IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

BEAM DYNAMICS IN THE ETA AND ATA 10 kA LINEAR INDUCTION ACCELERATORS: OBSERVATIONS AND ISSUES *

R. J. Briggs, D. L. Birx, G. J. Caporaso, T. J. Fessenden, R. E. Hester,
R. Melendez, V. K. Neil, A. C. Paul, K. W. Struve,

University of California
Lawrence Livermore National Laboratory
Livermore, California 94550

Summary

The 10 kA ETA and ATA linear induction accelerators are described. Beam instability is the major concern in these high current machines, and the current status of theoretical understanding, and experimental investigations with the 8 cavity ETA, are reviewed. Modifications to the induction cavities are described that have essentially eliminated the transverse resonant modes seen in the ETA.

I. Introduction

As discussed by Leiss in his review paper at the 1979 Particle Accelerator Conference,[1] linear induction accelerators are well suited for applications requiring a combination of high beam currents (> 1 kA), good beam quality, and modest particle energies. In this paper, we describe the LLNL 10 kA ETA/ATA induction accelerators, and we discuss in some detail the beam dynamics issues involved in extending the induction linac technology to this high beam intensity regime.

The Experimental Test Accelerator (ETA) has been operating since June 1979. This machine consists of a 2.5 MeV injector[2] and 8 accelerator units producing a (nominal) acceleration voltage of 250 kV per stage, for a nominal final energy of 4.5 MeV. The ETA has operated at greater than 80% of its design parameters; details on the operating performance of this machine are provided in the paper by Fessenden, et al., in these proceedings.[3]

The 50 MeV Advanced Test Accelerator (ATA) is being constructed at LLNL at the present time. This machine is based on the ETA technology, although many improvements have been made in the rep rate pulse power systems to improve the reliability and performance--these pulse power developments are described in the paper by Reginato, et al., in these proceedings.[4]

Important issues involved in the development of these high current linacs include:

(1) The development of reliable rep rate pulse power systems to drive the induction cavities. The basic ATA pulse power module delivers an output pulse of 250 kV, 20 kA, 70 nsec FWHM with a 50 nsec flat top into the accelerator and injector cavities. These systems operate at an average rep rate of 5 Hz, with a special 1 kHz "burst mode" output of 10 pulses. Achieving the required reliability and lifetime of the pulse power components for ATA required considerable development, and further research and development in this area--particularly in the high voltage Blumlein switch--is essential for many applications of the technology.

(2) The generation of high current, high quality electron beams. The ETA initially used a thermionic cathode operating at around 25 amps/cm^2, since cold cathode technology had not been demonstrated at the required 1 kHz rep rate and repeatibility. Achieving the design emission intensity with the thermionic cathodes in the actual injector vacuum environment proved troublesome, and a pulsed surface discharge type cold plasma cathode was subsequently developed that has proven to be highly reliable.[3,5]

