IL NUOVO CIMENTO Vol. 34 C, N. 4 Luglio-Agosto 2011
DOI 10.1393/ncc/i2011-10964-0

Colloquia: Channeling 2010

Spectral distribution of SPARC photoinjector electrons

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(ricevuto il 22 Dicembre 2010; pubblicato online il 19 Settembre 2011)

Summary. — SPARC is a photo-injector for production of high-brightness low-emittance electron beams to drive a FEL experiment in various configurations, including SASE-FEL radiation of 1–10 nm (SPARCX project). Due to a high-brightness source, the SPARC facility can be used to study the physics of ultrashort beams, plasma-wave based acceleration, production of X-rays by means of Compton backscattering, channeling of electron beams and other experiments. The initial process of electron beam generation inside the RF gun determines the main parameters of the electron beam. Interaction of electrons with high-frequency laser beam leads to modulation of the electron beam. In this paper we present electron beam spectral distribution for SPARC photoinjector parameters. The estimate of electron beam energy loss for such electron distribution also is given.

PACS `41.60.Cr` – Free-electron lasers.
PACS `41.85.Ct` – Particle beam shaping, beam splitting.

1. – Introduction

The free-electron laser (FEL) is a device that uses high-brightness (low-emittance, high peak current) electron bunches crossing a transverse periodic magnetic field to generate wavelength-tunable high-power electromagnetic radiation.

The SPARC project was proposed by the collaboration among ENEA-INFN-CNR-Università di Roma Tor Vergata-INFM-ST, and is progressing in the area of the Frascati National Laboratories [1]. The common denominator of SPARC project is to investigate the scientific and technological issues for production of high-brightness electron beams to drive a SASE-FEL experiment in the visible range [2]. In addition, SPARC is the injector prototype for SPARX project, a new high-brightness electron linac for generating SASE-FEL radiation in the 1–10 nm range [3, 4].

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Due to high brightness source, the SPARC facility might be used to study the physics of ultrashort beams, plasma-wave based acceleration, production of X-rays by means of Compton backscattering, channeling of electron beams and other experiments [3, 5-7]. Besides the physics, X-ray laser radiation can be used to research in chemistry, biology, medicine, in various applied sciences, which previously had not been possible [8].

The possibility of generation undulator radiation in the range of $\lambda \sim 1\,\text{nm}$ and less gives advantage to the SASE-FEL regime over a conventional FEL. This is due to the fact that at very short wavelengths, normal-incidence mirrors with sufficient high reflectivity for making an optical cavity resonator are unavailable [9]. Nevertheless the tuned SASE-FEL source allowing to control output radiation with high precision has not been done so far. Intensity and spectrum of laser radiation in the SASE-FEL regime depend on microbunching process in the undulator. Formation of microbunches is an unstable process and mainly depends on electron beam parameters at the entry of the undulator. Thus, the realization of the stable SASE-FEL regime first of all requires quality control of the electron beam from the moment of its generation.

2. – Electron beam spectral distribution for SPARC photoinjector parameters

The SPARC photoinjector involves a standard UCLA/SLAC/BNL 1.6 cell S-band RF gun (working at 2.856 GHz), operating at a peak accelerating gradient of $E_{ac} = 120\,\text{MV/m}$. The laser system including the Ti:Sa active medium is able to generate ultrashort radiation with a rise time less then 2 ps and variable pulse duration (4–10 ps). During interaction ($\tau \sim 10\,\text{ps}$) of ultraviolet laser beam ($E_0 = 190\,\text{MV/m}$) with a copper photocathode, electrons are emitted due to photoeffect. Such system allows to extract the electron beam with charge $\sim 1\,\text{nC}$ [2].

During the electron beam generation inside the SPARC photoinjector a high-frequency laser field ($\omega_0 \sim 10^{15}\,\text{s}^{-1}$) created by incident and reflected laser beams affects on all electrons.

As you can see [10], the action of this field results in modulation of the electron beam. Thus, in laser field the photocathode electrons experience either a deceleration or acceleration, forming a periodic structure of the electron beam in accordance with the period of a laser wave as shown in fig. 1.

Due to acceleration in external electric field and appearance of a periodic structure, electrons radiate and this radiation depends on electron beam parameters. To trace behavior of electrons in the SPARC photoinjector we need information about electron beam radiation.

In the present paper the radiation by electron beam is estimated taking into account the SPARC photoinjector parameters. Oblique laser incidence (at 70 degrees) has been taken in this task as shown in fig. 2.

