23/84 5-3 PPPL-2084

DR-014-0

PPPL-2084

UC20-A, B, D, F

I-14496

PPPL--2084

DE84 010748

FORMATION OF A 100- μ A TOKAMAK DISCHARGE
IN THE PRINCETON LARGE TORUS
BY LOWER HYBRID WAVES

By

F. Jobes et al.

MARCH 1984

MASTER

PLASMA
PHYSICS
LABORATORY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED.

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC07-76-CED-3073.

EXTERNAL DISTRIBUTION IN ADDITION TO TIC UC-20.

Plasma Res/Lab, Austr Nat'l Univ, AUSTRALIA
 Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. D. Palumbo, Dg XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.H. Sakenaka, Univ Estadual, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Telchmann, Univ of Montreal, CANADA
 Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Greenlavan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. Hannes Barnard, Univ British Columbia, CANADA
 Dr. M.P. Backynski, MPB Technologies, Inc., CANADA
 Zhengwu Li, SK Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, Academia Sinica, CHINA
 Dr. Peter Lukac, Komenského Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Radet, CEN-BPG, FRANCE
 AM Dupas Library, AM Dupas Library, FRANCE
 Dr. Tom Muai, Academy Bibliographic, HONG KONG
 Preprint Library, Cen Res Inst Phys, HUNGARY
 Dr. S.K. Trehan, Panjab University, INDIA
 Dr. Indra, Mohan Lal Das, Banaras Hindu Univ, INDIA
 Dr. L.K. Chevde, South Gujarat Univ, INDIA
 Dr. R.K. Chhajlani, Var Ruchi Marg, INDIA
 P. Kew, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Cuperman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ Di Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Giella De Palo, Assoc EURATOM-CNEN, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Prof. M. Yoshikawa, JAERI, Tokai Res Est, JAPAN
 Prof. T. Uchida, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Prof. Sigeru Mori, JAERI, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Satoshi Itoh, Kyushu University, JAPAN
 Tech Info Division, Korea Atomic Energy, KOREA
 Dr. R. Englund, Ciudad Universitaria, MEXICO
 Bibliothek, Fon-Inst Voor Plasma, NETHERLANDS
 Prof. B.S. Lilley, University of Waikato, NEW ZEALAND
 Dr. Suresh C. Sharma, Univ of Calabar, NIGERIA
 Prof. J.A.C. Cabral, Inst Superior Tech, PORTUGAL
 Dr. Octavian Petrus, ALI CUZA University, ROMANIA
 Prof. M.A. Hallberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Atomic Energy Bd, SO AFRICA
 Fusion Div, Library, JEN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Dr. Erik T. Karlson, Uppsala Universitet, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. W.L. Waise, Nat'l Bur Stand, USA
 Dr. W.M. Stacey, Georg Inst Tech, USA
 Dr. S.T. Wu, Univ Alabama, USA
 Prof. Norman L. Olsson, Univ S Florida, USA
 Dr. Benjamin Ma, Iowa State Univ, USA
 Prof. Magne Kristiansen, Texas Tech Univ, USA
 Dr. Raymond Askew, Auburn Univ, USA
 Dr. V.T. Tolok, Kharkov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Institute Gen. Physics, USSR
 Prof. T.J. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universität, W. GERMANY
 Nuclear Res Estab, Jülich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Dr. H.J. Kaeppler, University Stuttgart, W. GERMANY
 Bibliothek, Inst Plasmaforschung, W. GERMANY

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It
has been reproduced from the best available
copy to permit the broadest possible avail-
ability.

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

F. Jobs, 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

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

ABSTRACT

The development of non-inductive 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 PLT tokamak to initiate and drive the discharge current to a level in excess of 100 kA.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

LB
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

I. INTRODUCTION

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 non-inductive 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 tokamaks¹⁻⁴ and to maintain high currents (up to 400 kA) for times long compared with typical current decay times in the PLT and Alcator C tokamaks.⁵⁻⁶

Based on 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 OH 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 alone⁹ 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.

