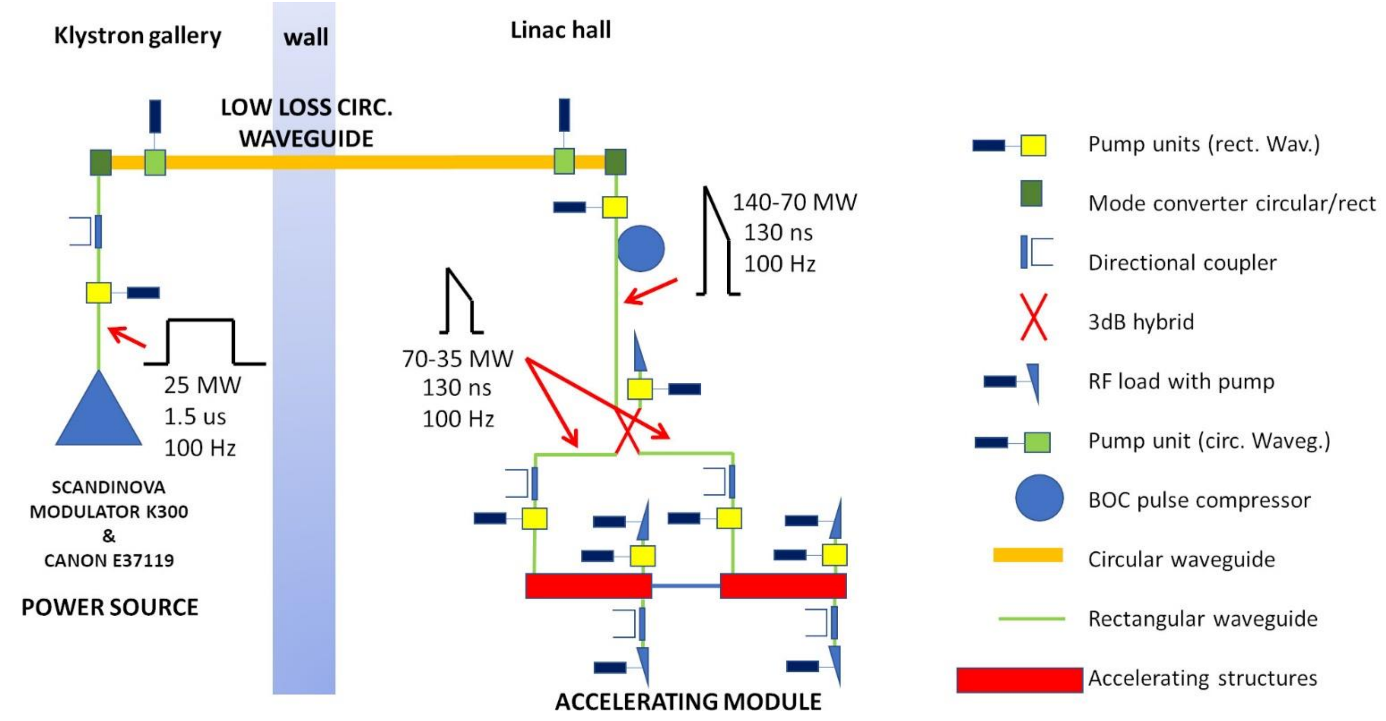
# Overview of the LINAC

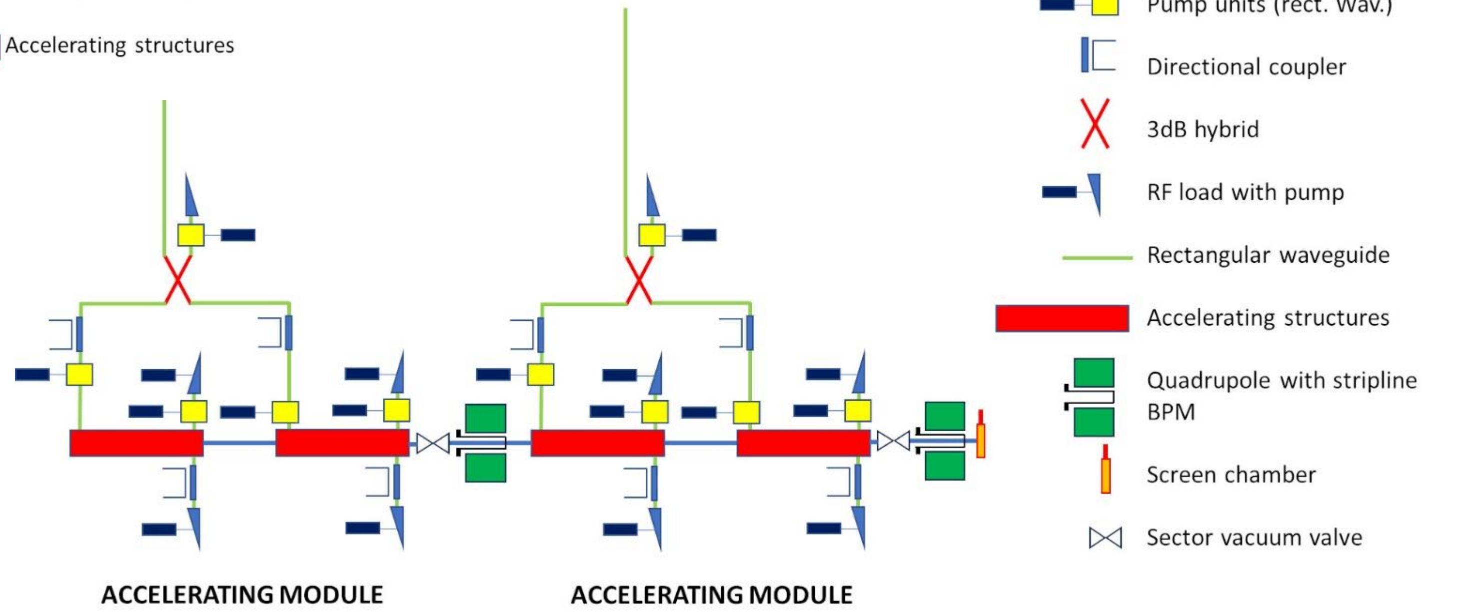
- ⇒ The Linac uses an **S-band photo-injector** followed by an **X-band LINAC** to produce a high brightness electron beam up to an **energy of 1 GeV** (**Q = 200-500 pC, $\varepsilon_{RMS} \leq$ 1 mm·mrad, PRF = 100Hz**).
- ⇒ The beam can be either injected directly in the FEL **undulators** or used to drive the **plasma module for PWFA** to further increase the energy.



