BEAM-BREAKUP AND IMAGE-DISPLACEMENT INSTABILITY COUPLING IMPEDANCES IN HIGH-CURRENT ELECTRON-BEAM INDUCTION ACCELERATORS

Brendan B. Godfrey and Thomas P. Hughes

Mission Research Corporation
1720 Randolph Road SE
Albuquerque, New Mexico 87106

Abstract

The beam breakup instability, together with its low frequency limit, the image displacement instability, is a potentially serious issue for high current electron induction accelerators. This paper generalizes earlier studies to obtain analytically derived coupling impedances for heavily loaded radial lines of arbitrary width, numerically determined coupling impedances for more complex gap geometries, and beam response to very low Q lines. In general, we find that instability growth can be suppressed adequately for terawatt devices by suitable choices of gap shapes, line-termination impedances, and magnetic field strengths.

Introduction

Several high current, electron beam, induction accelerators have been developed during the past decade. Examples are the 10 kA, 50 MeV Advanced Test Accelerator (ATA) and the 40 kA, 20 MeV Radial Line Accelerator (RADLAC). Electron induction accelerators have been used for free electron lasers, flash radiography, collective ion acceleration, and other applications. Increasing output power, improving beam quality, and reducing size and cost of such devices are topics of continuing research.

Minimizing the beam breakup instability is an important design issue. The instability grows exponentially from one acceleration gap to the next at an asymptotic rate per gap (in the low Q, single mode approximation) of $\nu c Z_\perp / 30\omega_c$.[1] ν is the beam current normalized to 17 kA, c is the speed of light, $Z_\perp$ is the transverse coupling impedance of the gap, and ω_c is the cyclotron frequency of the solenoidal guide field. With $B_z = 2$ kG and $Z_\perp = 7\ \Omega/\text{cm}$,[2] ATA has an asymptotic growth rate of 12% per gap, for instance. This implies a total beam breakup growth of about 10^6 in the 180 gap accelerator, even when slower, nonasymptotic growth in the first 80 or so gaps is taken into account.

S. Putnam and coworkers are exploring the Spiral Line Induction Accelerator (SLIA) concept, in which the beam pipe passes several times through a small number of induction modules.[3] Strong focusing is employed in the turns, and solenoidal focusing everywhere.[4] The beam breakup instability is unlikely to be serious in the 10 kA, 8.5 MeV proof-of-concept experiment now being designed.[5] However, the instability will degrade the beam seriously at energies above 25 MeV in future SLIA's, if the growth rate in not reduced substantially below that in ATA.[5]

We have carried out several theoretical studies in support of the SLIA program, three of which are summarized here.[5-7] The ATA gap model has been generalized to radial lines of arbitrary width. $Z_\perp$ ceases to increase linearly with gap width when the latter somewhat exceeds the beam pipe radius, according to this analysis. In addition, a new Q mode was discovered in the otherwise heavily damped gaps. A three-dimensional electromagnetic field computer program was developed to determine transverse impedances in more complicated geometries. A short coaxial transmission line inserted between the induction module and the beam pipe effectively eliminates beam breakup coupling between the two. Unfortunately, the coaxial line introduces new dipole resonances which we have not yet been able to suppress. Wakefields from either model can be used in a SLIA beam transport code to investigate instability growth. We find that the beam breakup growth rate in a hypothetical 10 kA, 50 MeV SLIA must be less than one-third that in ATA to avoid beam disruption. Achieving this seems feasible. Equal numbers of two gap geometries with nonoverlapping resonances gives a 40% reduction, for example.

Transverse Wakefields in Wide Radial Lines

Resonant modes in the ATA acceleration gaps are modeled surprisingly well using a radial transmission line terminated by a lumped impedance;[2] see Fig. 1. We have generalized the model to arbitrary frequencies and gap widths using the methods of Refs. 8 and 9. The computer code BBU solves the resulting matrix equations to obtain the dipole wakefield, W, as a function of frequency.[6]

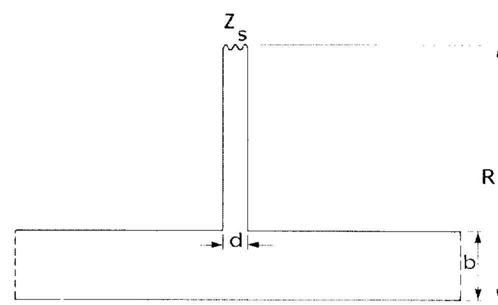

Figure 1. Idealized radial line geometry.

