191 3-26-86 WG

PPPL-2201 ②

DR-0891-5

I-20179

PPPL-2201

UC20-A,F

A ONE MILLIMETER WAVE INTERFEROMETER FOR THE MEASUREMENT OF LINE INTEGRAL ELECTRON DENSITY ON TFTR

By

P.C. Efthimion, G. Taylor, W. Ernst, M. Goldman,
M. McCarthy, H. Anderson, and N.C. Luhmann

MASTER

MARCH 1985

PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073.

NOTICE

Printed in the United States of America

Available from:

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price Printed Copy $ __*__ ; Microfiche $4.50

*Pages	NTIS Selling Price
1-25	$7.00
25-50	$8.50
51-75	$10.00
76-100	$11.50
101-125	$13.00
126-150	$14.50
151-175	$16.00
176-200	$17.50
201-225	$19.00
226-250	$20.50
251-275	$22.00
276-300	$23.50
301-325	$25.00
326-350	$26.50
351-375	$28.00
376-400	$29.50
401-425	$31.00
426-450	$32.50
451-475	$34.00
476-500	$35.50
500-525	$37.00
526-550	$38.50
551-575	$40.00
567-600	$41.50

For documents over 600 pages, add $1.50 for each additional 25-page increment.

PPPL--2201
DE85 008708

A ONE MILLIMETER WAVE INTERFEROMETER FOR THE MEASUREMENT OF LINE INTEGRAL ELECTRON DENSITY ON TFTR

P.C. Efthimion, G. Taylor, W. Ernst, M. Goldman,
M. McCarthy, and H. Anderson

Princeton University
Plasma Physics Laboratory
Princeton, New Jersey 08544

N.C. Luhmann
Department of Electrical Engineering
University of California
Los Angeles, California 90024

ABSTRACT

A two-pass interferometer at 285 GHz has been developed to measure the line-integrated electron density on the horizontal midplane of the Toroidal Fusion Test Reactor (TFTR). Presently, the interferometer employs a 2 mW solid state source to supply the launch wave, a 2 mm klystron oscillator, and a harmonic mixer to provide a superheterodyne front end. The transmission system consists of 25 meters of C-band rectangular waveguide, adjustable miter bends, and a spherical mirror in the vacuum vessel with a total round trip transmission loss of 21 dB. The interferometer signal-to-noise ratio is ≥ 50 dB. Utilization of a feed-forward tracking system provides long-term stable operation. The interferometer routinely provides real time feedback control for the gas injection system and a permissive for neutral beam operation.

INTRODUCTION

Electron density is a primary parameter in tokamak plasma physics research. The Tokamak Fusion Test Reactor (TFTR) at Princeton was built to study the behavior of high temperature, $T_e \geq 10$ keV, plasmas with line average densities up to $\bar{n}_e = 2 \times 10^{14} \mathrm{cm}^{-3}$. As well as ohmic heating, neutral beams and major radial adiabatic compression will provide the additional input power required to reach fusion reactor conditions. The 1 mm wavelength TFTR interferometer was designed to provide a two-pass line integral electron density measurement on the horizontal midplane. This orientation allows the density to be measured during major radial compression of the plasma. The interferometer also provides an input signal to the gas feedback control system that regulates the electron density and a threshold density permissive to prevent the neutral beams from firing when the plasma density is too low. A 1 mm wavelength was chosen for several reasons. Reliable 1 watt carcinotrons and 2 mW solid state sources are readily available at this wavelength. The cutoff density of the probing wave frequency, $10^{15} \mathrm{cm}^{-3}$, is more than three times higher than the highest density to be measured. Also, a low-loss oversized waveguide allows remote location of the interferometer to minimize environmental problems, and the interferometer can be made relatively insensitive to vibrations.

The interferometer is required to measure up to 500 fringes with possible power variations of nearly 50 dB during a TFTR plasma pulse. Homodyne systems can only provide a maximum dynamic range of 30 dB. A heterodyne system was therefore designed to allow continuous wave operation of the transmitting source, avoid amplitude modulation problems of swept systems, and reduce noise sidebands with a high (3.7 - 4.2 GHz) Intermediate Frequency (IF). A second harmonic mixer was originally adopted to avoid the use of a more expensive 1 mm wavelength local oscillator source.

INTERFEROMETER DESIGN

A. Microwave Section

Figure 1 shows a schematic diagram of the TFTR interferometer. In order to keep losses to a minimum over the 25 meter transmission path, a WR-187 (C-band) guide was used. The waveguide run consists of straight sections; quasioptical, adjustable, 90° miter H-bends; and a high voltage break. Severe restrictions against mounting the waveguide along the vacuum vessel inner wall precluded the use of single-pass transmission through the plasma, so a two-pass configuration was designed. The two-pass design consists of two open-ended WR-187 waveguides aimed at a stainless steel, spherical surfaced, rectangular mirror with a focal length of 200 cm mounted on the inner vacuum vessel wall. The antenna was mounted on a vacuum flange, side-by-side, with the microwave electric field parallel to the tokamak magnetic field. A fused silica vacuum window was used at the vacuum interface. After the antenna and mirror were aligned with a helium-neon laser, the measured round trip propagation loss inside the vacuum vessel was 6 dB in the absence of plasma. The bends and the waveguide were also aligned with a laser. After alignment the total transmission loss resulting from 25 meters of waveguide, eight bends, high voltage breaks, the vacuum window, and propagation loss through the tokamak, was better than 21 dB.

