PLASMA-FOCUSED CYCLIC ACCELERATORS*

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Introduction

The use of ambient plasma to neutralize the transverse forces of an intense particle beam has been known for many years. Most recently, the so-called ion-focused regime (IFR) for beam propagation has been used as a means of focusing intense electron beams in linear accelerators[1] and suggested for injecting an electron beam across magnetic field lines into a high-current cyclic accelerator.[2] One technique for generating the required background plasma for IFR propagation is to use a laser to ionize ambient gas in the accelerator chamber. For cyclic accelerators a technique is required for carrying the plasma channel and the beam around a bend. Multiple laser-generated channels with dipole magnetic fields to switch the beam from one channel to the next have been tested at Sandia.[3]

This paper discusses an alternative means of plasma production for IFR, viz. by using rf breakdown. For this approach the accelerator chamber acts as a waveguide. With a suitable driving frequency, a waveguide mode can be driven which has its peak field intensity on the axis with negligible fields at the chamber walls. The plasma production and hence the beam propagation is thereby isolated from the walls.

This technique is not limited to toroidal accelerators. It may be applied to any accelerator or recirculator geometry as well as for beam steering and for injection or extraction of beams in closed accelerator configurations.

Waveguide Analysis

The analysis of the waveguide modes in a torus or in a section of bent pipe can be computed numerically with codes such as MASK and ARGUS. For the present purposes, however, the waveguide modes for a torus with a rectangular cross section can be used. This configuration offers the advantage that its mode structure can be easily calculated analytically. Figure 1 shows a sketch of the model geometry. The torus extends from $r = a$ to $r = b$ in major radius and axially from $z = -z_o$ to $z = +z_o$. The transverse and axial wavenumbers, $k_\perp$ and k_z, may be expressed as

$$k_\perp^2 = \frac{\omega^2}{c^2} - \left[\frac{n\pi}{2z_o}\right]^2$$

$$k_z = \frac{n\pi}{2z_o}$$

where ω is the rf frequency and n is an integer which quantizes the axial wavenumber. The dispersion relations satisfied by the transverse wavenumber and the solutions for electromagnetic fields in the waveguide are given by

TE Modes

$$J_m'(k_\perp a)Y_m'(k_\perp b) - J_m'(k_\perp b)Y_m'(k_\perp a) = 0$$

$$E_r = \frac{m}{k_\perp r}\left[J_m'(k_\perp a)Y_m(k_\perp r) - Y_m'(k_\perp a)J_m(k_\perp r)\right]f_n(z)$$

$$E_\theta = i\left[J_m'(k_\perp a)Y_m'(k_\perp r) - Y_m'(k_\perp a)J_m'(k_\perp r)\right]f_n(z)$$

$$E_z = 0$$

$$f_n(z) = \cos\left[\frac{n\pi z}{2z_o}\right] \quad \text{for n odd}$$

$$= \sin\left[\frac{n\pi z}{2z_o}\right] \quad \text{for n even}$$

TM Modes

$$J_m(k_\perp a)Y_m(k_\perp b) - Y_m(k_\perp a)J_m(k_\perp b) = 0$$

$$E_r = k_z\left[J_m(k_\perp a)Y_m'(k_\perp r) - Y_m(k_\perp a)J_m'(k_\perp r)\right]f_n(z)$$

$$E_\theta = \frac{imk_z}{k_\perp r}\left[J_m(k_\perp a)Y_m(k_\perp r) - Y_m(k_\perp a)J_m(k_\perp r)\right]f_n(z)$$

$$E_z = -\frac{k_\perp}{k_z}\left[J_m(k_\perp a)\,Y_m(k_\perp r) - Y_m(k_\perp a)J_m(k_\perp r)\right]f_n'(z)$$

