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High power test results of the SPARC C-band accelerating structures

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HIGH POWER TEST RESULTS OF THE SPARC C-BAND ACCELERATING STRUCTURES

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Abstract

The energy upgrade of the SPARC photo-injector at LNF-INFN (Italy) from 180 to more than 240 MeV will be carried out by replacing a low gradient S-Band accelerating structure with two C-band structures. The structures are Traveling Wave (TW) and Constant Impedance (CI), with symmetric axial input couplers and have been optimized to work with a SLED RF input pulse. In this paper we present the results of the low and high power RF tests on the two fabricated structures that shown the feasibility of the operation at accelerating gradients larger than 35 MV/m.

INTRODUCTION

SPARC is a 180-MeV photoinjector test facility based on S-band (f=2856 MHz) accelerating structures in operation since 2001 at the INFN Frascati Labs.

An energy upgrade based on fabrication and installation of two C-band (f=5712 MHz) [1] sections has been proposed to exploit the larger accelerating gradients provided by the higher frequency and to explore a C-band acceleration combined with an S-band injector that, at least from beam dynamics simulations, was very promising in terms of achievable beam quality [2]. The use of C-Band structures for electron acceleration and production of high quality beams has been also proposed and adopted in several linac projects all over the world. The two main projects that adopted such type of structures are the Japanese Free Electron Laser in Spring-8 and the SwissFEL project at Paul Scherrer Institute (PSI). The new SPARC C-band structures are fed by a 50 MW klystron Toshiba ET37202. The high voltage pulsed modulator and the 400 W solid state driver for the klystron have been manufactured by ScandiNova (S) and MitecTelecom (CDN) respectively. The new system will also include a pulse compressor developed by the Institute of High Energy Physics (Beijing). Main design criteria, construction and RF test of the structures at low and high power are reported and discussed in this paper.

ACCELERATING STRUCTURES DESIGN CRITERIA AND REALIZATION

The C-band structures for SPARC have been developed at the LNF-INFN Laboratories with the support of an external company [3] for copper machining. The details of the electromagnetic design are reported in [1]. The main structure parameters are given in Table 1. The structures are Traveling Wave (TW) and Constant Impedance (CI), have symmetric waveguides input couplers and have been optimized to work with a RF pulse compressor. The input coupler includes a splitter while, the output one, has two symmetric ports connected to two RF loads. The SPARC linac operates in single bunch mode and the choice of a CI structure was made partly to reduce the fabrication costs but mainly to obtain a quasi-uniform accelerating field along the structure when the structure is fed by the SLED RF pulse. In fact, the decay of the RF pulse amplitude along the CI structure partially compensates the exponential profile of the compressed pulse, and the resulting RF accelerating gradient on the bunch grows by only 10% along the section. The mechanical drawings of the structure and of the reduced length (22 cells) prototype are given in Fig. 1.

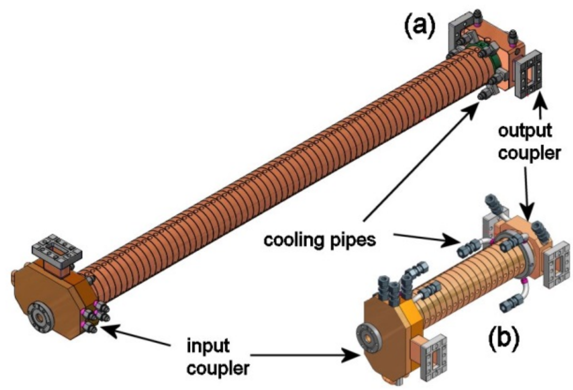

Figure 1: Mechanical drawing of the C-Band Structure (a) and prototype (b).

Table 1: Main C-Band Structure Parameters

PARAMETER	Value
Frequency (f_{RF})	5.712 [GHz]
Phase advance per cell	$2\pi/3$
Number of accelerating cells (N)	71
Structure length including couplers (L)	1.4 [m]
Cell length (d)	17.495 [mm]
Iris radius (a)	7 [mm]
Normalized group velocity (v_g/c):	0.0283
Field attenuation (α)	0.206 [1/m]
Shunt impedance (r)	82.8 [MΩ/m]
Filling time	150 [ns]
Accelerating gradient	>35 [MV/m]
Output power	$0.60 \cdot P_{in}$
Average dissipated power @ 10 Hz	59.6 [W]

The pictures of a cell stack and of the input coupler with integrated splitter are given in Fig. 2. Each cell was machined as a cup to include a single iris. The integrated cooling system employs six longitudinal cooling pipes. Three tuners capable to deform the outer wall in both directions have been inserted at 120° on the circumference of each cell. A high-precision turning machine has been used to machine the cells. A surface roughness < 50 nm has been obtained, with an absolute dimension accuracy in the ±2μm range.

