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NONINDUCTIVE CURRENT DRIVE EXPERIMENTS ON DIII-D, AND FUTURE PLANS

by

R. PRATER, M.E. AUSTIN,* F.W. BAITY,[†] R.W. CALLIS, S.C. CHIU,
J.S. deGRASSIE, R.L. FREEMAN, C.B. FOREST, R.H. GOULDING,[†]
R.W. HARVEY, D.J. HOFFMAN,[†] H. IKEZI, J. LOHR, R.A. JAMES,[‡]
K. KUPFER,[‡] Y.-R. LIN-LIU, T.C. LUCE, C.P. MOELLER, C.C. PETTY,
R.I. PINSKER, M. PORKOLAB,[‡] J.P. SQUIRE,[‡] and V. TRUKHIN[‡]

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*University of Maryland

[†]Oak Ridge National Laboratory

[‡]Lawrence Livermore National Laboratory

[‡]ORISE Postdoctoral Fellow

[‡]Massachusetts Institute of Technology

[‡]Kurchatov Institute

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R. Prater, M.E. Austin,* F.W. Baity,[†] R.W. Callis, S.C. Chiu, J.S. deGrassie, R.L. Freeman,
C.B. Forest, R.H. Goulding,[†] R.W. Harvey, D.J. Hoffman,[†] H. Ikezi, J. Lohr, R.A. James,[‡]
K. Kupfer,[§] Y.R. Lin-Liu, T.C. Luce, C.P. Moeller, C.C. Petty, R.I. Pinsker, M. Porkolab,[¶]
J.P. Squire,^{||} and V. Trukhin^{||}

General Atomics

P.O. Box 85608, San Diego, California 92186-9784, U.S.A.

Abstract

Experiments on DIII-D (and other tokamaks) have shown that improved performance can follow from optimization of the current density profile. Increased confinement of energy and a higher limit on beta have both been found in discharges in which the current density profile is modified through transient means, such as ramping of current or elongation. Peaking of the current distribution to obtain discharges with high internal inductance ℓ_i has been found to be beneficial. Alternatively, discharges with broader profiles, as in the VH-mode or with high beta poloidal, have shown improved performance. Noninductive current drive is a means to access these modes of improved confinement on a steady state basis. Accordingly, experiments on noninductive current drive are underway on the DIII-D tokamak using fast waves, electron cyclotron waves. Recent experiments on fast wave current drive have demonstrated the ability to drive up to 180 kA of noninductive current using 1.5 MW of power at 60 MHz, including the contribution from 1 MW of ECCD and the bootstrap current. Higher power rf current drive systems are needed to strongly affect the current profile on DIII-D. An upgrade to the FWCD system is underway to increase the total power to 6 MW, using two additional antennas and two new 30 to 120 MHz transmitters. Additionally, a 1 MW prototype ECH system at 110 GHz is being developed (with eventual upgrade to 10 MW). With these systems, noninductive current drive at the 1 MA level will be available for experiments on profile control in DIII-D.

*University of Maryland, College Park, Maryland, U.S.A.

[†]Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

[‡]Lawrence Livermore National Laboratory, Livermore, California, U.S.A.

[§]Oak Ridge Institute for Science and Education Postdoctoral Fellow.

[¶]Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A.

^{||}Kurchatov Institute, Moscow, Russia.

1. CURRENT DRIVE PROGRAM ON DIII-D

A program is actively underway on the DIII-D tokamak to develop means of control of the current profile. This program is motivated by observations on DIII-D and some other tokamaks that both energy confinement and beta limits can be improved through the proper choice of the current profile. On DIII-D, this has been demonstrated in a series of experiments in which the current profile has been modified through techniques which are inherently transient in nature: dynamic ramping of the plasma current or elongation [1,2]. By these means, discharges with a peaked current profile characterized by high internal inductance ℓ_i have been generated. These discharges have energy confinement times up to 3.6 times the L-mode scaling and beta values up to twice the Troyon limit. The improved energy confinement is manifested as an increase in both the density and temperature of the plasma. In experiments in which the density has been held constant through use of the divertor cryopump, the increase in confinement appears as a larger increase in temperature. These discharges in modes of improved confinement therefore become attractive targets for current drive, which is most efficient at high temperature and low density.