TEM Modes ($k_\perp = 0$)

$$\omega = ck_z$$

$$E_r = \frac{1}{r}f_n(z)$$

$$E_\theta = 0$$

$$E_z = 0$$

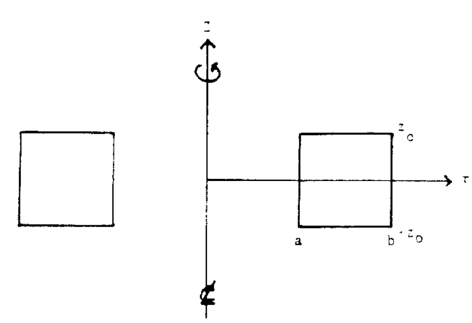

Fig. 1 Model Torus

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These relations have been analyzed numerically for modes with electric field which is well localized away from the accelerator walls. A torus with inner radius a = 90 cm, outer radius b = 110 cm, and with z boundaries at $\pm z_o = \pm 10$ cm has been chosen as an example. The modes with n = 1 have a single maximum in z, and therefore are the most suitable for the present purpose. The m = 0 mode will have no variation in the toroidal direction, and therefore is suitable for filling an entire torus with plasma. Higher m - number azimuthal modes can be used to produce plasma in a sector of size π/m. The m = 2 mode, for example, is matched to a 90-degree bend. Also, this technique is not limited to simple toroidal bends. The waveguide or accelerator tube can have any desired shape for beam steering or recirculation.

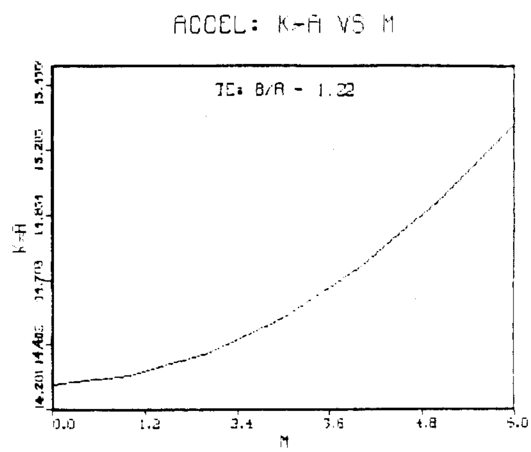

Fig. 2 $k_\perp a$ vs. m for the lowest radial TE mode with b/a = 1.22

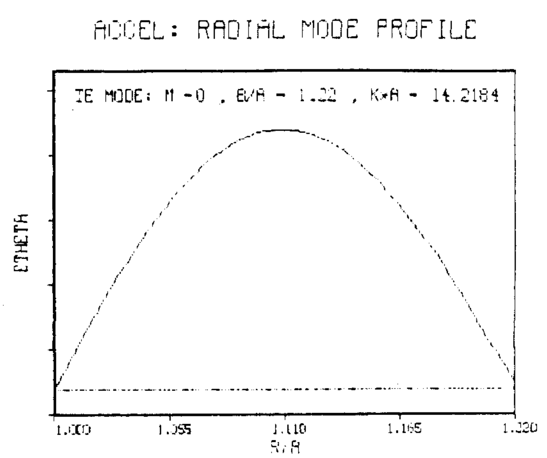

Fig. 3 E_θ vs. r/a for the lowest-radial, m = 0 TE mode with b/a = 1.22

For b/a = 1.22 the lowest solution of the TE dispersion relation is shown on Figure 2 as a function of the m-number. This lowest radial mode has the desired single-peak structure, as shown in Figure 3. The TE mode is preferable to the TM because for the TE mode the E_θ field vanishes at the metal walls and the E_r field is small everywhere, whereas the TM mode has an E_z field which is large at the z walls. The resulting frequencies are closely-spaced, but still distinguishable. The problem of driving the desired frequency and discriminating against unwanted modes requires study. In the asymptotic limit,[4] $k_\perp a \gg 1$, the modes are separated by

$$\frac{\Delta\omega}{\omega} \approx \frac{(b/a-1)^2}{2(b/a)\pi^2} \approx 0.2\% \text{ for } b/a = 1.22.$$

