Beam Breakup Calculations for the Second Axis of DARHT*

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Abstract

The accelerator for the second axis of the Dual Axis Radiographic Hydrodynamic Test (DARHT) facility will produce a 4-kA, 20-MeV, 2-μs output electron beam with a design goal of less than 1000 π mm-mrad normalized transverse emittance and less than 0.5-mm beam centroid motion. In order to meet this goal, the beam transport must have excellent optics and the beam breakup instability (BBU) must be limited in growth. Using a number of simulation codes such as AMOS and BREAKUP, we have modeled the transverse impedances of the DARHT-II accelerator cells and the electron beam response to different transverse excitations such as injector RF noise, magnetic dipole fields arising from the 90-degree bend between the cathode stalk and insulator column, and downstream solenoid alignment errors. The very low Q ($\sim$2) predicted for the most important TM dipole modes has prompted us to extend the BREAKUP code to be able to use the dipole wakefields calculated by AMOS in addition to the most usual discrete frequency BBU mode model. We present results for the predicted BBU growth and the empirical sensitivity to various machine parameters.

1 INTRODUCTION

As part of the Science-based Stockpile Stewardship Program (SBSS), a high current (2-4 kA), relativistic (20 MeV), electron beam accelerator for the second axis of DARHT is being designed and constructed over the next few years. A great deal of attention is being paid to generating a high brightness beam out of the injector and to preserving the low normalized emittance ($\varepsilon_N \leq 1000\,\pi$ mm-mrad) through the accelerator. Achieving this goal requires excellent transport optics and control of the beam breakup instability (BBU). Since BBU arises from dipole cavity modes in the induction cell gap regions excited by an offset beam, we are optimizing geometry of this region and determining the best positions for ferrite absorbers to reduce the BBU mode Q's as much as possible while still maintaining adequate safety margins for electric field stresses. Previous papers (*e.g.* [1]) have discussed these issues in the context of radiographic machines such as FXR and DARHT giving specific examples of gap and ferrite damper geometry. An accompanying paper [2] discusses growth of "corkscrew" transverse beam offsets from the convolution of temporal beam energy variations with solenoid misalignments.

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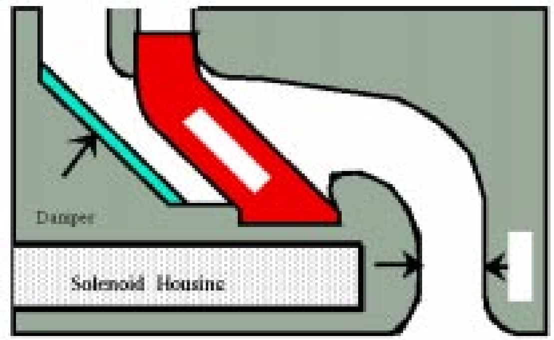

Figure 1: General gap and insulator geometry for the "standard" DARHT-2 accelerating cell.

AMOS code [3] calculations for the current design for the DARHT-2 "standard" 10-inch diameter cells, which comprise the last 80 of the total 88 accelerator cells, show quite low values for both the impedance and $Q\,(\approx\ 2)$ for the most important dipole modes. These low values have raised a minor concern that the usual way of using a small number (typically 2) of discrete, damped modes in the LLNL BREAKUP code for calculating beam BBU response and overall gain might be giving too optimistic a result. Moreover, the long duration ($\approx\ 2\,\mu$s) of the DARHT-2 pulse and the expected "shock" offset in the risetime portion of the pulse from dipole magnetic fields from the 90-degree bend between the cathode stalk and insulator column makes it important to calculate accurately BBU convection from the beam head back into the main body. Consequently, we extended the BREAKUP code to use dipole wake potentials input directly in the time domain from the AMOS code and calculated overall BBU growth in DARHT-2 cells arising from various initial excitations.

