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# REMOTE COMMISSIONING OF 400 kW 352 MHz AMPLIFIERS

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*Abstract*

In the framework of the European Spallation Source ERIC (ESS ERIC) In-Kind collaboration, Elettra Sincrotrone Trieste has the task to deliver 26 400 kW 352 MHz Radio Frequency Power Station (RFPS) units. They will feed the Spoke Cavities section of the proton Linac.

The RFPS manufacturing' contract has been awarded to the European Science Solutions consortium (ESS-C). The production of the amplifiers is well underway and it has reached a steady rate of delivery. Each RFPS is subject to a Factory Acceptance Test (FAT). In this contribution the main results of the FATs are presented, together with the FAT remote session protocol. This protocol has been specifically developed to cope with the restrictions on travels and meetings in person imposed by the COVID-19 pandemic.

## AMPLIFIER DESIGN

The amplifier delivers up to 400 kW of radiofrequency (RF) power at 352 MHz in pulsed regime, pulse 3.5 ms and 5% of duty cycle. Its design has been specified at length in the Tender documentation [1]. RF output pulse quality and stability, machine reliability and consumption optimization are the main requirements driving the amplifier design together with an easier servicing and modular design.

The RF power level is achieved combining two parallel amplification chains as shown in Fig. 1. Adjustable gain and phase are foreseen upstream both amplification arms to optimize the RF power sum balancing out possible gain drifts caused by ageing and RF cable length variances.

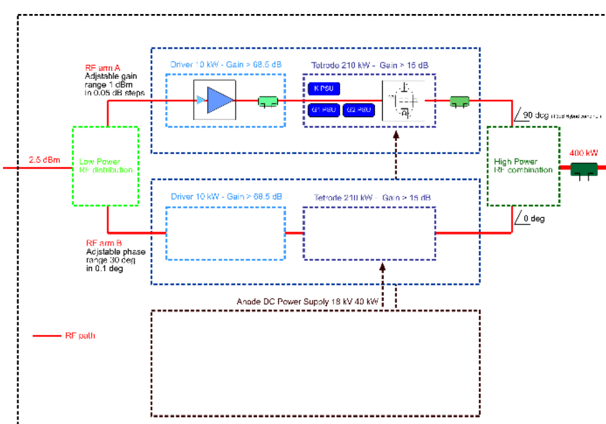


Figure 1: RF amplification chain layout.

The machine integrates the most recent technology of RF transistors up to ten kW and the well-known tetrode tubes use for the hundreds kW range. That implies a High Voltage (HV) circuit for the tube's anode and leads to a rigorous safety protection against human hazards and a fast interlock system to counteract the tube's trips and internal arcs. This complexity is however compensated by the large gain and the good efficiency achieved in a quite small machine size.

Because of the low value of the duty cycle, the amplifier efficiency has been improved by biasing the tubes and energizing the RF driver transistors only during the pulse duration. Therefore, the control grid power supply has been specifically designed with rugged IGBT solutions to withstand the impressed twice voltages pulsed regime while a dedicated set up has been implemented for the drain voltage power supply of the transistors.

All the main components of the amplifier have been arranged in standalone and modular racks for fast replacement. The electrical grid and lines have been therefore distributed and sized according to the individual unit's load. Several circuit breakers and sacrificial devices have been also implemented to protect each electrical load. The main electrical line can be cut any time by the external safety interlock in compliance with the safety rules preserving, at the same time, the tube's filaments operating time.


Figure 2: The complete amplifier.

The amplifier is built and delivered as a turn- key system, configured as shown in Fig. 2. It integrates a control system based on off-the-shelf PLC system and three custom made FPGA-based interlock boards. The PLC system controls process variables like temperature and flow rate in the milliseconds range and performs the proper machine switching on/off sequence. The FPGA based system performs the fast process variable data acquisition, synchronizes the whole amplifier with respect to the external pulse trigger and performs the fast interlock within the microseconds range. The two systems complement each other both in time response and control regime so that the net result is an amplifier control system suitable for:

- The safety interlock against human hazards.

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- The fast and slow interlock for the machine protection.
- The proper turn on/off sequence.
- The internal machine synchronization to optimize the energy consumption.
- The survey and interlock against misgiven commands, RF driving level and duration, repetition rate.
- The mitigation of the electrical grids voltage flicker due to the pulsed regime.
- The access in real time to the machine status and all parameters by means of the local display.
- The remote connection to the machine via Ethernet.

## VALIDATION

This amplifier is custom made for the specific application of the proton's Linac. Its design has been approved by a panel of experts prior to start the manufacturing of the first amplifier. In addition to this approval a probing measurement campaign has been performed on several pivotal components before their installation on the amplifier.

The first couple of TH595A Thales tetrodes and associated cavities has been extensively tested for 24 hours nonstop at the nominal RF pulse output power to test their performance and reliability for this application.

