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STABILITY OF COMPACT RECIRCULATING ACCELERATORS*

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Abstract

Beam stability in high-current recirculating accelerators using magnetic beam transport is investigated. We focus on three instabilities which have the potential for causing beam disruption: the three-wave, negative-mass and beam breakup instabilities. The three-wave instability is a parametric instability caused by strong-focusing fields like the helical quadrupole in the SLIA (Spiral Line Induction Accelerator). We have obtained approximate analytic expressions for the growth rate and the convection velocity of this instability. A simple numerical simulation code E3WAVE has been written to model the linear behavior of the instability. Its results confirm the analytic results in the appropriate limits. We have used E3WAVE to make predictions for the SLIA experiments presently under way. We also have investigated the short-wavelength negative-mass instability modes, which interact resonantly with cavity modes of the drift-tube. Particle simulations show that the main nonlinear effect of the instability is to create an energy spread on the beam, rather than leading directly to current loss. We have made progress in minimizing the beam breakup instability without resorting to ion focusing. By adding ferrite in the induction gaps to increase damping, and by using gaps that are considerably wider than usual, with correspondingly higher voltage, growth can be reduced to several e-foldings during a typical acceleration cycle.

Introduction

Recirculating accelerators offer the potential for generating high-power electron beams with a low number of inductive accelerating gaps. Recently proposed devices include the Spiral Line Induction Accelerator (PSI/SAIC), the Rebatron (NRL) and the IFRR (Sandia). The SLIA and Rebatron rely on magnetic fields to confine and transport the beam, while the IFRR uses plasma-assisted transport. Beam stability is an important issue for these devices, because it determines their peak operating current, and the length of the accelerating cycle. This paper examines beam stability in magnetic-transport devices.

Three collective instabilities have the potential for causing beam disruption, namely, the three-wave, beam breakup and negative-mass instabilities. The following sections present results on each of these, including possible ways to stabilize them.

Electromagnetic Three-Wave Instability

The three-wave is a parametric instability caused by periodic strong focusing fields like the helical quadrupole in the SLIA, shown in Figure 1. The origin of the instability is shown in Figure 2. A slow transverse mode on the beam acquires a high-frequency sideband by beating against the rippled quadrupole field, and this sideband then interacts with the TE_{11} mode of the waveguide. The linear theory of the three-wave interaction has been worked out, and growth-rate expressions have been derived in certain limits.[1,2] As the beam accelerates, the resonance in Figure 2 moves, so that the instability does not grow indefinitely for a given wavenumber. The total growth for a given wavenumber over the acceleration cycle is given by

$$\int \Gamma dt = \pi \dot{\gamma}^{-1} \min\left(\frac{1.24\nu\eta^2}{\omega_1}\, ,\ \frac{1}{4}\epsilon^2\gamma\Omega_\theta\right) \tag{1}$$

where $\dot{\gamma}$ is the rate of change of γ, ν is Budker's parameter, η is the TE_{11} cutoff frequency, ω_1 is the frequency of the electromagnetic mode at the intersection in Figure 2, ϵ measures the amplitude of the quadrupole field, and Ω_θ is the cyclotron frequency in the longitudinal magnetic field. Evaluating Equation 1 for typical SLIA parameters ($I = 1$ kA, $B = 5$ kG, $\epsilon = 0.3$, $\gamma = 3$ to 200) a total growth of 17 e-foldings is predicted for $\dot{\gamma} = 0.5$ ns^{-1} (i.e., a 250 kV gap every 30 cm).

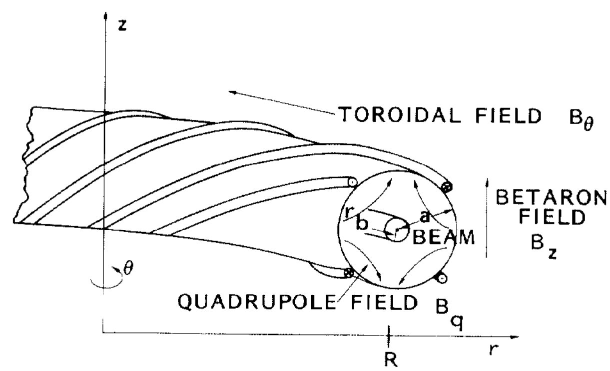

Figure 1. Magnetic fields in curved sections of SLIA.

