perature is about 50 keV.

Table I shows the averaged absorption measured in a number of simulations with different incident intensities and background electron temperatures. As expected, the absorption is strongly dependent on intensity, ranging from 1% or 2% at $I\lambda_{\mu}^2 = 10^{17}$ W μm^2/cm^2 to between 10% and 15% at $I\lambda_{\mu}^2 = 10^{18}$ W μm^2/cm^2. A weak dependence of the absorption on background electron temperature is also evident.

Of course, these one-dimensional simulations of normally incident light are intentionally ideal to isolate this physical process. Two-dimensional simulations of obliquely incident, p-polarized light show that resonance absorption is then quite efficient. The fractional absorption in a steepened profile peaks at about 50% for angles of incidence of about 20° and can be even larger when the critical surface becomes cratered and rippled. The heated electron temperature θ_h caused by resonance absorption is quite large at high intensity; for example, $\theta_h \sim 200$ keV for $I\lambda_0^2 = 10^{18}$ W μm^2/cm^2 and a background temperature of 4 keV. Two-dimensional simulations of normally incident light would include the oscillating two-stream and ion-acoustic decay instabilities. Simulations[6] have indicated that the absorption caused by these instabilities is modest in a steepened density profile, i.e., roughly 10% or less. The electrons are heated primarily along the electric vector of the light, in contrast to heating by resonance absorption and by the oscillating pondermotive force discussed here. For comparison, we note that the oscillating pondermotive force produces a fractional absorption of order 10% only when the light intensity is extremely large. The heated electrons are beamed inward and have a relatively modest temperature, given such a high light intensity. Since this process depends on the oscillating component of the pondermotive force, we do not expect it to be strongly modified if resonance absorption and parametric instabilities are simultaneously operative.

In summary, we have demonstrated a novel mechanism for the absorption of very intense laser light. The oscillating component of the pondermotive force generates an electrostatic field, which leads to electron heating. A model calculation shows that the electrostatic field is sizable for very intense light. Computer simulations with a relativistic particle code demonstrate significant absorption into electrons with a relatively modest temperature.

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Filamental quenching of the current-driven ion-cyclotron instability

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Experimental evidence is presented on the effect of the finite width of the current channel for the excitation of the current-driven ion-cyclotron instability. The results are in agreement with the nonlocal theory of Bakshi, Ganguli, and Palmadesso [Phys. Fluids **26**, 1808 (1983)].

Since their discovery over two decades ago,[1] ion-cyclotron waves have been an area of active research in the laboratory,[2] in the ionosphere-magnetosphere,[3] and in the solar corona.[4] The current-driven ion-cyclotron wave instability received its first theoretical treatment in the (local) theory of Drummond and Rosenbluth,[5] appropriate to a uniform, magnetized plasma, without magnetic shear, in which electrons drift along **B** field lines with the same drift velocity $\mathbf{v}_D$, at all points in the plasma. Their treatment, however, could not allow, among other things, for the effect that the finite width of the current channel of most laboratory experiments has on the excitation of the instability. This has been considered in the nonlocal theories of, e.g., Ganguli and Bakshi[6] and Bakshi, Ganguli, and Palmadesso.[7] They find that if the

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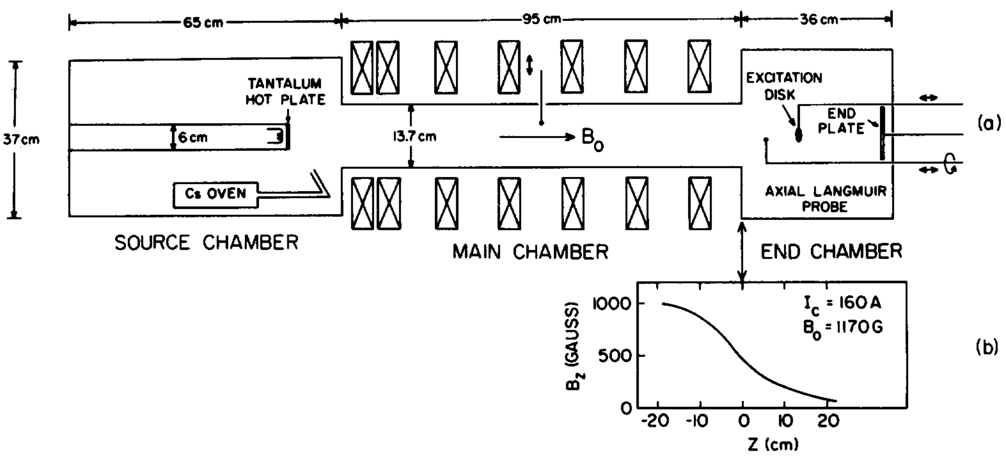

