WAKEFIELD EFFECTS ON THE BEAM ACCELERATED IN A PHOTOINJECTOR: PERTURBATION DUE TO THE EXIT APERTURE

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The influence of the photoinjector exit aperture on the wakefield generated by the strongly accelerated electron beam, has been theoretically studied in a companion paper [1]. In this communication we study the effects of such a wakefield on the beam, in that propagation stage where the beam approches the hole and enters it, i.e. the propagation stage where the influence of the photoinjector exit hole must be taken into account. First, the perturbated wakefield map $(\mathbf{E},\mathbf{B})(\mathbf{x},t)$ is shown for various instants, and for photoinjector and beam parameters corresponding to typical values on ELSA [2], the CEA-Bruyères-le Châtel high-current, high-brillance electron beam facility. Then, the effects on the beam quality are studied in terms of emittances, when the beam approaches the hole. These effects are compared to the corresponding ones, previously obtained for a wakefield map where the exit hole perturbation had been neglected [3]·

I. INTRODUCTION
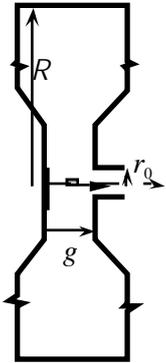
Fig.1.Schematic of an RF photo-toinjector cavity

In a companion paper [1], we have analytically calculated the wakefield map $(\mathbf{E},\mathbf{B})(\mathbf{x},t)$ generated by the accelerated electron beam in a photoinjector, when the effects due to the exit aperture (of radius r_0: Fig. 1) are taken into account. Let us recall that the term wakefield has been used with a rather different meaning than it has in the most usually considered case of ultrarelativistic coasting beams. The wakefield has been defined as the total electromagnetic field undergone by a beam electron, whether this field is generated by by the conducting walls under the beam influence, or by the other beam electrons (the space charge field is not negligible).

More precisely, in [1] analytical expressions of the wakefield scalar and vector potentials are given, which depend on the propagation phase considered. In the first: $t<g/c$, (where $t=0$ corresponds to the photoemission beginning), the beam-generated electromagnetic field has not yet reached the exit wall (anode). In the second: $g/c <t<t_g$, the beam-generated electromagnetic field has reached the exit wall, but the beam head is still above the exit aperture. In the third: $t_g <t <t_{qg}$ the beam penetrates the exit hole. For E_0=30 MV/m, τ =30 ps, g=6 cm (typical values for the ELSA photoinjector [2]), these three phases correspond to: $t<200$ ps, $200<t<250$ ps, and $250<t<280$ps respectively. The corresponding expressions of

E_z, E_r and B_θ as a function of r,z,t, result from these potentials, . Their numerical calculation for a given set of photoinjector and beam parameters has turned out to be a particularly difficult venture due to the very slow convergence of the various implied series or improper integrals. It is the reason why the results presented here are limited to phases 1 and 2. Calculations concerning phase 3 are still in progress.

It is also a reason to welcome possible checks of validity. Fortunately there are two of these, both very simple.

II. TWO CHECKS

There are two cases where the field maps obtained by the method described in [1] must be identical with those previously obtained [3] for a closed cavity: a) in the above "first phase", b) when the aperture radius r_0 vanishes. These two tests have been successfully carried out, as is shown in Fig. 2 and 3 given as examples (but the excellent agreement has been verified in many other cases).
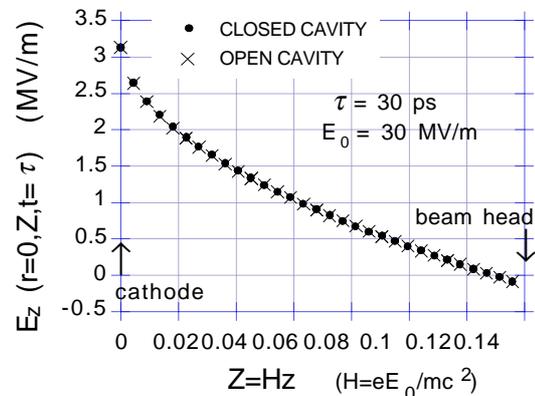
Fig. 2. $E_z(z)$ on the beam axis, as given by the closed- or open cavity modelling respectively, for $t=\tau$ (first phase)
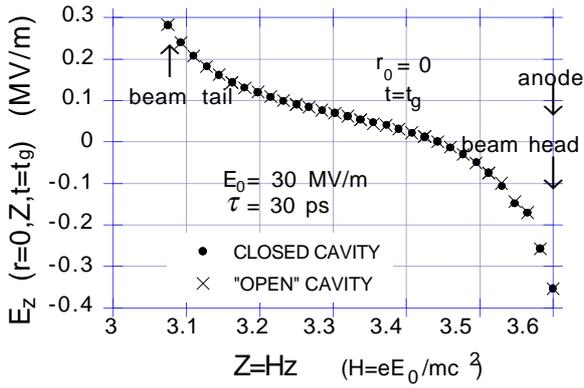
Fig. 3. $E_z(z)$ on the beam axis, as given by the closed- or open cavity modelling respectively, for $t=t_g$ (second phase) and $r_0=0$

