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WAKE POTENTIALS AND IMPEDANCES FOR THE ATA INDUCTION CELL *

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Abstract

The AMOS Wakefield Code is used to calculate the impedances of the induction cell used in the Advanced Test Accelerator (ATA) at Livermore. We present the wakefields and impedances for multipoles m=0, 1 and 2. The ATA cell is calculated to have a maximum transverse impedance of approximately 1000 Ω/m at 875 MHz with a quality factor Q = 5. The sensitivity of the impedance spectra to modeling variations is discussed.

Introduction

The ATA is an 80 meter long induction linac designed to accelerate a 10 kA electron beam to 50 MeV for a wide variety of applications. It consists of a 2.5 MeV injector and 190 induction cells of 250 kV each. The cells were designed to have low Q-values (Q < 10) in order to minimize spurious beam-cavity interactions. In practice the vacuum transport was limited to 6 kA by the onset of a beam breakup instability at 785 MHz. Early theoretical efforts identified the TM130 mode in the cell as the source of the instability.[1] In this paper we examine a more realistic model of the ATA cell using the AMOS Wakefield Code.[2] The AMOS code was developed to provide a more powerful method for designing low impedance cells for future high current induction linacs. The AMOS model of the ATA cell illustrates the power of this tool for evaluating induction cell designs. We present the wakefields and impedances for m=0, 1, and 2 as ATA benchmarks for improvement in future designs.

The Model

The AMOS model of the ATA induction cell is shown in Fig. 1. Beginning from the centerline at the bottom of the figure and moving upwards, the induction cell can be understood as a beam pipe with an accelerator gap connected to a radial transmission line which is terminated at its outer radius by a toroidal superstructure. This complex structure contains the vacuum-to-oil insulator, the oil, and the large ferrite toroid which provides the volt-seconds for the induction cell. The reflector at the top of the radial transmission line serves to direct beam-excited RF modes into a second thin ferrite toroid placed against the left wall of the cell where the modes are absorbed. The radius of the beam pipe is 6.725 cm and the width of accelerator gap is 2.70 cm. For modeling purposes, the cell is assumed to be cylindrically symmetric. The maximum radial extent is 41.5 cm and the end-to-end beam pipe length is 47.0 cm.

This model of the ATA cell is set up with the DRAGON geometric editor.[2] Zone sizes dr=2.24 mm and dz=2.25 mm provide a 30 zone resolution across the beam pipe and 12 zones across the radial transmission line. A few zone staircasing transition between the two is provided to reduce unrealistic diffraction scattering from the source charge. The DRAGON editor automatically zones up the cell interior, noting material changes. The typical ATA cell problem consists of about 20,000 zones. The insulator and oil have dielectric constants 5.6 and 2.3 respectively.

The left and right ends of the beam pipe are terminated with a 377 ohm impedance boundary condition (IBC).

The ATA cell is actually three dimensional (3D) where it connects to high voltage feeds at the top and bottom of the cell. Beam excited RF can always propagate out these coaxial feeds as TEM waves and thereby affect the impedance of the cell. In an attempt to model this port, we use a 250 ohm IBC at the top of the cell, equal to the wave impedance of the oil, and insert a metal septum which should help couple out 2D TEM waves. Adding the septum reduces the frequency of the dominant BBU mode a few percent and moves it closer to the experimental value.

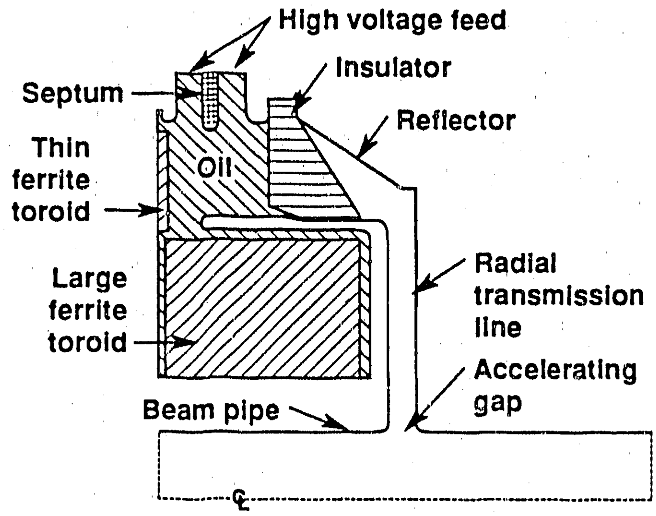

Fig. 1. DRAGON rendering of the ATA Induction Cell. The cell is rotationally symmetric about the axis, except for the power feeds.

