The Research of EAST Pedestal Structure and Preliminary Application

2016 Plasma Sci. Technol. 18 967

(http://iopscience.iop.org/1009-0630/18/10/967)

The Research of EAST Pedestal Structure and Preliminary Application*

WANG Tengfei (王腾飞), ZANG Qing (臧庆), HAN Xiaofeng (韩效锋),
XIAO Shumei (肖树妹), HU Ailan (胡爱兰), ZHAO Junyu (赵君煜)

Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

Abstract The pedestal characteristic is an important basis for high confinement mode (H-mode) research. Because of the finite spatial resolution of Thomson scattering (TS) diagnostic on Experimental Advanced Superconducting Tokamak (EAST), it is necessary to characterize the pedestal with a suitable functional form. Based on simulated and experimental data of EAST, it is shown that the two-line method with a bilinear fitting has better reproducibility of pedestal parameters than hyperbolic tangent (tanh) and modified hyperbolic tangent (mtanh) methods. This method has been applied to EAST type I edge localized mode (ELM) discharges, and the electron pedestal density is found to be proportional to the line-averaged density and the edge pressure gradient is found to be proportional to the pedestal pressure. Furthermore, the ion poloidal gyro-radius has been identified as the suitable parameter to describe the pedestal pressure width.

Keywords: two-line method, Thomson scattering, pedestal characteristic, pedestal models, EAST

PACS: *52.25.Fi, 52.55.Tn*

DOI: 10.1088/1009-0630/18/10/01

(Some figures may appear in colour only in the online journal)

1 Introduction

The H-mode in fusion plasma was first observed in the ASDEX tokamak [1]. The temperature and density profiles form steep gradients in the edge region of the H-mode plasma. This region has a transport barrier because a dramatic reduction in local heat and particle transport exists at the plasma boundary, and the height of the transport barrier is called the pedestal. Therefore, it is important to investigate the pedestal structure. However, investigation of the pedestal is challenging, not only because of the small spatial scales but also owing to the fast ELM bursts.

In EAST, the edge electron profiles are measured with a Thomson scattering (TS) system, which obtains data every 20 ms throughout a typical discharge [2−5]. This system is oriented along a vertical chord and has thirty measure points. This 90° Thomson scattering system employs a Nd:YAG laser beam to traverse 7 mirrors and then enters the vacuum chamber vertically. Due to the finite spatial resolution of the TS diagnostic, the pedestal structure is characterized with three functional forms. In order to analyze the pedestal characteristic, it is necessary to benchmark which method is more suitable for the EAST pedestal.

Benchmarking of the three methods and analysis of the pedestal characteristics are discussed in this paper. The rest of this paper is organized as follows. In section 2, the emphasis is laid on three different methods to fit the pedestal, and then three pedestal methods are tested with simulation and experimental data in section 3. In section 4, some preliminary pedestal characteristics are given. Finally, conclusion and future research are given in the last part.

2 The analysis methods

The pedestal profiles are characterized by their top value, width and gradient. Because of the finite spatial resolution of the TS diagnostic, it is more convenient to characterize the pedestal with a functional form. Three methods are used to fit the pedestal: the hyperbolic tangent function (tanh), modify hyperbolic tangent function (mtanh) and two-line method. The pedestal profile contains three regions: the edge of the core plasma, the pedestal and the scrape-off-layer (SOL). In the SOL parallel transport is dominating and inside the separatrix a transport barrier forms due to reduced transport. The TS diagnostic cannot measure the SOL region at present, and therefore this region is excluded and the pedestal top separates the two

*supported by National Natural Science Foundation of China (Nos. 11275233 and 11405206), and the National Magnetic Confinement Fusion Science Program of China (No. 2013GB112003), and Science Foundation of Institute of Plasma Physics, Chinese Academy of Sciences (No. DSJJ-15-JC01)

remaining regions. The hyperbolic tangent method [6] is the most commonly used method to analyze the pedestal characteristic [7−9]. This method uses a hyperbolic tangent function in the pedestal region and is supplemented with appropriate polynomial in the edge of the core plasma. Therefore, it is convenient to define the basic function by following formulae

$$\begin{aligned} &Y = A \times \mathrm{TANH}[2 \times (\mathrm{XSYM} - X)/\mathrm{WIDTH}] + B, \\ &\quad X > \mathrm{XKNEE}; \\ &Y = Y(\mathrm{XNKEE}) + \mathrm{SLOPE} \times (\mathrm{XNKEE} - X), \\ &\quad X < \mathrm{XKNEE}; \\ &\mathrm{PEDESTAL} = A + B,\ \mathrm{OFFSET} = B - A. \end{aligned} \tag{1}$$

