# ENERGY AND REPETITION RATE UPGRADE OF THE S-BAND RF SYSTEM OF THE FERMI LINAC*

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*Abstract*

FERMI is a single-pass linac-based FEL user facility covering the wavelength range from 80 nm to 4 nm and is located next to the third generation synchrotron radiation facility Elettra in Trieste, Italy. The first FEL line in operation (FEL-1) has been opened to users at the end of 2012, while the second FEL line (FEL-2) covering the shorter wavelength range down to 4 nm is in commissioning. In 2013 the linac energy will be increased following the full RF conditioning of the backward traveling wave accelerating structures and of the SLED cavities. The repetition rate has been also increased to 50 Hz following the installation of the new RF gun and the completion of the upgrade program of the klystron modulators. This paper discusses the strategies adopted for the energy and repetition rate upgrade of the S-band linac and provides a description of the status and of the first results.

## INTRODUCTION

FERMI is a FEL facility based on a warm linac followed by a single pass FEL [1]. Two FEL lines are installed: FEL-1 and FEL-2. The accelerator mainly consists of an RF photocathode gun, an S-band linac, an X-band structure, a laser heater, two bunch compressors and the beam transport line to the undulators of the two FEL lines.

The S-band linac is presently composed of sixteen accelerating structures. The first nine structures are forward traveling wave (TW) ones. Two of them are 3 m long and are from the old Elettra injector, while the remaining seven are 4.5 m long and are LIL type coming from CERN. The last seven structures of the machine are 6.2 m long backward traveling wave (BTW) type and are equipped with SLED systems. Also these structures were used in the old Elettra linac injector. The machine layout reserves the space for two more accelerating structures that will be added in the future [2].

Fifteen S-band 45 MW, 4.5 µs. pulsed klystrons are installed, powering the structures, the gun and the three RF diagnostic deflectors. Typical powering scheme is two structures per klystron for the TW case and one structure per klystron for the BTW one. The system is in operation on a 24h/day basis and the total operating hours/year is higher than 6000.

The commissioning of the facility is rapidly advancing [3]. The first FEL line (FEL-1) has been opened to the external users, while the commissioning of the second one (FEL-2) is advancing. FEL-1 is typically operating at 1.2 GeV beam energy and 10 Hz repetition rate. FEL-2 requires the increase of the beam energy to reach the final specifications in term of shorter wavelength. At the same time the installation of the new gun, capable of operating at 50 Hz, and the upgrade of the modulators, completed at the beginning of 2013, will allow to push the repetition rate of the machine from the present 10 Hz value to the design one, once the conditioning of the structures is completed.

## REPETITION RATE UPGRADE

All the modulators installed in the machine are pulse forming network (pfn) type (see Fig.1). The first six modulators installed in the machine were assembled using the hardware of the plants of the old Elettra injector to allow the start of the commissioning studies. For this reason they were limited to 10 Hz by the hardware. The pulse forming network, the pulse transformer and the klystron tank were replaced to allow higher dissipation due to the augmented duty factor. The pfn is now water-cooled and has a better pulse flatness, while the pulse transformer has a reduced core dissipation and pulse droop. The klystron tank is water-cooled and additional lead shielding was added to the tube. The high voltage power supply was also replaced with a new one that has a higher range of current and voltage and better stability.

Figure 1: One of the RF power plants.

In addition to the replacement of some of the major components, a revision of the modulators was carried on in order to optimize the operation at 50 Hz and the stability of the klystron anodic voltage. The resonant charging scheme has been replaced by direct charging of the pfn. This allows to avoid the use of big storage capacitors and inductors, which means a reduction in stored energy, in space and in the dielectric oil. Other

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advantages of the solution adopted are the improvements in the end of charge voltage repeatability and the reduction of the parasitic capacitance and inductance in the high current path.

Minor upgrades were also performed in the remaining modulators, already designed and assembled for the 50 Hz case. The upgrade activities of all the modulators were organized in order not to affect the commissioning calendar and were completed in time in January 2013.

