High-field side scrape-off layer investigation

Plasma profiles and impurity screening behavior in near-double null configurations


Invited Talk I-19
Presented at the 22\textsuperscript{nd} International Conference on Plasma Surface Interactions in Controlled Fusion Devices
Rome, May 30-June 3, 2016
1- Motivation
   Why study HFS SOL profiles and impurity screening?

2- Nitrogen impurity screening observations, HFS vs. LFS
   - HFS has excellent impurity screening, even in balanced-double-null
   - Parallel and perpendicular (ExB) impurity flows are important

3- HFS vs. LFS profiles in balanced double-null
   - ‘Narrow feature’ near LCFS on HFS maps to LFS

4- Summary, Next Steps
Solutions to critical plasma-material interaction and plasma sustainment challenges are needed in order to attain steady-state, net electricity from fusion ...

• Robust main chamber component lifetime solutions
  First wall components, including RF actuators, must survive the PMI onslaught of a DT reactor for sufficient time to be economically viable.

• Efficient, low PMI, heating and current drive technologies
  Achieving steady-state tokamak operation + net electricity production requires efficient (wall plug to plasma), low PMI RF actuator technologies that attain effective current profile control in a reactor.
Question: Can unique properties of the High-Field Side SOL be exploited to solve PMI and RF actuator challenges?

**HFS SOL is quiescent.**

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

Near sonic // flows ‘fill in’ HFS SOL.
HFS SOL Investigation: Plasma profiles and impurity screening in near double-null discharges

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(1) **HFS SOL is quiescent.**

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

(2) **HFS SOL has excellent impurity screening properties.**

Impurity Penetration Factors (PF) for impurity gases (N$_2$, CH$_4$) injected on the High-Field Side can be an order of magnitude lower than for impurities injected on the Low-Field Side.

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

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

Near sonic // flows ‘fill in’ HFS SOL.

Smick NF 53 (2013) 023001.

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**Smick JNM 337 (2005) 281.**
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Potential solution for dramatically reduced PMI:
- Locate all close-fitting first-wall structures, including RF actuators, on the High-Field Side
- Employ near-double null magnetic topology

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Potential solution for dramatically reduced PMI

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

  • Direct external control of plasma conditions at RF actuator interface (gap, flux balance)
  • Quiescent SOL; thin SOL; no ‘blobs’ – reduced wave interactions
  • No ELM load, runaway e\textsuperscript{−}, energetic ion orbit loss
  • Low neutral pressure – increased RF voltage
  • RF-generated fast e\textsuperscript{−} drift away from launcher
  • Reduce neutron flux on HFS above and below midplane

HFS SOL Investigation: Plasma profiles and impurity screening in near double-null discharges

B. LaBombard, PSI 2016
HFS launch is a potential game-changer for LHCD wave physics –
dramatic improvements in accessibility, efficiency, current profile control

Splitter and multi-junction fabrication techniques produce compact LHCD launchers that can fit on the inside wall and allow for neutron shielding (Vulcan [1], ARC [2]).

HFS launch is a potential game-changer for LHCD wave physics – dramatic improvements in accessibility, efficiency, current profile control


- Higher $|B|$ on HFS improves accessibility for low $n_\parallel$ waves [3,4].
- Produces dramatic improvement in wave penetration, off-axis CD – needed for current profile control.
- Current drive efficiency increases of ~40% or more can be obtained.

Splitter and multi-junction fabrication techniques produce compact LHCD launchers that can fit on the inside wall and allow for neutron shielding (Vulcan [1], ARC [2]).
HFS launch is highly beneficial for ICRF wave physics [1] – efficient IBW/ICW mode conversion; no ion tails; poloidal flow drive

• Incident fast wave (FW) power is absorbed nearly 100% via mode conversion (IBW/ICW)
• No formation of energetic ion tails
• No fast-ion loss, destabilization of energetic particle modes (fast alphas)
• IBW mode conversion has been found to produce flow drive in C-Mod [2] and TFTR [3]

**Question:** Does the HFS SOL retain good impurity screening attributes in Near Double-Null geometries?

As topology changes from LSN to DN:

- HFS SOL becomes narrower.
- HFS SOL parallel flows become weaker.

