DESIGN STUDY OF A SOFT X-RAY SASE-FEL SOURCE

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Abstract

FEL's based on SASE (Self Amplified Spontaneous Emission) effect are able to generate coherent radiation with unique features. In principle the brilliance of the source is several order of magnitudes higher than the Synchrotron Radiation Sources of third generation, and it is possible to reach the x-ray spectrum region with ultra-short pulses of hundreds femto-seconds. This source is believed to be a powerful tool to explore the frontiers of basic sciences, from physics to chemistry to biology. Intense R&D programs have started in USA and Europe, in order to understand the SASE physics and to proof the feasibility of these sources. The allocation of considerable resources in the Italian National Research Plan (PNR) brought to the formation of a CNR-ENEA-INFN-"Tor Vergata" University study group. An R&D program (SPARC Project) at LNF has been recently approved and close to start while schemes of a soft-X rays source ranging from 1.5 to 13 nm (SPARX Project) have been investigated and proposed to the Italian Government.

1 SCIENTIFIC CASE

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 X-rays are the ideal probe for determining the structure on the atomic and molecular scale. The big step in the peak brilliance, several orders of magnitude, expected with the FEL-SASE 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 crystallography of macro-molecules with single pulses.

2 FEL-SASE SOURCE

Two spectral complementary regions around 13.5 nm and 1 nm, are considered for the source. In order to generate the SASE-FEL at these wavelengths, it is necessary to produce a high brilliance beam to inject inside two long undulators. A preliminary analysis of the beam parameters required for such a source leads to values reported in Table 1.

Table 1: Beam parameters

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

We envisage to use the same beam to feed two undulators whose characteristics are discussed in Table 2-3.

Table 2: Undulator characteristics (first undulator)

Undulator 1 – UM1	
Type	Halbach
Period	3 cm
K	1.67 (@ 1.5 nm)
Gap	12.67 mm (@ 1.5 nm)
Residual field	1.25 T

Table 3: Undulator characteristics (second undulator)

Undulator 2 – UM2	
Type	Halbach
Period	5 cm
K	4.88 (@ 13.5 nm)
Gap	12.16 mm (@ 13.5 nm)
Residual Field	1.25 T

As in all laser systems, the FEL-SASE signal starts from chaotic noise which is then amplified (exponential growth) and eventually saturates. Those three different phases are clearly shown in Figs. 1-2 concerning the generation of radiation at 1.5nm and 13.5nm respectively. The typical "steps" in the exponential rise are due to beam focusing regions where there are no undulators (and therefore the light beam is not amplified).

The characteristics of the FEL-SASE radiation up to the 5^{th} harmonics, have been investigated by means of several codes: GINGER, GENESIS, MEDUSA, PROMETEO, PERSEO, and the results are shown in Table 4.

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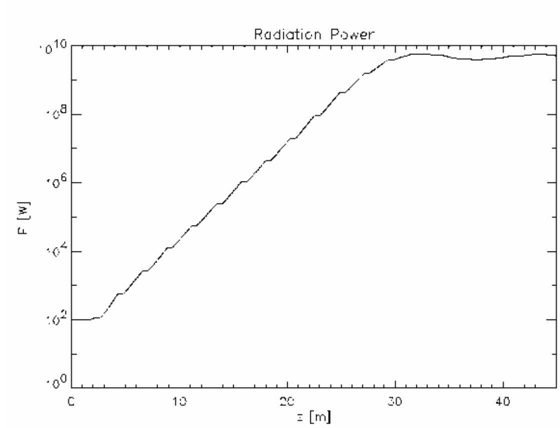

Figure 1: FEL signal evolution (λ=1.5 nm) along the undulator 1 (see Table 2).

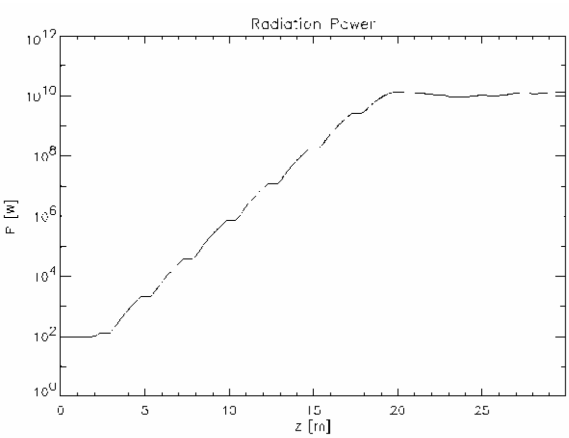

Figure 2: FEL signal evolution (λ=13.5 nm) along the undulator 2(see Table 3).

