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D. Johnson¹, B. LaBombard, Y. Lin, A. Mazurenko,
R. Nazikian¹, C.S. Pitcher, G. Taylor¹, S.M. Wolfe

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Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

¹Princeton Plasma Physics Laboratory, Princeton, NJ 08543.

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M.Greenwald, J.Hughes, J.Irby, D.Johnson [#], B.LaBombard, Y.Lin, A.Mazurenko,

R.Nazikian[#], C.S.Pitcher, G.Taylor[#], S.M.Wolfe

MIT, Plasma Science and Fusion Center, Cambridge MA, USA

[#] Princeton Plasma Physics Laboratory, Princeton NJ, USA

Abstract

In this paper we summarize the results of recent measurements of the high confinement mode (H-mode) edge transport barrier in Alcator C-Mod. A number of new, high resolution edge diagnostics provide measurements of plasma parameters (electron density and temperature, and impurities density) in the pedestal region. Pedestal parameters are measured both at the top edge of the plasma and at the midplane. Very narrow (2 - 5 mm) electron density and temperature and impurity density pedestals are observed. The impurity pedestal is located inside the density and temperature pedestals in the midplane measurements, but coincides with n_e pedestal at the top edge. Correlation of both width and height of the pedestals at the midplane is observed with global plasma parameters and core confinement characteristics. At the same time there are no clear indications of scaling for the electron density and impurity pedestal widths measured at the top of the plasma.

Introduction

A characteristic feature of the high confinement (H-mode) regime [1] is the formation of a transport barrier near the separatrix, where steepening of the density and temperature gradients is observed. Theoretical and experimental works [2-6] suggest strong dependence of the plasma core confinement on the edge parameters. Detailed studies of this pedestal region are important for understanding the H-mode physics, the mechanisms of the L-H transition and the subsequent confinement improvement. Consequently, with improvements of edge diagnostics in tokamaks, more attention is focused on experimental and theoretical investigation of the dependence of the confinement on the edge parameters, as well as of the behavior of the edge parameters themselves.

The goal of this paper is to present the results of recent measurements of the edge transport barrier structure in the Alcator C-Mod tokamak. Previous measurements of the temperature and x-ray emissivity pedestals in Alcator C-Mod [7,8] have shown that the transport barrier can be very narrow, with typical T_e width around 1 cm and x-ray emissivity width of the order of 1-2 mm. A number of new high resolution diagnostics have been installed on Alcator C-Mod to provide measurements of n_e and T_e pedestals with appropriate resolution. New results from these diagnostics are analyzed and compared in this paper.

Pedestal measurements.

The locations of the diagnostics in the Alcator C-Mod vacuum chamber are shown in Fig.1. The present diagnostics measure pedestal parameters at two poloidal locations – outboard midplane and top edge. The electron density and temperature profiles on top of the

plasma are measured by the edge Thomson scattering (TS) system, which has 1.3 mm spatial resolution (when mapped to the outboard midplane) and 30 Hz repetition rate. The temperature profile at the midplane is obtained with the multichannel electron cyclotron emission (ECE) diagnostic, which records T_e at 9 magnetic fields (radii) with instrument resolution of about 9 mm. For measuring the T_e profiles at the edge, a small B_T sweep (5%) is used to improve the detail in the profile. Visible continuum profiles are measured with a 2048 element 1-D CCD array, which images emission from the plasma in a passband at 536 ± 3 nm. The emission is dominated by free-free bremsstrahlung for $T_e > 20$ eV [9] and therefore the electron density profile can be obtained from the emissivity measurements. The toroidal midplane views are Abel-inverted to yield local emissivity profiles, with chordal resolution near the pedestal region of 2 mm, and time resolution of 4 ms. Soft x-ray emissivity is measured simultaneously at the top of the plasma and the outer midplane by photodiode arrays viewing the plasma edge region through 10 μ m beryllium filters. The filters cut out photons with energies below 600 eV. Each array has 38 detectors and has radial resolution better than 1.5 mm and down to 12 μ s time resolution.

