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FABRICATION, CONDITIONING, INSTALLATION AND COMMISSIONING WITH THE BEAM OF THE FIRST HIGH GRADIENT (HG) MODULE FOR THE FERMI LINAC UPGRADE

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Abstract

FERMI is the seeded Free Electron Laser (FEL) user facility at Elettra laboratory in Trieste, operating in the VUV to soft X-rays spectral range. In order to extend the FEL spectral range to shorter wavelengths, an upgrade plan for increasing the Linac energy from 1.5 GeV to 2.0 GeV is actually going on. After the successful testing of the short prototype of the new high gradient (HG) S-band accelerating structure up to an accelerating gradient of 40 MV/m, two full-length 3.0 m HG structures have been built and installed at the FERMI linac. In this paper, we report the low power measurement, conditioning results, and commissioning with the beam of the first HG module.

INTRODUCTION

The FERMI free-electron-laser (FEL), located at the Elettra Sincrotrone research center in Trieste, Italy is the 4th generation light source operating in Extreme-Ultraviolet (EUV) to the soft X-rays range. FERMI is presently driven by a 1.5 GeV, S-band radio-frequency linear accelerator (linac), outlined in Fig. 1. The upgrade plan of the FERMI aims

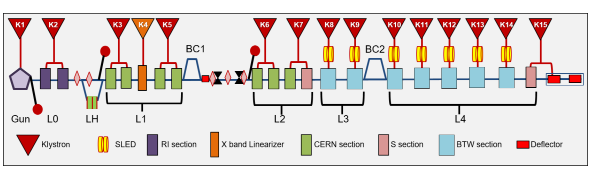

Figure 1: FERMI FEL linac layout (cartoon, not to scale).

to extend the FEL wavelength range to cover the nitrogen and oxygen K-edge by increasing the electron beam energy upto 2.0 GeV and the peak current greater than 1 kA [1, 2]. During this upgrade the seven, 6.4 m long, BTW structures in the high energy part of the linac (L3 and L4) which are limited presently to a maximum gradient of 24 MV/m would be replaced by the newly designed HG modules (one HG module consists of two HG structures of 3.0 m in length) which are designed to operate reliably up to an accelerating gradient of 30 MV/m as shown in Fig. 2. This energy upgrade will enable the FERMI to generate the beam up to 600 eV photon energy, covering the whole water window. In the first step, two such new HG structures are installed in place of S0a and one deflector at K15 increasing the beam energy to 1.7 GeV. In the next phase, 14 new HG structures would replace the present Backward Travelling Wave (BTW) sections reaching the final goal of 2.0 GeV. The first 3.0 m HG structure was conditioned and high-power tested at the cavity test facility of Elettra from May 2022 to August 2022. After receiving the 2nd HG structure first HG module is installed at FERMI linac during the summer shutdown in September 2022 for commissioning with the beam.

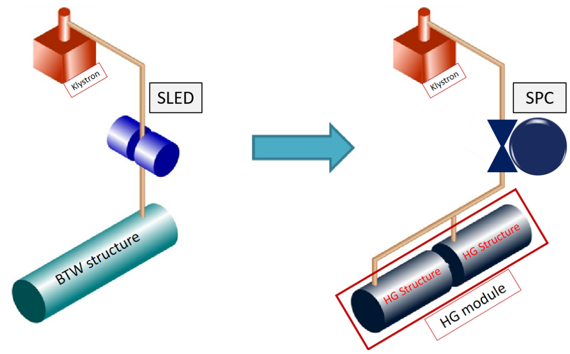

Figure 2: Sketch (cartoon) of the FERMI upgrade plan.

BRIEF OVERVIEW OF THE UPGRADE PLAN

The HG structures are constant gradient type accelerating structures operating in $2\pi/3$ phase advance mode [3, 4]. These HG structures are designed to operate reliably at an accelerating gradient of 30 MV/m with a very low breakdown rate (BDR) with low wakefields. The HG structures are fed using a customized version of duel-fed EC-type couplers as they have lower surface fields as compared to their MC counterparts [5]. All the geometrical parameters of an accelerating cell are summarized in Table 1. A short prototype was built at Paul Scherrer Institute (PSI) in Switzerland with the aim to verify the feasibility and reliability of the upgrade. The short prototype was fabricated using a technique developed at PSI which produces a tuning-free structure by adhering to very tight tolerances [6]. A high-power S-band test facility with the BOC type pulse compressor and National Instrument (NI) diagnostic hardware was commissioned at Elettra for conditioning and high-power testing of the short prototype [7]. The complete history of conditioning and high-power operation along with the exhaustive post-processing of the conditioning data is covered in [8]. In short, the prototype operated at an accelerating gradient

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of 40 MV/m for 450 million RF pulses with the BDR of 8×10^{-8} bpp. From the analysis of the data, it was clear that the short HG prototype met all the design criteria indicating that the RF design and the fabrication technique are up to mark for the production of the full 3.0 m HG structures.

