

# A framework for the development and testing of an edge pedestal model: Formulation and initial comparison with DIII-D data

W. M. Stacey

*Georgia Institute of Technology, Atlanta, Georgia 30332*

R. J. Groebner

*General Atomics, San Diego, California 92186*

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A framework has been formulated for the further development and testing of a predictive edge pedestal model. This framework combines models for the interaction of the various physical phenomena acting in the edge pedestal—transport, neutral fueling penetration, atomic physics cooling, MHD (magnetohydrodynamic) stability limit, edge density limit—to determine the pedestal widths and gradient scale lengths. Predictive models for some of these specific phenomena have been compared with DIII-D [J. L. Luxon, *Nucl. Fusion* **42**, 614 (2002)] measurements. It was found that a neutral penetration model for the density width and a MHD model for the maximum pedestal pressure for stability against ideal pressure-driven surface modes were roughly consistent with experimental observation, but that in both cases some refinements are needed. The major impediments to implementation of a predictive edge pedestal model within the framework of this paper are the lack of knowledge of transport coefficients in the pedestal and the unavailability of a usable characterization of the state-of-the-art MHD stability-limit surface in the space of edge parameters. Efforts to remedy these and other deficiencies and to establish a predictive model for the calculation of density, temperature and pressure widths and gradients in the edge pedestal are suggested. © 2003 American Institute of Physics. [DOI: 10.1063/1.1575233]

## I. INTRODUCTION

The importance of the edge pedestal region—the thin region of steep density and temperature gradients just inside the last closed flux surface—in establishing and maintaining high-confinement mode (H-mode) discharges in tokamaks is now widely recognized (e.g., Refs. 1–4). While the physics of the edge pedestal has been a subject of intensive research for a number of years (e.g., Refs. 5–9), and a number of phenomena involved in the edge pedestal have been identified and studied, a comprehensive framework for linking models of these various physical phenomena in a systematic way to obtain a predictive edge pedestal model has yet to emerge. The first purpose of this paper is to formulate a framework for systematically calculating the density and temperature gradient scale lengths and widths in the edge pedestal from models for the various physical constraints that must be satisfied in the edge pedestal. Since such a framework, together with models for the specific phenomena, would yield a predictive model if the various physical parameters appearing in it were known, the second purpose of this paper is to identify the presently unknown physical parameters that are important in determining the edge pedestal gradients and widths and to broadly suggest a program for their determination. The third purpose of the paper is to test specific models for the density width and for the maximum pedestal pressure by comparison with DIII-D data.

The paper is organized as follows. The various physics constraints which are operable in the plasma edge [transport, atomic physics cooling, magnetohydrodynamic (MHD) stability, neutral penetration fueling, density limits] are dis-

cussed briefly in Sec. II, where it is argued that the edge gradients must satisfy the transport constraints. In Sec. III, two models are formulated for the pressure width, corresponding to whether the MHD constraint is formulated as a constraint on the maximum pedestal pressure or a constraint on the maximum pedestal pressure gradient. A model for the density width that would be defined by a pedestal density limit constraint is also developed in Sec. III. Practical problems with using these models for the calculation of pedestal gradients and widths—most notably that the edge transport coefficients are unknown and the MHD constraints are not available in a form convenient for use—are identified in Sec. IV. In Sec. V, results from a range of different types of DIII-D [J. L. Luxon, *Nucl. Fusion* **42**, 614 (2002)] shots are compared with models for specific edge phenomena. A research program to provide the presently unavailable physical parameters which would lead to a predictive pedestal model is broadly suggested in Sec. VI. Finally, conclusions and recommendations are summarized in Sec. VII.

## II. PHYSICS CONSTRAINTS IN THE EDGE PEDESTAL

A complete edge pedestal model must be able to account for the steep gradients observed in the density and temperature in the plasma edge and for the distances, or widths, over which these steep gradients exist, in terms of the physical phenomena extant in the edge plasma. In this section, we briefly discuss several physical phenomena which we believe play a role in determining the gradients and widths in the edge of a diverted tokamak plasma.

## A. Transport and atomic physics constraints

The transport of particle and heat fluxes across the edge defines certain relationships among these fluxes, local transport coefficients and density and temperature gradients that must be satisfied. The density and temperature gradient scale lengths in the pedestal (the steep gradient region extending inward from the separatrix to the point at which the gradients become much less steep) can be related to the particle and heat fluxes flowing outward across the pedestal by the standard expressions for the diffusive particle flux ( $\Gamma = -D dn/dr + V_p n$ ) and for the conductive heat flux ( $q = Q - 5\Gamma T/2 = -n\chi dT/dr$ ). These fluxes are not constant across the pedestal region but vary due to neutral ionization particle sources and the cooling of the plasma by ionization, charge-exchange, elastic scattering and impurity radiation. The particle and heat balance equations can be integrated across the pedestal to obtain expressions relating the *average* gradient scale lengths in the pedestal region to the *average* particle and heat fluxes crossing the LCFS (separatrix), to the *average* transport coefficients in the pedestal region and to the *average* ionization particle sources and atomic physics cooling rates in the pedestal region,<sup>10</sup>

$$L_n(\Delta) \equiv - \left( \frac{1}{n} \frac{dn}{dr} \right)^{-1} = \frac{D}{\Gamma^{\text{sep}} - \frac{1}{2} \Delta v_{\text{ion}} - V_p}, \quad (1)$$

$$L_{Te}(\Delta) \equiv - \left( \frac{1}{T_e} \frac{dT_e}{dr} \right)^{-1} = \frac{\chi_e}{\left( \frac{Q_e^{\text{sep}}}{nT_e} - \frac{5}{2} \frac{\Gamma^{\text{sep}}}{n} \right) + \frac{1}{2} \Delta \left( \frac{n_z L_z}{T_e} + v_{\text{ion}} \left( \frac{E_{\text{ion}}}{T_e} + \frac{5}{2} v_{\text{ion}} \right) \right)}, \quad (2)$$

and

$$L_{Ti}(\Delta) \equiv - \left( \frac{1}{T_i} \frac{dT_i}{dr} \right)^{-1} = \frac{\chi_i}{\left( \frac{Q_i^{\text{sep}}}{nT_i} - \frac{5}{2} \frac{\Gamma^{\text{sep}}}{n} \right) + \frac{1}{2} \Delta \left( \frac{3}{2} v_{\text{at}}^c + \frac{5}{2} v_{\text{ion}} \right)}, \quad (3)$$

where  $V_p$  is the pinch velocity,  $v_{\text{ion}} \equiv n_0 \langle \sigma v \rangle_{\text{ion}}$  is the neutral ionization frequency,  $v_{\text{at}}^c$  is the charge-exchange plus elastic scattering frequency of previously unscattered ‘‘cold’’ neutrals,  $n_0$  is the neutral density, and  $n_z$  and  $L_z$  are the density and atomic transition radiation emissivity of impurities. The quantity  $\Delta$  is the width of the pedestal region between the separatrix and the top of the pedestal.