In addition to the high ℓ_i discharges, other modes of improved confinement have been achieved in DIII-D. These modes include the VH-mode, in which the current near the edge of the plasma generated by the bootstrap effect appears to play a crucial role; the second stable core, in which $q'(\psi)$ is negative near the axis; and the high β_p discharge, which exhibits improved confinement when the safety factor on axis $q(0)$ is greater than 2. In VH-mode, the energy confinement time is in the range 2 to 2.5 times the JET/DIII-D H-mode scaling and the beta (normalized by I_p/aB) is up to 4.2.

The purpose of the current drive program on DIII-D is to achieve the performance improvement of the improved confinement modes in a manner which can be projected to steady state. If successful, this can lead to reactors which require less plasma current to provide satisfactory confinement for ignition and which can operate at higher beta than expected from the usual limits on tokamaks. The reduction in plasma current also leads to reduced sensitivity of the power balance to the efficiency of the current drive technique. Bootstrap current is projected to provide a large fraction of the total current without a cost in power.

Experimental programs are underway on DIII-D on fast wave current drive (FWCD) [3,4] and electron cyclotron current drive (ECCD) [5] to develop means of controlling the current profile. The FWCD tends to be deposited where the electron temperature is highest, which is near the center of the discharge. FWCD is therefore particularly useful for generating discharges with high ℓ_i , in which the current is highly peaked on axis. ECCD has highest efficiency when it is localized near the axis, but it can also be conveniently placed well off axis by aiming the antennas toward the desired location or by changing the frequency or magnetic

field to move the resonance to the proper place. This is important for generating discharges in which the core is in the second stable regime. The combination of FWCD and ECCD will provide a unique degree of control over the current profile in DIII-D.

The experiments described in this paper were performed in DIII-D in double null configuration with major radius of 1.68 m, minor radius of 0.68 m, and elongation near 2. The working gas was deuterium. The walls of the vacuum vessel were fully covered by graphite tiles, and the vessel was boronized to reduce the gas recycling at the wall. Glow discharge cleaning in helium was also performed between discharges to reduce recycling. These techniques were effective in reducing the density increase which usually accompanies the application of fast wave power.

In these experiments electron cyclotron power was applied using the 60 GHz system. Up to 1.4 MW can be launched from the inboard wall. The launch angle is 15° from radial in the toroidal direction, which drives ECCD current in the same direction as the bulk plasma current. The ECCD so driven must be accounted for in the analysis.

1.1. Fast Wave Current Drive

The fast wave current drive antenna [6] is located on the outer midplane of the vessel, as shown in the midplane cross section view of Fig. 1. It has four current straps spaced 22 cm between centers. Each strap has a vacuum feedthrough to provide for independent phasing. The straps are 45 cm high and 11 cm wide. The antenna is powered by a 2 MW source operating at 60 MHz. The maximum power delivered to the plasma is 1.6 MW.

The Faraday screen used in these experiments is a single layer of inconel rods which are tilted to be parallel with the total magnetic field for plasma current of 0.5 MA and toroidal field of 1.0 T. The rods are plasma sprayed with a boron carbide coating approximately 0.1 to 0.3 mm thick, depending on the location of the measurement. This Faraday screen replaced a double layer, optically opaque, titanium carbide/nitride coated Faraday screen which was used in previous experiments.

Tuning of the antenna is facilitated by use of feedback control of the plasma position to keep the loading resistance of the antenna fixed, which is implemented through the digital control system that controls the parameters of the plasma equilibrium. This approach is capable of adjusting the loading quickly enough that the transmitter does not roll back at the L-H transition, which normally causes a large reflection of power due to the loading mismatch of the steeper density profile of the H-mode. Additionally, a decoupler was found to be very effective in countering the effect of the mutual inductance between the straps of the antenna in current drive phasing. The decoupler has proved very successful in generating the desired currents and phasing over a wide range of plasma conditions in DIII-D [7].

