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PRELIMINARY SIMULATIONS OF THE SPARX FEL

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Abstract

In this note we collect the results of preliminary simulations of a free electron laser (FEL) operating in self amplified spontaneous emission (SASE) and seeded configurations. The layout is compatible with the DAΦNE injector linac and the SPARC undulator. The simulations are devoted to provide a general view of the characteristics of the radiation which may be obtained with the SPARX experiment.

Introduction

In a previous note, the possibility of operating the DAΦNE injector linac as the driver of a SASE FEL experiment with the SPARC undulator was investigated [1]. A saturation length of about 15m at the wavelength of 10nm was found but an extensive analysis of the tunability range and of the main properties of the radiation was not given. In this note we extend the analysis to a series of different cases based on SASE and seeded schemes. The simulations are mainly devoted to give an overview of the properties of the radiation which may be obtained in a FEL experiment as SPARX and are not the result of an optimization procedure. In particular, it must be noted that similar results should be obtained with a different undulator than the one considered. This configuration, based on non-homogeneous undulator sections with different period lengths, should provide better flexibility, shorter saturation length in the water window spectral region, and should be better suited for a *seeding* scheme devoted to obtain shorter pulses and improved temporal coherence. The e-beam parameters used in the simulations are listed in Tab. I.

Tab I. *E-beam parameters*

Energy	1.0 – 1.4	GeV
Peak current	2	kA
Energy Spread	0.08	%
Emittance	1	mm mrad
Bunch Charge	1	nC
Rep. Rate	10	Hz

For what concerns the undulator magnets, it has been considered a SPARC-like undulator, which can be obtained by adding SPARC undulator sections to the six sections under construction [2] (Tab. II).

Tab. II. *Undulator Parameters*

Period	2.8	Cm
K	1.1 – 2.5	

The simulations have been carried out with PERSEO [3] in *steady state* and *time dependent* mode. The FEL source is continuously tunable in the range 15nm - 3 nm by varying the electron beam energy between 1.0 and 1.4 GeV and by changing the undulator strength K. The simulations have been performed at the wavelengths 15nm, 10nm, 5nm and 3nm.

A sketch of the laser beam temporal structure is shown in Fig. 1.

