PPPL--2583

DE89 006877

Ion Bernstein Wave Heating on the Compact Ignition Tokamak (CIT)

D. W. Ignat and M. Ono

Plasma Physics Laboratory, Princeton University

Princeton, New Jersey

Abstract: In the present plan, CIT is to be heated by power in the ion cyclotron range of frequencies (ICRF), and electron cyclotron heating (ECH) may be used if suitable rf sources can be developed. We consider the option of ion Bernstein wave heating (IBWH). The key points are that a simple vacuum waveguide launcher can be well-removed from high fluxes of heat and particles and that the development of a suitable source is straightforward. A practical point is that an IBWH waveguide launcher, including transition from coaxial power feeds, fits inside the shield wall surrounding CIT. To confirm IBWH as an option for CIT, experiments are needed on a shaped, H-mode plasma at high power. Successful experiments should be followed by a tube development program to allow CIT heating at 200 - 275 MHz.

1 Introduction

The ion Bernstein wave can deposit energy into thermal ions at several harmonics of the ion cyclotron frequency. At the edge of the plasma, the launched wave is an electrostatic electron plasma wave which propagates if the electron plasma frequency is above the wave frequency. Resonance with a unique component of a D-T plasma can be arranged by choosing the fifth harmonic of tritium, yielding a frequency f[MHz] = 25 B[Tesla]. For CIT at full parameters (10 to 11 Tesla), the frequency becomes 250 - 275 MHz, sufficiently high for a waveguide to fit into a port with the long dimension vertical, as required for proper coupling.

At a reduced field of 7 Tesla the fifth harmonic of deuterium can be used in a non-tritium plasma with a 250 MHz frequency. A 200 MHz frequency heats the fourth harmonic of deuterium without being affected by the tritium resonances.

Experimental results on PLT at the 0.65 MW level show good heating, *i.e.*, 6 eV/kW normalized at $\bar{n}$ of 10^{13} cm^{-3}, including a reduction in recycling and a reduction in the level of fluctuations as inferred from microwave scattering.

Experiments now planned on PBX-M, Alcator C-Modification, Doublet III-D, and FT-U should elucidate the ability of IBW to heat at high power, on noncircular plasmas, and with waveguides.

2 Frequency and Waveguide Considerations

From the point of view of experimental implementation, IBWH is especially interesting for modern tokamaks. The absorption takes place at low to medium harmonics of the ion cyclotron frequency. (Absorption at high harmonics is called lower hybrid mode conversion, and is a different discipline of plasma heating.) At low harmonics coil-style antennas with rf sources already built for ICRF experiments can yield data on IBWH with minimum expense. At medium harmonics the frequency is high enough that waveguide couplers can fit into the vacuum chamber.

To choose an appropriate harmonic consider Figure 1, where we plot resonant frequency versus magnetic field for the first several possible hydrogenic species and harmonics. Each line is broken in two halves, representing the high field (10 T) and reduced field (7 T) operation of CIT. The 11 Tesla possibility for operating CIT is not indicated to avoid unneccessary confusion in this diagram. The high field portion extends from peak field at 10 T down to 8.2 T, which represents the total field at the large major radius edge of the plasma. The poloidal contribution to the total field must be taken into account at the edge, as well as the shift of the plasma center outwards. The desired situation is to choose a frequency which heats one specie at one harmonic at the center, without having some other hydrogenic resonance on the low field approach to the center. For example, look at the fifth harmonic of tritium which resonates with 250 MHz *in the center at 10 T; the 250 MHz wave misses resonating* with the sixth tritium harmonic (= fourth deuterium = second protium) as it enters from the low field side. Therefore, the fifth harmonic of tritium is a suitable resonance.

On the other hand, the third deuterium harmonic is not suitable because of the presence of the fifth tritium harmonic on the low field side; likewise, the fourth tritium harmonic is not suitable because of the presence of the third deuterium harmonic on the low field side.