III. SOME SAMPLE FIELD MAPS

These correspond to the following beam parameters: $I=100$ A, $\pi a^2 = 1$ cm^2, $E_0=30$ MV/m, $\tau=30$ ps, $r_0=2$ cm, and to a beam reaching the photoinjector exit aperture ($t=t_g$)
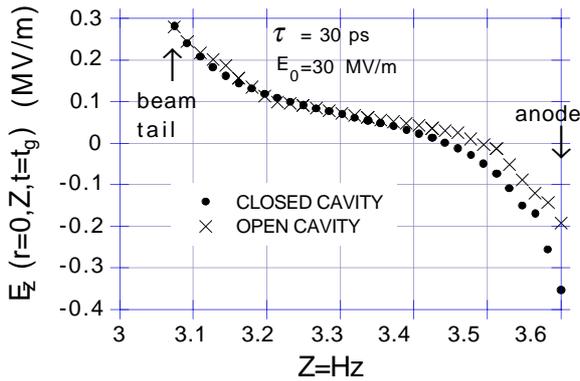
Fig. 4. $E_z(z)$ on the beam axis, as given by the closed- or open cavity modelling respectively, for $t=t_g$ (second phase)
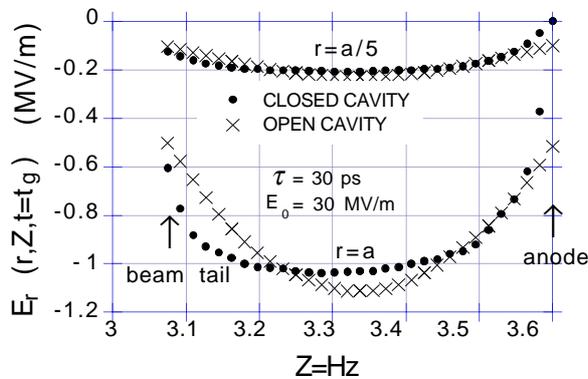
Fig. 5. $E_r(r,z)$ for $r=a$ and $r=a/5$, as given by the closed- or open cavity modelling respectively, for $t=t_g$ (second phase)
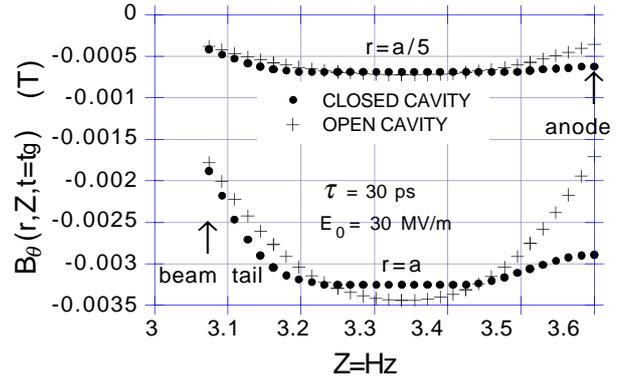
Fig. 6. $B_\theta(r,z)$ for $r=a$ and $r=a/5$, as given by the closed- or open cavity modelling respectively, for $t=t_g$ (second phase)

IV. CONSEQUENCES OF THESE APERTURE EFFECTS ON BEAM QUALITY (PHASE 2: THE BEAM PULSE APPROACHES THE EXIT APERTURE)

A. Used emittances

Beam quality will be defined by normalized whole-beam rms emittances:

$$\varepsilon_r = 2\,[<r^2><(\frac{p_r}{mc})^2> - <r\,\frac{p_r}{mc}>^2\,]^{1/2}$$

$$\varepsilon_z = 4\,[<\Delta z^2><(\frac{\Delta p_z}{mc})^2> - <\Delta z\,\frac{\Delta p_z}{mc}>^2]^{1/2},$$

where $<\,>$ means an average taken over the whole beam:

$$<G> = \int G(\mathbf{x},\mathbf{p}|t)\,f(\mathbf{x},\mathbf{p}|t)\,d^3x\,d^3p\,.$$

$\mathbf{x}$ is the position, $\mathbf{p}$ the momentum. The distribution function f is normalized to 1. $\Delta\mathbf{x}=\mathbf{x}-<\mathbf{x}>$, $\Delta\mathbf{p}=\mathbf{p}-<\mathbf{p}>$, where $<\mathbf{x}>$ and $<\mathbf{p}>$ are the beam-center position and momentum respectively.

B. Calculation of the radial and longitudinal emittances, as a function of time, with the ATRAP-LIVIE code

To study the effects on beam quality of the previously calculated wakefield, the ATRAP-LIVIE code has been used.