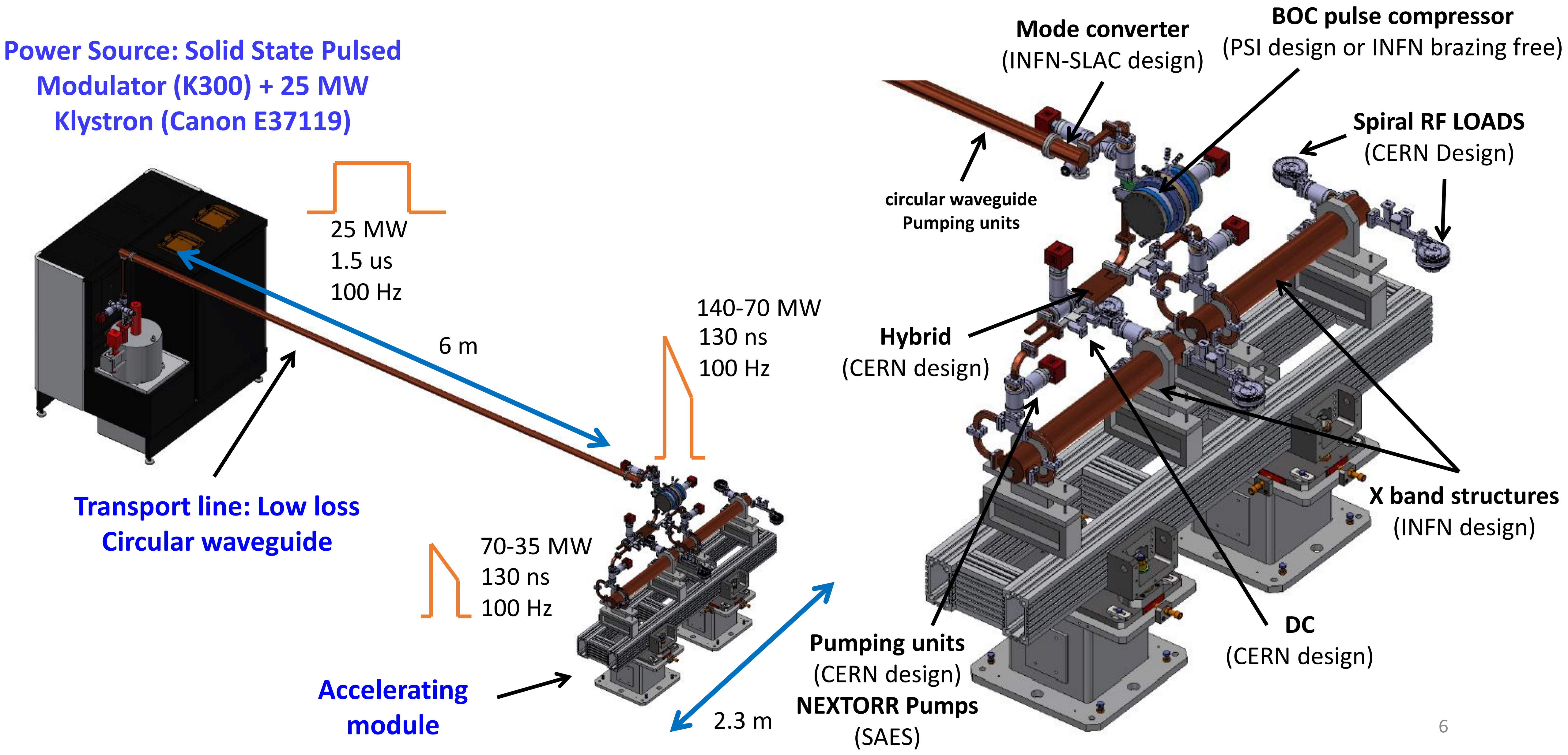

*Courtesy of E. Di Pasquale*

# X-band RF Module Schematic Layout



# X-band RF Module Layout



# RF MODULE POWER SOURCES: ORIGINAL OPTIONS

## BASELINE

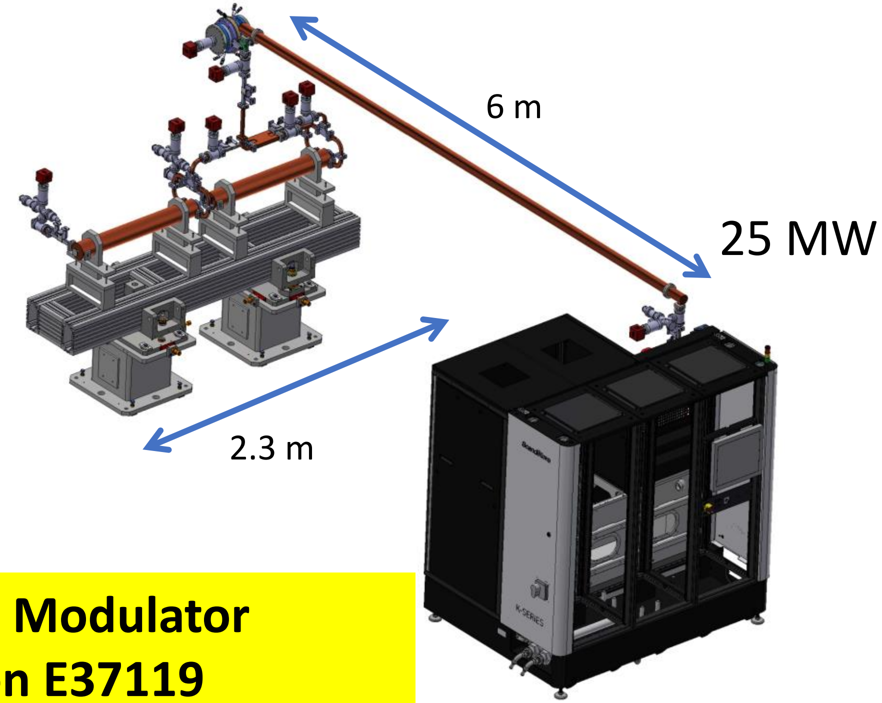
### CANON

» 1x BOC on one line

» Higher flexibility

» Lower Modulator power requirements

» Possible upgrade at high rep. rate of the Linac (400 Hz)




**K300 Modulator**
**Canon E37119**

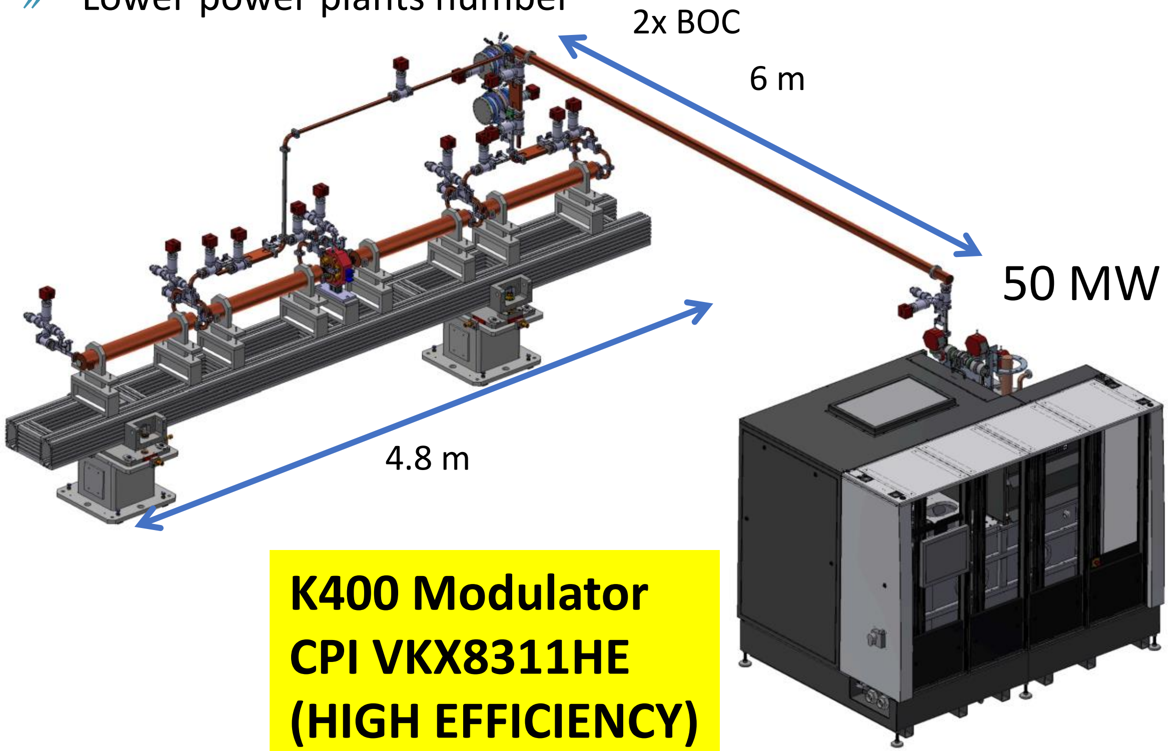
### CPI — OPTION

» 2x BOC on one line

» Less flexibility

» Different LE and HE module layout

» Lower power plants number

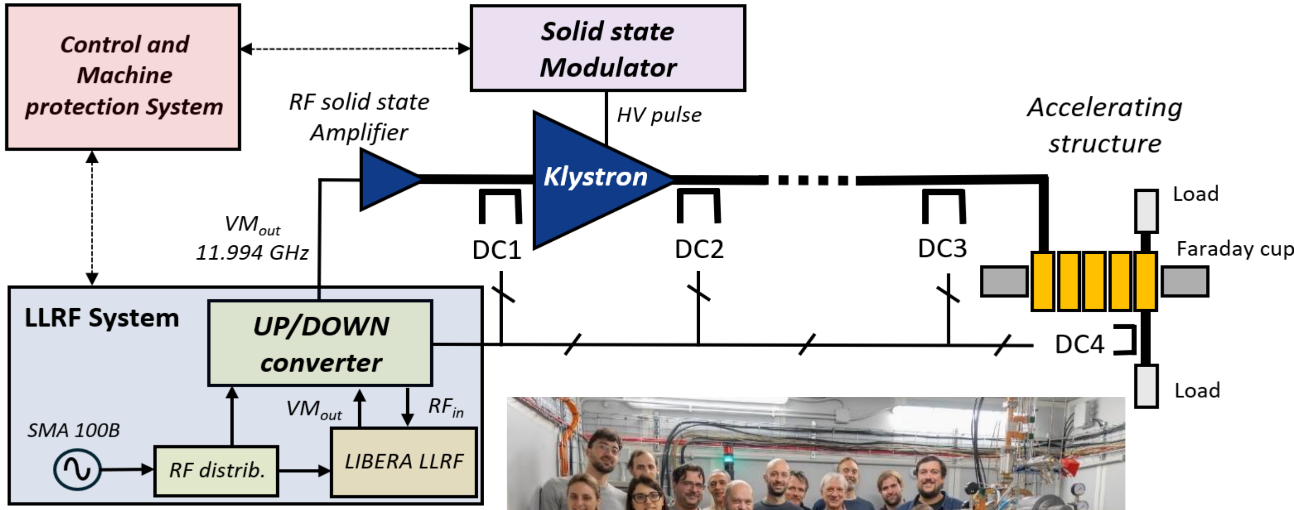



**K400 Modulator**
**CPI VKX8311HE**
**(HIGH EFFICIENCY)**

# 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
- 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 (that provided the klystron)** 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 |
| 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 |



