A FAST KICKER USING A RECTANGULAR DIELECTRIC WAKEFIELD ACCELERATOR STRUCTURE*

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Abstract

A rectangular two-beam dielectric wakefield accelerator (DWA) module is described which, when energized by a 14 MeV, 50 nC drive bunch moving in one channel, is shown to deflect a test bunch moving in a parallel channel which originates from an independent source. We show that such a module, 30 cm in length, can deflect transversely a 1 GeV electron by ~1 mrad in ~1 ns, after which a following bunch can pass without deflection. Apparatus required to accomplish this task consists of a laser/RF gun and an optional linac to generate the drive bunch. The associated DWA components could be used for kicker applications in a storage ring or a more energetic electron linear accelerator. An example described is tailored to a DWA demonstration project underway at the Argonne National Laboratory Wakefield Accelerator, but the design can be altered to allow for changes such as a lower-energy but still relativistic drive bunch. The device, through appropriate design, can deflect one out of several bunches in a storage ring, leaving the remaining bunches essentially unaffected by the structure.

INTRODUCTION

We describe a simple rectangular two-beam dielectric wakefield accelerator (DWA) module [1] that is energized by a 14-MeV, 50-nC drive bunch moving in one channel, that can deflect a witness or test bunch moving in the parallel second channel and which originates from a different source. We shall show that such an apparatus, no more than 30 cm in length, can deflect transversely a 1-GeV electron ~ 1 mrad in 1 nsec. The equipment that accomplishes this task consists of a small rf linac and associated DWA deflector components which would be used for kicker applications in a storage ring or more energetic electron linac accelerator. The structure described here is to be studied and developed for possible use in an existing or future facility where a fast kicker is required. This work has evolved via our ongoing study of two-channel rectangular DWA structures [2,3]. The RF generation mechanism for the structure proposed here is by creation of wakefields (Cherenkov radiation) induced by passage of a drive bunch along a dielectric-loaded drive channel. This radiation couples continuously into a parallel channel, without need for auxiliary coupling elements. A diagram for the cross section of the structure is shown in Fig. 1. The different widths of the drive and witness bunch channels cause a step-up transformer effect between the two channels: thus the drive bunch can produce large axial or transverse fields in the adjacent channel. The bunches we wish to deflect move in the smaller channel, phased so as to slightly lag behind the motion of the drive bunch which sets up the fields.

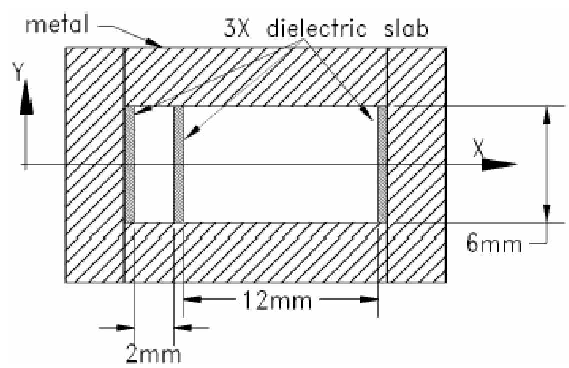

Figure 1: Cross-section of a two-channel DWA suitable for setting up transverse fields for deflecting bunches in the smaller channel by drive bunches moving in the larger channel. The dielectric here is Cordierite.

High fields can be sustained in ceramic dielectric structures [4] because the dielectric is exposed to intense fields for only a very short time, in this case, ~ 1 nsec. The response time of the unit is not determined by the slow filling time of the structure by electromagnetic energy, but rather by the much shorter time of the passing field pulses set up by the short bunches which generate the wakefield. Also, the structure is capable of micro-fabrication accuracy. The dielectric constants of such ceramics as alumina or Cordierite are flat in frequency in the relevant range and have no resonances that can complicate the operation of the device. They also have been found to not accumulate charge from passing bunches. We shall describe the wakefields that can be excited in our structure by a drive bunch, using a numerical code and analytic theory [3]. This theory has been validated by further studies of the problem using the Wakefield Solver Code of Microwave Studio.

PARTICLE DEFLECTION IN THE TWO-CHANNEL DWA KICKER

When this device is used as an accelerator, the witness bunch must be injected at a position along the axis of the

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structure where the transverse force on the particles is small, so that the bunch that is to be accelerated does not experience appreciable sidewise deflection. In Table I, we show parameters of a structure and bunch that are to be tested at the Argonne Wakefield Accelerator Facility (AWA). This 12-cm long module can be adapted to the present study by extending its length to 30 cm. In practice, the module does not need to be powered by a 14-MeV bunch; a relativistic bunch obtained from almost any rf photocathode gun would be suitable.