These transport relations uniquely determine the gradient scale lengths. Not all values of the gradient scale lengths are compatible with MHD stability, which indicates that not all combinations of transport coefficients, neutral and impurity concentrations, and particle and heat fluxes will lead to a stable solution. However, any stable solutions must satisfy Eqs. (1)–(3).

We note that it is also possible that the width of the edge pedestal is determined by a sharp, localized decrease in transport coefficient in the edge, the pedestal width corresponding to the region of transport coefficient reduction.

## B. MHD constraints

MHD stability constraints on the edge plasma due to finite wavelength modes are rather complex and must in general be calculated numerically (e.g., Ref. 11). These constraints define a relationship between the maximum pedestal pressure or the maximum pedestal pressure gradient and the pedestal width. The general relationship has not yet been systematically characterized in terms of a stability surface in edge plasma parameter space. However, simplified limiting cases can be so characterized, and we will use the form of the limiting cases to develop a pedestal model, which can then be generalized once the more general relationship is known.

One idealization of the MHD limit is the cylindrical geometry nominal ballooning mode limit, which we write in a form that explicitly or implicitly includes its generalization to include geometric, local shear, bootstrap current, finite-Larmor-radius and diamagnetic stabilization, access to second stability, peeling mode stability boundaries, etc.,<sup>12–16</sup>

$$-\frac{dp}{dr} \leq \left( -\frac{dp}{dr} \right)_{\text{crit}} = \frac{(B^2/2\mu_0)}{q_{95}^2 R} A_s(s) \left[ s_0 - \frac{2j_{\text{bs}}}{\langle j \rangle} \right] \equiv \alpha_c(s) \frac{(B^2/2\mu_0)}{q_{95}^2 R}. \quad (4)$$

Here the effects of bootstrap current,  $j_{\text{bs}}$ , on reducing edge shear,  $s_0$ , is shown explicitly and the effects of noncylindrical geometry, the physics of the  $s$ - $\alpha$  diagram for second stability access between ballooning and peeling mode limits, the stabilization of ballooning modes by diamagnetic and finite-Larmor-radius effects, etc. are implicitly contained in  $A(s)$ , hence in  $\alpha_c(s)$ . This idealization of the MHD pressure gradient limit imposes the inequality constraint

$$L_p^{-1} = L_n^{-1}(\Delta_n) + \gamma_e L_{Te}^{-1}(\Delta_p) + \gamma_i L_{Ti}^{-1}(\Delta_p) \leq (L_p^{-1})_{\text{crit}} \equiv \frac{1}{p} \left( -\frac{dp}{dr} \right)_{\text{crit}} \quad (5)$$

on the allowable values of the gradient scale lengths, i.e., on the allowable combinations of particle fluxes, transport coefficients and atomic physics reaction rates appearing in Eqs. (1)–(3) that will result in a stable solution. Here,  $\gamma_{i,e} \equiv T_{i,e}/(T_i + T_e)$ .

Note that relations (4) or (5) can be used to predict gradient scale lengths only when the plasma is operating up against the MHD stability limit (i.e., when the equality obtains). Even then, the transport relations (1)–(3) must be satisfied also. It is plausible that when the plasma is operating up against the stability limit the transport coefficients would be degraded as necessary so that both the transport and MHD constraints are satisfied.

Another approximation to the MHD constraint is the limit on the average pressure in the pedestal imposed by

stability against ideal pressure-driven surface modes in the narrow pedestal limit and in the presence of diamagnetic stabilization<sup>17</sup>

$$p \leq p_{\text{crit}} = \frac{(B^2/2\mu_0)}{q_{95}^2} \frac{8}{3} \left( \frac{1}{2} \gamma_i \left( \frac{\rho_i}{R} \right)^2 \right)^{1/3}, \quad (6)$$

where  $\rho_i$  is the gyroradius.

### C. Neutral penetration constraints

It is plausible physically that the fueling provided by the ionization of neutral atoms could cause the observed sharp buildup of density in the edge plasma, in which case the extent of neutral penetration into the edge plasma would be expected to play a role in determining the width of the sharp density gradient region. There are some theoretical indications that neutrals are involved in determining the edge pedestal width. Hinton and Staebler<sup>18</sup> predicted that the edge source of neutral atoms causes a pedestal width approximately equal to the neutral penetration distance. Mahdavi *et al.*<sup>19</sup> and Groebner *et al.*<sup>20</sup> recently extended an analytical model<sup>21</sup> for the density width of the pedestal which predicts a similar result, namely that  $\Delta_n = \lambda_{\text{ion}}$ , the ionization mean free path (mfp). They showed that this model was consistent with DIII-D data.

These models can be extended to take into account the effects of charge-exchange and elastic scattering in decreasing the neutral penetration by using the diffusion theory prediction<sup>22</sup> that the transport mfp,

$$\lambda_{\text{tr}} = \frac{1}{n \sqrt{\sigma_{\text{ion}} 3 \sigma_{\text{tr}}}} \quad (7)$$

rather than the ionization mfp, characterizes the penetration of neutrals into a plasma. Here  $\sigma_{\text{tr}} = \sigma_{\text{ion}} + \sigma_{\text{cx}} + 2\sigma_{\text{el}}/3A$ , and  $A$  is the neutral-to-ion mass ratio. Since the diffusion model predicts an exponential attenuation of neutrals ( $n_0 \sim \exp[-(r_{\text{sep}} - r)/\lambda_{\text{tr}}]$ ), it might be expected to produce a density pedestal with a shoulder occurring at about a penetration mean-free-path,  $\lambda_{\text{tr}}$ , inside the separatrix, leading to a prediction

$$\Delta_n \approx \lambda_{\text{tr}}. \quad (8)$$

It is possible that neutral penetration could also set the widths of the steep temperature gradient region, directly through the ionization and charge-exchange cooling terms and indirectly through the convection ( $\Gamma$ ) terms in Eqs. (2) and (3).

