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GENERAL ATOMICS

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Recent and Future Upgrades to the DIII-D Tokamak

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Research on the DIII-D tokamak focuses on support for next-generation devices such as ITER by providing physics solutions to key issues and advancing the fundamental understanding of fusion plasmas. To support this goal, the DIII-D facility is planning a number of upgrades that will allow improved plasma heating, control, and diagnostic measurement capabilities. The neutral beam system has recently added an eighth ion source and one of the beamlines is currently being rebuilt to allow injection of 5 MW of off-axis power at an angle of up to 16.5° from the horizontal. The electron cyclotron heating (ECH) system is adding two additional gyrotrons and is using new launchers that can be aimed poloidally in real-time by an improved plasma control system. The Fast Wave heating system is being upgraded to allow two of the three launchers to inject up to 2 MW each in future experiments. Several diagnostics are being added or upgraded to more thoroughly study fluctuations, fast ions, heat flux to the walls, plasma flows, rotation, and details of the plasma density and temperature profiles.

Keywords: DIII-D, tokamak, neutral beam, ECH, diagnostics, plasma control

1. Introduction

The DIII-D tokamak research program concentrates largely on investigations of fundamental plasma physics issues important to the designers of next-generation devices such as ITER. To facilitate these studies, several tokamak systems are being upgraded, including the auxiliary heating systems, plasma control system, and many of the plasma diagnostics.

To study higher energy plasmas, the power available from all auxiliary heating systems is being increased, including the neutral beam injectors, electron cyclotron heating (ECH) system and the fast wave system for heating ions. One of the four neutral beamlines is currently being rebuilt to allow off-axis injection to significantly affect the beam-driven current profile. The ECH system has been routinely operating six 1 MW class gyrotrons simultaneously, and is building the power supply and waveguide system to add a seventh gyrotron, with plans for an eighth. The fast wave system has recently doubled the input stage power on two of the three systems to provide more ion heating capability.

In Section 2, the upgrades to the auxiliary heating systems of the tokamak will be discussed. Section 3 briefly describes the improvements to the plasma control system (PCS). Section 4 summarizes some of the upgrades to the plasma diagnostics and conclusions are presented in Section 5.

2. Auxiliary Heating Systems

2.1 Neutral beams

Since 1996, seven ion sources have been available in the neutral beam system [1], each capable of injecting a nominal 2.5 MW for plasma heating. Prior to the most recent physics campaign, an additional source was made available when a new power supply was built, bringing the total power routinely available for physics experiments up to 20 MW. Six of the ion sources inject in the direction of the plasma current, I_p, and two are available for counter-injection (opposite the direction of I_p) [2]. Until now, all sources injected in the midplane. A major modification currently underway, however, will allow *off-axis* injection of 5 MW of power from one beamline (two sources). Large hydraulic actuators will be used to tilt the beamline from the usual midplane injection angle of 0° up to an angle of 16.5° for off-axis injection up to 40 cm below the plasma centroid (Fig. 1) [3].

The ITER device plans to use off-axis current drive to control the current profile. On DIII-D, off-axis beam heating will enable a significant modification of the plasma current profile, thus affecting one of the most critical parameters in a high performance plasma. To date, off-axis current drive has been available with modest levels of Electron Cyclotron Current Drive (ECCD), but in high β plasmas with significant beam power injected on axis, the current profile is dominated by the large level of central current driven by beam heating (NBCD). Figure 2 illustrates this phenomenon and shows that NBCD is as efficient as central heating for driving current, and is comparable to ECCD. The availability of off-axis NBCD starting in 2011 will allow carrying out valuable experiments to investigate control of the current profile.

2.2 ECH

During the 2009-10 physics campaign, six gyrotrons were routinely used for injection of electron cyclotron microwaves for heating the plasma. With a peak generated power of 4.5 MW at 110 GHz, the maximum

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injected power was approximately 3.5 MW. A pulse length limit of five seconds resulted in a maximum injected energy of 16.6 MJ.