We use a simple "get lost" model for the ferrite suggested by the experimental observation that the thin ferrite toroid readily absorbs microwaves with frequencies near 1 GHz. In this model, the two pieces of ferrite are replaced by respective 250 ohm IBC's which absorb normally incident RF modes. (Recently a more sophisticated magnetic loss model for the ferrite has been developed.[3] The main differences in the ATA impedances using the new ferrite model are noted below.)

Results

Wake potentials and impedances for the ATA cell described above are calculated with the AMOS Wakefield Code. AMOS uses finite difference time-domain techniques to calculate multipole moments of the wake potential. The impedance is then calculated from the Fourier transform of the wake potential. The wakes and impedances for the monopole (m=0), dipole (m=1), and quadrupole (m=2) moments of the ATA cell are summarized in Figs. 2-4.

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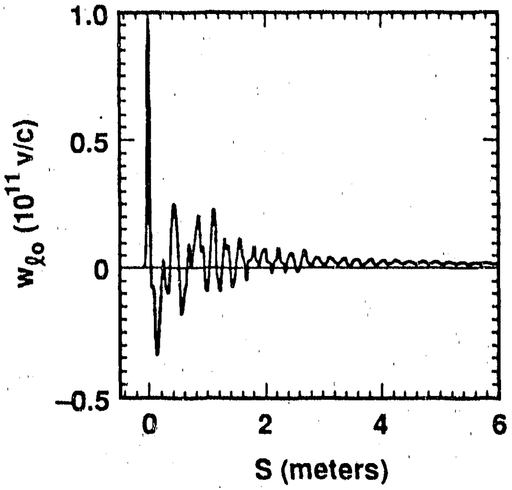

Fig. 2a. Longitudinal monopole wake potential $w_{\ell 0}(s)$ vs distance s for the ATA cell (m=0).

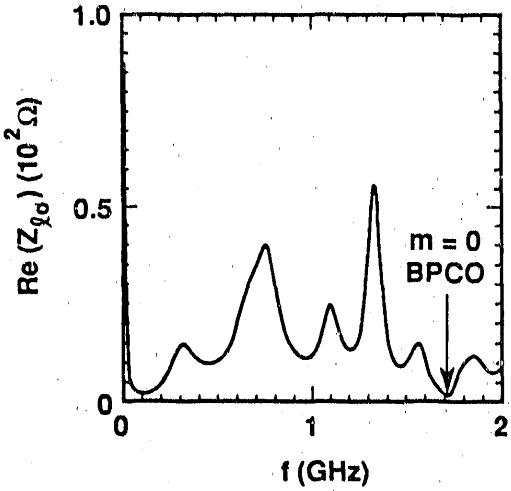

Fig. 2b. Longitudinal monopole impedance Re ($Z_{\ell 0}(f)$) vs frequency f for the ATA cell (m=0). The BPCO frequency f (TM_{01}) = 1.71 GHz.

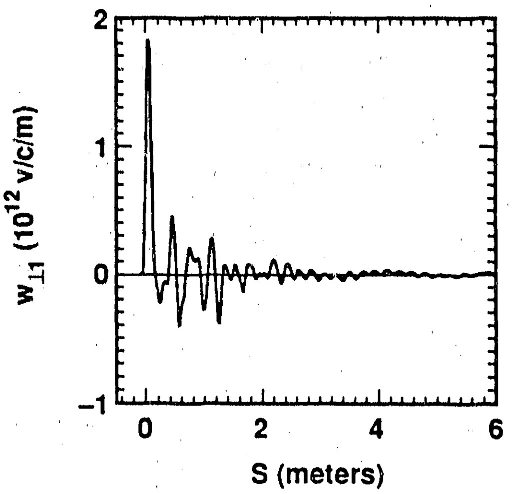

Fig. 3a. Transverse dipole wake potential $w_{\perp 1}(s)$ vs distance s for the ATA cell (m=1).

