Wakefield Effects on the Beam Accelerated in an RF-Photoinjector

J.-M. Dolique*, J.-L. Coacolo* and W. Salah
LPPG. Université Joseph Fourier-Grenoble I
BP 53, 38041 Grenoble Cedex 9
**and CEA-PTN.*
BP 12, 91680 Bruyères-le Châtel. France.

Abstract

For some years, the RF-photoinjector has been known as source of short, low-emittance electron beams. Among the causes of the emittance growth, which has to be minimized, RF- and self-field ("space charge") effects have been particularly studied, the latter being dominant for intense beams (cf. e.g.[1]). In this communication, we investigate theoretically the wakefield effects, in order to compare the global wall-field effects to the self-field ones, and also to compare the contributions of the different walls. As causality allows a pill-box modelling for photoinjectors, we use analytical expressions of the wakefield $(\mathbf{E},\mathbf{B})(\mathbf{x},t)$ established in two companion papers [2][3]. The results precise quantitatively the foreseeable dissymmetry between cathode(K)- and anode (A)- contributions. Moreover, as long as A-contribution may be neglected, these results are in excellent agreement with wake maps obtained by a completely different method starting from Liénard-Wiechert's formulæ [4][5]. That entforces the interest of a light code based on the latter method, and used in various previous publications (e.g. [1]). For numerical applications, the photoinjector of "ELSA", the CEA facility [6] is considered.

1 INTRODUCTION

The RF-photoinjector has been praised for some years as a source of low-emittance electron beams. This recognized high quality is more difficult to reach for intense beams, the main cause of quality loss being then the self-field (or space charge) effects.

The aim of this paper is to investigate another effect important for intense beams : the wakefield effect. As explained in companion papers [2],[3], the beam electromagnetic wake in a photoinjector is deeply different from the classical wake of a coasting ultrarelativistic beam, and that for essentially two raisons : a) the beam is not in uniform motion, but strongly accelerated ; b) causality prevents any beam electromagnetic influence at a distance from the emissive cathode greater than ct, if t=0 is the time at which photoemission begins.

Using analytic expressions obtained elsewhere [2],[3] for this geometry, we compare wakefield maps $(\mathbf{E},\mathbf{B})(\mathbf{x},t)$ with the corresponding free-space field maps, and discuss the rôle of the different walls.

2 CONSEQUENCES OF CAUSALITY. PHOTOINJECTOR AND BEAM MODELLING

2.1. *Causality and photoinjector modelling*

When interested by the effects of beam wake on beam quality one has to consider only that part of the wake which can act on the beam. This wake is an electromagnetic field generated by the walls, or some zone of them, under the electromagnetic influence of the beam. These photon transits take up finite times. A first consequence of causality is thus to restrict the part of photoinjector walls able to contribute to beam wake.

Let us consider, for instance, a typical photoinjector consisting in a cavity of revolution around the Oz axis, like the one shown in Figure 1. For an RF-field amplitude on the cathode E_0 of some tens of MV/m, it takes t_g<350 ps for the beam head to cross a photoinjector cavity having a gap g of say 6 cm. Within this time, the radial wall ($r=\mathcal{R}$=56 cm) is not reached by any electromagnetic signal coming from the beam. As for the transverse walls, only a fraction of them : $z=0$, $z=g$, $r<r_{max}$ can generate a wake able to influence the beam. Whatever the beam pulse duration τ, if τ<100 ps, and E_0, if E_0>10 MV/m, $r_{ma}<g$. Therefore, a pill box cavity modelling : $(0,g)\times(0,\mathcal{R})$ is well-founded, with any $\mathcal{R}>ct_g$~10 cm. A question arises however about this modelling : what is the influence of the anode hole ? For a relativistic coasting beam, experimental results [4] have shown a wake inside a bored pill box cavity practically the same as the one calculated for the corresponding hole-less cavity, even for a hole-radius/cavity-radius ratio as large as 1/3. It seems reasonable to assume that the same thing happens in the case of an accelerated beam for which β >0.9 in the greatest part of the cavity.

