Where is the edge in toroidal plasmas ?[1]

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Contents

Abstract

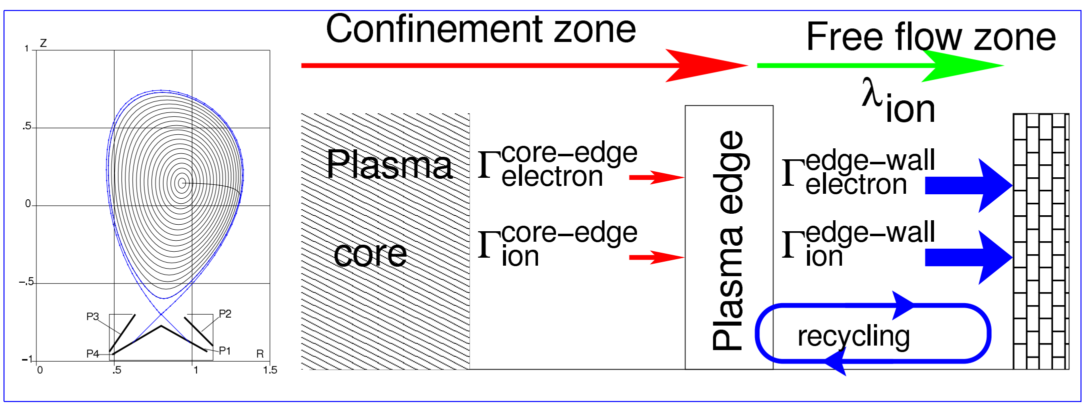
It is believed that by definition the plasma edge is the separatrix which separates the confinement zone from the convection dominated plasma periphery. Another belief is that the H-mode has a miraculous "edge transport barrier" providing a steep temperature pedestal in front of the last closed magnetic surface.

The DIII-D experiments with Resonant Magnetic Perturbations undermine both of these beliefs. Instead, the interpretation of these experiments suggests that the top of the edge electron temperature pedestal, rather than the separatrix, represents the end of the electron energy confinement zone, i.e. the edge for the electron temperature. On the other hand, the edge for the ion temperature and plasma density seems to be situated at the separatrix (or behind it).

The same experiments suggest the existence of intrinsic MHD perturbations near the separatrix (probably related to the Scrape Off Layer Currents measured on DIII-D by H. Takahashi) which determine the finite width of the electron temperature pedestal.

1 What is the plasma edge

Plasma edge separates the confinement zone from “free” flow



The plasma edge (probably two of them) is located approximately at one mean free path

$$\lambda_{\|,D,[m]} = 121\frac{T^2_{keV}}{n_{20}} \tag{1.1}$$

from the plasma facing surface.

Separatrix by definition seems to be the plasma edge

The "edge transport barrier"

The notion of "edge transport barrier" was introduced at the time of the discovery of the H-mode regime on Asdex in the early 80s

The "transport barrier" provides a steep temperature pedestal in front of the last closed magnetic surface.

Apparently obvious, the concept of the "edge transport barrier" contains many hidden inconsistencies

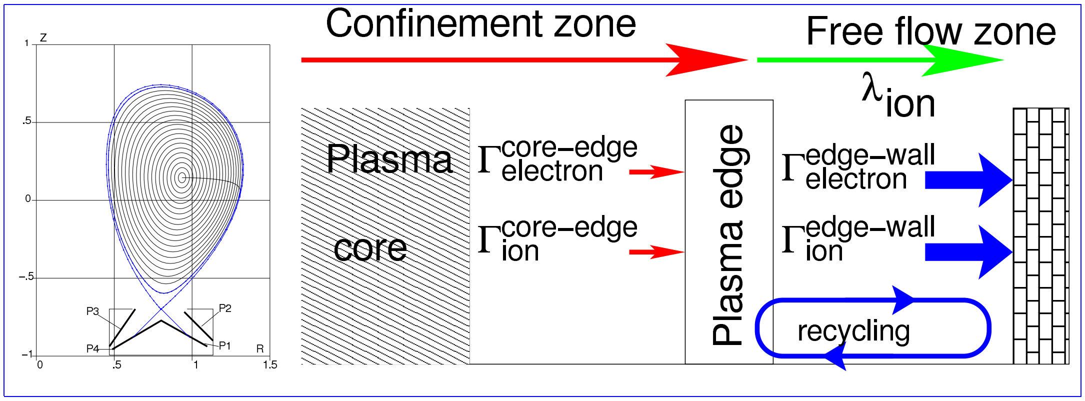
The points of the talk

The answers to the question of the title are suggested as:

