BEAM ENERGY UPGRADE OF THE FRASCATI FEL LINAC WITH A C-BAND RF SYSTEM*

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Abstract

In the frame of the SPARC-X project, the energy of the FEL accelerator SPARC, in operation at the INFN-LNF laboratories, will be upgraded from 180 to 250 MeV by replacing a low gradient S-band travelling wave section with two C-band units, completely designed and developed at the Frascati laboratories. The new system consists of a 50 MW klystron, supplied by a pulsed modulator and a RF pulse compressor to feed 2 high gradient C-band structures. This paper deals with the design of the full system, the C-band R&D activity and study of the related beam dynamics.

INTRODUCTION

The photoinjector SPARC [1] is an electron linac test facility, operating in the 150÷200 MeV energy range at the Frascati INFN Laboratories. It is specifically designed to generate low emittance, high peak current particle beams to perform SASE at 530 nm and seeded FEL experiments through a series of undulator magnets. The machine was funded by the MIUR (Italian Minister for University and Research) in 2001 and came into operation in 2008. It consists basically of three S-band travelling wave accelerating sections, supplied by two Thales klystrons. One klystron feeds 2 sections out of 3 with a pulse compressor (SLED) so that the input power per section is about 55 MW/0.8µsec.

So far, SPARC produced important results in the physics of FEL's and particle beams [2]. Lasing have been achieved routinely with significant photon amplification factor both at 530 nm and with the 3rd harmonic seeding process. Important bunch compression experiments have been successfully performed by adjusting the RF field phase of the 1st accelerating section. Compression factors of about 12 have been obtained [3] though at expense of a growth of the beam emittance, partially compensated by solenoids wrapped around the accelerating sections and a small reduction of the beam energy due to the bunch passage on the voltage zero-crossing.

SPARC BEAM ENERGY UPGRADE

In order to allow to lase in the UV region and improve the seeding experiment, it has been decided to increase the SPARC beam energy to 250÷260 MeV by replacing the third 3 m. long accelerating section with two, 1.5 meters, C-band structures. We cannot simply add the new sections for lack of space in the machine.

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The C-band (5712 MHz) allows to get accelerating gradient higher than those achievable with S-band units. RF fields > 35 MV/m have been already achieved [4]. So, with the C-band units in place of the S-band one we can get about 60-70 MeV more.

General Layout of the C-band System

The new machine layout, after the implementation of the C-band system, will be that shown in Fig. 1.

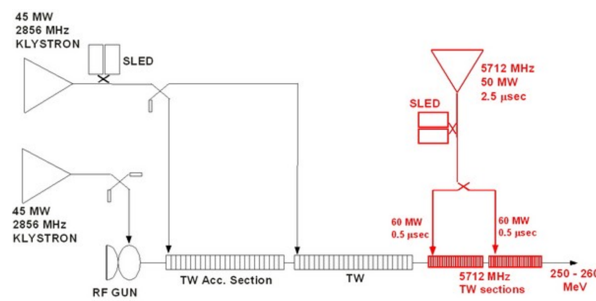

Figure 1: SPARC upgrading with a C-band system.

The new C-band power station will consist mainly of:

- C-band klystron, manufactured by Toshiba Ltd (JP)
- Pulsed HV modulator supplied by ScandiNova (S)
- WR187 waveguide system with double resonator pulse compressor.
- 500 W solid state klystron driver supplied by MitecTelecom (CDN)

The main specifications of the klystron and the modulator are listed in the Tables 1 and 2.

Table 1: Toshiba Klystron ET37202 specifications

Frequency	5712 MHz
Output RF power	50 MW max.
RF pulse length	2.5 µsec
Pulse rep. rate	50 pps max.
Gain	44 dB min
Efficiency	40 % min
Drive power	300 W

The klystron is the same model adopted by the Spring8 X-FEL. The pulsed modulator, selected with a public tender, will be supplied by the Swedish company ScandiNova. It is a fully solid state unit which, instead of the standard LC pulse forming network, employs a set of solid state switches in parallel. The switches, gated by a trigger signal, produce a medium voltage pulse at the primary of a step-up transformer whose secondary is connected to the klystron cathode. The modulator, including klystron and pulse transformer, is enough compact and well fits in the mid-gallery of the SPARC building. The klystron driver is the CW, class A, 500 W amplifier manufactured by MitecTelecom (CDN). It is a solid state unit, produced for satellite communication purposes, with small pulse-to-pulse phase variation and reduced latency (< 100 nsec) that is required to implement an effective phase feedback loop around the klystron.

