SINGLE SPIKE RADIATION PRODUCTION AT SPARC

V. Petrillo, Università di Milano, Milano, Italy
A.Bacci, L.Serafini, INFN, Milano, Italy
M. Boscolo, M. Ferrario, C. Vaccarezza, LNF, INFN, Frascati, Italy
G..Dattoli, L. Giannessi, M.Labat, C. Ronsivalle, ENEA, Frascati, Italy
S.Pagnutti, P. Ottaviani, ENEA, Bologna, Italy
L. Palumbo, M. Serluca, Università La Sapienza, Roma, Italy

Abstract

We describe a possible experiment aimed at generating sub-picosecond high brightness electron bunches with the SPARC photoinjector, which produce optical single spike radiation pulses in the regime of self-amplified spontaneous emission. The main purpose of the experiment is the production of short electron bunches as long as few SASE cooperation lengths by means of the Velocity Bunching technique. The measure of the properties of the electron beam, the determination of shape and spectrum of the radiation pulse and the validation of the single spike scaling laws will be analysed in order to foresee future operations at shorter wavelength with SPARX. We present in this paper start-to-end simulations of the beam production and FEL performance, statistical analysis and behaviour on the harmonics. The experience gained from this experiment will help in the configuration of the VUV and X-ray FEL SPARX to obtain FEL pulses below 10 fs.

INTRODUCTION

In the FEL emission two different regimes occur depending on the length L_b of the beam.

If the L_b is larger than 2π times the cooperation length L_c, the radiation presents a longitudinal structure constituted by several chaotic peaks, while, if the length of the beam is shorter than $2\pi L_c$, the radiation pulse is shaped in one single spike [1]. The properties of this regime are well-known in 1d: however, the study of single-spike ultra short radiation in the X rays range [2], as well as in the visible light [3], by means of start-to-end simulations from the photocathode to the end of the undulator, has shown that three-dimensional effects due to radiation diffraction and to non–ideal characteristics of the electron beam, i.e. emittance and energy spread, change considerably the properties of the emission process. A fundamental problem is also how to produce a suitable beam. We present first a one-dimensional analysis that shows the behaviour of the radiation on the harmonics. Then we present some numerical start-to-end FEL simulations made for realistic set of parameters in the case of the SPARC FEL, for some different beam with charge from 100 to 500 pC and energy from 100 to 150 MeV, and with different matching conditions. The performance of the various bunches are compared and the most interesting of them are discussed. Finally we show the shot to shot statistical properties of the radiation.

SCALING LAW

The single spike operation requires that the beam length L_b satisfies the following requirement:

$$L_b \le 2\pi L_c \tag{1}$$

with $L_c=L_{c1d}(1+\eta)$

where: $L_{c1d}=\lambda/(\sqrt{3}\,4\pi\rho)$ and η is defined as in [4] :

$$\eta = 0.45\eta_d^{0.57} + 0.55\eta_\varepsilon^{1.6} + 3\eta_\gamma^{2} + 0.35\eta_\varepsilon^{2.9}\eta_\gamma^{2.4} + 51\eta_d^{0.95}\eta_\gamma^{3} + 5.4\eta_d^{0.7}\eta_\varepsilon^{1.9} + 1140\eta_d^{2.2}\eta_\varepsilon^{2.9}\eta_\gamma^{3.2}, \tag{2}$$

with $\eta_d = L_{g1d}\lambda/(4\pi\sigma_x^2)$ term that accounts for radiation diffraction, $\eta_\varepsilon = \frac{4\pi L_{g1d}\varepsilon_{n,x}^2}{\sigma_x^2\gamma^2\lambda}$ for the emittance and $\eta_\gamma = 4\pi\frac{L_{g1d}}{\lambda_u}\frac{\delta\gamma}{\gamma}$ for the energy spread effects. In these last expressions $L_{g1d}=\lambda_u/(\sqrt{3}\,4\pi\rho)$ is the 1d gain length, $\varepsilon_{n,x}$ the normalized transverse emittance, $\delta\gamma/\gamma$ the energy spread and λ is the radiation wavelength given by the resonance condition $\lambda = \frac{\lambda_u(1+a_w^2)}{2\gamma^2}$.

