TRANSVERSE BEAM INSTABILITY IN A COMPACT DIELECTRIC WALL INDUCTION ACCELERATOR*

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Abstract

Using the dielectric wall accelerator technology, we are developing a compact induction accelerator system primarily intended for pulsed radiography. Unlike the typical induction accelerator cell that is long compared with its accelerating gap width, the proposed dielectric wall induction accelerator cell is short and its accelerating gap width is comparable with the cell length. In this geometry, the RF modes may be coupled from one cell to the next. We will present recent results of RF modeling of the cells and a prediction of the transverse beam instability on a 2-kA, 8-MeV beam.

INTRODUCTION

Taking advantage of the recent development of high gradient insulators and novel transmission line system [1-2], we are developing a compact 8-MeV, 2-kA, 20-30-ns induction accelerator system primarily intended for pulsed radiography. Figure 1 show the accelerator configuration, which consists of a 1.5-MV injector and thirteen 500-kV dielectric wall induction cells. High gradient insulators capable of tolerating electric field strengths of up to 20 MV/m are used in both the injector and the acceleration cells as the walls as well as the acceleration gaps. The thickness of the high-gradient insulator stack in the injector is 10 cm, which gives an average 15 MV/m field in the A-K gap. The insulator stack in the acceleration cell is 5 inch (12.7 cm) high, which gives a modest 3.93 MV/m acceleration field. Instead of having the focusing solenoids inside the accelerator cells like that on the conventional induction machines, pancake-like magnets between the cells are used to provide continuous focus. Therefore, the cell is almost all "gap". The conventional wisdom of suppressing the beam breakup instability and the image displacement instability by minimizing the gap width to reduce the transverse cell impedance is violated. Furthermore, the space between two neighboring gaps is only 2 inch (5.08 cm). The beampipe radius of the accelerator is 6.6 cm. In this geometry, the RF modes may be coupled from one cell to the next. To examine the effects of the geometry of the DWA induction cell on the beam transverse motion, we performed RF simulations of the cells. Based on the calculated wakefield impedance, the transverse beam motion is not an issue in this compact accelerator.

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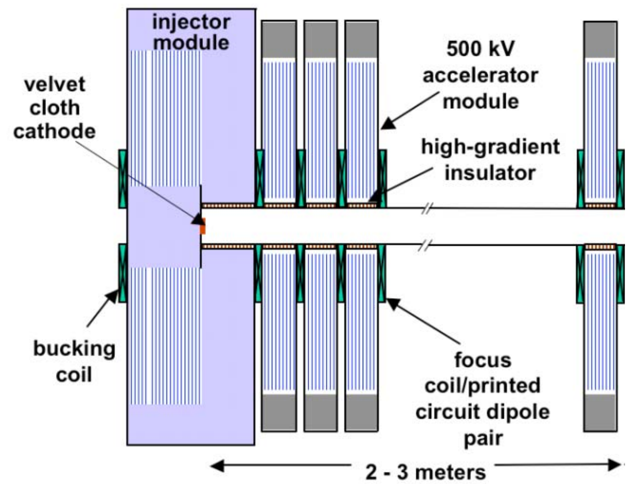

Figure 1: Dielectric wall induction accelerator configuration.

Figure 2: Dielectric wall accelerator structure with a ring around the beampipe and two Blumlein strips connecting to the ring. The beampipe radius of the structure is 6.6 cm.

WAKEFIELD IMPEDANCE

The dielectric wall accelerator (DWA) structure is composed of a circumferential ring around the beampipe and two straight or curved strips connecting to the ring as shown in Figure 2. In order to quantify the RF effects on the beam, AMOS 2.5-D finite difference time domain [3] calculations were performed to examine the wakefield impedance of the structure even though the DWA structure is a purely 3D structure. To include the 3D geometry, the effective impedance of the DWA structure was used in the RF simulations. For cases of thin rings shown in Figure 3, the contribution from the ring is small

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(or in the very least is at a high frequency) and so the strip effects are presumed to dominate the response. For a five inch long DWA stack with an impedance of 136Ω (68 Blumleins, at 2Ω per Blumlein), the transverse wakefield impedance is shown in Figure 4. To examine whether the RF modes are coupled between two neighboring cells, we have also calculated the wakefield impedance of two 12.7-cm DWA stacks with a 5.08-cm spacing between them. Once again, the beampipe radius is 6.6 cm. Its wakefield impedance is also shown in Figure 4. Since the two-cell impedance is about twice the one-cell impedance, there is very little mode coupling between the two neighboring cells even though those two cells are almost all gaps, and the separation between them is small.

