Princeton Plasma Physics Laboratory

PPPL-4073 **PPPL-4073**

Parametric Decay during HHFW on NSTX

J.R. Wilson, S. Bernabei, T. Biewer, S. Diem, J. Hosea,
B. LeBlanc, C.K. Phillllips, P. Ryan, and D.W. Swain

May 2005

Prepared for the U.S. Department of Energy under Contract DE-AC02-76CH03073.

PPPL Report Disclaimers

Full Legal Disclaimer

Trademark Disclaimer

PPPL Report Availability

This report is posted on the U.S. Department of Energy's Princeton Plasma Physics Laboratory Publications and Reports web site in Fiscal Year 2005. The home page for PPPL Reports and Publications is: http://www.pppl.gov/pub_report/

Office of Scientific and Technical Information (OSTI):

Available electronically at: http://www.osti.gov/bridge.

Available for a processing fee to U.S. Department of Energy and its contractors, in paper from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062

Telephone: (865) 576-8401

Fax: (865) 576-5728

E-mail: reports@adonis.osti.gov

National Technical Information Service (NTIS):

This report is available for sale to the general public from:

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

Telephone: (800) 553-6847

Fax: (703) 605-6900

Email: orders@ntis.fedworld.gov

Online ordering: http://www.ntis.gov/ordering.htm

Parametric Decay During HHFW on NSTX

J. R. Wilson[1], S. Bernabei[1], T. Biewer[1,3], S. Diem[1], J. Hosea[1,]
B.LeBlanc[1], C. K. Phillips[1], P. Ryan[2], D. W. Swain[2]

[1]*Princeton Plasma Physics Laboratory, Princeton, NJ USA*
[2]*Oak Ridge National Laboratory, Oak Ridge, TN*
[3]*Present address MIT, Cambridge, MA*

Abstract. High Harmonic Fast Wave (HHFW) heating experiments on NSTX have been observed to be accompanied by significant edge ion heating ($T_i >> T_e$). This heating is found to be anisotropic with $T_{perp} > T_{par}$. Simultaneously, coherent oscillations have been detected with an edge Langmuir probe. The oscillations are consistent with parametric decay of the incident fast wave ($\omega > 13\omega_{ci}$) into ion Bernstein waves and an unobserved ion-cyclotron quasi-mode. The observation of anisotropic heating is consistent with Bernstein wave damping and the Bernstein waves should completely damp in the plasma periphery as they propagate toward a cyclotron harmonic resonance. The number of daughter waves is found to increase with rf power and to increase as the incident wave's toroidal wavelength increases. The frequencies of the daughter wave are separated by the edge ion cyclotron frequency. Theoretical calculations of the threshold for this decay in uniform plasma indicate an extremely small value of incident power should be required to drive the instability. While such decays are commonly observed at lower harmonics in conventional ICRF heating scenarios they usually do not involve the loss of significant wave power from the pump wave. On NSTX an estimate of the power loss can be found by calculating the minimum power required to support the edge ion heating (presumed to come from the decay Bernstein wave). This calculation indicates at least 20-30% of the incident rf power ends up as decay waves.

