TEX (TEst stand for X-band) at LNF

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I. EuPRAXIA@SPARC_LAB project and linac
II. TEst stand for X-band
III. TEX facility components:
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   b. The LLRF system
   c. The Control system
   d. The building refurbishment
   e. The Safety System
   f. The Vacuum System
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IV. Conditioning of waveguides and loads
V. Current TEX Layout
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VII. Conclusions
The project EuPRAXIA@SPARC_LAB aims at constructing a FEL radiation source based on RF LINear ACcelerator combined with a plasma module [1,2].

The project is in a preparatory phase of the TDR for this machine.

The project is one of the pillars of the European Project EUPRAXIA (coord. R. Assmann, http://www.eupraxia-project.eu/) that has been included in the ESFRI 2021 Roadmap.

A new building, now under executive design phase will host the new Facility at LNF.

Overview of the RF LINAC DESIGN

The RF baseline of the LINAC is the X-band technology, and 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 boost the energy further before the undulators.

S-band (2.856 GHz) injector composed by a photocathode RF Gun and 1x 3m TW S-band structure and 3x 2m TW S-band structures.

X-band (11.994 GHz) booster composed by 16x TW, 0.9m accelerating structures with a nominal gradient of 60MV/m.

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To investigate and test the reliability of the X-band technology for the realization of this booster, all the components, from the source to the accelerating sections, must be tested at the nominal power and working conditions.

As first step in Dec. 2017 an agreement with CERN is signed by INFN.

Therefore, the first step was to install a copy of the CERN X-band station at LNF.

It was be in LNF building #7, very close to the SPARC_LAB area, formerly used for testing and conditioning of the DAFNE RF power plants and cavities.

The X-band test facility, called TEX [3], has been final commissioned last year (2022) in our laboratory and is currently in operation [4].

The main steps was:

- Decommissioning of the old RF Bunker used to test the DAFNE Cavity.
- Design and Commissioning of the new bunker, control room, computing room, storage and auxiliary system (logistics, fluids, safety, radioprotection system...).
- Request to the ALL the Authorities the authorizations.
- Modulator k400 procurement and installation of the klystron and components provided by CERN.
- Install RF other components.

The TEst-stand for X-band (TEX) is 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.

It provides all the challenges to build an accelerator with all the subsystems:

- **Vacuum system**
- **Safety system**
- **Control system**
- **LLRF system**
- **Fluids system**
- **Modulator**
- **Klystron**
The installation and commissioning of the **Modulator and klystron** has been completed in February 2022.

**The pulse stability** is measured at level of 10ppm during the SAT

**The klystron curve was verified respect the curve provided by CERN and CPI.**

### Pulsed Modulator: to be procured by INFN

<table>
<thead>
<tr>
<th>OPERATIONAL PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pulse Output</strong></td>
</tr>
<tr>
<td>Peak power in Klystron</td>
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<tr>
<td>Average power in Klystron</td>
</tr>
<tr>
<td>Klystron Voltage range</td>
</tr>
<tr>
<td>Klystron Current range</td>
</tr>
<tr>
<td>Inverse Klystron Voltage</td>
</tr>
<tr>
<td>Pulse length at 50% peak</td>
</tr>
<tr>
<td>PRF drop cycle</td>
</tr>
<tr>
<td>Top flatness (mT)</td>
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<tr>
<td>Amplitude stability</td>
</tr>
<tr>
<td>Trigger delay</td>
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<tr>
<td>Pulse to pulse jitter</td>
</tr>
<tr>
<td>Pulse length jitter</td>
</tr>
<tr>
<td><strong>Filament Output</strong></td>
</tr>
<tr>
<td>Klystron-Max voltage OC</td>
</tr>
<tr>
<td>Klystron-Max current DC</td>
</tr>
<tr>
<td>Hg. H2 Current stability</td>
</tr>
<tr>
<td>Pre-heating period</td>
</tr>
</tbody>
</table>

### Typical Operating Parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Voltage</td>
<td>410</td>
<td>kV</td>
</tr>
<tr>
<td>Beam Current</td>
<td>310</td>
<td>A</td>
</tr>
<tr>
<td>Frequency</td>
<td>11.994</td>
<td>GHz</td>
</tr>
<tr>
<td>Peak Power</td>
<td>50</td>
<td>MW</td>
</tr>
<tr>
<td>Ave. Power</td>
<td>5</td>
<td>kW</td>
</tr>
<tr>
<td>Sat. Gain</td>
<td>46</td>
<td>dB</td>
</tr>
<tr>
<td>Efficiency</td>
<td>40</td>
<td>%</td>
</tr>
<tr>
<td>Duty</td>
<td>0.009</td>
<td>%</td>
</tr>
</tbody>
</table>

### Output Power vs. Drive Power

- Green line: $V_k = 430$ kV
- Blue line: $V_k = 400$ kV

![Output Power vs. Drive Power graph]
The Low Level RF System The X-band LLRF systems was developed starting by the available on the market S-band system, the Libera LLRF, manufactured by Instrumentation Technologies, whose features and performance have been already reviewed for ELI-NP and SPARC_LAB for a similar architecture[3].

The systems has been adapted to work at 11.994 GHz by LNF RF team developing:

- a reference generation and distribution system able to produce coherent 2.856 GHz S-band and 11.994 GHz X-band references;
- an X-band up/down converter;
- Promising results have been obtained, with a measured amplitude and phase jitter of the klystron forward output power of 0.04 % and 20.7 fs respectively
- it does not seem the optimal choice for an X-band based LINAC for various discussed in the reference [3].

Figure 4. TEX LLRF rack.