The locations of observation volumes and viewing chords of the Thomson scattering, visible continuum and soft x-ray arrays in the vacuum vessel were measured to provide for measurements of the pedestal position. The error of the absolute position measurements of the visible continuum array and soft x-ray array are estimated to be ± 0.5 mm. The corresponding error for Thomson scattering diagnostic is about ± 2 mm. To compare the results from diagnostics at different poloidal locations, the measured profiles are mapped to the midplane along the field lines using EFIT reconstruction, assuming that the plasma parameters are constant on flux surfaces. The mapping process introduces additional error to the measured locations of

the pedestals for the top edge diagnostics. The systematic error related to the EFIT reconstruction process could be as large as ± 3 mm. The position of the electron temperature profile measured using ECE is determined using the EFIT reconstruction of the total magnetic field. The uncertainty in the field value ($\sim 0.5\%$) leads to an uncertainty in the ECE profile position of about 4 mm.

The pedestal parameters, such as width, amplitude, and position, are defined by fitting the profiles measured across the pedestal region with a hyperbolic tangent function [10]. It turns out that all the profiles that we consider here are well fitted by this function. A database has been constructed that includes the pedestal parameters for all the measured quantities, allowing us to identify correlations among the parameters and their scalings with global plasma parameters.

In Fig.2, typical results of pedestal measurements at a given time point during an Enhanced D-alpha (EDA) H-mode [11] are shown. As it was pointed out above, the ECE electron temperature profile is obtained using a small toroidal field sweep. The duration of the sweep is 100 ms. Therefore the profile represents electron temperature averaged over this period of time. In Fig.2 we compare the profiles from different T_e and n_e diagnostics averaged over 100 ms. The pedestal formation inside the separatrix during the H-mode is clearly seen on all the profiles. The TS electron density and temperature pedestals are very narrow, typically 2 - 8 mm wide. The TS T_e profile presented in Fig. 2a is 3 mm wide. The corresponding ECE profile is wider, $\delta \sim 9$ mm, and shifted by about 7 mm inward. The width of the ECE profile is equal to the width of the ECE instrument function, and the slightly higher pedestal value can also be a result of the convolution of the real profile with the response function of the diagnostic. The observed difference in locations of ECE and TS profiles is systematic and may be attributed to

systematic errors in position measurements of the diagnostics and EFIT mapping. The shift is within the combined uncertainties of both diagnostics and EFIT reconstruction. Therefore, present results indicate that the measured electron temperature profiles at the midplane and top edge of the plasma agree within experimental errors. Previously, in higher power discharges, higher and wider (δ up to 20 mm) temperature pedestals were observed with ECE diagnostics [15]. To make a final comparison of ECE and TS results further measurements are necessary with higher plasma heating power leading to a larger T_e pedestal when ECE measurements are not limited by the diagnostic resolution.

Assuming that the visible continuum emissivity is dominated by free-free bremsstrahlung, the measured emissivity profile $E(r)$ is proportional to the square of electron density, Z_{eff} and a weak function of temperature, and the electron density profile can be derived as:

$$n_e(r) \propto \left(\frac{E(r) \cdot \sqrt{T_e}}{z_{\text{eff}} \cdot (-1.207 \cdot \log(h\nu/T_e) + .556.)} \cdot \exp(h\nu/T_e) \right)^{1/2}$$

Assuming constant Z_{eff} across the pedestal, it is possible to derive the electron density profile from the emissivity data using the measured temperature profile. Such a derived density profile is shown in Fig. 2b. To obtain this profile a *tanh* fit to the temperature pedestal measured with Thomson scattering and mapped to the midplane was used. A constant $Z_{\text{eff}}=1.2$ was assumed. The resulting density profile is about twice as wide as the TS profile. This is typical for EDA H-mode measurements. It should be noted, however, that there are cases when the bremsstrahlung derived profile is much wider than TS profile (up to five times as wide) and other cases with approximately the same width.

Thorough investigations of the plasma radiation spectra and of the atomic processes in the plasma in the vicinity of the density pedestal show that the measured visible continuum

emissivity is the free-free bremsstrahlung emissivity of the plasma [9]. Therefore, the only assumption not supported directly by experimental evidence, which is used when deriving the density profile, is the assumption of constant Z_{eff} across the pedestal region. The derived electron density is inversely proportional to the square root of Z_{eff} . Thus, if we suppose that Z_{eff} is not constant, it would need to have a sharp rise in the pedestal region to produce the bremsstrahlung emissivity consistent with the TS measured density profile. This seems to contradict the results of the impurity density measurements (see discussion below) showing decreasing impurity concentration at the location of the density pedestal. If the drop in impurity concentration is large enough to affect significantly the value of Z_{eff} it can only widen the density profile derived from the bremsstrahlung measurements.

