BBU CALCULATIONS FOR BEAM STABILITY EXPERIMENTS ON DARHT-2*

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Abstract

The DARHT-2 (Dual-Axis Radiographic Hydrodynamics Test) facility is expected to produce a 2-kA, 20-MeV, 2-μs flattop electron beam pulse. Normal operation requires that the beam exit the accelerator with a transverse oscillation amplitude no larger than 10% of the beam radius. The beam break-up instability (BBU) can contribute to the transverse motion. It arises from the interaction between the beam and the cavity modes of the accelerating cells. In support of the beam stability experiments, simulations of BBU for DARHT-2 have been carried out using the Lamda code. The simulations used fits to experimental data for the transverse impedance of the cells. Lamda was benchmarked against results calculated with the LLNL code BREAKUP. For nominal transport parameters, simulation results show that the BBU grows by only a factor of 2-3. For a magnetic field reduced by a factor of 5, BBU growth is over a factor of 100, and the "image displacement" instability is significant.

INTRODUCTION

The DARHT-2 linear induction accelerator is designed to produce a 2-kA, 20-MV, 2-μs flat-top electron beam with a small time-integrated spot-size on an x-ray converter target. This requires excellent magnetic transport and control of the BBU instability. BBU arises from the interaction between the beam and the cavity modes of the accelerating cells. The injector noise and misalignments of the magnets seed the BBU in the accelerator. During the Phase-II commissioning of DARHT-2, one of the major objectives of the Long Pulse Beam Stability Experiments (LPE) was to test acceptability of the BBU growth for the final machine configuration using scaled parameters [1]. We performed BBU simulations with the transport code Lamda [2] for a 2.5-MV, 1.4-kA beam using two magnetic tunes, a nominal tune and a reduced magnetic field tune. The goal of these calculations was to provide guidance for the experiments. We used a symmetrized model to fit the experimental impedance data [3]. We compared Lamda with calculations by the BREAKUP code [4]. The results of simulations for LPE parameters are presented.

TRANSVERSE IMPEDANCE

In a study by Briggs et al. [3], the transverse impedance of the DARHT-2 cells was measured. We modify the resonant-mode model fit to the data used in Ref. [3] by symmetrizing $Z_\perp(\omega)$ about $\omega=0$, as required for physical correctness. We write the function η in $Z_\perp = -j\sqrt{\frac{\mu_0}{\varepsilon_0}}\frac{w}{\pi b^2}\eta \quad (\Omega/cm)$ (w is the cell gap width and b is the beam pipe radius) as

$$\mathrm{Im}(\eta) = \sum_n \left\{ \frac{\eta_{Mn}}{1+[2Q_n(\omega/\omega_{0n}-1)]^2} - \frac{\eta_{Mn}}{1+[2Q_n(-\omega/\omega_{0n}-1)]^2} \right\}$$

$$\mathrm{Re}(\eta) = \sum_n \left\{ \eta_0 + \frac{\eta_{Mn}(\omega/\omega_{0n}-1)}{1+[2Q_n(\omega/\omega_{0n}-1)]^2} + \frac{\eta_{Mn}(-\omega/\omega_{0n}-1)}{1+[2Q_n(-\omega/\omega_{0n}-1)]^2} \right\}$$

Fig.1 compares the symmetrized model to the data from Ref. [3]. The same method is applied to obtain the transverse impedance of the accelerator cells. The fitting parameters are similar to those in Ref [3] (cf. Table 2).

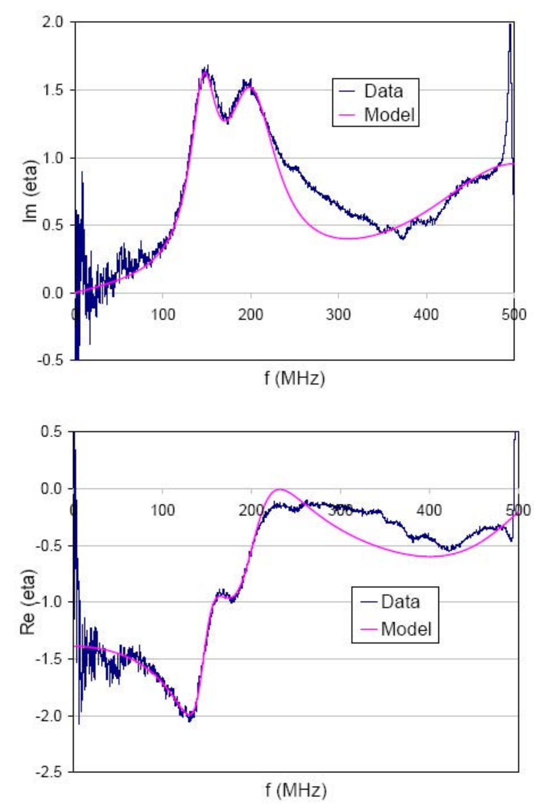

Figure 1: Transverse impedance for DARHT-2 injector cells. The experimental data and the symmetrized model are in blue and pink, respectively.

