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LOWER-HYBRID CURRENT DRIVE WITH OPPOSING OHMIC DRIVE ON PLT†

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ABSTRACT

Two distinct conditions where the rf phase velocity is directed opposite to the ohmically induced electron drift have been studied experimentally:

(I) rf current ramp-up ($\dot{I}_p > 0$), where an induced electric field opposes the current increase;

(II) rf current ramp-down, where waves are launched opposite the electron drift direction for a decaying plasma current.

The time behavior of the electron tail is inferred from hard X-ray (30-750 keV) emission as a function of angle to $\underline{B}_o$. In cases (I) and (II) we find that the emission amplitude in the reverse (opposite the LH phase velocity) direction increases throughout the rf pulse, while it is constant in the forward direction. This increase indicates that some high-energy electrons are accelerated or are even running away in the direction opposite to the main rf-produced tail. It also indicates for case (I) that the electric field in the plasma center has been reversed by the rf current drive.

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I. INTRODUCTION

Radio frequency (rf) current drive in combination with opposing electric fields is of practical importance in tokamak operating scenarios where the rf is used to ramp-up the plasma current or where the rf is used to maintain the plasma current fixed while the OH primary current is being reversed.[1] In fact, rf current drive interacts with electric fields whenever the tokamak discharge is not in a steady state, i.e., $\dot{I}_{OH} \neq 0$, $\dot{I}_{EF} \neq 0$, $\dot{I}_p \neq 0$, or $\dot{\ell}_i \neq 0$, where I_{OH} is the ohmic primary current, I_{EF} is the vertical field current, I_p is the plasma current, and ℓ_i is the plasma internal inductance. The experiments discussed in this paper were done using the 800 MHz lower hybrid system on the PLT tokamak. Two conditions where the rf phase velocity is directed opposite to the ohmically induced $[\underline{E} \sim (1/2\pi R_o)\ (-V_{OH} + L\dot{I}_p + 1/2 I_p \dot{L})]$ electron drift (v_{ph} parallel to $\underline{E}$) have been studied:

(I) rf current ramp-up ($\dot{I}_p > 0$), where an induced electric field opposes the current increase;

(II) rf waves launched opposite the electron drift direction for a decaying plasma current.

The OH primary current was held nearly constant in these experiments, so that electric field effects due to the changing plasma current, and, to a lesser extent, changing plasma inductance could be studied.

II. EXPERIMENTAL RESULTS

The isotropy of the rf produced electron tail is inferred from measurements of hard X-ray emission (30–750 keV) as a function of angle to the external magnetic field, $\underline{B}_o$. This is possible because the hard X-ray emission patterns are strongly shifted toward the direction of incident electrons for electron energies typical of lower hybrid current drive. Figure 1 shows X-ray intensity emission patterns for a 100 keV electron. Distortions of the electron distribution at lower energies (< 30 keV) may also affect the performance of current drive, but measurements of the distribution anisotropy at these energies are more difficult due to the more isotropic bremsstrahlung emission. Changes of the hard X-ray spectrum as a function of time during the rf pulse are taken as evidence of electric fields in the plasma. Since the tail temperature is high, rather small electric fields with loop voltages of ~ 0.1 V for case I and ~ 0.25 V for case II will subject 100 keV electrons to the Dreicer field for runaways and thus should strongly affect the electron tail.

Figure 2 shows the plasma current, internal inductance, and applied rf power for condition (I). The plasma current is ramped-up at a rate of ~ 60 kA/sec using 200 kW of lower hybrid power with a phasing of $\Delta\phi$ ~ -90° between waveguides. Coupling calculations for this case indicate that ~ 85% of the rf power travels in the electron drift direction with a spectrum peaking at $n_\parallel$ ~ 2.25, and the remaining 15% travels in the opposite direction with $n_\parallel$ ~ 7.

