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 accelerators. We report here on comprehensive numerical studies and planned experimental investigations of BBU and its mitigation in dielectric wakefield accelerators. An experimental program is planned at the Argonne Wakefield Accelerator facility that will focus 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. The numerical part of this research is based on a particle-Green's function beam dynamics code (BBU-3000) that we are developing. The code allows rapid, efficient simulation of beam breakup effects in advanced linear accelerators. The goal of this work is to compare the results of detailed experimental measurements with accurate numerical results and ultimately to study the use of external FODO channels for control of the beam in the presence of strong transverse wakefields.

INTRODUCTION

The dynamics of the beam in structure-based wakefield accelerators 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. Beam breakup effects resulting from parasitic wakefields provide a potentially serious limitation to the performance of dielectric structure based wakefield accelerators as well.

We report here on the status and recent results from the project "Beam Breakup Instability in Dielectric Structures", an experimental and numerical investigation of BBU and its mitigation. 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.

The experimental program focuses on BBU measurements at the AWA facility in a number of high gradient and high transformer ratio wakefield devices.

New pickup-based beam diagnostics are under development that will provide improved methods for studying parasitic wakefields. A substantial portion of the recent efforts have involved engineering development of the techniques needed to match the bunch length from the AWA linac to the wavelength of the 13.4 GHz dielectric test structure for the ramped bunch train/enhanced transformer ratio experiment [5].

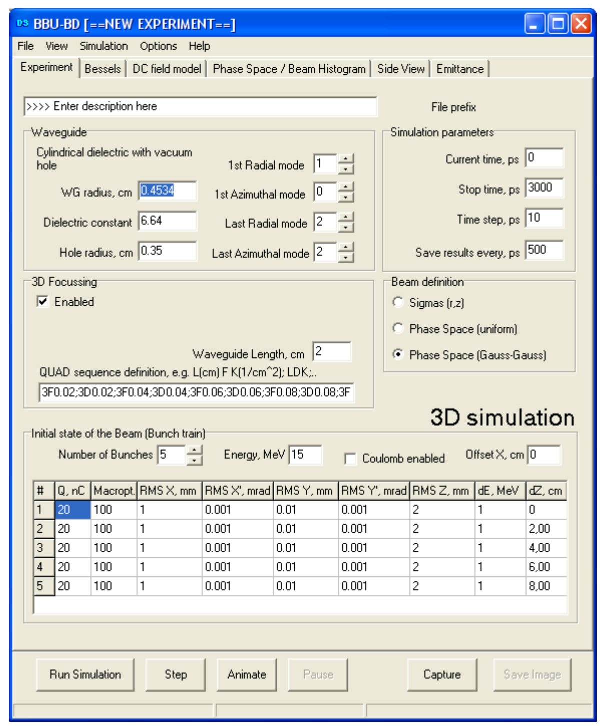

Figure 1. Main screen of the user interface is used for experiment setup definition. Version 2.0 allows specifying 3D beams in Phase Space as upright Twiss ellipses. Uniform and Gaussian initial macroparticle distributions are supported.

SOFTWARE DEVELOPMENT

Building on an existing beam breakup code that was also developed by us [1] 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, BBU-3000, based on analytic Green's functions for single particle fields in axisymmetric dielectric loaded structures.

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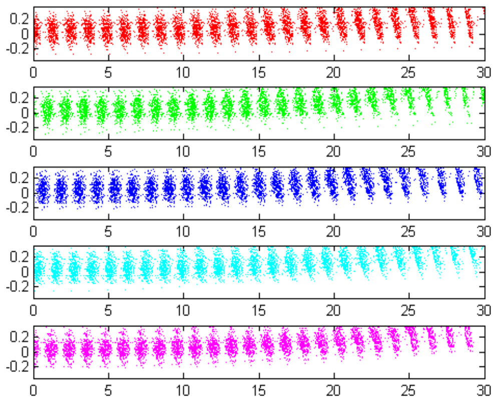

Figure 2. Snapshots of the electron distributions in the x-z plane traversing the 26GHz decelerator [3] (five-bunch train computed using BBU-3000). The frames top to bottom show bunches 1-5 at 40ps intervals. The bunches are injected with an initial offset of 0.4mm in the positive x direction. Initial energy of each bunch is 20MeV. Distances in cm; the vertical extent of each plot corresponds to the width of the vacuum channel (±0.35 cm). About 60% of the intensity of the last bunch has been lost by the time it exits the structure.

The new capabilities of BBU-3000 emphasize features important for more accurate treatment of BBU in wakefield structures and for comparison of numerical simulations with laboratory measurements [7].

Figure 1 shows the main window of the user interface for BBU-3000. Both the user interface and internal beam representation have been upgraded to facilitate 3D simulations. In the 2D case, the beam is described in a cylindrical coordinate system; the 3D beam is described using Cartesian coordinates. 3D beam trains can now be defined from the GUI, by entering parameters of an upright Twiss Ellipse in $x-x', y-y', z-\Delta E$ phase space. Two models were developed for the initial charge distribution inside the phase space ellipse: uniform and Gaussian. Changing simulation modes happens automatically by selecting appropriate beam definition model radio button on the “Experiment” tab. The option of converting the Twiss ellipse to arbitrary alpha/beta in all planes was implemented as well from the “Phase Space/Beam Histogram” tab.

A parallelized multicore version of the code without space charge has been implemented and tested. Multicore machines in general have a numerical co-processor for each core, so multicore parallelization should be feasible. It is also feasible to modify existing code to run computing at every time step as independent processes for each available core. These processes are implemented in the separated physics code, so the approach is easily generalizable for cluster computing.

