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FAST-WAVE ICRF HEATING FOR EBT-P*

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Introduction

The EBT concept evolved from a set of experiments with electron cyclotron heating (ECH) in simple mirror geometry conducted at Oak Ridge in the 1960's. It was thought that the relativistic electron rings which are formed at the midplane of the mirror near the second harmonic resonance zone might provide basic stability to a simple bumpy torus configuration. Thus, the EBT-I experiment was constructed in 1973. EBT-I quickly confirmed the predictions and was upgraded to what is called EBT-S (for "scale") in 1978 with the application of 28-GHz ECH from a gyrotron, which was developed for this purpose.

Also in 1978, the United States Department of Energy conducted a review of all alternate concepts (to tokamaks and mirrors) for the magnetic confinement of fusion plasmas in order to select the most promising one for an aggressive "Proof-of-Principle" test. The EBT concept was selected for this test, and the EBT-P project was begun. After a design competition among four industrial consortia, the McDonnell Douglas Astronautics Company was selected as the principal industrial participant with the Oak Ridge National Laboratory for the design, construction, and operation of the EBT-P machine, which will be built in Oak Ridge for operation beginning in about 1986.

A comparison of the parameters achieved in the EBT-I and EBT-S devices and those expected in EBT-P at various stages of its operation are presented in Table 1.

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Table 1

Physics Parameters*

Parameter	EBT-S	EBT-P Ease		EBT-P Upgrade
N_{coils}	24	36	36	36
R (m)	1.5	4.5	4.5	4.5
B_{res} (T)	1.0	2.1	2.1	3.2
n (cm^{-3})	2×10^{12}	1.0×10^{13}	1.5×10^{13}	3×10^{13}
T_e (keV)	1.0	2.0	5.0	7.5
T_i (keV)	0.05	0.4	2.5	5.0
Core β at annulus (%)	0.4	1.5	5.0	8.0
τ_{Ee} (ms)	5	30	60	60
$n\tau_{Ee}$ (cm^{-3} s)	10^{10}	3×10^{11}	10^{12}	2×10^{12}
P_{ECRH} (MW) (bulk heating)	0.2	0.8	1.2	+
(profile heating)	0.05	0.4	0.4	+
P_{ICRH} (MW)	0.025	0	2.0	+

*All densities and temperatures are nominal values with a nominal 30% uncertainty.

+Additional ICRH power, ECRH at 90 GHz, higher field operations, and ARE coils will be used to attain the upgrade parameter objectives.

Maximum input power to torus is limited to 5 MW cw.

Since core plasma production and the stabilizing relativistic electron rings in an EBT are provided by ECH, some means of direct ion heating must be employed in order to achieve the ion parameters needed for fusion without requiring excessive, and hence uneconomical, amounts of ECH. Of the several candidates considered (neutral beams, lower hybrid heating, slow and fast wave heating in the ion cyclotron range of frequencies), fast-wave ICRF heating was selected as the most promising for EBT-P. As a result of this decision, a program to demonstrate the feasibility of fast-wave ICRF heating in EBT geometry was initiated on EBT-S. After a study phase involving TRW and McDonnell Douglas, McDonnell Douglas was selected to provide

engineering and fabrication of antennas and matching circuits and to participate in the experiments to be conducted on EBT-S.

The experiments on EBT-S have provided the basic understanding of fast-wave ICRF heating in a steady-state EBT plasma and form the database necessary for the design of the ICRF heating system for EBT-P. These experiments have demonstrated that ICRF heating is indeed a viable heating method in EBT geometry.

Description of EBT-P

A conceptual drawing of EBT-P is shown in Fig. 1. It will consist of 36 sectors (compared to 24 for EBT-I/S). The magnets will be superconducting with a design field of 4.2 T on axis to permit operation with both 60 GHz and 90 GHz as the primary ECH frequency. The basic design parameters and the expected plasma parameters are listed in Table 1. EBT-P represents a major step in the EBT program, with a tripling of the size, a five-fold increase in ECH power, and an order of magnitude increase in density and ion temperature.

Fig. 1. Artist's conception of EBT-P showing the major vacuum components, superconducting magnets and associated equipment, and the rf heating manifolds.

