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STUDY OF A C-BAND HARMONIC RF SYSTEM TO OPTIMIZE THE RF BUNCH COMPRESSION PROCESS OF THE SPARC BEAM

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Abstract

The SPARC linac at the INFN Frascati Labs is a high brilliance electron source with a wide scientific program including production of THz and Thomson backscattering radiation, FEL studies and plasma wave acceleration experiments. The linac is based on S-band RF and consists in an RF Gun followed by 3 accelerating structures, while an energy upgrade based on 2 C-band accelerating structures is ready to be implemented. Short bunches are ordinarily produced by using the linear RF bunch compression concept. A harmonic RF structure interposed between the Gun and the 1st accelerating structure can be used to optimize the RF compression by a longitudinal phase space pre-correction, allowing to reach shorter bunches, a much more uniform current distribution and in general to control better the whole compression process. Here we report the results of numerical studies on the SPARC bunch compression optimization through the use of a harmonic cavity, and the design of a C-band RF system to implement it. The proposed system consists in a multi-cell SW cavity powered by a moderate portion of the total RF power spilled from the C-band power plant already installed for the linac energy upgrade.

INTRODUCTION

The SPARC_LAB [1,2] linac at the INFN Frascati Lab produces high brightness electron beams by means of the Velocity Bunching (VB) [3], a technique that preserves the low emittance value shown by the beam at the photo-injector GUN exit [4,5,6].

In the last few years the worldwide interest in high brightness electron beams moved towards very low charge ($0.5 - 20\ pC$) ultra-short bunches. This interest is aimed at performing experiments like single spike X-ray Free Electron Laser (XFELs) [7,8], Plasma Wake Field Acceleration (PWFA) [9] and Laser Wake Field Acceleration (LWFA). To satisfy the request of ultra-short, high quality bunches, the VB process can be improved by adding a High Harmonic Cavity (HHC) to pre-correct the bunch Longitudinal Phase Space (LPS) to shorten and flatter the charge distribution. The HHC is also an additional tool to shape the beam in peculiar configurations, such as comb-like distributions [10].

The LPS pre-correction scheme in the Magnetic Bunch Compressors (MBCs) is already well known [11] and the nonlinear term in the beam LPS coming from the curvature (second-order term) of the accelerating RF can be fully compensated by a decelerating HHC. The required correction field to compensate the curvature of the main accelerating RF is given by:

$$V_h \cos\phi_h = -V_{acc} \cos\phi_{acc} / n^2 \qquad (1)$$

where V_h, V_{acc} and ϕ_h, ϕ_{acc} are the amplitudes and phases of the harmonic and accelerating voltages respectively, and $n = f_h / f_{acc}$ is the harmonic number. According to Eq. 1 the larger the harmonic number, the lower the beam deceleration required for LPS linearization. At LCLS (SLAC's XFEL), a fourth harmonic of the S-band linac (2.856 GHz) is used, while at the European XFEL and FLASH (Germany) the third harmonic of the main L-band linac (1.3 GHz) is used.

The main difference between MBCs and VB pre-correction schemes is related to the space charge effects, that are negligible for MBCs while are a major issue for the VB that needs to be performed at quite low energies (4-7 MeV). The VB [3] is based on the slippage of not fully relativistic bunches on the accelerating RF wave towards the capture phase, and the bunch distribution in the LPS at the end of the process is affected not only by the RF curvature, but also by space charge effects that are damped by the energy increase but enhanced by compression. The final result is more a distortion than a simple curvature of the LPS, and cannot be easily compensated following the Eq. 1 as for the MBCs case. This difference is crucial; as a matter of fact the correction efficiency is no longer related to the harmonic order as in Eq. 1, but rather to the bunch deceleration before the injection into the first RF accelerating section downstream the Gun where VB takes place, as it is reported in the next paragraph.

SIMULATIONS

To better understand the LPS deformation due to Space Charge (SC) effects we started simulating an ideal VB compression case at SPARC using only the first two S-band accelerating cavities. We considered a large 1nC bunch charge to stress the SC effects, 10ps flat-top (no rise-time) laser pulse, at the cathode, with a uniform transverse profile of 1mm (R_{max}). The Gun was powered at 140 MV/m (6.5 MeV at the exit) and the two TW cavities respectively at 23 MV/m and 33 MV/m. The first

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TW cavity with an injection phase of -88.6 Deg, with the aim to reach the maximum compression (1/4 of synchrotron oscillation in the LPS). The results of the simulation are shown in Fig. 1: on the left, with SC turned off, LPSs and the binning on the longitudinal dimension for 2000 macro particles; on the right, the same tracking, with SC turned on. In the figure, to give a full description of the dynamic, are shown the distributions at 2, 3, 4, 5 and 6 meters (the VB starts at 1.5m and after 6 meters the evolution is frozen). Although both the cases (SC ON/OFF) show a peak current on the head (demonstrated experimentally for the VB [3]) the beam dynamics is very different and the two behaviours diverge at 4 meters (the red point). As expected in the SC OFF case, the RF curvature imprints the LPS and sets the limit of the final achievable bunch compression. With the SC ON (real case) the Coulomb repulsive forces prevent the bunch head over-compression [12]; the particles are stacked on the bunch head and the RF curvature is much less evident. As mentioned in the introduction, in this case the HHC pre-correction does not have to work on the RF curvature, but, as shown in Fig. 2, it has to stack more electrons on the bunch tail to compensate the head overpopulation associated to the VB compression process. Here to point out the effects of the HHC, a 50 MV/m accelerating field was considered.

