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# Key Quantities for ITB Formation and Sustainment

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**ABSTRACT.**
An international ITB database has been constructed to address primarily power threshold scaling, confinement scaling and underlying physics in ITB plasmas. For the power threshold scaling, a precise definition of ITB is required. Either the temporal separation of temperatures in two neighboring measurement channels or the discontinuity in gradients in temperature profiles is often used to judge the ITB formation. However, both of these criteria become unclear for low heating power approaching the threshold for the ITB formation. Given this uncertainty in determining ITB existence,parameters are sought which will better define the time and spatial location of ITB. A parameter frequently employed is $R_{geo}/L_T$ where $R_{geo}$ is the plasma major radius and $L_T$ is the local temperature gradient scale length. Another parameter is $\rho_T^* = \rho_S/L_T$ where $\rho_S$is the local ion gyroradius at the sound speed; $\rho_S = (m_i T_e)^{1/2}/(Z_i e B_t)$,$m_i$ is the ion mass, $Z_i$ is the ion charge number and $B_t$ is the toroidal field [1]. This parameter has a strong $B_t$ dependence and no $R_{geo}$ dependence i contrast to $R_{geo}/L_T$. The existence of ITBs in JET plasmas can be inferred in regions of space-time where $\rho_T^* > \rho_{ITB}^*$, where $\rho_{ITB}^*$ is some critical value. Interestingly,a constant value of $\rho_{ITB}^*$, 0.014 ,is valid for a large variety of JET discharges heated by NB and IC with $B_t$ = 1.8-4.0 T when $L_{Te}$ is used as $L_T$. As a first step in finding a parameter or a key quantity that can be generally used to judge the ITB existe ce,the validity of $\rho_T^*$ is investigated for various devices in this paper.

## 1. ANALYSIS METHOD

Profile data from the following devices are used in this study;Alcator C-MOD (C-MOD),ASDEX Upgrade (AUG), CHS, DIII-D, FTU, JET, JT-60U, LHD, MAST, T-10, TCV and Tore Supra (TS). Here CHS and LHD are heliotron-type helical devices and the others are tokamaks. The data cover a wide region of $R_{geo}$ = 0.69-3.75m (a factor of 5.4) and $B_t$ = 0.53-5.28T (a factor of 10). To fix critical values for the ITB formation precisely,it is most efficient to use the values at the location and time of ITB emergence determined from the time evolution of profiles.In this study, to find critical values using a limited number of time slices,values at the boundary of ITB in radial profiles are used. Values of $R_{geo}/L_{Te}$ ($R_{geo}/L_{Ti}$) and $\rho_S/L_{Te}$ ($\rho_i/L_{Ti}$)are evaluated at the foot of $T_e$-ITB ($T_i$-ITB) and just outside the ITB. Here $\rho_i$ is a gyroradius of thermal ion; $\rho_i = (m_i T_i)^{1/2}/(Z_i e B_t)$. The temperature scale length $L_T$ is evaluated using the temperature gradient along the major radius, namely, by $L_T = T/(dT/dR)$. Whe the temperature profiles are given as a function of normalized radius $\rho$, dT/dR was evaluated by $dT/dR = (1/a)dT/d\rho$, where a is the horizontal minor radius. The location of ITB foot is defined as the point where $d/d\rho$ ($R_{geo}/L_T$) has its maximum,though other definition is also used in some cases where the maximum of $d/d\rho$ ($R_{geo}/L_T$) cannot be clearly determined.An example is shown in Fig.1. Since $\rho_i/L_{Ti} \propto T_i^{1/2} R_{geo}/L_{Ti}$, $\rho_i/L_{Ti}$ tends to have larger values inside the ITB than at the edge,which is a favorable nature to define the region of ITB in a radial space.Our purpose is to find critical values of $R_{geo}/L_{Ti}$ and $\rho_i/L_{Ti}$, $(R_{geo}/L_{Ti})^{crit}$ and $(\rho_i/L_{Ti})^{crit}$, to define the ITB region.Since both of $R_{geo}/L_{Ti}$ and $\rho_i/L_{Ti}$ change rapidly ear the ITB foot,it is not easy to determi e critical values that can be applied to a whole discharge duration from a single time slice data especially in a strong or "box-type"ITB. In this study,critical values are defined as the average of the value at the ITB foot and that outside the ITB with error bars covering these two values as shown in Figs.1(b) and (c).