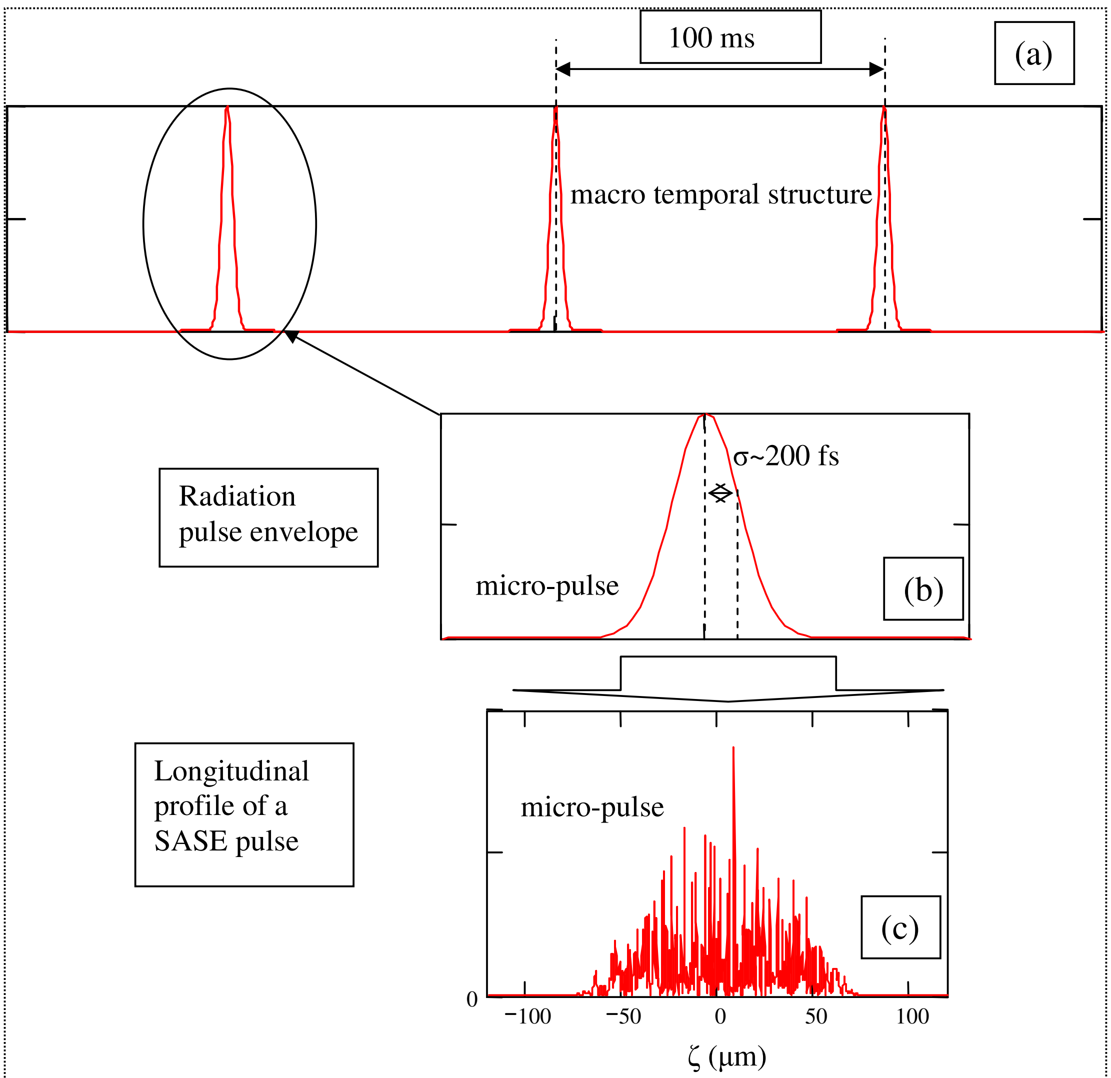

Fig. 1. *Temporal profile of the radiation generated by the FEL source The specific example shown in fig. 1.c corresponds to a simulation in time-dependent mode at 5 nm and 1.4 GeV of beam energy.*

The micro-pulse shown in Fig.1,b represents the envelope of the radiation pulse, which is constituted by a series of uncorrelated spikes of length < 1μm (Fig. 1.c). Apart from the micro-pulse length and its profile detail in Fig. 1.c (relevant to a *SASE* pulse at 5 nm), which may depend on the wavelength and on the SASE/seeded configuration, the pulsed structure of Fig. 1 is common to all the analysed configurations.

SASE mode

A summary of the simulation results in SASE mode is listed in Tab. III. The radiation beam cross section has been estimated as equivalent to the e-beam cross section. It has been assumed that the e-beam is transported along the undulator with a Twiss matching parameter $\beta=4.5m$ in all the configurations. A detailed analysis of the transport beam-line and of the specific *matching* conditions for these configurations will be the subject of forthcoming work. The saturation lengths shown in Tab.III refer to the effective magnetic length of the undulator. The physical dimension of the overall undulator will be larger once the gaps between the undulator segments and their possible detrimental effect on the gain and the gain length will be considered.

Tab. III – *Summary of the simulations results.*

Wavelength (nm)	3	5	10	15
Beam Energy (GeV)	1.4	1.4	1.0	1.0
UM Strength K	1.1	1.83	1.86	2.49
Sat. Length (m)	36	18	15	13
Pulse Energy (mJ)	1	1.9	1.7	2
Peak Power (GW)	4	7	5	9
Peak Power Dens. (GW/cm^2)	4 10^4	7 10^4	5 10^4	6 10^4
Beam size @ saturation (r.m.s. μm)	40	40	50	50
Bandwidth (%)	0.15	0.22	0.3	0.4
1st order coherence length (μm)	0.7	0.9	1.5	2
Pulse length (r.m.s. fs)	100	120	130	130
Flux (Phot./s/0.1%bw)	4 10^{25}	9$10^{25}$	1.5 10^{26}	2 10^{26}
Brightness (Phot/s/0.1%bw/(mm-mrad)^2)	3 10^{30}	8 10^{30}	7 10^{30}	1 10^{31}
Shot to Shot power fluctuations (%)	12	14	16	18

