PERSPECTIVES OF COHERENT X-RAY SOURCE IN ITALY

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Abstract

Last year the Italian Government launched a call for proposals to our national research institutions for the design and construction of an Ultra-Brilliant X-ray Laser: 94 million ¤ is the total funding for this initiative. The Italian community responded by submitting two proposals for a similar machine, basically consisting of a few GeV Linac driving a SASE-FEL operated at a minimum wavelength around 15 Å. Here we describe the essential features of the two proposals: SPARX has been prepared by a collaboration among CNR-ENEA-INFN and Universita' di Roma "Tor Vergata", while FERMI@ELETTRA by INFM and Sincrotrone Trieste. We will also illustrate the status of the R&D project SPARC, aiming at the design and construction of an advanced 150 MeV photo-injector for generating a high brightness electron beam to drive a SASE-FEL in the optical range. This project has been approved by the Italian Government to conduct an R&D activity aimed to be strategic on the way to the coherent X-ray source; it is pursued by a CNR-ENEA-INFN-Universita' Tor Vergata-INFM-ST collaboration and will be located in the INFN National Laboratory at Frascati.

1 INTRODUCTION

Driven by the large interest that 4th generation light sources, *i.e.* X-ray SASE FEL's, have raised world-wide in the synchrotron light user community, as well as in the particle accelerator community, and following solicitations arising from several Italian national research institutions, in the year 2001 the Italian Government launched a long-term initiative devoted to the realisation of a large scale ultra-brilliant and coherent X-ray source in Italy. The initiative was modulated into two phases, with anticipated budgets of 11 M¤ and 96 M¤ respectively: the first phase is meant to be a 3 year R&D program strategically oriented to explore the feasibility and the most crucial issues of the system which is expected to be designed and built in the second phase, aimed at the construction of the radiation source in a 5-6 year time scale. To pursue this program, the Italian Government published two calls for proposals, in March 2001 (named FISR) and in December 2001 (named FIRB), for the two phases respectively. In March 2002 the proposal SPARC, here described, was approved, among others, to be funded with 9.5 M¤ over the available total budget in the FISR call (11 M¤): funding should be delivered soon, allowing a prompt start-up of the project. In the meanwhile, two proposals, submitted in February 2002 at the FIRB call, are waiting a final decision of approval: one of these, SPARX, is tightly correlated to the approved R&D project SPARC, as explained in the following sections, the other one, FERMI@ELETTRA, is competing with SPARX to obtain the 96 M¤ funding from our Government.

The scientific case for these initiatives is recognised to be quite deep by the whole community of synchrotron light users. X-rays from synchrotron light sources are today widely used in atomic physics, plasma and warm dense matter, femto-second chemistry, life science, single biological molecules and clusters, imaging/holography, micro and nano lithography. The big step in the peak brilliance, several orders of magnitude, expected with the SASE-FEL sources will open new frontiers of research. New techniques in X-imaging, time resolved spectroscopy can be applied in the field of material science, biology, non linear optics. Of particular relevance are the diffractive techniques with coherent radiation on biologic tissues that allow the single-pulse crystallography of macro-molecules.

In the following we will present through different sections the status of the R&D project SPARC (Sec.2), the proposals SPARX (Sec.3) and FERMI@ELETTRA (Sec.4).

2 THE R&D PROJECT SPARC

The overall SPARC project consists of 4 lines of activity aiming at several goals: their common denominator is to explore the scientific and technological issues that set up the most crucial challenges on the way to the realisation of a SASE-FEL based X-ray source. These are:

1) *Advanced Photo-Injector at 150 MeV*

Since the performances of X-ray SASE-FEL's are critically dependent on the peak brightness of the electron beam delivered at the undulator entrance, we want to investigate two main issues - generation of the electron beam and bunch compression via magnetic and/or RF velocity bunching - by means of an advanced system delivering 150 MeV electrons, the minimum energy to avoid further emittance dilutions due to time-dependent space charge effects [1].