## 3. RESULTS

Critical values of $R_{geo}/L_{Te}$ and $\rho_s/L_{Te}$ for $T_e$ ITBs are shown in Fig.2. Here,EC heating was employed in TCV, CHS, T-10, JT-60U and LHD, while LH+EC heating in FTU, IC heating in TS and LH or NB+IC or NB+IC+LH in JET. The electron densities are distributed in a wide range; $n_e(0) < 2\times 10^{19}\ m^{-3}$ in EC heated discharges and JET data in LH phase while $n_e(0)=(5\text{-}11)\times 10^{19} m^{-3}$ in FTU and TS. The critical values of $R_{geo}/L_{Te}$ lie in 5 to 20. In DIII-D, very strong ITB data is used, which resulted in a large critical value in the present analysis; the values ear the lower boundary seem to be valid for the ITB criterion.The dispersion is larger in $(\rho_s/L_{Te})^{crit}$ than in $(R_{geo}/L_{Te})^{crit}$. In T-10, FTU and JET (and DIII-D),critical values of $\rho_s/L_{Te}$ are close to the JET criterion, 0.014, while TCV and CHS have larger values and TS, JT-60U and LHD have lower values; $\rho_s/L_{Te}$ reaches 0.03 outside the ITB in TCV.

Figure 3 shows critical values of $R_{geo}/L_{Ti}$ and $\rho_i/L_{Ti}$ for $T_i$ ITBs and $n_e$ ITB (C-MOD).I C-MOD,where off-axis IC heating was employed,the peaking of density was remarkable with small changes in the temperature gradient and hence the scale length of pressure $L_p$ was used instead of $L_T$. All other data are from NB heated plasmas,some of which were also heated by LH,IC and EC in addition to NB.In DIII-D,QDB discharges with positive magnetic shear have low values of $R_{geo}/L_{Ti}$ and $\rho_i/L_{Ti}$, $(R_{geo}/L_{Ti})^{crit} < 5$,than weak/negative shear discharges. In JET and JT-60U, no large differences are observed between reversed shear discharges and weak positive shear discharges (optimized shear in JET and high $\beta_p$ H- mode in JT-60U). In JT-60U plasmas with low beta ($\beta_N$ <1), low values $\rho_i/L_{Ti}$, $(\rho_i/L_{Ti})^{crit}$ <0.005, are observed. Recently ITBs has been observed in MAST [2] and NSTX [3], in which large values of $(\rho_i/L_{Ti})^{crit}$ >0.03 are obtained.

## DISCUSSION

Both of $\rho_i/L_{Te}$ ($T_e$ ITB)and $\rho_i/L_{Ti}$ ($T_i$ ITB)have been distributed in a wide range exceeding one order; for $T_e$-ITB $(\rho_s/L_{Te})^{crit}$ > 0.03 in TCV and CHS while $(\rho_s/L_{Te})^{crit}$ ~0.003 in TS and for Ti-ITB $(\rho_i/L_{Ti})^{crit}$ >0.03 in MAST while $(\rho_i/L_{Ti})^{crit}$ ~0.003 in JT-60U. In Fig.4, ratios of • s and • i to Rgeo are plotted.It is found that $\rho_s/R_{geo}$ or $\rho_i/R_{geo}$ is large in devices with small $R_{geo}$, TCV, CHS and MAST, except for high field devices, FTU and C-MOD, while JT-60U and TS plasmas with low foot temperatures have low values due to large radii and high magnetic fields.

