AN X-BAND DIELECTRIC-BASED WAKEFIELD POWER EXTRACTOR*

C. Jing[#], A. Kanareykin, S. Antipov, P. Schoessow, Euclid Techlabs LLC, Solon, OH 44139,U.S.A.
S. Weathersby, J. Lewandowski, V. Dolgashev, S. Tantawi, SLAC, Menlo Park, CA, 94309, U.S.A.
M. Conde, J. G. Power, W. Gai, ANL, Argonne, IL 60439, U.S.A.
I. Syratchev, CERN, Geneva, Switzerland

Abstract

An X-band dielectric-based wakefield power extractor is under development to provide high power rf for Two Beam Acceleration. A low surface electric field to gradient ratio and low fabrication cost are two main advantages of the dielectric-loaded accelerating /decelerating structure. We designed a 12 GHz dielectric-based power extractor which has a similar performance to the CLIC PETS, with 23 mm beam channel, 240 ns pulse duration, and 135 MW output per structure using the CLIC drive beam. In order to study potential rf breakdown issues, as a first step we built a 11.424 GHz dielectric-based power extractor scaled from the 12 GHz version. A high power rf test will be conducted using the SLAC 11.424 GHz high power rf source. The structure has been conditioned up to ~40 MW rf power without the observation of destructive breakdown. Meanwhile, the 12 GHz fully featured dielectric power extractor has been finished as well.

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. The dielectric-based power extractor can be designed very close to PETS in terms of key parameters. 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 wakefields. Another option is to use a dielectric loaded waveguide. The applications of dielectric loaded waveguides 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:

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

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, v_g 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 rms bunch length σ_z, the bunch form factor can be calculated as

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

12 GHz DWPE

Generally, in order to obtain 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

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[#] jingchg@hep.anl.gov

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, the 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

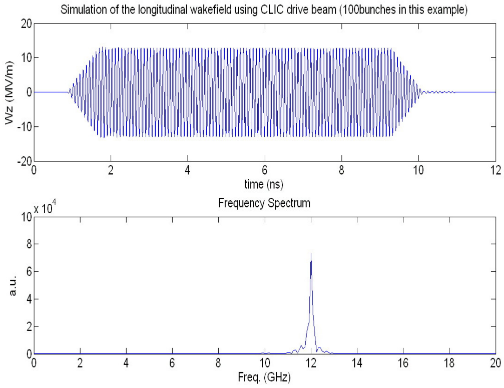

Figure 1: The longitudinal wakefield signal for a 12 GHz dielectric based RF power extractor excited by a bunch train. The parameters used in the simulation are: bunch train of 100 bunches with charge of 8.4 nC each; bunch length 1 mm; parameters of the 12 GHz dielectric-based power extractor as in Table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

As shown in Fig. 2, the whole power extractor is designed in three separate parts: dielectric-loaded waveguide, rf choke adaptor to match the impedance, and output coupler. The dielectric PETS we developed uses quartz as the material because of its low cost, low dielectric constant (favors wakefield generation in this particular design), and low loss. In order to damp the transverse wakefield, we first metalize the quartz tube with 100 microns of sputtered copper on the outer surface of the tube. Then, we etch off a number of slots along the copper coating so that only axial surface currents are allowed to flow along the copper inner surface. The non-axisymmetric hybrid modes that are comprised of all six cylindrical field components will require azimuthal surface currents on the region of the conductor boundary and thus will leak out past the slots. A lossy SiC-AlN tube located outside the slots will heavily attenuate the hybrid modes. Meanwhile, the TM_{01} (or generally TM_{0n}) modes will maintain good propagation characteristics with only a slight deterioration of Q due to the increased surface current intensity between the slots compared to a continuous conducting boundary. Since the ratio of total slot width to the overall circumference is small, this perturbation of the TM_{0n} modes can be ignored. The deflecting modes (hybrid modes) in a dielectric-lined circular waveguide are the HEM_{nm} modes. The lowest deflecting mode is the HEM_{11} mode, which is at 11.139 GHz for this dielectric PETS design. The calculated Q of this dipole mode drops from 9000 without damping down to 20 using the damping method described here.

All parts of the dielectric PETS have been completed (see Fig. 3). A copper ring was brazed to one end of metalized quartz tube working as a stopper to locate the position of the dielectric tube as well as the rf absorber sleeve. The position is finally locked through a copper end plug at the beam entrance. Four cooling channels are brazed to the outside of copper housing.

