

Upgrade of the C-band pulsed power solid-state modulator at SPARC_LAB

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Abstract

This paper reports the recent upgrade of the ScandiNova solid-state pulsed modulator used in the C-band RF power station of the SPARC_LAB Linac and the first results obtained during the consequent operation. The system has been upgraded in order to solve some critical issues occurred during the use of modulator and klystron for the RF pulse compressor conditioning. The main actions that have been carried out, are: (i) the installation of a brand new kind of socket for the klystron connection (ii) the installation of additional and more precise diagnostics for the high voltage pulse generated by the modulator, (iii) the replacement of the low inductance cables between switching units and transformer primary. During the upgrade work, additional criticalities have been detected and technical solutions have been implemented in order to solve them. The status of the entire C-band RF power system and all the works performed on the modulator system are extensively treated in this document.

1 - The RF power system at SPARC_LAB

In Figure 1 is reported the schematic layout of the SPARC_LAB Linac radiofrequency (RF) system.

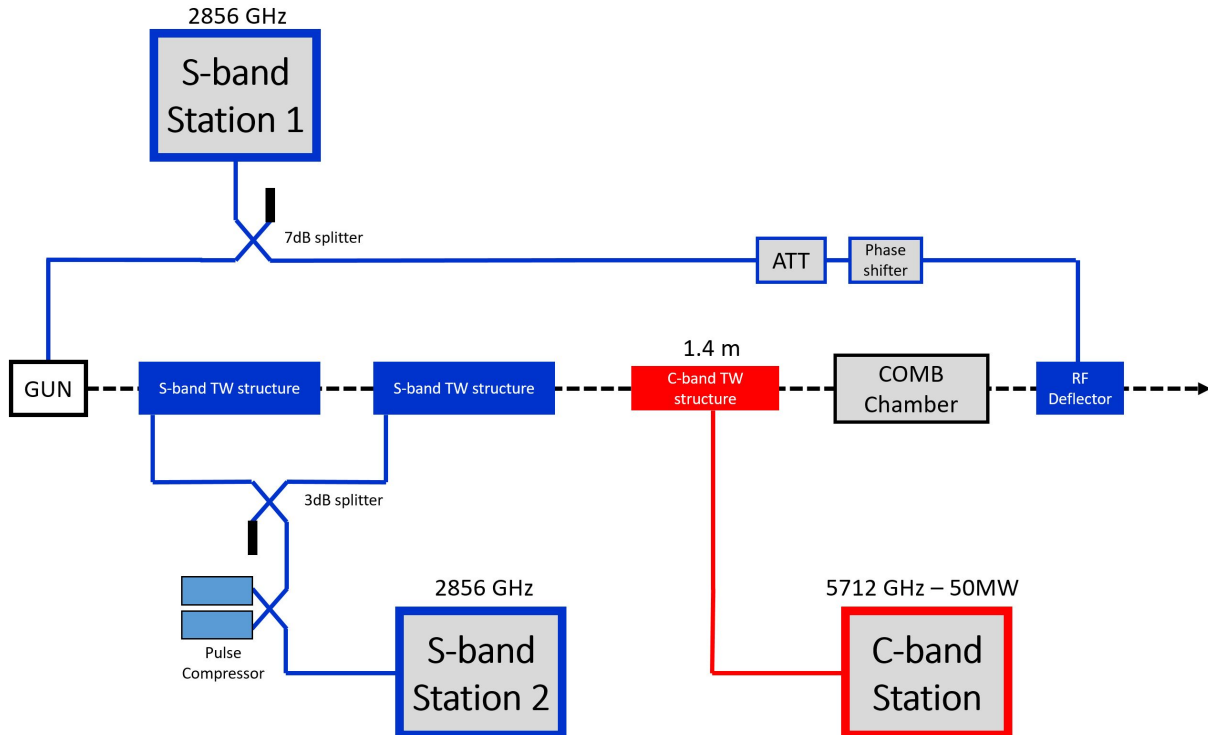


Figure 1: SPARC_LAB Linac RF System layout

Three power stations, working at two different frequencies, compose the system. The first two are S-band (2856 MHz) power sources, each one composed by a Thales TH2128C klystron powered by a conventional PFN (pulse forming network) modulator produced by PPT. These sources are able to generate RF pulses of 45 MW saturated power for 4.5 μ s at 10 Hz. The first source feeds the RF Gun and a RF deflector, while the second source feeds two 3m S-band SLAC type accelerating structures by means of a pulse compressor system (SLED [1]). The SLED is used to increase the peak power at the input of the structures by a factor 3 shortening the pulse length to 0.8 μ s. The power downstream the pulse compressor is, then, divided through a 3dB splitter, so to achieve the 52 MW requested by the sections to reach the maximum accelerating gradient. The last power source is C-band (5712 GHz) and it is composed by a Toshiba [2] E37202 klystron powered by a K2 ScandiNova [3] solid-state modulator and driven by a 400 W solid state driver amplifier manufactured by Microwave Amplifier [4]. This source directly feeds a 1.4 m travelling wave C-band accelerating structure. Originally, the accelerating structure was powered by a C-band “SKIP” RF pulse compressor [5], but it has been removed due to its high discharge rate when powered by RF. The C-band accelerating structure has been design and brazed at INFN-LNF and is extensively described in [6].

2 - C-band power source upgrade