Now consider operation at reduced field, specifically 7 T. Tritium resonances are shown dashed since the tritium probably would not be present in low field discharges. A possible choice is the fourth deuterium harmonic (= second protium) at 200 MHz or the fifth deuterium harmonic at 250 MHz. The resonance for the fourth deuterium harmonic is unaffected by tritium which might be in the plasma, whereas the fifth deuterium harmonic is not practical if tritium is present.

The height of the ports in CIT is about 1 m. A waveguide near cutoff supports a frequency $f = 3 \cdot 10^8$ (m/sec)/(2 · 1 m) = 150 MHz. Therefore, IBWH can be launched by waveguide into CIT at full field and also at reduced field.

Waveguides with a broad dimension of 1 m launch the power at the plasma, but do not have to carry the power into the tokamak area. Instead, coaxial transmission of power is desirable from the rf source to the coupling structure at the plasma.

Figure 2 illustrates, with a scale drawing, a top view of a possible installation. Four coaxial lines pass through a shield at the bottom of the drawing, and couple power into four waveguides. The waveguides taper in the narrow dimension at the entrance to a port flange, but the broad dimension of the waveguide remains the same. The transmission continues without further transition to the plasma. Figure 3 shows a side view of the same installation.

Power flow into a port should be similar to the case of ion cyclotron heating, about 3 MW or more. This represents about 1 kW/cm^2.

3 Coupling of Waves to Plasma and Plasma to Waveguide

The ion Bernstein wave propagates at densities such that the electron plasma frequency is above the excitation frequency. Therefore, a coupler should be placed close to a density of $5 \cdot 10^8$ / cm^3. Some coupling calculations indicate that best results are obtained for a density ten times this, so for the sake of discussion, assume that the waveguide aperture is in plasma of $1 \cdot 10^{10}$ /cm^3 density. At such a density, the plasma thermal loading is small, in the range of a kilowatt per square meter.

This simple calculation needs to be enhanced by results from a coupling code, including expected edge density profiles, and analysis of the heat fluxes. Issues of $k_\parallel$ spectrum, pondermotive effects, field strengths, etc. need study also.

Another good coupling regime occurs at higher aperture density — $n_r \approx 10^{12}$ cm^{-3} — where direct excitation takes place ($f \leq f_{pi}$). Since the CIT scrape-off density profile is not known precisely, this additional coupling regime offers flexibility to the IBWH waveguide coupling. Of course, the thermal loading on the coupler increases as the density rises.

Because of the low density required for coupling, IBWH should be compatible with an H-mode plasma.

4 Previous Experimental Results

The IBW concept was established at low power on ACT-1 at PPPL, and then moved to a tokamak experiment on JIPPT-IIU in Nagoya, Japan. In terms of power and heating, the most successful results were on PLT, where ion temperature was raised from 0.5 keV to 2.0 keV with 500 kW of power. Scaling studies of minority heating and 3/2 harmonic heating show 6 eV·kW/10^{13}·cm^{-3} over the range 0.1 MW to 0.7 MW. Other interesting aspects of the work on PLT are a possible decrease in edge turbulence and an increase in particle confinement associated with IBWH.[2]

Experiments at the 180 kW level were carried out on Alcator C. Heating and improved particle confinement were found, consistent with the PLT results.

5 Experiments Needed in the Near Term

Experiments are planned on PBX-M at 2-4 MW and D-III-D at 2 MW with induction loop antennas in the period 1989-1990. In these experiments, IBWH in diverted, shaped and H-mode plasmas at high power will be investigated. Waveguide experiments with 450 MHz on FT-U at 1 MW are planned for 1990 and onward. The FT-U IBWH experiment offers for the first time a capability to launch ion Bernstein waves via a CIT-relevant waveguide launcher. In theory, the coupling physics of a waveguide IBWH launcher is simpler than that of a loop antenna with Faraday shields. In practice, the absence of a loop and Faraday shield from the plasma region can be expected to reduce operational problems, such as generating impurities, increasing recycling, and breakdown near the antenna. Performance on a waveguide launcher compared to a loop antenna with Faraday shields is an important future topic for the IBWH experiments.

