HIGH POWER TEST RESULTS OF THE SPARC C-BAND ACCELERATING STRUCTURES

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1. C-BAND @ SPARC

2. DESIGN AND REALIZATION

3. HIGH POWER TEST

4. NEXT STEP: HOM DAMPED-HIGH REP. RATE C-BAND ACCELERATING STRUCTURES FOR ELI-NP GAMMA BEAM SYSTEM
SPARC_LAB is a facility @ LNF-INFN based on the unique combination of **high brightness electron beams** with **high intensity ultra-short laser pulses** oriented to a wide spectrum inter-disciplinary leading-edge research activities.
The energy upgrade of the SPARC photo-injector at LNF-INFN from 170 to more than 240 MeV will be done by replacing a low gradient S-Band accelerating structure with two C-band structures. The structures are TW and CI, have symmetric axial input couplers and have been optimized to work with a SLED RF input pulse. In the SPARC photoinjector the choice of the C-band for the energy upgrade was dictated by the opportunity to achieve a higher accelerating gradient, enabled by the higher frequency, and to explore a C-band acceleration combined with an S-band injector that, at least from beam dynamics simulations was very promising in terms of achievable beam quality.
Structure design criteria:

- **CONSTANT IMPEDANCE** (all equal irises) to simplify the fabrication and to reduce the unbalance between the accelerating field at the entrance and at the end of the structure, due to the combination of power dissipation along the structure and SLED pulse profile.

- **LARGE IRISES WITH ELLIPTICAL SHAPE** to
  
  - reduce the peak surface field obtaining at the same time an average accelerating field $>35$ MV/m with the available power from the klystron;
  
  - reduce the filling time of the structure and, consequently, the RF input pulse length thus reducing the breakdown rate;

  - reduce the dipole wake intensity

  - increase the pumping speed.

- **WAVEGUIDE COUPLER design** based on “low pulsed heating” couplers for high gradient operation of X Band structures (SLAC).
The high-power test started on November 5, 2010 and was completed on December 13, 2010. For almost one month of processing, from November 5 until December 2, more than **10^8 RF pulses of 200 ns** width were sent into the structure with a repetition rate of **50 Hz**. For a couple of days the RF pulse length was changed to 300 ns and for one day (November 12) the repetition rate was decreased to 25 Hz. On November 15, SKIP was switched on.

After the high power test the structure has been **cut in slices** for an **internal inspection**. We have identified the signs of craters and discharges mainly in the first accelerating cell after the input coupler, as expected, because the highest field values are excited at the beginning of CI structures.
The main problems were related to the fact that we do not have a vertical >1.5 m long oven for brazing and we had to braze the structures in several steps.

Each brazing step is a structure “stress”, requires a full control of the process and introduces unknowns since the success of the brazing cannot be guarantee at 100% even with a long experience.

The design, machining and brazing of a new (complicated) structure (such as the SPARC C-band structures), require a strong activity of R&D and prototyping at least in the first phase to investigate all possible criticalities (RF, mechanical).

For the SPARC C-band structures, we have fabricated only one small prototype before starting the construction of the first complete structure and this is the reason why we had to re-machine and re-cut the first structure a couple of time. In other words the first structure has been a prototype.

At LNF-INFN this experience has been the first experience of a complete in-house design, realization and test of a such long multi-cell TW structure. We gain a lot (a lot) of experience thanks to this work.
LOW POWER RF MEASUREMENTS ON FINAL C-BAND STRUCTURES

First fabricated C-band structure

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>final structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>5.712 [GHz]</td>
</tr>
<tr>
<td>Phase advance per cell</td>
<td>$2\pi/3$</td>
</tr>
<tr>
<td>Number of accel. cells</td>
<td>71</td>
</tr>
<tr>
<td>Structure length</td>
<td>1.4 [m]</td>
</tr>
<tr>
<td>Group velocity/c</td>
<td>0.0283</td>
</tr>
<tr>
<td>Field attenuation</td>
<td>0.206 [1/m]</td>
</tr>
<tr>
<td>Average accelerating field</td>
<td>&gt;35 MV/m</td>
</tr>
<tr>
<td>Shunt impedance (r)</td>
<td>82.9 [MΩ/m]</td>
</tr>
<tr>
<td>Filling time</td>
<td>150 [ns]</td>
</tr>
<tr>
<td>Surf. peak E field/Acc. field</td>
<td>2.17</td>
</tr>
<tr>
<td>Surf. Peak H field@ 35 MV/m</td>
<td>87.2 [kA/m]</td>
</tr>
<tr>
<td>Pulsed heating @ 35 MV/m</td>
<td>&lt;1 °C</td>
</tr>
<tr>
<td>Av. dissipated power @ 10 Hz</td>
<td>59.6 [W]</td>
</tr>
</tbody>
</table>

The new C-band power station will consist mainly of:
- C-band klystron, manufactured by Toshiba Ltd (JP)
- Pulsed HV modulator supplied by ScandiNova (S)
- WR187 waveguide system with power pulse compressor.
- 500 W solid state klystron driver supplied by MitecTelecom (CDN)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>5712 MHz</td>
</tr>
<tr>
<td>Output RF power</td>
<td>50 MW (max).</td>
</tr>
<tr>
<td>RF pulse length</td>
<td>2.5 μsec</td>
</tr>
<tr>
<td>Pulse rep. rate</td>
<td>50 pps max.</td>
</tr>
<tr>
<td>Gain</td>
<td>44 dB min</td>
</tr>
<tr>
<td>Efficiency</td>
<td>40 % min</td>
</tr>
<tr>
<td>Drive power</td>
<td>300 W</td>
</tr>
</tbody>
</table>
C-BAND STRUCTURES: HIGH POWER TEST BENCH @SPARC

