STUDIES OF BEAM BREAKUP IN DIELECTRIC STRUCTURES*

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Abstract

Beam breakup (BBU) effects resulting from parasitic wakefields provide a potentially serious limitation to the performance of dielectric structure based wakefield accelerators. We report on planned experimental and numerical investigation of BBU and its mitigation. The experimental program focuses on BBU measurements in a number of high gradient and high transformer ratio wakefield devices. New pickup-based 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 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 results of detailed experimental measurements with the accurate numerical results and to design an external FODO channel for the control of the beam in the presence of strong transverse wakefields.

INTRODUCTION: SIMULATION CODE

The dynamics of the beam in structure-based wakefield accelerators [1] leads to beam stability issues not ordinarily found in other machines. In particular, the high current drive beam in an efficient wakefield accelerator loses a large fraction of its energy in the decelerator structure, resulting in physical emittance growth, increased energy spread, and the possibility of head-tail instability for an off axis beam, all of which can lead to severe reduction of beam intensity. For the case of a ramped bunch train device that uses a series of bunches with a specified envelope to achieve an enhanced transformer ratio [2], beam losses represent a serious impact on performance since correct operation requires that the ratios of the bunch intensities remain constant.

The use of a quadrupole focusing to control single bunch beam breakup in linear accelerators is used in the well-known technique of BNS damping. The application of this technique to wakefield devices is a somewhat more complex problem because of the much greater spread in bunch intensities (and hence energy profiles) required to be handled by a given quadrupole channel. The design of experiments to study beam breakup effects in this class of devices requires new and more physically realistic simulation and optimization software.

We have developed a code (DWA-BD-07) to study BBU effects in dielectric loaded wakefield structures. In these devices the intensity of the drive bunch required to achieve high accelerating gradients also sets prohibitively tight limits on the injection tolerances without some capability for mitigation. An analysis based on this code showed 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 main approach for these simulations was developed in reference [3] where the breakup of a single drive beam was studied.

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 the macroparticle currents as sources.

New capabilities have been implemented in DWA-BD-07 that emphasize features important for more accurate treatment of BBU in wakefield structures and for comparison of numerical simulations with laboratory measurements. Most important of these upgrades are:

- 3D particle algorithm. Field calculations are made via calls to an external process. In addition to being able to simulate the full 6D phase space. This framework greatly simplifies implementation of new algorithms.
- Beam definition. The user can now specify either uniform or Gaussian particle distributions in the phase ellipse for a given emittance. (Previous versions of the code were restricted to specifying the rms width of the beam in z and r.) Arbitrary initial offsets of the distribution from the axis of the structure are also implemented.
- 3D beamline specifications with more realistic beamline model. Beamline elements can be individually specified as opposed to the simple tapered FODO channel model used previously.
- Replacement of particle push algorithm. The new version of the code uses a Runge-Kutta algorithm to advance the electrons in time. This provides improved accuracy and stability especially for extended computations compared to the first order (Euler) algorithm used in earlier versions.
- Finite waveguide length effects; heuristic group velocity correction algorithm. Another major improvement over the legacy 2D version was introducing an algorithm for finite group velocity corrections. The original code was based on the assumption that the bunch appears instantaneously in a waveguide of infinite length. This approach is suited for studying short range wakefields and single bunch beam breakup effects, but its accuracy is not adequate for some aspects of the current project, where accounting for transitional effects is of extreme

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importance for multibunch trains significantly exceeding the structure length.

The wakefield rf pulse is effectively shortened in duration because the tail of the pulse is moving as well with velocity v_g. During initialization the new code computes group velocities for all the modes that are to be used in the given waveguide structure. The fields for each mode are calculated as before. For each mode the algorithm then zeros the fields from $z=0$ to $z=v_g t$. Since the energy of the mode for $z<v_g t$ has moved into the rf pulse, the mode field amplitudes are corrected by the factor $\sqrt{c/(c-v_g)}$. The particle push is then performed as before.

BEAM BREAKUP SIMULATIONS

Using the upgraded beam breakup code we have modeled a series of experiments that are planned at the AWA facility. Investigation of the beam dynamics, particularly for the transverse instability, is an essential requirement for the project of developing practical wakefield devices because of the strong transverse wake forces generated from an offset high current beam. A summary of the parameters for these experiments is given in Table 1.