The design of the antenna and optical system was influenced by constraints imposed by plasma refraction[1] and mechanical stability. Plasma refraction is most serious at high densities ($\gtrsim 10^{14}$ cm^{-3}) and for small plasmas ($\lesssim$ 45 cm) where density gradients are maximum. Measurements made on the effects of tilt of the spherical mirror indicate that deflections of more than 5 milliradians cause a significant reduction in power at the receiving antenna.

The two WR-187 guides were installed parallel to each other along the distance from the vacuum vessel to the data acquisition room. Figure 2 shows schematically the layout of the interferometer microwave and IF sections. The 1 mm source output is tapered to a WR-90 waveguide (X-band) using a low mode conversion Gaussian nonlinear taper to minimize the losses associated with using WR-3 (200-325 GHz) components. The design philosophy was directed towards low-loss quasioptical components,[2] e.g., power splitters, diplexers, E and H bends, and phase shifters, which were fabricated at Princeton.

Initially, we successfully employed a 1 watt carcinotron source that normally operated at power levels of several hundred milliwatts. This provided an excellent signal-to-noise ratio (≥ 90 dB in the last IF stage of the interferometer), but it had a relatively short operation life of typically less than 1000 hours, and also required expensive and complicated high voltage power supplies. Recently, we installed a 95 GHz Gunn oscillator with a varactor diode frequency tripler which provides 2 mW of 285 GHz power, sufficient to meet the design requirement of 50 dB final IF signal-to-noise. This solid state source has now operated over a wide range of plasma conditions. Its frequency stability is superior to the carcinotron and it requires a relatively simple, low voltage, power supply.

RF power from the 1 mm source is fed into a four port power splitter which consists of two 90° H-plane miter bends in a WR-90 guide mounted back-to-back and separated by a membrane consisting of 60 lines/inch electroformed copper mesh on a 0.07 mm mylar tape substrate. A reference path diplexer, with a similar construction to the power splitter, combines the local oscillator from a 2 mm klystron and the 1 mm reference signal. The output of the diplexer is fed to a reference signal mixer via a Gaussian taper. The mesh in the diplexer is reflective to the 2 mm local oscillator signal and is low-loss (~ 0.5 dB) to the 1 mm reference signal. The reference mixer is a commercial Schottky-barrier-diode. Since the mixer is designed for fundamental frequency operation, there is no optimal matching for either the fundamental or second harmonic, so a 40 dB conversion loss results.

The return transmission guide from TFTR tapers into a harmonic mixer mounted in a cross-guide configuration. This device was developed at UCLA by N. Luhmann and is illustrated in Fig. 3. The mixer has a conversion efficiency of 15 dB which allowed us to abandon the carcinotron in favor of a solid state source. The local oscillator klystron can be tuned from 136 - 144 GHz with a 40 milliwatt minimum output power. A WR-8 waveguide is used to distribute the local oscillator to the signal and reference harmonic mixers.

B. Intermediate Frequency (IF) Section

In heterodyne receiver systems the local oscillator is usually locked to the transmitter frequency. However, experience with tokamak operation has shown that electromagnetic interference can make conventional frequency locking techniques unreliable. To overcome this difficulty, a broadband superheterodyne tracking circuit was adopted.[3]

An IF tracking network is used to offset frequency drifts in the transmitter and the local oscillator (LO). A second LO operating at 3.7 GHz is used to down-convert the plasma and reference IF signals to a second IF nominally at 300 MHz. The reference signal still includes any frequency offsets in the transmitter or the 2 mm LO. This is up-converted by mixing with a 500 MHz LO. The up-converted signal is passed through a band-pass filter (800±150 MHz) and a wide-band amplifier to function as an LO for another mixer used to down-convert the plasma signal. A coaxial delay line in the circuit compensates for the differences of signal delay due to the unequal lengths of the transmitter and reference paths. Otherwise, spurious frequency modulation can result in phase errors in the plasma density induced phase shift. In this mixing stage the offsets in the 2 mm LO and the 1 mm transmitter frequency are cancelled leaving only the 500 MHz signal modulated by the density phase shift.

There is an additional down conversion at a third IF operating at 30 MHz. Both reference and phase change signals are processed through phase-lock-loop circuits and a fringe counter.[4] The overall system frequency drift is then determined only by the frequency drift of the final LO, which is a 30 MHz crystal controlled, low-drift oscillator. The effectiveness of the feed-forward tracking technique is illustrated in Fig. 4 where the output of a spectrum analyzer is shown for the 3.7 - 4.2 GHz IF and the 30 MHz IF. The 2-3 MHz frequency modulation in carcinotron output frequency is completely absent in the 30 MHz IF signal.