Table 4: 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 3rd harm.	2 10^{8} W	5 10^{9} W
Peak Power 5th harm.	3 10^{7} W	2 10^{8} W
Brilliance**	1.8 10^{31}	2 10^{32}
Brilliance** 3rd harm.	10^{29}	10^{31}
Brilliance** 5th harm.	9 10^{28}	3 10^{29}

With the two undulators it is possible to cover a bandwidth from 1.2nm to 13.5nm, with the first harmonic, and a bandwidth from about 0.4nm to 4nm, using the 3rd harmonic, which exhibits still a considerable peak power, as shown in Fig. 3.

It is worth noting that the spontaneous synchrotron radiation power emitted by the beam inside the two undulators is (at least) two orders of magnitude higher than in the 3rd generation light sources (see for example Fig. 4).

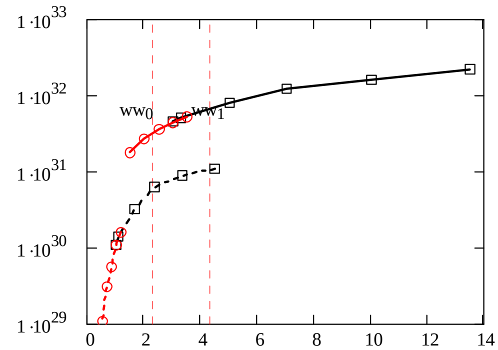

Figure 3: Brilliance** as a function of the λ (nm) at constant energy.

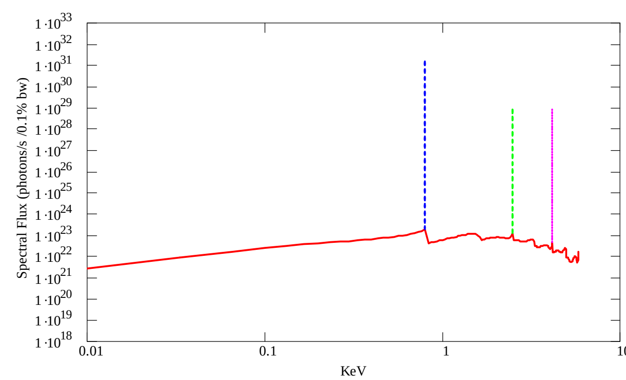

Figure 4: Spectral flux for three FEL harmonics compared to the synchrotron light contribution (see Table 2, 2.5 kA).

3. LINAC R&D AND LAY-OUT

The accelerator dedicated to the FEL-SASE source has the task of accelerating ultra-brilliant electron bunches up to the energy of 2.5 GeV. Given the charge Q in the bunch and the r.m.s. dimensions σ_x, σ_y, σ_z, the brilliance is defined as: $B_n = 2I/\varepsilon_n^2$, where $I= cQ/\sqrt{2\pi}\sigma_z$ is the peak current and $\varepsilon_n=\gamma\sigma_x\sigma_y$ the normalized emittance.

The nominal values for the proposed source are: energy E=2.5 GeV (γ=4892), peak current 2.5 kA, normalized emittance 2 µm, energy spread 0.1%. A beam with these characteristics hasn't yet been generated; however, it is believed to be achievable with the current R&D world-wide activity on photo-injectors and bunch compressor schemes.

A dedicated R&D program (SPARC project) is envisaged at LNF-INFN, in collaboration with CNR and ENEA. Its aim is the generation of electron beams with ultra-high peak brightness and the generation of resonant higher harmonics in the SASE-FEL process. The proposed scheme (Fig. 5) consists of a RF gun operated at

