PPPL-2172 I-18432 DR-0656-4 PPPL-2172

UC20-F

CHARGE-EXCHANGE RECOMBINATION SPECTROSCOPY MEASUREMENTS OF ION TEMPERATURE AND PLASMA ROTATION IN PBX

By

K.P. Jaehnig, R.J. Fonck, K. Ida and E.T. Powell

NOVEMBER 1984

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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

PPPL--2172

DE85 003709

CHARGE-EXCHANGE RECOMBINATION SPECTROSCOPY MEASUREMENTS OF ION TEMPERATURE AND PLASMA ROTATION IN PBX

K.P. Jaehnig, R.J. Fonck, K. Ida and E.T. Powell

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08544

The primary diagnostic on PBX for ion temperature measurements is charge-exchange recombination spectroscopy of low Z ions, wherein fast neutrals from the heating neutral beams excite spectral lines from highly excited states ($n > 4$) of hydrogenic O, C, and He via charge-exchange collisions with the respective fully stripped ions. Since the neutral beams on PBX provide relatively low velocity neutrals (i.e., D^0 beams at 44 keV), the best signals are obtained using the near-UV lines of O^{7+}(e.g., $n = 8-7$, 2976 Å). Off-line analysis of the Doppler broadened and shifted line profiles includes non-linear least squares fitting to a model line profile, while a simplified on-line fast analysis code permits between-shot data analysis.

I. INTRODUCTION

The determination of ion temperature and plasma rotation in the PBX tokamak is routinely accomplished via charge-exchange recombination spectroscopy (CXRS).[1,2] The recombination process

$$H^{o}+A^{Z+}\rightarrow H^{+}+A^{(Z-1)+}(n,\ell)$$

involves charge-exchange collisions of fully ionized low Z impurity ions and fast neutrals (44 keV H^{o} or D^{o}), from the heating neutral beam. The resulting hydrogenic ion is in a highly excited ($n > 4$) state, and radiative decay ($\Delta n = 1$) yields spectral lines from the extreme ultraviolet to the visible spectral regions.

Motivation for the use of CXRS for ion temperatures on PBX (a modified form of the PDX tokamak) arises from the need for ion temperature data for the determination of plasma thermal energy content. Other traditional spectroscopic techniques utilize magnetic dipole lines or forbidden transitions in the UV region[3] or resonance lines in the X-ray regime[4]; these lines are not readily measurable at the low electron temperatures ($\lesssim$ 1.5 keV) in PBX. The CXRS technique provides spatially localized information, at the intersection of the spectrometer line-of-sight and the neutral beam, whereas the other techniques are more spatially ambiguous. In addition, the CXRS method requires only one spectral line to provide profile information across the plasma.

While the CXRS technique may utilize a variety of impurity ions (e.g., He^{+} 4686 Å was used on the PDX[1] and Doublet-III[5] tokamaks), it is desirable to utilize an intrinsic impurity such as C or O to avoid perturbations due to impurity injection.

This paper presents the experimental configuration currently in use on the PBX tokamak for the determination of ion temperature and toroidal rotational velocity via the CXRS technique and discusses preliminary results and analysis.

On PBX, the choice of ion species and spectral lines used has been primarily determined by the relatively low D^0 beam energy of ~ 22 keV/amu. At this energy, only the primary beam component has a sufficiently high cross section to get reasonable signal-to-noise ratios for a few candidate lines of O^{7+} and C^{5+} above the air cutoff ($\lambda \gtrsim 2000$ Å). The choice of longer wavelengths, i.e., above the cutoff of optical fibers, is preferred, since this eases the task of optically coupling the spectrometer and the tokamak.

Interference from background radiation of the $\Delta n = 1$ lines emitted from the cool plasma periphery is more severe in C^{5+} than O^{7+} for lines with $\lambda >$ 1000 Å. This intrinsic emission is due somewhat to electron impact excitation of C^{5+} or O^{7+} near the plasma edge but more predominantly to charge-exchange recombination reactions of the fully stripped ions with the background thermal neutrals. The O^{7+} transition at 2976 Å ($n = 8$-7) has been found to provide the best signal-to-noise ratio without interference from other spectral features. A more detailed discussion of the factors influencing the choice of spectral lines for use with the CXRS technique is discussed elsewhere.[1]

II. APPARATUS

The current configuration of the PBX heating neutral beams is shown in Fig. 1. The beam injection angle for the NW and E beams is nearly perpendicular, with tangency radii of 35 cm. The S and SW beams inject tangentially into the plasma, with tangency radii of 130 cm. The primary beam energy is 44 keV and the FWHM horizontal beam width is 16 cm.