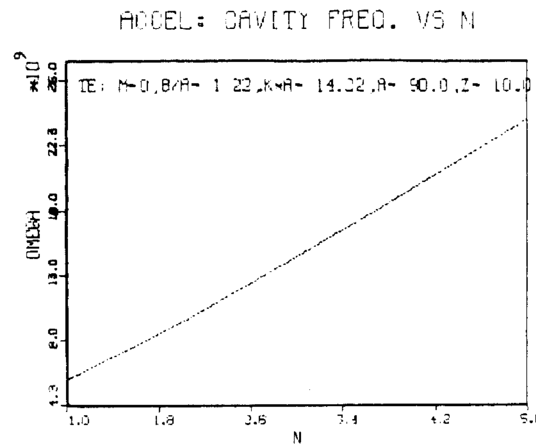

Fig. 4 Mode frequency, ω vs. n for the lowest-radial m = 0 TE mode with b/a = 1.22, a = 90 cm, z_o = 10 cm

The m=0 TE lowest-radial mode frequency is plotted against the axial n-number in Figure 4, which shows an rf frequency near 1 GHz for n=1.

Figure 5 shows a contour plot of the E_θ field for the lowest-radial m=0 TE mode. This figure shows the desired mode pattern for IFR plasma production. The lowest radial TE mode with n=1 yields this field profile in the r-z plane. The azimuthal variation, given by the m-number, is chosen to achieve the desired azimuthal plasma profile.

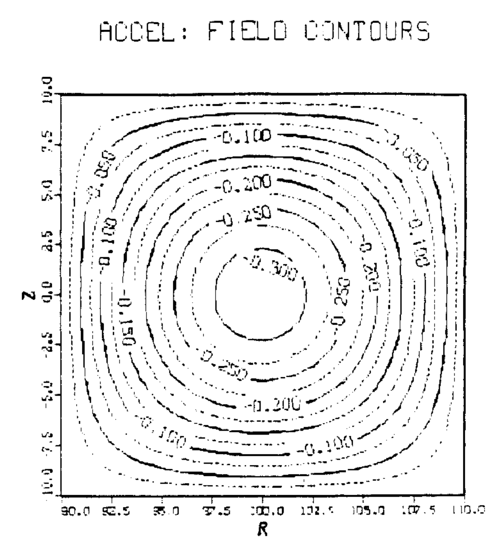

Fig. 5 Contours of constant E_θ for the lowest-radial m = 0 TE mode with b/a = 1.22, 1 = 90 cm, z_o = 10 cm, n = 1.

Microwave Breakdown and Plasma Loading

High-frequency gas-discharge breakdown occurs when the rf electric field is large enough that some electrons acquire sufficient kinetic energy to ionize the atoms.[5,6] Electron production by ionization during breakdown then balances electron losses by diffusion, recombination, or attachment. Typically free diffusion is the dominant electron loss channel, although attachment is significant in gases such as air and oxygen. The electric field required for gas breakdown is mainly a function of the gas pressure, with a broad minimum of approximately 100 V/cm at a pressure of 1-10 Torr.[5] This field corresponds to roughly 15 W/cm^2 of rf power over the waveguide aperture, or 6 kW of rf over the 20cm x 20cm aperture used in the numerical results presented above. The actual rf power required will depend on the mode used, the fraction of the aperture which is desired to break down, wall losses and other rf attenuation.

The plasma channel will act as a perturbation in the waveguide, causing absorption of rf and perturbing the desired mode configuration. If $\omega_p^2/\omega^2 \ll 1$, the perturbation due to the plasma channel will be small. The IFR propagation mode requires only a weak plasma, $n_p = n_b/\gamma^2$. For an rf frequency of ~1 GHz, the ratio of the plasma frequency, ω_p, to the rf frequency is given by

$$\frac{\omega_p}{\omega} = \frac{0.45}{(\gamma/50)\, a_b\,[\mathrm{cm}]} \left[\frac{I_b}{100\ \mathrm{kA}} \right]^{1/2} ,$$

where a_b is the beam radius. These effects will be tolerable for beam currents of $<$ 100 kA, $\gamma \gtrsim 50$ and beam radius $\gtrsim$ 3cm.

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