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Modification of H-mode pedestal structure with lower hybrid waves on Alcator C-Mod

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Abstract

The application of lower hybrid waves (LH) in H-mode plasmas on Alcator C-Mod can result in significant reduction of core particle inventory, with no significant degradation of energy confinement. This phenomenon has been observed in steady enhanced D_α (EDA) H-mode targets, which are sustained by ion cyclotron RF auxiliary heating, in which pedestal density n_{ped} is usually tied firmly to plasma current I_P and shows a strong resilience to changes in the edge neutral source. Upon application of up to 1MW LH power, n_{ped} is reduced by up to 30%, while the temperature profile increases simultaneously such that the pressure pedestal remains constant or is slightly increased. Steady EDA H-mode operation with no edge-localized modes (ELMs) can be maintained while edge collisionality is reduced by factors of reductions of 2—4. Elevation of scrape-off layer (SOL) density and electric currents accompany the application of LH (at levels as low as 400kW) with a fast time response ($\sim 10^{-2}$ s), while full density pedestal relaxation and core density reduction occur on longer time scales ($\sim 10^{-1}$ s). A similarly prompt counter-I_P change in the edge toroidal velocity is also observed in response to LHRF, followed on longer time scales by a counter-I_P change in the central rotation. The range of time scales of the plasma response may indicate that the radial locations of LH interactions (*i.e.*, SOL *vs.* core), and power deposition mechanisms, are evolving in time. Understanding the responsible physical mechanisms and applying them to a broad range of H-mode discharges could provide a tool for improving density control, affecting edge MHD stability and applying modulation for transport studies.

I. Introduction

In tokamak plasmas, the edge pedestal in H-mode plays a dominant role in determining global confinement properties. Therefore, physical mechanisms governing pedestal structure must be understood for confident extrapolation of confinement to burning plasma devices. In addition, there may be a need for enhanced pedestal control capability, established for example by external modification to edge transport. Pedestal studies on the Alcator C-Mod tokamak[1] have shown a clear correlation of edge particle transport, and resulting density pedestal structure, with plasma current.[2] Plasma transport appears to clamp edge density gradients, yielding a density pedestal that is strongly resilient to changes in the edge neutral source.[3] Finding mechanisms for breaking the correlation of H-mode density with current, thus allowing improved density control, is a key goal of C-Mod pedestal research.

While launching lower hybrid range of frequency (LHRF) waves into H-mode plasmas on Alcator C-Mod, we have observed repeatable reductions of pedestal density and, consequently, core particle inventory.[4,5] Discharges with reduced particle confinement have been maintained steady state, with no degradation in energy confinement. LHRF thus provides a potential tool for decoupling particle and thermal transport in the pedestal and reducing operating collisionality at a given normalized pressure β. This paper provides a description of the experiments that were performed and the observations associated with this phenomenon.

II. Experimental setup

These experiments used the lower hybrid system on C-Mod[6] to launch 4.6 GHz waves into steady H-mode target plasmas. Levels of steady state coupled power ranged from 600 to 1100 kW. The launched spectrum was chosen to have a peak parallel refractive index $n_\parallel$ of 2.3, except in a few cases, noted later. For target discharges we chose stationary H-modes with low density, sufficient to allow core LH wave accessibility. Low-current (450—600kA) enhanced D_α (EDA) H-modes[7,8] in D, formed with ion cyclotron range of frequency (ICRF) heating on H minority, were found to be suitable

targets. H-mode density was kept as low as possible by operating in a nearly double null equilibrium biased slightly toward upper single null (USN). The separation between primary and secondary separatrices at the midplane in these cases was ~4—5mm. The USN configuration has the ion grad-B drift direction pointing away from the primary x-point, which has been shown to promote a lower natural pedestal density, both on C-Mod[9] and on DIII-D[10]. Also in this equilibrium, the outer strike point is placed near the upper chamber cryopumping slots, further reducing the edge fueling source. Electron density at the top of the pedestal $n_{e,ped}$ was below $2x10^{20}m^{-3}$ in all cases prior to LH turn-on, which ensures wave accessibility for $n_{\parallel}>2.1$ at the operating field, $B_T=5.4T$. The conditions tested are summarized in Table 1.

Several components of the C-Mod diagnostics set [11] were used to evaluate these discharges. Profiles of n_e and T_e in the core and edge plasmas were diagnosed with 30Hz Thomson scattering (TS), and divertor probes provided information on plasma flux to the plates. Additional diagnostics which proved useful for these experiments include a hard x-ray camera for measuring bremsstrahlung from fast electrons, x-ray spectroscopy for core plasma rotation, passive charge exchange recombination spectroscopy (CXRS) for estimates of edge plasma flows, tangential edge Ly_{α} emissivity arrays for inferring neutral density, magnetic pick-up coils for B fluctuations and phase contrast imaging (PCI) for measuring line-integrated density fluctuations.

