THE FIRST EXPERIMENT OF A 26 GHZ 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. We have developed a 26 GHz 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. The first high beam experiment has been performed at Argonne Wakefield Accelerator facility. The experimental results successfully demonstrated a 15 ns 26 GHz rf pulse generated from the wakefield extractor with a bunch train of 16 bunches. Meanwhile, a short ~ 20 MW rf pulse has been achieved with a bunch train of 4 bunches. Beam Breakup has prevented charge transport through the power extractor at intensities beyond 10 nC. We are performing simulations to develop methods to alleviate the BBU effect.

DIELECTRIC-BASED WAKEFIELD POWER EXTRACTOR

Wakefield effects are very important considerations for accelerator design because they are the major source of beam instabilities such as bunch lengthening, head-tail turbulence and emittance growth. However, the wakefield energy generated by a charged particle beam also can be used to accelerate an appropriately phased trailing beam or can be extracted by a high efficiency RF coupler working as a high power RF source. Generally, the RF packet generated by a single particle bunch lasts a few nanoseconds. A properly spaced bunch train can stack the RF pulses from each bunch so that both the pulse length and amplitude are increased [1]. Due to the ease with which the RF power characteristics can be changed by manipulating the decelerator and its drive bunches, 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. A successful example is the CLIC PETS (Power Extraction and Transfer Structure) which can provide ~240 ns, 135 MW rf power using ~100 A beam current [2].

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 [3]. 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 acceleration structures, where it is expensive and difficult to precisely fabricate conventional iris-loaded copper structures. Some other advantages of using dielectric based structure include the potentially higher breakdown threshold, easy parasitic mode damping, and very low enhancement of the ratio of electric field on the dielectric surface over that on axis.

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A 26 GHZ DIELECTRIC BASED WAKEFIELD POWER EXTRACTOR

We have recently developed a 26 GHz dielectric based wakefield power extractor (Fig.1). Its major design parameters are presented in ref. [4]. 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 26 GHz signal). After machining the three parts are brazed together with the flanges at the three open ends. The flange and corresponding gasket for the RF output port are specially designed to allow the high power RF transmission without an RF discontinuity while maintaining high vacuum. Three 10 cm long Forsterite tubes, with a dielectric constant of 6.64 and Q=10000 at 10 GHz, are loaded in the circular waveguide to generate a 26 GHz high power rf wave with an ultra-relativistic

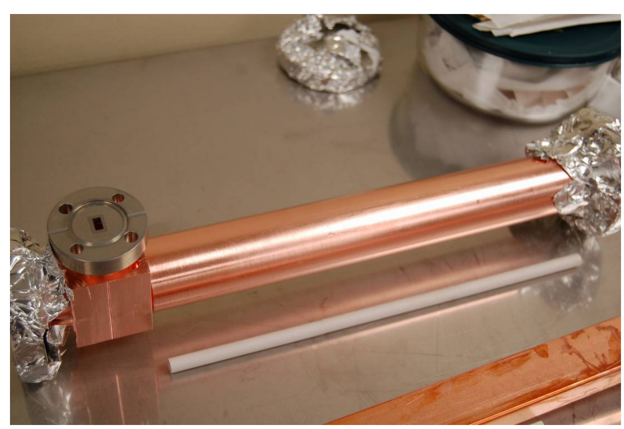

Figure 1: Fabricated 26 GHz dielectric-based wakefield power extractor and dielectric (consisting of three 10-cm long dielectric tube segments) prior to loading.

drive beam. Note that there is no transverse mode damping feature in this prototype dielectric-based wakefield power extractor. The transverse mode damping scheme in a dielectric loaded accelerating structure is discussed in ref. [5].