## ENERGY UPGRADE

The energy of the electron beam should be increased to 1.5 GeV for FEL-2 to reach the shorter value of the design wavelength range. Table 1 reports the parameters of the energy gain and power from the klystrons for FEL-1 used until May 2013.

Table 1: Energy Gain (on crest) for FEL-1 (May 2013)

| Section type | Energy gain | Klystron power |
|---|---|---|
| TW - 3m | ~ 47 MeV | 32 MW @ 2 µs |
| TW - 4.5 m | ~ 55 MeV | 32 MW @ 2 µs |
| BTW - 6.2 m | ~ 120 MeV | 22 MW @ 3 µs |

Although the energy target should be achievable with the present set of structures, it must be remembered that the machine foresees the installation of two more structures, both in terms of space and available power from the not used output ports of the already installed klystrons. These two structures will contribute with additional 100 MeV to the electron beam energy budget.

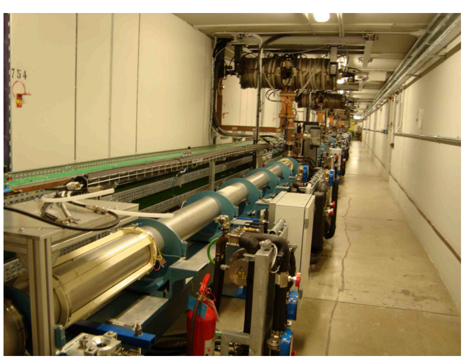

Figure 2: One of the SLED equipped BTW structures.

The increase of energy is obtained by raising the accelerating gradient in the BTW structures (Fig.2) so that their energy gain is in the 150 MeV/structure range. For these structures, equipped with SLED, there is RF power available still maintaining a reasonable safety margin, since operating peak power will be around 32 MW. However, it should be considered that in the past operation in the former injector of Elettra these structures suffered of heavy breakdown phenomena when pushed to high gradient. For this reason till the beginning, a phase modulation of the SLED phase reversal was introduced to lower the peak electric field. Following the preliminary test that showed the advantages of this technique [4], this procedure was routinely applied on all the plants.

For the TW structures, which are powered in pairs, the possible increase in energy is limited by the available power with the present set-up. Since the target energy could be reached only with the improved gain in the BTW structures and considering also that increasing the energy gain in the TW structures would require a re-optimization of the present working parameters at the first bunch compressor, it was decided to leave them untouched.

## CONDTIONING RESULTS AND OPERATION

For the commissioning of the plants at 50 Hz and for the conditioning to 1.5 GeV, two periods were allocated so far in the present year: four weeks in May and one week in August. During the first period, both 50 Hz and RF conditioning was performed, while in the second only further 10 Hz RF conditioning was done.

At the end of the first period 1.5 GeV (on crest) at 50 Hz were reached. However, due to the fact that the breakdown rate was still too high, there was no possibility to extend the conditioning period and since the machine was required to operate at 10 Hz in the following runs, it was decided to set the maximum working energy of the machine at 1.46 GeV (on crest) at 10 Hz. In August further conditioning was performed at 10 Hz and the peak energy achieved was increased to 1.54 GeV. It must be noted that the result was only limited by the allocated time.

Table 2: Energy Budget after the Conditioning Periods

| Section | 50 Hz -May'13 | 10 Hz -Aug'13 |
|---|---|---|
| TW – 3m | ~ 47 MeV | ~ 47 MeV |
| TW- 4.5 m | ~ 55 MeV | ~ 55 MeV |
| BTW -6.2 m | ~139 MeV | ~149 MeV |
| Linac energy (on crest) | 1.46 GeV | 1.54 GeV |

The increase to 50 Hz of the power plants was achieved without any issue. In particular there was no change in the plant fault rate and in the frequency of the klystron arcs, which account for the major number of trips of the system. The TW structures, where only frequency rate upgrade was performed and no increase in gradient was required, reached the target value in few days.

