then it is found that $N \simeq 1.2$ for the south beam and 2.4 for the north beam. In 11 534 the correlation is not as good but a value of $N \simeq 1.2$ is obtained.

In conclusion it can be said that the time and spatially resolved $2\omega_0$ and $\frac{3}{2}\omega_0$ measurements have begun to provide the data necessary for an understanding of the laser-beam–plasma interactions occurring in the region of the critical surface. The spatial resolution of the $2\omega_0$ and $\frac{3}{2}\omega_0$ streaked results provides critical and quarter-critical surface trajectories. This gives information on the hydrodynamics of the ablation region. Time-resolved scale lengths provide information for absorption studies. Intensity histories of the plasma emissions should yield information on the processes that lead to the plasma emissions.

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Synchrotron Radiation from the ATC Tokamak Plasma*

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The synchrotron radiation emitted from the adiabatic toroidal compressor (ATC) tokamak plasma along a major radius was measured over a band of frequencies (35 GHz $< f < 450$ GHz with resolution $f/\Delta f \approx 2$ and rise time $\tau < 10$ μsec) that included the electron cyclotron frequency and its first few harmonics. The radiation is at least 50% polarized ($\vec{E}_{\text{wave}} \perp \vec{B}$). Radiation due to runaway electrons increases sharply and coincidentally with the appearance of positive spikes in the loop voltage and decays exponentially after the onset of an $m = 2$ oscillation in the plasma.

Costley and co-workers[1,2] recently reported on measurements of the spectral distribution and the polarization of the synchrotron radiation emitted by the CLEO and TRF tokamak plasmas (parallel and perpendicular to the major radius) over a frequency band (30 GHz $< f < 450$ GHz) that included the electron cyclotron frequency ($\omega_c = eB/m$) and its first few harmonics. They found, contrary to expectation based on theoretical analysis of simple plasma models,[3-5] that (1) the intensity was greater than would be expected for plasmas with the electron temperatures produced by these devices, (2) the intensity was spatially isotropic, and (3) the radiation was unpolarized. Their apparatus consisted of a scanning Michelson interferometer and Putley[6] detector combined to make a Fourier-transform spectrometer. This system, which has the advantage of excellent frequency resolution ($\Delta f \approx 20$ GHz, i.e., $f/\Delta f = 10$ at 200 GHz), required 10 msec to scan the frequency range of interest and produce a Fourier transform of the spectral distribution of the observed radiation. This meant that they were able to obtain valid spectra only for those stable tokamak discharges for which the plasma parameters were nearly constant over a 10-msec interval.

This Letter reports measurements of the synchrotron radiation emitted by the adiabatic toroidal compressor[1] (ATC) tokamak plasma over the same band of frequencies, with an apparatus that had a worse frequency resolution ($f/\Delta f \sim 1-2$), but much better time resolution (< 10 μsec) than that used by Costley and co-workers.[1,2] Consequently, we concentrated on effects occurring on a time scale shorter than 10 msec and obtained a number of results not discussed in the present theory of synchrotron radiation in tokamas. We hope they will act as a stimulus to new theoretical work.

One comparison is possible with the previous results.[1,2] The radiation emitted by the ATC plasma along a major radius is at least 50% polarized with $\vec{E}_{\mathrm{wave}} \perp \vec{B}$, while that observed from CLEO and TFR is unpolarized. This is possibly related to the difference in reflection characteristics of the vacuum-chamber walls in the respective machines.

The apparatus used to make the measurements reported here consisted of a five-channel Putley[6] detector with fixed-bandwidth wire-mesh filters ($f/\Delta f \approx 2$) in each channel. The arrangement and technique of using these combined filter and cryogenic detector systems is described elsewhere.[8,9] The radiation emitted by the ATC plasma is divided equally among the five channels that span the 35- to 450-GHz interval.

The material that follows summarizes the observations of synchrotron radiation from the ATC plasma for both normal and abnormal discharge conditions. For most of the results reported here, the emitted radiation, particularly at the higher harmonics of the electron cyclotron frequency, is due primarily to runaway electrons that have significant velocity components perpendicular to the toroidal magnetic field. They are identified by their strong emission at higher harmonics.

The general characteristics of the ATC tokamak plasma are described in detail elsewhere[7]; some of its nominal parameters are (1) uncompressed state, $B_{\mathrm{toroidal}} = 15$ kG, $T_e = 1000$ eV, $n_e = 2\times10^{13}$ cm^{-3}, and $I = 60$ kA; and (2) compressed state, $B_{\mathrm{toroidal}} = 34$ kG, $T_e = 2000$ eV, $n_e = 1\times10^{14}$ cm^{-3}, and $I = 120$ kA.

