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H-Mode Pedestal Studies in Alcator C-Mod

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Introduction:

During the enhanced confinement regime of operation for tokamak plasmas (H-mode) a transport barrier is formed near the separatrix. Sharp gradients of temperature and density are observed in this pedestal of the plasma. Study of the pedestal region is important for understanding the physics of H-mode. This paper presents results of recent experiments on the Alcator C-Mod tokamak aimed at understanding relationships between pedestal parameters and local plasma parameters as well as global confinement.

On Alcator C-Mod a set of high resolution diagnostics is installed that measures electron temperature and density profiles in the pedestal region at different poloidal locations along the last closed flux surface. Detailed description of the diagnostics can be found [1,2]. In this paper we will concentrate on the results obtained with the edge Thomson scattering system, which measures T_e and n_e profiles at the top edge of the plasma with spatial resolution of 1.5 mm and time resolution of 33 msec. This diagnostic allows us to observe formation of the pedestal at the L-H transition and its evolution during controlled plasma parameter scans. Normally, very steep T_e and n_e H-mode gradients are measured, with pedestal widths as small as 2 mm. Electron pressure profiles are reconstructed using the ne and Te measurements and evolution of the pressure gradient in the pedestal region is analyzed. The measured profiles are parametrized using a *tanh* [3] function and a database has been constructed that contains pedestal parameters and a set of relevant plasma parameters measured at the Thomson time points. This allows us to study scalings of the pedestal parameters. It was found that both temperature and pressure pedestal height and gradient increase with input power and plasma current. At the same time, no clear scaling of pedestal width with plasma current was observed. The dependence of the pedestal gradient and height on heating power and plasma current may be combined into a $P_e^{PED}, \nabla P_e \propto W_s$ scaling.

Pedestal profiles measurements.

Measured L-mode and H-mode electron temperature and density profiles are shown in Fig.1 The profiles are measured by the Thomson scattering diagnostic at the top edge of the plasma and then mapped to the midplane using EFIT equilibrium reconstruction, assuming that T_e and n_e are constant on a given flux surface. Formation of the H-mode pedestal is clearly seen. Both T_e and n_e pedestals are located inside the last closed flux surface, with the "foot" of the pedestal on or inside the separatrix. The midpoint of the temperature pedestal is typically located slightly inside that of the density (by .5 – 1.5 mm) so that the region of the maximum density gradient is situated at relatively low values of electron temperature. Thus the pressure gradient tends to be dominated by $n_e \nabla T_e$

term. The *tanh* fit of the density pedestal is shown in Fig.1b and definitions of pedestal parameters (width δ, height T_{ePED}, and location r_{PED}) are illustrated. Typically, the height of the temperature pedestal varies from 100 to 600 eV, depending on input power and confinement quality, and the width of the barrier lies in the range from 2 to 10 mm. The width of density pedestals vary over a similar range, although the n_e barrier is usually narrower than δ_T. The density pedestal height varies systematically with the core density, scaling approximately as $n_{ePED} \propto 0.7 n_{e0}$ [1]. Using the T_e and n_e profiles, electron pressure profiles are reconstructed (Fig. 1a).

Pedestal parameters scalings

Due to statistical errors, natural T_e and n_e fluctuations, and imperfection of the *tanh* fit, the measured parameters of T_e and n_e pedestal vary considerably even in a steady state H-mode. The scatter of the pedestal amplitude values can be as high as 20%, while the scatter in width reaches 30%-40%. Therefore, to obtain more reliable scalings of the pedestal parameters with plasma parameters, several series of steady state shots were taken with the parameter under study being varied from shot to shot. The pedestal width and height obtained from the *tanh* fit were then averaged over the steady state phase taking into account estimated measurements errors.

Two basic parameter scans were performed – a scan of the input RF power at constant plasma current and a scan of plasma current. This allows us to study dependencies of pedestal parameters on net input power, to determine correlations between pedestal parameters and confinement characteristics and to study scalings with local plasma parameters, such as poloidal field, edge temperature, and ion gyroradius.