Keywords: RF Heating, Parametric Decay, Spherical Torus

PACS: 52.50.Qt, 52.55.Hc

INTRODUCTION

High Harmonic Fast Wave (HHFW) heating and current drive has been explored on NSTX since its inception. The interest in HHFW is motivated by the need for electron heating and current drive to aid in steady-state non-inductive operation, a crucial component in demonstrating the attractiveness of the spherical tokamak (ST) reactor concept. HHFW was predicted to be an attractive option to meet this need[1], particularly for the high beta plasmas that naturally occur in ST's. As previously reported [2], efficient electron heating and current drive via HHFW have been found on NSTX. Some anomalies were observed in the details of the results, particularly in the dependence on antenna phasing. Faster wave phasings, smaller toroidal mode number, were found to be less effective than expected [3]. With the installation of a new diagnostic to measure the edge ion temperature and plasma rotation [4], a new piece of puzzling evidence was found. The edge ion temperature (over ~ 10 – 15 cm of the minor radius inside the periphery of the plasma), as measured by Doppler broadened line emission from both impurity and majority ion species, was seen to increase during the rf pulse. This temperature increase indicated a Maxwellian heating in the perpendicular component of the ion distribution function. Direct ion heating from the fast wave is not expected at such a high harmonic and low edge temperature. In searching for an explanation of this heating, which was reminiscent of that observed in direct launch Ion Bernstein Wave heating (IBW) [5], an edge probe was installed on NSTX and connected to a spectrum analyzer. Frequency peaks that were consistent with IBW originating via parametric decay were observed. In the following we will review parametric decay theory as applied to NSTX HHFW heating and then describe in detail the experimental observations. The decay mechanism postulated here has been observed in laboratory plasmas [6,7]

PARAMETRIC DECAY THEORY

The theory of parametric decay in the ion cyclotron range of frequencies has been elaborated in a paper by Porkolab [8]. If one examines the Vlasov equation in the presence of a linear rf wave

$$\frac{\partial f}{\partial t} + \vec{v} \bullet \nabla_x f + \frac{q}{m}\left(\frac{\vec{v} \times \vec{B}}{c} + \vec{E} + \vec{E}_0 \cos\omega_0 t\right) \bullet \nabla_v f = 0 \qquad (1)$$

the solutions of the zero order orbit equations are:

$$x_d = -\frac{q}{m}\frac{E_{0\perp}\cos\omega_0 t}{\omega_0^2 - \Omega^2}\ ,\ \ y_d = \frac{\Omega}{\omega_0}\frac{q}{m}\frac{E_{0\perp}\sin\omega_0 t}{\omega_0^2 - \Omega^2}\ ,\ z_d = -\frac{q}{m\omega_0^2}E_{0\parallel}\cos\omega_0 t \qquad (2)$$

As can be seen, the particle drift orbits are mass dependent, therefore the ions and electrons will drift apart creating a zeroeth order charge separation oscillating at the driving frequency ω_0. This charge separation represents a source of free energy that can drive instabilities in the plasma. Looking at the first order perturbation to Eq. 1 the ansatz

$$f_k^{(1)}(\vec{r},\vec{v},t) = F(\vec{r},\vec{u},t)\exp(-i\vec{k} \bullet \vec{x}_d) \qquad (3)$$

is introduced. This assumption is essentially a transformation to the oscillating frame of reference in which there is no induced drift. Also, the driving field is assumed to have infinite wavelength, k_0=0. The first order equation is then

$$\frac{\partial F}{\partial t} + \vec{u} \bullet \nabla_x F + \left(\vec{u} \times \vec{\Omega}\right) \bullet \nabla_u F = -\frac{q}{m}E_k^{(1)} \bullet \left(\nabla_u f_0\right)e^{i\vec{k} \bullet \vec{x}_d} \qquad (4)$$

$\vec{k}\bullet\vec{x}_d$ can be written as $\mu\sin(\omega_0 t-\beta)$ where

$$\mu=\frac{q}{m}\left[\left(\frac{E_{0\parallel}k_z}{\omega_0^2}+\frac{E_{0y}k_y}{\omega_0^2-\Omega^2}\right)^2+\frac{\left(E_{0x}k_y\right)^2\Omega^2}{\left(\omega_0^2-\Omega^2\right)^2\omega_0^2}\right]^{1/2} \qquad (5)$$

and β is a phase angle which is unimportant. The solution to the first order equation (4) can be found by the method of characteristics, i.e.

$$F\left(r,u,t\right)=\frac{q}{m}\int_{-\infty}^{t}dt'\nabla_{x'}\phi\left(r',t'\right)\bullet\nabla_{u'}f_0 e^{i\mu\sin(\omega_0 t-\beta)} \qquad (6)$$