The tangential hard X-ray spectra early and late in the rf pulse are shown in Fig. 3. The spectra in Fig. 3b were taken with a NaI detector viewing the plasma center almost tangentially to the magnetic field with the waves and the electrons carrying the current approaching the detector. This viewing direction is labeled θ_d = 28°. The spectra in Fig. 3a were taken with the same view but with the plasma current, the fields, and rf phasing reversed (θ_d = 152° direction). Emission in the θ_d = 28° direction is about a factor of four higher than the θ_d = 152° direction, which is typical of all current

current drive cases we have studied. There is no significant change with time in the X-ray spectrum as viewed at $\theta d \approx 28°$, i.e., in the wave direction. This is also typical during steady-state conditions (there is an initial transient for the first 50 ms while the fast tail is being formed). However, the spectrum viewed at $\theta d \approx 152°$ shows a small but significant increase in X-ray emission as a function of time during the rf pulse, which implies a force accelerating electrons in the direction opposite to the wave phase velocity. The direction of this force agrees with the direction of the induced electric field, $\underline{E} = (1/2\pi R_0)\, L\dot{I}_p$, caused by increasing the plasma current. The induced electric fields due to other changing currents are small and are all in the opposite direction. The spectrum viewed at $\theta_d = 152°$ does not change with time when the current is not ramped-up, which shows that the buildup of the reverse spectrum for the ramp-up case (I) is not due to delayed scattering of electrons from the forward tail. We conclude for the ramp-up case (I) that the rf driven current turns off, and in fact reverses, the electric field in the plasma center, so that the rf current drive works against the inductive field.

Another case where rf driven currents oppose an electric field occurs when the waves are launched opposite the electron drift for a decaying plasma current (case II). The expectation would be that the plasma current should decrease even faster than with no rf. Figure 4 shows the plasma current and internal inductance for a case where 270 kW is launched primarily in the direction opposite to the electron drift. The decay of the plasma current turned out to be much less than if there had been no rf. Figure 5 shows hard X-ray spectra viewed at $\theta d = 28°$ and 152° to the wave phase velocity and taken at times 300 ms apart. The striking feature of these spectra is the evolution of an energetic tail viewed at $\theta d = 152°$, i.e., opposite to the direction of the waves. The tail gradually becomes more energetic with time during the rf pulse, indicating that electrons are running away in the original electron drift direction. The direction of electron runaway is again consistent with acceleration by an electric field induced by the changing plasma current. A quantitative comparison of the amplitudes of the spectra on both sides of Fig. 5 is unfortunately not possible because the count rate was too high when the data were taken, so that some counts were lost. The basic conclusions regarding the direction of acceleration of the electron tail are not affected.

In this discussion we have neglected effects due to changing plasma current profiles, although the $\beta_\theta + \ell i/2$ signals indicate that these effects could be important. More theoretical modeling will be required to investigate these effects. Experimentally, a radial scanning hard X-ray detector would be helpful for unfolding the parallel spectra as a function of radius.

III. CONCLUSION

Two cases where rf driven currents oppose electric field induced currents have been studied. For rf current ramp-up (case I), the increase of the intensity of the $\theta d \simeq 152°$ spectrum indicates that the rf driven current has reversed the electric field in the plasma center. For the attempted current "ramp-down" (case II), the $\theta d \simeq 152°$ spectrum becomes even more distorted and energetic, and the expected current ramp-down is not observed. Taken together, these data suggest that the rate of current ramp-up or ramp-down by rf may be limited by distortions of the electron spectrum set up by the opposing induced electric field due to $L\dot{I}_p$. We propose that the condition $L\dot{I}_p \lesssim E_D 2\pi R_o$ may constitute an approximate limit on the rate of current change during rf current drive, where E_D is the Dreicer field, i.e., the field at which electrons run away, evaluated for superthermal (~ 100 keV) electrons. There is qualitative agreement with this criterion from attempts to ramp-up the plasma current. The extra power required to ramp the current up exceeds the power necessary to increase the inductive energy ($1/2\ LI_p^2$). For case (I) this extra power amounts to ~ 140 kW compared to ~ 30 kW going into the inductive fields. More experimentation is required to generalize these observations to other plasma conditions with different density, current, temperature, rf phasing, and rf power.

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REFERENCE

[1] N.J. Fisch, "Current Generation in Toroidal Plasmas," Proceedings of the Third Joint Varenna-Grenoble International Symposium on Heating in Toroidal Plasmas, March (1982), p. 841.

FIGURE CAPTIONS

FIG. 1 X-ray intensity versus emission angle for a 100 keV electron.

