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ABSTRACT

In lower hybrid (LH) discharges, the number of suprathermal electrons is limited by the upper bound on the current density from the $q = 1$ condition, which is caused by the onset of the $m=1$ MHD instability. The stored energy of suprathermal electrons, measured in terms of a poloidal beta, scales with plasma current as I_p^{-1} . Potentially, these bounds represent very restrictive conditions for heating in larger machines. Consequently, it seems necessary to perform experiments where the electrons are driven in both directions, parallel and antiparallel to the magnetic field, i.e., bidirectional scenarios like anticurrent drive or balanced injection. Data from PLT relevant to these ideas are discussed.

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I. BIDIRECTIONAL SCENARIOS

It is the purpose of this paper to point out (a) that severe limitations exist in ordinary lower hybrid (LH) current drive discharges in regard to the number of suprathermal electrons as well as to the kinetic energy stored in the energetic tail, and (b) that these limitations can be overcome in bidirectional scenarios like anticurrent drive, balanced injection, or strong current rampup.

Let us first consider a limit on the number density of suprathermal electrons. It is probably safe to assume that the central safety factor q has a value close to 1. Then the central suprathermal current density j_{sth} and the number density of suprathermal current carriers n_{sth} is fixed,

$$q_{cyl} = 1 \rightarrow j_{sth} = e n_{sth} \overline{\beta}_z c \leq 2B_T / (\mu_0 R) \rightarrow$$

$$n_{sth} = (2B_T) / (e \mu_0 \overline{\beta}_z c R) \quad , \quad (1)$$

where B_p and B_T are the poloidal and toroidal magnetic field, r and R the minor and the major radius of the tokamak, $\overline{\beta}_z = \overline{v}_z/c$ the average velocity of suprathermal electrons normalized to the velocity c of light, and μ_0 the permeability of the vacuum. For PLT, $n_{sth} \sim 10^{11} \text{ cm}^{-3}$. In standard current drive discharges, the quantity $\overline{\beta}_z$ is close to 1.^{1,2} The suprathermals consequently represent less than 1% of the electrons in discharges with central plasma densities larger than 10^{13} cm^{-3} . If the mechanism for heating during LH current drive is that rf power is first transferred from waves to suprathermal electrons, and then from suprathermal to thermal electrons, this would impose a limitation on the heating power that can be applied by lower hybrid heating.

Consider now limitations in the stored energy. The stored energy in current drive discharges consists of three contributions: (a) kinetic energy E_{therm} of thermal particles, (b) kinetic energy E_{sth} of suprathermal electrons, and (c) magnetic energy associated with the plasma current I_p , $E_{\text{magn}} = (L_{\text{int}} I_p^2)/2$. In typical current drive discharges, the magnetic energy is the largest, and the suprathermal kinetic energy the smallest quantity,

$$E_{\text{magn}} > E_{\text{therm}} \gg E_{\text{sth}} . \quad (2)$$

The first half of Eq. (2) is valid because the internal inductance l_i tends to be much larger than the poloidal beta, β_p . In order to see the validity of the second half of Eq. (2), we measure the suprathermal kinetic energy in the form of a poloidal beta³:

$$\beta_{\text{Psth}} = [2\mu_0/B_p^2(a)] (1/\pi a^2) \int_0^a (\bar{\gamma} \bar{\beta}^2 m_0 c^2 n_{\text{sth}} 2\pi r) dr . \quad (3)$$

Here, a is the limiter radius and $\bar{\gamma}$ the relativistic mass factor $(1 - v^2/c^2)^{1/2}$ averaged over all suprathermal electrons in a cubic centimeter. In typical current drive discharges, $\bar{\gamma}$ has a value ≤ 2.1 .² In Eq. (1), the number of suprathermal electrons is proportional to the suprathermal current density, and we can write Eq. (3) in a slightly different form:

$$\beta_{\text{Psth}} \leq 2 \langle \bar{\gamma}^2 / \bar{\beta}_z \rangle (I_A / I_p) , \quad (4)$$

where the Alfvén current is $I_A = (4\pi m_0 c / \mu_0 e) = 17$ kA. The brackets $\langle \rangle$ represent suitable radial averages. Equation (4) says that β_{Psth} for

unidirectional scenarios becomes of order one only for low plasma currents. In a machine like PLT with currents around 400 kA, the suprathermal energy is always small compared to the magnetic energy, and it is comparable to the thermal energy only in discharges with very low density, where $\beta_{\text{ptherm}} \ll 1$. If we apply more rf power than needed for keeping the current stationary, the result will be current rampup, i.e., an increase of unwanted magnetic energy.

