VOLUME 52, NUMBER 12 PHYSICAL REVIEW LETTERS 19 MARCH 1984

# Formation of a 100-kA Tokamak Discharge in the Princeton Large Torus by Lower Hybrid Waves

F. Jobes, J. Stevens, R. Bell, S. Bernabei, A. Cavallo, T. K. Chu, S. Cohen, B. Denne, P. Efthimion, E. Hinnov, W. Hooke, J. Hosea, E. Mazzucato, R. McWilliams, R. Motley, S. Suckewer, G. Taylor, J. Timberlake, S. von Goeler, and R. Wilson

*Princeton Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544*

(Received 19 December 1983)

The development of noninductive current drive is of great importance in establishing the tokamak as a long-pulse or steady-state fusion reactor. Lower hybrid waves, carrying 200 kW of power at 800 MHz, have been launched into the Princeton Large Torus tokamak to initiate and drive the discharge current to a level in excess of 100 kA.

PACS numbers: 52.55.Gb, 52.80.-s

Up to the present time tokamak devices have been inherently pulsed, because they rely on a transformer to drive the plasma current. This current, in interaction with a transverse magnetic field, provides the restoring force needed to hold the plasma column in equilibrium away from the vacuum walls. Prospects for the tokamak as a fusion reactor would be greatly enhanced by the development of a reliable method of steady-state current drive.

A number of methods for achieving noninductive current drive, all employing beams of radiation or particles, have been suggested. The only method which has succeeded in sustaining all of the plasma current in the absence of induction has been lower-hybrid current drive: Space-charge waves, excited in the outer plasma layers by phased waveguide arrays, propagate to the center of the torus, where they interact resonantly with the hot plasma electrons, forming a unidirectional hot-electron tail, which can carry all of the plasma current. This method has been used to supplement the transformer drive in the JFT-2, WT-2, Versator II, and JIPP-T-II tokamaks[1-4] and to maintain high currents (up to 400 kA) for times long compared with typical current decay times in the Princeton Large Torus (PLT) and Alcator *C* tokamaks.[5,6]

On the basis of present experimental results, maintenance of a steady-state plasma current in large future tokamaks by rf power alone appears to be difficult because of the high power requirements, but rf power should play a useful role in extending the current capabilities of present and future tokamaks by assisting the transformer during current ramp-up and transformer recycling.[7,8] With these applications in mind, groups on PLT, WT-2, and JIPP T-II have recently demonstrated that lower hybrid waves can drive the plasma current above 4–10 kA in target plasmas created either by the lower hybrid waves alone[9] or by electron cyclotron resonance.[10,11] In this Letter we report successful efforts to create a target plasma and to raise the plasma current to 100 kA by lower hybrid waves, unassisted by induction from the primary transformer or by the application of power at the electron cyclotron frequency.

The experiment was carried out in the PLT tokamak,[12] a torus with minor radius 0.4 m and major radius 1.32 m, at a toroidal field of 20 kG. Up to 200 kW of rf power at 800 MHz was injected into the plasma from a six-element waveguide array in an outside port. Current drive was achieved with two different couplers, one a narrow, 2-cm waveguide grill ($n_{\parallel} = ck_{\parallel}/\omega \sim 3.5$) and the other a broad 3.55-cm grill ($n_{\parallel} \sim 2$). In each case the background gas, deuterium at a pressure of $(1-2)\times 10^{-5}$ Torr, was broken down by the rf fields and a plasma of line-average density $\approx 10^{12}$ cm$^{-3}$ was formed. The phase angle between the individual guides during this 10–30 msec initial stage was set equal to 0° to minimize wave reflection at the mouths of the waveguides prior to plasma formation.

Following the breakdown stage the waveguide phase was electrically switched to 90° or 135° so that the waves would propagate toroidally in one direction and drive an electron current. With the narrow grill, it was then possible to initiate and raise the plasma current with the lower hybrid waves; simultaneously the vertical field, necessary to maintain the plasma torus in equilibrium, was raised by the normal PLT feedback control. With the broad coupler, however, careful programming of the vertical field proved necessary. As shown in Fig. 1 the rf power was turned on with the vertical field biased at $\sim 30$ G, at a level somewhat higher than that estimated to cancel the stray fields from the toroidal field. The vertical field was then slowly decreased

