BEAM DYNAMICS STUDIES FOR THE SPARXINO LINAC*

M. Boscolo, M. Ferrario, V. Fusco#, M. Migliorati, L. Palumbo, B. Spataro, C. Vaccarezza, INFN-LNF, Frascati, Italy
L. Giannessi, M. Quattromini, C. Ronsivalle, ENEA, Frascati Italy
L.Serafini, INFN-MI, Milano, Italy.

Abstract

The first phase of the SPARX project is a R&D activity focused on developing techniques and critical components for future X-ray FEL facilities. The SPARXINO test facility, that will generate an ultra-high peak brightness electron beam at 1 GeV, is included in this research program and it will use the 800 MeV linac of DAΦNE. The facility will allow driving a single pass FEL experiment in the range of 3-5 nm, both in SASE and seeded configurations. A peculiarity of this linac design is the choice of integrating a rectilinear RF compressor (producing a 300-500 A beam) with a magnetic chicane for a further compression up to 1 kA. In this paper we discuss the dynamics of the beam which is in the space charge dominated regime. Start to end simulations and preliminary stability studies are also reported.

INTRODUCTION

The first phase of the SPARX [1] project consists mainly in two lines focused on developing techniques and critical components for future X-ray FEL facilities. These activities will be carried out on one side at SPARC [2], with extensive studies on beam dynamics and FEL physics. On the other side it is under study an even more ambitious project, SPARXINO, consisting in the use of existing Frascati 800 MeV linac, operating now as injector system for DAΦNE Φ-factory [3], to produce an ultra-high peak brightness electron beam at 1GeV.

The SPARXINO layout

Fig.1 schematically represents the SPARXINO linac. As concern the photo-injector, the layout is similar to the SPARC linac with the first travelling wave structure (TW) set to operate in the RF compression state.

Focusing solenoids are placed around the two TW structures to compensate emittance degradation and an X band cavity [4] is placed before the SPARC linac to compensate the longitudinal emittance growth induced afterwards by the RF compression process.

A transfer line (TL1) follows the SPARC photo-injector to drive the beam to the entrance of the first SPARXINO linac (L1) which consists of five TW structures.

Another transfer line (TL2) matches the beam to a magnetic compressor.

Finally the beam passes through a third transfer line (TL3) and it is injected in the final SPARXINO linac made of ten TW structures. All the TW structures are of the SLAC type; they are 3 m long, their frequency is about 3 GHz with an accelerating field of 25 MV/m.

The SPARXINO lattice is embedded in the existing lattice of the DAΦNE linac.

Previous studies [5] demonstrated that setting appropriately the RF compressor phase and tuning the solenoids around the first and second TW, a peak current of 450 A beam can be obtained outside the photo-injector with a good control of emittance. Moreover the 450 A bunch can propagate along L1 and L2 using the existing DAΦNE quadrupoles placed around the TW structures [6].

THE SPACE CHARGE REGIME AND THE INVARIANT ENVELOPE CONDITION

When a bunch propagates, space charge and emittance pressure influence its beam dynamics; a space charge or an emittance dominated bunch can be recognized evaluating its laminarity parameter [7]

$$\rho = \frac{I\sigma^2}{2\gamma I_A \varepsilon_{th}^2} \tag{1}$$

where $\gamma = 1 + T / mc^2$ is Lorentz factor and T is the beam kinetic energy, σ is the rms bunch spot size, ε_{th} is the thermal emittance, I is the beam peak current and I_A=17 kA is the Alven current.

The laminarity parameter ρ is the ratio between the space charge term and the emittance term in the transverse envelope equation.

When ρ>>1 the space charge collective force is dominant with respect to the emittance pressure (that is

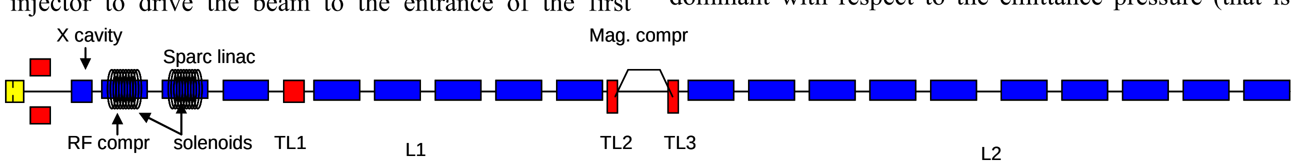

Figure 1: SPARXINO schematic layout.