In Fig. 2 the pulse shape and the spectrum of the radiation pulse at 15 nm are shown. The plots are relevant to a longitudinal position z = 15.2 m, in fully saturated conditions. In SASE mode the FEL radiation is the result of the amplification of the e-beam shot noise and is characterized by the presence of a large number of peaks with typical duration corresponding to the coherence length (see Tab. III). In this regime the power has shot to shot fluctuations as indicated in the last row of Tab. III.

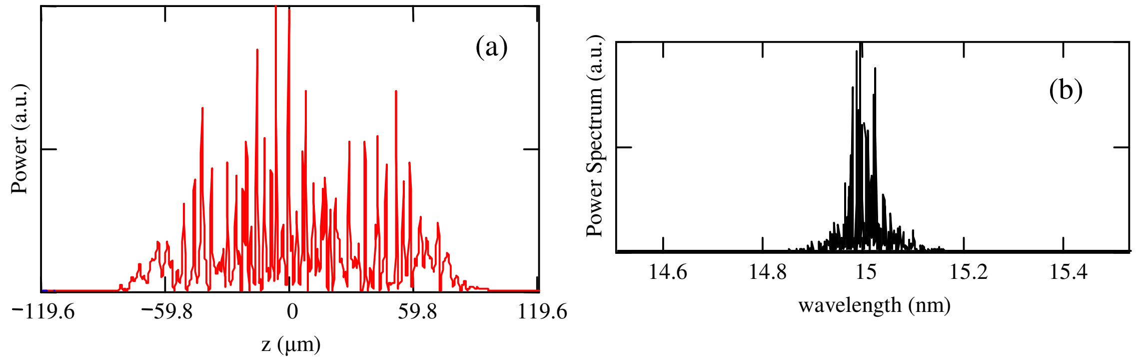

Fig. 2. *Spatial (a) and spectral (b) pulse shape of the SASE radiation pulse at 15 nm.*

Seeded mode

The shot-to-shot fluctuations and the temporal coherence of the FEL can be improved by injecting a seed in the amplifier. In these conditions the shot-to-shot fluctuations are determined by the stability and the coherence of the input source. We have repeated the simulation at 15 nm by injecting a seed with Gaussian profile, rms length of 20 fs. The seed energy is 2.7 nJ, corresponding to a peak power of 50 kW. Such a source may be realized with the mechanism of the high order harmonic generation in gas jet (HHG) [4] and an experimental test of this scheme is under development at SPARC [5]. In Tab. IV a list with the main characteristics of the seeded FEL is shown.

Tab. IV *Main parameters of the seeded FEL at 15nm. Note that the flux and the brightness are given in 0.01% of the bandwidth instead of 0.1% as in Tab. III, because in the seeded regime the linewidth is much narrower than in SASE mode, and it is narrower than 0.1%.*

Wavelength (nm)	15
Beam Energy (GeV)	1.0
UM Strength K	2.49
Sat. Length (m)	9
Pulse Energy (mJ)	0.7
Peak Power (GW)	20
Peak Power Dens. (GW/cm^2)	$1\ 10^5$
Beam size @ saturation (r.m.s. μm)	50
Bandwidth (%)	0.04
1^{st} order coherence length (μm)	10
Pulse length (r.m.s. fs)	30
Flux (Phot./s/0.01%bw)	$4\ 10^{26}$
Brightness [Phot/s/0.01%bw/$(mm\text{-}mrad)^2$]	$2\ 10^{31}$
Shot to Shot power fluctuations (%)	-

According to the parameters listed in Tab. IV we notice that:

1. The energy per pulse is lower than in SASE mode (Tab. III). In seeded mode only a portion of the e-beam is efficiently used for light amplification.
2. The saturation length is substantially reduced with respect to the SASE regime.