The electron pressure profiles can be reconstructed using measured n_e and T_e both at the midplane and top edge. Since the electron pressure is the product of temperature and density, the width of the pressure pedestal would be determined by the narrowest of the n_e and T_e profiles. Assuming that the electron temperature profiles are the same at the midplane and at the top edge, as seen from previous discussion, we can calculate the pressure profiles using the TS and bremsstrahlung measurements. An example of pressure profiles reconstruction is shown in Fig.3 . It is seen that within measurements errors the pressure pedestal at the midplane matches closely the top edge profile, except for a narrow region near the top of the pedestal. The widths, and therefore the gradients, of the midplane and of edge profiles are much closer than in case of densities.

To summarize, sharp electron density and temperature gradients are observed in the region near the top of the plasma, with pedestal width varying from 2 to 8 mm for both n_e and T_e . Wider barriers are measured at the midplane, with density pedestal width ranging from 4 to

20 mm, and electron temperature width in the range 8-20 mm, probably limited by the spatial resolution of the ECE diagnostic. All the barriers are observed to be inside the last closed flux surface, with the bottom of the pedestals located near the separatrix. The results seem to indicate, that at the pedestal region the electron density varies along flux surfaces, with density pedestal wider at the midplane than near the top edge of the plasma, although further experimental investigations are necessary to make a definite conclusion.

The x-ray emissivity exhibits even sharper gradients in both upper and midplane profiles (Fig. 2c). The width of the pedestal on the midplane varies from 2 to 6 mm, while the width of the pedestal near the top of the plasma is usually smaller, 1.5 to 2.5 mm. The midplane x-ray profile is located inside the last closed flux surface, about 10 mm from the bremsstrahlung and TS density pedestal, while the top x-ray pedestal is located roughly at the same place as the TS density profile. The difference in locations of the top and outboard midplane x-ray emissivity pedestals, which is about 10 mm, is much larger than the combination of the 1.5 mm uncertainty in the location of the x-ray views and 3 mm EFIT mapping error. The x-ray emissivity pedestals at the top and outboard midplane are not located on the same EFIT flux surfaces, and do not have the same shape. A possible explanation of the fact that the x-ray emissivity, and therefore the impurity density pedestal, is located inside the electron density barrier at the midplane is a strong inward impurity pinch coinciding with the region of strong n_e gradients. The existence of the inward pinch near the H mode edge region has been demonstrated in Alcator C-Mod [12] and is seen in other tokamaks as well [13,14]. The highly resolved edge profiles now available should make it possible to localize the pinch region with high accuracy. Analysis of this effect and of the origin of the midplane-top x-ray pedestal asymmetry is work in progress and will be addressed in a future publication.

Pedestal parameter scalings.

Studies of the H-mode transport barrier on Alcator C-Mod and other tokamaks have shown that the confinement of the core plasma is correlated with the pedestal parameters. The systematic investigation of these correlations in C-Mod is made possible with addition of the high resolution edge diagnostics. Further improvements of the diagnostics, together with better understanding of the errors of the mapping process, are necessary to obtain reliable scalings. Also systematic scans of the global plasma parameters have not yet been conducted with all of the new diagnostics available. However some preliminary results are obtained and reported here.

In Alcator C-Mod mainly two H-mode regimes are observed – ELM free regime and Enhanced D-alpha (EDA) regime [11]. The ELM-free regime is characterized by high particle confinement time which leads to rapidly rising core electron and impurity density and radiated power. Thus, the ELM-free H-mode can not be maintained in steady state and usually ends in radiative collapse. In contrast, the EDA regime has energy confinement time comparable with that in ELM-free but lower impurity confinement, and can last for the whole duration of the RF heating pulse. Time evolution of core and pedestal electron density measured by TS is illustrated in Fig. 4 (a) for both ELM-free and EDA H-mode cases. In both cases the pedestal is formed more quickly than the initial core density rise. This is seen very clearly in case of EDA, when the pedestal density, n_e^{ped} , reaches a steady state value 50-100 ms before the central density. On the other hand, in all cases there is a strong correlation between pedestal height and central

density after the transition, as seen in Fig. 4 (b), with the ratio of $n_e^{\text{ped}}/n_{e0} \sim 0.7$. A similar correlation is observed between the bremsstrahlung pedestal height and core density.

