

# FAST WAVE CURRENT DRIVE IN DIII-D

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**ABSTRACT**

The non-inductive current drive from fast Alfvén waves launched by a directional four-element antenna was measured in the DIII-D tokamak. The fast wave frequency (60 MHz) was eight times the deuterium cyclotron frequency at the plasma center. An array of rf pickup loops at several locations around the torus was used to verify the directivity of the four-element antenna. Complete non-inductive current drive was achieved using a combination of fast wave current drive (FWCD) and electron cyclotron current drive (ECCD) in discharges for which the total plasma current was inductively ramped down from 400 to 170 kA. For discharges with steady plasma current, up to 110 kA of FWCD was inferred from an analysis of the loop voltage, with a maximum non-inductive current (FWCD, ECCD, and bootstrap) of 195 out of 310 kA. The FWCD efficiency increased linearly with central electron temperature. For low current discharges, the FWCD efficiency was degraded due to incomplete fast wave damping. The experimental FWCD was found to agree with predictions from the CURRAY ray-tracing code only when a parasitic loss of 4% per pass was included in the modeling along with multiple pass damping.

**1. INTRODUCTION**

Ongoing experiments in the DIII-D tokamak are aimed at demonstrating fast wave current drive (FWCD) and confirming the theoretical basis in the ion cyclotron range of frequencies. The expected high current drive efficiency and good penetration of the fast wave to the center of a high temperature plasma makes FWCD an attractive method for sustaining the plasma current in tokamak fusion power plants. In DIII-D, FWCD is typically used in conjunction with electron cyclotron current drive (ECCD) which also heats the electrons. These non-inductive current drive techniques will provide control of the current profile for the advanced tokamak program in the near future when higher source power is available.

Previous experiments in DIII-D found efficient direct electron heating by fast waves using a symmetric antenna phasing [1]. Initial FWCD experiments used a single four-element toroidally phased antenna array to launch the fast waves with a highly directional spectrum [2,3]. The antenna was fed by a single 2 MW, 60 MHz transmitter. The coupled spectrum was peaked at  $|n_{\parallel}| \simeq 5$  for  $\pi/2$  phasing between adjacent elements.

**2. FWCD ANTENNA DIRECTIVITY**

An array of rf pickup loops at several locations around the torus was used to study the propagation and absorption of fast waves. The loops measured the amplitude, phase, and polarization of the detected wave as a function of time. The directivity of the waves launched by the antenna can be clearly seen from two sets of pickup loops, each located toroidally one-third of the way

around the torus in opposite directions from the antenna. For a non-directional antenna phasing, shown in Fig. 1(a), which launched equal power in both toroidal directions, both sets of pickup loops detected rf waves which traveled a direct path from the antenna to the loops (deduced by noting that the slow oscillation in the detected phase with changing density is the expected behavior for waves traveling a direct path). For co-current drive antenna phasing, shown in Fig. 1(b), only the pickup loop in the toroidal direction of the launched wave received a direct signal; the loop in the opposite direction detected the wave only after many bounces (evident from the fast oscillations in the detected phase due to the longer path length). This is direct evidence that the antenna spectrum is strongly weighted in the expected toroidal direction.