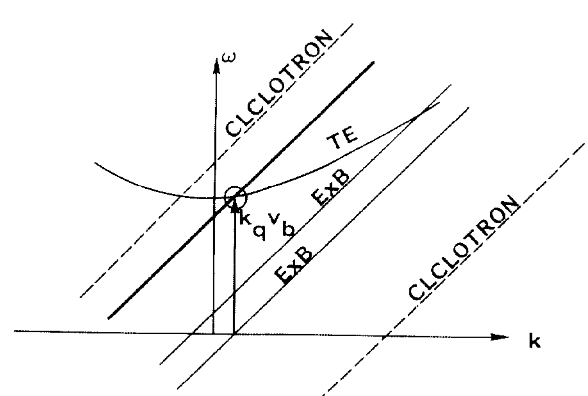

Figure 2. Qualitative illustration of the origin of the three-wave interaction. k_q is the quadrupole wavenumber, and v_b is the beam velocity.

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In order to study the instability in finite systems, and to look at stabilizing mechanisms, a numerical code E3WAVE has been written.[3] The beam is modeled as a string of rigid disks, and the code can be run either in the beam or laboratory frame. The simulations are initialized by giving the first beam disk a sideways displacement. A wavepacket develops and convects back from the head, growing exponentially in amplitude. The wavenumbers of the beam displacement and the electromagnetic field, denoted by k_b and k_{em}, respectively, differ by the wavenumber of the quadrupole field, k_q, as required by the 3-wave matching condition.[1] E3WAVE has been used to make predictions for the present parameters of the SLIA experiment, assuming a 3.6 m drift tube. The results are given in Table 1. The growth is very sensitive to the axial magnetic field.

Table 1. Growth Predicted for 800 A, 700 kV PSI Experiment.

Axial Field (kG)	Quadrupole Gradient (gauss/cm)	Amplification
5.0	535	5
2.5	535	10^2
0	370	10^7

In ongoing work, we are attempting to reduce growth by minimizing the quadrupole gradient, using quadrupole focusing only the curved sections of the drift-tube, and using wave reflections to inhibit propagation of the TE_{11} mode.

Beam Breakup Instability

The beam breakup instability (BBU) is caused by the interaction of the transverse motion of a beam with non-axisymmetric resonant cavity modes in the acceleration gaps. In the 200-gap ATA accelerator, growth of 12% per cell was observed before ion-focused transport was introduced to suppress it. With magnetic transport, growth of 10^{16} is predicted for a 100 MV, 10 kA SLIA using ATA-type gaps ($Q = 5$, $Z_\perp = 35\ \Omega$). Several damping mechanisms have been proposed, including the use of nonlinear focusing from sextupole[4] and octopole[5] magnets, and an energy spread on the beam.[6] Here, we look at the potential for minimizing growth by using fewer, wider, gaps with higher voltages. Conventional, narrow-gap theory predicts that the gap transverse impedance, $Z_\perp$, increases linearly with the width d. Since growth is proportional to $Z_\perp$, this theory indicates no advantage in using fewer, wider gaps. By obtaining an exact solution for the fields in the gap, however, we find that $Z_\perp$ does not scale linearly with d as d becomes larger than the pipe radius, b. The $Z_\perp$ calculated for $d/b = 8/3$, for example, is just three times larger than the $Z_\perp$ for $d/b = 1/3$. Further improvement is obtainable if the gap termination impedance Z_s can be reduced to the free-space value Z_0. (The ATA gaps are estimated to have $Z_s = 2Z_0$). This may be achievable simply by placing more ferrite at the end of the gap. Assuming $Z_s = Z_0$, $d/b = 8/3$, we find that BBU growth for a 100 MV, 10 kA SLIA using fifty 2-MV gaps is reduced to just three e-foldings.