In Table 1 are compared the pre-correction performances of X-band (4th harmonics) and C-band (2nd harmonics) HHCs on the previous ideal case. The X-band HHC reaches a compression factor that is only 10% larger than the C-band one (93 μm vs. 106 μm), considering an equal beam energy decrease of 2.5 *MeV* for both cases.

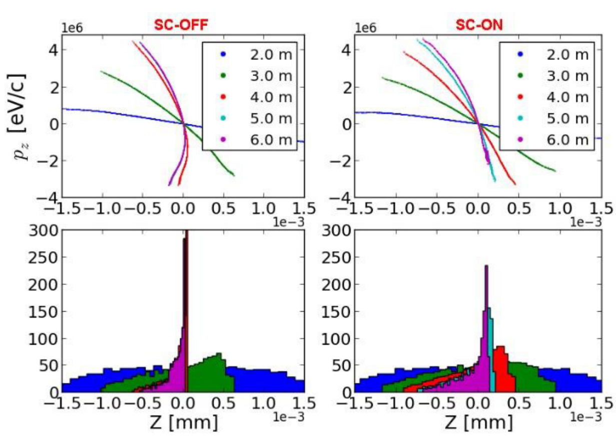

Figure 1: Snapshots of longitudinal phase spaces at 2,3,4,5, 6 m (VB starts a 1.5 m) during VB compression with SC ON and OFF (top), and macro particles longitudinal binning (bottom).

As shown in Table 1, a larger deceleration produces a stronger compression; a ΔE of 3 MeV corresponds to a final bunch length of 75 μm in both cases. However the normalized emittance associated with these working points is roughly doubled, since at low energies strong decelerations cause emittance degradation. In the analysis are compared an X-band TW section with 11 cells, a C-band TW cavity with 11 cells and a C-band SW cavity with 3 cells. The two 11 cells TWs are simply scaled (C-band twice long than X-band). The C-band SW and the 11 cells X-band TW are in principle compact enough to fit with the limited space available at SPARC in between the Gun and the first S-band TW section. According to our calculations based on VB and including SC, and in contrast with Eq. 1 and MBCs theory, there are not significant disadvantages in choosing C-band rather than X-band for the SPARC HHC. On the other hand, the availability of a power plant already installed represents a sufficient practical motivation to base the SPARC HHC project on C-band RF.

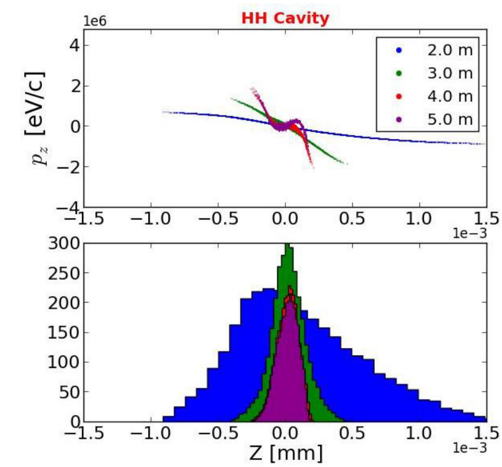

Figure 2: VB compression behaviour with the High Harmonic Cavity (HHC). The HHC is at 1.3 m from the cathode, the VB cavity at 1.5 m. Snapshots of the LPSs at 2, 3, 4 ant 5 m (top), and longitudinal binning - current distributions (bottom).

Table 1: C-band and X-band High Harmonic Correction Cavities Comparison and the Non-corrected VB Case

Type band	Grad. [MeV/m]	Decreased E [MeV]	$\sigma_z[\mu m]$	$\varepsilon_{n,x}[\mu m]$
Nothing	-	-	200	1.7
C-3 Cells	31	2.5	106	2.4
C-11 Cells	17.5	3.0	75	4.0
X-11 Cells	28	2.5	93	2.0
X-11 Cells	35	3.0	75	4.0

The HHC can improve the VB performances in the “COMB beam” scheme required by the forthcoming PWFA experiments at SPARC_LAB.

In Fig. 3 are summarized the simulation results for a “three bunches driver” scheme where a train of 3 bunches of 200 pC charge, < 30 μm long and separated by 1ps is required at the plasma interaction. A comparison of the bunch LPSs in VB configuration with (right) and without (left) HHC is reported in Fig. 3. Clearly, the case with HHC shows much more uniform charge distribution with a final length σ_z< 32 μm for each bunch along the train.

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Also the bunch over-cross process occurring during VB is faster in presence of the HHC, i.e. the bunches stay overlapped for a shorter time reducing the emittance growth. Quantitatively, according to simulations the total normalized emittance is reduced from 3.5 µm to 2.6 µm.