Fig. 1 is the application of the hyperbolic tangent method and is able to provide a good fit for EAST H-mode edge profiles. XKNEE, PEDESTAL, WIDTH and XSYM are the transition point between the edge of the core plasma and the pedestal region, the top value of pedestal, the effective pedestal width and the max gradient point in the pedestal region, respectively. In order to conveniently compare with other methods, the pedestal width is defined as the distance from the position of pedestal top to the plasma OFFSET point.

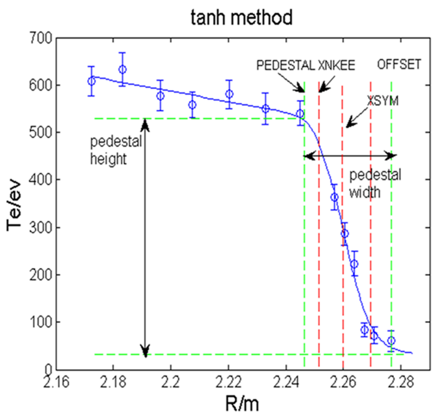

Fig.1 Definition of fit function based on hyperbolic tangent (tanh) method. Circular points represent EAST Thomson scattering experimental data and error bar. Y is electron temperature and X is radial coordinate. Solid line is the fit of the tanh function to the EAST data and dashed line is pedestal parameters

Compared with the hyperbolic tangent function, the modified hyperbolic tangent function (mtanh) [10] adds a relaxation coefficient. By varying this coefficient, a different shape of fitting is obtained and one of the most accurate fittings is chosen. Eq. (2) is the basic function for this method. An example of applying the mtanh method is shown in Fig. 2. The coefficient α is set to value 0.05, which has a minimum logarithmic root mean square (RMS) deviation.

$$\begin{aligned} &Y = A \times \mathrm{MTANH}(\alpha, z) + B \\ &\mathrm{MTANH}(\alpha, z) = [(1 + \alpha \times z)\exp(z) - \exp(-z)] \\ &\qquad\qquad /[\exp(z) + \exp(-z)] \\ &z = 2 \times (\mathrm{XSYM} - X)/\mathrm{WIDTH} \\ &\mathrm{PEDESTAL} = A + B, \mathrm{OFFSET} = B - A. \end{aligned} \tag{2}$$

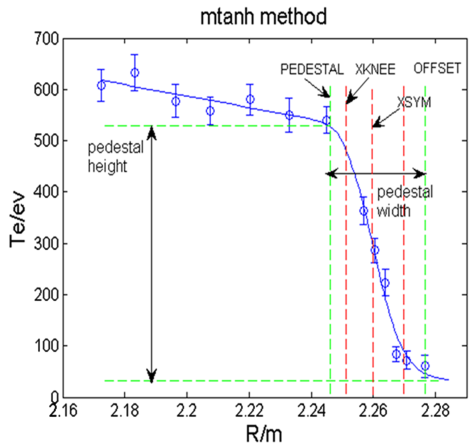

Fig.2 Definition of fit function based on modified hyperbolic tangent (mtanh) method. Circular points represent EAST Thomson scattering experimental data points with error bars. Solid blue line is the fit of mtanh function to the data

Compared with the other two approaches, the two-line method [8] uses two different gradient lines to fit the pedestal and the edge of the core plasma. Because of EAST TS experimental uncertainties, these gradients can be approximated with constants. Thus the shape of the pedestal can be fitted with the following functional form:

$$\begin{aligned} Y &= a2(a0 - X) + a1, X \leq a0 \\ Y &= a3(X - a0) + a1, X > a0 \end{aligned}\ ; \tag{3}$$

where $a0$ is pedestal top position, $a1$ is the value of pedestal top, $a2$ is the gradient of the edge of the core plasma, and $a3$ is the pedestal region gradient. The width of the pedestal is defined as $x_{\mathrm{sep}} - a0$ where x_{sep} is the location of the plasma separatrix. One example of using the two-line method is shown in Fig. 3.

