HIGH POWER RF GENERATION FROM A W-BAND CORRUGATED STRUCTURE EXCITED BY A TRAIN OF ELECTRON BUNCHES

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Abstract

We report on the generation of multi-megawatt peak RF power at 91 GHz, using an ultrarelativistic electron bunch train to excite electromagnetic fields in a high-impedance metallic corrugated structure. This device can be used as a power source for high gradient acceleration of electrons. To achieve precise control of the wakefield phase, a long range wakefield interferometry method was developed in which the RF energy due to the interference of the wakefields from two bunches was measured as a function of the bunch separation.

INTRODUCTION

High power RF sources with frequencies beyond microwave regime has many applications in particle accelerators, communications, radar, etc. One approach to realize high power RF of high frequency is based on the beam-driven RF generation. Beam-driven devices use wakefields from a high charge drive bunch (or bunch train) to generate RF pulses with stable phase and amplitude necessary to accelerate a witness beam in both the collinear acceleration and the two beam acceleration schemes [1]. The individual RF pulse generated by a single bunch are due to the interaction of the structure's EM modes with the EM fields of the bunch and the total RF pulse generated by the bunch train is the superposition of the individual RF pulses.

NUMERICAL STUDY

Wake Function of the TM01 Mode

The sketch of the high-impedance W-band corrugated structure is show in Fig. 1(a). The W-band radiator consists of two identical copper plates, one side of the plate was milled out to form a series of grooves, or half capsule cells, which form periodic resonant cavities when the corresponding sides of the two plates face each other. Similar to the conventional disc-loaded Traveling Wave (TW) accelerating structure, the fundamental mode of structure is TM_{01} mode. It is designed to have 120 degree phase advance per cell. The aperture between the two plates $2a = 0.94$ mm when the frequency of the TM01 mode $f_0 = 91$ GHz; the period length in Z direction $d = 1.1$ mm; the half length of groove in the

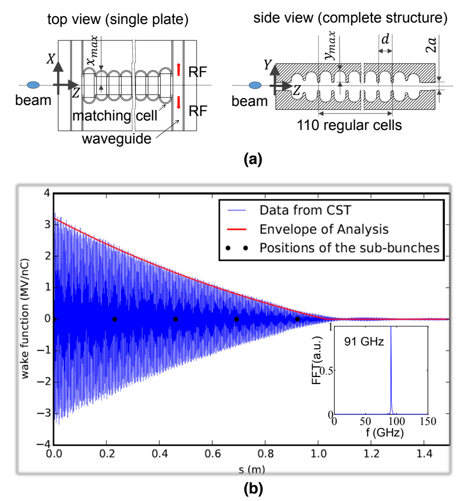

Figure 1: (a) sketch of the W-band structure, (b) wake function and frequency spectrum of the TM01 mode.

Y direction $y_{max} = 1.25$ mm; and the depth of the groove $x_{max} = 0.9$ mm. Besides, the group velocity $v_g = 0.105c$, $R/Q = 83.3$ kΩ/m, structure attenuation $\alpha = 3.54$/m, and loss factor per unit length $\kappa = 13.3$MV/m/nC. The total length of the grooved structure $L_s = 123$ mm.

The wake function is used to describe the integrated effect on the witness particle from the wakefield excited by a drive particle along the whole structure [2]. The wake function of the TM01 mode in the W-band structure is:

$$w_{\parallel}(s) = -w_0 \cdot H(s)(1 - s/l_w)(s \le l_w) \cdot cos(ks) \quad (1)$$

where $w_0 = 2\kappa_L L_s e^{-\frac{\alpha s}{l_w/L_s}}$ is the amplitude of wakefield with the consideration of the structure attenuation, k is wave number, $H(s)$ is the Heaviside step function. And the wakefield duration excited by a single particle (bunch) $l_w = L_s(1/\beta_g - 1) = 3.4$ ns.

Figure 1(b) shows the comparison of the numerical simulation of the wakefield function of the W-band structure using CST [3] and the analysis envelope calculation by Eq. 1. The wake function in the TW structure has a decreasing envelope versus s, which implies the wakefield travels out of the structure in a finite time. The finite duration of the wakefield leads to the RF power saturation after a certain number

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of bunches in a train. The black dots indicates the separation between sub-bunches in the train is 23.06 cm (1.3 GHz), the long range wakefield from the sub-bunches will add up inside the structure.