The results shown in this paper correspond to plasma currents of 1, 0.8 and 0.6 MA, with RF power varying from 0.5 to 2.5 MW, toroidal magnetic field B_t=5.3 T and line averagel density n_{e0}=1.3x10^{20} m^{-2} in L-mode. H-modes obtained under these conditions are typically the Enhanced D_α type [4]. At lower RF power levels, the character of the H-modes sometimes changes to ELMy, with short irregular bursts of type III ELMs.

Fig.2 shows the results of an ICRF heating power scan at constant plasma current (I_p=0.8 MA). Edge profiles of electron temperature, density and pressure are shown at three levels of total input power of 3.3, 2.3, and 1.5 MW, corresponding to ICRF power of 2.7, 1.5 and 0.5 MW. In this series of shots very clear correlation is observed between P_{RF} level, stored energy W_s, total input power $P_{tot}=P_{RF}+P_{ohmic}$, and power flow across the separatrix $P_{SOL}=P_{tot}-P_{rad}$, which makes it impossible to see whether the pedestal parameters scale differently with those variables. It is seen from Fig.2 that while the electron density pedestal does not respond to changes of heating power, the electron temperature and pressure pedestals grow with P_{tot}. The observed correlation of T_e^{PED} with P_{tot} and W_s is in agreement with previous Alcator C-Mod results [5]. In addition, decreasing widths of the T_e and P_e pedestals, and, therefore, sharply increasing maximum values of ∇T_e and ∇P_e with P_{tot} are now seen. This scaling

of T_e gradient differs from that found with lower resolution ECE measurements at the midplane. WE are investigating whether this is due to instrumental effects or there is a real midplane-top edge asymmetries. Assuming that the ion temperature profile is similar to that of T_e, total maximum pressure gradients in excess of 5000 kPa/m are inferred. Preliminary estimates indicate that these gradients are at or above the ideal ballooning stability limit.

A similar input power scan was performed for plasma current of 1 MA, and two RF power levels were studied at $I_p = 0.6$ MA. Increases of T_e^{PED} and P_e^{PED} and maximum temperature and pressure gradients with heating power are observed for all plasma currents. The scaling is best seen when P_e^{PED} and ∇P_e are plotted against power across the separatrix P_{SOL} (Fig.3). At constant P_{SOL} larger amplitudes and maximum gradients are seen at higher I_p for both P_e and T_e pedestals.

There is also a marked increase of density pedestal height with I_p (Fig.4). Although the n_e^{PED} is correlated with central density, n_0, and n_0 is known to increase with plasma current, the observed correlation $n_e^{PED} \propto I_p$ is stronger then $n_e^{PED} \propto n_0$, suggesting that the observed scaling is not entirely related to the central density increase. The density pedestal width also increases with increasing plasma current, leading to a nearly constant density gradient over the studied current range. At the same time, the width of the electron temperature pedestal does not change systematically with current. Thus, the increase of ∇T_{emax} and ∇P_{emax} with I_p is due to the growth of the pedestal height with current.

The obtained results can be interpreted as an indication of correlation of the edge pedestal parameters (height and gradient in particular) with the global confinement. In Fig.5 the pressure pedestal height and gradient are plotted against the stored energy W_s. Very clear correlation is seen for both P_e^{PED} and ∇P_e. The first result is consistent with previous observations on Alcator C-Mod of a strong correlation of the temperature pedestal height and the stored energy [5]. It also can be conclude now, that as the stored energy increases the edge pedestal not only rises but becomes sharper.

Conclusions.

Correlations of H-mode pedestal parameters with plasma current and RF heating power were studied. Both pedestal temperature and pressure height and gradient were found to increase with heating power and I_p. At the same time, no clear scaling of pedestal width with plasma current was observed. These results are in contrast to observations on DIII-D and JT-60U, where scalings of the type $\delta \propto 1/B_p$ was found [6]. On C-Mod, there is an indication that density pedestal width is growing with poloidal field. However, the studied range of plasma current was quite narrow and the edge conditions (amount of impurities and radiated power) were different for different values of I_p. Therefore more experiments are needed to make more definite conclusions about the B_p scaling of the pedestal width.

