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Lower hybrid current drive and current rampup data obtained on JT-60 are analyzed. Both the current drive efficiency and the current rampup efficiency are similar to those obtained in smaller tokamaks. The stored energy and the pressure anisotropy of the current-carrying superthermal electrons are obtained from magnetic measurements. The distribution function of the superthermal electrons is modelled by a three-temperature Maxwellian with a flat tail extending to the accessibility energy in the forward direction, a perpendicular temperature of 150keV, a backward parallel temperature of 250keV, and a backward-to-forward ratio of 2. These results are consistent with expectations based on a detailed numerical modelling and the model distribution functions inferred previously on smaller tokamaks.

Keywords: JT-60, Lower Hybrid Current Drive, Superthermal Electrons, Distribution Function, Pressure Anisotropy, Lower Hybrid Current Rampup

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JT-60における低域混成波による電流駆動及び立ち上げ実験の解析

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（1987年11月6日受理）

JT-60で得られた低域混成波による電流駆動及び電流立ち上げ実験データの解析を行なった。電流駆動効率，立ち上げ効率ともに中型装置で得られている値に近い。電流を担う高速電子の蓄積エネルギー及び圧力非等方性を磁気測定により得た。高速電子の分布関数は，正方向には近接性条件により与えられるエネルギーまでのびる平担なテイル，150 keVの垂直温度，250 keVの逆方向の平行温度，及び逆正方向比2の三温度マクスウェル分布で表わせる。これらの結果は，詳細な数値解析や中型装置において推察された分布関数に基づく予測と矛盾しない。

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1. Introduction

Lower hybrid current drive has been studied extensively in small and medium size tokamaks during the past several years[1]. Both lower hybrid current drive and current rampup were applied to a large tokamak for the first time on JT-60[2]. Typical current drive and rampup data obtained during the period from June to October, 1987 are analyzed. The stored energy and pressure anisotropy of the superthermal electrons for a typical current driven plasma are obtained from magnetic measurements. Analysis of these data are performed by fitting the experimental data with a model distribution function. The result is compared with theoretical predictions and results obtained in smaller tokamaks.

A typical lower hybrid current driven plasma is described in Sec. 2.1. Modelling of the superthermal electron tail distribution function is described in Sec. 2.2. A typical lower hybrid current rampup plasma is described and the rampup efficiency is evaluated in Sec. 3. Finally, the conclusions are presented in Sec. 4.

2. Lower Hybrid Current Drive

2.1 Characterization of a Typical Current Driven Plasma

Fully noninductive current drive of 1MA was achieved by lower hybrid waves in the density regime $\overline{n}_e \simeq 1\times 10^{19}\mathrm{m}^{-3}$. A typical current driven discharge is shown in Fig. 1. Lower hybrid wave power was injected from the current drive coupler into an ohmic target plasma. The ohmic primary current I_F was feedback controlled to maintain the plasma current at 1MA. With the application of lower hybrid power (the first pulse), the plasma current is replaced entirely by rf driven current and the inductive power input vanishes as signified by the zero slope of the ohmic primary current ($\dot{I}_F$=0) and the zero loop voltage. (The second rf pulse was used to study electron

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Information about the current carrying electron tail can be obtained from the analysis of magnetic data. As an example, the shot shown in Fig. 1 is analyzed. The stored energy of the ohmic plasma (before rf injection) obtained from the diamagnetic measurement was 170kJ, which agrees to within 10% with the value predicted by the JT-60 ohmic scaling law[3] derived previously based on kinetic measurements. The corresponding perpendicular poloidal beta is $\beta_{p\perp}=0.121$. The value of the equilibrium quantity $\beta_p^{equ}+l_i/2$ obtained from magnetic fitting was 0.856, where $\beta_p^{equ}=(\beta_{p\parallel}+\beta_{p\perp})/2$, and l_i is the normalized internal inductance. During the steady state phase of lower hybrid current drive, $\beta_{p\perp}$ increases to 0.204 and $\beta_p^{equ}+l_i/2$ increases to 1.023. The change of internal inductance during the rf pulse is estimated to be $\Delta l_i=0.019$ by assuming that $\dot{\beta}_p=0$ during the steady state current drive phase so that the time rate of change of $\beta_p^{equ}+l_i/2$ during this period is entirely due to $\dot{l}_i$, and that $\dot{l}_i$ is constant during the rf pulse. The change of poloidal betas are thus calculated to be $\Delta\beta_{p\perp}=0.083$ and $\Delta\beta_{p\parallel}=0.232$. Further, the change in the stored energy of the bulk plasma electrons and ions is estimated to be small compared to the stored energy of the superthermal electrons since the electron temperature obtained from pulse height analysis of soft X-ray emission ($T_e^{PHA}=3keV$) does not change from the ohmic phase to the current drive phase. This result is consistent with the findings on Alcator C[4]. Therefore, the parallel and perpendicular components of the electron tail poloidal betas can be estimated to be $\beta_{p\parallel}^{tail}\simeq0.23$ and $\beta_{p\perp}^{tail}\simeq0.08$. From these estimates, we infer the anisotropy factor for the electron tail pressure to be $\beta_{p\parallel}^{tail}/\beta_{p\perp}^{tail}\simeq2.8$ and the total electron tail energy to be

