

# OPERATIONAL EXPERIENCE WITH THE FERMI@ELETTRA S-BAND RF SYSTEM\*

A. Fabris<sup>#</sup>, P. Delgiusto, F. Gelmetti, M. Milloch, A. Milocco, F. Pribaz, C. Serpico, N. Sodomaco,  
R. Umer, L. Veljak, Sincrotrone Trieste, S.S. 14 – km. 163,5, in Area Science Park, 34149  
Basovizza, Trieste, Italy

### Abstract

FERMI@Elettra is a single-pass linac-based FEL user-facility covering the wavelength range from 100 nm (12 eV) to 4 nm (310 eV) and is located next to the third generation synchrotron radiation facility Elettra in Trieste, Italy. The machine is presently under commissioning and the first FEL line (FEL-1) will be opened to the users by the end of 2012. The 1.5 GeV linac is based on S-band technology. The S-band system is composed of fifteen 3 GHz 45 MW peak RF power plants powering the gun, eighteen accelerating structures and the RF deflectors. The S-band system has been set into operation in different phases starting from the second half of 2009. This paper provides an overview of the performance of the system, discussing the achieved results, the strategies adopted to assure them and possible upgrade paths to increase the operability of the system.

### INTRODUCTION

The FERMI@Elettra FEL facility is based on a warm linac followed by a single pass seeded FEL [1]. Two FEL lines are foreseen: FEL-1 which produces fundamental output wavelength from 100 to 20 nm and FEL-2 which will extend the operation down to 4 nm applying High Gain Harmonic Generation schemes. The main parameters of the machine are reported in Table 1.

Table 1: Machine Parameters

Parameter	FEL-1	FEL-2	Unit
Wavelength	100-20	20-4	nm
Electron beam energy	1.2	1.5	GeV
Bunch charge	0.8	1	nC
Peak current	850	500	A
Bunch length (FWHM)	400	600	fs
Norm. emittance (slice)	0.8-1.2	1.0-2.0	mm mrad
Energy spread (slice)	150-250	100-200	keV
Repetition rate	10-50	50	Hz

The accelerator consists of an RF photocathode gun, an S-band linac, an X-band structure, a laser heater to control the uncorrelated energy spread and the beam

transport system to the undulators. The machine is presently working at a repetition frequency of 10 Hz, which will be increased to 50 Hz in May 2013.

The commissioning of the facility is rapidly advancing and FEL-1 will be opened to external users at the end of the present year. Commissioning of FEL-2 will progress in the remaining time with the target of the first test experiment during 2013.

### PRESENT STATUS OF THE S-BAND SYSTEM

Sixteen S-band accelerating structures are installed in the FERMI linac (Fig.1). The first nine structures are TW ones, while the last seven are BTW type and are equipped with SLED. Two more TW structures will be added in the future. They will replace the first two structures that will be finally relocated along the machine.

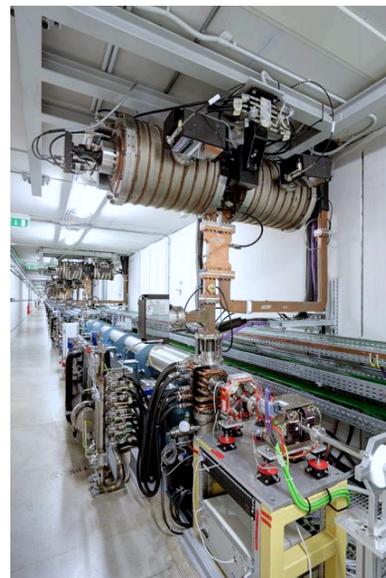


Figure 1: View of the linac from the high-energy end.

