The Small Angle Slot Divertor Configuration Facilitates Core-Edge Integration

Presented by

H.Y. GUO

With contribution and support from

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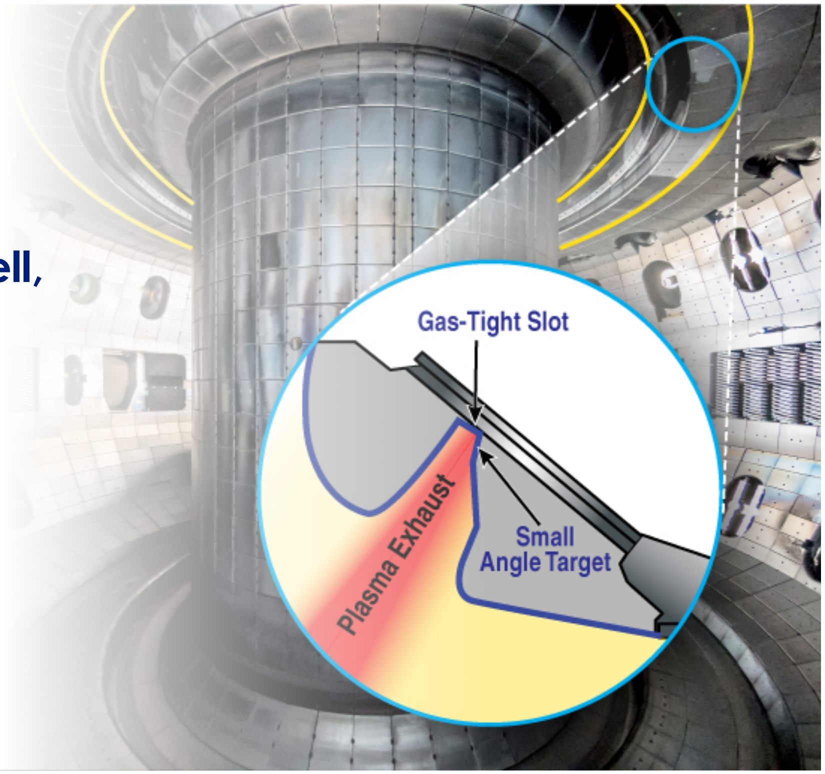

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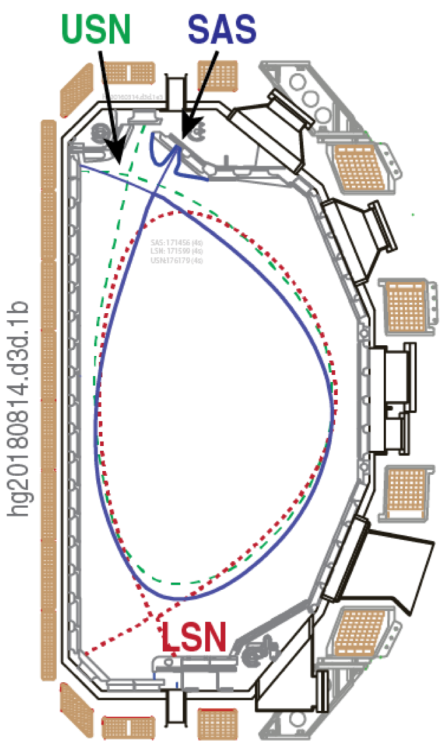
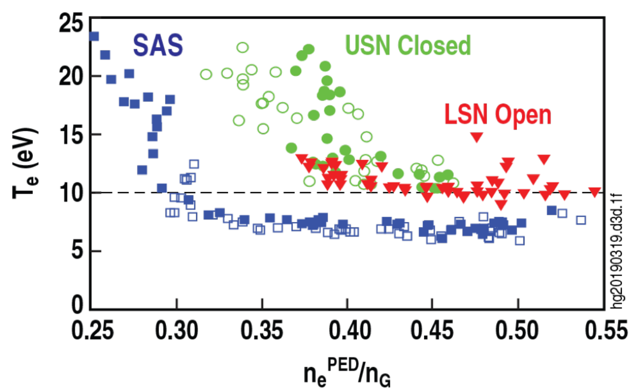
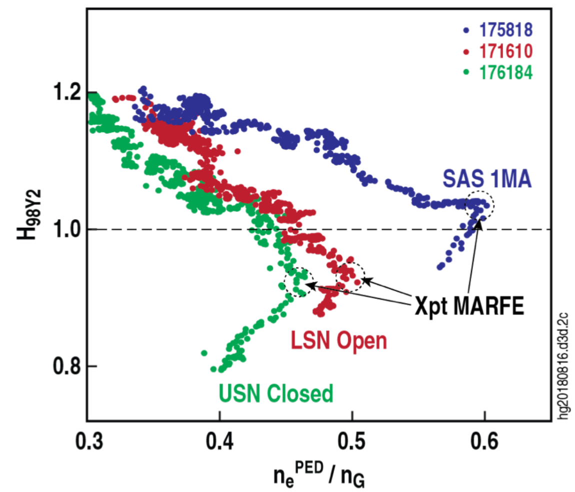
A New Small Angel Slot Divertor Is Being Evaluated on DIII-D for Improving Divertor Dissipation with a High Performance Core