A newly installed array of rf pickup loops was placed at several locations (shown in Fig. 1) to study the propagation and absorption of fast waves. The loops on the centerpost were placed behind the tiles, and the loops on the outer wall were in port cavities. The outer

FIG. 1. A cross-section at the midplane of DIII-D showing the FWCD antenna, the rf pickup loops labeled A through G (loops A and B do not lie on the midplane but are projected to the midplane), and the reflectometer.

wall probes A and B were placed above and below the midplane in order to lie approximately along a field line from the antenna. In all locations, measurements of both the fluctuating poloidal magnetic field $\tilde{B}_p$ and the toroidal field $\tilde{B}_t$ were made. Each magnetic fluctuation signal was beat with the applied rf and detected in quadrature, giving $|\tilde{B}_p| \sin \phi$, $|\tilde{B}_t| \sin \phi$, $|\tilde{B}_p| \cos \phi$, and $|\tilde{B}_t| \cos \phi$, where ϕ is the phase angle. Therefore, the phase, amplitude, and polarization of the detected wave are available as a function of time at the location of each loop.

The rf pickup loops illustrate some properties of the launched wave. Figure 2 shows an example for the beginning of a discharge. The antenna is phased (0,0,0,0) and the fast wave power is very low, about 10 W. The signal in Fig. 2(d) is $|\tilde{B}_t| \sin \phi$ from the loop directly across the plasma from the antenna (loop E in Fig. 1), and Fig. 2(e) shows the signal in quadrature to that in Fig. 2(d), from the same probe. These signals show a low frequency variation, which is due to the change in the phase at the pickup loop relative to the phase of the signal applied to the antenna caused by the gradual rise in density, Fig. 2(c). There is superimposed a high frequency component, which is due either to fluctuations in density or to components of the wave which travel a longer distance, maybe once around the torus, on the way to the pickup loop. The signal picked up on loop A, shown in Fig. 2(f), shows that the wave travels toroidally as well as directly across the plasma for 0° phasing. This can be understood from a study of the dispersion relation at high ω/Ω_i .

FIG. 2. Data from the startup phase of a discharge with very low power FW power in the (0,0,0,0) phasing. (a) Plasma current, (b) fast wave power, (c) line averaged density from a CO₂ interferometer, (d) the signal $|\tilde{B}_t| \sin \phi$ from pickup loop E of Fig. 1, (e) the signal $|\tilde{B}_t| \cos \phi$ from the same loop, and (f) the signal $|\tilde{B}_t| \sin \phi$ from loop A.

The pickup signals like those shown in Fig. 2 indicate the delay between the launched and the detected waves. The phase delay is proportional to the speed of the wave between the launcher and the detector. The phase velocity across the plasma is expected to be the Alfvén speed, $v_A = (B^2/M_i n)^{1/2}$, where M_i is the ion mass and n is the ion density. From this expression, $n = B^2 \phi^2 / \omega^2 L^2 M_i$, where L is the path length of the wave across the plasma.

Figure 3 shows the right hand side of this equation as a function of time for loop E for the discharge of Fig. 2. Also shown is the density derived from the CO₂ interferometer. A correction factor of order unity has been applied to get the best agreement, since the average ion mass is not well known early in the discharge. Figure 3 shows that the Alfvén speed is an excellent description of the propagation speed of the wave.

FIG. 3. Line averaged density, from the discharge of Fig. 2. Also shown is the quantity $c\phi^2$, where c is a constant. Here, ϕ is derived from the signals shown in Fig. 2(d) and 2(e).

