New insights on scrape-off layer profiles and turbulence in Alcator C-Mod

enabled by a scanning MLP

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Invited talk presented at the 21st Joint EU-US Transport Task Force Meeting
Leysin, Switzerland – September 5-8, 2016
Acknowledgements

D. Brunner, T. Golfinopoulos, A.Q. Kuang, J.L. Terry, …

and the entire Alcator Team
We must do this empirically.

But progress towards this goal would be greatly accelerated by:

Sorting out physics behind narrow heat flux width ($1/B_\theta$ scaling) and projection to reactor

Develop quantitative predictive models for SOL transport/profiles and main-chamber fluxes that capture observed dependences

- plasma conditions (e.g. Greenwald fraction)
- poloidal location (e.g. HFS vs. LFS)
- magnetic topology (e.g. double-null, single-null)
- divertor topology ...

We have studied the C-Mod SOL in detail and most recently are exploiting the capabilities of a new Mirror Langmuir Probe (MLP) diagnostic.

This talk presents some key observations that (I hope) will encourage as well as challenge the development of first-principles physics models ...
Key Messages

(1) SOL exhibits a well-defined structure that is largely invariant – similar in limited vs. diverted topologies, L- vs. H-mode, ... Near / Far SOL profiles, shear layer, structure velocities, 1/B\(\theta\) heat flux width, ...

(2) ‘Narrow heat flux width’ feature = ‘near SOL’.

(3) Bursty, interchange-like transport dominates far SOL; Drift-like turbulence (and modes) dominate near SOL. => Example: Quasi-Coherent Mode

(4) HFS/LFS transport asymmetries (for background plasma and impurities) are very large, with profound consequences. => May be exploited to solve critical PMI challenges in reactors
What is a Mirror Langmuir Probe (MLP)?
Mirror Langmuir Probe\(^1\)

An electronic device that adjusts its I-V response \textit{in real time} to match that of an actual Langmuir probe

- Fast-switching voltage bias applied to actual Langmuir Probe (LP) and Mirror Langmuir Probe (MLP)

\[ V_{\text{bias}}: \text{3-State Voltage Waveform} \]

\[ V^+ \quad V_f \quad V^- \]

\[ 0.9 \ \mu s \]

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- By active feedback, $I_{sat}$, $T_e$ and $V_f$ ‘controls’ are adjusted so that I-V from MLP and LP are identical.

MLP I-V Model:

$$I = I_{sat} \{\exp[(V-V_f)/T_e] - 1\}$$

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- Time-averages (~1 ms) of $T_e$ and $I_{sat}$ signals are used to adjust for optimum bias waveform.

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Result:
- MLP system maintains optimum “triple probe bias” dynamically.
- \(I_{sat}\), \(T_e\) and \(V_f\) at 1.1 MHz are obtained by fitting digitized I-V data (post processing)

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MLP bias is implemented separately on 4-electrodes on a C-Mod horizontal scanning probe drive

MLP simultaneously measures $\tilde{n}, T_e, \tilde{\phi}$ on all 4 electrodes ($\sim 1 \mu s$)
MLP bias is implemented separately on 4-electrodes on a C-Mod horizontal scanning probe drive

Enables new capabilities:
- High resolution \( n, T_e, \Phi \) profiles
- Structure velocities
- Fluctuations and transport

Particle flux
\[
\Gamma_r = \langle \vec{n} \vec{E}_\theta \rangle / B
\]

Heat fluxes
\[
Q_{cr} = (5/2) \langle \vec{P}_e \vec{E}_\theta \rangle / B
= \langle 5/2 T_e \Gamma_r \rangle + (5/2) \langle n \vec{T}_e \vec{E}_\theta \rangle / B
\]

Turbulence mode structure
\( k_\theta \) resolved \( \vec{n}, \vec{T}_e, \vec{\Phi} \) and relative phase angles

Momentum fluxes
\[
\langle \vec{V}_r \vec{V}_\parallel \rangle, \langle \vec{n} \vec{V}_r \vec{V}_\parallel \rangle, \langle \vec{V}_r \vec{V}_\theta \rangle, \langle \vec{n} \vec{V}_r \vec{V}_\theta \rangle
\]
Q: What is the origin of the ‘narrow heat flux feature’ seen on divertor target plates?
   ... with $1/B_\theta$ scaling
   ... that is a challenge for ITER and future reactor designs?