In the present study, it is found that the critical values of $\rho_s/L_{Ti}$ or $\rho_i/L_{Ti}$ are not constant but are distributed in a wide range. The variation seems to be mainly caused by changes in $\rho_s/R_{geo}$ or $\rho_i/R_{geo}$, and the critical values of $R_{geo}/L_T$ vary within a rather smaller range than the critical values of $\rho_s/L_{Te}$ or $\rho_i/L_{Ti}$. Dependence of $R_{geo}/L_{Ti}$ on the ion temperature at the ITB foot, $T_i^{foot}$ in JT-60U plasmas is shown in Fig.5. $R_{geo}/L_{Ti}$ seems to increase with $T_i^{foot}$ for fixed $B_t$,which means $\rho_i/L_{Ti}$ changes more widely than $R_{geo}/L_{Ti}$ since $\rho_i$ at the ITB foot is proportional to $(T_i^{foot})^{0.5}$. On the other hand,in the JET Bt scan data with $q_{95}$ constant,variation in $\rho_s/L_{Te}$ was smaller than that in $R_{geo}/L_{Te}$. More work is required to find what parameters determi e critical values of LT for the ITB formation.

## SUMMARY

Critical values of temperature scale length LT for the ITB formation have been investigated in various devices using the ITPA international ITB Database.Large variations in the ratio of ion gyroradius $\rho_s$ or $\rho_i$ to $L_T$ are found in some cases. It is suggested that the critical values of $\rho_s/L_{Te}$ and $\rho_i$ /$L_{Ti}$ depend on plasma parameters or other quantities tha $\rho_s$ ($\rho_i$) should be introduced to normalize LT.

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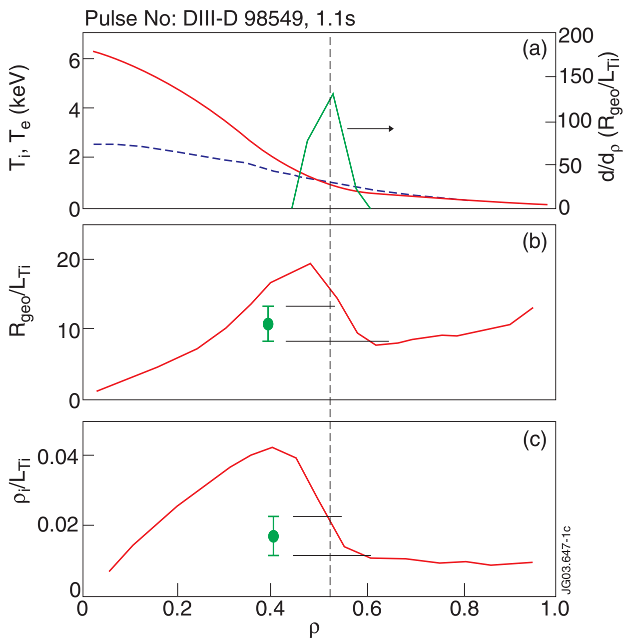


*Figure 1:Radial profiles of (a)$T_i$, $T_e$, $d/d\rho$ ($R_{geo}/L_{Ti}$),(b)$R_{geo}/L_{Ti}$ and (c) $\rho_i/L_{Ti}$ in a DIII-D weak shear ELMy H-mode plasma with $T_i$ ITB.The location of ITB "foot"is denoted by a vertical dotted line. The circles with error bars are "critical"values.*

