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A HIGH GRADIENT SOLUTION FOR INCREASING THE ENERGY OF THE FERMI LINAC

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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, a feasibility study for increasing the Linac energy from 1.5 GeV to 1.8 GeV is actually going on. The design of new S-band accelerating structures, intended to replace the present Backward Travelling Wave sections, is presented. Such design is tailored for high gradient operation, low breakdown rates and low wakefield contribution. In this paper, we will also present the first, short prototype that has been built in collaboration with Paul Scherrer Institute (PSI).

INTRODUCTION

FERMI has achieved its nominal performance goals by the production of photon energies above 300 eV. However, there is a great demand from scientific community to cover the whole water window by reaching both the nitrogen and oxygen K-edges. This will require the extension of the photon energy up to 600 eV. FEL simulations show that this goal can be achieved by increasing the electron beam energy from the present value of 1.5 GeV up to 1.8 GeV, while the beam peak current should be pushed up to 1 kA. This is not possible in the current configuration due to some limitations with the seven, 6.4 m long, BTW structures in the high energy part of linac. Presently, maximum accelerating gradient is limited to 24 MV/m due to high break down rate in BTW structures while the small beam aperture (5 mm in radius) also introduces significant longitudinal and transverse wakefields. To solve all these issues an upgrade of FERMI Linac is currently under study. In the upgrade scenario each BTW structure would be replaced by two, 3.2m long, structures fed by the same power source. This upgrade would ensure the reliable accelerating gradient of 30 MV/m at 50 Hz and increase in beam energy from 1.5 GeV to 1.8 GeV.

RF DESIGN

RF Coupler Design

The RF coupler is the region more prone to RF breakdown and surface degradation. An extensive comparison between magnetic-coupled (MC) and electric-coupled (EC) RF couplers is made in [1]. In EC-RF couplers the input power coming from the source is directly coupled to the accelerator through a circular iris in the broad wall of the WR284 waveguide. A customized version of dual-fed-EC coupler is chosen for the new, high gradient, structures, due to significantly lower surface fields as shown in Fig. 1.

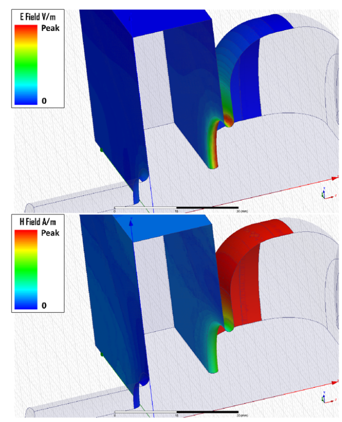

Figure 1: Surface fields for the EC-Coupler.

Accelerating Cells Design

The complete design of new accelerating structures is reported in [2]. Since the new accelerating module has to replace an existing BTW structure, the length for each accelerating section shall not exceed 3.2 m. It was calculated that 90 accelerating cells, each of 33.332 mm length, can be accommodated in that space. All the geometrical parameters of an accelerating cell are summarized in Table 1. Disk thickness of 2.5 mm allows to achieve high shunt impedance and double rounding ensures a quality factor of 15800. Constant gradient throughout the structure is maintained by designing the cells according to the following condition.

$$v_{g,i} = \frac{\omega_0 L_{\text{structure}}}{Q_0} \frac{\left[1 - \left(1 - e^{-2\tau}\right) \frac{(i-1)L}{L_{\text{structure}}}\right]}{\left(1 - e^{-2\tau}\right)} \quad (1)$$

The value of the attenuation constant τ of 0.385 Neper is dictated by the optimal filling time of 650 ns for efficient RF pulse compression. To achieve 1.8 GeV the new structure has to work at 30 MV/m gradient which is considerably high for typical S-band accelerators. Higher gradient means higher surface fields which would translate to higher break down rates. In order to lower the peak electric field in the cell, an elliptical rounding is introduced and optimized using HFSS. Cell surface fields and modified Poynting vector [3]

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have been calculated and compared with those of the BTW structures and the results are reported in Table 2. As it is shown, in the new design the surface magnetic field will be approximately seven times lower, so no limitation due to pulse heating phenomenon will occur. According to the criterion defined int the frame of the CLIC X-Band high gradient program by CERN-SLAC-KEK [3], the expected breakdown rate has also been evaluated: in particular, the value of $|S_c|$ will result in a breakdown rate probability of nearly $8.7 \cdot 10^{-20}$ bpp/m at a gradient of 24 MV/m and $1.4 \cdot 10^{-16}$ bpp/m at 30 MV/m.

