PERSPECTIVES OF THE S-BAND LINAC OF FERMI

A. Fabris[#], P. Delgiusto, M. Milloch, C. Serpico, Elettra-Sincrotrone Trieste S.C.p.A., Trieste, Italy
A. Grudiev, CERN, Geneva, Switzerland

Abstract

The S-band linac of FERMI, the seeded Free Electron Laser (FEL) located at the Elettra laboratory in Trieste, has reached the peak on-crest electron energy of 1.55 GeV required for FEL-2 with the present layout. Different ways are being considered to extend the operating energy of the S-band linac up to 1.8 GeV. At the same time upgrades on the existing systems are investigated to address the requirements of operability of a users facility. This paper provides an overview of the developments that are under consideration and discusses the requirements and constraints for their implementation.

INTRODUCTION

FERMI, the Italian seeded FEL facility located in Trieste, consists of two FEL lines. FEL-1, covering the wavelength between 100 and 20 nm, is already open to external users. FEl-2, covering the shorter wavelength range down to 4 nm, will be opened to external users in the next calls for proposals [1]. The linac is based on warm S-band technology and it is presently composed of fifteen 3 GHz 45 MW peak RF plants powering sixteen accelerating structures, the gun and the RF deflectors.

BRIEF OVERVIEW OF THE S-BAND RF SYSTEM OPERATION

After the conditioning periods dedicated in August 2013, the on-crest electron energy has reached 1.55 GeV [2], which means achieving the design 1.5 GeV operating energy once losses for chirp compensation and linearization by deceleration in the fourth harmonic X-band cavity are taken into account. Operating energy is actually set according to the requirements for users' experiments. The working points of the structures are fixed to the maximum gradient achievable for a reliable operation. When less beam energy is required, some of the last structures are set off-line providing the redundancy that is very useful to ensure the operation for the users. Although presently the repetition rate of the machine is 10 Hz, operation at 50 Hz of the modulators has been validated on long time period (few months). Klystron peak power is typically in the range between 32 and 36 MW. Uptime of the S-band system during users period in 2013 has been 93.5 % with klystron arcs accounting for the major number of faults.

After these first years of commissioning and operation, possible developments have been analysed to correct the major downtime sources, increase safety margins and redundancy and extend operating margins of the machine especially in terms of peak energy.

#alessandro.fabris@elettra.eu

ACCELERATING STRUCTURES

The machine is composed of three types of accelerating structures. After the gun, the first two are 3.2 m long forward travelling wave (FTW) used in the old Elettra injector. These are followed by seven 4.5 m long LIL type FTW structures, donated by CERN, and by seven 6.1 m long backward travelling wave (BTW) SLED equipped structures from the old Elettra injector.

New Accelerating Structures

The layout of the machine reserves space and availability of power outputs from the klystrons along the linac for two additional 3.2 m long structures. Being the same length of the first two structures, this gives the opportunity to replace these two structures with new ones optimised for the needs in the injector part of the linac. The structures presently in operation will be then relocated along the machine in the space available.

The new structures will be FTW, $2\pi/3$, constant gradient, disk loaded and with minimised phase and amplitude asymmetries in the coupler cells, to minimize the induced kick on the beam. The main design parameters are listed in Table 1 [3]. The structures will be built by RI Research Instruments GmbH. Delivery is planned in Spring 2015, followed by high power RF conditioning in the test stand, expected to take place in summer 2015. Considering the FERMI schedule, installation in the machine is expected in the first months of 2016. These two structures will provide additional 100 MeV to the energy budget.

Table 1: Requirements for the new accelerating structures

Parameter	**Value**
Working frequency	2998.01 MHz
Maximum input	25 MW
Maximum pulse duration	5 μs
Maximum repetition rate	50 Hz
Filling time	< 1.5 μs
Q factor	>13000
Target shunt impedance	> 60 $M\Omega m^{-1}$
Energy gain@16 MW	> 48 MeV
Input coupler type	symmetric 180 degree

New Accelerating Modules

The last part of the linac is based on the already available 6.1 m long BTW structures from the old Elettra injector. These structures are made up of magnetic

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ISBN 978-3-95450-142-7

coupled, nose-cone cavities with a small iris radius (5 mm), designed to achieve high operating gradient, i.e. up to 30 MV/m. These structures are equipped with pulse compression system and presently can provide an energy gain of 150 MeV.