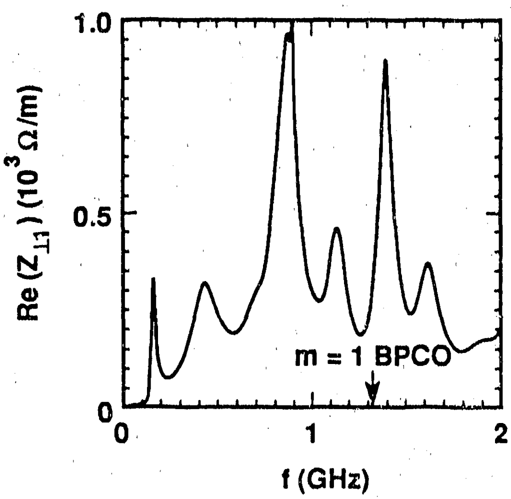

Fig. 3b. Transverse dipole impedance Re ($Z_{\perp 1}(f)$) vs frequency f for the ATA cell (m=1). The BPCO frequency f (TE_{11}) = 1.31 GHz.

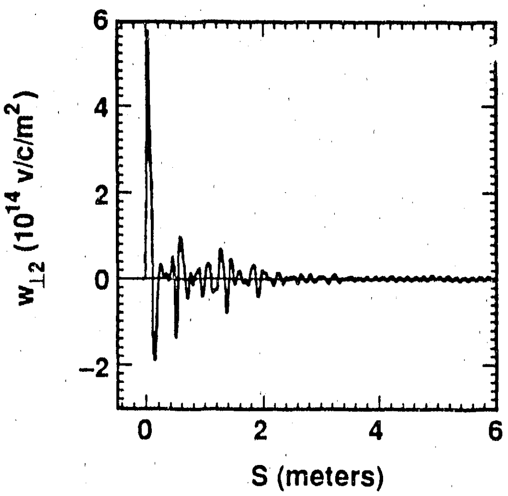

Fig. 4a. Transverse quadrupole wake potential $w_{\perp 2}(s)$ vs distance s for the ATA cell (m=2).

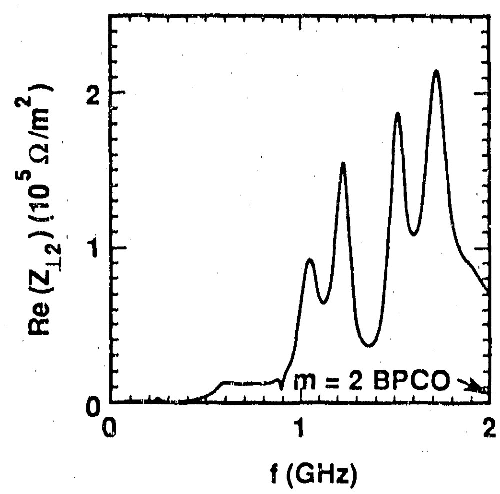

Fig. 4b. Transverse quadrupole impedance Re ($Z_{\perp 2}(f)$) vs frequency f for the ATA cell (m=2). The BPCO frequency f (TE_{21}) = 2.17 GHz.

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Wake potentials extending 6 meters behind the test charge are plotted in Figs. 2a-4a. In each case the wake rapidly decays due to the energy loss out the high voltage cable and/or into the thin ferrite toroid. Ocassionally, as shown in Fig. 4a, the wake decays into a persistent oscillation. Such a situation may indicate the presence of one or more high-Q modes in an otherwise low-Q cell. These modes are undamped because their mode pattern is negligible where the damping materials are located.