The dependence of the pedestal gradient and height on heating power and plasma current may be combined into a $P_e^{PED}, \nabla P_e \propto W_s$ scaling. While no clear dependence of the pedestal width with stored energy is observed, the pedestal grows and sharpens as W_s is increased. It is, of course, not apparent from these observations whether P_{ePED} is affecting W_s or vice versa. It should be noted, that this result is in agreement with observations on ASDEX Upgrade [7], where the pressure pedestal gradient was found to be correlated with stored energy for a wide range of plasma parameters.

Acknowledgement.

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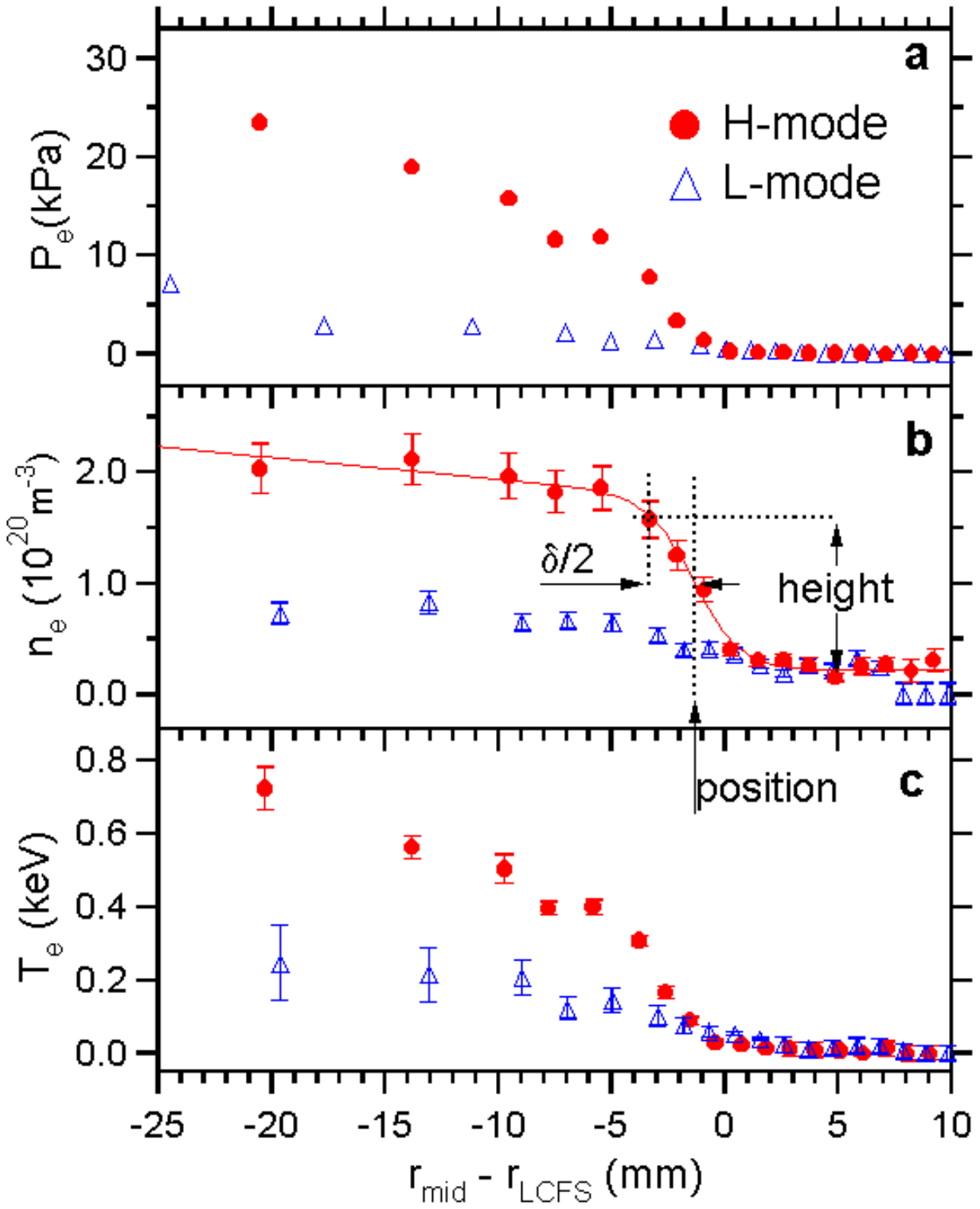7. C. S. Pitcher et al. Phys. Plasmas 4(7), p.2577 (1997)