The BTW structures operation at the gradient for 1.5 GeV at 50 Hz showed a still too high breakdown rate and therefore they need further conditioning to assess their ultimate performance. During the RF conditioning most of the vacuum spikes were detected by the ion pumps near to the structure input, which seems to suggest that breakdown events took place in the structure input coupler and cells. This is in-line with the observation




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performed on these structures in the past and with the simulation performed [5]. The main hardware issue was the failure of the ceramics of the reflected power port of the directional couplers between the SLED output and the accelerating structures input, which occurred three times.

Following the conditioning period, the structure are normally set to the maximum gradient reached that allows both sufficient reliability for the machine operation and consolidation of the results. The experience shows a nice decrease of the total number of vacuum trips with time (Fig. 3).

As for the next conditioning phases, since most of the time, for example when working for FEL-1, the beam energy required is lower than the maximum available, one or two sections are set off-line. On these structures, conditioning can continue without the need of dedicated time. The target is to establish the operation at 50 Hz in view of the experiments with internal users that are scheduled for Fall 2014.

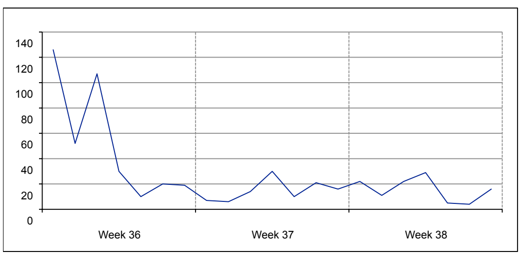


Figure 3: Trend of vacuum faults/week after conditioning.

## OUTLOOK AND NEXT ACTIVITIES

The experience has shown that the performance of the directional couplers installed between SLED and structures input must be improved. Numerical simulations have been carried on to revise the design with the support of the components supplier. According to the simulations, the simple reduction of the coupling hole diameter, to reduce the coupling from the present 50 to 65 dB, should allow a reduction of the maximum electric field to an expected safe value. This should allow to operate in a safer condition without the need to revise the waveguide circuit layout. The amplitude of the RF samples from the coupler is still sufficient for the needs of monitoring and measurements with the LLRF. Other alternatives are also under investigation, but these should be seen in conjunction with the boundary conditions of the space available between SLED output and structure input. Other interlocks will be added on the reverse power from the structure, as the one that already protects the klystron, to preventively stop the operation of the plant.

On all the SLEDs a simple linear phase modulation has been applied up to now. A study on the optimization of the parameters of the phase modulation is in course with the target of obtaining a flatter pulse and a lower peak field in the accelerating structure while keeping the energy gain [6].

Although the target energy of FEL-2 should be achieved with the present layout of the machine, the energy budget will be further increased with the installation of the two remaining structures. The procedure for their acquisition is in course and it is expected to install them in 2015. This installation will provide additional 100 MeV.

Another possibility to increase the energy could be to install SLED cavities for the CERN type structures, as also suggested by the MAC committee. Although the filling time of these structures will not allow a maximum efficiency of the SLED process, from a preliminary calculation this could allow to obtain an additional margin of 100 MeV at a relatively moderate cost. Of course this possibility should also be verified with the operating range of other parts of the machine, such as the bunch compressors, and with eventual interferences with the present layout of the machine.

## CONCLUSIONS

The S-band RF system of the FERMI linac is in routine operation, accumulating more 6000 operating hours per year. The upgrade of all the plants to 50 Hz has been completed.

The increase of the linac energy is in course, up to now 1.54 GeV at 10 Hz were reached on crest. Further conditioning is required to further slightly increase of some tens of MeV this value, as required for the lower wavelength range, taking into account the margin needed for the X-band and the need to operate some structures off-crest, and to extend these results at 50 Hz.

Further increase in the maximum energy could be reached with the installation of the two accelerating structures foreseen in the machine layout and with the possible upgrade with SLED of some of the TW structures.

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