Well, it also appears in inner-wall limited plasmas...
Insight is gained by looking at C-Mod inner-wall limited discharges\(^1\)

Motivation: Look for ‘Narrow \(\lambda_q\)’ feature in the SOL that could explain IR camera ‘footprints’ on JET and elsewhere\(^2\)

\[ 0.22 < \frac{n}{n_G} < 0.35 \] – low recycling regime

\[ 0.4 \ 0.6 \ 0.8 \ 1.0 \ 1.2 \]

\[ \text{Plasma Current (MA)} \]

\[ 4 \ 5 \ 6 \ 7 \]

\[ \text{Toroidal FIeld (tesla)} \]

\[ q_{95} = 2.7; \kappa = 1.17 \]

\[ q_{95} = 3.1; \kappa = 1.31 \]

\[ q_{95} = 3.2; \kappa = 1.24 \]

\[ q_{95} = 4.1; \kappa = 1.16 \]

Experiment produced 21 IWL plasmas

focus on these two cases


Ip = 1.0 MA, $B_T$=6.4 tesla

1.1 MHz data sampling. Each trace has ~40,000 points.
Data: Scanning Mirror Langmuir Probe

Ip = 1.0 MA, B\_T = 6.4 tesla

Fluctuations are not noise!
MLP resolves ‘bursty’ events of SOL.
Normally difficult to assess ‘time-averaged’ profiles

1.1 MHz data sampling. Each trace has ~40,000 points.

New Insights on SOL profiles & turbulence ...
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Data: Scanning Mirror Langmuir Probe

Ip = 1.0 MA, Bₜ=6.4 tesla

Density

Electron Temperature

Plasma Potential

Probe Floating Potential

Average of 4 electrodes + 200 μs smoothing

Ip = 1.0 MA, Bₜ=6.4 tesla

Mit PSFC

New Insights on SOL profiles & turbulence ...

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Data: WASP\textsuperscript{1} (conventional probe)

\[ Ip = 1.0 \text{ MA}, \quad B_T = 6.4 \text{ tesla} \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{wasp_diagram.png}
\caption{WASP diagram with electrode positions and probe floating potential graph.}
\end{figure}

\begin{itemize}
    \item **Density**
    \item **Electron Temperature**
    \item **Plasma Potential**
    \item **Probe Floating Potential**
\end{itemize}

\[ \text{Average of 2 ‘upstream’ electrodes + smoothing} \]

\[ \text{Density: } 10^{20} \text{ m}^{-3} \]
\[ \text{Electron Temperature: eV} \]
\[ \text{Plasma Potential: volts} \]
\[ \text{Probe Floating Potential: volts} \]

\[ Rho (\text{mm}) \]

\[ -4 \quad -2 \quad 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \]

Profiles exhibit typical ‘Near’ and ‘Far’ SOL zones.

Electron Pressure

Parallel Heat Flux,
$q// = 7 \text{T}_e \text{ J} \text{sat}$

‘Narrow heat flux feature’ = Near SOL zone

Ip = 1.0 MA, $B_T = 6.4$ tesla
MLP data cleanly resolve $q_{\parallel}$ profile features

Fit ‘near’, ‘far’ $\lambda_q$ to MLP profiles and look for trends...

$\lambda_{pe1} = 1.2$ mm
$\lambda_{pe2} = 12$ mm

$\lambda_{q1} = 1.1$ mm
$\lambda_{q2} = 10$ mm

$q_{\parallel} = q_1 \exp(-\rho/\lambda_{q1}) + q_2 \exp(-\rho/\lambda_{q2})$
MLP data cleanly resolve $q_{\parallel}$ profile features

Fit ‘near’, ‘far’ $\lambda_q$ to MLP profiles and look for trends...

