DESIGN OF A 26 GHZ WAKEFIELD POWER EXTRACTOR*

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Abstract

High frequency, high output power, and high efficiency RF sources have compelling applications in accelerators for high energy physics. The 26 GHz RF power extractor proposed in this paper provides a practical approach for generating high power RF in this particular frequency range. The extractor is designed to couple out RF power generated from the high charge electron bunch train at the Argonne Wakefield Accelerator (AWA) facility traversing a dielectric loaded waveguide. Designs are presented including parameter optimization, electromagnetic modeling of structures and RF couplers, and analysis of beam dynamics.

INTRODUCTION

Stable high power RF sources, because of numerous potential applications in a number of areas, have been pursued for decades using different technologies over different frequency bands [1-2]. The frequency range between Ku to low Ka band (20-30 GHz) is still an open window. An approach to generate high power rf in this particular frequency band is to use wakefield power extraction. This technique extracts energy from the Cherenkov radiation (wakefield) of a high current relativistic electron beam in a predetermined frequency slow wave structure. In the process, the beam kinetic energy is converted into electromagnetic energy at the mode frequency. The RF power produced is collected at the downstream end of the structure and coupled out for other applications.

The Argonne Wakefield Accelerator facility located at Argonne National Laboratory has a unique capability of providing high quality, high charge, and short bunch length beams using their 1.3 GHz photoinjector RF gun. According to their upgrade schedule, within the next three years the facility will be able to generate a 20 MeV bunch train (>16 bunches) with up to 40 nC charge per bunch by using a new high QE CsTe cathode and an additional 30 MW klystron. This represents an opportunity for testing high charge related applications like the proposed 26 GHz wakefield RF power extractor. In addition, the short bunch length of the AWA beam (~1.5 mm) allows us to design the high frequency power extractor without losing much conversion efficiency; the form factor of the electron bunch still includes 70% of the 20th harmonic of the beam frequency, 1.3 GHz×20 = 26 GHz.

We are proposing a dielectric based structure to generate and transport the RF energy to other applications. The principal goal of this project is the development and demonstration of power extractors that can eventually provide a 26 GHz high power RF source at the AWA facility for other users and applications. The design of a successful 26 GHz RF power extractor can be easily scaled to other operating frequencies.

DIELECTRIC BASED POWER EXTRACTOR

Structure Design

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. In wakefield extraction, a high charge, (typically 20 – 40 nC), short, (1 – 4 mm) electron drive beam (bunch/bunch train) generates electromagnetic Cherenkov radiation (wakefields) while propagating down the vacuum channel; the generated RF power can be harvested through a high efficiency RF coupler.

The deflecting (hybrid) modes in dielectric-lined circular waveguides are the HEM_{nm} modes, driven when the beam is not perfectly axisymmetric. The lowest deflecting mode is the HEM_{11} mode, and it is the most harmful mode for acceleration due to the transverse force it exerts on the beam particles. This can lead to the beam breakup instability, causing beam loss and concomitant reduction of efficiency.

We have calculated the major parameters characteristic of the designed 26 GHz power extractor (summarized in Table 1) as the basis for an estimate of the generated RF power. The parameters of both TM_{01} and HEM_{11} modes are presented. (The Quality factor Q in Table 1 is computed based only 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 of the structure.)

Output Coupler Design

The wakefield signal excited by the beam will propagate along the structure with a group velocity determined by the geometry of the structure, and will be extracted through an output coupler to a WR-34 rectangular waveguide. An optimized coupling slot and chamber can implement high conversion efficiency between the fundamental mode in the dielectric-loaded circular waveguide, TM_{01}, and the dominant mode in the rectangular waveguide, TE_{10} within the operating frequency range, and simultaneously maintain a low

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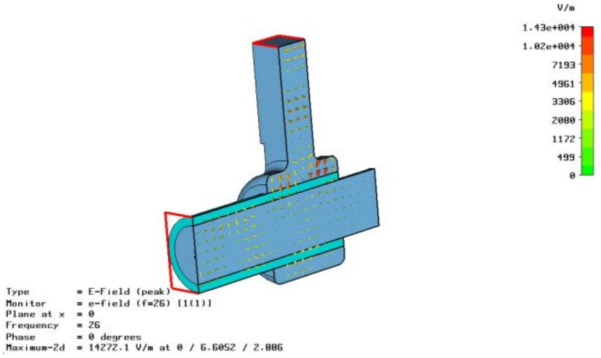
transmission of the deflecting mode (HEM_{11}). Figure 1 shows a simulation of the electric field pattern of the TM_{01} mode in the output coupler (the RF input port is a rectangular waveguide in the simulation). Its S-parameters are shown in Fig. 2, in which we can see that the transmission of the TM_{01} mode is nearly 95% over the 1 dB bandwidth of 300 MHz (curve S2(2),1(1)), and less than 2% of the energy from the HEM_{11} mode can be transmitted in the same frequency range (S2(1),1(1)). More detailed optimization will be performed before fabrication of the structure.