The quality and the stabilization time of the RF pulse of the 10 kW drivers has been tested at different rise times of the pulse to optimize its efficiency versus any RF envelope overshooting as shown in Fig. 3.

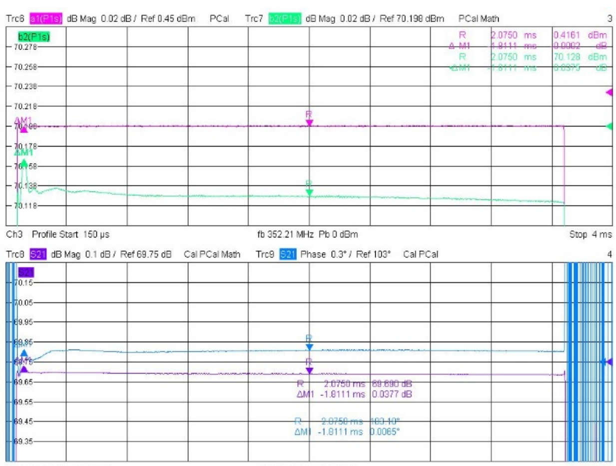

Figure 3: 10 kW Driver RF pulse amplitude (Trc 6) and phase (Trc 8) compared with the driving signal (Trc 7 and Trc 9). RF overshooting has been mitigated by modulating the drain voltage 200 µs before the RF pulse start.

Control grid power supply has been tested commuting the output voltage between -400 Volt, no biasing or blanking value, and -200 Volt, suitable for tube biasing, at 5% of duty cycle for 4 ms pulse duration on a dynamic load at 2 A nominal current. The measured voltage stability was better than 0.08% for the single pulse while the long duration test of 30 minutes showed a stability better than 0.2%. Control grid voltage recovery time with respect to a ± 100% load step change is lower than 20 µs. Voltage overshooting and undershooting during load transition is better than 0.4%. Power supply inhibition time is below 10 ms while specification asks for 20 ms.

Screen grid power supply works at constant output and has reached the required output voltage precision and stability and the most important performance of inhibition time below 5 µs. These results ensure good tetrode tube performances. Moreover the intrinsic inhibit time response measured on the G1 and G2 power supply units matches the requested interlock time sequence for the tube protection.

Intervention time and proper sequence of the tetrode interlock signals has been tested on bench. According to the tube protection procedure, the RF driving signal shall be first cut, then the G2 screen grid voltage is inhibited, the anodic HV circuit is opened and eventually the G1 control grid voltage is inhibited. The RF is cut within 200 ns and the interlock logical signal sequence lasts 3 µs, see Fig. 4.

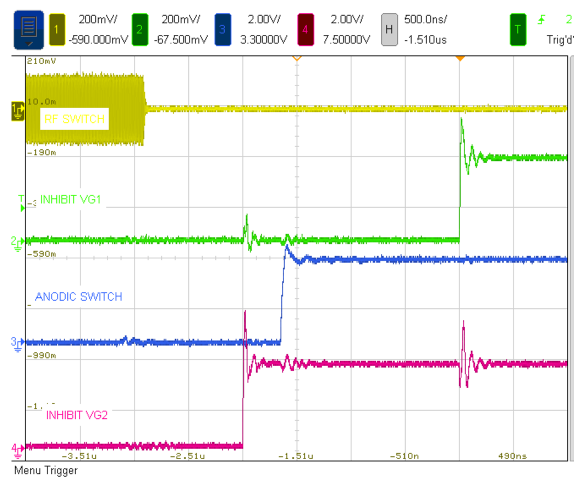


Figure 4: Fast interlock signals.

The solid state HV Astrol switch that is implemented to fast interrupt the anodic Direct Current (DC) circuit has been successfully tested at more stringent conditions than the nominal ones in pulsed regime [2].

Many other validation tests have been carried out preventing design flaws and underestimation. The project schedule has been delayed because of this validation process. Nevertheless this process has provided a larger degree of awareness on the amplifier's requested performance and on how to perform an effective FAT. Moreover this process has been realized before the pandemic time when all the involved persons could meet in person. They learned to work together and to share expertise. The amplifier's mature design has been reached and the FAT basis has been formed during this process.

## FAT

Once the main components have been validated the first amplifier, out of 26, has been carefully tested. Its successful commissioning was the main requisite for the next amplifier's mass production. Scope of the first amplifier FAT was not limited to its compliance to the specification. A great deal was taken in order to optimize the use of such a complex machine. Simple commands and strict procedures

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were automatically implemented through few push buttons and an intuitive data display. At the same time expert users were given the degree of freedom to tune the machine parameters and to perform a complete amplifier check up by means of additional menus and a proper set of analogic signals.