6 Plan for IBWH on CIT

CIT can use IBWH without significant modification to ports and floor space. Power in the range 200-300 MHz can be provided after a four-year lead time to modify the existing Klystrode device of Varian Associates with support from CIT for non-recurring engineering ($1000K), and install the rf source.

The best strategy for CIT is to encourage the planned experiments on PBX-M and FT-U, while watching progress on the ICRF and ECRF physics and technology for the mainline CIT program. A decision can be made in 1992-3 to transpose some heating power to the IBWH.

Acknowledgements

This work was funded by the United States Department of Energy, Office of Fusion Energy, under contract DE-AC02-76-CHO-3073, and was encouraged by H. P. Furth and J. A. Schmidt. This report is adapted from CIT Document AA-881018-PPL-04.

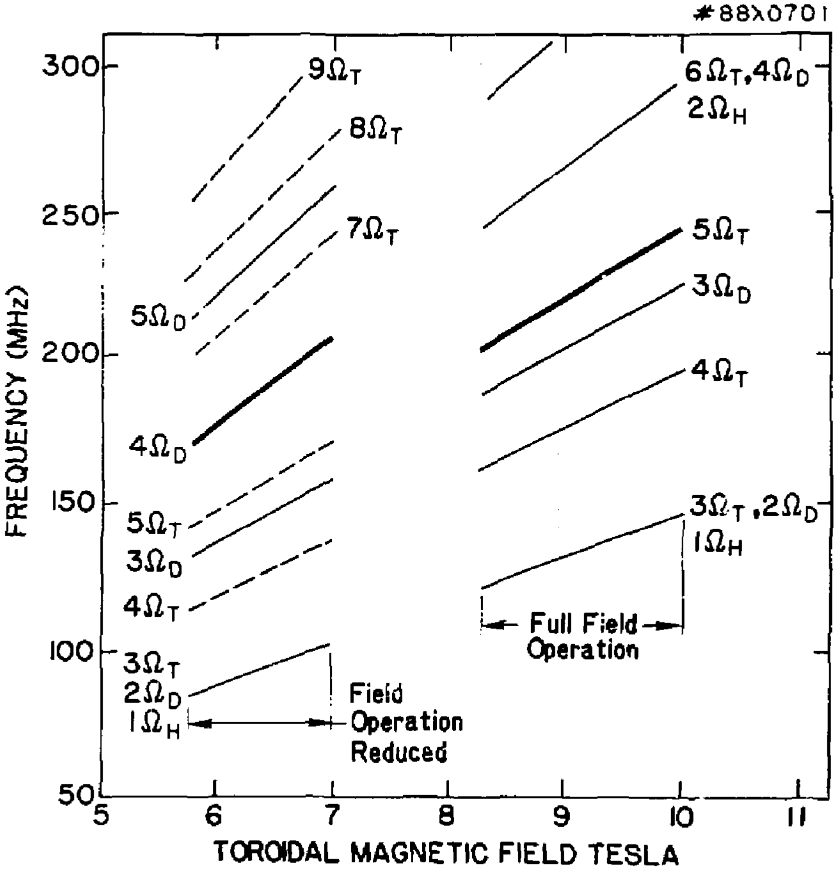
Bibliography

1. M. Ono, "Ion Bernstein Wave Heating Theory and Experiment," in a Course and Workshop on Applications of RF Waves to Tokamak Plasmas, Varenna, Italy, September, 1985, edited by S. Bernabei, U. Gasparino and E. Sindoni, produced for the International School of Plasma Physics, pages 197 to 235.

2. M. Ono, P. Beiersdorfer, R. Bell, et al., "Effects of High-Power Ion Bernstein Waves on a Tokamak Plasma," Physical Review Letters, Volume 60, pages 294-296 (1988).