As the ATC plasma went from its uncompressed to its compressed state, the synchrotron-radiation intensity increased. This is as expected since the density, temperature, and magnetic field all increased. However, the radiation intensity continues to increase during the compressed phase while plasma density and temperature are decreasing. The intensity increase is greatest at the higher harmonics of the electron cyclotron frequency. Typically, the intensity at the third harmonic increases by a factor of 6.5 with an e folding time of 6 msec while the plasma temperature and density each decrease by a factor of 2. This behavior is a result of the increasing dominance of runaway electrons in the discharge and illustrates one aspect of the usefulness of measuring synchrotron radiation in the exploration of electron distributions in tokamak plasmas.

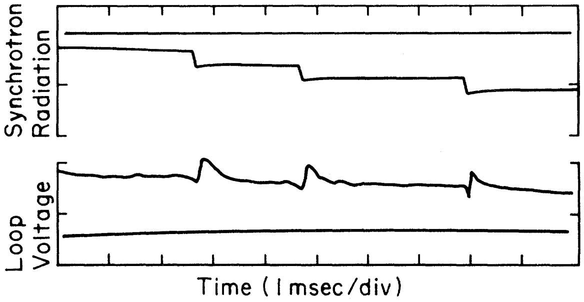

FIG. 1. Increase in radiation coincident with positive voltage spikes. These oscilloscope traces show the radiation, predominately at $2\omega_{ce}$, and the loop voltage (5 V/div). The straight horizontal traces are zero radiation level and zero voltage level.

Figure 1 shows the loop voltage (lower trace) and the radiation intensity (upper trace) as recorded in one channel of the detector (38 GHz $< f <$ 110 GHz) for an uncompressed discharge with many runaway electrons. The steplike, sequential, sudden (<10 μsec) changes in the radiation intensity are correlated with the positive voltage spikes in the loop-voltage trace. The variation of other quantities in a similar tokamak discharge was reported by Vlasenkov *et al.*[10] The signals in all the detector channels increase proportionally during these steps, from which it is concluded that the spectrum is probably unchanged during them. One possible explanation is that a velocity-space instability pitch-angle scatters additional runaway electrons at each positive voltage spike, thus increasing the number of radiating electrons. This would result in a spectrum-preserving increase in radiation intensity $[\propto v_\perp^2 \times J_n'^2(nv_\perp/c)]$ and could be consistent with a positive voltage spike.

In some otherwise normal ATC discharges, an $m = 2$ oscillation is detected by magnetic probes. Coincident with the onset of the $m = 2$ oscillations, the synchrotron-radiation intensity commences to decrease exponentially with time and continues to do so until the signal vanishes into the detector noise, which is above the thermal-radiation level, as shown in Fig. 2. This behavior is explained by noting that it is thought that these $m = 2$ oscillations disrupt magnetic surfaces within the plasma causing a loss of runaway electrons[11] which are the primary source of the observed radiation.

The polarization angle and degree of polarization were measured by passing the collimated, unfiltered (35 GHz $< f <$ 450 GHz) synchrotron radiation through a rotating (8000 rpm) polarizer

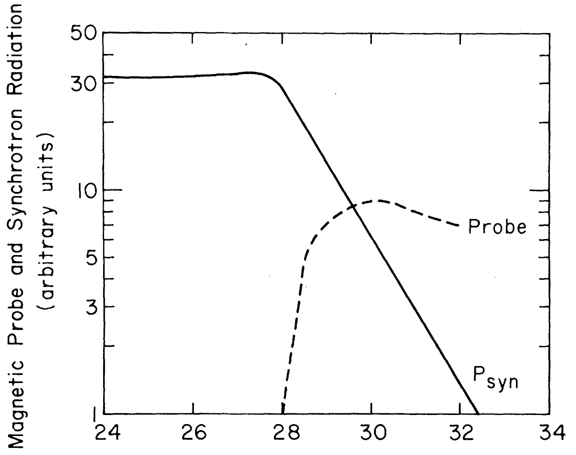

FIG. 2. Decay of radiation after onset of $m=2$ instability. The solid line is the synchrotron radiation signal, P_{syn}. The broken line is the amplitude of the magnetic-probe signal indicating the presence of the $m=2$ instability.

before it went to the detector. Figure 3 shows the detected signal recorded after compression of an ATC discharge. The period of the modulation of the signal corresponds to the period of rotation of the polarizer. The maxima occur when the polarizer is oriented so that waves with their E vector perpendicular to the toroidal axis are transmitted, as would be expected from a simple model of synchrotron radiation for ATC parameters. The degree of polarization is at least 50%. Measurement of the polarization offers access to the electron-temperature and current-density profiles,[4] although our measurements are not yet precise enough to extract this information. The general increase in intensity is characteristic of the compressed ATC plasma as mentioned earlier.