Several tests, like the toughness of the HV circuit grounding resistor against repetitive discharges in a row and the RF power combiner performances were tested only on the first machine to confirm the design and production quality. Fortunately, the first amplifier FAT was carried out with the Elettra team attending in person to the tests together with the supplier. This interaction has been pivotal to successfully wrap up the first amplifier FAT.

For the next machines Elettra was forced to reconsider all the FAT procedure because of the imposed travelling restrictions and the public health protection rules to counteract the COVID-19 pandemic. Attending the FAT of the next amplifiers was not an option neither the project freezing. Solution was to adopt a FAT written protocol and to apply it point to point during the several remote FAT video conferences as shown in Fig. 5.

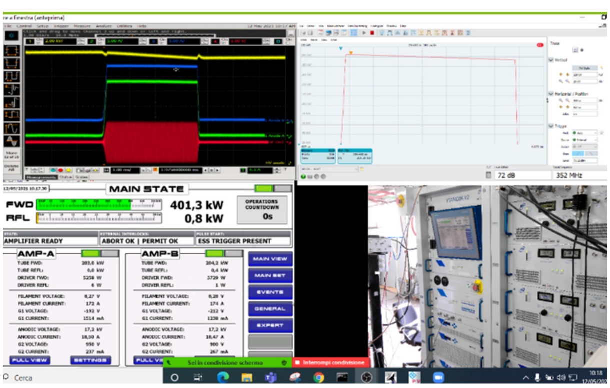


Figure 5: FAT remote session.

This protocol details every step of the tests according to a well-defined test's priority. First all the RFPS fast and interlock alarms are tested at minimal and nominal RF output power. Then the calibration of all the process variable is verified. Once the machine' protection is checked and the output data are validated, the tube tuning optimization, the gain and efficiency of all the amplification chains and the machine electrical consumption are tested. RF pulse set up, rise time and frequency parameters are measured. Electrical grid voltage flicker mitigation is validated. Eventually the intra pulse and pule to pulse RF quality is tested. Last test is the 24 hours nonstop reliability run at nominal RF power, whose results are recorded as shown in Fig. 6.

Pre-requisite to start the FAT is a complete lists of test reports on the electrical insulation, cooling system and individual amplifier components performances that shall be carried out by the supplier itself.

Several instruments are remotely connected so that their output data are continuous and immediately verified by the Elettra team: scopes, scalar and network analysers, power meters and so on. A WEB camera allows to monitor the physical machine and the PLC smart server allows to share the local amplifier display in real time. All the test data and results are stored in a file-sharing drive.

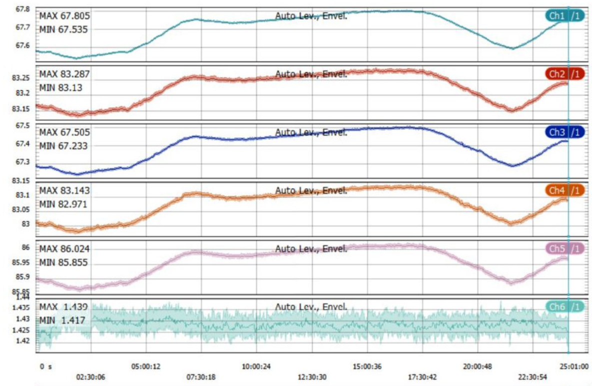


Figure 6: RF power data in dBm for all the amplification stages recorded over 24 hours. The RF power drift is due to the cooling water temperature poor stabilization.

The drawback of being not physically present at the FAT is compensated by a huge flexibility in scheduling it since no travel shall be arranged in due time. Remote FAT can be interrupted and resumed with short notice. The remote FAT procedure is effective thanks to the full cooperation of all the involved parties. Without this collaboration the virtual FAT is not sustainable. Skilful communication, transparency in the tests handling and shared goals are the essential ingredients for a successful remote FAT. The initial steep learning curve has now reached a steady regime.

To this date eleven amplifiers out of 26 have been successfully tested and the remote FAT procedure is at full speed.

## CONCLUSION

Because of the amplifier complexity, its main component's validation phase has been the appropriate first step towards the FAT set up. The validation allowed the full understanding of the relevant measures and results.

COVID-19 pandemia started during the FAT phase and forced a paradigm shift on the execution of an acceptance test. By rethinking the FAT procedure with a step-by-step protocol and a real-time remote sessions to carry out the tests with the on-line instrumentation, the project can continue with no interruption and deliver on time as foreseen. The remote commissioning success is ensured not only by the very good amplifier performances, but primarily by the excellent cooperation between the involved teams.

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[2] C. Pasotti *et al.*, "Radio Frequency Power Stations for ESS LINAC SPOKE Section", in *Proc. IPAC'19*, Melbourne, Australia May 2019, pp. 4346-4348. doi:10.18429/JACoW-IPAC2019-THPTS102