By expanding the exponential in a Bessel series

$$\exp\left[i\mu\sin(\omega_0 t-\beta)\right]=\sum_{n=-\infty}^{\infty}J_n(\mu)\exp\left[in(\omega_0 t-\beta)\right] \qquad (7)$$

the integration of (6) is simplified. The charge density is given by

$$\rho=q\int duF(r,u,t)$$

Because of the oscillating exponential in (6) the charge density also exhibits oscillation with beat frequencies $n\omega_0$. Further, since the electrons and ion charge densities oscillate by different amounts the earlier mentioned charge separation appears. By Fourier transforming, the following expression for the charge density is obtained:

$$\rho_0(k,\omega)=q\int d^3uF(\vec{k},\vec{u},\omega)=-\frac{k^2}{4\pi}\sum_n J_n(\mu)e^{-in\beta}\chi_\sigma(\omega,k)\phi(\omega+n\omega_0,k) \quad (8)$$

where χ is the linear susceptibility. Substituting into Poisson's equation yields

$$\phi(k,\omega)=\frac{4\pi}{k^2}\sum_\sigma\sum_n J_n(-\mu)e^{-in\beta}\rho_\sigma(\omega+n\omega_0,k) \qquad (9)$$

combining (8) and (9) yields the dispersion relation. Clearly, it is an infinite set of equations of order n. Making the simplest non-trivial assumption, for $\mu<1$, we can keep only three modes ω, $(\omega\pm\omega_0)$. Further, assuming that $(\omega, \mathbf{k})$ is a low frequency ion mode and $|\omega\pm\omega_0| >> \omega$ the three coupled equations can be solved to yield [9]

$$\varepsilon(\omega^-,k^-)\varepsilon(\omega,k)=-\frac{1}{8}\left|\mu_i-\mu_e\right|^2\left[(\chi_i-\chi_i^-)(\chi_e-\chi_e^-)\right] \quad (10)$$

where $\varepsilon(\omega,k) = 1+\Sigma\chi_j(\omega,k)$ is the dielectric constant, χ_j is the susceptibility of species j, and μ is the parametric coupling constant defined in equation (5). In the following the side band mode $\omega^- = \omega-\omega_0$, will be assumed to be an ion Bernstein wave and the low frequency mode may be either another Bernstein wave or a quasi-mode (a dissipative mode where $\omega-\Omega\sim k_{\|}v_{ti}$ or $\omega= k_{\|}v_{te}$ which exists only when driven by the pump). Examining μ for the parameters of NSTX, $\omega\sim 13\Omega_i$, and it is clear that the dominant term is the second one, due to the polarization drift

$$\mu_\sigma \sim \frac{eZ_\sigma}{m_\sigma}\frac{E_y^2 k_y^2}{\left(\omega_0^2-\Omega_\sigma^2\right)^2}$$ and if the upper sideband is a resonant IBW wave

$$\varepsilon(\omega^-) = -i(\gamma_0+\gamma_2)\left|\frac{\partial\varepsilon}{\partial\omega_R^-}\right|$$ where $\gamma_2 = \varepsilon_{\mathrm{Im}}(\omega^-)/\left|\partial\varepsilon/\partial\omega_R^-\right|$ is the damping rate at the side band then the dispersion relation (10) yields

$$\left(\gamma_0+\gamma_2\right)\left|\frac{\partial\varepsilon}{\partial\omega_R^-}\right| = \mathrm{Im}\frac{1}{4}\left[\frac{eZ_i}{m_i}\frac{\left(E_y k_y\right)^2}{\left(\omega_0^2-\Omega_i^2\right)^2}\left(\frac{(\chi_e(\omega)-\chi_e(\omega^-))(\chi_i(\omega)-\chi_i(\omega^-))}{\varepsilon(\omega,k)}\right)\right] \quad (11)$$