### D. Edge density constraints

There are edge density limits of the form

$$n \leq n_{\text{crit}}. \quad (9)$$

For example, the stability of a poloidally uniform plasma edge against the onset of multifaceted asymmetric radiation from the edge (MARFEs) requires that the average pedestal density be less than MARFE,<sup>23</sup> where

$$n_{\text{MARFE}}^2 \equiv \{f_{\text{cond}} Q_{\perp} [\nu L_T^{-2} + (C^{(2)} - 1) L_n^{-1}]\} / \left\{ T \left[ f_z \left( (\nu + 1 - C^{(2)}) \frac{L_z}{T} - \frac{\partial L_z}{\partial T} \right) + f_0 \left( \frac{E_{\text{ion}} \langle \sigma v \rangle_{\text{ion}}}{T} \left( \nu - \frac{T}{\langle \sigma v \rangle_{\text{ion}}} \frac{\partial \langle \sigma v \rangle_{\text{ion}}}{\partial T} \right) \right) \right] \right\} + f_0^{\text{cold}} \left( \frac{3}{2} (\langle \sigma v \rangle_{\text{cx}} + \langle \sigma v \rangle_{\text{el}}) \left( \nu - 1 - T \frac{\partial (\langle \sigma v \rangle_{\text{cx}} + \langle \sigma v \rangle_{\text{el}}) / \partial T}{(\langle \sigma v \rangle_{\text{cx}} + \langle \sigma v \rangle_{\text{el}})} \right) \right) \right\}, \quad (10)$$

where  $f_{\text{cond}}$  is the conductive fraction of the heat flux,  $\nu$  characterizes the temperature dependence of the thermal diffusivity ( $\chi \sim T^{\nu}$ ),  $C^{(2)}$  is an order unity constant associated with the thermal friction and the other terms have been previously defined.

A softer density limit might be the edge density at which short radial wavelength thermal instabilities<sup>24</sup> that degrade edge transport become unstable.

### III. PEDESTAL PRESSURE AND DENSITY WIDTHS

A framework for calculating pressure widths from MHD stability limits and transport constraints and for calculating density widths from density limits is outlined in this section. Pressure width calculations are carried through for two specific models for the MHD stability limit.

#### A. MHD constraint on pressure

We first consider the situation where the MHD constraint is formulated as a limit on the pedestal pressure of the form

$$p_{\text{ped}} \leq p_{\text{crit}}(\Delta, \dots) \quad (11)$$

where the general dependence of this limit on the pedestal width and other parameters<sup>25</sup> is indicated.

If the plasma is operating at the limiting pressure [i.e., if the equality obtains in Eq. (11)], then it is straightforward to derive an expression for a pressure width by integrating the definition of the pressure gradient scale length,  $L_p^{-1} = -(dp/dr)/p$  from the top of the pressure pedestal to the separatrix, using a constant average  $L_p$ . Relating the critical pressure to the pressure in the pedestal region then leads to an expression for the pressure pedestal width

$$\Delta_p = L_p(\Delta_p) G(\Delta_p), \quad (12)$$

where

$$G = \begin{cases} \ln\left(2 \frac{p_{\text{crit}}}{p_{\text{sep}}}\right) & \text{when } p_{\text{crit}} \text{ corresponds to } p_{\text{av}} \equiv \frac{1}{2}(p_{\text{ped}} + p_{\text{sep}}), \\ \ln\left(\frac{p_{\text{crit}}}{p_{\text{sep}}}\right) & \text{when } p_{\text{crit}} \text{ corresponds to } p_{\text{ped}}. \end{cases} \quad (13)$$

If we use Eqs. (1)–(3) to evaluate  $L_p^{-1}(\Delta_p) = L_n^{-1}(\Delta_p) + \gamma_e L_{T_e}^{-1}(\Delta_p) + \gamma_i L_{T_i}^{-1}(\Delta_p)$ , Eq. (12) becomes a quadratic equation in  $\Delta_p$ , which has the positive solution

$$\Delta_p = \frac{b}{2a} \left[ \sqrt{1 + \frac{4aG}{b^2}} - 1 \right] \quad (14)$$

where

$$a \equiv \frac{1}{2} \left[ -\frac{v_{\text{ion}}}{D} + \frac{\gamma_i}{\chi_i} \left( \frac{3}{2} v_{\text{at}}^c + \frac{5}{2} v_{\text{ion}} \right) + \frac{\gamma_e}{\chi_e} \left( \frac{n_z L_z}{T_e} + v_{\text{ion}} \left[ \frac{E_{\text{ion}}}{T_e} + \frac{5}{2} \right] \right) \right],$$

$$b \equiv \left[ \frac{\Gamma^{\text{sep}}}{n} - V_p + \frac{\gamma_i}{\chi_i} \left( \frac{Q_i^{\text{sep}}}{n T_i} - \frac{5}{2} \frac{\Gamma^{\text{sep}}}{n} \right) + \frac{\gamma_e}{\chi_e} \left( \frac{Q_e^{\text{sep}}}{n T_e} - \frac{5}{2} \frac{\Gamma^{\text{sep}}}{n} \right) \right]. \quad (15)$$

If we assume that the density width is already known (e.g.,  $\Delta_n = \lambda_{\text{tr}}$ ) and should be used in Eq. (1) [i.e.,  $L_p^{-1}(\Delta_p) = L_n^{-1}(\Delta_n) + \gamma_e L_{T_e}^{-1}(\Delta_p) + \gamma_i L_{T_i}^{-1}(\Delta_p)$ ], we once again obtain Eq. (14), but now with

$$\Delta_p = \frac{2 \left[ (L_p^{-1})_{\text{crit}} - L_n^{-1}(\Delta_n) - \frac{\gamma_e}{\chi_e} \left( \frac{Q_{\perp e}^{\text{sep}}}{n T_e} - \frac{5}{2} \frac{\Gamma_{\perp}^{\text{sep}}}{n} \right) - \frac{\gamma_i}{\chi_i} \left( \frac{Q_{\perp i}^{\text{sep}}}{n T_i} - \frac{5}{2} \frac{\Gamma_{\perp}^{\text{sep}}}{n} \right) \right]}{\left[ \frac{\gamma_e}{\chi_e} \left( \frac{n_z L_z}{T_e} + v_{\text{ion}} \left( \frac{E_{\text{ion}}}{T_e} + \frac{5}{2} \right) \right) + \frac{\gamma_i}{\chi_i} \left( \frac{3}{2} v_{\text{at}}^c + \frac{5}{2} v_{\text{ion}} \right) \right]}. \quad (17)$$

Here we have assumed the use of the neutral penetration density width of Eq. (8) to evaluate  $L_n^{-1}$ . Had we assumed that the same pressure width obtained for the density as for the temperature, then  $L_n^{-1}$  would be absent in the numerator of Eq. (17) and a term like the first term in the expression for  $b$  given by Eq. (15) would appear in the denominator of Eq. (17).

$$a = \frac{1}{2} \left[ \frac{\gamma_i}{\chi_i} \left( \frac{3}{2} v_{\text{at}}^c + \frac{5}{2} v_{\text{ion}} \right) + \frac{\gamma_e}{\chi_e} \left( \frac{n_z L_z}{T_e} + v_{\text{ion}} \left[ \frac{E_{\text{ion}}}{T_e} + \frac{5}{2} \right] \right) \right],$$

$$b = \left[ \frac{\Gamma^{\text{sep}}}{n} - \frac{1}{2} \Delta_n v_{\text{ion}} - V_p + \frac{\gamma_i}{\chi_i} \left( \frac{Q_i^{\text{sep}}}{n T_i} - \frac{5}{2} \frac{\Gamma^{\text{sep}}}{n} \right) + \frac{\gamma_e}{\chi_e} \left( \frac{Q_e^{\text{sep}}}{n T_e} - \frac{5}{2} \frac{\Gamma^{\text{sep}}}{n} \right) \right]. \quad (16)$$