Figures

1. Possible Resonances for Ion Bernstein Wave Heating. Resonant frequency for several hydrogenic ions (protium, deuterium, tritium) is plotted against toroidal field in two bands, one ending at 7 Tesla, and one ending at 10 Tesla. The extent of each band toward lower frequency represents the decrease in total field toward the outside major radius. In considering the total field, the poloidal field is important at the large major radius edge: therefore, the change in total field is less than the change in toroidal field in the range plotted. Heating can be centralized with fifth harmonic tritium, and the fourth harmonic deuterium, and no other resonances can compete for absorption.
2. Top view of a 4-waveguide coupling structure at the plasma, including the coaxial transmission lines which carry power to the experimental region. The figure is approximately to scale, as shown.
3. Side view of the installation shown in Figure 2. The aspect ratio of the waveguide is accurately shown by comparing Figures 2 and 3.



#88X0701
FREQUENCY (MHz)
TOROIDAL MAGNETIC FIELD TESLA
300
250
200
150
100
50
5
6
7
8
9
10
11
$9\Omega_T$
$8\Omega_T$
$7\Omega_T$
$5\Omega_D$
$4\Omega_D$
$5\Omega_T$
$3\Omega_D$
$4\Omega_T$
$3\Omega_T$
$2\Omega_D$
$1\Omega_H$
Field Operation Reduced
$6\Omega_T, 4\Omega_D$
$2\Omega_H$
$5\Omega_T$
$3\Omega_D$
$4\Omega_T$
$3\Omega_T, 2\Omega_D$
$1\Omega_H$
Full Field Operation