The electron coupling term has been dropped since $\omega/\Omega_e << 1$. The instability will grow when the right hand side is positive. The first possibility is $\varepsilon(\omega,k) = 0$, corresponding to a resonant lower frequency wave. It is very difficult to match both frequency, $\omega + \omega^- = \omega_0$, and wavenumber, $k + k^- = 0$ for two resonant IBW waves. The other way to get the right hand side large is for $\chi_i(\omega)$ to be large. This can happen when $\omega = n\Omega_I$, where n is an integer. This is the ion-quasi mode, quasi since $\varepsilon(\omega) \neq 0$. The quasi mode has no k dependence so satisfying k matching is trivial. With χ_i large only the electron susceptibilities remain and for $\omega=\Omega_I$ they can be written as

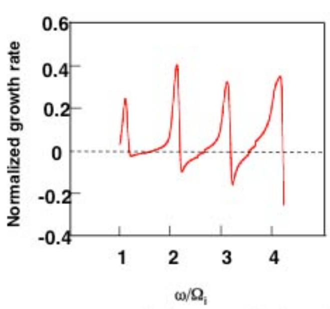

Figure 1. Parametric decay normalized growth rate for NSTX edge plasma

$$\chi_e(\omega)-\chi_e(\omega^-) = i\sqrt{\pi}\omega\frac{\left(1-k_\perp^2\rho_e^2\right)}{k_{\|}v_{te}}$$ which will be positive when $1-(k_\perp\rho_e)^2$ is positive, which is easily satisfied. In fig. 1 we show a numerical evaluation of eq. 11 for NSTX edge parameters, $T_e = T_i = 50$ eV, $n_e = 2 \times 10^{18}$ m^{-3}, B = 2.3 kG, $k_{\|}= \Omega_i/0.7v_{te}$, $f_0 = 30$ MHz and an assumed $E_y = 1$ statvolt/cm. This value of $k_{\|}$ was found to maximize the growth rate at $\omega=\Omega_i$. Different values of $k_{\|}$ maximize the growth rate at the harmonics. The first four harmonics are seen to be unstable for NSTX parameters.

EXPERIMENTAL RESULTS FROM NSTX

The NSTX HHFW system has been described previously [10]. A Langmuir probe was inserted between two of the antenna modules and is placed in the scrape-off plasma in the shadow of the rf protection tiles. The probe was connected via a high frequency fiber optic link to a spectrum analyzer. A filter is placed in-line to attenuate the 30 MHz rf by ~30 dB in order to protect the analyzer. The spectrum analyzer was swept in frequency during the rf pulse. A typical spectrum obtained during HHFW heating on NSTX is shown in fig. 2.

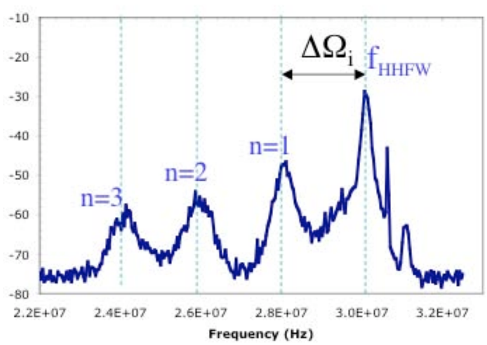

Figure 2. Frequency spectrum from Langmuir probe

Three lower sidebands are clearly seen. The frequency separation between peaks corresponds to the edge ion cyclotron frequency. When the toroidal magnetic field was lowered from 4.5 kG to 3.0 kG the frequency separation decreased as expected if the side bands for IBW decay waves. The number of sidebands is found to increase with applied rf power; for example in He discharges with $k_T = 14\ m^{-1}$, the second peak appears for powers greater than 0.65 MW and the third for powers greater than 1.3 MW. At fixed rf power the number of side bands increases with decreasing toroidal wave number applied to the HHFW antenna, suggesting that the fast wave electric field in the surface of the plasma increases with the launched wavelength. A side band above the pump frequency is occasionally seen at the highest applied rf power levels.