In order to enlarge the number of suprathermal electrons and their stored kinetic energy, we consider bidirectional scenarios where electrons are accelerated in both directions parallel and antiparallel to the magnetic field. These bidirectional scenarios include the following cases:

- (a) Anticurrent Drive: Lower hybrid waves are launched in the direction opposite to the drift of the current-carrying electrons by proper phasing of the LH grill. A tail of electrons is consequently created in this direction. In the direction of the electron drift, electron runaway takes place in the electric field resulting from the decay of the plasma current.⁴ This scenario represents probably the most efficient way to create a large number of suprathermal electrons. It may not be the most desirable scenario for machine operation because the electrons may gain very high energy in the runaway process.
- (b) Balanced Injection: LH waves are launched in both directions parallel and antiparallel to the magnetic field. This scenario is most easily accomplished by phasing of the grill in the mode $0, \pi, 0, \pi$, etc. On PLT, the phasing $0, 0, \pi, \pi$, etc. created a more favorable, faster wave spectrum.

- (c) Strong Current Rampup: a sizable electric field exists because of $L(di/dt)$, and electron runaway takes place in the reverse direction.⁴ This scenario seems not efficient. However, it might have advantages because of the large electron heating associated with current drive.⁵

II. MEASUREMENTS OF THE SHAFRANOV PARAMETER

It has been observed on PLT that very large increases of the modified Shafranov parameter $\tilde{\Lambda} = \beta_P + l_i/2$ occur during anticurrent drive, and it has been speculated that these increases are due to the suprathermal poloidal beta, although changes of l_i cannot be ruled out. A systematic attempt on PLT to maximize these increases in $\tilde{\Lambda}$ - hoping to find $\tilde{\Lambda}$'s so large that it would be impossible to explain them by l_i - was not successful. However, the fact that we cannot prove that the large $\tilde{\Lambda}$ values are due to β_{Psth} , does not mean that there did not exist large β_{Psth} values in the experiment. We, therefore, want to document these cases here.

In Fig. 1 we show the time history of the plasma current, the density, and the cylindrical Shafranov parameter $\tilde{\Lambda}_{cyl}$ for a low density anticurrent drive discharge. $\tilde{\Lambda}_{cyl} = [(4\pi RB_V/\mu_0 I_P) + (3/2) - \ln(8R/a)]$. The plasma current is raised to 200 kA with the OH transformer and then left to decay. The anticurrent drive should theoretically increase the decay of the current; in practice it inhibits the decay because of runaway electron formation (higher conductivity). The Shafranov parameter increases immediately after the rf is turned on and rises afterwards slowly to a value in excess of 2. The first rise is probably due to creation of suprathermal electrons, the second, slower rise due to the decay of current. (According to Eq. (3), $\beta_{Psth} \sim I^{-2}$ for constant suprathermal content.) It was further observed that the

peak of the radial X-ray emission shifts outwards in time and it was suspected that this phenomenon is caused by an outward shift of the magnetic axis with respect to the outermost plasma surface due to high β_{psth} . However, PEST code simulations indicate that an outward slippage of the whole plasma column occurred due to an imperfection in the PLT coil system. The PEST code calculations for time $t = 650$ ms are shown in Fig. 2. The computations assumed that the axis coincided with the peak of the hard X-ray emission and that $q=1$ on axis. The calculations indicated that the measured values of $\tilde{\Lambda}_{cyl}$ were too large because of the outward shift. The true $\tilde{\Lambda}$ was 1.2, and was mostly due to $l_i/2 = 0.9$. Therefore, it is still not fully certain that the large Shafranov parameters are caused by the suprathermal poloidal beta.