$Ip = 1.0\ MA, B_T = 6.4\ tesla$

Electron Pressure, $p_e$

Parallel Heat Flux, $q_{\parallel}$

Change-in-slope feature at LCFS

$q_{\parallel} = q_1\exp(-\rho/\lambda_{q1}) + q_2\exp(-\rho/\lambda_{q2})$

$\lambda_{pe1} = 1.2\ mm$

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Parallel Heat Flux, $q_{\parallel}$

$q_{\parallel} = q_1 \exp(-\rho/\lambda_{q1}) + q_2 \exp(-\rho/\lambda_{q2})$

$\lambda_{pe1} = 3.0$ mm

$\lambda_{pe2} = 95$ mm

$\lambda_{q1} = 2.6$ mm

$\lambda_{q2} = 44$ mm
MLP data cleanly resolve $q_{\parallel}$ profile features

Fit ‘near’, ‘far’ $\lambda_q$ to MLP profiles and look for trends...

Electron Pressure, $p_e$

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q// = $q_1 \exp(-\rho/\lambda_{q1}) + q_2 \exp(-\rho/\lambda_{q2})$

Ip = 0.4 MA, $B_T=4.0$ tesla

New Insights on SOL profiles & turbulence ...

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Result from $I_p$ and $B_T$ scan: ‘Near’ $\lambda_q$ scales $\sim 1/I_p$
Result from $I_p$ and $B_T$ scan: ‘Near’ $\lambda_q$ scales ~ $1/I_p$

Makes contact with $\lambda_q \sim 1/I_p$ scaling seen in EDA H-modes, low density L-modes (C-Mod)\textsuperscript{1} and H-modes from multi-machine database\textsuperscript{2}.

\[\lambda_q \sim 1/I_p\]

**Implication:** ~ same physics sets $\lambda_q$ under a wide range of conditions

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\[\lambda_q \text{ Data from Scanning MLP}\]

<table>
<thead>
<tr>
<th>$q_{95}$</th>
<th>$\kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
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</tr>
</tbody>
</table>

**Inner Wall Limited**

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\[\lambda_{q,IR} \sim 1/I_p\]

\[\lambda_{q,LP} \sim 1/I_p\]

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Experiment$^1$: Does presence of separatrix affect LFS SOL profiles?

Test: Run identical ohmic L-mode discharges, with LCFS topology varying from Double-Null to Inner-Wall-Limited

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Double-Null
- X-points define LCFS
- Elongation ~ 1.65

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Inner-Wall-Limited
- X-point flux surface is \(\sim 3\ \lambda_p\) beyond LCFS
- Elongation \(\sim 1.35\)

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- X-point flux surface is $\sim 3 \lambda_p$ beyond LCFS
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Track systematic changes (if any) of the LFS SOL profiles

\textsuperscript{1} LaBombard, APS 2008 (http://www-internal.psfc.mit.edu/~labombard/APS2008_Talk.pdf)
Experiment¹: Does presence of separatrix affect LFS SOL profiles?

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**Double-Null**
- X-points define LCFS
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**Inner-Wall-Limited**
- X-point flux surface is ~3 $\lambda_p$ beyond LCFS
- Elongation ~ 1.35

Track systematic changes (if any) of the LFS SOL profiles

Are steep pressure gradients near the LCFS affected by separatrix location?

[1] LaBombard, APS 2008
Result: LFS SOL profiles are robustly insensitive to location of separatrix flux surface

- Diverted profiles are reference
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- Diverted profiles are reference
- Separatrix sweep has no effect on steep gradients in Near SOL
- Steep gradients do not appear in Far SOL when separatrix is positioned there
Q: Why is LFS SOL profile insensitive to separatrix location?

Q: What sets the breakpoint between ‘near’ and ‘far’ zones?

Q: ....

Let’s examine the SOL structure in detail with the MLP...
MLP reveals SOL structure in detail –

‘Near’ SOL region

Profiles shifted to put plasma potential maximum at LCFS

Diverted

Density

Breakpoint

Electron Temperature

Plasma Potential

New Insights on SOL profiles & turbulence ...

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MLP reveals SOL structure in detail –

‘Near’ SOL region

Profiles shifted to put plasma potential maximum at LCFS

Shift is consistent with power balance analysis, $T_{e,sep} \sim 60$ eV
MLP reveals SOL structure in detail – 
very similar in diverted and limited discharges

New Insights on SOL profiles & turbulence ...

