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H-Mode Pedestal Physics Studies in Local Dimensionless Identity Experiments

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The characteristics of the H-mode density pedestal are determined by a balance between two competing processes – plasma transport across the region and neutral particle fuelling of the edge plasma. Identifying the relative role of plasma physics vs atomic physics of neutral fuelling is important for advancing our understanding of H-mode pedestal. A dimensionless identity technique can be used for this purpose, which is based on the fundamental fact that conservation of dimensionless plasma parameters (collisionality ν^*, normalized plasma pressure β, and normalized gyroradius ν^*) leads to invariance of plasma physics with respect to changes of dimensional parameters (plasma density n_e and temperature T_e) [1]. A first experiment applying this technique to tokamak pedestal studies was carried out on the Alcator C-Mod and DIII-D tokamaks [2]. In this paper we compare the results of that experiment with the results of another experiment on JET and C-Mod and present a preliminary analysis of neutral fuelling in the discharges under consideration on all three tokamaks with the one-dimensional kinetic neutral transport code KN1D [5].

The approach employed in the edge dimensionless identity experiments was described in detail in [2]. To achieve identical dimensionless parameters on two tokamaks the values of plasma density, temperature, magnetic field and plasma current should be scaled as a^{-2}, $a^{-1/2}$, $a^{-5/4}$, and $a^{-1/4}$ respectively, where a is the minor radius of the plasma. Plasmas were created in a pair of tokamaks (C-Mod and DIII-D, and C-Mod and JET) with identical shape (triangularity, elongation, aspect ratio) and plasma current and field appropriately scaled with minor radius .Then plasma density and input power were scanned to obtain H-modes with identical values of ν^*, ρ^*,and β on top of the pedestal. Pedestal profiles were measured with high resolution Thomson scattering diagnostics in order to compare dimensionless parameters in the pedestal region. The results of these measurements are presented in Figure 1. In this figure the measured widths (in normalized poloidal flux coordinates) of density and temperature pedestals are plotted against the corresponding pedestal heights for two pairs of tokamaks under study. The results from JET and DIII-D can not be compared directly since plasmas with different shapes and q values were used in C-Mod/DIII-D and C-Mod/JET experiments.

The widths of temperature and density pedestals as measured by Thomson scattering diagnostics fluctuate considerably even in the steady state H-mode. Analysis of the pedestal data on C-Mod shows that these fluctuations reflect real ones of the pedestal profiles in H-mode plasmas. It is seen from Fig.1 that in the region where heights of the density pedestals match on both tokamaks, the pedestal width fluctuates between the same values. Also, the envelope of the height vs width dependencies is similar in both experiments. In particular, there is a clear tendency of the upper boundary of density pedestal width to increase with the pedestal height. The same trend is also observed for the temperature pedestal. Because of the fluctuations in width, we clearly can not expect to find an exact match of the pedestal profiles on both machines, even if the edge plasma physics is absolutely similar. However, the absence of discontinuity between measured width-heights distributions on either machine suggests that a high degree of similarity is achieved in the discharges under consideration. It should also be noted that edge LIDAR diagnostics on JET do not have enough spatial coverage to map the whole pedestal profile. The JET data points shown in Fig.1 represent the highest temperatures and densities measured by that diagnostic and the widths are calculated as the distance between these points and the foot of the pedestal. Therefore the JET data do not necessarily represent real pedestal heights achieved in the experiment, and but they do indicate that pedestal gradients scale appropriately. Overall, the data presented show that when dimensionless parameters are matched locally at a certain point within the H-mode pedestal profile on two different tokamaks, the whole profiles of these parameters become similar in the pedestal region.

