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Conceptual design of a high-brightness linac for soft X-ray SASE-FEL source

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Abstract

FELs based on SASE are believed to be powerful tools to explore the frontiers of basic sciences, from physics to chemistry to biology. Intense R&D programs have started in the USA and Europe in order to understand the SASE physics and to prove the feasibility of these sources. The allocation of considerable resources in the Italian National

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Research Plan (PNR) brought about the formation of a CNR–ENEA–INFN–University of Roma "Tor Vergata" study group. A conceptual design study has been developed and possible schemes for linac sources have been investigated, leading to the SPARX proposal. We report in this paper the results of a preliminary start to end simulation concerning one option we are considering based on an S-band normal conducting linac with high-brightness photoinjector integrated in an RF compressor.

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Keywords: High-brightness beams; Soft X-ray FEL

1. The SPARX proposal

Driven by the large interest that X-ray SASE FEL's light sources have raised world-wide in the synchrotron light scientific community, as well as in the particle accelerator community and following solicitations arising from several Italian national research institutions, the Italian Government launched in 2001 a long-term initiative devoted to the realization in Italy of a large-scale ultra-brilliant and coherent X-ray source. The allocation of considerable resources in the Italian National Research Plan (PNR) brought about the formation of a CNR–ENEA–INFN–University of Roma "Tor Vergata" study group. A conceptual design study has been developed and possible schemes for linac sources have been investigated leading to the SPARX proposal.

Two spectral complementary regions around 13.5 and 1.5 nm, are considered for the radiation source. In order to generate the SASE-FEL at these wavelengths, it is necessary to produce a high-brightness 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.

We report in the next sections the results of a preliminary start-to-end simulation concerning one option we are considering based on an S-band normal conducting linac.

The basic scheme is shown in Fig. 1 and consists of an advanced high-brightness photoinjector followed by a first linac that drives the beam up to 1 GeV with the correlated energy spread required to compress the beam in a subsequent magnetic chicane. The second linac drives the beam up to 2.5 GeV while damping the correlated energy spread taking profit of the effective contribution of the longitudinal wake fields provided by the S-band accelerating structures. A peculiarity of this linac design is the choice to integrate a high-brightness photoinjector in a rectilinear RF compressor, as recently proposed [1], thus producing a 300–500 A beam in the early stage of the acceleration. The potentially dangerous choice to compress the beam at low energy (<150 MeV) when it is still in the space charge dominated regime, turns out not to be a concern provided that a proper emittance compensation technique is adopted [2], a possibility that is not viable in a magnetic chicane. In addition, the propagation of a shorter bunch in the first linac reduces the potential emittance degradation caused by transverse wake fields, and longitudinal wake fields can be controlled by a proper phasing of the linac.

Table 1
Electron beam parameter

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	%

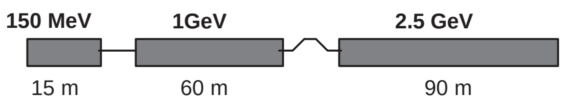

Fig. 1. Linac scheme of SPARX project.

2. High-brigthness photoinjector with RF compressor

The injector preliminary design considers a 1.6 nC bunch 10 ps long (flat top) with 1.2 mm radius, generated inside a 1.6-cell S-band RF gun of the same type of the BNL-SLAC-UCLA one [3] operating at 140 MV/m peak field equipped with an emittance compensating solenoid. Three standard SLAC 3-m TW structures, each one embedded in a solenoid, boost the beam up to 150 MeV. With a proper setting of accelerating sections phase and solenoids strength, applying the compression method described in Ref. [2], it is possible to increase the peak current preserving the beam transverse emittance. In the present case, we have got with PARMELA simulation a bunch average current of 440 A with a normalized rms emittance below 1 mm mrad. The low compression ratio (a factor of 3) has been chosen to keep the longitudinal emittance as low as possible in order to simplify the second compression stage. We used the first two TW sections as compressor stages in order to achieve a gradual and controlled bunching, the current has to grow about at the same rate of the energy, and we increased the focusing magnetic field during the compression process. An optimized RF compressor parameters set is reported in Table 2.

Fig. 2 (above) shows the current growth during bunch compression until 150 MeV, envelope and emittance evolution are also reported (below), showing the emittance compensation process driven by the solenoids around the accelerating section that keep the bunch envelope close to an equilibrium size during compression [2].

A dedicated R&D program (SPARC project [5]) is envisaged at LNF-INFN in collaboration with CNR–ENEA–INFM–ST–Tor Vergata University.

Table 2
RF compressor parameters

TW section	I	II	III
Gradient (MV/m)	15	25	25
Phase (deg.)	−88.5	−67	0 (on crest)
Solenoid field (G)	1120	1400	0

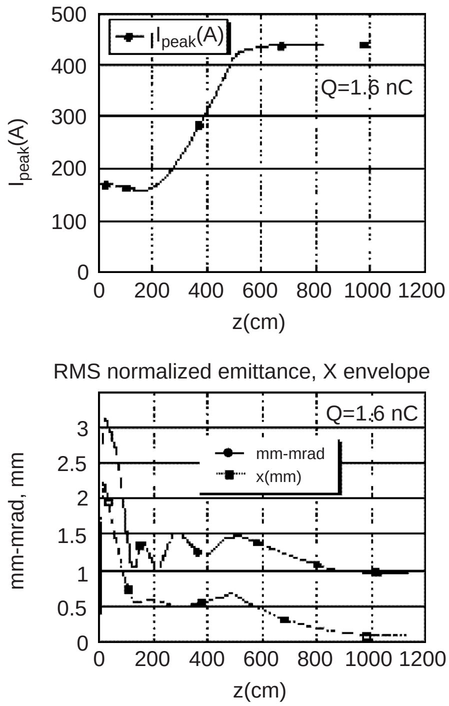

Fig. 2. Rms current (above), rms norm. emittance and rms beam envelope (below) along the injector, up to 150 MeV.