During the commissioning of the C-band system, different critical issues have occurred in the power source. After few working hours, a vacuum leak at the cathode ceramic of the klystron was detected. After the klystron removal, a hole in the klystron ceramic and a serious damage on the socket of the modulator have been discovered. In particular, in the modulator tank, many different points of the klystron socket, were burnt by a hard discharge event. The occurrence of these failures has highlighted the need to upgrade some components of the modulator and plan a work program to prevent the repetition of similar issues. Therefore, the broken klystron has been shipped back to Toshiba, for ceramic analysis, and replaced with a new one. Thus together with the ScandiNova engineers, three main hardware interventions have been planned: an upgrade of the klystron socket, the installation of new diagnostics inside the oil tank and the substitution of the HV cables feeding the pulse transformer. Furthermore, the grounding system of the entire modulator has been optimized by creating a central node. These interventions aimed to improve the reliability, safety and performance of the entire system, in order to minimize failures of the klystron. In the following chapters, the three main interventions are described in detail.

2.1 - Klystron socket upgrade

The original socket of the K2 ScandiNova modulator consisted in a plug composed by four metallic rods. Three feed the klystron cathode with the modulator HV. The electrical connection is realized by means of brush, charged by spring contacts. The fourth (central) rod feeds the filament (see Figure 2). These rods were mounted on a metal corona ring sustained by a bakelite triangular plate. The triangular bakelite socket plate together with an additional dielectric base plate, separates and isolates the corona ring from the klystron cathode. On the lower side of the plate, the corona ring was linked to two twisted cables that were connected directly to the high voltage side of the pulse transformer. After the last klystron fault, it seemed that the bakelite layer of the socket plate did not hold the isolation required in the horizontal plane causing a discharge.

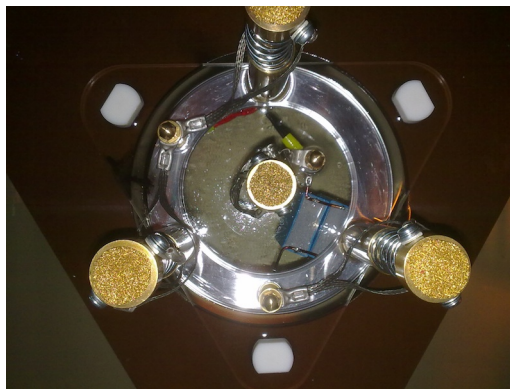


Figure 2: Old klystron Socket inside the modulator oil tank. Damages caused by arcs are present and visible on the left of the base plate near the corona ring.

The socket upgrade consisted of the complete removal of the old support and all its parts. This has been replaced with a new one composed by a more rigid insulating socket plate that supports, on the

lower side, a metallic cap that terminates a coaxial cable. The coaxial cable is realized by a copper empty tube, tailored for this application, and two twisted cables (2x2.5 mm² red and 2x2.5 mm² black) used as inner conductors (see Figure 3). The black and red cables transport the high voltage (HV) signal, up to 366 kV, to the klystron cathode. Furthermore, there is a potential difference between them, equal to the filament voltage. In order to keep this potential difference, they are divided by two 680 nF capacitors on the klystron side and two on the transformer side (see Figure 4). On the klystron side these two cables are simply screwed to the filament and the cathode of the klystron and are connected to the socket through banana plugs, to which the cables coming from the transformer are screwed. This new socket has a simpler and more rigid structure on the transformer side with the coaxial copper tube, and provides a higher insulation around the klystron cathode and filament area with respect to the previous one.