What follows is a partial survey of BBU results for parameters centered about nominal ATA values: $d/b = 0.34$, $R/b = 3.6$, and $Z_s = 2$. (Z_s is normalized to 377 Ω, the impedance of free space.) The complete survey provides the basis several useful observations.[6]

(1) The qualitative scaling of W with d and b switches from d/b^2 to $1/b$ as d/b is increased above unity.

(2) Quantitative scaling of W with large d/b is complicated by additional modes in the radial line. A weakly damped mode trapped in the mouth of the radial line appears for $d/b \approx 1$.

(3) Dangerous modes can occur at any frequency up to the TM cutoff of the beam pipe. The most serious modes typically have frequencies just below the TE cutoff.

(4) W is minimized by choosing $Z_s \approx 1$, for which it is nearly as low as that of a reflectionless termination.

(5) Although the number and placement of resonances depend strongly on R/b, the magnitude of W is relatively insensitive to it.

We begin by varying the line termination impedance. $Z_s = 0$ or ∞ corresponds to vanishing of the tangential electric field or its normal derivative at $r = R$. There is no energy dissipation below the TE cutoff in these two limits, and $Im(W)$ is identically zero. Resonance frequencies are well approximated by the mode frequencies of a pill-box cavity. As Z_s is moved toward unity, the resonant frequencies are relatively unchanged while mode damping grows. The minimum transverse impedance is achieved for $Z_s \approx 1$, where modes are so heavily damped that they become indistinct, as in Fig. 2.

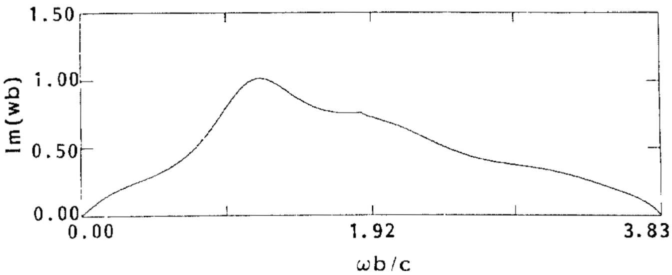

Figure 2. Imaginary part of W for radial line with $R/b = 3.6$, $d/b = 0.34$, and $Z_s = 1$.

Since $Z_s = 1$ is optimal, we next vary d/b while keeping the line termination impedance fixed at that value. W is nearly constant in shape for $d/b < 0.7$ but increases in magnitude linearly as d/b, corroborating the small d/b scaling of Ref. 2. Departure from linear scaling begins to be evident for $d/b = 1.0$. $Im(W)$, although similar in shape between $d/b = 0.5$ and 1.0, increase by a factor of only 1.6. Still another new feature arises for $d/b = 2.0$, Fig. 3. The prominent mode near $\omega b/c = 1.6$ is the lowest frequency wave with axially varying E_z in the radial line. By analogy with a metallic pill-box cavity, such modes occur for $\omega b/c > \pi b/d$. If the resonance is ignored, however, the continuing trend of ever weaker variation of W with d/b is evident. Although resonances appear and disappear as d/b is increased, the average magnitude of the wake potential remains more or less constant. This is particularly evident at low frequencies, the image displacement instability limit.[9]

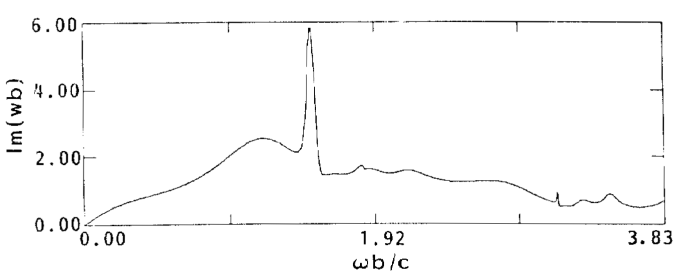

Figure 3. Imaginary part of W for radial line with $R/b = 3.6$, $d/b = 2.0$, and $Z_s = 1$.