- SAS achieved a dissipative divertor (T_e<10 eV) over a large range of n_e relative to other divertors in DIII-D
- Higher confinement & Xpt MARFE onset at higher n_e for ion $B \times \nabla B$ away from X_{pt} as for advanced tokamaks

Guo, NF 2019

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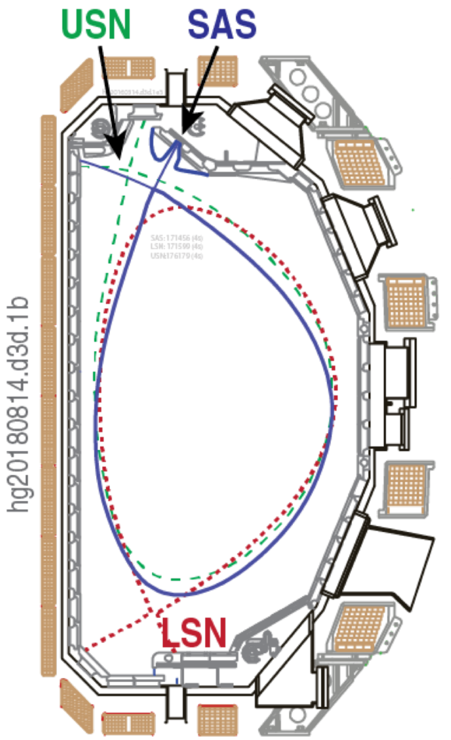

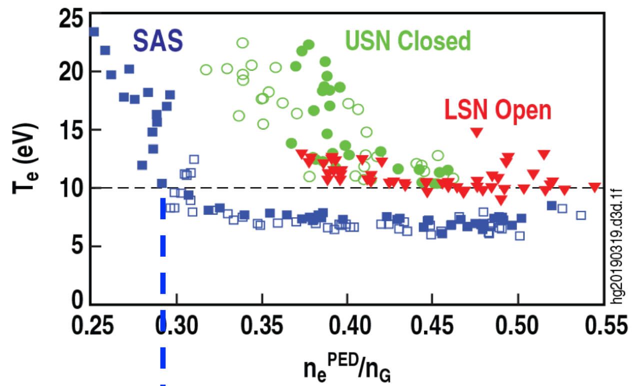

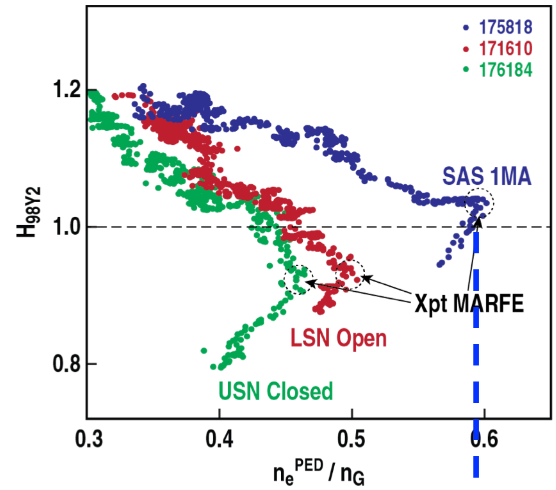

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SAS widens the window of H-mode operation compatible with dissipative divertor conditions

