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RADIO FREQUENCY POWER STATIONS FOR ESS LINAC SPOKE SECTION

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Abstract

26 equivalent 400 kW peak power Radio Frequency Power Station (RFPS) units will be provided by Elettra as part of the Italian In Kind (IK) contribution to European Spallation Source ERIC (ESS). The RFPS will be installed in the LINAC "Spoke Section". Each machine will power a single superconducting spoke cavity in pulsed operation at 352.21 MHz. The RFPS is a complete system that operates unmanned, based on a combination of solid state and tetrode amplification's stages. The tender specification, the RFPS main features and requested performances are reported here paper.

INTRODUCTION

Elettra owns the full technical and managerial charge for delivering the 26 RFPS to ESS according to the IK contribution cooperation agreement among Elettra, ESS and INFN [1].

The RFPS complexity and their number demand to outsource their manufacture to a private enterprise using the tendering procedures in accordance with the public procurement Italian Law.

Key element of this procedure are the Tender specifications that include the RFPS technical specifications and performances, the contract management and the Quality Control and Assessment (QC/QA) rules. The contractual links on the project phases, management and QC/QA are largely identical to the lines and principles of the IK cooperation agreement. Tender specifications include also rules and standards for any machine safety topic in compliance with the European Union directives.

Elettra and ESS fully share on the Tender specifications. The RFPS is specified with some innovative technical solutions for the modulator and the power supplies and a simple and quite established RF amplification chain. The adopted technology is a good balance between off the shelf and custom designed parts to contain costs with no detriment in performances and machine efficiency. Tender specifications suggests also a cooperation between Contract and Customer to improve the design and the RFPS features.

RFPS design, fabrication and commissioning shall meet:

- Stability of the output RF pulse.
- Reproducibility of the output pulse for the same input.
- Reliability for 24/7 operations.
- High efficiency minimizing the energy consumption.

Together with the RFPS security and safety assessment, those are the starting points for a RFPS successful design.

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RFPS SPECIFICATION

The RFPS will operate at a single frequency, 352.2 MHz, 3.5 ms pulse length, repetition rate 14 Hz and 5% of duty cycle up to 400 kW peak power.

Main requirements on the output pulse envelope are therefore the pulse droop, overshooting and following error with respect to the ideal RF one. The maximum pulse droop must be ≤ 0.25 dB. Any pulse overshooting and following error shall die out within 500 µs, which is the maximum stabilization time for the pulse as shown in Fig. 1.

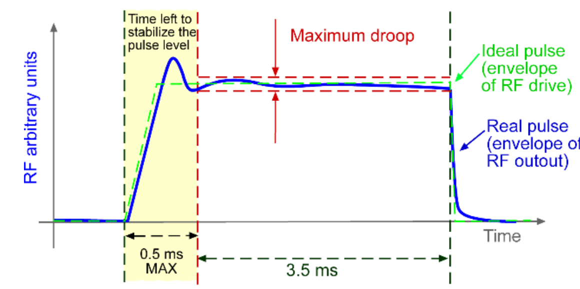

Figure 1: Ideal RF output pulse (green line) and the most likely RF output pulse (blue one).

Stability between pulses is mandatory. The maximum amplitude and phase variation between following pulses shall be within ± 0.5% and ± 0.5° respectively, measured at the very same delay time with respect to the pulse trigger.

For the proton beam acceleration, the 352 MHz RF amplified output signal shall achieve a challenging spectral purity: -23 dBc @ 100 kHz, -20 dBc @ 1 kHz and -18.2 dBc @ 300 Hz offset with respect to the carrier signal. This goal is met if all the active components are carefully designed and built for the impressed pulse operation.

RF Sources

After investigation and several tests on the available RF power sources, the tetrode tube is the best available option for performances, costs and overall machine simplification [2]. The chosen model is the Thales TH 595 A and the RF cavity TH18595A [3, 4]. The nominal output power is 210 kW peak at 352 MHz. Two tubes in parallel will achieve the required 400 kW peak. A RF pre-driver delivers each tube up to 7 kW. A solid-state based amplifier can easily achieved this power level nowadays but the RF pre-driver design shall take into account and mitigate the thermal cycle of the transistors. Moreover, the amplifier power supplies shall withstand the pulsed operation output voltage regulation.