The directionality of the antenna can be clearly seen from the signals from pickup loops A and B. Figure 4 shows a discharge at high power, 1.5 MW, in which the antenna phasing is $(0, 0, \pi, \pi)$. For this antisymmetric phasing, the wave is launched with equal power in the forward and backward toroidal directions. The large size of the low frequency components of Fig. 4(e) and (f), representing the signals from probes A and B, show that the wave travels directly from the antenna to those locations. The signal from directly across the plasma, however, has only a high frequency component, which indicates that the wave arrived there only after traveling a path much longer than the distance from the antenna to loop A or B.

For current drive phasing, $(0, \pi/2, \pi, 3\pi/2)$, the wave should travel in a single toroidal direction. This is shown in Fig. 5, for much the same conditions as for Fig. 4 except the

FIG. 4. Data from a discharge with 1.5 MW of fast wave heating with antisymmetric phasing $(0, 0, \pi, \pi,)$. (a) Plasma current, (b) fast wave power, (c) line averaged density, and the signals $|\vec{B}_t| \sin \phi$ (d) from pickup loop A of Fig. 1, (e) pickup loop A, and (f) pickup loop B.

antenna phasing. For current drive phasing, the direct pickup on loop B has disappeared, but the low frequency component, representing pickup after a short path length, remains on loop A. This is direct evidence that the spectrum is strongly weighted in the expected toroidal direction. Note that for these two discharges there was no ECH heating applied, so the electron temperature was low, about 1.5 keV, which makes the damping of the fast wave weak.

FIG. 5. Same as Fig. 4, except the antenna phasing is the directional current drive phasing ($0, \pi/2, \pi, 3\pi/2$).

Three types of fast wave current drive experiments were performed. In the first, the plasma was held in L-mode with fixed plasma current. On different discharges, the current was changed in order to determine the conditions under which the maximum fraction of the plasma current could be maintained noninductively. In the second type of FWCD experiment, the plasma current was ramped rapidly down just before or during the FWCD. In the third, the plasma was put into the H-mode through high power neutral beam injection before the FWCD was applied. The first two types of experiments used low toroidal field, about 1 T, along with second harmonic 60 GHz ECH. The high electron beta and high electron temperature

generated in this manner improve the single pass damping, but the density is limited to below $1.5 \times 10^{19} \text{ m}^{-3}$ by the ECH cutoff. The experiments with NBI were performed at 1.9 T, which was chosen to minimize the second harmonic hydrogen minority damping which can be a moderately strong absorber in NBI discharges with higher ion temperature.

The method of analysis follows that of work reported previously [5,3]. The profiles of electron density, electron temperature, and Z_{eff} are measured experimentally and used along with the reconstruction of the equilibrium from magnetic measurements to determine the resistance of the plasma from neoclassical theory. The bootstrap current is also calculated from the profile information. Then, assuming that the electric field is fully equilibrated inside the plasma, the surface loop voltage (after accounting for the time variation of the flux between the measurement loop and the surface of the plasma) which is needed to drive the current remaining after the bootstrap current is subtracted can be calculated from the current and resistance. This voltage can be compared with the measured voltage to determine the current which is driven noninductively.

Experiments with fixed plasma current showed that the largest fraction of the plasma current was supported noninductively when the total plasma current was 0.3 MA. The plasma was scanned from 0.2 MA to 0.5 MA to determine the current at which the noninductive fraction (FWCD, ECCD, plus bootstrap) was maximum. For currents significantly smaller than 0.3 MA, the electron temperature was too low for effective absorption of the fast wave, while at higher currents the relative fraction of the noninductive current fell. At 0.3 MA, up to 0.18 MA of the current was driven noninductively using 1.5 MW of fast wave power plus about 1 MW of ECH power. The divertor cryopump was used to help control the density rise which normally accompanies fast wave power; by this means, the density rise was held to a few times 10^{18} m^{-3} , out of a total density of about $1 \times 10^{19} \text{ m}^{-3}$. These FWCD results represent a moderate improvement over results presented previously, due primarily to increased rf power.