Table 1: Parameters of 26 GHz 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



Type = E-Field (peak)
Monitor = e-field (f=26) [1(1)]
Plane at x = 0
Frequency = 26
Phase = 0 degrees
Maximum-2d = 14272.1 V/m at 0 / 6.6052 / 2.006

Figure 1. Electric field map of the fundamental mode in the output coupler for the proposed 26 GHz dielectric based RF power extractor. (Simulation using CST Microwave Studio®.)

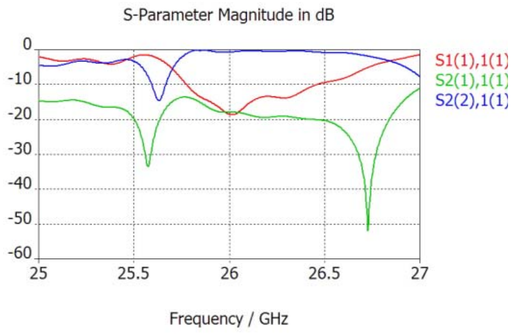


Figure 2. The simulated S-parameters of the monopole/dipole modes in the output coupler for the proposed 26 GHz dielectric based RF power extractor. Symbols in the legend, from the top to the bottom, represent reflection of the rectangular waveguide (TE_{10}), coupling of the dipole mode (TE_{10} -HEM_{11}), and coupling of the monopole mode (TE_{10} -TM_{01}).

Output Power Estimate

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, average current, and output power level. 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 the electron bunch can be estimated from the equations presented in [3]. We first consider a 20 nC single bunch with bunch length of 1.5 mm. Using the parameters of Table 1, we can obtain the generated wakefield gradient of 15.3 MV/m, RF power of 8.2 MW, and a drain time of 3 ns. A MAFIA® simulation is shown in Fig. 3 as a comparison; very good agreement with our estimated values is obtained.

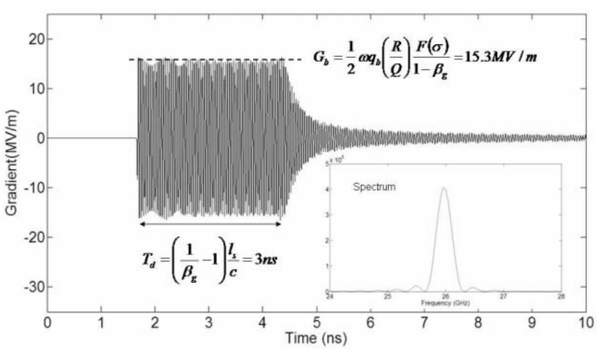


Figure 3. Comparison of the wakefield signal from the MAFIA simulation and the analytic estimate

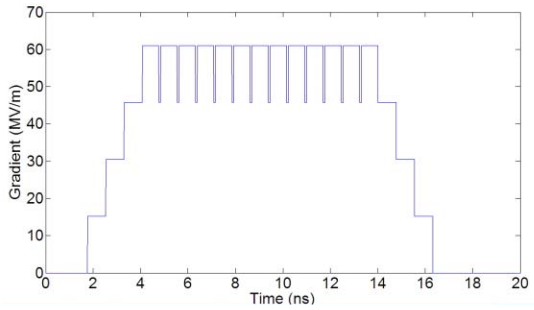


Figure 4. Envelope of the wakefield gradient for a 26 GHz dielectric based RF power extractor excited by a bunch train.

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For the same structure, using a 20 nC bunch train (bunch spacing T_b=770 ps for the AWA linac), we can obtain a steady output power of 148 MW and 56 MV/m peak gradient. Figure 4 shows the envelope of the wakefield gradient for the case of a bunch train consisting of 16 bunches with charge of 20 nC each. The comb-like feature at the top of the simulation curve is caused by the relatively short drain time ($T_d \approx 4T_b$). The energy loss is 5.7 MeV for the last bunch in the bunch train, in the acceptable range for the 20 MeV AWA beam.