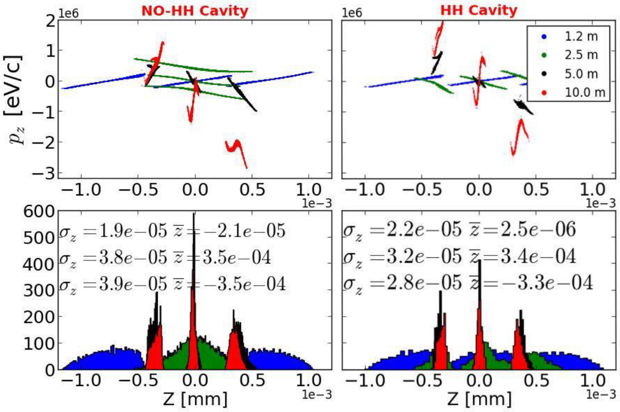

Figure 3: Snapshots of longitudinal phase spaces at 1.2, 2.5, 5, 10 m from the cathode of a 3 bunch comb beam during VB compression with and without HHC (top), and macro particles longitudinal binning (bottom).

SPARC HARMONIC SYSTEM DESIGN

The SPARC HHC will be installed between the RF gun and the first S-band accelerating section which also acts as RF compressor. Since the available space is limited, the only viable solution is to use a few cells (actually 5) standing wave (SW) resonant cavity.

A 40 MW C-band (f = 5712 MHz) power plant has been already installed, tested and put in operation at SPARC to drive one or two (depending on the experiment) Travelling Wave (TW), constant impedance accelerating structures aimed at boosting the beam energy up to ≈ 230 MeV. A pulse compressor system is also installed, capable to almost double the integrated accelerating field in the TW sections for a given klystron output peak power.

Table 2: SPARC Harmonic Cavity Design Parameters

Parameter	Value
Structure type	SW, 5 cells, π mode
Max accelerating gradient	23 MV/m
Surface peak field	62 MV/m
Unloaded quality factor Q_0	12000
R/Q	365 Ω
Optimal input coupling factor β	3.16
RF power (flat pulse)	2 MW (300 ns)
RF power (compressed pulse)	0.9 MW (2350 ns)

The simplest and most convenient choice is to power the C-band SPARC harmonic cavity draining the needed RF power from the existing power plant downstream the pulse compressor through a suitable (-13 dB) directional coupler. Waveguide devices such as a variable attenuator, a 360° variable phase shifter and a ferrite circulator need to be placed along the RF power line to the HHC input coupler, to provide full control of the harmonic voltage on the beam and to preserve the matching to the RF source. The design values of the most relevant parameters of the SPARC harmonic cavity are listed in Table 2, while the e.m. CAD model of the simulated 5 cell cavity including colour map of the fields is shown in Fig. 4.

The SPARC C-band power plant will operate either in flat or compressed RF pulse regime. In fact, when performing PWFA experiments [10] only one C-band TW accelerating section will be used, while the second one will be removed to accommodate the beam-plasma interaction chamber. In this configuration the available klystron power is sufficient to drive a single TW section to the nominal gradient of 35 MV/m, so that the pulse compressor will be detuned and a flat RF pulse of duration < 300 ns will be used. The input coupling coefficient of the harmonic cavity has been chosen to optimize the efficiency in this operation modality. Being the pulse duration limited to 300 ns, to reduce the breakdown probability in the TW section, an input coupling coefficient β ≈ 3.16 has been calculated as the best trade-off to reduce the filling time at the expense of the RF power transmission to the cavity.

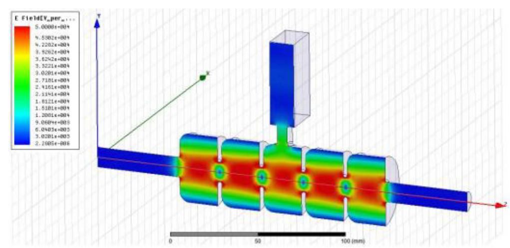

Figure 4: SPARC harmonic cavity model.

For other experiments using both C-band TW sections, the RF pulse compressor will be used to provide the maximum beam energy gain. As shown in Fig. 5, in this modality the SW harmonic cavity is more efficient and provides about a 50% larger accelerating field for a given RF source peak power.

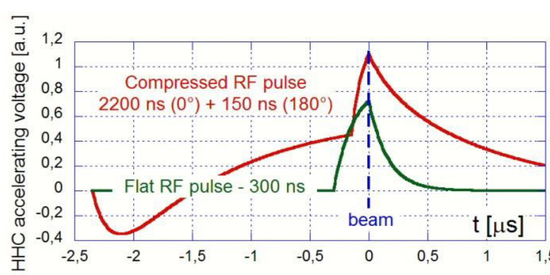

Figure 5: Harmonic cavity accelerating voltage profile.

CONCLUSION

The installation of a C-band (f = 5712 MHz), 5 cells SW HHC in between the RF Gun and the 1st TW S-band accelerating section at the SPARC_Lab linac has been planned to generate ultra-short, low emittance and uniform bunches suitable for a variety of advanced experiments.

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