Omega-P, Inc.

Final Report on DoE 2011 SBIR Phase I Grant DE-SC0006226
Topic 66a: Advanced Concepts and Technology for High Energy Accelerators
**HIGH-GRADIENT, HIGH-TRANSFORMER-RATIO
DIELECTRIC WAKE FIELD ACCELERATOR**

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Final Report on Phase I DoE SBIR grant DE-SC000 6226
Topic 66a: Advanced Concepts and Technology for High Energy Accelerators. *Advanced
Accelerator Concepts and Modeling*

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Work on this project was carried out by Omega-P, Inc. senior staff member Dr. Gennadij Sotnikov, by Omega-P, Inc. senior consultant Professor Thomas C. Marshall, and by Dr. Sergey Shchelkunov working under a sub-grant to Yale University. Dr. Jay L. Hirshfield, working as Principal Investigator, set goals for the project and coordinated activities of the participants.

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I. EXECUTIVE SUMMARY

The Phase I work reported here responds to DoE's stated need "...to develop improved accelerator designs that can provide very high gradient (>200 MV/m for electrons...) acceleration of intense bunches of particles." Omega-P's approach to this goal is through use of a ramped train of annular electron bunches to drive a coaxial dielectric wakefield accelerator (CDWA) structure. This approach is a direct extension of the CDWA concept from acceleration in wake fields caused by a single drive bunch, to the more efficient acceleration that we predict can be realized from a tailored (or ramped) train of several drive bunches. This is possible because of a much higher transformer ratio for the latter.

The CDWA structure itself has a number of unique features, including:

- a high accelerating gradient G , potentially with $G > 1$ GeV/m;
- continuous energy coupling from drive to test bunches without transfer structures;
- inherent transverse focusing forces for particles in the accelerated bunch;
- highly stable motion of high charge annular drive bunches;
- acceptable alignment tolerances for a multi-section system.

What is new in the present approach is that the coaxial dielectric structure is now to be energized by—not one—but by a short train of ramped annular-shaped drive bunches moving in the outer coaxial channel of the structure. We have shown that this allows acceleration of an electron bunch traveling along the axis in the inner channel with a markedly higher transformer ratio T than for a single drive bunch.

As described in this report, the structure will be a GHz-scale prototype with cm-scale transverse dimensions that is expected to confirm principles that can be applied to the design of a future THz-scale high gradient (> 500 MV/m) accelerator with mm-scale transverse dimensions. We show here a new means to significantly increase the transformer ratio T of the device, and thereby to significantly improve its suitability as a flexible and effective component in a future high energy, high gradient accelerator facility. We predict that the T of a high gradient CDWA can be increased by a substantial factor; this enhancement is dramatically greater than what has been demonstrated heretofore. This large enhancement in T that we predict arises from using a train of three or four drive bunches in which the spacing of the bunches and their respective charges are selected according to a simple principle that requires each bunch lose energy to the wakefields at the same rate, so as not to sacrifice drive beam efficiency—as would be the case if one bunch exhausted its available energy while others had not.

It is anticipated that results from the study proposed here can have a direct impact on design of the dielectric accelerator in a TeV-scale collider concept, and in the accelerator for an x-ray FEL.

II. IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM OR OPPORTUNITY, AND TECHNICAL APPROACH

IIA. Introduction

The DoE 2011 SBIR Phase I Program Solicitation sought grant applications under Topic 66a: *Advanced Concepts and Technology for High Energy Accelerators—Advanced Accelerator Concepts and Modeling*. There, grant applications were sought “...to develop improved accelerator designs that can provide very high gradient (>200 MV/m for electrons...) acceleration of intense bunches of particles.” Omega-P, Inc. submitted a Phase I proposal that was approved for study of a ramped bunch train (RBT) of annular bunches that are to drive a coaxial dielectric wakefield accelerator (CDWA) structure [1]. The present document summarizes results obtained from this Phase I study [2]. The experimental work proposed for Phase II will be done following completion in August 2012 of our currently funded Phase II study of the single-drive bunch CDWA (DoE SBIR Phase II grant DE-SC000-0924). The proposed study is thus a direct extension of the CWFA concept from acceleration in wake fields caused by a single drive bunch, to the more efficient acceleration that we predict can be realized from a tailored (or ramped) train of several drive bunches that is possible because of a much higher transformer ratio for the latter.

The CDWA structure itself has a number of unique features, including:

- a high accelerating gradient G , potentially with $G > 1$ GeV/m;
- continuous energy coupling from drive to test bunches without transfer structures;
- inherent transverse focusing forces for particles in the accelerated bunch;
- highly stable motion of high charge annular drive bunches;
- acceptable alignment tolerances for a multi-section system [3].

What is new in the present approach is that the module is now to be energized by—not one—but by a short train of ramped annular-shaped drive bunches moving in the outer coaxial channel. It shall be shown below that this allows acceleration of an electron bunch traveling along the axis in the inner channel with a markedly higher transformer ratio T than for a single drive bunch [2]. Fig. IIA.1 is a schematic drawing that illustrates the arrangement for a single drive bunch.

As described here, the module will be a GHz-scale prototype with cm-scale transverse dimensions that is expected to confirm principles that can be applied to the design of a future THz-scale high gradient (> 500 MV/m) accelerator with mm-scale transverse dimensions [1,3]. We show here a new means to significantly increase the transformer ratio T of the device, and thereby to significantly improve its suitability as a flexible and effective component in a future high energy, high gradient accelerator facility. We shall establish that the T of a high gradient CDWA can be increased by a substantial factor; this enhancement is dramatically greater than what has been demonstrated heretofore [4]. This large enhancement in T that we predict arises from using a train of three or four drive bunches in which the spacing of the bunches and their

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FIG. IIA.1. Schematic of the CDWA structure, showing a single annular drive bunch followed by an accelerated witness (or test) bunch that moves along the axis.

respective charges are selected according to a simple rule [2], as described in Section IIB. A principle that we seek to maintain in the choice of the drive bunch charges and spacings is to require that each bunch lose energy to the wakefields at the same rate, so as not to sacrifice drive beam efficiency—as would be the case if one bunch exhausted its available energy while others had not.

