Observation of High-Frequency Radiation and Anomalous Ion Heating on Low-Density Discharges in Alcator*

A. A. M. Oomens and L. Th. M. Ornstein
Association EURATOM–Fundamenteel Onderzoek der Materie,
Fundamenteel Onderzoek der Materie–Instituut voor Plasmafysica, Rijnhuizen, Jutphaas, The Netherlands

and

R. R. Parker
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

F. C. Schüller
Association EURATOM–Fundamenteel Onderzoek der Materie,
Fundamenteel Onderzoek der Materie–Instituut voor Plasmafysica, Rijnhuizen, Jutphaas, The Netherlands

and

R. J. Taylor
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

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A radiation spectrum ranging from 300 MHz to 5 GHz is observed in low-density discharges in Alcator. At the lower end this spectrum is strongly peaked at a frequency corresponding to the ion plasma frequency. The emission occurs if the ratio of the drift velocity to the thermal speed of the electrons exceeds 0.45 for discharges in hydrogen or 0.2 in deuterium. The onset of the radiation correlates with the production of energetic ions.

Operations of the Alcator tokamak with well-conditioned vacuum walls result in discharges in which the plasma density n_e decreases with time.[1,2] As the current density produced in the device is also high (because of the strong toroidal field, $B_T \approx 40$–60 kG, and the small radius, $R = 54$ cm), tokamak operation with a relatively large (order unity) ratio of electron drift to thermal velocity $\langle\xi\rangle \equiv \langle u_\parallel / v_{\text{therm}}\rangle$ (averaged over the radial profile) can be realized. Since plasmas with a high value of the streaming parameter $\langle\xi\rangle$ are known to be unstable in linear geometry (for example, to ion-acoustic modes in the case $T_e > T_i$) we have been led to search for evidence of similar instabilities in the Alcator device. Additional motivation for this work was provided by the observation of high ion temperatures ($T_i \approx T_e$) even though the electron-ion energy equilibration rate is much slower than the ion-energy containment time. In this Letter, we report the discovery of a band of strong rf emission in the vicinity of the ion plasma frequency, ω_{pi}, extending from ω_{pi} to $(5$–$10)\omega_{pi}$. The higher frequencies tend to occur first in time and correlate with the onset of low-level hard-x-ray emission (total dose ~1 mR near the limiter) and intense suprathermal synchrotron radiation. The emission of the peak in the vicinity of ω_{pi} occurs always a few milliseconds later and correlates with the appearance of energetic ions (ion temperature T_i up to 1.2 keV). Thus we identify the ω_{pi} radiation as being connected with anomalous ion heating.

Initial measurements of the low-frequency part of the emission spectrum were taken by using an insulated piece of the limiter which was connected by a thin wire inside the vacuum chamber to a coaxial transmission line. Because of mismatches in the characteristic impedances of the resulting coaxial system, the observed spectrum was not a faithful replica of the excitation of the limiter probe. In addition, it was not possible to observe the higher-frequency portion ($\gtrsim 2$ GHz) of the spectrum which was initially observed via a horn connected to an S-band wave-guide port (used for an rf-heating experiment). In order to improve the frequency response and provide continuity between the low- and high-frequency portions of the spectrum, a small molybdenum-tipped probe, 0.6 mm in diameter, was installed. The probe is movable and can be positioned at any point within the 2.5-cm shadow of the limiter. Two spectrum analyzers were used in obtaining the spectra, a Tektronix 7L12 for the range 300–2000 MHz (resolution 10 MHz) and a Nytek 8011C

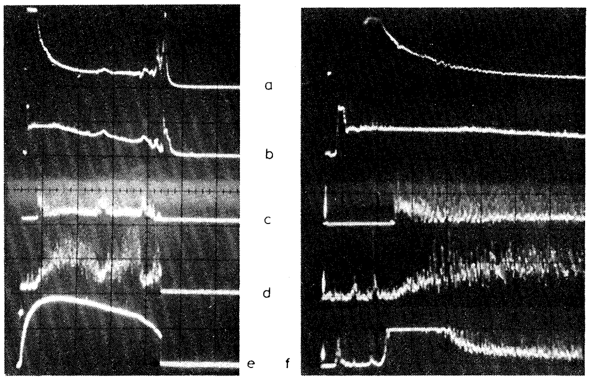

FIG. 1. Typical example of a low-density discharge in Alcator. (a) Loop voltage, 1 V/div; (b) electron density, 1.2×10^{13} cm^{-3}/div; (c) total rf emission (arbitrary units); (d) charge-exchange neutrals: energy setting ~2.5 keV; (e) discharge current, 65 kA/div; (f) x-ray emission energy > 200 keV. Sweep speed: left-hand traces, 50 msec/div; right-hand traces, 10 msec/div.