Taking as a starting point theoretical calculations of space-charge effects in strongly accelerated beams, based on the Liénard-Wiechert formulæ (J.-M. DOLIQUE [5]), this code has been developed by J.-L. COACOLO [6]. The use of the Liénard-Wiechert formulæ to describe the electromagnetic interaction between beam electrons provides a rigourous description of beams where (as in photoinjector beams) momenta are very spread, with important relativistic retardation- and radiation field effects.

The ATRAP-LIVIE code gives, at each time t, the positions and momenta of beam electrons, which evolve under the influence of the space-charge field, of the cathode electromagnetic reaction, and possibly of other external fields such as a magnetic focusing field.

If axisymmetry is postulated, the beam is allowed to start from the cathode with arbitrary radial and axial profiles.

In order to isolate the wakefield effects of the anode (with aperture or without) by comparaison with the previously obtained analytical field map, we have imposed the approximations of the analytical model in question, i.e. a purely longitudinal motion witth a uniform radial profile, on ATRAP-LIVIE. The subroutine computing the space-charge and cathode-image fields is disconnected, and the wakefield map deduced from the previous analytical model introduced as an external field.

To emphasize the specific effect of the exit aperture, wakefield maps for closed or open cavity have been successively introduced.

A. Whole-beam radial emittance

This is shown in Fig.7 as a function of time ($t=0$ corresponds to the beginning of photoemission), between $t=g/c$ and $t=t_g$.
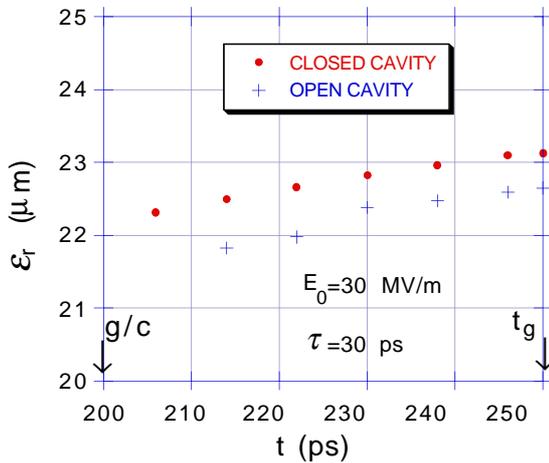
Fig. 7. Whole-beam radial emittance as a function of time. $t=0$ corresponds to the beginning of photoemission, $t=t_g$ to the time when the beam head reaches the exit aperture.

Taking the aperture into account leads to a small radial emittance decrease, of about 3% at maximum.

B Whole-beam axial emittance

This is shown in Fig. 8 as a function of time.
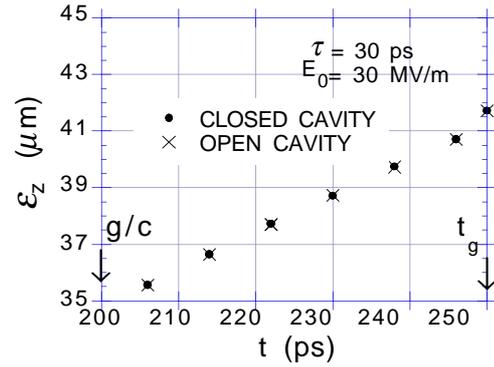
Fig. 8. Whole-beam axial emittance as a function of time.

It appears that for the parameters chosen, the influence of the exit aperture, in terms of beam quality, is slight concerning the transverse emittance: $(\Delta\varepsilon_\perp/\varepsilon_\perp)(z) \sim 3\%$ at maximum, and negligible concerning the axial emittance.

To complete this paper, we recall the results previously obtained concerning the wakefield of a closed cavity for a beam approaching the anode [3]. They had quantitatively specified the expected deep dissymetry between the conducting walls regarding their contribution to the total wakefield, besides the space-charge contribution. (Given that the radial walls have no time to contribute, these conducting walls are the cathode and the anode).

Thus, concerning the effects on whole-beam emittances, the correction $(\Delta\varepsilon_\perp/\varepsilon_\perp)(z)$ entailed by taking the anode contribution into account had been found to be less than 5% at maximum (a maximum reached for $t=t_g$, and for $E_0=10$ MV/m; for $E_0=30$ MV/m, the maximum was of the order of 1 %).

The field map perturbation due to the aperture in the anode has an effect of the same order of magnitude, i.e. small, on the transverse emittance of a beam reaching this exit aperture.

As shown in Fig. 7, this correction is of the order of 3% for $E_0=30$ MV/m. It could be of the order of 10% for $E_0=10$ MV/m.

Of course, one can expect a stronger effect when the beam enters the drift tube: $t>t_g$. Calculations on this point are in progress with the theoretical model [1].

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