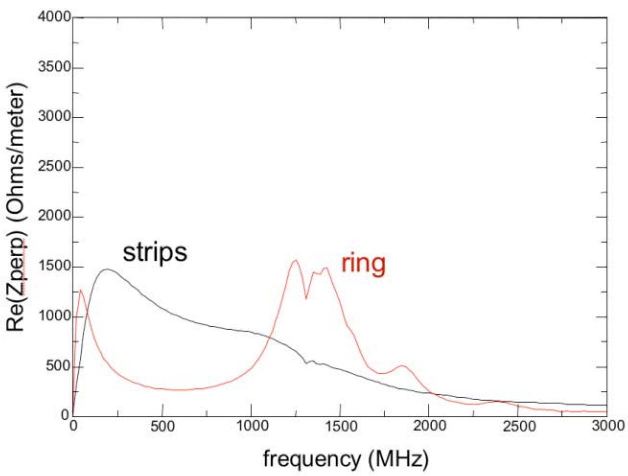

Figure 3: A 5-inch DWA stack simulated as a ring and as a strip

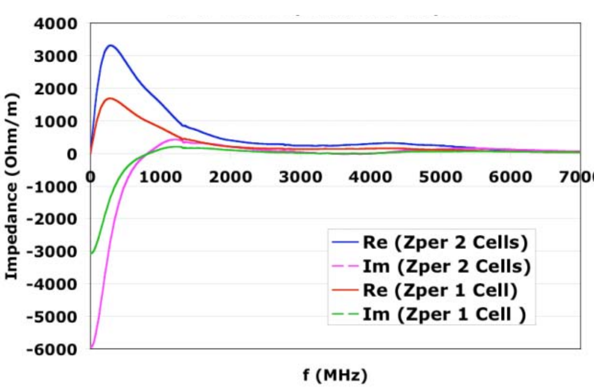

Figure 4: Wakefield impedance for a 5-inch DWA stack cell and for two 5-inch cells separated by 2 inches.

BEAM BREAKUP INSTABILITY

We now estimate the growth of the beam breakup instability. For a long pulse beam, i.e., $\omega_o\tau >> G\Gamma$, the maximum number of e-foldings is given by $GQ\Gamma$, and the asymptotic growth reaches the maximum at the beam time $\tau = 2GQ^2\Gamma/\omega_o$, where

$$G = \frac{\omega_o}{L}\frac{Z_\perp}{Q}\frac{I}{I_o},$$

$$\Gamma = \int_0^z \frac{dz'}{\gamma k_c(z')},$$

ω_o is the resonance angular frequency, L is the cell periodicity, I is the beam current, I_o ~ 17 kA is the nonrelativistic Alfven current, and k_c is the cyclotron wavenumber. The compact 8-MeV DWA is less than 2.5 m long from the cathode to the accelerator exit so that the beam extracted from an injector with a Pierce column could be easily transported to the accelerator exit without using any magnets [4]. However, to ensure that the growth of the beam breakup instability is negligible, the solenoid field given in Figure 5 is chosen, which gives Γ ~ 687. The impedance spectra in Figure 4 have very broad

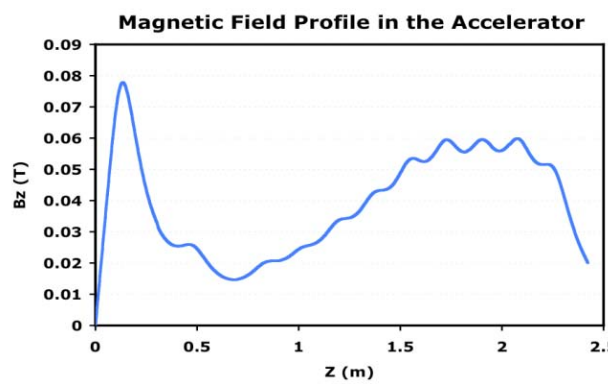

Figure 5: Optimized magnetic field profile for the 7.75-MeV beam

peaks, which indicate that the resonance mode's Q value is small. A very small Q would cause the impedance peak to down shift significantly to a lower frequency. Therefore, we should not simply read the resonance frequency off Figure 4. In order to estimate the BBU growth quickly without kicking the beam centroid with the wakefield data computationally, we fit the real part of the single cell impedance in Figure 4 with the real part of the transverse impedance of a single mode, i.e.,

