ION CYCLOTRON HEATING EXPERIMENTS IN EBT-S*

F. W. Baity, W. A. Davis, O. C. Eldridge, J. C. Glowienka,
D. L. Hillis, D. A. Rasmussen, and R. K. Richards

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830 USA

J. H. Mullen and T. L. Owens

McDonnell Douglas Astronautics Company
St. Louis, Missouri 63166

MASTER

DISCLAIMER

Abstract

Fast-wave heating and propagation experiments in the ion cyclotron range of frequencies (ICRF) have been carried out on EBT-S under steady-state conditions at power levels up to 20 kW and under pulsed conditions at power levels up to 100 kW. The waves were launched using a single Faraday-shielded loop antenna installed on the midplane of one of the 24 cavity sectors. Substantial ion heating was observed at frequencies above the second harmonic for hydrogen plasmas and at frequencies above the third harmonic for deuterium plasmas, corresponding with the onset of wave propagation around the torus. The heating under these conditions is anomalous. In the case of deuterium plasmas, a small residual concentration (2-5%) of hydrogen was heated, but this component did not appear to affect the deuterium heating.

Introduction

Experiments with ICRF heating on EBT-S were undertaken to provide the physics and technology base for application of fast-wave ion heating on the next-generation proof-of-principle EBT experiment, EBT-P, currently in the design phase and scheduled to begin operation in the mid-1980's. Auxiliary ion heating will be needed on EBT-P in order to understand ion behavior in EBT geometry and in order to attain plasma beta values of approximately 5%. The size and parameters of the EBT-S experiment preclude propagation of wave energy toroidally at the fundamental frequency of hydrogen, so that minority heating in the two-ion hybrid regime cannot be expected outside the antenna cavity. Toroidal wave propagation in EBT-S occurs at frequencies above the second harmonic frequency of hydrogen, where wave damping by the plasma ions is expected to be small. Wave propagation in EBT-P will be much

improved, with several modes present at the fundamental frequency for hydrogen.

The EBT-S experiments are conducted steady-state so that active cooling of the antenna and Faraday shield is necessary. In addition the plasma in EBT-S is formed by electron cyclotron heating, so that the antenna is required to be compatible with a high level of microwave radiation.

This paper describes only the ion heating results obtained with charge-exchange analyzers. Power coupling and wave propagation are described in another paper in this session [1].

Description of Apparatus

The installation of the ICRH antenna is shown schematically in Fig. 1. The antenna covers a poloidal angle of 120°, is water-cooled,

Fig. 1. Schematic drawing of the antenna and matching circuit installation on EBT-S. The vacuum variable capacitors are remotely tuned during operation. The antenna is mounted in a modified cavity sector midway between two toroidal magnetic field coils.

and is surrounded by a double aluminum Faraday shield, which is also
water-cooled for steady-state operation. The antenna connects to a
broadband matching circuit consisting of three remotely-tuned vacuum
variable capacitors, which cover the frequency range of 15-50 MHz. The
two large "parallel" capacitors are also water-cooled to permit
steady-state operation. The present system is limited to 20 kW steady
state in the T-mode by the Faraday shield cooling. A new Faraday
shield with improved cooling has been designed which will allow
operation at 100 kW steady state. The coax line to the matching
circuit comes from an array of rf power sources, including a 20-kW cw,
2-30 MHz transmitter, a 100-kW cw, 5-30 MHz transmitter, and a
1.5-kW cw broadband amplifier covering the entire frequency range of
the system. The best power coupling in the range of the high power
transmitters occurs at 30 MHz. Therefore, measurements of heating as a
function of power were conducted at 30 MHz, primarily, and measurements
as a function of frequency were made with several hundred watts coupled
to the plasma.