Table 1: RF Parameters of the HG Structures

Parameter	Value	Unit
f_0	2,998.01	MHz
Mode	$2\pi/3$	
$L_{structure(active)}$	2,919.89	mm
L_{cell}	33.332	mm
N_{cell}	84	
a(iris)	11.130→ 8.801	mm
b(cell outer radius)	41.546→ 41.076	mm
or(outer bending radius)	13	mm
t(disk thickness)	2.5	mm
R_{shunt}	72→ 81	MΩ/m
Q_o	≈15,850	
v_g/c	2.07→ 0.97	
t_f	645	ns
τ	0.385	N_p

HG MODULE FABRICATION AND COLD MEASUREMENTS

After the successful testing of the short prototype one HG module, consisting of two HG structures of 3.0 m each in length, was fabricated at PSI. Cold tests including the low-power RF measurements for HG1 and HG2 structures were performed at PSI and the results are shown in Figs. 3 and 4 respectively.

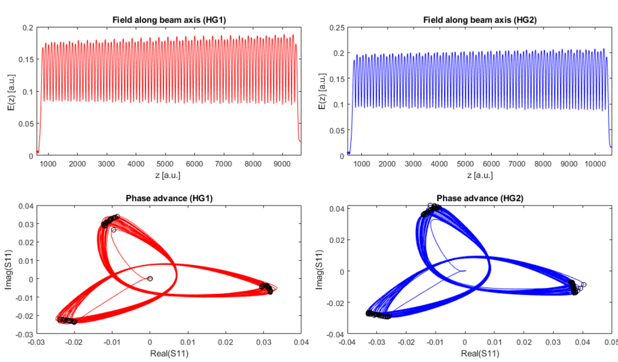

Figure 3: Low power measurement results of HG module.

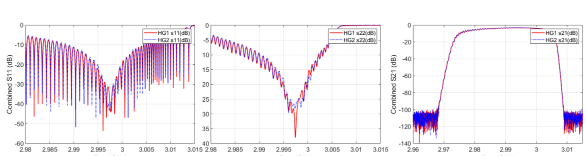

Figure 4: Measured S parameters of HG module.

CONDITIONING OF HG1 STRUCTURE

The first high gradient structure (HG1) was conditioned at the S-band cavity test facility of Elettra. The HG1 structure was installed at the test facility in the FERMI linac tunnel during the shutdown of April 2022 as shown in Fig. 5. The total conditioning process was manual and completely supervised. The RF power was increased slowly while the vacuum and reflected faults were monitored round the clock during the conditioning process of the HG1 structure. The total conditioning process can be broadly divided into two phases. Phase I consisted of conditioning with a shorter pulse length (350 ns) while phase II consisted of conditioning and constant power operation with a pulse length of 700 ns, equal to the filling time of the HG structure. Phase I concluded with 80 million pulses when the HG1 structure reached the target accelerating gradient of 30 MV/m with a short pulse length of 350 ns. After reaching this level phase II started immediately with the increase of pulse length to 700 ns, equal to the filling time of the HG structures, while RF power was reduced to keep the BDR low. The first part of phase II (conditioning) was completed with 100 million pulses when the HG1 structure reached an accelerating gradient of 30 MV/m. In the last part of phase II (constant power operation), the system was left to condition for 180 million pulses with 75 MW input power and a pulse length of 700 ns. Generated conditioning data was analysed using MATLAB tool and results can be seen in Fig. 6.

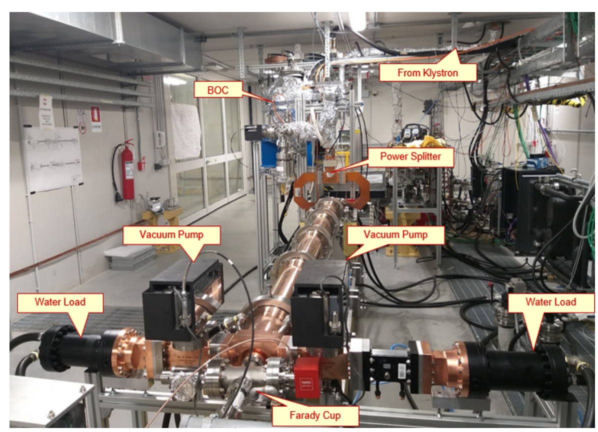

Figure 5: HG1 structure installed at the FERMI's cavity test facility

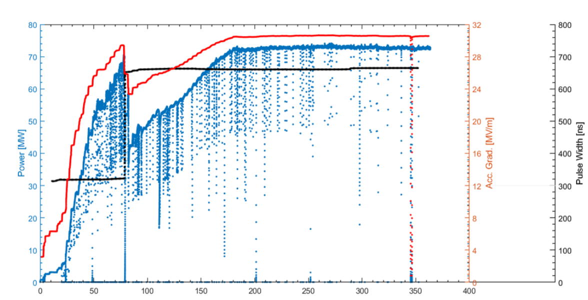

Figure 6: History plot of conditioning of HG1 structure.