Table 2: Pulsed modulator specifications

Type	Fully Solid State
Modulator peak power	128 MW
Output voltage range	0 ÷ 370 kV
Output current range	0 ÷ 350 A
Pulse rep. rate	0 ÷ 10 pps
Pulse length (top)	≥ 2.5 μsec
Top flatness	< ± 0.5 %
Amplitude stability	< ± 0.1 %
Pulse length FWHM	≥ 4 μsec
Pulse to Pulse jitter	< ± 4 nsec

WR187 under vacuum copper waveguides will be used to carry the RF power to the C-band accelerating sections. They are available from the industry together with RF windows, power splitters and directional couplers. The RF losses of the WR187 @ 5712 MHz are ≈ 0.03dB/m, therefore the waveguide losses for the 15 m total length are about 10 %.

THE C-BAND STRUCTURES

We chose to design and develop the C-band travelling wave (TW) accelerating structures at LNF with the collaboration of local firms. Also, to make easier the design and the fabrication we studied a constant impedance structure, instead of a constant gradient one since this is not essential if we use a pulse compressor. Furthermore, the accelerating mode $2\pi/3$ was chosen as it is the most efficient one.

The design activity aims to:

1) optimize the single cell profile to minimize the surface electric field and reduce the discharge rate of the structure.
2) study and develop the "beam-pipe" coupling concept
3) study and develop the dual-feed power coupler to minimize the multipole field effects generated by the asymmetric feeding.
4) design a double-cavity pulse compressor along the same lines as the SKIP-type one [5] used at Spring8.

Single Cell Optimization

The Fig. 2 shows the single cell shape, optimized to reduce the peak surface electric field with an average gradient of 35 MV/m. The optimization was done including the pulse compressor that is with the real RF pulse. The large iris radius (7 mm) allows better pumping speed and higher group velocity. In this way it is possible to shorten the RF pulse length reducing average power and discharge probability. The maximum surface field results 100 MV/m from HFSS© simulations and is considered a safe value for a discharge-free operation.

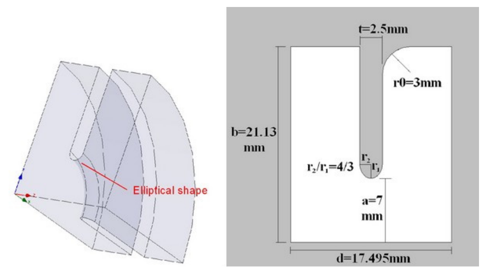

Figure 2: Single cell design.

Beam-pipe RF coupler

The concept of beam-pipe coupling, in alternative to the cell coupling has been proposed at SLAC for the high gradient X-band cavities [6]. This solution has been applied to SPARC (see Fig. 3).

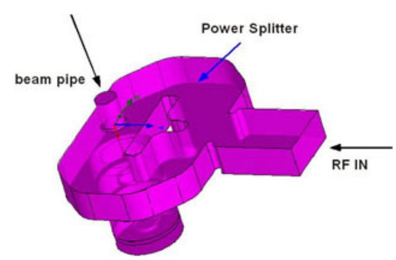

Figure 3: RF Coupler.

Its main advantage is that the RF field on the coupling slot edge is weaker than in case of the RF cell coupling. This reduces the risk of discharge and excessive heating of the in-out slots. The RF power is applied symmetrically onto the beam pipe by means of the waveguide splitter depicted in the picture. In this way, the dipole component of the field is completely cancelled in the coupling cell.

The C-band prototype

A 50 cm long prototype is being manufactured in a Italian firm at the time of this conference. It consists of 20 RF cells that will be brazed in the high vacuum furnace available at LNF. The prototype will be vacuum and low power tested and, after that, high power tested in the KEK C-band test stand (JP). Figure 4 shows a CAD drawing of the prototype. The calculated main parameters of the prototype are listed in Table 3.