In order to evaluate Eqs. (14) and (15) or (16), we need to know the particle and heat fluxes through the pedestal, the pedestal transport coefficients, the neutral atom density in the pedestal and the separatrix pressure, and to have an algorithm or value for the MHD pressure limit  $p_{\text{crit}}$ . We further note that the general relationship for  $p_{\text{crit}}$  depends on the pressure width, so that  $G = G(\Delta)$  in Eq. (12), implying the need for an iterative solution. This dependence is found in numerical calculations of some DIII-D shots to be approximately<sup>25</sup>  $p_{\text{crit}} \sim \Delta^{2/3}$ , so that  $G(\Delta) \sim \ln(\Delta^{2/3})$  has a weak dependence on  $\Delta$ , and an iterative solution may be expected to converge quickly.

As a concrete illustration of the above formalism, let us assume that  $p_{\text{crit}}$  is given by the idealized limit on the average pedestal pressure for stability against surface ideal pressure-driven surface modes given by Eq. (6). Then this expression for  $p_{\text{crit}}$  would be used in the first form of Eq. (13) to evaluate  $G$  and the pressure width would be evaluated from Eq. (14), using either Eqs. (15) or (16) to evaluate the parameters  $a$  and  $b$ . In this case,  $G$  does not depend on  $\Delta$  and there is no need to iterate. This model for the pedestal width yields values in the range seen experimentally (Sec. V) when used in DIII-D model problem calculations.<sup>22</sup>

### B. MHD constraint on pressure gradient

Now let us consider the case in which the MHD constraint is formulated as a limit on the pressure gradient of the form of Eqs. (4) and (5). Again assuming that the equality obtains in Eqs. (4) and (5), Eqs. (1)–(3) can be used to evaluate  $L_p^{-1}$  in Eq. (5) and the resulting equation can be solved for  $\Delta_p$ ,

We reiterate that these expressions for the pressure widths are valid only if the pedestal pressure and pressure gradient are at the limiting values; i.e., only if the equalities obtain in relations (4) and (5) and (9). On the other hand, they have the feature that if the measured pressure gradient or pedestal pressure is substituted for  $(-dp/dr)_{\text{crit}}$  or  $p_{\text{crit}}$ , respectively, then Eq. (12) or (17) will predict the measured

TABLE I. Experimental pedestal results. [Flux surface averaged values of widths and gradient scale lengths.  $L_n = \Delta_n^{\text{ex}} / \ln(n_{\text{ped}}^{\text{ex}} / n_{\text{sep}}^{\text{ex}})$ , etc.;  $L_p^{-1} = L_n^{-1} + \gamma_e L_{Te}^{-1} + \gamma_i L_{Ti}^{-1}$ ;  $\gamma_x = T_x / (T_e + T_i)$ ;  $\Delta_p = L_p \ln(p_{\text{ped}}^{\text{ex}} / p_{\text{sep}}^{\text{ex}})$ .]

Shot	Time ms	$I$ MA	$B$ T	$P_{\text{nb}}$ MW	$K$	$\delta$	$q_{95}$	$n_{\text{eped}}$ $e^{19}/m^3$	$\Delta_{ne}$ cm	$T_{\text{eped}}$ eV	$\Delta_{Te}$ cm	$L_n$ cm	$L_{Te}$ cm	$L_{Ti}$ cm	$L_p$ cm	$\Delta_p$ cm
97887	2230	1.5	2.1	7.1	1.84	0.88	4.9	3.8	7.3	1370	7.3	4.0	2.2	3.5	1.7	6.7
87085	1620	1.2	1.6	2.8	2.08	0.86	5.5	2.8	10.4	685	10.4	6.2	2.6	10.6	2.8	7.4
97979	3250	1.4	2.0	6.5	1.75	0.75	3.9	6.3	3.5	525	5.0	3.3	2.6	6.2	1.8	5.8
93045	3700	1.6	2.1	5.0	1.84	0.41	4.1	4.0	5.3	1150	5.3	2.8	2.7	3.8	1.5	6.0
92976	3210	1.0	2.1	5.0	1.78	0.33	5.7	4.9	3.6	215	7.2	6.0	4.2	10.3	3.2	7.7
98893	4000	1.2	1.6	2.0	1.77	0.14	3.1	8.3	2.2	120	2.2	1.5	1.5	10.1	1.0	3.2
106005	3000	1.2	1.5	4.3	1.78	0.14	3.1	4.6	4.6	460	4.6	2.7	2.1	5.3	1.5	4.8
106012	3000	1.2	2.1	4.3	1.78	0.13	4.2	4.6	4.4	395	5.9	2.4	2.3	10.3	1.5	4.7

pressure width if the correct values of transport coefficients, heat and particle fluxes, and atomic physics parameters are used in their evaluation, thus providing a good test for predictions of these latter quantities.

### C. Density width

If the density width is determined by neutral penetration, then  $\Delta_n = (1 - 2)\lambda_{\text{tr}}$ .

If, on the other hand, the density width is set by a pedestal density limit constraint of the form of Eq. (9), then integrating  $L_n^{-1} = -(dn/dr)/n$  from the top of the pedestal to the separatrix, holding  $L_n$  constant, yields

$$\Delta_n = L_n(\Delta_n)G(\Delta_n) \quad (18)$$

where  $G$  is defined by Eq. (13), but now in terms of  $n$  rather than  $p$ .

### D. Transport reduction width

As mentioned previously, it is also possible that a region of sharply localized reduction in transport coefficients defines the width of the edge pedestal. In fact, MHD pressure limits, neutral penetration and a sharply localized decrease in transport in the edge relative to the core all may be important, under different circumstances, in determining the density and temperature widths of the edge pedestal. One of our purposes in this paper is to provide a framework for calculating the edge pedestal widths within which various hypotheses can be compared systematically with experimental data. To our knowledge, no specific model for pedestal width determination by a localized transport reduction mechanism has yet been proposed.