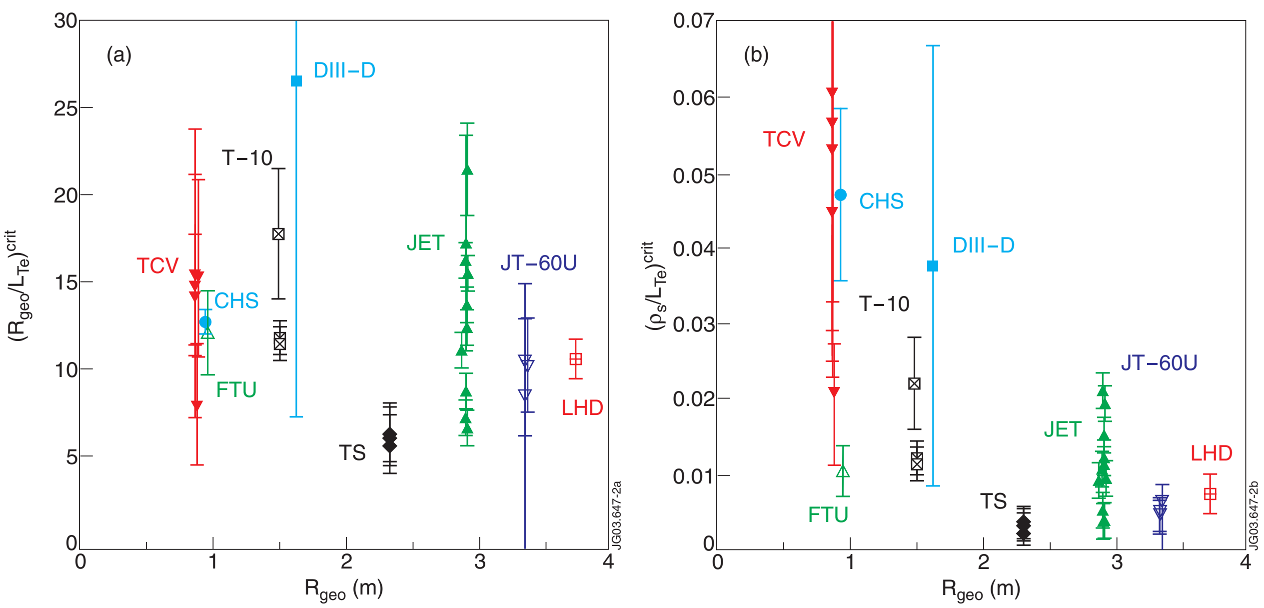


*Figure 2: Critical values of (a)$R_{geo}/L_{Te}$ and (b) $\rho_s/L_{Te}$ for $T_e$ ITB.*

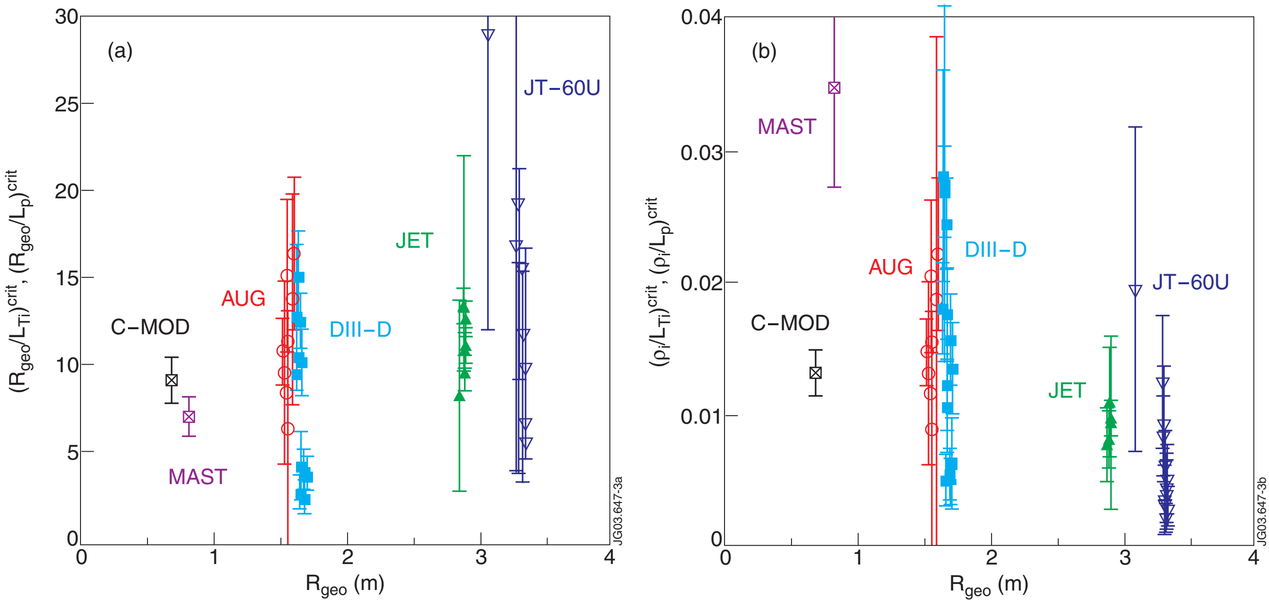


*Figure 3: Critical values of (a) $R_{geo}/L_{Ti}$ and (b) $\rho_i/L_{Ti}$ for $T_i$ ITB. For Alcator C-MOD, scale length of pressure, $L_p$ is used instead of $L_{Ti}$.*