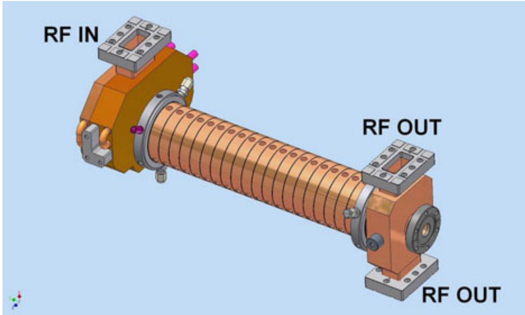

Figure 4: CAD drawing of the C-band prototype.

Table 3: C-band prototype main parameters

Frequency	5712 MHz
Type	TW, 2π/3, CI
Number of RF cells	20
Iris diameter	14 mm
Group velocity/c	0.0278
Field attenuation	0.22/m
Shunt impedance per meter	75 MΩ
Filling time	42 nsec
Peak surface E-field	81 MV/m @ 40 MW
Average accelerating field	35 MV/m @ 40 MW
Total structure length	500 mm

STUDY OF THE BEAM DYNAMICS

The beam dynamics study has been addressed by means of particle tracking simulations performed with the help of the TSTEP and ELEGANT codes [7, 8]. A 200 pC beam, generated by a 6 ps long laser pulse, has been tracked with the TSTEP code from the photocathode exit up to the energy of 90 MeV, i.e. after the second S-band section. An RF compression factor of three has been applied obtaining a beam with rms length $\sigma_z \approx 180\ \mu m$ and rms energy spread $\sigma_\delta \approx 1.1$ %. For the c-band particle tracking the ELEGANT code is used where the longitudinal short range wakefield have been calculated from [9]:

$$W_L(s) \approx \frac{Z_0 c}{\pi a^2}\Phi(s)\exp\left(\frac{\pi s}{4 s_0}\right) erfc\left(\sqrt{\frac{\pi s}{4 s_0}}\right) \tag{1}$$

where a is the iris radius, c is the velocity of light, Z_0 =377 Ω, and

$$s_0 = \frac{g}{8}\left(\frac{a}{\alpha(g/L)L}\right)^2 \tag{2}$$

with g the cavity length, L the periodicity; it has been taken $\alpha = 0.465$. For the transverse wakefield we have:

$$W_X(s) = \frac{4 Z_0 c s_0}{\pi a^4}\Phi(s)\left[1-\left(1+\sqrt{\frac{s}{s_0}}\right)\exp\left(-\sqrt{\frac{s}{s_0}}\right)\right] \tag{3}$$

where the value of s_o has been modified by K. Bane fitting with numerical results and becomes [9]:

$$s_0 = 0.169\frac{a^{1.79} g^{0.38}}{L^{1.17}} \tag{4}$$

In Fig. 5 the simulation results are presented for an accelerating field of $E_{acc} \approx$ 35 MV/m that brings the energy up to ≈ 200 MeV.

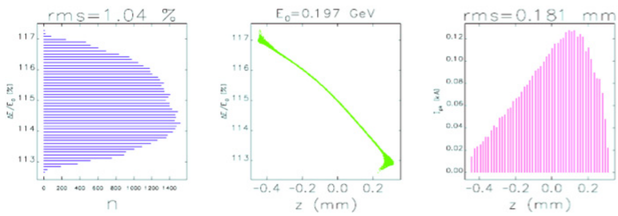

Figure 5: Longitudinal energy and current distribution of the tracked 200 pC electron beam, (Np=50kp).

In Fig. 6 the projected emittance evolution is reported for the on axis case (black curve) and for a 500 μm horizontal off axis random (blue curve) and cumulating for the two sections (red curve). A maximum dilution of the 5% is observed for the emittance, that allows to estimate the alignment tolerance for this case.

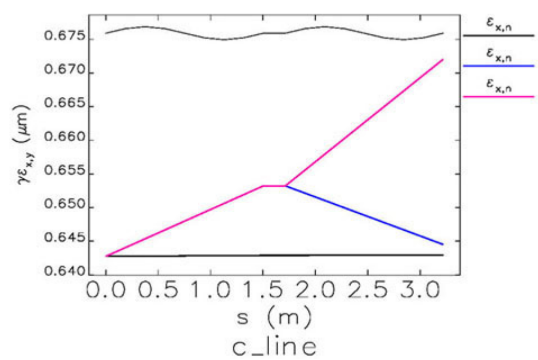

Figure 6: Horizontal emittance dilution as effect of random (blue curve) and cumulating (red curve) accelerating sections misalignment Δx=500 μm.

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