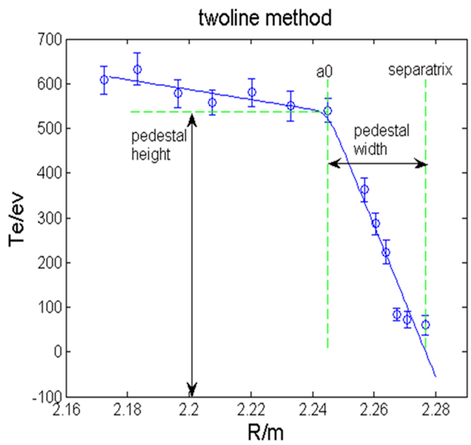

Fig.3 Definition of fit function based on two-line method. Circular points show EAST Thomson scattering experimental data and error bar. The solid line is the fit of the two line function to the data

3 Benchmark of methods

In order to test which method is more suitable to characterize the EAST edge pedestal, two benchmark [10] schemes are applied. One is to use simulation pedestal profile data with known pedestal parameters and the other is to use similar discharges whose pedestal parameters are expected to be unchanged. The simulated pedestals consist of two regions (the edge of the core plasma, and the pedestal) with different pedestal parameters. The preset data are distributed normally around this curve. In EAST the pedestal region ranges from 2.25 m to 2.29 m in major radius. Presently, the TS data have 13 points at the plasma edge (seven points in the edge of the core plasma, six points in pedestal), and the spatial resolution of six points in the pedestal is 0.5 cm from 2.26 m to 2.285 m. At least 19 points are planned in the future (at least ten points in the pedestal with 0.3 cm spatial resolution from 2.26 m to 2.29 m). One example of the preset pedestal profile is shown in Fig. 4. The preset pedestal profile is based on TS measurements and fitted by a tension spline function [11] with some artificial adjustments. The error between experimental data and the fitted profile is within 10%.

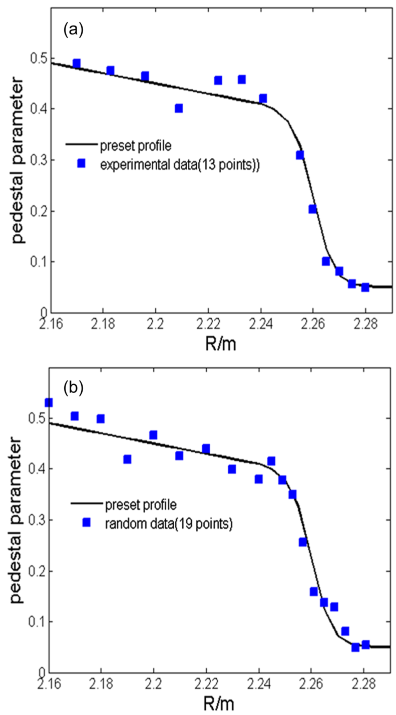

Fig.4 (a) Example of 13 points preset pedestal profile. The preset pedestal profile is indicated with the solid black line and experimental data are indicated with blue squares, (b) 19 points preset pedestal profile. The preset pedestal profile is the same as 13 points and is interpolated using19 points radial position of TS with random error 0%–10%