A 1.0-m focal length Ebert spectrometer is coupled to the plasma by two quartz lenses, and a plane mirror located in front of a quartz window port. The intersection of the spectrometer sightline and the NW heating beam is varied on a shot-to-shot basis by rotating the plane mirror about its vertical axis. With this arrangement, a scan along the plasma midplane is achieved. An aperture in the optical train defines an f/10 optical system.

Optical access to both the NW perpendicular and the SW tangential beam is desirable, since for a given plasma discharge, a single beam may not be utilized for the entire beam heating period. Therefore, a fiber optically coupled telescope system is installed to view across the SW beam. The output of the fibers is fed directly into the spectrometer entrance slit. At present, only one viewing system can be utilized for a single discharge, since the installation of the fiber system necessarily obscures optical access to the NW beam viewing optics. Future experimental upgrades will alleviate this limitation.

The low wavelength limit of the optics viewing the NW beam is approximately 2500 Å. This is presumably due to the uncoated aluminuum mirrors which are used for beam steering. The fiber optically coupled system cuts off at wavelengths shorter than about 3500 Å, due to both internal coating of the machine window port and the transmission characteristics of the optical fibers used. Other groups working with fiber systems have reported good performance down to the 3000 Å range.[6]

For the results discussed here, the spectrometer was used in third order to measure the CXRS line of O^{7+} at 2976 Å. In this spectral regime, the 1180 grooves/mm grating had a reciprocal dispersion of 2.2 Å/mm. A blocking filter was installed in front of the entrance slit to eliminate spectral interference from overlapping orders of diffraction. Spectrometer wavelength and dispersion calibrations are accomplished with a simple Hg pen lamp.

The output of the spectrometer is coupled to an intensified photodiode array detector (Princeton Applied Research Corporation, Model 1420). Full or partial readout of the intensified portion of the array can be performed with a flexible integration time of 2 to 100 ms per spectral scan. These parameters can be varied on a shot-to-shot basis, being tailored to the spectral line of interest, thus allowing for intrinsic variations of line intensities while accommodating maximum flexibility of time resolution. The CAMAC-based data acquisition system can store 32 K of data per plasma discharge, and is similar to that developed by Fonck, Ramsey, and Yelle,[7] where detailed interfacing of the electronics is described.

The photodiode array has 700 active pixels with a 25-μ center-to-center spacing which are coupled to an 18-mm, proximity-focussed microchannel plate image intensifier. With a 50-μ wide entrance slit, the instrumental profile is detector limited and nearly Lorentzian with a FWHM of 8.2 pixels or 0.45 Å in third order.

III. DATA AND ANALYSIS

At present, the primary spectral lines used in conjunction with the CXRS technique on PBX are the n = 8-7 transition of O^{7+} at 2976 Å, and the n = 4-3 He^+ transition at 4686 Å. The following discussion will focus on data and analysis for the O^{7+} spectral line, since our earlier work describes the He^+ analysis in detail.[1] In general, an ion temperature and plasma rotational velocity are obtained by determining the Doppler broadened width of the profile and measuring the shift of the line center from a reference wavelength.

Sample spectra from three times in a neutral beam heated discharge are shown in Fig. 2. The prominent line observed at 2983.8 Å is from the OIII 2 $p3s\,^1P^0$- $2p3p\,^1D^0$ transition excited by electron collisions at the plasma edge. This line provides a convenient reference wavelength from which to measure the O^{7+} wavelength shift due to plasma rotation. Uncertainty in the wavelength separation of the two lines results in a velocity uncertainty relative to the OIII edge emission of $\leq 0.3 \times 10^6$ cm/sec. A marked intensity rise of 0^{7+} is evident with the onset of the neutral beam heating period, while the amplitude of OIII remains relatively steady throughout. Edge rotation can be measured by perpendicular and tangential observations of the OIII transition at 2983.8 Å. For the spectra shown in Fig. 2, the entrance slit width was 200 μ, rather than the 50-μ width used routinely.

