INSTALLATION AND TESTS OF THE X-BAND POWER PLANT FOR THE FERMI@ELETTRA PROJECT

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Abstract

FERMI@Elettra, the fourth generation light source facility at the Elettra Laboratory in Trieste, Italy, foresees an X-band accelerating section downstream the first bunch compressor to linearize the beam longitudinal phase space. The RF power for the structure is produced by a SLAC XL5 klystron, a scaled version of the XL4 tube, operating at the European frequency of 11.992 GHz. The 50 Hz klystron modulator is based on a standard pulse forming network (PFN) design, with a thyratron and pulse transformer, with which Elettra has extensive experience. We report on the installation and tests of the first high power RF station.

INTRODUCTION

FERMI@Elettra [1] is a soft X-ray 4th generation light source facility, in an advanced commissioning phase at the Elettra Laboratory in Trieste. It is based on a normal conducting S-band linac and a seeded FEL, with operation that covers two different X-ray ranges: FEL1 (1.2 GeV, 100-20 nm), and FEL2 (1.5 GeV, 20-4 nm).

The main parameters of the FERMI project are shown in Table 1.

Table 1: FERMI Main Parameters

Parameter	*FEL1*	*FEL2*
Wavelength (nm)	80-20	20-4
Electron beam energy (GeV)	1.2	1.5
Bunch charge (nC)	0.5-0.8	
Peak current (A)	600–900	
Bunch length (FWHM, fs)	600	
Normalized emittance (slice, μrad)	≤ 1.2	≤ 1.0
Energy spread (slice, KeV)	≤ 250	≤ 150
Repetition rate (Hz)	10–50	

In order to produce high density electron bunches, the machine is equipped with two magnetic bunch compressors, the first at 320 MeV (BC1), see Fig. 1, and a second at roughly 750 MeV (BC2). These compressors shrink the beam pulse width and increase the beam peak current to the required 800 A. To compensate for the non-linearities induced in the beam by the off-crest acceleration in L1, a short X-band (12 GHz) accelerating structure is installed in L1, see Fig. 1 [2]. This structure has been developed in the framework of a collaboration between Sincrotrone Trieste (ST), CERN and PSI.

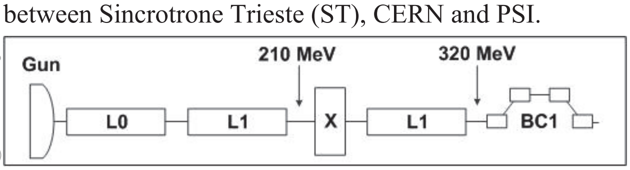

Figure 1: Machine layout up to the first bunch compressor.

For an efficient linearization at BC1 (320 MeV), the X-band structure has to operate in a decelerating mode with $V_x/V_s=1/N^2$, corresponding to V_x=20 MV, for N=4.

Considering its active length (0.75 m) and a safety margin of 20%, the maximum operating gradient of the section should not exceed 30-32 MV/m - a very conservative figure at 12 GHz. To reach the required gradient the structure needs no more than 20 MW of RF power at the coupling iris. Details on the structure, design, and construction can be found in [3].

RF POWER PLANT: LAYOUT AND REQUIREMENTS

The layout of the X-band power plant is shown in Fig. 2 [4]. The main RF generator is a scaled version of the SLAC XL4 klystron. The new tube, XL5, operates at the European frequency of 11.992 GHz and was developed at SLAC [5] to support European research programs in high energy physics and FEL development (i.e. CLIC, FERMI@Elettra, SwissFEL). At a beam voltage below 450 KV, the XL5 klystron can deliver more than 50 MW peak power, with an efficiency greater than 40% and a gain of 50 dB. It can operate with a pulse width of 1.5 μs at a rep-rate of 50 Hz.

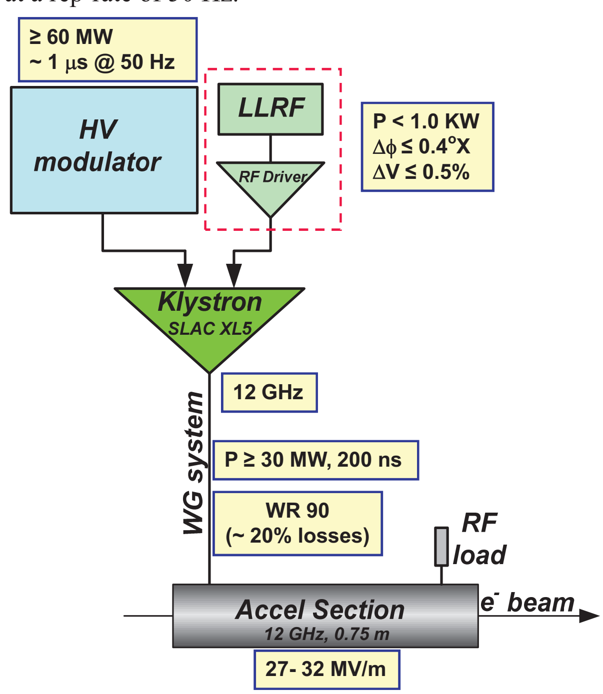

Figure 2: X-band plant layout and main requirements.