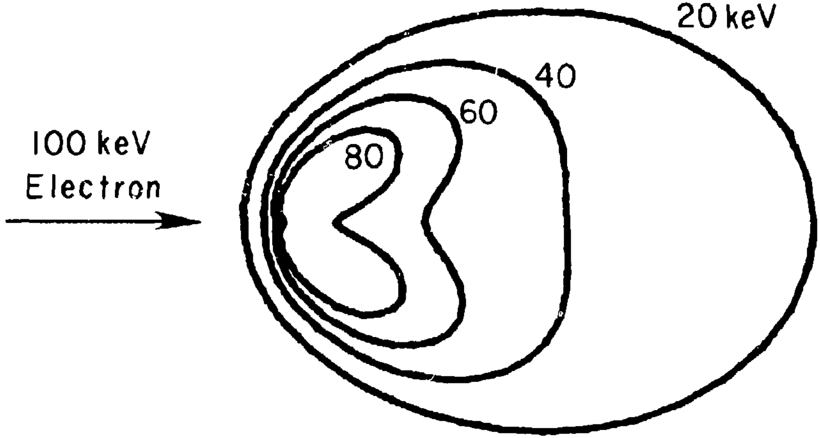
FIG. 2 Plasma current and $\beta_\theta + \ell_i/2$ versus time for a current ramp-up case. The line-average density is 2×10^{12} cm^{-3}, rf power is 200 kW, and phasing is $\Delta\phi = -90°$.

FIG. 3 Tangential photon spectrum viewing (a) nearly anti-parallel ($\theta d \approx 152°$) and (b) parallel ($\theta d \approx 28°$) to the direction of the wave for the discharge shown in Fig. 2.

FIG. 4 Plasma currents and $\beta_\theta + \ell_i/2$ versus time for case II. The line-average density is 5×10^{12} cm^{-3}, rf power is 270 kW, and rf phasing is $\Delta\phi = +90°$. The rf power is launched predominately in the direction opposite the electron drift.

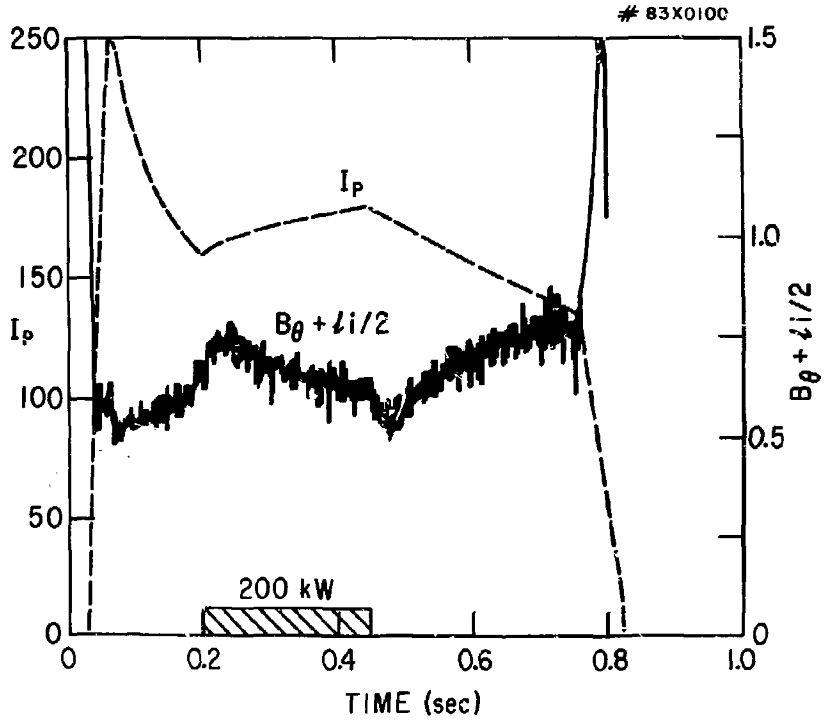
FIG. 5 Tangential photon spectrum viewing (a) nearly parallel ($\theta_d \approx 28°$) and (b) anti-parallel ($\theta d \approx 152°$) to the direction of the wave for the discharge shown in Fig. 4.