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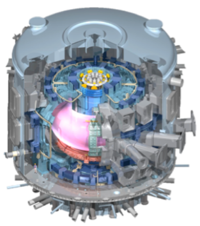
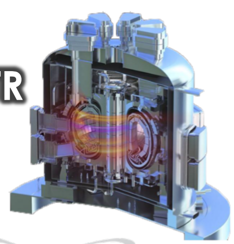
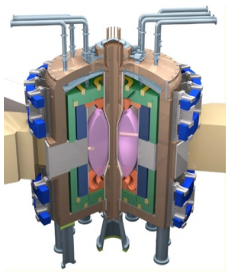
Taming the Plasma-Materials Interface Poses One of the Grand Challenges for Steady-State Fusion

- **Fusion power plants must continuously remove high heat & particle flux**
  - Cannot tolerate erosion of PFCs
  - *Solution goes beyond achievements in present devices or ITER*

Metrics	ITER	CFETR	FNSF
P/R (MW/m)	~20	~20	30~45
B_T (T)	5.3	~5	~5
Pulse length (s)	400	~10^{3-6}	~10^6
n/n_{GW}	~1	~ 0.5-0.7	~ 0.5
β_N	2 – 3	2 – 3	2 – 4







➢ **Requirements**
  - Divertor target load: $q_\perp \leq$ 10-15 MW/m^2
  - Divertor plasma temperature: $T_e \leq$ 5-10 eV
  - Compatibility with high performance fusion core (e.g., n_e/n_G ~ 0.5 for FNSF)

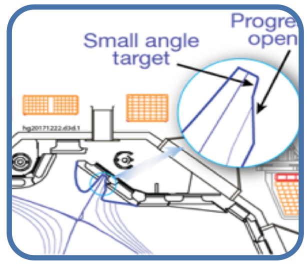
Addressing Power Exhaust in Tokamaks Is Presently Recognized as One of the Major Remaining Open Issues for Fusion Reactors

Major Approaches toward Divertor Optimization

Divertor Heat Flux

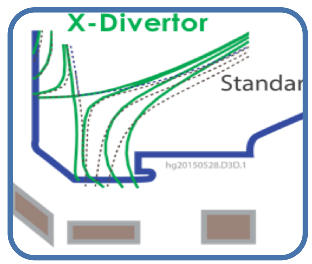
$$q_{target} = \frac{(1-f_{rad})P_{sep}\sin(\theta_{div})}{4\pi\lambda_q f_{exp} R_{st}}$$

(Single-Null Divertor)



Divertor Closure

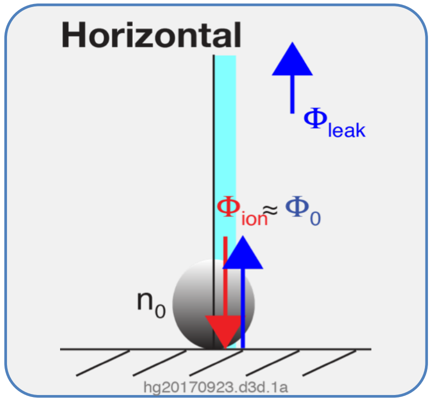
- Making effective use of recycling neutrals to enhance divertor energy & momentum dissipation (f_{rad}, θ_{div})



Magnetic Configuration

- Improve detachment control via increased poloidal flux expansion or toroidal flux expansion (f_{exp}, R_{st}), *such as snowflake, long-leg and super-X divertor.*

Advanced Divertors Require Effective Use of Neutral and Impurity Dissipation Processes



- **Horizontal – Flat target (DIII-D):**

  Direct recycling neutrals toward upstream

  ➠ *strong leakage via both SOL & private flux region*

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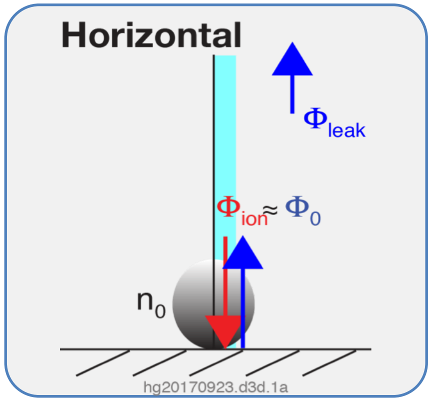