In EDA H mode regime, the value of n_e^{ped} increases with current, or decreases with q_{95} , in both top and midplane locations. Since the bremsstrahlung emissivity is a weak function of electron temperature, the width of the density profile is usually equal to the emissivity width within the measurements error. Thus the bremsstrahlung emissivity width is used for scaling studies. The midplane density pedestal width correlates well with n_e^{ped} , plasma current and magnetic field in the EDA regime. Wider pedestals, with lower ∇n_e , correspond to lower current and higher q . In contrast, in ELM free H modes, no clear scalings of the midplane pedestal width are observed, although the width is generally smaller than in case of EDA H mode. These results are similar to previously reported midplane pedestal impurity scalings [8]. The impurity pedestal is narrower in the ELM-free regime, and its width increases with decreasing current. The temperature barrier width also increases with increasing T_e pedestal height. It was shown previously [15] that the midplane temperature pedestal height and width increase with increasing power flux across the edge region.

No clear scaling of the x-ray or electron density pedestal widths on top of the plasma was observed with any plasma parameters. On the other hand, the bremsstrahlung width, measured at the midplane, is correlated with the core confinement time (Fig.5) and possibly other parameters, although further experiments are necessary to establish the scalings. The lack of observed scalings of the density pedestal width on top of the plasma may be explained by fluctuations of the width which, combined with the generally narrow barrier, mask any possible dependencies.

Conclusions.

Detailed measurements of electron density and temperature and impurity density pedestals have been carried out in Alcator C-Mod using set of new high resolution edge diagnostics. Sharp gradients of the plasma parameters are observed to form at the separatrix during H-mode. Initial experimental work has focussed on studying relations of pedestal parameters with global plasma parameters and confinement characteristics. Clear asymmetries between the top of the plasma and the midplane are observed in location and width of impurity density pedestals. The top impurity density pedestal is narrower than the profile measured at the midplane (~ 2 mm as opposed to ~ 4 mm at the midplane) and the midplane profile is located farther inside the separatrix. The results also indicate that there may be a similar asymmetry in electron density pedestal width, with density pedestal wider at the midplane than near the top of the plasma, although further experimental investigations are necessary to make a definite conclusion. Scalings of pedestal parameters with plasma parameters are much less clear in impurity and electron density pedestals measured at the top edge than in ones measured at the midplane.

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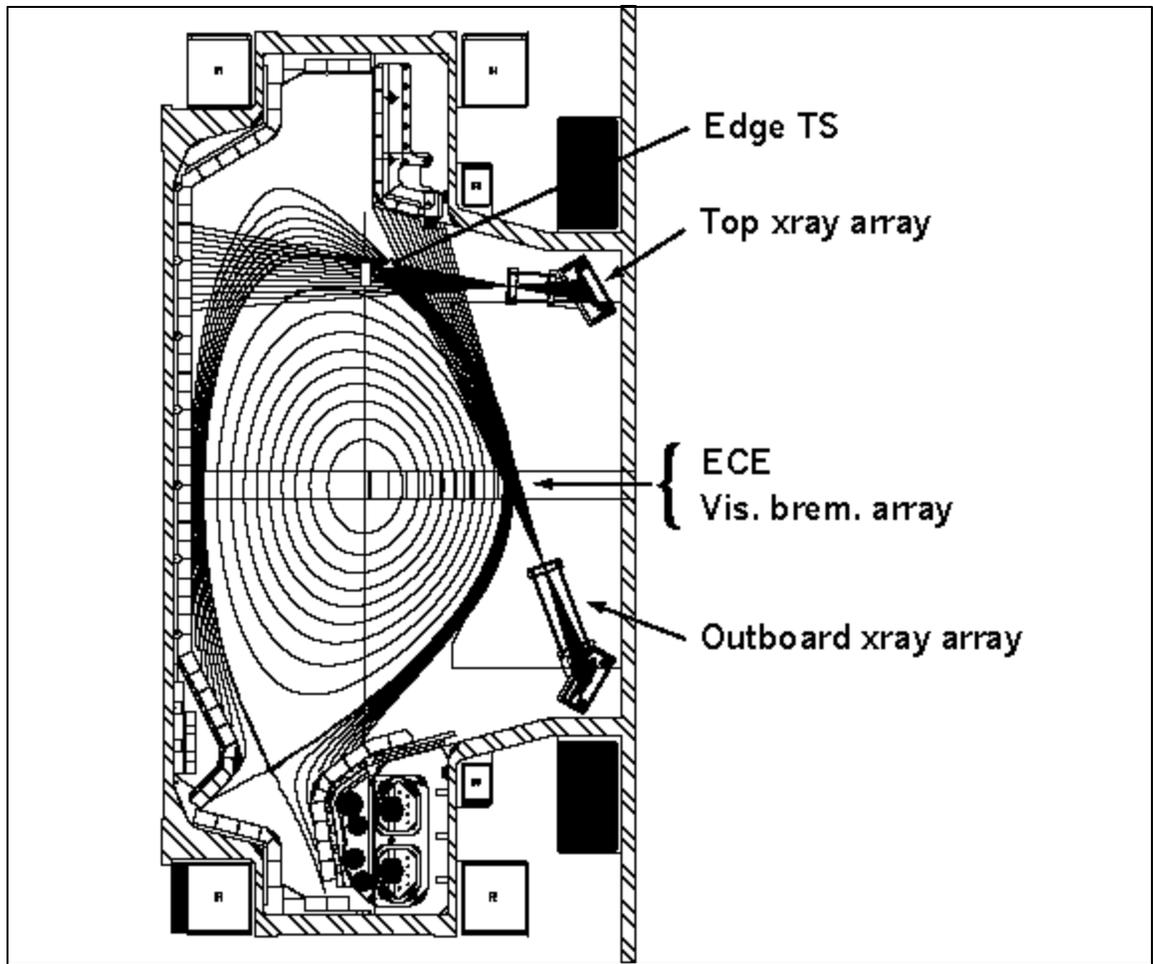