1. **There could be three distinct plasma edges: one for T_e, one for T_i, and one for n.**
2. **The edge for the electron temperature is situated at the tip of the temperature pedestal.**
3. **The edge for the ion temperature and the plasma density seems to be at the separatrix.**
4. **There is no such thing as the "edge transport barrier" in the T_e pedestal zone. Instead, this zone has no confinement.**

2 Simple Edge Recycling Model

Analysis comes from LiWF, which requires recycling $R \ll 1$



The plasma edge, understood as a transition zone from diffusive transport to a convective one, is located approximately at one mean free path

$$\lambda_{\|,D,m} = 121\frac{T^2_{keV}}{n_{20}} \tag{2.1}$$

from the plasma facing surface. For $T_{edge} > 1$ keV the mean free path $\lambda_{\|,D,m}$ can be as large as $\simeq 1$ km or more.

Energy flux to the wall

Edge plasma temperature is determined by the particle fluxes self-consistently with power (Krasheninnikov)

Across the last mean free path, λ_D, in front of PFC surface the energy is carried out by moving particles

$$\begin{aligned}\frac{5}{2}\Gamma^{edge-wall}_{electron}T^{edge}_{e} &= \int_V P_e dV - \frac{\partial}{\partial t}\int_V \frac{3}{2} nT_e dV,\\ \frac{2}{5}\Gamma^{edge-wall}_{ion}T^{edge}_{i} &= \int_V P_i dV - \frac{\partial}{\partial t}\int_V \frac{3}{2} nT_i dV.\end{aligned} \tag{2.2}$$

In its turn the particle fluxes to PFC are related to the fluxes from the core by recycling coefficients $R_{i,e}$

$$\Gamma^{edge-wall}_{ion} = \frac{\Gamma^{core-edge}_{ion}}{1-R_i}, \qquad \Gamma^{edge-wall}_{electron} = \frac{\Gamma^{core-edge}_{electron}}{1-R_e} \tag{2.3}$$

In the Lithium Wall Fusion (LiWF)

$$\Gamma^{edge-wall}_{e,i} \simeq \Gamma^{core-edge}_{e,i}$$

T_{edge} is a boundary condition

T_{edge} is not sensitive to transport coefficients near the plasma edge

$$T_e^{edge} = \frac{2}{5} \cdot \frac{1 - R_e}{\Gamma_e^{core-edge}} \left(\int_V P_e dV - \frac{\partial}{\partial t} \int_V \frac{3}{2} n T_e dV \right),$$
$$T_i^{edge} = \frac{2}{5} \cdot \frac{1 - R_i}{\Gamma_i^{core-edge}} \left(\int_V P_i dV - \frac{\partial}{\partial t} \int_V \frac{3}{2} n T_i dV \right) \qquad (2.4)$$

and serves as a **boundary condition** for the confinement zone.

In the LiWF regime this implies that

$$T_{edge} \simeq T_{core}$$

Widespread among plasma physicists and wrong boundary condition

$$T_{edge} = T_b = \text{const}$$

leads to misconceptions, like "the edge transport barrier".

Temperature pedestal

The simple recycling model is consistent even with the temperature pedestal profile as soon as R is a function of distance from the edge

$$T_e^{edge}(x) = \frac{2}{5} \cdot \frac{1 - R_e(x)}{\Gamma_e^{core-edge}} \left(\int_V P_e dV - \frac{\partial}{\partial t} \int_V \frac{3}{2} n T_e dV \right),$$
$$R_e \simeq 1 - R_{edge} \frac{x}{x_{edge}}, \qquad (2.5)$$

where $x = 0$ is at the separatrix.

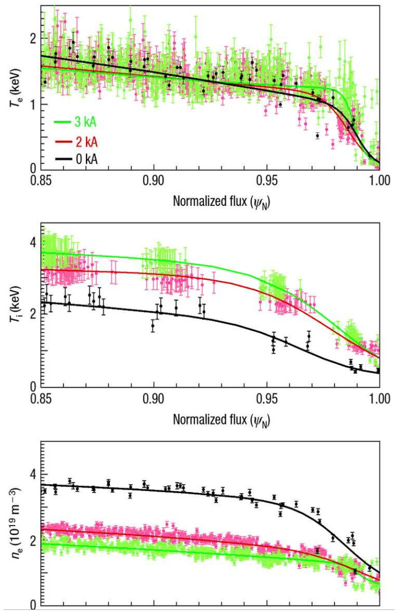
Transport coefficients near the edge do not affect the level of temperature pedestal and its profile. Other processes do.