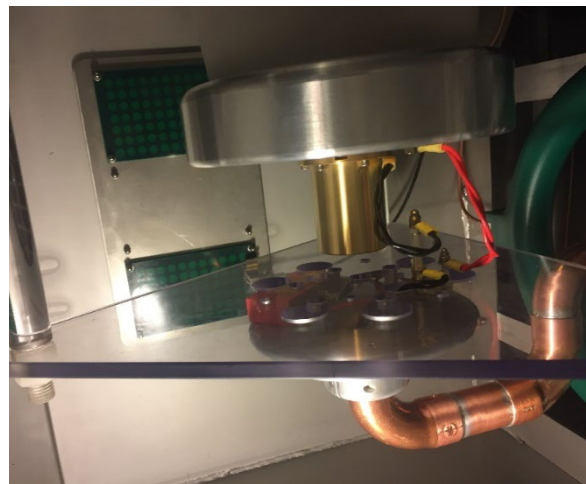


Figure 3: Pictures of the new socket in place without insulating oil.

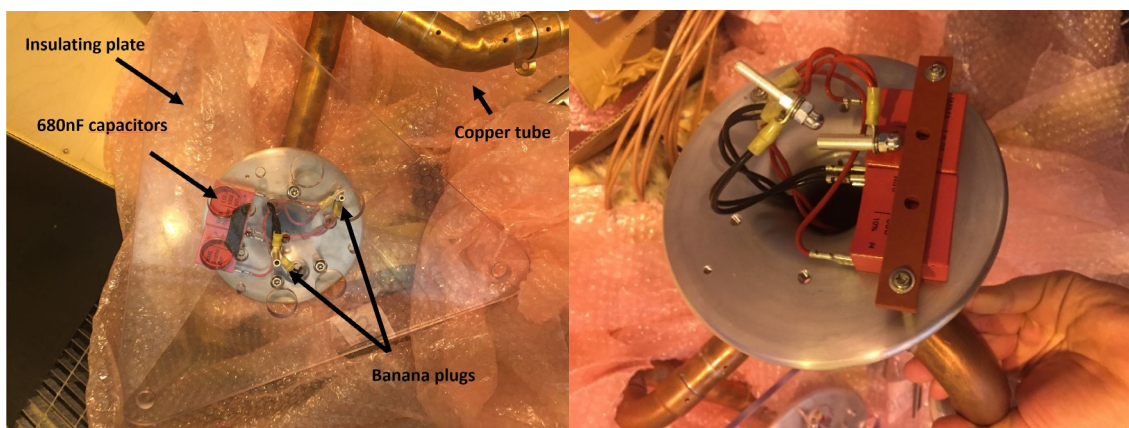


Figure 4: (a) Picture of the new klystron socket and (b) detail of connectors on the transformer side.

2.2 - New diagnostics for the HV pulse

At the time of the last klystron fault, the lack of precise diagnostics needed for the output pulse characterization has led to dangerous damages of the devices. For instance, the serious deterioration found on the original bakelite socket or on the klystron ceramic, in fact, were not anticipated by any warning or interlock of the system.

To this regard, the distortions of the output pulse shape can be used to identify malfunctions inside the tank, and thus to interlock the modulator, in order to prevent damages to the devices. To detect such distortions, a calibrated capacitance voltage divider (CVD) and a current transformer (CT) have been installed inside the tank (see Figure 5).



Figure 5: (Left) Capacitor Voltage Divider manufactured by Stangenes, (Right) Current Transformer manufactured by Pearson Electronics Inc.

The CVD has a transformer ratio equal to 1:30000 and the CT 0.1 V/A. The outputs of the diagnostics are connected to the lid of the tank where there is a feed through with insulated BNC connectors accessible from outside the tank. An oscilloscope is connected to these connectors with a calibrated 5 m long cable, allowing to measure the voltage (V_k) and the current (I_k) signals of the HV pulse just at the input of the klystron. The oscilloscope can be also programmed, applying a mask on the input signals, in order to stop the modulator trigger when the signals mask is broken, e. g. due to a discharge or other issues inside the tank. On the software Graphical User Interface (GUI) of the modulator, the value of V_k and I_k measured by two other diagnostics are reported. The voltage V_k is read by two capacitive boards, working as voltage divider, installed on the tank wall near the klystron cathode (see Figure 3). A current transformer installed on the low voltage side of the pulse transformer reads the current I_k . Both these diagnostics have been recalibrated to match the value read by the oscilloscope from the new CT and CVD.

During the diagnostics installation the pulse transformer has been removed and some slight discharge traces have been noticed at the bottom of the steel tank. These could be due to small discharges occurred between the basket that supports the transformer connected to the tank lid and the bottom of the tank. Both the basket and the tank are grounded to the tank lid but small potential differences can induce these small discharges. Hence, a fiberglass sheet has been placed at the bottom of the oil tank to avoid discharges and a new ground cable linked to the lower side of the basket has been connected directly to the tank lid.

