http://w3.pppl.gov/~zakharov/LEZ-130514.pdf

Are “transport barriers” a zone of good confinement or of its collapse[1]

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Abstract

For more than 3 decades, sharp electron temperature jumps at the plasma edge in H-mode or in ITBs in the plasma core are interpreted as regions with suppressed transport - "transport barriers".

The key assumption in this interpretation is the existence of the perfect magnetic surfaces. In fact, for the plasma edge there is no minimal experimental or theory reason for plasma having good magnetic surfaces at the edge. Instead of the widespread but baseless assumption, the relaxing of it leads to the understanding of temperature pedestals, consistent with the basic experimental data and free of plasma physics miracles, like "transport barriers".

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1 Discovery of H-mode and ETB

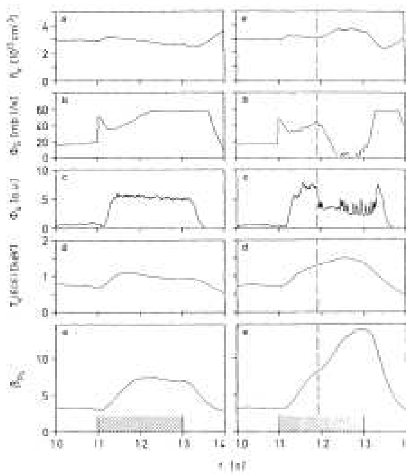


FIG. 1. Time dependence of various plasma param-

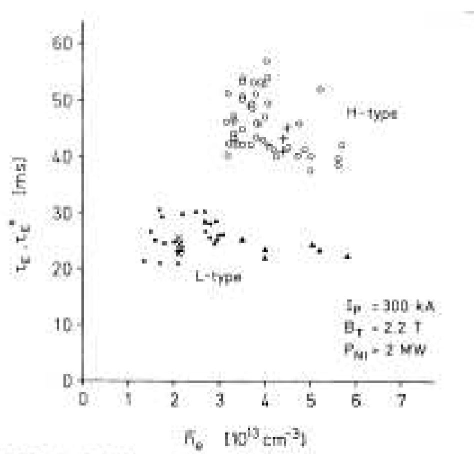


FIG. 2. Global energy confinement time vs average

“Regime of Improved Confinement and High Beta in. Neutral-Beam-Heated Divertor Discharges of the ASDEX Tokamak”

F. Wagner, at al Phys. Rev. Letters, 49, 1408, (1982)

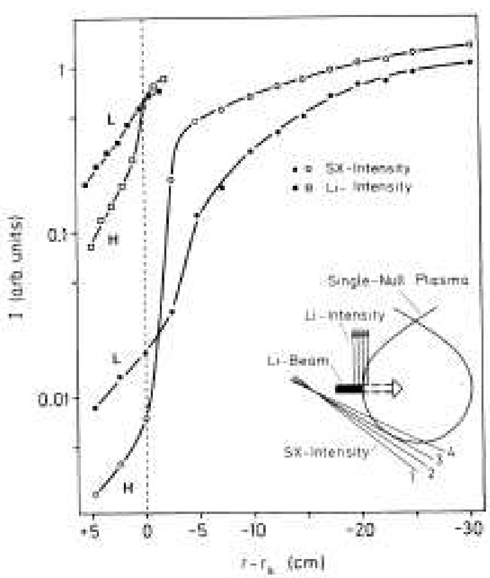
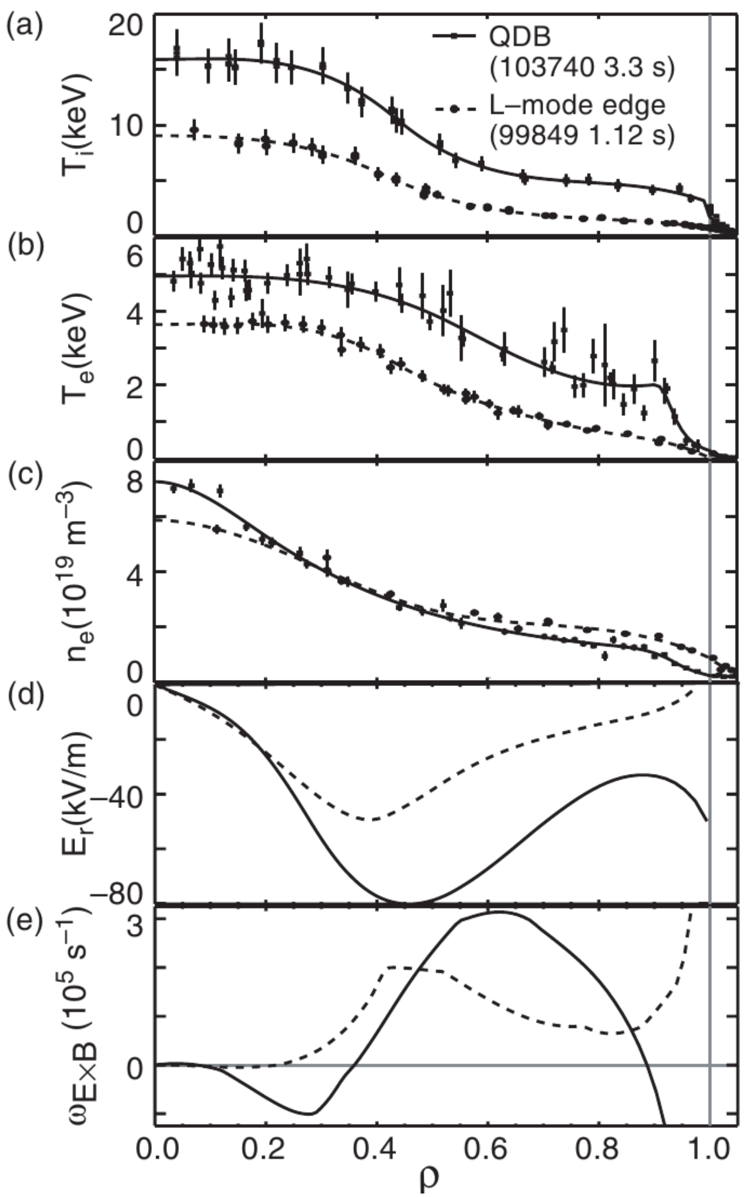