II. EXPERIMENTAL DETAILS

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 were injected into the plasma from a 6-element waveguide array in an outside port. Current drive was achieved with two different couplers, one a narrow, 2-cm waveguide grill ($n_{\parallel} = c k_{\parallel} / \omega \sim 3.5$) 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 $\sim 10^{12} \text{ cm}^{-3}$ was formed. The phase angle between the individual guides during this 10-30 msec initial stage was set to 0° to minimize wave reflection at the mouth 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 ~ 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 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 1/4 the internal field energy ($\beta_0 + \beta_i/2 = 0.4$ from Fig. 1; $\beta_0 < 0.1$). We are unable to account for most of the rf input energy: collisional dissipation (at the 0.1 W/A level measured in earlier experiments⁵) 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 1/5 to 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. 2a). 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. 2b). These data yield an upper limit to the hot electron radius since the degree of contamination by x-ray emission from the walls at $r = 20$ cm is uncertain. This uncertainty also prevents any meaningful evaluation of the time evolution of the 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 CV emission indicates $T_e > 200$ eV at $r = 10$ cm. Spectroscopic measurements of Doppler broadening of carbon V show that the carbon ion temperature is ~100 eV, at $r = 10$ cm.

Fast electrons also radiate in the microwave range near the plasma frequency¹⁵ 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. 2a) 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.

III. DISCUSSION

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 ($n_1 \sim 2$ @ 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 wavenumber 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 surface¹⁷ 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 indicates 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 Acquisition staff. We are grateful for continued support from Dr. H. P. Furth.

This work was supported by the U.S. Department of Energy Contract No. DE-AC02-76-CH0-3073.

References

- ¹T. Yamamoto et al., Phys. Rev. Lett. 45, 716 (1980).
- ²T. Maekawa et al., Phys. Lett. 85A, 339 (1981).
- ³S. C. Luckhardt et al., Phys. Rev. Lett. 48, 152 (1982).
- ⁴K. Ohkubo et al., Nucl. Fusion 22, 203 (1982).
- ⁵S. Bernabei et al., Phys. Rev. Lett. 49, 1255 (1982).
- ⁶M. Porkolab et al., in Proc. of 9th Intern. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, (IAEA, Vienna, 1983) Vol. I, p. 227.
- ⁷N. J. Fisch, in Proc. of Joint Varenna-Grenoble Inter. Symposium, (Commission of the European Communities, Brussels, 1982) Vol. III, p. 841.
- ⁸W. Hooke et al., in Proc. of 9th Inter. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, (IAEA, Vienna, 1983) Vol. I, p. 239.
- ⁹S. Bernabei, Bull. Am. Phys. Soc. 27, 960 (1982).
- ¹⁰S. Kubo et al., Phys. Rev. Lett. 50, 1994 (1983).
- ¹¹K. Toi, K. Ohkubo, K. Kawahata et al., private communication.
- ¹²D. Grove et al., in Proc. of Conf. on Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna, 1977) Vol. I, p. 21.
- ¹³J. Stevens et al., In Proc. of 3rd Joint Varenna-Grenoble Inter. Symposium (Commission of the European Communities, Brussels, 1982) Vol. II, p. 455.
- ¹⁴S. von Goeler et al., In Proc. of 5th Topical Conf. on RF Plasma Heating (University of Wisconsin, Madison, Wisconsin, 1983) p. 96.
- ¹⁵P. C. Efthimion et al., Bull. Am. Phys. Soc. 26, 975 (1981).
- ¹⁶N. J. Fisch, Phys. Rev. Lett. 41, 873 (1978).

- ¹⁷P. T. Bonoli, R. C. Engle, and M. Porkolab, in Proc. of 5th Topical Conference on Radio Frequency Plasma Heating (University of Wisconsin, Madison, 1983) p. 72.
- ¹⁸V. V. Parail and O. P. Pogutse, Sov. J. Plasma Phys. 2, 125 (1968).
- ¹⁹C. S. Liu et al., Phys. Rev. Lett. 48, 1479 (1982).

Figure Captions

FIG. 1. (a) Time evolution of the lower hybrid driven plasma current in PLT. (b) Vertical field intensity; (c) line-averaged plasma density; (d) loop voltage; (e) $\beta_0 + \lambda_1/2$.

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.

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 2nd and higher harmonics of the electron cyclotron frequency (≥ 117 GHz).

Fig. 1

Fig. 2

Fig. 3