2.3 - Replacement of the HV cables

The modulator is composed by a certain number of switching units (SUs) each one containing 6 solid state switch (IGBT) connected to the primary windings of the transformer by low inductance cable. In the intervention, these cables have been replaced by new ones characterized by an even lower inductance.

These new cables (see Figure 6) should provide a better profile of the HV output pulse of the modulator with a faster rising edge. Both the new and the old cables have the same type of “card-edge” connectors. The connection is provided by inserting the card connector inside a slot and by fixing the cable with screws. The maximum sustainable average power of this system does not allow to work at a repetition rate higher than 50 Hz. Hence, in the new modulator models these connectors have been replaced with new ones easier to connect and able to sustain higher repetition rates (up to 100 Hz).

The card edge connector of the cables is connected directly to the tank lid by feedthroughs that are connected to the primaries of the transformer. Before the connection to the primaries, the 1 kV signal from the SU goes through a tuning circuits (LC) used to flatten the modulator signal and to compensate the capacitors discharge during the generation of the pulse. In addition, this tuning circuit is integrated in the feedthroughs and a foil of Kapton is used to isolate the different internal connections. During the inspection, we found a burn mark in one of these foils and so, in order to improve the system reliability, a double layer Kapton foil has been installed for all the feedthroughs.

To modify the feedthrough and to install the diagnostics, the transformer has been removed from the tank. In order to check the insulation of the transformer all the coils of the primary windings have been tested with an insulation resistance tester at 2500 V_{dc}. Then, the tank and the transformer have been washed with oil before the installation. After closing the tank, the oil has been changed and tested. In this modulator the oil is constantly moving inside the tank and filtered. The filter cartridge has been replaced, together with the oil dehumidifier salts on the top of the tank lid.

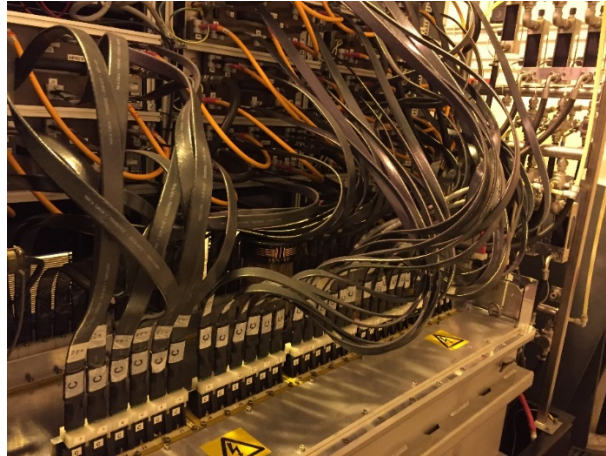


Figure 6: New low inductance cables installed.

3 - Preliminary results

After the modulator upgrade a conditioning phase of the waveguide system and the RF structure has been performed. In order to prevent klystron faults, the signals from the modulator have been continuously monitored by an oscilloscope and the klystron output power was limited to guarantee a reasonable safety margin. At the beginning, a pulse compressor with a 1.2 μs RF signal was used to amplify the klystron output power, but after some discharge events it has been removed and the RF signal length has been set to 200 ns. Recent operation of the C-band system has been performed with the modulator setup reported in Figure 7. The CVD and CT signals measured by the oscilloscope are reported in Figure 8. With a voltage set of 920 V on the SU, a voltage equal to 321 kV fed the klystron cathode and this allowed to reach a klystron output power higher than 30 MW. Considering the waveguide attenuation, this corresponds to a peak power of about 26 MW at the input of the C-band accelerating structure. Figure 9 reports the RF signals at the output of the klystron and at the input of the accelerating structure at the working point needed in the last operation of the linac (23.5 MW average at the input of the structure). Since the modulator upgrade, the system has been in operation (Trigger status) for approximately 500 hours and no major faults on the klystron have happened. However, a random noise still persists on the modulator signals measured by the oscilloscope, but it is not present on the RF signal at the output of the klystron. Hence, we concluded that it is uncorrelated with the klystron cathode area and that it could derive from the electrical power network.