A self-test facility can introduce a phase change of up to 1024 π radians to simulate fringes, which can be monitored by the data acquisition system.

SYSTEM PERFORMANCE

Figure 5 shows a typical density signal acquired with the 1 mm interferometer on TFTR. The density in this illustration rises to a line integral value of nearly $5 \times 10^{15} \mathrm{cm}^{-2}$. These data were acquired for a plasma with a minor radius of 83 cm, so that line average density was $3 \times 10^{13} \mathrm{cm}^{-3}$. During the evolution of the plasma discharge, "sawteeth" fluctuations (shown enlarged in the inset) can be clearly seen. The interferometer successfully tracks through these and a minor disruption at the end of the discharge. The performance of the gas injection feedback system is shown in Fig. 6. The upper trace shows the programmed line integral density (dashed curve) and the measured density (solid curve). The signal from the interferometer is used to control the gas flow rate into TFTR, shown in the lower trace, to maintain the preprogrammed waveform automatically. The interferometer has now operated daily on TFTR for nearly two years and has provided data for confinement studies.[5]

A 400 MHz fast phase tracking circuit is being tested which will allows operation of the interferometer during periods of fast density fluctuations.

ACKNOWLEDGMENT

This work supported by U.S. DoE Contract No. DE-AC02-76-CHO-3073.

REFERENCES

[1] W.P. Allis, IRE Transactions MTT-9, 79 (1961).

[2] H.J. Butterweck and F.C. de Ronde, Phillips Tech. Rev. 29, 86 (1968).

[3] J. Doane, Rev. Sci. Instrum. 51 (3), 317 (1980).

[4] A.J. Greenberger, Princeton Plasma Physics Laboratory Report PPPL-1466, August 1978.

[5] P.C. Efthimion *et al.*, Phys. Rev. Lett. 52, 1492 (1984).

FIGURE CAPTIONS

Fig. 1. Simplified schematic showing the layout of the interferometer on TFTR. Two C-band guides, run in parallel, carry the transmitted and received signal. The 90° bends are adjustable quasioptical miter H-bends. Final alignment was performed with a Helium-Neon laser.

Fig. 2. Block diagram of the microwave and IF sections in the interferometer. A superheterodyne feed-forward tracking system provides immunity against frequency drift in the 1 mm transmitter and 2 mm local oscillator.

Fig. 3. Photograph of the UCLA harmonic mixer used as the plasma signal mixer in the interferometer. Two micrometer adjustments allow tuning of the mixer for optimum performance. The mixer has a conversion efficiency of 15 dB.

Fig. 4. Frequency stability of the feed-forward tracking IF section is illustrated in these traces obtained on a spectrum analyzer. The upper trace shows the 3.7 - 4.2 GHz IF stability when the interferometer was configured with a carcinotron source, typically variations of 2-3 MHz were measured. However, the 30 MHz IF section (lower trace) shows a stability of better than 10 kHz.

Fig. 5. Typical density signal from the interferometer during a 1.4 MA plasma current discharge on TFTR. Large "sawtooth" oscillations are clearly visible which correlate with electron temperature sawtooth fluctuations. The interferometer tracks through these sawteeth and a minor disruption at the termination of the discharge.

Fig. 6. The upper trace shows the performance of the density feedback system. The dashed curve is the preprogrammed line integral density and the solid curve is the density measured with the 1 mm interferometer. The density signal was used to drive the gas flow rate, shown in the lower trace to maintain the preprogrammed density.

