Development of 26GHz Dielectric-Based Wakefield Power Extractor

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Abstract. High frequency, high power rf sources are needed for many applications in particle accelerators, communications, radar, etc. In this article we present a design of a 26GHz high power rf source based on the extraction of wakefields from a relativistic electron beam. The extractor is designed to couple out rf power generated from a high charge electron bunch train traversing a dielectric loaded waveguide. Using a 20nC bunch train (bunch length of 1.5 mm) at the Argonne Wakefield Accelerator (AWA) facility, we can obtain a steady 26GHz output power of 148 MW. The extractor has been fabricated and bench tested, with the first high power beam experiments to be performed in the coming year.

Keywords: Dielectric-Loaded Accelerating (DLA) structures, wakefield, high power rf source.
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INTRODUCTION

Stable high power RF sources, because of their numerous potential applications in a number of areas have been pursued for decades using different technologies over different frequency bands. A 26GHz RF power extractor based on the dielectric-loaded structure is proposed to provide an option for any application in this frequency range. The technique we use is to extract energy from the Cherenkov radiation of a high current relativistic electron beam in a slow wave structure of predetermined frequency. When charged particles travel through a properly designed slow wave structure, they will lose energy due to the interaction between the particles and this structure. The radiated energy (high power rf wave) can be extracted to accelerate a second beam, or for other purposes requiring high power electromagnetic waves. Generally, the RF packet generated by a single particle bunch lasts a few nanoseconds (detailed formulae are shown in [1]). A properly spaced bunch train can stack the RF pulses from each bunch so that both the pulse length and amplitude are increased. Due to the ease with which the RF power characteristics can be changed by manipulating the decelerator and its drive bunch, this scheme may overcome some of the limitations of other conventional high-power RF systems at frequencies above X-band and power levels beyond a few hundred megawatts.

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Efficient RF power generation first requires the drive bunch energy to be efficiently coupled into the desired decelerator mode (typically TM_{01}) and then, that the RF output coupler efficiently extracts this mode power into the output waveguide. Since it's the simplicity and some other potential advantages, the applications of dielectric loaded waveguide as accelerating structures have been under extensive study for the past two decades. The use of dielectric-loaded waveguide as part of an RF power extractor was first proposed in 1991 [2] and later, a 7.8GHz structure generated 50MW of power by a 4-bunch train [3]. A 21 GHz structure was also tested at the CTF2 [4].

In general, a high RF power is generated when several decelerator design constraints are met: (i) the inner radius should be large to allow for high beam-charge transmission but small enough to keep high; (ii) the length should be long to increase the field superposition in multi-bunch excitation; (iii) the group velocity should be small in multi-bunch excitation for stronger field superposition but also sufficiently large to reduce the rise time; (iv) the attenuation coefficient should be small to reduce losses. In other words, the final design is a tradeoff among these requirements.

The major parameters for both the fundamental decelerating mode (TM_{01}) and the deflecting mode (HEM_{11}) of the 26GHz dielectric-based wakefield power extractor are presented in Table 1. The Quality factor Q in Table 1 is computed based on the copper wall losses and the dielectric loss factor of 10^{-4}; the R/Q of HEM_{11} mode is calculated assuming a 1 mm offset of the beam trajectory from the axis. The dispersion curves of both modes are plotted in Fig.1. Dielectric tubes are provided by Euclid Techlabs [5]. The ceramic material is based on Forsterite which has a dielectric constant of 6.64 and Q=10000 at 10 GHz.

TABLE 1. Parameters of 26GHz Dielectric Based RF Power Extractor.

Geometric and accelerating parameters	value
ID / OD of dielectric tube	7 mm /9.068 mm
Dielectric constant	6.64
Loss tangent	1×10^{-4}
Length of dielectric tubes	300 mm
Synchronous frequency of TM_{01}/HEM_{11} mode	26 GHz/23.5 GHz
Group velocity	0.25c/0.42c
R/Q of TM_{01}/HEM_{11} mode	9788(Ω/m)/ 556(Ω/m/mm)
Q of TM_{01}/HEM_{11} mode	2950/3372

The wakefield signal excited by the beam will propagate along the structure with the group velocity, and will be extracted through an output coupler to a WR-34 rectangular waveguide. An optimized coupling slot and chamber can implement high efficiency conversion between the fundamental TM_{01} mode in the dielectric-loaded circular waveguide and the dominant TE_{10} mode in the rectangular waveguide within the operating frequency range, and simultaneously maintain a low transmission of the HEM_{11} deflecting mode. Figure 2 shows the final output coupler design of the dielectric-based 26GHz power extractor. One tuning pin is used in this design. The output RF power is propagated out to a standard WR34 rectangular waveguide through a tapered transition. In general, the dual port design can heavily suppress the coupling out of the dipole mode. However, in this proof of principle experiment, we finally selected a single port scheme that can significantly reduce the complexity of the fabrication work while maintaining a significantly damped coupling of the dipole mode as well. The simulation shows that ~600MHz bandwidth can be achieved with a ~97% rf power transfer efficiency. A key contribution to this large bandwidth is the slightly bigger diameter of the empty waveguide between the dielectric-loaded decelerator and the rectangular waveguide. This broadband simulation result also provides a very good mechanical tolerance in the next stage engineering design. In addition, in the simulation, the fundamental transverse mode, HEM_{11} is damped to < -20dB over the full range of the passband