The FEL parameter ρ, in terms of the beam average current I, of the radial r.m.s dimension σ_x of the beam, of the undulator parameter $K_0=\sqrt{2}\,a_w$ and period number $k_u=2\pi/\lambda_u$, of the Lorentz factor of the beam γ can be written as:

$$\rho = \left[\frac{1}{16}\frac{I}{I_A}\frac{K_0^2[JJ]^2}{\gamma^3\sigma_x^2 k_u^2}\right]^{1/3} \tag{3}$$

where I_A=17 KA is the Alfven current and JJ $=(J_0(\xi)-J_1(\xi))$, J's are Bessel function of argument $\xi = \frac{a_w^2}{2(1+a_w^2)}$.

In (3) the current I is defined as $I=cQ/L_b$ with L_b the whole beam length if the beam current is flat top, or

$L_b=\sqrt{2\pi}\sigma_z$ with σ_z the r.m.s. length, if the longitudinal beam profile is Gaussian.

The single spike condition is:

$$L_b=2\pi L_{c1d}\,(1+\eta) \qquad (4)$$

and the Q vs L_b scaling law becomes

$$Q=\left(\frac{\pi^2 I_A}{3\sqrt{3}c}\right)\left(\frac{\lambda_u(1+a_w^2)^3}{K_0{}^2[JJ]^2}\right)\left(\frac{\sigma_x^2}{L_b^2\gamma^3}\right)(1+\eta)^3 \qquad (5)$$

where the factor η contains a further irrational dependence on I.

The number of spikes in the radiation pulse is:

$$N_s=L_b/(2\pi L_{c1d}(1+\eta)) \quad . \qquad (6)$$

OPERATION AT 300-500 pC, 100-130 MeV

In the SPARC operation, the electron bunch is compressed by means of the technique of the velocity bunching. As the electron beam enters the sections of the linac not in crest, the final energy of the beam is in general lower than the nominal value of 150 MeV. Furthermore, the control of the emittance is easier for beams with charge smaller than the nominal value of 1 nC. We have therefore considered beams with energies of about 120 MeV, with charge from 300 to 500 pC. The compression factor has been limited to 3-3.5 for a FWHM length of the beam of 110-170 μm. The emittance is 1.5-3 μm and the total energy spread is around 1%. We have changed the undulator parameter a_w in order to vary the wavelength.

With all these quantity fixed, one can obtain the transition from the multiple to single spike regime by varying the matching of the beam to the undulator and the quadrupole magnetic field that rule the value σ_x at the entrance and along the propagation in the wiggler. In this way the gain and cooperation lengths increase and the number of spikes gets lower.

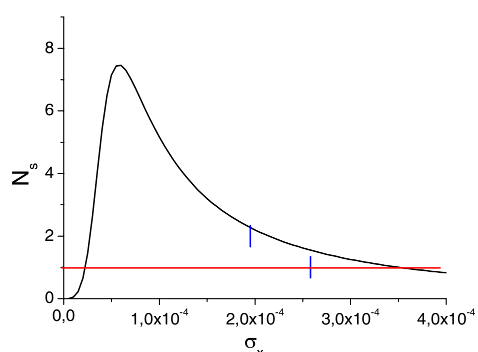

Figure 1: N_s vs σ_x for Q=500pC, ε_x=2 mm mrad, $\Delta\gamma/\gamma$=0.38%.

In Fig 1, the number of spikes N_s is shown as function of σ_x for Q=500pC, ε_x=2 mm mrad, $\Delta\gamma/\gamma$=0.38%, λ=500 nm. As can be seen the single spike condition can be achieved with a value of σ_x of the order of 400 μm.

Several different beams have been simulated in the case of the beam line and undulator of SPARC [5] by scaling the parameters from the 1 nC working point by means of the scaling law at the cathode $\sigma_{xyz}\sim Q^{1/3}$ [6], and using a laser pulse length of σ_t=1 psec, illuminating a region of R=0.4 mm. The compression of the beam has been done by means of the technique of the velocity bunching. All the simulations have been made by means of the code PARMELA [7].