The real part of the monopole, dipole, and quadrupole impedances up to 2 GHz are given in Figs. 2b-4b. It is clear from the multiple resonances in each plot that the test charge has excited many modes in the cell. An arrow in each plot indicates the frequency of the beam pipe cutoff (BPCO) for that multipole moment. Below that frequency the modes are localized in the vicinity of the cell and evanesce into the beam pipe. Above the BPCO modes can propagate in the pipe. The persistent wake potential oscillation in Fig. 4a generates a narrow spike in the impedance spectrum near the BPCO just off scale in Fig. 4b. Resonances near and above the BPCO may be sensitive to the IBC used to terminate the ends of the beam pipe and should be viewed with caution.

Discussion

The AMOS Wakefield Code and the Dragon Geometric Editor were originally benchmarked on the ATA induction cell because it was the subject of intensive theoretical and experimental work on the beam breakup (BBU) instability.[1] This work terminates the radial transmission line with a 754 ohm surface impedance and predicts a transverse impedance of 940 Ω/m for the ATA cell.[4,5] The present effort adds the large superstructure which is attached to the radial line and introduces different material properties into the cell. Model parameters are attributed to specific cell components. Finally, the simulation is carried out in the full space of possible 2D mode excitations and therefore allows for the appearance of new BBU modes and/or fine structure in the impedance spectra.

Physically, the m=1 BBU instability occurs when the beam enters a cell off-axis. The beam can excite RF modes in the cell which kick the beam further off-axis. From Fig. 3b we find that the well known "TM130" resonance for the ATA cell is calculated to be at 875 MHz and has a maximum transverse impedance of approximately 1000 Ω/m and a Q-value of 5 (FWHM). These values are essentially the same as derived from Ref. 1. On the other hand, the wake potential and impedance spectrum exhibit substantially more resonant structure than previously.

Numerous calculations have been made to test the sensitivity of the BBU spectrum to changes in the geometry, material properties, and boundary conditions of the large superstructure. It is possible, for example, to smooth out the satellite resonances around the "TM130" resonance. Other calculations suggest that this resonance may actually be a superposition of three resonances between 700-900 MHz. (Fig. 3b hints at this possibilty.) The different components can be seen more clearly by varying the impedance of the high voltage port. We also discovered a high-Q "insulator" resonance at 1.26 GHz. Though this resonance lies near the TE11 cutoff frequency of the ATA beam pipe, an extensive series of calculations with longer beam pipes prove that the mode is actually evanescing into the pipe and is not an artifact of its termination. This resonance is not present in Fig. 3b because it was surgically removed by placing a 159 ohm wave-matched impedance on top of the insulator. The same result is presumably accomplished in the actual accelerator by putting a ferrite impregnated "putty" ring around the insulator to absorb this mode.[6]

It is interesting to compare these results with those obtained by using the new magnetic loss model for the ferrite.[3] The IBC model used for Figs. 2 - 4 for the ferrite means we have replaced ferrite surfaces by wave-matched impedances which would absorb normally incident microwaves. The magnetic loss model, on the other hand, adds a magnetic conductivity term to Faraday's Law and applies to the whole ferrite volume. The real part of the relative permeability, the dielectric constant, and the magnetic conductivity are measured to be 1.0, 13, and 7.4 x 10^4 Ω/m at 875 mHz. AMOS simulations of the ATA cell with these values produced impedance spectra as complex as before. In general, the wakes and spectra are only somewhat larger than those shown in Figs. 2-4. However, the maximum transverse impedance of the "TM130" resonance has increased to 1400 Ω/m and Q = 10.

Conclusions

Monopole, dipole, and quadrupole wake potentials and impedances have been calculated for a 2D model of the ATA linear induction cell using the AMOS Wakefield Code. The microwave loss mechanisms in the cell are dominated by the high voltage feed and the strategically placed thin ferrite toroid. The massive ferrite toroid is too recessed to absorb microwaves effectively. New induction cell designs are exploring ways to reduce cell Q's even further by moving the large ferrite toroid into a more prominent position vis-a-vis the cavity modes.[2] Finally, we note that there is calculational evidence that the well known "TM130" BBU mode in the ATA accelerator may be a triplet of modes, the final resolution of which will depend on modeling the 3D transition to the high voltage feeds.

Acknowledgements

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