The pedestal profiles are characterized by their top value, width and core gradient. Fig. 5 shows the EAST characteristic ranges for pedestal parameters and each simulation needs a preset profile like Fig. 4. Using the preset profile, each simulation consists of 100 profiles with the same properties and 0%–10% random error. Pedestal parameters (top, width and gradient) of each simulated profile with different preset pedestal parameters are determined with different pedestal methods. This gives a single mean value with a certain relative deviation for each simulation, method and pedestal parameter. In the left picture of Fig. 5, the pedestal top and width are fixed, and only the core gradient is changed from 1 to 6. Generally, the temperature profile is more peaked than the density profile. Therefore, a core gradient in arbitrary units of 1–3 is for the density profile while 1–6 for the temperature and pressure profiles on EAST. The result of the core gradient simulation is presented in Fig. 6. The change of core gradient has no clear effect on the two-line method. However, tanh and mtanh methods show clear change of 10%–15% in pedestal top and width. The probable reason is that the (modified) hyperbolic tangent function is a symmetric algorithm with a symmetric point in the pedestal region. The symmetry of the pedestal profile is broken with a high core gradient and the mtanh's ability to fit asymmetric profiles is diminished. Especially, the asymmetry is more obvious with SOL region data, which have not been measured on EAST. Therefore, the high core gradient profile cannot be fitted to tanh and mtanh methods. In the middle of Fig. 5, the pedestal width and core gradient are kept constant but the pedestal top is varied from 300 eV to 700 eV. The simulation result of the pedestal top is illustrated in Fig. 7. All three methods show no obvious changes in the pedestal top while the pedestal width is influenced. The change is diminished with the pedestal top increase. The probable reason is that the SOL region cannot be measured by TS diagnostics, and therefore the transition region between the pedestal and the SOL is not smooth enough for low pedestal top cases. In the right of Fig. 5, the pedestal top and core gradient are kept constant but the pedestal width varies from 2 cm to 4 cm. In Fig. 8, three methods in the pedestal top are not influenced by the pedestal width scan but they show a change about 5%–15% in pedestal width especially in 2 cm width. The large relative deviation for the case of 2.0 cm pedestal width is due to the finite radial resolution of TS data.

In the experimental analysis [10], the pedestal profiles are not presented. In order to get useful statistics, the EAST global parameters with plasma current 500 kA, toroidal field 2.3 T, NBI and LHW heating power 3.7 MW, line-averaged density 3.3×10^{19} m^{-3}, elongation 1.7 and triangle 0.4 are chosen to compare the two-line and the mtanh method. Twenty independent time slices with the previous parameters are expected to be reproducible pedestal parameters. The result is shown in Table 1. The two-line method shows significantly reduced scatter especially for pedestal temperature.

It is tested with simulated and experimental data that the two-line method is better than hyperbolic tangent (tanh) and modified hyperbolic tangent (mtanh) method. Then the 13 points profile (Fig. 4(a)) is compared with 19 points profile (Fig. 4(b)) using the using the two-line method. There is no obvious difference in the case of the pedestal top, but an obvious difference in the case of the pedestal width, as shown in Fig. 9. In detail, the pedestal widths vary markedly with the changing of pedestal top in 13 points profiles, as shown in Fig. 9(b). The probable reason is that the spatial resolution in the pedestal region is better in the case of 19 points. Fig. 9(c) shows a large relative deviation for the 13 points case with a 2.0 cm pedestal width, which is also due to the finite radial resolution. Therefore, the 19 points profile is better than the 13 points profile for the two-line method.

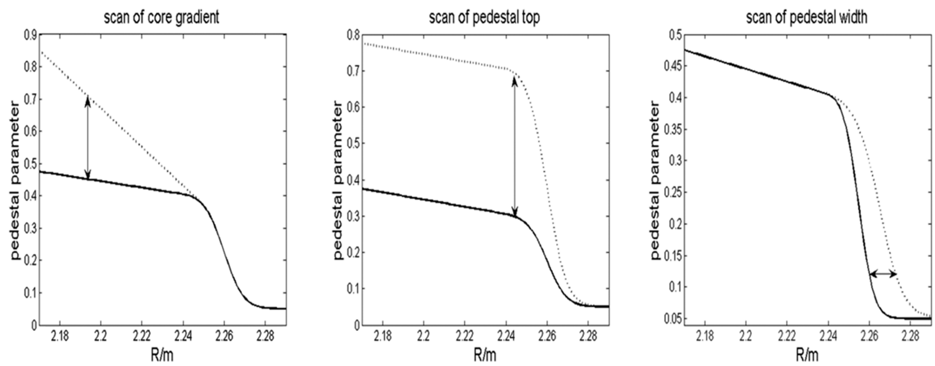

Fig.5 The simulation pedestal profiles. In the left of picture the pedestal top and width are unchanged. Only the core gradient is varied from 1 to 6. In the middle of the picture, the pedestal width and core gradient are kept constant but the pedestal top is varied between 300 eV to 700 eV. In the right of picture, the pedestal top and core gradient are kept constant but the pedestal width is varied between 2 cm to 4 cm