BEAM DYNAMICS

Investigation of the beam dynamics, particularly for the transverse instability, is a core part for the project of developing a wakefield power extractor due to the strong transverse forces from an offset high current beam. For the power extractor, using the dielectric-based design as an example, the generated longitudinal wakefield amplitudes are 15.3 MV/m for a single 20 nC bunch and 56 MV/m for bunch train. Large amplitude longitudinal wakefields also imply that strong transverse deflecting forces will be generated if the drive beam in the structure is misaligned. This deflecting field can have serious detrimental effects on the accelerated beam from the head - tail single bunch break up instability of the accelerated beam, resulting from the leading particles in an offset bunch driving HEM modes that in turn deflect the electrons in the tail of the bunch. The deflected tail electrons will eventually be driven so far off axis that all or most of the particles will be lost by scraping on the inner walls of the dielectric waveguide. Figure 5 shows the transverse wakefields in the 26 GHz dielectric-based RF power extractor generated by a single 20 nC, 20 MeV bunch at 1 mm offset from the structure center. The bunch length used in the calculation is 1.5 mm. Two major dipole modes (HEM$_{11}$ at 23.5 GHz and HEM$_{21}$ at 35.75 GHz) contribute and are included in this case.

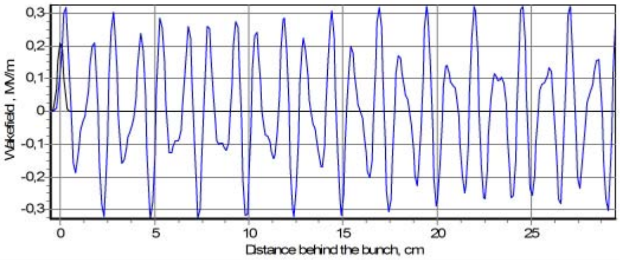

Figure 5. Transverse wakefield in the 26 GHz dielectric-based power extractor.

We are developing a particle-based code to simulate the beam dynamics inside the structure [4]. Figure 6 shows the results for a single bunch traversing the structure; we plan to make extensive use of this tool for modeling beam breakup effects in the power extractor.

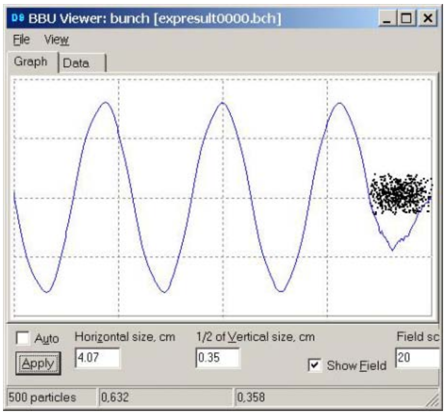

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Figure 6. Simulation using our particle code of the longitudinal wake of a single drive bunch passing through the power extractor. Studies of the beam dynamics of a bunch train are planned.

DESIGN OF A 26 GHZ BIDIRECTIONAL COUPLER AND LOAD

The major diagnostic component required to evaluate the 26 GHz RF power extractor is a bidirectional coupler. Here we propose a device based on the use of H-plane coupling holes. A CAD drawing illustrating the device is shown in Fig. 7. This design is able to provide a -60 dB coupling coefficient over a few hundred MHz bandwidth by optimization of the hole dimensions and separation. The specifically designed neutral gender flange can hold a vacuum of up to 10^{-9} Torr for the rectangular waveguide connections. Two pin probes will match the bidirectional RF signals to conventional coaxial ports.

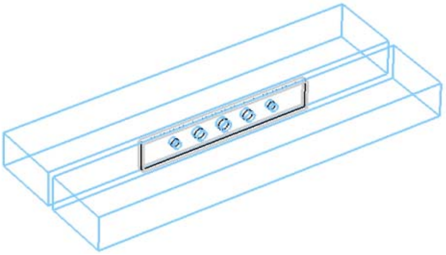

Figure 7. 3D wire frame view of the 26 GHz H-plane vacuum sealed bidirectional coupler (pin probes are not shown).

For simplicity, in the beam experiment we will use a few meters of lossy WR-34 waveguide made of stainless steel as the 26 GHz RF load. Ports will be machined in the waveguide for emplacement of ion pumps.

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