Design, Fabrication and High Power RF Test of a C-band Accelerating Structure for Feasibility Study of the SPARC photo-injector energy upgrade

Alesini, D. (INFN/LNF) *et al*

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DESIGN, FABRICATION AND HIGH POWER RF TEST OF A C-BAND ACCELERATING STRUCTURE FOR FEASIBILITY STUDY OF THE SPARC PHOTO-INJECTOR ENERGY UPGRADE

D. Alesini, R. Boni, G. Di Pirro, R. Di Raddo, M. Ferrario, A. Gallo, V. Lollo, F. Marcellini (INFN/LNF, Frascati (Roma)), T. Higo, K. Kakihara, S. Matsumoto (KEK, Ibaraki), G. Campogiani, A. Mostacci, L. Palumbo, S. Persichelli, V. Spizzo (Rome University La Sapienza, Roma), S. Verdú-Andrés (TERA, Novara and IFIC (CSIC-UV), Valencia)

Abstract

The energy upgrade of the SPARC photo-injector from 160 to more than 260 MeV will be done by replacing a low gradient 3m S-Band structure with two 1.4m high gradient C-band structures. The structures are travelling wave, constant impedance sections, have symmetric waveguide input couplers and have been optimized to work with a SLED RF input pulse. A prototype with a reduced number of cells has been fabricated and tested at high power in KEK (Japan) giving very good performances in terms of breakdown rates ($\approx 10^{-6} bpp/m$) at high accelerating gradient (>50 MV/m). The paper illustrates the design criteria of the structures, the fabrication procedure and the high power RF test results.

INTRODUCTION

SPARC is a test-facility in operation at the Frascati Laboratories of the INFN and is aimed to produce high brightness electron beams to drive SASE-FEL experiments in the visible light exploring all the most critical issues of the future X-ray source subsystems. The beam is generated by a 1.6 cells standing wave RF gun and accelerated with three constant gradient, 2π/3, travelling wave structures [1]. The SPARC energy will be upgraded from ~160 to more than 260 MeV by replacing a low gradient S-band travelling wave section with two 1.4 m long C-band structures [2]. The main motivations for this upgrade are both the shifting of the SASE radiation closer to the ultraviolet region and the improving of beam dynamics and seeding experiments. The choice of the C-band instead of the S-band was dictated by different considerations: (a) to explore the C-band acceleration combined with an S-band injector that, at least from beam dynamics simulations [3], seems very promising for the achievable beam quality; (b) to reach higher accelerating gradients and therefore higher energies in a shorter length; (c) to gain experience with a rather new RF technology in the light of further upgrades of the SPARC photo-injector. Other important laboratories have proposed or use the C-band technology for FELs (e.g. PSI in Switzerland and Spring8 in Japan). Synergies with these laboratories have been also considered and collaborations have been started. The new C-band structures will be 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 respectively by ScandiNova (S) and MitecTelecom (CDN) and have been already installed and power tested at LNF. The new system will also include a pulse compressor presently under development. The C-band structures have been developed in the LNF Laboratories of the INFN with the support of local firms. Since an important requirement, for the new system, is to reach an average accelerating gradient >35 MV/m (with a total energy gain >100 MeV), a prototype with a reduced number of cells was fabricated and high-power tested in KEK (in the framework of a collaboration between the two laboratories) to verify the validity of all technical choices.

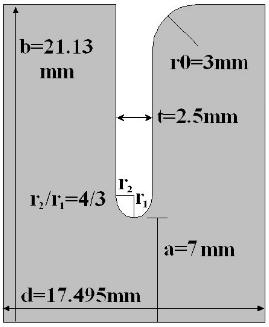

Fig. 1: Single cell final dimensions

C-BAND STRUCTURE DESIGN

The C-band structures are travelling wave constant-impedance (CI) sections. A detailed illustration of their design criteria can be found in [4]. The CI choice has been proposed to ease the mechanical design, the fabrication process and to reduce the cost of each structure. This choice has been also addressed to obtain a quasi-uniform accelerating field along the structure since the decay of the RF pulse amplitude along a CI section is compensated by the exponential shape of the SLED pulse, resulting in a rather constant profile of the RF field along the structure [4]. The iris apertures have been chosen as large as possible to simultaneously obtain: (a) the lowest peak surface electric field; (b) an average accelerating field of (at least) 35 MV/m with the available power from the klystron; (c) the highest pumping speed; (d) the shortest filling time of the structures that allows feeding the units with a shorter RF pulse with a reduction of the breakdown probability. The final single cell profile with its main dimensions is given in Fig. 1 while Table I reports the main parameters for both the prototype and the final structure.

The adopted input and output couplers are of the "waveguide type" [5], which allows obtaining simultaneously a very low pulsed heating and a compact and symmetric feeding system. A careful analysis of the multi-polar field components introduced by the waveguide coupler has been also carried out [4].