FIG. 2. Radial profiles of the SX (2-μm Be filter) and

“Development of an Edge Transport Barrier at the H-Mode Transition of ASDEX”

F. Wagner, at al Phys. Rev. Letters, 53, 1453, (1984)

Quiescent H-mode regime on DIII-D



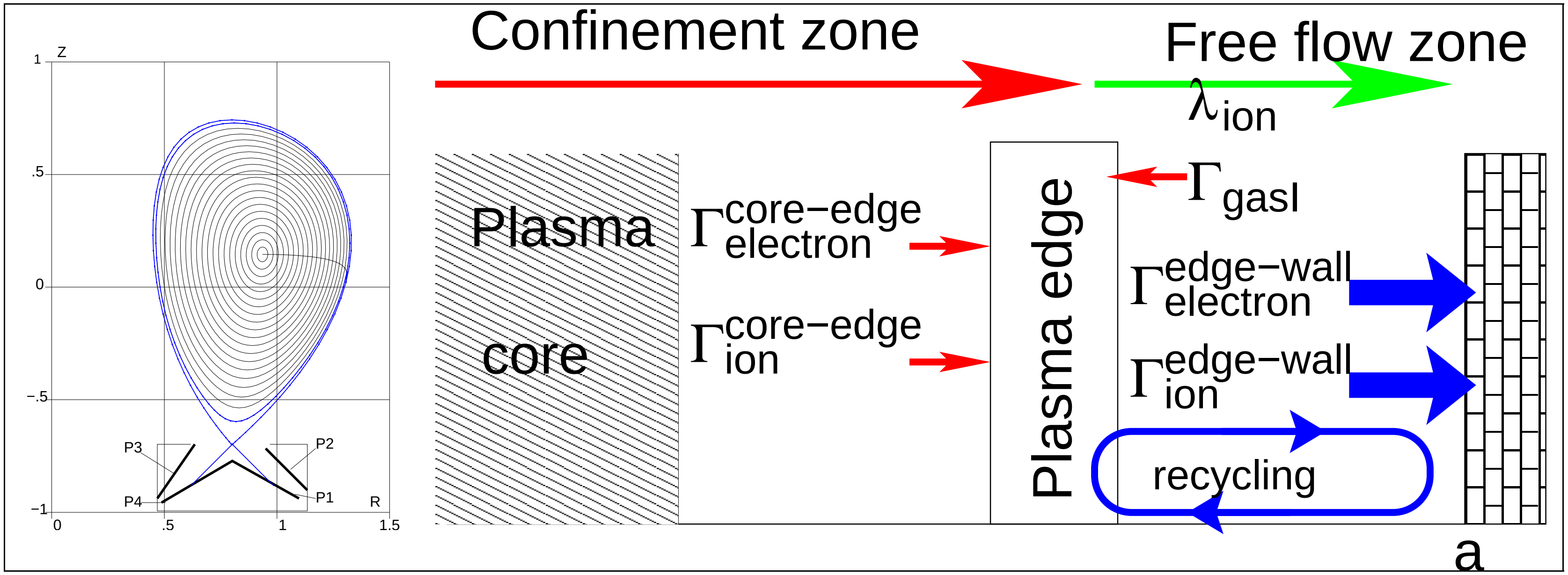
"The quiescent double barrier regime in DIII-D" by C. M. Greenfield, K. H. Burrell, E. J. Doyle et al. Plasma Phys. Control. Fusion 44 (2002) A123-A135.

Figure 4. Kinetic profiles from a QDB (103740) and ITB with an L-mode edge (99849). (a) Ion and (b) electron temperatures, (c) electron density, (d) radial electric field, and (e) E x B shearing rate.

There are many similar pictures from different regimes on DIII-D and from other machines.

The record $T_i^{ped} \simeq 6$ kV was achieved in QHM regime.

The basic assumption is that the plasma confinement zone (core) extends till the separatrix



In the core heat flux

$$q = -n\chi\nabla T. \tag{2.1}$$

Accordingly, the sharp temperature gradient automatically means reduction of χ till the neo-classical level in consistency with experimental data - the transport barriers.

Wow, such an unbelievable gift to FES plasma physicists from the tokamak edge plasma !

The number of publications, highlights, grant applications, XPs, related to the ETB is countless (certainly measured by thousands) - the plasma edge is the key to magnetic fusion.

3 The logic of LiWF: from the plasma edge to the core

1998 ***High edge temperature is natural for the plasma with a pumping walls (Krasheninnikov)***

1999 $T^{edge} \simeq \int PdV/\Gamma \simeq E^{NBI}/5$, ***edge temperature is similar to*** T^{ped}

2000 ***R.Stambaugh. APS-2000. Quiescent Double Barrier H-Mode regime on DIII-D***

2004 ***K.Burrell, APS-2004, by saying "Edge Harmonic Oscillations do not affect the pedestal temperature" has triggered the understanding that the tip of the temperature pedestal is the end of the confinement zone:*** $T^{ped} \equiv T^{edge}$