## IV. PRACTICAL PROBLEMS

Equations (1)–(3) define the density and temperature gradient scale lengths, and Eqs. (8) or (18) and (14) or (17) define the density and pressure widths. In principle, each of these relations could be tested directly against experiment and then implemented as a pedestal model. However, there are some practical difficulties. First, the edge transport coefficients are generally unknown. Second, evaluation of these equations requires a calculation of particle and heat fluxes from the core plasma across the pedestal and a calculation of the recycling neutral flux and neutral densities in the pedestal region. Third, state-of-the-art evaluation of MHD stability

limits on the edge pedestal requires extensive numerical computation, and no characterization of the stability surface  $p_{\text{crit}}(\Delta)$ ,  $(-dp/dr)_{\text{crit}}$ , or  $\alpha_c(s)$  that embodies this state-of-the-art MHD theory is yet available. Fourth, the expressions for the pressure widths and Eq. (18) for the density width are only valid if the pedestal pressure and pressure gradient are at the MHD limiting values and the pedestal density is at the limiting value, whereas the MHD constraints are inequality constraints allowing lesser pressures and pressure gradients, and similarly for the density limit constraint of Eq. (9). While all of these matters are being worked on, it is not yet possible to construct a purely predictive pedestal model. Thus, one purpose of this paper is to propose a framework for the further development and systematic testing of a model for calculating pedestal widths and gradient scale lengths, with the ultimate objective of developing a predictive pedestal model.

## V. COMPARISON WITH DIII-D PEDESTAL DATA

In this section, we undertake an examination of the pedestal data from a range of DIII-D shots and a comparison of some of the above elements of a pedestal model with that data.

### A. Experimental data

Radial distributions of electron density and temperature are available from Thomson scattering diagnostics, and radial distributions of ion temperature are available from charge-exchange recombination diagnostics. For H-mode shots, the existence of edge pedestals (regions of steep gradients in the edge) are readily discernible in such data for the electron density and temperature and sometimes for the ion temperature.

A set of H-mode shots spanning a variety of operating conditions (plasma current  $I$ , magnetic field  $B$ , plasma elongation  $\kappa$  and triangularity  $\delta$ , safety factor  $q_{95}$ , heating power  $P_{\text{nb}}$ , gas fueling rates, etc.) and with a wide range of pedestal temperatures  $T_{\text{ped}}$  and densities  $n_{\text{ped}}$  were chosen for investigation. All of the shots were in the lower single null divertor configuration, except 87085 which was upper single null, and the indicated triangularity corresponds to the null location.

Some of the relevant experimental parameters for these shots are given in Table I. The actual measured quantities

TABLE II. Comparison of measured and calculated pedestal parameters.

Shot	$\Delta_{ne}^{ex}$ (cm)	$\lambda_{tr}$ (cm)	$C_{mfp} = \frac{\Delta_{ne}^{ex}}{\lambda_{tr}}$	$\Delta_{Te}^{ex}$ (cm)	$C_{crit} = \frac{1}{2}x$ ( $p_{pedx} + p_{sepx}$ ) / $p_{crit}$	$C_{mhd} = \frac{(dp/dr)_{ex}}{(dp/dr)_{nom}}$	$T_{eped}$ (eV)	$\delta$	$\kappa$	$q_{95}$
97887	7.3	6.1	1.20	7.3	1.13	12.08	1370	0.88	1.84	4.9
87085	10.4	8.1	1.29	10.4	0.87	5.42	685	0.86	2.08	5.5
97979	3.5	2.3	1.49	5.0	1.08	6.79	525	0.75	1.75	3.9
93045	5.3	4.9	1.09	5.3	1.04	9.15	1150	0.41	1.84	4.1
92976	3.6	2.6	1.39	7.2	0.58	2.41	215	0.33	1.78	5.7
98893	2.2	1.4	1.58	2.2	0.30	2.66	120	0.14	1.77	3.1
106005	4.6	3.5	1.32	4.6	0.38	3.25	460	0.14	1.78	3.1
106012	4.4	4.1	1.07	5.9	0.34	3.08	395	0.13	1.78	4.2

were the electron density and temperature widths; the electron densities, electron temperatures and ion temperatures at the separatrix and at the pedestal; and the average electron density, electron temperature and ion temperature gradient scale lengths over the pedestal region constructed from  $L_x = \Delta_x / \ln(x_{ped}/x_{sep})$ . The pressure gradient scale length was then constructed from the identity  $L_p^{-1} = L_n^{-1} + \gamma_e L_{Te}^{-1} + \gamma_i L_{Ti}^{-1}$ , where  $\gamma_x = T_x / (T_e + T_i)$ ; and a characteristic pedestal pressure width was defined  $\Delta_p = L_p \ln(p_{ped}^{ex}/p_{sep}^{ex})$ . When there was no distinct pedestal in the ion temperature profile, the pedestal value of the ion temperature was taken as the value at the location of the electron temperature pedestal.

Note that the experimental widths and gradient scale lengths given in the tables are the measured values mapped onto the effective cylindrical model that is used to calculate the theoretical quantities. This mapping, which is described in the Appendix, is done in order to obtain a consistent comparison between calculated and measured quantities. The mapped values are somewhat larger than the values usually reported.

A wide variety of H-mode shots were chosen for analysis. As shown in Table I, which is ordered according to decreasing triangularity, the triangularity spanned the range  $0.13 \leq \delta \leq 0.88$ , the beam power spanned the range  $2.0 \leq P_{nb} \leq 7.1$  MW, and the safety factor spanned the range  $3.1 \leq q_{95} \leq 5.7$ . Three of the shots were density limit shots in which continuous gas fueling was used to increase the density to near or above the Greenwald limit; the pedestal parameters are shown for the times of maximum density for 92976 ( $n/n_{GW} = 0.67$ ) and 98893 ( $n/n_{GW} = 1.40$ ) and just before the start of gas puffing in 97979. Shot 87085 was a VH mode shot, and the time for which the pedestal data are shown was during the early, ELM-free stage of the discharge. Shot 97887 is another VH shot with a long ELM-free period early in the discharge; the pedestal parameters are shown for a time just prior to the first ELM, which has been analyzed in detail.<sup>11</sup> Shot 93045 used strong cryo-pumping to achieve high pedestal temperature, while shots 106005 and 106012 had strong gas puffing.

## B. Testing of elements of pedestal theory

The core and divertor/scrape-off layer plasma were modeled as described in Ref. 26 for the purpose of providing a background plasma for the neutral transport calculation and

for calculating particle and heat fluxes into the pedestal region from the core. (The neutral transport calculation and a comparison with DIII-D measurements are described in Ref. 27.) The measured edge plasma densities were used in the neutral attenuation calculations, and the neutral sources and the plasma particle confinement were adjusted to obtain the measured line average density, in order to calibrate the neutral calculation and the particle flux from the core to the scrape-off layer in the experiment. The measured energy confinement time was used in the global plasma energy balance, and the calculated core radiation was adjusted to match experiment, in order to calibrate the total conductive heat flux through the pedestal to experiment. The calculated radiation in the divertor and scrape-off layer were also adjusted to match experiment in order to calibrate the background divertor plasma used in the neutral recycling calculation.