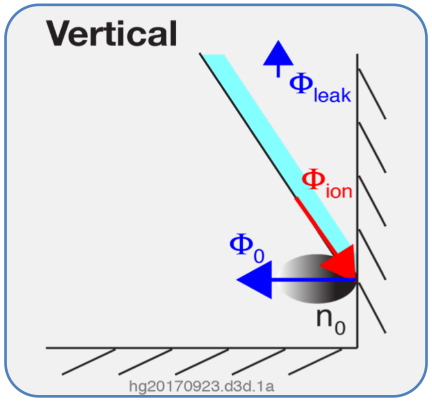

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- **Vertical – Slant target (AUG, JET, ITER):**

  Direct recycling neutrals toward separatrix

  ➠ *reduce SOL leakage and enhance plasma cooling near strike point*

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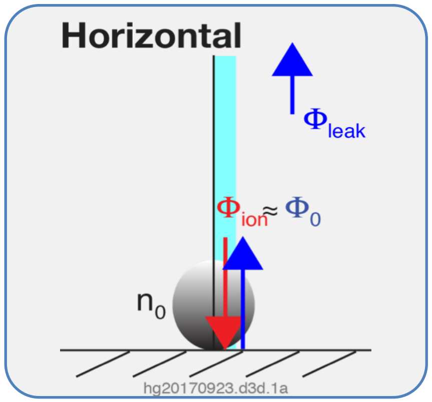

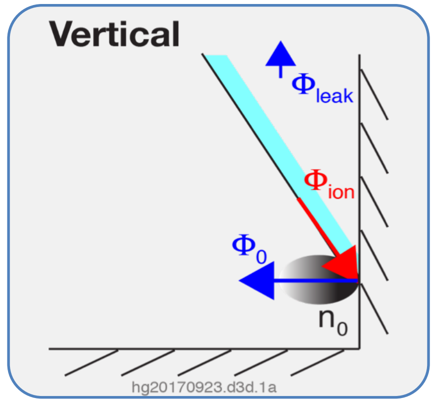

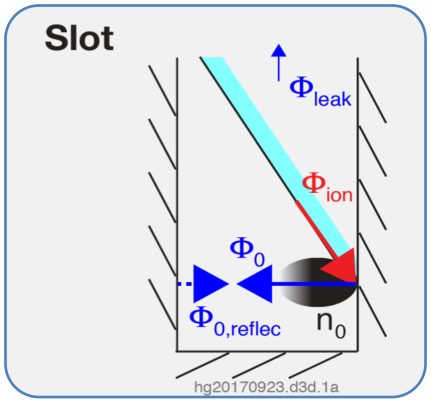

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  ➠ *reduce SOL leakage and enhance plasma cooling near strike point*

