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Analysis of the transverse kick to beams in low-frequency photoinjectors due to wakefield effects

Wa'el Salah [a,b,c,*], Roger M. Jones [b,c], J.-L. Coacolo [d]

[a] Physics Department, The Hashemite University, Zarqa 13133, Jordan
[b] School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK
[c] Cockcroft Institute of Science and Technology, Daresbury, Cheshire WA4 4AD, UK
[d] Institute de Physique Nucléaire d'Orsay, 91406 Orsay Cedex, France

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ABSTRACT

A time domain analysis of the normal modes in a cavity is used to obtain an analytical expression for the transverse momentum imparted to particles within an accelerated electron beam in a low frequency photoinjector. These analytical expressions form the basis of detailed simulations on the transverse momentum imparted to an accelerated beam. This analysis of the wakefields employs a modified form of the Panofsky–Wenzel theorem in which additional velocity dependent effects are taken into account. Simulations are presented for parameters of the ELSA photocathode.

1. Introduction

The progress of a charged particle beam through a cavity excites an electromagnetic field (e.m) which interacts back on the beam itself. This e.m field can be decomposed into a longitudinal component which influences the energy spread of the beam and a transverse component which causes an emittance dilution of the beam and can give rise to a beam break up instability [1–7]. This e.m field is conveniently represented as a wakefield which results from the influence of the e.m field scattered off the cavity wall and this we refer to as the geometric wakefield, or from Ohmic losses in the walls. The latter gives rise to resistive wall instability [8,9] and will not be studied in this paper. The focus of this paper is on the geometric wakefield. In either case, the wakefield may be viewed as an image charge setup by the beam which interacts back on the beam.

For a beam traveling ultra-relativistically (essentially at the speed of light) then the Panofsky–Wenzel theorem [10] relates the transverse component to the longitudinal wakefield. This formula is very convenient in beam dynamics simulations where the transverse momentum imparted to the beam is required. However, it is valid for a strictly ultra-relativistic beam. In the low-velocity regime, in a photocathode for example, velocity dependent corrections will be required. Here we drive these additional correction terms and obtain general relation between the transverse and longitudinal wakefield valid for non-relativistic and ultra-relativistic beams. These effects are particularly relevant in photocathodes where the initial acceleration of the beam takes place. Currently, there are several numerical computer codes available for modeling electron sources geometries which are able to include the effects of space charge fields. Among of these codes, we mention the classical code PARMELA [11] which incorporates electrostatic space–charge effects and TREDI [12] which incorporates e.m space charge forces using Lienard–Wiechart potentials in free space. These codes have been extensively used for simulating photoinjectors [13]. There are several approximations employed in these codes. In particular, the accelerating cavities are assumed to be electromagnetically decoupled from each other. These approximations require the deflecting field (higher order modes fields within the cavity) to be localized and to not propagate along the accelerator. These modes are excited by the beam and their relative amplitudes are dependent on the temporal length of the beam and on the velocity of the beam. However, these computer codes do not in general take into account these effects. These assumptions are quite accurate when the beam is sufficiently far from the cathode. However, the underlying assumptions are invalidated in the immediate vicinity

*Corresponding author at: Physics Department, The Hashemite University, Zarqa 13133, Jordan. Tel.: +962 5 390 33 33; fax: +962 5 390 33 49.
E-mail addresses: wnsalah@hotmail.com, wsalah@hu.edu.jo (W. Salah).

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of the cathode. This is indeed the case when we consider electrons at their initial stage of the emission from the photocathode. Furthermore, in many photoinjectors the length of the cavity is not negligible in comparison to that of the bunch. For example, for the ELBE [14] photocathode the beam is 2 mm long and the cavity is approximately 37.7 mm long. Finally we note that simulations using particle in cell (PIC) codes such as MAFIA [15,16] includes these space charge and wakefield effects. However, there is a limited analysis of wakefield effects from an analytical perspective and in the present work we develop equations for the e.m field in terms of the excitation current.

Recently, analytical techniques for computing e.m potentials in low frequency photoinjectors have emerged in which bunch acceleration is assumed constant [17]. Here we employ a similar technique to analyze the transverse momentum kick imparted to the beam in a photocathode cavity. We note that the effects of these e.m potentials or wakefields on the beam have been successfully studied in connection with the beam break up [3–7] in which the beam is assumed to be ultra-relativistic and is assumed to be essentially traveling with the velocity of light. Our analysis does not make this assumption as in photoinjectors the beam is traveling substantially less than the velocity of light and hence additional velocity-dependent effects must be taken into account.

We begin the analysis by following a time dependent formulation [18] for the ELSA photoinjector shown in Fig. 1 (where g is the cavity length, $\Re$ and r_0 are the hole and cavity radii, respectively). The ELSA facility is a high brightness 18 MeV electron source dedicated to electron irradiation, γ-rays and picoseconds hard and soft X-rays. It consists of a 144 MHz RF-photoinjector producing short bunches which are further accelerated to an energy varying from 2 to 18 MeV using two additional 433 MHz accelerators cavities [19].