It is anticipated that results from the study proposed here can have a direct impact on design of the dielectric accelerator in a TeV-scale collider concept, and in the accelerator for an x-ray FEL. These designs are described in recent papers presented at the 2011 Particle Accelerator Conference (C. Jing *et al*, paper THP078) and at the 2011 International Particle Accelerator Conference (C. Jing *et al*, paper TUPO021).

Recently, interest in DWA physics directed toward an advanced high-gradient accelerator has been enhanced by a finding that some dielectrics can withstand very high fields (> 1 GV/m) for the short times during the passage of charged bunches along a dielectric-lined channel [5], as well as work showing that T can well exceed unity for a two-channel configuration [1]. In the first channel a drive bunch develops a high gradient wakefield which accelerates a witness bunch moving in the adjacent channel. A conventional RF linac can supply the drive bunches, whose energy can be efficiently coupled continuously to the witness bunches. However, other than high accelerating gradients, a two-beam accelerator should have other features, including a high transformer ratio, so as to minimize the number of drive beam segments needed to achieve a given final test beam energy. By virtue of its geometry, a two-channel structure can develop a larger transformer ratio than the single-channel collinear DWA (where drive and witness bunches move along the same path). But in addition we have found there is the possibility of independently controlling T for a fixed two-channel structure by varying the strength and timing of bunches in a train having as few as three or four bunches. In principle, high values of T can be achieved for structures composed of detuned resonant cavities [12], including dielectric-loaded cavities, when driven by long-train collinear beams moving along the structure axis. However, the concept discussed in this proposal is limited to instantaneous excitation of a non-

resonant (smooth) dielectric-lined waveguide by a train of only a few bunches, and thus would apply to an accelerator operating at a high repetition rate for the test bunches.

Transformer ratio T , a measure of the efficacy by which energy from a drive bunch is transferred to a test bunch in any two-beam accelerator, is typically < 2 in a collinear device, namely one in which the drive bunch and the bunch to be accelerated (“witness” bunch) travel along the same path [6-9]. T is customarily defined to be the ratio of the peak accelerating field seen by the witness bunch to the average energy loss of particles in the drive bunch [6,7]. On the other hand, some authors [4,8,9] use the ratio of the maximum energy gain of the witness bunch to the maximum energy loss of the drive bunch. Generically speaking, two means have so far been used to increase T . One is to use a train of drive bunches that have charges and spacings determined by a simple algorithm [4,10,11] [a “ramped bunch train” (RBT)] to drive wakefields in a collinear device; this has been demonstrated experimentally [4], where enhancement by a factor of 1.75 was obtained. Another approach is to decouple the drive and witness bunch channels entirely, and to transfer RF energy from the drive channel to the test channel using an intermediate transmission structure: as at CLIC [13] and the AWA facility [14,15]. In the latter experiment, $T = 3.4$ was obtained. Recent studies have considered the use of single ramped-current bunch to improve transformer ratio [16,17] in a single-channel DWA. However, unlike CLIC where the accelerating gradient is limited to ~ 100 MeV/m because of the metallic structure, the dielectric two-beam accelerator we are studying promises a gradient $\sim 300 - 900$ MeV/m. Also, the CDWA has a smooth bore structure that transfers energy continuously from the drive bunch to the test bunch, unlike CLIC where there are many side-coupled transfer structures.

Our recent efforts to develop a non-metallic two-channel coaxial wakefield accelerator structure that incorporates both channels in one assembly [1] has found that $T \sim 3 - 6$ on the axis of the second accelerating channel that carries a witness bunch, as depicted in Fig. 1A.1. A computational study has found that this configuration can stably transport a short train of drive bunches, as well as the witness bunch, satisfactorily [1,2,3]. Comparison of T for the ramped bunch train to that of the single drive bunch is taken here as a fair indication of enhancement in T . Unlike other projects that have investigated various methods to increase transformer ratio of the dielectric wakefield accelerator, ours focuses on the two-beam system, which starts with a structure that has an inherently larger transformer ratio.

Here we give an example to show how the performance of an accelerator is influenced by the transformer ratio. In a hypothetical dielectric wakefield structure, let us suppose that a single 14 MeV drive bunch sets up a gradient $G = 50$ MeV/m for the witness bunch, and suppose that $T = 4$. Drive bunch electrons, which should then lose energy at a rate of 12.5 MeV/m, would travel only 1.12 m while the witness bunch electrons would gain 56 MeV. Now, instead, suppose that a ramped train of several 14 MeV drive bunches in the same structure can provide only $G = 28$ MV/m, but that $T = 20$. In that case, the drive bunches can travel 10 m while the witness bunch gains 280 MeV. (The numbers for this illustration are based on examples in [2].) This example, which omits the influence of beam loading, illustrates the at-times advantageous trade-off between T and G : the higher- G /lower- T case leads to a shorter active length, but five times the

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number of drive beam segments, while the higher- T /lower- G case implies a longer active length but fewer drive beam segments.

In the following, we show that it is possible to employ the RBT technique in the two-channel CDWA structure to increase T . But not only can T be increased, it can also be *controlled*, as it is no longer determined by the structure properties and bunch parameters alone, but also by the structure of the ramped bunch train as well. In evaluating our results in a form useful for comparison, we take the definition of T to be the ratio of the peak accelerating field acting on the witness bunch to the (identical) maximum energy loss of each of the bunches in the drive train. We can compare our results for T for e.g. a four-bunch train with that for a single bunch having the same aggregate charge of all the drive bunches in the RBT. The ratios of bunch charges within the drive bunch train and the spacing between bunches that optimize T is specific to the structure being studied, but we find a considerable increase in T can be obtained. This is potentially a useful method to optimize an accelerator design that uses CDWA modules.

