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Status of the SPARC project

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Abstract

In this paper we report on the final design of the SPARC FEL experiment which is under construction at the Frascati INFN Laboratories by a collaboration between INFN, ENEA, ELETTRA, Un. of Rome (Tor Vergata), CNR and INFM. This project comprises an advanced 150 MeV photo-injector aimed at producing a high brightness electron beams to drive a SASE-FEL experiment in the visible using a segmented 12 m long undulator. The project, finally approved and funded early this year, has a 3 year time span, with the final goal of reaching saturation on the fundamental of the SASE-FEL and studying the resonant non-linear generation of harmonics. Peculiar features of this project are the optimized design of the photo-injector to reach minimum emittances by using flat-top laser pulses on the

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photocathode, and the use of an uncompressed electron beam of 100 A peak current at very low emittance to drive the FEL. Results of start-to-end simulations carried out to optimize the performances of the whole system are presented, as well as the status of the construction and assembly of the system components. Activities planned for a second phase of the project are also mentioned: these are mainly focused on velocity bunching experiments that will be conducted with the aim to reach higher peak currents with preservation of low transverse emittances.

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Keywords: Photo-injector; High brightness electron beam; SASE-FEL; Non-linear resonant higher harmonics

1. Introduction

The overall SPARC Project consists of 4 main lines of activity. A *150 MeV Advanced Photo-Injector* aimed at investigating the generation of high brightness electron beams and their compression via magnetic and/or velocity bunching. This beam will be used to drive a *SASE-FEL Visible-VUV Experiment*: this is aimed to investigate the problems related to the beam matching into a segmented undulator and the alignment with the radiation beam at 500 nm, as well as the generation of non-linear coherent higher harmonics. In parallel, R&D activities are pursued at different sites on *X-ray Optics and Monochromators*, to analyze radiation-matter interactions in the spectral range of SASE X-ray FELs. Studies of *Soft X-ray table-top Sources* are also part of the SPARC program, with an anticipated upgrade of the present compact source at INFM-Politecnico Milano, delivering 10^7 soft X-ray photons in 10–20 fs pulses by means of high harmonic generation in a gas. In the following we present an overview of the system under construction at the Frascati National Laboratories of INFN, aiming at reaching the scientific and technological goals indicated in the first two topics listed above.

A 3D model of the whole system is illustrated in Fig. 1: the photo-injector, the FEL undulator, the beam dump and the undulator by-pass beam line are hosted inside a dedicated underground bunker which is 36 m long and 14 m wide.

The 150 MeV photo-injector consists of a 1.6 cell RF gun operated at S-band (2.856 GHz, of the BNL/UCLA/SLAC type) and high-peak field on the cathode (120 MV/m) with incorporated metallic photo-cathode (Cu or Mg), generating a 6 MeV beam [1]. The beam is then focused and matched into 3 SLAC-type accelerating sections, which boost its energy up to 150–200 MeV.The first section is embedded in solenoids in order to provide additional magnetic focusing to better control the beam envelope and the emittance oscillations [2]. The photo-cathode drive laser is a Ti:Sa system with the oscillator pulse train locked to the RF. To perform temporal flat top laser pulse shaping we will manipulate frequency lines in the large bandwidth of Ti:Sa, either using a liquid crystal mask in the Fourier plane for nondispersive optic arrangement or a collinear acousto-optic modulator [3] (DAZZLER). We aim achieving a pulse rise time shorter than 1 ps.

The photo-injector design is by now completed and is reported in a dedicated TDR [4] with full specification of each system component: all bids for acquisition of main components have been so far launched, so we expect to be on schedule with delivery of RF gun, laser system, RF sources and linac accelerating sections. The expected start of installation for the photo-injector components is

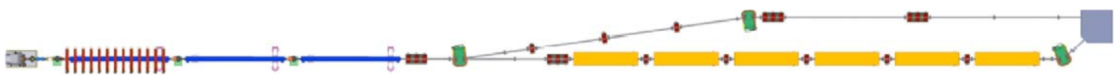

Fig. 1. A map view of the SPARC photo-injector and FEL undulator systems: from left to right, the RF gun, the first linac section embedded in solenoids, the two additional linac sections, the 6 undulator sections, the beam dump and the undulator by-pass beam line are visible.

confirmed for spring of 2005. The first beam at full energy is expected by the beginning of 2006.