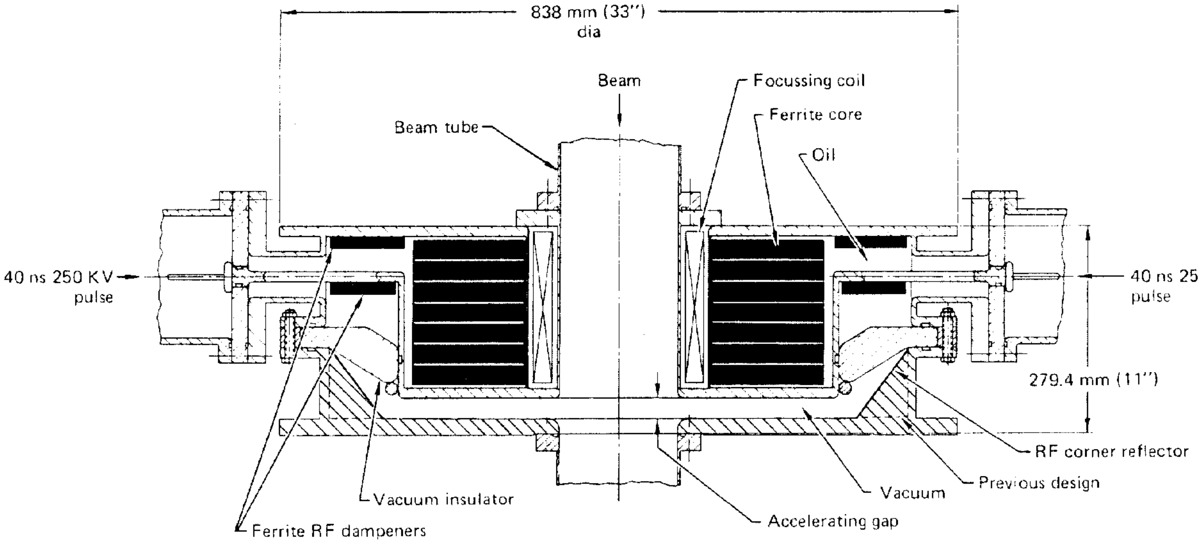

Fig. 1. The 250 kV ETA accelerating cavity modified to damp the cavity oscillations.

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*LLNL is operated by Univ. of Calif. for DOE, W-7405-Eng-48 and by LLNL for DOD/DARPA (ARPA Order 3718) monitored by NSWC N60921-80-WR-W0188.

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(3) The stable transport of high current beams through the accelerator. Elimination of beam instabilities in the accelerator is the major risk involved in achieving the desired intensities and pulse lengths in these machines. This topic is the major subject of the present paper.

II. Beam-Cavity Coupling and Basic Focusing Requirements

The coupling of the pulse power systems to the electron beam in an induction machine does not involve resonant cavity structures as it does in an r.f. accelerator. The Blumlein (pulse line) outputs are fed to the induction cavities via transmisison lines that are long enough to provide transit-time isolation of the 40 ns (ETA)/70 ns (ATA) drive pulses, and the characteristic impedance of the transmission lines (e.g., Z_o = 12 ohms in ATA) are approximately matched to the parallel combination of the beam load and the resistive compensation load.[3] (The induction cavities are actually fed from two opposite sides in a balanced mode to minimize deflections of the beam; the 12 ohm impedance referred to is the parallel combination of two 24 ohm cables.) The ferrite core in the cavity (see Fig. 1) presents an impedance to the drive lines that is much larger than Z_o (unless the ferrite saturates), allowing the line output voltage to appear across the accelerating gap shown in Fig. 1.

The simplified schematic of the induction cavity shown in Fig. 2 displays these ideas. The compensation resistor in ETA/ATA is normally chosen to match the drive line with a 10 kA beam present, and divide the output power (current) equally (i.e., $Z_L = 2Z_o$ = 24 ohms). In the absence of the beam, the cavity voltage then rises to only 1.33 times its nominal 250 kV loaded value.

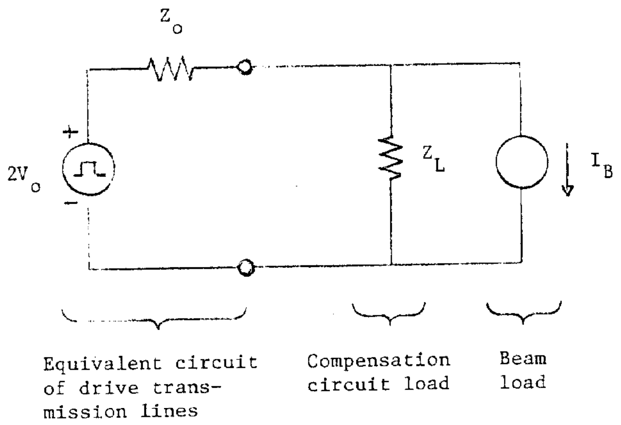

Fig. 2. Simplified schematic of induction unit.

The beam optics of the high current injector has been described elsewhere.[2] After extraction from the injector, the beam focusing is essentially a continuous solenoidal magnetic field. The focusing requirements in ETA and at the low energy end of ATA are complicated by the necessity to stay well below the space-charge limited current. For a beam radius a that is less than 1/2 of the pipe radius b, the limiting current I_{el} is given approximately by

$$I_{el}(\text{kA}) = \frac{17(\gamma^{2/3}-1)^{3/2}}{1 + 2\ln(b/a)}$$

The solenoidal magnetic focusing field B_s determines the beam radius through the condition.

$$B_s(\text{kG})a(\text{cm}) = \left[1.36\ I(\text{kA})/\gamma\right]^{1/2} .$$

The value of B_s must be chosen small enough to have "a" be large enough to remain well below the limiting current. But the magnetic field must also be large enough to overcome the defocusing effects of the accelerating gaps if the beam centroid is displaced from the axis of the pipe. The criterion for stability of the coherent transverse motion to such a low frequency displacement is[6]

$$B_s b = \left[1.36\ I(\text{kA})\ \gamma w/L\right]^{1/2} ,$$

in which w is the width of the accelerating gap and L is the gap separation. This requirement applies in the limit of quasi-static (dipole) electric and magnetic images and is commonly called the image displacement phenomena.