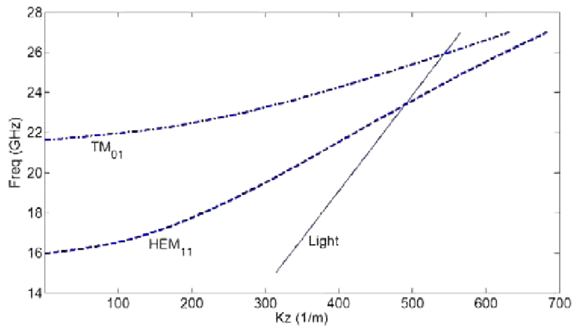

FIGURE 1. Dispersion curves of the fundamental monopole and dipole modes in a 26 GHz dielectric based RF power extractor. The luminal (vphase=c) line is also shown.

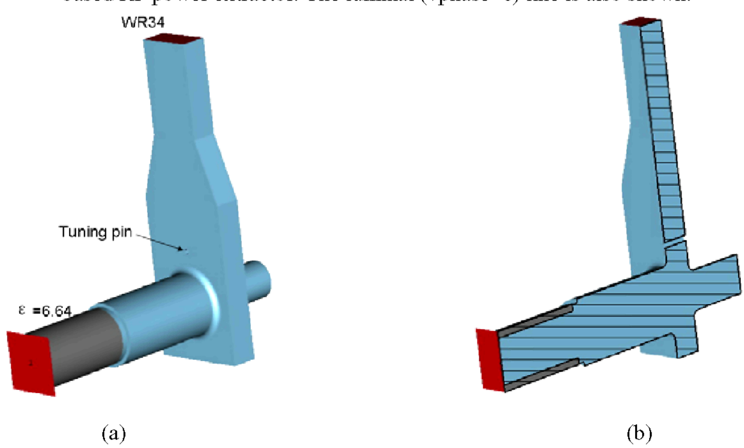

FIGURE 2. The final output coupler design for our proposed 26 GHz dielectric based RF power extractor, modeled using CST Microwave Studio®: (a) overview (b) cross sectional view.

Our proposed 26 GHz RF power extractor will be tested at Argonne Wakefield Accelerator facility that can provide 1-100 nC 15 MeV single bunches (bunch length of 1.5-3mm) using its present Mg cathode and 40 nC 20 MeV bunch trains (bunch spacing of 773 ps) using the planned high QE cathode (CsTe) and additional 30 MW klystron. The RF power produced by a 20 nC single bunch with bunch length of 1.5 mm is estimated to be 8.2 MW, and drain time of 3 ns. Using a 20nC bunch train, for example, which consists of 16 bunches, we can obtain a steady output power of 148 MW with 56 MV/m peak gradient in >10ns. The energy loss of the last bunch in the bunch train is 5.7 MeV, in the acceptable range for the 20 MeV AWA beam.

FABRICATION AND BENCH TEST

The whole power extractor is designed to be machined in three parts: dielectric-loaded waveguide, coupler block, and downstream beam channel (doubling as an RF cutoff for the 26GHz signal). After machining the three parts are brazed together with the flanges at the three open ends. The standard CF flange uses a knife edge and copper ring (gasket) to seal the vacuum and the center area always has a gap where they connect together. This gap has a choke effect for the rf signal and it may lead to an breakdown in the high power RF transport. Therefore, we specially designed a flange and corresponding gasket for the RF output port so that the high power RF signal can be transmitted without an RF discontinuity while maintaining high vacuum (see Fig.3). This flange is a unisex design. In addition to the knife edge it has a protruding rectangular lip which presses against the lip of the connected flange through a copper gasket. The gasket used for this flange is not a regular copper ring but a copper disk with a rectangular opening at the center. In order to ensure both openings from gasket and flange are well aligned in the installation, a locating post is also designed on the flange to hold the orientation of the copper gasket (not shown in Fig.3).