Ceramic windows and power splitter

RF Loads

RF Pickup TRANS

C-Band structure

Ion pumps

RF pickup FW-RW

From KLY

Ion pumps
1) The RF conditioning has been done in three steps:
   ⇒ test of the **Klystron system** terminated into a load
   ⇒ test of the **waveguide system** up to the SPARC hall terminated into a load
   ⇒ test of the **first accelerating** structure

2) The high power test on the first C-band structure started on **Nov. 2013**. We operated at **10 Hz with the nominal pulse width of 165 ns** (slightly longer than the filling time of the structure).

3) We progressively increased the power from the klystron (increasing the HV of the modulator) monitoring:
   ⇒ the **current absorption of the 4 ion pumps** (3 connected to the structure and 1 to the waveguide);
   ⇒ the **RF signals from pickups**.
1) The *conditioning procedure was semi-automatic* and the switch-off on the HV were caused by:

- **operator**
- **ion pumps current absorption** above a certain threshold (50 μA corresponding to a vacuum of 10⁻⁷ mbar) including the ion pump absorption directly connected to the KLY output;
- **KLY interlocks** (tube vacuum, modulators interlocks);

2) We normally operate at a *vacuum level in the structure between 5⋅10⁻¹⁰ mbar and 2⋅10⁻⁹ mbar*.

3) The *duration of the RF conditioning (not h24) was about 10-15 full days equivalent*! We have finally reached:

- **38 MW input power in the structure** (44 MW from the klystron), *nominal rep. rate and pulse length*.
- the corresponding accelerating field was **36 MV/m peak and 32 MV/m average**
- **BDR <10⁻⁵** but even less because a correct measurements of the BDR require a long time and we would to test both structures in a shorter time!
- **340 KV modulator voltage**
The SKIP SLED has been fabricated in IHEP (Beijing). It has been fixed to the SPARC experimental hall ready for waveguide connection.
C-BAND LLRF

A **stable and flexible digital low level RF system** to control the input to the RF amplifiers and monitor the RF signals of the high gradient C-band accelerating structures at SPARC test facility has been designed and fabricated by PSI Institute in the framework of the **TIARA project**. The **LLRF system has been integrated into the SPARC control system** by implementing an EPICS/LabVIEW interface using the EPICS CA drivers in LabVIEW programming environment that is fully compatible with the SPARC_LAB control system.

**Analogue part**
- Number of RF signal receivers: 12 + 4 spares
- RF Frequency 5.712 GHz
- IF Frequency 39.666 MHz
- Bandwidth (3dB) ±18 MHz
- Phase resolution < 15 fs or 0.03 deg
- Amplitude error ≈ 0.1 dB (10 dB range)

**Digital part**
- 16 ADC channels (to sample IF waveforms)
- 4 DAC channels (for vector modulator control)
- FPGA for signal processing
- EPICS server implemented in the main CPU
In the context of the ELI-NP Research Infrastructure, to be built at Magurele (Bucharest, Romania), an advanced Source of Gamma-ray photons is planned, capable to produce beams of mono-chromatic and high spectral density gamma photons. The Gamma Beam System is based on a Compton back-scattering source. Its main specifications are: photon energy tunable in the range 1-20 MeV, rms bandwidth smaller than 0.5% and spectral density larger than $10^4$ photons/sec.eV, with source spot sizes smaller than 10-30 microns.

For this LINAC high gradient/high rep rate and damped structures (for multi-bunch operation) are required to allow an high gamma flux and a compact source.

### Parameters

<table>
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</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge</td>
<td>250 pC</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>32</td>
</tr>
<tr>
<td>Bunch distance</td>
<td>16 ns</td>
</tr>
<tr>
<td>C-band average accelerating gradient</td>
<td>33 MV/m</td>
</tr>
<tr>
<td>Norm. emittance</td>
<td>0.2-0.6 mm·mrad</td>
</tr>
<tr>
<td>Bunch length</td>
<td>&lt;300 μm</td>
</tr>
<tr>
<td>RF rep Rate</td>
<td>100 Hz</td>
</tr>
</tbody>
</table>
Since the ELI-NP linac operation is necessarily multi-bunch, in order to achieve the requested photon flux, the structures have been designed with an effective damping of the HOM dipoles modes to avoid BBU instabilities. The solution adopted for the ELI-NP structures is based on a waveguide damping system, similar to the design adopted for the CLIC structures, but the mechanical design has been strongly simplified with respect to CLIC-type structures to reduce the cost and to simplify the fabrication.
CONCLUSIONS

1. C-Band “adventure” started @ LNF for the SPARC energy upgrade-single bunch operation.

2. The first prototype (22 cells) has been tested at gradients >50 MV/m.

3. The two final C-band structures have been designed, fabricated and tested at high power reaching stable operation at gradients of 35 MV/m.

4. The next and important step is the realization of damped-high rep rate C-band structures for multi-bunch acceleration developed for the ELI-NP Gamma Beam System.

...THANK YOU FOR YOUR ATTENTION