The edge ion temperature measurement is obtained from toroidal and poloidal viewing arrays of the Edge Rotation Diagnostic (ERD), that measures the Doppler broadened emission from both HeI and CIII ions [4]. By projecting these views onto the perpendicular and parallel directions a bi-Maxwellian temperature is found as shown in fig. 3 for helium ions. The perpendicular temperature increases strongly with rf power while the parallel temperature remains close to the local electron temperature. This perpendicular ion temperature increase is observed in the outer, ~10-15 cm, region of the plasma [11].

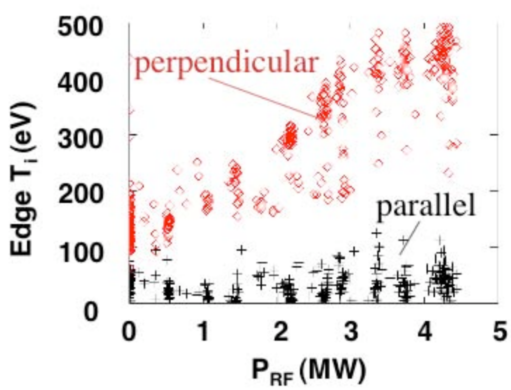

Figure 3 Perpendicular and Parallel Edge ion temperature as a function of rf power

DISCUSSION

The probe spectra indicate the presence of IBW waves in the NSTX edge plasmas. Detection of decay peaks is not un-common in ICRF experiments [12-14]. Only in the case of direct Bernstein wave excitation [13] has it been inferred that significant amounts of power are involved. By solving the IBW dispersion relation for the observed frequencies it is possible to predict where the IBW power will be deposited in the plasma. The IBW wave is predicted to propagate inward until it reaches a cyclotron harmonic where all of the power will be damped. For NSTX this means that the heating should take place in the outer ~10 cm of the plasma in agreement with the ERD observations. The power in the low frequency quasi-mode is locally damped since the mode is non-propagating but, since the partitioning of power between the two side bands is proportional to their frequency, less than ten percent of the decay power is in the quasi-mode. The IBW wave deposits its energy into the low energy ($<v_{ti}$) part of the ion distribution function, hence the distribution function is expected to remain essentially Maxwellian. The IBW wave heats the perpendicular part of the ion distribution function, so a bi-Maxwellian response can be expected. This was seen in earlier direct IBW experiments [9] and, again, is in agreement with the ERD measurement. It is nearly impossible to get an estimate of the power lost into decay waves from the probe measurements; an absolute calibration of the probe response would be required the probe would need to be scanned everywhere in the edge plasma. Therefore, in order to get an estimate of the amount of rf power that is being channeled into the decay waves, the following ansatz is made: all the decay power flows to the ions and the ions then lose all their energy to the cooler electrons via collisions and the electrons lose all of their energy out of the plasma in a time short compared to the ion relaxation time (in these plasmas this time is of order 1 ms). By