III. Plasma response to LHRF

Application of LHRF to the H-mode plasmas studied generally resulted in a clear reduction in plasma density, along with increases in plasma temperature. Figure 1 shows time traces from such a discharge. When LH is used at similar power levels and the same phasing to drive current in L-mode discharges, no such density reduction is observed, suggesting the effect is primarily related to changes in the edge pedestal. Indeed, examination of the full temperature and density profiles indicates that core particle and thermal transport is not substantially changed by the LHRF, and that the effects on the discharge stem from changes to the pedestal structure. As shown in Figure 2, T_e profiles have similar gradient scale lengths in the core before and during application of LHRF.

Density profiles actually become slightly more peaked during LHRF, in a fashion that is consistent with empirical scaling laws of density peaking with collisionality.[12] Looking with higher resolution at the pedestal region, we observe a clear decrease in $n_{e,ped}$ and a relaxation in the density gradient within the pedestal. Concurrent with this change in density, the temperature pedestal increases such that the pedestal pressure profile remains nearly invariant. This result implies a triggered enhancement to particle transport while maintaining similar levels of overall energy confinement.

Despite the changes in the pedestal parameters, the H-modes remain in the EDA regime, with particle and impurity transport continuously regulated by an edge quasi-coherent mode (QCM). The QCM is observed on the PCI diagnostic and fast magnetic pick-up coils throughout the application of LH, though with some changes in frequency and amplitude. No edge-localized modes were observed either in the target H-modes or in those with LH applied. Typically in EDA H-modes, pedestal collisionality and pressure gradient do not vary independently,[2,3] and so it is remarkable that these discharges can have a fourfold decrease in ν^*_{95} while maintaining nearly identical pressure pedestals.

As Figure 1 illustrates, the plasma establishes a new stationary state in response to the LH pulse on a time scale of order 100ms, which is considerably longer than the energy confinement time, typically less than 30ms in these low-I_P discharges. However, we also observe some rather prompt effects on the edge plasma, which suggest direct wave interaction with the edge. In fact, changes to the scrape off layer (SOL) occur within milliseconds of LH turn-on. Rapid increases in SOL density are detected as increases in Ly_α emissivity outside the last closed flux surface (LCFS), and are also recorded as increases in plasma flux to swept-voltage divertor probes. Examples of these prompt effects are shown in Figure 3. The effects on the SOL are observable with P_{LHRF} as low as 400kW, and appear to increase in magnitude as LHRF ramps up. Notably, similar increases in SOL density have been observed in high density L-mode plasmas.[13]

Pedestal profiles as measured by TS evolve continuously during the LH ramp-up, as shown in Figure 4. To construct the profiles in Fig. 4b, data from three identical discharges in Fig. 4a were averaged in order to reduce scatter. Increase in SOL density and reduction in $n_{e,ped}$ are both very slight 10ms into the LH pulse, though after 43ms,

with $P_{LHRF}\sim800kW$, the pedestal modification is unmistakable. Interestingly, substantial relaxation of the gradient is not seen until the LH reaches its programmed flattop value of 900kW. It is also during the flattop phase that the line-integrated density reaches its minimum value and significant gains in core temperature are achieved.

In addition to the density and temperature, toroidal rotation is also seen to respond in different locations on varied time scales. As shown previously,[14] central rotation becomes more counter-current following the application of LH into H-mode, just as is the case in L-mode plasmas. Figure 5 shows a change in rotation ΔV of approximately -35km/s that lags the initial application of LH by more than 100ms. On the other hand, edge toroidal rotation is seen to become more counter-current promptly after LH turn-on, with a net change of -15km/s occurring over approximately 50ms. While the change in core rotation is roughly consistent with the LHCD-induced ΔV in L-modes, the edge rotation decrease is likely the result of a prompt modification to the edge plasma.

IV. Discussion

It is clear that the application of LHRF is affecting significantly the characteristics of its H-mode targets, particularly in terms of particle confinement and rotation. Furthermore, the time-dependent response of these discharges suggests that the LH waves may be influencing the H-mode via interactions at different locations, and at different times. In principle, driving current in the core plasma with LH, particularly at large values of r/a, could effect the pedestal structure and MHD stability. However, lower hybrid current drive (LHCD) in these H-modes appears to be quite small, based on experimental data. Though there is an increase in hard x-rays during the LH pulse, which plateaus as the core density reaches its minimum value, the net count rate is over an order of magnitude below that expected from robust LHCD. Also, the approximately 40% drop in measured loop voltage is roughly consistent with what one would expect from the observed T_e rise and consequent resistivity drop.