The lessened dependence of W on d/b for $d/b > 1$ has two causes. Electromagnetic fields responsible for the beam breakup instability are concentrated near the corners of the gap for $d/b > 1$. Therefore, further increasing d/b does not enhance the total force on the beam much. A second ameliorating factor is the transit-time effect. A beam particle traversing a wide gap samples a range of phases of the oscillating forces, which partly cancel as a result.[2] This effect first has a strong influence on W at frequencies near the TE cutoff for $d/b \approx 1.7$.

Transverse Wakefields in Coaxial Lines

Electromagnetic coupling among multiple beam pipes passing through a single induction module is a concern in recirculating induction accelerators, such as SLIA. Asymmetric power feed to off center beam lines is another possible problem. Both issues are addressed by Miller's shielded line design,[10] a single-beam-pipe version of which is depicted in Fig. 4. The

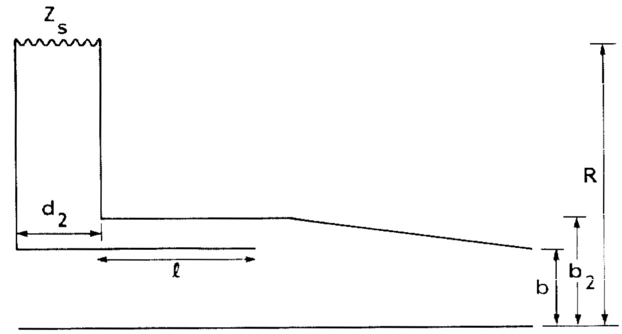

Figure 4. Idealized shielded gap geometry.

short coaxial line also helps to decouple beam breakup oscillations in the induction module.

Analytically determining transverse wakefields of shielded gap configurations is impractical. Instead, wakefields are computed in the time domain using the three-dimensional, finite difference, electromagnetic field solver from the IVORY plasma simulation code.[11] IVORY accommodates a wide variety of geometries and boundary conditions. Details of the wakefield numerical algorithm are described in Appendix C of Ref. 7.

Beam breakup modes excited in the coaxial line itself are an obvious potential source of difficulty for the shielded line concept. Consider the simplest possible realization of the junction between the coaxial line and the drift tube, illustrated in Fig. 5. Continuity of the dipole radial electric field, and other components not shown, requires that a wave of opposite polarity be launched up the coaxial line. To the extent that the traveling wave is reflected upstream, a dangerous standing wave is created in the coaxial line. Radiation into the drift tube is inhibited by the abrupt impedance change at the junction as well as by the eventual contraction of the beam pipe to its upstream radius.

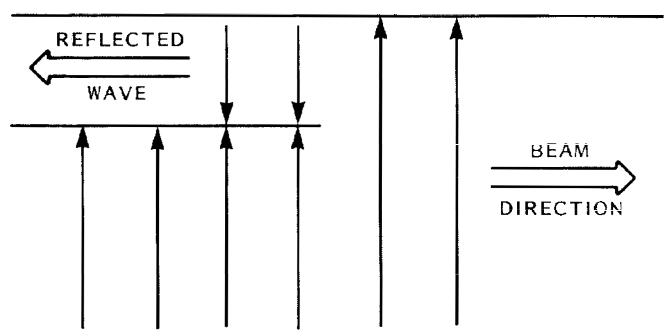

Figure 5. Basic junction between coaxial line and drift tube, showing dipole TE wave launched in coaxial line by field of passing, off center beam. E_r fields are shown.

IVORY simulations of various coaxial line configurations support this picture.[7] A simple coaxial line terminated at the far end by a metal plate supports a sequence of high-Q resonances with frequencies $(n - 1/2)\pi c/l$, n a positive integer. Adding heavy dissipation to the outer wall of the coaxial line eliminates all but the fundamental mode, but its coupling impedance actually is enhanced. We also placed a second line to the right of the gap either to produce destructive interference at the gap or to couple energy out of the first line. Instead, the second coaxial line enhances the wakefields in all cases considered.