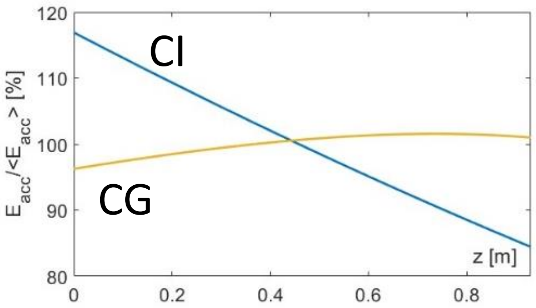

**LLRF system**

**50 MW RF Source**

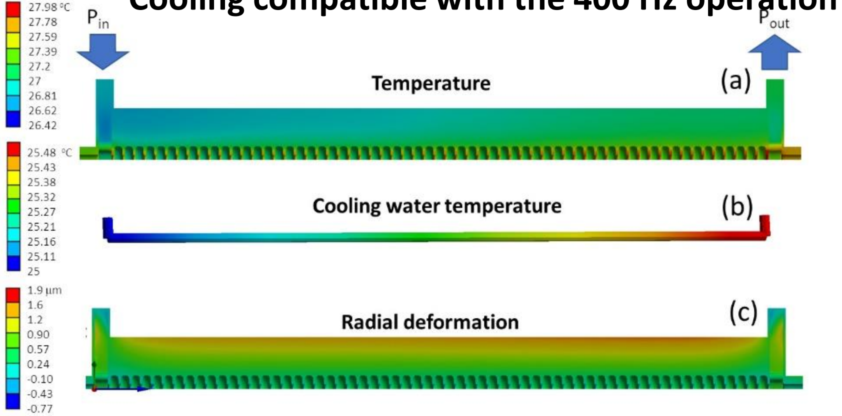
**VKX8311A Klystron**


[3] F. Cardelli et al., 13th Int. Particle Accelerator Conf. IPAC22, Bangkok, Thailand, Jun. 2022, paper TUPOPT061
[4] L. Piersanti et al. "RF power station stabilization techniques and measurements at LNF" In Proc. IPAC24 - TUPR01.
[5] L. Piersanti et al. "Design and test of a klystron intra-pulse phase feedback system for electron linear accelerators" Photonics 2024, 11(5), 413.

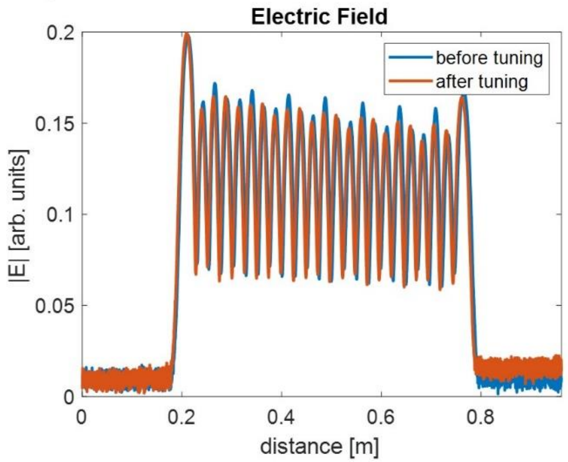
# EuPRAXIA X-band structure power test

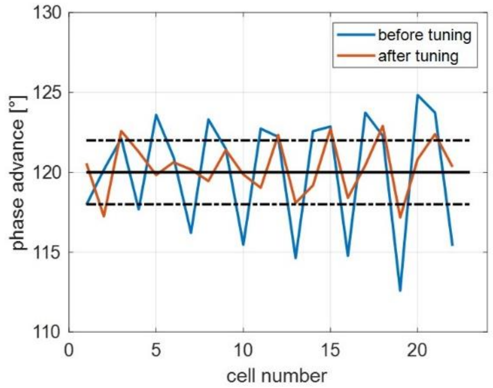


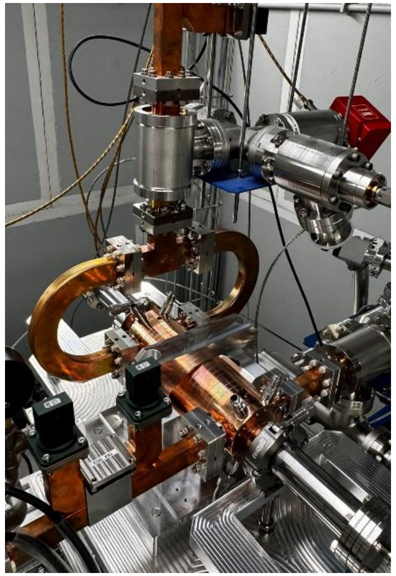

**Cooling compatible with the 400 Hz operation**

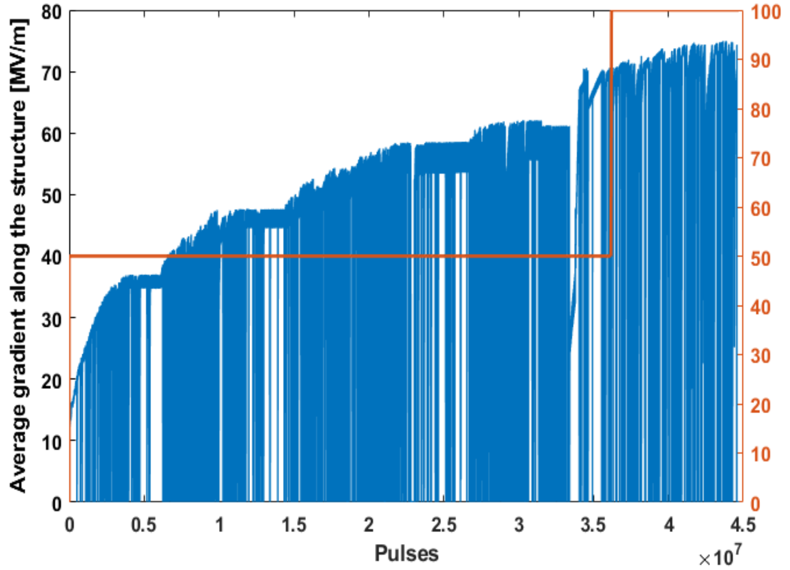



| PARAMETER | Value | |
|---|---|---|
| | CG | CI |
| Frequency [GHz] | 11.9942 | |
| **Average acc. gradient [MV/m]** | **60** | |
| Structures per module | 2 | |
| **Iris radius a [mm]** | **3.85 - 3.15** | **3.5** |
| Tapering angle [deg] | 0.04 | 0 |
| **Struct. length $L_s$ act. Length [m]** | **0.94** | |
| No. of cells | 112 | |
| Shunt impedance R [MΩ/m] | 93-107 | 100 |
| Effective shunt Imp. $R_{sh\_eff}$ [MΩ/m] | 350 | 347 |
| Peak input power per structure [MW] | 70 | |
| Filling time [ns] | 130 | |
| Peak Modified Poynting Vector [W/μm$^2$] | 3.6 | 4.3 |
| Peak surface electric field [MV/m] | 160 | 190 |
| **Repetition Rate [Hz]** | **100 (400)** | |



