STUDY OF THE TRANSVERSE BEAM MOTION IN THE DARHT PHASE II ACCELERATOR*

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Abstract

The accelerator for the second-axis of the Dual Axis Radiographic Hydrodynamic Test (DARHT) facility will accelerate a 4-kA, 3-MeV, 2-μs long electron current pulse to 20 MeV. The energy variation of the beam within the flat-top portion of the current pulse is ± 0.5%. The performance of the DARHT Phase II radiographic machine requires the transverse beam motion to be much less than the beam spot size which is about 1.5 mm diameter on the x-ray converter. In general, the leading causes of the transverse beam motion in an accelerator are the beam breakup instability (BBU) and the corkscrew motion. We have modeled the transverse beam motion in the DARHT Phase II accelerator with various magnetic tunes and accelerator cell configurations by using the BREAKUP code. The predicted sensitivity of corkscrew motion and BBU growth to different tuning algorithms will be presented.

1 INTRODUCTION

Transport simulations of the beam from the exit of the injector to the accelerator exit have been performed for the second axis of the Dual Axis Radiographic Hydrodynamic Test (DARHT) facility [1]. The motivation for performing these simulations was to establish engineering tolerances and design criteria to ensure that the DARHT-II facility meets performance goals. These goals are to produce four 60-ns long pulses, each with a time-integrated x-ray dose of 1000 R at one meter, with a 1 - 2 mm time-integrated x-ray spot. Transverse motion of the beam is a principle limitation in achieving the desired accelerator performance. Leading causes of the transverse beam motion typically are the beam breakup instability driven by injector noise and misalignments, and the corkscrew motion [2] caused by misalignments and chromatic aberration of optical elements. In this paper, we show that both corkscrew motion and misalignment driven beam breakup instability can be controlled effectively by using the corkscrew tuning V algorithm [3].We have also examined growth of beam breakup instabilities in these cells for various accelerator configurations.

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2 CONFIGURATION AND DESIGN PARAMETERS FOR DARHT II

The accelerator is arranged in eleven 8-cell blocks with pumping ports located between cell blocks. About one hundred solenoids are used to transport the beam. Three different cell configurations were used in the transport simulations. Two configurations are for a beam line aperture of 25.4 cm and differ only in the insulator/gap design of the cells. The final configuration has a larger, 35.6 cm, aperture for the first 8-cell block followed by ten 8-cell blocks with a 25.4 cm aperture.

To achieve the performance criteria of x-ray dose and spot size, the normalized Lapostolle emittance (95% of beam current) at the x-ray converter has to be no greater than 1500 π-mm-mr, and the transverse beam motion should be no greater than 10% of beam radius. The designed beam parameters are:

1) current of 4 kA in a 2 μs pulse with 200 ns rise time,
2) energy at the injector exit of 3 MeV ± 0.5% increasing to 20 MeV ± 0.5% at the accelerator exit, and
3) emittance (4 x Lapostolle emittance) at the injector exit of 500 π-mm-mr increasing to less than 1000 π-mm-mr at the accelerator exit.

3 BBU INSTABILITY AND TRANSVERSE IMPEDANCE

The beam breakup instability arises from the beam interacting with the accelerating cells' dipole TM modes. The transverse impedance is a measurement of the strength of the interaction. As the beam axis is offset from the cavity axis, these modes extract energy from the leading part of the beam and deflect the trailing part of the beam transversely. This instability typically sets the upper limit for a transportable beam current and the lower limit for the focusing field.

3 .1 Equations Governing BBU

The BBU instability is a convective instability. For the misalignment driven beam breakup instability, the maximum number of e-fold in the beam breakup instability growth is given by

$$\alpha = \frac{c}{l}\frac{I}{I_o} Z_{\perp} \int_0^L \frac{dz'}{\gamma k_c(z')} \ , \qquad (1)$$

and the peak growth will occur in the pulse after a time

$$\tau = 2\alpha Q/\omega_o \quad , \qquad (2)$$

where I is the beam current, I_o = 17 kA, $Z_\perp$ is the transverse cell impedance for the BBU mode frequency ω_o. The gap separation is l, and the accelerator length is L. For an electron beam pulse with a long rise time, the beam breakup instability driven by misalignment starts to grow at the head of the pulse and may not propagate into the flat-top portion of the pulse before the beam leaves the accelerator. Therefore, the beam breakup instability driven by misalignment is generally not a threat to a DARHT-II pulse with long rise time. In contrast, the beam breakup instability driven by injector noise would appear throughout the pulse length. BBU growing from injector noise a significant concern for the DARHT-II beam transverse motion.