$W^{tail}=W_{\parallel}^{tail}+W_{\perp}^{tail}\simeq 190$kJ, which is comparable with the bulk stored energy of 170kJ. These values of the electron tail stored energy and pressure anisotropy can be compared with estimates based on the angular profile measurements of the plasma hard X-ray spectra[5,6] and the results of a detailed numerical simulation[7].

The global energy confinement time of the LHCD plasma is 0.12sec, which is comparable with the values predicted by the L-mode scaling laws of Goldston[8] and Kaye and Goldston[9]. A similar result has been obtained for LHCD plasmas on Alcator C[4]. For comparison, the global energy confinement time of the ohmic plasma prior to rf injection is 0.23sec. There is some ambiguity in the definition of the incremental confinement time in a purely auxiliary heated plasma (i.e., $P_{OH}=0$). If the incremental confinement time is defined as the ratio of the incremental stored energy to the incremental input power $\Delta W/\Delta P$, its value is 0.08sec. The L-mode scaling proposed by Shimomura and Odajima[10] would predict a value of 0.07sec.

2.2 Modelling of the Electron Tail

The electron tail distribution function is modelled by a three-temperature Maxwellian[5] of the form $\exp(-p_{\parallel}^2/2mT_{\parallel}-p_{\perp}^2/2mT_{\perp})$, where the parallel temperatures in the forward direction ($T_{\parallel f}$) and the backward direction ($T_{\parallel b}$) are allowed to be different. For simplicity, the distribution function is assumed to be independent of minor radius[5], and the forward plateau is assumed to be flat ($T_{\parallel f}=\infty$) in the region of waves $p_1<p_{\parallel}<p_2$, where p_1 and p_2 are the the limits on the parallel momenta which are determined by quasi-linear Landau damping and accessibility, respectively[7]. The distribution function is assumed to fall off as $\exp(-p_{\parallel}^2/2mT_{\perp})$ beyond the accessibility limit ($|p|>p_2$). The backward plateau is allowed to start from a different parallel momentum so that $f(-p_1)/f(+p_1)\equiv f_-/f_+\neq 1$ is allowed. Although this is a considerably simplified model of the actual distribution function, it should be adequate to characterize the overall features of the superthermal electron distribution function. The height of the plateau is determined by requiring that the plasma current (obtained by calculating the parallel velocity moment) be carried entirely by the tail electrons. Once the tail distribution function is obtained, the tail stored energy and the pressure anisotropy can be calculated by taking appropriate moments ($(\gamma-1)mc^2$ for energy, $p_\parallel^2/m\gamma$ for parallel pressure, $p_\perp^2/2m\gamma$ for perpendicular pressure[11]) and compared with the estimates from the magnetic measurements.