The GENRAY ray tracing package and CQL3D Fokker-Plank solver have been used extensively[13] to evaluate wave propagation and damping in plasmas with LHRF applied, both in the H-mode cases considered here and in L-mode cases. It is seen that the

expected LH penetration into core plasma and subsequent wave damping are sensitive to modeled conditions of the SOL and pedestal region. Though initial modeling of an example H-mode discharge, without SOL plasma included, indicated a modest amount of off-axis current drive from LH, inclusion of SOL interactions have reduced the expected value of I_{CD} to no greater than 22kA, or f_{CD}<4%. Collisional damping of the LH waves in the SOL and reduced transmission through the density pedestal are both factors that could result in an enhanced fraction of LH power depositing outside the LCFS. Interestingly, modeling of the pre-LH and LH-modified phases of the H-mode show that the relaxed density pedestal improves LH wave penetration inside the LCFS. Also, the elevated pedestal and core temperatures in the final H-mode allow more efficient damping of the penetrating waves. Thus, the application of LHRF has altered the conditions of the target discharge such that LH current drive or heating can be more readily achieved.

Because LH driven current is not thought to be significant, particularly in the early stages of LH ramp-up, prompt edge interaction is likely responsible for the initial pedestal modification. This could take the form of a direct wave interaction in the pedestal region, which excites radial particle transport and rapidly "fills" the SOL with plasma. Alternately, the edge modification could be initiated by the onset of enhanced ionization in the SOL, which could affect pedestal dynamics both by raising collisionality at the LCFS and by providing enhanced screening to neutrals. Flow characteristics in the pedestal region could also play a role in regulating particle transport, via changes in ExB shear stabilization of turbulence. As discussed above, pedestal rotation becomes more counter-current, simultaneous with the initial phase of n_e profile modification. It remains to be seen whether this demonstrates direct momentum input in the edge or a damping of intrinsic co-current rotation by enhanced SOL density.

Another intriguing observation in these discharges is the appearance of electric currents in the SOL, concurrent with the application of LH. These are observed, by means of grounded divertor probes, to flow a few mm outside the LCFS, and are prevalent in high density LHCD L-modes as well.[13] The currents are assumed to flow parallel to the magnetic field, and under this assumption are in the same direction as the bulk plasma current. Perturbations in the local magnetic field introduced by these currents could play a further role in regulating the properties of the H-mode transport barrier.

6

The results presented here do not rule out the possibility that core damping of LH plays a role in sustaining the favorable pedestal modification. It is particularly striking that the final stage of pedestal modification, which includes relaxation of the n_e gradient and sharp increase in $T_{e,PED}$, occurs well after the prompt changes in the edge, and is somewhat contemporaneous with the onset of hard x-rays from the core. If some amount of core LH damping is necessary to achieve this full effect, then one might expect reductions in core temperature to be deleterious in these H-modes. Indeed, it is seen that drops in T_e resulting from either sudden impurity injections or chronic buildup of impurities due to deteriorating wall conditions tend to arrest the density reduction. Figure 6a illustrates that density pedestal modification is not obviously dependent on net LH power and phasing, with the magnitude of the density change varying considerably at $P_{LH} \sim 900kA$. In contrast, the density relaxation is highly dependent on P_{RAD}, as seen in Fig. 6b.

V. Conclusions and future work

Substantial modification to the pedestal and core properties of EDA H-modes has been achieved with the application of LHRF, resulting in stationary discharges with reduced particle inventory and similar levels of thermal confinement. Notably, the application of LH breaks a typically firm correlation between pedestal density and plasma current by a substantial amount. The effects of the LH are observed at different physical locations and at varied time scales. Prompt increases in SOL density and parallel currents are observed upon LH turn-on as is the beginning of a counter-I_P change in edge rotation. The edge rotation reaches its minimum value in tens of milliseconds, while, on time scales of ~100ms, pedestal and core densities reach their fully relaxed state, while T_e and hard x-ray counts plateau. The fully stationary discharge is achieved only after 150ms, when core toroidal rotation completes its counter-I_P reduction.

Understanding the physical mechanisms responsible for these H-mode modifications may enable their application to a broad range of H-mode discharges. This would provide a tool for improving density control, affecting edge MHD stability and applying modulation for transport studies. An attractive possibility is the extension of steady EDA

operation to lower than typical values of collisionality. The causes of these modifications are at this time largely a matter of speculation. There is almost certainly a degree of direct interaction of LH waves with the edge plasma, which is responsible for at least the initiation of the pedestal modification. It is also possible that some degree of core interaction is necessary to sustain the observed effects. Future experiments will be performed with a redesigned LH launcher with improved power handling, and will help to sort out the relative importance of edge *vs.* core interaction and the types of interactions which are important. Specifically, we will test whether thresholds for these effects exist in the LHRF power, and we will vary the phasing between CD (co-I_P and counter-I_P) heating phasing. Continued LH modeling will be pursued, with full-wave representation an active area of advancement.[15]

Acknowledgments

Table 1: Experimental conditions in which LHRF has been applied to EDA H-modes

Toroidal Field	Plasma Current	Range of target $n_{e,ped}$	LH Phasing	LH power
5.4T	450kA	$0.9—1.1 \times 10^{20} m^{-3}$	$n_{\parallel}$=1.9, 2.3, 2.8	600—750kW
5.4T	600kA	$1.4—1.8 \times 10^{20} m^{-3}$	$n_{\parallel}$=2.1, 2.3, 2.6	700—1100kW

Figure Captions

Figure 1: A 600kA EDA H-mode (a) triggered with ICRF and with LH applied from 1.1 to 1.4s. (b) Core density is depressed by the LH pulse. (c) Core T_e rises and (d) plasma stored energy shows a slight increase.