2. Start-to-end simulations for the FEL experiment

A basic choice of SPARC phase 1 is to drive the FEL with an uncompressed beam: it was a decision by the project group to postpone the study of magnetic compression and velocity bunching to phase 2 of the project, as explained in Section 3. As a consequence, in order to make the FEL saturate with the natural beam current produced by the photo-injector one has to deliver at the undulator entrance a very high-quality (brightness) beam, i.e. with very low rms slice emittance and energy spread. To this aim we designed a photo-injector based on the Ferrario working point [2] lay-out to achieve full emittance compensation at the linac exit, where the emittance is no longer sensitive to envelope oscillations [5]. The selected beam parameters are listed in Table 1: they slightly differ from those of a previous analysis [6] because of the desire to keep a reasonable FEL saturation length with a bunch charge close to 1 nC. A peak current in excess of 100 A along a substantial fraction of the bunch is anticipated, despite the slight debunching caused in the gun to linac drift by the longitudinal space charge field. By properly matching the beam into the linac, set for on-crest acceleration at a gradient of 25 MV/m, the final rms normalized transverse emittance is minimized at the linac exit (155 MeV), with a nominal value of 0.75 μm as predicted by simulations: the corresponding slice emittance is about 0.6 μm over a substantial fraction of the bunch. A detailed analysis of errors and misalignments [4] in the system leads us to evaluate an upper limit for these two quantities as reported in Table 1, i.e. 2 μm for the rms normalized emittance and 1 μm for the slice emittance. The behavior of relevant beam parameters over the bunch slices is shown in Fig. 2: the energy spread is well below 0.06% for all slices and the current is above 100 A for 54% of the bunch slices. Matching this beam into the segmented undulator (parameters listed in Table 1) requires the use of two triplets in the transfer line in order to reduce the beta function of the beam down to about 1.5 m (average): to assure focusing in the horizontal plane along the undulator, single quadrupoles are located in undulator drift sections. Start-to-end simulations were performed using PARMELA [7] and GENESIS [8]: the result on FEL performances is shown in Fig. 3, where the FEL power growth along the undulator is plotted. Saturation power is reached at nearly 10^8 W in about 12 m of total length including drift sections, leaving some margin of extra undulator length. This comes out to be

Table 1
SPARC FEL experiment parameter list

Electron beam energy (MeV)	155
Bunch charge (nC)	1.1
Cathode peak field (MV/m)	120
Laser radius spot size on the cathode (mm, hard edge)	1.13
Laser pulse duration, flat top (ps)	10
Laser pulse rise time (ps) 10% → 90%	1
Bunch peak current at linac exit (A)	100
Rms norm. transv. Emittance at linac exit (μm); includes thermal comp. (0.3)	<2
Rms slice norm. emitt. (300 μm slice)	<1
Rms uncorrelated energy spread (%)	0.06
Undulator period (cm)	2.8
Undulator parameter, K	2.14
FEL radiation wavelength (nm)	499
Average beta function (m)	1.52
Expected saturation length (m)	<12

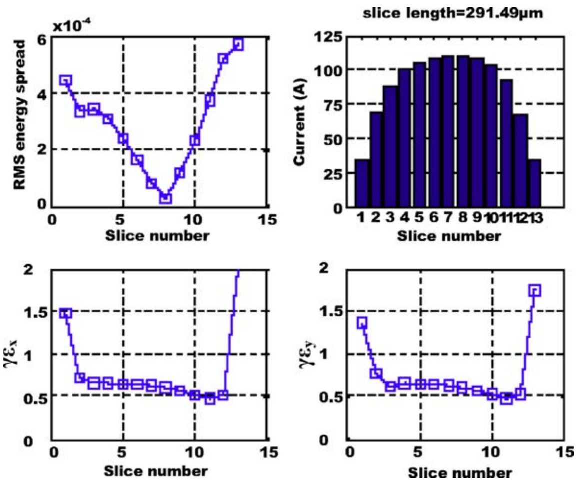

Fig. 2. Computed beam slice parameters at the photo-injector exit (energy spread, current, rms normalized emittance in x and y planes): the slice thickness is about 300 μm.

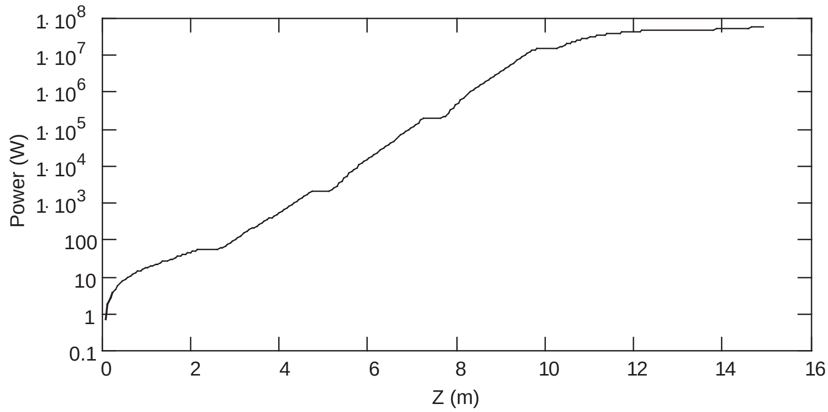

Fig. 3. FEL power growth simulated with GENESIS.