Fig.1 Edge diagnostics on Alcator C-Mod

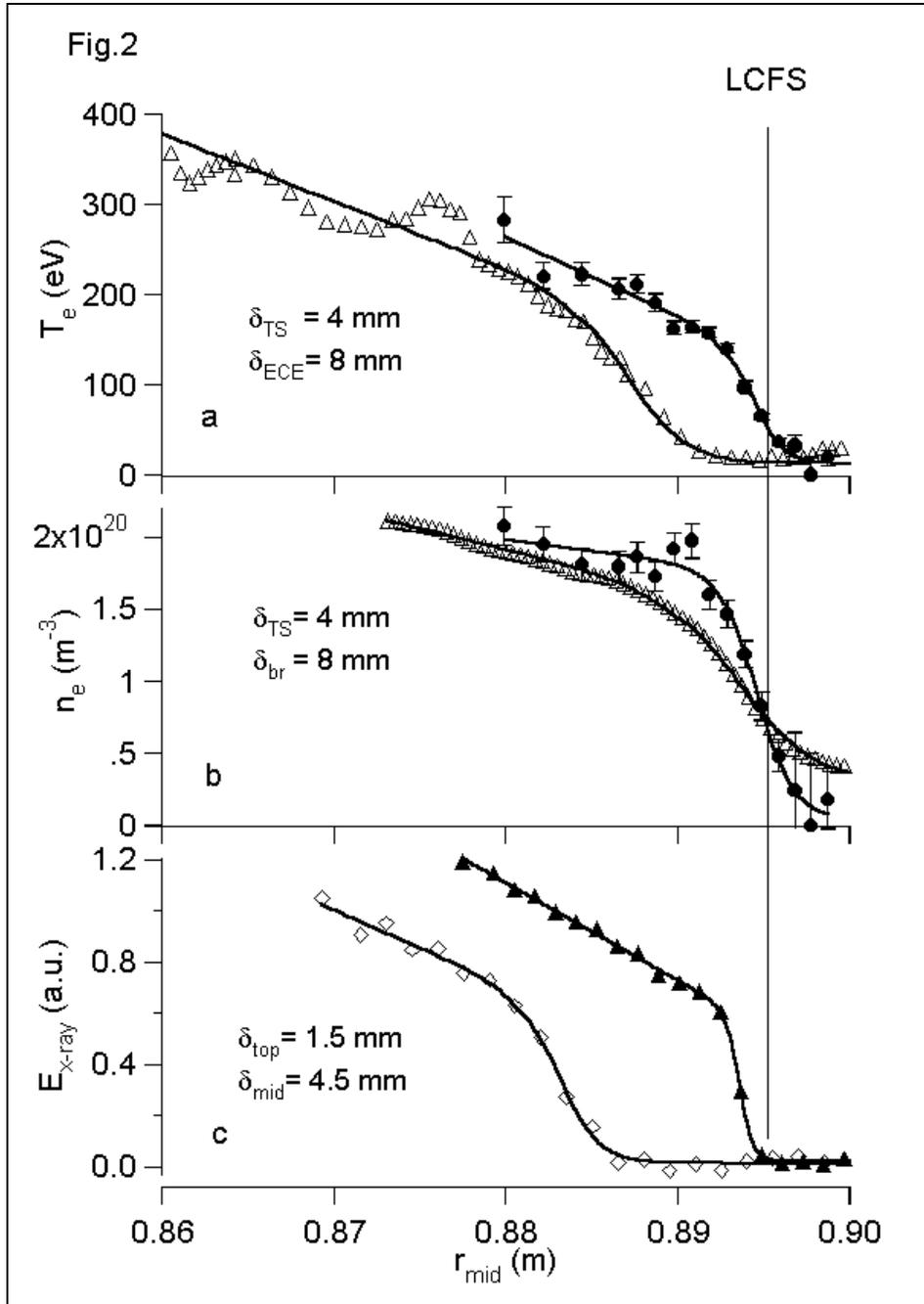


Fig.2. Pedestal profiles measured on top of the plasma and at the midplane. (a) electron temperature, triangles – ECE, circles – TS, (b) electron density, triangles – bremsstrahlung, circles – TS (c) x-ray emissivity, diamonds – midplane, triangles – top edge. The measured profiles are shown with the results of the \tanh fits (solid line) and widths δ .