The pedestal profile is defined in steady state by a balance between the divergence of the charged particle flux and the ionization source inside the separatrix as $\nabla \bullet \Gamma = -S$. The spatial extent of the ionization source S may not scale with dimensionless plasma parameters since neutral particles penetration characteristics depend on absolute values of plasma temperature and density rather than on dimensionless parameters. In particular, one dimensional fluid models [3,4]. suggest that neutral penetration length, and consequently density pedestal width, should scale inversely with pedestal density, $L_n \sim a^2$. To study this problem further, modelling of neutral transport was carried out using a one-dimensional kinetic neutral transport code KN1D [5]. The code solves the kinetic equation for neutral atoms and molecules for specified plasma profiles and geometry. When using the code we constructed the model plasma profiles based on Thomson scattering and scanning probe measurements on C-Mod. The profiles from plasmas obtained in the identity experiments on other machines were modelled from C-Mod profiles by applying appropriate scaling factors to the geometry and density and temperature values. The results of the analysis based on pedestal profiles, which represent similar profiles of dimensionless variables, are show in Fig. 2

On the left panel three density profiles are shown that model the measured profiles on three tokamaks. Thus, for example, the “JET” profile has density which is a factor of $(a_{JET}/a_{C\text{-}Mod}) = 16$ lower than C-Mod density and the profile is 4 times wider. On the right panel the resulting profiles of neutral deuterium are shown, normalized to the value of neutral density on the separatrix for comparison. The widths of the profiles are scaled with the ratio of minor radii, which is 2.5 for DIII-D/C-Mod and 4 for JET/C-Mod. Although the absolute values of electron density scale as a 2 between different profiles, the neutral penetration length shows a scaling with minor radii which is very close to linear. This result can be better understood by looking at the profiles of neutral penetration scale length, defined as $L_n = n_n/\nabla n_n$ and ionization source, shown in Fig.3.

Also shown in Fig.3 are ionization mean free paths (dashed lines) calculated with the values of n_e and T_e on top of the pedestals. In the SOL the density and temperature gradient scale lengths are large compared to the ionization length. In this region (negative radial coordinates in Fig.3) the neutral penetration lengths do scale approximately as a^2, as suggested by fluid models. In the H-mode pedestal region, where n_e and T_e gradient scale lengths become much shorter, kinetic effects lead to almost linear scaling of the neutral penetration length with minor radius. The ionization sources shown in the right panel of Fig.3 are defined by the product of neutral density and ion density profiles and the maximum of the sources are located in the outer part of the pedestal in all three cases. The locations of the ion sources in the pedestal region also scale linearly with minor radius for dimensionlessly matched pedestals. This suggests that in the sharp gradient region of H-mode pedestal the fluid model of the neutral transport is not accurate and kinetic effects lead to weaker scaling of neutral penetration length with minor radius. It should be noted that this conclusion is valid only for the model that assumes that plasma fueling is dominated by sources at the vacuum vessel walls. Further 1D modelling aimed at the study of the kinetic effects and neutral transport in the pedestal region is under way.