- **Basic Slot (C-Mod):**

  Also reduce neutral leakage via private flux region

  ➠ *enhance neutral build-up inside divertor*

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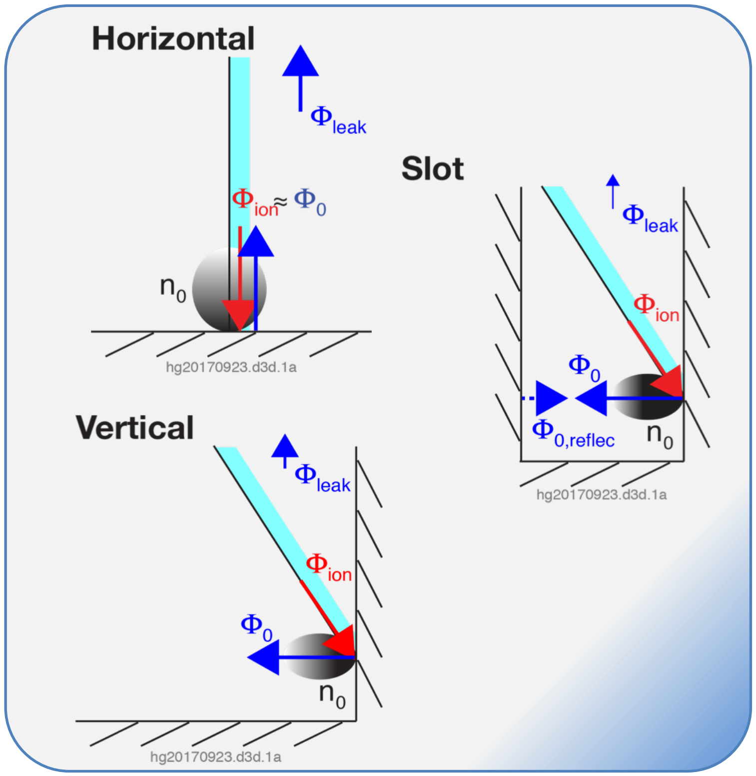
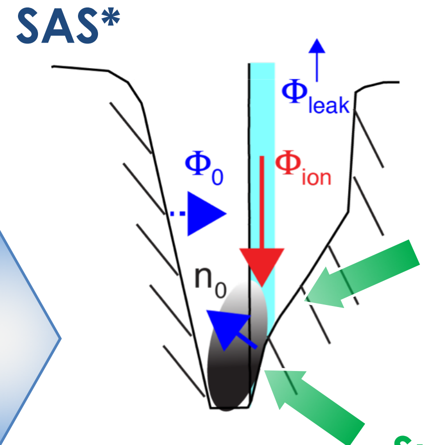
SAS Exploits and Extends a Number of Features of Well-Established Divertor Designs, Leveraging both Divertor Closure and Target Shaping



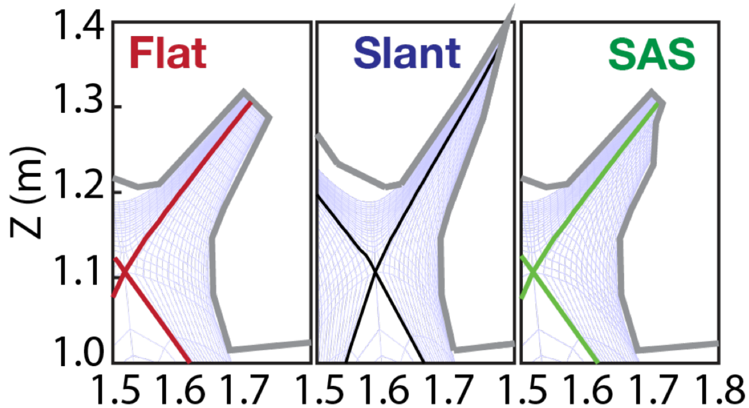


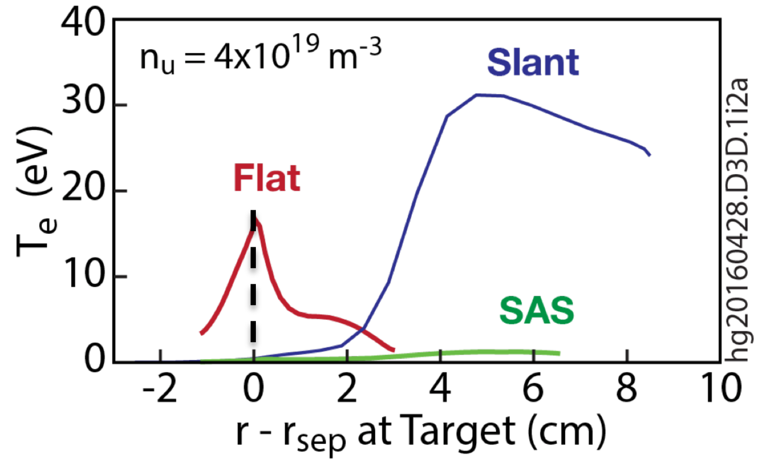
Progressive slot opening toward far-SOL: Spread neutrals in far SOL extending detachment across target

Small target angle in near-SOL: Directs recycling neutrals near the strike point to initiate detachment

***SAS**: Small Angle Slot, also stands for "Slot with Advanced Shaping" ⇒ *JAERI's V-shaped slot which is another example of SAS concept*