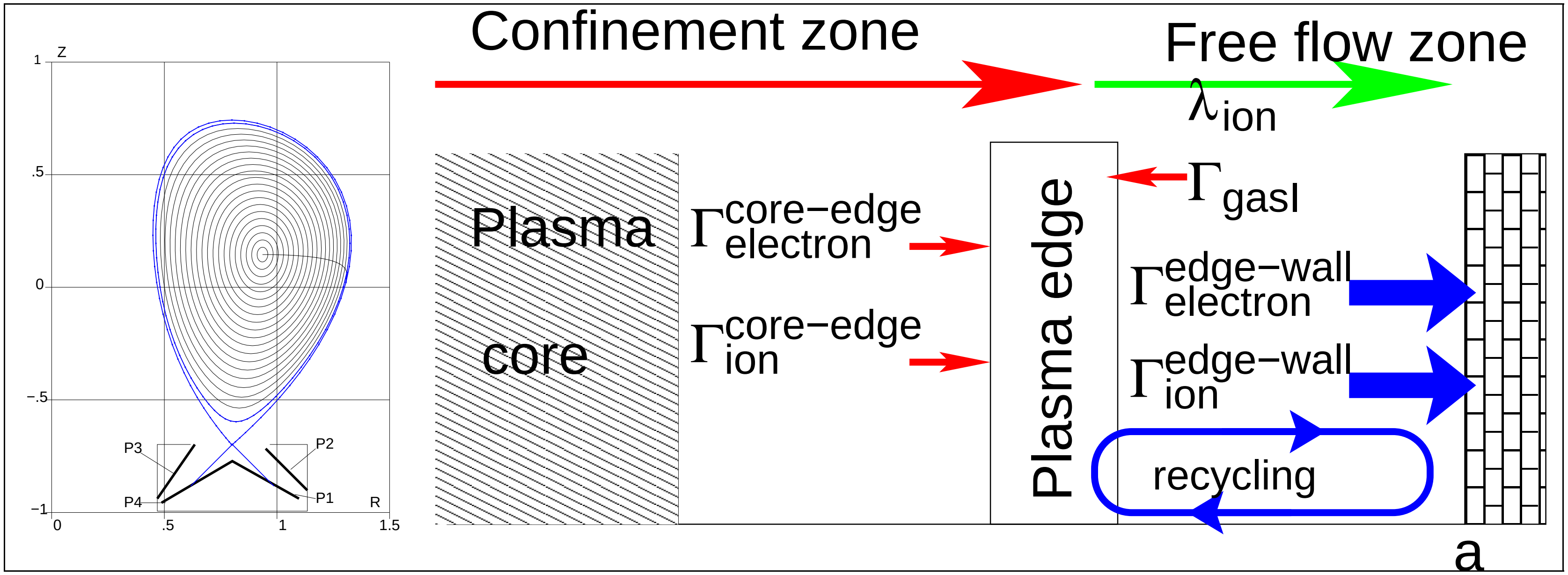
2005 ***The confusion of naive expectation to reduce the*** T^{edge} ***by RMP on DIII-D was envisioned.***

2005 ***The edge was basically understood. Stabilization of ELMs by Li was predicted.***

2008 ***The basic theory of the pedestal was presented to RMP Modeling Workshop, August 25-26, GA, San Diego CA. L.E.Zakharov "Where is the edge in toroidal plasma". The same time the crap of screening was introduced (Boozer, Becoulet).***

2012 ***The outstanding damage being made by the core transport theory to magnetic fusion was specified and spelled out.***

The plasma edge is the end of the confinement zone



(here, Γ is the particle flux, Γ^{gasI} is the gas influx to the plasma surface)

Recycling $R_{i,e} \neq 0$ amplifies particle fluxes from the plasma and the gas puff

In conventional plasma	***In LiWF regime***
$\Gamma^{edge\rightarrow wall}_{i,e} = \frac{\Gamma^{NBI}+\Gamma^{gasI}}{1-R^{ecycl}_{i,e}} \gg \Gamma^{NBI}$	$\Gamma^{gasI} < \Gamma^{NBI}, \Gamma^{edge\rightarrow wall}_{i,e} \simeq \Gamma^{NBI}$

Tedge is the boundary condition for the core transport

From the edge the energy fluxes are transported to the wall by the particle flux:

$$\begin{aligned}
\frac{5}{2}\Gamma_e^{edge-wall}T_e^{edge} &= \underbrace{\int_V P_e dV}_{\substack{heat\ \ source\\ for\ \ electrons}}, \quad T_e^{edge} = \frac{2}{5}\frac{1-R_e}{\Gamma^{core-edge}+\Gamma^{gasI}}\int_V P_e dV,\\
\frac{5}{2}\Gamma_i^{edge-wall}T_i^{edge} &= \underbrace{\int_V P_i dV}_{\substack{heat\ \ source\\ for\ \ ions}}, \quad T_i^{edge} = \frac{2}{5}\frac{1-R_i}{\Gamma^{core-edge}+\Gamma^{gasI}}\int_V P_i dV.
\end{aligned} \tag{3.1}$$

These Krasheninnikov's boundary conditions determine $T_{e,i}^{edge}$

Four effects, determining the edge temperature, are revealed here explicitly:

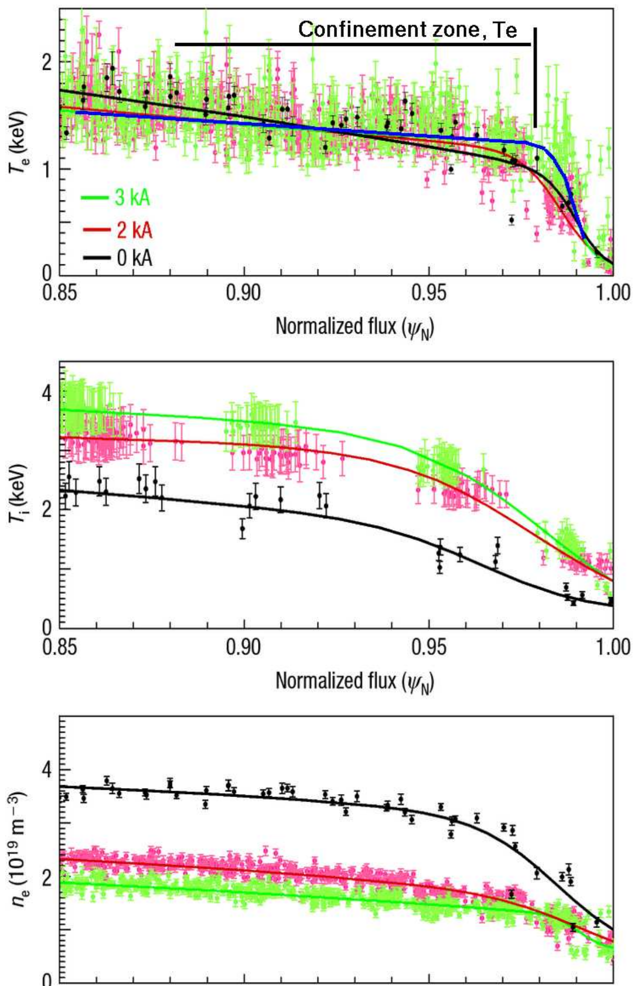
1. ***Recycling $1-R$ (i.e., wall conditions) is the most critical***
2. ***Total heating power $\int PdV$***
3. ***Core confinement $\Gamma^{core-edge}$***
4. ***Outgasing of the walls Γ^{gasI}***