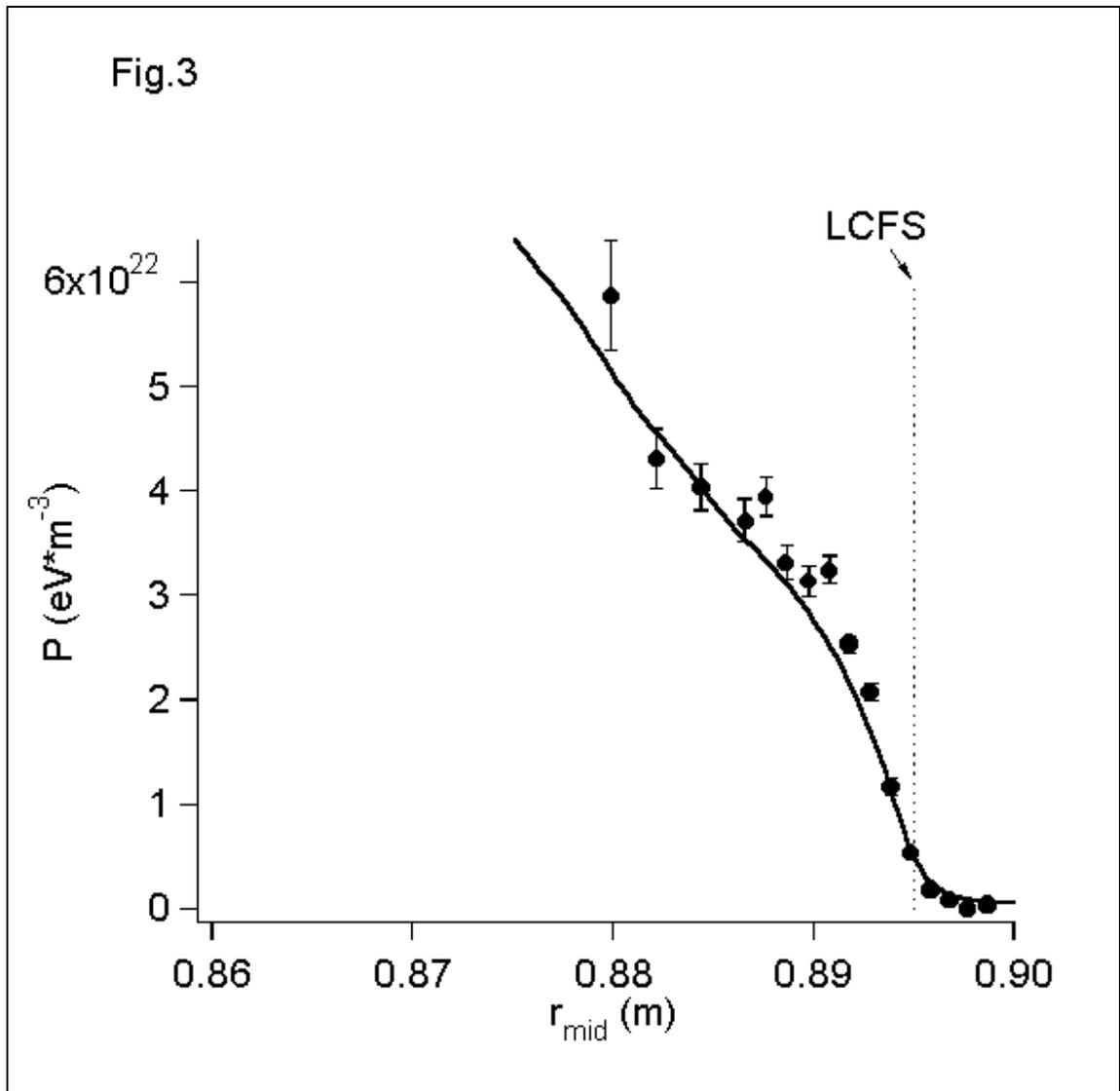


Fig.3 Electron pressure profiles obtained with the results of bremsstrahlung measurements at the midplane (solid line) and TS at the top edge (circles)

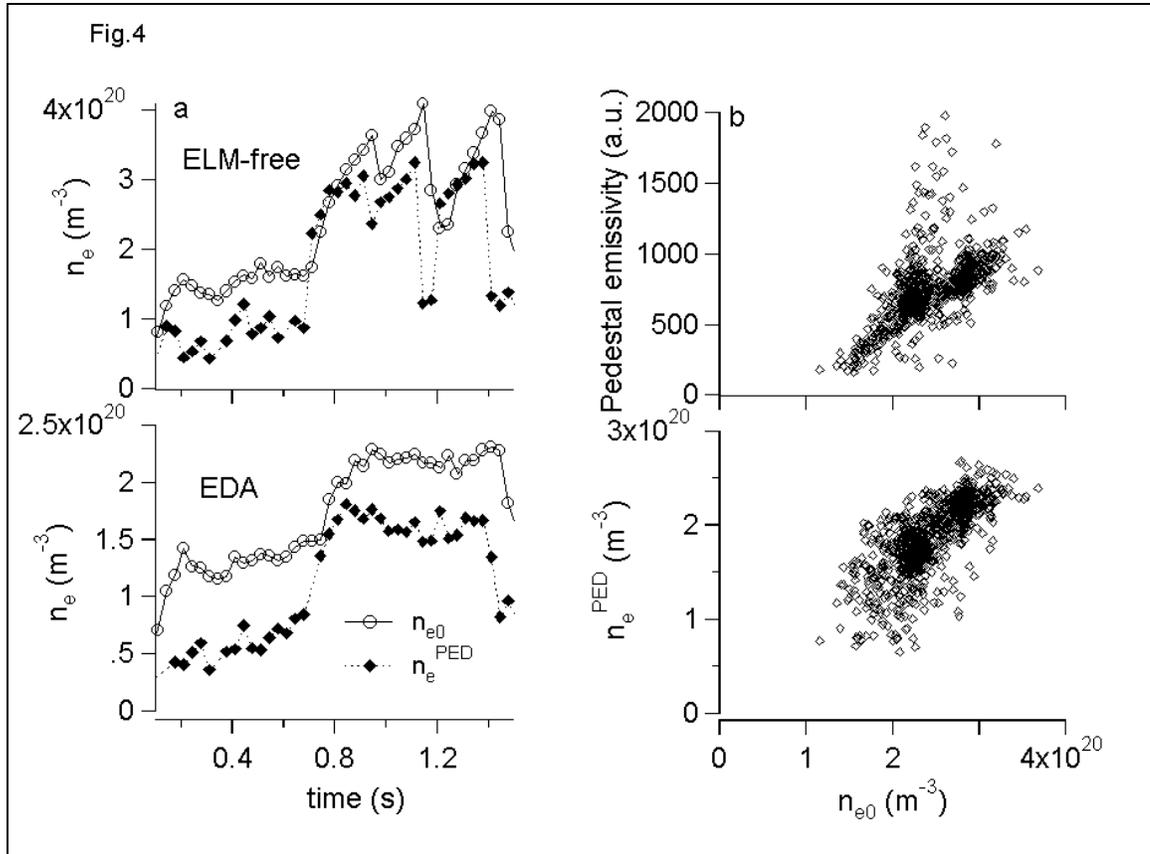


Fig.4 (a) Time evolution of electron density pedestal height n_e^{PED} and central plasma density n_{e0} for EDA and ELM-free H-mode, and (b) scaling of n_e^{PED} with n_{e0} seen both at the midplane (pedestal emissivity height scaling) and near the top of the plasma

