BEAM BREAKUP INSTABILITIES IN DIELECTRIC STRUCTURES*

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Abstract

We report on the experimental and numerical investigation of beam breakup (BBU) effects in dielectric structures resulting from parasitic wakefields. The experimental program focuses on measurements of BBU in a number of wakefield devices: (a) a 26 GHz power extraction structure; (b) a high gradient dielectric wakefield accelerator; (c) a wakefield structure driven by a high current ramped bunch train for multibunch BBU studies. New beam diagnostics will provide methods for studying parasitic wakefields that are currently unavailable at the AWA facility. The numerical part of this research is based on a particle-Green's function beam breakup code we are developing using the approach described in [1] that allows rapid, efficient simulation of beam breakup effects in advanced linear accelerators. The goal of this work is to be able to compare the accurate numerical results with the results of detailed experimental measurements and to design the external focusing system for the control of the beam in the presence of strong transverse wakefields.

INTRODUCTION

Investigation of the beam dynamics, particularly for control of transverse instabilities, is an essential part of the development of practical wakefield accelerators. Single bunch beam breakup can be a major source of inefficiency for high current acceleration techniques such as wakefield acceleration. An initially small beam injection error into the accelerating structure leads to deflection of the bunch tail by transverse wakefields from the head (Fig. 1). These injection errors are amplified as the beam propagates; the bunch tail couples more strongly to the parasitic (HEM_{mn}) modes and is deflected further off axis until beam loss occurs through scraping on the structure walls or (at least) an unacceptable growth in emittance occurs.

It is difficult to control single bunch BBU. Reducing the injection error to the point at which it becomes unimportant requires impossibly high tolerances. Damping techniques that rely on the use an absorber with mode filtering [2] of the parasitic wake cannot attenuate rapidly enough to affect single bunch BBU although they can be useful in the multibunch case. A third option is some variant of BNS damping [3], where a FODO lattice around the accelerating structure is used to confine the bunch in the beam channel.

Our efforts are focused on BBU studies in dielectric loaded accelerator (DLA) structures. We plan to provide new instrumentation at the AWA [4] to study BBU effects in several high gradient DLA devices, and to upgrade our BBU simulation code to be able to model the experiments that are planned.

*Work supported by DOE SBIR Phase I Funding.
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BBU EXPERIMENT

The AWA facility, where we plan to perform the dielectric structure BBU experiments, can provide 20 nC, short bunch length (1.5 mm) bunches or bunch trains with its upgraded high QE cathode. The rms beam size in x and y in the test section (Fig. 2) is less than 0.7 mm over a length of a 20 cm.

For the 26 GHz dielectric test device (see Fig. 3) the longitudinal wakefield amplitudes generated 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. Two major dipole modes (HEM_{11} at 23.5 GHz and HEM_{21} at 35.75 GHz) contribute to BBU in the 26 GHz structure.

Transverse Wake Diagnostics at the AWA

Several diagnostic systems are currently in use at the Argonne Wakefield Accelerator facility to measure longitudinal wakefields: 1) an RF probe mounted on the test structure to record the wakefield signals in the time domain; 2) an integrating current transformer (ICT) immediately downstream of the test structure to measure the transmitted beam charge; 3) an energy spectrometer (resolution $\Delta E/E$ =0.2% with the tungsten slit set to 300 μm) to measure the beam energy; and insertable phosphor screens that are viewed with CCD cameras and used to measure the transverse shape and position of the beam. Figure 2 shows the downstream beamline configuration at the AWA with the test structure, ICT, beam slit, and energy spectrometer.

Wakefield measurements of dielectric-loaded accelerators have been successfully demonstrated using the witness beam technique [4]. The longitudinal wake potential from a drive bunch is mapped out by measuring the energy gain/loss of the following witness bunch as a function of the drive-witness delay using a magnetic spectrometer.

Transverse wakefields in a test structure were measured in a similar fashion from the deflection of the witness beam in the nonbend plane of the spectrometer as a function of delay [2]. The test device could be moved transverse to the beam axis on a motorized stage to measure the dependence of the transverse wake on the beam offset from the axis of the structure. The beam intensities available in the earlier experiment were insufficient to observe BBU effects but the success of the measurement techniques suggest upgrades to the AWA test beamlines and diagnostics that could be effective for BBU studies with the larger beam currents now available. A remotely controlled stage for transverse positioning of the test device is a planned addition. The test wakefield structure will be mounted to the beamline with bellows having sufficient play to allow the stage to sweep the beam across the entire diameter of the beam channel.