Ion Heating Results

In the absence of direct ion heating, the ions in EBT-S gain
energy by collisions with plasma electrons or by some anomalous
process. Since the best estimate of the neutral particle density from
spectroscopy is 2×10^{10} cm^{-3}, the average ion temperature is limited
by charge-exchange to ~10 eV. However, in the T-mode of operation,
when the stabilizing relativistic electron rings are present, one or
more high-energy tails is always observed with the charge-exchange
analyzers. These tails increase in density as the TM-transition, which
is the low pressure limit of the T-mode, is approached. The tails are
almost nonexistent in the cold, high-density C-mode (without rings).
Recently, highly resolved H_α spectra have shown the existence of high
energy neutral H atoms, arising from charge exchange. These spectra
show a two-component ion energy distribution, with a bulk temperature
of ~10-15 eV and a tail at 60-75 eV representing typically 10% of the
core plasma ions. This high energy tail is also measured with the
charge-exchange analyzers, which sometimes observe another tail at
several hundred eV, but at a still lower percentage of the total ions.
A comparison of the medium energy tail densities calculated from
spectroscopy and charge-exchange gives an absolute calibration for the
charge-exchange density measurements, provided the plasma ions are
isotropic. The source of these high energy tails is unknown.

The addition of ICRF heating results in a substantial enhancement
of both the density and temperature of the high energy tail components,
with little, if any, change in the bulk ion temperature. This is a
consequence of the fact that the ion energy lifetime is considerably
shorter than the ion-ion energy equilibration time under normal EBT-S
conditions. High energy ion tails are produced even in the C-mode
during ICRF heating. In the C-mode the antenna loading is higher than
in the T-mode (70% power coupling to the plasma at 30 MHz for a typical
C-mode condition compared to 45% coupling in the middle of the T-mode
with 100 kW of ECH). This is presumably due both to the increased

density in the C-mode and to the proximity of the plasma to the antenna in the absence of relativistic electron rings.

The temperature and density of the high energy tail increases with increasing amounts of ICRF heating, as shown in Fig. 2 for a 95% deuterium plasma in the T-mode at 30 MHz, measured four cavities (60° toroidally) from the antennas. The plasma parameters for this data were: a magnetic field strength on axis in the cavity midplane of 0.725 T (1.4 T in the mirror throats), an ECH power of 100 kW at 28 GHz, and a background pressure of 1×10^{-5} Torr. The straight lines represent Maxwellian fits to the experimental data points. This graph was produced by assuming that the measured flux was due entirely to deuterons with little proton contribution. Mass analysis of the charge-exchange flux carried out using another charge-exchange analyzer, located on the antenna cavity, indicated that protons indeed contribute little for energies below $\sim$1.5 keV.

Fig. 2. Experimental distribution functions as a function of ion energy and least-squares Maxwellian fits for several different ICRF heating power levels. The fitted portion of each spectrum represents a tail on a much lower energy bulk ion temperature distribution. This data was obtained with a charge-exchange analyzer four cavities from the antenna for a deuterium plasma in the T-mode.

The calculation of the density of this high energy tail distribution is complicated by the fact that the energetic ions may be very anisotropic. The charge-exchange analyzers are all oriented to measure ions with only perpendicular energy. Without detailed knowledge of the pitch angle distribution of the ions, the density cannot be explicitly calculated from the charge-exchange data, but can be expressed in terms of $T_\parallel$. Analysis of the data shown in Fig. 2 in this manner is plotted in Fig. 3. Note that the apparent tail density increases rapidly as the applied ICRF heating power is increased, while the tail temperature increases only moderately.

Measurements of ion heating as a function of applied frequency were carried out with 300 W coupled into the plasma. The somewhat surprising result was that the heating increased steadily as the frequency was raised to the maximum frequency of the matching circuit. At 50 MHz only the third and higher harmonics of hydrogen and the fifth and higher harmonics of deuterium are present in the plasma. Fig. 4 shows the several-fold increase in the raw charge-exchange signal four cavities from the antenna as the applied frequency was increased to

Fig. 3. Calculated tail temperatures and densities from the data shown in Fig. 2. The measured density is a function of the anisotropy of the tail component, thus the dependence on $T_\parallel^{-1/2}$ indicated in the right-hand ordinate.