Edge temperature does not depend on transport coefficients near the edge.

This property of T^{edge} allows to determine the position of the plasma edge experimentally

Energy confinement zone

RMP experiments on DIII-D have determined the size of the confinement zone



0 kA, 2 kA, 3 kA $I_{RMP-coil}$

T.Evans at al., Nature physics 2, p.419, (2006)

For the first time the confinement zone for electron energy was specified at RMP Modeling Workshop, August 25-26, 2008

1. ***The pedestal*** $T_e^{pedestal}$ ***is found insensitive to RMP*** $\rightarrow$ $T_e^{pedestal}$ ***is the*** T_e^{edge} $\rightarrow$
   The tip of the T_e ***pedestal is the boundary of the confinement zone for electrons.***
2. ***RMP do penetrate into the confinement zone:***
   The gradients
   $$n'(x),\ T_e'(x)$$
   in the core are reduced by RMP - no indication of "screening".
3. ***Different positions of the "edge" for*** T_e, T_i, n_e ***are possible***

The pedestal is situated outside the energy confinement zone.

There is no electron energy confinement in the pedestal region.

4 Basic mistake in the core-transport based logic

The unconditional application of diffusive transport model $q = -\chi \nabla T$ for interpretation of experiments had never been justified.

There is no minimal theory or experimental reason for assumption that the confinement zone with perfect magnetic surfaces at the plasma periphery.

A.I.Braginskii in Reviews of Plasma Physics v.1, 1961 explains the basics of the diffusive transport.

226 S. I. BRAGINSKII

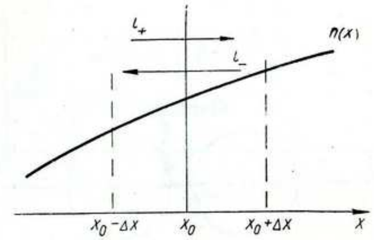


Fig. 4

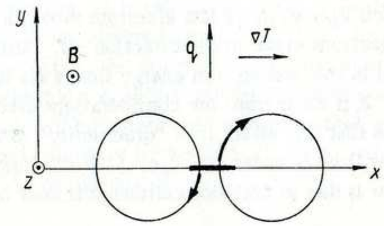


Fig. 5

Let us first consider diffusion. Diffusion occurs in a specified medium which we will assume to be fixed and not affected by the particles that diffuse through it.

Assume that the particle density is $n(x)$ (Fig. 4) and that each particle is displaced through a distance Δx, with equal probability for motion to the right or to the left, in the time τ between two successive collisions. In unit time, the plane $x = x_0$ is traversed in the positive direction (from the left) by half of the particles which experience collisions in the layer between $x_0 - \Delta x$ and x_0; the other half of the particles move to the left as a result of collisions. Assuming that $n(x)$ does not change greatly over a distance Δx so that

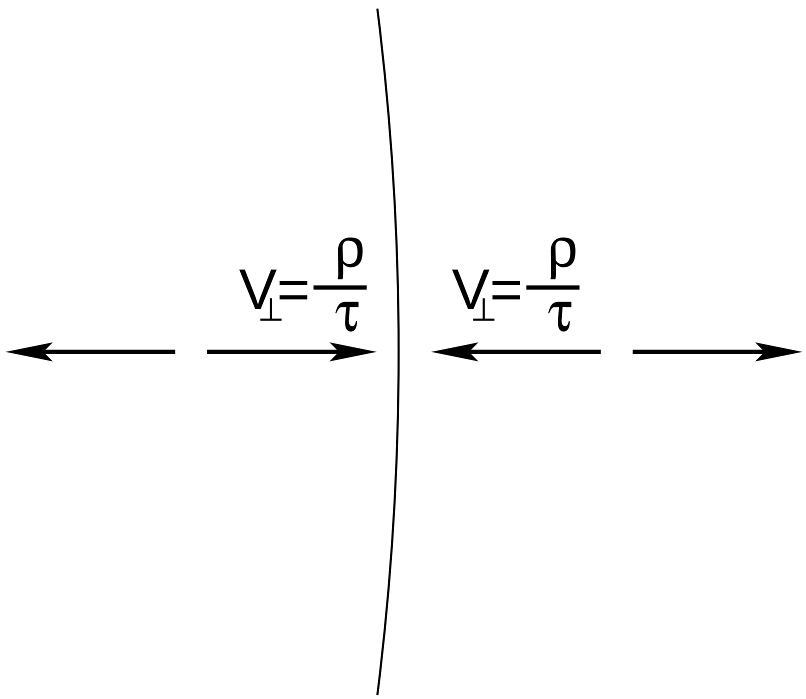
$$n(x) = n(x_0) + \left.\frac{\partial n}{\partial x}\right|_{x=x_0} (x - x_0),$$

we find that the unidirectional flux from the left is

$$i_+ = \frac{1}{2}\int_{x_0-\Delta x}^{x_0} \frac{1}{\tau} n(x)\, dx = \frac{1}{2}\left[n(x_0) - \frac{\partial n}{\partial x}\frac{\Delta x}{2}\right]\frac{\Delta x}{\tau}.$$

