DEVELOPMENT OF AN X-BAND DIELECTRIC-BASED WAKEFIELD POWER EXTRACTOR FOR POTENTIAL CLIC APPLICATIONS*

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Abstract

In the past decade, tremendous efforts have been put into the development of the CLIC Power Extraction and Transfer Structure (PETS), and significant progress has been made. However, one concern on the manufacturing cost of the PETS remains, particularly considering the quantities needed for a TeV machine. A dielectric-based wakefield power extractor in principle is much cheaper to build. A low surface electric field to gradient ratio is another big advantage of the dielectric-loaded accelerating/decelerating structure. We are currently investigating the possibility of using a cost-effective dielectric-based wakefield power extractor as an alternative to the CLIC PETS. We designed a 12 GHz dielectric-based power extractor which has a similar performance to CLIC PETS with parameters 23 mm beam channel, 240 ns pulse duration, 135 MW output per structure using the CLIC drive beam. In order to study potential rf breakdown issues, as a first step we are building a 11.424 GHz dielectric-based power extractor which is scaled from the 12 GHz version, and plan to perform a high power rf test using the SLAC 11.424 GHz high power rf source.

MOTIVATION

The CLIC Power Extraction and Transfer Structure (PETS) is one of the key components in the CLIC two-beam acceleration scheme. According to the 2008 CLIC design parameters [1], 71568 PETS units total are needed for this 3 TeV machine, contributing a large portion of the overall cost. After more than a decade of effort, PETS has evolved to a relatively mature design. However, due to its complicated geometry, tight machining tolerance (35 microns), and fabrication process, the cost of PETS (even for mass production) will still be high. A Dielectric-based Wakefield Power Extractor (DWPE), because of its simple geometry, can save significant costs if it meets the CLIC requirements. In terms of key parameters, the dielectric-based power extractor can be designed very close to PETS. However, its real performance has to be investigated under a high power or high current drive beam.

DIELECTRIC POWER EXTRACTOR

PETS uses a metallic corrugated waveguide working as a decelerator, where the electron drive beam loses kinetic energy and generates the wakefields. Another option is to use a dielectric loaded waveguide. The applications of dielectric loaded waveguide as accelerating structures have been under extensive study for the past two decades. The basic RF structure is very simple - a cylindrical, dielectric tube with an axial vacuum channel is inserted into a conductive sleeve. The dielectric constant and the inner and outer radii of the dielectric tube are chosen to adjust the fundamental monopole mode frequency generated by passing beam (here the TM_{01} mode). The phase velocity of the mode will equal the beam velocity ~ c. Such a simple geometry makes dielectric-lined waveguides attractive candidates for high frequency band accelerating structures, where it is expensive and difficult to precisely fabricate conventional iris-loaded copper structures. Some other advantages of using dielectric based structure include a potentially higher breakdown threshold, easy parasitic mode damping, and very low enhancement of the ratio of the electric field on the dielectric surface to that on axis. 7.8 GHz and 26 GHz DWPE prototypes have been successfully built and tested at the Argonne Wakefield Accelerator (AWA) facility; tens of MW rf output were achieved [2].

In the most of cases, the dielectric based decelerator is a constant impedance structure because of the uniformity of the dielectric constant and beam channel along the structure. The generated RF power by an ultra-relativistic bunch train in such a decelerator is given by:

$$P = \frac{1}{4}\frac{\omega}{v_g}\frac{r}{Q}L^2 I^2 F^2 \left(\frac{1-e^{-\alpha L}}{\alpha L}\right)^2, \qquad (1)$$

where I is the beam current (the charge per bunch over the bunch spacing), L is the active length of the decelerator, ω is the angular frequency of the RF mode, vg is the group velocity, *[r/Q]* is the shunt impedance per unit length divided by the quality factor, α is the attenuation per unit length, and F is the single bunch form factor. For a Gaussian bunch with an *r.m.s.* bunch length σz, the bunch form factor can be calculated as

$$F = \exp\left[-\left(\frac{\omega}{c}\sigma_z\right)^2 \Big/ 2\right], \qquad (2)$$

In the design of a wakefield power extractor, the generated high power RF pulse will be guided out at the end of the decelerator using an output coupler which should be capable to convert the waveguide mode in the decelerator (usually the TM_{01}) to the mode in the transport waveguide (e.g. the TE_{10} mode in a rectangular waveguide) very efficiently, and sustain the high power RF wave without breakdowns.