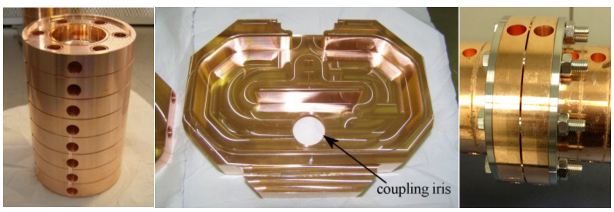

Figure 2: From left: a stack of cells, input coupler and final central junction between two half structures.

The cells of the first structure have been joined in two stacks and brazed in two halves with the input and output couplers at LNF, since the dimensions of the LNF oven do not allow brazing the whole accelerating cavity. The procedure for brazing together the two stacks was very delicate. After failing the first attempt, we had to modify the central junction between the two half structures, as shown in Fig. 2, before the final successful brazing of the two stacks held by special supports in a horizontal oven. The picture of the final fabricated structure under low power RF test is given in Fig. 3.

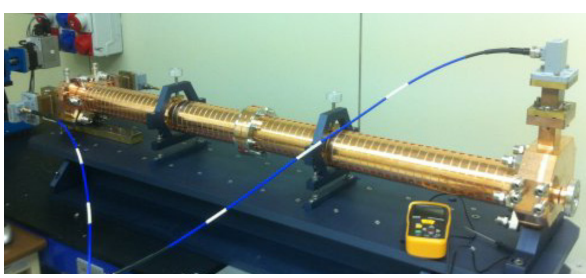

Figure 3: C-band accelerating structure under test.

LOW AND HIGH POWER TEST RESULTS

On bench RF measurements were done on both fabricated structures and tuning of the electrical field phase advance per cell was performed following the procedure described in [4]. The measured electric field (using the bead pull technique) before and after the tuning of the first section and the phase advance per cell are given in Figs. 4 and 5 respectively. Similar results have been obtained on the second structure. The reflection coefficient at the input port was < -25 dB for both.

Before the construction of the complete C-band structures, a prototype with a reduced number of cells has been realized (Fig. 1b) and high power tests have been carried out at KEK (Japan) by an INFN Frascati team in the framework of an INFN-KEK collaboration. The details of the high power test results on the prototype are reported in [1]. Experimental results demonstrated the prototype capability of withstanding accelerating gradients of 50 MV/m with breakdown rates of ~10^{-6} per pulse per meter.

The first complete structure has been installed in the SPARC hall for high power test on October 2013 (Fig. 6). The RF conditioning has been done in three steps: (a) test of the Klystron system terminated into a load; (b) test of the waveguide system up to the SPARC hall terminated into a load; (c) test of the accelerating structure.

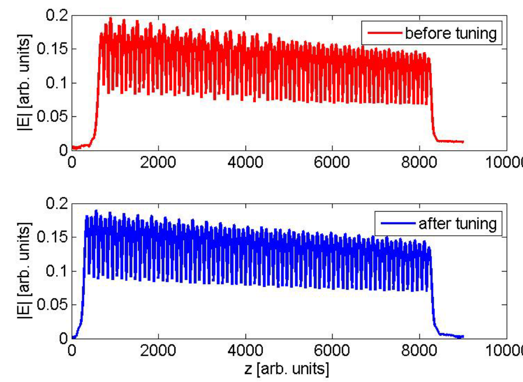

Figure 4: Electric field before and after tuning

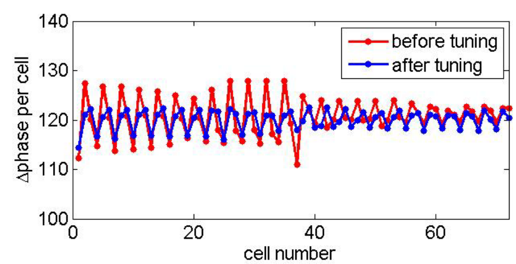

Figure 5: Phase advance per cell before/after the tuning.

The high power test of the first C-band structure started on November 2013. The pulse repetition rate was 10 Hz with a nominal pulse width of 165 ns (slightly longer than the filling time of the structure). The klystron power was progressively increased (by increasing the HV of the modulator) and the current of four ion pumps connected around the structure and the RF signals from pickups were monitored.