BEAM EXPERIMENT

In order to evaluate the real performance of the structure we have developed, we performed a beam test at the Argonne Wakefield Accelerator (AWA) facility, which has the capability of producing high current bunch trains from its L-band photoinjector. The experimental setup is shown in Fig.2. The 26 GHz high power RF signal from the output port of the power extractor is transported to the diagnostics through the WR34 waveguide under ultra high vacuum. Considering the low average power generated in our experiments (The operational repetition rate of AWA facility is usually less than 5 Hz.), we developed a SiC based 26 GHz high power RF load. The major diagnostic component required to evaluate the 26 GHz RF power extractor is a 26 GHz RF power detection system. Since the forward and backward RF signals will be well separated in time by tens of nanoseconds due to the use of a long WR-34 waveguide in the beam experiment instead of a bidirectional coupler, we can then use one RF pin probe to detect the RF signal in both directions. We have developed a 26 GHz RF power detector. In this design, a pair of arc slots is designed to couple out a small portion of the generated RF. This specially designed coupling slot is to establish the TEM mode and suppress unwanted TE modes for the RF pin probe. The commercially available RF pin probe used in the detector can hold ultra high vacuum through the use of a 1.33" CF flange. The output end of probe is a standard 3.5 mm connector. -51 dB coupling coefficient at 26 GHz was measured using a network analyzer. The detected signal is recorded by a Tektronix 16 GHz real-time digital oscilloscope after down conversion to ~11.424 GHz (LO=14.576 GHz) by a heterodyne rf circuit box. A high quality bandpass filter (center frequency 11.424 GHz; bandwidth 228 MHz) is used to effectively suppress the unwanted signals from

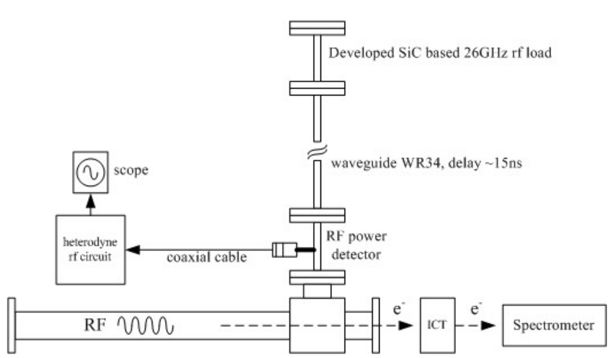

Figure 2: Experimental setup for the beam tests.

the beamline and leakage from the local oscillator.

The bunch train data is shown in Fig. 3. 16 bunches with interbunch separation of 770 ps (one period of 1.3 GHz, the frequency of AWA photoinjector) were generated and passed through the 26 GHz power extractor. We can see that a 10 ns flat top 26 GHz rf pulse has been achieved (The measured frequency shows 16 MHz off).

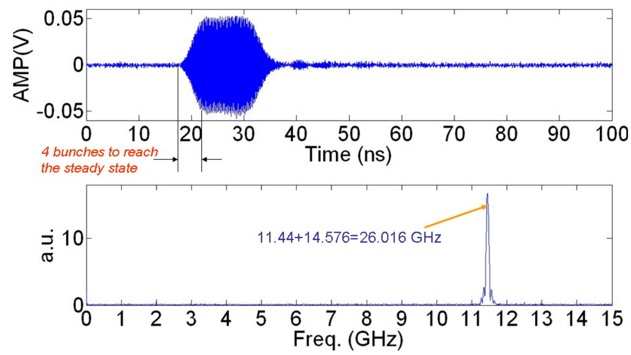

Figure 3: The down-converted rf signal and its frequency spectrum obtained in the beam test of the 26 GHz wakefield power extractor. A 14.576 GHz local oscillator was used to down-convert the signal. A bunch train consisting of 16 bunches was used.

We swept the charge for the 16-bunch-train; 2 nC per bunch was achieved, equivalent to 1.1 MW of rf power. Limited by the QE of the photocathode at the AWA injector at that time, we were not able to run a higher charge with the main laser pulse split into 16 pulses. However, for this particular power extractor, the generated rf power will reach the steady state after the first four electron bunches. Therefore, we can test the structure at a higher rf power level by using a 4-bunch-train. Figure 4 plots the charge dependence for the 16-bunch-train case. We can see that the voltage captured in the scope trends linearly as predicted as a function of the charge.