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12 GHz DWPE

Generally, in order to obtain a high RF power from the electron beam, a large diameter beam channel and a long effective length are preferred in the structure design. However, in a real experimental design, limited by realistic beam quality issues including energy, emittance, bunch length, and spacing, the wakefield power extractor has to be built using a compromise among various parameters like the structure length, beam aperture, group velocity, *R/Q*, etc. to maintain a reasonable drain time (defined as $L(1-\beta_g)/V_g$, where $\beta_g=V_g/c$), average current, and output power level. Our proposed 12 GHz dielectric-based RF power extractor is to serve as an alternative to the CLIC PETS that has been optimized based on CLIC drive beam parameters and other considerations. Therefore, the major parameters are chosen to match that of PETS. Table 1 shows the comparison of our dielectric-based power extractor and CLIC PETS [1], where we can see they are almost identical except for the electric field on the dielectric surface.

The RF power produced by the electron bunch can be estimated from Eqn. (1). Considering the CLIC drive beam, an 8.4 nC bunch train with bunch length of 1 mm, and bunch spacing of 83 ps, we can obtain the generated wakefield gradient of 12.6 MV/m, RF power of 142 MW, and drain time of 816 ps. A MAFIA® simulation and its frequency spectrum are shown in Fig. 1 as a comparison; a very good agreement with our estimated values is obtained. In the simulation, a single-bunch response of the power extractor is obtained using CST-Particle Studio®; then the multi-bunch response will simply be the sum of the N single responses, each being delayed by T_b (bunch spacing). 100 bunches were used in the simulation shown in Fig. 1.

Table 1: Comparison of the Dielectric Based Power Extractor and CLIC PETS

Parameters	**PETS**	**DWPE**
Beam Aperture (mm)	23	23
Effective Length (cm)	21.3	23
Group velocity	0.453c	0.485c
R/Q(ohm/m)	2290	2172
Q	7200	7317
Generated Power (MW)	135	142
Esurf(MV/m/135MW)	56	20

11.424 GHz VERSION DWPE FOR HIGH POWER RF TEST

From the electric and geometric point of view (Table 1) a dielectric-based wakefield power extractor is a very good alternative to meet the CLIC requirements. However, its performance has to be experimentally demonstrated. A high power rf test is a necessary first step toward a practical wakefield power extractor. Many potential issues, like rf breakdown, can be exposed in a high power rf test. Since the operation frequency of the CLIC scheme, 12 GHz, is very close to the frequency of SLAC X-band klystrons, 11.424 GHz, an 11.424 GHz version of DWPE is under development, and will be tested soon. The major parameters of the 11.424 GHz DWPE are very similar to the 12GHz one except for the beam aperture which is modified to match the size of SLAC high power mode launcher.

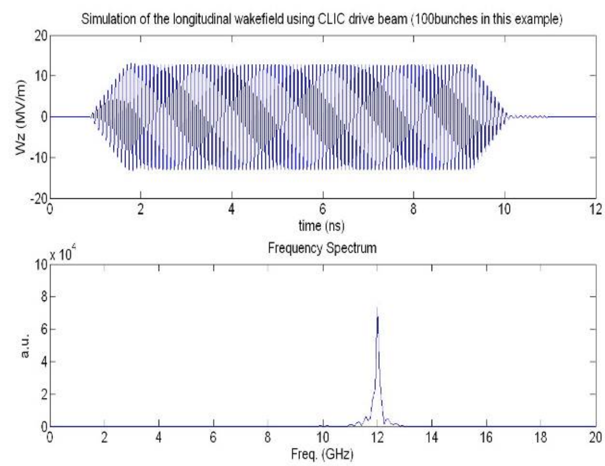

Figure 1. The longitudinal wakefield signal for a 12 GHz dielectric based RF power extractor excited by a bunch train. The parameters used in the simulation are: bunch train of 100 bunches with charge of 8.4 nC each; bunch length 1 mm; parameters of the 12 GHz dielectric-based power extractor as in Table 1.

As shown in Fig. 2, the whole power extractor is designed in three separate parts: dielectric-loaded waveguide and two rf chokes. Two customized 4-1/2” flanges (severing for both rf and vacuum seal connections) are designed to connect three parts together. In addition, in order to connect to the SLAC high power mode launcher (rf coupler), two 2-3/4” SLAC flanges are brazed to the other side of the rf chokes. It notes that a tiny (0.1mm) step is designed inside one 4-1/2” flange at the rf choke side, which is used to locate the position of the quartz tube during assembling the whole structure. The induced RF reflection from this tiny bump should be negligible. The developed X-band DWPE is using quartz as the loaded material because of its low cost, low dielectric constant (favours the wakefield generation this particular design), and low loss.

The impedance matching section for the 11.424 GHz power extractor is scaled from the 12 GHz version. Detailed 3D EM simulations have been performed to optimize the design, particularly to minimize the surface field on the choke. Figure 3 shows the amplitude of electric field inside this transition part (normalized to 1W of input rf power), where we can see the peak field on the surface appears near the choke bending. But it is only slightly higher than the field on other surfaces. It is estimated ~25MV/m on the choke surface per 135MW rf input; ~20MV/m on the quartz surface. In terms of rf breakdown triggered by electric field, if it exists, the surface field in this structure should not be a concern.