Supplementary Ion Heating Objectives

There are three basic objectives for supplementary ion heating on EBT-P. They are: to study ion transport, to test core plasma beta limits to stability, and to develop the technology necessary for future EBT machines. Concerning the first objective, very little is known about ion behavior in EBT-S due to the dominance of charge-exchange losses of ion energy. The size and density of EBT-P should reduce charge-exchange losses to modest levels. Anomalous ion tails are observed and ambipolar potential wells (for ions) are measured in EBT-S. Supplementary ion heating on EBT-P should allow independent control of these parameters for study. Secondly, one of the advantages of the EBT concept as a fusion reactor candidate is the possibility of stable operation at high beta values. Stability theory predicts that the core plasma should be stable at least to a value of 5% at the rings. Supplementary heating will be necessary to provide sufficient ion parameters to attain this level. Finally, should EBT-P fulfill its goals, another objective of supplementary ion heating will be to develop the coupler and tuner technology for future EBT devices.

Rationale for Fast-Wave ICRF Heating

Fast-wave ICRF heating appears to be the most promising method of direct ion heating for EBT-P for a number of reasons. First, it utilizes conventional hardware, which is already developed, and which can be easily installed on a modified EBT-P cavity sector. Only a small number of antenna structures should be required because the wave energy can be propagated to adjacent cavities. Also, high-power steady-state rf sources in the needed frequency range (60-90 MHz) are readily available from industry. The effectiveness of ICRF heating has been adequately demonstrated on a number of tokamak experiments similar in size and plasma parameters to EBT-P, and on EBT-S. Finally, predictions for EBT-P show improved wave coupling efficiency to the plasma and greatly improved wave propagation properties over EBT-S.

Implementation of ICRF Heating on EBT-P

The implementation of ICRF heating on EBT-P will be based on the present status of ICRF heating on EBT-S. This means the use of loop antennas similar to the present design, mounted in a cavity sector midplane. The antennas on EBT-P might be designed for a central feed, as opposed to the end-fed type now in use on EBT-S, if access is limited by cryogenic or ECH hardware at the top and bottom of the machine. The frequency will be selected to launch the second or third harmonic for hydrogen, as is currently done. The antennas and tuners will be designed to operate steady-state at several hundred kilowatts, a level already achieved in pulsed experiments on present tokamaks, although pulsed operation may be used for testing plasma stability limits if necessary due to budgetary considerations. Since EBT-P is a steady-state machine, operation with deuterium as a fill gas is not

planned, in order that there be no significant personnel radiation hazard due to neutron activation.

The power requirements are dictated by the goal of achieving 5% beta. This requires a combined electron and ion kinetic energy density of 1.4×10^{14} keV/cm^3. Assuming a plasma density of 1.5×10^{13} cm^{-3}, this means that T_e = 4-6 keV and T_i = 2-3 keV must be attained. Based on neoclassical scaling for the core electrons, sufficient ECH power (1.2 MW) is planned to produce the needed electron temperature. Approximately 2 MW of supplementary ion heating is needed to assure attainment of the necessary ion temperature. A possible upper limit to the ion temperature is predicted based on adiabatic arguments. This value is derived by scaling the quantity ρ_i/L, where ρ_i is the ion gyroradius and L is the characteristic magnetic scale length, from EBT-S, and is equal to 3 keV. ρ_e/L scaling is used for predicting the relativistic electron ring temperature in EBT-P. This scaling for electrons has been verified in a wide range of electron cyclotron heated mirror experiments, and is assumed to hold for ions as well. The amount of power required is determined by power balance, which depends on the edge neutral density. Thus, to launch a total power of 2 MW in the plasma, 4-6 antennas should be sufficient to achieve the ion parameters for the stability tests.

Summary

Supplementary ion heating will play a major role in advancing the physics understanding of bumpy tori in EBT-P. Fast-wave ICRF heating is the method selected for EBT-P because of the successful ICRF heating experiments on tokamaks and on EBT-S. Given neoclassical electron behavior, then 2 MW of ICRF heating in the range of 60-90 MHz should be sufficient for the achievement of all the goals for ion heating, including 5% core plasma beta at the rings.