DESIGN, MANUFACTURING AND INSTALLATION OF TWO DUAL-FEED ACCELERATING STRUCTURES FOR THE FERMI INJECTOR

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Abstract

FERMI is a seeded Free Electron Laser (FEL) driven by a warm S-band Linac. In the injector region, two 3-meter long Forward Traveling Wave (FTW) accelerating structures, coming from the old Elettra injector, were installed.

In order to improve the e-beam quality at higher bunch charge, it was decided to replace the existing ones with two dual-feed accelerating structures. Those structures have been designed and manufactured by RI Research Instruments GmbH and delivered to Elettra in July 2015.

The following paper will report about the RF design and the manufacturing of the new structures. Details about the RF conditioning and the installation will also be illustrated.

INTRODUCTION

FERMI, the seeded FEL facility located in Trieste, consists of two FEL lines covering the wavelength range between 100 nm down to 4 nm [1].

The FEL is driven by an S-band, warm Linac powered by 15 RF plants. The injector region [2] was equipped with two 3-meter long Forward Traveling Wave structures from the main injector of the Elettra storage ring, namely S0A and S0B.

The existing structures were constant gradient ones, with an average iris radius of 9.73 mm and a shunt impedance of 67.1 MΩ/m [3]. Both the structures were equipped with single-feed RF couplers. Due to this, an evident head-tail kick was affecting the beam, slightly worsening the beam emittance in the injector region.

To further improve the e-beam quality and increase the overall Linac energy as well, it was planned to replace the existing structures with new dual-feed accelerating sections [4] [5] and move the old structures in the high energy part region of the Linac.

The new structures were commissioned to RI Research Instruments GmbH. In the following sections RF design and manufacturing of the structures are described. Also, results from the RF high power conditioning and beam commissioning are reported.

RF DESIGN

Table 1 lists the main rf parameters that are the basis for the structure design. The rf properties for the S-band cells have been simulated with the CST Microwave Studio [6] Eigenmode solver and the SUPERFISH [7] code.

Table 1: RF Design Parameters of the S-band Structures

Parameter	Value	Unit
Cavity length	3375	mm
Operating frequency	2998.01	MHz
Phase advance per cell	$2\pi/3$	-
Nr. regular cells	96	-
Av. shunt impedance (sim.)	60.5	MΩ/m
Gradient @ 16MW (sim.)	14.5	MV/m

The rf design of the travelling wave structures follows the approach described by Paul Scherrer Institute (PSI) for their C-Band structures [8]. A constant accelerating gradient along the structure is maintained by designing the group velocities of the TM010 mode in the accelerating cells in a way that the following equation is satisfied.

$$\frac{v_{g,n}}{\left(\frac{r}{Q}\right)_n} = \frac{v_{g,n-1}}{\left(\frac{r}{Q}\right)_{n-1}} e^{-2\alpha_{n-1}L_{cell}}$$

Here $v_{g,n}$ is the group velocity of the n-th cell, r_n is the shunt impedance, Q_n the quality factor of the n-th cell and L_{cell} the cell length. A MATLAB script was written to derive the exact cell parameters from this iterative design approach.

The rf power is coupled symmetrically to the input coupler cell. The fraction of the power that is not dissipated in the structure is decoupled from the cavity by an also symmetric output coupler cell. Both coupling cells incorporate a racetrack shape cell design to suppress the quadrupole component of the fields to less than 0.01% within the dimension of the beam tube aperture.

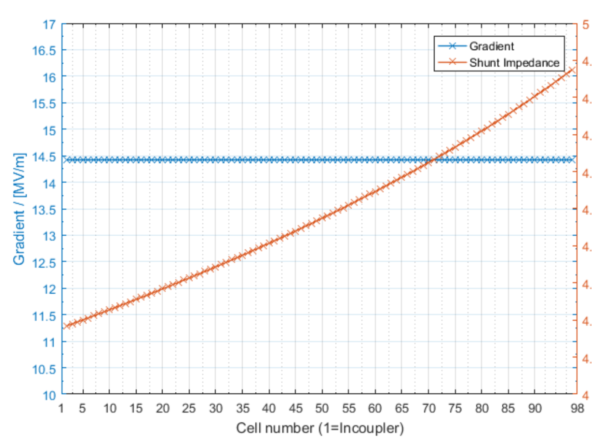

Figure 1: Variation of r/Q and resulting const. gradient.

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MANUFACTURING

The two cavities are delivered as systems ready for installation. The structures are assembled on their final girder together with a cooling water manifold and the RF power splitter at the input coupler. The first cavity furthermore includes a focussing solenoid.