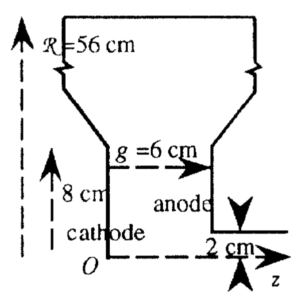

Fig. 1. Schematic of ELSA photoinjector

2.2. *Beam modelling*

The beam, carrying a total current I, is assumed to be radially uniform, with radius a). Its axial current profile is uniform, with stiff front and back, and time lenght τ.

The RF accelerating E-field is assumed to be constant, which is a good approximation for the injector"ELSA", the working frequency of which is 144 MHz, as long as the pulse duration τ satisfies $\tau \ll 7$ ns.

3 REDUCED COORDINATES. CHOSEN PARAMETERS

3.1. Reduced coordinates

The analytical expressions of the wakefield $(\mathbf{E},\mathbf{B})(\mathbf{x},t)$ taken from [2] or [3], that we shall use, contain reduced coordinates and quantities based upon the characteristic lenght $H^{-1} = mc^2/eE_0$, where e and m are the electron charge and mass respectively, and E_0 the RF-electric field amplitude on the photoinjector cathode: $R=Hr$, $Z=Hz$, $\rho=H\mathcal{R}$, $G=Hg$; $T=Hct$, $\mathcal{T}=Hc\tau$.

3.2. Chosen parameters

The photoinjector of the "ELSA" facility (CEA, PTN, Bruyères-le-Châtel) is taken as an exemple. It has a wide range of possible working parameters. The chosen parameter set for some sample wakefield maps presented hereunder is : I=100 A, πa^2=1 cm², E_0=30 MV/m, τ=30 or 100 ps.

4 WAKEFIELDS AT DIFFERENT TIMES COMPARED WITH THE CORRESPONDING FREE-SPACE FIELDS

4.1 At the end of photoemission : $t=\tau$. Cathode wake field

Fig.2 shows, for $t=\tau$, i.e. at the end of photoemission, the beam-generated axial E-field E_z, on the axis (r=0), as a function of the reduced abscissa $Z=Hz$. This field is compared to the one the beam would generate in free space. At $t=\tau$, the anode is not yet reached by any electromagnetic signal, so that the cathode is the only wall which plays a rôle in the wake field. As shown in Fig.2, the latter is easily interpreted as sum of the free-space field and of a E_z>0 due to the positive images of beam electrons in the cathode.

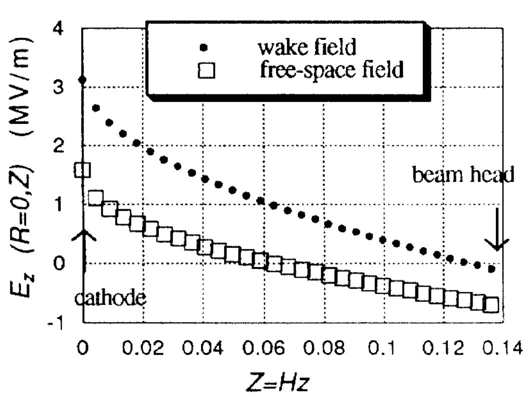

Fig. 2. $E_z(R$=0,$Z)$: wakefield and free-space field for $t=\tau$

4.2. When beam head reaches the photoinjector exit ($z=g$) : $t=t_g$

Fig. 3 a and b show $E_z(R=0,Z)$ and $E_r(R=A,Z)$ for $t=t_g$, the time at which the beam head reaches the photoinjector exit $z=g$.