The shot shown in Fig. 1 was analyzed using this model. The upper limit on the parallel momentum of the quasi-linear plateau is determined by the accessibility ($n_\parallel^{acc}$=1.25 for this case), and the lower limit by the total rf current. The three parameters, $T_\perp$, $T_{\parallel b}$, and f_-/f_+ are adjusted (within reasonable bounds) to reproduce both the stored energy and the pressure anisotropy of the electron tail. First, if f_-/f_+=1 is assumed the experimentally obtained stored energy and pressure anisotropy can be reproduced with $T_\perp$=200keV and $T_{\parallel b}$=750keV, but cannot be reproduced with a reasonable value for $T_{\parallel b}$ (500keV at most)[5-7]. In order to match the experimental data with a lower $T_{\parallel b}$, f_-/f_+ has to be greater than one to maintain the negative rf current. The backward tail is expected to start at a lower energy than the forward tail (i.e., f_-/f_+>1) because the waves traveling in the negative direction ($n_\parallel$<0) have lower phase velocities (i.e., larger $|n_\parallel|$)[7]. If $T_{\parallel b}$ is taken to be equal to $T_\perp$, f_-/f_+=3.5 is required for $T_{\parallel b}=T_\perp$=120keV. However, $T_{\parallel b}$ is expected to be larger than $T_\perp$ because of the existence of the waves traveling in the negative direction ($n_\parallel$<0), which allows for a smaller f_-/f_+ compared to a rather high value of 3.5. For a more reasonable value of f_-/f_+=2, the experimental stored energy and pressure anisotropy can be adequately described by $T_\perp$=150keV ($50\times T_e$) and $T_{\parallel b}$=250keV, both of which are quite reasonable values. The electron tail distribution function integrated over $p_\perp$, corresponding to this set of parameters, is shown in Fig. 2.

The sensitivity of the results to variations in these three parameters is shown in Fig. 3. The open circle indicates the experimentally inferred values for W^{tail}/I_{rf} and $\beta_{p\parallel}^{tail}/\beta_{p\perp}^{tail}$. The error bars indicate uncertainties in these values assuming a 10% error in the bulk stored energy and a 100% error in the evaluation of Δl_i. It can be seen that uncertainties in $T_{\parallel b}$ and f_-/f_+ arise from the uncertainty in W^{tail}/I_{rf}, and can be determined with an accuracy of approximately 10%, given the present model. On the other hand, the uncertainty in $T_\perp$ is mainly due to the uncertainty in $\beta_{p\parallel}^{tail}/\beta_{p\perp}^{tail}$, and has a larger uncertainty of approximately 30%.

3. Lower Hybrid Current Rampup

Current rampup by lower hybrid waves was investigated in a lower density regime $\bar{n}_e \lesssim 0.5\times10^{19}\mathrm{m}^{-3}$ with up to 2MW of injected power from the current drive coupler. The plasma current was allowed to decay inductively after plasma initiation. The ohmic primary current I_F was maintained at a constant level $\dot{I}_F=0$ so that no inductive power was supplied by the ohmic primary circuit. A typical shot is shown in Fig. 4. The plasma current was ramped up from 0.46 to 0.60MA in 6.4sec at $\bar{n}_e \simeq 0.3\times10^{19}\mathrm{m}^{-3}$ with $P_{LH}=1.6\mathrm{MW}$. Since this power level is approximately 3.5 times the power required to maintain a steady state current, the rampup efficiency should be nearly the optimum value at this density and current[12]. The current rampup efficiency is defined as[13] $\eta_r=(\dot{W}_{PF}-P_{ext}+V^2/R)/P_{rf}$ where $W_{PF}=LI_p^2/2$ is the poloidal field energy, P_{ext} is the external inductive power input, and V^2/R is the resistive power loss. The inductance $L=L_{ext}+L_{int}$ is the total inductance of the plasma loop. Inductive power from the equilibrium field coils are small in JT-60 because of small mutual inductances between the plasma and the equilibrium field coils. For the case shown in Fig. 4, $LI_p\dot{I}_p=83\mathrm{kW}$, $\dot{L}I_p^2/2=-1.6\mathrm{kW}$, $P_{ext}=2.5\mathrm{kW}$, $V^2/R=4.2\mathrm{kW}$, so that the rampup efficiency $\eta_r=5.3\%$. The evaluation was performed over the last two seconds of the rf pulse in order to avoid transient effects[12]. The rampup efficiency was observed to parameters is shown in Fig. 3. The open circle indicates the experimentally inferred values for W^{tail}/I_{rf} and $\beta_{p\parallel}^{tail}/\beta_{p\perp}^{tail}$. The error bars indicate uncertainties in these values assuming a 10% error in the bulk stored energy and a 100% error in the evaluation of Δl_i. It can be seen that uncertainties in $T_{\parallel b}$ and f_-/f_+ arise from the uncertainty in W^{tail}/I_{rf}, and can be determined with an accuracy of approximately 10%, given the present model. On the other hand, the uncertainty in $T_\perp$ is mainly due to the uncertainty in $\beta_{p\parallel}^{tail}/\beta_{p\perp}^{tail}$, and has a larger uncertainty of approximately 30%.