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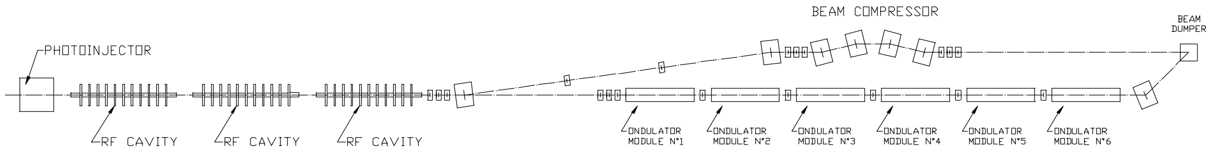

Figure 1: Lay-out of the SPARC system

2) SASE-FEL Visible-VUV Experiment

In order to investigate the problems related to matching the beam into an undulator and keeping it aligned to the radiation beam, as well as the generation of non-linear coherent higher harmonics, we want to perform a SASE FEL experiment with the 150 MeV beam, using a segmented undulator with additional strong focusing, to observe FEL radiation at 500 nm and below.

3) X-ray Optics / Mono-chromators

The X-ray FEL radiation will provide unique radiation beams to users in terms of peak brightness and pulse time duration (100 fs), posing at the same time severe challenges to the optics necessary to guide and handle such radiation. This project will pursue also a vigorous R&D activity on the analysis of radiaton-matter interactions in the spectral range typical of SASE X-ray FEL's (from 0.1 to 10 nm), as well as the design of new optics and mono-chromators compatible with these beams.

4) Soft X-ray table-top Source

In order to test these optics and to start the R&D on applications, the project will undertake an upgrade of the presently operated table-top source of X-rays 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. This will be a very useful bench-test for the activities performed in item 3 above.

In the following, the lay-out and planned activities for items 1 and 2 will be presented in more details, being these more related to the particle accelerator field.

2.1 Advanced Photo-Injector

Two are the main goals of this activity in the context of the SPARC project: a) acquiring an expertise in the construction, commissioning and characterisation of an advanced photo-injector system and b) the experimental investigation of two theoretical predictions that have been recently conceived and presented by members of the SPARC group. These are: the so-called Ferrario's working point[1] for high brightness RF photo-injectors and the velocity bunching technique to apply RF bunch compression[2] through the photo-injector, with emittance preservation.

The 150 MeV injector will be built inside an available bunker of the Frascati INFN National Laboratories: the general lay-out of the system is shown in Figure 1.

It will consists of: a 1.6 cell RF gun operated at S-band (2.856 GHz, BNL/UCLA/SLAC type [3]) with high peak field on the cathode (120-140 MV/m) and incorporated metallic photo-cathode (Cu or Mg), generating a 6 MeV beam which is properly focused and matched into 2 SLAC accelerating sections.

Our simulations[5] using PARMELA indicate that we can generate with this system a beam like that needed by the FEL experiment at 150 MeV: this requires a 150 A peak current in the bunch with rms normalized emittance lower than 2 μm and energy spread below 0.1 %. Scaling the Ferrario's working point up to 1.6 nC bunch charge (instead of the nominal 1 nC) we were able to achieve in simulations a rms normalized emittance of 1.2 μm at the Linac exit, with the requested peak current and a rms correlated energy spread over the bunch equal to 0.14% . However, the slice energy spread, calculated over a 300 μm slice length (comparable to the anticipated slippage length), is well below 0.05 % all over the bunch.

2.2 SASE-FEL Experiment

This will be conducted using a permanent magnet undulator made of 6 sections, each 2.5 m long, separated by 0.3 m gaps hosting single quadrupoles focusing in the horizontal plane. The undulator period is 3.3 cm, with an undulator parameter k_W= 1.88. Simulations performed with GENESIS show an exponential growth of the radiation power along the undulator: almost 10^8 Watts at saturation can be reached after 14 m of total undulator length, on the fundamental harmonic at 530 nm. Preliminary evaluations of the radiation power generated into the non-linear coherent odd higher harmonics show that 10^7 and $7x10^5$ W can be reached on the third and fifth harmonics, respectively.