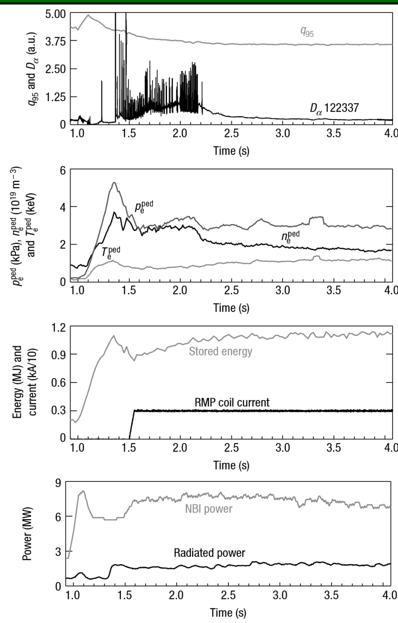
Instead of T_{edge} itself, perturbations of transport coefficients do affect T'_{edge} at the core side of the plasma edge.

RMP experiments on DIII-D are perfectly consistent with this (LiWF) understanding, rather than with the 28 year old "edge transport barrier" fantasy

DIII-D made crucial input to LiWF

DIII-D experiments have confirmed that the pedestal value of T_{edge} is not affected by RMP. The gradients n' and $T'_{edge-core}$ are affected





0 kA, 2 kA, 3 kA $I_{RMP-coil}$ *T.Evans at al., Nature physics 2, p.419, (2006)*

There is no confinement in the "edge transport barrier" zone

RMP interpretation

Toroidal plasma may have 3 different plasma edges: two for electron and ion temperatures, and a separate one for plasma density

The edge for the electron temperature is situated at the tip of the temperature pedestal.

For the ion temperature and the plasma density, the edge seems to be at the separatrix.

In the zone of the electron temperature pedestal the confinement is essentially absent. Instead of mysterious "transport barrier" properties, the $T_e(x)$ profile is determined by recycling (Simple Recycling Model)

$$T_e^{edge}(x) = \frac{2}{5}\frac{1-R_e(x)}{\Gamma^{core-edge}_{electron}}\left(\int_V P_e dV - \frac{\partial}{\partial t}\int_V \frac{3}{2} n T_e dV\right), \qquad (2.6)$$
$$R_e(x) = 1 - R_{edge}\frac{x}{x_{edge}},$$

where $x = 0$ is at the separatrix.

Scrape Off Layer Currents

SOLCs are present even in the most quiet plasma

SOL current and MHD activity in DIII-D

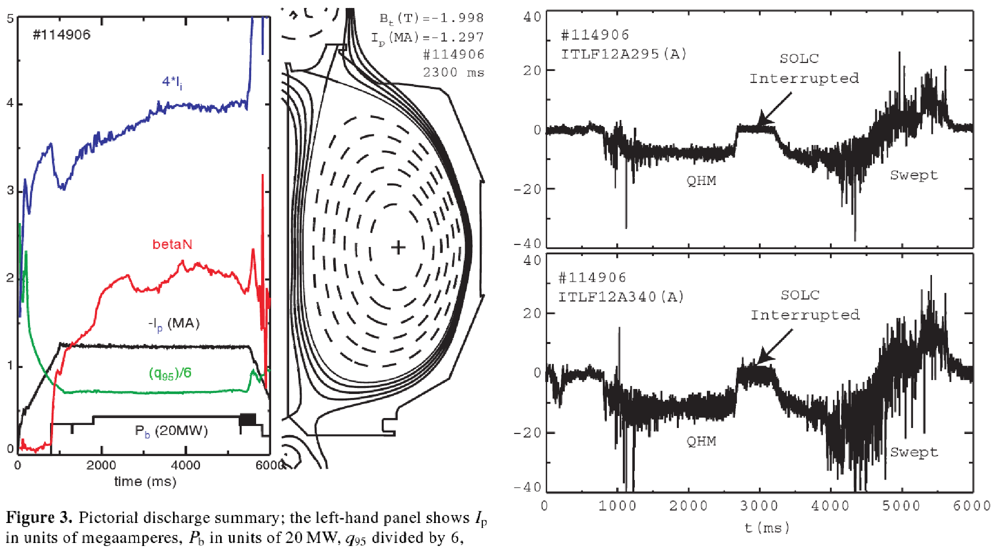


Figure 3. Pictorial discharge summary; the left-hand panel shows I_p in units of megaamperes, P_b in units of 20 MW, q_{95} divided by 6, β_N, ... sho... SOI... exte... plas... to f... cou...

Todd Evans, Hiro Takahashi and Eric Fredrickson (NF,2004) have found a link between SOLCs and MHD activity on DIII-D. SOLCs are the first candidate for intrinsic perturbations, which determine the width of the temperature pedestal.

3 Summary.

The answer to the title question is indeed very simple: the plasma edge is located at the tip of the temperature pedestal. Behind it there is no confinement.