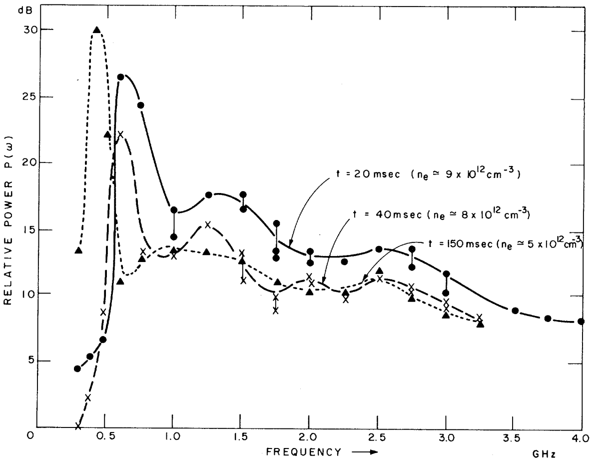

FIG. 2. Spectral emission from a discharge in hydrogen; shot-to-shot measurements were taken at $B_\varphi = 40$ kG, $I = 100$ kA.

analyzer (resolution 50 MHz) for the range 1–20 GHz. A best fit for the amplitude scales of the two different spectral ranges is found if the responses of the analyzers are estimated to differ by 8 dB. The spectra were recorded by either repeated, fast (10 msec) sweeping of the analyzer, or by shot-to-shot scanning of the passband frequency.

Typical discharge conditions for obtaining the anomalous ion-heating regime are toroidal field B_T from 25 to 55 kG, plasma current I_p from 40 to 160 kA, average electron density $\bar{n}_e$ from 4×10^{12} to 1.4×10^{13} cm^{-3}, and discharge duration as long as 400 msec. In Fig. 1, we show a typical example of the time evolution of various quantities during a low-density discharge in Alcator. In Fig. 2, we present the spectra obtained at three moments in time during the discharge. A strong peak at the lower end of the spectrum is found at frequencies corresponding to $f_{pi} = 210 \times (n_e/A)^{1/2}$, where A is the ion mass number and the units of n_e are inverse cubic centimeters. This dependence is displayed in Fig. 3, where we have plotted the density calculated by assuming the peak of the spectrum to correspond with f_{pi} versus the actual average density as measured by either 4- or 2-mm interferometers or by Thomson scattering, which has been calibrated relative to the interferometers. A 30-dB drop in the intensity is observed just below f_{pi}, and when the average density decreases during a discharge pulse, this cutoff moves accordingly.

The spectrum extends to several gigahertz, where the emission level becomes comparable to the sensitivity of the analyzer [~ 45 dBn (decibels relative to 1 nW)]. The highest frequency still detectable decreases in time as the average density decreases, from about 3.5 to 3 GHz, in the

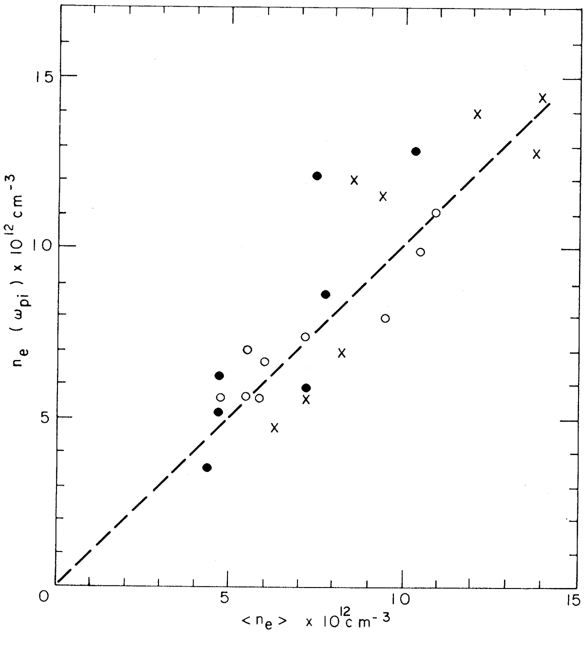

FIG. 3. The electron density $n_e(\omega_{pi})$ calculated when the measured peak frequency is interpreted as ω_{pi} versus the measured average electron density $\langle n_e \rangle$, as measured with microwaves in hydrogen (○) or by means of Thomson scattering in hydrogen (●) and deuterium (×).

example shown in Fig. 2. The average density decreases from about 9×10^{12} to 5×10^{12} cm^{-3} in these discharges. Withdrawing the probe by fixed intervals over 2.4 cm from a radial location just behind the shadow of the limiter to a position near the wall of the chamber, the detected power was found to decrease gradually by 10 dB over all frequencies; the shape of the spectrum remained invariant. This suggests that the shape of the spectrum is not affected by the transmission properties of the cold-plasma zone within the shadow of the limiter.