2.3 Further Experiments

As shown in Figure 1, the SPARC lay-out anticipates two main upgrades that will be implemented in a second phase of the project: a third accelerating section, inserted between the RF gun and the 2 previous sections, and a parallel beam line containing a magnetic compressor.

The new section will be designed to study RF compression: it will support travelling waves at an adjustable phase velocity in order to exploit the full potentialities of the velocity bunching technique[2]. Its design and construction will proceed in parallel to the commissioning of the initial SPARC injector system. These tests of RF compression assume great relevance in our R&D program[4] since the SPARX Linac foresees the use of a mixed compression scheme, as illustrated below.

Recent results[6] obtained in simulations with PARMELA show the possibility to reach bunch peak current in excess of 500 A at the exit of the photo-injector with normalized emittances below 1 μm. The rms current carried by the bunch is plotted in Fig.2 vs. the distance along the photoinjector (taking the SPARC lay-out as in Fig.1): although it reaches 325 A, the current distribution within the bunch, as shown in Fig.4, displays a peak value close to 600 A.

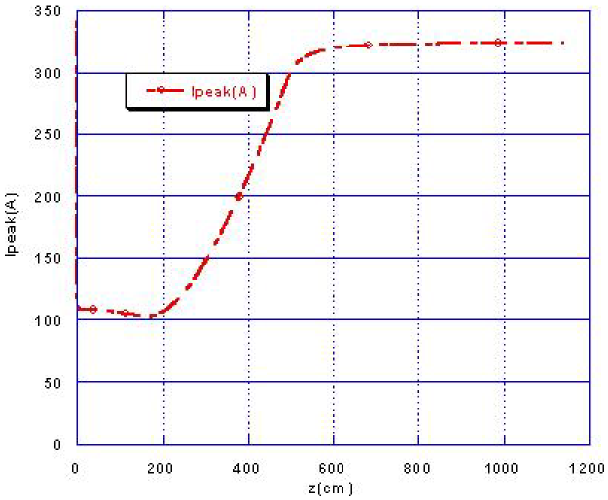

Figure 2: Rms Bunch current evolution along the photo-injector with RF Compression.

By properly focusing the beam with additional solenoids placed around the accelerating structures, the beam envelope can be taken under control as prescribed by the invariant envelope model (generalized to the RF compressor as described in Ref.4). This brings to a correct emittance compensation effect as shown in Fig.3, with a final rms normalized emittance of 0.75 μm.

The second beam line shown in Fig.1 will allow to conduct experiments on magnetic compression: we want to experimentally investigate CSR induced effects on emittance degradation and surface roughness wake-field effects, without interfering with the FEL experiment.

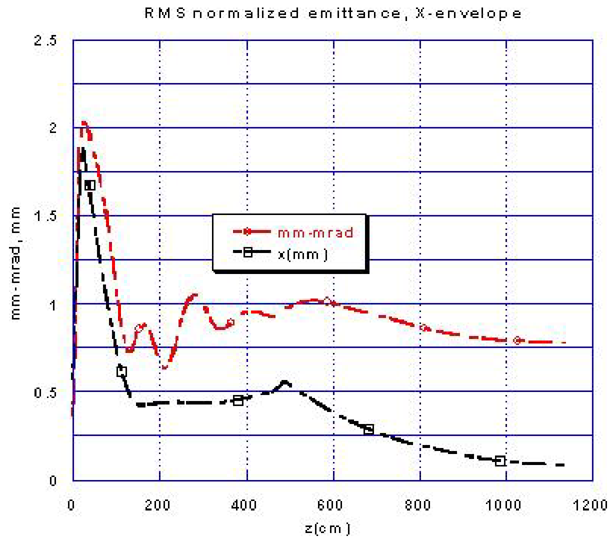

Figure 3: Emittance (red line) and envelope (black line) evolution along the photo-injector with RF Compression.