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#valeria.fusco@lnf.infn.it

the bunch is in the space charge dominated regime), viceversa when ρ<<1 the bunch is in the emittance dominated regime.

A theoretical description of the emittance compensation process [8] demonstrates that, in the space charge regime, the emittance oscillates because of mismatches between the space charge forces and the external focusing gradient. Such oscillations can be damped and controlled by injecting the beam at a waist,

$$\sigma' = 0 \tag{2}$$

and by letting the beam propagate under the so-called invariant envelope condition

$$\sigma_{INV} = \frac{1}{\gamma'}\sqrt{\frac{2I}{I_A(1+4\Omega^2)\gamma}} \tag{3}$$

where $\gamma' = eE_{acc}/m_e c^2$ and E_{acc} is the accelerating field while the normalized focusing gradient is

$$\Omega^2 = \left(\frac{eB_{sol}}{mc\gamma'}\right)^2 + \begin{cases} \approx 1/8\,\mathrm{SW} \\ \approx 0\,\mathrm{TW} \end{cases}$$

The invariant envelope condition in SPARXINO

The invariant envelope condition can be applied in the SPARXINO case as well. Infact substituting Eq.3 into Eq.1, the threshold energy between the space charge regime and the emittance regime [7] is

$$\gamma_{TH} = \frac{I}{\gamma' I_A \varepsilon_{th}} \tag{4}$$

Tab. 1 shows the main electron beam parameters at different positions along the linac. As a consequence of the longitudinal compression, the threshold energy calculated from Eq.4 (last row of Tab. 1) shows the bunch is still in the space charge. Note that in this case the threshold energy and the laminarity parameter have been calculated assuming a thermal emittance of 0.6 μrad, in brackets we report the value for a thermal emittance of 0.3 μrad used in simulations.

Table 1: Electron Beam parameters at different positions as computed by the Homdyn code

	L1 input	L2 input	L2 output
T [MeV]	184	524	1182
I_{peak} [A]	450	1228	1228
Δγ/γ%	0.58	0.51	0.04
ε_{nx} [μrad]	1.1	1.04	1.2
ρ	7 [30]	7 [30]	7 [30]
σ_{INV}	0.268	0.274	0.182
γ_{TH}	980 [1961]	2783 [5566]	2783 [5566]

The invariant envelope condition has been applied in SPARXINO, for the above reasons, at the entrance of L1 and after the magnetic compression at the entrance of L2.

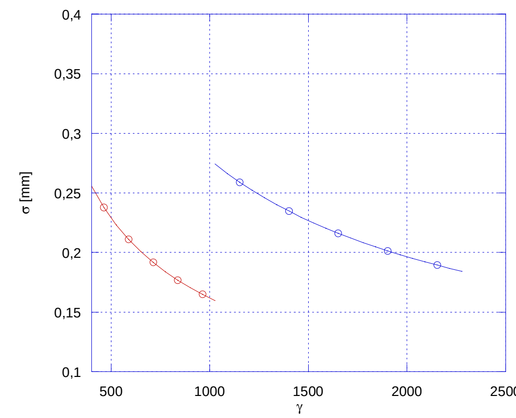

Figure 2: Invariant rms spot size according to Eq.3 versus the relativistic parameter γ, for I=450A and I=1200A, before and after the magnetic compressor.

Fig.2 represents the invariant rms spot size as a function of γ before (I=450A) and after the magnetic compression (I=1200A).

Simulations results with Homdyn and Parmela

The Homdyn and the Parmela codes have been used to test by simulations the conditions of Eq.2 and Eq.3. The codes show a remarkable agreement and the simulations give good results as can be seen from fig.3 and fig.4. It is worth to underline the results have been obtained without quadrupoles around the TW structures, that is the RF focusing is sufficient to control the beam spot size. This choice could prevent the beam from instabilities due, for example, to quadrupoles misalignments.

The second solenoid around the SPARC's linac and the TL1 are sufficient to obtain the invariant envelope condition on L1.

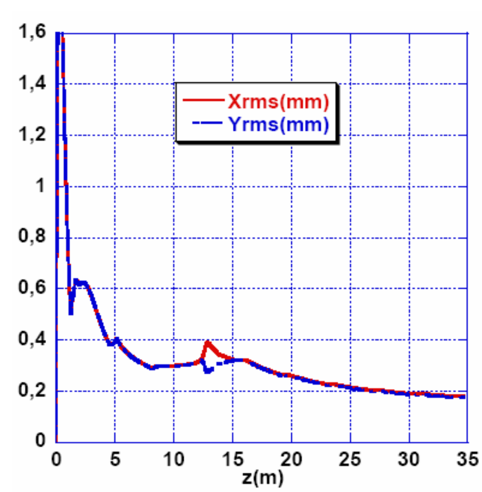

Figure 3: Rms spot size for Parmela up to the magnetic compressor.