Table 1: RF Parameters of Accelerating Structure

Parameter	Value
f_0 [MHz]	2998.01
Mode	$2\pi/3$
$L_{\text{structure}}$ [mm]	3175
L_{cell} [mm]	33.332
N_{cell}	90
a (iris) [mm]	$11.38 \rightarrow 8.98$
b (cell outer radius) [mm]	$41.61 \rightarrow 41.11$
t (disk thickness) [mm]	2.5
or (bending radius) [mm]	13
R_{sh} [MΩ/m]	$71 \rightarrow 80$
Q_0	≈ 15850
v_g/c	$221 \rightarrow 104$
t_f [ns]	645
τ [Neper]	0.38

Table 2: RF Parameters for the First Regular Cells

Parameter	HG	BTW
Acc. Gradient [MV/m]	24	24
RF Pulse length [ns]	670	770
$E_{\text{surf,Max}}$ [MV/m]	62	85
$H_{\text{surf,Max}}$ [kA/m]	54	368
$S_{\text{c,Max}}$ [MW/mm^2]	0.36	2.1
BDR [bpp/m]	$8.7 \cdot 10^{-20}$	$5.4 \cdot 10^{-8}$

BEAM DYNAMICS STUDY

Particle Beam Dynamics

The FERMI Linac provides nowadays an electron beam of 1.5 GeV mean energy, and a total relative energy spread <0.1%. The beam energy chirp in FERMI is strongly affected by the longitudinal wakefield excited by the BTW structures. In Fig. 2, the difference of iris radii of structures in section L0-L2 ($\approx$ 10 mm) and in section L3-L4 (5 mm) generates different short-range wakefields, which in turn affect the final beam emittance and longitudinal phase space.

Extensive analysis is done in [4] to estimate wake functions of the new structures. To investigate the effect of weaker longitudinal wakefield on the final energy chirp, the

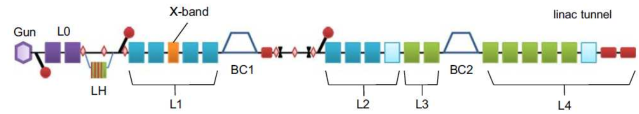

Figure 2: FERMI Linac layout.

1D code LiTrack is used. To keep the energy spread <0.1%, the new structures would be operated off-crest by 10° with a final beam energy of 1.782 GeV. Results of longitudinal phase space are shown in Fig. 3 while comparison of final projected emittance growth for present FERMI Linac and after the replacement of BTW structures is shown in Fig. 4.

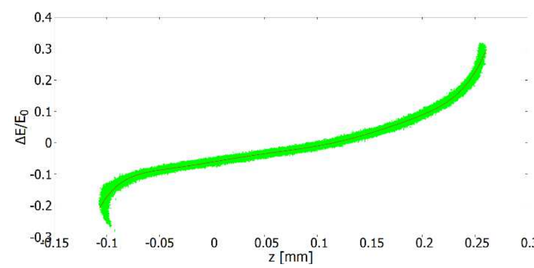

Figure 3: Longitudinal phase space at the linac end and its fit.

PROTOTYPE FABRICATION AND COLD MEASUREMENTS

The design of the cavity is based on solutions developed at PSI for the production of 120 C-band accelerating structures for SwissFEL [5]. Recently PSI produced also two X-band T24 prototypes tested at CERN at high power showing encouraging results for high gradient application. The technology applied to the present S-band cavity is very similar. The cups have one half cell machined on each side in order to have the brazing plane in the middle of the cell. Sharp edges in the cells stop the melted brazing material from flowing into the cells. Air channels give the possibility to check for vacuum tightness after brazing. This design is possible thanks to the absence of any tuning feature. The cooling circuits are integrated in the cups. The alignment is based on a shrink-fit design and the cups are heated (Δ T = 50°C) before stacking. All cups and the two couplers were produced by the company VDL ETG Precision BV, Eindhoven. All cups have been controlled by metrology and all the inner profiles of the regular cups are all well within the specified tolerances (specified ±4 µm; from metrology ±1 µm) and the average surface roughness (Ra) is below 25 nm.