Solver modifications to enable parallelization have been completed and are currently under testing. We have successfully tested our design on a dual core machine, with a slightly older version of the solver (one time step for all particles). A BBU-3000 simulation for 1200 particles was run on dual core CPU. Built-in Windows software was used to diagnose code performance. We have achieved close to 100% utilization of the two processors and expect that good performance scaling will be obtained on machines with multiple cores.

Table 1. Parameters of the planned dielectric structure BBU experiments at the Argonne Wakefield Accelerator.

	a (mm)	*b* (mm)	*L* (cm)	ε	Beam
Power Extractor [3]	3.5	4.534	30	6.64	*20 nC train, spacing = 23.1 cm*
Ramped Bunch Train [5]	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*

UPCOMING BBU EXPERIMENTS

Using the upgraded BBU-3000 code we have modeled a series of experiments that are planned at the AWA facility. Investigation of the beam dynamics, particularly for transverse instabilities, 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. Parameters for these experiments are summarized 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.

The Power Extractor is a 26GHz wakefield-based rf source and is treated in another paper at this conference [3]. A BBU-3000 simulation of the power extractor experiment using a 5×20nC bunch train is shown in Figure 2. In this case, use of external focusing is not planned and beam intensity suffers accordingly. Only about 40% of the charge of bunch 5 is transmitted through the structure.

Wakefield transformer ratio enhancement has been successfully demonstrated using a ramped bunch train in a dielectric based accelerating structure in a previous experiment [2]. However, in that experiment, the maximal energy transformation ratio was limited by the unavoidable mismatch of the wavelength of the fundamental mode of the wakefield with the bunch length (σ_z=2 mm) of the new Argonne Wakefield Accelerator (AWA) drive gun.

Figure 3. Crystals and rotational mount used to lengthen the bunch length of the AWA beam so that the bunch length can match the wavelength of the DLA structure in the transformer ratio enhancement experiment [5].

Recently, a solution for implementing the enhanced transformer ratio scheme for R>>2 using the current AWA facility has been developed. The bunch will be lengthened using a UV laser pulse stacking technique [4].

Two birefringent BBO (β-Barium Borate) crystals (Fig.3) will stretch the AWA laser pulse from 8 ps to 26.5 ps providing a better match to the 13.625 GHz structure wavelength. Two (non-optimized) pulse stacking simulations for the AWA are shown in Fig.4. Using an a-cut, α-BBO crystal with GVM= -0.957 ps/mm and assuming the nominal AWA laser pulse with λ = 248 nm, τ_{FWHM} = 8.16 ps, and rise time (10%-90%) =5.86 ps we obtain the results shown. A single crystal of length: L_1 = 7.393 mm produces two Gaussian pulses with their peaks separated by Δt=7.077 ps. The net pulse length for the two-Gaussian case is $\tau_{2FWHM} = \tau_{FWHM}+\Delta t$ = 15.24 ps. Two crystals of length L_1 = 7.393 mm and $L_2 = 2\times L_1$ = 14.786 mm yielding a pulse length $\tau_{4FWHM} = \tau_{FWHM}+3\times\Delta t$ = 29.4 ps.

In the high gradient experiment we will 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. The maximum transmission as a function of the strength and longitudinal taper of the quad channel enclosing the structure was calculated using BBU-3000.

The focusing channel in this case consists of six 4 cm quadrupoles. The first quad is horizontally focusing with a strength of 1.04 kG/cm, and the taper is 0.75. Figure 5 shows the spatial and energy profiles of the beam for the best case of 54% transmission through the structure.

SUMMARY

A project to study beam breakup in dielectric structures is underway. The software effort is based on development of the BBU-3000 code. 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.

We have used the new code to model the dielectric structure BBU experiments planned for this project. 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.

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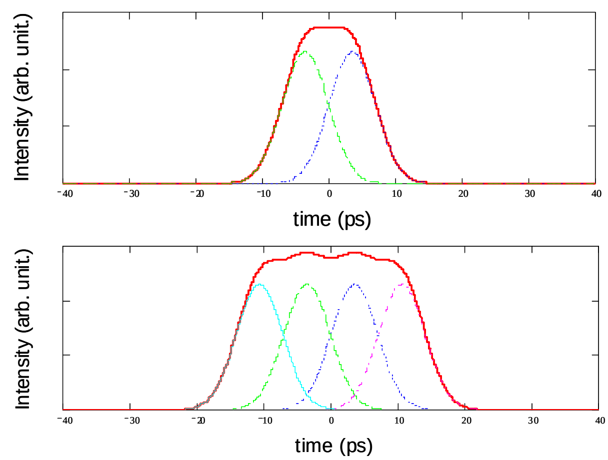

Figure 4. Simulations of two (non-optimized) laser pulse stacking cases for use at the AWA with an a-cut, α-BBO crystal.

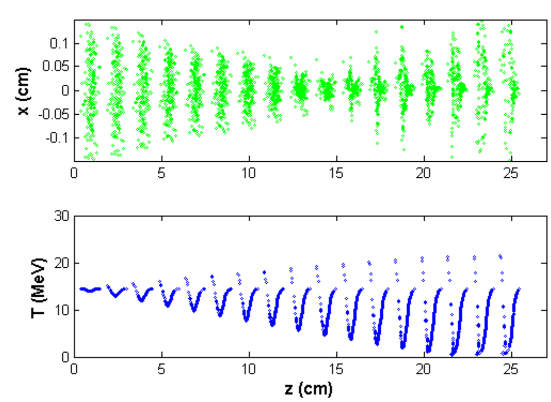

Figure 5. High gradient experiment, maximum transmission case. Top: transverse profile; Bottom: Longitudinal phase space. The results are shown at 50ps intervals; z is the axial position along the structure.