A COAXIAL TWO-CHANNEL DIELECTRIC WAKEFIELD STRUCTURE FOR TWO-BEAM ACCELERATION EXPERIMENTS AT SLAC*

G.V.Sotnikov[1,2#], T.C. Marshall[3,2], J.L. Hirshfield[2,4], , S.V. Shchelkunov[4]

[1]NSC Kharkov Institute of Physics and Technology, Kharkov, Ukraine
[2]Omega-P, Inc., New Haven Connecticut, USA
[3]Columbia University, New York City, USA
[4]Yale University, New Haven, Connecticut, USA

Abstract

Results of analytical and numerical investigations of a coaxial dielectric wakefield accelerator structure (CDWA) for experiments at FACET (SLAC) on two-beam acceleration are presented. For these experiments it is proposed to use ~1THz structure with two nested silica cylindrical shells having these diameters: outer shell, OD = 2mm, ID = 1mm; inner shell OD = 360µm, ID = 100µm. A conventional CDWA structure is energized by an annular drive bunch travelling in the annular vacuum channel. Our analytical studies prove clearly that an annular drive bunch can be substituted by a solid bunch having the same charge. For the simulation we used the SLAC drive bunch parameters: energy is 23 GeV, charge is 3nC, axial RMS size is 20µm, transverse RMS size is 10 µm. This bunch sets up at the central channel axis an accelerating gradient of ~1 GeV/m.

INTRODUCTION

The use of wakefields produced by a relativistic "drive bunch" charge moving inside a dielectric-lined channel to accelerate a following "witness" bunch has promise for making a linear Collider with gradient ~ 1-3GeV/m [1,2], and has received modest attention for the past 25 years [3-5]. More recently, there is experimental evidence [6], consistent with theoretical expectation [7], that certain dielectric materials can withstand the brief (nsec) pulses of high intensity radiation associated with passage of a drive bunch through the dielectric structure. Drive bunches having relativistic energy and charge of several nC can produce a train of THz wakefields having intensity > 1GeV/m in a hollow coaxial dielectric structure of mm-scale transverse dimension [8]. This, together with the use of a smooth-bore structure (DWA) that can accelerate positrons or electrons, has recommended the concept for further study as an "advanced" linear Collider accelerator module. The simplest structure, a hollow cylindrical dielectric tube with an outer metallic surface, in which the drive and witness bunches travel the same path, is unfortunately afflicted with stability problems, and its transformer ratio (**TR**) is no larger than 2. In order to avoid these problems, other structures, such as a wide rectangular channel lined with dielectrics [9] that is excited by a sheet beam, or a coaxial two-channel structure that is excited by an annular bunch, have been proposed and studied [8,10,11] computationally and analytically.

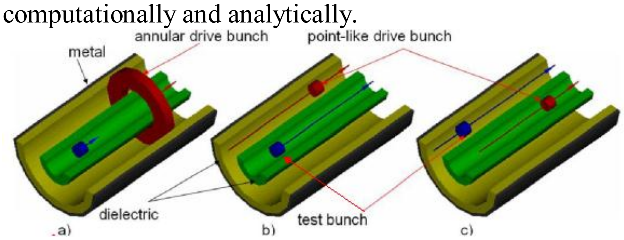

Figure 1: The CDWA structure excited in three different ways by a drive bunch (red), to accelerate a witness bunch.

We have planned at FACET (SLAC) proof-of-principle experiments E-207 to test a mm-scale THz CDWA. Because SLAC cannot provide at present a drive bunch of annular shape we propose to substitute such a bunch by a solid bunch having the same charge. In what follows, we shall show that a solid drive bunch will establish the same wake fields we wish to study. Furthermore, we shall show how we may obtain information from this study whereby the data can be compared with theoretical simulations obtained with the CST STUDIO code. This is possible because of the reciprocity principle [12].

We will consider three regimes of operation of the CDWA (see Fig.1): a) conventional CDWA; b) the CDWA with a point-like drive bunch that moves in the annular channel while the witness bunch accelerates along the central channel axis, c) "inverse" CDWA when the structure excited by a solid drive bunch that moves along the central channel axis while the witness bunch samples its wakefield as it moves along the annular channel. Certain of these field components are simply related, as we shall establish in the next section. This allows us to study regimes b) and c) at FACET, and relate the measurements made there to the desired operation with an annular drive bunch, conventional regime a).

CDWA UNIT FOR E-207 EXPERIMENTS

Parameters of CDWA structure under investigation are listed in Table 1. The CDWA structure with similar parameters will be tested at SLAC.