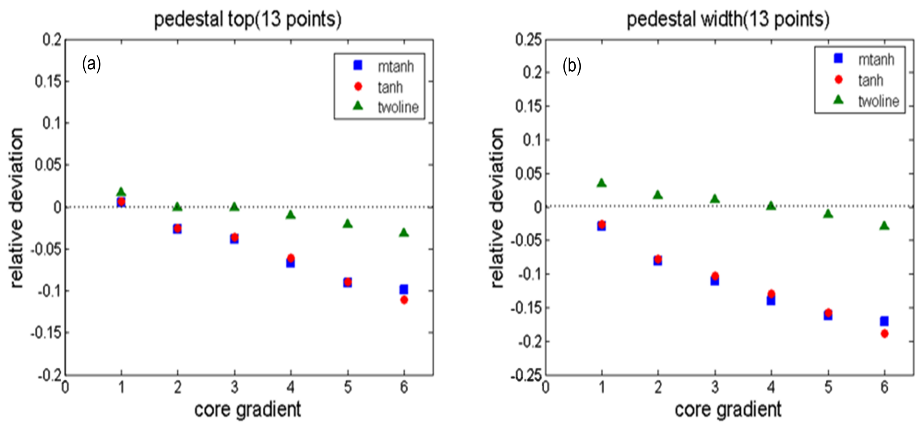

Fig.6 The result of three pedestal methods simulation with scanning of the core gradient (a) pedestal top deviation with 13 points, (b) Pedestal width deviation with 13 points

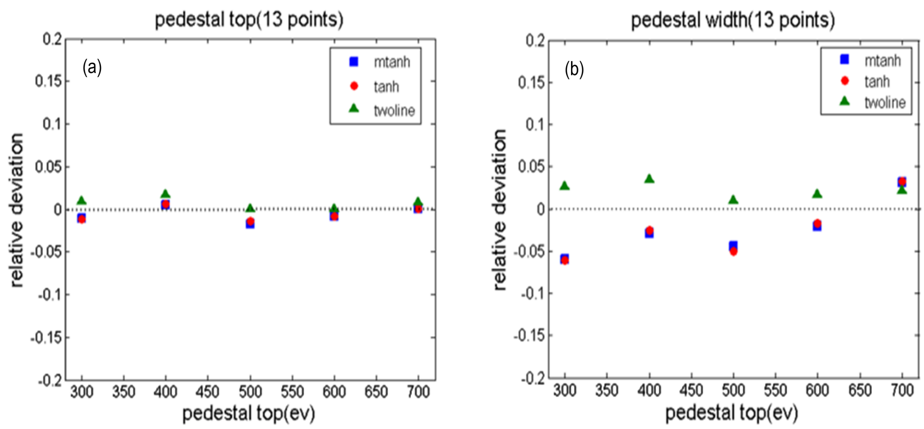

Fig.7 The simulation result of three pedestal methods, the pedestal width and core gradient are kept constant but the pedestal top is varied. (a) Pedestal top deviation with 13 points, (b) Pedestal width deviation with 13 points

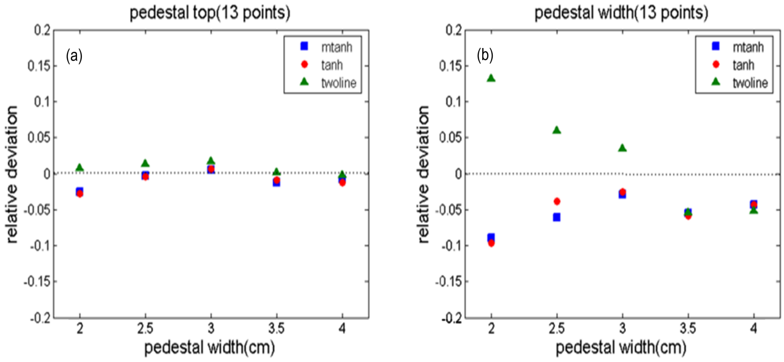

Fig.8 The simulation result of three pedestal methods with pedestal width changed. (a) Pedestal top deviation with 13 points, (b) Pedestal width deviation with 13 points