For some ATC discharges, the radiation was not dominated by runaway electrons. In this case the synchrotron-radiation intensity should be close to that from a thermal-electron distribution, as observed by Cano.[12] It was not possible to make absolute synchrotron-radiation-intensity measurements on ATC, and our apparatus was not adequate to resolve the thermal spectrum. Therefore, to investigate these discharges, we compared the time variation of the measured radiation intensity with the expected variation of intensity from the thermal plasma, taking account of temporal density and temperature variations. The values of temperature and density were obtained from laser-beam-scattering measurements

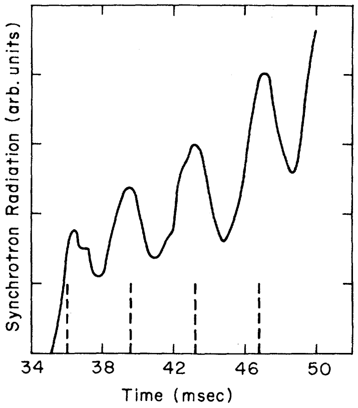

FIG. 3. Oscilloscope trace of ATC synchrotron radiation transmitted through rotating polarizing element. The vertical lines show the polarizer orientation for maximum transmission of the mode, with $\vec{E}_{\text{wave}} \perp \vec{B}_{\text{toroidal}}$.

averaged over many discharges. The measured radiation signal is from a single discharge. Figure 4 compares the total synchrotron radiation (solid line) over the band 35–450 GHz with the calculated intensity (points) for a thermal distribution. The measured and calculated intensities were normalized at 20 msec. The good agreement suggests that the radiation comes from thermal electrons rather than runaways.

Figure 5 shows that approximately 100 μsec after the 100-kW, 5-msec pulse of rf power used in the lower-hybrid heating experiments[13] has been turned off, there is a rapid, order-of-magnitude increase in the intensity of the synchrotron radiation over that which would occur for the same discharge without the rf heating. The higher lev-

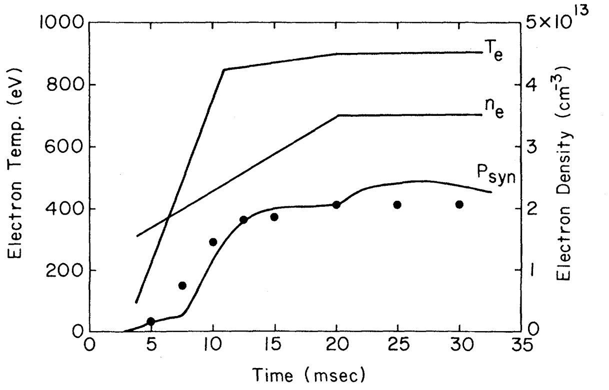

FIG. 4. Thermal level of synchrotron radiation. The time dependence of the central density and temperature are plotted. The dots are calculated values of P_{syn}. The solid line is the measured radiation power. The calculated values were normalized at $t=20$ msec.

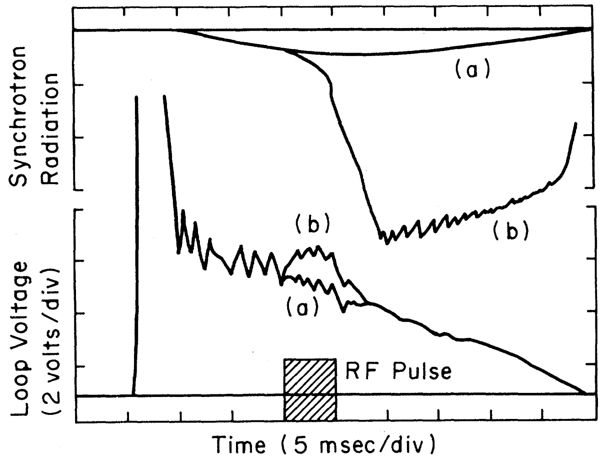

FIG. 5. The upper oscilloscope trace is the synchrotron radiation with (curves *b*) and without (curves *a*) the lower-hybrid heating pulse emitted by ATC. The lower trace is the discharge loop voltage (2 V/div).

el of radiation continues to the end of the discharge and has a small 1-kHz modulation superposed on it. A possible explanation is that the rf pulse accelerates some electrons along the toroidal magnetic field. These electrons then pitch-angle scatter, giving rise to the increased radiation level, and then they remain confined for the rest of the discharge. If the signal level prior to the application of the rf power is due to thermal electrons in the discharge, then the runaway density would have to be 10^{10} cm^{-3} to account for the increased radiation. The radiating electrons have approximately 100-keV energies, which would indicate that about 10% of the heating power went into the production of runaways.

These measurements of synchrotron radiation, with good time resolution, and those done by Costley and co-workers with good frequency resolution, show that many features of the electron distributions in tokamaks can be explored in useful and convenient ways. This is a theoretically intensive diagnostic that is most useful when it is possible to compare the calculated intensity for an appropriate plasma model with the results. A system that includes an improved version of the apparatus used for the measurements reported here and a Fourier-transform spectrometer will be used on the PLT tokamak device to study its synchrotron emission.

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