3 .2 Transverse Impedance

Three DARHT-II accelerator cell configurations have been designed [4]. The configurations differ primarily in the geometry of the insulator and aperture size. However, only the impedance and frequency of the primary resonant modes are required for the purpose of the simulations. Table 1 lists the pertinent cell characteristics for BBU calculations. Note that $Z = c\, Z_\perp/\omega_o$. "Initial" and "current" refer to the insulator/gap designs under consideration.

Table 1: Impedances of different cell configurations

Design	Freq. (MHz)	Z/Q (Ω)	Q
Initial (25.4 cm ID)	262	34.9	2.0
	580	1.1	7.2
	672	3.9	6.9
Current (25.4 cm ID)	200	37.6	1.9
	535	7.3	3.8
Current (35.6 cm ID)	171	25.4	2.0
	443	4.3	4.2

4 CORKSCREW MECHANISM AND TUNING STRATEGY

Corkscrew motion is a differential oscillation of the beam centroid between the leading and trailing portions of a beam pulse driven by chromatic aberration of the focusing elements and misalignment of the machine. The DARHT-II accelerator's alignment requirement is to meet the alignment specification of the first axis of DARHT accelerator's: random 3-σ magnetic tilt to be 1.95 mrad and random 3-σ magnet offset to be 0.45 mm. There are about one hundred of solenoids with steering/correction coils along the DARHT-II accelerator.

The magnetic tune was chosen to focus the electron beam from an 8 cm radius at the exit of the injector to a 6 mm radius as rapidly as possible without adversely affecting the current distribution. The 6 mm radius is then maintained through the remember of the accelerator. The rapid increase in magnetic field slows the BBU growth as seen in equation (1).

The DARHT-I alignment specifications is expected to produce a corkscrew amplitude of several millimeters by the end of the accelerator without corrective measures. The "tuning-V" steering algorithm has demonstrated an order of magnitude reduction in corkscrew on the ETA-II accelerator. In the simulations described below, only one steering coil per 8-cell block was used to implement the steering algorithm.

5 SIMULATION RESULTS

The BREAKUP code was used to model the beam centroid's transverse motion in the DARHT-II accelerator. Both motion due to the BBU instability and corkscrew motion was included. Three different configurations were simulated. The gain factor, a figure of merit for BBU growth, is defined as BBU amplitude divided by the injector noise amplitude. The goal is to have a gain factor ≤ 20, or 3 e-folds based on an injector noise amplitude of 100 microns. The goal for the amplitude of the transverse motion, including corkscrew and BBU, is 0.6 mm.

Examples of the simulation results for misalignment errors are shown in Figures 1 and 2. The beam pulse was simulated for 350 ns including a 200 ns rise time. An energy variation of ±5% was imposed on the 150 ns of flat-top to model the effect of corkscrew on the longer 2-μs pulse. Two observations can be made from the results. First is that the BBU motion, the fast oscillation at the start of the pulse, extends only a short distance into the pulse and is insignificant compared to the corkscrew amplitude. Second, the V-tuning steering correction reduced the corkscrew amplitude by over an order of magnitude. The effects of injector noise and misalignment are shown in Fig. 3. The BBU motion extends throughout the pulse as expected while the corkscrew amplitude is relatively unchanged from the no noise case.

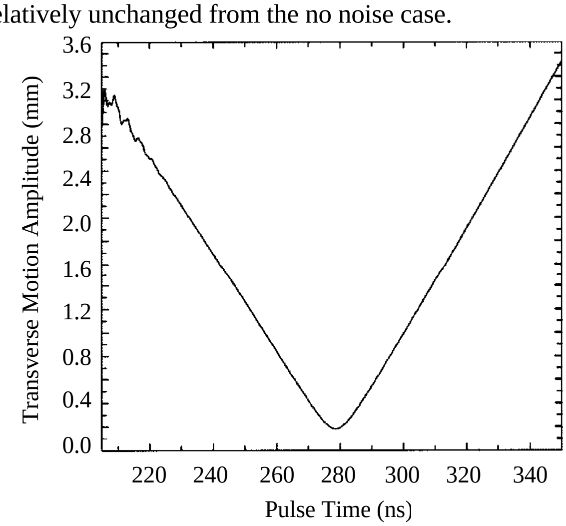

Figure 1. Simulated transverse beam centroid motion driven by misalignments with no steering correction.