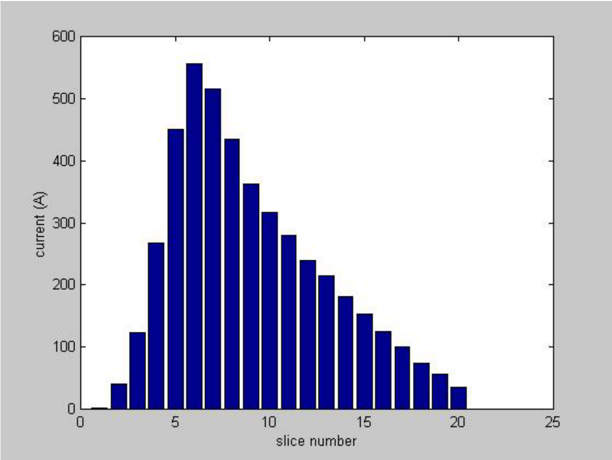

Figure 4: Bunch current distribution after RF Compression.

3 THE PROPOSAL SPARX

Two spectral complementary regions, around 13.5 nm and 1.5 nm, have been considered for this source: the first has many applications requested by future users, the second is the minimum achievable with the anticipated budget.

Table 1: Beam parameters

Beam Energy	2.5	GeV
Peak current	2.5	kA
Emittance (average)	2	μm
Emittance (slice)	1	μm
Energy spread (correlated)	0.1	%

In order to drive a SASE-FEL at these wavelengths, it is necessary to produce a very high brightness beam, as shown by the list of parameters reported in Table 1.

We envisage the use of the same beam to feed two undulators whose characteristics are listed in Table 2: both are anticipated to be of Hallbach type (1.25 T residual field).

Table 2: Undulator characteristics

	First undulator	Second undulator
Period	3 cm	5 cm
K	1.67 (@ 1.5 nm)	4.88 (@ 13.5 nm)
Gap (mm)	12.67 (@ 1.5 nm)	12.16 (@ 13.5 nm)

The SASE-FEL radiation characteristics have been investigated by means of several codes: GINGER, GENESIS, MEDUSA, PROMETEO, PERSEO, and the results are shown in Table 3.

Table 3: FEL-SASE expected performances

Wavelength (λ)	1.5 nm	13.5 nm
Saturation length	24.5 m	14.5 m
Peak Power	10^{10} W	4 10^{10} W
Peak Power 3° harm.	2 10^{8} W	5 10^{9} W
Brilliance (standard units)	1.8 10^{31}	2 10^{32}
Brilliance 3° harm.	10^{29}	10^{31}

Using two undulators allows to cover a bandwidth from 1.2nm to 13.5nm on the fundamental, while from 0.4nm to 4nm using the 3rd harmonic, which exhibits still a considerable peak power.

The SPARX Linac layout is shown in Fig.5. After the SPARC injector, a first 60m Linac section accelerates the beam up to 1 GeV, where the magnetic bunch compressor is located. The last 90 m Linac section boosts the beam up to 2.5 GeV before injection into the undulators. Adiabatic damping and longitudinal wake-fields are crucial in this Linac section to correct the correlated energy chirp applied to the bunch before the magnetic compression.

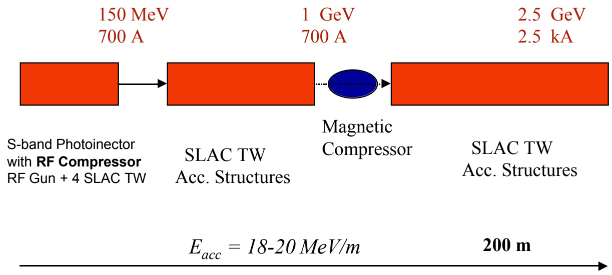

Figure 5: Linac scheme of SPARX project.