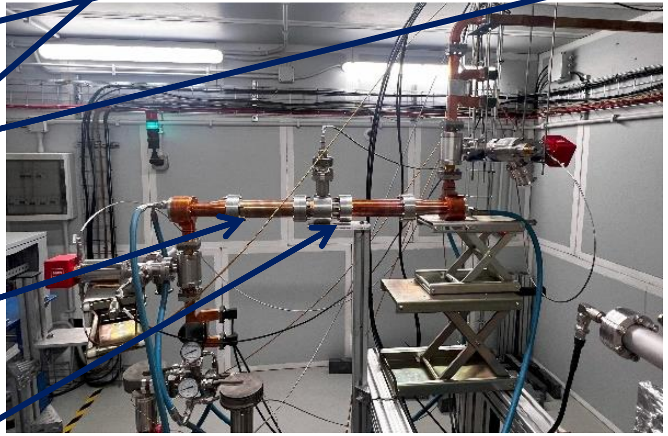



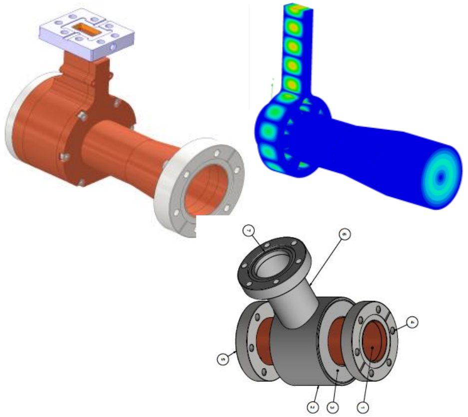





# TEST AND REALIZATION OF X-BAND WAVEGUIDE COMPONENTS

| COMPONENT | DESIGN BY | STATUS | LEVEL OF POWER TO BE TESTED FOR EUPRAXIA MODULE | TEST DONE SO FAR |
|---|---|---|---|---|
| Pump units (rect. Wav.) | CERN | Fabricated and installed @ TEX | 25 MW 1.5 µs and 70-35 MW 0.13 µs Compressed pulse 100 Hz | 45 MW, 1 µs, 50 Hz, $P_{avg}$ = 2.25 kW |
| Directional coupler | CERN | Fabricated and installed @ TEX | 25 MW 1.5 µs and 70-35 MW 0.13 µs compressed pulse 100 Hz | 45 MW, 1 µs, 50 Hz, $P_{avg}$ = 2.25 kW |
| Splitter | CERN | Fabricated and installed @ TEX | 70-35 MW, 0.13 µs Compressed pulse 100 Hz | 35 MW, 0.6 µs, 50 Hz, $P_{avg}$ = 1 kW |
| RF load | CERN | Fabricated and installed @ TEX | 18-9 MW 0.13 µs compressed pulse 100 Hz | 17 MW, 0.6 µs, 50 Hz, $P_{avg}$ = 0.5 kW |
| Mode converter circular/rect | INFN | Fabricated and Installed @ TEX | 25 MW 1.5 µs 100 Hz | 35 MW, 1 µs, 50 Hz, $P_{avg}$ = 1.75 kW |
| Pump unit (circ. Waveg.) | INFN | Fabricated and Installed @ TEX | 25 MW 1.5 µs 100 Hz | 35 MW, 1 µs, 50 Hz, $P_{avg}$ = 1.75 kW |
| 3dB hybrid | CERN | Delivered | 140-70 MW 0.13 µs Compressed pulse 100 Hz | |
| BOC pulse compr. | PSI | Delivered | 140-70 MW 0.13 µs Compressed pulse 100 Hz | |





# TEX Upgrade with new Power Sources

Currently, the test stand TEX is based on **CPI VKX8311A** Klystron **on loan from CERN** already **commissioned** and **in operation.**
Three other klystrons are being installed at TEX:

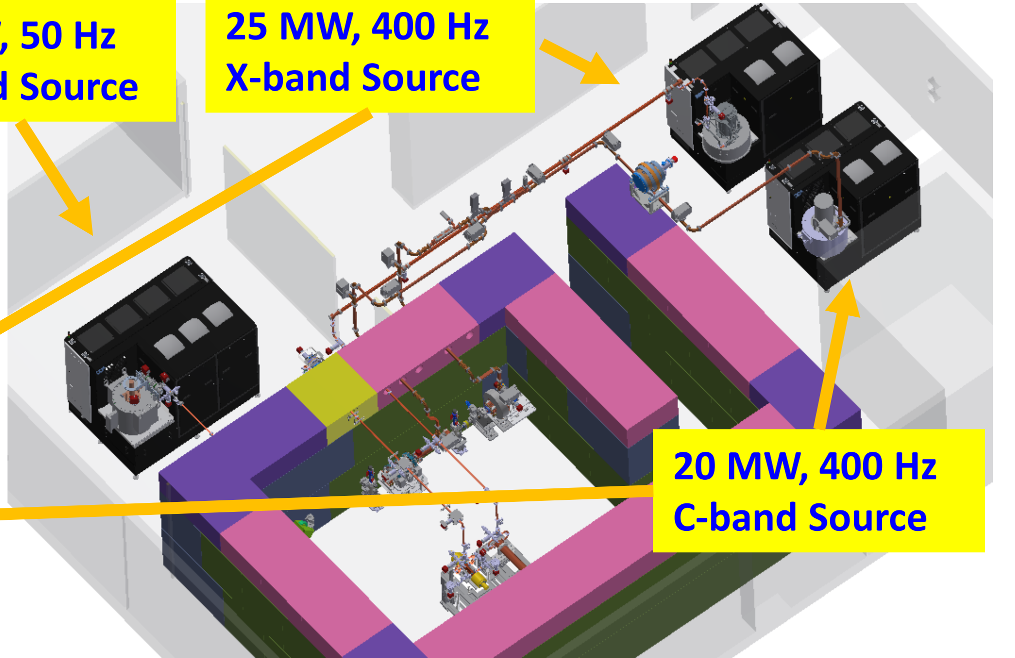
1. **CANON X Band 25 MW, 400 Hz E37119**
   **Status**:
   - *FAT of the klystron done @ CANON on a PFN modulator 11/2023, 25 MW, 10 Hz, t=1.5us*
   - *FAT of the RF source @Scandinova 05/2024, full power in diode mode*
   - *Modulator and klystron positioned at TEX*

3. **CANON C Band E37217**
   **Status**:
   - *FAT of the klystron done @ CANON on a PFN modulator 11/2023, 20 MW, 10 Hz, t=2.5us*
   - *FAT of the RF source @Scandinova 05/2024, full power in diode mode*
   - *Modulator and klystron positioned at TEX*

2. **CPI X Band 50 MW, 100 Hz High efficiency VKX8311HE**
   **Status**:
   - Tender has been done, realization phase (expected delivery from CPI Sept 2025)

The **commissioning of these sources** and the waveguide networks is scheduled for January 2025, after the installation of the cooling and power systems that will serve these sources.

| Parameter | Unit | Canon E37119 | CPI VKX8311HE | CPI VKX8311 | Canon E37217 |
|---|---|---|---|---|---|
| Frequency | MHz | 11994 | | | **5712** |
| Vk beam voltage | kV | 312 | 415 | 420 | 280 |
| Ik cathode current | A | 199 | 201 | 320 | 240 |
| Peak RF output Power | MW | 25 | 50 | 50 | 20 |
| Average RF output power | kW | 15 | 7,5 | 7,5 | 21 |
| Modulator Average power | kW | 80 | 25 | 48 | 80 |
| RF pulse length | µs | 1,5 | | | 2.5 |
| Repetition Rate | Hz | 400 | 100 | 100 | 400 |
| Gain | dB | 47 | 50 | 47 | 50 |
| Efficiency | % | 40 | 55 | 38 | 40 |
| Perveance | µp | 1.16 | 0.75 | 1.15 | 1 |



# New RF Power Sources: Detailed Parameters

## Canon E37119

| Parameters | Symbol | Units | Min. | Max. | Notes |
|---|---|---|---|---|---|
| Frequency | f | MHz | 11993 | 11995 | |
| Heater Voltage | Ef | V | --- | 22 | 3, 24 |
| Heater Current | If | A | --- | 22 | 3 |
| Heater Current (surge) | If(surge) | A | --- | 28 | 3 |
| Heater Warm-up Time | tk | minutes | 60 | --- | |
| Peak Forward Beam Voltage | epy | kV | --- | 335 | 4 |
| Peak Inverse Beam Voltage | epx | kV | --- | 30 | |
| Peak Cathode Current | ik | A | -10 | 225 | |
| Peak Drive Power | pd | W | --- | 500 | 5 |
| Peak RF Output Power | po | MW | --- | 25.5 | |
| Average RF Output Power | Po | kW | --- | 15.3 | |
| Collector Dissipation | Pcol | kW | --- | 100 | |
| Pulse Width(duration) (epy) | t(epy) | µs | --- | 3.5 | 6 |
| Pulse Width(duration) (rf) | t(rf) | µs | --- | 1.5 | 7 |
| Pulse Repetition Rate | prr | pps | --- | 400 | |
| Load VSWR (occasionally) | σL | | --- | 1.4:1 | 8,9 |
| Load VSWR (stable condition) | σL,s | | --- | 1.2:1 | 9 |
| Coolant Flow (collector) | Qw | l/min | 65 | --- | 10 |
| Coolant Flow (body) | Qw | l/min | 15 | --- | 10 |
| Coolant Flow (window) | Qw | l/min | 1.8 | 3 | 10 |
| Inlet Coolant Temperature | Tw,i | centigrade | 5 | 35 | 10, 11 |
| Outlet Coolant Temperature | Tw,o | centigrade | --- | 65 | 10 |
| Coolant Pressure Collector | Pw,c | MPa | --- | 1 | 10 |
| Body | Pw,b | MPa | --- | 0.8 | 10 |
| Window | Pw,w | MPa | --- | 0.3 | 10 |
| Waveguide Pressure (Vacuum) | PW/G | Pa (Torr | --- | $1.3\times10^{-5}$ ($1\times10^{-7}$) | 13 |
| Environmental temperature | Te | Centigrade | 0 | 40 | 12 |
| Environmental humidity | H | % | 0 | 90 | 11, 12 |
| Ion pump Voltage | Eip | kV | 3.1 | 3.9 | 2 |