Fig. 1

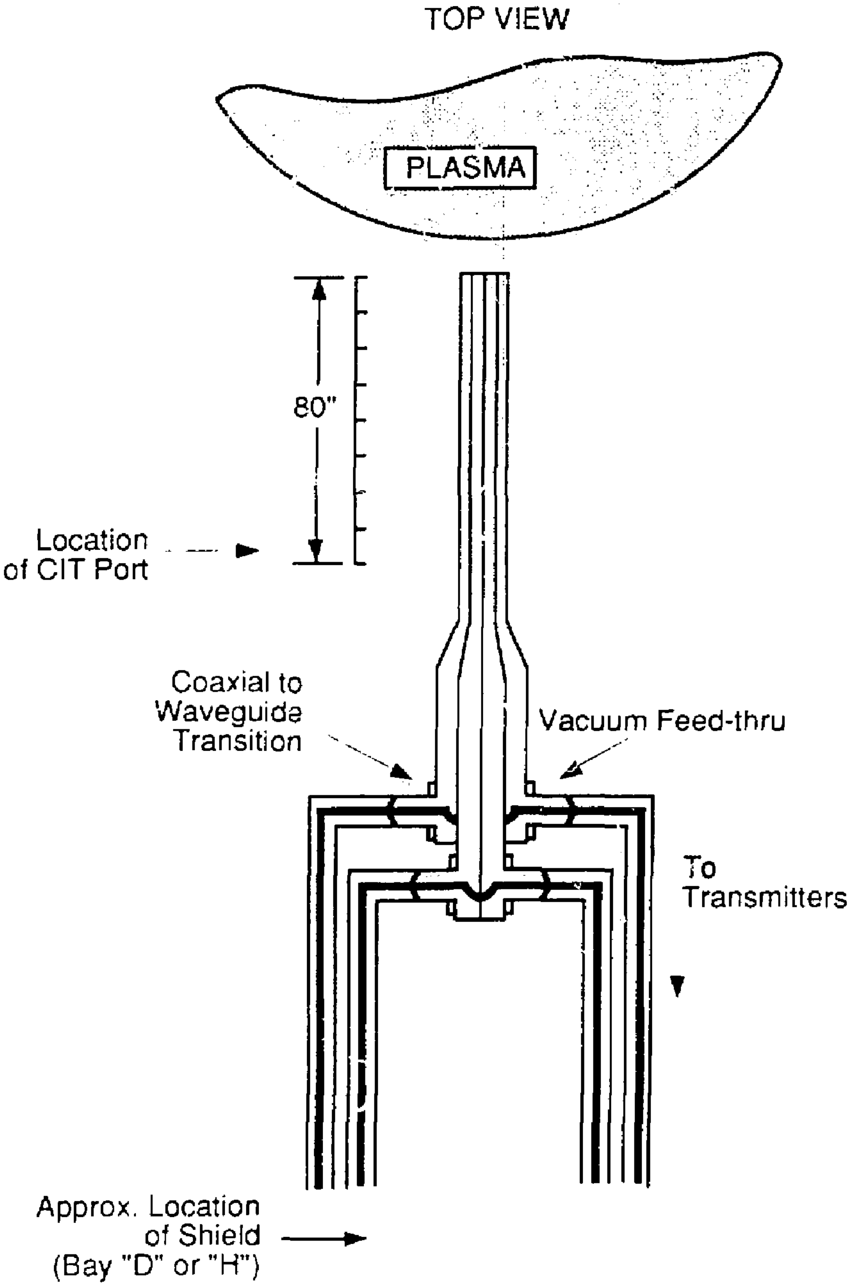
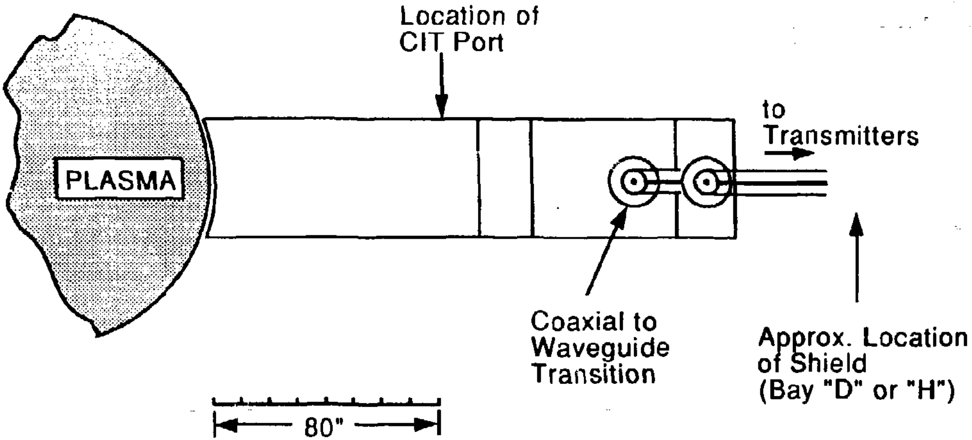

TOP VIEW
PLASMA
80"
Location of CIT Port
Coaxial to Waveguide Transition
Vacuum Feed-thru
To Transmitters
Approx. Location of Shield (Bay "D" or "H")