Start-to-end simulations[7] performed using PARMELA and ELEGANT show the possibility to reach the anticipated beam performances (listed in Table 1) at least in the central slices of the bunch (about 60% of bunch charge). The longitudinal phase space distribution of the bunch at the Linac exit is plotted in Fig.6, while the current distribution of different bunch slices is reported in Fig.7: the normalized rms slice emittance is lower than 2 µm.

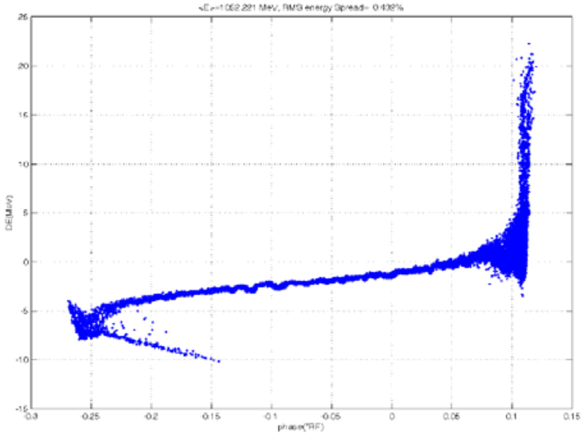

Figure 6: Longitudinal phase space distribution of the bunch at Linac exit.

The slice energy spread is well below 0.1 %, except for the bunch tail which exhibits a huge current spike accompanied by large energy spread and slice emittance.

These preliminary results, clearly not yet optimized, show for the first time the possibility to operate a Linac in a mixed compression scheme: velocity bunching performing RF compression in the photo-injector combined to a single stage magnetic compression at intermediate energy (1 GeV).

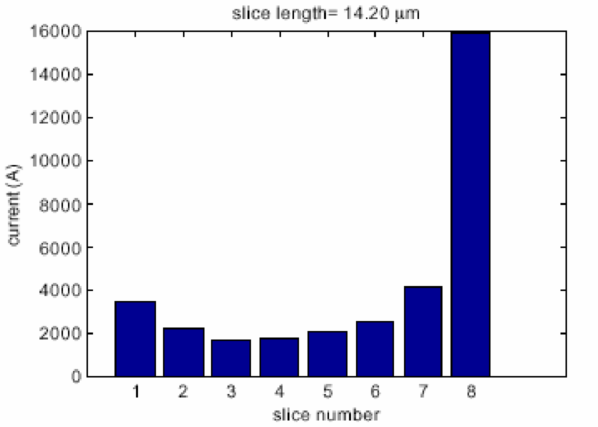

Figure 7: Current distribution of bunch slices at Linac exit.

The anticipated budget is: 34 M¤ are estimated for the Linac, 10 M¤ for the undulators, 10 M¤ for the radiation beam lines and 13 M¤ for contingency. In conclusion, SPARX is proposing an innovative solution for the Linac which relaxes the criticality of the beam compression process and seems more reliable for the achievement of the SASE-FEL beam brightness requirements. The

Universita' di Roma "Tor Vergata", member of the collaboration, is ready to donate the land for the construction of a 1.5 Km tunnel hosting the Linac and radiation beam lines in case of approval of the SPARX proposal.

4 THE PROPOSAL FERMI@ELETTRA

The proposal is articulated along three lines of development allowing gradual improvements and consolidation of technologies. These are schematically:

1) Use of the existing 1 GeV Linac with a new photo-injector and bunch compressor(s) for the production of 40 nm radiation. Commissioning of 40 nm beamline in 2.5 years. Open to Users after 3.5 years.
2) Use of the Linac with increased beam quality for a second beamline at 10 nm. Commissioning of beamline in 3.5 years. Open to Users after 4.5 years.
3) Extension of the Linac up to 3 GeV and improvement of beam quality for operation at 1.2 nm (in parallel with other developments). Commissioning in 5.5 years and open to Users after 6.5 years.