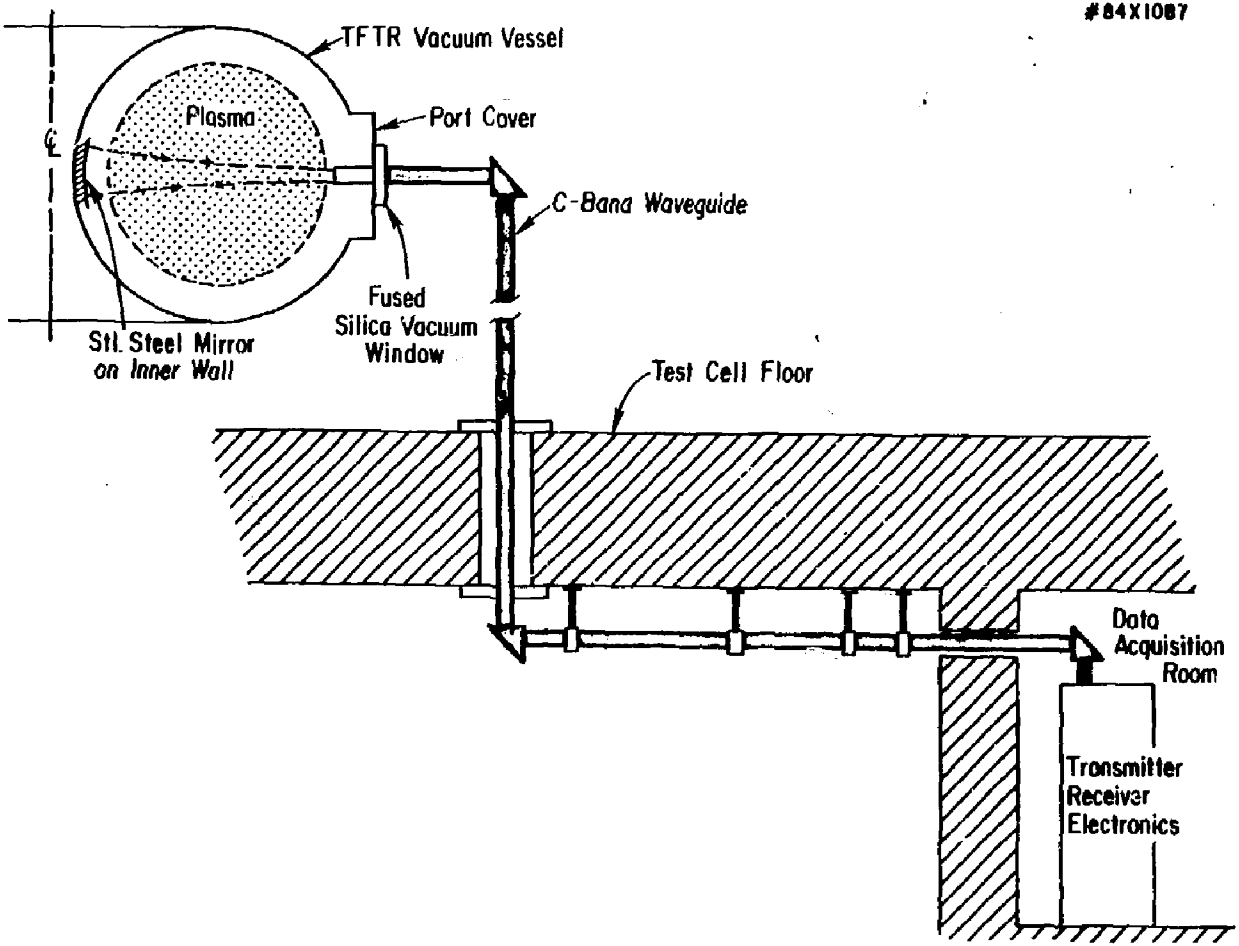

#84X1087
TFTR Vacuum Vessel
Plasma
Port Cover
℄
C-Band Waveguide
Fused Silica Vacuum Window
Stl. Steel Mirror on Inner Wall
Test Cell Floor
Data Acquisition Room
Transmitter Receiver Electronics