There are hopes that studies of MHD effects related to the electric contact between plasma and PFC and SOLC can uncover the phenomenon determining the width of the temperature pedestal and resolve the mystery regarding dependence of MHD stability on the edge plasma density.

4 Impact on fusion

Without Li in mind DIII-D has made crucial contributions to LiFW, which include discovery of the QHM regime and RMP experiments

Krasheninnikov's boundary condition, which predicts a finite Tedge, is supposed to have a profound impact on our approach to the fusion relevant energy confinement.

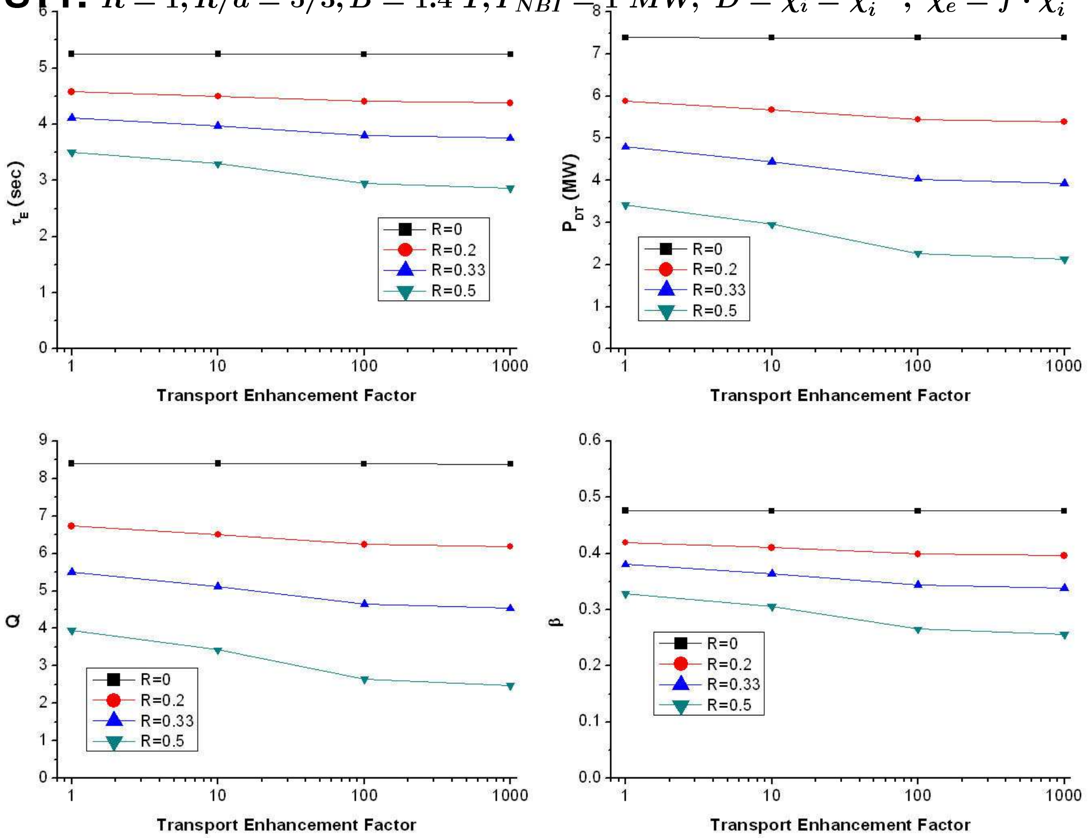
For controlled fusion anomalous electron thermo-conduction energy losses were and remain to be the major problem.

Are we really trapped into such a problem?

The low recycling LiWF regime suggests the best possible, diffusion based confinement, which is independent on anomalous electrons

Breaking with anomalous electrons

ST1: $R = 1, R/a = 5/3, B = 1.4\ T, P_{NBI} = 1\ MW,\ D = \chi_i = \chi_i^{neo},\ \chi_e = f \cdot \chi_i^{neo}$



Still no breaking on horizon

Only plasmas with recycling coefficient $R_{i,e} < 0.5$ are relevant to controlled fusion

1. Before 1999 for 30 years the fusion program (with $R \simeq 1$) was struggling with anomalous electron thermo-conduction.

2. Since 1999 (when the LiWF concept was outlined for the first time) the same program (with same $R \simeq 1$) ignores the LiWF recept for fusion and is wasting time and resources for the struggle with the same anomalous electron thermo-conduction, which is getting more sophisticated with time.

3. Now, in 2008 still there is no indication that this OFES program (with the same $R \simeq 1$) is going to stop wasting the time and resources on the struggle with the same "anomalous" electrons and start a meaningful fusion development (based on the LiWF concept).