Figure 2. Profiles of n_e and T_e from Thomson scattering, before (black) and during (red) LH pulse, as a function of normalized poloidal flux. Vertical dashed lines indicate the LCFS. Profiles inside the LCFS (a, b) suggest little alteration to core transport; pedestal profiles (c, d) are significantly modified.

Figure 3. Prompt effects are observed in the SOL shortly after LH turn-on (first dotted line), continuing toward LH flattop (second dotted line) and in advance of full global density depression (third dotted line). (a) Net LH power. (b) Line-averaged density. (c) Ly_α emissivity at the LCFS (black) and in the SOL (blue) (d) Ion saturation current at a divertor probe mapping to 5mm outside the LCFS at the midplane.

Figure 4. Three nearly identical discharges (purple, orange and cyan) are used to study pedestal evolution with LHRF applied. Shown are time traces of (a) ICRF power, (b) LH power, (c) radiated power, (d) line-integrated density and (e) n_e at the top of the pedestal and in the SOL from Thomson scattering. The vertical dashed lines indicate the Thomson measurement times. Their colors correspond to the profiles at right, which are obtained by fitting a modified tanh to TS data, averaged over multiple pulses in the three discharges. (f) SOL density increases and $n_{e,PED}$ reduction is seen promptly during LH ramp up, while full gradient relaxation occurs in the LHRF flattop. (g) $T_{e,PED}$ rises in concert with the density depression, obtaining its highest value in the LH flattop. (h) The pressure pedestal is nearly invariant.

Figure 5. (a) Lower hybrid input power into H-mode previously shown in Figures 1 and 3. (b) Measured pedestal (diamonds) and near SOL (squares) n_e from Thomson scattering. (c) Counter-I_P change in pedestal toroidal rotation measured by line-integrated CXRS (violet) and core ΔV_ϕ From x-ray spectroscopy (red).