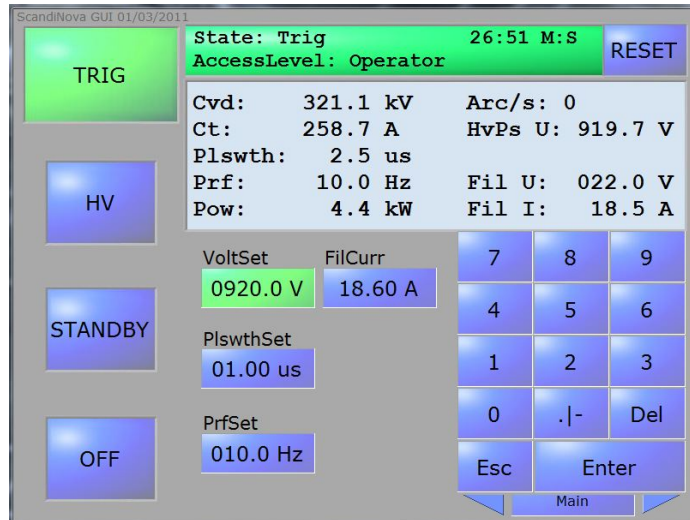


Figure 7: C-band modulator setup from the ScandiNova GUI

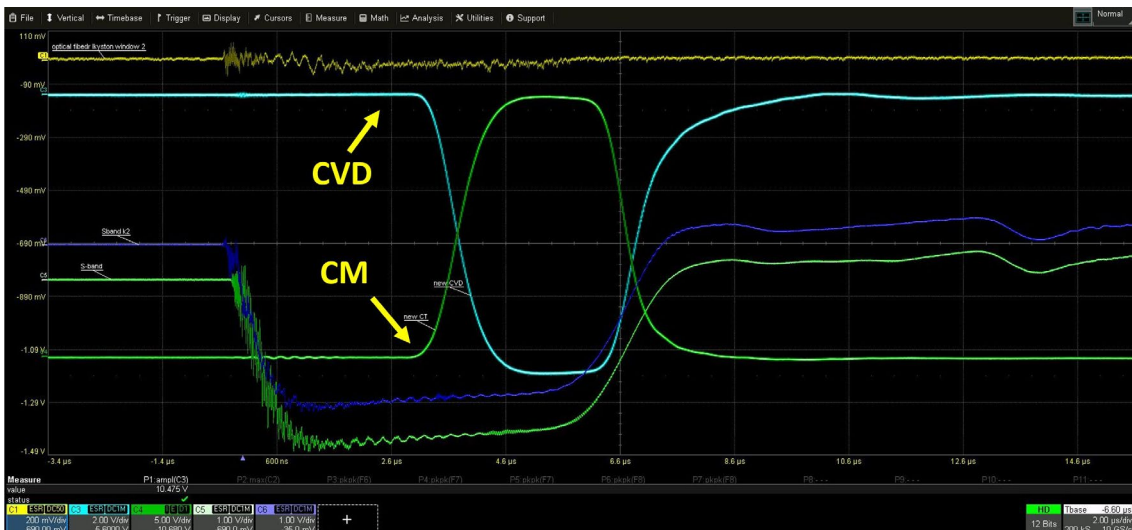


Figure 8: CVD (green) and CT (cyan) signals measured by the oscilloscope.

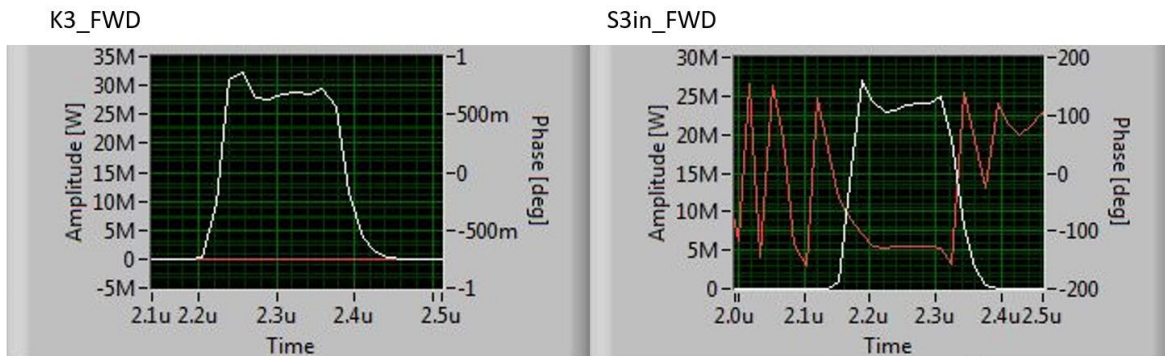


Figure 9: (Right) Output RF signal from the klystron K3_FWD, and (Left) input RF signal to the accelerating structure S3in_FWD.

Acknowledgements

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