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4. Conclusions

Results obtained during lower hybrid current drive and current rampup experiments on JT-60 ohmic target plasmas were analyzed. The current drive efficiency and the current rampup efficiency are both comparable to typical values obtained in smaller scale experiments. These results provide a basis for more confident extrapolation to future devices. However, larger efficiencies have also been reported when lower hybrid current drive is combined with neutral beam heating[2], which is encouraging for future devices with large auxiliary heating powers.

The stored energy and pressure anisotropy of the superthermal electrons are evaluated based on magnetic measurements for a typical current driven plasma. The electron tail can be characterized by a three temperature Maxwellian model with a flat plateau up to the accessibility energy in the forward direction, a perpendicular temperature of $T_{\perp}$=150keV, a backward parallel temperature of $T_{\parallel b}$=250keV, and a backward-to-forward ratio of f_{-}/f_{+}=2. These values are in general agreement with the predictions of a detailed numerical simulation[7] and the results obtained from the angular distribution of plasma hard X-ray spectra on smaller scale experiments[5,6]. The global energy confinement time of the lower hybrid current driven plasma at I_p=1.0MA and $\bar{n}_e \simeq 1.2\times10^{19}\mathrm{m}^{-3}$ is similar to that predicted for the L-mode.

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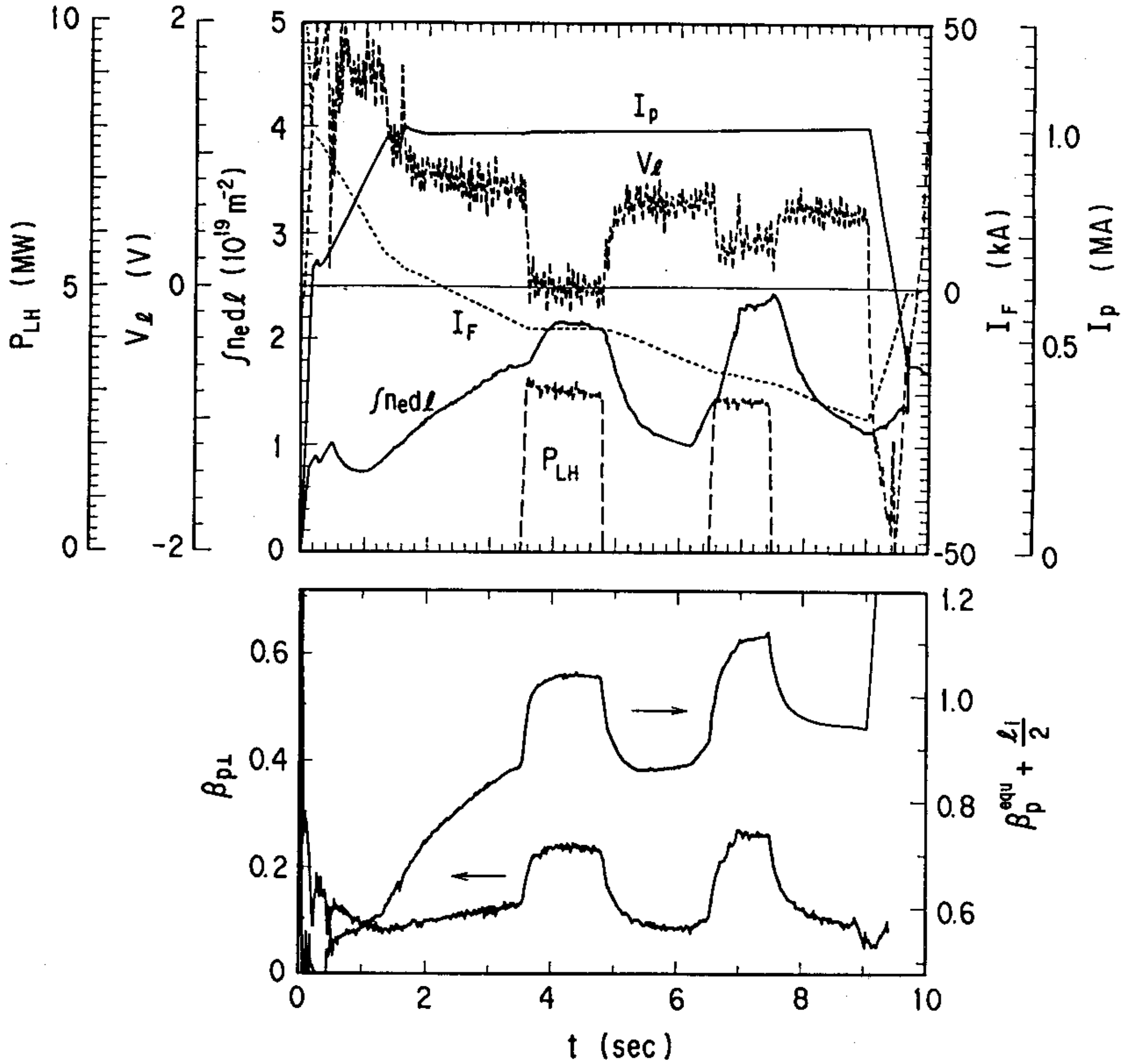