#83X0102



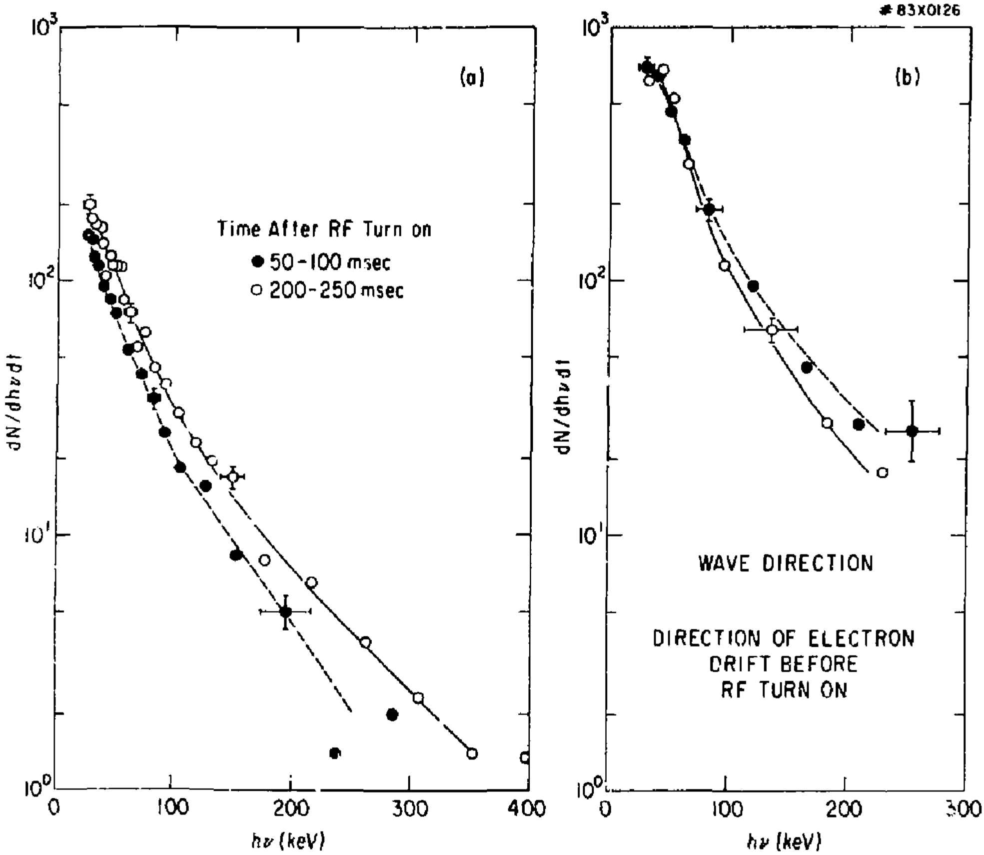
X-Ray Intensity
Pattern

Fig. 1



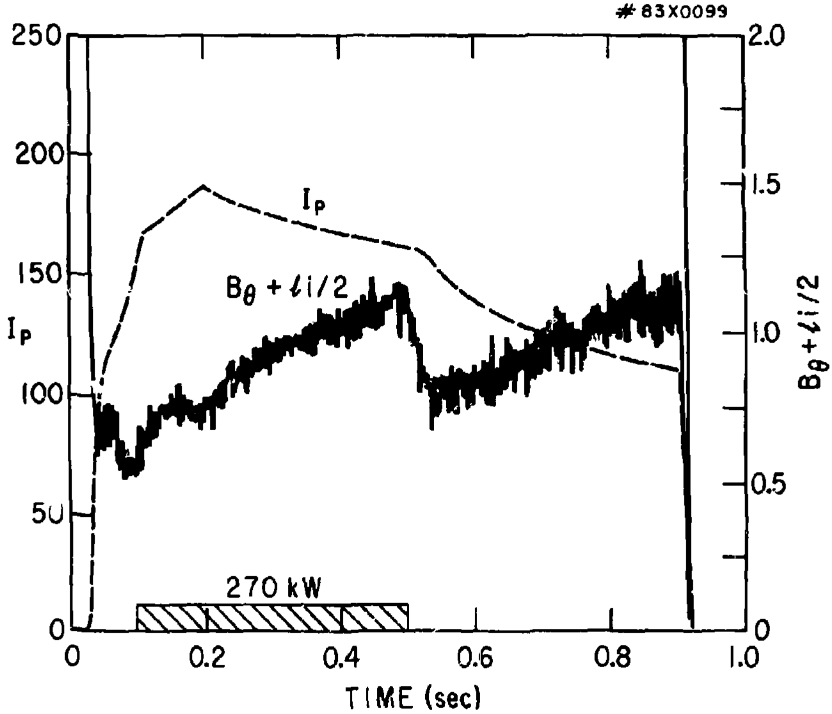
83X0100
250
200
150
100
50
0
I_P
I_P
$B_\theta + \ell i/2$
200 kW
0
0.2
0.4
0.6
0.8
1.0
TIME (sec)
1.5
1.0
0.5
0
$B_\theta + \ell i/2$

