RF POWER GENERATION AND COUPLING MEASUREMENTS FOR THE DIELECTRIC WAKEFIELD STEP-UP TRANSFORMER

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Abstract. The dielectric wakefield transformer (DWT) is one route to practical high energy wakefield-based accelerators. Progress has been made in a number of areas relevant to the demonstration of this device. In this article we describe recent bench measurements and beam experiments using 7.8 and 15.6 GHz structures and discuss some remaining technical challenges in the development of the DWT.

INTRODUCTION

Dielectric loaded structures driven by the wakefields of a high current electron beam have been under study for some time as high frequency high gradient accelerators [1]. The simplicity of this method, as well as the relative ease with which parasitic higher order modes can be damped [2] compared to conventional structures operating at a comparable frequency makes this technology an attractive option for future high energy e^+e^- linear colliders.

A simple collinear drive-witness beam geometry suffers from inefficiencies due to the single bunch beam breakup instability of the drive beam unless unrealistic injection tolerances are imposed. Collinear devices are also limited to transformer ratios < 2, and beam staging is difficult. To circumvent these problems, a transformer geometry is used [3], where the drive and witness beams pass through separate structures (figure 1). The rf pulse generated by the drive beam is transferred via waveguide to a second structure which is adjusted to have the same fundamental frequency but smaller group velocity and transverse dimensions, thus providing an accelerating field step up by compressing the rf pulse. A drive structure can be designed with sufficiently low transverse impedance [4] to avoid beam breakup problems. Multiple drive bunches are used, spaced by an integral multiple of the rf period, to provide a long accelerating pulse.

Initially it was useful to operate with a collinear drive and witness beam geometry in order to probe directly the fields generated in the drive structure. Measurement

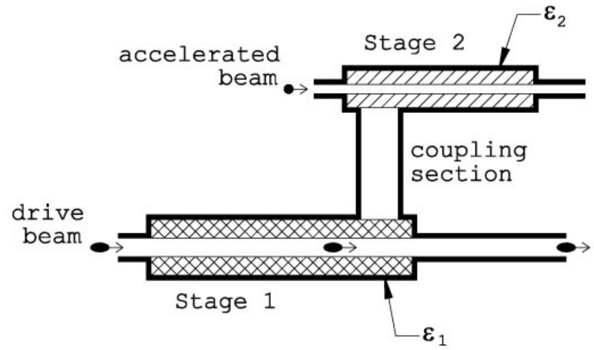

FIGURE 1. Schematic diagram of the dielectric wakefield transformer.

of the accelerating gradient also permitted indirect measurement of the rf power generated. Details of these measurements can be found in reference [6]. This paper is focussed on recent work involving coupling optimization between the drive and accelerating tubes and with direct measurements of the rf power generated using the intense electron source available at the Argonne Wakefield Accelerator [7].

STRUCTURE DESIGN

The structures used for these experiments were designed to demonstrate the physics of the DWT while at the same time being compatible with the beam parameters currently available at the AWA. The device parameters are summarized in Table 1.

TABLE 1. Parameters for the dielectric structures considered here. a (b) is the inner (outer) radius, L is the structure length, $c\beta_g$ is the group velocity, and E_z^{max} is the maximum wakefield accelerating gradient.

f (GHz)	Stage	a (mm)	b (mm)	L (mm)	ϵ	β_g	E_z^{max} (MV/m)
7.8	I	6	11.15	110	4.6	.24	3.2
	II	3	5.41	160	20	.05	8
15.6	I	5	7.22	140	4.6	.31	8
	II	1.5	2.7	140	20	.05	28

The dielectrics used are Cordierite which has $\epsilon = 4.6$ and MCT20, with $\epsilon = 20$. Both of these materials are low-loss ceramics which can be easily machined to the dimensions required [9]. Quality factors > 5000 have been measured for these structures. With optimized coupling, the 7.8 GHz structure has a transformer ratio of 2.5, while that of the 15.6 GHz device is 3.6.

BENCH MEASUREMENTS AND RF COUPLING OPTIMIZATION

In the original concept for the DWT [3], the coupling between structures was accomplished by smoothly deforming the dielectric tubes and coupling the rf through a short unloaded section of waveguide which acted as a quarter wave transformer. This scheme involves no mode conversions and was found to be very efficient based on 2D numerical simulations [8]. The difficulty of deforming the ceramic tubes used as dielectrics led to an alternative method of rf coupling, using a section of rectangular waveguide as shown in figure 1.

The coupling of rf from the drive tube into the accelerating tube involves obtaining efficient broadband ($\Delta f/f \simeq 5-10\%$) power transfer with two mode conversions, from cylindrical TM_{01} to rectangular TE_{10} and back again. The problem of coupling optimization in the DWT was found to involve considerably more effort than a few hours work by a “halfway decent electrical engineer” as anticipated [5]. A lengthy trial and error procedure of coupling slot adjustments and network analyzer measurements was necessary to obtain reasonable coupling between the structures.