4.1 Unidirectional fluxes and diffusive transport

Diffusive transport $\mathrm{q} = n\chi\nabla T$ ***is a result of cancellation of opposit unidirectional fluxes***



$$\rho^e_{cm} = 0.75 \cdot 10^{-2} \frac{\sqrt{T^e_{keV}}}{B},$$
$$\rho^i_{cm} = 0.32 \frac{\sqrt{\mu T^i_{keV}}}{B_T},$$
$$\nu_e = 1.38 \cdot 10^5 \cdot \frac{\lambda_e}{15} \cdot \frac{n_{20}}{T^{3/2}_{keV}}, \qquad (4.1)$$
$$\nu_i = 2580 \cdot \frac{\lambda_i \sqrt{2}}{17\sqrt{\mu}} \cdot \frac{n_{20}}{T^{3/2}_{keV}},$$
$$V^e_{\perp,m/s} = 10.3 \cdot \frac{\lambda_e}{15} \cdot \frac{n_{20}}{B_T T_{keV}},$$
$$V^i_{\perp,m/s} = 8.31 \cdot \frac{\lambda_i}{17} \cdot \frac{n_{20}}{B_T T_{keV}}$$

$$V^e_{\perp,m/s} \simeq V^i_{\perp,m/s} \simeq 10 \frac{n_{20}}{B_T T_{keV}} \qquad (4.2)$$

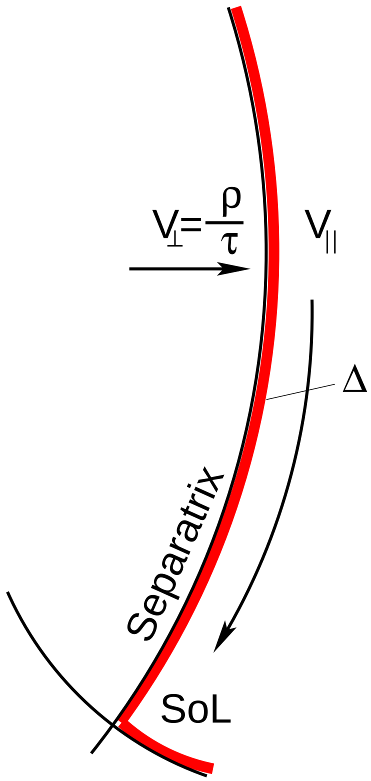
Diffusive transport is a result of mutual compensation of unidirectional fluxes

$$\mathrm{q} \simeq \frac{5}{2}\left[(nTV_\perp)_{a-\rho} - (nTV_\perp)_{a+\rho}\right] \simeq -\frac{5}{2}\rho\nabla\,(nTV_\perp) \qquad (4.3)$$

4.2 Unidirectional fluxes and parallel losses

After crossing the separatrix the unidirectional flux is converted into parallel flux

Perfect magnetic surfaces are assumed



Parallel velocities

$$V^e = \frac{\sqrt{T_e}}{\sqrt{m_e}} \simeq 1.32 \cdot 10^7 \sqrt{T_{keV}},$$
$$V^i = \frac{\sqrt{T_i}}{\sqrt{m_i}} \simeq 3.1 \cdot 10^5 \sqrt{T_{keV}}. \quad (4.4)$$

Free flow case, connection length is shorter than the mean free paths $L < \lambda$.

$$\lambda_m^e = 93 \cdot \frac{15}{\lambda_e} \cdot \frac{T_{keV}^2}{n_{20}}, \quad \lambda_m^i = 125 \cdot \frac{17\sqrt{\mu}}{\lambda_i\sqrt{2}}\frac{T_{keV}^2}{n_{20}}. \quad (4.5)$$

$$\frac{5}{2}nT^{edge}V_\perp L_{pol} 2\pi R = \frac{5}{2}nT^{edge}V_\| \Delta 2\pi R \frac{L_{pol}}{L} \quad (4.6)$$

The thickness Δ of plasma layer with open field lines sufficient to destroy the diffusive transport is determined simply by

$$\frac{\Delta}{L} \geq \frac{V_\perp}{V_\|} \quad (4.7)$$

4.3 Criterion of destruction of diffusive transport

The part of the core with destroyed magnetic surfaces has parallel transport dominant over diffusive one if the width of the perturbed region Δ

$$\Delta_{cm} \geq \frac{L_m}{12.5 \cdot 10^3} \cdot \frac{n_{20}}{B_T T_{keV}^{3/2}}, \quad L < \lambda_e \tag{4.8}$$

The connection lengths of the order of 12 km (!) are able to destroy the diffusive transport

The replacement of free flow by the parallel thermal conduction $\chi_{\|} = 3.2 V_{\|} \lambda_e$ introduces a factor $L/(3.2\lambda_e)$ leading to a complementary estimate

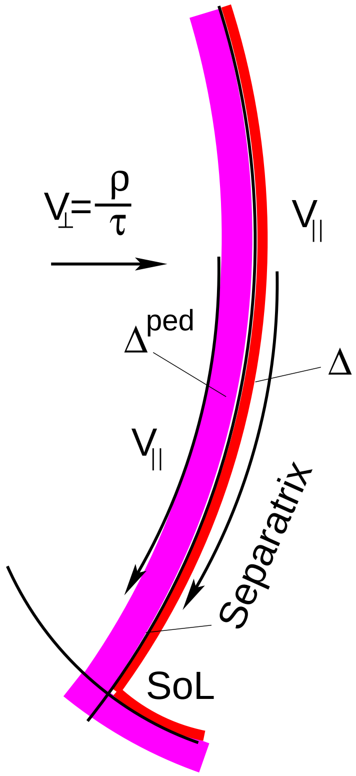
$$\Delta_{cm} \geq \frac{L_m^2}{12.5 \cdot 10^3 \lambda^e} \cdot \frac{n_{20}}{B_T T_{keV}^{3/2}} \simeq \left(\frac{L_m}{3.7 \cdot 10^3}\right)^2 \cdot \frac{n_{20}^2}{B_T T_{keV}^{7/2}}, \quad L > \lambda_e \tag{4.9}$$

Still the connection lengths of the order of 3.7 km (!) within a region of 1 cm are able to destroy the diffusive transport.