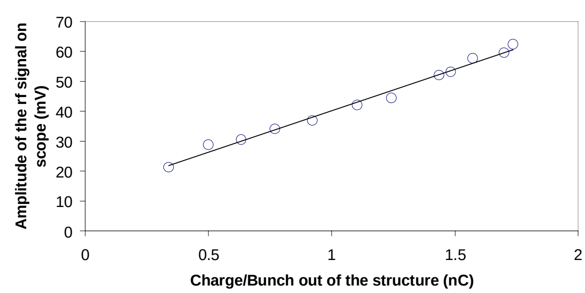

Figure 4: The measured rf signal strength in the scope increased linearly with the transported charge. The bunch train consisted of 16 bunches.

The ultimate goal for this 4-bunch-train experiment is to transport 20 nC per bunch electrons through the structure, which will in turn generate ~150 MW of 26 GHz rf power out of the wakefield power extractor. The results from the charge sweep are plotted in Fig. 5.

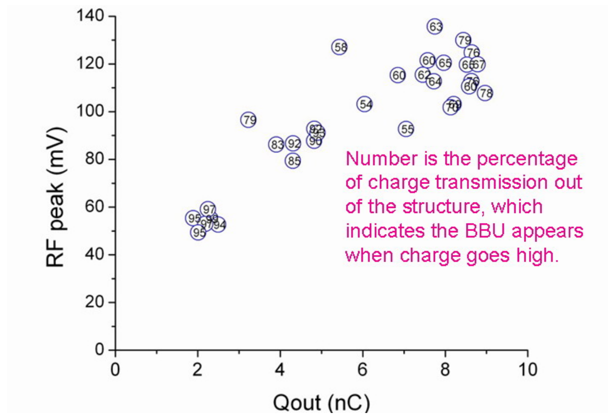

Figure 5: The measured rf signal strength in the scope increased with the transported charge (charge measured out of the power extractor). The bunch train consisted of 4 bunches.

9nC/bunch was obtained in this run which is equivalent to 30 MW of rf power as inferred from MAFIA simulation. 17 MW was measured after the calibration. The longer bunch length in the high charge situation and the coupler loss are main contributors to the lower measured rf power compared to the simulation. The fraction of the beam charge transmitted through the structure is also indicated in Fig. 5. Note that the percentage of the charge out of the power extractor varied significantly (from ~60% to ~80%) when the charge at the entrance exceeded 12 nC per bunch. The main reason of this low transmission rate was discovered to be the BBU effect, which was verified by the BBU-3000 code (under development at Euclid Techlabs through the support of DoE SBIR funding).

The generated longitudinal wakefield amplitudes are 15.3 MV/m for a single 20 nC bunch and 56 MV/m for a 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 deflection 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. Major dipole modes in the 26 GHz dielectric-based rf power extractor are HEM_{11} at 23.5 GHz and HEM_{21} at 35.75 GHz. Figure 6 shows the total intensities of the bunches in a five-bunch train as a function of time. The bunches enter the structure at successive rf periods of the linac (23 cm spacing) and the structure length is 30 cm. Each bunch is offset initially from the center of the structure by 0.4 mm in the positive x direction. The largest bunch intensity losses caused by scraping on the vacuum channel correspond to no worse than 60% in the plot, which agrees with the experimental observation. We are currently investigating approaches to overcome the BBU effect for this structure including FODO lattice or solenoid field around the structure. On the other hand, this justifies the need for a fully featured (including transverse mode damping) dielectric-based wakefield power extractor.

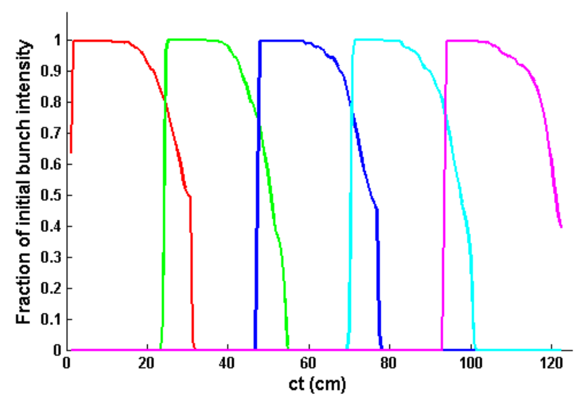

Figure 6: Intensity vs. time for the five bunch simulation. Different color represents different electron bunch in a bunch train.

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