As shown in [10], the dependence of the electron trajectory on the action of the magnetic component of a laser field is negligible. The nonrelativistic electron energy radiation in the frequency range dω at long range is given by the following [11]

$$\mathrm{d}E(\omega) = \frac{2e^2}{3\pi\, c^3} \left| \int_{-\infty}^{\infty} \ddot{\vec{r}}(t) e^{i\omega t} \mathrm{d}t \right|^2 \mathrm{d}\omega .$$

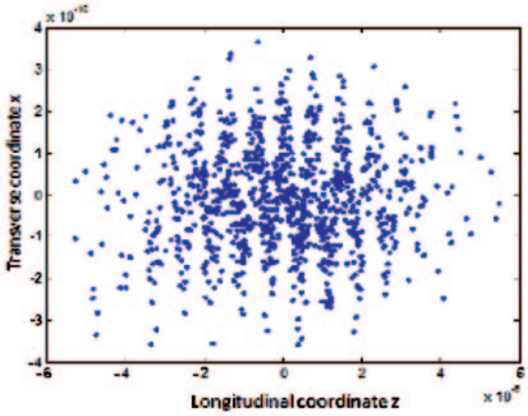

Fig. 1. – Spatial distribution of the electron beam near the SPARC photocathode under laser radiation effect. Time duration of laser beam ∼ 1 ps. Note that only a part of the electron bunch is shown. In fact the number of electrons is much larger [10].

Therefore, a spectral distribution function is defined as follows:

$$f(\omega)=\frac{\mathrm{d}E(\omega)}{\mathrm{d}\omega}=\frac{2e^2}{3\pi c^3}\left[\left|\int_{-\infty}^{\infty}\ddot{x}(t)e^{i\omega t}\mathrm{d}t\right|^2+\left|\int_{-\infty}^{\infty}\ddot{z}(t)e^{i\omega t}\mathrm{d}t\right|^2\right], \tag{1}$$

where $\ddot{x}(t)$ and $\ddot{z}(t)$ are determined by the electron motion equation:

$$\begin{aligned}\ddot{z}(t)&=\frac{eE_{ac}}{m}-\frac{eE_0}{m}\sin\theta\left\{\sin(\omega_0 t-\vec{k}_i\vec{r})+\alpha\sin(\omega_0 t-\vec{k}_r\vec{r})\right\},\\ \ddot{x}(t)&=\frac{eE_0}{m}\cos\theta\left\{\sin(\omega_0 t-\vec{k}_i\vec{r})-\alpha\sin(\omega_0 t-\vec{k}_r\vec{r})\right\}.\end{aligned}$$

The phase of laser fields (incident and reflected) in the point of electron position at the

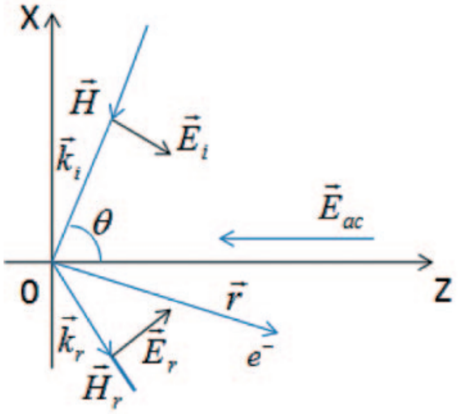

Fig. 2. – Interaction fields scheme near the SPARC photoinjector cathode.

time t can be written as

$$\begin{aligned}\omega_0 t - \vec{k}_i \vec{r} &= at^2 + b_1 t + \beta_1 - 2\alpha\delta \sin(at^2 + b_2 t + \beta_2),\\ \omega_0 t - \vec{k}_r \vec{r} &= -at^2 - b_2 t - \beta_2 - 2\delta \sin(at^2 + b_1 t + \beta_1),\end{aligned}$$

where $\delta \sim 10^{-5}$, $a = \omega_0 e E_{ac} \cos\theta / 2mc$, $\beta_1 + \beta_2 = 2\omega_0 c^{-1} C_3 \cos\theta$, b_1 and b_2 depend on the projection of initial electron velocity. For nonrelativistic velocity of electron beam we can take $b_1 = -b_2 \approx \omega_0$.

Then we use the Fourier transform for computing the first and second terms in eq. (1):

$$\begin{aligned}\int_{-\infty}^{\infty} \ddot{x}(t) e^{i\omega t} \mathrm{d}t &= -\frac{eE_0}{2im} \cos\theta \sqrt{\frac{\pi}{2a}} e^{-i\beta_1} \left[G_1(\omega) - \alpha e^{i(\beta_1+\beta_2)} G_2(\omega)\right],\\ \int_{-\infty}^{\infty} \ddot{z}(t) e^{i\omega t} \mathrm{d}t &= -\frac{eE_0}{2im} \sin\theta \sqrt{\frac{\pi}{2a}} e^{-i\beta_1} \left[G_1(\omega) + \alpha e^{i(\beta_1+\beta_2)} G_2(\omega)\right].\end{aligned}$$