** The brilliance is given in photons/sec/0.1%bw/(mm mrad)^2

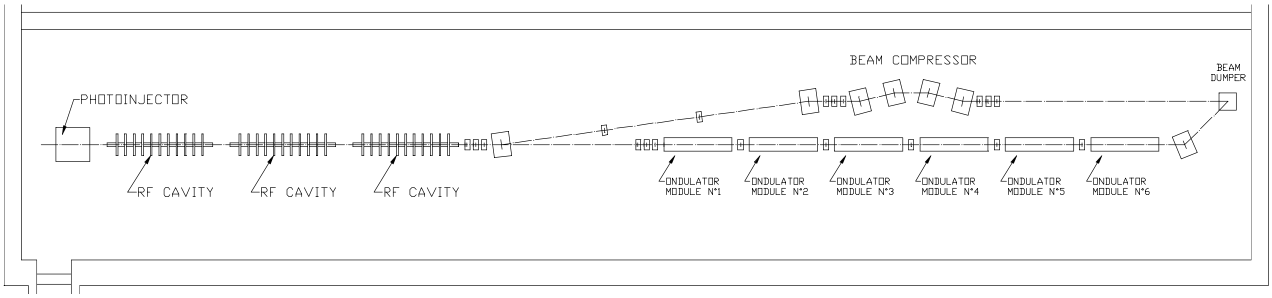

Figure 5: Schematic layout of SPARC R&D project

S-band (2.856 GHz) and high peak field on the cathode (120-140 MeV/m) with incorporated metallic photo-cathode (Copper or Mg), generating a 6 MeV beam which is properly focused and matched into 3 accelerating sections of the SLAC type (S-band, travelling wave).

The peak current will be in excess of 150-200 A and will drive a SASE-FEL experiment at 520 nm, performed with a 12m undulator following the linac. The normalised emittance and the peak beam current along the injector are shown in Fig. 6. The project has been approved by the Italian Government and expected to be founded soon.

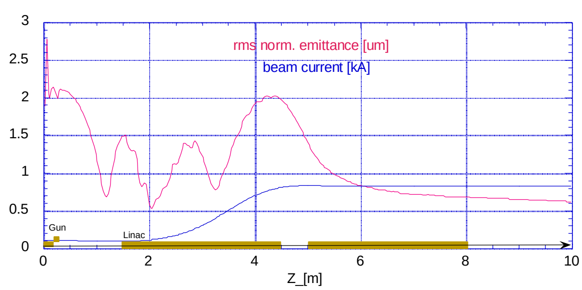

Figure 6: Beam current and normalised transverse emittance along the injector (with RF compression).

The soft X-ray project, SPARX, has been recently proposed with the schematic layout given in Fig.7. After the SPARC injector, a first 60m long accelerating section will accelerates the beam up to 1 GeV, before entering in a magnetic bunch compressor to increase the current intensity (Fig. 7). The last 90 m section will then produce the 2.5 GeV beam to be injected in the undulators. The beam parameters evolution along the whole SPARX machine is shown in Fig. 8.

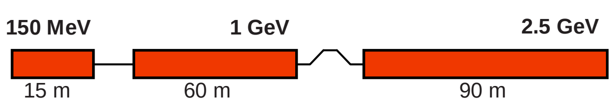

Figure 7: Linac scheme of SPARX project.

4 CONCLUSIONS

A coherent soft X ray source based on the FEL-SASE mechanism, is of great interest for many fields of applications, from basic science to industrial and medical applications. A study group gathering researchers from the major Italian research institutions (CNR, ENEA, INFN) started a conceptual design of such a source. The conceptual design was proposed to the Italian

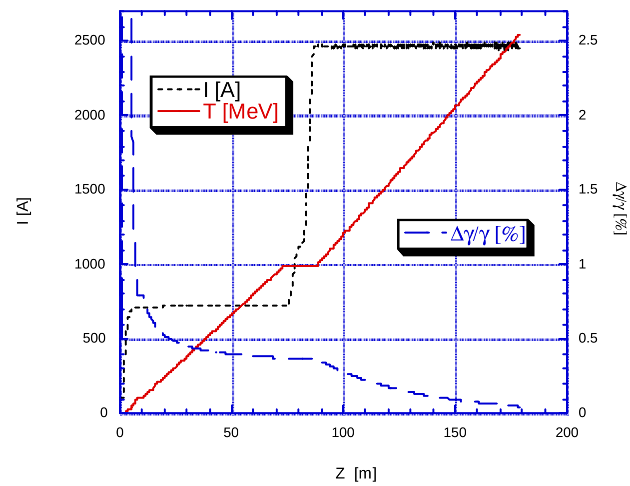

Figure 8: Beam parameters along the SPARX machine.

Government following a call for proposals issued in December 2001. The source will consist of a high brilliance photo-injector optimised for the production of very low emittance (2 μm) beams at150 MeV, and whose first accelerating section is used as RF bunch compressor,able to reach a peak current of the order of 700-800A. The R&D program for such an injector (SPARC) has already been approved and it is expected to be funded soon. After the injector, two Linacs and a magnetic compressor at 1 GeV allow a high peak current and a high quality beam, to reach the energy of 2.5 GeV. The beam is then injected into two undulators in order to generate FEL-SASE radiation (from 1.5 to 13 nm). Eventually five radiation lines bring the radiation inside an experimental area. The proposed site is the campus of the University of Rome "Tor Vergata".

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6 REFERENCES

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