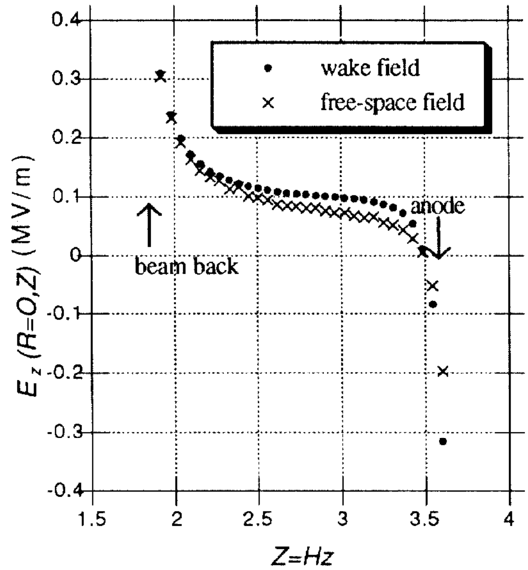

Fig. 3a $E_z(R$=0,$Z)$: wakefield and free-space field for $t=t_g$,

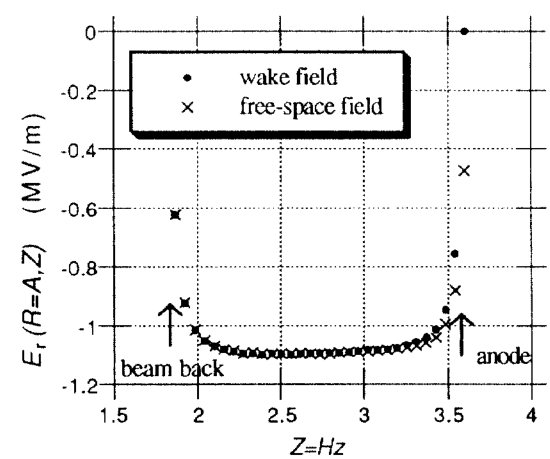

Fig. 3b $E_r(R$=A,$Z)$: wakefield and free-space field for $t=t_g$,

They emphasize the strongly dissymmetric influence of cathode and anode. For E_z, even at $t=t_g$, it is the supplementary positive field due to the cathode images which dominates, except in the immediate vicinity of the anode. As for E_r, it is essentially a self-field (or "space charge" field) except once again in the immediate vicinity of the anode, which imposes E_r=0.

One may expect that this dissymmetry, which could have been qualitatively foreseen, is quantitatively a decreasing function of E_0. We plan to investigate the range E_0<30 MV/m, but the lenght of numerical computations necessary to map the wakefield did not allow this before EPAC 94's beginning.

5 K-WAKEFIELD : COMPARAISON BETWEEN THE PRESENT CALCULATION AND A PREVIOUS ONE BASED ON A LIENARD-WIECHERT FORMULATION

At PAC 91 conference [5], two of us (JMD and JLC) had presented a formulation of self-field effects in the intense beams of RF-photoinjectors, which took as starting point Liénard-Wiechert's formualæ. This method was applied to the study of photoemission self-field limit, and emittance growth during the first stage of electron acceleration. It allowed to provide results under analytical form, on the contrary of the most often used codes wich solve numerically the complete set of Maxwell's equations.

Wall effects were taken into account by images in the cathode.

This Liénard-Wiechert approach being radically different from the ones [2],[3] used for the results presented here, it is interesting to compare them, as shown on Fig. 4 at $t=\tau=100$ ps (end of photoemission) for $E_z(R=0,Z)$, $E_r(R=A,Z)$. There is a complete agreement. This strengthens the interest of the Liénard-Wiechert formulation of self-field effects, a method which, since PAC 91, has been applied to study emittance growth in increasingly complex situations (e.g. [1])