Fig.1 Measured electron (a) pressure, (b) density and (c) temperature edge profiles in L and H mode.
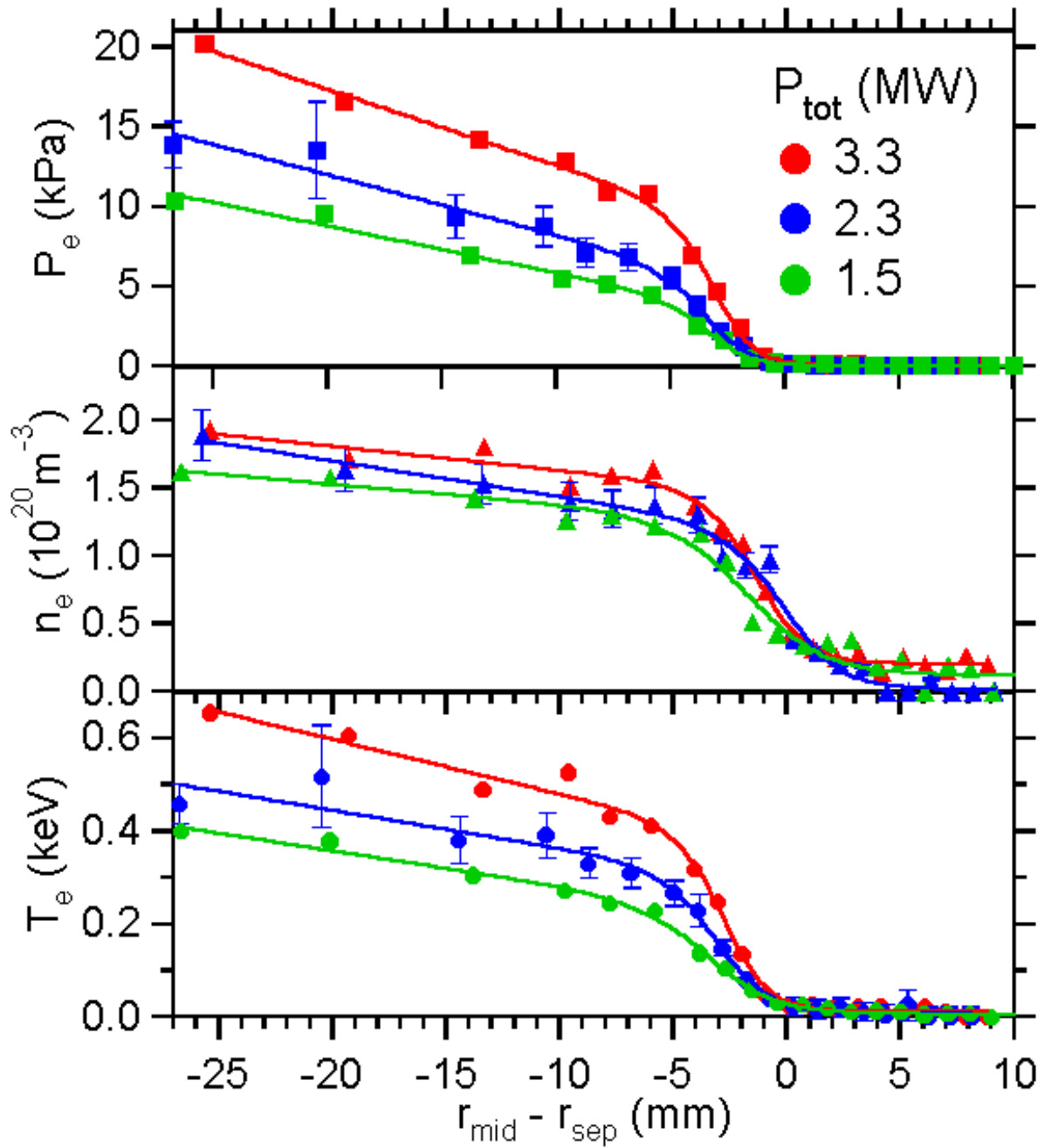
Fig.2 P_e, n_e and T_e profiles at three levels of input