Detailed analysis of the profiles is done with an interactive multiparameter fitting program. A nonlinear least squares fitting routine fits data to a polynomial background and one or more Gaussian profiles, as shown in Fig. 3. To determine a temperature and velocity profile for a beam heated plasma with this approach requires a large investment of computing time and interactive operator effort. In an effort to make the CXRS technique a more responsive real-time diagnostic for general machine operations, an on-line analysis program was developed which produces temperature and velocity time profiles automatically between plasma discharges ($\Delta t \sim 5$ min).

The real-time fitting algorithm is computationally streamlined in the following manner. First, a preset spectral range of interest is examined, and the endpoints of this range are used to derive a crude linear background component for the data. The background is then subtracted from the data set and the mean and standard deviation of this difference data are taken. Since the spectral profile is assumed to be roughly Gaussian, the mean of the distribution represents the line center, and the standard deviation is a measure of the line width. This method provides a reliable initial parameter estimate for further calculations and has proven to be computationally stable with respect to spurious noise-induced spikes in the data which otherwise tend to disrupt the fitting procedure.

With these first estimates for the line center at P_o and line width $P_{1/2}$, the program starts an iterative loop and moves out 2.5 standard deviations on either side of P_o and selects ± 5 pixels about the 2.5σ points to form a subset of 22 pixels from which a more precise linear background is determined by a least squares fit. With this new background, a $\pm 2\sigma$ data set about P_o is now background corrected, and the natural logarithm of the subtracted data is taken. The logarithmic data are then least squares fit to a quadratic polynomial; the weighting function for the fit is taken to be the square of the background-subtracted data. The coefficients of the quadratic polynomial provide new values for P_o and $P_{1/2}$ which are then iteratively fed back to the top of the loop. Convergence takes two iterations and is both rapid and well behaved.

The ion temperature value obtained from $P_{1/2}$ is adjusted to account for the effects of atomic fine structure broadening. This correction is usually on the order of 5% or less.[1] The calculated rotational velocity is geometrically corrected to the true rotational velocity at the neutral beam/spectrometer sightline interaction region.

Uncertainties in the calculated results are typically not dominated by statistical noise in the data, but are more sensitive to the exact range of data which is being fit and other fit-related parameters. Nevertheless, agreement with results from the interactive multiparameter fitting program is within 5%, and the great improvement in calculational speed is obviously advantageous for real-time diagnostic information. A sample output display is shown in Fig. 4.

Radial profiles of temperature and rotation velocity are built up on a shot-to-shot basis by changing the spectrometer sightline across the neutral beam. At the plasma edge, the shape of the O^{7+} line departs from the Gaussian profile observed further into the plasma. The assumption of a single Gaussian fit to derive an ion temperature is no longer valid, and the full multiparameter fitting routine must be used. Observations at the edge, without injection by the NW neutral beam, show excitation of the O^{7+} 2976 Å line. This may be due to electron collisional excitation of hydrogenic O^{7+} or charge exchange of O^{8+} with the high density of thermal neutrals present at the plasma edge. In either case, careful interpretation of spectral profiles from the edge region is necessary. A modulated neutral beam source and a phase-locked detector system would enable discrimination between the charge-exchange signal from the beam interaction region and interfering emission resulting from edge phenomena.

IV. CONCLUSION

Charge-exchange recombination spectroscopy is a simple and reliable diagnostic tool for the determination of ion temperature and plasma rotation. Preliminary work on the PBX tokamak has used a simple optical system and a heating neutral beam to measure temperature and velocity as functions of time and radial position. A simplified on-line fast analysis code provides between-shot data analysis. Work to date has utilized the 2976 Å $n = 8\text{-}7$ transition of O^{7+}, which provides the best signal for PBX plasma discharge parameters.

ACKNOWLEDGMENTS

The authors wish to thank P. Roney for the software development and support required for data acquisition and analysis. Useful conversations with R. Groebner are gratefully acknowledged. This work was supported by the U.S. Department of Energy, Contract No. DE-AC02-76-CHO-3073.

REFERENCES

[1] R.J. Fonck, D.S. Darrow, and K.P. Jaehnig, Phys. Rev. A 29, 3288 (1984).

[2] R.C. Isler and L.E. Murray, Appl. Phys. Lett. 42, 355 (1983).

[3] S. Suckewer et al., Phys. Rev. Lett. 43, 207 (1979);
H. Eubank et al., Phys. Rev. Lett. 43, 270 (1979).

[4] S. von Goeler, M. Bitter et al., Proc. Course Diagnostics for Fusion Reactor Conditions, Vol. 1,(Varenna, Italy, September 6-17, 1982).