### 1. Density width

One of the elements of pedestal theory discussed in the previous section that can be tested directly against experiment is the density width of Eqs. (7) and (8). If neutral penetration determines the density width, then the measured density widths should be similar to the corresponding transport mean free paths. As shown in Table II, the ratio  $C_{mfp} = \Delta_{ne}^{ex}/\lambda_{tr}$  is in the range  $1 \leq C_{mfp} \leq 1.6$ . It is clear that the transport mpf not only has about the same magnitude as the measured density width, but, with the exception of the last two shots, the density width and the transport mpf vary among shots in the same way. (This single exception arises from a lower separatrix density and hence better neutral penetration in 106012 than in 106005.) This comparison supports the previous indications<sup>18–20</sup> that neutral penetration plays an important role in determining the pedestal width, at least the density pedestal width.

A core MARFE took place in shot 92976 just after 3210 ms, at approximately the pedestal density predicted by  $n_{MARFE}$  of Eq. (10). Using Eq. (10) for  $n_{crit}$ , Eq. (18) predicts a density width of 5 cm, which is somewhat greater than the measured density width of 3.6 cm. MARFEs did not take place and were not predicted by Eq. (10) in any of the other shots.

The experimental electron temperature width was the same as the density width in five shots and was larger than the density width in three shots.

TABLE III. Evolution of pedestal parameters in shot 87085.

Time (ms)	$P_{nb}$ (MW)	$n_{ped}$ ( $10^{19}/m^3$ )	$T_{e,ped}$ (eV)	$T_{i,ped}$ (eV)	$\Delta_n = \Delta_{Te}$ (cm)	$\Delta_p$ (cm)	$L_n$ (cm)	$L_{Te}$ (cm)	$L_{Ti}$ (cm)	$L_p$ (cm)	$C_{mfp}$	$C_{crit}$	$C_{mhd}$
1440	5.15	1.68	422	425	7.8	2.7	3.3	1.6	10.3	1.6	0.79	0.31	2.45
1620	7.54	2.81	687	1000	10.4	7.4	6.2	2.6	10.6	2.8	1.29	0.87	5.42
1770	11.54	3.92	1162	1374	14.7	10.3	7.7	3.4	14.5	3.5	2.14	1.68	9.23

## 2. Limiting pressure

If the pressure-driven surface modes of Ref. 17 are limiting the pedestal pressure, then one would expect the average pedestal pressure to be comparable to  $p_{crit}$  of Eq. (6). As shown in Table II, the average pressure in the pedestal region is comparable to or less than the value obtained by evaluating Eq. (6) for  $p_{crit}$ , for all shots. This result is consistent with an earlier comparison based on a much larger number of DIII-D shots.<sup>28</sup> The shots (97887,87085,93045,97979) with higher pedestal temperatures have pressures that are about equal to or slightly exceed  $p_{crit}$  while the shots with the lower edge temperatures have pressures that are about  $1/3$ – $2/3 p_{crit}$ . However, the shots with higher pedestal temperatures are also shots with a greater degree of shaping (higher triangularity). This suggests either: (1) that all the shots are operating at an edge pressure limit similar to that given by Eq. (6) and that Eq. (6) needs a temperature and/or shape correction factor; or (2) that the constraint equation is correct but the lower temperature/lower triangularity shots are operating below the pressure limit. Shot 97887 experiences an ELM shortly after the time analyzed,<sup>11</sup> hence may be considered to be operating at the pedestal pressure stability limit, which is only 13% greater than predicted by Eq. (6).

## 3. Pressure gradient

In the last column of Table II, we show the experimental pressure gradient normalized to the nominal ballooning mode theory prediction of the critical pressure gradient in the pedestal, in cylindrical geometry,  $(-dp/dr)_{nom} = (B^2/2\mu_0)/q_{95}^2 R$ . Numerical calculations in noncylindrical flux surface geometry typically predict nominal limiting pressure gradients that are roughly a factor of 1.5–2 over the cylindrical limit.<sup>25</sup> Furthermore, it has long been recognized<sup>12,15,16</sup> that DIII-D has access to the second stability regime. Access to second stability has been measured to increase the limiting pressure gradients by another factor that scales roughly linearly with plasma triangularity up to a value of 3 at  $\delta=0.5$ .<sup>28</sup> Based on these previous considerations, the high triangularity shots 97887 ( $\delta=0.88$ ), 87085 ( $\delta=0.86$ ), and 97979 ( $\delta=0.75$ ) might be expected to exceed the cylindrical nominal ballooning limit by a factor of 6 or more, consistent with their  $C_{mhd}$  shown in Table II. As mentioned above, shot 97887 is at the edge stability limit<sup>11</sup> (an ELM occurs shortly after 2230 ms). These values of  $C_{mhd}$  and the larger value for shot 93045 ( $\delta=0.41$ ) are not inconsistent with recent calculations of pressure gradients at the limiting conditions for MHD.<sup>11</sup> The shots with lower values of triangularity and of  $C_{mhd}$  are probably not in the second stability regime.<sup>25</sup>

## 4. Evolution of pedestal parameters

In the early, ELM-free phase of shot 87085, the injected neutral beam power was increased in steps from 5 to 15 MW, providing a good case for the examination of the evolution of pedestal parameters vis-à-vis the various inequality constraints. Pedestal parameters at three times during this early phase of the shot are shown in Table III. The pedestal density and temperatures and density and pressure widths increased, while the slopes of the density, temperature and pressure gradients relaxed (gradient scale lengths increased), with beam power. The evolution of the density width from less than  $\lambda_{tr}$  to twice  $\lambda_{tr}$  with increasing beam power, hence increasing pedestal temperatures, would seem to indicate that something other than just neutral penetration is involved in the determination of the density width for this shot.

The evolution of the pedestal pressure from well below the critical pressure of Eq. (6) at low pedestal temperature to well above it at high pedestal temperature is consistent with the shot-to-shot comparisons shown in Table II and would seem to indicate that Eq. (6) needs a temperature correction factor. The increase in pedestal pressure gradient with increasing beam power shown in the last column and the absence of ELMS during this early phase of the discharge would seem to indicate that the plasma is not operating at a pressure gradient limit of the type given by Eqs. (4) and (5).

## VI. TOWARDS A PREDICTIVE PEDESTAL MODEL

If the transport coefficients were known, the particle and heat fluxes from the core and the recycling neutral fluxes from the edge could be calculated, and then the average density and temperature gradient scale lengths in the pedestal could be calculated from Eqs. (1)–(3). If the multiplier  $C_{mfp}$  that characterizes the amount by which the density width exceeds the transport mean free path was known, then the density width could be calculated from Eq. (7). If, in addition, the functional dependence of  $p_{crit}$  or  $(-dp/dr)_{crit}$  on the plasma operational parameters ( $q_{95}$ ,  $\kappa$ ,  $\delta$ ,  $I$ , etc.) were known from MHD stability calculations, the pressure width could be calculated from Eq. (14) or (17), respectively. However, these things are not known, and their determination defines the next necessary steps in the development of a predictive pedestal model. We suggest that the framework described in this paper for calculating pedestal widths and gradient scale lengths from models for the various physical phenomena taking place in the edge can be used for the further development and testing of a predictive edge pedestal model.