Table 1: Main C-band structure parameters

PARAMETER	prototype	final structure
Frequency	5.712 [GHz]	
Phase advance per cell	2π/3	
Number of accel. cells	22	71
Structure length	0.54 [m]	1.4 [m]
Group velocity/c	0.0283	
Field attenuation	0.206 [1/m]	
Series impedance (Z)	34.1 [MΩ/m^2]	
Shunt impedance (r)	82.9 [MΩ/m]	
Filling time	50 [ns]	150 [ns]
Surf. peak E field/Acc. field	2.17	
Surf. Peak H field@ 35 MV/m	87.2 [kA/m]	
Pulsed heating @ 35 MV/m	<1 ^{o}C	
Av. dissipated power @ 10 Hz	7.6 [W]	59.6 [W]

PROTOTYPE FABRICATION AND LOW POWER RF TEST

The picture of the fabricated prototype is given in Fig. 2. The input coupler has a single feed and integrates the power splitter while the output one has two symmetric ports to be connected to two RF loads. The picture of a single cell is given in Fig. 3(a). Each cell has been machined as a "cup" and includes one iris. The cooling system has been integrated in each cell with 6 cooling pipes. Three tuners at 120^o have been inserted. They can be used to deform the outer wall of each cell in both directions. Each cell has been machined with a high precision turning machine. The surface roughness was less that 50 nm while the precision on dimensions was ± 2 µm.

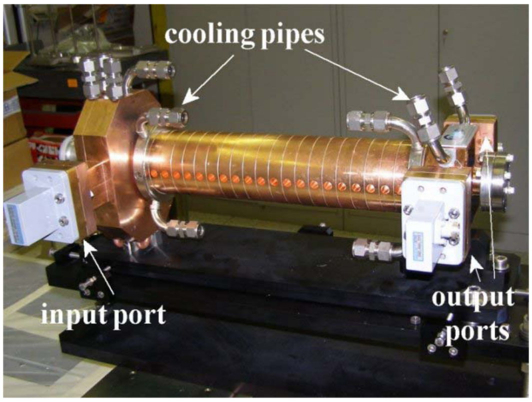

Fig. 2: the C-band prototype power tested at KEK.

A detail of the input coupler before brazing is given in Fig. 3(b): it was realized by milling a single copper bulk with a computer controlled machine and then closed with a blanking plate brazed into the coupler itself, together with the input flange. The obtained surface roughness was less than 200 nm with a precision in all dimensions of ± 10µm. The picture of the output coupler is given in Fig. 3(c): to minimize the number of brazing processes and for a faster manufacturing, the inner surface of the output couplers have been realized with the electric discharge machining technique (EDM). The obtained surface roughness was <1 µm with a precision of ± 20µm.

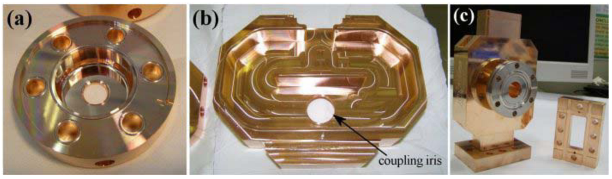

Fig. 3: (a) single cell; (b) input and (c) output couplers.

The structure was brazed in a vacuum furnace through different steps at LNF. The main problem we encountered was related to a small angular tilt of the output coupler with respect to the main axis of the cells column. For this reason we made a cut of the matching cell of the output coupler, we re-machined the coupling cell and re-brazed again the full body.

RF measurements have been done at each brazing step and after the final brazing process. The reflection coefficient after the final brazing was about -18 dB while the expected one was less than -30 dB. This higher reflection coefficient was due to the detuning of the cells and of the input/output couplers matching cells mainly due to the brazing process and assembly. This detuning is also visible from the measurements of the longitudinal electric field on axis, given in Fig. 4(a)-(b).

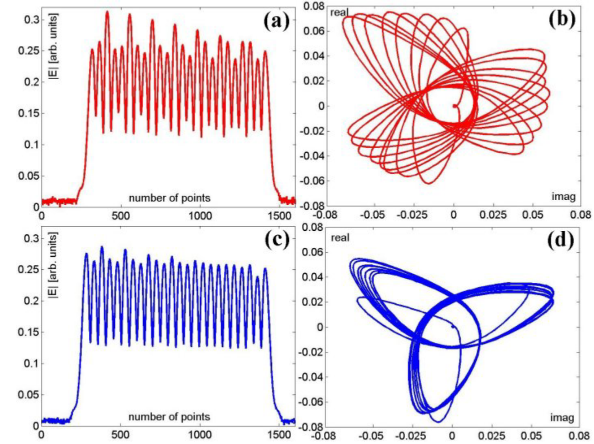

Fig. 4: Measured longitudinal electric field on axis before (a)-(b) and after (c)-(d) tuning.