Could it be that the narrow HFS SOL in Double Null makes HFS impurity screening ineffective – maybe even worse than LFS?

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Experiment: Compare relative screening of HFS/LFS SOLs by injecting calibrated $N_2$ gas puffs into otherwise identical discharges

- Inject $N_2$ from HFS and LFS
**Experiment:** Compare relative screening of HFS/LFS SOLs by injecting calibrated N$_2$ gas puffs into otherwise identical discharges

- Inject N$_2$ from HFS and LFS
- Record core N content by monitoring N$^{5+}$ and N$^{6+}$ line intensities (VUV spec.)
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with Mirror Langmuir Probe Bias

Fast-switching bias electronics provides $I_{\text{sat}}$, $T_e$, and $V_f$ measurements at 1.1 MHz.
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**Diagram:**

- HFS Scanning Probe
- LFS Scanning Probe
- HFS \( \text{N}_2 \) Gas Puff
- LFS \( \text{N}_2 \) Gas Puff

**Mach Probe**

‘Mach Probe’
4 Electrode set

**With Mirror Langmuir Probe Bias**

Fast-switching bias electronics provides \( I_{\text{sat}}, T_e, \) and \( V_f \) measurements at 1.1 MHz.
**Experiment:** Compare relative screening of HFS/LFS SOLs by injecting calibrated N\textsubscript{2} gas puffs into otherwise identical discharges

- 45 ohmic L-mode discharges where investigated
  - 5.4 tesla forward field, $B \times \nabla B$ pointing down

**Topology Scan**
- Lower Single Null,
- Double Null,
- Upper Single Null

**Density & Current Scan**
- in Balanced Double Null
  - Plasma density (x2)
  - Plasma current (x2)
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

![Graph showing electron pressure, density, electron temperature, parallel flow, and density profiles.](image)
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
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Balanced Double Null
- Electron pressure maps between HFS-LFS only at LCFS
- Parallel flow to divertor reduced
(Estimated) nitrogen ionization source is very close to LCFS on HFS

Near Balanced Double Null

Balanced Double Null

HFS N₂ Ionization Profile

LFS N₂ Ionization Profile
Observation: $N_2$ gas injected on HFS midplane produces a ‘maypole plume’ – evidence of quiescent SOL with strong flow.

Maypole plume wraps around the center stack toward the lower divertor in a Lower Single Null discharge.
Quantifying Impurity Screening: A ‘proxy Penetration Factor’ is defined as $N^{6+}$ line brightness divided by $N_2$ injection rate.

Core N content \[ \frac{\partial N_N}{\partial t} = PF \cdot \Gamma_{N_2} - \frac{N_N}{\tau_p} \]

Penetration Factor

Core N confinement time

When \[ \frac{N_N}{\tau_{loss}} \gg \left| \frac{\partial N_N}{\partial t} \right| \], $N_N$ is proportional to injection rate.

Proxy Penetration Factor:

\[ PF_{proxy} = \frac{N^{6+} \text{ line brightness}}{\Gamma_{N_2}} \]
Results from Topology Scan:
HFS SOL retains good N screening, even in Double Null

HFS SOL Investigation: Plasma profiles and impurity screening in near double-null discharges

B. LaBombard, PSI 2016
- Double Null HFS PF is factor of ~2.5 smaller LFS PF

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Unexpected: Largest HFS PF occurs with a 5 mm bias towards Lower Single Null
Results from Density & Current Scan in Balanced DN:
PFs do not depend on density or current over range studied
Plume Dispersal Observations:
Maximum HFS PF occurs when N plume has weak poloidal flow

View of HFS N ‘plume’
$\delta R_{sep} = -12$ mm – Lower Null

Front view

Expanded View on Next Slides
Plume Dispersal Observations:
Maximum HFS PF occurs when N plume has weak poloidal flow

\[ \delta R_{sep} = -12 \text{ mm} \]

- 'Maypole' plume
- Strong directed // flow to lower divertor
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**Lower Null**

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- Strong directed parallel flow to lower divertor

\[ \delta R_{sep} = 0 \text{ mm} \]