Table 1. Twenty independent time slices in the similar plasma parameters. The results of mtanh and two-line average top values, width (cm) and standard deviation are shown

		$T_{\rm e,ped}$ (eV)	$\Delta T_{\rm e}$	$n_{\rm e,ped}$ (10^{19} m^{-3})	$\Delta n_{\rm e}$	$P_{\rm e,ped}$ (kPa)	$\Delta P_{\rm e}$
mtanh	mean	467.2	2.83	4.22	3.33	3.14	3.17
	deviation	0.0795	0.18	0.051	0.121	0.061	0.11
twoline	mean	418	2.94	4.2	3.16	3.04	3.13
	deviation	0.06	0.088	0.05	0.08	0.06	0.086

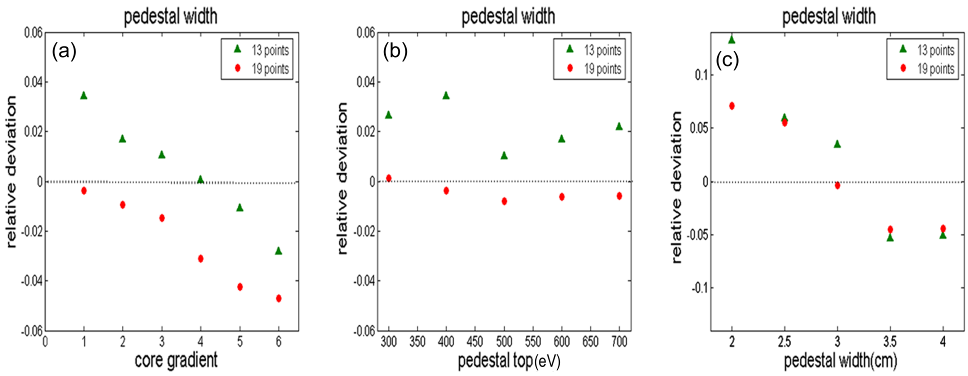

Fig.9 Comparison of 13 points with 19 points based on the two line method in pedestal width. (a) Scanning of the core gradient, (b) Scanning of the pedestal height and (c) scanning of the pedestal width

In summary, the 19 points is better than 13 points because the pedestal spatial resolution is improved. Therefore, at least 19 points are expected to be adopted in the future. The mtanh and tanh methods are effective in a wide range of parameters but subject to the profile's asymmetry. Therefore, those methods are not suitable to fit high core gradient profiles (temperature profiles). The two-line method is not influenced by the asymmetry profile and it is useful for analyzing large data sets. The mtanh and tanh methods have clear advantages in analysis of electron transport. However, the preliminary pedestal characteristic is relevant at present. In a word, the two-line method should be chosen to analyze the EAST type I ELM pedestal structure in section 4.

4 Pedestal characteristics

4.1 Pedestal height and gradient

It is important to achieve a predictive capability for the pedestal top under the assumption of $T_{\rm e}=T_{\rm i}$ in the pedestal region. In previous research, plasma global parameters such as plasma current, toroidal field, line-averaged density, heating power, electron collisionality or configuration parameters have strong correlation with pedestal temperature. However, any of the usual parameters are not suitable to describe the pedestal temperature and therefore, the combination of global parameters can be better to fit it. The density profile between the edge and the magnetic axis is generally rather flat in H-mode discharges. Therefore, the pedestal density is a linear relation with the line averaged electron density, as shown in Fig. 10. Because the density range is not enough, the range of plasma parameters should be expanded in the future. If pedestal pressure can be calculated, the pedestal density will be provided to predict the pedestal temperature. The pedestal pressure gradient is important in pedestal physics and has a close connection with the MHD stability of ELM. The pedestal gradients strongly correlate with the pedestal top. Fig. 11 illustrates that the pedestal pressure gradient is linear with the pedestal pressure. The common idea is suggested that the pedestal pressure gradient is limited by the first ballooning mode instability [12]. If the pressure gradient within the pedestal region is constant, then the increase of pedestal width would automatically mean the increase of pedestal height. Therefore, the focus of the next part is to investigate two models for predicting the pedestal pressure width.