In the SoL the dominant role of the parallel transport is well-known and undisputable.

4.4 Criterion explains the edge pedestal

With kms long connection lengths the same criterion is applicable for the plasma edge

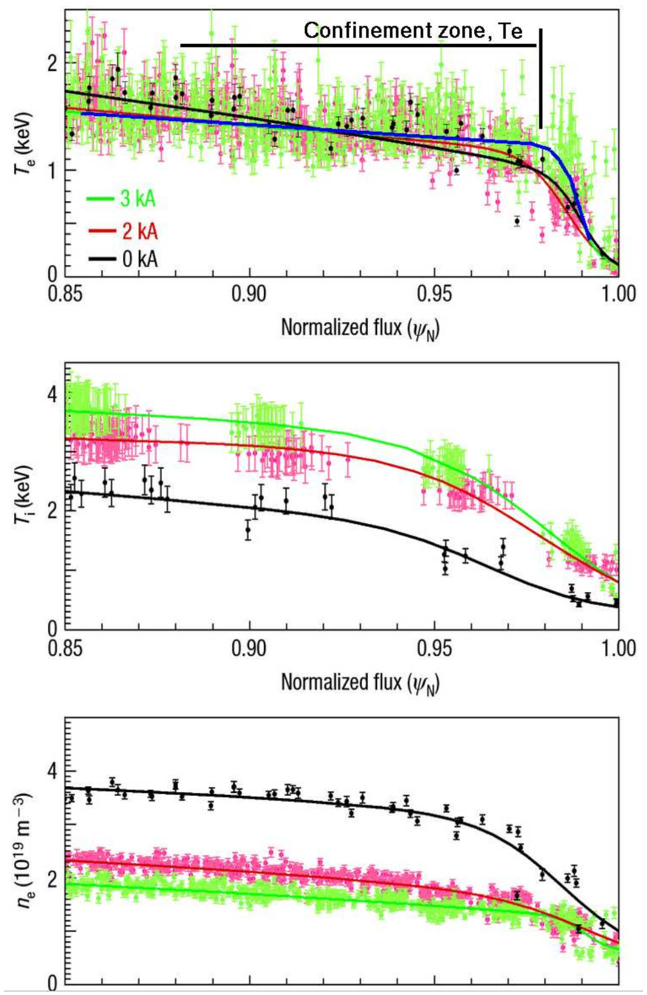


$$\Delta^{ped}_{cm} \geq \frac{L_m}{12.5\cdot 10^3}\cdot\frac{n_{20}}{B_T T^{3/2}_{keV}},\quad L<\lambda_e,$$
$$\Delta^{ped}_{cm} \geq \left(\frac{L_m}{3.7\cdot 10^3}\right)^2\cdot\frac{n^2_{20}}{B_T T^{7/2}_{keV}},\quad L>\lambda_e \qquad (4.10)$$

The density and temperature dependence of Δ are consistent with experimental observations of pedestal regions.

5 LiWF pedestal theory is consistent with experiments

RMP experiments on DIII-D have determined the size of the confinement zone



0 kA, 2 kA, 3 kA $I_{RMP-coil}$

T.Evans at al., Nature physics 2, p.419, (2006)

1. ***The magnetic field in the*** T_e ***pedestal is already highly perturbed, making pedestal insensitive to RMP.***
2. ***The edge*** T_e ***pedestal is right behind the confinement zone for electrons.***

   There is no electron energy confinement in the pedestal region.

3. T_e, T_i, n_e ***have different extents of the confinement zone.***
4. ***As the boundary condition for the core transport*** T_e^{edge} ***is unshakable by RMP.***
5. ***The screening of RMP is a fantasy of TTF. RMP do penetrate into the confinement zone. The gradients***

$$n'(x),\ T_e'(x)$$

   in the core are clearly reduced by RMP.

6. ***The edge density drops due to enhanced transport in the core resulting from RMP penetration.***
7. ***Reduced*** n^{edge} ***and elevated*** T_e^{edge} ***(as well as reduced SoL currents) result in shrinking the edge pedestal.***

SOLCs exist even in the most quiet plasma. They are the key to the understanding of the plasma edge.

SOL current and MHD activity in DIII-D

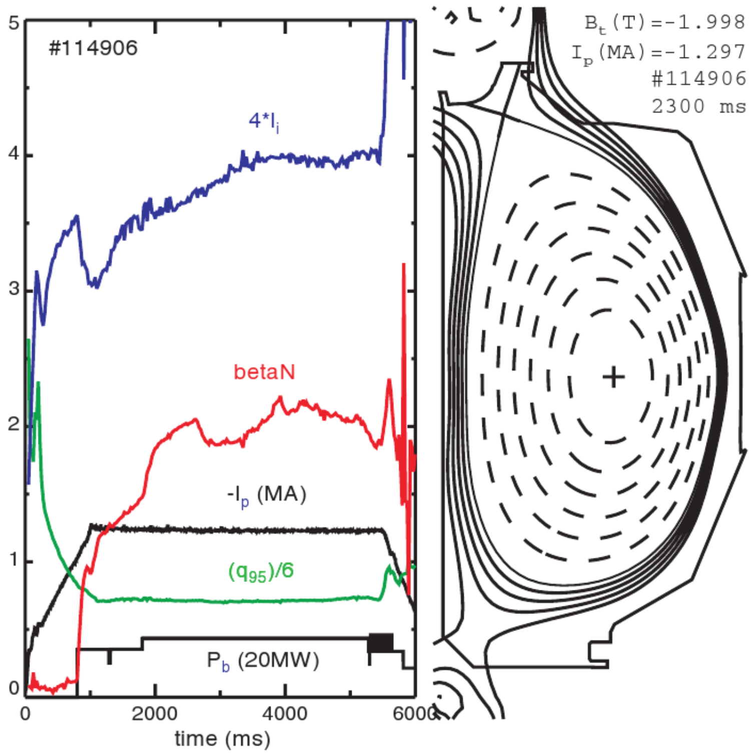


Figure 3. Pictorial discharge summary; the left-hand panel shows I_p in units of megaamperes, P_b in units of 20 MW, q_{95} divided by 6, β_N, and the nominal no-wall limit (here, 4 li). The right-hand panel shows the plasma boundary and four exterior flux surfaces in the

