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EXPERIENCE AND DEVELOPMENTS ON THE S-BAND RF POWER SYSTEM OF THE FERMI LINAC

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Abstract

The S-band linac of FERMI, the seeded Free Electron Laser (FEL) located at the Elettra laboratory in Trieste, operates on a 24/7 basis accumulating more than 6000 hours of operation per year. The performance and operability requirements of a user facility pose stringent specifications on reliability and availability on all the systems of the machine and in particular on the RF power plants. This paper provides a review and discusses the operational experience with the S-band power plants, klystrons and modulators, operating at S-band in FERMI. Based on the satisfactory results and following return of experience, upgrades of the existing power plants are being implemented in the continuous effort of extending the operability and availability of the systems. A description of these activities and an overview of the other developments under consideration on the RF power plants are also provided.

INTRODUCTION

FERMI, the Italian seeded FEL located in Trieste, consists of two FEL lines, FEL-1 and FEL-2, covering the wavelength range between 20 and 100 nm and between 4 and 20 nm respectively. Both the two FEL lines are now open to external users [1]. The accelerator is based on a 1.5 GeV S-band linac. Fourteen 3 GHz 45 MW peak RF plants are installed to power sixteen accelerating structures, the RF gun and the three RF deflectors. Two more accelerating structures will be added at beginning of 2016 [2]. An additional power plant is installed to provide a hot-spare backup solution for the first two. This power plant is also used as a test bench for R&D purposes.

POWER PLANTS DESCRIPTION

RF power requirements for the plants are typically around 33 MW peak, with the exception of the plant that powers the gun and the low energy deflector where the needs are around 21 MW. Each power plant is composed of a 45 MW klystron and modulator. All plants are designed to operate at 50 Hz pulse repetition rate [3]. Figure 1 shows one of the RF plants.

All klystrons are TH2132A from Thales. This tube can provide up to 45 MW in pulsed mode, 4.5 μs at 100 Hz. Typical peak beam cathode voltage and current for maximum output are 310 kV and 350 A.

All modulators are line PFN type and were assembled by local companies under FERMI design. The main parameters are summarised in Table 1. The high voltage power supply is a 50 kV, 2 A capacitor charging power supply from FuG with a specified pulse-to-pulse repetition accuracy better then 100 ppm at 50 Hz. The switching element is a thyratron (CX1536X) from E2V.

Figure 1: One of the FERMI S-band plants.

Table 1: Modulator Parameters

Parameter	Value
Maximum operating voltage	320 kV
Maximum delivered current	350 A
Repetition frequency	50 Hz
RF pulse width	4.5 μs
Risetime/falltime	< 2 μs
Pulse flatness	< ± 1 %

OPERATIONS AND STATISTICS

The RF plants are in operation continuously on a 24 hours 7/7 basis for about 6500 operating hours per year. The uptime of the entire S-band system for year 2014 has been 93 %. This comprises as well the downtime due to the other parts of the RF system such as waveguides and accelerating structures. The main sources of downtime are klystron arc discharges that amount to roughly 70 % of the total number of faults. These faults are power dependent and are randomly distributed, although three plants show a much higher arc rate.

Mean lifetime of the klystrons in operation is 32,000 hours. This value is presently assumed for spare parts management. It must be noted that this statistics is evolving and we have the two oldest klystrons that have exceeded 70,000 hours of operation. However, now these have been installed in the less demanding plants in terms of RF output. Typical failure mechanism is a too high arc rate at the operating voltage, which eventually prevents reaching or maintaining the target klystron beam parameters. Klystrons operation is continuously monitored. High voltage conditioning and heater curve

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optimization are routinely scheduled every year or are performed in case the failure rate increases.

Mean lifetime of the thyratrons is 18,000 hours. Thyratrons aging has also shown to be one of the main sources of stability worsening of the RF power pulse due to the possibility of internal arcs in the tube. Although reservoir pressure optimization can sometime help to attenuate temporarily the effect, in case this problem is observed, preventive replacement is scheduled at the earliest convenience.

STABILITY MEASUREMENTS

The stability specifications of the S-band RF system are 0.1° in phase and 0.1 % in amplitude [4]. Neglecting other effects, the phase stability requirement, clearly more stringent than the amplitude one, translates in a stability specification of better than 180 ppm of the klystron high voltage at 300 kV. Following this, the HV power supply stability has been specified to better than 100 ppm.

A campaign of measurements on the plants has been performed to characterise the actual stability of the PFN and klystron voltages. A commercial high performance differential amplifier (Lecroy DA1855) has been used. This implements a high precision voltage generator and a low overdrive recovery time comparator in order to accurately monitor the pulse-to-pulse repeatability. The standard deviation over 1000 pulses has been calculated, averaging this result over several different measurements.

The results of these measurements show that the stability of the voltage measured at the PFN is better than 25 ppm while the measured reproducibility of the klystron voltage is, in the worst case analysed, 35 ppm corresponding to 0.02° at S-band at 300kV. This shows that the stability of the klystron high voltage is very high and in line with similar applications. It also shows that the power supplies are working much better than the guaranteed specifications. The worsening of the stability figure is due to the thyratron switching drop variations, which introduce a worsening of the reproducibility of the voltage at the klystron cathode side by a factor ranging between 1.5 and 3.

MODULATORS UPGRADES

As written above, klystron arcs represent the major number of faults. The number of arcs, generally around 1.2 per day and per plant, is considered normal by the manufacturer, comparing also similar applications at the same power levels. Although they have short duration and are automatically reset, actions have been examined to reduce the impact on the availability of the system. Recipes, as HV conditioning and optimization of klystron parameters, have proven to be beneficial but not conclusive.