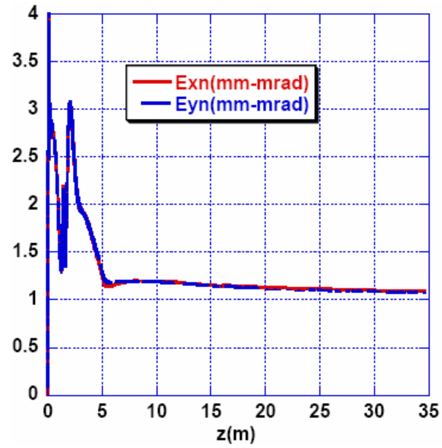

Figure 4: Rms normalized emittance for Parmela up to the magnetic compressor.

Finally the Homdyn code has been used to obtain a preliminary simulation up to the end of L2. The beam is driven after the magnetic compression by TL3 at the entrance of L2 with its invariant envelope condition.

The magnetic compressor is modelled by Homdyn as a wiggler period [9] and it does not include coherent synchrotron radiation effects. A preliminary study of the coherent synchrotron radiation effects has already been done and further studies are planned to take into account simultaneously space charge and coherent synchrotron radiation. Longitudinal wake fields effects in the accelerating structures are included in Homdyn calculations.

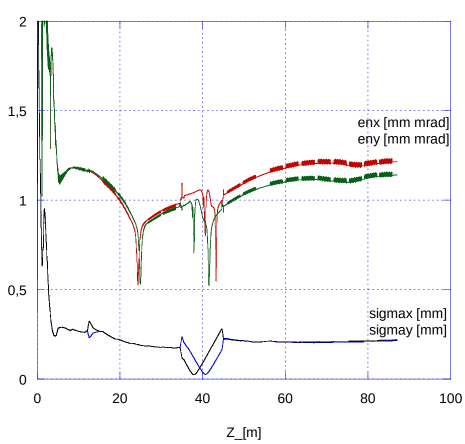

Figure 5: Rms normalized emittance and rms spot size as computed by Homdyn in Sparxino.

The emittance oscillates with plasma frequency along the SPARXINO structures and the oscillation period gets longer as the bunch energy increases (see Fig.5). The invariant envelope condition ensures the control of the emittance oscillation but it does not guarantee the oscillation phase corresponds to a minimum outside the linac. A systematic parametric study is under way in order to obtain a better tuning with an absolute minimum of emittance at the L2's exit.

WAKE FIELDS IN SPARXINO

A preliminary evaluation of the longitudinal and transverse wake fields with Homdyn [10] is also reported here.

Longitudinal wake fields in the photo-injector influence the phase tuning in the RF compressor; when longitudinal wake fields are included, the energy spread induced along the bunch slows down the bunch's tail thus requiring a greater RF compression phase.

Fig.6 shows the current versus the longitudinal position when the system is optimized to obtain a peak current of 450 A with longitudinal wake fields included. Turning off wake fields the RF phase is not optimized anymore and the current increases.

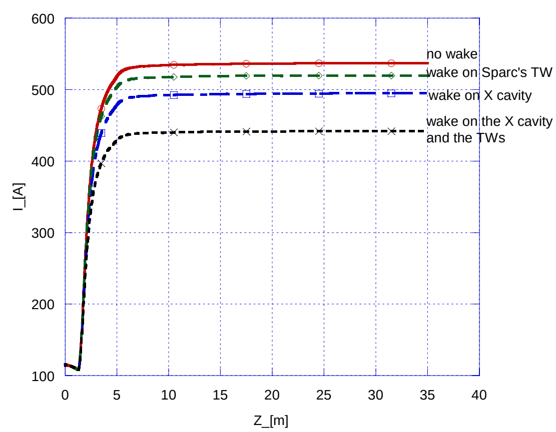

Figure 6: Current versus the position up to the end of L1. From the top: no wake fields, wake fields only in the TW structures, wake fields only in the x band cavity and finally wake fields in both the x cavity and the TW structures.

The X cavity gives the main contribution to the longitudinal wake fields as shown in fig.6.

The magnetic compressor, as a preliminary study, uses a R_{56}=26 mm and the energy spread required to obtain a bunch compression of a factor ~2 is $\Delta\gamma/\gamma\%$=0.5.