Table 1: Parameters used for THz CDWA

Frequency of dominant mode (E_{04})	473 GHz
External diameter of outer coaxial cylinder	2.0 µm
Inner diameter of outer coaxial cylinder	1.0 µm
External diameter of inner coaxial cylinder	0.36 mm

* Supported by the US Department of Energy, Office of High Energy Physics, Advanced Accelerator R & D.
#sotnikov@kipt.kharkov.ua

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Inner diameter of inner coaxial cylinder	0.1 mm
Relative dielectric constant ε	3.75
Bunch axial RMS dimension σ_z	20 µm
Outer drive bunch diameter (annular bunch)	0.83 mm
Inner drive bunch diameter (annular bunch)	0.53 mm
Point-like bunch transverse RMS size σ_r	10 µm
Bunch energy	23 GeV
Bunch charge, Q_{drive}	3 nC

In Fig.2 are shown axial profiles of axial wakefields for the conventional regime of CDWA operation when the structure is excited by an annular drive bunch traversing the annular vacuum channel. The maximum accelerating gradient in the central channel is 0.95 GeV/m, average decelerating force on drive bunch particles is 0.2 GeV/m, so the transformer ratio for this device is ~5.

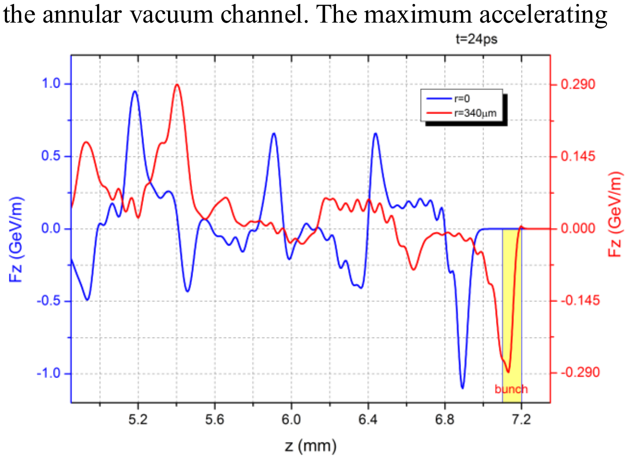

Figure 2: Longitudinal force axial profile at the center of the annular vacuum channel (red line) and at the central channel axis (blue line) in the case of conventional CDWA [8]. Yellow rectangle shows the location of the drive bunch particles.

The longitudinal component of force acting on a witness bunch for the three ways of excitation of the structure is given in Fig. 3. The component $F_z(z)$ is the same at corresponding locations where the witness bunch resides. The witness bunch in either of these cases would experience an accelerating force ~ 0.95 GeV/m if located at z ~ 5.18mm. This figure shows convincingly that an annular drive bunch can be replaced by a point drive bunch located in the annular channel, as we must do at FACET. Understanding is provided from analytic theory [8] where it is found that the on-axis longitudinal wakefield amplitude depends on an integral over the eigenfunctions $e_{zn}(r_0)$, where n is the radial index and r_0 is the location of an element of drive bunch charge. It turns out that the eigenfunction is nearly constant across the radius of the annular channel, so the integral is insensitive to the transverse bunch charge profile.

Furthermore, each azimuthal mode amplitude is proportional to the modified Bessel function $I_m(\kappa r)$

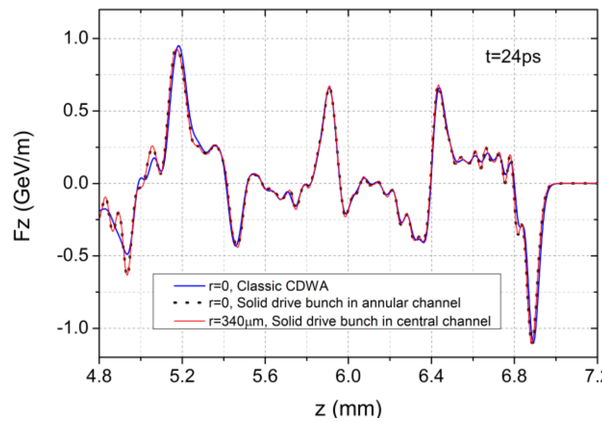

Figure 3: Axial profile of wakefield registered by witness bunch for three regimes of operation of the CDWA: a) blue line - conventional CDWA; b) black dots - solid drive bunch is in the annular channel, c) red line - "inverse" CDWA .

where κ is the transverse wavenumber and m is the Bessel function order. For regions close to the axis with $\kappa r \ll 1$, $I_m(\kappa r) \sim (\kappa r)^m$. Thus the only contribution is from the symmetric monopole term which is valid for the on-axis field from a point bunch and generally true for an annular bunch.

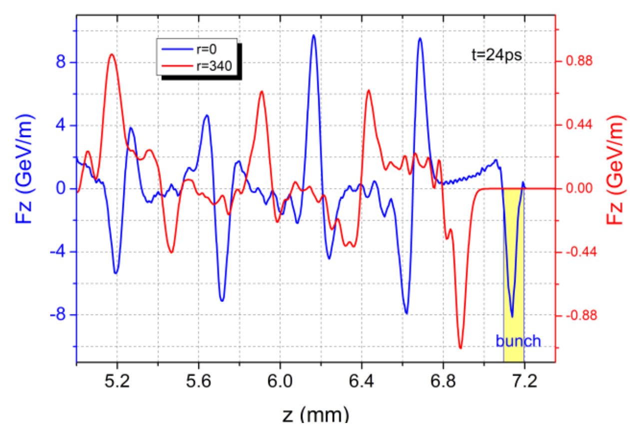

Figure 4: Longitudinal force axial profile at the center of the annular vacuum channel (red line) and at the central channel axis (blue line) in the case of "inverse" CDWA.