[5] R.J. Groebner, N. Brooks, K. Burrell, and L. Rottler, Appl. Phys. Lett. 43, 920 (1983).

[6] R.J. Groebner, private communication (1984).

[7] R.J. Fonck, A.T. Ramsey, and R.V. Yelle, Appl. Optics 21, 2115 (1982).

FIGURE CAPTIONS

Figure 1. Schematic of experimental setup on PBX for CXRS measurements.

Figure 2. Spectral line profiles of O^{7+} 2975.7 Å and O^{2+} 2983.8 Å showing the time evolution of the charge-exchange line. (a) A spectral scan at 380 ms, before neutral beam injection. The O^{2+} line is strong throughout the discharge. (b) At 400 ms with the start of neutral beam injection, the O^{7+} signal is present. (c) At 680 ms, the O^{7+} line has broadened and has shifted towards shorter wavelength.

Figure 3. Spectral line profile of O^{7+} 2975.7 Å line at t = 500 ms into a beam heated plasma discharge. The data are fit to a single Gaussian profile (solid line) and a linear background. The residual differences between the data and the fitted function are shown below the data sample.

Figure 4. Ion temperature and velocity profiles as output by the on-line fast analysis code. Perpendicular beam injection from t = 400 - 700 ms, with tangential beam injection from t = 550 - 700 ms. .

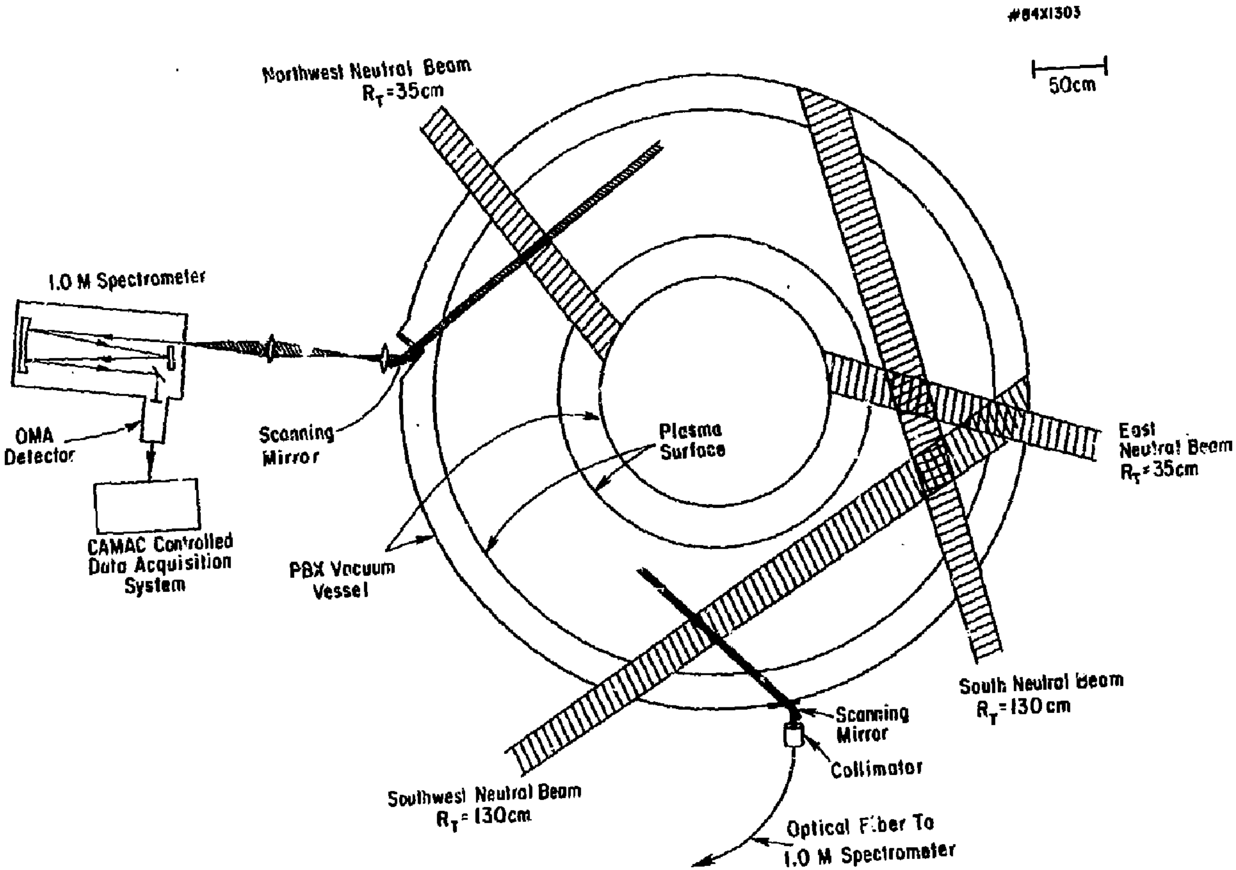
#84X1303
50cm
Northwest Neutral Beam
R_T=35cm
1.0 M Spectrometer
OMA Detector
CAMAC Controlled Data Acquisition System
Scanning Mirror
Plasma Surface
PBX Vacuum Vessel
East Neutral Beam
R_T=35cm
South Neutral Beam
R_T=130 cm
Scanning Mirror
Collimator
Southwest Neutral Beam
R_T=130cm
Optical Fiber To 1.0 M Spectrometer