Fig. 1

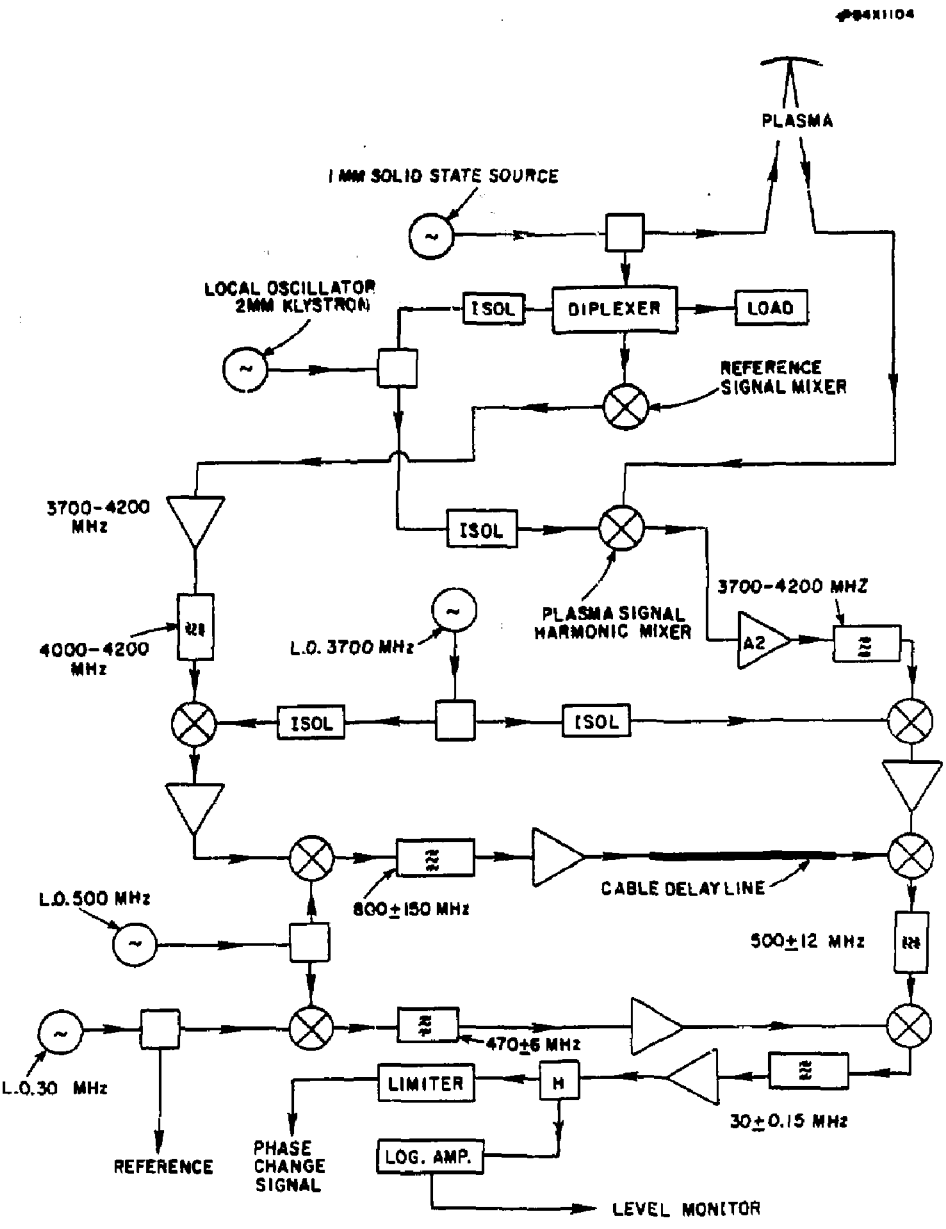

#84X1104
PLASMA
1 MM SOLID STATE SOURCE
LOCAL OSCILLATOR 2MM KLYSTRON
ISOL
DIPLEXER
LOAD
REFERENCE SIGNAL MIXER
3700-4200 MHz
ISOL
PLASMA SIGNAL HARMONIC MIXER
3700-4200 MHZ
4000-4200 MHz
L.O. 3700 MHz
A2
ISOL
ISOL
CABLE DELAY LINE
800±150 MHz
L.O. 500 MHz
500±12 MHz
470±6 MHz
L.O. 30 MHz
LIMITER
H
30±0.15 MHz
REFERENCE
PHASE CHANGE SIGNAL
LOG. AMP.
LEVEL MONITOR