power at $I_p = 0.8$ MA. Rising T_{ePED} and P_{ePED} as well as temperature and pressure gradients are observed.
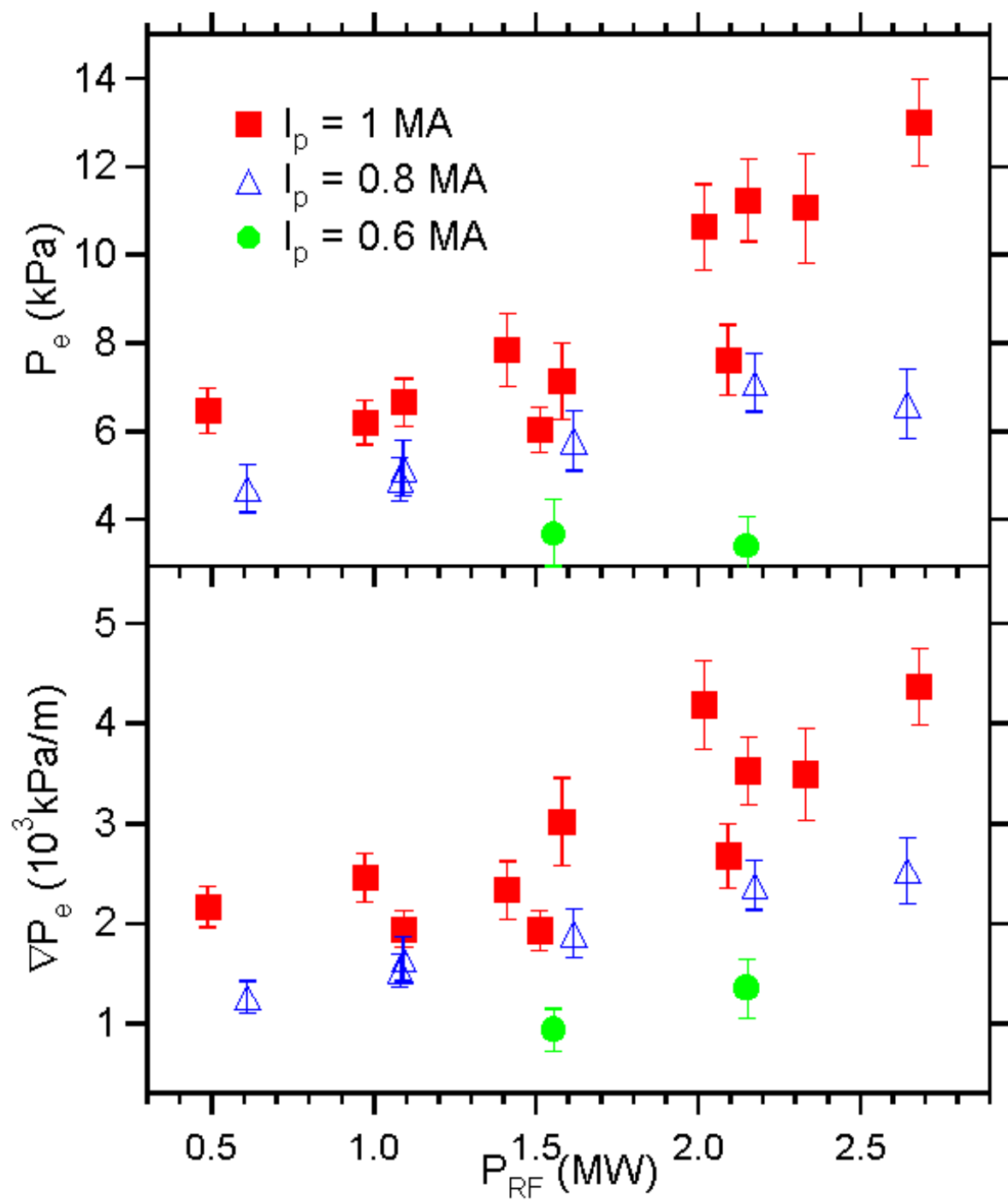
Fig.3 Electron pressure pedestal height and