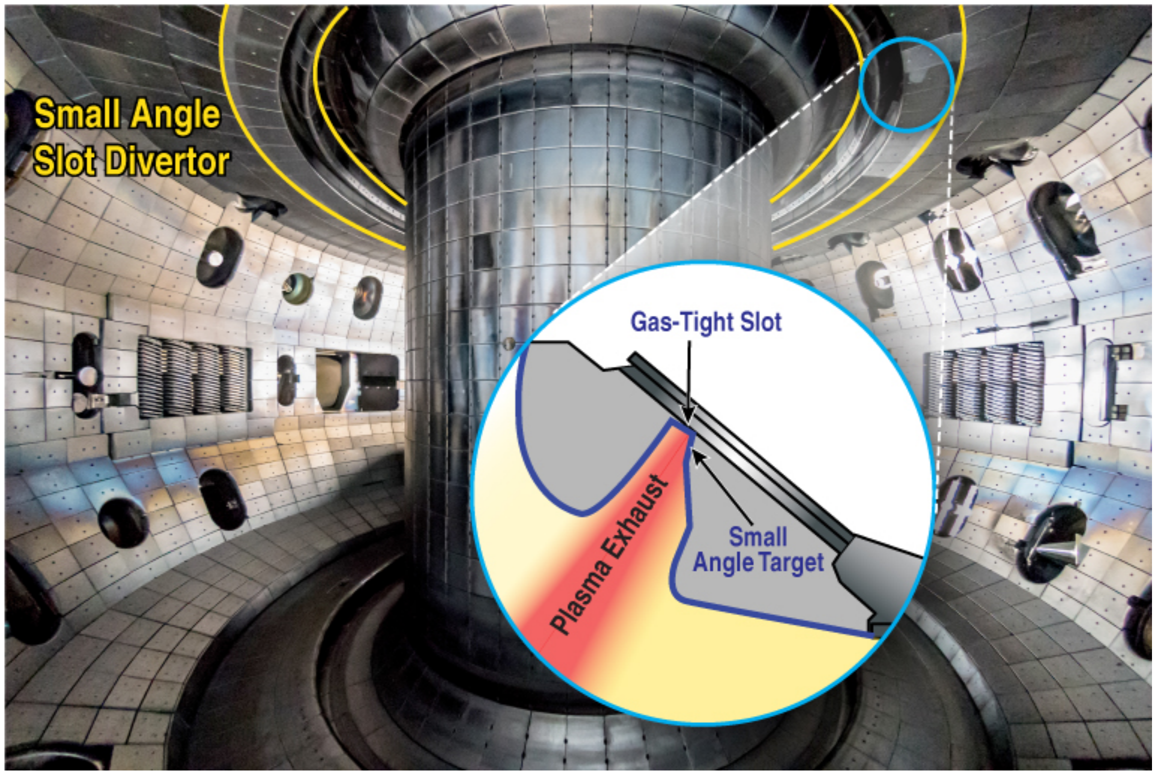
SOLPS Modeling Indicates SAS Should Be Able to Achieve Detachment at Lower Main Plasma Density Than Both Horizontal and Vertical Targets