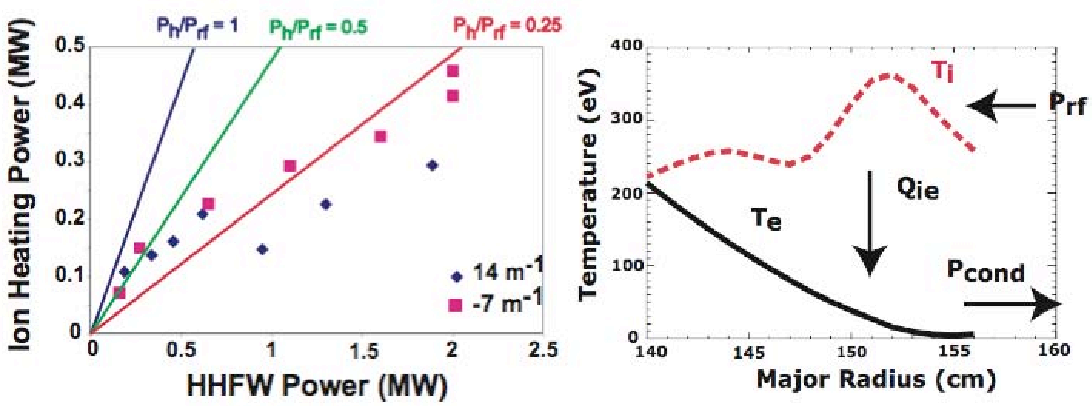

Figure 4. Rf power going into edge ion heating (a) Ion heating power for two antenna phasings as a function of rf power. (b) Power is calculated by integrating Q_{ie} versus radius and assuming power flows as in figure.

this ansatz an estimate of any one of these processes yields a value for all three. Since the collisional power transfer from the ions to electrons:

$$Q_{ie}(r) = \frac{3m_e}{m_i}\frac{n(r)k_B}{\tau_e}(T_i(r) - T_e(r)) \qquad (12)$$

where $\tau_e = \frac{3\sqrt{m_e}(k_B T_e)^{3/2}}{4\sqrt{2\pi}n_e \Lambda e^4}$ is the collisional relaxation time, can be calculated knowing only the radial dependence of the temperature difference and density, it is the easiest of the three to obtain. In fig. 4 we show sample temperature profiles and values of the integral of $Q_{ie}(r)$ over the outer part of the plasma where T_i exceeds T_e for helium plasmas.

It can be seen that at high power levels as much as 25% of the applied rf is showing up in edge heating power. The deviation from a straight line fit in fig4a may be indicative of either an overestimate of the edge heating power at low applied power levels due to using the full density in the calculation or an underestimate at high values of the applied heating power if some of the edge ion energy leaves the plasma directly without transferring to the electrons. To some extent the later effect must be occurring since the ERD measurements also indicate a change in the edge rotation consistent with an edge electric field that would be produced from ions being lost directly from the edge.

SUMMARY

Heating of the perpendicular component of the ion distribution function for the outer part of the NSTX plasma has been observed during HHFW heating and current drive experiments. An interpretation in terms of parametric decay of the incident fast wave into ion Bernstein waves and an ion-quasi mode is presented. Frequency components consistent with IBW are observed on a spectrum analyzer connected to a langmuir probe inserted in the scrap-off plasma. The theory is presented and a low threshold in power is calculated for NSTX parameters. The ion Bernstein wave is expected to damp in the outer 10-15 cm of the plasma radius and heat the ions perpendicular component in agreement with the experimental observations.

ACKNOWLEDGMENTS

This work supported by DOE Contract No. DE-AC02-76CH03073.

REFERENCES

1. Ono, M., “High harmonic fast waves in high beta plasmas”, *Physics of Plasmas* **2**, 4075 (1995).
2. Wilson, J. R. *Physics of Plasmas* **10**, 1733 (2003).
3. Hosea, J.C. this conference
4.. Biewer, T. M. Bell, R., Feder, R. et al. *Rev. Sci. Instrum.* **75**, 650 (2004).
5. Ono, M. et al. *Phys. Rev. Lett.* **60**, 294 (1988).

6. Ono, M. Porkolab, M. and Chang, R.P.H., *Phys. Rev. Lett.* **38**, 962 (1977).
7. Skiff, F. Ono, M., and Wong, K.L., *Physics of Fluids*, **27**, 1051 (1984).
8. Porkolab, M., *"Symposium on Plasma Heating and Injection"* Varenna Italy 1972.
9. Porkolab, M., *Fusion Eng. Design* **12**, 93 (1990).
10. Ryan, P. M., et al., *Fusion Engineering and Design* **56-57**, 569-573 (2001).
11. Biewer, T. M. et al. *Physics of Plasmas* **12**, 056108 (2005)
12. Nieuwenhove, R van, et al., *Nuclear Fusion* **28**, 1603 (1988).
13. Pinsker, R. I., et al. *Radio Frequency Power in Plasmas,* 314 (1989).
14. Rost, J. C. et al., *Physics of Plasmas,* **9**, 1262 (2003).