An analysis of the waveform of the anodic voltage and current after an arc was performed to study possible improvements in the system. The waveforms with the original design of the modulators have shown a high reverse voltage after an arc due to parasitic elements and load mismatch, as shown in Fig. 2. This effect makes the klystron prone to arc again as soon as the HV pulse is reapplied. Therefore, a waiting time and a reduction in the applied HV, followed by a ramp to reach the final value, were needed in order to re-establish the operating parameters. To prevent this effect, a modification of the modulator has been studied and implemented starting with the sections showing a higher arc rate. The modification limits the reverse voltage and damps the oscillations following an arc event. The results on the klystron waveform are shown in Fig. 3.

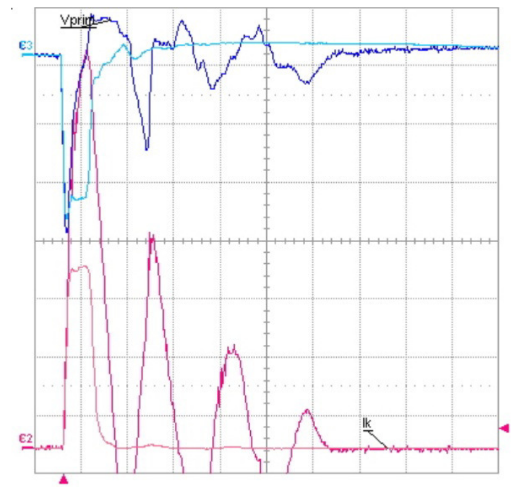

Figure 2: Klystron voltage (blue) and current (purple) before circuit modification. Darker colours show the curves in case of an arc.

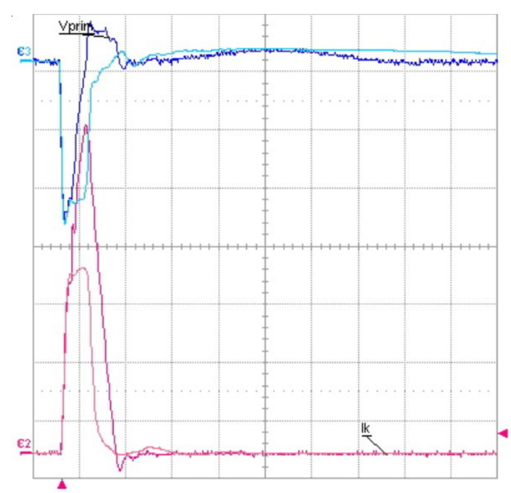

Figure 3: Klystron voltage (blue) and current (purple) after circuit modification. Darker colours show the curves in case of an arc.

Following the circuit modifications, two recovery approaches were studied:

- Case 1: klystron pulsing is stopped only if three, or more, arcs happen in 1 second. Klystron HV is then slowly ramped.

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- Case 2: klystron pulsing is stopped after each arc. The same high voltage is reapplied after a short waiting time (20 sec).

The results are shown in Table 2. It is evident from the data that both the solutions tested show a relevant improvement in the uptime, while the latter shows also a decrease in the total number of arcs detected. This solution is now operational in three plants at 10 Hz and the concept is now being upgraded to 50 Hz and extended to all the plants.

Table 2: Comparison of the Results with the Two Recovery Approaches

Mode	Downtime variation	Arc number variation
Case 1	-73 %	+20 %
Case 2	-83 %	-19 %

THYRATRONS AND SOLID-STATE SWITCHES

Thyratron aging can affect the stability of the RF pulse from the klystrons. Measurements performed on the machine have shown correlations between small variations in the drop voltage and in the klystron anode voltage. This variation may cause deterioration of the RF pulse stability as also confirmed by measurements with the LLRF system. In two cases the stability worsening was so important that the component should be replaced. The variations in the thyratron drop voltage could be related to internal arcs in the tube, generally with aging.

Thyratrons have a variable lifetime and represent a not negligible operating cost. The increase of the repetition rate to 50 Hz in 2016 is expected to affect the lifetime of the tubes, since this is mainly depending on the number of pulses.

In the last years solid-state switches that can replace thyratrons in similar applications have been developed and have been tested in different places, see for example [5] and [6]. Solid-state switches should be free of the instabilities that may affect thyratron operation. They promise a much longer operating lifetime and a much lower annual operating cost.

To study the feasibility of implementing a solid-state switch in the FERMI modulators, a development project has been launched exploiting the possibility to test the solution on the spare modulator and coordinating this with the upgrades to mitigate the effects of the klystron arcs. A solid-state switch produced by APP has been chosen [7], see Fig. 4. This consists of multiple series connected thyristors, designed for high di/dt, high voltage and pulsed power operation. The component will be extensively tested to validate the feasibility of the solution. Considering the availability of the spare plant, which is also used for other R&D activities, it is expected to have the first results in the second half of 2015.

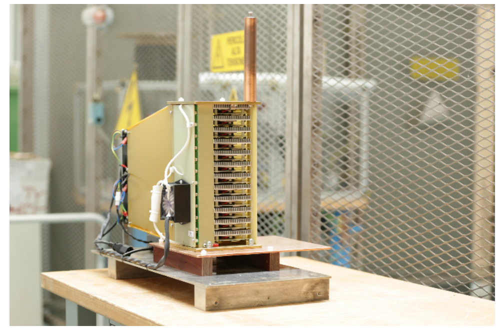

Figure 4: The solid-state switch being prepared for installation in the spare modulator.

CONCLUSION

FERMI is a users' dedicated facility, therefore availability, reliability and operability are important factors for all the systems of the machine and in particular for the S-band RF. Continuous effort is dedicated to fully characterize and monitor the operating results of the RF power plants of the linac to analyse the performance, study and implement upgrades when necessary. The feasibility study for the implementation of solid-state switch in place of thyratrons will provide important information for further possible development plans.

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