Long Range Wakefield Interferometry Method

In order to figure out the phase information of the W-band RF pulse, we put up the scheme of the long range wakefield interferometry method with two drive bunches. Consider two drive bunch case : each bunch generates a wakefield pulse as shown in the Fig 2 (a), the wakefield electric field gradient $\vec{E}$ add up with phase information. It is just a simple superposition of two vectors of $\vec{E_1} = E_1\cos(\theta_1)$ and $\vec{E_2} = E_2\cos(\theta_1)$, where E_1, θ_1 and E_2, θ_2 are the wakefield gradient and phase excited by bunch 1 and bunch 2 respectively. The RF power $P \propto |\vec{E}|$, the expected total power $P_t \propto |E_1|^2 + |E_2|^2 + 2E_1E_2\cos(\Delta\theta)$, where $\Delta\theta = \theta_2 - \theta_1 = k\Delta Z_{21}$. With the wakefield wave number k and the separation between two bunches ΔZ_{21}, the expression of $\Delta\theta = k\Delta Z_{21}$, which means when scanning the separation between two bunches, the added RF power varies as a cosine function which repeating the wave length of $\lambda = 2\pi/k$ as shown in Fig 2 (b). Thus the wakefield waveforms are mapped and the wakefield phase information are known in this way .

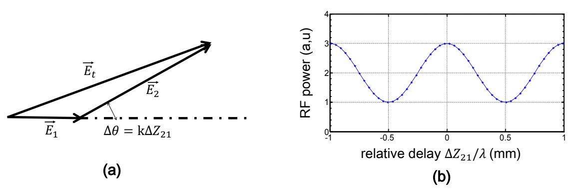

Figure 2: (a) sketch of the superposition of the long range wakefield from two drive bunches, (b) wakefield mapping as the total RF energy varies with the relative delay between two drive bunch.

EXPERIMENT MEASUREMENT

Set Up at the AWA Facility

The experiment was performed at the Argonne Wakefield Acceleration Facility (AWA) at Argonne National Laboratory [4]. Figure 3 shows the layout of the experiment. A 65 MeV electron bunch train was used to excite the W-band structure. The train from the linac was focused with quadrupoles and its trajectory was adjusted with trim magnets to pass it through the center of the W-band structure. The charge of a single bunch in the train was varied from 0.1 nC to 3 nC during the experiment. Each bunch had a longitudinal Gaussian distribution and corresponding rms bunch length of 0.2 mm to 0.6 mm. Note, the longer bunch lengths at higher charge are due to stronger space charge effects. The integrating current transformers (ICT) were used to record the charge of the drive beam before and after the W-band structure respectively to optimize the percentage of charge transmitted.

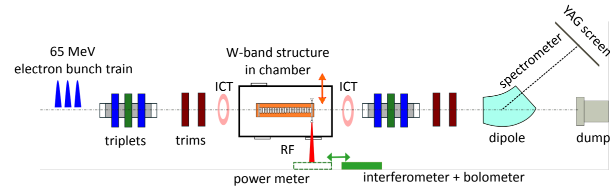

Figure 3: Schematic of the experimental setup.

The RF extracted from the accelerating structure was characterized by two direct methods and one indirect method. The RF pulse exited the structure through the WR10 horn antenna, passed through a quartz window mounted on the vacuum chamber, and propagated into the detection system. A calibrated photo-acoustic energy meter was used to measure the RF pulse energy and a Michelson interferometer with a helium-cooled bolometer was used to measure the time domain characteristics of the RF pulse. In addition to the direct measurements of the RF pulse, the kinetic energy of the electron bunches was measured with a spectrometer to indirectly characterize the wake since the electron bunches lose energy to generate the wakefield. Taken together, these methods were used to characterize the interaction of various bunch trains with the W-band wakefield structure.

Single Bunch Results

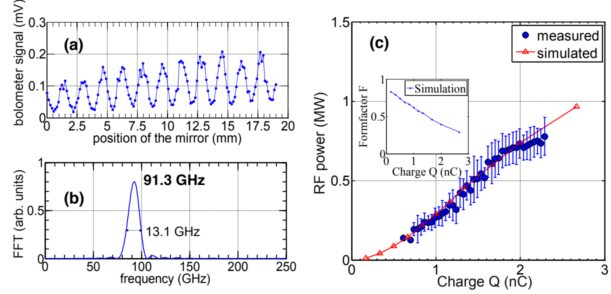

Figure 4: single bunch experiment results. (a)measured autocorrelation curve, (b) measured frequency spectrum (FFT of the data in figure (a)), (c) comparison of the measurements with simulations on the RF power verses the drive bunch charge.