Figure 1

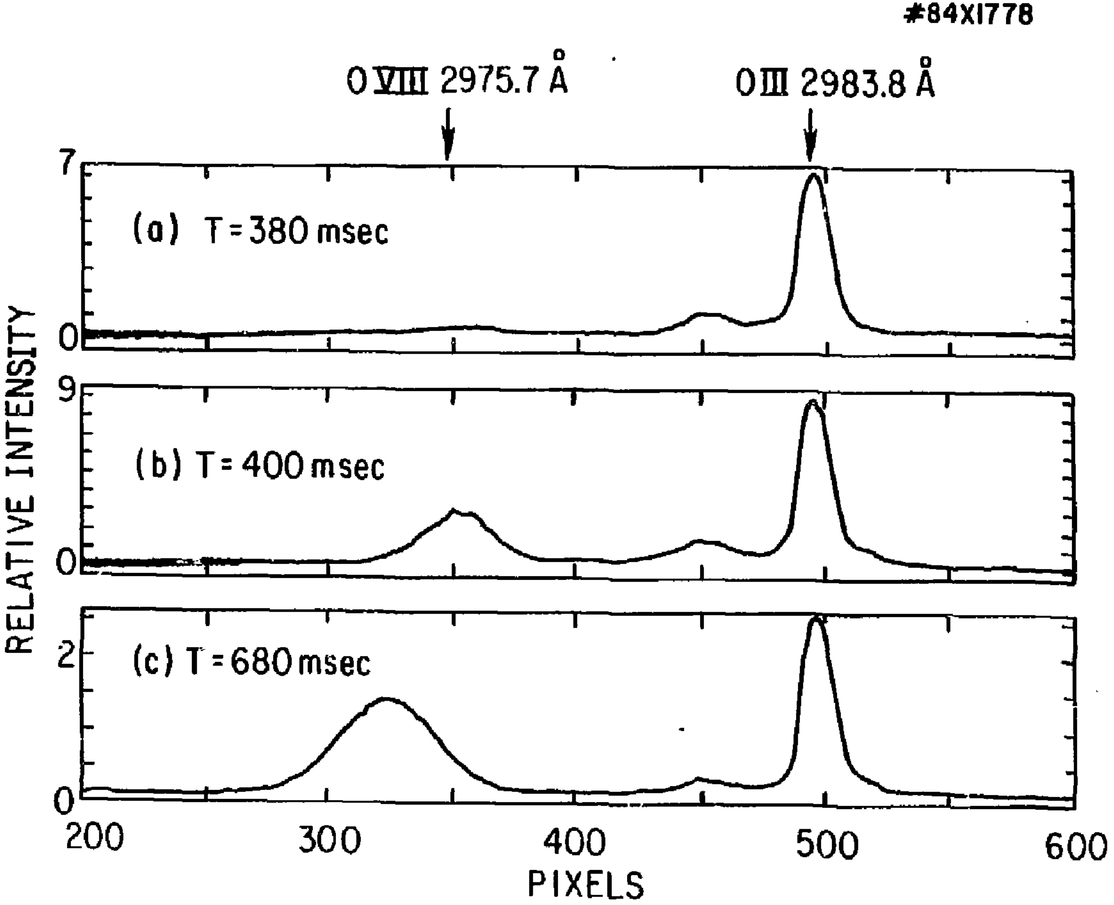
#84X1778
O VIII 2975.7 Å
O III 2983.8 Å
(a) T=380 msec
(b) T=400 msec
(c) T=680 msec
RELATIVE INTENSITY
7
0
9
0
2
0
200
300
400
500
600
PIXELS