An analytical expression for the transverse momentum imparted to the electrons inside the beam will be employed. The longitudinal fields are analyzed and related to the transverse fields by application of a modified form of the Panofsky–Wenzel theorem [10] which includes velocity-dependent effect. By applying the causality principle we are able to simplify the effects associated with the actual cavity, illustrated in Fig. 1, to an analysis of the e.m fields in a pill-box cavity. According to analytical and semi-empirical results [20,21] the exit hole influence can be neglected as long as $r_0/\Re \ll \frac{1}{3}$. A first consequence of causality principle—which prevents the beam's field influence at a distance from the emissive cathode greater than ct—is thus to restrict the part of the photoinjector walls able to contribute to the beam wake. For an RF-field on the cathode E_0 with an amplitude of a few tens of MV/m, it takes approximately 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 ($r = \Re = 56$ cm) is not reached by the e.m signal eminating from the beam. This means that only a small fraction of the transverse wall (located z=0, z=g, $r \prec r_{\max}$) can generate a wake which is able to influence the beam. Therefore, a pill-box cavity model is well-founded and is illustrated in Fig. 1, for $\Re \succ ct_g$ (c being the speed of light and t_g is the time at which the beam head reaches the photoinjector exit).

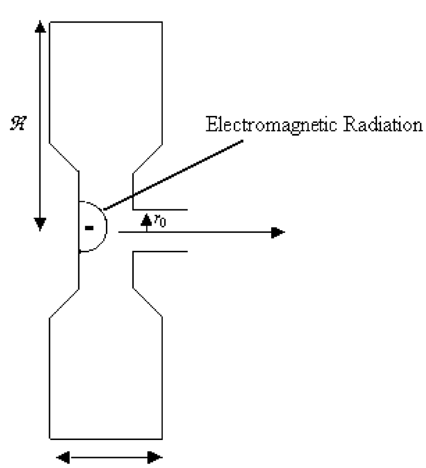

Fig. 1. Schematic representation illustrating the essential geometry of the ELSA photoinjector (144 MHz cavity).

Panofsky and Wenzel considered the transverse momentum imparted to an ultra-relativistic particle moving parallel to the axis of the cavity with a velocity equal to that of light. If g is the length of the cavity, then the transverse momentum $p_\perp$ is given

$$p_\perp = \int_0^t F_\perp \, dt = \frac{e}{v}\int_0^g [E_\perp + (\vec{v} \times \vec{B})_\perp] \, dz \tag{1}$$

where $\vec{F}$ is the force exerted on the particle, e is the electron charge, $\vec{E}$ and $\vec{B}$ are the electric and the magnetic wakefields, respectively, $\vec{v}$ is the particle velocity, z is the distance along the axis and $\perp$ denotes perpendicular components.

Since $|\vec{v}| \approx c$, the particle direction remains unchanged by the transverse force. Panofsky and Wenzel have shown that the above equation can be simplified by expanding the right-hand side of it in terms of a vector and scalar potential [10]. Moreover, for an ultra-relativistic beam the scalar term is zero in this formulation. However, we consider beams which are not necessarily traveling ultra-relativistically and indeed initially the beam travels non-relativistically when it is emitted from the cathode. A rigorous description of this situation based on the normal mode analysis model in a pill-box cavity is the aim of this paper. The transverse momentum expression will be computed for the photoinjector schematized in Fig. 1. The RF-accelerating field will be assumed to be constant and we note that for ELSA photoinjector (which operates at 144 MHz), this is a good approximation provided the pulse duration $\tau \ll 7$ ns.

2. Derivation of transverse momentum kick for an accelerated electron beam

2.1. Problem setup

The transverse momentum $p_\perp$, imparted to a particle with a velocity $\vec{\beta}$ (normalized with respect to the velocity of light) and an amount of charge Q at time t inside the beam accelerating in the z-direction through the RF cavity schematized in Fig. 1, is given as an integral over the duration of the force

$$p_\perp(r,z,t) = \int_{t_i(z=z_q)}^{t_f(z)} F_\perp(r,z,t)\,dt = Q(t)\int_{t_i(z=z_q)}^{t_f(z)} [E_\perp(r,z,t) + (\vec{\beta}(z,t)c \times \vec{B}(r,z,t))_\perp]\,dt \tag{2}$$

where the initial limit of integration $t_i(z=z_q)$ denotes the time at which the tails of the beam is located at longitudinal coordinate z_q, $t_f(z)$ denotes the time for an element of the beam at location z, $Q(t)$ is the amount of charge included between z_q and z in the time interval $\Delta t = t - t_i$, $\vec{\beta}(z,t)$ is the beam velocity. The beam velocity $\vec{\beta}(z,t)$ and acceleration $\vec{\gamma}(z,t)$ are shown to be parallel to the accelerated field $\vec{E}_0$ and independent of time [18]:

$$\vec{\beta}(z,t) = \beta(z)\vec{u}_z$$
$$\vec{\gamma}(z) = \gamma(z)\vec{u}_z \tag{3}$$