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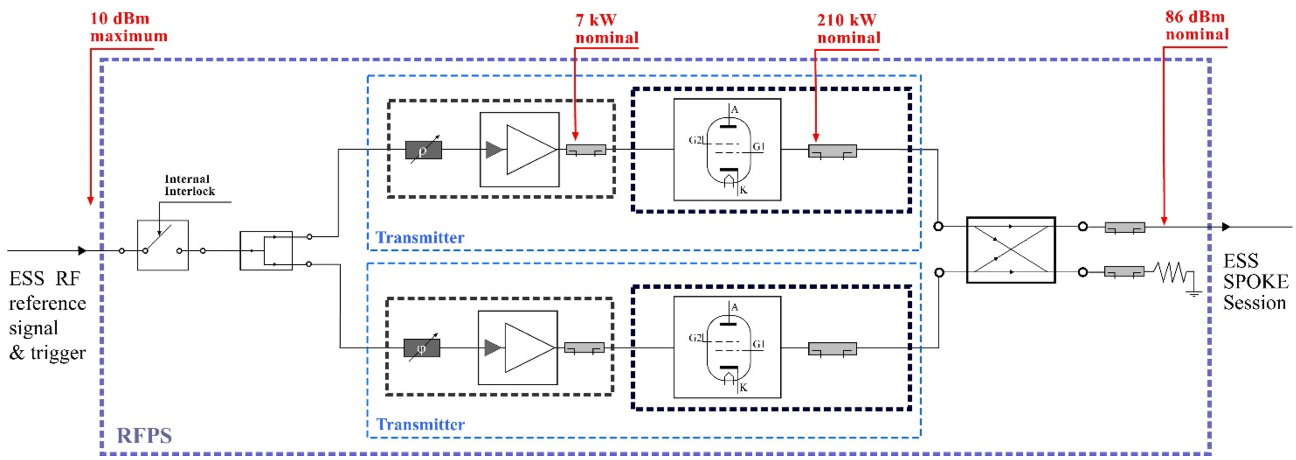

Figure 2: RF amplification of the RFPS: two equivalent transmitters, driven by the same RF signal, will operate in parallel to achieve the requested output power level.

RFPS Layout

The RFPS machine consists in two equivalent transmitters, each one having a RF pre-driver followed by a tetrode tube's amplification chain. A unique RF input distribution line with phase and input level attenuation static adjustment capability on each RF branch will drive both transmitters. Their output power adds together through a 3 dB hybrid combiner. Figure 2 shows the full RF amplification chain.

The RFPS shall be equipped with a local display to access the main machine parameters and commands and a set of physical quantities sampled with instrumentations, like oscilloscopes, power meter and so on.

Specifications ask for the highest modularity, the installation of the components in side connected cabinets and the easiest access to any component for maintenance purpose.

Compactness of the RFPS is also an issue.

High Voltage Tetrode Modulator

The modulator is the High Voltage (HV) power electronic converter that supplies the anode of the tetrodes with electrical pulsed power. A single modulator will supply both tetrode anodes since the Spoke cavity does not foresee a single transmitter operation. Nominal anode HV and current for each tube are 16.5 kV and 19 A (peak value) respectively. Even if the requested peak power is around 630 kW for both tetrodes, the average power is relatively low, 32 kW. The use of a capacitor bank suitable to storage the amount of needed energy is mandatory. The capacitor bank is rated for a total capacity $\geq$ 160 μF to minimize the voltage droop across its terminal during the current drawn (partial discharge) and to full recharge in 70 ms. Energy consumption of the modulator is effectively minimized implementing switched mode power converters [5].

The modulator large capacitors usually store potentially dangerous energy at a level that can damage the tube itself and the surrounding circuit in case of arcing phenomena due to conductors or internal tube electrodes break down. To prevent these phenomena the modulator implements a protection circuit that monitors any current surge or short circuit and fast interrupt the HV supply.

Astrol Electronic AG has built and provided ESS a dedicated HV solid-state switch 18 kV-50. Figure 3 shows the switch installed in the modulator prototype assembled in the ESS test stand. The entire modulator prototype built according to the specification has been successfully tested on a resistive load at full power. The HV switch has passed the "wire test" as recommended by the tube manufacturer. Further tests are planned on the modulator prototype concerning the electrical grid voltage-flicker issues due to the impressed pulsed operation.