## Canon E37119

| Parameters | Symbol | Units | Min. | Max. | Notes |
|---|---|---|---|---|---|
| Frequency | f | MHz | 5711 | 5713 | |
| Heater Voltage | Ef | V | --- | 24 | 3, 4, 5, 27 |
| Heater Current | If | A | --- | 24 | 5 |
| Heater Current (surge) | If(surge) | A | --- | 30 | 5 |
| Heater Warm-up Time | tk | minutes | 60 | --- | |
| Peak Forward Beam Voltage | epy | kV | --- | 280 | 6, 7 |
| Peak Inverse Beam Voltage | epx | kV | --- | 30 | 7A |
| Peak Cathode Current | ik | A | -10 | 240 | 8, 8A |
| Peak Drive Power | pd | W | --- | 500 | 9 |
| Peak RF Output Power | po | MW | --- | 21 | |
| Average RF Output Power | Po | kW | --- | 21 | |
| Collector Dissipation | Pcol | kW | --- | 100 | |
| Pulse Width(duration) (epy) | t(epy) | µs | --- | 5.0 | 10 |
| Pulse Width(duration) (rf ) | t(rf) | µs | --- | 2.5 | 11 |
| Pulse Repetition Rate | prr | pps | --- | 400 | |
| Load VSWR (occasionally) | σL | | --- | 1.4:1 | 11A |
| Load VSWR (stable condition) | σL | | --- | 1.2:1 | 11B |
| Coolant Flow | | | | | |
| Collector | Qw | ℓ/min | 65 | --- | 12, 14 |
| Body | Qw | ℓ/min | 15 | --- | 12, 14 |
| Waveguide | Qw | ℓ/min | 2 | 3 | 12, 14 |
| Inlet Coolant Temperature | Tw,i | °C | 5 | 35 | 12, 12A |
| Outlet Coolant Temperature | Tw,o | °C | --- | 65 | 12, 14 |
| Coolant Pressure | | | | | |
| Collector | Pw | MPa | --- | 1 | 12 |
| Body | Pw | MPa | --- | 0.8 | 12 |
| Windows and waveguide | Pw | MPa | --- | 0.3 | 12 |
| Waveguide Pressure (Vacuum) | PW/G | Pa (Torr | --- --- | $1.3\times10^{-5}$ ($1\times10^{-7}$) | 13 |
| Environmental Temperature | Te | °C | 0 | 40 | 12A |
| Environmental Humidity | H | % | 0 | 90 | 12A, 12B |
| Ion pump Voltage | Eip | kV | 3.1 | 3.9 | 2 |

## VKX-8311A3

Communications & Power Industries

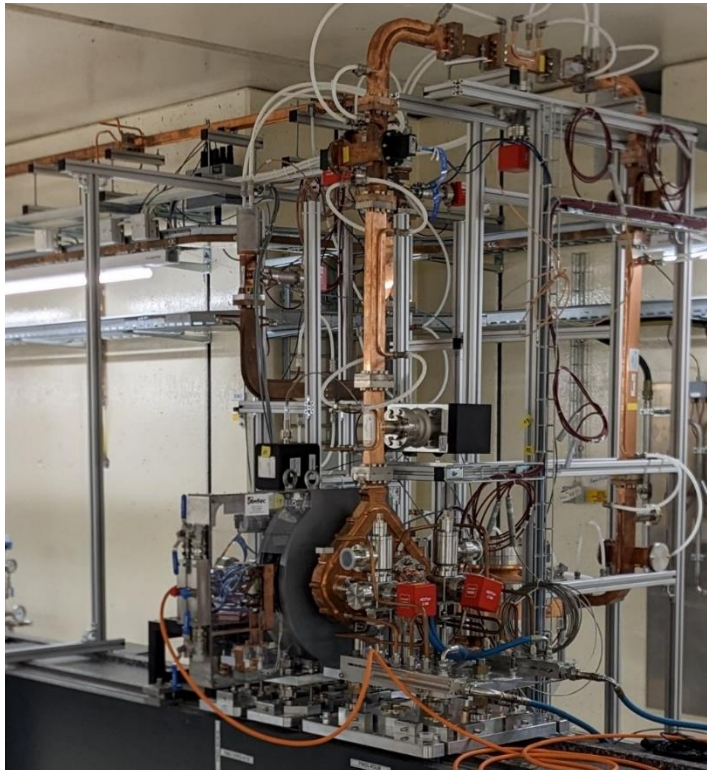
| PARAMETER | UNITS | VALUE |
|---|---|---|
| RF Frequency | MHz | 11994.2 |
| Bandwidth at -1dB | MHz | ≥ 10 |
| **RF Power:** | | |
| Pout - Peak Power at the output flange of the klystron [*] | MW | ≥ 45 |
| Average RF Power | kW | ≥ 3.75 |
| Maximum Klystron peak Current | A | 240 |
| Maximum High voltage applied to the cathode | kV | 450 |
| Trf, RF Pulse length (at -3dB) [*] | µs | 1.5 |
| HV Video Pulse length (FWHM) | µs | ≤ 3.5 |
| Repetition Rate [*] | Hz | 100 |
| Tolerable peak reverse voltage | kV | ≤ 30 |
| Efficiency at peak power | % | ≥ 46 |
| RF gain at peak power | dB | ≥ 47 |
| Perveance | $\mu A/V^{1.5}$ | ≥ 0,67 |
| Variation of anodic current (at klystron peak power) within +/-5% cathode heater power variation | % | ±3 |
| **Stability of RF output signal over the range of 0.5-1.0 of max. power and 0.75 -1.0 of max. cathode HV to be:** | | |
| RF input vs output phase jitter [**] | RF degree | ± 0.5 max |
| RF amplitude jitter | % | ± 0.25 max |
| Fraction of RF power in 2nd harmonic | dB | ≤ -20 |
| Pulse failures (arcs etc.) during 24-hour continuous test period | | ≤ 1 |
| Radiation at 1 m distance from klystron | µSv/h | ≤ 1 |