The narrow iris has a huge impact on beam dynamics in terms of longitudinal and transverse wakefields. At high bunch current it is necessary to put off-crest some structures in the last part of the linac with a consequent decrease in the final output energy of the beam. This loss could reach even 130 MeV at 800 pC beam charge. In addition the BTW structures suffer of heavy breakdown phenomena when pushed at higher gradient and this represents a limit to their operation.

For these reasons, a study on a possible replacement for the BTW structures has started. To minimize the impact in terms of costs and installation, this upgrade should be designed to fit in the space now occupied and optimized for the power available from the existing plants.

The preliminary design studies has lead to concentrate on a solution based on a module composed of two 3 m long FTW constant gradient structures (see Fig. 1) with 10 mm iris radius, i.e. two times the one of the presently operating BTW structures. An analysis on the expected breakdown rate (BDR) based on the modified Poynting vector [4] for 25 MV/m accelerating gradient shows a good expected value of about 2 10^{-15} for 672 ns structure filling time.

Longitudinal and transverse dynamics have been also evaluated for this preliminary design [5], [6]. With the new structures at high current the loss with respect to on-crest operation is expected to be reduced to 20 MeV. The expected emittance growth with the same linac optics, accelerating gradient and equivalent misalignment has been calculated to be lower than 0.1 µm, compared to the 1-2 µm observed value for the present linac configuration. Finally, shorter structures are expected to have smaller bookshelfing effect and smaller distortion.

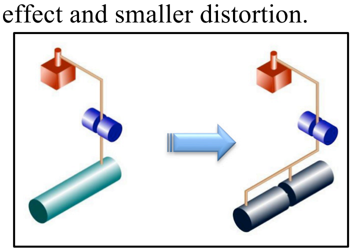

Figure 1: New accelerating module.

Based on the promising preliminary results, the study will continue with electromagnetic and mechanical simulations and beam dynamics calculations. The purpose is to design a prototype that will be tested at high RF power to validate the project. Following this, the scheduling of a replacement program will be analysed.

SLEDs on 4.5 m long FTW Structures

The possibility of equipping the seven LIL type structures with SLEDs system has been examined. This structures provide typically 58 MeV energy gain each. For a first evaluation the parameters of the SLED cavities installed in the MAX IV linac [7] have been used (Q factor around 100000, filling time of 1.5 µsec and beta of 6). These cavities fit in the available space.

The results of the calculation are summarised in Table 2 for 36 MW peak RF power and 4 µs pulse. The total energy gain for seven structures is around 120 MeV, roughly what can be achieved with two more accelerating structures operated as they are today. The accelerating gradient will be around 17 MV/m so it will not be increased critically. It must be noted that, for this preliminary calculation, off the shelf components were considered and therefore there is some margin of optimization. An eventual installation of the SLEDs could be performed in steps, allocated in the machine shutdowns, considering also the need of few upgrades in the waveguide circuit due to the increased peak power. Beam dynamics simulations will be done to confirm the highest acceptable energy at the bunch compressor.

Table 2: Comparison of Operation with and without SLED for the 4.5 m FTW Structures (36 MW power, 4µs pulse)

	Gradient (MV/m)	**Energy gain (MeV)**
No SLED	13	58
With SLED	17	76

RF POWER PLANTS

The RF power is provided by fifteen 45 MW S-band klystrons powered by line type modulators. The delivered power is typically around 75 to 80 % of the maximum value. The stability achieved is 32 ppm on the klystron voltage, which means 0.02° at S-band.

Modulator Modifications

The major source of downtime of the S-band is related to klystron arcs, although these faults are of short time duration. The number has already been reduced by optimising the klystron ramps and filament heating. However, a modification of the modulator circuit is under study to reduce the associated downtime. The scope is to decrease the switch-on time after an arc, which implies reducing the reverse voltage on the klystron after an arc, in addition to modification to the PLC interlock management. It must be noted that this will apply only in case of single arcs. In case of repetitive arcs, the re-start will be done with the same ramp as it is today.