Fifteen 45 MW peak klystron (TH2132A) are installed, each one powered by pfn based modulators (Fig.2). Fourteen klystrons provide RF power to the accelerating structures, to the gun and to the low and high-energy RF deflectors. Two main power distribution schemes are used: one klystron feeding two TW structures or one klystron feeding one high gradient BTW structures. A spare power plant provides a backup solution to the first two, powering either the RF gun or the structures before the laser heater. The change of the operating mode is

\*Work supported by the Italian Ministry of University and Research under grants FIRB-RBAP045JF2 and FIRB-RBAP06AWK3  
<sup>#</sup>alessandro.fabris@elettra.trieste.it

performed by an array of remotely controlled waveguide switches.

Each RF plant is equipped with a low level RF (LLRF) system that maintains the stability of the RF below 0.1 % and  $0.1^\circ$  at 3 GHz. The system now in operation is an intermediate system, which implements a commercial processing board instead of the one specifically designed for FERMI and now in construction. All the needed loops are implemented such as amplitude, phase, cable calibration and phase locking. SLED phase reversal and phase modulation have been also implemented by means of the LLRF.



Figure 2: One of the fifteen modulators

The S-band RF system has been gradually set into operation starting with the first installation of the plant for the gun in the second half of 2009 [2]. All the fifteen RF plants and sixteen accelerating structures are now in operation. The machine routinely operates on a 24 hours basis for the commissioning of the accelerator and of the beamlines. The operating energy of the machine is 1.2 GeV and the repetition rate is 10 Hz.

## ENERGY AND REPETITION FREQUENCY UPGRADE

Two major goals are foreseen for 2013: the upgrade of the repetition rate, following the installation of the new RF gun designed for 50 Hz, and the commissioning activities of FEL-2. Besides the proof of the double stage HGHG scheme, the latter also implies the upgrade of the machine energy to 1.5 GeV.

The transition to 50 Hz requires an upgrade of the modulators operation. This is particularly important for the first six built that, for time constraints, were installed re-using the components of the previous Elettra injector and therefore are limited by the hardware to 10 Hz. The upgrade of these modulators implies an almost complete rebuild, since many of the main components, such as pfn, pulse transformers, etc. have to be replaced. In addition, the upgrade activities must not affect the commissioning calendar and therefore they can be generally done only in the already planned shutdowns. The process is advancing according to the schedule and it will be completed in May 2013.

The energy upgrade to 1.5 GeV will be mainly realized by increasing the energy gain in the BTW high gradient accelerating structures, increasing the RF power and the RF pulse length. For the remaining structures there will be no major changes since an increase in the energy gain is basically limited either by the available RF power and the constraints due the energy requirements at various points along the machine, like the bunch compressors and the laser heater. The RF conditioning will be done using the automatic software already developed and available via the machine control system.

Table 2 shows the energy budget on crest for the two operating energies for FEL-1 and FEL-2. This should be decreased by the effects of:

- the deceleration of the X-band cavity (20 MeV typically);
- the longitudinal wakefields when operating at high bunch current (expected 30 MeV at 1.5 GeV);
- the loss in energy gain if running some structures off-crest for beam dynamic optimization.

Table 2: Energy gain per structure and total energy budget

Type	Quantity	1.2 GeV	1.5 GeV
Gun	1	5 MeV	5 MeV
TW-Elettra	2	47 MeV	47 MeV
TW-LIL	7	57 MeV	57 MeV
BTW	7	110 MeV	154 MeV
<b>Total energy</b>		<b>1268 MeV</b>	<b>1576 MeV</b>

In order to achieve the required energy gain in the BTW structures, overcoming the limitations encountered in their operation as injector for Elettra, the SLEDs will be phase modulated. This feature has been already implemented in all the plants with SLED since it has in any case a beneficial effect on the reliability. A preliminary test was done on one plant to investigate the energy gain limits [3]. After a first optimization of the parameters of a linear phase modulation, in this structure an energy gain of 165 MeV was reached, corresponding to an accelerating gradient of 27 MV/m. The klystron was operating at 38 MW peak power and 4  $\mu$ sec pulse width. These results give confidence in the reaching of the target energy for FEL-2. Further studies will be done to evaluate the advantages of using a non-linear phase modulation to get a flatter RF pulse.