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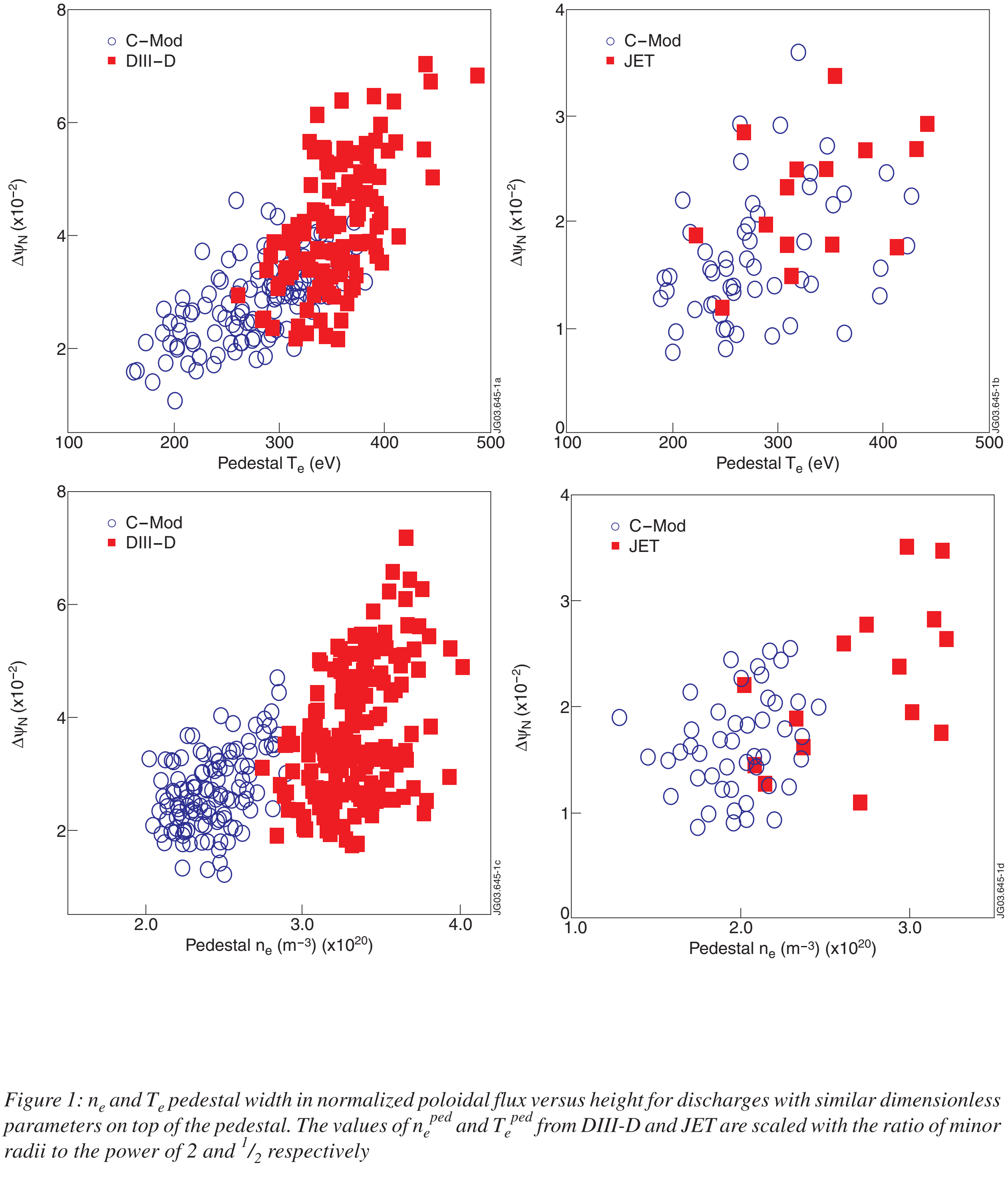

Figure 1: n_e and T_e pedestal width in normalized poloidal flux versus height for discharges with similar dimensionless parameters on top of the pedestal. The values of n_e^{ped} and T_e^{ped} from DIII-D and JET are scaled with the ratio of minor radii to the power of 2 and $^1/_2$ respectively