In modeling the quadrupole channel strength profile (taper) is assumed to vary linearly with distance along the structure. There are a number of considerations in specifying the optimal gradient and profile in a wakefield device. One is that the physical emittance of the bunch is growing as it loses energy so an increasing field profile is indicated. Furthermore, in the case of multiple drive bunches in a train, the energy profile of each bunch can differ along the structure.

Power Extractor 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. Transverse wakefields in the 26 GHz dielectric-based RF power extractor generated by a single 1.5 mm, 20 nC, 20 MeV bunch at 1 mm offset from the structure center will generate two major dipole modes (HEM_{11} at 23.5 GHz and HEM_{21} at 35.75 GHz); both are included in the simulations.

The feasibility of the experiment depends on whether adequate beam transmission can be obtained in the presence of transverse deflections caused by beam offsets. In ref. [3] it was shown that a quadrupole channel around the decelerator could be used to control beam breakup; however the use of external focusing is not planned for this project. Fig. 1 shows the intensity of a single bunch as a function of axial position and initial offset from the center of the decelerator structure. (We use the AWA beam parameters at the structure entrance: rms radius = 1mm, rms length = 2mm, Q = 20nC, Energy = 20 MeV.)

Except for the case of no offset, beam losses become noticeable around the half length of the structure. Even for an offset of 0.4 mm, the transmitted beam intensity is about 40%., and should be adequate for making measurements using phosphor screen and electronic probe diagnostics.

Ramped Bunch Train The use of a beam pulse with a triangular current profile to improve the transformer ratio in collinear wakefield accelerators has been studied by a number of authors [4,5]. The difficulty of shaping a single linac pulse can be bypassed by using a ramped intensity bunch train where the bunches are spaced on successive rf crests of the drive accelerator. By selecting the frequency of the wakefield structure to be a multiple of the linac rf frequency the effect of a single triangular bunch can be obtained.

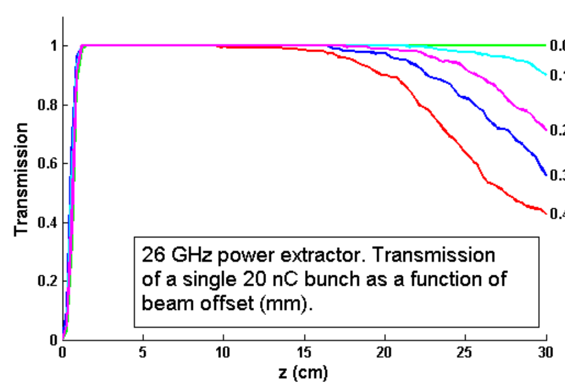

Figure 1. Relative intensity loss of a single bunch propagating through the 26GHz structure.

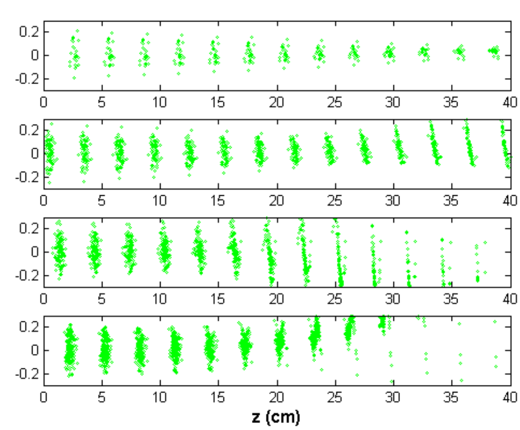

Figure 2. Example of severe BBU in RBT experiment. Offset = .1 mm, linear taper. (x-z plane electron distributions at 100 ps intervals, top to bottom: bunches 1-4 respectively.)

In ref. [2] we reported on a preliminary experiment on transformer ratio enhancement using two bunches of increasing charge. We plan an experiment with an upgraded system for creating a ramped bunch train of four pulses of increasing charge 5-15-25-35 nC. Transport of four unequally charged bunches experiencing different wakefields makes the design of a focusing system for the RBT experiment particularly challenging. For the case with no focusing channel, the fraction of the beam transported is 1.00:0.96:0.87:0.46 for the four bunches. Use of focusing channels with a linear profile resulted in significantly larger beam losses, particularly for the fourth, highest charge bunch (Fig.2).

