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GENERAL ATOMICS

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Applications of Electron Cyclotron Waves in the DIII-D Tokamak

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Abstract. Electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) have progressed from being the subject of experiments to being a prime tool for carrying out experiments on other topics. ECH has different characteristics than neutral beam heating: ECH heats only the electrons, heats very locally and controllably, does not inject momentum or particles, and may be arranged to drive highly localized currents or to just heat. These differences make ECH useful in a very wide range of experiments.

Keywords: ECH, ECCD, tokamak
PACS: 52.55.)s, 52.35.Hr, 52.50.Sw

INTRODUCTION

Over the last few years, electron cyclotron heating (ECH) and electron cyclotron current drive (ECCD) have progressed from being the subject of experiments, on the DIII-D tokamak and other devices, to being a prime tool for supporting experiments on a wide range of other topics. These experiments make use of the different characteristics of EC wave heating [1] compared to neutral beam injection (NBI) heating: ECH heats only the near-thermal electrons; it heats very locally at the location of the intersection of the cyclotron resonance and the EC beam, which can be robustly controlled by the experimenter; it does not inject momentum or particles; and it may be arranged to drive highly localized currents or to heat only. These differences make ECH useful for a very wide range of experiments where these differences from NBI are significant.

ECH SYSTEM IN 2008

For the 2008 experiment campaign on DIII-D the ECH system [2] consisted of five gyrotrons with frequency 110 GHz and nominal power of 1 MW each. Allowing for 10% overhead between the nominal peak power and the typical operating power and the transmission line losses of around 25% [3], the typical power injected into the DIII-D vessel per gyrotron was 0.65 MW. In the 2008 experiment campaign on DIII-D, ECH was used in 35% of the discharges, 895 of the total 2550. Figure 1 shows that the averaged ECH power (time-integrated power divided by the total pulse length) exceeded 3 MW for many shots and that there is little secular trend, either upward or downward, over the course of the year once the fifth gyrotron became available at around shot 132000. The pulse length, shown in Fig. 2, extends to 3.5 s for many shots. (In 2009, a sixth gyrotron was added and over 12 MJ was injected into the plasma with 4 s pulse lengths.)

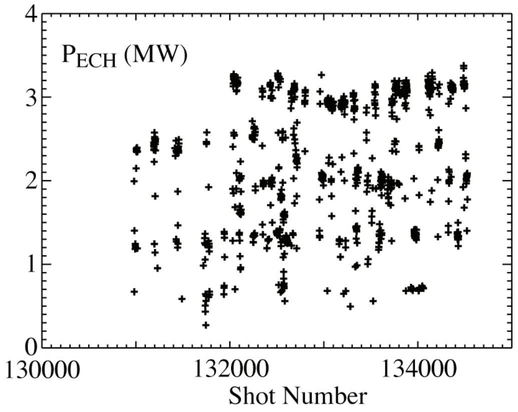

FIGURE 1. Average injected ECH power versus shot number for the 2008 campaign.

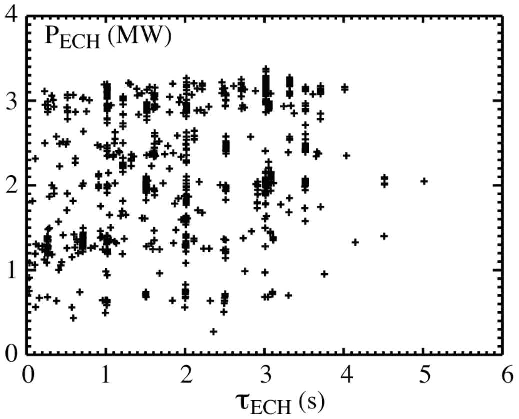

FIGURE 2. ECH average injected power versus pulse length for all shots in the 2008 campaign.

EXPERIMENTS USING ECH IN 2008

Because of its unique characteristics, ECH was applied in a large number of experiments in 2008, including the following:

ITER Physics and Support

- 2nd harmonic ECH pre-ionization and ramp-up
- Demonstration of ITER steady-state discharge
- H-mode power threshold for EC and NBI and its dependence on torque
- Model-based control of the current profile
- L-H turbulence dynamics as a function of torque in hydrogen plasmas
- Enhanced disruption mitigation with magnetic perturbations.