Following these preliminary calculations, the complete geometry of the shielded line, Fig. 5, was simulated. Generally, wide radial lines terminated with $Z_s \approx 1$ work best, because the waves in the coaxial line can mode-convert into the radial line and damp at the termination. Figure 6 is a typical wakefield result. A well terminated simple radial line, Fig. 2, is superior. Further improvements possibly can be made, however. A corner reflector opposite the junction between the coaxial and radial lines might direct more wave energy up the radial line to be absorbed, as might a more rounded junction. More judicious placement of absorber material also may help. Nonetheless, it is not clear that such changes, which more tightly couple the radial and coaxial lines, will lead to wake potentials smaller than those of the radial line alone. They also may defeat the original purpose of the coaxial line. Additional research is required.

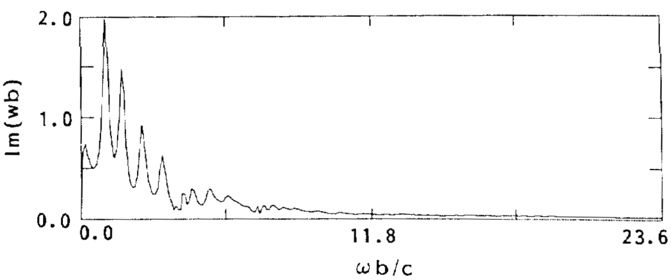

Figure 6. Imaginary part of W for the shielded line of Fig. 4 with $b_2/b = 1.33$, $l/b = 2$, $R/b = 3.6$, $d_2/b = 1$, and $Z_s = 1$.

Application to Recirculating Induction Accelerators

The beam breakup instability is unlikely to be significant in the SLIA proof-of-concept experiment. To provide a theoretical basis for scaling to higher energies, we have computed beam breakup growth in a hypothetical 10 kA, 50 MeV SLIA.[5] The beam, injected at 2.5 MeV, is accelerated through 160 gap-turns, each imparting 0.3 MeV. The vertical field strength is chosen to provide matching in the turns, and a 0.5 kG/cm stellatron field gradient is applied there. A uniform 5 kG guide field is used throughout. For convenience, the induction modules are patterned after the ATA design, scaled to a beam pipe radius of 3 cm; $Z_s = 2$. This configuration is not optimal for an actual accelerator but allows easy comparison with ATA and the upcoming SLIA experiment. All three have the same theoretical beam breakup instability growth per gap.

Transport in the spiral line is modeled with the BALTIC code,[7] which treats the beam as a string of uniformly spaced rigid disks. Only transverse oscillations are allowed. Curvature is introduced by a centrifugal force. Gap fields are represented in the thin lens approximation, with transverse wakefields obtained numerically from the BBU or IVORY codes.

BALTIC simulations indicate that the beam breakup growth per gap in the hypothetical SLIA must be reduced by a factor of three relative to ATA to avoid beam disruption. Results are not sensitive to the strength of the stellatron fields unless they are applied within a quarter wavelength of the gaps. Several methods are available to reduce instability growth to an acceptable value. Using two types of acceleration gaps with nonoverlapping resonances, doubling the axial magnetic field strength, more heavily damping the gap fields (i.e., reducing Z_s to about 1.5), enlarging the gap width to 8/3 the beam pipe radius while holding the voltage stress constant and reducing the number of gaps, or increasing the pipe radius by 40% each is capable of reducing growth per gap by a factor of two. Combining any two of the techniques should render the 50 MeV SLIA design stable to beam breakup. In addition, nonlinear focusing may serve to limit beam transverse oscillations to small amplitudes.[12,13]

Using multiple gap configurations with interlaced resonances is particularly attractive. A BALTIC calculation of the SLIA configuration with $R/b = 3.6$ and 4.8 in alternate gaps reduces the average growth rate by 40%. However, alternating three line lengths, $R = 3.6$, 4.5, and 5.4, give negligible further improvement. The broad resonances simply overlap too much.[5]

Acknowledgments

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