Resonant interaction of the coherent transverse beam oscillations with characteristic rf modes of the accelerating cavities may require a considerably stronger magnetic field throughout most of the ATA accelerator, as discussed in the following sections.

In practice all three of the above relations are satisfied in ETA, and in ATA up to 10 MeV, by choosing a sufficient gap separation L. In ETA the value of B_s is about 400 G at the end of the gun and it increases to about 800 G at the end of the machine. The limiting current is not a restriction above about 5 MeV, and it is planned that the value of B_s in ATA will increase to a maximum of 3 kG at 6 MeV and remain uniform thereafter. This higher value is considered desirable for suppresion of transverse coherent instabilities of the resonant or resistive type. The incoherent motion of particles within the beam will dictate the profile of B_s up to the 3 kG value. The profile must be such as to minimize fluctuations in the beam envelope.

III. Cavity Mode Studies

Since the beam-cavity coupling for power transfer does not involve any resonant structures in an induction machine, it should also be possible <u>in principle</u> to have the acceleration cavity structure free of any high-Q transverse (or longitudinal) modes over a wide frequency band. This is the main advantage induction accelerators have over other accelerator types in regard to the suppression of instabilities and high current operation. In this section, we summarize the results of our cavity mode studies and the modification in the ETA cavity that was required to make this "in principle" advantage a reality.

The mode measurements were made by driving a probe inserted in the cavity with a sweep oscillator, picking up the signal with a separate probe, and displaying its amplitude on a spectrum analyzer. The result is an amplitude versus frequency plot of the transmission of the cavity with the peaks corresponding to cavity resonances. It was then possible to make various changes to the cavity, and to insert lossy material into the cavity at various locations. Typically, TDK or Stackpole ferrite blocks were used as the lossy material, since these have an attenuation of 10 db/cm around 1 GHz.[7]

Tests were initially done by Birx[7,8] on the ETA accelerating cavity. He found resonances, but all had modest Q's (< 100) because of the large volume of ferrite housed in the cavity. The modes were identified by field mappings and classified by comparing them to the modes of a cylindrical pill box of similar dimensions. The TM_{1n0} modes are of greatest interest for transverse beam breakup interactions, since they have the largest transverse component of magnetic field on the axis. The mode frequencies and Q's are listed in Table 1. Modes higher than 1.2 GHz, the waveguide cutoff frequency of the beam tube, were not considered. A spectrum analyzer scan of the undamped cavity in the 200 to 1200 MHz range is shown in Fig. 3(a). The dominant modes seen with the drive and signal probe locations used for this scan are the TM_{110}, TM_{020}, TM_{130}, TM^*_{130}, and the TM_{140} modes. The TM^*_{130} mode at 890 MHz has a very high Q, but it does not couple to the beam very strongly. It arises from a quarter wavelength resonance within the ceramic insulator which serves as the oil vacuum interface. The TM_{120} mode is not discernible in this scan because of the poor coupling to that mode with the probe orientation used, and because of mode splitting due to asymmetries of the cavity. The transverse interaction impedance for these modes was also determined; it is of order $Z/Q = 10\text{-}15$ ohms in all cases except the TM^*_{130} (which was too small to measure).

Table 1
Beam Breakup Modes of the ETA Cavity

Mode	Frequency	Q_{undamped}	Q_{damped}
TM_{110}	345	40	*
TM_{120}	605	50	*
TM_{130}	830	41	<10
TM_{140}	1120	24	<10

*Not measurable

It was found that the Q's of the TM_{110} and TM_{120} modes could be reduced to well below 10 by placing ferrite on the drive blades and back side of the accelerator cavity. The Q of the TM_{130} mode remained above 17, however. It was found that the relatively high Q of the higher frequency mode is due to reflections from the insulator. This problem can be overcome by placing a metal reflector in the corner near the insulator, as shown in Fig. 1. The angle is chosen to bring a TM wave in at the Brewster angle into the ceramic, thus eliminating the reflection at the first surface. The reflection from the oil-ceramic surface is also reduced by the reflector because of a more favorable angle of incidence. Any wave which gets into the oil side is very strongly attenuated by the ferrite.