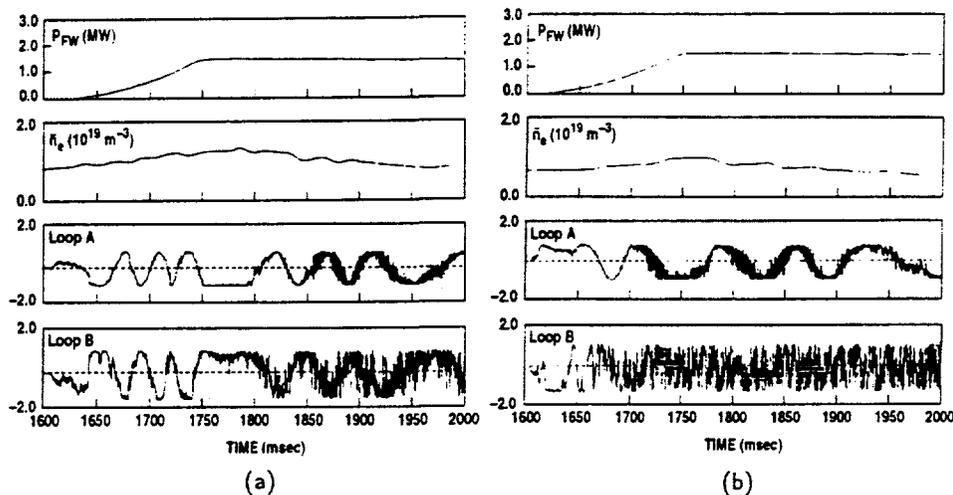


FIG. 1. Time behavior of fast wave power, line averaged plasma density, and the signals  $|\vec{B}_t| \sin \phi$  from pickup loops A & B in the co- and counter-directions relative to the FWCD antenna for (a) a non-direction antenna phasing, and (b) co-current drive antenna phasing.

### 3. FWCD EXPERIMENTS

#### 3.1. Partial Current Drive Discharges

Current drive experiments in DIII-D have coupled up to 1.6 MW of fast wave power with one antenna; this has been combined with an additional 1.1 MW of second harmonic electron cyclotron heating (ECH). The magnetic field strength for these experiments was 1.1 T, and the plasma current was varied from 0.2 to 0.5 MA on a shot-to-shot basis. The plasma shape was single null divertor, the working gas was deuterium, and a divertor cryopump was used to reduce the density rise during fast wave injection.

For discharges with partial non-inductive current drive, the level of rf current drive was determined by comparing the plasma resistance deduced from the measured surface loop voltage and plasma current (excluding the calculated bootstrap current) with that calculated from neoclassical resistivity, as illustrated in Fig. 2 for a 300 kA L-mode discharge with combined FWCD and ECCD. The ECH system was used to heat the electrons prior to fast wave injection to increase the fast wave damping; for these conditions the fast wave was observed to heat the electrons with the same efficiency as ECH. Figure 2 shows that in the ohmic phase of the discharge, the measured loop voltage ( $V_L$ ) and the calculated loop voltage assuming no rf current drive ( $V_L^*$ ) agree to within error bars ( $\pm 0.03$  V). However,  $V_L$  is significantly lower than  $V_L^*$  during fast wave injection, indicating the presence of rf current drive. The rf current drive was determined to be 135 kA during the combined FWCD and ECCD phase; the bootstrap current was calculated to be an additional 45 kA. The ECCD was computed to be 30 kA, thus the FWCD was deduced to be 105 kA during the combined rf phase. After the termination of the ECH pulse, the FWCD determined from the loop voltage analysis decreased to 45 kA. When the antenna phasing was changed from co-current drive to a non-directional phasing, no FWCD outside the error bars was observed.

The measured FWCD efficiency increased linearly with electron temperature, as shown in Fig. 3. The electron temperature was varied by applying ECH, as illustrated in Fig. 2. The theoretical FWCD efficiency, depicted as a straight line in Fig. 3, was calculated using the CURRAY ray-tracing code which assumed multiple pass absorption of the fast waves [4]. The favorable electron temperature scaling implies that the FWCD efficiency in a self-sustained plasma should increase by more than an order of magnitude over the DIII-D values.