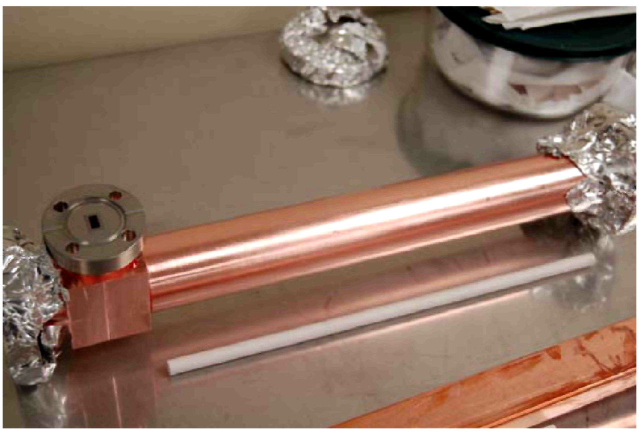

FIGURE 3. Fabricated 26GHz dielectric-based wakefield power extractor and ceramic tubes prior to loading (consisting of three 10-cm long dielectric tubes).

In order to bench test the wakefield power extractor, a TEM-TM_{01} mode launcher was designed to convert the TEM mode to the TM_{01} mode for the dielectric-loaded waveguide. The mode launcher consists of a center pin with a disc on the tip, and a grounded copper plug inserted into the copper sleeve. The simulated RF power transmission of this mode launcher is 97% in the 25–27GHz range. The bandwidth of the mode launcher is much wider than that of the RF output coupler, thus the insertion loss of the mode launcher is negligible. At the output port of the power extractor, a vacuum RF flange is used to connect to the WR34 waveguide. In the bench test, a commercial WR34 waveguide-coax adapter is used to convert the TE_{10} mode to the TEM mode for the output cable. The S-parameters of the combined mode-launcher and power-extractor system were measured, with the results plotted in Fig. 4. The system has a measured insertion loss S_{21} = -2.3dB at 26GHz. By subtraction of the loss from the adaptor (0.5dB), the loss due to the power extractor is 1.8dB corresponding to a power coupling efficiency of 66%, without considering the mismatch between the output coupler to adaptor. The theoretical loss, based on the copper losses at 26GHz and the loss tangent of the dielectric tube, is 1dB or 80%. The difference between the measurement and theoretical values may result from resonances caused by multiple reflections from the joints of the three dielectric tube segments. The reflection coefficient S_{11} in Fig. 4 shows this effect. In the actual beam test setup, the dielectric tubes will be compressed firmly by a copper plug at the upstream end that is expected to reduce these joint reflections and improve the overall RF transmission.

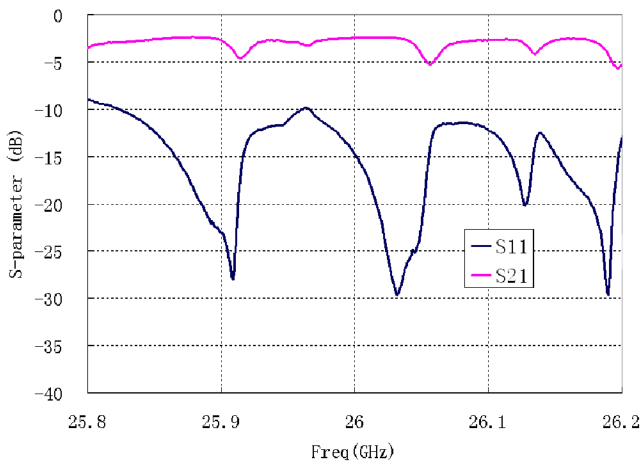

FIGURE 4. The measured S-parameters of the power extractor..

EXPERIMENTAL PLAN

The most important part of the experimental plan for the project is the beam test of the 26GHz power extractor using a bunch train. The electron bunch train will be formed by applying a laser pulse train to the new photoinjector rf gun at AWA facility. Up to 16 bunches may be used in the experiment. A >10ns flat top, ~150MW, 26GHz pulsed RF signal will be generated. It will be the first high power RF source in this frequency band. Both the pulse length and power level may vary depending on the available beam conditions. The successful demonstration of this scheme can be easily scaled to other frequencies. We will also have an experimental study of the dipole modes excited in the dielectric-loaded accelerators using the new dipole mode probes, and then a design of a dipole mode damped dielectric-based wakefield power extractor. This represents a very important step towards the development of a practical wakefield power extractor based high power RF source.

ACKNOWLEDGMENTS

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REFERENCES

1. F. Gao, etc., *Phys Rev. ST AB*. **11**, 041301(2008).
2. E. Chojnacki, W. Gai, P. Schoessow and J. Simpson, Proceedings of Particle Accelerator Conference, San Francisco, May 6-9, pp.2557-2559 (1991)
3. F. Gao, etc., this proceedings.
4. D. Newsham, et al, Particle Acceleration Conference, Portland, Oregon, 1156, (2003). IEEE, (2003).
5. www.euclidtechlabs.com