In this manner the Q's of the TM_{130} and the TM_{140} modes are also reduced to below 10, as can be seen in Fig. 1(b). Additionally it was found that the Q of the TM^*_{130} mode can be reduced by placing a ring of ferrite around the outer edge of the insulator. Although the Q for this mode is still about 16, as can be seen in Fig. 3, it has a very low interaction impedance and is therefore not considered serious.

Tests were also run on the ATA cavity, which has slightly different dimensions. Similar Q's were found, all of which were reducible to below 10 by using the same techniques.

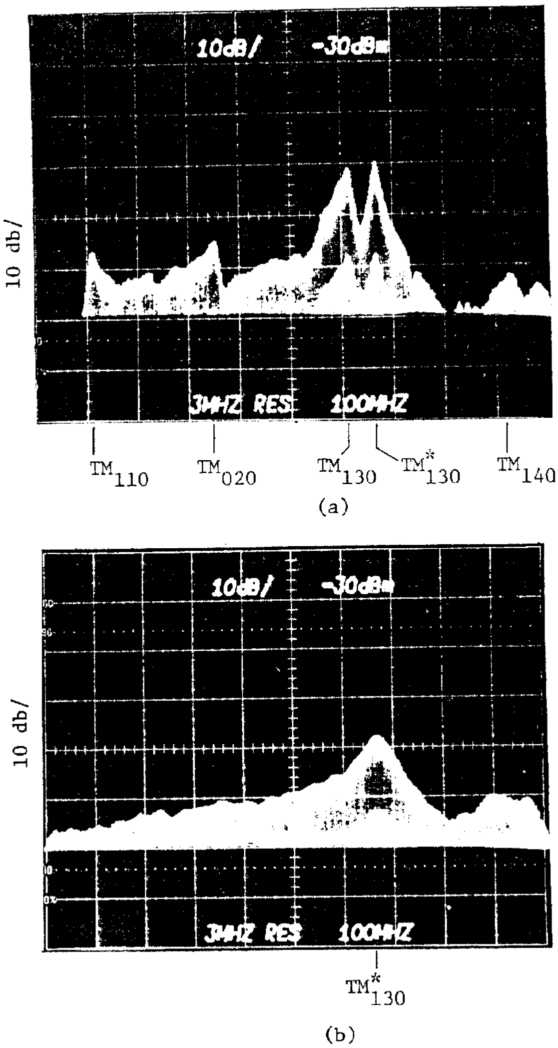

Fig. 3. Spectrum analyzer scans of the ETA cavity from 200 to 1200 MHz
(a) undamped, (b) damped.

IV. ETA Experimental Observations

The induction cavities currently in use on ETA are the original (undamped) version having the high-Q modes listed in Table 1. A search for transverse beam oscillations was carried out using r.f. loops inserted at three positions down the length of the accelerator. The loops were oriented to give the derivative of the B_θ field. A spatially growing beam oscillation at 830 MHz, corresponding to the TM_{130} cavity mode, was found. No other oscillations were observed to grow. The 830 MHz oscillations are not always present with a given "tune;" their occurrence is generally associated with high current operation and fast current risetimes (< 5 ns).

An example of the spatial growth that has been seen is displayed in Fig. 4, showing the r.f. signal and spectrum at three positions in the accelerator. In (b) the derivative of the beam current is seen as the large "spike" at the beginning and end of the pulse. The beam breakup oscillation appears as a higher frequency oscillation in the middle of the pulse. Note also that the oscillation does not grow exponentially in time throughout the pulse. The