Full development of this concept requires solving related problems that impact wakefield physics. One such problem is to demonstrate that the CDWA can be driven by a single annular bunch or train of programmed bunches provided by a reliable source. ANL personnel have produced annular bunches in the past, and express confidence in being able to generate annular bunch or bunches as needed for the current and proposed projects. This is being partly addressed by the aforementioned currently-funded CDWA Phase II, and we show preliminary results in Section IIG.

Ultimately, another issue is that of suspending the central dielectric tubing, required for a full-scale facility. We advocate for that the use of a flexible supporting carbon nanotube fiber filament (a few microns in diameter) that is very strong and by virtue of its low Z should scatter few electrons in the drive bunch. The central tubing could be centered by a servo-mechanism acting on the fiber that is linked to an alignment diagnostic. This will require a separate development project. We believe that such a development project is best motivated by experiments such as are described in this proposed Phase II, that can generate justifiable enthusiasm and a sense of priority for the CDWA concept.

Recently, we published [18] a paper on our experimental findings regarding a two-channel *rectangular* dielectric wakefield accelerator. In addition to confirming the validity of our numerical studies (Fig. IIA.2) obtained using the same methods as we propose below, it also turns out that that this rectangular structure can function as a practical “fast kicker” (<1 ns) [19] that might find use e.g. in a synchrotron facility where a small part of a circulating bunch requires transverse deflection out of the ring.

Fig. IIA.2. Experimental data (above) and computational/theory modeling (below) from our recent rectangular DWA experiment at AWA. Left: energy gain of witness bunch, for drive bunch “on” or “off”; right: deflection of witness bunch (note different witness bunch delays in the left/right cases). “Pos” refers to horizontal location of drive bunch.

We have also found that a short drive bunch in a mm-scale THz CDWA can produce prodigious quantities of THz radiation ($\sim 1\text{J}/\text{shot}$, power level $\sim 5\text{GW}$) that might find application in security work where a pyroelectric camera image of a large object is required. Such a mm-scale THz structure has been approved by FACET for testing at their facility in June 2012; this device will develop $G \sim 1\text{ GeV}/\text{m}$ using their drive bunch.

IIB. Technical Approach

Task 1 of the Phase I proposal committed Omega-P to seek designs for a microwave-scale CDWA ramped bunch train prototype for study at ANL in order to identify the capabilities and potential problems of this concept with respect to a future high-energy accelerator. In this section, a brief introduction and commentary is made for the physics involved in these designs. Phase I tasks have been carried out by part-time Omega-P scientist Dr. Gennady Sotnikov, otherwise employed at Kharkov Institute of Physics and Technology (theory and simulation); consultant Professor Thomas Marshall of Columbia University (theory and solution of technical problems); Dr. Sergey Shchelkunov of Yale University working under a sub-grant from Omega-

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P (equipment design, construction, and experimental testing); and principal investigator Professor Jay Hirshfield of Yale University and Omega-P (supervision, theory, and solution of technical problems). The project has been assisted by staff at ANL (particularly Dr. Manoel Conde), who are expected to be collaborators in the forthcoming experiments.

We now proceed to illustrate how the new algorithm for determining the bunch train charges and spacings will improve the transformer ratio of a specific design of CDWA, such as we shall study at AWA in a series of experiments. We take the definition of transformer ratio as the ratio of the peak wakefield following the drive bunch train to the peak energy loss of the drive bunches. We make use of the PIC Solver of the CST Particle Studio, which is part of the CST Studio Suite 2010 bundle. Figure IIB.1 illustrates how the ramped bunch train is prepared using CST: a series of “virtual” cathodes within the CDWA structure emit the bunches with the required charge and spacing. (This trick was required because a single cathode in CST can only emit bunches having the same charge.) The virtual cathodes are imagined to be made of non-perfectly-electrically-conducting material having unity permittivity and permeability (namely, vacuum) and they are transparent to electrons. The charge, initial energy, and initial shape of the bunch are specified at the surface of the virtual cathode.

Fig. IIB.1. Layout of the computational CDWA structure. At the right side are shown 4 cathode rings that emit 4 different bunches along the longitudinal axis. Bunches travel from top right to bottom left in the annular space between the two dielectric cylinders.

We next determine if there is some choice of drive bunch charges and spacings that will improve T , but yet result in a potentially sizeable wakefield amplitude. To obtain improved transformer ratio we proceed from the following, which is strictly proved for the collinear single-mode device: wakefields with maximum transformer ratio are generated by drive bunches whose particles lose the same energy [10,11]. From this fact it follows that for a train of point bunches with repetition period equal to a half wakefield wavelength (or one and a half wavelengths), to obtain the maximum transformer ratio the bunch charge should rise from head to tail in the train as the ratios of odd integer numbers. For the Gaussian longitudinal density of a bunch the charge Q_n of the n^{th} bunch should change according to the relation $Q_n = Q_1[1 + T(n-1)]$, where Q_1 is the charge of the first bunch, and T is the transformer ratio from a single bunch [11]. In the case of a multimode device, such a simple formula does not exist, therefore to obtain desirable locations of bunches and values of their charges it is necessary to run simulations, the number of

which is equal to the number of bunches in the train. First, a calculation with one bunch is carried out, a location of the maximum of an accelerating field in the drive bunch channel is determined, and at this location the second bunch is placed and a new calculation of structure excitation is performed. At the location of the second bunch, the superposition is such that the field there becomes decelerating. Then, each subsequent drive bunch is to be located at the maximum of the accelerating field from the prior bunches, and the charge of the n^{th} bunch is set according to the formula: $Q_n = Q_1[1 + T_{n-1}]$, where T_{n-1} is the transformer ratio after the $(n - 1)^{\text{st}}$ bunch.