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INSTALLATION OF THE HG MODULE AT THE FERMI LINAC

After the successful conditioning of the HG1 structure, the first HG module (HG1 and HG2 structures) was installed at the FERMI linac in place of one short section (S0a) and one deflector to gain more energy at the very start of the upgrade [9]. Figure 7 shows the HG module installed in the FERMI tunnel. The HG2 structure was installed directly at the FERMI linac without conditioning, with the idea to condition it during the machine operation. The FERMI winter run started in October 2022. During the first six weeks of the run, the two HG structures were desynchronized with the beam to decouple the operation of FEL and the conditioning of sections. The conditioning of the second structure (HG2) is in progress, following a similar trend to that of the first structure (HG1) conditioned offline at the cavity test facility of Elettra. Operating with the beam we had the opportunity to verify the effective gradient in the HG structures, which perfectly matches the calculated energy gain indicating that both the HG structures are in phase.

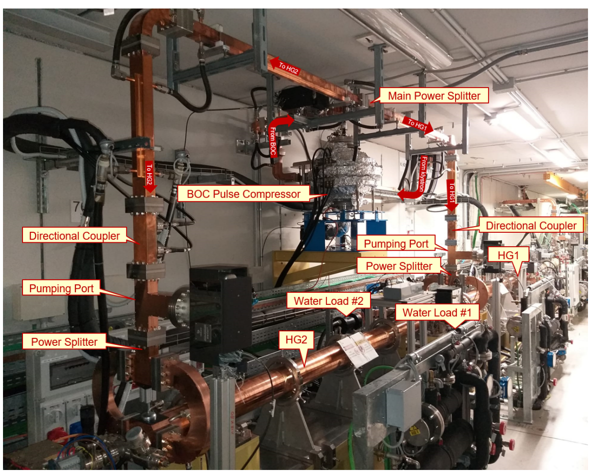

Figure 7: HG module installed in the FERMI linac tunnel.

CONCLUSIONS

The fabrication and installation of the first HG module at the FERMI linac was the first step towards the energy upgrade of the FERMI linac to reach the final energy goal of 2.0 GeV. The low power measurements and conditioning of the HG1 structure up to an accelerating gradient of 30 MV/m with the BDR of 6×10^{-8} bpp/m prove the validity of the RF design of the HG structures. The HG module is installed on the FERMI linac for operation with the beam. The measurement of the beam energy verified that both the HG structures are in phase as the installation is done without any phase shifter. We may conclude that the HG structures met all the design criteria. The presented results show that the design of the FERMI linac upgrade plan is ready to move forward.

REFERENCES

[1] L. Giannessi, C. Masciovecchio *et al.*, "FERMI 2.0, Conceptual design report", Sincrotrone Trieste, Italy, 2022.

[2] C. Serpico *et al.*, "A High Gradient Solution for Increasing the Energy of the FERMI Linac", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2525–2527. doi:10.18429/JACoW-IPAC2018-WEPMF067

[3] C. Serpico, N. Shafqat, A. Grudiev, and R. Vescovo , "High gradient, high reliability, and low wakefield accelerating structures for the FERMI FEL", *Rev. Sci. Instrum.*, vol. 88, p. 073303, 2017. doi:10.1063/1.4993742

[4] N. Shafqat, S. Di Mitri, C. Serpico, and S. Nicastro, "Design study of high gradient, low impedance accelerating structures for the FERMI free electron laser linac upgrade", *Nucl. Instrum. Meth. Phys. Res. Sect. A*, vol. 867, pp. 78–87, 2017. doi:10.1016/j.nima.2017.04.018

[5] C. Serpico, A. Grudiev, and R. Vescovo , "Analysis and comparison between electric and magnetic power couplers for accelerators in Free Electron Lasers (FEL)", *Nucl. Instrum. Meth. Phys. Res. Sect. A*, vol. 833, pp. 8–14, Oct. 2016. doi:10.1016/j.nima.2016.06.131

[6] U. Ellenberger *et al.*, "Status of the Manufacturing Process for the SwissFEL C-Band Accelerating Structures", in *Proc. FEL'13*, New York, NY, USA, Aug. 2013, paper TUPSO17, pp. 245–249.

[7] N. Shafqat *et al.*, "Commissioning of S-band Cavity Test Facility at Elettra for Conditioning of High Gradient Structures for the Fermi Linac Upgrade", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2846–2848. doi:10.18429/JACoW-IPAC2019-WEPRB021

[8] N. Shafqat, C. Serpico, and T. G. Lucas, "Design and high-power test of a short prototype of high gradient S-band accelerating structure for the FERMI free electron laser upgrade", *Nucl. Instrum. Meth. Phys. Res. Sect. A*, vol. 979, p. 164472, Nov. 2020. doi:10.1016/j.nima.2020.164473

[9] N. Shafqat, C. Masciovecchio, M. Milloch, F. Gelmetti, A. Milocco, and M. Trovo, "Conditioning and High Power Test Results of First 3.0 m High Gradient Structure for FERMI Linac Energy Upgrade", presented at the FEL2022, Triest, Italy, Aug. 2022, paper TUP08, unpublished.