Figure 6. (a) Pedestal and SOL n_e without LHRF (circles) and with LHRF (diamonds, squares, triangles), in H-modes with I_P=600kA, P_{ICRF}=1.8MW. The density modification is not obviously dependent on net P_{LH} or phasing, and exhibits significant variability at 800—900kW. The LHRF effect on the pedestal is more prominent when radiated power is reduced: (b) Pedestal and SOL density vs. P_{RAD} (c) Pedestal T_e. (d) Pedestal p_e. The horizontal dashed lines represent mean values in the pre-LH H-modes.
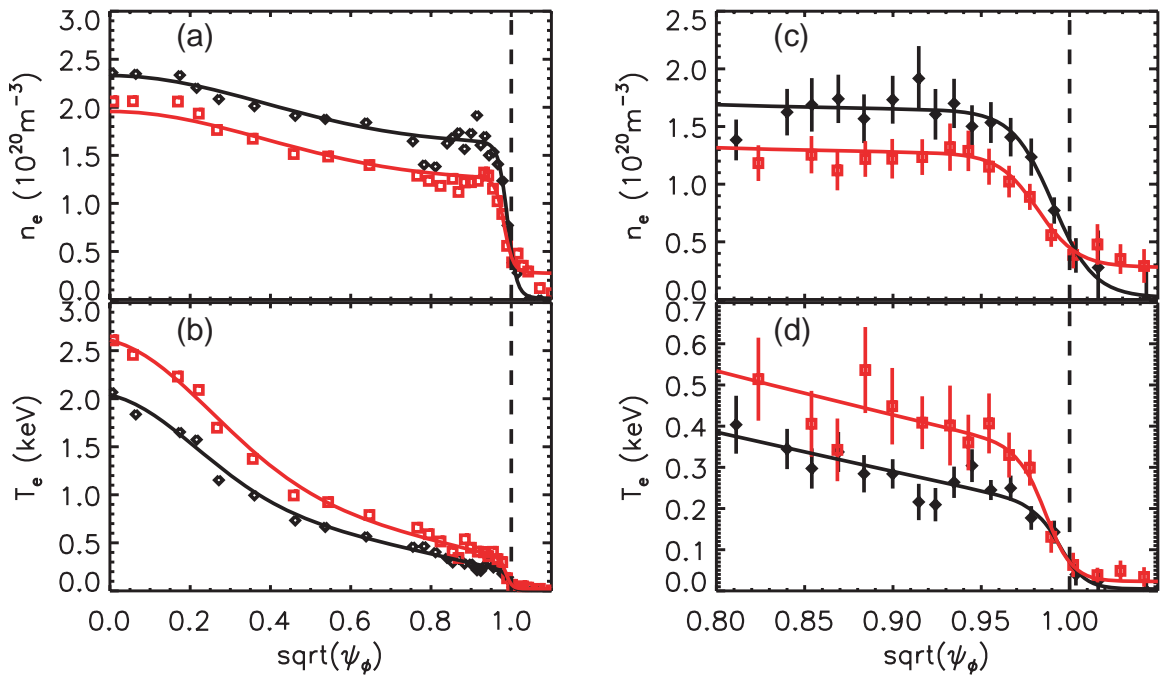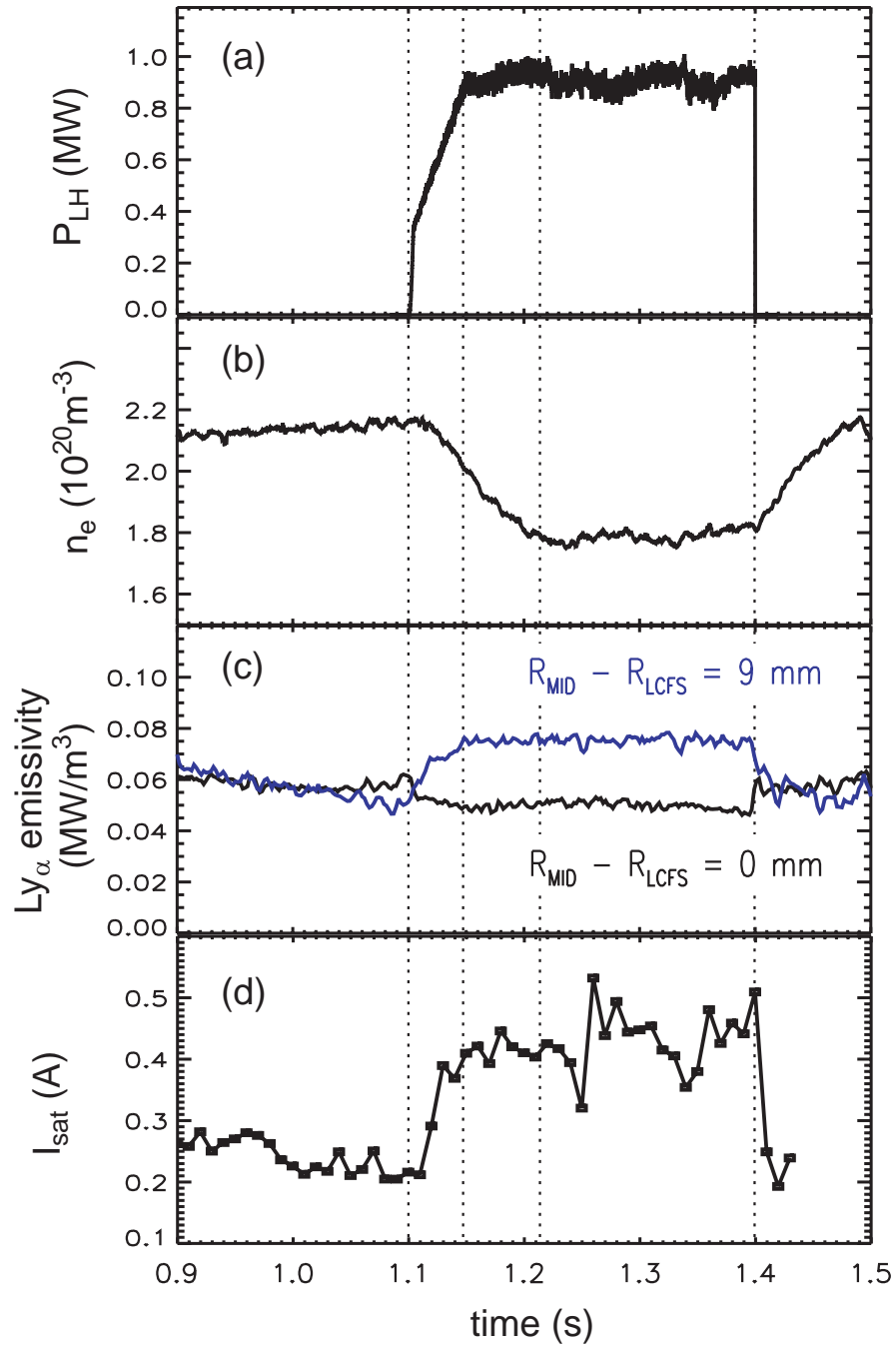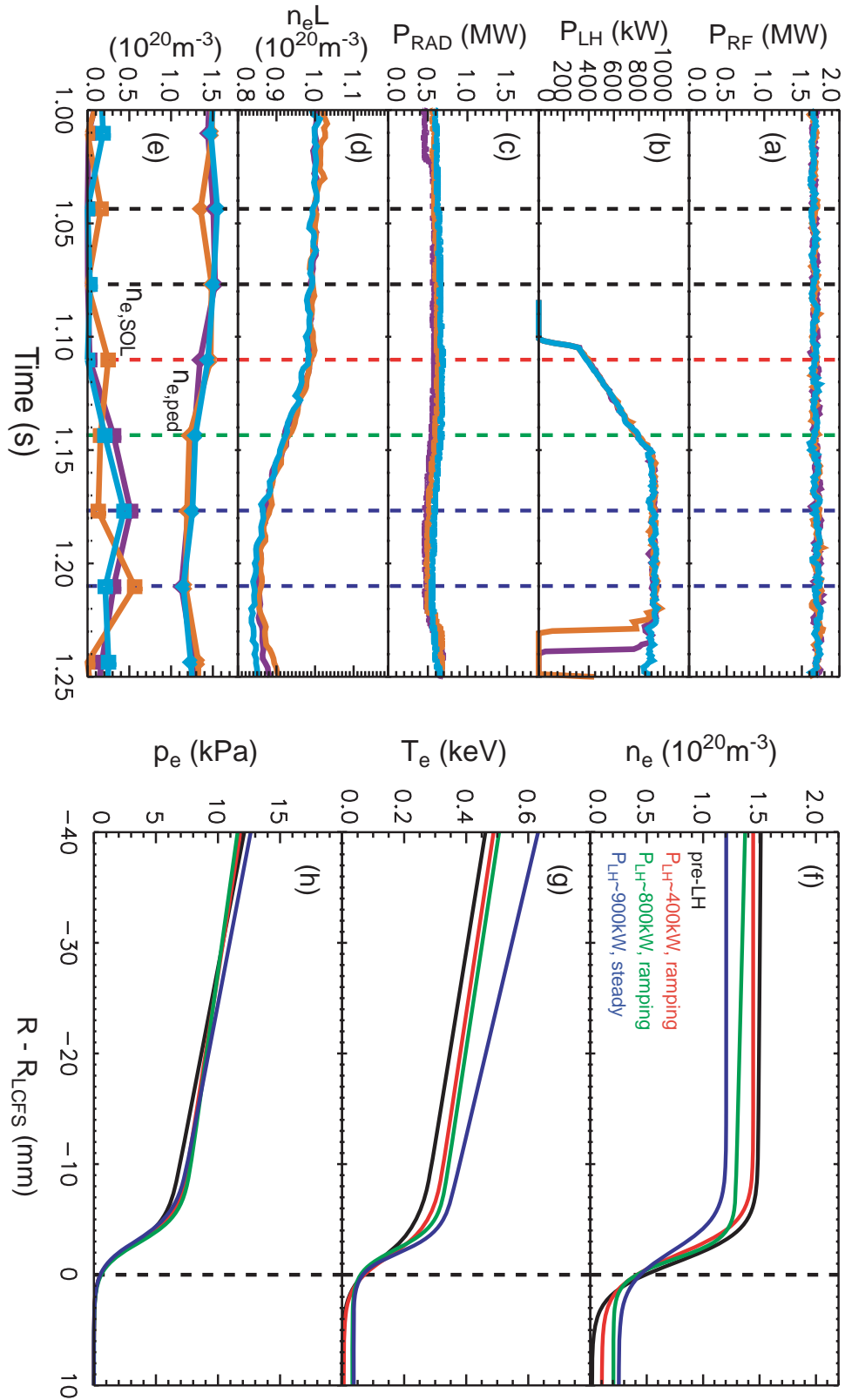