An illustration of improved transformer ratio is provided by the results shown in Figs. IIB.2 and IIB.3. In Fig. IIB.2 the spacing of three equally-charged bunches is one wakefield period so that the wakefield is built up to maximum amplitude; the resulting transformer ratio is 3.25, which is approximately the same transformer ratio as is obtained for a single bunch having the same total charge with this design. In Fig. IIB.3 is shown the wakefield set up by a train of three ramped bunches for which the spacing between the bunches is approximately 1.53 wakefield periods and the charge ratios are 4.5:2.75:1, also maintaining the constant total drive bunch charge at 30 nC. The T from the last bunch is 7.9, a factor of 2.4 times as large as the T for the simple 3-bunch train of equal charges spaced by one wakefield period. Notice the peak wakefield amplitude following the third drive bunch in the central channel is only $G = 9$ MeV/m, down from 12 MeV/m in the uniform drive train case. This prescription for the drive bunch charge and spacing was obtained by striving for uniform drive bunch deceleration, which in this case is found to be approximately 1.1 MeV/m. This example establishes that a considerable enhancement of T is possible with only a few bunches in a multimode CDWA structure using this flexible RBT method. The more complex algorithm (in comparison with [4,11]) for the bunch charge distribution and bunch locations is related to the multimode excitation of the CDWA (Fig. IIB.2 shows the multimode behavior of the wakefield excited by a single drive bunch). Of course, for single-mode structures, the conventional algorithm applies.

Fig. IIB.2. Wakefield set up by three equally charged bunches (total, 30 nC) spaced apart by one wakefield period. Red curve is axial force $F_z(z)$ behind the train of annular drive bunches in the annular space; blue curve is $F_z(z)$ in the central channel where a witness bunch might be located.

Fig. IIB.3. Wakefield set up by a train of ramped bunches, total charge = 30 nC. One notes the enhanced transformer ratio, as compared with that in Fig. IIB.2.

An exploded view of the CDWA structure we intend to use in Phase II is shown in Fig. IIB.4. The dominant modes of our structure that are excited by the bunch train, are at 13 and 46.5 GHz. The structure uses two nested thin cylinders of alumina, obtained from Ortech Ceramics, the outer one of which is coated with UHV deposited copper. The annular bunches set up a wakefield which is directed onto the common cylinder axis where a suitably-delayed witness bunch having small charge is to be accelerated by these wakefields. The front and rear aligners hold the ceramic tubes, and are spaced apart on the mounting platform (purple). The aligners space and support the suspended inner dielectric cylinder by three narrow vanes made of stainless steel. While these vanes intercept narrow portions of the annular drive bunch, they should cause little trouble for the experiment, as it is only 10cm in length. The drive bunch may be entirely intercepted by a beam stop (not shown in Fig. IIB.4) at the exit end of the unit; or a small portion of it, and the witness bunch, may be diverted to the diagnostic hardware, chiefly the AWA energy analyzer (not shown). Aperturing of the drive bunch by mean of a small hole in the beam stop is necessary so that accurate energy measurements may be made. Not shown is hardware for positioning and aligning the unit in its vacuum chamber.

Formation of an Annular Beam. It is obvious that tests of the performance of the CDWA structure described above rest upon availability at ANL/AWA of a sequence of suitable annular bunches. For single-bunch experiments, with a test module similar to what is depicted in Fig. IIB.4 that is currently awaiting installation at AWA, preliminary results have already been obtained by J.G. Power at ANL on formation of annular bunches. The basic technique used is to illuminate the photocathode in the RF gun where the bunch is created with an annular laser beam, rather than a beam with a Gaussian profile. The annular bunch must then be transported, magnified, and focused to the diameter needed for the experiments. While this exercise is ongoing at the time of writing of this proposal, initial results indicate that success will eventually result in formation of a suitable annular bunch profile. Generation of a tailored sequence of such annular bunches will use a laser beam splitting technique described in Section IV. Images of annular beam profiles obtained by Dr. Power are shown in Fig. IIB.5.

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Fig. IIB.4. Exploded view of the CDWA structure.

Fig. IIB.5. Images obtained by Dr. J.G. Power of ANL showing preliminary results on formation of an annular bunch. In this case, the outer diameter of the bunch is about 40 mm. Marked non-uniformity of the bunch is clearly in evidence, indicating that further adjustment in laser illumination and cathode uniformity are needed—and are planned—to to create a bunch suitable for the planned single- and multiple-bunch experiments.

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While ANL colleagues express confidence that the bunch profile can be improved by future work, the irregular shape of the drive bunch shown in Fig. 1B.5 raises the question of how such irregularities—unavoidable to some degree in any experiment -- may affect the measurements we plan to make. Analysis shows that these irregularities should have little effect on the axial wakefield force experienced by the witness bunch. From analytic theory [1] it is found that the on-axis longitudinal wakefield force amplitude depends on an integral over the wakefield eigenfunctions $e_{zn}(r_o)$, where n is the radial index and r_o is the location of an element of drive bunch charge. It turns out that these eigenfunctions are 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 $I_m(\kappa r)$ where κ is the transverse wavenumber and m is the Bessel function order. For regions close to the axis with $\kappa r \ll 1$, one has $I_m \sim r^m \sim 0$ for $m \geq 1$. Thus the only contribution is from the symmetric monopole ($m = 0$) term; this is valid for the on-axis field from a point drive bunch and generally true for an annular drive bunch such as shown in Fig. 1B.5. This argument would not apply to the radial force, which could deflect and distort the witness bunch due to lack of drive bunch azimuthal symmetry; however, our test module is too short for such effects to become important.

III. DEGREE TO WHICH PHASE I HAS DEMONSTRATED TECHNICAL FEASIBILITY

IIIA. Introduction

In this section we describe the technical accomplishments of the Phase I High-Gradient, High-Transformer-Ratio Dielectric Wakefield Accelerator project (referred to henceforward as “RBT” after “ramped bunch train”). First among these, as previously mentioned, is the publication of a paper in *Physical Review Special Topics – Accelerators and Beams* [2] in 2011 which presents a study of a CDWA structure that is excited by a train of ramped charge bunches, prepared according to our new algorithm. This published paper provides a basis for what follows, and for the examples that illustrate the results we expect to obtain in an experiment to be done at AWA. The first comprehensive theory underlying the CDWA was published in 2009 [1]; it provides the basic theoretical understanding of the two-channel coaxial dielectric structure. In this section we summarize results that were listed as goals of our Phase I project. These are divided into six parts, so as to address the specific Tasks set forth in the Phase I proposal.