Considering our needs, the XL5 performance greatly exceed the FERMI requirements in terms of RF power. Two XL5 klystrons for FERMI have been already

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assembled at SLAC, the first tube (ser. No. 1B) was delivered in Trieste last August and is now routinely working on the machine. The second tube, to be used as a spare, is currently at SLAC undergoing RF activation and final acceptance tests.

Figure 2 also shows the main sub-systems of the RF station, with their operating parameters, in terms of peak power and RF stability, based on the FERMI requirements with 20% over-head.

INSTALLATIONS AND TESTS

The 50 Hz HV modulator has been designed and assembled in house. It is based on the same design used for the S-band plants, now in routine machine operation. A picture of the plant taken during its activation and tests on waveguide water loads is shown Fig. 3 with the main parameters summarized in Table 2.

Figure 3: X-band power plant under test on water loads.

It uses a standard topology with a pulse forming network (PFN), thyratron, and pulse transformer. The PNF was redesigned for a shorter pulse and proper matching to the new tube while trying not to exceed a 2.5 µs pulse width. The pulse transformer was changed with a 20:1 step-up transformer for reaching higher voltages (up to 450 KV). Special attention has been given to the HV pulse shape and the overall operating conditions of the high power circuit. We used a high stability power supply that directly charges and regulates the high voltage at the PFN. No charging elements or de-Qing circuits are used.

Table 2: Modulator Main Operating Parameters

Parameter	*Value*
Peak voltage (KV)	450
Peak current (A)	360
Pulse duration at 99% (µs)	0.7
Pulse width at 50% (µs)	2.5
Pulse rise time (µs)	≤ 0.7
Max inverse voltage (KV)	< 100
Pulse repetition rate (Hz)	50
Pulse ripple (%)	< 1
Pulse to pulse stability (%)	≤ 0.1
HV charging voltage (KV)	0-50
HV power supply stability (%)	≤ 0.01
Max energy from the HV PS (kJoule/sec)	25

This configuration provides a PFN shot-to-shot voltage stability better than 50 ppm. For the power switch we use a double gap thyratron, E2V CX1536X, assembled in an oil tank for liquid cooling, and equipped with a double pulse trigger system.

Figure 4 shows Klystron V-I pulses at 405KV/307A. They are in good agreement with expectations and have a pulse flat-top well beyond the 100 nsec required by the filling time of the RF structure.

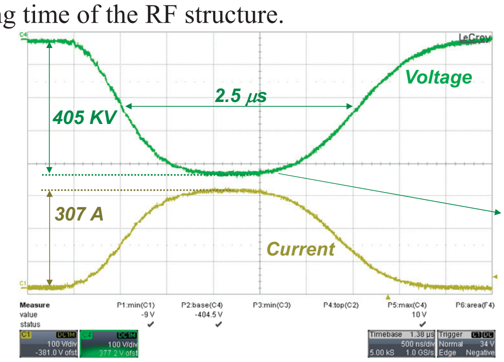

Figure 4: Klystron V-I pulses at 405 KV-307A.

The RF plant assembly was completed by the end of October 2011. Two CERN WG loads and two WR 90 bi-directional couplers were installed at the klystron output allowing for both RF and calorimetric measurements of the produced power.

Figure 5 shows the layout of the RF drive system and power measurement. The LLRF controller is based on the existing S-band digital system with an up/down frequency converter chassis for 12 GHz operation. A commercial 2 kW TWT amplifier is used as the klystron driver.

A precise calorimetric measure of the klystron power at the WG loads was implemented, using a specifically developed LabView application. This allowed the measurement of the power wasted on the klystron body and collector, with and without RF, as well as the RF power dissipated in the two WG loads. The same system was also used as a protection interlock, preventing klystron damage during its operation in case of excessive or anomalous beam losses on the body (i.e. exceeding 1% of the total beam power).