TABLE IV. Pedestal transport coefficients. [Inferred from measured gradient scale lengths and calculated ionization rates, atomic physics cooling rates and radiation rates in pedestal, using the relationships between conductive heat flux and gradient scale lengths, etc., given in Eqs. (1)–(3).]

Shot	$D + L_n V_p$ (m <sup>2</sup> /s)	$\chi_e$ (m <sup>2</sup> /s)	$\chi_i$ (m <sup>2</sup> /s)	$Q_{\perp}^{\text{sep}}$ (MW/m <sup>2</sup> )	$\Gamma_{\perp}^{\text{sep}}$ (e21/m <sup>2</sup> s)	$L_n^{-1}$ (cm)	$L_{Te}^{-1}$ (cm)	$L_{Ti}^{-1}$ (cm)
87085	0.68	0.71	0.36	0.11	0.20	6.2	2.6	10.6
92976	0.58	0.87	0.31	0.08	0.34	6.0	4.2	10.3
93045	0.05	0.14	0.16	0.08	0.08	2.8	2.7	3.8
97979	0.13	0.42	0.65	0.10	0.19	3.3	2.6	6.2
98893	0.05	0.25	0.57	0.03	0.18	1.5	1.5	10.1
106005	0.10	0.55	1.04	0.08	0.12	2.7	2.1	5.3
106012	0.10	0.68	1.29	0.08	0.13	2.4	2.0	10.3

## A. Transport coefficients

### 1. Development and testing of theoretical transport models

Needless to say, theoretical models for edge transport coefficients are needed. Equations (1)–(3), together with measured gradient scale lengths, temperatures and densities, and calculated neutral densities and particle and heat fluxes, can be used to systematically test various models for pedestal transport coefficients.

### 2. Inference of transport coefficients

As an interim measure until validated theoretical transport models are available, we suggest that edge transport coefficients be inferred from experimental data and, guided by theory, be correlated against plasma and operating parameters. The measured gradient scale lengths, temperatures and densities, together with calculated neutral densities and particle and heat fluxes, can be used to infer the edge transport coefficients from Eqs. (1)–(3).

As an example, we inferred transport coefficients for some of the shots discussed above. In order to carry out this calculation with the interpretive code<sup>26</sup> that we are using (but not in general), it was necessary to assume the split between ion and electron conductive heat fluxes (1:1) into the pedestal from the core and to assume that there was no significant ion–electron equilibration in the short time required for heat to flow across the pedestal region. Inferred values of the pedestal transport coefficients for some of the shots investigated in this paper are given in Table IV.

With reference to Eqs. (1)–(3), the differences in transport coefficients shown in Table III from shot to shot are due to differences in measured gradient scale lengths, differences in pedestal temperature and density, differences in neutral concentration (varying from 0.0018 in heavily gas fueled shot 92976 to 0.0001 in shot 93045), and the difference in conductive fraction of the heat fluxes into the pedestal from the core (about 88–94% for all shots except the heavily gas fueled shots 92976 and 98893 which had about 80% conductive heat flux). Neglect of the atomic physics terms would have decreased  $\chi_i$  and  $\chi_e$  and increased  $D$  by  $O(10\%)$ .

One might suspect a significant outward edge pinch velocity for the first two shots.

It is notable that  $\eta_i = L_n/L_{Ti} < 1$  for all of these shots, indicating that ITG (ion temperature gradient) modes would be suppressed in the pedestal. On the other hand,  $\eta_e$

$= L_n/L_{Te} > 1$  for all of these shots, suggesting the possible presence of ETG (electron temperature gradient) modes.

Calculations of this type could be carried out for a large number of shots spanning a wide range of plasma operating parameters ( $q_{95}$ ,  $\kappa$ ,  $\delta$ ,  $I$ , etc.), and the results could be correlated to these parameters to obtain fitted transport coefficients that could be used in a predictive pedestal model and for other purposes. Any such correlation should be guided by theoretical identification of the probable governing parameters. We note that a similar type of correlation of inferred edge transport coefficients has been carried out for ASDEX–UG.<sup>29</sup>

## B. MHD pressure or pressure gradient limits

The functional dependence of  $p_{\text{crit}}$  or  $(-dp/dr)_{\text{crit}}$  on the plasma operational parameters ( $q_{95}$ ,  $\kappa$ ,  $\delta$ ,  $I$ , etc.) could be determined by calculating the conditions for instability onset for a wide range of equilibria, using the state-of-the-art MHD codes (e.g., Refs. 11 and 30) that incorporate noncircular flux surface geometry, local shear and bootstrap current effects, diamagnetic stabilization, access to second stability between ballooning and peeling mode stability boundaries, etc. These results could be used to characterize a MHD stability surface in the relevant edge parameter space. Such a characterization should, of course, be benchmarked against experiment. Analytical or tabular representation of the results would then allow the calculation of pressure widths, once the transport coefficients have been determined.

## C. Neutral penetration density width limits

Further refinements of the existing models for neutral penetration and its effect in determining the density width are suggested by the rough consistency found in the paper and previously between the predictions of simple neutral penetration models and experimental data for the density width. In addition, the functional dependence of the parameter  $C_{\text{mfp}} = \Delta_{ne}^{\text{exp}}/\lambda_{\text{tr}}$  on the plasma operational parameters ( $q_{95}$ ,  $\kappa$ ,  $\delta$ ,  $I$ , etc.) could be determined by comparing the calculated transport mean free path with the measured density width over a large number of shots with operating parameters spanning a broad range.

## VII. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The interactions of various physics constraints that determine the physics parameters of the edge pedestal have been formulated into a framework for calculating the density, temperature and pressure gradients and widths in the edge pedestal. Transport constraints relate the average heat and particle fluxes, the average transport coefficients and the average gradients in the pedestal. The average heat and particle fluxes in the pedestal, in turn, are related to the more readily determined heat and particle fluxes across the separatrix by atomic physics cooling and ionization particle source rates in the pedestal. The penetration of neutrals into the pedestal determines the distance over which ionization effects are important, and hence may determine the width of the pedestal, at least the density width. MHD stability constraints impose a maximum pressure or maximum pressure gradient constraint that can be used, together with the transport and atomic physics constraints on the gradients, to determine the pressure width, if the plasma is operating at the MHD limit.