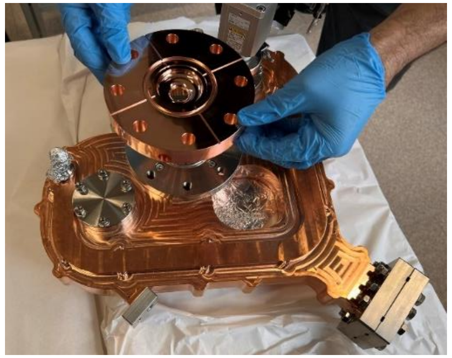
# C-BAND GUN @ TEX

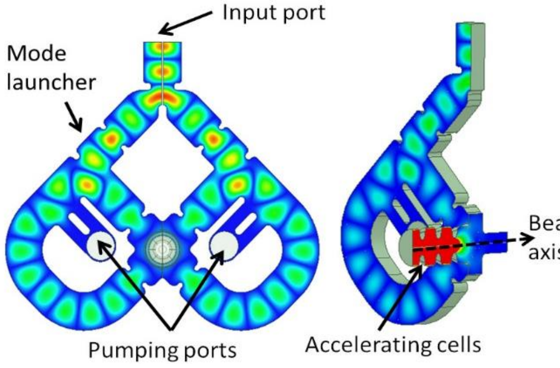
Istituto Nazionale di Fisica Nucleare

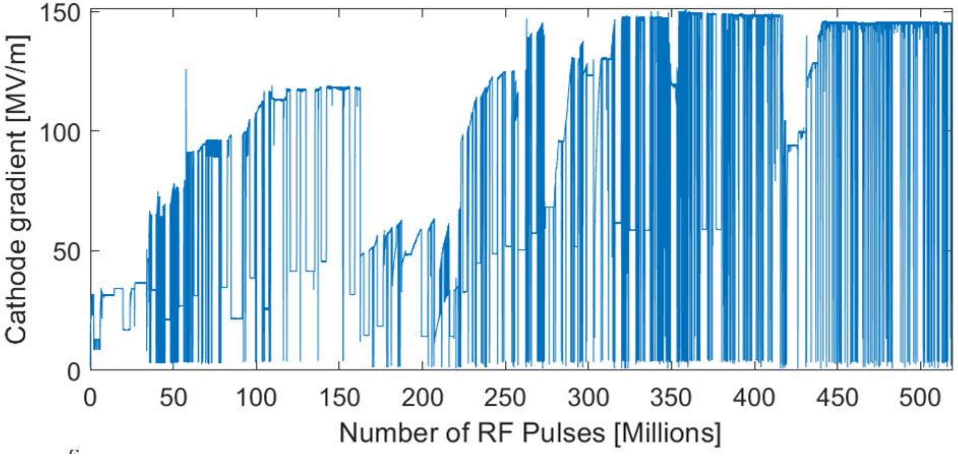
PAUL SCHERRER INSTITUT

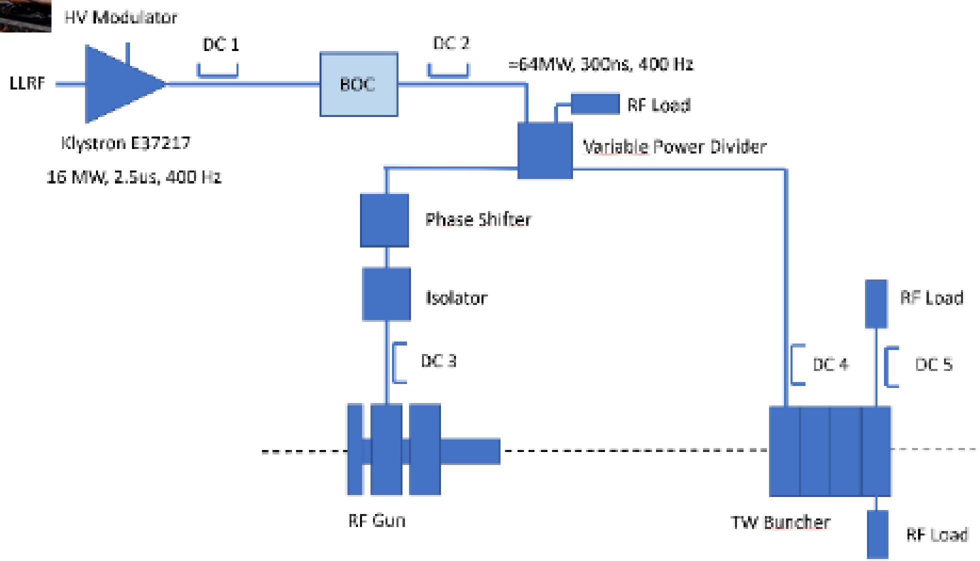
- ⇒ A new **C band RF photo-gun** with the **brazing free** technology has been designed, built, assembled and installed at PSI (with solenoid and vacuum chamber): **I-FAST project**.
- ⇒ The design is compatible with the **400 Hz** operation
- ⇒ The high power tests showed **~160 MV/m** cathode peak field limited w/o gun limitation.
- ⇒ The C band gun **will be installed in the TEX** facility and used for high beam quality generation and experiments.
- ⇒ The possibility of a full **C band injector for EUPRAXIA@SPARC_LAB** is also being considered for the possibility to operate at 400 Hz.







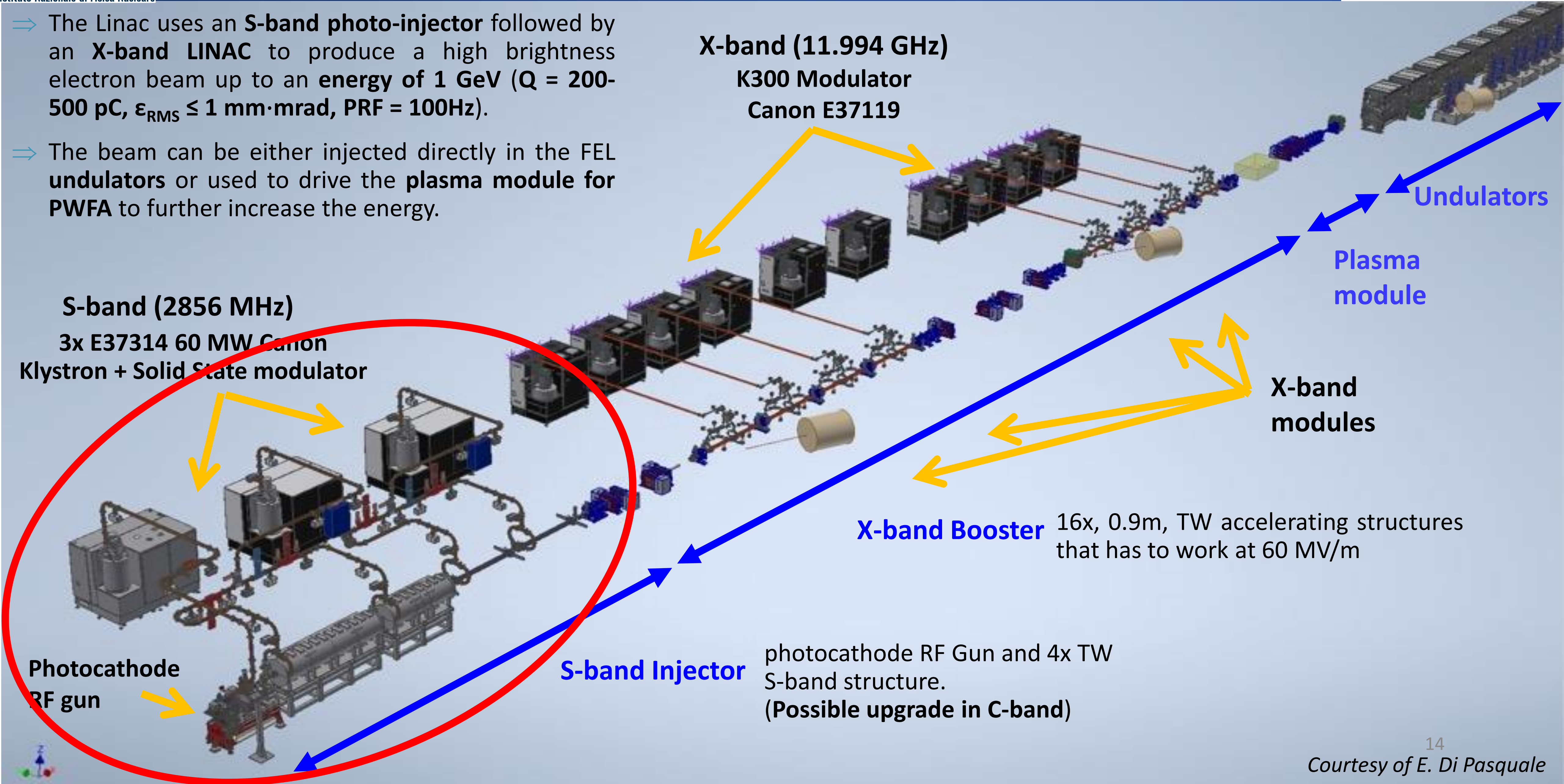




*[6] D. Alesini et al. "Design, realization and high power test of the new brazed free C-band Photo-Gun" In Proc. IPAC24 – THAN01*