III. HARD X-RAY MEASUREMENTS

Besides the magnetic data, hard X-ray measurements indicate that the number of suprathermal electrons is larger in anticurrent drive and balanced injection discharges. The evidence is that the hard X-ray emission does not saturate with increasing rf power for anticurrent drive, whereas it saturates for current drive. Also, considerably more X rays are emitted in high power anticurrent drive discharges than during current drive. Unfortunately, large uncertainties remain about the actual number of suprathermals in the discharge since there was no tangential hard X-ray detector available during the experiments to permit a full analysis of the distribution function of the energetic electrons.^{1,2}

Figures 3 and 4 show relevant X-ray data for current drive and for anticurrent drive, respectively. The hard X-ray intensity from the central chord of the vertical hard X-ray array integrated over all photon energies is plotted versus rf power. In order to interpret the data, we discuss the

nature of the X-ray emission. The slope of the hard X-ray emission has a value of roughly 40 to 90 keV. For a comparison of the suprathermal emission, one consequently wants to sum over all photon energies down to ~ 15 keV. This is not possible for the current drive case because appreciable heating occurs ($T_e = 5$ keV) and one would sample also the thermal spectrum. In Fig. 3 we consequently have used various filter foils. The case without a foil has a cutoff of ~ 15 keV because of air absorption. The stainless steel foil cuts off at ~ 30 keV, the $1/8$ " Cu foil at ~ 120 keV. We believe that the stainless steel foil shows the right dependence on rf power, although the level is a little too low because the foil cuts off the low energy spectrum. The X-ray intensity for the current drive is initially larger than for anticurrent drive. For low rf power, an electric field is still present, and field and waves work together to produce the maximum amount of suprathermal electrons. For large rf power, the hard X-ray emission saturates for current drive. A small increase of the intensity is still observed for high powers; it may be due to electron runaways in the reverse direction during current rampup¹ although $V \leq 0$ for $P_{rf} \geq 600$ keV in this case. The hard X-ray emissions for anticurrent drive and balanced injection behave similarly and increase linearly with rf power. For high rf powers, the hard X-ray emission for anticurrent drive is more than twice the emission during current drive.

IV. DISCUSSION

We have provided evidence that the number of suprathermal electrons in bidirectional discharges is much larger than in normal current drive discharges for large rf powers. In bidirectional scenarios, we observe very large Shafranov parameters, and the hard X-ray emission is larger by a factor of 2 and does not saturate for high rf power. Admittedly, large uncertainties

exist with respect to the number of suprathermal electrons. Hopefully, this can be improved in experiments with more rf power. An important question is why we see less heating for bidirectional scenarios.^{5,6} A possible explanation is that the electrons tend to be more energetic for anticurrent drive and that they leave the discharge instead of thermalizing in the plasma. The heating of the limiter on PLT seems to point in this direction. On the other hand, it seems to us that this is a very complex question because of the sawtooth stabilization that accompanies current drive, and because we do not know whether wave heating or improvement of confinement near the plasma center are crucial for causing the large temperature increases.

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FIGURE CAPTIONS

Fig. 1 Anticurrent drive discharge at low density n_e and low plasma current I_p , exhibiting a large value of the Shafranov parameter $\Lambda = \beta_p + I_i/2$. The OH power was switched off after the initial rise of the plasma current to 220 kA. The rf power of 615 kW with phasing of $+75^\circ$ for the 16-waveguide coupler and $+60^\circ$ for the top coupler was switched on at time $t = 200$ ms. The toroidal magnetic field B_T was 30 kG.

Fig. 2 PEST code simulation of the discharge shown in Fig. 1 at time $t = 650$ ms. The current distribution was chosen so that the safety factor q on axis was close to one and so that there was little current in the outer regions of the plasma. The pressure profile was chosen to have a similar shape as the current profile. The peak pressure was chosen so that the magnetic axis was at the major radius where the hard X-ray emission peaked.

Fig. 3 Hard X-ray intensity (integrated over all photon energies) versus rf power for a variety of different foils for a current drive discharge. ($I_p = 500$ kA, $n_e = 1.2 \times 10^{13} \text{ cm}^{-3}$, $B_T = 30$ kG, $\Delta\phi_{16wg} = -75^\circ$, $\Delta\phi_{top} = -60^\circ$.)

Fig. 4 Hard X-ray intensity (no absorber foil) versus rf power for an anticurrent drive discharge. ($I_p = 530$ kA, $n_e = 1.2 \times 10^{13} \text{ cm}^{-3}$, $B_T = 30$ kG, $\Delta\phi_{16wg} = +90^\circ$.)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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