Available models for some of the specific phenomena involved in determination of edge pedestal parameters were compared to pedestal data from a set of DIII-D shots that spanned a wide range of triangularity,  $q_{95}$ , beam heating power, gas fueling rates, etc. The measured density widths were found to be between 1.0 and 1.6 times the neutral penetration mean free path (i.e., the distance over which the neutral density attenuated by a factor of  $1/e$ ). In over half of the shots considered, the temperature width was the same as the density width.

A prediction of the maximum pedestal pressure for stability against ideal MHD pressure-driven surface modes<sup>17</sup> was roughly in agreement with experimental observation. For shots with pedestal temperatures in the keV range the agreement was good, but for shots in the few hundred eV range the measured pedestal pressure was less than the prediction by a factor of 2–3.

There are presently two major impediments to implementing a pedestal model such as described in this paper as a predictive model for gradients and widths in the edge pedestal—the lack of knowledge of the transport coefficients in the edge and the unavailability of the results of state-of-the-art MHD stability limit calculations in a usable form. Thus, at the present time, the framework for a pedestal model presented in this paper is intended primarily to guide the further development of a predictive pedestal model. In this vein, the correlation of transport coefficients inferred from edge pedestal measurements of gradients and the characterization a stability surface in edge parameter space from state-of-the-art MHD stability limit calculations are suggested as important next steps towards a predictive pedestal model.

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## APPENDIX: “MEASURED” WIDTHS AND GRADIENT SCALE LENGTHS

The measured values of widths reported in this paper are generally larger than are reported for DIII-D. The reasons for this are discussed in this appendix.

The code that we use to calculate the various widths and gradients discussed above treats an effective cylindrical plasma that conserves the area over the outer flux surfaces of the elongated DIII-D plasma, in the elliptical approximation. The minor radius of the effective cylindrical plasma that conserves flux surface area is  $a_{\text{eff}} = a((1 + \kappa^2)/2)^{1/2}$ , where  $a$  and  $\kappa$  are the minor radius and elongation of the elongated plasma, respectively.

The electron density and temperature from which the experimental pedestal widths and gradient scale lengths are determined are measured along a vertical chord through the plasma well outboard of the center of the plasma. In order to compare these measured widths and gradient scale lengths with quantities calculated with the effective cylindrical model described above, it is first necessary to map the measured widths and gradient scale lengths onto the effective cylindrical model. The measured densities and temperatures are fit with cubic spline polynomials as functions of the toroidal flux surface coordinate,  $\rho$ , which varies from 0 to 1. Visual inspection of the data points and their spline fit vs  $\rho$  (GAPROFILES) is used to determine the  $\rho$  values corresponding to the inner and outer edges of the transport barrier. We identify the value of the radius,  $r$ , in the effective cylindrical model that corresponds to the toroidal flux surface coordinate,  $\rho$ , in DIII-D by the transformation  $r = \rho a((1 + \kappa^2)/2)^{1/2}$ , where  $a$  is the minor radius in the horizontal midplane at the last closed flux surface (about 60 cm) in the elongated DIII-D plasma. Then, the  $\rho$  values at the inner and outer edges of the barrier are converted into a width of the barrier for an effective cylindrical plasma. The gradient scale lengths are readily obtained once the width is available, as described in the title to Table I. We interpret both the calculated and the transformed measured widths and gradient scale lengths as flux surface averaged values.

Note that the measured widths and gradient scale lengths usually reported for DIII-D are distances measured along the vertical chord passing through the Thomson scattering lines of sight in the upper outboard quadrant of DIII-D; alternatively, the values are sometimes mapped to the outboard midplane, where they are compressed a factor of 1–2. Thus, the “flux surface average” values of widths and gradient scale lengths given in the tables are inherently larger than the values usually reported, because of the mapping procedure. In addition, the values of widths obtained from fits of a tanh function (TANHFIT) are often reported as vertical distances along the vertical Thomson chord, rather than as radial distances, and are determined by automated fitting of a hyperbolic tangent to the data points, rather than by the visual identification of the pedestal location used in this paper.

We have examined the differences in widths that are caused by (1) the use of the effective cylindrical model, and (2) the use of the GAPROFILES data rather than the TANHFIT data to determine the measured widths. First, we constructed an effective cylindrical model that conserved the volumes within the flux surfaces as computed from the equilibrium reconstruction (EFIT) data. The averaged measured widths from the EFIT cylindrical model were 1.0–1.5 times larger than the actual measured values at the Thomson location and 1.5–3.0 times larger than the actual measured values projected to the outboard midplane.

Next, we tested the elliptical approximation used in the paper by comparing density widths mapped from the measured data onto the EFIT volume-conserving cylindrical model with the elliptical approximation of a volume-conserving cylindrical model,  $r = \rho\kappa^{1/2}a$ . Widths mapped by the two methods agreed to within 10–20% for all cases discussed in this paper, with the EFIT mapping leading to consistently smaller widths. From this, we surmise that the slightly different area conserving elliptical approximation mapping used in this paper also overpredicts averaged measured widths by only 10–20%.

Comparison of density widths constructed from the same experimental data by visually determining the pedestal location and by automatically fitting the data with a hyperbolic tangent to determine the pedestal location indicated that the former procedure determined density widths that were generally 20–60% larger, for the shots considered in this paper, but that was a factor of 2 larger in one case (#87085) and was 10% smaller in another case (#98893). The determination of pedestal widths is still at the frontier of experimental research, and there are a number of possible explanations for these differences.

The calculated neutral penetration mean free path in cm depends on the plasma density distribution in  $r$  space in the edge of the model on which the calculation is based. If the density increases gradually from the separatrix value with distance (in  $r$  space) into the plasma, the mean free path will be relatively longer than if the density increases steeply with distance into the plasma.

The experimental density profile is in rho space, or flux surface space. Since our calculation model is cylindrical, we map the experimental density profile in rho space into a density profile in  $r$  space, as described above. We then use this experimental density profile in  $r$  space both to calculate the neutral penetration mean free path and to identify the pedestal location, hence the density width, in  $r$  space. This leads to a comparison of self-consistent theoretical and experimental quantities.

If we calculated the penetration length in cm in the real plasma geometry, we would get different results at different poloidal locations because the density at the separatrix is the same but the density gradient in  $r$  space is steeper towards the outboard midplane and more gradual towards the  $X$  point;

i.e., the separation between flux surfaces in  $r$  space is smallest towards the outboard midplane and greatest towards the  $X$  point. In the cylindrical model, in which the density gradient is in effect a poloidal average of the density gradients in the real geometry, we calculate a single “average” neutral penetration mean free path that we report in the paper. We would expect this average mean free path calculated in the cylindrical model to be close to the poloidal average of the mean free paths calculated at different poloidal locations in the real geometry, for reasons discussed in this appendix. In fact, the cylindrical model is constructed so that the mean free path in cm will be close to the poloidal average of the mean free path in cm that would be calculated from the real geometry.

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