Substituting the results into eq. (1), we obtain the equation for energy spectral distribution of one electron for the SPARC photoinjector parameters:

$$\begin{aligned}(2)\quad f(\omega) = {}& \frac{\mu_0 e^3 E_0^2 \cos\theta}{24\pi m \omega_0 E_{ac}}\\ & \times \left[\left|G_1(\omega) - \alpha e^{i(\beta_1+\beta_2)} G_2(\omega)\right|^2 + \tan^2\theta \left|G_1(\omega) + \alpha e^{i(\beta_1+\beta_2)} G_2(\omega)\right|^2\right],\end{aligned}$$

where $G_1(\omega)$ and $G_2(\omega)$ are the functions of only two variables (time and frequency):

$$\begin{aligned}G_1(\omega) &= e^{i\frac{(\omega-\omega_0)^2}{a}} \left[(C(z_0 - z) - C(-z)) - i(S(z_0 - z) - S(-z))\right],\\ G_2(\omega) &= e^{-i\frac{(\omega-\omega_0)^2}{a}} \left[(C(z_0 + z) - C(z)) + i(S(z_0 + z) - S(-z))\right],\end{aligned}$$

and $C(z)$, $S(z)$ are Fresnel integrals; $z_0 = \tau\sqrt{2a/\pi}$, $z = (\omega - \omega_0)\sqrt{2/a\pi}$.

Equation (2) shows that if the reflection coefficient (α) approaches zero, electrons coherently emit the radiation. The presence of reflected laser wave leads to the dependence of radiated energy on electron spatial distribution as shown in fig. 3.

It is important to underline the difference in the radiated energy for different reflection coefficients. There is no contribution of a reflected wave to the energy spectrum in case of $\alpha = 0.01$ (fig. 3,a). At the α increase the radiated intensity, in part of a spectrum corresponding to reflected wave, also increases as presented in figs. 3,b,c. For the case of total reflection ($\alpha = 0.99$) the spectrum reaches its frequency-integrated maximum by intensity, due to the electron emission in the field of both incident and reflected laser beams (fig. 3,d).

To estimate the spectral distribution of all the electrons extracted from the SPARC photocathode for the period of $\tau \sim 10\,\mathrm{ps}$, let us discuss the process of electron emission. Let us assume that the concentration of electrons generated near the cathode surface ($S \sim 1\,\mathrm{mm}^2$) is $N_t \cong I_0 S / 2\hbar\omega_0$, where $I_0 = (1-\alpha) I_i$ is the intensity of transmitted wave. If $N_t(t)$ is the number of electrons at the moment t, then the time of electron motion is $\tau - t$. Hence, taking into account eq. (2) we can obtain spectral distribution for all $N_{e^-} = N_t \tau \sim 10^{10}$ electrons as shown in fig. 4.

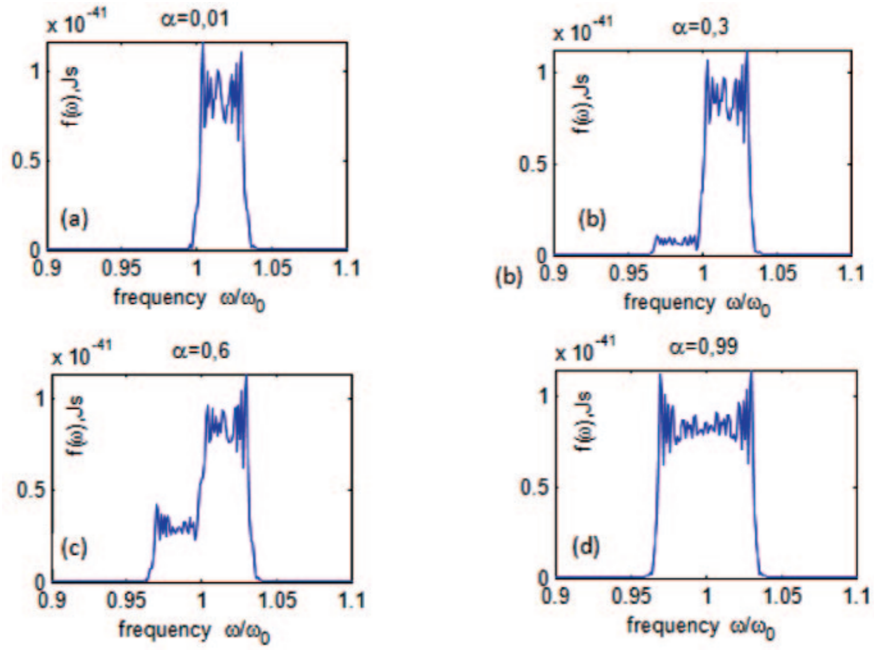

Fig. 3. – Spectral destribution of one electron near the SPARC photoinjector cathode for different reflection coefficients: a) $\alpha = 0.01$, b) $\alpha = 0.3$, c) $\alpha = 0.6$, d) $\alpha = 0.99$.