3. The peak power, as well as the brightness and the flux are higher. The FEL process is more efficient in extracting energy from the e-beam in the seeded region.
4. The coherence length has increased by a factor 10. This parameter is related to the coherence properties of the seed. In this numerical example a fully coherent seed has been assumed and the FEL pulse is close to the Fourier limit. This is confirmed by the shape of the radiation pulse and the spectrum as shown in Fig.3. The plots refer to a longitudinal coordinate along the undulator of 9.2 m, at saturation.
5. The flux and the brightness have been calculated in 0.01% of the bandwidth instead of 0.1% as in Tab. III. In the seeded regime the line-width is much narrower than in SASE mode, and it is narrower than 0.1%.
6. Shot-to-shot fluctuations have not been calculated. In seeded mode they depend on a series of factors as stability of the e-beam and of the seed-sources that it is not possible to analyse in this overview. However these sources of shot-to-shot fluctuations exist also in SASE regime. In seeded mode there are not intrinsic fluctuations associated to the electronic shot noise as in SASE.

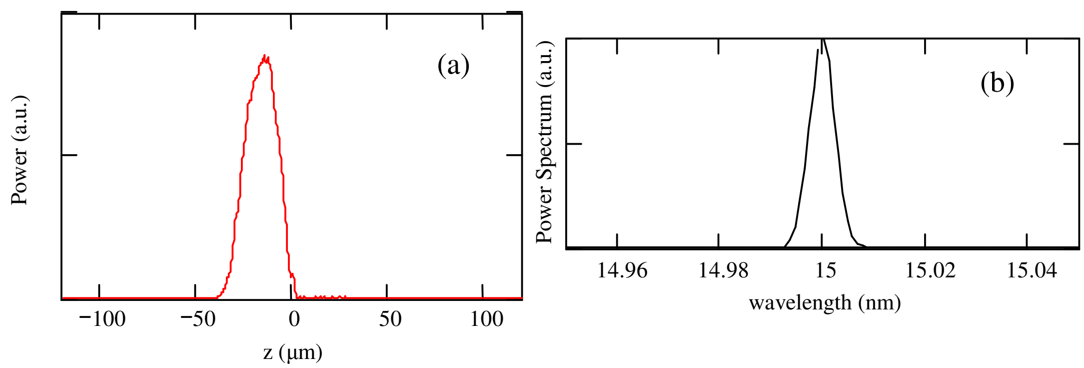

Fig. 3. Spatial *(a) and spectral (b) profile of the laser pulse at the wavelength of 15nm in seeded regime. The longitudinal coordinate along the undulator is 9.2 m, corresponding to the saturation of the seeded portion of the beam.*

The seeded configuration exhibits a number of advantages with respect to SASE, mainly in terms of stability and coherence. In order to be effective the seeding scheme, it is however necessary to seed with a sufficient power. At the short wavelength of the SPARX operating range (3nm - 7nm), the available seed power decreases and becomes comparable to the spontaneous emission which is responsible of the spiky behaviour of the SASE FEL. When this happens the advantages of seeding are lost [6]. An alternative is that of configuring the FEL with a first section which operates as a non-linear e-beam harmonic modulator, in order to generate a suitable seed pulse on the 3rd or 5th harmonic. With this scheme it is possible to extend the improvements of seeding to the shorter wavelengths down to the water window.

By exploiting a particular cascade scheme [7] it is also possible to generate ultrashort pulses. An example is given by the parameters listed in Tab. V.

Tab. V – *Parameters relevant to the last stage of a FEL cascade in superradiant regime.*

Wavelength (nm)	5
Beam Energy (GeV)	0.8
Pulse Energy (μJ)	5
Peak Power (GW)	3
Bandwidth (%)	0.04

Pulse length (r.m.s. - fs)	0.6

The scheme is based on a particular property of the superradiant pulse propagation in FELs, and will be studied in the future with practical example. The pulse energy is reduced with respect to SASE mode or standard seeded mode, but the result is the generation of extremely short radiation pulses (< 1fs, r.m.s.) in the soft x-ray region of the spectrum.

References

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