Table I: Parameters of DWA unit to be tested at AWA

LSM_{31} design mode frequency	29.965 GHz
acclerator channel width	2.0 mm
drive channel width	12 mm
structure height	6.0 mm
slab-1 thickness	1.237 mm
slab-2 thickness	2.288 mm
slab-3 thickness	1.051 mm
slab relative dielectric constant	4.76
drive bunch RMS dimensions, $2s_x$ ´ $2s_y$ ´ $2s_z$	6.0×2.0×4.0 mm^3
drive bunch energy	14 MeV
drive bunch charge	50 nC

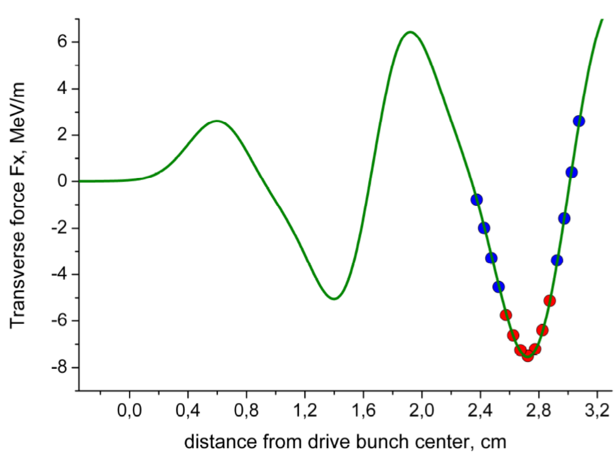

Figure 2: Computed transverse force from the wakefield behind the drive bunch, at the center of the witness channel. The dots represent axial locations of rows of test particles whose motions are described below.

In this module, the drive bunch sets up wakefields in the drive channel which are stepped-up in the witness channel by a factor akin to the Transformer Ratio; in this case this ratio is 12.6 and the axial wakefields are ~ 6 MeV/cm. However, when the device is operated as a kicker, the witness bunch to be deflected is injected where the transverse force is large; this force, ~ 8 MeV/m acting on a representative 1GeV witness bunch to be deflected, is shown in Fig. 2. The witness bunch is delayed a certain amount of time behind the drive bunch, so as to locate the witness bunch in a position where the deflecting force is large, e.g., z = 2.7cm. The transverse deflection X is given approximately by the formula

$$X \approx (F_x / 2\gamma m)\left(L / c\right)^2 ,$$

where L/c is the time for the witness particle to traverse the structure (1 nsec for L = 30cm). A 1-GeV electron would thereby be deflected approximately 0.3 mm or 1 mrad as it travels through the module. The X-component of transverse deflection of 1-GeV test particles in the 30-cm long version of the AWA test module is shown in Fig. 3. The deflection in the Y direction is much smaller. This shows that a witness bunch, 1 mm × 1 mm in cross section, will not contact the walls of the 2-mm wide witness channel during its transit through the structure. The particles lose approximately 1 MeV energy during this passage (decelerating phase of the F_z force). At AWA, it is expected that drive bunches as large as 100 nC may be expected, and this, together with improvements in transformer ratio, could result in comparable deflections for electrons ~ 5 GeV energy.

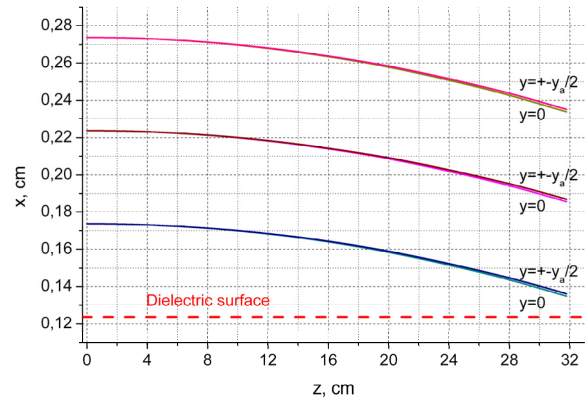

Figure 3: The X-position of 9 test accelerated particles moving through the 2-channel DWA structure.

How fast can the kicker act? The simple answer is the transit time through the structure, approximately 30 cm or 1 nsec needed to cause the deflection in the case of GeV electrons. Another bunch can be dealt with shortly thereafter, by roughly 1 nsec. The structure, once excited by the passage of the first drive bunch, allows the electromagnetic energy of the wakefield to drain away from the end at approximately the speed of light, so the next entering bunch should set up fields without complicated interference arising from any retained radiation from the previous bunch. This occurs because the openings at each end are large compared with the area of the dielectric slabs.