2 AMOS-CALCULATED WAKE POTENTIALS

Fig. 1 presents the rough geometry of a standard DARHT-2 cell. The gap width is 2.54 cm while the gap voltage is nominally 193 kV. A Mycalex insulator separates the oil-filled Metglas and transmission line from the high vacuum ($\leq 10^{-7}$ T) beam pipe region. One or more damping ferrites will be used in the upstream side of the insulator.

The AMOS code calculates the wakefields left behind by an ultrarelativistic test charge propagating by an accelerating gap. Given the high degree of damping in the DARHT-2 accelerating cell, the wake potential near a gap remains large for only a few ns after passage of the test particle. Nonetheless, we recorded the wake for 100 ns with a resolution of a 3.3 ps which, for purposes of BBU calculations in the BREAKUP code, was then averaged down to 65 ps, equivalent to a Nyquist frequency of about 7.5 GHz. The strongest dipole modes lie at approximately 190 and 630 MHz and should be well-resolved at 65 ps resolution. In Fig. 2 we plot the wake potential both on a linear scale out to 25 ns (upper plot) and on a semilogarithmic scale out to the full 100 ns of the AMOS calculation. In the first 10 or so ns one can see the two aforementioned BBU modes interfering and rapidly ($\tau_{damp} \approx 2.7$ ns) dropping in amplitude. At times greater than about 15 ns, there is a weakly damped ($\tau_{damp} \approx 32$ ns), very low amplitude, high frequency wake extending out to the full 100 ns. The plot of $Z_\perp(\Omega)$ indicates that this is a mode centered around 1300 MHz, just below cutoff of the TM_{01} mode at 1.44 GHz. An examination of the phase of the transverse impedance versus ω shows that the two primary modes have similar values of $\approx +1$ radian.

3 COMPARISON OF BBU GROWTH ALGORITHM RESULTS

The BREAKUP code has been recently upgraded to utilize various Fortran90 features both to improve its maintainability and to permit more flexible memory management. With these changes, we were able to extend its capabilities to exploit the direct wakefield potentials produced by the AMOS code as opposed to the more usual method of expressing the transverse wake impedance as a sum of discrete modes. In order to examine how well the discrete mode approach was predicting BBU growth in the DARHT-2 , we compared total growth at the end of the ~50-m transport lattice for a number of different excitations at the injector exit. These cases included: (a) "shock" excitation due to a uniform 100-μm transverse offset convolved with a very short (10 ns) current risetime as might be produced by beam-head "cleanup region" tentatively being considered (b) a time-varying beam offset produced by a 3-G dipole bend field in the A-K gap with a more moderate 40-ns risetime for the injector current and energy (c) a transverse oscillation at 90 MHz (as is predicted for a dipole RF mode in the injector column vacuum tank) of 100-μm amplitude together with a rapid 10-ns risetime for the current and energy (d) the sum of transverse oscillations at 190 and 630 MHz (the strongest dipole BBU modes in the standard DARHT-2 cells), both initially excited at 50-μm amplitude (e) a 100-μm amplitude 170 MHz excitation, corresponding to the strongest BBU mode in the first 8 so-called injector cells (14-inch diameter) of DARHT-2.

Each of these cases was run twice with the BREAKUP code, first employing the wakefield formulation and second employing the discrete mode approximation. In the latter case, the $Z_\perp$'s for the two modes were 337 and 306 Ω/m and the Q's 2 and 4, respectively, to which was added a zero-frequency displacement mode impedance of 95 Ω/m. The beam parameters were 4-kA current, 3.2-MV injector energy, 88 identical gaps which accelerate the beam to a