In table I, the main parameters of two examples of the beams studied are reported.

Table 1: Parameters of some of the Beam Studied

Q pC	**Energy MeV**	**$\varepsilon_{x,n}$ μm**	**$\Delta\gamma/\gamma$ %**	**C**	**σ_z, μm**	**I_{peak} kA**
300	121.6	1.7	1.	3.5	162	300
500	121.6	2.7	1.2	3.4	126	500

Table 2: a_w, λ (nm), σ_x. Radiation properties: N_{sp}: Number of radiation spikes, P_{max}: Maximum power (MW), E: Total energy, $\sigma^{z,}{}_{rad}$: Radiation length, b_w: Normalized bandwidth

Q (pC)	**a_w**	**λ (nm)**	**σ_x μm**	**N_{sp}**	**P_{max} MW**	**E μJ**	**$\sigma^{z,}{}_{rad}$ μm**	**b_w %**
300	1.3	680	100	1	20	4	55	1
500	1	515	95	1	48	10.4	44	1

We analyse first the case at 500 pC. Its phase space together with the current profile I (A) vs z (μm) are presented in Fig 2.

In Fig. 3 the slice emittance ε_x and ε_y (left axis) and the slice energy spread $\Delta\gamma/\gamma$ are shown along the beam coordinate t (s).

The beam has been injected in the undulator of SPARC to produce radiation. The radiation simulations have been made by uploading the electron phase spaces in GENESIS 1.3 [8].

We have achieved the single spike condition by varying the transverse dimension inside the undulator. This can be done by managing the current in the focussing quadrupoles placed in the drifts between the sections of the undulator for reaching the right transverse dimension of the electron beam. In Fig 4 two different transports of the beam at 500 pC are reported. The red curve represents the transverse dimension σ_x vs z with the field of the quadrupoles set at dB/dz=5 T/m, for the blue one, instead, dB/dz=1.7 T/m. The average value of $R=(\sigma_x{}^2+\sigma_y{}^2)^{1/2}$ along the line is 195 μm in the first case, while R=258 μm for the second. The number of spikes obtained in these cases is reported in Fig 1 with vertical lines and shows that the single spike condition requires σ_x>300 μm.

The main characteristics of the radiation are presented in table 2.

The total energy of the radiation at the end of the undulator is 10.4 μJ.

In Fig 5 radiation pulse and spectrum at the end of the undulator are shown.

In Fig 6 the phase space and the current of a second case at Q=300 pC is shown.

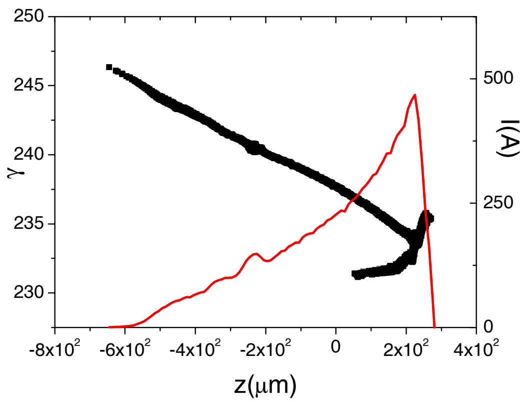

Figure 2: Left axis: γ vs t. Right axis: Current I (A) vs z (μm) for Q=500 pC and E=121.6 MeV.

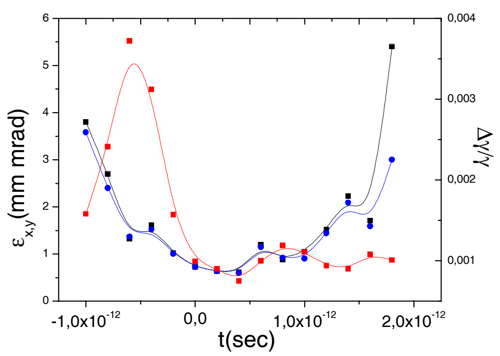

Figure 3: Left axis: Slice transverse emittance ε_x and ε_y (in mm mrad) along the beam vs t (sec). Right axis: Normalized energy spread Δγ/γ for 500 pC and 121.6 MeV.