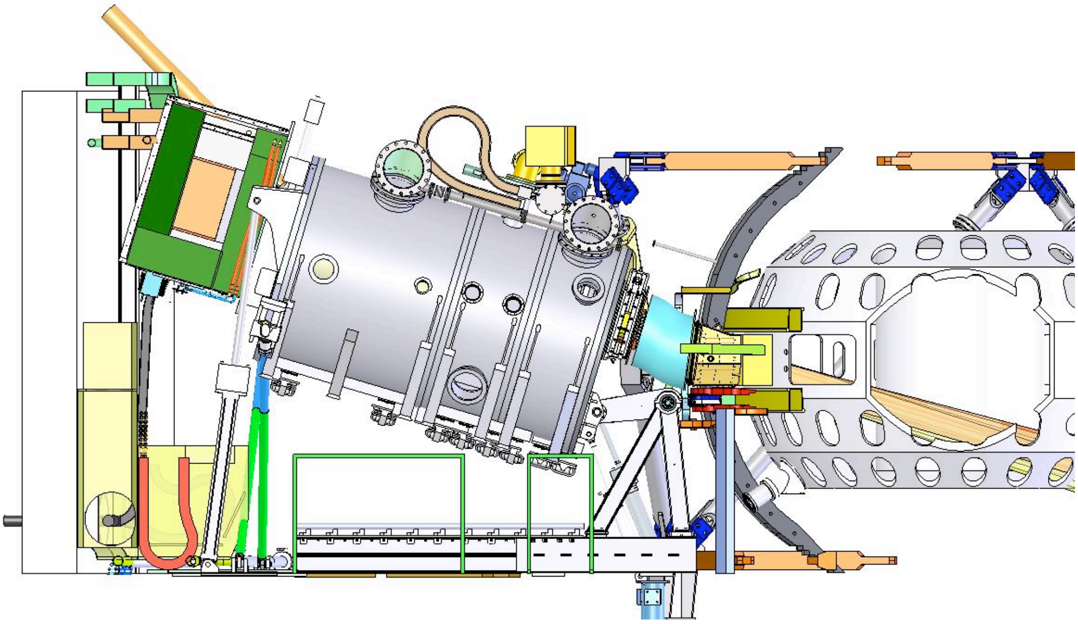

Fig. 1 Injection of up to 5 MW of off-axis power from a tilted beamline will be possible in 2011. Shown above is beam injection (into cutaway vessel) at maximum 16.5° off-axis, depositing power up to 40 cm below the plasma major radius.

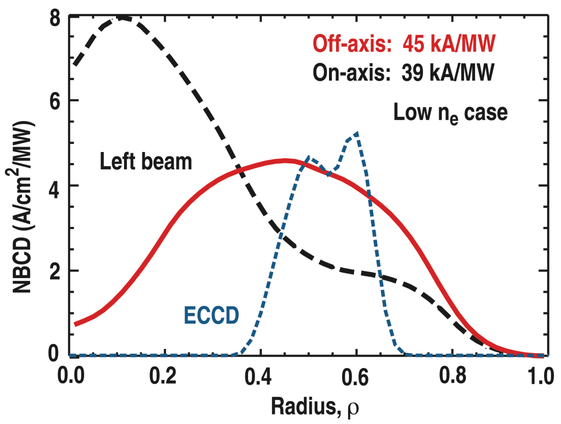

Fig. 2 Transport modeling predicts on- and off-axis NBCD and ECCD current drive efficiencies to be comparable.

Planned ECH upgrades call for the addition of two more gyrotrons to the system in the future. The output power of the first of these new “depressed collector” gyrotrons will be 1.2 MW. A prototype of this gyrotron was tested several years ago and the new system is currently being built. The gyrotron vault is being expanded to accommodate the new tube and the power supply and waveguide are under construction. Factory tests of the first new gyrotron are scheduled for completion by July 2011. The second new gyrotron will operate at 117.5 GHz at a power level of 1.5 MW and the design of this system has been initiated. Long-range plans call for a 15 MW ECH system based on this gyrotron.

The ECH system is making additional improvements by rebuilding the waveguide runs from the gyrotron vault to the vacuum vessel, eliminating several miter bends to increase the delivered power to the plasma. Also, new electric motors have been implemented recently on the steerable mirrors in the launcher, allowing the ECH launch angle into the plasma to be controlled by the PCS during the discharge (Section 3).

2.3 Fast wave

The DIII-D Fast Wave system consists of three 4-strap antennas, each connected to a high power amplifier for launching radio frequency waves into the plasma. Two antennas are powered by 90 MHz transmitters that have recently been upgraded to 2 MW. Operation of these two systems for short pulses has already been achieved. The other transmitter operates at 1.5 MW with a frequency of 60 MHz. The power coupled to the plasma from Fast Wave was increased recently with the use of localized antenna gas puff systems. The discreet gas puff systems increase the density at the plasma edge near the antenna, thereby improving the power coupling.

Additional Fast Wave system upgrades include the construction of a new arc high loading detector (HLD) that allows an increase in the ratio of forward to reflected power. The HLD enables antennas to operate at higher power during H-mode plasmas, for example, even in the presence of perturbations such as ELMs, which would normally have produced arc faults. Future upgrades to the fast wave system include the movement of antennas closer to the plasma, additional discreet gas puffing, and increasing the pulse lengths of the 2 MW systems.