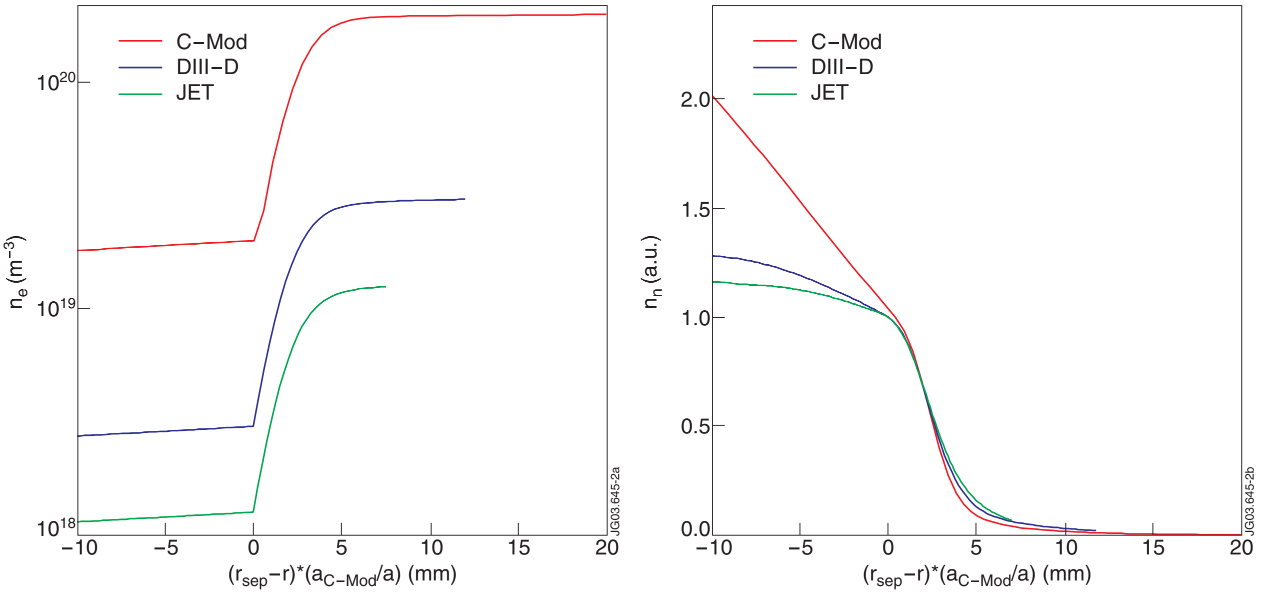

Figure 2: Modelled density profiles (left) and resulting neutral density profiles (right) from KN1D code. The radial coordinates are scaled with ratio of minor radii.

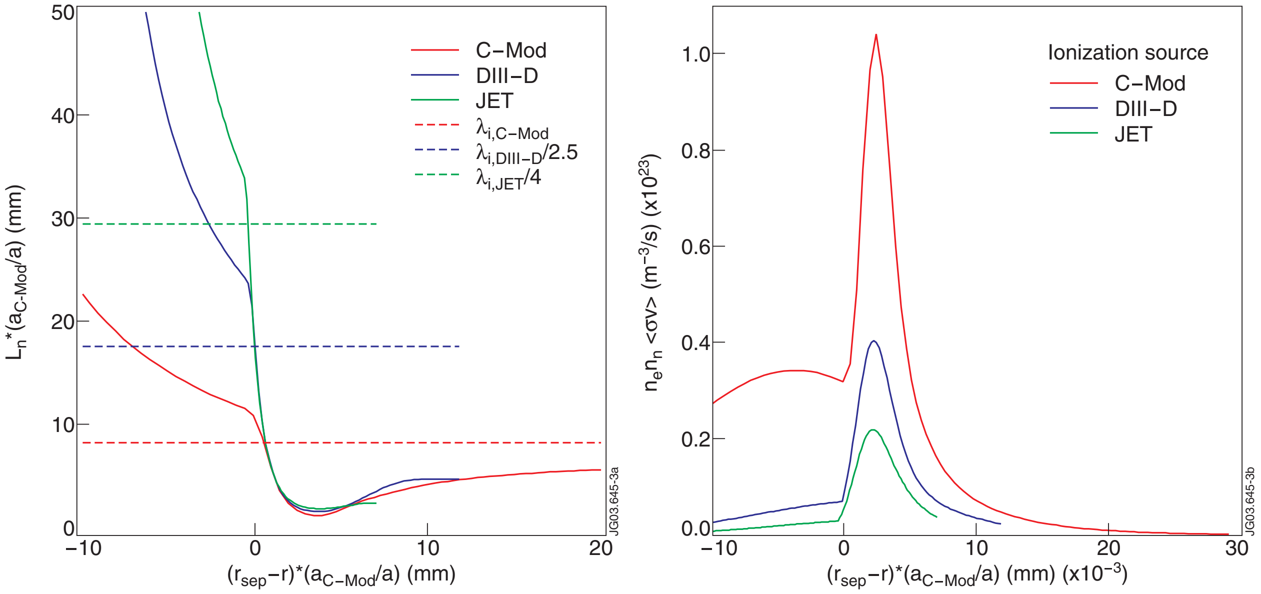

Figure 3: Calculations of neutralpenetration length (left) and ionization source $n_e n^n$<σv> (right) for modelled pedestal profiles with identical dimensionless parameters on top of the pedestal and varied pedestal widths. Dashed lines on the right panel are scaled ionization mean free paths for corresponding pedestals.