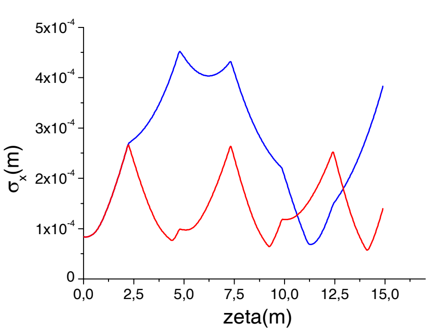

Figure 4: Q=500, E=121.6 MeV. Red curve:σ_x vs z for dB/dz=5T/m, Blue curve: dB/dz=1.7T/m.

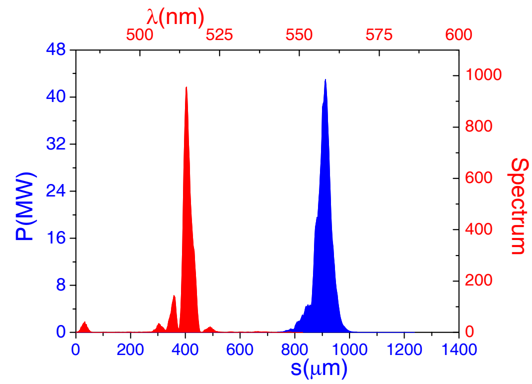

Figure 5: blue: pulse shape P (MW) vs s(μm) at z= 14 m. Red curve: spectrum vs λ(nm) for Q= 500 pC, E=121.6MeV, dB/dz=1.7 T/m.

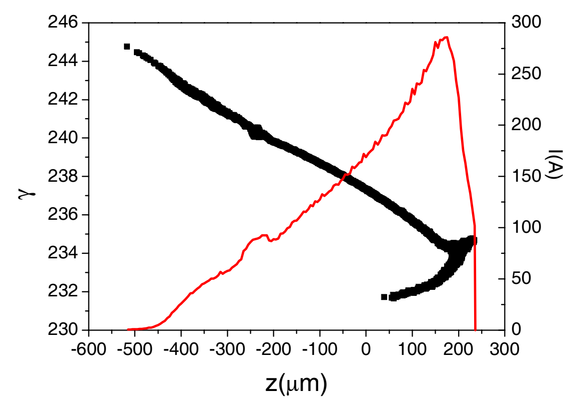

Figure 6: Left axis: γ vs z. Right axis: Current I (A) vs z for Q=300 pC and E=121.6 MeV.

Beam and radiation properties are presented in Table I and II. In the case at 300 pC the radiation wavelength is 680 nm, obtained with aw=1.3. The quadrupoles have been set at 2 T/m. The shape of the radiation is single spiked, the maximum power is 20 MW and the total energy is 4 μJ.

STATISTICAL ANALYSIS

The radiation in the single spike regime is strongly affected by shot to shot fluctuations.

We have performed a statistical analysis by changing the seed in the random generator of the particle phase space. For the case at 300 pC, the radiation shape at the end of the undulator is shown in fig 8, while the distribution in energy is shown in fig 7. The data relevant to both cases at 300 and 500 pC are presented in Table III, where the average value of the energy, the most probable value, the FWHM dispersion and the r.m.s dispersion and the dispersion value obtained by a Gaussian fit are shown.

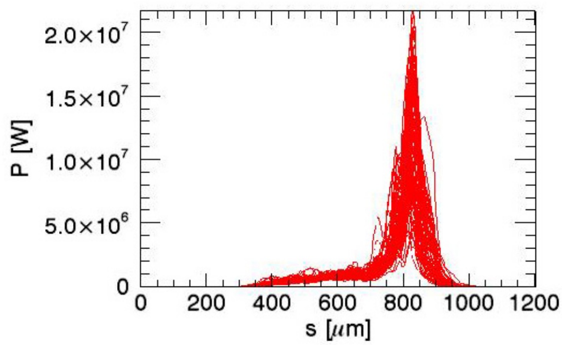

Figure 7: Shot to shot variation for the case at 300 pC. Number of shots: 90.