Figure 2

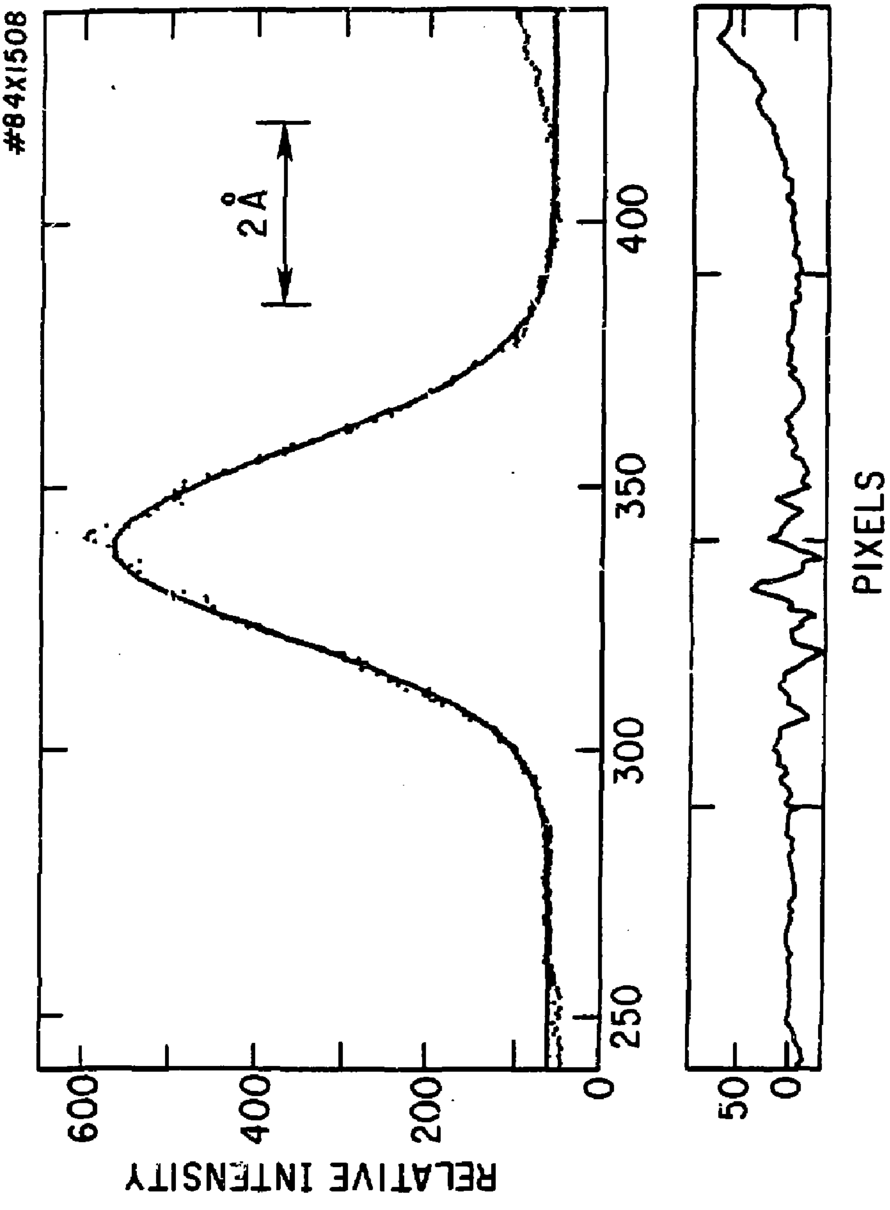
#84X1508
2 Å
RELATIVE INTENSITY
600
400
200
0
250
300
350
400
50
0
PIXELS