FIG. 1. (a) Schematic cross-sectional view of the Iowa Q machine. (b) Axial variation of the B_z field in the region near and into the end chamber. For this case a coil current of 160 A produced a field $B_0 = 1170$ G in the center of the main chamber. The arrow indicates the $Z = 0$ position in parts (a) and (b). Electrostatic ion-cyclotron waves are produced by applying an appropriate bias to the axially moveable excitation disk, and are detected either in the disk current or by various Langmuir probes.

width of the current channel is reduced to just a few ion Larmor radii, the instability is completely quenched. They refer to this phenomenon as *filamental quenching*.[7] Indications of the presence of this phenomenon have been available since the first laboratory experiments on the ion-cyclotron wave instability and, more recently, from, e.g., the work of Sato.[8]

Here we report on a systematic test of the filamental quenching effect, performed on the single-ended Iowa Q machine. A schematic diagram of the device is shown in Fig. 1(a). Plasma is produced by surface ionization of cesium atoms on a hot (~2200 K) tantalum plate 6 cm in diameter and is confined radially by a magnetic field of up to ~7 kG. The magnetic field is nonhomogeneous and varies along the axis of the device into the end chamber, as shown in Fig. 1(b). The ion-cyclotron wave instability is excited, in the usual manner, by drawing current to a metallic disk moveable along the axis of the device, and is detected either in the current oscillations of the disk itself or by means of various (axially and radially moveable) Langmuir probes.

Figure 2 is a plot of the oscillation frequency versus disk position, as detected by the exciter disk or by a probe. The local ion-cyclotron frequency is also shown for comparison. The arrow indicates the location at which, for the particular conditions of Fig. 2, excitation of the fundamental mode ceases. By performing measurements similar to those of Fig. 2, but with various disk diameters and different currents in the magnet coils, we have been able to obtain the diagram shown in Fig. 3. Here the disk radius r_D is plotted as a function of r_i^*, the ion Larmor radius at the location of the disk, for which the instability is quenched. The line $r_D = r_i^*$ is also shown.

Evidently, the filamental quenching operates at widths of the current channel comparable to the local Larmor radius, in agreement with the conclusions of Bakshi, Ganguli, and Palmadesso[6] (see, e.g., their Fig. 1). The small departure from the $r_D = r_i^*$ line for the 1.27 cm disk is most likely related to the large density perturbation introduced by this large disk.

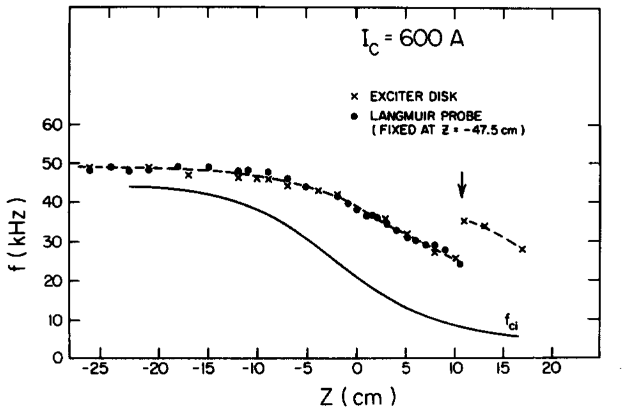

FIG. 2. Oscillation frequency versus exciter disk (0.64 cm radius) position (×). Oscillation frequency detected by a fixed Langmuir probe in the center of the main chamber, $Z = -47.5$ cm (●). The arrow indicates the Z position at which excitation of the fundamental mode ceases. The solid line is the local ion-cyclotron frequency.