pressure gradient as functions of heating power for different values of plasma current
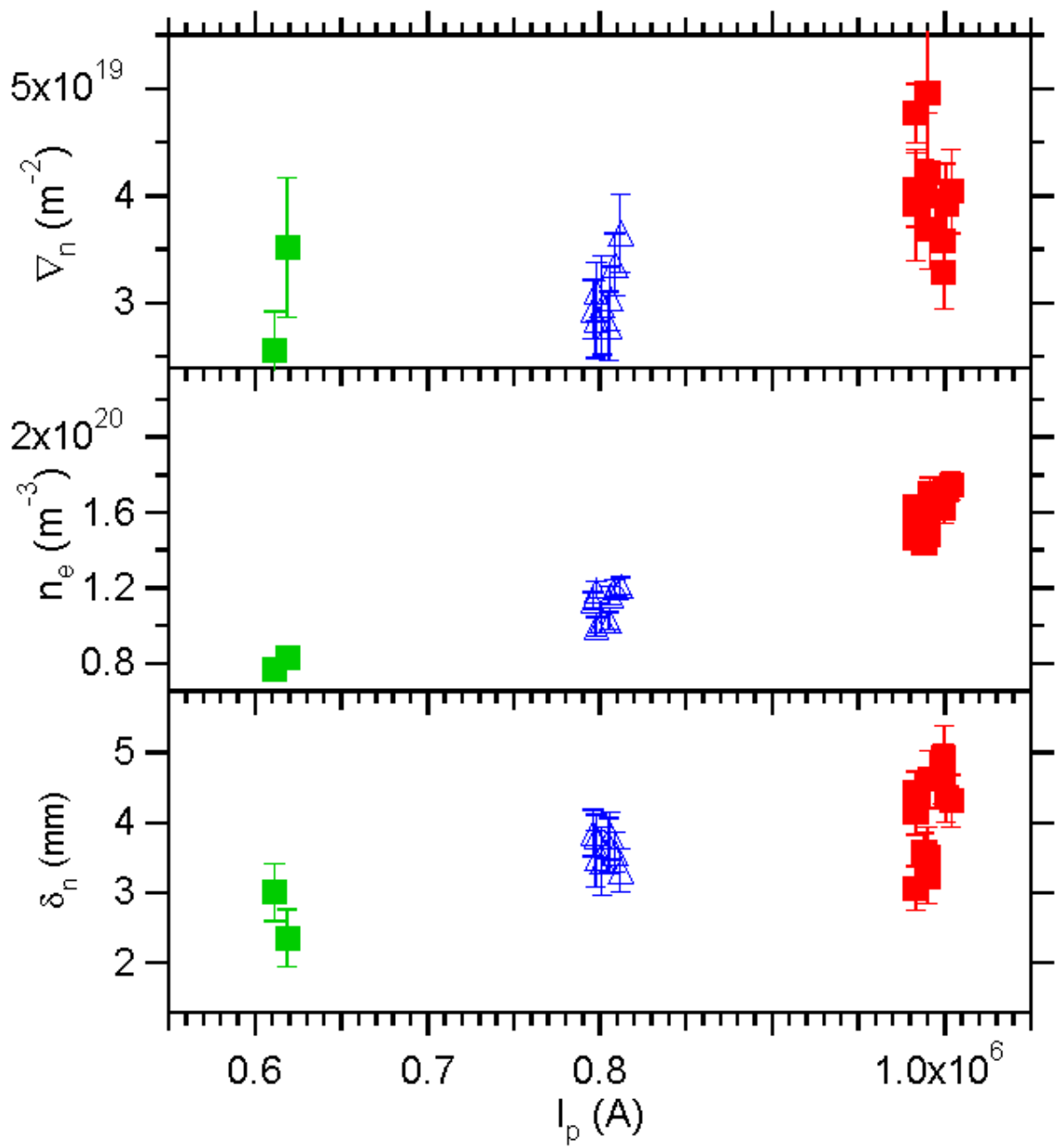
Fig. 4 Scalings of electron density pedestal height, width and maximum gradient with plasma current