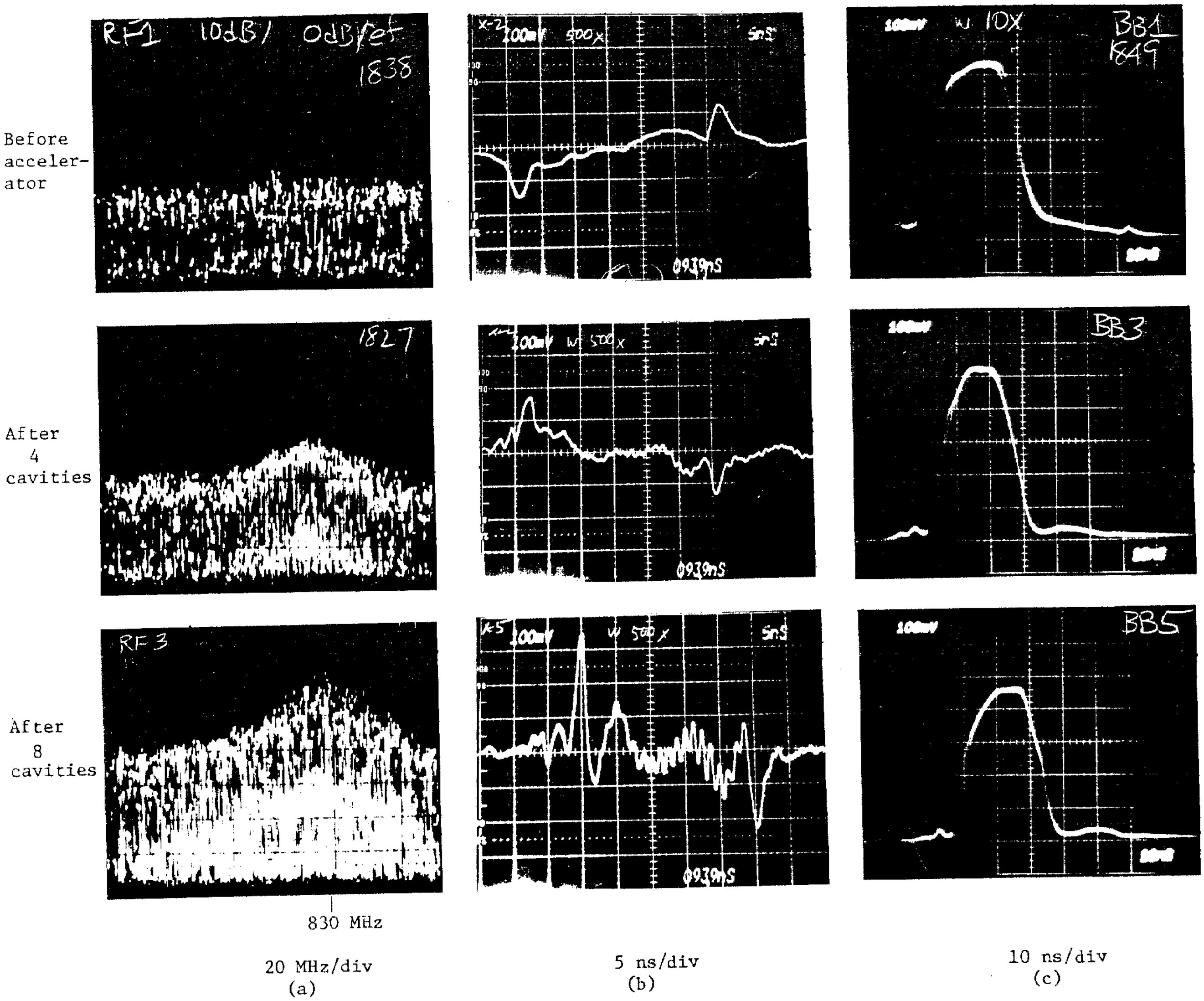

Fig. 4. R.F. loop signal at 830 MHz before the accelerator, after four accelerator cavities, and after eight cavities. (a) Spectrum analyzer over 600 shots. Vertical scale is 10 db per division. (b) R.F. signal at 50 V per division. (c) Beam current at 1 kA per division at the three positions.

magnitude of the oscillation calculated from this data is found to be approximately one cm. This is independently confirmed by the beam position monitors. In the spectrum analyzer scans in (a), which are averages of over 600 shots, the 830 MHz oscillation is seen to grow down the length of the machine.

The instability has also been studied as a function of beam parameters. It is found that the magnitude of the oscillation is strongly dependent on the beam current. Reducing the current by a factor 2/3 reduces the r.f. magnitude a factor of 4. Lengthening the beam pulse width does not change the r.f. magnitude, further indicating that the instability is not exponentially growing in time.

Presently the ETA accelerating cavities are being modified to incorporate a corner reflector and the additional ferrite shown in Fig. 1. Not shown, but also being included, is a ring of ferrite embedded rubber around the outer edge of the ceramic insulator. The ATA cavity design has also been similarly changed.