Figure 3

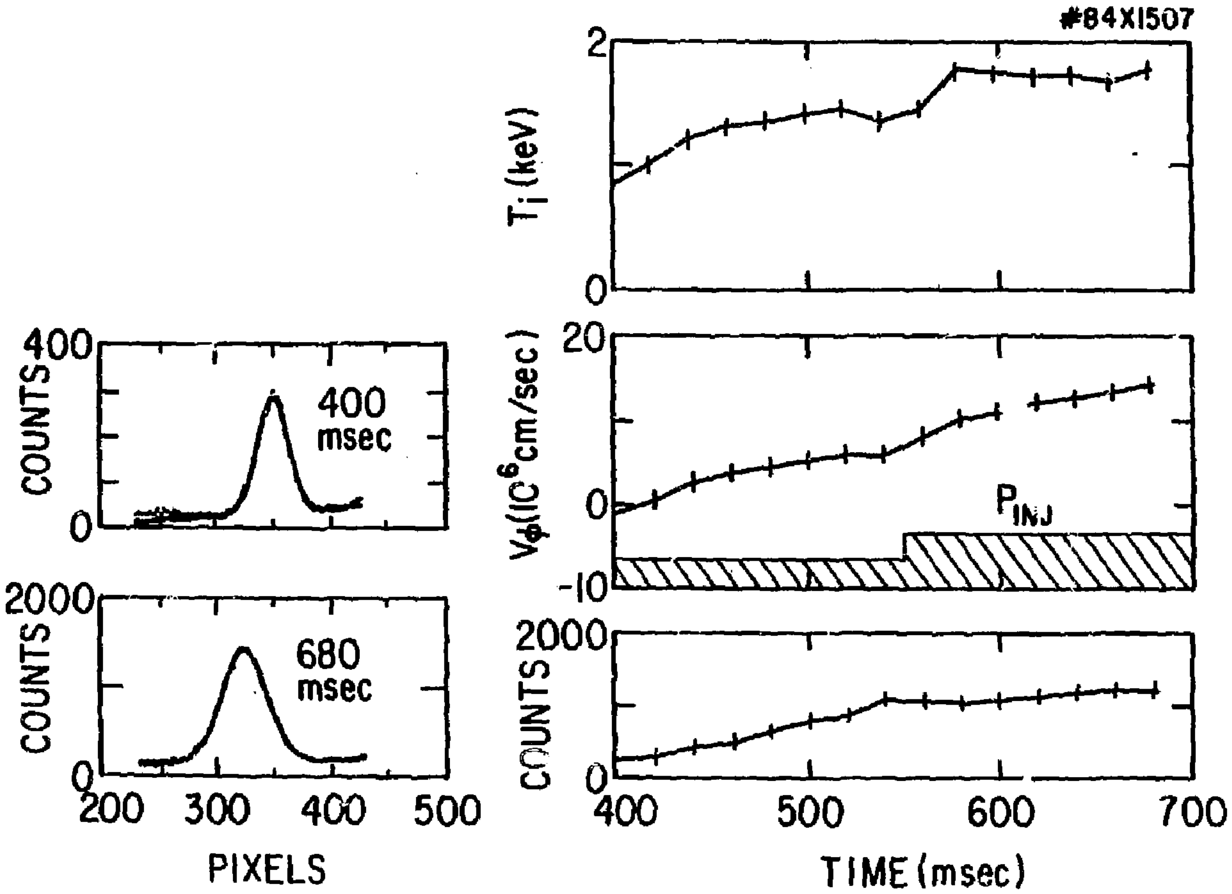
#84X1507
2
0
Ti (keV)
20
0
-10
Vφ(10^6 cm/sec)
P_INJ
2000
0
COUNTS
400
500
600
700
TIME (msec)
400
0
COUNTS
400 msec
2000
0
COUNTS
680 msec
200
300
400
500
PIXELS

Figure 4

EXTERNAL DISTRIBUTION IN ADDITION TO TIC 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
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, Var Ruchi Marg, INDIA
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-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. England, Civdad Universitaria, MEXICO
Bibliotheek, Fom-Inst Voor Plasma, NETHERLANDS
Prof. B.S. Liley, 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. Hellberg, 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 Recherchesen, Ecole Polytech Fed, SWITZERLAND
Dr. W.L. Weise, Nat'l Bur Stand, USA
Dr. W.M. Stacey, Georg Inst Tech, USA
Dr. S.T. Wu, Univ Alabama, USA
Prof. Norman L. Oleson, 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 Universitat, W. GERMANY
Nuclear Res Estab, Julich Ltd, W. GERMANY
Librarian, Max-Planck Institut, W. GERMANY
Dr. H.J. Kaeppler, University Stuttgart, W. GERMANY
Bibliothek, Inst Plasmaforschung, W. GERMANY