COMPARISON WITH BREAKUP CODE

Chen et al. have published BBU results from BREAKUP code simulations for nominal DARHT-2

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parameters [4]. We repeated these simulations using Lamda. The beam parameters were 2-kA current, 3.2-MV injector energy, a total of 88 cells with 80 accelerator cells (193kV each) and 8 injector cells (175kV each). For each resonant mode, a single frequency excitation with the amplitude of 0.1 mm was applied on the beam initially. Lamda simulation results are given in Table 1, showing reasonable agreement with Ref. [4].

Table 1: Comparison with LLNL BREAKUP code

f_n (MHz)	Amplitude at gap 88 Lamda(mm)	Amplitude at gap 88 BREAKUP(mm)
200 (inj. cell)	0.20	0.16
500 (inj. cell)	0.132	0.115
168.5 (acc. cell)	0.22	0.155
236 (acc. cell)	0.258	0.225
572 (acc. cell)	0.262	0.26
$Z_\perp$=0	0.103	0.105

LPE PARAMETERS

The LPE configuration has fewer cells and less current than the final DARHT-2 configuration. The beam parameters were 1.4-kA current, 2.5-MV injector energy, a total of 56 cells with 6 injector cells (100kV each) and 50 accelerator cells (100kV each). The magnetic field profile and the beam radius for a nominal tune are presented in Fig. 2. This tune is designed to remove most of the off-energy beam head in the beam clean-up zone located after the injector cells at ~ 500 cm. To observe the BBU for the LPE configuration, another tune with the axial magnetic field reduced by a factor of 5 is selected. This tune is also plotted in Fig. 2.

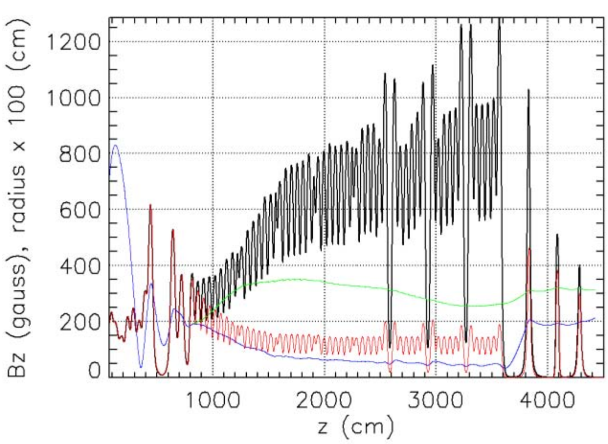

Figure 2: Axial magnetic fields and beam edge radius for the LPE nominal tune (black and blue, respectively) and a magnetic field reduced by 5 (red and green, respectively)

Nominal Tune

In order to examine the BBU, we used a trapezoid shape for the beam current waveform, with a 50-ns rise-time. As in the benchmark calculations above, for each resonance, the beam is given a single-frequency perturbation with the amplitude of 0.1 mm at the exit of injector. Then the amplitudes at gap 32 and gap 56 were measured. Simulation results are presented in Table 2. We also calculate beam displacement for an initial perturbation with all resonant BBU frequencies, i.e. $x = \sum_n 0.05\sin(2\pi f_n)$ mm. The final amplitude in Table 2 is on the order of 0.2 ~ 0.3 mm. These values are within the requirements for DARHT-2 for transverse motion, i.e. less than 10% of beam radius. Note also that the beam displacement does not differ significantly from the middle (gap 32) to the end of accelerator (gap 56).

Table 2: Prediction of BBU for nominal LPE parameters with initial excitation of 0.1 mm

f_n (MHz)	$Z_\perp$(Ω/cm)	Q	Amplitude at gap 32 (mm)	Amplitude at gap 56 (mm)
146	1.14	4.0	0.149	0.072
200	1.25	2.75	0.171	0.138
500	0.93	2.0	0.166	0.114
168.5	0.96	15	0.169	0.144
236	2.57	2.5	0.218	0.224
572	2.78	5.9	0.228	0.245
All			0.329	0.322
$Z_\perp$=0			0.168	0.095

Reduced B_z Tune

We now consider a case where the magnetic field is reduced by a factor of 5. As expected, with reduced B_z, stronger BBU is observed (see Figs. 3 and 4). As displayed in Fig. 4, the maximum amplitude of the displacement grows exponentially with the distance.

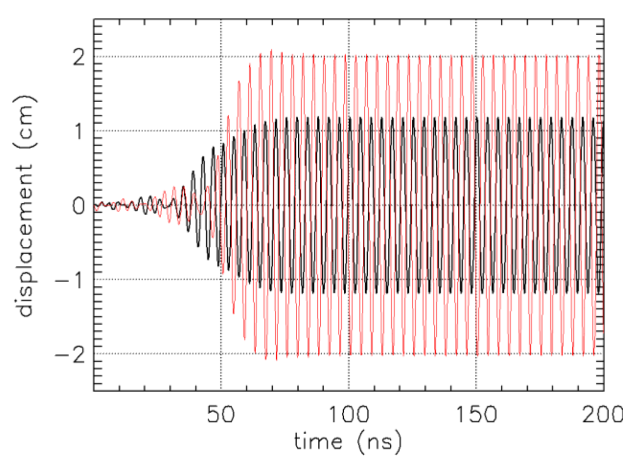

Figure 3: Beam *x, y* centroid positions (black and red respectively) after 56 cells with an initial 0.1 mm excitation at f = 236 MHz for the reduced B_z case.