High Gradient In this experiment we use a very small aperture dielectric structure and attempt to push a single high current bunch through it to generate a very large peak gradient. Given the size of the beam channel (1.5mm) in the device we already know that there will be considerable beam scraping at the entrance. In this set of simulations we studied the maximum transmission as a function of the strength and longitudinal taper of the quad channel enclosing the structure.

The focusing channel in this case is assumed to consist of six 4 cm quadrupoles. The first quad is assumed to be horizontally focusing with a strength given in Table 2, which shows the beam transmission as a function of the focusing channel properties. Figure 3 shows the spatial and energy profiles of the beam for the best case of 54% transmission through the structure.

Table 1. Parameters of the planned dielectric structure experiments

	a (mm)	b (mm)	L (cm)	ε (mm mr)	Beam
Power Extractor	3.5	4.534	30	6.64	*20 nC train, spacing = 23.1 cm*
Ramped Bunch Train	3	3.667	40	16	*5-15-25-35 nC train, spacing=23.1 cm*
High Gradient	1.5	7.49	25.4	3.78	*Single 100 nC bunch*

SUMMARY

Building on an existing beam breakup code developed by us [3] we have implemented software for rapid, efficient simulation of beam breakup effects in advanced linear accelerators, with a particular emphasis on modeling BBU in dielectric structures. We have developed a flexible 2D and 3D Windows code, **DWA-BD-07,** based on analytic Green's functions for the single particle fields in axisymmetric dielectric loaded structures. A number of new features have been incorporated including a second order accurate particle push, finite group velocity correction, arbitrary focusing channels around wakefield structures, and new graphics.

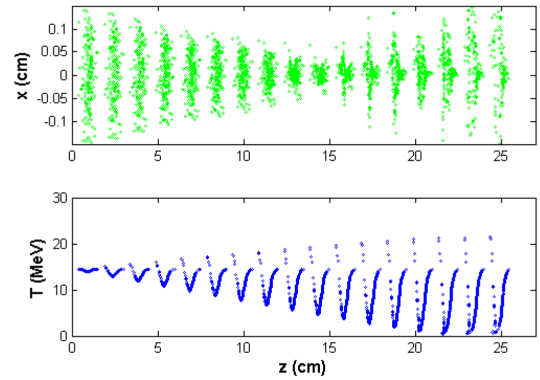

Figure 3. Maximum transmission (case 6 Table 2). Top: transverse profile; Bottom: Bunch kinetic energy. The data is shown at 50ps intervals; z is the axial position along the structure.

We used the new code to model a number of planned BBU experiments. The results of the simulations show that these experiments are feasible at the AWA. Furthermore, the usefulness of a linearly tapered quad channel in controlling beam breakup is confirmed. The ramped bunch train experiment is a possible exception may require a more complicated magnetic focusing profile to obtain optimal transmission of the entire bunch train.

Table 2. Beam transmission in the high gradient experiment for 100 nC pulse. Quad strength refers to the first quad in the FODO channel. Positive taper defines a focusing strength increasing along the channel.

Quad Strength (10^{-6} dyn/cm)	Quad Taper	% 100 nC Transmitted
0	-	20
2	0	23
1	0	33
1	0.5	24
0.5	0.5	41
0.5	0.75	54
0.5	1	38

REFERENCES

[1] P. Schoessow *et al.,* J. Appl. Phys. 84 663 (1998)
[2] C.Jing *et al.*, *Phys. Rev. Lett.* **98,** 144801 (2007)
[3] W. Gai *et al*., *Phys. Rev. E*, 55, 3481-3488 (1997)
[4] K. L. Bane, P. Chen, and P. B. Wilson, IEEE Trans. Nucl. Sci. **32,** 3524 (1985).
[5] P. Schutt, T. Weiland, and V. M. Tsakanov, *Proc. Second All-Union Conference on New Methods of Charged Particle Acceleration* (Erevan, USSR, 1989).