The phasing of the antenna clearly impacts the magnitude of the driven current. A matched pair of discharges, one with co-current drive phasing and one with symmetric phasing $(0, \pi, \pi, 0)$, was analyzed for FWCD. Analysis of these discharges, including error analysis, showed $92 \pm 40 \text{ kA}$ of driven current in the co-FWCD case and $31 \pm 40 \text{ kA}$ in the symmetric case. This demonstrates the ability of the analysis technique to discriminate current drive from heating. (In this analysis, counter-current drive cases were avoided due to the complication of the large effect of counter current drive on the sawteeth [3].)

The current drive efficiency of FWCD in this regime is about $\eta = 0.02$ to $0.03 \times 10^{20} \text{ A/m}^2\text{W}$. The new data points are shown in Fig. 6 along with the data points previously published [4]. It appears from this figure that the measured efficiency is improving linearly with electron temperature.

In the second set of experiments, in which FWCD was combined with a ramp-down of the plasma current, full current drive was demonstrated. For these experiments, the plasma current was ramped down from 0.4 MA to around 0.2 MA during combined FWCD and ECH injection. The purpose of the current ramp was to generate a discharge with high confinement

FIG. 6. The current drive efficiency as a function of central electron temperature.

relative to that of a steady discharge of the same current, due to the improved current profile (high ℓ_i) which is generated when current is removed preferentially from the outer part of the discharge. In this manner, a discharge with improved characteristics (higher temperature and lower current to support) is generated. The resultant high ℓ_i profile is also expected to more closely match the profile of driven current characteristic of FWCD.

Discharges with co-FWCD and with symmetric phasing were compared. During and just after the current ramp, the loop voltage was negative in order to decrease the current in accordance with the preprogrammed decrease in the reference current. In the co-FWCD case, the surface loop voltage was observed to remain negative while the high power FWCD and ECH were applied, as shown in Fig. 7. Changing the FWCD antenna phasing from co-current to a nondirectional phasing ($0, \pi, \pi, 0$) resulted in a more positive loop voltage, the analysis of which found no measurable current drive. This is shown in Fig. 8. These results indicate that complete current drive was achieved, albeit for a short period, and the amount of current drive depends upon the phasing of the FWCD antenna. The measured FWCD efficiency for

FIG. 7. Data from a discharge with symmetric antenna phasing (0, π , π , 0). (a) Fast wave power (dashed line) and ECH power (solid line), (b) plasma current (dashed line) and internal inductance ℓ_i (solid line), (c) poloidal beta β_p , and (d) surface loop voltage. The solid circles in (d) are the calculated loop voltage, assuming no current drive but including the calculated bootstrap current. The toroidal field is 1.1 T and the density is $0.85 \times 10^{19} \text{ m}^{-3}$.

full current drive cases is in reasonable agreement with the values determined experimentally for discharges with fixed current, as shown by the data point for a ramp-down case in Fig. 6.

In the third set of experiments, FWCD power was applied to H-mode discharges with several MW of neutral beam heating. The principal difficulty was coupling high power through the edge of the plasma in the presence of ELMs (Edge Localized Modes). For low frequency

FIG. 8. Data from a discharge with current drive phasing $(0, \pi/2, \pi, 3\pi/2)$. Same signals and conditions as for Fig. 7.

“giant” ELMs, the large changes in the plasma density near and just outside the separatrix caused very large excursions in the loading. This behavior is shown in Fig. 9. Typically, the loading increases during a giant ELM by a factor 5, from 1 to 2 Ω to nearly 10 Ω . These large increases in loading have the same effect on the VSWR as an arc would have, and therefore they invariably trip the reflected power monitor and cause the transmitter to roll back. This severely limits the power which may be applied to the plasma in the presence of giant ELMs.