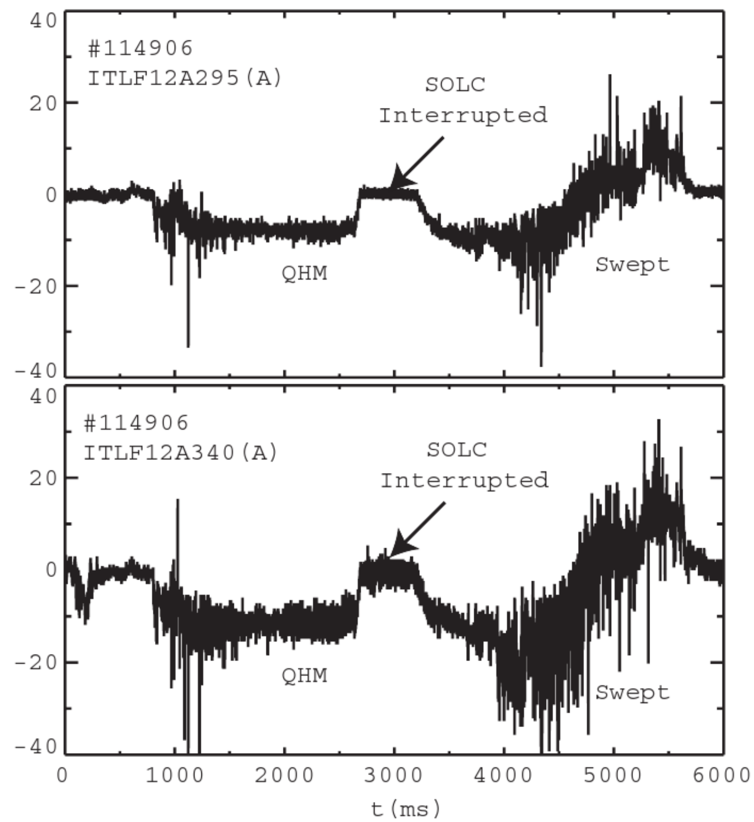


Figure 4. Signals from tile current sensors in tile ring #12 A in the discharge shown in the previous figure. It has a period of QHM over

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.

counter-NBI.

6.1 Physics of thermoelectric SoL currents

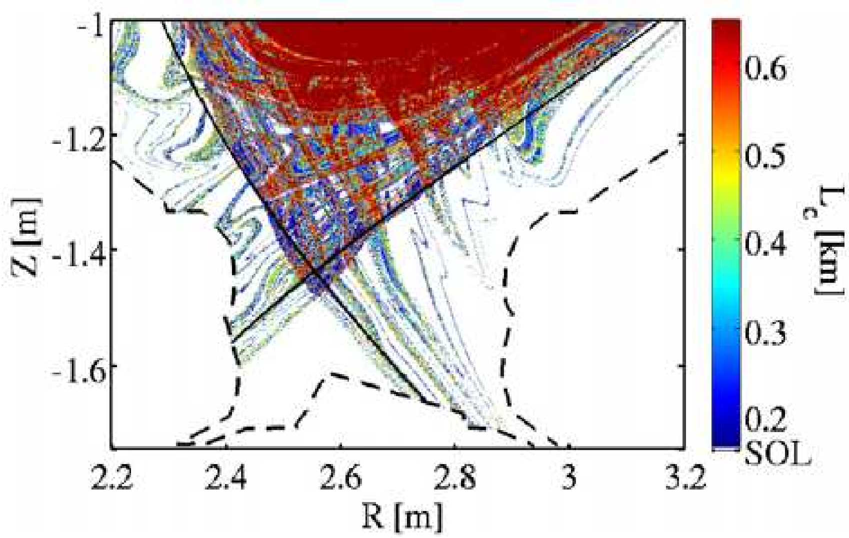
Any asymmetry in distribution function along field lines in SoL drives the SoL currents

Basic theory: P.J.Hartour. "Current flow parallel to the field in a scrape off layer", Contrib. Plasma Phys. 18 4/5 p. 417-419 (1988)

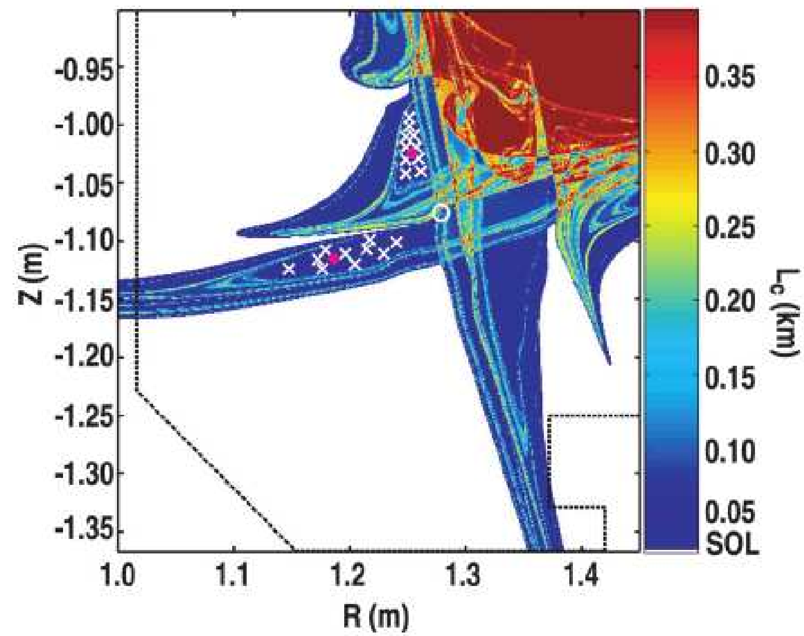
Theory and measurements on JET: P.J. Harbour, D.D.R. Summers, S. Clement, et al. "The X-point Scrape-Off Plasma in JET with L- and H-modes", Journal of Nuclear Materials 162-164 236-244, (1989)