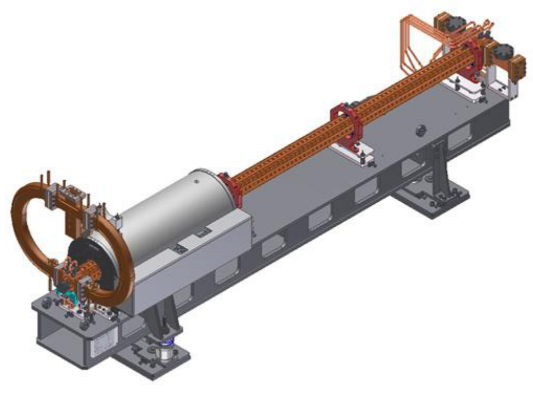

Figure 2: CAD model of the linac assembly E-1.

All turning and milling operations on rf surfaces of the cavity have been performed with diamond tools. The surface quality of the turned OFHC copper cells was measured to be Ra<0.08µm. The cavities have been rf tuned with 4 port beadpull measurements and passed all specified factory acceptance tests and a vacuum baking. Measured RF parameters are reported in Table 2.

Table 2: Measured RF Parameters at FAT

Parameter	Cavity E-1	Cavity E-2	Unit
Frequency f_{oper}	2998.01	2998.01	MHz
S_{11} @ f_{oper}	-28.9	-33.5	dB
Aver. phase error	1.6	2.6	deg
Aver. amp. error	2.4	3.1	%

The manufacturing duration for the two linac assemblies was seven months and the structures have been delivered on time within the scheduled downtime period of FERMI.

HIGH POWER RF CONDITIONING

In summer 2015, both the structures were installed in the FERMI Test Facility for the high power conditioning.

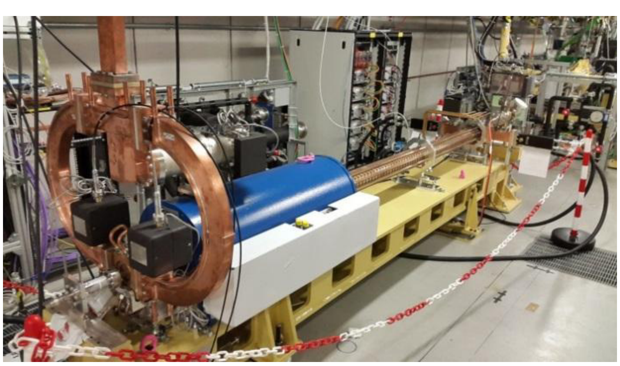

Figure 3. Installation of the E-1 in the Test Facility.

Even if those structures have a filling time of nearly 900 ns and should be routinely operated at nearly 19 MW (klystron output power), the high power conditioning was performed up to 22 MW and 4000 ns with a 50 Hz repetition rate. Figure 4 shows the vacuum profile of the ion pumps installed in the system.

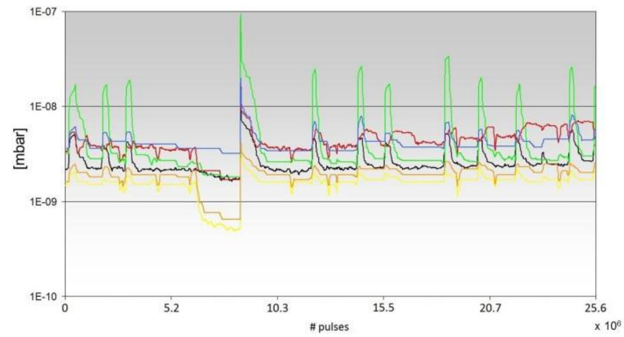

Figure 4. Vacuum profile in Structure E-2.

Two small ion pumps were installed in close proximity of the input coupler, to improve the pumping capacity. Ion pumps were also installed at the output coupler as well (see Figure 3).

The high pumping capacity together with the Research Instruments high cleaning standards made it possible to operate with a pressure of nearly $3{\cdot}10^{-9}$ mbar from the very beginning of the conditioning process. This pressure was kept for all the conditioning period and no outgassing phenomena were observed.

The RF conditioning was completed in approximately 2 weeks for cavity E-1. It took longer for cavity E-2 (approximately 4 weeks), but it was mostly related to frequent klystron arcs experienced during the conditioning period.

INSTALLATION AND COMMISSIONING

In January 2016, a long shutdown was scheduled for the replacement of the old structures in the injector region.