External Distribution

Plasma Research Laboratory, Australian National University, Australia
Professor I.R. Jones, Flinders University, Australia
Professor João Canalle, Instituto de Fisica DEQ/IF - UERJ, Brazil
Mr. Gerson O. Ludwig, Instituto Nacional de Pesquisas, Brazil
Dr. P.H. Sakanaka, Instituto Fisica, Brazil
The Librarian, Culham Science Center, England
Mrs. S.A. Hutchinson, JET Library, England
Professor M.N. Bussac, Ecole Polytechnique, France
Librarian, Max-Planck-Institut für Plasmaphysik, Germany
Jolan Moldvai, Reports Library, Hungarian Academy of Sciences, Central Research Institute for Physics, Hungary
Dr. P. Kaw, Institute for Plasma Research, India
Ms. P.J. Pathak, Librarian, Institute for Plasma Research, India
Dr. Pandji Triadyaksa, Fakultas MIPA Universitas Diponegoro, Indonesia
Professor Sami Cuperman, Plasma Physics Group, Tel Aviv University, Israel
Ms. Clelia De Palo, Associazione EURATOM-ENEA, Italy
Dr. G. Grosso, Instituto di Fisica del Plasma, Italy
Librarian, Naka Fusion Research Establishment, JAERI, Japan
Library, Laboratory for Complex Energy Processes, Institute for Advanced Study, Kyoto University, Japan
Research Information Center, National Institute for Fusion Science, Japan
Dr. O. Mitarai, Kyushu Tokai University, Japan
Mr. Adefila Olumide, Ilorin, Kwara State, Nigeria
Dr. Jiangang Li, Institute of Plasma Physics, Chinese Academy of Sciences, People's Republic of China
Professor Yuping Huo, School of Physical Science and Technology, People's Republic of China
Library, Academia Sinica, Institute of Plasma Physics, People's Republic of China
Librarian, Institute of Physics, Chinese Academy of Sciences, People's Republic of China
Dr. S. Mirnov, TRINITI, Troitsk, Russian Federation, Russia
Dr. V.S. Strelkov, Kurchatov Institute, Russian Federation, Russia
Kazi Firoz, UPJS, Kosice, Slovakia
Professor Peter Lukac, Katedra Fyziky Plazmy MFF UK, Mlynska dolina F-2, Komenskeho Univerzita, SK-842 15 Bratislava, Slovakia
Dr. G.S. Lee, Korea Basic Science Institute, South Korea
Dr. Rasulkhozha S. Sharafiddinov, Theoretical Physics Division, Insitute of Nuclear Physics, Uzbekistan
Institute for Plasma Research, University of Maryland, USA
Librarian, Fusion Energy Division, Oak Ridge National Laboratory, USA
Librarian, Institute of Fusion Studies, University of Texas, USA
Librarian, Magnetic Fusion Program, Lawrence Livermore National Laboratory, USA
Library, General Atomics, USA
Plasma Physics Group, Fusion Energy Research Program, University of California at San Diego, USA
Plasma Physics Library, Columbia University, USA
Alkesh Punjabi, Center for Fusion Research and Training, Hampton University, USA
Dr. W.M. Stacey, Fusion Research Center, Georgia Institute of Technology, USA
Director, Research Division, OFES, Washington, D.C. 20585-1290

The Princeton Plasma Physics Laboratory is operated
by Princeton University under contract
with the U.S. Department of Energy.

Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
Internet Address: http://www.pppl.gov