What about the perturbing effect of the DWA on a sequence of bunches we don't want to deflect? The kicker might be installed in a storage ring, and this ring might contain several bunches that we don't want to deflect (along with one we do want to deflect). What is the effect of the DWA on the bunches that are to be left undisturbed in the ring? Specifically, we take one of these to have Q = 1 nC, W = 1 GeV, and it passes through the witness channel (30 cm length) when there is no drive bunch accompanying it. We take this witness bunch to have $2\sigma_z$ =7 mm and its cross section to be 1 mm × 1mm. The questions are: what is the average drag field and energy loss of this bunch from the wakefield it sets up, and what deflection in its own transverse force field might we expect along its 30 cm travel distance? The computed drag field is such that the bunch loses about 30 keV in moving through the module, and the bunch center is deflected ~ 2 μm transversely; these values are small enough so that the undeflected bunches in the ring are not appreciably disturbed. The wakefields set up by this typical bunch contain only mW levels of power. The reason for this is that the unwanted wakefields depend on the bunch length that excites them: choosing the bunch length to be ~ the wakefield period (as we have done in this example) will minimize excitation.

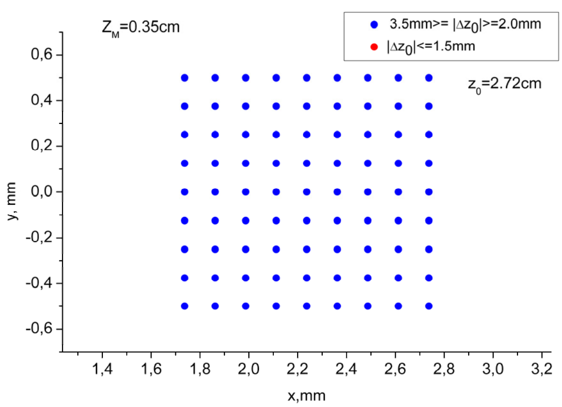

Figure 4a: Test particles at the input end of the DWA structure. Red particles are hidden behind blue ones.

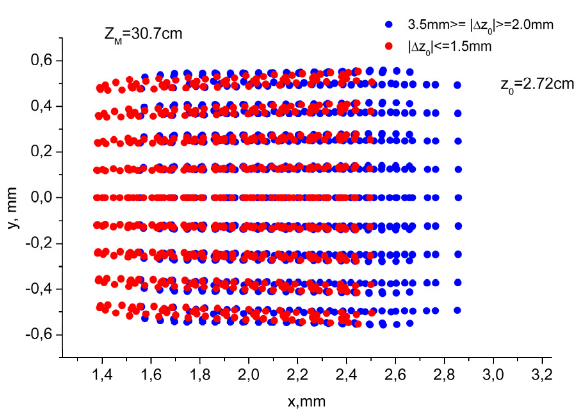

Figure 4b: Test particles at the output end of the DWA structure.

Next we show how this kicker can deflect a short (10 psec) slice of a longer bunch. An array of 9 × 9 × 15 test witness particles is positioned around the axial location z_0 = 2.72 cm as shown in Fig. 2; "red" particles lie within 1.5 mm of z_0 and "blue" particles lie between 2.0 and 3.5 mm. The grid (Fig. 4a) is approximately 1mm square (note, the blue particles hide the red ones). These test particles are followed first to the end of the structure (Fig. 4b) under the influence of the transverse force of the co-moving wakefield, and then allowed to move freely an additional 1m (Fig. 4c), where it is apparent that most of the red particles can pass to the side, and most of the blue particles can be intercepted by, a suitably-positioned beam stop. The selected group of red particles has pulse length ~ 10 psec.

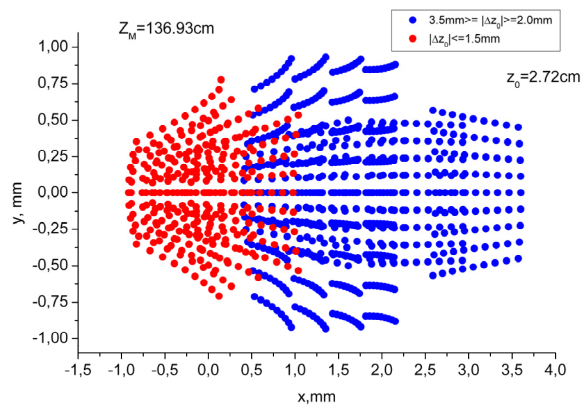

Figure 4c: The array of witness test particles after travelling an additional 1 m beyond the structure. Note the vertical (Y) focusing/defocusing.

The design of the kicker can be regulated by two factors: the choice of drive bunch parameters (charge, length, etc.) which determine the size of the wakefield transverse forces set up in the witness channel that can deflect all or part of the witness bunch, and the choice of structure dimensions, which affect the wakefield period and determine the distribution of power among the various excited modes. The deflection by the kicker can be controlled also by varying the timing between the drive bunch and the deflected witness bunch.

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