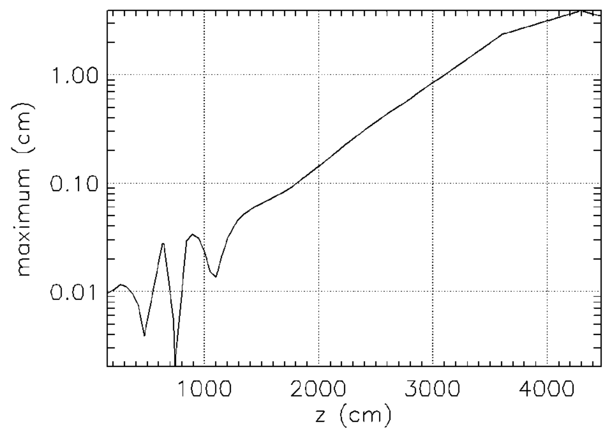

Figure 4: The maximum amplitude of the centroid vs. z for excitation at f=236MHz, showing that BBU grows exponentially with distance (slope $=1.75\times10^{-3}$ cm^{-1}).

The simulation results for each resonant frequency are summarized in Table 3. As shown in Table 3, the final displacement at gap 56 is between 10 to 50 mm, which is 30-150% of the beam radius (~ 30 mm).

Table 3: Prediction of BBU for a reduced B_z tune with initial excitation of 0.1 mm

f_n (MHz)	$Z_\perp$(Ω/cm)	Q	Amplitude at gap 32 (mm)	Amplitude at gap 56 (mm)
146	1.14	4.0	1.76	14.20
200	1.25	2.75	2.63	34.53
500	0.93	2.0	1.16	7.21
168.5	0.96	15	2.89	42.03
236	2.57	2.5	2.32	23.46
572	2.78	5.9	1.96	16.03
All			4.60	53.01
$Z_\perp$=0			0.46	0.49
constant offset			0.73	1.18

Image Displacement Effect

The displacement computed by Lamda includes both the BBU instability and "image displacement" instability. The image displacement effect occurs at the accelerating gaps, where the electrical and magnetic images of a displaced beam do not cancel to order γ^{2}, as they do in a smooth pipe.

To verify the role of the image displacement effect, we calculated the centroid displacement using only the image displacement force at the gaps:

$$\frac{\Delta p_x}{mc} = \frac{Z_i(\omega=0)(\Omega/\mathrm{cm})}{30}\frac{I_b(\mathrm{kA})}{17.045}x$$

where Z_i (ω=0) is the image displacement impedance, which is 1.34 (Ω/cm) for the injector cells and 2.07 (Ω/cm) for the accelerator cells. Simulation results in Fig. 5 show that for an initial beam offset of 0.1 mm, the beam displacement is 0.09 mm at gap 56 for the nominal tune and 1.18 mm for the reduced B_z case. This result shows that the image displacement instability is negligible for the nominal parameters, and is significant for the reduced B_z case with a growth factor of ~10 after 56 cells.

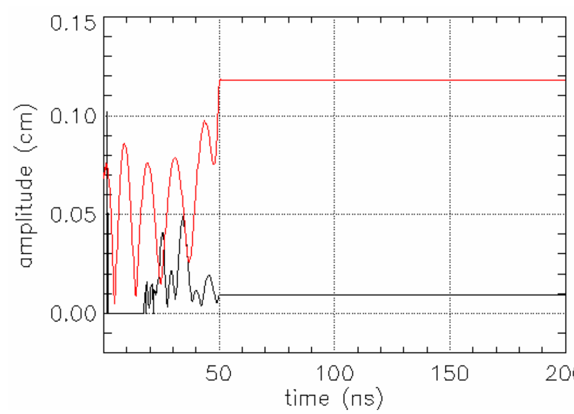

Figure 5: Beam centroid at gap 56 using gap image displacement impedance only, for the nominal case (black) and the reduced B_z (red).

CONCLUSIONS

We have presented Lamda simulations of BBU for the DARHT-2 accelerator. The gap transverse impedance parameters were obtained by fitting to experimental impedance data. The results of benchmarking show good agreement with the BREAKUP code. For nominal transport parameters, simulation results show that the BBU growth is negligible. For a magnetic field reduced by a factor of 5, BBU growth is over a factor of 100, and a significant image displacement effect is observed.

ACKNOWLEDGMENTS

R. Briggs provided the data used to obtain $Z_\perp(\omega)$ fits for both the injector and accelerator cells.

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