Fig. 2



SIDE VIEW

Fig. 3

EXTERNAL DISTRIBUTION IN ADDITION TO UC-20

Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
Plasma Research Lab., Australian Nat. Univ., AUSTRALIA
Prof. I.R. Jones, Flinders Univ., AUSTRALIA
Prof. F. Cap, Inst Theo Phys, AUSTRIA
Prof. M. Heindler, Institut fur Theoretische Physik, AUSTRIA
M. Goossens, Astronomisch Instituut, BELGIUM
Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
Commission-European, Dg-XII Fusion Prog, BELGIUM
Prof. R. Boucique, Laboratorium voor Natuurkunde, BELGIUM
Dr. P.H. Sakanaka, Instituto Fisica, BRAZIL
Instituto De Pesquisas Espaciasi-INPE, BRAZIL
Documents Office, Atomic Energy of Canada Limited, CANADA
Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA
Dr. H.M. Skarsgard, University of Saskatchewan, CANADA
Dr. H. Barnard, University of British Columbia, CANADA
Prof. J. Teichmann, Univ. of Montreal, CANADA
Prof. S.R. Sreenivasan, University of Calgary, CANADA
Prof. Tudor W. Johnston, INRS-Energie, CANADA
Dr. C.R. James, Univ. of Alberta, CANADA
Dr. Peter Lukac, Komenskeho Univ, CZECHOSLOVAKIA
The Librarian, Culham Laboratory, ENGLAND
The Librarian, Rutherford Appleton Laboratory, ENGLAND
Mrs. S.A. Hutchinson, JET Library, ENGLAND
C. Mouttet, Lab. de Physique des Milieux Ionisés, FRANCE
J. Radet, CEN/CADARACHE - Bat 506, FRANCE
Univ. of Ioannina, Library of Physics Dept. GREECE
Dr. Tom Mual, Academy Bibliographic Ser., HONG KONG
Preprint Library, Hungarian Academy of Sciences, HUNGARY
Dr. B. Dasgupta, Saha Inst of Nucl. Phys., INDIA
Dr. P. Kaw, Institute for Plasma Research, INDIA
Dr. Philip Rosenau, Israel Inst. Tech, ISRAEL
Librarian, Int'l Ctr Theo Phys, ITALY
Prof. G. Rostagni, Univ Di Padova, ITALY
Miss Clelia De Palo, Assoc EURATOM-ENEA, ITALY
Biblioteca, Instituto di Fisica del Plasma, ITALY
Dr. H. Yamato, Toshiba Res & Dev, JAPAN
Prof. I. Kawakami, Atomic Energy Res. Institute, JAPAN
Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
Direc. Dept. Large Tokamak Res. JAERI, JAPAN
Prof. Satoshi Itoh, Kyushu University, JAPAN
Research Info Center, Nagoya University, JAPAN
Prof. S. Tanaka, Kyoto University, JAPAN
Library, Kyoto University, JAPAN
Prof. Nobuyuki Inoue, University of Tokyo, JAPAN
S. Mori, JAERI, JAPAN
Librarian, Korea Advanced Energy Res. Institute, KOREA
Prof. D.I. Choi, Adv. Inst Sci & Tech, KOREA
Prof. B.S. Liley, University of Waikato, NEW ZEALAND
Institute of Plasma Physics, PEOPLE'S REPUBLIC OF CHINA
Librarian, Institute of Phys., PEOPLE'S REPUBLIC OF CHINA
Library, Tsing Hua University, PEOPLE'S REPUBLIC OF CHINA
Z. Li, Southwest Inst. Physics, PEOPLE'S REPUBLIC OF CHINA
Prof. J.A.C. Cabral, Inst Superior Tecnico, PORTUGAL
Dr. Octavian Petrus, AL I CUZA University, ROMANIA
Dr. Johan de Villiers, Fusion Studies, AEC, SO AFRICA
Prof. M.A. Hellberg, University of Natal, SO AFRICA
C.I.E.M.A.T., Fusion Div. Library, SPAIN
Dr. Lennart Stenflo, University of UMEA, SWEDEN
Library, Royal Inst Tech, SWEDEN
Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
Centre Phys des Plasmas, Ecole Polytech Fed, SWITZERLAND
Bibliotheek, Fom-Inst Voor Plasma-Fysica, THE NETHERLANDS
Dr. D.D. Ryutov, Siberian Acad Sci, USSR
Dr. G.A. Eliseev, Kurchatov Institute, USSR
Dr. V.A. Glukhikh, Inst Electrophysical Apparatus, USSR
Dr. V.T. Tolok, Inst. Phys. Tech. USSR
Dr. L.M. Kovrizhnykh, Institute Gen. Physics, USSR
Nuclear Res. Establishment, Julich Ltd., W. GERMANY
Bibliothek, Inst. Fur Plasmaforschung, W. GERMANY
Dr. K. Schindler, Ruhr Universitat Bochum, W. GERMANY
ASDEX Reading Rm, IPP/Max-Planck-Institut fur Plasmaphysik, W. GERMANY
Librarian, Max-Planck Institut, W. GERMANY
Prof. R.K. Janev, Inst Phys, YUGOSLAVIA