B. LaBombard, EU-TTF 2016
MLP reveals SOL structure in detail – very similar in diverted and limited discharges

Profiles of normalized RMS fluctuation level are similar
MLP reveals SOL structure in detail – very similar in diverted and limited discharges

Profiles of fluctuation PDF Skewness are similar
Common Feature: Robust ExB shear layer at LCFS
Common Feature: Robust ExB shear layer at LCFS

New Insights on SOL profiles & turbulence ...

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Electron Pressure

Diverted

Ideal ballooning growth rate

Electron Pressure

Limited

ExB shear

\( \nabla V_{ExB} \)

\( \frac{C_s}{\sqrt{\lambda_p R / 2}} \)

\( \nabla V_{ExB} \)

\( \frac{C_s}{\sqrt{\lambda_p R / 2}} \)
Plasma flows appear constrained: \[\sim\text{toroidal rotation outside LCFS (LFS)}\]
Plasma flows appear constrained: ~toroidal rotation outside LCFS (LFS)
Plasma flows appear constrained: \(\sim\) toroidal rotation outside LCFS (LFS)

- Poloidal projections of parallel flow and ExB cancel in SOL

\[ \Rightarrow \] Plasma motion is \(\sim\) pure toroidal rotation there
Plasma flows appear constrained: ~toroidal rotation outside LCFS (LFS), ~ExB flow compensating ion diamag. just inside LCFS

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=> Plasma motion is ~ pure toroidal rotation there
Plasma flows appear constrained: ~toroidal rotation outside LCFS (LFS), ~ExB flow compensating ion diamag. just inside LCFS

- Poloidal projections of parallel flow and ExB cancel in SOL
  => Plasma motion is ~ pure toroidal rotation there

- ExB tends to cancel ion diamagnetic flow (using e⁻ diag. as proxy) just inside LCFS
  => Consistent with neoclassical constraints
Plasma flows appear constrained: ~toroidal rotation outside LCFS (LFS), ~ExB flow compensating ion diamag. just inside LCFS

Similar features in Limited and Diverted plasmas
Plasma flows appear constrained: \( \sim \) toroidal rotation outside LCFS (LFS), \( \sim \) ExB flow compensating ion diamag. just inside LCFS.

**Implication:** Plasma potential profile -- defined by transition between open and closed field lines and associated ambipolarity constraints -- is a dominant physics component that controls SOL structure.
**Potential Insight:** Breakpoint between ‘near’ and ‘far’ SOL is closely associated with location that fluctuations change from drift to interchange-like.

![Graph showing electron pressure, fluctuation time delay, and poloidal velocity with a breakpoint highlighting](image-url)
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Fluctuation propagation changes from electron to ion dia. direction near breakpoint.

Fluctuations are drift-like in near SOL

$$V_{\text{fluct}} \sim V_{\text{ExB}} + V_{\text{de}}$$
Potential Insight: Breakpoint between ‘near’ and ‘far’ SOL is closely associated with location that fluctuations change from drift to interchange-like.

Near-Far breakpoint is where $V_{\text{ExB}} + V_{\text{de}} \sim 0$; $V_{\text{ExB}}$ shear small.

Fluctuation propagation changes from electron to ion dia. direction near breakpoint.

Fluctuations are drift-like in near SOL $V_{\text{fluct}} \sim V_{\text{ExB}} + V_{\text{de}}$

... and interchange-like in far SOL $V_{\text{fluct}} \sim V_{\text{ExB}}$
Potential Insight: Breakpoint between ‘near’ and ‘far’ SOL is closely associated with location that fluctuations change from drift to interchange-like.
New Insight:

Drift-wave like turbulence near LCFS plays the key role of enhancing particle transport in the pedestal of C-Mod EDA H-modes.

Mirror Langmuir Probe measurements reveal that the Quasi-Coherent Mode (QCM) is a drift-like mode that spans the LCFS...
Mirror Langmuir Probe investigation of Quasi-Coherent Mode

Experimental setup:

- Setup ohmic EDA H-mode
- Plunge probe across QCM mode layer
- Record $k_{\theta}, \tilde{n}, \tilde{T}_e, \tilde{\Phi}$ response
- Deduce mode character (drift, interchange, ...)