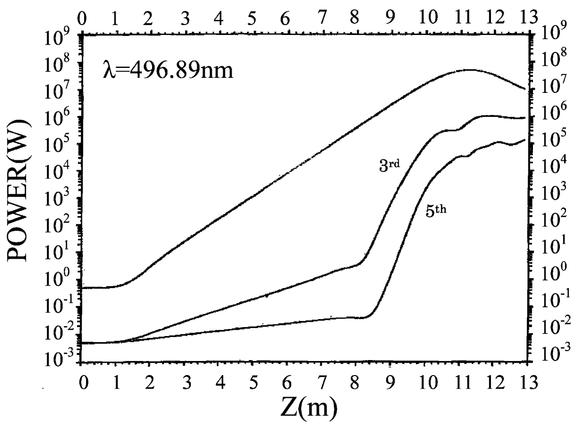

Fig. 4. FEL power growth on fundamental, third and fifth harmonic.

important for the study of non-linear higher coherent harmonics: as a matter of fact, the power growth on the third and fifth harmonic, plotted in Fig. 4 as computed by the code PROMETEO [9], shows that saturation on these harmonics is reached some distance downstream that on the fundamental, hence requiring some additional undulator length. The saturation power level comes out to be nearly 2 and 3, respectively, orders of magnitude lower than the fundamental.

3. Phase 2 of the project

As previously mentioned, phase 1 of the SPARC Project was restricted to the use of uncompressed beams to drive the FEL experiment, mainly because of budget limitation issues. Full implementation of beam compression is foreseen in SPARC phase 2. As illustrated in Fig. 1, the second and third accelerating sections in the linac are not embedded in solenoids: in phase 2, expected to start in 2006, we plan to add solenoids to these sections in order to provide additional focusing along all the linac with flexible magnetic field profile. This is one of the most relevant demands of the velocity bunching technique [10]: it is needed to fully control envelope oscillations during compression, which in turns determine the

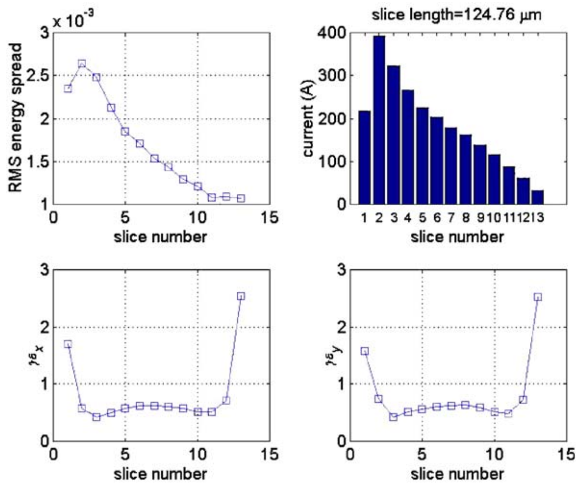

Fig. 5. Slice parameters at linac exit with weak velocity bunching.

minimum emittance achieved. A magnetic compressor will also be installed on the second beam line to study CSR effects and emittance degradation issues. An example of possible performances that can be obtained by applying velocity bunching to the beam and by properly using the additional solenoid focusing provided in the last two sections, is shown in Fig. 5. By injecting the beam into the first section at -83°RF (0°RF corresponds to on-crest acceleration) at 25 MV/m, the beam current is raised up to 200 A for 40% of the bunch slices, with a slice at 400 A, while the slice emittance is kept below 0.6 μm for most slices (total rms normalized emittance is about 1.4 μm). We plan to perform a dedicated experimental investigation for characterizing the full potentiality of the velocity bunching technique.

References

[1] D.T. Palmer, The next generation photoinjector, Ph.D.Thesis, Stanford University.
[2] M. Ferrario, et al., Homdyn Study for the LCLS RF Photoinjector, SLAC-PUB 8400.
[3] F. Verluise, et al., Opt. Lett. 25 (2000) 572. See also S. Stagira, Proceedings of the Workshop on Laser Issues for Electron RF Photoinjectors, SLAC-WP-025, 2002.
[4] L. Palumbo, J.B. Rosenzweig (Eds.), Technical Design Report for the SPARC Advanced Photo-Injector, in publication.
[5] L. Serafini, J.B. Rosenzweig, Phys. Rev. E 55 (1997) 7565.
[6] D. Alesini, et al., Nucl. Instr. and Meth. A 507 (2003) 345.
[7] L.M. Young, J.H. Billen, Parmela, LA-UR-96–1835, 2000.
[8] S. Reiche, Nucl. Instr. and Meth. A 429 (1999) 243.
[9] G. Dattoli, et al., ENEA Report RT/INN/93/09 1993.
[10] L. Serafini, M. Ferrario, AIP Conf. Proc. 581 (2001) 87.