For plasma currents below 0.3 MA, the FWCD efficiency degraded rapidly; the fast wave heating efficiency also decreased, indicating that the fast wave absorption for these low- $\beta$  plasmas was incomplete. As shown in Fig. 4, the  $T_e$ -normalized FWCD efficiency (without ECH) decreased by a factor of two when the first pass absorption fell below 4%. This data suggests that a weak loss mechanism may be competing with the direct electron damping of the fast wave. If this loss mechanism was on the order of a few percent per pass, then it would be negligible for cases of strong damping but important for cases of weak damping. A comparison of the experimental FWCD with the theoretical FWCD calculated by the CURRAY code, shown in Fig. 5, supports the existence of a parasitic loss since the disagreement between the calculated and measured current drive increases as the first pass absorption decreases. Including an *ad hoc* parasitic loss of 4% per pass in the CURRAY computation resulted in good agreement between the theoretical and experimental FWCD for cases of both weak and strong fast wave damping.

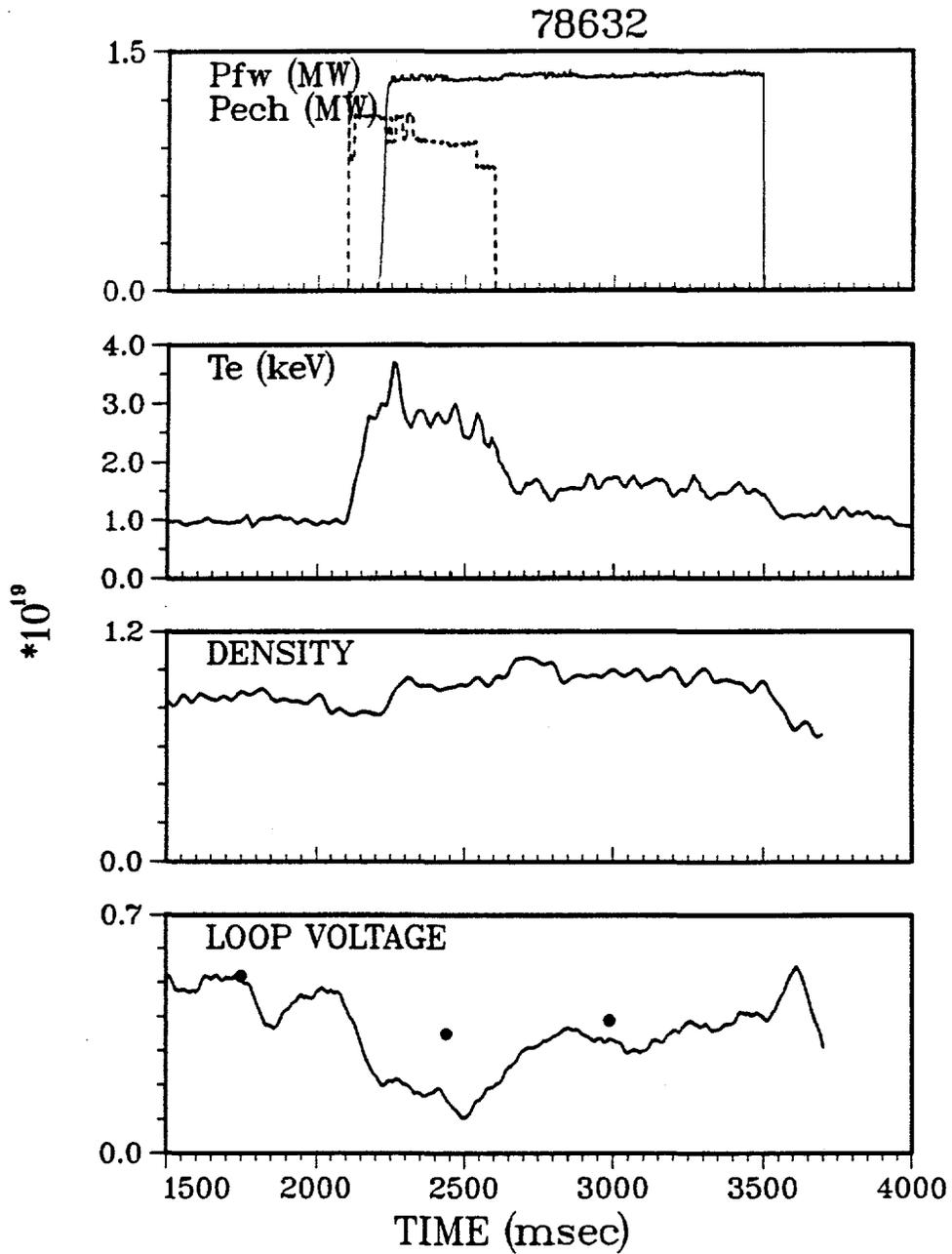


FIG. 2. Time behavior of steady current discharge with combined FWCD at 60 MHz and second harmonic ECCD at 60 GHz ( $I_p = 300$  kA,  $B_T = 1.1$  T). The solid circles represent the calculated loop voltage assuming no rf current drive ( $V_L^*$ ).

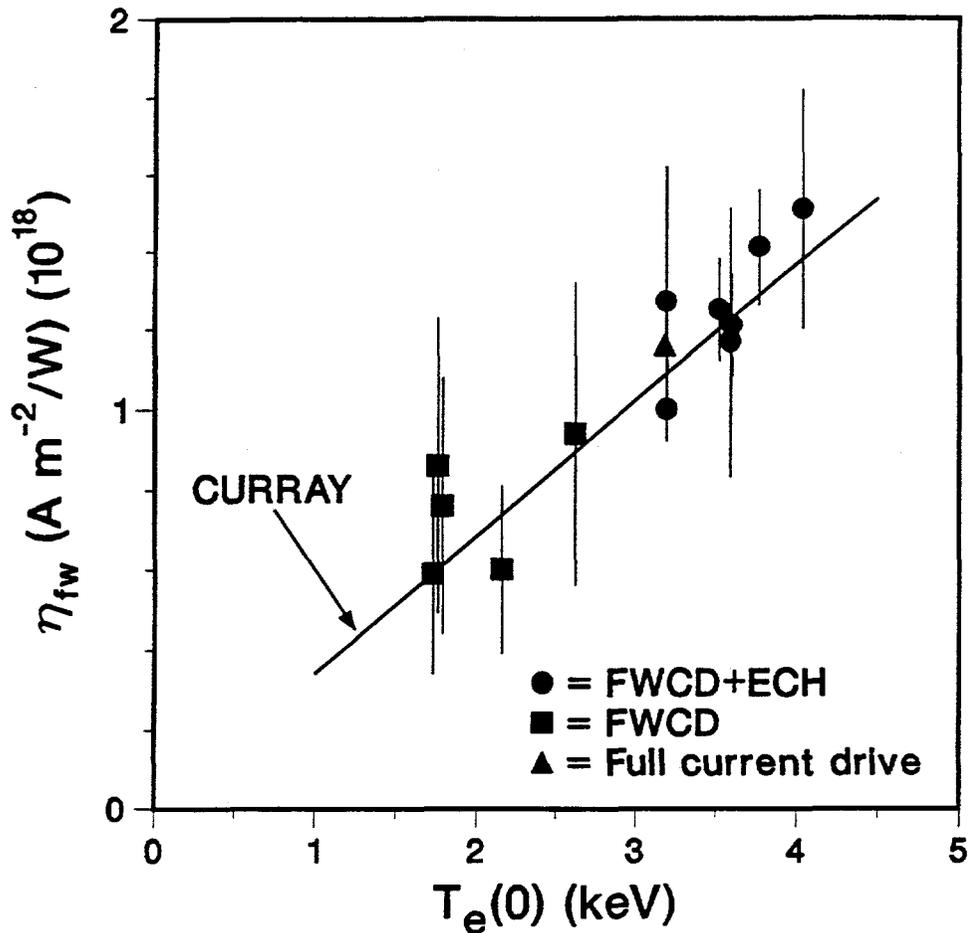


FIG. 3. Measured FWCD efficiency as a function of the central electron temperature. The theoretical scaling from the CURRAY ray-tracing code is also shown (a parasitic loss of 4% per pass was assumed).