MLP passes through mode layer – reveals density fluctuation with frequency and wavenumber of QCM

- Mode exists near LCFS; radial mode width ~3 mm FWHM, consistent with GPI
- Frequency, poloidal wave number and propagation in electron diamagnetic direction -- consistent with $B_\theta$ probe, PCI and GPI diagnostics
New Insights on SOL profiles & turbulence ...

Snapshot of QCM: large amplitude, ~in-phase, density, electron temperature and potential fluctuations

Profiles from East electrode

Density

Electron Temperature

Plasma Potential

\[ \frac{\Delta n}{\langle n \rangle} \sim 30\% \quad \frac{\Delta T_e}{\langle T_e \rangle} \sim 45\% \quad \frac{\Delta \Phi}{\langle T_e \rangle} \sim 45\% \]

\( I_{sat} \) Fluctuation Power

\( 80 \) kHz < \( f < 120 \) kHz

Time (\( \mu \)sec) after 1.196 sec

\[ \begin{align*} 
\text{Density} & \\
\text{Electron Temperature} & \\
\text{Plasma Potential} & 
\end{align*} \]
New Insights on SOL profiles & turbulence ... B. LaBombard, EU-TTF 2016

Snapshot of QCM: large amplitude, ~in-phase, density, electron temperature and potential fluctuations

Cross Power Spectrum: Density and Potential

Potential lags Density with a phase angle of ~ 16 degrees

\[ V_r = \frac{\langle \tilde{n}\tilde{E}_\theta \rangle}{\langle n \rangle B} \approx 10 \text{ m/s} \]

=> Drift wave

=> Drives transport
New Insights on SOL profiles & turbulence ...

Snapshot of QCM: **large amplitude, ~in-phase, density, electron temperature and potential fluctuations**

Cross Power Spectrum: **Density and Potential**

Potential lags **Density** with a phase angle of ~ 16 degrees

$$V_r = \langle \tilde{n} \tilde{E}_\theta \rangle / \langle \tilde{n} \rangle B \sim 10 \text{ m/s}$$

=> Drift wave

Simple Boltzmann electron response?

Compute $$n_B$$ required to satisfy

$$n_B = \langle n \rangle \exp \left[ (\Phi - \langle \Phi \rangle) / T_e \right]$$

$$n_B$$ is ~1.5x larger than measured $$\tilde{n}$$

**Not** a simple Boltzmann response

Quasi-coherent mode propagates at electron diamagnetic drift velocity in the plasma frame ~ embedded in the broadband turbulence of the near SOL

Velocities computed from East electrode profiles

\[ V_{dpe} = \frac{\nabla_r n T_e \times b}{nB} \]
\[ V_{de} = \frac{T_e \nabla_r n \times b}{nB} \]
\[ V_{ExB} = \frac{b \times \nabla_r \Phi}{B} \]

QCM frequency is quantitatively consistent with \( k_\theta \sim 1.5 \text{ rad/cm mode} \) near the LCFS propagating with velocity between \( V_{dpe} \) and \( V_{de} \) in the plasma frame.
These QCM observations have potentially important implications.

Can a drift-like mode can be *externally driven near the LCFS?* If so, it might offer a means to control impurity uptake in H-modes.

In C-Mod, we have recently performed such a proof-of-concept experiment, successfully exciting a QCM-like drift-wave mode near the LCFS with a ‘shoelace antenna’\textsuperscript{1,2}.

Details will be presented by Ted Golfinopoulos at the November APS meeting in San Jose, CA.

What about the HFS SOL?
The HFS SOL exhibits some amazing properties.

**HFS SOL is quiescent.**

Fluctuation-induced radial transport is essentially zero on high field side.

Near sonic // flows ‘fill in’ HFS SOL.
The HFS SOL exhibits some amazing properties.

HFS SOL is quiescent.
Fluctuation-induced radial transport is essentially zero on high field side.

HFS SOL has excellent impurity screening properties.
Impurity Penetration Factors (PF) for impurity gases (N\textsubscript{2}, CH\textsubscript{4}) injected on the High-Field Side can be an order of magnitude lower than for impurities injected on the Low-Field Side.

\[
PF = \frac{\text{Core Impurity Ions}}{\text{Local Impurity Injection Rate}}
\]

Leading explanation - No HFS interchange turbulence + strong // flow to divertor.

New Insights on SOL profiles & turbulence ...