Fig. 1 A typical lower hybrid current driven shot. Hydrogen plasma, B_T=4.4T, I_p=1.0MA, $\bar{n}_e \simeq 1.2\times10^{19}m^{-3}$, P_{LH}=3.0MW. The trace labelled I_F is the ohmic primary current. Also shown are $\beta_{p\perp}$ obtained from diamagnetism and $\beta_p^{equ}+l_i/2$ obtained from magnetic fitting.

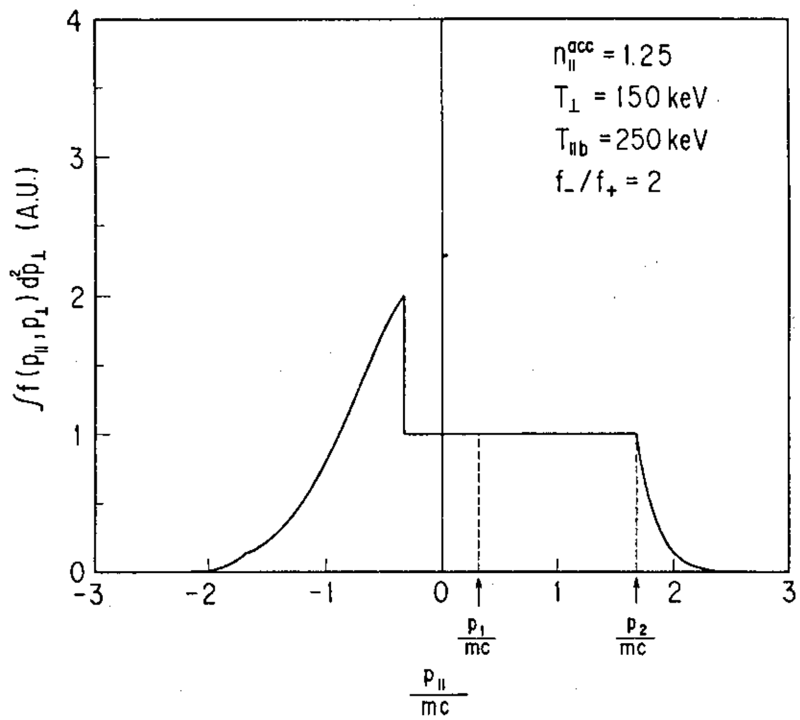

Fig. 2 The electron tail distribution function integrated over $p_\perp$ for $n_\parallel^{acc}$=1.25, $T_\perp$=150keV, $T_{\parallel b}$=250keV, f_-/f_+=2.