The relative power, $P(\omega_{pi})$, of the emitted radiation at f_{pi} as a function of $\langle\xi\rangle$ is found to have a distinct threshold at values of 0.45 for hydrogen and 0.2 for deuterium discharges as shown in Fig. 4. There are also indications that the presence of impurities leads to a decrease in the emitted power. We define $\alpha \equiv \langle u_{\parallel}/v_{\text{therm}}\rangle\langle\eta/\eta_{\text{cl}}\rangle$, where $\langle\eta/\eta_{\text{cl}}\rangle$ is the average over the radial profile of the ratio of the measured resistivity to classical resistivity. In the regime of interest, α is nearly independent of $\langle u_{\parallel}/v_{\text{therm}}\rangle$. In contaminated discharges the value of $\langle\eta/\eta_{\text{cl}}\rangle$ is increased, so that a higher value of α can be taken as an indication for a higher contamination level at the same value of $\langle\xi\rangle$ in different discharges. For the same value of $\langle\xi\rangle$ those discharges with higher value of α have $P(\omega_{pi})$ decreased by 15 to 20 dB (see Fig. 4).

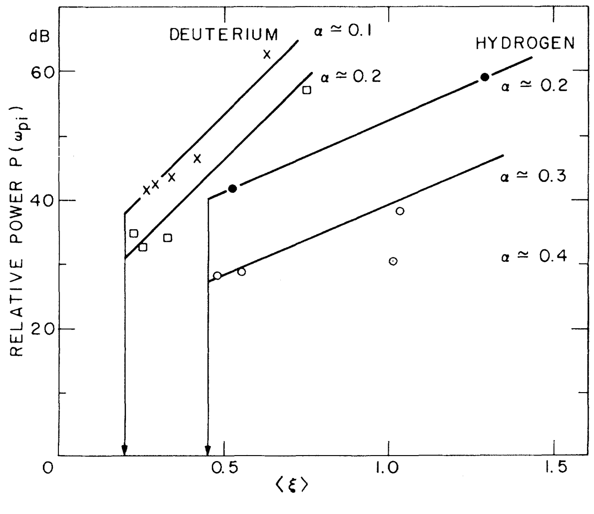

FIG. 4. Relative power level $P(\omega_{pi})$ of the radiation emitted at ω_{pi} versus the streaming parameter $\langle\xi\rangle$. The parameter α is taken as an indication of the degree of contamination of the plasma.

The fact that the emission is cut off below ω_{pi} tends to rule out turbulence associated with the usual current-driven ion-acoustic waves. A tentative explanation is presented below. In this low-density regime of operation there is experimental evidence that the distribution function of the current-carrying electrons tends to run away as a whole ("slide-away regime," see Ref. 1), while part of the electrons remains trapped. According to a theoretical model[3] current-driven modes can be excited in such a regime. The upper branch of the solution of the relevant dispersion relation represents waves at $\omega \sim \omega_{pe}\cos\theta$, where ω_{pe} is the electron plasma frequency and θ is the angle between the wave vector k and the magnetic field; these waves could be related to the high-frequency part of the observed spectrum. The lower branch of the dispersion relation corresponds roughly to $\omega \sim \omega_{pi}$; probably these modes are observed as the low-frequency peak of the spectrum. Since $\omega_{pi} \approx kv_{\text{thermi}}$, these modes can interact strongly with the bulk of the ions and could account for the observed enhanced ion heating.

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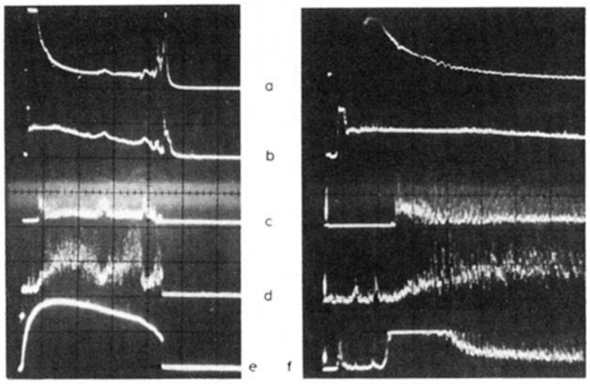
[1] U. Ascoli-Bartoli *et al.*, in *Proceedings of the Fifth International Conference on Plasma Physics and Controlled Nuclear Fusion, Tokyo, Japan, 1974* (International Atomic Energy Agency, Vienna, Austria, 1975), Vol. II, p. 191.

[2] G. J. Boxman *et al.*, in *Proceedings of the Seventh European Conference on Controlled Fusion and Plasma Physics, Lausanne, Switzerland, 1975* (European Physical Society, Geneva, 1975).

[3] B. Coppi *et al.*, in *Proceedings of the Seventh European Conference on Controlled Fusion and Plasma Physics, Lausanne, Switzerland, 1975* (European Physical Society, Geneva, 1975), Vol. I, p. 170.



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