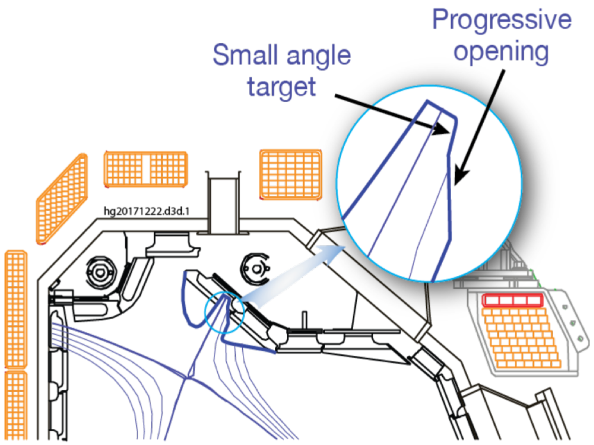


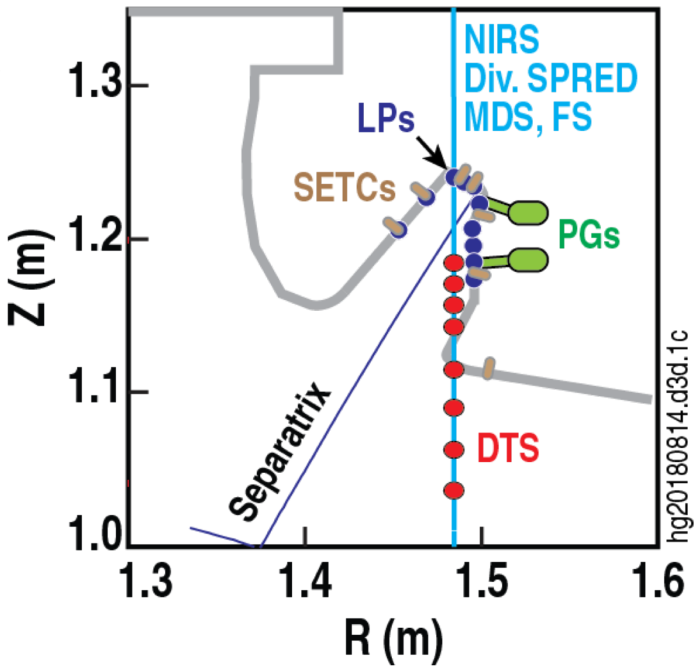
- **Flat target:** T_e remains high near strike point until much higher upstream densities
- **Slant – ITER-like target:** Achieving detachment near strike point at a higher density; and T_e remains high at far target
- **SAS:** Enabling detachment at relatively low upstream n_e; and also low T_e over entire target

A Prototype SAS Divertor Is Being Evaluated on DIII-D to Examine Potential Benefits of Slot Divertor and to Validate Models



SAS Features an Extensive Set of Diagnostics for Quantifying Plasma Behavior inside the Slot





- Langmuir probes
- In-tile pressure gauges
- Divertor Thomson Scattering
- Surface eroding thermocouples
- Spectroscopy

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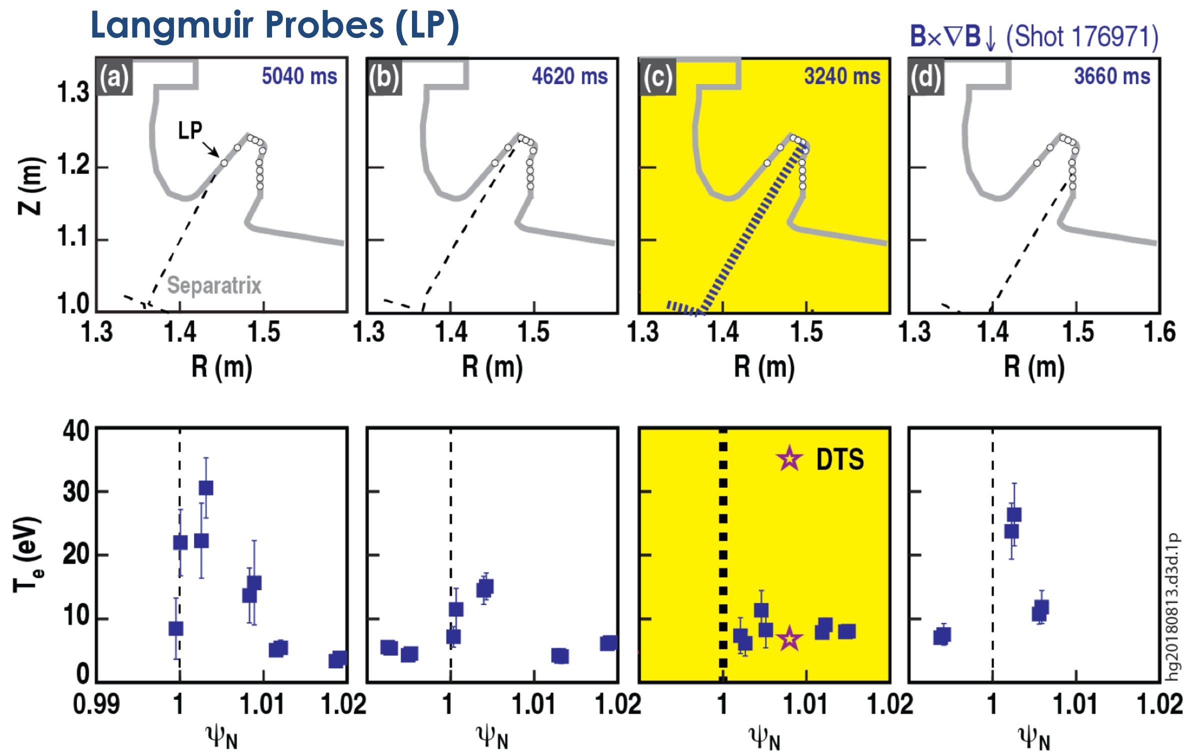
Tests on DIII-D Showed that SAS Can Leverage Geometric Benefits & Effect of Drifts to Facilitate Dissipative Divertor Operation