Fig. 4 . Uncorrected charge-exchange signal as a function of
energy for different applied ICRF heating frequencies, taken with the
charge-exchange analyzer four cavities from the antenna. This data was
obtained with a deuterium plasma in the T-mode. No enhancement of the
charge-exchange signal is observed until the onset of toroidal wave
propagation which occurs at about 30 MHz under these conditions.

50 MHz. The threshold frequency of 30 MHz corresponds to the onset of
wave propagation around the torus as measured by rf loop probes in
several cavities. The heating mechanism responsible for this behavior
is not yet understood. The complete EBT geometry, with strong magnetic
field gradients, both radially and toroidally, makes theoretical
modeling quite difficult.

Effects of ICRF Heating on Other Plasma Parameters

The effects of ICRF heating on other core plasma parameters are slight. No change has been observed in either the electron temperature or impurity concentrations. A slight reduction in the core plasma density ($\sim$10-15%) was observed with 15-20 kW of ICRF heating, as was a slight reduction in the ambipolar potential well depth. The major effect besides the observed ion heating has been an enhancement in the relativistic electron ring stored energy. The ring energy has been doubled at 20 kW of ICRF heating. The source of this ring enhancement is not understood.

Conclusions

Fast-wave ICRF heating has been demonstrated to be an effective method of increasing the ion energy in EBT-S. Ions several cavities from the single antenna are heated when wave propagation occurs. The heating improves with increasing frequency up to the limit of the matching circuit. This heating at high harmonics of the ion cyclotron frequency is anomalous. In addition, anomalous increases in the total stored energy of the relativistic electron rings is observed during ICRF heating. Further studies at higher power levels are planned.