Figure 2 shows the bench measurement setup. A tapered launcher in combination with a tapered dielectric is used to achieve good coaxial to cylindrical waveguide coupling. A waveguide to coax adapter is located at the end of the rectangular waveguide. S_{21} is measured from the tapered launcher to the coaxial coupler output.

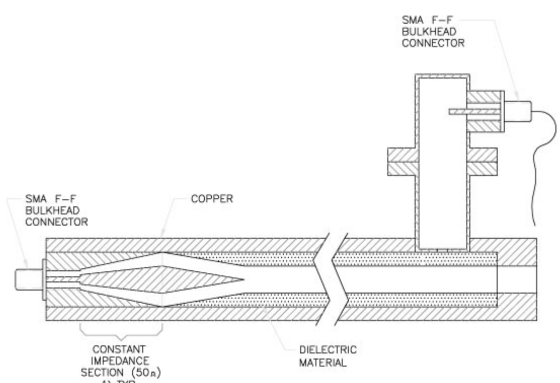

FIGURE 2. Bench measurement setup for dielectric structure to waveguide coupling measurements.

The coupling slot is located about $\lambda_{wake}/4$ from the end of the dielectric waveguide and is longer in the azimuthal direction than in the axial. The slot allows the azimuthal magnetic field from the dielectric structure to "leak out" into the rectangular transfer waveguide where it induces a transverse electric field. The coupling slot was gradually widened and lengthened to maximize S_{21} and thus optimize the coupling into the transfer waveguide.

Figures 3-4 show the best results for the two stages of the 7.8 GHz structure. The best coupling obtained (from dielectric tube to wave guide) corresponds to $S_{21} \simeq 1.1$ db (stage I) and $S_{21} \simeq 1.8$ dB (stage II). Results for the 15.6 GHz device are similar. Work is currently underway to measure the coupling from stage I to stage II for the full transformer assembly.

BEAM MEASUREMENTS

The stage I dielectric tube and waveguide assembly with the coupling optimized is installed in the test section of the AWA (fig.5). The rf from the wakefield of the beam in the stage I structure is coupled out through the waveguide to coax adapter to a calibrated rf diode detector via a -60 dB bidirectional coupler. The diode is placed in a lead shielding enclosure to avoid radiation damage to the diode. The diode signal is sent to the control room where it is read out using a digital oscilloscope.

Figure 6 shows a plot of rf power vs beam charge for single drive bunches in the 7.8 GHz structure. Although there is some scatter in the data due to shot to shot bunch length variations, a clear quadratic dependence of rf power on charge is observed, indicating that coherent generation of rf is occurring in the structure.

The multiple drive bunches essential for generating the long rf pulse necessary for the eventual operation of the DWT were generated by optically splitting and appropriately delaying the laser pulse to the drive gun. The present experiment used a bunch train of 4 bunches of 10 nC each (limited by available laser power), spaced by 3.07 ns ($= 4T_{linac} = 24\ T_{wake}$).

Figure 7 shows the envelope of the rf macropulse generated by the bunch train. Since the length L of the dielectric structure is 11 cm, the rf micropulse length for a single drive bunch is $(L/c)((1-\beta_g)/\beta_g) \simeq 1$ ns which is smaller than the bunch spacing, so that the individual micropulses are visible in the envelope. The difference in amplitudes of the peaks is due to slight misalignments in the beam splitting optics, resulting in different intensities for the micropulses.

Figure 8 shows the power output from the 15.6 GHz structure. Although the power output is low due both to poor beam transmission through the small aperture of the tube and longer than optimal drive bunch lengths, the observed rf coupling is good. Improved results are expected with planned improvements in the linac performance.

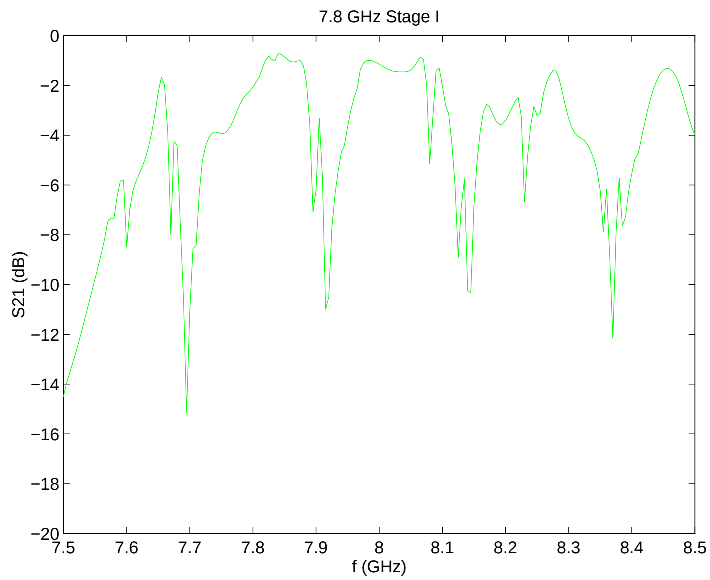

FIGURE 3. Measured S_{21} for stage I of the 7.8 GHz DWT structure.