V. Computational Model of Beam Breakup Instability

The beam breakup instability has been investigated computationally for both ETA and ATA, using a model similar to the one described in Ref. 9. It is assumed that the accelerating units have characteristic electromagnetic modes of the TM_{1no} type characterized by a resonant frequency ω_n, a quality factor Q_n, and a transverse coupling impedance Z_n/Q. Only one mode is treated at a time. The units are independent in that each is excited by transverse coherent beam oscillations. No signal propagates from one unit to another in the absence of the beam. The units are identical but not necessarily azimuthally symmetric. Variation of beam current and energy with time during the pulse is included, but there is no instantaneous energy spread. Transit time effects are not included in the present version of the code, and the beam's transverse displacement does not vary with axial distance over the region of interaction with a unit.

Both the focusing field and the beam energy are allowed to vary from unit to unit. Computations of the instability growth in ETA use the actual magnetic field profile commonly employed in the experiment. In the computational model, the initial conditions for instability growth are usually fixed by setting the beam displacement at unit one equal to a constant value in time--the finite beam current risetime then "shock-excites" the transverse modes accordingly. In the real world, the excitation is more complex but the relative growth of the r.f. mode amplitude through the rest of the machine can be directly compared with experiment.

To model the ETA experiment, we considered the TM_{130} mode with a frequency of 800 MHz, a coupling impedance of 15 ohms, and a Q of 60, (which is sufficiently high to render valid the single mode approximations in the code). Calculations were performed for I = 6 kA, a constant energy out of the gun of 2 MeV with 200 keV acceleration per unit, and a solenoidal magnetic focusing field that varies from 400 G to 800 G down the machine. For an initial constant displacement of Y_o(cm) and a beam rise time of 10 ns the calculations predict the transverse oscillation amplitudes at 800 MHz shown in Table II.

Table II
Computations of the TM_{130} Mode growth in ETA

Oscillation amplitude after accelerator unit	#2	#4	#8
at t = 30 nsec	$10^{-2}Y_o$	$10^{-1}Y_o$	$2Y_o$
at t = 50 nsec	$10^{-2}Y_o$	$2Y_o$	$12Y_o$

The predicted growth is considerably higher than is observed experimentally, which is not too surprising since the theoretical approximations all tend to overestimate the growth. The predicted pattern of growth in time is also not well represented in the actual data, as noted in Section IV. One potentially-important effect that will be included in future calculations is the energy variation in time through the pulse.[3] The effective transverse coupling impedance in this relatively low Q system may also be overestimated, and better measurements are underway.

To calibrate the importance of lowering the cavity Q's in ATA, calculations were also carried out for the ATA geometry assuming the same coupling impedance and resonant frequency of the units as before. For Q values above about 12, the instability is disastrous for 50 nsec pulse lengths. For I = 10 kA, initial energy 2.5 MeV with 250 keV per unit, the transverse oscillation amplitude grows with about 1/3 e-fold per unit. Although the single mode theory is highly questionable for very low Q parameters, a calculation was also made with Q = 8 and Z/Q = 8 ohms (reasonable choices for the modified cavities with extra damping and corner reflector matching). The amplitude at 10 MeV was reduced to less than 0.1 Y_o in this case.

A dramatic reduction in the beam breakup growth with lowered Q and/or $Z_\perp/Q$ is expected on the basis of simple asymptotic growth rate formulas;[9] for example, the maximum growth of the mode with constant energy and focusing field, valid for long pulse lengths, is proportional to exp Γ_M, with

$$\Gamma_M \propto n\left(\frac{Z_\perp}{Q}\right) Q\ I/B_s$$

and n the number of units.

VI. Concluding Comments

The cavity modifications described in Section III have essentially eliminated all the resonances, at least below the frequency regime where the beam pipe supports propagating waves. In this situation, the beam breakup mode is in a "resistive limit"; rough analytic estimates of the growth through the ATA machine in this case indicate a narrow margin of safety at best with a 3 kG focusing field.

Future theoretical efforts will concentrate on the development of code models better able to describe the (multi-mode) resistive regime, improved correlation of predictions with the ETA data, and a better understanding of the beam interactions in the frequency regime where waveguide modes can propagate in the beam pipe. Data from the ETA is encouraging thus far on the latter question, but the understanding is far from complete. Finally, we mention that induction machines in this pulse length regime should allow gas pressures in the beam transport region where ion focusing effects could play an important stabilizing role in the growth of transverse oscillations.[10]

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