Figure 3: HV Switch in the ESS modulator prototype.

G1, G2 and Filament Power Supply

Tender specification recommends a good off the shelf Filament Power Supply Unit (PSU). On the contrary, the tetrode G1 control grid and G2 screen grid electrodes PSU shall be custom made for this application. Aim of the dedicated design is an improved efficiency and a high dynamic performance of the regulated voltage. To achieve the required efficiency, better than 85%, and a voltage recovery time $\leq$ 150 μs for a load step change of ±100%, a switch mode power converter topology is recommended. The PSU shall also have self-protecting interlocks against short circuit and current limitation capabilities in compliance with the prescription for the tetrode tube protection. G1 nominal

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voltage and current are -400 V_{DC} and 2 A; G2 nominal voltage and current are 1000 V_{DC} and 0.5 A.

Additional performance of the G1 control grid PSU is the blanking capability. It means avoiding the tube biasing outside the pulsed operation, leading to a further increase of energy saving. Therefore, G1 shall repeatedly switch from –400 V_{DC} (no biasing) to -210 V_{DC} (tube idle current) following the impressed pulsed operation.

Figure 4: G2 PSU and control prototype boards.

ESS and Elettra have designed, simulated and built a G2 power supply prototype according to the specifications as shown in Fig. 4. It is currently under test to verify the performances and the results are promising. G2 PSU tests in the final RFPS machine are planned shortly.

Interlock and Control

Interlock and control systems are at the core of the RFPS machine. The Internal Interlock System (IIS) shall be fail-safe, printed circuit board based, hardwire connected with no microcontroller. The IIS must protect each RFPS component and part from any failure. Besides to the modulator HV and tube protection, the RF input switch performs a protection's key role. It will route the RF signal towards the downstream amplification chains if and only if all the safety boundary conditions are met and it will quickly remove the RF driving signal in case of faults. IIS shall be as fast as needed for the machine protection and have a rugged reliability when concerning the personal safety. The RFPS shall also acknowledge any external interlock that inhibits the RFPS operation.

RFPS control system implements the proper procedures and commands for the RFPS operation both in local and in remote mode with a data acquisition process-time in compliance with the 14 Hz repetition rate.

System Integration

The RFPS shall fit in with all the ESS service gallery auxiliary system smoothly and seamless. This topic has not been underestimated and one section of the Tender specifications encloses all the connection's details from and to the systems in the ESS service gallery.

VALIDATION, FAT AND SAT

Twenty-six RFPS units are going to be built and commissioned. The contract envisages the construction of a first RFPS unit, called pre-series, that undergoes to a "validation process", followed by the mass production of the remaining ones. Tests are foreseen on any RFPS pre-series part that can be characterized as a standalone unit. Then the entire pre-series will be extensively tested to establish the ultimate structural design for the series construction. Minor design modifications and further optimizations can be taken into account and implemented at this stage if needed. Test and validation begin is planned during late spring and the first whole RFPS shall be commissioned within end of October.

All the 26 units, including the pre-series, will be tested at the manufacturing premises, Factory Acceptance Test (FAT) procedure. The successful FAT is essential for the machine acceptance and the RFPS shipment to ESS site approval.

An intensive measurement campaigns and test will be performed on the pre-series at the ESS site in the final installation layout, Site Acceptance Test (SAT) procedure. During the SAT, all the RFPS parameters shall comply with the specified and measured ones during the FAT with no degradation or deviation.

Final acceptance of all the RFPS IK contribution is foreseen at ESS within one month from the last delivered machine, System Acceptance Review (SAR). The SAR examines the delivered goods, the technical documentation, the inspection, the demonstration, the test data and the analyses that support their verification, as defined in verification plans and verification reports.

CONCLUSION

This paper presents a short overview of the most meaningful specifications for the RFPS. The RFPS is a complex machine with challenging performances. Elettra and ESS have designed and tested some prototypes to support the Tender specification choices and to start a fruitful collaboration with the Tender Contractor.

A carefully design followed by a manufacturing, commissioning and installation quality assurance program involving all the stakeholders is essential to meet the goal.

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