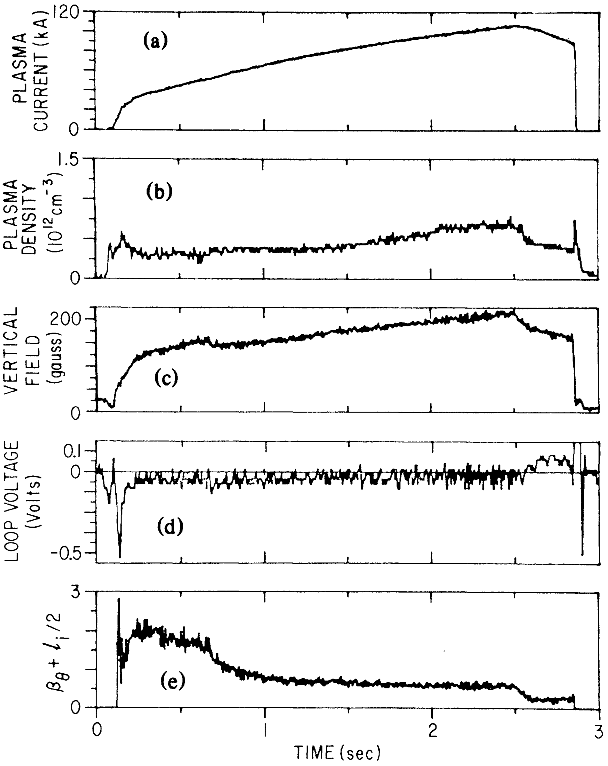

FIG. 1. (a) Time evolution of the lower-hybrid-driven plasma current in PLT; (b) line-averaged plasma density; (c) vertical field intensity; (d) loop voltage; (e) $\beta_\theta + l_i/2$.

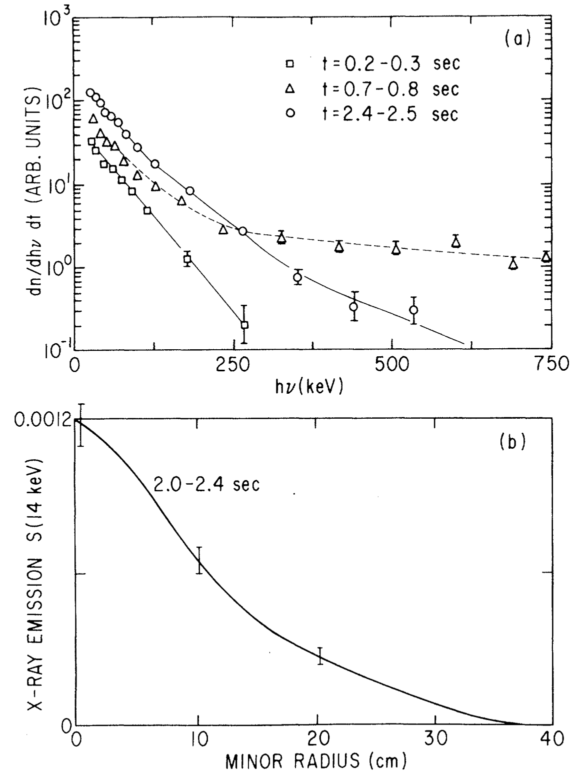

FIG. 2. (a) Hard-x-ray spectra in three different time intervals during the PLT discharge; (b) radial variation of a soft-x-ray (10–30 keV) intensity. The error bars reflect variations that occur for different time groups.

towards zero and ramped up sharply over ~ 20 msec. With the application of rf power the plasma current rose quickly to 30 kA at a rate of ~ 200 kA/sec, followed by a 2-sec rise to 100 kA at a 35-kA/sec rate. During the discharge the line-average density was $10^{12}$ cm$^{-3}$ or less. There was no gas puffing.

The one-turn loop voltage, shown in Fig. 1, is measured across an insulating gap in the vacuum vessel. The product of this voltage and the plasma current is proportional to the net Poynting flux flowing into the vacuum vessel. In normal tokamak operation this quantity is positive, but in this experiment, the loop voltage is negative, so that the Poynting flux flows outward from the plasma into the external poloidal fields.