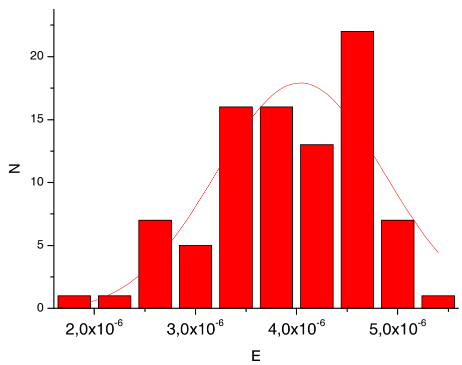

Figure 8: Energy distribution: Number of shots N as function of Energy (J).

Table 3: Statistical Properties of the Radiation

Q (pC)	<E> (μJ)	ΔE(μJ) rms	ΔE(μJ) FWHM	σ_E(μJ)	most prob	N
300	3.89	0.72	1.6	1.66	4.6	90
500	10.32	4.46	8	4.2	10	50

1-D HARMONICS ANALYSIS

A one-dimensional analysis has been performed with the code PROMETEO with particular emphasis on the determination of the shape and intensity on the harmonics. In fig 9 the growth of the radiation is shown, for ρ=9.75 10^{-3}, λ=500 nm and dimension of the beam σ_z=13 μm for the first, third and fifth harmonics. Saturation for the third harmonics occurs at 4 m at 27 MW of power. In fig. 10 the shape of the third harmonics is shown at different position along the undulator, showing the clean and spiked shape. The excitation of harmonics can be a method for producing single spike radiation at higher frequency or it can be useful in the diagnostics.

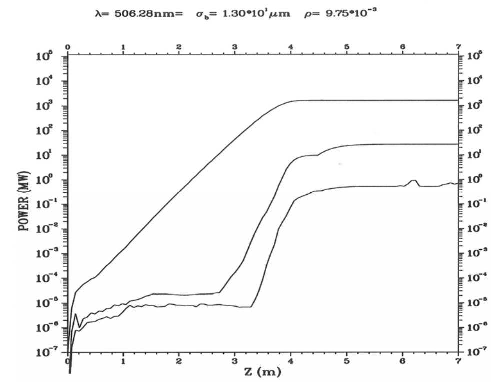

Figure 9: Growth of the radiation power vs z(m) for the first, the third and fifth harmonics ρ=9.75 10^{-3} and λ=500 nm.

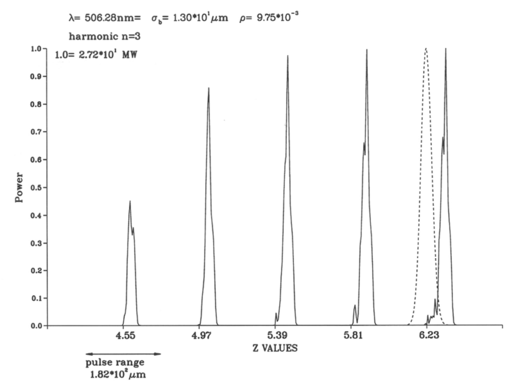

Figure 10: Pulse shape of the third harmonics vs z.

CONCLUSIONS

The production of single spike, clean pulse of radiation in the SPARC device at 500 nm has been analysed for realistic parameters. The velocity bunching method of compression allows to obtain bunches with very much peaked profiles. In this way, only the part of the charge in the higher current slices contributes to the radiation emission. The radiation pulse is short and single spiked, the energy yield is of order of few μJ. The statistical analysis shows a reasonable stability of the process. Singe spike production can be achieved also on the harmonics.

REFERENCES

[1] R. Bonifacio et al. PRL 73 (1994) 70
[2] J. Rosenzweig et al. NIMA 593, 45 (2008)
[3] M.Boscolo et al, NIMA 593 137 (2008)
[4] M. Xie in Proc. of the 1995 PAC, IEEE, Piscataway, NJ,1995, p.183
[5] M. Ferrario et al. PRL 99 (2007) 234801
[6] M. Boscolo et al.: SPARC BD-note BD-07-006
[7] L.M. Young, LANL Report No.LA-UR-96-1835 S
[8] S. Reiche: NIM A 429 (1999) 243