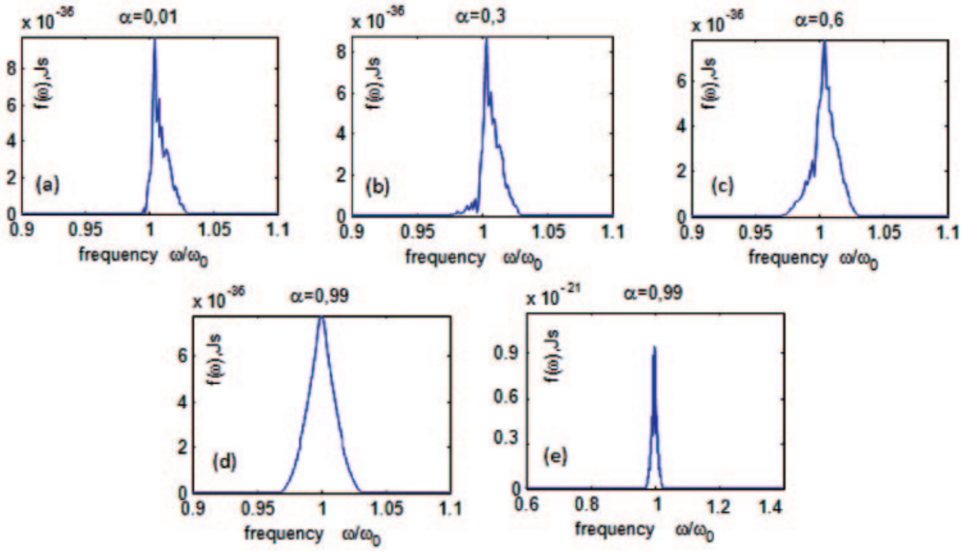

Fig. 4. – Spectral distribution for electron beam near the SPARC photoinjector cathode. For any reflection coefficient α the number of electrons equals 10^3 (a, b, c, d), and 10^{10} (e).

For electron bunches we observe similar dependences as for a single electron (comparison between figs. 3 and 4). When the intensity of the reflected laser beam goes up, the radiation spectrum becomes broader too. Analysis of the electron beam spectral distribution reveals the amount of energy radiated by electrons, of about 10^{-8} J for the time $\tau \sim 10\,\mathrm{ps}$, that is by four orders of magnitude smaller than the total energy of electron beam. Meanwhile, in the absence of electron beam modulation, radiated energy by the electron beam for the interval $\tau \sim 10\,\mathrm{ps}$ might be about 10^{-18} J. Great difference between radiated energy of the electron beam with and without modulation is due to the presence of coherent effects. In this condition we have the opportunity to trace the behavior of electrons in high-frequency laser beam in dependence of the degree of modulation in real experiments. That can be useful in order to control the electron beams in the initial stage of the beam forming.

3. – Conclusion

We have considered radiation of electron beam under SPARC photoinjector parameters. As it was shown in [10], due to high-frequency laser field the electron beam modulation occurs. Coherent effects that are due to the beam modulation lead to an energy radiation increase in 10 orders of magnitude. It gives us advantage for testing the process of electron beam modulation and using that for electron beam control in the initial stage. Moreover, periodic structure of electron beam may be of interest from a perspective preliminary microbunching before an undulator stage.

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The present paper has been done within the PhD works (AP and AD). AP and AD gratefully acknowledge the support of LNF INFN. AP is grateful to the “Channeling 2010” Organizing Committee for the financial support that made possible the author’s participation in the conference.

REFERENCES

[1] Alesini D. *et al.*, *Proc. of the 2003 Particle Accelerator Conference* (2003).
[2] Cianchi A. *et al.*, *Phys. Rev. ST Accel. Beams*, **11** (2008) 032801.
[3] Renieri A., *Nucl. Instrum. Methods A*, **507** (2003) 507.
[4] Palumbo L., *The SPARX-FEL project*, *Proc. of IPAC’10, Kyoto* (2010).
[5] Bacci A. *et al.*, *Nucl. Instrum. Metheds A*, **608** (2009) 90.
[6] Giannessi L. *et al.*, *Nucl. Instrum. Methods A*, **593** (2008) 132.
[7] Dabagov S. B. and Zhevago N. K., *Riv. Nuovo Cimento*, **31** (2008) 491.
[8] Ragozin E. N. and Sobel’man I. I., *Phys. Usp.*, **47** (2004) 195.
[9] Andruszkow J. *et al.*, *Phys. Rev. Lett.*, **85** (2000) 18.
[10] Podlesnaya A. S. *et al.*, *J. Phys.: Conf. Ser.*, **236** (2010) 012035.
[11] Landau L. D. and Lifshitz E. M., *Course of Theoretical Physics*, Vol. **2** (Nauka, Moscow) 1988.