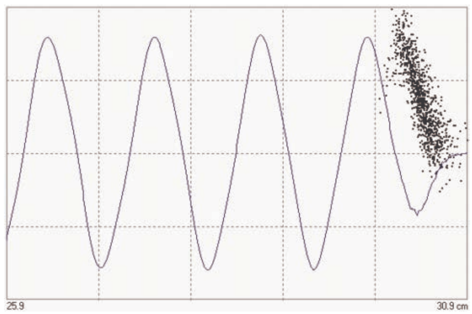

Figure 1: Beam breakup simulation for the 26 GHz power extractor using DWA-BD-02. (15 MeV, 20 nC beam, 1.5 mm rms length, 0.1 mm initial offset, E_z~ 18 MV/m).

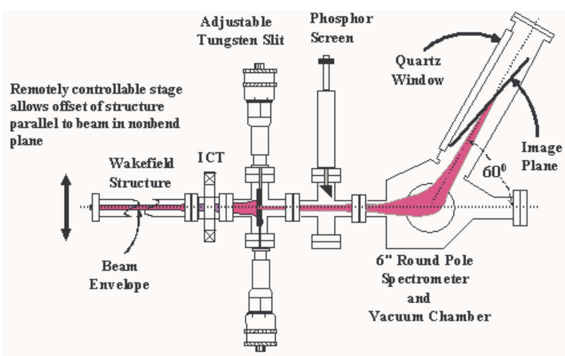

Figure 2: Test section of the AWA showing the placement of the test device. Note that the motion of the stage is actually orthogonal to the bend plane of the spectrometer.

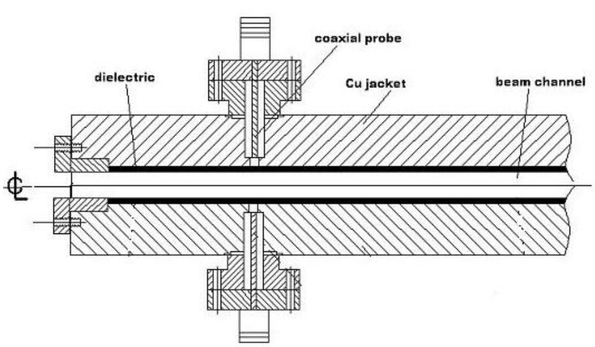

Figure 3: Cross section through the 26 GHz test structure. The vacuum channel diameter is 7 mm. A pair of coaxial probes mounted 180° apart monitor the radial component of the electric field. Time evolution of the wake is given by the sum and difference signals ($\Sigma \rightarrow TM_{0n}$, $\Delta \rightarrow HEM_{mn}$.)

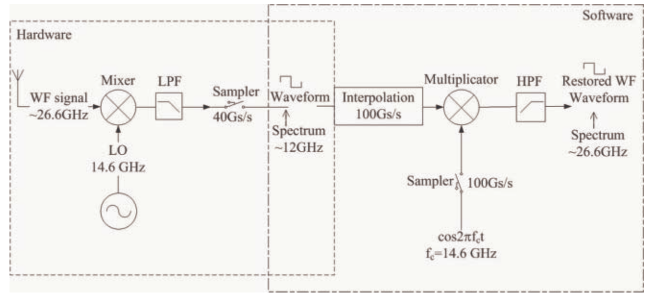

Figure 4: Block diagram of the heterodyne wakefield rf measurement technique. The wakefield signal for the beam breakup measurement is the difference of the radial components of the electric fields from field probes mounted 180 degrees apart on the dielectric loaded test structure.

A phosphor screen downstream of the test structure can be used to diagnose beam breakup. The frame from the DWA-BD-02 calculation in Fig 1 shows the r-z distribution of a high current bunch injected off axis into a dielectric structure. The transverse wake from the head of the bunch deflects the tail, leading to a loss of particles into the wall of the dielectric tube. The occurrence of this effect will distort the transverse bunch shape from its initial circular form. The measured transverse shape can be compared directly with the simulation results provided the linearity of the phosphor and camera can be determined. Scraping of the deflected beam will also need to be avoided, as the secondary electrons and gammas will provide an unacceptable background to the measurement. Provided scraping is not an issue a simple statistical moment extraction algorithm could be used to characterize both the simulation and experimental data and perform an unbiased comparison.

A method that is capable of measuring the time dependence of the beam breakup signal uses field probes to transform the varying electric field behind the moving electron bunch into an RF signal that can analyzed by available instruments. Figure 3 shows the 26 GHz dielectric power extractor test structure [6] with two field probes installed diametrically opposite on the outer wall of the device but at the same axial position to sense the radial component of the electric field. The probes will detect all modes with a radial electric field component on the dielectric boundary. To isolate the transverse (HEM_{mn}) modes responsible for BBU the difference signal between the probes will be measured. By symmetry the TM mode fields will be canceled while the dipole modes that contribute most strongly to BBU will be reinforced.