$$Z(f) = \frac{i\,2\pi f_o^3 \left(\frac{Z_\perp}{Q}\right)\Big/ c}{f_o^2 - f^2 - i\,f f_o/Q},$$

where f_o is the mode's resonance frequency. The fit,

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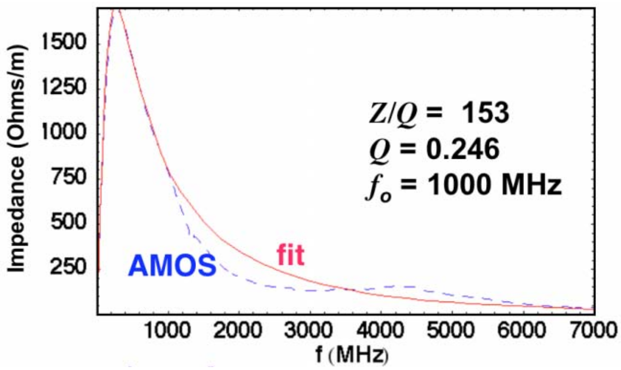

Figure 6: Single cell wakefield impedance and fit

shown in Figure 6, gives us a resonance frequency of 1000 Mhz. For comparison, the impedance spectra peak at about 250 Mhz in Figures 4 and 6. The fit also gives an impedance ($Z_\perp /Q$) of 153 and Q value of 0.246 for the cell's resonance mode. The maximum BBU growth on the beam in the compact 8-MeV DWA would then be only 1.2 e-fold growth. Conventional linear induction accelerators, like DARHT and FXR, are usually designed to accept a nominal 5 e-fold BBU growth. This 1.2 e-fold maximum asymptotic growth would occur at the very beginning of the beam head with $\omega_o\tau \sim 0.6$. Note that $\omega_o\tau >> G\Gamma$ is violated here. Nevertheless, our estimation indicates that the BBU growth is insignificant. The absolute DC value of the real part of the cell impedance given in Figure 3 is larger than that of the single mode model since those high frequency modes are not included in the single mode impedance. Using the real part of the cell impedance in Figure 3 and the magnetic tune in Figure 5, we have found that the DC image displacement instability, typically a very minor parametric instability in a periodic LIA system, is also negligible. Note that using the impedance value from 2.5D RF calculations here is only an attempt to bound the potential BBU and image displacement instability growth. Full 3D wakefield calculations are required to obtain the accurate impedance.

CORKSCREW

The beam centroid's corkscrew motion is caused by the chromatic aberration and misalignment of the solenoid system. This compact DWA induction accelerator only has 15 magnets. Even though the magnetic field tune is large enough to suppress the beam breakup instability significantly, the total phase advance of the accelerator using the magnetic tune shown in Figure 5 is only about 1.64 radians. It is reasonable to assume that the total differential phase advance within the beam due to its energy variation is much smaller. The corkscrew amplitude for this system is given by

$$A \approx \sqrt{n}\, \delta l \frac{\delta\gamma}{\gamma} \phi_{tot} ,$$

where n is the number of magnets, δl is the rms misalignment, $\delta\gamma/\gamma$ is the energy variation, and ϕ_{tot} is the total phase advance. The nominal beam radius at the x-ray converter target is 1 mm. Assuming that the machine performance specifications require the corkscrew amplitude to be less than 10% of the beam radius and that the alignment specification is 0.1 mm, the energy acceptance for meeting the corkscrew specification would be a generous ±15.7%.

CONCLUSIONS

We are developing a compact 8-MeV, 2-kA, 20-30-ns induction accelerator system primarily intended for pulsed radiography. Although 3D wakefield calculations are needed to get accurate wakefield impedance, we have performed 2.5D calculations to bound the DWA structure's impedance. The high accelerating gradient of the DWA has significantly shortened the total accelerator length. Hence, the growth of beam breakup instability and the image displacement instability is negligible. The shortened accelerator also relaxes the constraints on the energy variation and alignment.

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