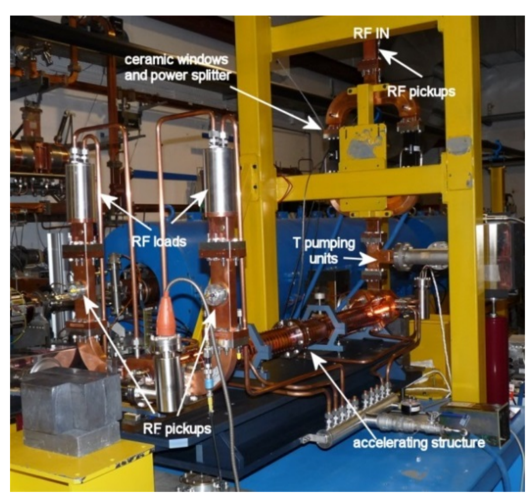

Figure 6: C-Band structure installed in SPARC for high power tests.

The conditioning procedure was semi-automatic and the switch-off on the HV were caused by: (a) operators; (b) threshold on the ion pumps current absorption (50 μA corresponding to a vacuum of 10^{-7} mbar) including the ion pump absorption directly connected to the KLY output; (c) KLY interlocks (tube vacuum, modulators interlocks).

A picture of the control panel used for the conditioning is given in Fig. 7. Three acquisition channels monitored the RF signals. A typical event of discharge monitored by the increase in vacuum pressure is given in Fig. 8. In normal operation conditions the pressure in the structure was between $5 \cdot 10^{-10}$ mbar and $2 \cdot 10^{-9}$ mbar.

Figure 7: Control panel for high power test (ch 2 forward signal, ch 3 reflected signal, ch 4 transmitted signals).

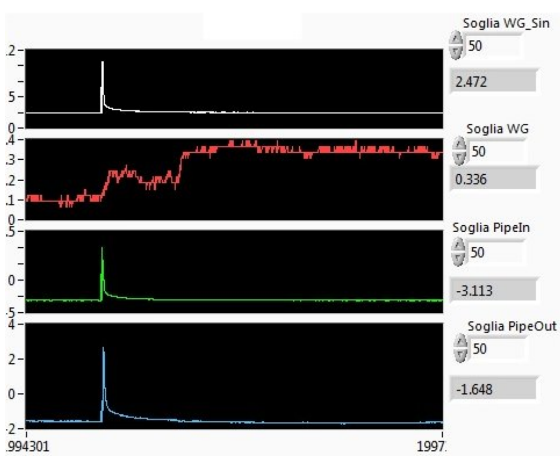

Figure 8: Typical event of discharge monitored by the increase in vacuum pressure.

The RF conditioning for the first RF structure lasted about 10-15 full equivalent days. As a result, it was reached: (a) 38 MW input power in the structure (44 MW from the klystron), nominal repetition rate and pulse length; (b) corresponding accelerating field was 36 MV/m peak and 32 MV/m average;(c) BDR $<10^{-5}$ or less, not measured yet since a correct measurement of the BDR requires a long time; (d) 340 kV modulator voltage. The RF conditioning of the second RF structure started on late December 2013 and was concluded on February 2014 with similar results.

A stable and flexible digital low level RF system to control the input to the RF amplifiers and monitor the RF signals of the high gradient C-band accelerating structures at SPARC test facility has been designed and fabricated by PSI Institute in the framework of the TIARA project [5].

A modular approach has been pursued with two main blocks: an analog front-end and a digital data processing. All C-band RF signals are down converted to an IF frequency. Commercially available FMC A/D modules then digitize those signals, the data is digitally demodulated on several VME64x FPGA/PowerPC processing boards to provide baseband I/Q and amplitude/phase information. The LLRF output signal, that feeds the klystron driver, is generated by a high-speed FMC D/A module that drives the inputs of a vector modulator. The average phase and amplitude of the output signal can be changed pulse-to-pulse, as well as the RF pulse shape, if necessary. The LLRF system has been integrated into the SPARC control system by implementing an EPICS/LabVIEW interface using the EPICS CA drivers in LabVIEW programming environment that is fully compatible with the SPARC_LAB control system. The conditioning of the second C band accelerating structure was performed by means of this interface, integrated in a “conditioning console” application also including vacuum reading and RF power station control, as shown in Fig. 7.

CONCLUSIONS

The C-Band structures for the SPARC energy upgrade have been designed, built and tested at the INFN-LNF Labs with the support of local firms for machining and brazing. They are TW and CI, with an integrated axial symmetric input coupler. High power tests have demonstrated the structure capability of withstanding operation accelerating gradients larger than 35 MV/m. A stable and flexible C-band digital low level RF system has been also developed and integrated in the SPARC control system.

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