**Double Null**

- No directed parallel flow
- Strong ExB flow towards upper divertor
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**Lower Null**

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$\delta R_{sep} = -6 \text{ mm}$
**Maximum HFS PF**

- Weak net flow in $\sim$ toroidal direction

$\delta R_{sep} = 0 \text{ mm}$
**Double Null**

- No directed $\parallel$ flow
- Strong $ExB$ flow towards upper divertor

Suggests that poloidal projection of $ExB$ and parallel impurity flow may be cancelling in HFS SOL – i.e., impurities not swept to divertor.
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Maximum HFS PF

δ$R_{sep}$ = 0 mm
Double Null

- No directed // flow
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Weak net flow in ~ toroidal direction
UV photodiode array reveals poloidal dispersal of $N^{4+}$ ions

UV-enhanced photodiode array

- Provides spatially-resolved measure of $N^{4+}$ dispersion (2p-2s NV lines, 123.88 and 124.28 nm)

- Note: $N^{4+}$ peaks near separatrix region ➞ photodiode signals track dispersion of impurities in SOL
N\textsuperscript{4+} Dispersal Observations

Lower Single-Null

Change in Photodiode Voltage

Lower Single Null, $\delta R_{sep} = -11$ mm

Snapshots in time as gas is injected

[Diagram showing field line mapping to N\textsubscript{2} injection and gas puff location]

HFS SOL Investigation: Plasma profiles and impurity screening in near double-null discharges

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Field-aligned flow to lower divertor (‘maypole’)  

- Dominant parallel flow to lower divertor  
- Evidence that N$^{4+}$ drifts vertically ($\text{ExB}$) from field line  

Result: excellent impurity ‘flushing action’ to divertor
N\textsuperscript{4+} Dispersal Observations

Upper Single-Null

Field-aligned flow to upper divertor (‘maypole’)

- Dominant parallel flow to upper divertor

- Evidence that N\textsuperscript{4+} drifts vertically (ExB) from field line

Result: excellent (the best) impurity ‘flushing action’ to divertor
N⁴⁺ Dispersal Observations

Balanced Double-Null

Dominant $ExB$ drift to upper divertor

- Evidence that N⁴⁺ is dominated by $ExB$ drift towards upper divertor

Result: good impurity ‘flushing action’ to divertor
N\textsuperscript{4+} Dispersal Observations

Un-Balanced Double-Null (\(\delta R_{sep} = -5\) mm)

Mix of competing parallel and ExB drift contributions

Early during puff:
- ExB flow to upper divertor dominates

Late during puff:
- Parallel flow to lower divertor with strong vertical ExB from field line

Result: poor impurity ‘flushing action’ to divertor – consistent with PF results.
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Profile Comparison in Balanced Double Null
Near SOL Gradients in $n$, $T_e$ are ~identical HFS to LFS

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HFS SOL is entirely composed of the ‘narrow feature’ seen on LFS

HFS density drops by two orders of magnitude in 6 mm

![Graph showing plasma profiles and impurity screening in near double-null discharges.](image-url)
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~1/$I_p$ scaling?
Summary: HFS SOL impurity screening characteristics explored vs. magnetic topology (LSN, DN, USN)

• Balanced Double Null – $N_2$ injected on the HFS is found to be a factor of ~ 2.5 better screened than LFS, despite very narrow HFS SOL

=> good news for the idea of employing HFS launch RF in DN

• HFS screening is least effective (1.5 x LFS) when the poloidal projection of plasma flow (parallel + $E \times B$) is minimized. This occurs in unbalanced DN, with x-point biased toward $B \times \nabla B$ direction.

• HFS screening is most effective (5 x LFS) in unbalanced DN, with x-point biased away from $B \times \nabla B$ direction.

Note: this configuration favors I-mode confinement regime
**Summary:** HFS vs. LFS SOL profiles compared in balanced double-null

- Pressure e-folding lengths on HFS and LFS SOLs are similar near the LCFS in balanced DN; HFS simply lacks the broad ‘shoulder’ that is present on the LFS.

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We will pursue HFS/LFS screening in balanced double-null EDA H-modes and I-modes during Alcator C-Mod’s final run campaign.
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Thank you for your attention!