Preliminary tests have been performed on the spare modulator with positive results and the modification will be implemented and tested also on the other modulators starting from next autumn.

Solid-State Switches

FEL operation requires a high stability of the RF in the accelerating structures. One of the major sources of stability worsening was found related to internal arcs in the thyratron, especially with aging. In some cases this has lead to an early replacement of the tube. Figure 2 shows the correlation of the amplitude readings (in

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arbitrary units) with the phase residual in case of correct operation, while Fig. 3 shows the same values in presence of thyratron arcs. All the values are peak-peak. In case of arcs a number of pulses falls outside the central region leading to stability deterioration. The trend can be clearly monitored with the LLRF. Optimization of the reservoir pressure, accurate monitoring of thyratron operation and preventive replacement are used to mitigate and keep under control this effect.

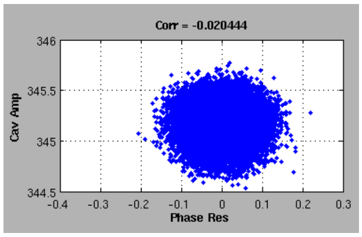

Figure 2: Amplitude vs. phase in correct operation.

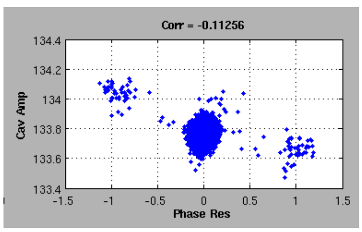

Figure 3: Amplitude vs. phase in presence of arcs.

Solid-state switches with capabilities of replacing the thyratrons adopted in the modulators have been recently developed [8]. They consist of multiple series connected fast turn-off thyristors, which are designed for pulsed power operation, high di/dt and high voltage. To verify the possible implementation of these devices on the FERMI RF plants, an R&D project has been launched. Also in this case modifications to the modulators are required to prevent excessive reverse voltage on the switch in case of klystron arcs. The solution will be preliminarily tested on the test stand and, if successful, gradually implemented on the machine. It is expected to be ready for the first tests by the end of the year.

OTHER DEVELOPMENTS

The present layout of the machine foresees a hot-spare replacement only for the first two plants, powering the gun and the first two structures. Operation has shown that also the following two plants, which are used to impose a chirp on the electron beam for effective bunch compression, are fundamental. Therefore the possibility to install one new spare plant, which could quickly replace these two in case of problems via a waveguide switches matrix, is under study, considering the availability of spaces and services.

In-vacuum waveguide directional couplers are installed at the input ports of the structures. Some failures on the ceramic vacuum view ports have been experienced, in particular in the couplers installed after the pulse compressor system where the peak power can reach more than 100 MW. A new design for directional couplers with lower coupling and a different layout of the ceramic window has been commissioned to MEGA Industries and will be tested in the next months.

The completion of the installation of the new processing boards of the LLRF units will allow to extend the capabilities of the system adding new measurement channels and new functionalities such as a possible implementation of an intra-pulse feedback [9].

ENERGY BUDGET

The present maximum on-crest energy is 1.55 GeV. Other 100 MeV could be obtained with the new accelerating structures and 120 MeV if SLEDs are installed for the LIL structures. This leads to a target energy of 1.77 GeV that can be further increased if the LIL structures gradient can be slightly increased and if also some of the remaining 3.2 TW structures are sledded. All this leads to the consideration that a target peak energy of 1.8 GeV should be reached. Redundancy for off-crest operation could then be obtained with the exchange of one high-energy deflectors with an additional structure, if the possibility of moving one of the two deflectors after the undulator chain will be pursued.

CONCLUSIONS

With the installation of the two structures now being ordered, the FERMI linac layout will be completed. In parallel with the scheduled activities of operation and maintenance, possible developments are being studied to enlarge the performance in terms of reliability, functionalities and to increase the higher peak electron beam energy.

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ISBN 978-3-95450-142-7