### 3.2. Complete Current Drive Discharges

Discharges with 100% non-inductive current drive were achieved for short periods with combined FWCD and ECCD by rapidly ramping the current down from 0.4 to 0.17 MA (see Fig. 6). This allowed the creation of a discharge with high confinement compared to that of a stationary discharge of the same current. The higher temperature achieved in this manner resulted in more complete absorption of the fast wave at lower plasma currents, thus increasing the current drive efficiency. After the current ramp down, the surface loop voltage was observed to remain negative for as long as the FWCD and ECCD were applied, approximately 20 energy confinement times and 3 current

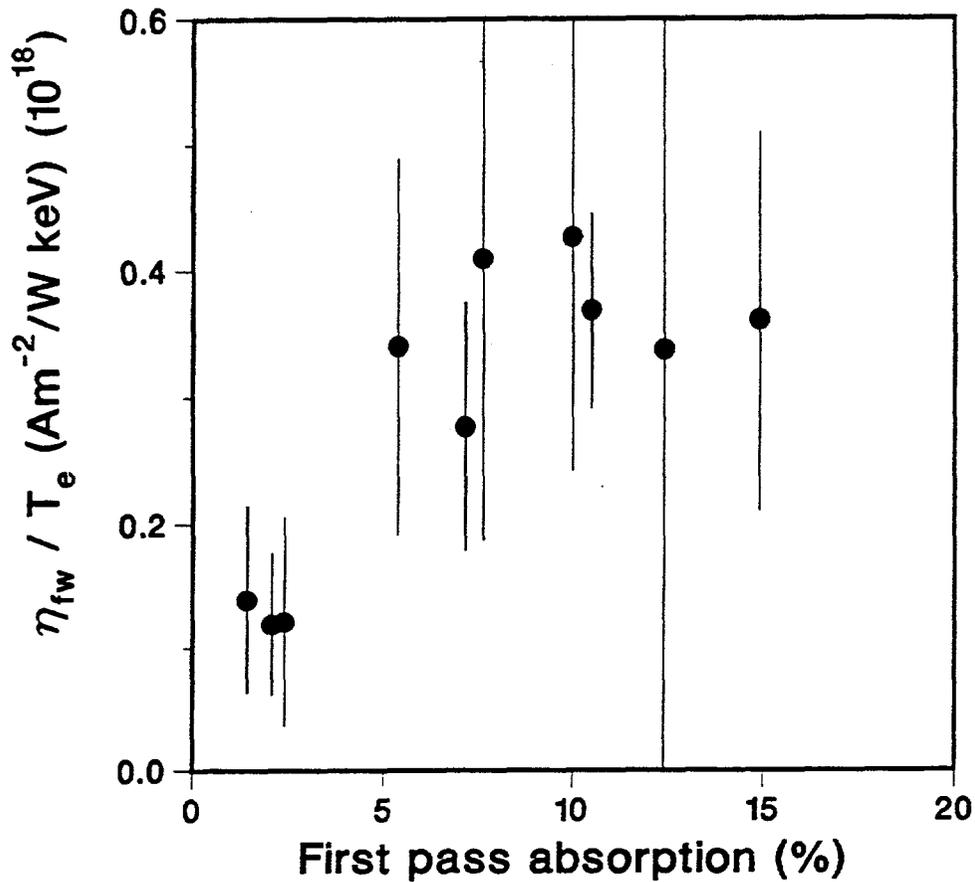


FIG. 4. Experimental FWCD efficiency normalized to central electron temperature as a function of the calculated first pass absorption during FWCD without ECH assistance.

profile relaxation times. The FWCD efficiency measured for full current drive cases, shown in Fig. 3, is in agreement with partial current drive cases and theoretical calculations. Changing the FWCD antenna from co-current to a non-directional phasing resulted in a positive loop voltage, the analysis of which found no measurable FWCD. These results indicate that complete current drive was achieved and that the amount of current drive depends upon the antenna phasing and good absorption of the wave.