This approach provides a method of studying the evolution of the instability as the bunch propagates through the structure; the harmonic content of the waveform will change as the bunch tail is deflected farther away from the device axis and a larger proportion of HEM modes are excited. Measurements of the HEM waveforms will be performed at different transverse offsets and beam intensities to map out the behavior of the instability.

Because of limited bandwidth and sampling rates of available oscilloscopes, we cannot observe the high frequency test signals in the time domain directly. Rather, the high frequency signal is downconverted to a lower frequency and then reconstructed by postprocessing the data. A block diagram of the experimental configuration is shown in Figure 4. The sum or difference signals are mixed with a local oscillator and the resulting rf pulse is recorded using a fast digital oscilloscope. This is especially well suited for the transient effects that we wish to measure in the evolution of single bunch BBU.

The digitized waveform is exported to the software post-processor which performs the inverse function of the hardware subsystem to restore the original signal. The signal flow in the post- processor is as follows: the digitized downconverted wakefield signal is interpolated to raise the sampling rate up to 100 Gs/s to match the sampling rate of the 14.6 GHz digital local oscillator. These two signals are mixed and the final step is to use a digital high pass filter to block the low frequency interference from the signal multiplication. All data processing is performed using the MATLAB® software environment.

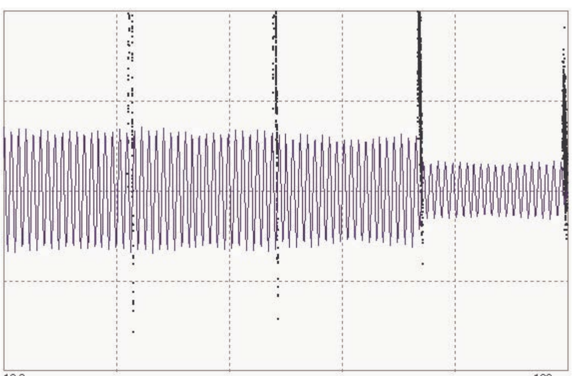

Figure 5: Beam Breakup Simulation of the 26 GHz Wakefield Power Extractor, bunch train case of 4 bunches.

BBU SIMULATIONS

Simulations of these experiments build on a test code originally used to study single bunch BBU effects in dielectric loaded wakefield structures [1]. It was shown that BBU effects could be controlled by the addition of a FODO channel around the wakefield device with the focusing strength of the elements decreasing along the beam axis to compensate for the energy loss of the beam.

The code does not self-consistently compute the wakefields; instead, the analytic expressions for the longitudinal and transverse mode fields are used to compute the wakefields at each time step using macroparticle currents as sources. The particle-Green's function approach incorporates all the necessary physics for rapid, efficient simulation of beam breakup effects in advanced linear accelerators.

The code includes both longitudinal and transverse beam dynamics. The drive beam (or train) currently is assumed to have a two-dimensional Gaussian charge distribution, although any other bunch shape can be used in the future. The drive bunch train charge distributions can be varied to provide any appropriate bunch charge sequence inside the train. We assume that during the small time step of the simulation both transverse and longitudinal fields remain constant. The program simulates the 2D-dynamics of an electron bunch in a dielectric-filled circular waveguide. (Other types of structures could be simulated by incorporating the appropriate Green's functions.)

The simulation uses Euler's method. For a "snapshot" of a bunch's configuration we calculate all the fields, based on their location in a waveguide and pulse. Next, new positions and pulses are calculated assuming acting forces are constant during a short interval of time. To be able to simulate the bunches emitted with non-zero offset off Z axis, the code has a module for exact calculation of dispersion equation. Fig. 5 presents 4 bunch train BBU simulations for the 26 GHz power extractor, 20 MeV, 20 nC beam, 1.5 mm rms length, 0.1 mm initial offset, bunch spacing 770 psec.

CONCLUSION

It was realized early on in the development of wakefield acceleration that beam breakup represented an obstacle to achieving the required efficiencies. Either lower drive beam currents would need to be used or difficult to achieve beam injection tolerances would be required. A third possibility, the use of a focusing channel around the decelerator, was recognized as a suitable alternative. Numerical results based on the DWA-BD-02 Green's function-particle code [1] confirmed this.

The work proposed here represents an opportunity to carry out detailed high accuracy simulations of BBU effects in realistic wakefield devices built as part of the ANL program. Coupling the simulation work with experiments at the AWA offers a unique opportunity to "close the loop" between experiment and numerical modeling of BBU effects. The beam diagnostics we propose to develop will provide instrumentation not currently available at the AWA. Finally, although while not one of the goals of the proposal, it is worth pointing out that the new BBU code being developed by us could, with continued upgrades, eventually evolve into a general purpose next generation linac simulation tool.

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