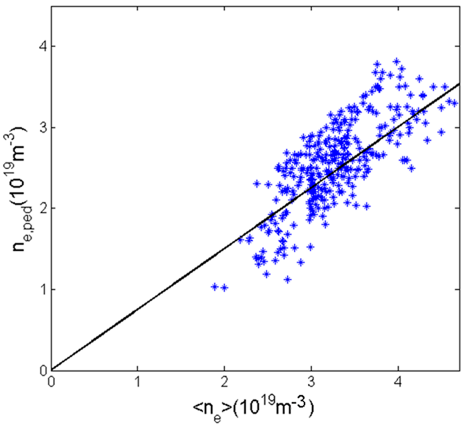

Fig.10 The pedestal electron density compared with the line averaged electron density

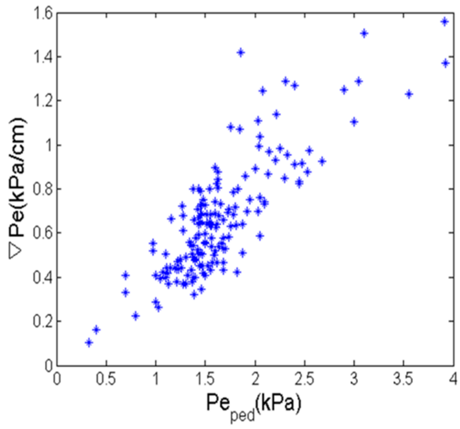

Fig.11 The pedestal pressure gradient plotted against the pedestal top value of electron pressure

4.2 Pedestal width

The idea that transport barrier formation is due to the suppression of turbulence is supported by wide experimental and theoretical [13−15] results. The most important is the nature physics theory of the suppression. A simple model is based on neutral penetration [16]. The neutrals can penetrate inside the separatrix where the main plasma particle, momentum, and energy balance are modified to impact the H-mode pedestal region. In this model, the length that neutral particles penetrate into the plasma is assumed to be the pedestal width. Therefore, the pedestal width is inversely proportional to the pedestal density, as illustrated in Fig. 12. In Shaing's model [17] based on ion orbit loss, the predicted pressure width of the pedestal is proportional to aspect ratio and ion poloidal gyro-radius ($\Delta \propto \sqrt{\varepsilon}\rho_\theta = \sqrt{\varepsilon}q\rho/\kappa_{95}$, κ_{95} is the elongation at the 95% magnetic surface, κ_{95}=0.914κ), as shown in Fig. 13. The ion orbit loss model with pedestal pressure width is in better agreement with the EAST experiment than the neutral penetration model. At present, the pedestal structure analysis is restricted by the narrow range of experimental data on EAST. Therefore, in the future it will be very useful to expand the range of plasma parameters in the EAST pedestal database.