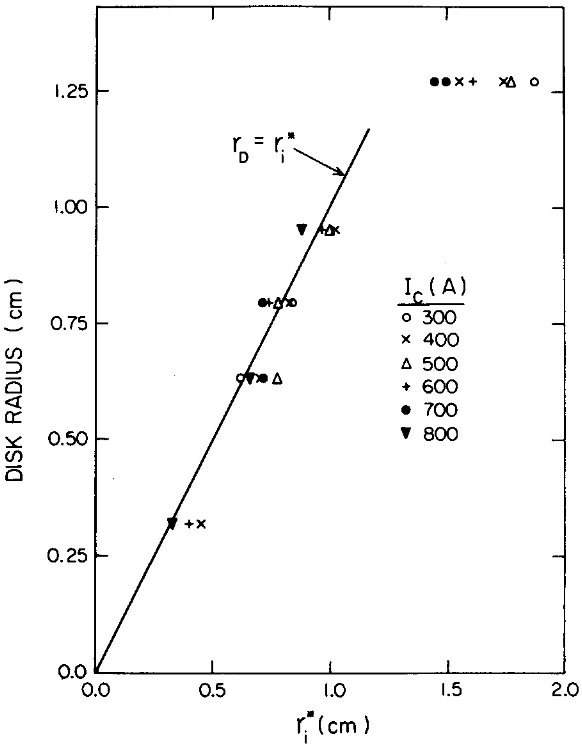

FIG. 3. Plot of exciter disk radius r_D vs r_i^*, the ion gyroradius at the location of the disk for which the instability is quenched, for various magnet coil currents between 300 and 800 A. The exciter disk radii used were: 0.32, 0.64, 0.79, 0.95, and 1.27 cm. The solid line is the line $r_D = r_i^*$.

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Extraction and propagation of an intense, rotating electron beam

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A hollow relativistic electron beam produced in a strong axial magnetic field has been extracted into a neutral gas cell where the field is zero. In the field-free region, equilibrium is dictated by a balance between the $v_z \times B_\theta$ radial pinch force and the centrifugal outward force. Extraction and propagation of these beams has been studied experimentally with a variety of diagnostics. A strong, low-frequency filamentation instability is observed after extraction. In general, 80% of the beam energy has been extracted and propagated 75 cm. Beam equilibrium properties are in good agreement with simple theory with the exception of the azimuthal plasma current.

Both intense electron beam propagation in initially neutral gas[1–5] and the interaction of rotating electron beams with plasma[6–10] are subjects of significant interest. Neutral gas propagation has been studied in connection with such areas as plasma heating,[7] collective ion acceleration,[1] and laser excitation. Rotating beam phenomena are important in areas such as plasma confinement,[9] electron ring acceleration, accelerator transport,[11,12] and betatron acceleration.[13]

Previous studies of rotating beams in initially neutral gas or plasma have typically treated the case of beam confinement by an applied magnetic field. With one exception, beam propagation experiments without external magnetic fields have been performed with nonrotating beams. Sethian *et al.*[9] studied the case of a rotating beam of low average axial velocity confined by its self-generated B_z field. The dominant feature of the rotating beam equilibrium in gas for our experiment is a balance between the rotational, or centrifugal, force and the inward pinch force caused by the interaction of the beam with its own B_θ field. To estimate the equilibrium properties, we treat an infinitesimally thin, hollow beam emitted from a cathode of radius r_c in a region of axial magnetic field B_c. Conservation of canonical angular momentum between the source region and the zero-field region gives the azimuthal particle velocity for a particle at radius a as

$$v_\theta = \omega_c r_c^2 / 2a, \tag{1}$$

where $\omega_c = eB_c/\gamma m$, γ is the relativistic factor, and the other symbols have their usual meanings. The pinch force is zero inside the beam and has the value $\mu_0 Ice/2\pi a$ outside the beam (I is the net current, and we have made the relativistic approximation $v_z = c$). We therefore take the particle orbit-averaged force to be approximately $\mu_0 Ice/4\pi a$. Combining (1) and the force balance condition, we find the cold beam

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