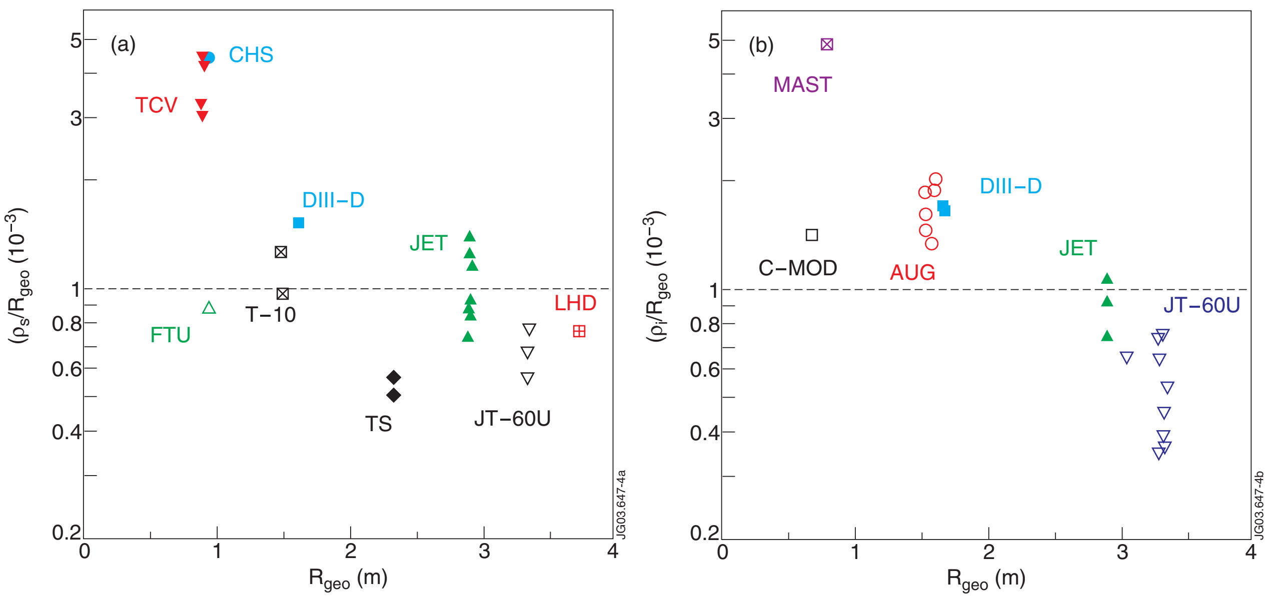


*Figure 4: (a) $\rho_s/R_{geo}$ and (b) $\rho_i/R_{geo}$ at the ITB foot as functions of $R_{geo}$.*

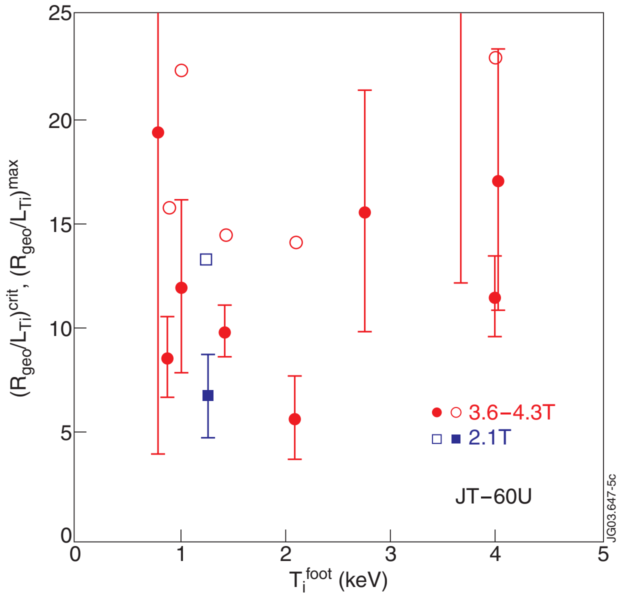


*Figure 5: Dependence of $R_{geo}/L_{Ti}$ on the ion temperature at the ITB foot in JT-60U plasmas. Closed symbols denote the critical values while open ones denote the maximum values.*