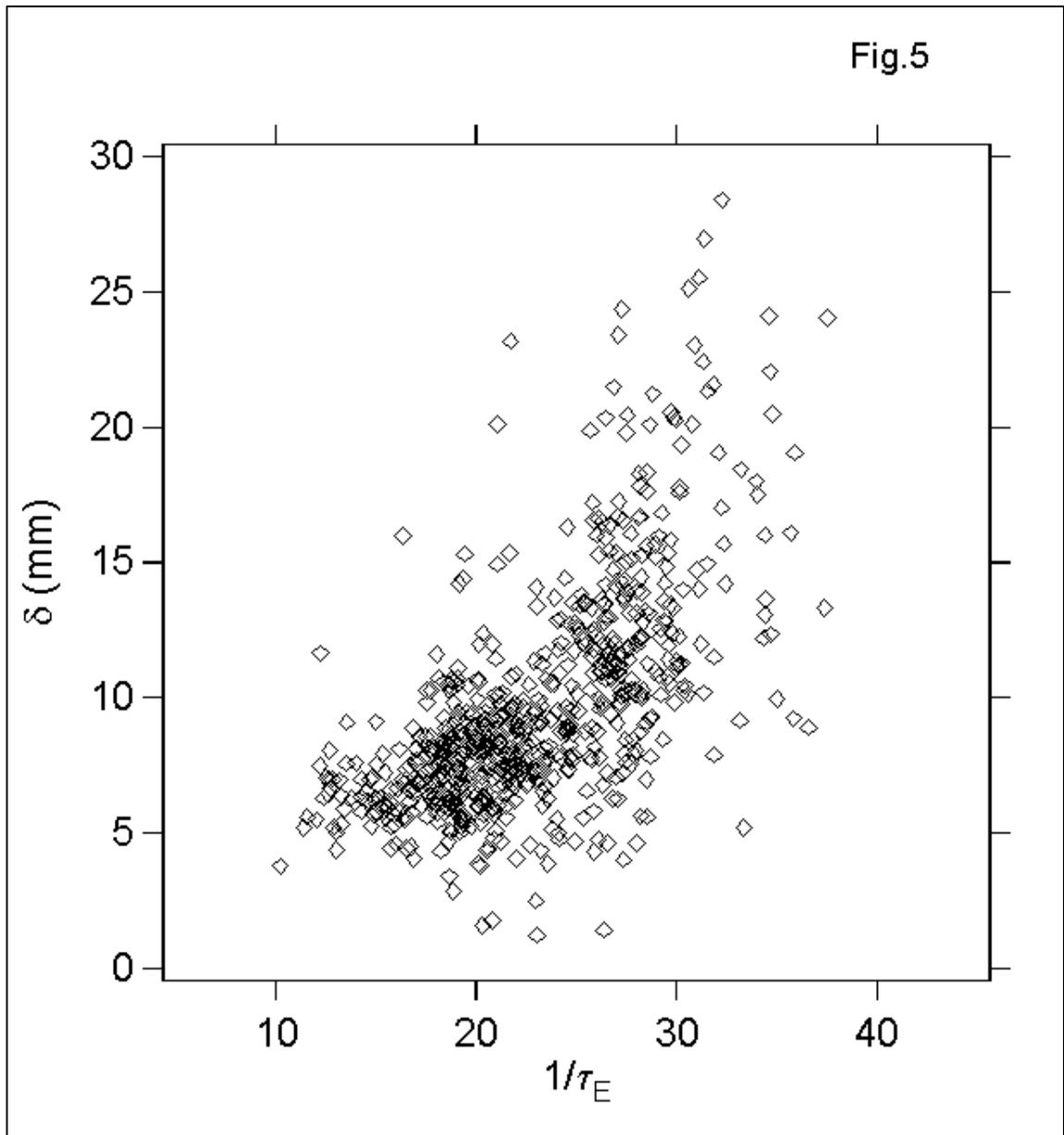


Fig.5 Observed correlation of the bremsstrahlung emissivity pedestal width and energy confinement time (including both EDA and ELM-free results).