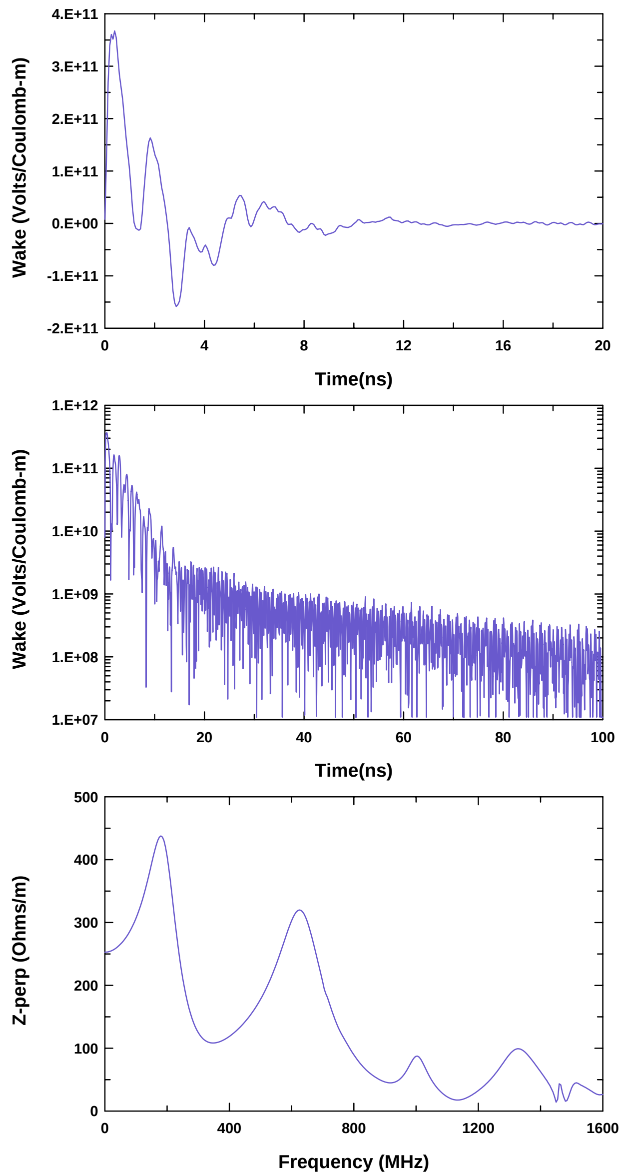

Figure 2: Dipole wake potential versus time and transverse impedance $Z_\perp(\Omega)$ calculated by the AMOS code for a "standard" 10-inch diameter DARHT-2 accelerating cell.

final 20-MV energy, and magnetic field tune which ramps nearly linearly from 0.25 to 2.0 kG over the full lattice. No solenoid tilts or time-varying gap voltages (apart from a 5-ns Gaussian rise and fall time) were used in these runs.

Table 1 displays a sample of some of the resultant comparison. For most of the cases, both the peak final offset versus time (which generally occurs just past the end of the current rise time) and an average over the time corresponding to the current flat top are given, both determined at the end of the transport lattice. One sees that the full temporal wake formulation and the discrete mode formulation give quite similar results, seldom differing by more than 50% even though the accumulated BBU growth in case (d) exceeds 30. Consequently, we believe the predictions concerning overall BBU growth in the DARHT-2 accelerator

Table 1. Final BBU Amplitudes (mm) from different initial excitations

Excitation Type ⇒	(a) Shock		(b) 3G Bend		(c) 90 MHz Inj.		(d) 190 + 630 MHz	(e) 170 MHz
	peak	average	peak	average	peak	average	average	average
WAKEFIELD	0.29	0.035	0.24	0.025	0.45	0.09	0.68	0.48
DISCRETE MOD E	0.27	0.029	0.58	0.042	0.29	0.08	0.51	0.88