# Overview of the LINAC

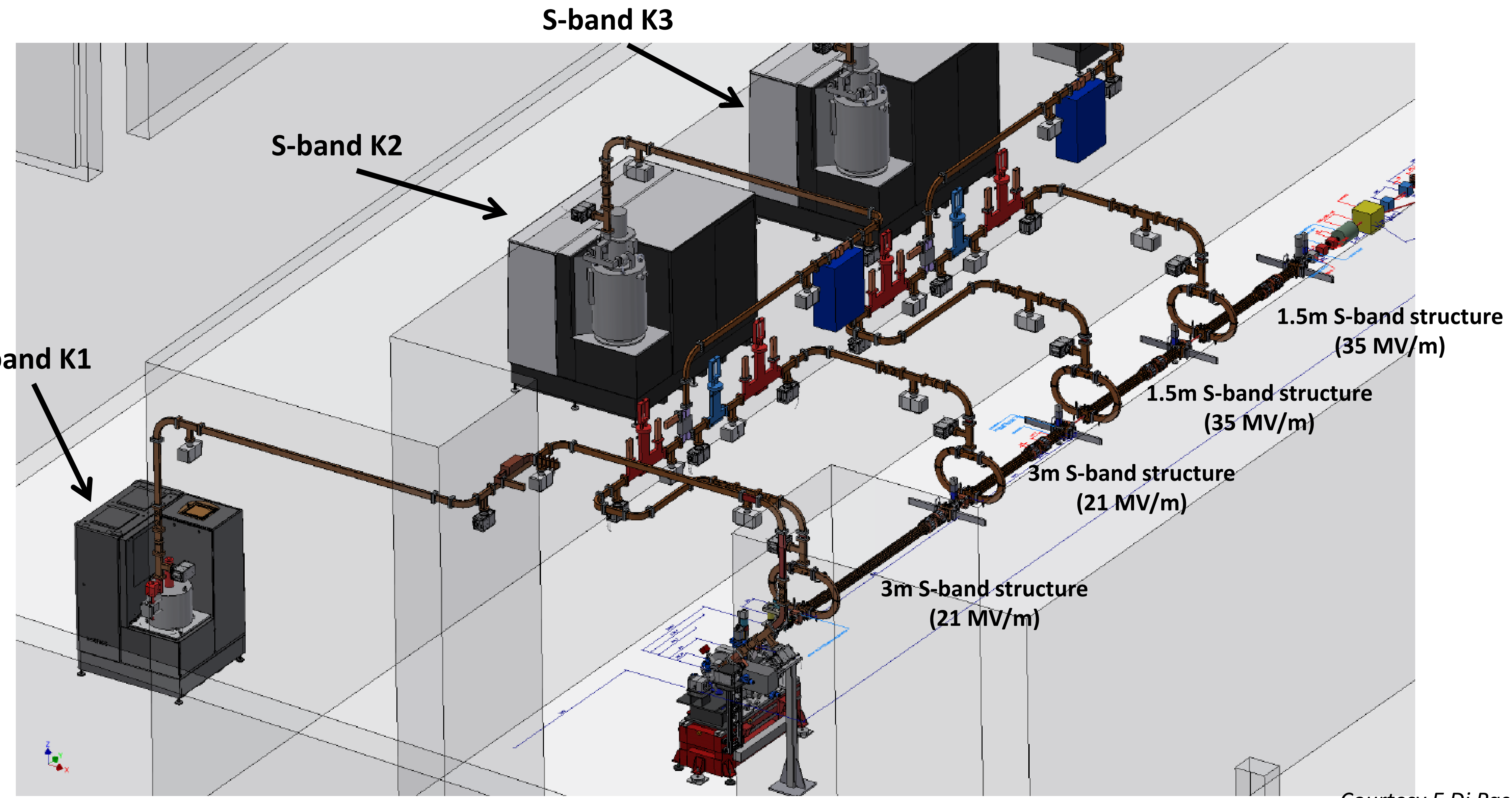
- The Linac uses an **S-band photo-injector** followed by an **X-band LINAC** to produce a high brightness electron beam up to an **energy of 1 GeV** (**Q = 200-500 pC, $\varepsilon_{RMS} \leq$ 1 mm·mrad, PRF = 100Hz**).
- The beam can be either injected directly in the FEL **undulators** or used to drive the **plasma module for PWFA** to further increase the energy.





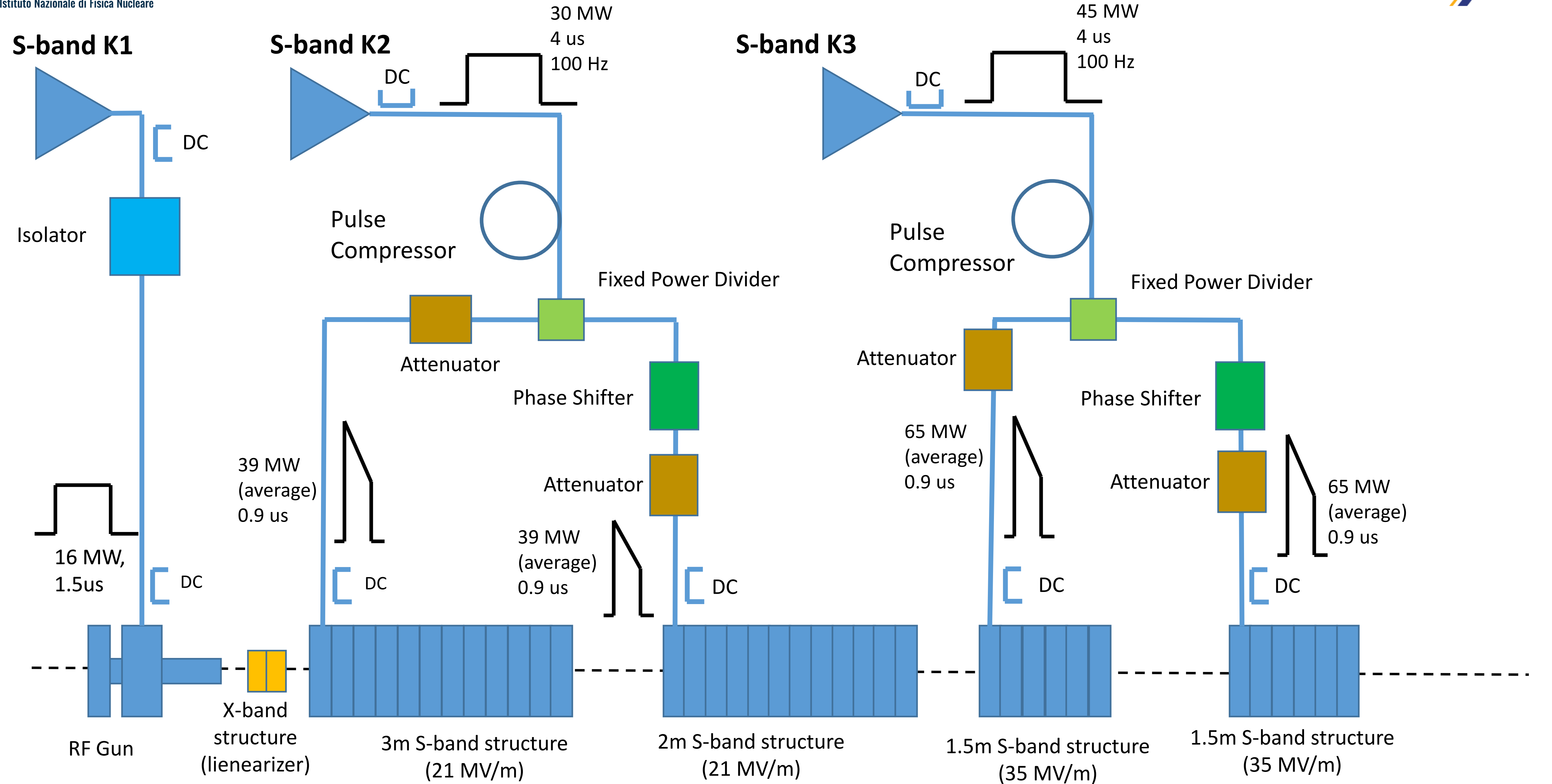

*Courtesy of E. Di Pasquale*

# S BAND INJECTOR MECHANICAL LAYOUT




*Courtesy E Di Pasquale*

# S BAND INJECTOR RF SCHEMATIC LAYOUT



# S BAND STRUCTURES PARAMETERS

| PARAMETER | Structure lenght | |
|---|---|---|
| | 3 m | 2 m |
| Frequency [GHz] | 2.856 | |
| Average acc. gradient [MV/m] | **21** | **35** |
| Number of Structures | 2 | 2 |
| Iris radius a [mm] | 11.76 | 10.65 |
| Tapering of structure | 2π/3 C.I. | |
| No. of cells | 85 | 57 |
| Shunt impedance R [MΩ/m] | 56 | 59 |
| Effective shunt Imp. $R_{sh\_eff}$ [MΩ/m] | 109 | 114 |
| Peak input power in the structure [MW] | 67.2 | 120 |
| Input power averaged over the pulse [MW] | 38.6 | 69 |
| Average dissipated power [kW] | 3 | 5.1 |
| $P_{out}/P_{in}$ [%] | 32 | |
| Filling time [ns] | 920 | |
| Peak Modified Poynting Vector [W/μm$^2$] | 0.43 | 1 |
| Peak surface electric field [MV/m] | 70 | 115 |
| Unloaded SLED/BOC Q-factor $Q_0$ | 150000 | |
| External SLED/BOC Q-factor $Q_E$ | 21000 | |
| Required Kly input power (w/o att.)[MW] | 12.1 | 21.5 |
| RF pulse [μs] | 4 | |
| Rep. Rate [Hz] | 100 | |