3. Plasma control system

The PCS is a collection of high-speed processors that collect digital signals from various diagnostics, run algorithms, and output commands to plasma "actuators" such as power supplies, heating systems, etc. [4]. Several improvements have been made recently to improve the performance, increase speed, and update the hardware. A new cPCI-based system has replaced an older VME system in the analog output section. User interface graphics have been modernized by using Qt instead of Kylix, which also facilitates easier sharing with remote sites for remote operation and collaborative experiments.

A new Profile Control Algorithm has been developed for the PCS that uses real-time safety factor (q) profile calculations to perform feedback control on actuators affecting I_p, neutral beam injection, plasma density, and ECH power. A successful test was carried out in which the ECH launch mirrors were controlled from the PCS during a plasma discharge. Changing the injection angle of the ECH power by moving the mirrors allows ECCD to be deposited at a specific location within the plasma. This technique can stabilize MHD modes, for example, by driving current at the "O" point of an island to decrease the island width. Figure 3 shows an example of a successful test in which the ECCD power is swept across the region in the plasma where the m/n=3/2 mode is resonant. A clear reduction in the mode amplitude is evident when the power is deposited in the location of the resonance.

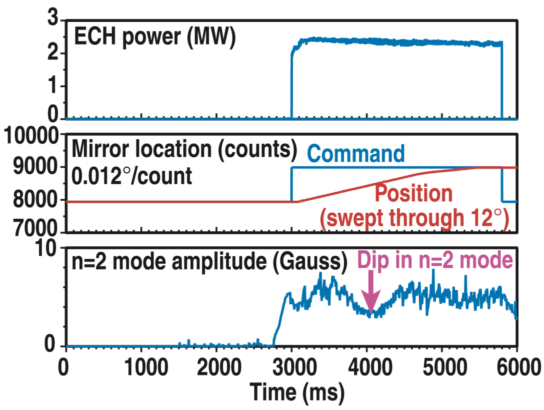

Fig. 3 ECCD deposition location is swept by programmed mirror movement, affecting the amplitude of the n=2 mode.

4. Diagnostics

Advances in fast-framing camera technology have allowed the development of high-resolution visible imaging for studying phenomena at the core of plasmas in DIII-D. A variety of high-energy phenomena are studied by imaging emissions from various contributors that include bremsstrahlung, injected neutrals, and Doppler-shifted D_α light from fast ions [5,6]. For example, the Fast Ion D_α diagnostic (FIDA) [7] uses charge-exchange recombination spectroscopy on fast ions interacting with injected neutral beams. The large Doppler shift moves the emissions away from the otherwise overwhelming D_α background and allows the study of fast ion acceleration by Fast Wave injection, fast ion transport by MHD modes and microturbulence, and fast-ion driven instabilities.

The beam emission spectroscopy (BES) system measures the D_α emission from the neutrals injected into the plasma or a neutral gas. Beam injection into neutral helium gas is a useful process, since it eliminates all other sources of emission in the system bandpass filter except the Doppler-shifted D_α light. The resulting signal is processed to remove camera vignetting and each column of pixels is normalized to produce the result shown in Fig. 4, where the vertical profile of the injected neutral beam has been imaged. The resolution is good enough to measure the beam divergence (on the order of 1°) as it propagates through the plasma. FIDA and BES system upgrades planned for the near future include adding image intensifiers for a factor of ~200 increase in gain and larger bandwidth operation. Additional viewing angles will result in better velocity-space resolution. An image splitter or additional camera will be added to simultaneously acquire and image the data from beam deposition and large bandwidth fluctuations, as well as lower bandwidth FIDA data.

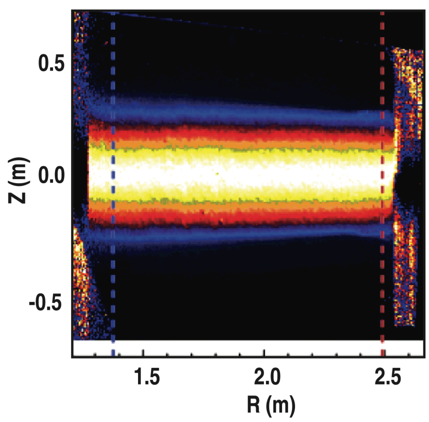

Fig. 4 BES diagnostic uses data from beam injection into helium gas to measure vertical profile of neutrals. Variation with radius yields beam divergence.

A new electron cyclotron emission imaging (ECEI) diagnostic was commissioned on DIII-D that measures electron temperature fluctuations using a radial and vertical array of 320 detectors [8]. The instrument has high spatial and temporal resolution and provides the capability to study and image MHD activity such as tearing modes, sawteeth, and Alfvén eigenmodes. Dual objective lens systems control the focusing from the edge to the core and large aperture zoom optics provide a wide range of vertical plasma coverage. An example of the kind of data this system can provide is shown in

Fig. 5, where a sawtooth crash is imaged. This diagnostic has also provided the first 2-D images of Alfvén eigenmode activity on DIII-D. Future upgrades to the ECEI system are planned that will enhance its capabilities, enabling it to be more efficiently utilized in upcoming experimental campaigns.