As for achieving results of experiments with two-channel dielectric structures, the publication In 2012 of our paper in *Physical Review Special Topics –Accelerators and Beams* [18] shows our capability to obtain and interpret data of the type we seek in the proposed RBT project.

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IIIB. Design for the AWA Structure and T Enhancement (Tasks 1,5)

By way of introduction to what follows, we begin by showing maps of the axial and radial wake electric fields in our CDWA structure that result from the passage of one 30 nC annular drive bunch (Fig.IIIB.1a,b). (It should be noted that the electric fields are not the same as the force fields that act on the particles.) We have shown previously [1,11] that the motion of the annular bunch is more stable than a point-like drive bunch in a single-channel structure, and that a witness bunch (or test bunch to be accelerated in the central channel) is stable against radial motion as it moves along the central channel.

Fig. IIIB.1a. Map of electric wakefield axial component $E_z(r,z)$. The annular bunch has traveled from left to right. Black lines indicate dielectric boundary surfaces in cross-section.

Fig. IIIB.1b. Map of electric wakefield radial component $E_r(r,z)$; annular bunch is at right. Note that the electric field in the outer dielectric shell adjacent to the metallic boundary is not large.

Thus, this structure enjoys advantages that recommend it for further study as a high energy accelerator, despite the complication of suspending the central dielectric tube—to be discussed below. A series of bunches with adjustable charge and spacing will reinforce the fields and/or T .

The AWA facility, which has undergone an upgrade recently, provides individual drive bunches with a charge up to 50 nC and energy of 14 MeV, so the design described here uses the appropriate charge, energy, and dimensions of these bunches, and the equipment we will provide in Phase II can be accommodated in a test chamber compatible with the AWA beamline hardware and vacuum requirements. Furthermore, the train of bunches that we propose to employ has an overall length that can be generated by the AWA laser, rf gun, and linac system,

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albeit with somewhat different bunch energies which are not a problem for the success of our study. The constraints are as follows:

1. The overall length of the annular drive bunch train together with its following “point-like” witness bunch should be substantially less than the quarter-period of the AWA rf source that powers the gun and linac. This rf source is 1.3 GHz (23-cm wavelength) so the quarter period is 5.75 cm. As it turns out, the bunch train we wish to create would be ~2-3 cm in overall length.
2. The length of the apparatus should be enough to set up wakefields that will generate measurable energy changes of the bunches and yet permit transport of the bunches through the hardware without requiring a complicated arrangement of transport elements. We have chosen to make the apparatus 10 cm in length and enclose it completely in its own vacuum chamber. This has worked satisfactorily for us in our past study of a *rectangular* DWA structure [18], and we are using the same chamber for these experiments as for our current CDWA single annular bunch experiment.

Table I lists the parameters of the structure and the bunches we are proposing to use. These structure dimensions are approximately one-half those of the CDWA being studied now at AWA for single bunch operation. The alumina dielectric can be obtained from Ortech Ceramics, and is available in the desired sizes. The mounting hardware (Fig. IIB.4) is also a scaled down version as well.

Table I. Coaxial structure (using Ortech alumina)

external radius of outer coaxial cylinder R_e	6.35 mm
inner radius of outer coaxial waveguide R_i	4.77 mm
accl. channel radius (inner radius of inner coaxial cylinder) a	1.20 mm
external radius of inner coaxial cylinder b	1.98 mm
relative dielectric constant ϵ	9.8
bunch axial RMS dimension $2\sigma_z$ (Gaussian charge distribution)	1.0 mm
outer drive bunch radius (box charge distribution)	4.12 mm
inner drive bunch radius	2.62 mm
bunch energy	14 MeV

The results we describe in this section depend on assumptions we have made about the drive bunch charge and its charge distribution. For these, we have used parameters in the range provided by AWA. The radial distribution of charge in the bunch has been simplified to a box

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distribution. We next show results relating to the building-up of the transformer ratio in this structure; these relate to the Tasks 1a and 1b of the Phase I project and we use our algorithm [2] for increasing T by choice of bunch spacing and charge. Fig. IIIB.2 shows the computed (simulated) longitudinal accelerating force $F_z(z)$ acting upon a test charge moving along the central axis of the device (in blue), and also along a line centered on the annular bunch and extending along the annular space (in red). [$F_z(r)$ is nearly constant across the annular channel.] The drive bunch, shaded in yellow, has moved from left to right so that its head is located at $z = 168$ mm; we have taken its charge to be 30 nC. The drive bunch is taken to have a Gaussian charge distribution along the axis, with $\sigma_z = 1.0$ mm, but the wings of the Gaussian are truncated so that its full length is 5 mm. At 152.4 mm, the peak longitudinal force $F_z = G = 25.3$ MeV/m, which corresponds to $T = 2.9$ when figured on the maximum drag force inside the drive bunch of 8.66 MeV/m. (For simplicity in interpreting and comparing the forthcoming results, we have taken the definition of T here to be the ratio of the peak acceleration force on the witness bunch to the peak deceleration force acting within the drive bunch.) It is clear that the 46 GHz mode, wavelength = 6.44 mm, is being excited by the drive bunch. If additional drive bunches (totaling 30 nC) are arranged to reinforce the wakefield by spacing them by the wakefield period, we find that the transformer ratio, $T = 3.25$ (Fig. IIB.1), is changed only slightly.

Fig. IIIB.2. Axial force profiles along the center of the annular channel (red), and along the axis of the central channel (blue) set up by a single (yellow) 30nC $\sigma_z = 1$ mm annular drive bunch that extends to 5mm total length.