Fig. 2

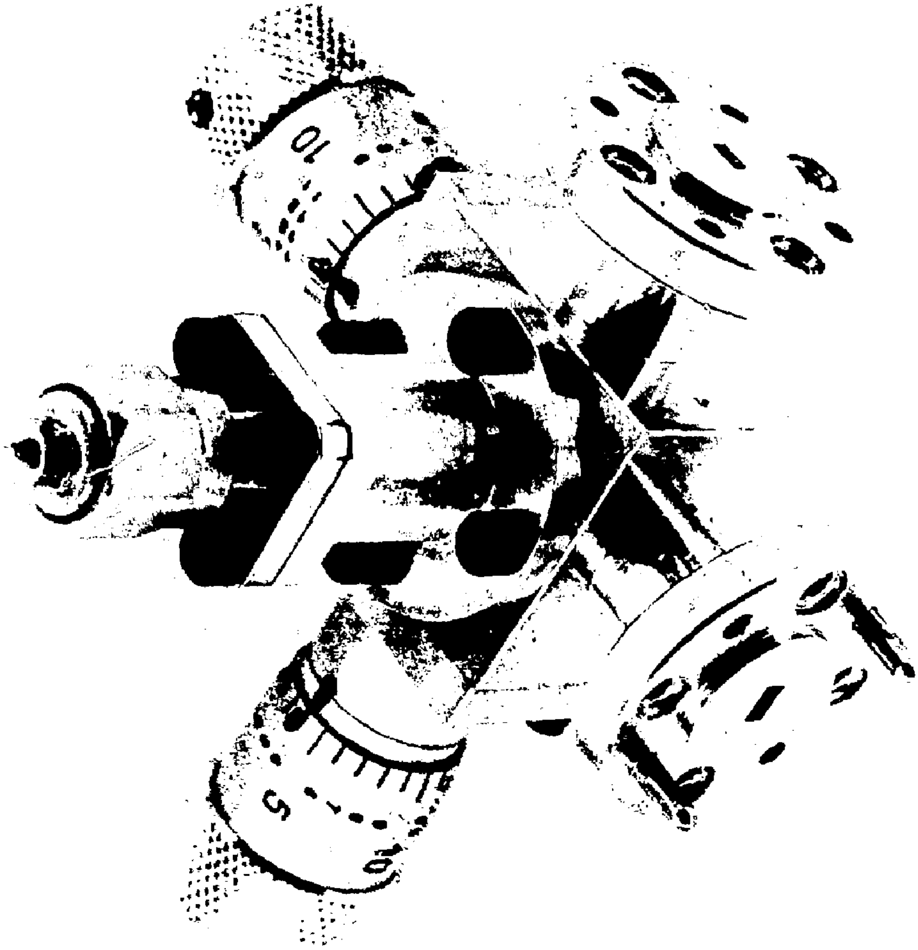
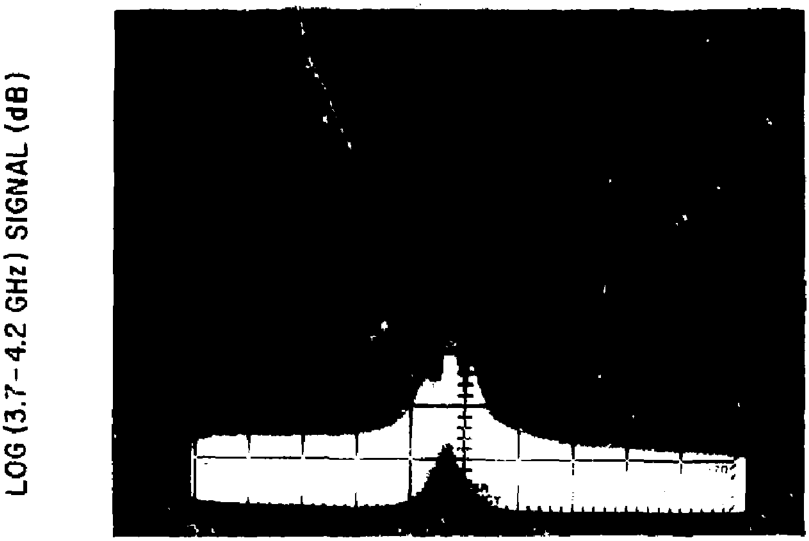
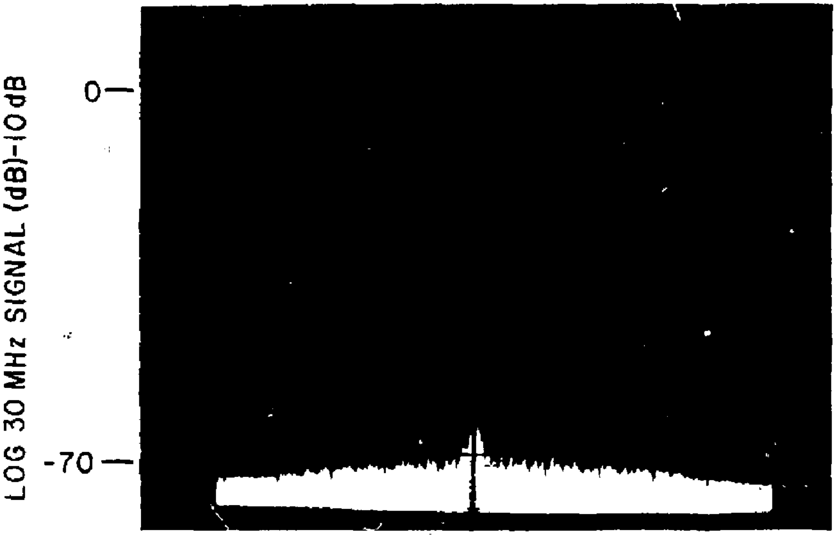