#### 4. CONCLUSIONS

Up to 195 kA of non-inductive current drive has been measured in DIII-D (out of 310 kA), of which 110 kA was attributed to FWCD (the rest being ECCD and bootstrap current). Complete non-inductive current drive was achieved using a combination of FWCD and ECCD in discharges for which the

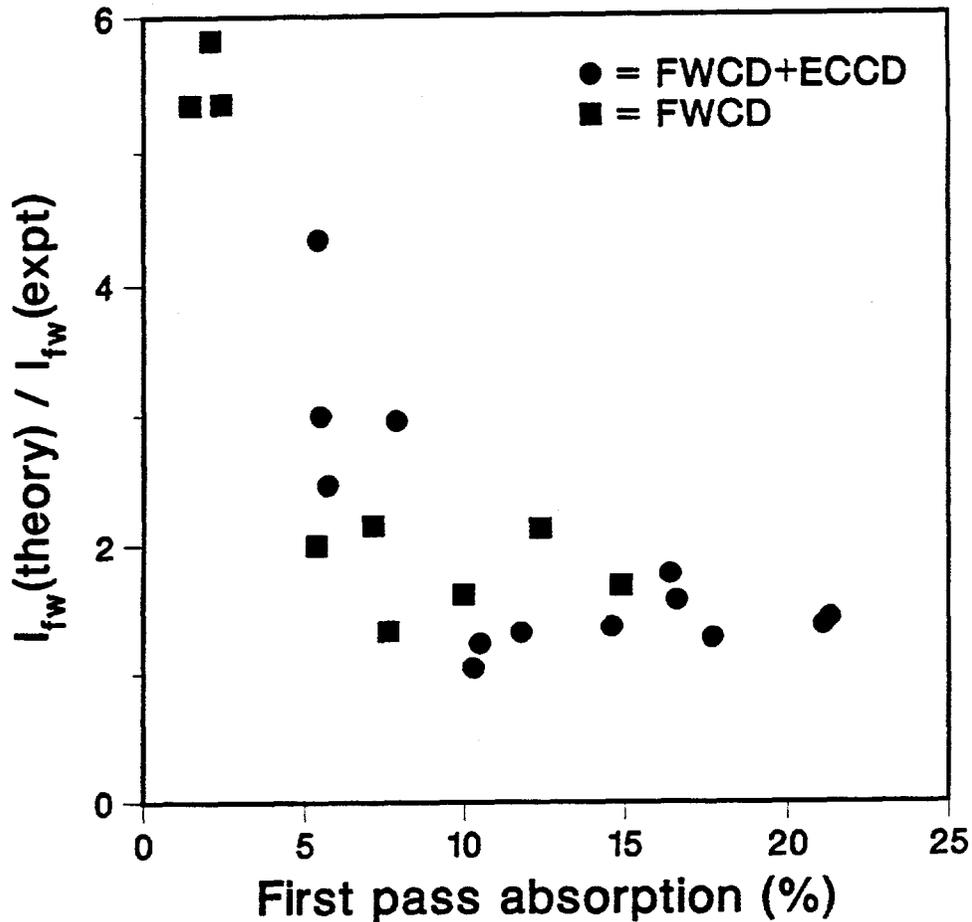


FIG. 5. Ratio of theoretical FWCD from CURRAY (assuming no parasitic loss) to measured FWCD as a function of the calculated first pass absorption.

total plasma current was inductively ramped down from 400 to 170 kA. The FWCD efficiency was observed to increase with central electron temperature.

In 1994 the DIII-D FWCD system is being upgraded with the installation of two  $2 \times 4$  (poloidal  $\times$  toroidal) phased antenna arrays connected to two variable frequency (30–120 MHz) transmitters. This should increase the level of FWCD to 0.3–0.4 MA. With the addition of 3 MW of 110 GHz ECH, which will allow higher FWCD efficiencies to be achieved, non-inductive currents of  $\sim 1$  MA are expected in advanced tokamak scenarios.