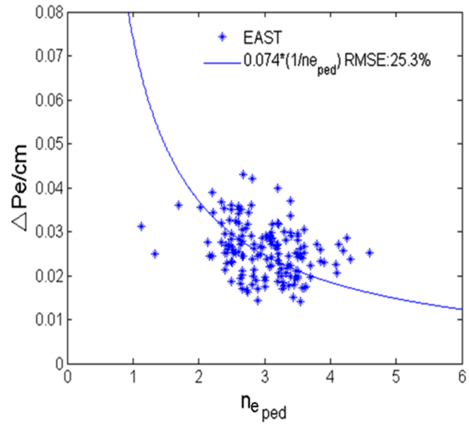

Fig.12 Pedestal pressure width defined by pedestal density

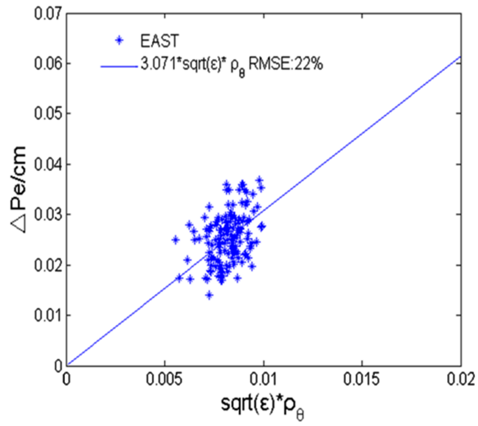

Fig.13 Pedestal pressure width defined by ion poloidal gyro-radius and aspect ratio

5 Conclusion and future research

Three different methods to characterize the pedestal are benchmarked on EAST in this paper. Those methods are tested with simulated and experimental data. In simulation the pedestal profile is preset with known parameters. The tanh and mtanh methods are clearly influenced by the high core gradient because the symmetry of the pedestal profile is broken. The two-line method shows a slight influence in the wide range of parameters except the narrow pedestal width. For a series of 20 independent profiles from experiments with the same conditions, the two-line method is also proved to be better than the mtanh method.

The 19 points profile is better than the 13 points profile in the simulation results. Therefore, at least 19 points are expected to be used in the future. The two-line method is utilized to analyze the pedestal characteristic at present. Any of the usual parameters are not suitable to describe the pedestal temperature. In contrast, the pedestal electron density has a linear relation with the line averaged electron density. Therefore, if the pedestal pressure is calculated, the pedestal temperature would be predicted with pedestal density. The edge pressure gradient is linear with the pedestal pressure value and the general idea is assumed that the pressure gradient is limited by the first ballooning mode. The ion orbit loss model with pedestal pressure width is in better agreement with the EAST experimental result than the neutral penetration model. It should be noted that some width models such as plasma dimensionless parameters are not discussed in this paper and detailed comparisons between the pedestal pressure width models and experimental data need to be carried out to further understand the underlying physics.

References

1 Wagner F, Becker G, Behringer K, et al. 1982, Phys. Rev. Lett., 49: 1408

2 Zang Q, Zhao J Y, Yang L, et al. 2010, Plasma Science and Technology, 12: 144

3 Yang L, Wan B N, Zhao J Y, et al. 2010, Plasma Science and Technology, 12: 284

4 Han X F, Shao C Q, Xi X Q, et al. 2013, Review of Scientific Instruments, 84: 053502

5 Chen H, Zhao J Y, Zang Q, et al. 2015, J. Fusion Energy, 34: 9

6 Groebner R J, Osborne T H. 1998, Physics of Plasmas, 5: 1800

7 Osborne T H, Burrell K H, Groebner R J, et al. 1999, Journal of Nuclear Materials, 266–269: 131

8 Osborne T H, Ferron J R, Groebner R J, et al. 2000, Plasma Phys. Control. Fusion, 42: A175

9 Snyder P B, Wilson H R, Ferron J R, et al. 2002, Physics of Plasmas, 9: 2037

10 Schneider P A, Wolfrum E, Groebner R J, et al. 2012, Plasma Phys. Control. Fusion, 54: 105009

11 Cline A K. 1974, Commun. ACM, 17: 218

12 Zohm H. 1996, Plasma Phys. Control. Fusion, 38: 105

13 Burrell K H. 1997, Physics of Plasmas, 4: 1499

14 Snyder P B, Groebner R J, Leonard A W, et al. 2009, Physics of Plasmas, 16: 056118

15 Snyder P B, Osborne T H, Burrell K H, et al. 2012, Physics of Plasmas, 19: 056115

16 Onjun T, Bateman G, Kritz A H, et al. 2002, Physics of Plasmas, 9: 5018

17 Shaing K C. 1992, Phys. Fluids B, 4: 290

(Manuscript received 22 October 2015)
(Manuscript accepted 6 April 2016)
E-mail address of WANG Tengfei: wtf@ipp.ac.cn