For the single bunch experiment, the measured autocorrelation curve with a interferometer is shown in Fig 4(a), the fundamental frequency (f_0) is 91.3 GHz, and the relatively broad bandwidth $BW = 13.1$ GHz is due to the limit range of the interferometer. And the RF pulse energy as a function of beam charge was also measured in the single bunch experiment. The compared to simulation are shown in Fig 4(b). The electromagnetic code CST was used to simulate the RF energy generated by the beam with RF losses (structure attenuation) included. The RF power depends on the electron bunch parameters according to $P \propto Q_b^2 \cdot F(\sigma_z)$ [5], where Q_b is the single bunch charge and $F(\sigma_z)$ is the bunch form factor. To estimate the form factor $F(\sigma_z)$ as a function of Q_b, the beam dynamics code ASTRA [6] was used for start

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to end beamline simulations to determine the electron beam parameters in the W-band structure. This showed that $F(\sigma_z)$ decreases with Q_b due to space charge effects which results in the slower power growth with charge than would occur if $F(\sigma_z)$ were constant.

Precise Mapping of the Wakefield

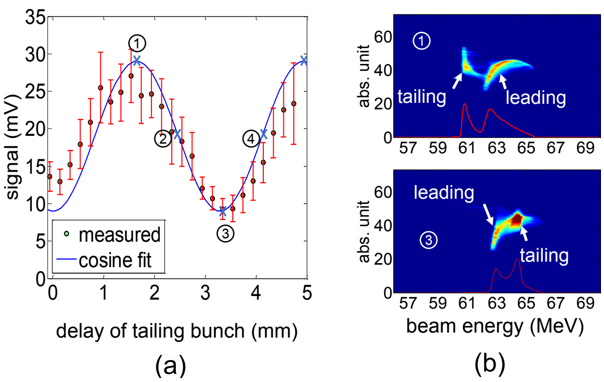

Figure 5: (a) Measured RF energy vs. the relative delay of the tailing bunch. Labels ① ~ ④ correspond to different relative wakefield phases when the leading bunch and the trailing bunch add. (b) Measured energy distribution of the two bunches, in case ①, the trailing bunch was decelerated by the wakefield from the leading bunch; in case ③, the trailing bunch was accelerated.

The energy will vary between minimum and maximum as the delay of trailing bunch is scanned (Fig. 5(a)) with the cycle repeating at the RF wavelength, 3.3 mm. In case ①, the individual wakes add constructively, generating the maximum RF energy. In case ③ however, the wake of the trailing bunch interferes destructively, so the output RF energy is minimal, which does not drop completely to zero since the RF pulses don't fully overlap in time due to bunch separation.

The energy change of the trailing bunch also depends on the bunch separation (Fig. 5(b)). (Note, the leading bunch loses the same energy regardless of the position of the trailing bunch since its wake doesn't affect the leading bunch.) In case ①, the trailing bunch gets decelerated by the wake from the leading bunch. It losses more energy than the leading bunch and contributes to the maximum RF amplitude. In case ③ however, the trailing bunch rides on the acceleration phase so that it gains energy from the wake of the leading bunch. Energy measurements of the two bunches are consistent with the RF energy descriptions in cases ① and ③.

High Power with Bunch Train

For higher RF output power, three drive bunches are applied in the experiment, proper bunch spacing was set with the newly developed two-beam (wakefield) interferometry method described above. Three bunches with different energy losses are clearly visible as shown in Fig. 6(a). The blue dashed line gives the simulated energy spectrum of 3 bunches, each of 2 nC effective charge, passing through the W-band structure. These agree well with the experimental observation on the spectrometer. The average energy loss of bunch 1 through 3 was 1.3 MeV, 3.2 MeV, 4.4 MeV respectively, indicating coherent superposition of wakefields for maximum radiated power. Given the energy meter measurement of 18 mJ per pulse, we calculate the maximum peak power of 4.8 MW (in agreement with the simulation of a 3×2 nC bunch train) and peak accelerating gradient of 85 MV/m.

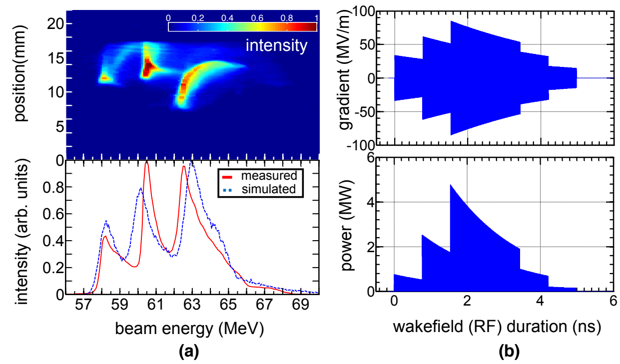

Figure 6: (a) beam energy distributions with 3 bunches of 2 nC drive beam after the W-band structure, (b) derived output RF pulse power and the wakefield gradient.

SUMMARY

In summary, a W-band wakefield corrugated structure driven by a bunch train was experimentally characterized. A two-beam wakefield interferometry measurement was developed as a high sensitivity technique for wakefield characterization and precise RF phase control in wakefield acceleration. A 5 MW RF pulse was generated corresponding to an accelerating gradient of 85 MV/m.

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