In Fig.4 are shown axial profiles of axial wakefields for the "inverse" CDWA. From Fig.4 it follows that the axial field along the central channel is then approximately one order of magnitude larger (~10 GeV/m) in comparison with excitation regime b), but the maximum wakefield in the annular space is again 0.95 GeV/m at z= 5.18mm, the same field that a point drive bunch located in the annular channel sets up in the central channel. This provides evidence that a reciprocity principle is governing "Green's function" excitation in a two-channel structure (for regimes (b) and (c), the source and the observation point are interchanged). This is key to linking the FACET experimental results to data that apply to the annular drive bunch operation.

In Fig. 5 we show maps of the radial wakefield $E_r(r,z)$

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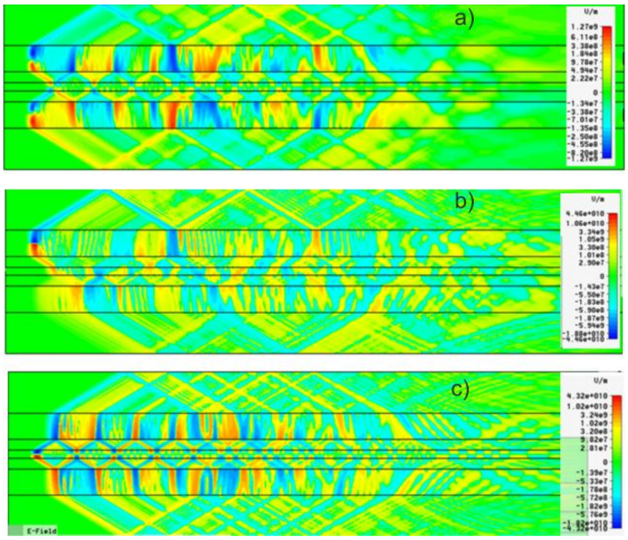

Figure 5: Transverse wakefield component $E_r(r,z)$ map for three operation regime (see Fig.1). Bunch moves right to left, length shown is 7.5mm. Note color scale changes.

for the three drive bunch cases shown in Figs. 1. We point out an interesting situation that applies to the fields at the outer surface when the drive bunch moves in the central channel: the fields at the metallic surface of the unit are modest here, unlike the case of the single-channel device [6] where high fields occur that can destroy the metallic coating.

DATA EXPECTED AND INTERPRETED

It is impossible to obtain data for the experiment E-207 by measuring the energy change of a witness bunch, at least insofar as FACET is presently structured. However, we can obtain and interpret the following data. We shall begin by observing the overall amount of THz radiation emitted by the device when the point drive bunch moves, respectively, in the annular channel and in the central channel. The intensity of the radiation, which scales as Q_{drive}^2, is proportional to the drag force exerted on the drive bunch by the wakefields it sets up. The ratio of the THz radiation signals for the two point drive bunch locations therefore provides the ratio of drag forces [for drive bunch in the central channel] / [for drive bunch in the annular channel], which is predicted by theory (in the ratio, calibration factors of the THz radiation diagnostic cancel) to be 4.0 for a unit with central channel ID = 150microns, and 5.3 when the central channel ID = 100microns. If we use the CST code to determine the energy loss of the electrons over a fixed distance of travel to determine this ratio, the 150micron channel ratio is 3.7 and the 100micron channel ratio is 5.7, a satisfactory check. Next, one can determine the energy loss of the drive bunch as it moves along the central channel. For the given bunch charge and channel diameter, we expect the average drag force to be ~ 5GeV/m, so the energy loss of the drive bunch should be $\leq$ 1.5% of its initial energy for a 6cm long unit, an amount that is within the capability of the FACET energy analyzer to measure. (At present the radial dimensions of the FACET drive bunch are somewhat too large to permit this measurement, but it is likely that the performance can be improved in the future). Now, combining this measurement with the THz measurement, we can infer the drag force of the drive bunch when it is located in the annular channel. This will permit us to compute the longitudinal component of wakefield in the central channel that is set up by the point drive bunch in the annular channel—and that, as we have shown in previous section, is the same as the longitudinal wakefield set up there by the annular bunch. In this way we can largely characterize the performance of this THz CDWA structure as it may operate in the future when it is excited by a high energy annular drive bunch (however, the energy of the drive bunch need be only ~ 5 GeV).

CONCLUSION

Our theoretical studies and numerical simulations show that for the wakefield experiments with our CDWA at FACET, an annular drive bunch can be replaced by a point-like drive bunch that travels in the annular vacuum channel or the central vacuum channel. Axial wakefields registered by the witness bunch travelling in the opposite vacuum channel will be the same as in the case of a conventional CDWA when the annular drive bunch traverses the annular channel. Simulated bunch motion for regimes b) and c) shows that the drive bunch will move with tolerable distortion a distance ~6-8 cm (the length of our unit for SLAC experiments). Data obtained from experiments with point-like bunches will allow us to draw conclusions about the accelerating gradient and transformer ratio in the case of a conventional CDWA.

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