Approximately 4% (~ 20 kJ) of the total rf energy input to PLT was converted into poloidal field energy. Of this energy approximately 20% resided in the fields internal to the plasma. In turn the kinetic energy in the plasma (including the hot-electron tail) was less than $\frac{1}{4}$ the internal field energy ($\beta_\theta + l_i/2 = 0.4$ from Fig. 1; $\beta_\theta < 0.1$). We are unable to account for most of the rf input energy: collisional dissipation (at the 0.1-W/A level measured in earlier experiments[5]) should absorb less than 12 kJ of energy; energy exchange with the vertical field should be negligible. More than 90% of the rf power must therefore flow into unmonitored channels, such as rf leakage from the plasma, radiation, and loss of fast electrons to the limiters. The conversion efficiency is only $\frac{1}{5}$ to $\frac{1}{6}$ of that measured at higher current levels in inductively initiated discharges.[13]

Hard-x-ray measurements at 90° to the magnetic field show a rising level of x rays during the discharge [Fig. 2(a)]. The 40-kV x-ray tail "temperature" is good evidence that the current is carried primarily by a fast electron tail similar to that observed in earlier current maintenance experiments.[14] Soft-x-ray emission (10–30 keV) shows that the fast electrons are centered on axis and are spread out over a minor radius of ~ 12 cm [Fig. 2(b)]. These data yield an upper limit to the hot-electron radius since the degree of contamination by x-ray emission from the walls at $r = 230$ cm is uncertain. This uncertainty also prevents any meaningful evaluation of the time evolution of the

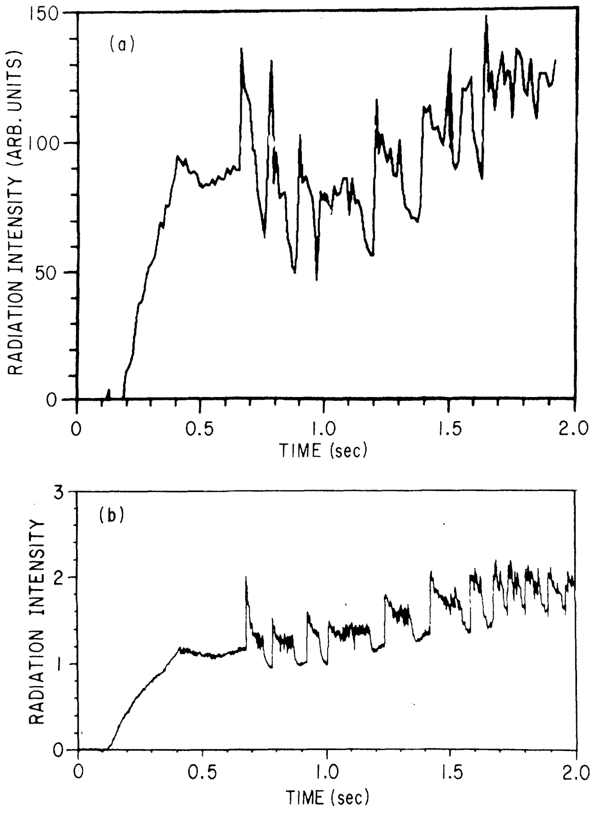

FIG. 3. (a) Time variation of the total microwave emission (5–24 GHZ) near the electron plasma frequency; (b) time history of the microwave emission near the second and higher harmonics of the electron cyclotron frequency ($\geqslant 117$ GHz).

x-ray profiles. The very soft ($< 10$ keV) emission from the main body electrons shows a slow rise in the central electron temperature from 300 to 400 eV during the discharge. The electron temperature at $r = 10$ cm varies from 250 to 350 eV. Evidence from carbon-ion C *V* emission indicates $T_e > 200$ eV at $r = 10$ cm. Spectroscopic measurements of Doppler broadening of C *V* show that the carbon ion temperature is $\sim 100$ eV, at $r = 10$ cm.

Fast electrons also radiate in the microwave range near the plasma frequency[15] and the harmonics of the electron cyclotron frequency (Fig. 3).[2] The intensity of this radiation rises gradually with the current until $t = 0.6$–$0.8$ sec, when strong oscillations begin. A second tail in the x-ray spectrum [Fig. 2(a)] appears at the onset of these oscillations. In past work on PLT this behavior has been associated with velocity-space instabilities in the fast electron tail,[15] triggered by the simultaneous application of rf power and electric fields internal to the plasma column. In these experiments the instabilities may be driven by a fast electron tail in the reverse direction, accelerated by the negative 0.1- to 0.5-V loop voltage arising from the current rise.