Figure 5. Measured amplitude and phase jitter of klystron output forward power. The measurements refer to 20 MW, 300 ns at 50 Hz repetition rate RF pulses.

TEX Facility: the control system

- TEX has selected a standardized, field-proven controls framework, EPICS, which was originally developed jointly by Argonne and Los Alamos National Laboratories.
- Currently we proceed in the integration of all the hardware equipment present at TEX. IOCs and support modules for any family of device have developed or acquired from repositories, as shown in Table 1.
- An instance of EPICS Archiver Appliance from SLAC to handle the data storage of the facility.
- About User Interfaces (UI) we involved, Table 2, reliable state-of-art graphic interfaces tool to simplify maintenance and improve user experience, Fig. 4 and 5, for TEX operators and users[4].

A SAN for the long-term store - in this storage stage, we store data at a granularity of a month. This stage is physically located at CNAF data center, the INFN European Open Science Cloud (EOSC) pillar of the INFN.

TEX Facility: The building refurbishment

» A new control room
» A new meeting room
» A new computing center
» A modulator area
» A new concrete bunker
TEX Facility: the safety system


» compliance with:
  » • IEC-61508 standard on “Functional Safety”
  » • NCRP reports 88 on “Radiation Alarms and Access Control Systems”
  » • ANSI reports 43.1 on “Radiation Safety for the Design and Operation of Particle Accelerator”

» For these reason we developed Personnel Safety System (PSS) and Machine Protection System (MPS) through FPGA based devices [5, 6] to provide hard-wired, fast and reliable protection to TEX

The Vacuum system in TEX was provided by Accelerator Division Vacuum Service with the support of Mechanical Service.

Since the Device Under Test could change rapidly in a TEST Facility, a lot of efforts is required to define vacuum operation procedure for the X band components (cleaning, backing......).

In 6 months we pass from a configuration A to configuration B to configuration C.

The control of the vacuum quality is provided by the TEX Control System and the Vacuum Status Control panel is available to the operators as the vacuum gauge value and vacuum level value deducted by the ion pump current.

A) RF load: leak check.  
B) RF Spiral load.  
C) A T24 CLIC structure and spiral loads
TEX cooling system is based on the EuPRAXIA@SPARC_LAB project guidelines developed by Technical Division at LNF. To reduce the facility opex, the system doesn’t use chiller or cooling tower but it’s based on adiabatic dry cooler and two independent circuits[†].

1) The secondary cooling system keeps the modulator temperature setpoint (28°C) mixing cold water from the dry cooler and the modulator exhaust water. The primary system cools the water through the adiabatic dry cooler with minimization of electrical cost and water consumption. A demineralization system maintains the water conductivity at the level required by the system components (< 1µS/cm). The cooling circuit test for the RF components is performed with a Peltier chiller with thermal stability designed better than 0,03°C.

2) A PLC based system controls all the cooling system variables and adjusts parameters actuator to maintain the process variable at the setpoint value. Remote control and operation is allowed by a SCADA system.

3) The bunker thermalization and ventilation is provided by a AHU installed on the bunker rooftop and will be controlled by the same SCADA as the cooling .

[†] S. Cantarella et al. Private communication.
A conditioning run of the waveguide distribution line terminated on two 3D printed Titanium Spiral Load 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 work in the building.

The FWD Klystron power has been gradually increased with an automatic conditioning routine integrated in the control and machine protection system [7].

In April 2023 we installed inside the bunker a CERN accelerating section of the T24 CLIC type. The complete setup is being implemented in these weeks.
Next TEX activities:

- A **BOC pulse compressor** will be integrated in the layout in order to increase the available power provided by PSI.
- Study of design on Pump. Unit, Dir Coupler, Loads, Mode Converter, BOC and section is ongoing.
- All the elements of the baseline design of the X band module of the **EuPRAXIA@SPARC_LAB** will be procured by in house or in outsourcing and it will be tested at TEX in the next years [8-10].

[8] F. Cardelli IPAC2023 X Band Activities at INFN-LNF (MOOG1)
A new Modulator for the CANON E37119 (nominal value 25MW 400 Hz) is scheduled to be installed in 2024.

A new HE Klystron CPI VKX8311HE it’s ordered, and it will be tested at TEX.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Canon E37119</th>
<th>CPI VKX8311HE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>MHz</td>
<td>11994</td>
<td></td>
</tr>
<tr>
<td>Vb beam voltage</td>
<td>kV</td>
<td>318</td>
<td>415</td>
</tr>
<tr>
<td>Ik cathode current</td>
<td>A</td>
<td>197</td>
<td>201</td>
</tr>
<tr>
<td>Peak drive power</td>
<td>W</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Peak RF output Power</td>
<td>MW</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Average RF output power</td>
<td>kW</td>
<td>15</td>
<td>7.5</td>
</tr>
<tr>
<td>Modulator Average power</td>
<td>kW</td>
<td>75.2</td>
<td>25</td>
</tr>
<tr>
<td>RF pulse length</td>
<td>us</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>Hz</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>Gain</td>
<td>dB</td>
<td>47</td>
<td>50</td>
</tr>
<tr>
<td>Efficiency</td>
<td>%</td>
<td>40</td>
<td>55</td>
</tr>
</tbody>
</table>
Conclusions and Acknowledgements

- **EuPRAXIA@SPARC_LAB** is the next INFN-LNF project.
- **TEX (Frascati Test stand for X-band):** is the facility to test all RF components and X band prototypes at the nominal power/gradient. It has been commissioned and in operation.
- A **T24 CLIC structure** test is started yesterday.
- A design and procurement of **X-band RF components** of for EuPRAXIA RF module have been purchased and will be tested at TEX.
- An upgrade program of the facility is ongoing.

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