Fig. 3



SWEEP RATE=5 MHz/Div



SWEEP RATE=50 KHz/Div

Fig. 4

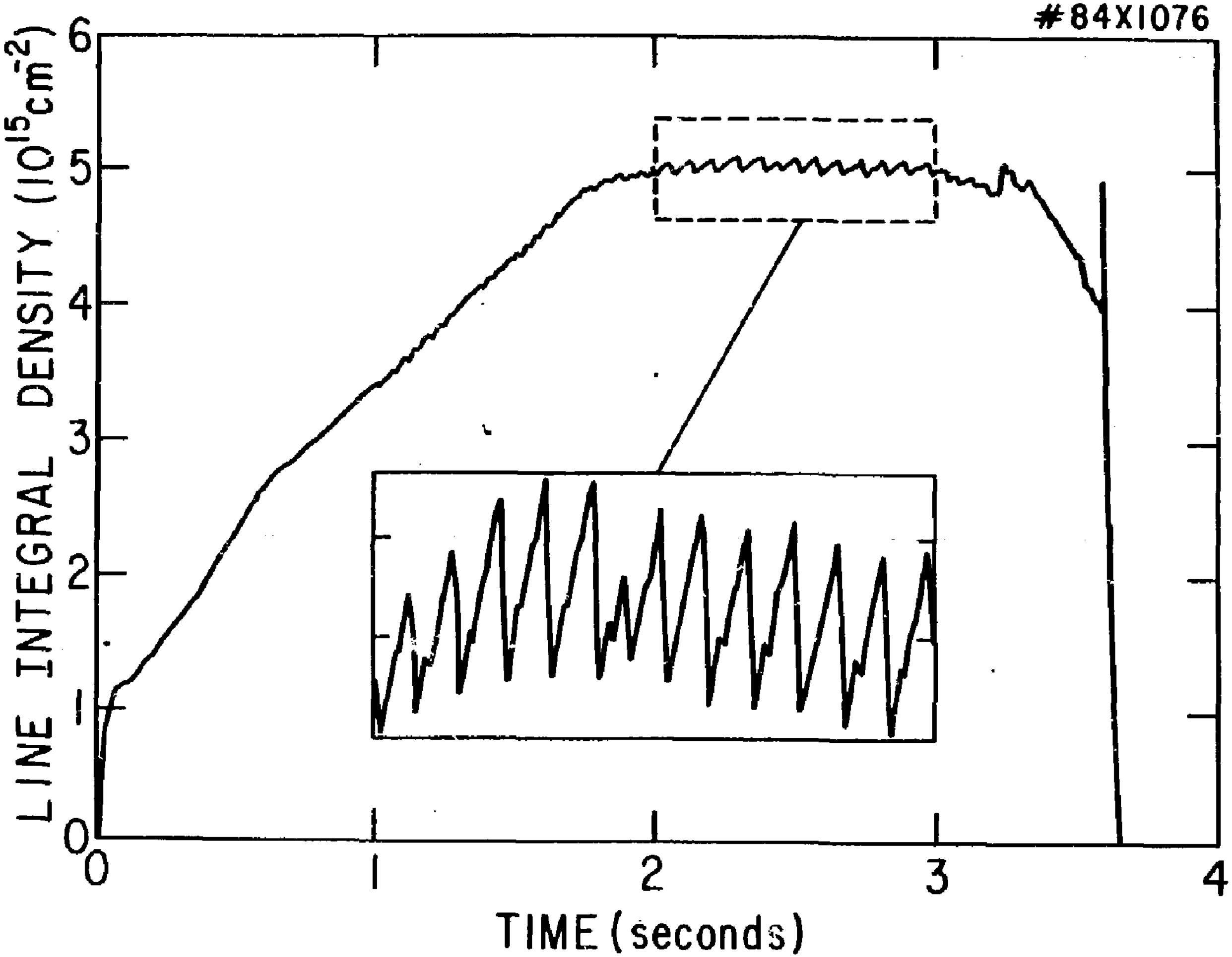

#84X1076
LINE INTEGRAL DENSITY ($10^{15}cm^{-2}$)
0
1
2
3
4
5
6
0
1
2
3
4
TIME (seconds)