This work represents the first use of lower hybrid waves for the dual purpose of creating a target plasma in a tokamak and driving the plasma current well into the range of typical tokamak operation for which closed magnetic surfaces are assured. One of the couplers ($n_\parallel \sim 2$ at 90° phase) requires special programming of the vertical magnetic field. We believe that the initial boost of 0.01 V-sec by the vertical field is needed to generate a seed current of electrons in the $> 20$-keV energy range. At these energies there is sufficient power in the rf wave spectrum to accelerate the electrons to higher energies before they are lost along poorly developed magnetic-flux surfaces.

The quasilinear theory of rf current drive,[16] which has motivated and guided much of the experimental effort in this field, is inadequate to explain the results of this experiment. According to this theory, current drive can be successful only if the number of fast electrons near the low-velocity end of the wave-number spectrum is sufficient to carry the current. In the experiments on WT-2 the fast electrons are provided by cyclotron resonance heating. In our experiment there is no obvious source of fast electrons in the 1–30-keV range except during the first 20 msec of the discharge. The wave spectrum launched by the grill may possibly be broadened by repeated reflections of the lower hybrid waves at the surface[17] or by nonlinear wave interactions.[18, 19] Alternatively, the energy density of the waves may build up to such a level that trapping and other strongly nonlinear processes occur.

This work indicated that tokamak designers now have new options for plasma current drive, so that machine design and operation can be radically altered in an effort to achieve a more efficient and practical reactor.

It is a pleasure to acknowledge the invaluable contribution of the High Power rf Group, the PLT technical staff, and the Data Acquistion staff. We are grateful for continued support from Dr. H. P. Furth.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-76-CH03073.

---

[1] T. Yamamoto *et al.*, Phys. Rev. Lett. 45, 716 (1980).

[2] T. Maekaewa *et al.*, Phys. Lett. 85A, 339 (1981).

[3] S. C. Luckhardt *et al.*, Phys. Rev. Lett. 48, 152 (1982).

[4] K. Ohkubo *et al.*, Nucl. Fusion 22, 203 (1982).

[5] S. Bernabei *et al.*, Phys. Rev. Lett. **49**, 1255 (1982).

[6] M. Porkolab *et al.*, in *Proceedings of the Ninth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1-8 September 1982* (International Atomic Energy Agency, Vienna, 1983), Vol. 1, p. 227.

[7] N. J. Fisch, in *Proceedings of the Third Joint Varenna-Grenoble International Symposium* (Commission of the European Communities, Brussels, 1982), Vol. 3, p. 841.

[8] W. Hooke *et al.*, in *Proceedings of the Ninth International on Plasma Physics and Controlled Nuclear Fusion Research, Baltimore, 1-8 September 1982* (International Atomic Energy Agency, Vienna, 1983), Vol. 1, p. 239.

[9] S. Bernabei, Bull. Am. Phys. Soc. **27**, 960 (1982).

[10] S. Kubo *et al.*, Phys. Rev. Lett. **50**, 1994 (1983).

[11] K. Toi, K. Ohkubo, K. Kawahata *et al.*, private communication.

[12] D. Grove *et al.*, in *Proceedings of the Sixth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, West Germany, 1976* (International Atomic Energy Agency, Vienna, 1977), Vol. 1, p. 21.

[13] J. Stevens *et al.*, in *Proceedings of the Third Joint Varenna-Grenoble International Symposium* (Commission of the European Communities, Brussels, 1982), Vol. 2, p. 455.

[14] S. von Goeler *et al.*, in *Proceedings of the Fifth Topical Conference on Radio Frequency Plamsa Heating* (University of Wisconsin, Madison, Wisconsin, 1983), p. 96.

[15] P. C. Efthimion *et al.*, Bull. Am. Phys. Soc. **26**, 975 (1981).

[16] N. J. Fisch, Phys. Rev. Lett. **41**, 873 (1978).

[17] P. T. Bonoli, R. C. Engloda, and M. Porkolab, in *Proceedings of the Fifth Topical Conference on Radio Frequency Plasma Heating* (University of Wisconsin, Madison, Wisconsin, 1983), p. 72.

[18] V. V. Parail and O. P. Pogutse, Sov. J. Plasma Phys. **2**, 125 (1968).

[19] C. S. Liu *et al.*, Phys. Rev. Lett. **48**, 1479 (1982).