Several other upgrades are planned for various diagnostics on DIII-D. The Doppler Backscattering (DBS) system is being improved to measure higher wavenumber density fluctuations (k ~ 2-3 cm^{-1}) to study zonal flows and flow shear. The correlation electron cyclotron emission system is being coupled to the DBS system to study correlated temperature and density fluctuations. In the near future, a fast charge exchange recombination system will be added to study ion fluctuations.

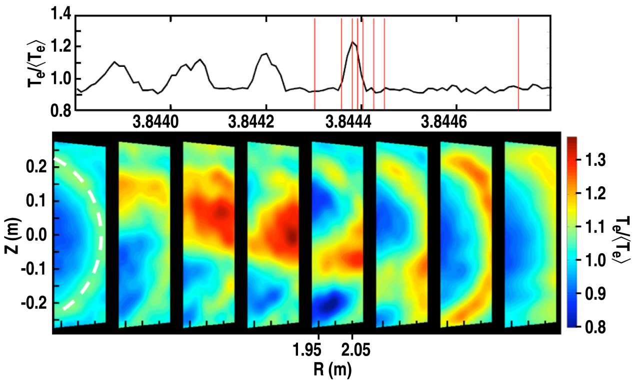

Fig. 5 High-resolution ECE fluctuation data, showing a typical sawtooth crash, or localized reconnective event near the q=1 flux surface (shown by dashed line at left). Top plot is the time trace (near 3.84 s) from one of the 160 channels used to create the eight 2-D plots in R-Z space, at times marked by the red vertical lines.

Following the success of the prototype Fast Ion Loss Detector system over the last year, a second system is being installed on the outer midplane of the tokamak. Both systems measure losses of beam ions to the outer wall and are used to diagnose loss mechanisms associated with MHD activity such as Alfvén eigenmodes. A new High Resolution Edge Thomson Scattering system is being designed and installed that will compliment the existing Thomson Scattering system to further diagnose the pedestal region where very steep gradients exist. A spatial resolution on the order of 3 mm is expected, well below the presently known width of the pedestal. A new tangential periscope is also being designed and fabricated that will house both visible and infrared cameras. The new system will allow fast, high resolution diagnosis of heat flux and localized events in the lower divertor and outer midplane near the limiters. Finally, a new soft x-ray camera is being installed below the midplane of the tokamak that will image fine structures such as magnetic islands associated with 3-D magnetic fields applied by perturbation coils. The camera will look tangentially at the lower X-point region where these islands are expected to be spatially large due to the local flux expansion.

5. Conclusions

The DIII-D tokamak continues to evolve in order to remain at the forefront of fusion research. Upgrades are being made to the auxiliary heating systems, plasma control system, and plasma diagnostics to facilitate experiments that explore higher performance plasmas and more ITER-relevant physics regimes. Some of the most exciting future capabilities described here include the off-axis neutral beam injection system currently under construction, increased ECH and Fast Wave power, real-time feedback control of the ECCD injection angle, and some new high resolution 2-D imaging diagnostics.

Acknowledgments

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References

[1] A.P. Colleraine, et al., “The DIII-D Long Pulse Neutral Beam System,” Proc. 11th Symp. on Fusion Engineering, Austin, Texas (1985) p. 1278.

[2] J.T. Scoville, Fusion Sci. and Technol. **52**, 398 (2007).

[3] P.M. Anderson, “Mechanical Design of the Positioning System for DIII-D Off-axis Neutral Beam,” Proc. 23rd Symp. on Fusion Engineering, San Diego, California (2009).

[4] B.G. Penaflor, et al., Fusion Eng. & Design **84,** 1484 (2009).

[5] M.A. Van Zeeland, et al., Nucl. Fusion **50**, 084002 (2010).

[6] M.A. Van Zeeland, et al., Plasma Phys. Control. Fusion **52**, 045006 (2010).

[7] W.W. Heidbrink, et al., “Fast-ion D-alpha Measurements of the Fast-ion Distribution Function,” Proc. 18th Topical Conference on High-Temperature Plasma Diagnostics, Wildwood, New Jersey, 2010, accepted for publication in Rev. Sci. Instrum.

[8] B. Tobias, et al., “Commissioning of Electron Cyclotron Emission Imaging (ECEI) Instrument on the DIII-D Tokamak and First Data,” Proc. 18th Topical Conference on High-Temperature Plasma Diagnostics, Wildwood, New Jersey, 2010, accepted for publication in Rev. Sci. Instrum.