Fig. IIIB.3 shows the distribution of drive bunch particle energies at the end of the run (in this case, for a unit length of 16.5cm); notice the spread of particle energies is about 1.6 MeV. Maintaining the total charge at 30 nC, we now add a second bunch (Fig. IIIB.4), whereupon we find T increases to 5.26, while the peak wakefield amplitude decreases to $G = 12.7$ MeV/m.

Fig. IIIB.3. Distribution of drive bunch particle energies from single bunch operation.

Fig. IIIB.4. Same as Fig. IIIB.2, but now two drive bunches having total charge 30 nC and spaced ~ 1.5 wakefield periods of the 6.44 mm wakefield mode. The bunch charge ratios are 2.75:1. Second bunch has the most charge.

Next (see Fig. IIIB.5), maintaining the total charge of the train at 30 nC, we use three drive bunches and program their charges and positions as described in reference [2]. The ratio of charges is taken to be 4.5:2.75:1 and we find that T has increased to nearly 8 while the peak accelerating axial force declines to $G \sim 9$ MeV/m. Fig. IIIB.6 shows the bunch train, and Fig. IIIB.7 shows the energy distribution of drive bunch charges. Comparing Fig. IIIB.7 with the corresponding one for the single drive bunch, the spread of energies of the drive bunch particles has narrowed from 1.6 MeV to only 0.3 MeV, whilst the overall energy loss has decreased. Thus, although the gradient has decreased, all particles now lose nearly the same energy, 1.13 MeV/m, as is also evident from examining the drag forces on the three bunches in Fig. IIIB.5.

Fig. IIIB.5. Wakefields set up along the annular channel (red) and central channel (blue) by three programmed drive bunches.

Fig. IIIB.6. Time profile of the three drive bunches described in Fig. 2B.5. The bunch RMS width $\sigma_z = 1.0$ mm and each bunch length is truncated at 5 mm.

Fig. IIIB.7. Energy distribution of the three ramped drive bunches in Fig. IIIB.5 at 165 mm.

Finally, we show in Fig. IIIB.8 wake fields due to four ramped drive bunches, again having total charge = 30 nC, in charge ratios 6.06:4.5:2.75:1. The T is now 9.7. Comparing the length of the three drive bunch plus witness bunch train (29.5 mm) with the four drive bunch plus witness bunch train (41 mm), we believe a three drive bunch train will be suitable to demonstrate the effects we wish to study, while the four drive bunch train may be too long compared with the 57.5 mm quarter-period of the AWA accelerator system. The three bunch train length extends ~ 2 cm, so the individual energies of the drive bunches may be expected to vary by ~ 2 MeV out of 14 MeV; this variation of bunch energy has not presented problems in bunch transport in the past (e.g. Sec IIE), and indeed may be helpful to distinguish the individual bunches as detected by the energy analyzer.

Investigation of a different structure design has demonstrated [2] an improvement of T from 3.25 to 17; thus the results obtained above depend on the bunch and structure properties. For our example (Table I), the structure design was constrained by the need to provide the three or four ramped bunches from the given rf linac system at AWA.

Fig. IIIB.8. Wakefields resulting from a four-drive-bunch train.

IIIC. Bunch stability study (Task 6)

To study the stability of the drive bunch train, we make use of the PIC Solver of the CST Particle Studio, which is part of the CST Studio Suite 2010 bundle. We have chosen the total charge to be 30 nC, which we believe will not tax the AWA rf photocathode gun system unduly. The stability of the bunch train has been studied to ensure the bunches remain mostly undisturbed as they move along the apparatus. This is shown in Fig. IIIC.1, which gives an end-on view of the complete three bunch train (above, a) and a side view of the train, after it has moved 18.7 cm (below, b). This distance of motion is larger than we plan to use in the experiment, and it shows that the bunches are not appreciably distorted (the last bunch, which has the largest charge, shows the most distortion), nor do particles contact the walls. It should be noted that the low (14 MeV) energy and high charge of these bunches makes the transport more

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challenging than for the more likely application where several GeV drive bunches with lower charge would be used (Section IIE). The stability of the witness bunch in the CDWA has already been found to be excellent [1,3]. Further work to identify the cause of distortion shown in Fig. IIIC.1 needs to be done.

Fig. IIIC.1. Motion of the 14-MeV ramped drive bunch train (moves right to left) shown at $t = 0.622$ ns from entry. Front view (top) and side view (bottom) of the bunch train studied in Fig. IIIB.5. Total charge of the bunch train = 30 nC.

IIID. Tradeoff between transformer ratio T and gradient G (Task 8)

The results presented in Section IIIB indicate that as the transformer ratio increases, the acceleration gradient decreases. While this is generally true, the details of this relationship depend on the specific properties of the structure and the bunches. A natural question arises as to how robust this method of optimization of the transformer ratio will be; namely, its sensitivity to fluctuations in charge distribution between the bunches or changes in the distances between the bunches. To answer this question, we performed a series of computations for a four bunch train in which the ratio of the last bunch charge Q_4 to the first bunch charge Q_1 was varied, while the other parameters of the bunch train, including total charge, were fixed. The results of computations are shown in Fig. IIID.1 for a choice of parameters given in reference [2].

Maximum transformer ratio of 18.6 is achieved for the charge ratio $Q_4/Q_1 = 4.8$. Decreasing the charge ratio from optimal by 10%, the transformer ratio falls to a value of 17. Increasing the optimal charge ratio by 10%, transformer ratio falls to a value 13.8. Thus we can conclude that 20% uncertainty in the RBT charge distribution does not cause a catastrophic change of the transformer ratio. From these computations we find also the accelerating gradient is even less sensitive to the charge fluctuations. For the same 20% range of the charge variation the value of the accelerating gradient changes from 26.7 to 29.5 MeV/m.

Fig. IID.1. Transformer Ratio (blue symbols) and accelerating gradient (black symbols) versus the ratio of the last bunch charge to the first bunch charge. The structure and system parameters for this computation are given in reference [2].