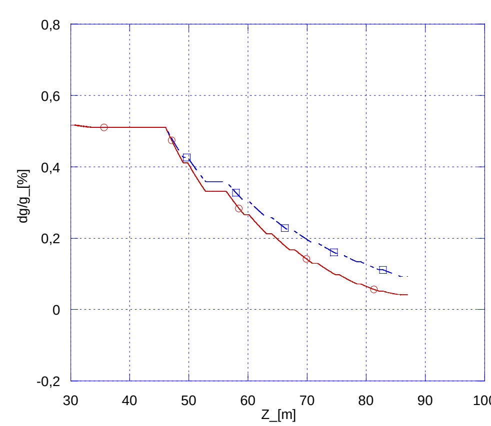

Figure 7: Energy spread in L2 with (lower plot) and without wake fields.

The energy spread properly introduced by L1 to compress the bunch in the following magnetic compressor section, is partially compensated by the longitudinal wake fields of L2 as it is shown in fig.7.

The optimum energy spread is obtained letting the bunch propagate slightly off crest in L2. As fig.8 shows, a phase of about 30º still allows obtaining a final energy of about 1,2 GeV with an energy spread of 0.05%.

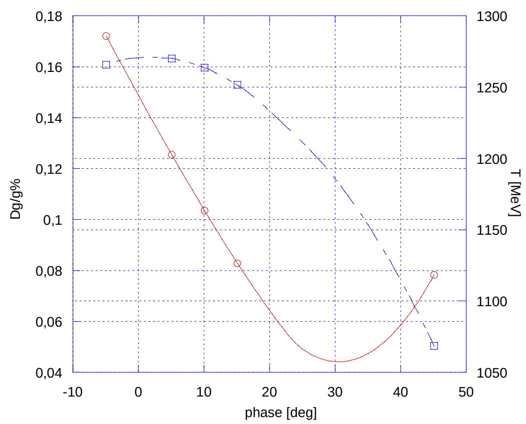

Figure 8: Energy spread and rms energy versus phase in L2.

As a conclusion a preliminary evaluation of transverse wake fields is given when the third TW of the SPARC photo-injector is misaligned by 0.1 mm as shown in fig.9.

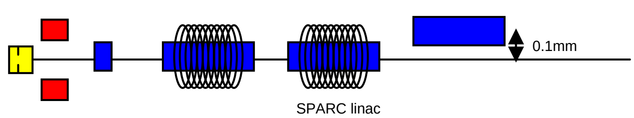

Figure 9: SPARC's photo-injector with a misalignment of 0.1 mm on the third TW structure.

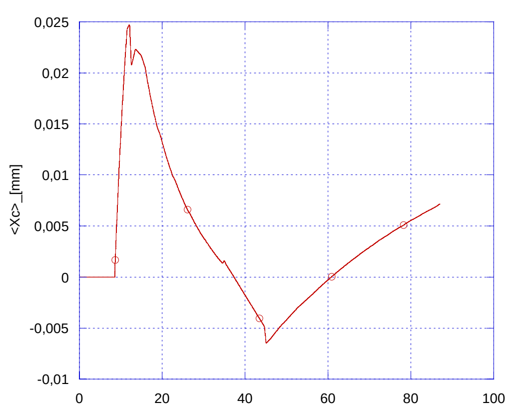

Figure 10: Bunch's centroid in the SPARXINO's devices.

In this case the bunch's centroid doesn't walk too far from the axis (see fig.10), the transverse wake fields are weak and they do not affect the emittance.

CONCLUSIONS

The general layout of SPARXINO and its beam dynamics have been studied: the beam is in the space charge dominated regime thus the invariant envelope condition has to be applied to control and damp emittance oscillations.

It's worth noting, by the use of this condition, the RF focusing is sufficient to control the beam rms spot size without using external quadrupoles thus simplifying machine alignment procedures.

A 1.2 GeV bunch having a peak current of 450A and a projected normalized emittance of about 1mm mrad has been obtained.

An evaluation of the longitudinal wake fields' effect is reported. Their contribution has to be taken into account when setting parameters such as phases along the linacs to get the right RF compression or the right energy spread.

Finally transverse wake fields, evaluated by misaligning the last TW structure of the photo-injector, are negligible.

A stability study and an optimization of the magnetic compressor to take into account simultaneously space charge and coherent synchrotron radiation and their effects are under way.

ACKNOWLEDGEMENT

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