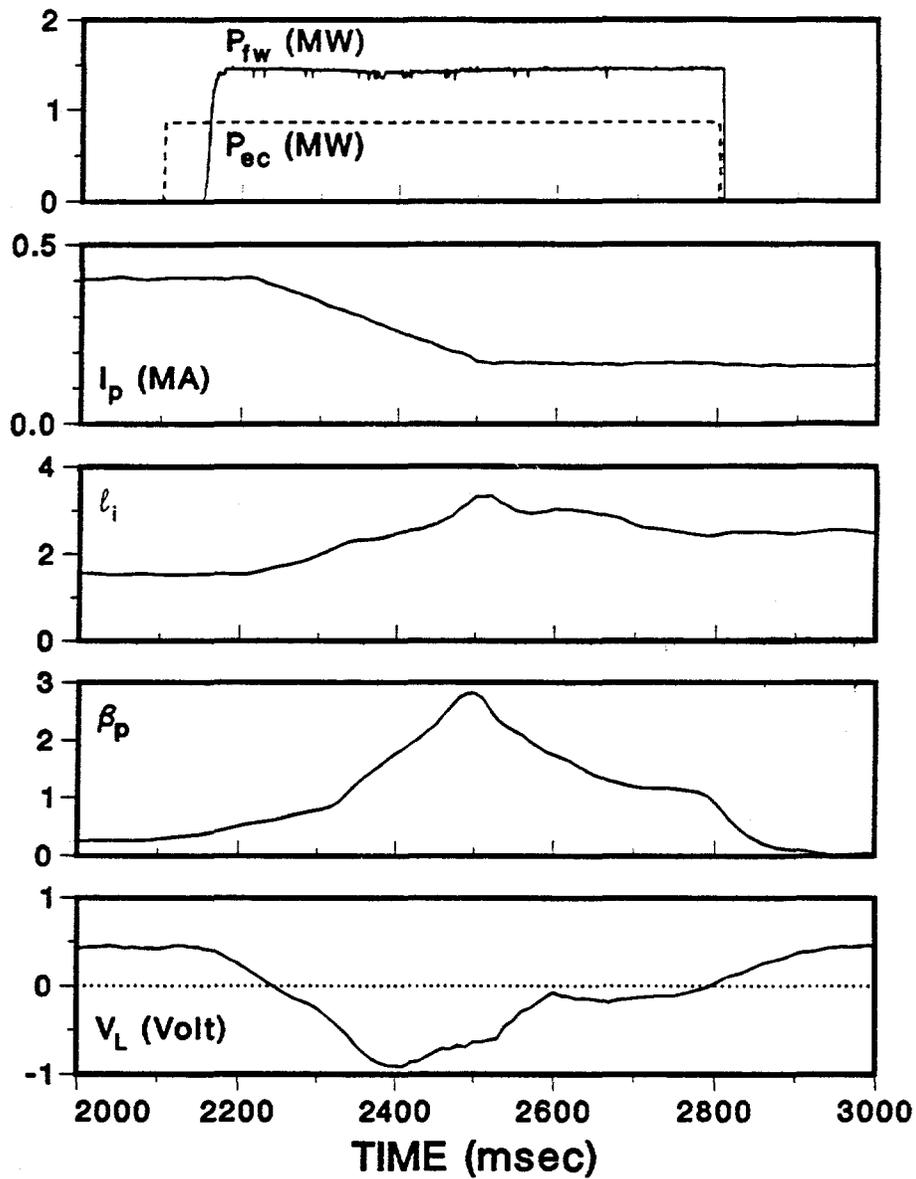


FIG. 6. Time history of negative current ramp discharge with combined FWCD and second harmonic ECCD for co-current drive antenna phasing ( $B_T = 1.1$  T,  $\bar{n} \approx 1 \times 10^{19} \text{ m}^{-3}$ ).

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