Scenario Development

- Fully noninductive discharges
- Simultaneous control of resistive wall modes and neoclassical tearing modes
- Physics of stability and beta limits in hybrid discharges
- Effect of ECH/ECCD on H-mode pedestal characteristics and ELMs
- High beta steady-state hybrid discharges
- Increase β_N to 5 in discharges with high internal inductance
- Effect of core rotation on scrape-off layer flows

Transport of Energy or Momentum

- Balanced NBI and intrinsic rotation
- Beta dependence of non-resonant field torques
- Effect of plasma shape, density, and temperature on intrinsic rotation
- ExB and magnetic shear effects on turbulence and transport
- Characterization of trapped electron mode (TEM) turbulence

- Turbulence and transport modifications in ECH plasmas
- Validation of the scaling of transport models with elongation
- Confinement versus squareness

Stability

- NTM detection by oblique ECE and automated control by ECCD
- RWM stability in slowly rotating high beta plasmas
- Control of beta-induced Alfvén-acoustic eigenmodes
- Test of models of nonlinear resistive MHD
- Effects of rotation and error fields on 2/1 NTM characteristics
- Effects of rotation and fast ions on sawteeth

Source Physics

- Validation of neutral beam physics models
- Off-axis NBCD using vertically shifted plasmas
- Verification of neutral beam torque profiles

This list of experiments illustrates how the unique characteristics of EC waves are exploited in actual practice. Many topical groups outside the traditional constituency for wave experiments have used ECH or ECCD for applications in their experiments. The use of ECH does entail some restrictions on plasma parameters — e.g., the toroidal field may need adjustment to bring the resonance to the right location in the plasma, and the density must be kept below the cutoff density around $7\text{x}10^{19}$ m^{-3} — so the value of the ECH must clearly exceed the costs to these experiment activities.

These experiments may be divided into several groups according to the role of ECH in the experiment. One major group is experiments that use ECH to raise the electron temperature, taking advantage of the heating of electrons well into the thermal distribution, so that little distortion of the electron distribution function takes place. A special case of experiments in which ECH is used to heat electrons is when it is used to control or modify the gradient of the electron temperature, in order to assess the role of ∇T_e on plasma turbulence. In one such experiment the ECH was divided into two parts with equal power, and one half was aimed at $\rho=0.44$ while the other half was aimed at $\rho=0.63$. Modulating the power to the two locations out of phase produced conditions where the total power was constant while the ∇T_e was varied. (See Ref. 4 for a greater discussion of the technique.) This can be seen in Fig. 3, where the ECH heating profile in Fig. 3(a) produced the temperature profile of Fig. 3(b). Fluctuation diagnostics were used to study the effect of the gradient change on plasma turbulence and transport.

Other experiments made use of the current drive aspect of EC waves, a regime which can be accessed by applying the EC waves with a toroidal component. ECCD has been found helpful for experiments aimed at demonstrating full noninductive current support under high performance conditions, e.g., and for experiments in which the ECCD is used to control — either suppress or enhance — MHD activity. In “hybrid” discharges, in which a small neoclassical tearing mode appears to broaden the current profile, ECCD has been used to adjust the island size for studying the effect of island size on performance. In some high performance discharges, the limiting factor on beta is the appearance of an m=2/n=1 tearing mode, and here a broad application of ECCD in the region of q=2 can avoid having the mode appear, as shown in Fig. 4.

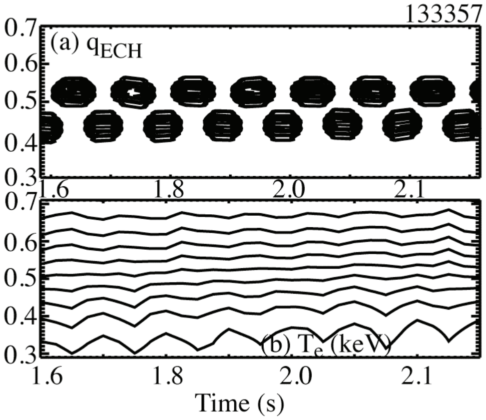

FIGURE 3. (a) ECH power density profile and (b) electron temperature contours from electron cyclotron emission (ECE) versus time for an experiment on using ECH to periodically modulate the temperature gradient.

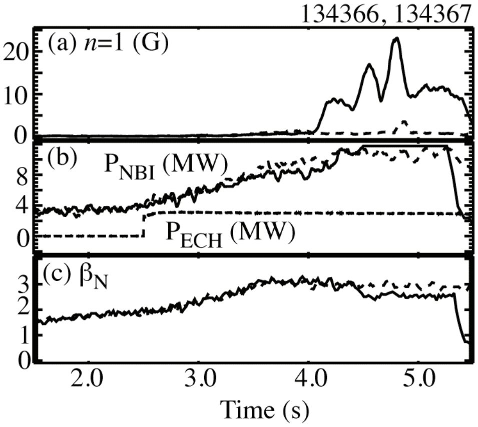

FIGURE 4. Comparison of two discharges, one with ECCD broadly placed in the region where q=2 (solid lines) and one without ECCD (dashed lines). (a) 2/1 mode amplitude, (b) injected NBI and ECCD powers, (c) normalized beta.

DISCUSSION

In most parameter ranges, the physics of EC waves is believed to be sufficiently well-understood that the main focus of the EC program has moved to other experiments where the unique characteristics of ECH and ECCD can be exploited to elucidate physical effects relating to plasma transport and stability. Advanced Tokamak scenarios, control of MHD instabilities, studies of microturbulence and its behavior, and many other topics are being addressed using EC waves.

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