The cold measurements, i.e. bead pulling and S-parameter were performed at PSI. Since the structure does not have any possibility of tuning it was mandatory to fabricate it as close as possible to the operating frequency. The operating temperature is 36.4°C, only 1.4°C higher than the design value (35°C). The field along the structure, as shown in Fig. 5

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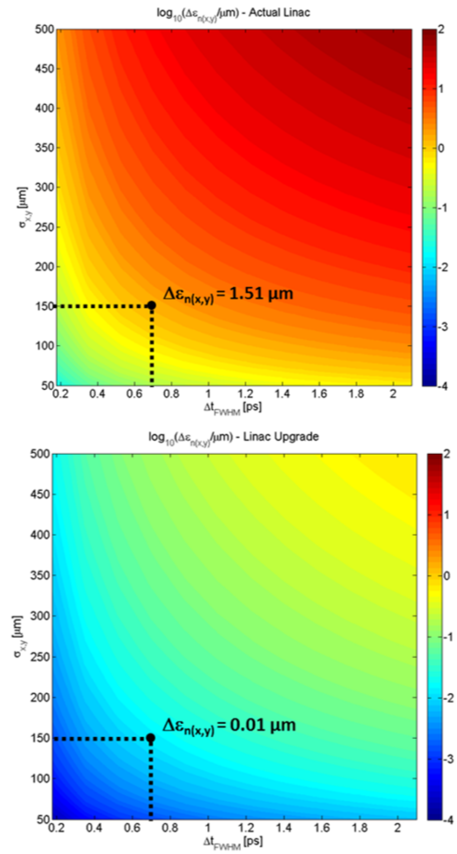

Figure 4: Transverse normalized emittance growth (either horizontal or vertical) through L3 and L4 as a function of the bunch duration (FWHM) and of Linac-to-beam relative misalignment (rms) for the present FRMI Linac (top) and for the Linac upgrade.

is perfectly flat and the mismatch is below -30 dB at both couplers.

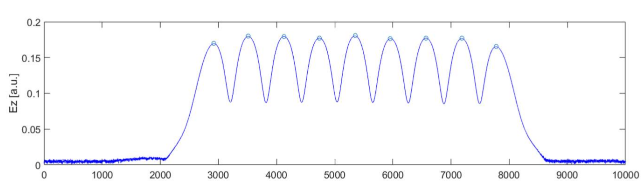

Figure 5: Results of bead pull test at PSI.

CONCLUSION

Beginning of April 2018, the prototype has been installed in the cavity test facility (CTF) at FERMI for high power testing, as shown in Fig. 6. Starting from May 2018, a full set of experimental data on breakdown rate and breakdown location will be collected at different operating gradients to prove the operability of the structure at the required working points and the feasibility of the upgrade. Based on the test results, a detailed and complete upgrade proposal for the FERMI linear accelerator will be drafted in the beginning of 2019.

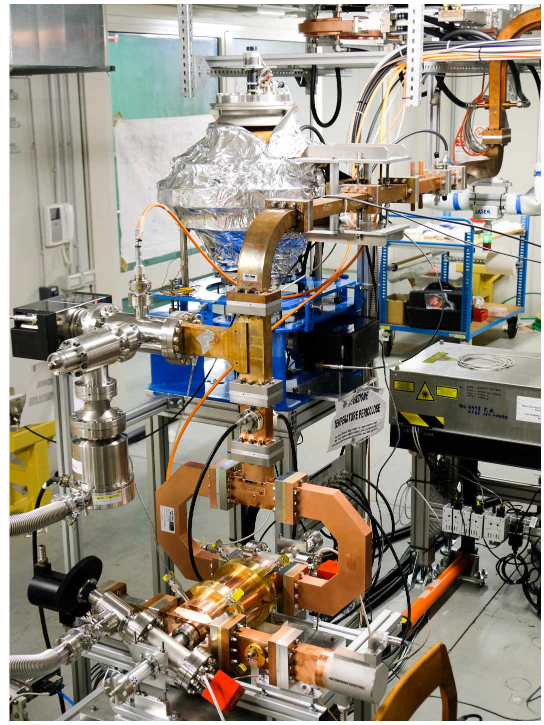

Figure 6: Prototype installed at CTF in the FERMI linac tunnel.

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