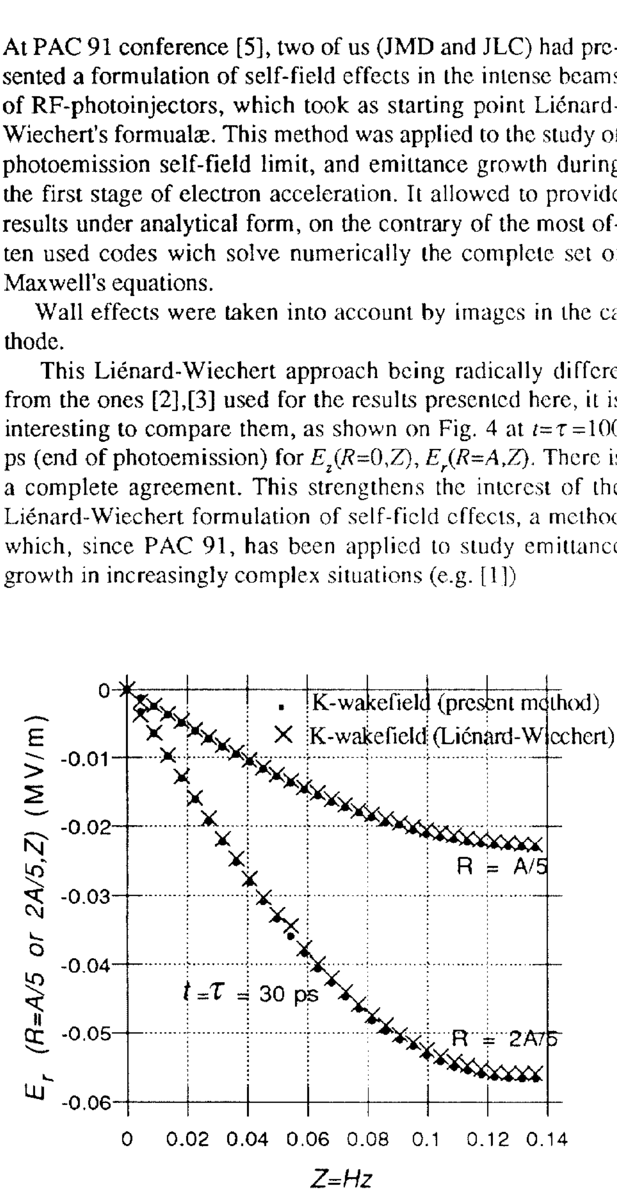

Fig. 4. On an exemple, comparaison between wakefields obtained by the present method or by Liénard-Wiechert's one

6 CONCLUSION

When accelerated in a RF-photoinjector, an intense electron beam pulse drives an electromagnetic wake composed of two parts : a direct "free space" wake, and an indirect one due to the reaction of conducting walls. Owing to causality, the part of walls for which electromagnetic reaction can act on the beam, during its flight from cathode K to anode A, is limited to a portion of K and A near enough to the photoinjector axis along which the beam travels. This allows the use of the simple pill box geometry as photoinjector model for studying the influence of wall s.

This study has been made with the help of analytical expressions of wakefield established in [2] and [3].

During a first part of beam flight, the only cathode can generate a wall wake. This is of the same order as the direct free-space wake.

When the beam approaches the anode, this wall should be able to play also a rôle in the global wake.

One could foresee a dissymmetry between K- and A wakes, increasing with E_0.

For E_0=30 MV/m, a typical present value in the ELSA photoinjector we have chosen for numerical application, this dissymmetry is very strong. Even at $t=t_g$, it is the K-wake which dominates, except in the immediate vicinity of the anode.

At the end, we have compared the K-wake field presented in this communication, and deduced from analytical resolutions of Maxwell's equations described in two companion papers, to the one previously obtained by a completely different method, starting from Liénard-Wiechert's formulaæ. There is an excellent agreement, what strengthens the interest of a light code based on the latter method. This code does not take the A-wake into account : it appears that, for $E_0 \geq$ 30 MV/m, this approximation is justified.

7 REFERENCES

[1] J.-M. Dolique and J.-L. Coacolo, "Quality of the self-field dominated beam, with arbitrary aspect ratio, of a high-intensity magnetically focused RF gun", Nucl. Instr. and Meth. A 340, 1994, pp. 231-236

[2] J.-M. Dolique, "Wakefield driven by the strongly accelerated beam of an RF photoinjector", this Conference

[3] J.-M. Dolique and W. Salah,"Time-dependent normal mode analysis of the wakefield generated in cylindrical cavity by an accelerated charged particle beam", this Conference

[4] J.-M. Dolique and J.-L. Coacolo, "Relativistic acceleration and retardation effects on photoemission of intense short pulses in RF photoinjectors, 91-PAC Conference, San Francisco, USA, May 1991, pp.233-235

[5] J.-M. Dolique and J.-L. Coacolo, "Self-limiting current density in field-photoemission of intense short relativistic electron beams", 92-EPAC Conference, Berlin, FRG, March 1992, pp. 771-773

[6] R. DeiCas, S. Joly *et al.*, "Photoemission studies and commissioning the ELSA-FEL experiment", Nucl. Instr. and Meth. A 318, 1992, pp. 121-126

[7] H. Figueroa *et al.*, Phys. Rev. Lett. 60, 2144 (1988)