Intensive rf breakdown studies in the recent years indicate that RF pulse heating might be one of main factors to cause rf breakdowns in metallic accelerating structures [3]. Unlike the average thermal effect that is a volume temperature rise due to the rf power dissipation in the accelerating structure (it can be cured by cooling system), the rf pulse heating is an instant phenomenon occurring in the skin depth of metallic surface. Contraction and expansion of the metal surface due to the local temperature variation by the rf pulse heating will cause the metal fatigue on the surface, which might lead to a rf breakdown. The single layer dielectric accelerating structure intrinsically has a low electric field (Es/Ea<<1 in a general case) but high magnetic field on the metal surface [4]. However, for a DWPE structure, due to the large beam hole, Es/Ea~1 and magnetic field on the metal surface is reduced. In the simulation (not shown) the peak magnetic field is 78.7kA per 135MW rf input. Considering the rf pulse length of CLIC PETS design, 240ns, the calculated rf pulse heating for the developed 11.424GHz quartz power extractor is only 1.3 degrees, which is far below the well know limit, 50 degrees.

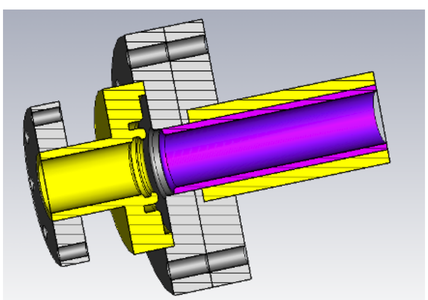

Figure 2. Simplified 3D view of the engineering design of the developed 11.424GHz version of DWPE (half). Gray: stainless steel; yellow: copper; Magenta: quartz.

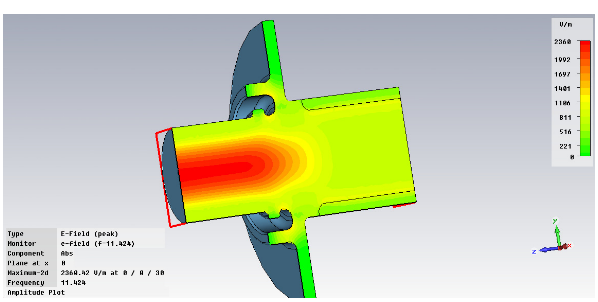

Figure 3. E-field amplitude distribution in the matching section for our proposed 11.424 GHz dielectric based power extractor. Value is normalized to 1W rf input in the simulation.

The complete structure has been fabricated and bench tested. Figure 4a shows the assembled structure with two SLAC high power rf couplers. Additional adaptors were used for the bench test. S-parameters were measured using a network analyzer. The measured S-parameters (S21—transmission and S11-reflection) are shown in Fig.4b. ~0.8dB insertion loss and ~-16dB reflection were measured at 11.424GHz. However, because of the lack of WR-90 waveguide calibration kit, we can only calibrate to the type N coaxial ports. In this situation, the real performance of the structure is supposed to better than the measurement results. To verify this, we also measured the S-parameters of the assembled two SLAC couplers. The results are ~0.5dB insertion loss and ~-16dB reflection. Therefore, the developed 11.424GH version DWPE should have less than 0.3dB insertion loss and -16dB reflection.

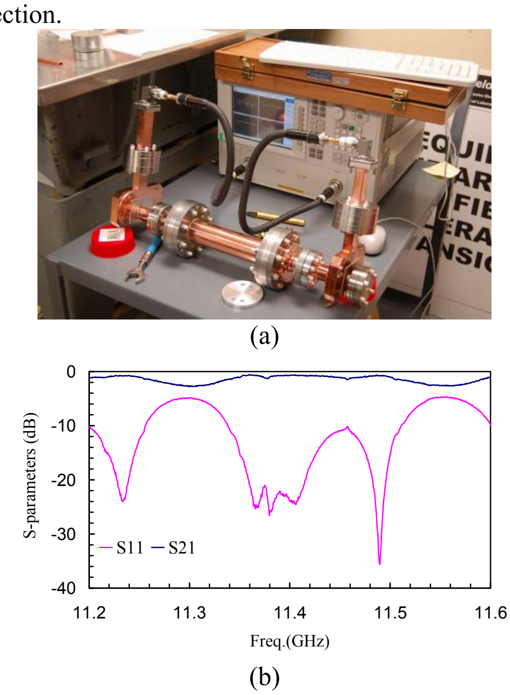

Figure 4. S-parameter measurement of the assembled 11.424 GHz DWPE (with two couplers from SLAC): (a) measurement setup; (b) results.

CONCLUSION

In conclusion, a 12GHz dielectric based wakefield power extractor has been designed to provide an alternative to CLIC PETS. As the first step toward this goal, an 11.4GHz version structure is under construction. It will be tested using an external high power rf.

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