Its aim is the generation of electron beams with ultra-high peak brightness to drive a SASE-FEL experiment at 520 nm, performed with a 12 m undulator after the linac.

3. The linac

The accelerator dedicated to the FEL-SASE source has the task of accelerating high-brightness electron bunches up to the energy of 2.5 GeV including a second compression stage. Linac1 consists of 15 S-band TW structures, operating at 20 MV/m and the beam is propagated 20° off crest. In Linac2, additional 24 accelerating structures are foreseen with the same gradient and the beam is propagating on crest. The beam optics consists in a FODO lattice. The nominal values for the proposed source have been reported in Table 1.

The 10 k macro-particles beam generated by PARMELA has been propagated through Linac1,

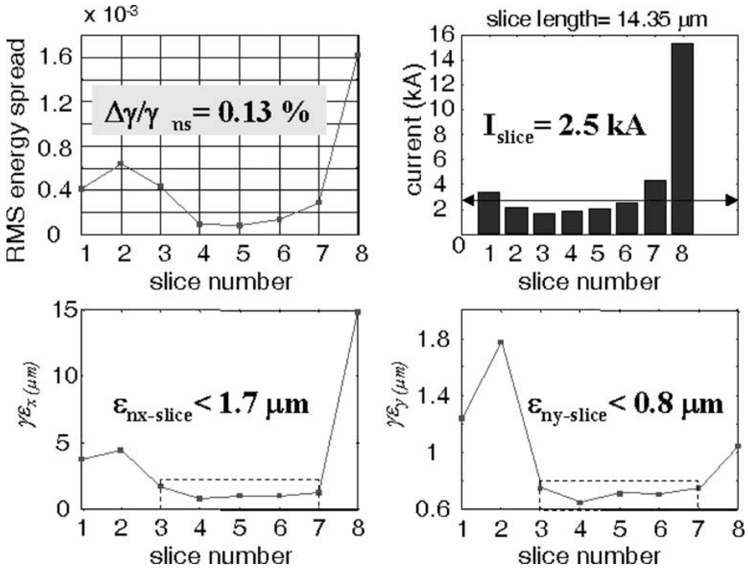

Fig. 3. Energy spread, peak current and transverse emittances along the bunch.

Magnetic Compressor and Linac2 with the code ELEGANT. The correlated energy spread induced by Linac1 is 0.6% in order to compress the beam by a factor of 6 in the 15 m-long magnetic chicane with an $R_{56} = 48$ mm. At the exit of Linac2, the required parameters for FEL operation have been achieved over more than 50% of the bunch length, as shown in Fig. 3.

A further improvement is expected by fully optimizing the compression scheme and by using a fourth harmonic cavity [4] for the linearization of the longitudinal phase space distribution.

4. The FEL-SASE source

We envisage using the same beam to feed two undulators whose characteristics are reported in Table 3. The characteristics of the FEL-SASE radiation up to the fifth harmonics, have been investigated by means of several codes: GINGER, GENESIS, MEDUSA, PROMETEO, PERSEO, and the results are shown in Table 4 and Fig. 4.

With the two undulators, it is possible to cover a bandwidth from 1.2 to 13.5 nm, with the first harmonic, and a bandwidth from about

Table 3
Undulators characteristics

	Undulator 1 at 1.5 nm	Undulator 2 at 13.5 nm
Type	Halbach	Halbach
Period	3 cm	5 cm
K	1.67	4.88
Gap	12.67 mm	12.16 mm
Residual field	1.25 T	1.25 T

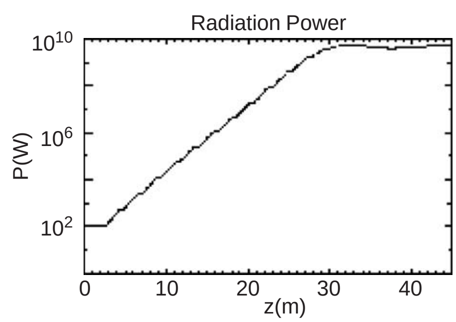

Fig. 4. FEL signal evolution ($\lambda = 1.5$ nm) along undulator 2. The typical "steps" in the exponential rise are due to beam focusing regions where there are no undulators.

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 3° harm.	2×10^{8} W	5×10^{9} W
Peak power 5° harm.	3×10^{7} W	2×10^{8} W
Brilliance[a]	1.8×10^{31}	2×10^{32}
Brilliance* 3° harm.	10^{29}	10^{31}
Brilliance* 5° harm.	9×10^{28}	3×10^{29}

[a] The brilliance is given in photons/s/0.1% bw/(mm mrad).

0.4–4 nm, using the third harmonic, which exhibits still a considerable peak power, as reported in Table 4.

Time-dependent FEL simulations, performed using the particle distributions produced by the start-to-end simulations presented in the previous section, are in progress, showing saturation for 50% of bunch slices after 30 m of active undulator length. These first preliminary results are encouraging and will be the starting point for further optimizations.

5. Conclusions

A preliminary start-to-end simulation of the SPARX proposal has been presented. The possibility to integrate an RF compressor into a linac for FEL application has been investigated for the first time. The 1 nC case with 120 MV/m peak field on the gun is also under investigation.

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