Fig. 5

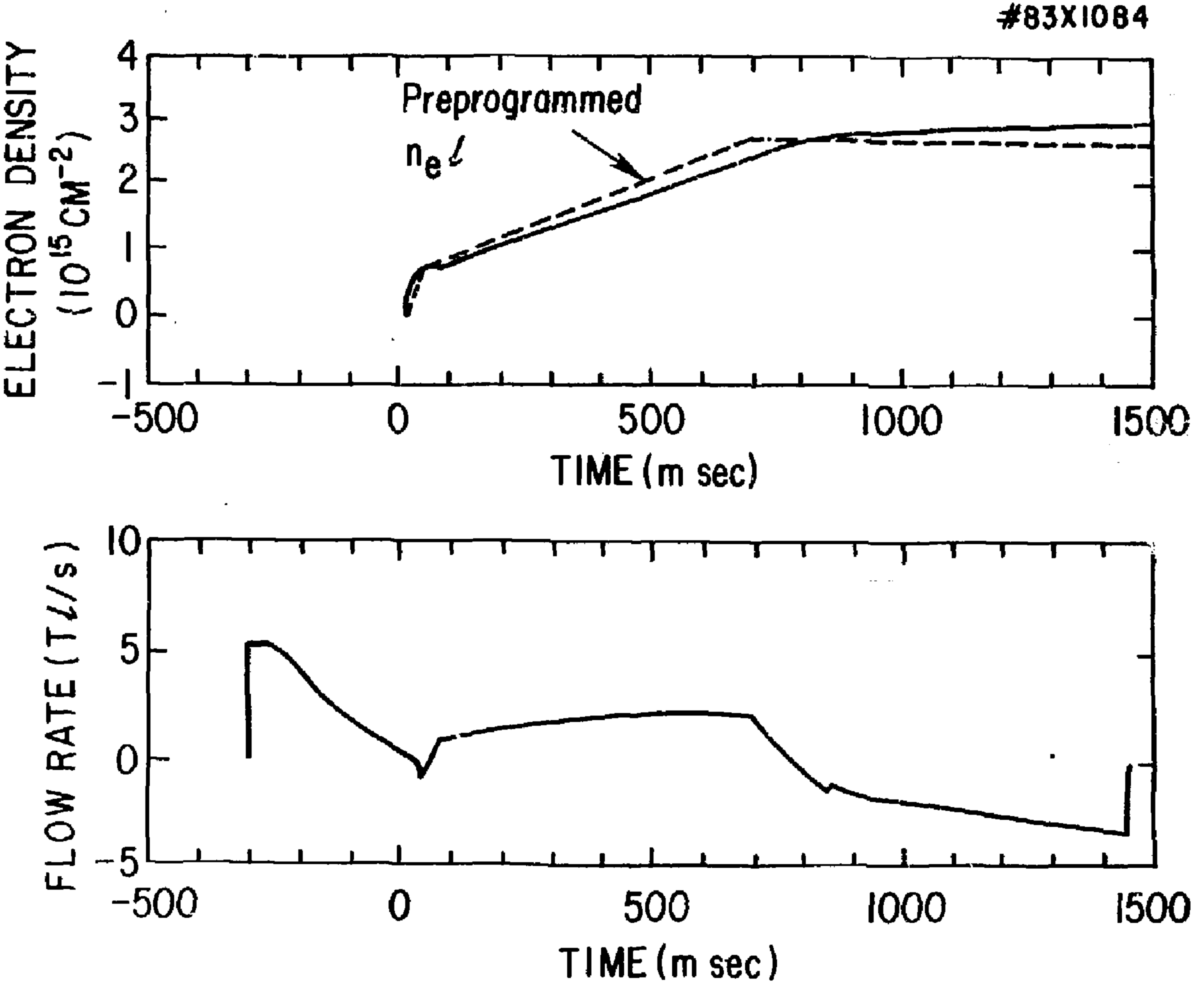

#83X1084
ELECTRON DENSITY (10^{15} CM^{-2})
4
3
2
1
0
-1
Preprogrammed
$n_e \ell$
-500
0
500
1000
1500
TIME (m sec)
FLOW RATE ($T\ell$/s)
10
5
0
-5
-500
0
500
1000
1500
TIME (m sec)

Fig. 6

EXTERNAL DISTRIBUTION IN ADDITION TO UC-20

Plasma Res Lab, Austra 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. Sakanaka, Univ Estadual, BRAZIL
Dr. C.R. James, Univ of Alberta, CANADA
Prof. J. Teichmann, Univ of Montreal, CANADA
Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
Prof. S.R. Sreenivasan, University of Calgary, CANADA
Prof. Tudor W. Johnston, INRS-Energie, CANADA
Dr. Hannes Barnard, Univ British Columbia, CANADA
Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA
Chalk River, Nucl Lab, CANADA
Zhengwu Li, SW Inst Physics, CHINA
Library, Tsing Hua University, CHINA
Librarian, Institute of Physics, CHINA
Inst Plasma Phys, Academia Sinica, CHINA
Dr. Peter Lukac, Komenskeho Univ, CZECHOSLOVAKIA
The Librarian, Culham Laboratory, ENGLAND
Prof. Schatzman, Observatoire de Nice, FRANCE
J. Radet, CEN-BP6, FRANCE
AM Dupas Library, AM Dupas Library, FRANCE
Dr. Tom Mual, Academy Bibliographic, HONG KONG
Preprint Library, Cent Res Inst Phys, HUNGARY
Dr. S.K. Trehan, Panjab University, INDIA
Dr. Indra Mohan Lal Das, Banaras Hindu Univ, INDIA
Dr. L.K. Chavda, South Gujarat Univ, INDIA
Dr. R.K. Chhajlani, Vikram Univ. INDIA
Dr. B. Dasgupta, Saha Inst, INDIA
Dr. P. Kaw, 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 Clelia De Palo, Assoc EURATOM-ENEA, ITALY
Biblioteca, del CNR EURATOM, ITALY
Dr. H. Yamato, Toshiba Res & Dev, JAPAN
Direc. Dept. Lg. Tokamak Dev. JAERI, JAPAN
Prof. Nobuyuki Inoue, 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
Dr. D.I. Choi, Adv. Inst Sci & Tech, KOREA
Tech Info Division, KAERI, KOREA
Bibliotheek, Fom-Inst Voor Plasma, NETHERLANDS
Prof. B.S. Liley, University of Waikato, NEW ZEALAND
Prof. J.A.C. Cabral, Inst Superior Tecn, PORTUGAL
Dr. Octavian Petrus, ALI CUZA University, ROMANIA
Prof. M.A. Hellberg, University of Natal, SO AFRICA
Dr. Johan de Villiers, Plasma Physics, Nucor, 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
Centre de Recherchesen, Ecole Polytech Fed, SWITZERLAND
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.M. Boyd, Univ College N Wales, WALES
Dr. K. Schindler, Ruhr Universitat, W. GERMANY
Nuclear Res Estab, Julich Ltd, W. GERMANY
Librarian, Max-Planck Institut, W. GERMANY
Bibliothek, Inst Plasmaforschung, W. GERMANY
Prof. R.K. Janev, Inst Phys, YUGOSLAVIA