The two RI structures were installed in place of the existing S0A and S0B and the waveguide layout was changed to accommodate the new cavities. Then, the sections S0A and S0B were moved to the high energy part of the Linac, as shown in Figure 5.

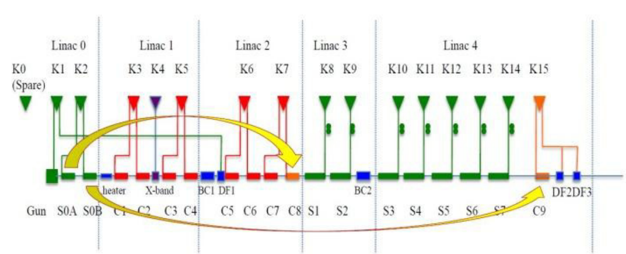

Figure 5. Relocation of S0A and S0B in the high energy part of the machine.

When S0A and S0B were installed in the injector, we measured the vertical kick provided to the bunch by the vertical single-feed RF coupler as a function of the RF accelerating gradient. We set the trajectory feedback in order to centre the beam on the beam position monitors (bpms) before and after the first section, i.e. S0A, and we changed the accelerating gradient. To compensate the dipole field induced by the input coupler it was necessary to apply a strong vertical kick at the entrance of S0A which resulted to be proportional to the accelerating gradient (~330 µrad per MV/m).

The blue curve in Figure 6 shows the transverse kick at the entrance of the section S0A as a function of the accelerating gradient. The curve crosses the y-axis at -0.6 mrad: this offset was mainly due to small trajectory error still present even when the accelerating gradient was 0. This means that at the maximum accelerating gradient, the bunch centroid was transversally kicked by the input coupler with an angle of about 5mrad. This was compatible with a phase asymmetry of 2.5deg of the electric field in the input coupler. We repeated this measurement with the new sections, and the data has been compared and plotted in Figure 6.

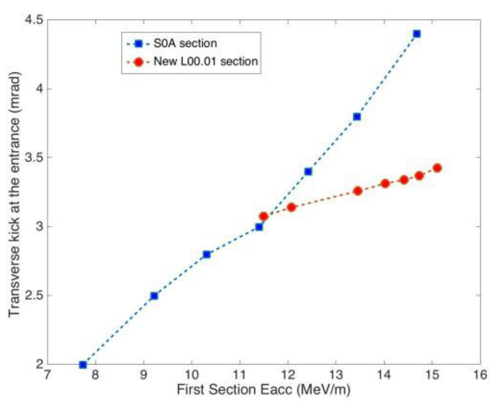

Figure 6: Transverse kick versus accelerating gradient given by a dipole steerer at the entrance of the L00 first section necessary to centre the beam before and after the RF section itself.

The new section equipped with a dual-feed RF input coupler relevantly reduced the transverse kick to about 90 µrad per MV/m. In this case the trajectory error was about 2 mrad, that translates in a ~1.4mrad kick at the maximum gradient, compatible with a phase asymmetry of about 0.1deg. This value was in agreement with the RF design specification.

The residual dipole electric field ΔE/E has been estimated to be less than 1% (for the previous sections ΔE/E was approximately 5%) bringing to a significant benefit in terms of e-beam emittances.

In February 2016, normalized emittances of 0.7 and 0.9 mm mrad in the horizontal and vertical plane respectively were measured in the 100 MeV diagnostic section. These values at 700 pC resulted to be 10-15% smaller than the previous ones.

The measured maximum Linac energy now available is 1629 MeV. The maximum operating energy, with compressed and linearized electron beam phase space, at 700 A of nominal current, is currently about 1550 MeV.

CONCLUSION

Two structures for the replacement of the existing FTW sections in the injector region were commissioned to Research Instruments GmbH. A dual feed configuration was requested to reduce the head-tail kick affecting the beam in the low energy region.

RI delivered the two cavities as systems ready for installation. In summer 2015 the two cavities were installed in the FERMI Test Facility and RF power conditioned. In January 2016 the two cavities were installed in the injector while the existing ones were deployed in the high energy region of the Linac where the beam is less sensitive to the head-tail kick induced by the residual dipole component.

After the installation few weeks were then devoted to the e-beam commissioning. A relevant reduction of the transverse kick induced by the input coupler has been measured, with an important benefit to the beam emittance: at 700 pC normalized emittances of 0.7 and 0.9 mm mrad in the horizontal and vertical plane were measure at the exit of the injector. These values resulted to be 10-15% smaller than the ones with the previous sections.

Adding two sections also increased the maximum available FERMI linac energy to 1629 MeV and to 1550 MeV in the nominal 700 A beam-compressed configuration.

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