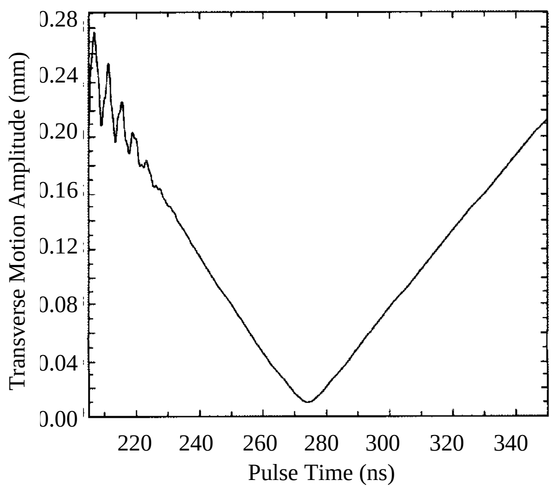

Figure 2. Simulated transverse beam centroid motion driven by misalignments with steering corrections. Note the change in vertical scaling from Fig. 1.

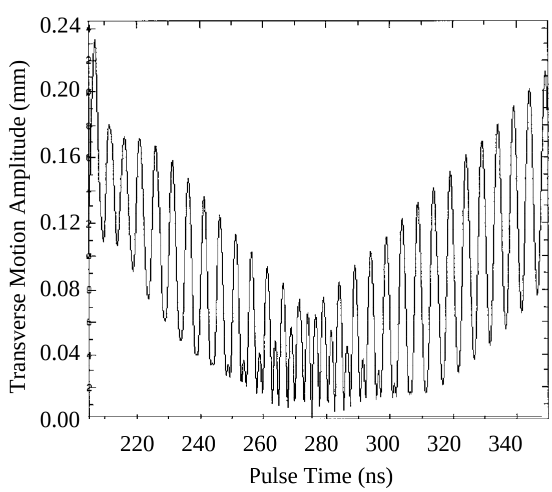

Figure 3. Simulated transverse beam centroid motion driven by misalignments and injector noise. V-tuning steering corrections used.

Results of the different configurations are summarized below. For all cases, the simulations included both misalignment and injector noise. The gain factor at the end of the first 8-cell block is listed in the results to emphasize the effect of the low focusing fields at the start of the accelerator. The first configuration modeled consisted of eleven 8-cell blocks with an aperture of 25.4 cm and used the "initial" cell impedance parameters. Results are shown in Table 2.

Table 2. BBU growth for "initial" accelerator cell design

Mode Frequency (MHz)	Gain Factor at exit of 1st block	Gain Factor at accelerator exit
262	2.9	132.7
672	2.1	115

Corkscrew amplitude at accelerator exit is 0.24 mm.

The second configuration modeled consisted of eleven 8-cell blocks with an aperture of 25.4 cm and used the "current" cell impedance parameters. Results are shown in Table 3.

Table 3. BBU growth for "current" accelerator cell design

Mode Frequency (MHz)	Gain Factor at exit of 1st block	Gain Factor at accelerator exit
200	3.1	34.3
535	3.1	34.3

Corkscrew amplitude at accelerator exit is 0.24 mm.

The third configuration modeled consisted of a 35.6 cm aperture 8-cell block followed by ten 8-cell blocks with apertures of 25.4. All cells used the "current" cell impedance parameters. Results are shown in Table 4.

Table 4. BBU with larger aperture first 8-cell block

Mode Frequency (MHz)	Gain Factor at exit of 1st block	Gain Factor at accelerator exit
170	1.9	12.2
200	1.5	10.7

Corkscrew amplitude at accelerator exit is 0.16 mm.

6 SUMMARY

Corkscrew motion can be kept well within design goals for the expected accelerator misalignments by applying the V-tuning algorithm. The BBU instability growth required the lower impedance characteristics associated with the larger aperture cells to stay below the desired gain factor. A possible factor not considered in the BBU growth is loss of the low energy head of the beam. This would lead to a faster rise time as the pulse travels down the accelerator. The gain factor will remain the same, so the issue is the magnitude of the shock excitation due to the short rise time and misalignments. If this excitation is no more than the injector noise, the BBU growth should remain within design goals.

7 ACKNOWLEDGMENTS

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8 REFERENCES

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