IIIE. Enhanced transformer ratio T for a THz Structure (Task 7)

We have studied the applicability of the ramped drive bunch train for three bunches that drive a high gradient THz CDWA structure [2]. This study is repeated here using a new example. One question is whether the removal of wakefields due to the group velocity's phenomena [20] will permit the superposition of wakefields from the train of delayed drive bunches, because the THz structure is very lightly loaded with dielectric and thus the wave group velocity is very close to the particle velocity. It turns out that indeed all three drive bunches do not completely outrun the back front of the Cherenkov radiation in the short distance that we can study here. However, the back front of the wakefields does drop back significantly from each bunch of the train, enough so that one may locate the following bunch as to engage the desirable effect of wakefield superposition that results in an enhanced T . Thus this RBT technique can find application in small mm-scale, THz collider-type structures. An example of this is shown in Fig. IIIE.1a for a silica dielectric CDWA structure (Table II) that has a radius 1.0 mm, where it can be seen that the wakefield amplitude builds up progressively behind the three programmed drive bunches. The three 23 GeV annular drive bunches with charges totaling 3 nC and RMS

length factor $\sigma_z = 20 \mu\text{m}$ set up a peak longitudinal wakefield amplitude of 349 MeV/m with $T = 6.9$, which is to be compared with a wakefield $\sim 950 \text{ MeV/m}$ with $T = 3.2$ from a single 3 nC bunch (Fig. III.E.1b). This example is modeled on a THz structure that we will be testing with a single “point” bunch at FACET in the future (not as part of this grant proposal). Thus, it shows that the ramped bunch train, when exciting a THz collider-type structure, can provide not only satisfactory transformer ratio but also a high gradient. However, we point out that a lower energy drive bunch train would be more suitable than the SLAC 23 GeV bunch in an actual application. This design uses a sturdy silica supporting tube into which is positioned and supported a smaller silica inner tube. The outer tubing surface must be coated with a metallic film.

Table II. Paramaters for a fused silica THz structure and bunch.

External radius of outer dielectric tube R_e	1000.0 μm
Inner radius of outer dielectric tube R_i	500.0 μm
External radius of inner dielectric tube r_e	180.0 μm
Inner radius of inner dielectric tube r_i	50.0 μm
Relative dielectric constant ϵ : (fused silica: http://www.technicalglass.com/technical_properties.html)	3.75
Bunch axial RMS dimension σ_z (Gaussian charge distribution)	20.0 μm
Bunch energy	23 GeV
Bunch charge	3nC

Fig. III.E.1a. Transformer ratio enhancement by *three* programmed annular drive bunches in a THz CDWA. Maximum drag forces (red) on the yellow drive bunches are $\sim 50 \text{ MeV/m}$. The turquoise rectangle is at the location of a possible witness bunch.

Fig. III.E.1b. Wakefields set up by a *single* annular drive bunch: maximum gradient (blue curve) is 0.95 GeV/m, maximum drag (red curve in yellow bunch) is 0.29 GeV/m.

If we increase the drive bunch length parameter to $\sigma_z = 40 \mu\text{m}$, then the transformer ratio is found to increase from 3.3 (single bunch) to 9.2 (three ramped bunches, see Fig. III.E.2). If the bunch train were to consist of only *two* bunches, the transformer ratio becomes 6.4, nearly as large as the three ramped bunch case of Fig. III.E.1a; and the accelerating gradient is then 440 MeV/m rather than 332 MeV/m.

Fig. III.E.2. Effect of increasing the bunch length to $\sigma_z = 40 \mu\text{m}$ on the transformer ratio of a three ramped bunch train. Turquoise box shows location where a test bunch to be accelerated would be located.

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This latter example helps answer the question: “why is a ramped bunch train necessary?” The design of the two-channel structure may depend on a variety of possibilities and needs related to the facility in which it operates (e.g bunch length, as above). The ramped train allows T to be chosen to secure another advantage, that of improving the efficiency of the overall device by arranging that all drive bunches lose energy at the same rate. We find that a train of only 2-3 ramped bunches are sufficient to demonstrate this effect, and to already secure an efficiency advantage.

The THz structure generates prodigious quantities of THz radiation. An example of the spectrum of radiation produced by a single “point” 3 nC bunch that travels along the central channel of the device is shown in Fig. IIIE.3; the bunch excites several THz modes. The total peak power radiated is computed to be 4.8 GW. The radiation scales as Q^2 , and a much lower bunch energy than 23 GeV would be satisfactory providing the bunch length is appreciably less than the wavelength ($\sim 300 \mu\text{m}$). This aspect of the work we describe relates to areas of potential commercialization, e.g. security, particularly involving large objects where high power would be required for pyroelectric imaging.

One might inquire why a single-channel DWA might not be a simpler alternative to the CDWA in this THz –production application. In both single- and two-channel structures the outer surface of the dielectric should be coated with a metalized film to retain the radiation within the structure. In the single channel DWA, the fields are very intense at the outer surface and may vaporize the metallic surface coating, whereas for the CDWA the fields are much weaker there (Figs. IIIB1.a,b). Therefore, we expect very little trouble from breakdown at the metal film due to the high wakefields that are largely “confined” within the inner dielectric structures of the CDWA.

Fig. IIIE.3. Spectrum of emitted THz radiation.

IIIF. Measuring Transformer Ratio (Task 3)

Determination of the transformer ratio will is an important task. Referring to Section IIIB and Figures IIIB.3 and IIIB.7, the task is straightforward if the spectrum of particle energies can be determined (for both decelerated drive bunch particles and accelerated witness bunch particles) with sufficient accuracy. In connection with measurements made with the AWA equipment for our rectangular DWA experiment [18] we have found that accurate energy measurements to within $\sim 25 - 50$ keV can be made on witness bunch electrons when the drive bunch charge is ~ 15 nC. But, as we have also found in that experiment, the *drive bunch* energy loss measurement presents challenges because of its large charge (which may introduce errors due to space charge effects) and smaller energy loss (compared with the witness bunch). The space charge effect will be much less important in the CDWA and RBT experiments, because the annular bunch will have lower charge density than a “solid” point-like drive bunch; also a small hole in the drive bunch beam stop can be used to form a “beamlet” that can be directed into the energy analyzer. To determine the drive bunch energy loss, we find the spectrum of energies will extend from a maximum energy loss to a minimum energy loss. The latter is zero, because electrons at the leading edge of the first drive bunch suffer no energy loss and maintain their injected energy as the bunch moves.