Klystron **Canon** E37314

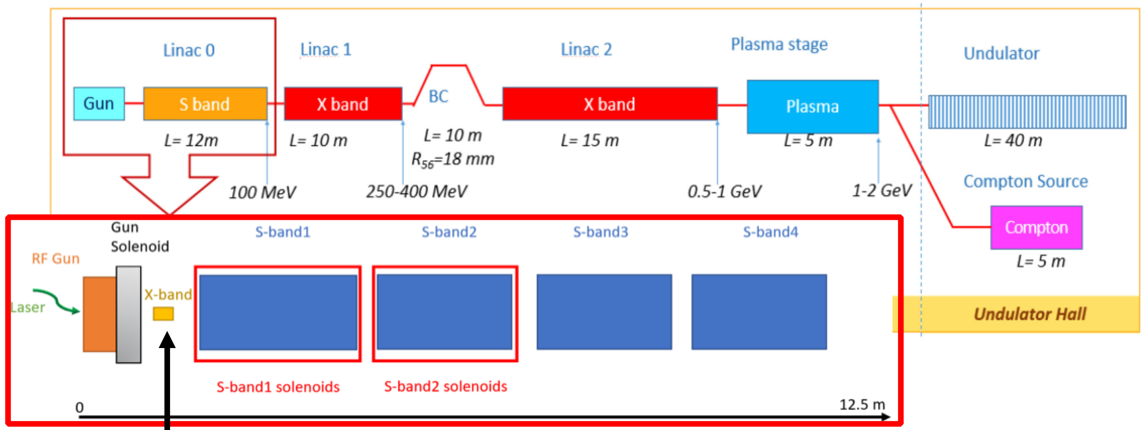
| PARAMETER | Value E37314 |
|---|---|
| Frequency [GHz] | 2,856 |
| Maximum ouput power [MW] | 60 |
| Average power [kW] | 24 |
| Efficiency (%) | 41 |
| Gain (dB) | 53 |
| Pulse Length (μs) | 4 |
| Rep. Rate [Hz] | 100 |
| Beam Voltage [kV] | 360 |
| Beam current [A] | 412 |

Required klystron powers (considering the waveguide attenuation):
K2 ⇒~30-35 MW
K3 ⇒~45-50 MW

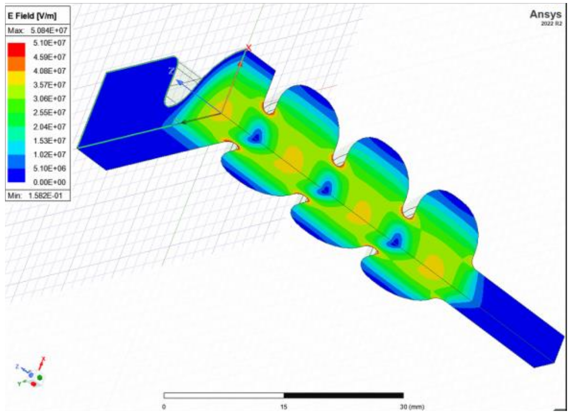
**K1: Modulator k300 + Klystron Canon E37314**

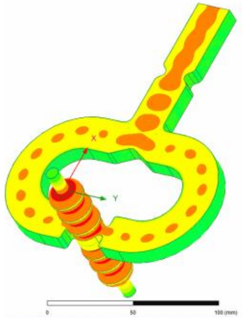
**K2&K3: Modulator k400 + Klystron Canon E37314**

# X-band Linearizing Cavity and POLARIX deflectors

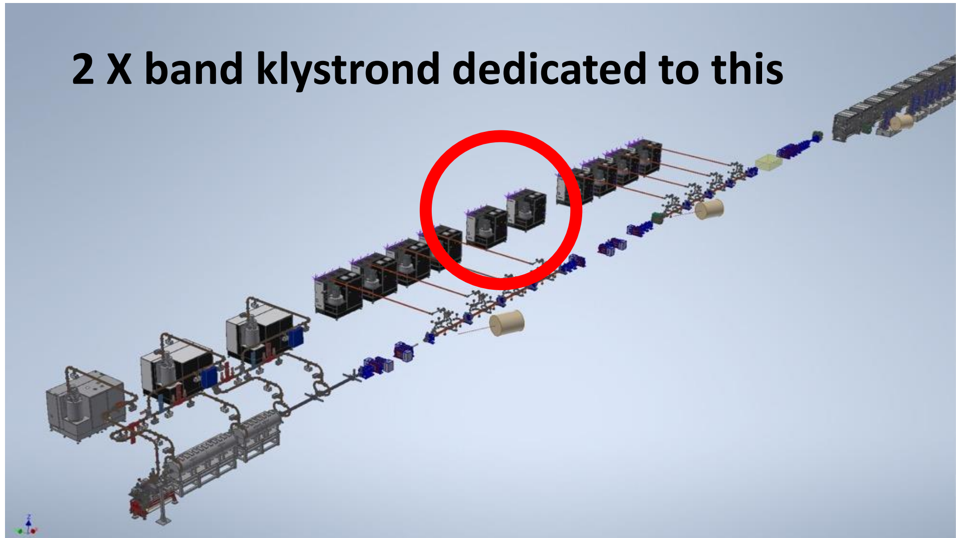



| X-band | |
|---|---|
| Resonant frequency | 11.9942 GHz |
| E acc | 20 MV/m |
| E peak | 38 MV/m |
| Number of cells | 7 |
| Length | 11 cm |



| a = 4 mm | TW | SW |
|---|---|---|
| f | 11.9942 GHz | 11.9942 GHz |
| Q | 6600 | 8,600 |
| Vg | 3.6 % | - |
| r | 85.3 MΩ/m | 80 MΩ/m |
| Eacc | 16.5 MV/m | 16.3 MV/m |
| alpha | 0.63 1/m | - |
| Lt | 10 cm | 10 cm |
| Coupling β | - | 2 |
| Fill time Tf | 9.3 ns | - |
| Build up τ | - | 76 ns* |
| Pin | 3.2 MW | 0.37 MW |



INFN LNF Istituto Nazionale di Fisica Nucleare

# X-BAND/S-BAND LLRF ACTIVITIES

EuPRAXIA

Requirements phase jitter (compliant with BD requirements):
- **0.02 deg S band** (S-band RF stability state of the art (PSI))
- **0.06 deg X band**

*[1] L. Piersanti et al. "RF power station stabilization techniques and measurements at LNF" In Proc. IPAC24 - TUPR01.*
*[2] L. Piersanti et al. "Design and test of a klystron intra-pulse phase feedback system for electron linear accelerators" Photonics 2024, 11(5), 413.*

⇒ **We cannot develop the system in house** because of the complexity, dimension, maintenance for a user facility.

⇒ **2 industrial partners** willing to participate to X-band LLRF R&D (Instrumentation Technologies - solid LLRF experience, Safran - new to high frequency applications);

⇒ The **internal procedures** for the tender for the production of the whole LLRF system should **start by the end of 2024**;

⇒ Detailed **jitter studies on X-band power station carried out at TEX facility in February 2024** [1] (no klystron loop):
1. Driver added jitter: <0.04 deg rms
2. Klystron added jitter: <0.04 deg rms
3. LLRF added jitter (tender spec.): <0.015 deg rms
4. **Estimated RF station jitter: <0.06 deg rms**

⇒ **Dedicated stability measurements** will be carried out at SPARC in S band after the SABINA upgrade.

⇒ We believe also that **with solid state modulator and klystron loops** we can have an additional jitter reduction from new fast intra-pulse phase feedback system [2] to be evaluated for S-band and X-band stations at SPARC and TEX respectively.

⇒ **Jitter compression down to 0.019 deg rms already demonstrated for C-band** station at SPARC in Dec 2023.

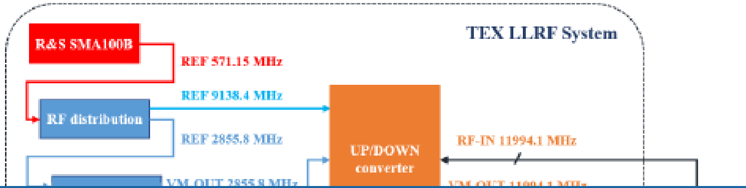



Figure 3: TEX facility RF block diagram.

EX LLRF rack.


*Courtesy RF group*

# Highlights

⇒ **EuPRAXIA@SPARC_LAB** is the next INFN-LNF facility. It is the beam driven pillar of the European EuPRAXIA project

⇒ The new machine include **10 X band power stations**: baseline **CANON E37119**

⇒ **TEX (Frascati Test stand for X-band)** is of fundamental importance to validate all the X band components, structures

- A new X-band RF source based on the **E37119 klystron** (25 MW, 400Hzwill be commissioned at TEX in the next months, together with a **C-band** source for C-band photoinjector testing.
- A **high efficiency klystron 50 MW VKX8311HE** developed by CPI/CERN should be commissioned in end 2025.

⇒ Many **X-band RF components** of the EuPRAXIA RF module have been purchased and tested at nominal power other will be tested soon:

- The X-band BOC from PSI
- The hybrid

# THANK YOU FOR YOUR ATTENTION!

⇒ **X-band structures**: An intensive prototyping activity is ongoing exploiting the new vacuum furnace at LNF (Two **full-scale mechanical prototypes,** the **20 cells CI RF prototype,** A **full-scale 0.9m RF prototype** for high power test is in production**.**

⇒ **For the S band Injector 60 MW CANON Klystron are foreseen**

***Aknowledgements***:

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