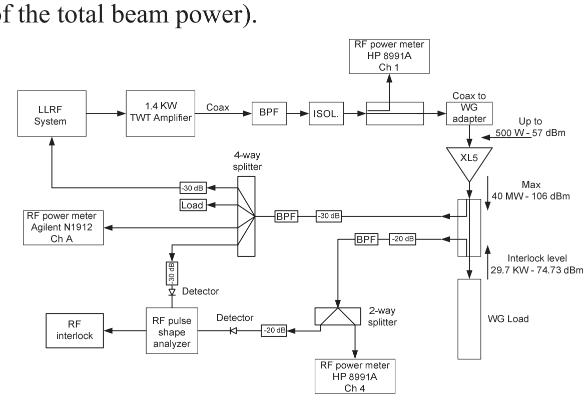

Figure 5: LLRF drive system and power measurement.

Table 3 summarizes the main operating parameters of the XL5-1B klystron collected during its activation. We found good agreement between the data collected with the

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calorimetric system, and that provided by the RF directional couplers. For obvious reason, this matching was particularly evident when operating with RF pulses longer than 300 nsec.

We have operated the Klystron in diode mode up to 410 KV. We decided to limit our operation considering that, at these power levels, the tube calibration curves supplied us by SLAC showed a saturated RF output power well beyond the needs of the FERMI project.

Table 3: Operating Parameters of the XL5-1B Klystron

Anodic voltage (KV)	Anodic current (A)	μ–Perv. (μP)	Body power (W)	Collec. power (KW)	Beam losses (%)	Output RF (MW)
350	245	1.18	83	8.4	0.98	9.1
360	259	1.20	79	9.0	0.88	12.1
370	267	1.19	91	9.6	0.95	15.7
380	278	1.19	98	10.2	0.96	19.5
390	289	1.19	89	10.9	0.82	24.3
400	300	1.19	93	11.6	0.8	29.2
410	311	1.18	100	12.0	0.81	34.5

During the 232 hours of operation in diode mode there were very few arcs, mainly when we passed over 400 KV, from which the system immediately recovered. During the klystron activation, we also experienced some noise on the cathode ion pump power supply, induced by the HV pulse. The problem was quickly solved with an improved and more accurate power supply filtering.

The tube has operated 678 hours with RF going to waveguide loads and a pulse length up to 500 nsec. Also for this activation, with the exception of some vacuum trips on the loads, there were no particular problems. To keep an adequate vacuum level, we were only obliged to slow our conditioning process.

Figure 6 shows the XL5-1B gain curves taken during the RF activation of the tube. The same chart also shows the klystron operating point required to have the 20 MeV "energy gain" from the X-band structure.

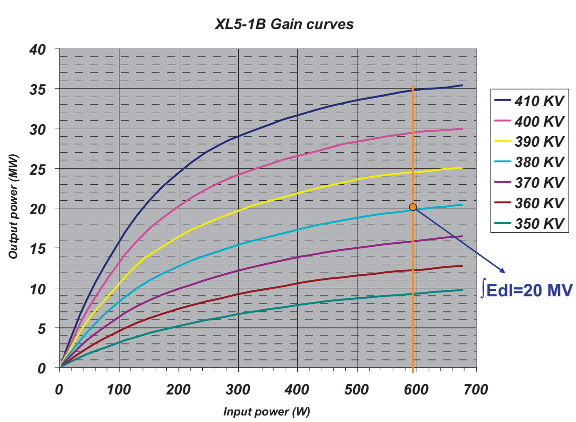

Figure 6: XL5-1B gain curves.

The structure and waveguides were connected to the klystron in February 2012. The conditioning of the entire system took approximately 250 hours over the course of three weeks. A peak gradient of 30 MV/m was reached in the accelerating section with only few RF breakdowns. For the first 100 hours, the vacuum level in the WG circuit, near the mode converters and vacuum valve assembly, was quite poor, staying 2-3 10E-7 mbar and only slowly improving toward the 10E-8 range. After 250 hours the entire circuit was better than 1-2 *10E-8 mbar.

The first tests with the beam have been carried out at the beginning of March 2012, with the system showing good performance, except for some instabilities on the beam energy spread/jitter probably induced by the LLRF system. More details on this aspect are reported in [6].

CONCLUSION

The X-band system for the FERMI@Elettra FEL project has been completed and assembled on the machine. It will be used to linearize the beam longitudinal phase space before the first bunch compressor. The first XL5 klystron has been successfully activated up to 35 MW peak power, 500 nsec pulse width, 50 Hz rep-rate, and is now operating on the machine supplying the accelerating structure with roughly 20 MW of RF power.

We have not experienced any particular problems in reaching these power levels and the whole system is now operating with excellent reliability. For example, it has been in continuous operation for few days, at 10 Hz, without a single fault. In addition, for not-continuous operation, we had no faults on over 7*10E6 pulses.

At present a strong effort has been undertaken to improve the phase and amplitude stability of the LLRF system, finding the best operating conditions. For our application these parameters are very important and greatly affect the compression process and the FEL operational stability.

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