For small frequent “grassy” ELMs, however, the effect is much smaller, as illustrated in Fig. 9. The ELMs are changed from giant to grassy by increasing the neutral beam power. Under this condition, it appears that the loading is able to average over the ELMs and produce loading which is independent of the phase of the ELM. The average loading stays at

FIG. 9. Data from discharge #79681 with large ELMs and from discharge #79476 with grassy ELMs. (a,f) Net coupled FW power, (b,g) light sensed by a photodiode as a measure of the ELM frequency, (c,h) the reflection coefficient for each of the two feed lines, (d,i) the loading resistance of the antenna, and (e,j) the gap between the separatrix and the outer wall. The power is low, 60 kW, for the discharge with giant ELMs, so that the transmitter will not be rolled back by the large reflection coefficient. The antenna phasing is current drive phasing.

an acceptable level in the neighborhood of 2Ω . The peak fast wave power which has been coupled in such discharges is 1 MW. These discharges were at higher density than normally used for current drive experiments, and due to the relatively low power and high density, current drive effects were not measurable.

1.2. Electron Cyclotron Current Drive

Experiments on DIII-D have found currents of up to 0.1 MA driven by ECCD, using about 1 MW of power at 60 GHz [5]. The experiments were performed in discharges with total current of 0.3 to 0.5 MA, densities of 1 to $2 \times 10^{19} \text{ m}^{-3}$, electron temperatures of 2.0 to 3.6 keV, Z_{eff} of 2.5 to 5.5, and toroidal field of 2 T. In these discharges, the electron distribution function is nearly Maxwellian, with no strong superthermal features.

In all cases, the current driven by ECCD is less than the total plasma current. This implies that an electric field remains in the plasma, and the modification of the distribution function due to the electric field has a measurable effect on the current driven by the electron cyclotron waves. At the same time, the ECH can generate a perpendicular tail which can pitch angle scatter into the parallel direction and increase the conductivity of the plasma even for fixed temperature of the bulk of the distribution. For these reasons, it is important to perform the analysis of the data using a Fokker-Planck code which includes these effects. Good agreement is obtained between the Fokker-Planck code and the experiment.

2. FUTURE PLANS

In order to support full quasi-steady state current drive with control over the profile of the current, new fast wave and ECCD systems are being prepared for DIII-D as part of the advanced tokamak program. These systems will provide the needed flexibility and power to support the development of discharges with improved confinement and beta limits.

The fast wave current drive system for DIII-D is being upgraded by 4 MW in the 30 to 120 MHz frequency range [8], in addition to the existing 2 MW, 30 to 60 MHz system. Two new ABB transmitters will be used to drive two new four-strap antennas. The transmitters have been installed, and installation of the antennas is scheduled for early 1994. The antennas will have recessed side walls, which improves the $k_{\parallel}$ spectrum but increases the mutual inductance, making the decoupler more important. The transmission and matching lines will be similar to those now installed on DIII-D, but with some important improvements. Resonant loops and a decoupler will be used in a manner very similar to that in the present installation, except that the resonant loops and decoupler will have elements to support operation over a range of frequencies. Another improvement is to use ceramic insulated, pressurized coaxial transmission lines. This system should be operable in mid-1994.

A new high power ECH system is also under development for DIII-D [9]. This system will operate at 110 GHz, using gyrotrons in the power range 0.5 to 1 MW. Such gyrotrons are being developed by Varian and by Gycom, and both types will be tested on DIII-D. A prototype transmission line has been installed for tests which will take place when a long pulse gyrotron is ready. The small diameter (31.75 mm) corrugated evacuated transmission line is expected to be suitable for powers well in excess of 1 MW. Bends are made through phase-corrected mitre bends. The antenna is a copper plated graphite plate which focuses and steers the beam with external control over the direction of the beam in the vertical plane.

Modeling of transport and current drive in DIII-D shows that 4.6 MW of fast wave power plus 2.5 MW of neutral beam power or ECH power can support a fully noninductive high ℓ_i discharge with average beta of 2% and total current of 1 MA. In order to achieve a second stable core configuration, it is necessary to drive current well off axis, and ECH is suitable for this purpose. With 8.5 MW of ECCD, 0.4 MA of current can be driven near $r/a \approx 0.5$, which supports the current profile expected to be stable to a beta above 5.7%.

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