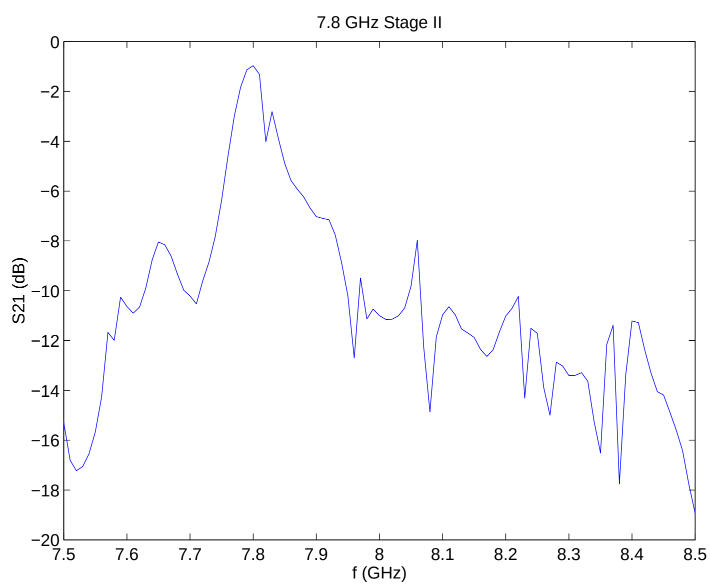

FIGURE 4. S_{21} for stage II of the 7.8 GHz DWT structure.

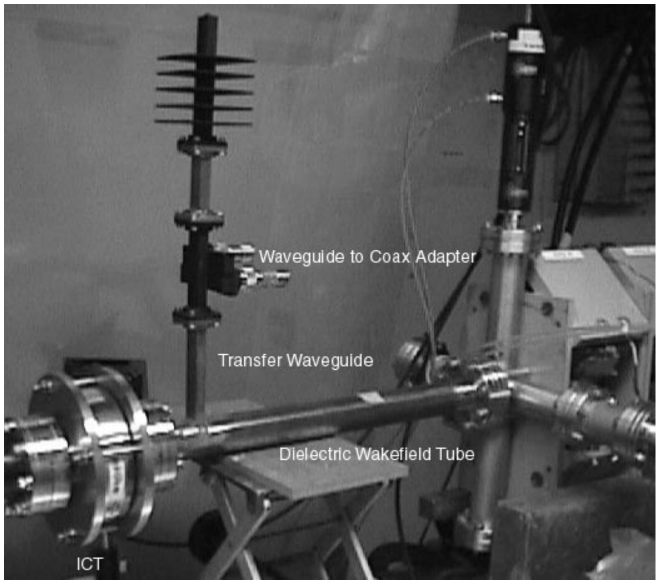

FIGURE 5. Dielectric structure and transfer waveguide in place for beam measurements of power output.

FUTURE EXPERIMENTS

The next task to be accomplished is the integration of the two stages and bench measurements of the coupling. A tapered pickup (analogous to launcher described above) for the stage II structure will be needed, but it is expected that little further coupling slot adjustment will be required.

Direct two beam acceleration in stage II will require some modifications to the AWA. The Y-chamber where the drive and witness beams are combined for collinear device wakefield measurements will be removed, and stage I will be mounted directly to the end of the drive linac. Stage II will be mounted to the end of the witness beam line and the transfer waveguide will be made sufficiently long to connect the two stages. The spectrometer magnet will be moved to a position immediately downstream of the stage II device. This arrangement avoids the drive and witness beam losses in the present chicane section, and also provides for easier tuning since the drive and witness beamlines are completely independent. Using a train of 8x20 nC drive bunches separated by $2T_{linac}$ (well within the capabilities of the existing drive linac), accelerating gradients of 10 (30) MeV/m can be obtained using the 7.8 (15.6) GHz structure parameters in Table 1. While the achievable gradients are modest, the experiment will demonstrate all the essential features of the DWT.

In the long term, improved beam quality would permit much higher gradients to be obtained. A design for a new photoinjector for the AWA drive linac has been developed [10] and with the improved emittance and bunch length available gradients > 100 MeV/m are attainable.