The tuning of the structure has been carried out (for time schedule reasons) only after the high power tests at KEK. We have implemented [6] the procedure illustrated in [7]. The result of the field measurements after tuning is given in Fig. 4(c)-(d). The measured reflection coefficient after tuning was <-30 dB. A residual detuning of the cell (and therefore a field flatness unbalance) is still visible and it was not possible to compensate it. Possible reasons of these small residual errors are discussed in [6] and are still under discussion.

HIGH POWER TEST RESULTS

A detailed description of the high power test and results is given in [8]. The C-band test area at KEK is mainly composed of a klystron driven by a PFN modulator, a 22m-long low loss transport line, a SLED-type pulse compressor and a concrete vault of test area. The picture of the structure prototype under test in the radiation shield room is given in Fig. 5.

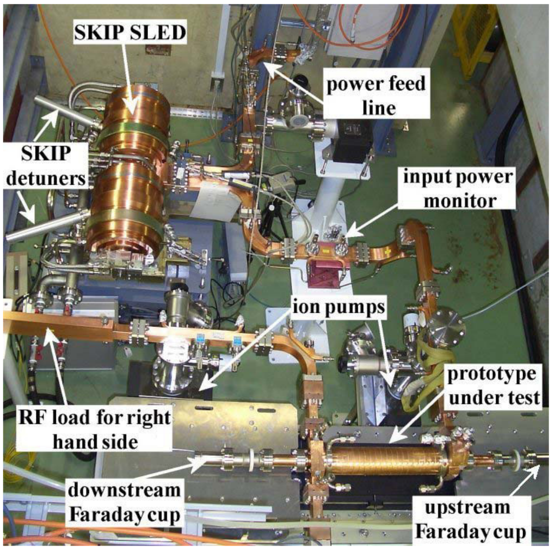

Fig. 5: Experimental setup inside the shielded room.

The high power test started on 5th November and finished on 13th December, 2010. For almost one month of processing, from 5th November until 2nd December, more than 10^8 RF pulses of 200 ns pulse width were sent into the structure with a repetition rate of 50 Hz. For a couple of days the RF pulse length was changed to 300 ns and for one day the repetition rate was decreased to 25 Hz. On 15th November the SKIP was switched on. Fig. 6 illustrate with a snapshot the whole test history and the klystron output power P_K.

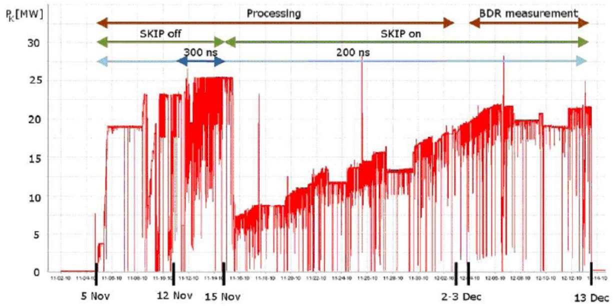

Fig. 6: History of the high power test.

The breakdown rate (BDR) dependence on the accelerating gradient is given in Fig. 7. The blue squares correspond to the BDR measurements performed during the structure conditioning. The red circles are the BDR measurements performed after the structure conditioning. As shown in the figure, the structure performance has significantly improved with conditioning and BDR of the order of 10^{-6} bpp/m has been reached at accelerating gradients of 50 MV/m. A detailed analysis of the distribution of breakdown events along the structure has also been done looking at the time signals (reflected and transmitted) in every breakdown event [8]. This analysis shows the existence of a hot region in the output coupler (probably due to the described surgery in the fabrication process). The cut of the structure (that will be done at LNF) to inspect the inner surface will be decisive to confirm our guess.

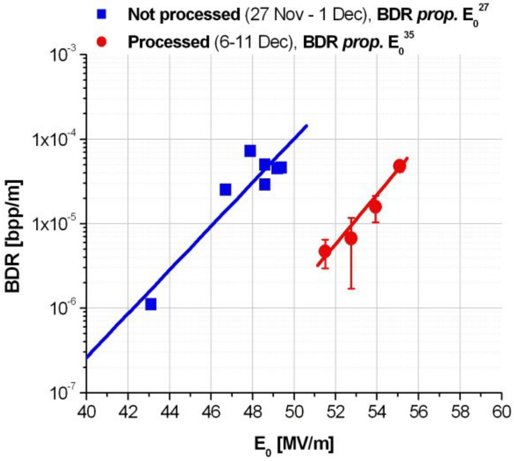

Fig. 7: Breakdown rate at different field values.

CONCLUSIONS

Two 1.4 m long C-band travelling wave constant-impedance structures will be installed in the SPARC FEL for the beam energy upgrade from 160 to more than 260 MeV. In the paper we illustrated the design criteria of these structures. A prototype with a reduced number of cells has been fabricated and tested at high power at KEK giving very good performances in terms of breakdown rates at high accelerating gradient (>50 MV/m). Detail of the fabrication process, tuning procedure and high power RF test results have been presented and discussed.

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