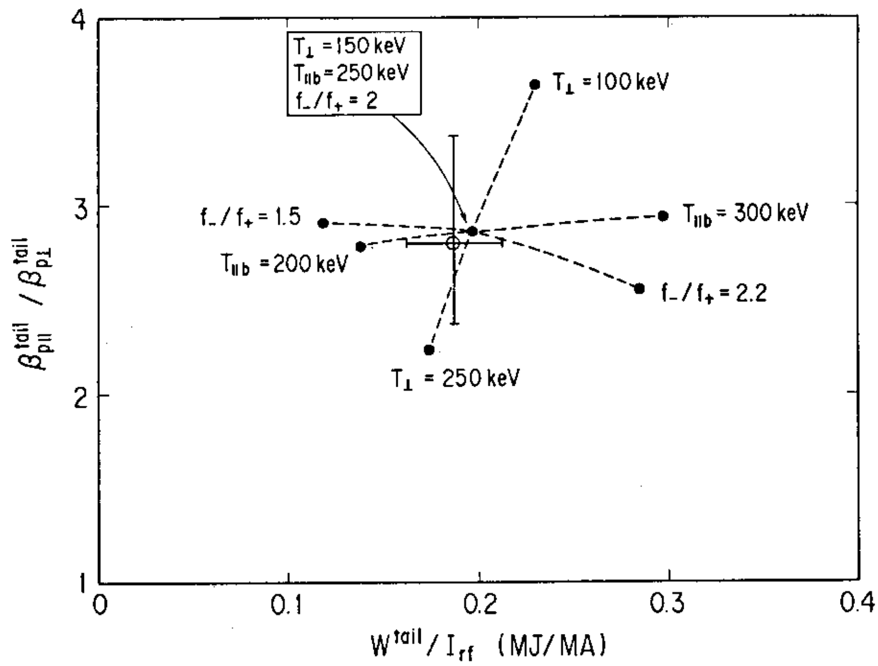

Fig. 3 Sensitivity of the calculated values of W^{tail}/P_{rf} and $\beta_{p\parallel}^{tail}/\beta_{p\perp}^{tail}$ to variations of the adjustable parameters $T_\perp$, $T_{\parallel b}$, and f_-/f_+.

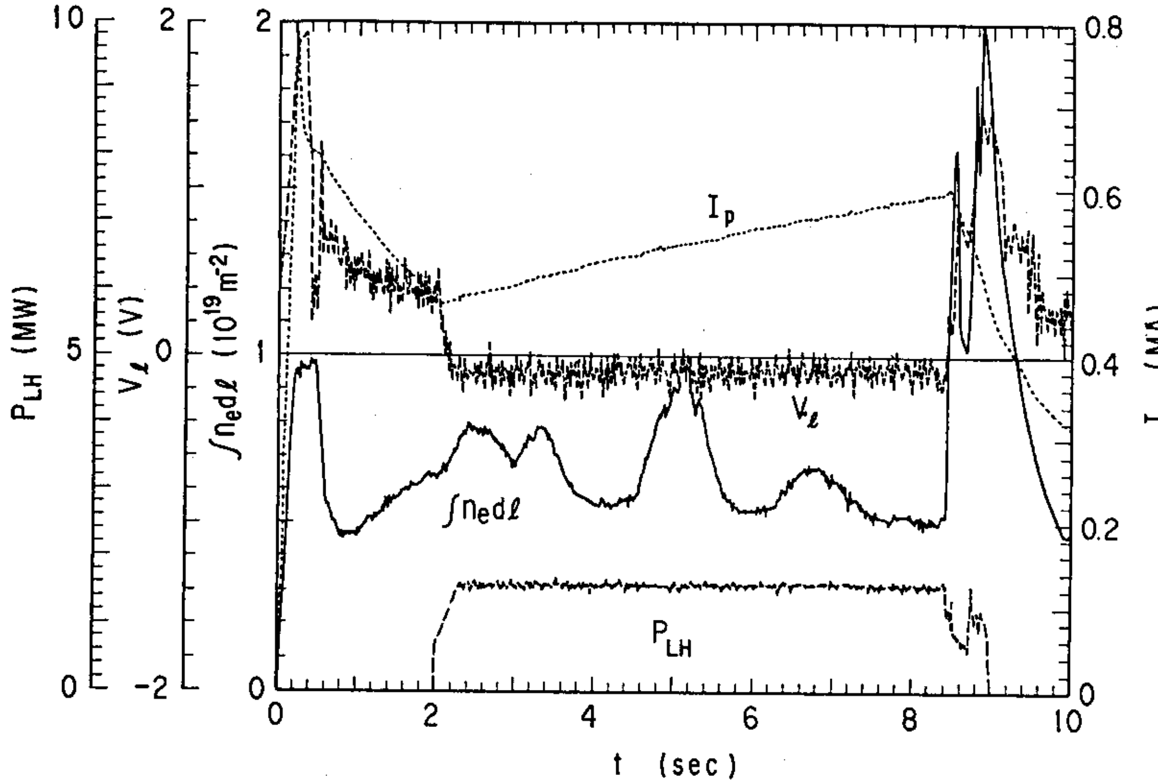

Fig. 4 A typical current rampup shot. Hydrogen plasma, B_T=4.4T, $\overline{n}_e \simeq 0.3\times10^{19}m^{-3}$, P_{LH}=1.6MW.