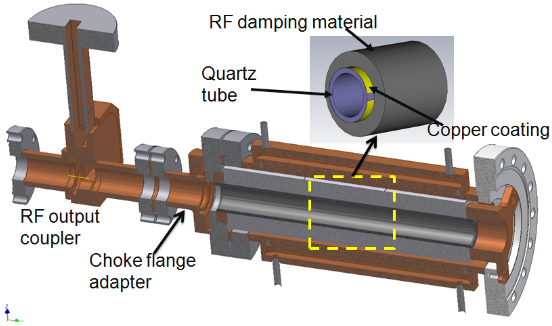

Figure 2: Engineering design of the dielectric PETS.

Figure 3: Components of the dielectric PETS.

11.424 GHz VERSION DWPE FOR HIGH POWER RF TEST

From the electrical and geometric points of view (Table 1) a dielectric-based wakefield power extractor is a very good alternative for meeting 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 PETS, 12 GHz, is very close to the frequency of SLAC X-band klystrons, 11.424 GHz, an 11.424 GHz version of the DWPE was also fabricated and tested. The major parameters of the 11.424 GHz DWPE are very similar to the 12 GHz except for the beam aperture which is modified to match the size of the SLAC high power mode launcher.

The structure was bench tested at SLAC before the high power rf experiment. ~0.3 dB insertion loss and ~-18 dB reflection were measured at 11.424 GHz. A bead pull test was performed as well (see Fig.4). It showed that the gradient in the DWPE is less than 1/3 of the gradient in the coupler.

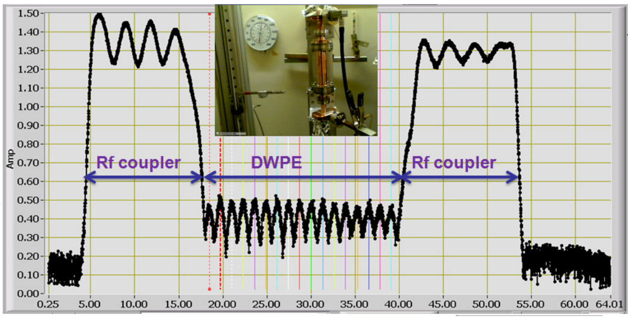

Figure 4: The bead pull setup and results for the 11.4 GHz DWPE.

The structure was tested at the SLAC ASTA facility. Figure 5 shows the conditioning history in one day (~8 hrs) which shows that as the input rf power was increased from 28 MW to 39 MW (maximum level of the single klystron output) while the vacuum remained below 10^{-8} Torr. The pulse length used fir the data in Fig. 5 was 100 ns. We also tested longer pulse lengths, 150 ns and 200 ns. Multipactor is initiated after ~6 MW rf input at 120 ns from the rising edge of rf pulse. We tried to drive the structure to higher rf power with a use of SLED pulse compressor, but we were unable to complete the high power tests because of the tight running schedule at ASTA facility. During the entire conditioning process, we did not observe any destructive breakdowns (the dielectric breakdown usually is destructive when it occurs); this will be confirmed through post-experimental examination. We also observed that the vacuum of the structure remained at a relatively high level when the structure was conditioned from the cold state (as in the first 30 minutes of conditioning every day). A plausible explanation is the 'dust' stirred out by high power rf during the conditioning is re-absorbed on the dielectric surface when the rf is off for a certain period of time.

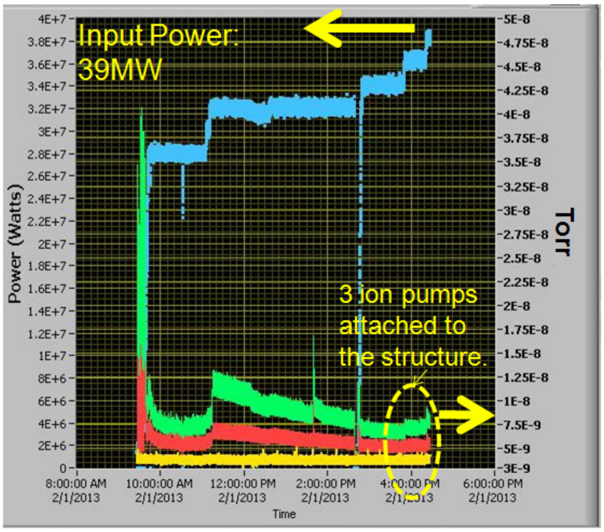

Figure 5: The conditioning history of the 11.4 GHz dielectric PETS over an 8 hour period at the SLAC ASTA facility.

CONCLUSION

In conclusion, the encouraging rf test results of 11.4 GHz dielectric PETS show the great potential of using cost-saving dielectric based structure in high power rf applications.

REFERENCES

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[2] C. Jing, et al, Proc. Advanced Accelerator Concepts: 14th Workshop, edited by S. Gold and G. Nusinovich, (2010):370-375.