## NEXT IMPLEMENTATIONS

### *New Accelerating Structures*

The layout of the machine allows for the installation of two more accelerating structures powered by the existing plants. This gives the opportunity to move the first two structures along the machine and replace them with structures optimized for the beam dynamics needs at low

energy and high charge. The specification of the two structures calls for minimized phase and amplitude asymmetries in the coupler cells, to minimize the induced kick to the beam due to the multipole field components. The input and output coupling cells shall be of the dual-feed racetrack type with diametrically opposed sidewall-coupling aperture. Symmetrical feed coupling should allow to erase the dipole transverse momentum on the beam due to the total phase and amplitude symmetries in the coupling iris plane, while racetrack geometry permits to minimize quadrupole field components [4]. Each of the two structures will contribute with 50 MeV to the energy budget. This will extend the energy margin or allow operation at higher energy.

### LLRF

The processing board presently used is a commercial board (LLRF4) and will be replaced by a new board under construction. This will allow to extend the capabilities of the system due to the higher computing power, adding new functionalities, such as intra-pulse feedback or real time communications between LLRF units.

The present feedbacks are inter-pulse feedbacks and correct the RF drive to the klystron between pulses. This corrects mainly drifts in phase and amplitude, but does not correct jitter contribution which could be generally associated with modulator instabilities, for example due to the HV power supply or the pfn. In an intra-pulse feedback the information at beginning of the pulse is acquired and the correction applied inside the same pulse. This implementation requires higher performance capabilities on the processing hardware that should be achieved with the new board. The main issue to be taken into account for an intra-pulse feedback is the latency time, which is due to different contribution, such as the structure filling time, the digital acquisition time and the digital processing time.

The structure filling time varies from 0.8 to 1.5  $\mu\text{sec}$  depending on the structure type and is the main contributor to the latency time. Since in the FERMI case the RF pulses are 4  $\mu\text{sec}$  width, this makes not efficient to include the structure in the loop. Therefore a sample of the RF field at the output of the klystron will be acquired and used, allowing also the advantage of shorter cables.

Due to the high acquisition accuracy of the LLRF (0.017°, 0.029%), there is no need of averaging so we do not expect problems due to the digital acquisition time. The new board features low latency ADCs, high FPGA clock frequency and double data rate DACs, so also the digital processing time issue should be very much under control. Finally, the measurements taken on FERMI show that the phase and amplitude trend of the RF pulse can be considered constant between pulses. This leads to the conclusion that single amplitude and phase correction can be used within pulse.

## RELIABILITY ANALYSIS AND RELATED ASPECTS

In the last years the effort has been mainly concentrated on installation aspects. The completion of these activities is shifting the attention on reliability and availability aspects. Some of these issues were already considered during the design phase, for example leading to the construction of a spare modulator. Some other aspects are being analyzed based on the operational results.

Current availability of the S-band system is 93 %, which is sufficient for the commissioning phase and the first users' periods. Klystron-modulator systems are the main source of short resettable faults affecting the uptime. A testing program has been launched to understand these events and figure out how to reduce them. Similar analysis will be applied to the other parts of the systems.

Other availability aspects are being considered, such as the ones related to reduction of the time needed for klystron or thyatron replacement. The possibility of having other spare plants cannot be pursued due to space limitations, so the spares should be ready to use for replacement. This is especially valid for the klystron in order to reduce activation and HV conditioning time once installed.

## CONCLUSIONS

The commissioning of FERMI@Elettra is progressing and FEL-1 will be opened to external users at the end of 2012. The S-band RF system has been gradually set into operation during these years and it is being upgraded for 50 Hz operation. Fifteen RF power plants and sixteen accelerating structures are in operation, allowing the reaching of the required electron beam energy. Stability of the fields is well in specification as confirmed by the measurements on the beam parameters, such as the beam time jitter. Continuous efforts on reliability aspects are pursued since these are key points a users' facility.

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