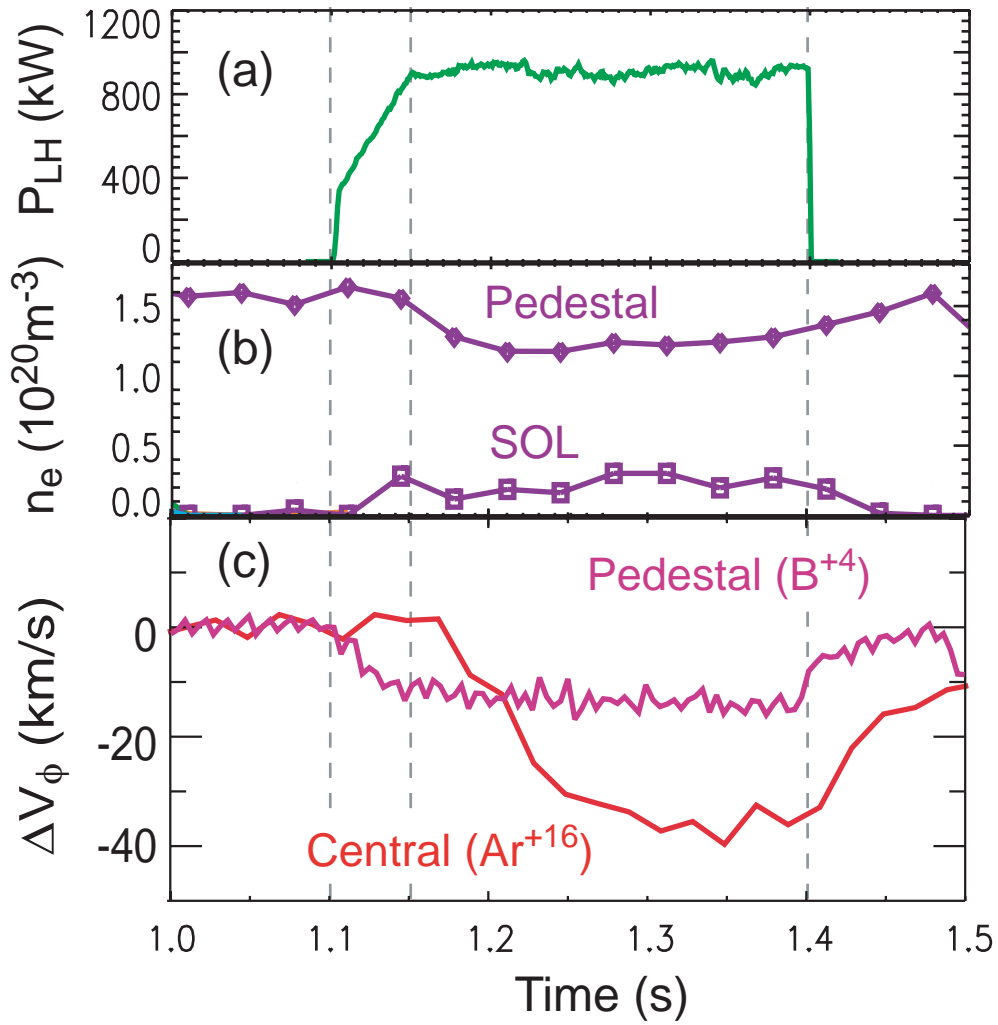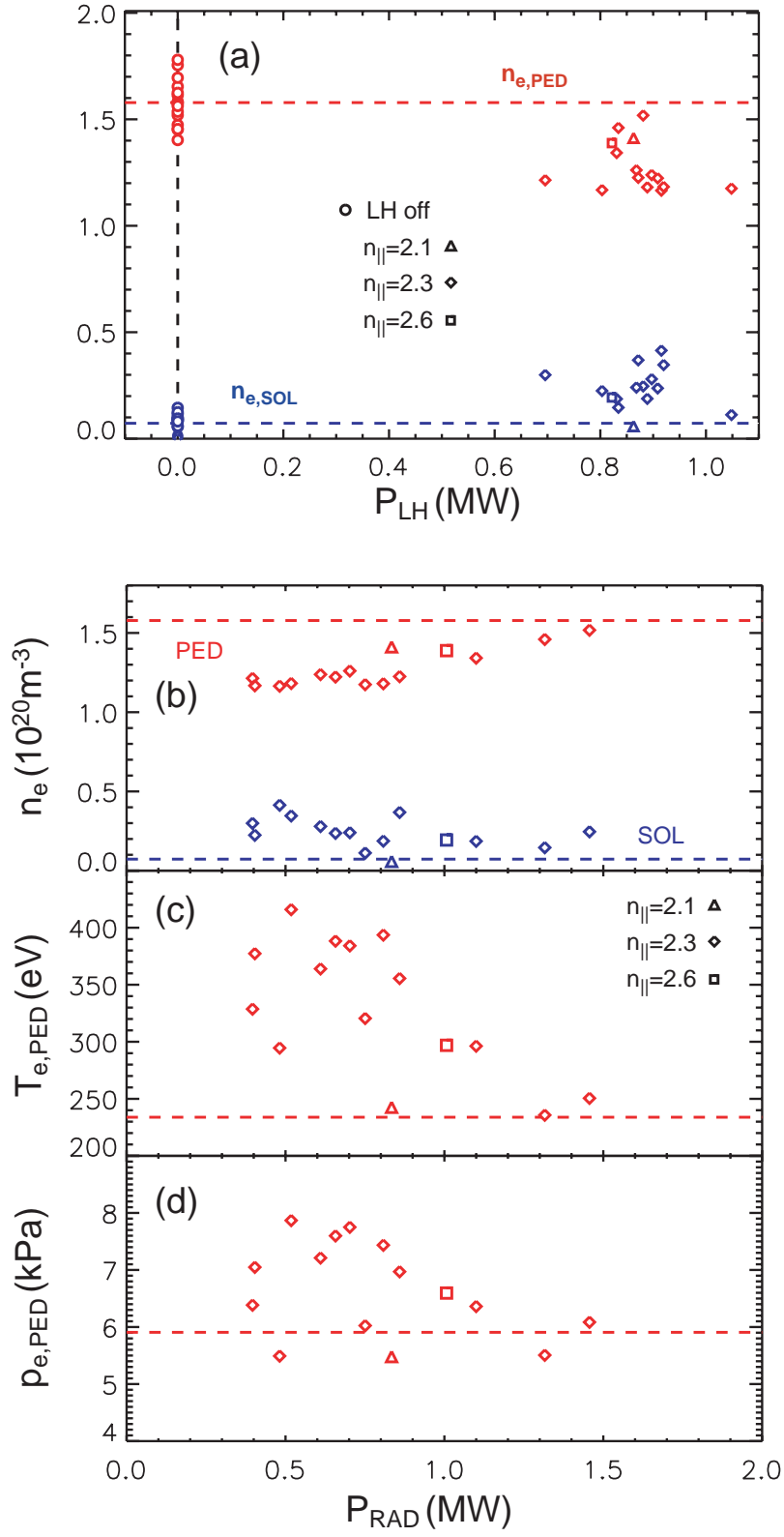
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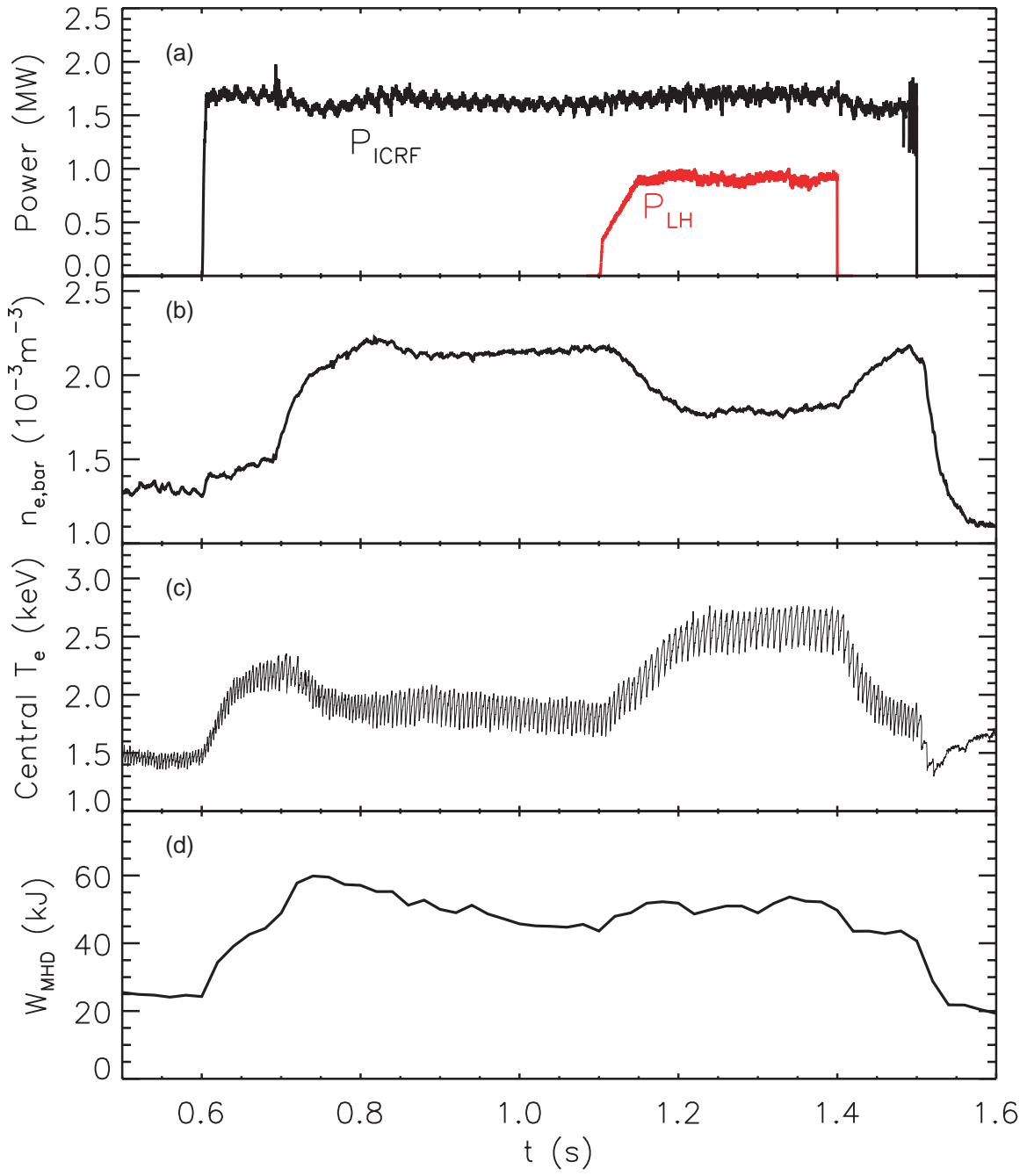
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