Nevertheless, we have studied other methods to determine T that do not involve measuring the energy distribution of the drive bunch, only a low charge witness bunch. We briefly describe these in what follows, although we intend to pursue the study further as need arises. The new method to measure T does not change the configuration of the CDWA. It involves measurement of the energy change of a witness bunch, and by a second (smaller) witness bunch located behind the first witness bunch (both located on the structure axis). It is a two-step measurement. Let us begin by taking the simple case of a wakefield set up by a single drive bunch. First, the energy increase of a witness bunch Q_{ac} is measured when it is positioned on the axis in an accelerating force maximum (E_z^d) of the wakefield in the central channel set up by the single drive bunch Q_d that moves in the annular channel. Then, with no drive bunch, the energy change of a second witness bunch, also on the axis, having even smaller charge and trailing the first witness bunch is obtained, to measure the longitudinal force maximum (E_z^{acc}) of the wakefield set up by the leading witness bunch. For the wakefield set up by the leading witness bunch at the axis of the central channel we compute, using a single mode assumption and beginning with Eq. 39 of [1] using the analytical theory:

$$E_z^{ac}(r_{ac}, \xi) = \frac{Q_{ac}}{Q_d} \times T \times E_z^d(r_{ac}, \xi)$$

in terms of the field in the central channel set up by the drive bunch. Here, $\xi = v_0 t - z$, r_{ac} measures the radial location of the witness bunch (e.g. $r_{ac} = 0$), and T is defined by Eq. 66 of [1]. This will be a satisfactory approximation if the fields are nearly flat across the radius and the bunches are short in the axial direction. To test this formula, we take our GHz CDWA [1] that is driven by a 50 nC annular bunch that generates a peak 16 MeV/m wakefield on-axis in the structure (computational theory result). If we put a 1 nC witness bunch on the axis, with *no* annular drive bunch, the axial longitudinal wakefield from this witness bunch is shown in Fig.

2F.1 to be ~ 1.3 MeV/m. The computed transformer ratio of this structure from a numerical simulation is already known to be 3.6. From the above formula, F_z (witness bunch) = F_z (drive bunch) $\times (Q_{\text{witness}}/Q_{\text{drive}}) \times T = 16$ MeV/m $\times (1/50) \times 3.6 = 1.17$ MeV/m, which is close to the numerically computed value shown in Fig. IIIF.1.

We have used the above method to determine T for the ramped bunch train example shown in Fig. IIIB.5. Whereas we found $T \sim 8$ computationally, the new technique predicts $T \sim 6$. The lack of accuracy here is probably caused by multimode effects, but the new technique still provides a promising first estimate, considering a ramped bunch train is being used!

Fig. IIIF.1. Axial wakefield of a 1 nC witness bunch traveling alone down the GHz structure described in Section VI of the 2009 *Phys. Rev. ST AB* paper, reference [1].

IIIG. Bunch Formation and Transport (Tasks 2,4)

Numerical studies have been made for bunch production at the AWA RF photocathode gun and transport through the AWA beam-line system downstream leading to the location of our structure. In the past these numerical tools (Impact-T software) have proved to be successful in guiding experimental work at AWA including our work with the rectangular DWA. Fig. IIIG.1 shows the drive and witness bunches after they have been created at the cathode. The initial radius of the annular bunch at the RF photocathode is ~ 5 mm [Task 4], and the code shows this bunch (beam envelope) can be transported at least 4 m to the structure and then passed along the entire 10 cm length of the CDWA, without intercepting its walls (Fig. 2G.2). This demonstrates that an annular drive bunch containing ~ 30 nC followed by a small, delayed witness bunch can be created and successfully transported through our structure [Task 2], a scaled-down replica of the CDWA unit we are currently testing at AWA. Transport is assisted by the use of three solenoid coils (borrowed from Yale Beam Physics Lab) positioned along the beamline. As the structure is supported in this design by three vanes, there should be no problem with passing the bunch into the unit or aligning the central dielectric cylinder (such as might have been the case

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for a foil suspension technique). In these simulations, the halo mask in front of the structure is ignored, so some of the electron macroparticles can stray into the dielectric elements and are counted as lost.

Fig. III G.1. Drive and witness bunches after the photocathode (simulation by Dr. Daniel Mihalcea, AWA). Drive bunch energy = 14.8 MeV; witness bunch energy = 12.8 MeV, energy spread = 0.5 MeV RMS. Witness bunch delay is 1.7 cm behind drive bunch.

Fig. III G.2. Showing compression of radius and size of drive and witness bunches, as obtained using the Yale coil set.

III H. CONCLUSION TO SECTION III

Results presented in Sections III A - III G show that all tasks outlined in the Phase I proposal for this project have been successfully completed.

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Relevant Publications

1. "Nonlinear Theory of Wakefield Excitation in a Rectangular Multizone Dielectric Resonator," Galaydych K.V., G.V. Sotnikov, Phys. Rev. ST Accel. Beams **14**, 011302 (2011).
2. "Improved Ramped Bunch Train to Increase the Transformer Ratio of a Two-Channel Multimode Dielectric Wakefield Accelerator," G.V. Sotnikov, T.C. Marshall, Phys.Rev. ST Accel. Beams **14**, 031302 (2011).
3. "Comparison of experimental tests and theory for a rectangular two-channel dielectric wakefield accelerator structure," S.V. Shchelkunov, T.C. Marshall, G. Sotnikov, J.L. Hirshfield, W. Gai, M. Conde, J. Power, D. Mihalcea, Z. Yusof, Phys. Rev. ST Accel. Beams **15**, 031301 (2012).