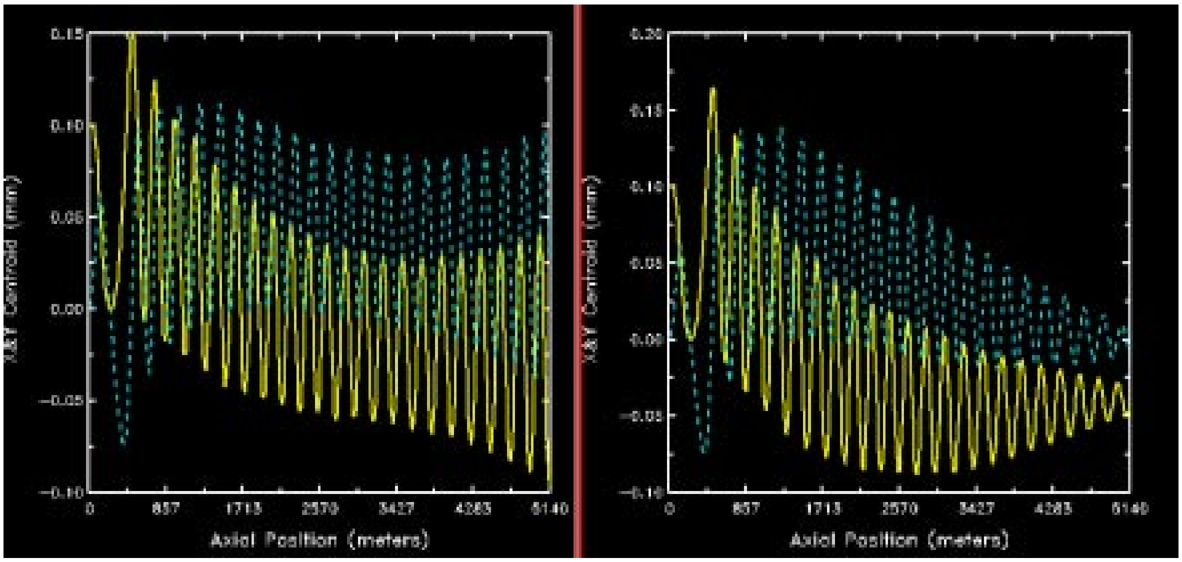

Figure 3: x and y centroid positions versus z at t=40 ns for "shock"-excited BBU as computed by the BREAKUP code. The left plot is from a run utilizing the temporal wakefield potential, whereas the right used a discrete mode formulation.

made previously with the BREAKUP code, including those in the low Q regime, are reasonably accurate.

Nonetheless, there are differences in the detailed results between use of the two formulations. Fig. 3 plots the $x(z)$ and $y(z)$ centroids at $t = 40$ ns for the case (a) (shock excitation) described above, 30 ns beyond the position at which the current flat top begins. In the left plot (temporal wake formulation), there is some initial damping of the centroid oscillations (as would be expected from the rapidly increasing solenoidal field in the first 10 meters of the lattice) but then they begin to grow to a final peak-to-peak amplitude of about 150μm. In contrast, the discrete mode formulation run shows continued adiabatic damping throughout the full 50 m. The underlying cause of this difference is likely associated with a somewhat faster convective velocity for the instability and details of the low frequency (≤ 150 MHz) instability spectrum not modeled exactly in phase and amplitude by the discrete mode formulation. For the specific case of DARHT-2 in which the pulse length is extremely long compared with the net convection of BBU, these differences will be important only in the first few per cent of the pulse.

4 CONCLUSION

We have extended the BREAKUP code to use the full temporal dipole wake potentials produced by the AMOS code and investigated the sensitivity of DARHT-2 BBU growth predictions to use of this model as compared with the more usual discrete mode formulation. Despite the predicted low Q's of the current DARHT-2 accelerator cell design, we find that over a fairly broad range of initial transverse excitations, the two formulations give similar overall results. While there are differences in the details, these appear to arise mainly in the front portion of the pulse where the beam current and/or energy vary rapidly with time. Hence, unless the main body of the pulse is extremely short in duration or there are numerous BBU modes whose very low Q's cause significant overlap in the frequency domain, we believe the discrete mode formulation is reasonably accurate for BBU growth prediction.

5 REFERENCES

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