Refined theory: G.M. Staebler, F.L. Hinton. "Currents in the scrape-off layer of diverted tokamaks", Nucl. Fusion 29 1820 (1989)

$$J_{\parallel} \propto J_{iSat}\gamma(\Delta T_A^{SoL}) \propto en^{SoL}\sqrt{T_A^{SoL}}\Delta T_A^{SoL}. \qquad (6.1)$$



A. Wingen, T. E. Evans, and K. H. Spatschek. "Effect of thermoelectric current splitting on the magnetic topology in DIII-D" Phys. Plasmas 18, 042501 (2011)



M. Rack, A. Wingen, Y. Liang, K.H. Spatschek, D.M. Harting, S. Devaux and JET-EFDA contributors. "Thermoelectric currents and their role during ELM formation in JET", Nucl. Fusion 52 074012 (2012)

Nothing like this is coming from PPPL

6.2 Edge "transport barrier": a fantasy or a reality

In figure, the normal person see the same sudden drop of ion and electron temperature at the plasma edge. The certified experts of TTF see a remarkable "transport" barrier

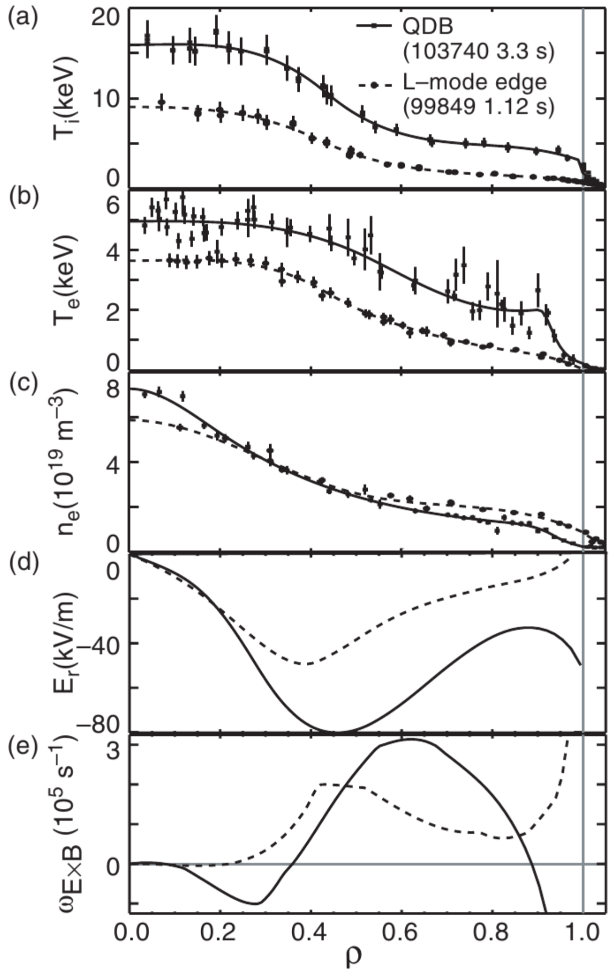


Figure 4 Kinetic profiles from a QDB (103740) and ITB with an L-mode edge (99849). (a) Ion and (b) electron temperatures, (c) electron density, (d) radial electric field, and (e) E x B shearing rate. *The picture of an H-mode below was taken arbitrarily from paper "The quiescent double barrier regime in DIII-D" by C. M. Greenfield, K. H. Burrell, E. J. Doyle et al. Plasma Phys. Control. Fusion 44 (2002) A123-A135. There are many similar pictures from different regimes on DIII-D and from other machines.*

What GK theory sees on these plots is a sharp gradient of electron temperature in the pedestal region, which is located inside the separatrix ($\rho = 1$). For GK this automatically means the presence of two zones of confinement: a core and the "edge transport barrier" (ETB) with suppressed radial transport.

At the same time, a normal physicist would notice a similar sharp gradient on the ion temperature. In this example it is clearly located outside the separatrix. Nobody would suggest a transport barrier in the open field line region where there is no confinement. A normal physicist would reasonably suggest that the sharp electron temperature gradient has the same reason - open field lines, rather than mythical "edge transport barrier". Accordingly the pedestal region has no electron confinement.

DIII-D experiments with QHM and especially with RMP have confirmed common sense and the interpretation of a normal physicist: for electrons the confinement zone extends from the magnetic axis to the top of the temperature pedestal. In the pedestal region not only there is not any transport "barrier", there is no confinement at all.

Shear flow stabilization at the plasma edge has been certified as a great achievement of gyro-kinetic theory. In fact, this is an outstanding example in a series of failures of FES theory.

7 Summary

- ***The kinetic effect of cancellation of diffusive transport is revealed and the corresponding criteria (4.8,4.9) are identified.***
- ***Destruction of magnetic structure and strong parallel transport exceeding unidirectional plasma energy/particle fluxes leads to the steepening of temperature profiles.***
- ***The dependencies of Δ on n, T are consistent with experimental observations.***
- ***This property of the parallel transport explains the edge temperature pedestal and basic phenomena observable in tokamak experiments.***
- ***The core confinement zone does NOT extend to the pedestal region.***
- ***Applied to the plasma core, the same effect may explain formation of internal temperature pedestals in the zones with strong magnetic perturbations and destroyed confinement.***

Regarding the question in the title

“Are "transport barriers" a zone of good confinement or of its collapse”

the answer is obvious: "collapse".

As the recycling coefficient in the present, irrelevant to fusion, plasma regimes in tokamaks is close to 100 %, the fraction of fake papers from TTF factory on transport barriers is similarly close to 100 %.