References

1. J. H. Mullen, T. L. Owens, and A. L. Henderson, McDonnell Douglas Astronautics Company; F. W. Baity and O. C. Eldridge, Oak Ridge National Laboratory, "Fast-Wave Ion Cyclotron Wave Propagation and Coupling Experiments on Elmo Bumpy Torus," Third Joint Varenna-Grenoble International Symposium, Grenoble, France, March 22-27, 1982.
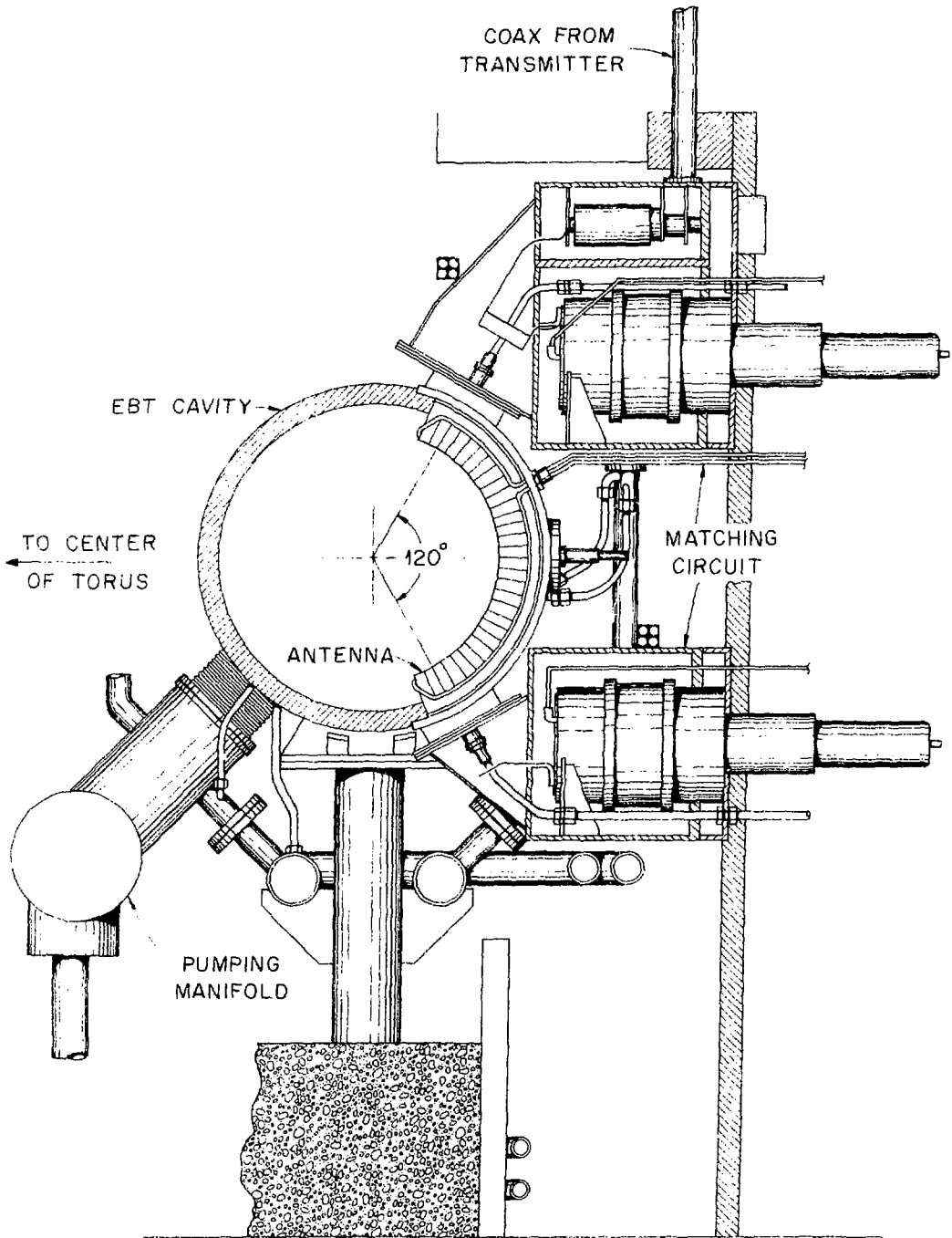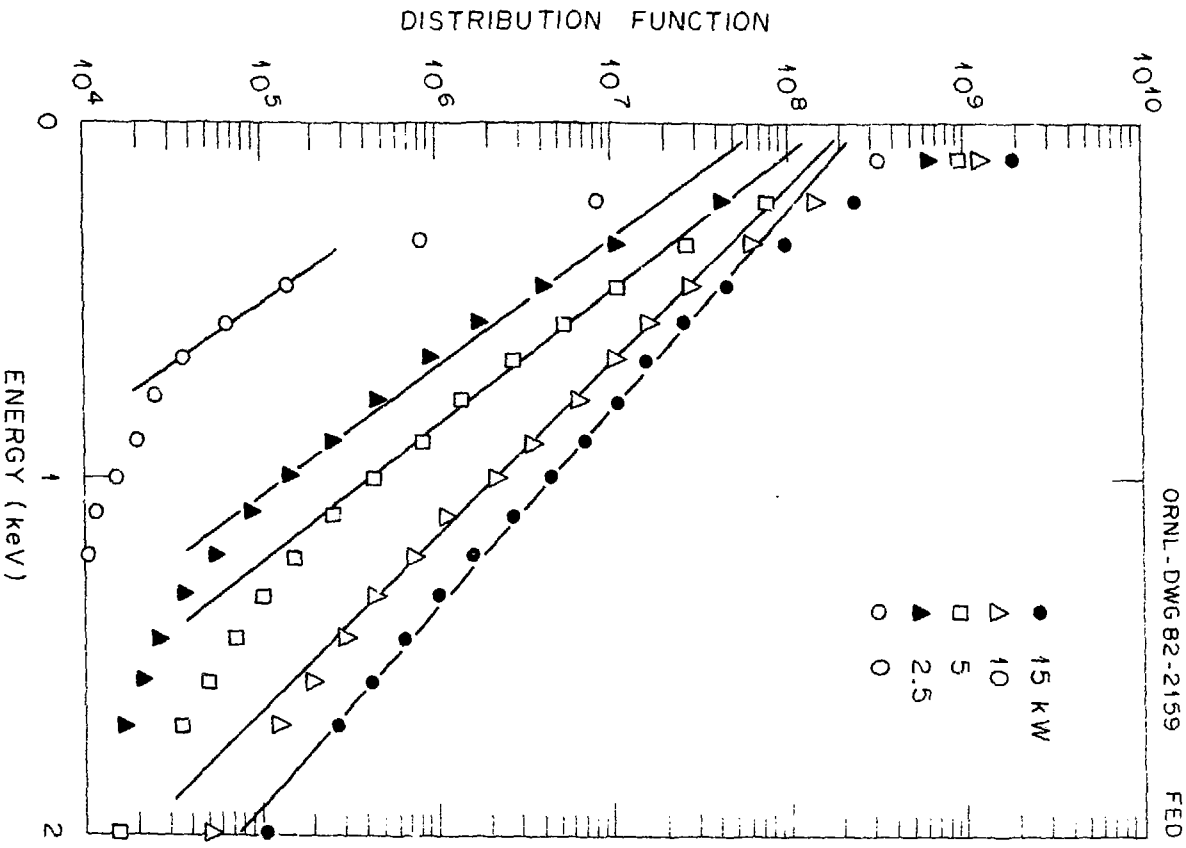
COAX FROM
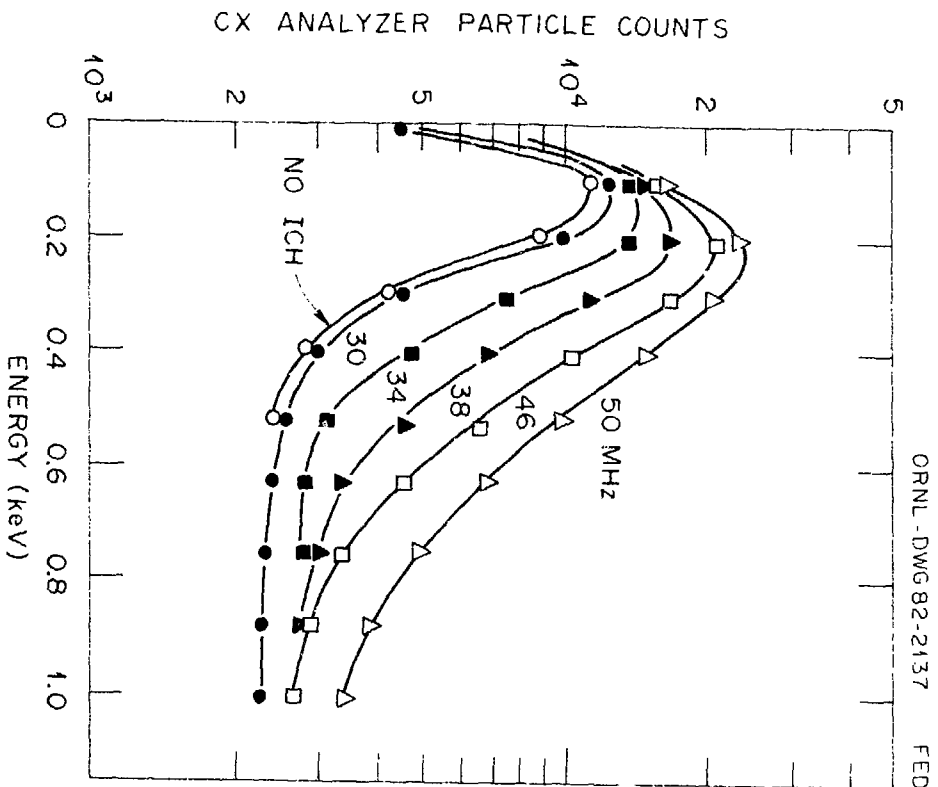TRANSMITTER

EBT CAVITY

TO CENTER
OF TORUS

120°

ANTENNA

MATCHING
CIRCUIT

PUMPING
MANIFOLD

Fig. 1

DISTRIBUTION FUNCTION

ENERGY (keV)

ORNL-DWG 82-2159   FED

15 kW
10
5
2.5

Fig. 2

CX ANALYZER PARTICLE COUNTS

ENERGY (keV)

NO ICH

30
34
38
46
50 MHz

ORNL-DWG 82-2137   FED

Fig. 4