Fig. 2



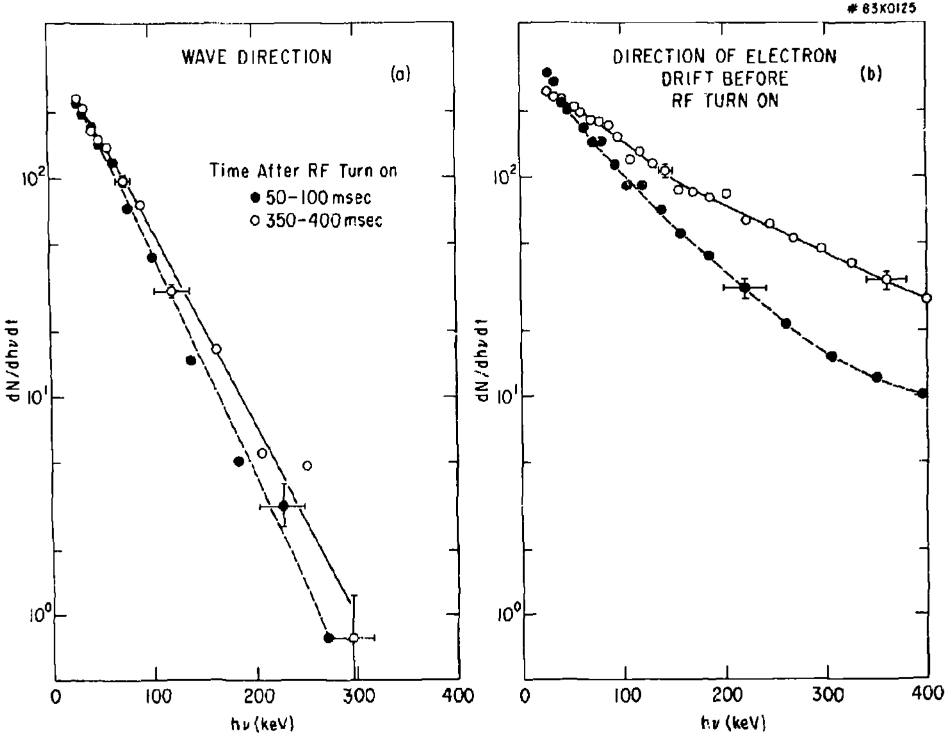
#83X0126
(a)
(b)
Time After RF Turn on
● 50-100 msec
○ 200-250 msec
dN/dhνdt
hν (keV)
WAVE DIRECTION
DIRECTION OF ELECTRON
DRIFT BEFORE
RF TURN ON

Fig. 3



83X0099
250
200
150
100
50
0
I_p
I_p
$B_\theta + \ell i/2$
270 kW
0
0.2
0.4
0.6
0.8
1.0
TIME (sec)
2.0
1.5
1.0
0.5
0
$B_\theta + \ell i/2$

Fig. 4



83X0125
WAVE DIRECTION
(a)
Time After RF Turn on
50-100 msec
350-400 msec
DIRECTION OF ELECTRON
DRIFT BEFORE
RF TURN ON
(b)
dN/dhνdt
10²
10¹
10⁰
0
100
200
300
400
hν (keV)

Fig. 5

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