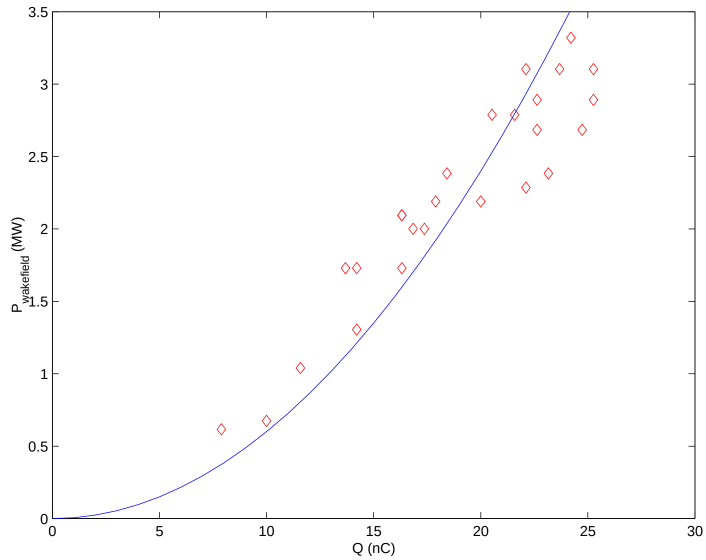

FIGURE 6. Rf power vs drive bunch charge, 7.8 GHz dielectric structure. The scatter in the data is due to bunch length fluctuations.

SUMMARY

Considerable progress has been made towards a demonstration of the dielectric wakefield transformer. Some of the major steps on the way– optimizing the rf coupling from dielectric to transfer structure, multiple drive bunch generation in the AWA linac, and direct measurement of the rf generated by the beam– have been successfully achieved. We have some confidence that the remaining tasks can be accomplished without any major difficulties.

ACKNOWLEDGEMENT

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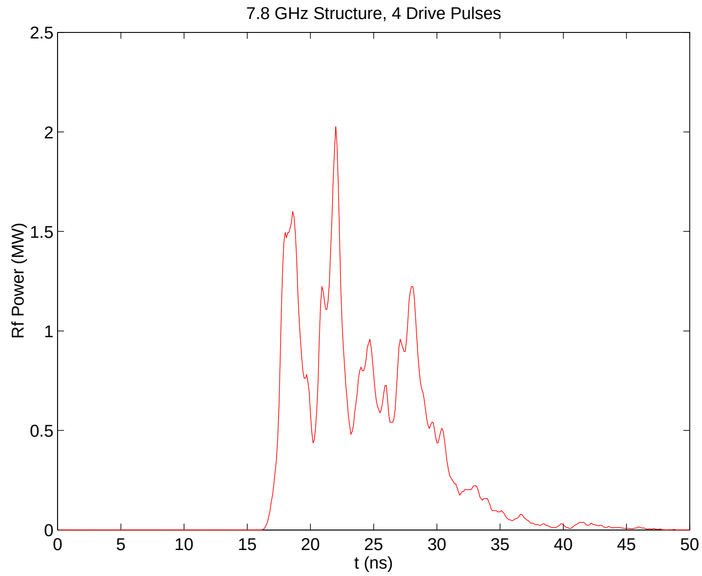

FIGURE 7. Rf macropulse envelope for train of 4 drive bunches, 7.8 GHz structure.

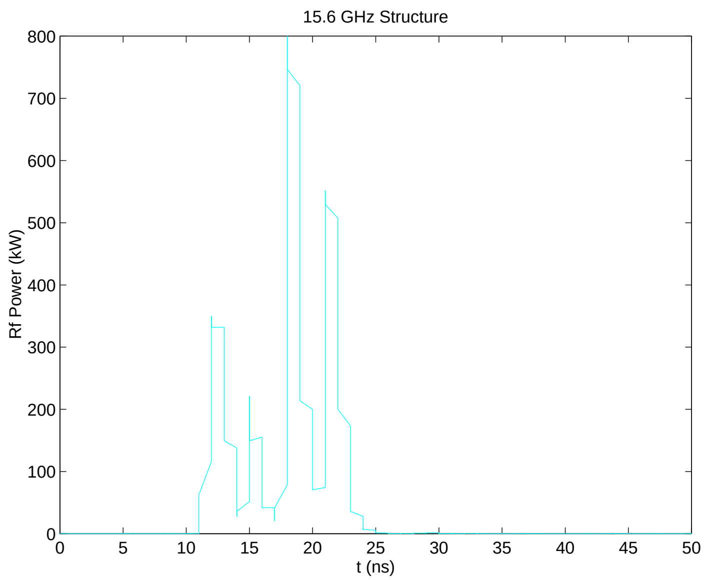

FIGURE 8. Measured rf macropulse envelope for a train of 4 drive bunches in the 15.6 GHz structure. The nonuniformities in peak power from bunch to bunch are due to imperfect alignment of the beam splitting optics.

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