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HFS SOL profiles and flows are controlled exquisitely by magnetic X-point balance

Near Balanced Double Null

- Electron pressure maps between HFS-LFS *in common flux region*
- Sharp break in HFS profiles beyond
HFS SOL profiles and flows are controlled exquisitely by magnetic X-point balance

Near Balanced Double Null
- Electron pressure maps between HFS-LFS in common flux region
- Sharp break in HFS profiles beyond

Balanced Double Null
- Electron pressure maps between HFS-LFS only at LCFS
- Parallel flow to divertor reduced

New Insights on SOL profiles & turbulence ...

B. LaBombard, EU-TTF 2016
HFS-LFS Profile Comparison in Balanced Double Null

Near SOL Gradients in $n$, $T_e$ are ~identical HFS to LFS

- **Double exponential** profile observed in LFS SOL
- **Single exponential** observed in HFS SOL
  – no Far SOL ‘shoulder’ feature
HFS-LFS Profile Comparison in Balanced Double Null

Near SOL Gradients in $n$, $T_e$ are ~identical HFS to LFS

- Double exponential profile observed in LFS SOL
- Single exponential observed in HFS SOL
  – no Far SOL ‘shoulder’ feature
- Magnitude of electron pressure e-fold in near SOL is ~ same HFS/LFS
HFS-LFS Profile Comparison in Balanced Double Null

Near SOL Gradients in \( n, T_e \) are \(~\text{identical}\) HFS to LFS

- Double exponential profile observed in LFS SOL
- Single exponential observed in HFS SOL
  – no Far SOL ‘shoulder’ feature
- Magnitude of electron pressure e-fold in near SOL is \(~\text{same}\) HFS/LFS
  
  HFS SOL is entirely composed of
  
  the ‘narrow feature’ seen on LFS
  
  HFS density drops by two orders of magnitude in 6 mm
New Insights on SOL profiles & turbulence ...

B. LaBombard, EU-TTF 2016

**HFS-LFS Profile Comparison in Balanced Double Null**

*Near SOL Gradients in $n$, $T_e$ are ~identical HFS to LFS*

- Double exponential profile observed in LFS SOL
- Single exponential observed in HFS SOL
  – no Far SOL ‘shoulder’ feature
- Magnitude of electron pressure e-fold in near SOL is ~ same HFS/LFS
  HFS SOL is entirely composed of the ‘narrow feature’ seen on LFS
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$n/n_G = 0.22$

$$22.5 \exp(-\rho/1.73) + 9.2/\exp(-\rho/8.37)$$

$$25.6 \exp(-\rho/1.62)$$

$$29.1 \exp(-\rho/2.77) + 28.3/\exp(-\rho/14.9)$$
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~1/Ip scaling?
New Idea: Exploit unique properties of the High-Field Side SOL to solve PMI and RF actuator challenges

- Locate all close-fitting first-wall structures, including RF actuators, on the High-Field Side
- Employ near-double null magnetic topology

Potential solution for dramatically reduced PMI

- Direct external control of plasma conditions at RF actuator interface (gap, flux balance)
- Excellent impurity screening (recently verified for near – double null plasmas\(^1\))

Plus a host of other benefits ...
- Quiescent SOL; thin SOL; no ‘blobs’ – reduced wave interactions
- No ELM load, runaway e\(^-\), energetic ion orbit loss
- Low neutral pressure – increased RF voltage
- RF-generated fast e\(^-\) drift away from launcher
- Access to excellent wave physics (LHCD and ICRF heating)
- Reduce neutron flux on HFS above and below midplane

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Key Messages

(1) SOL exhibits a well-defined structure that is largely invariant – similar in limited vs. diverted topologies, L- vs. H-mode, ...
   Near / Far SOL profiles, shear layer, structure velocities, $1/B_\theta$ heat flux width, ...

(2) ‘Narrow heat flux width’ feature = ‘near SOL’.

(3) Bursty, interchange-like transport dominates far SOL;
    Drift-like turbulence (and modes) dominate near SOL.
    => Example: Quasi-Coherent Mode

(4) HFS/LFS transport asymmetries (for background plasma and impurities) are very large, with profound consequences.
    => May be exploited to solve critical PMI challenges in reactors