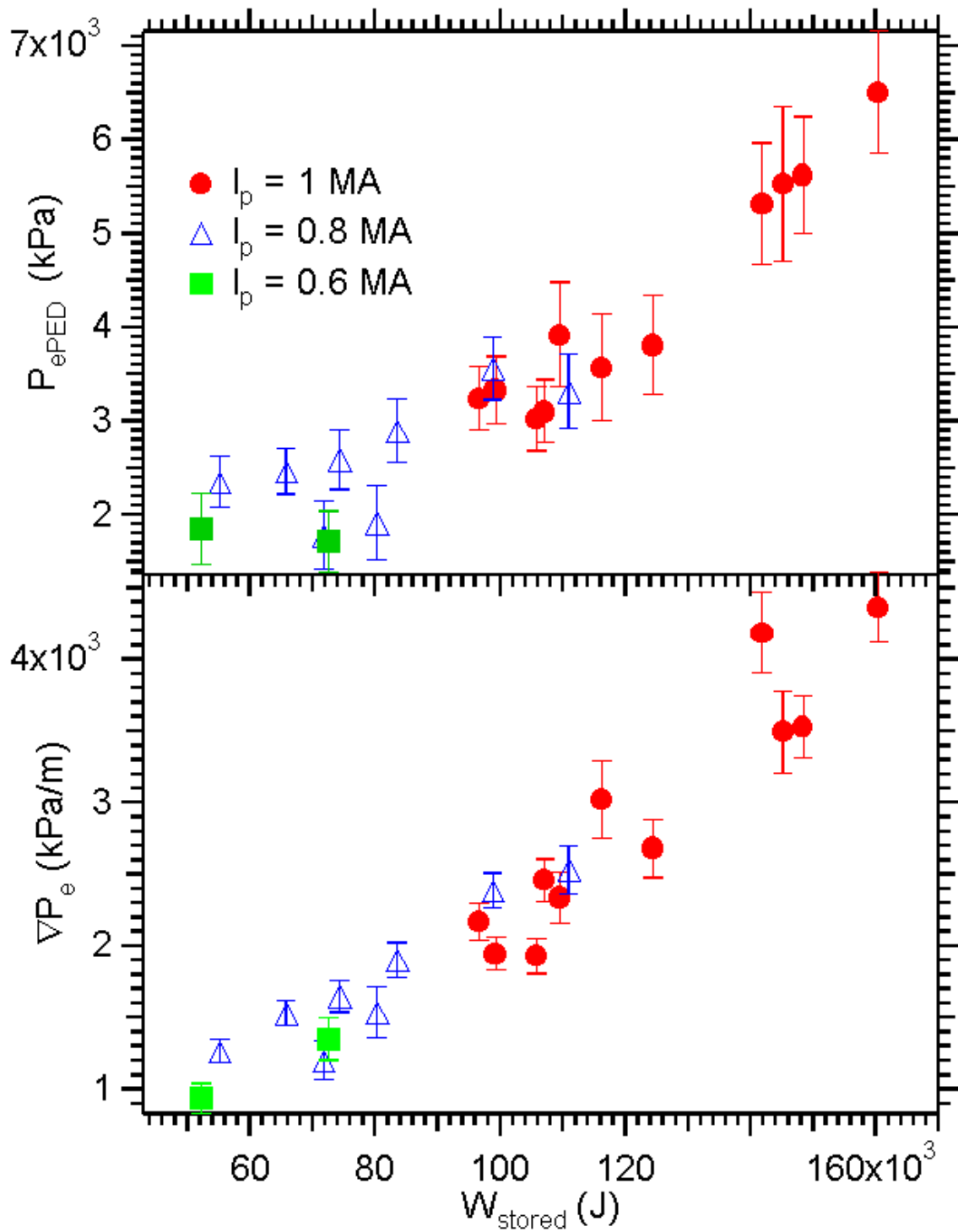
Fig. 5 Correlation of pressure pedestal height and gradient with stored energy for all studied values of plasma current and heating power