More conventional ways of reducing BBU growth include increasing the axial guide field, increasing the pipe radius b, and varying the resonant frequency from gap to gap.[7]

Beam breakup is discussed in more detail in a companion paper.[8]

Negative-Mass Instability

The negative-mass instability a well-known effect in conventional high-energy circular accelerators. It arises from the curvature of the particle orbits, which can make the particles respond to longitudinal forces as if their inertia were negative. The instability has been observed in the UCI stellatron,[9] which has a magnetic field configuration very similar to that of the SLIA. The instability caused the loss of about 300 A out of an initial current of about 1.3 kA.

For a monoenergetic beam, the fastest-growing negative-mass modes are those with high toroidal mode-number ℓ which can resonate with an electromagnetic cavity mode. Qualitatively speaking, resonance is possible because the electromagnetic mode is bunched against the outer wall of the curved drift-tube (cf. Figure 3 below), and thus has a longer path to travel than the beam, which is centered in the drift-tube. In a torus, the beam resonates with a TE mode at modenumber

$$\ell \approx \frac{3\pi}{2}\left(\frac{R}{2a}\right)^{3/2} \approx 70 \qquad (2)$$

for $R = 1$ m, $a = 9$ cm. We have used the 3-D code IVORY to simulate the resonant negative-mass instability for a non-accelerating beam in a torus with modified betatron focusing. For a 10 kA, $\gamma = 10$ beam in a 5 kG toroidal field, we find that a very large energy spread ($\gamma = 3$–23) develops on the beam in about 50 ns. As shown in Figure 3, this leads to transverse drifts, and, given enough time, will result in current loss. We have also simulated $\gamma = 20$ and 40, and observe the development of spreads of $\gamma = 13$–26 and 37–43, respectively. Thus, the nonlinear energy spread decreases in both relative and absolute terms as the initial beam energy increases.

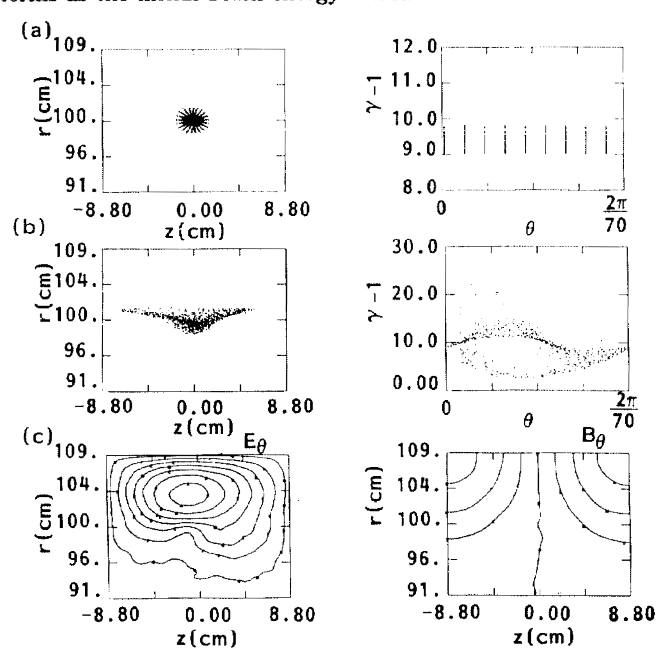

Figure 3. IVORY simulation of resonant negative-mass instability mode for parameters in Table 1 and $\gamma = 10$, showing (a) initial and (b) nonlinear particle positions and energies, and (c) $\ell = 70$ field contour plots.

To properly evaluate the likely impact of the negative-mass instability, it will be necessary, in future work, to include the effects of beam acceleration and strong focusing (i.e., quadrupole fields).

Acknowledgments

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