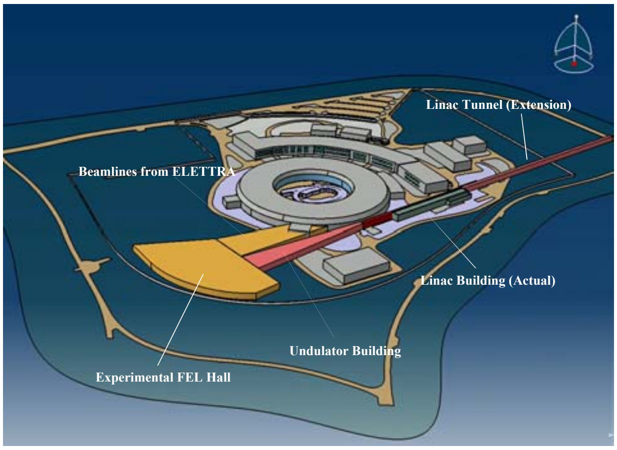

Figure 8: FERMI@ELETTRA anticipated lay-out.

A bird-view of the designed lay-out is presented in Fig.8, showing the X-ray FEL system in connection to the presently operated third generation synchrotron light source facility. The main electron beam parameters are listed in Table 4 for different phases of the project.

Table 4: Electron Beam Parameters

Wavelength (nm)	100,40,10	1.2
Beam Energy (GeV)	1.0	3.0
Bunch Charge (nC)	0.38	1.0
Peak Current (kA)	0.6	2.5
Norm. Emittance (μm)	2.0	2.0
Energy Spread (%)	0.05	0.05

Validation of these values is based on simulations [8] performed with ELEGANT. The anticipated performances of the radiation source at shorter wavelengths are reported in Table 5.

Table 5: Radiation Beam Parameters

Wavelength (nm)	10	1.2
Undulator Period (cm)	3.19	3.26
Undulator Parameter	1.18	1.24
Gain Length (m)	1.3	2.6
Peak Brightness (st. un.)	9.4×10^{29}	5.5×10^{31}
Average Bright. (st. un.)	2.9×10^{19}	1.1×10^{21}

In order to improve stability, reproducibility and temporal control of the radiation pulses, FEL seeding based on High Gain Harmonic Generation is anticipated at 40 and 10 nm. At 1.2 nm the development of a seeding scheme is under study: if not possible, SASE operation will be pursued. Major details are reported at this conference in Ref.8.

5 CONCLUSIONS

The Italian Government is expected to nominate soon an international committee to review the two proposals presented here, with final decision foreseen by this year. The design of an Italian Coherent X-ray Source should start in 2003 with the aim to deliver a TDR by the end of 2004.

6 ACKNOWLEDGEMENTS

We are indebted to many colleagues for the material provided and for many useful discussions: *C. Bocchetta, P. Dattoli, P. Emma, M. Ferrario, L. Giannessi, L. Palumbo, A. Renieri, C. Ronsivalle, C. Sanelli and C. Vaccarezza* .

7 REFERENCES

[1] M. Ferrario et al., *Homdyn Study for the LCLS RF Photoinjector* , in The Physics of High Brightness Beams, World Sci., ISBN 981-02-4422-3, June 2000
[2] L. Serafini and M. Ferrario, AIP CP 581, 2001, pag.87
[3] D.T. Palmer, PhD. Thesis, Stanford University
[4] M. Boscolo et al., *Beam Dynamics Study of RF Bunch Compressors for High Brightness Beam Injectors* , EPAC-2002 Proceedings
[5] L. Serafini et al., *A R&D Program for a High Bright. El. Beam Source at LNF* , EPAC-2002 Proceedings
[6] C. Ronsivalle, *private communication*
[7] C. Vaccarezza, *private communication*
[8] G. D'Auria et al., *The FERMI Project at Trieste: a Linac Based Bright Photon Source* , this conference