- **Flat $T_e \lesssim 10\ eV$ when strike point is placed near the outer small angle target for Ion $B\times\nabla B$ Drift away from SAS (LPs and DTS)**

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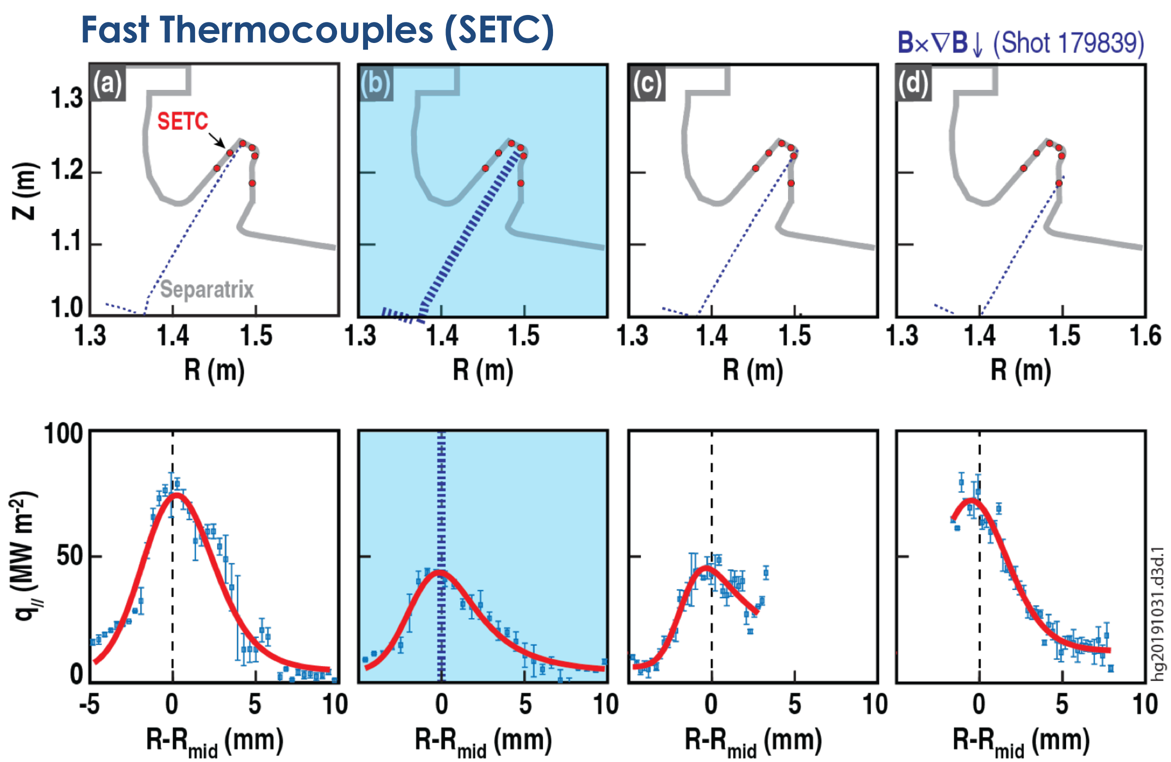

- **Flat $T_e \lesssim 10\ eV$** when strike point is placed near the outer small angle target for Ion $B\times\nabla B$ Drift away from SAS (LPs and DTS)

- **Lower peak $q_{//}$** when strike point is placed near the outer small angle target (Fast thermocouples)

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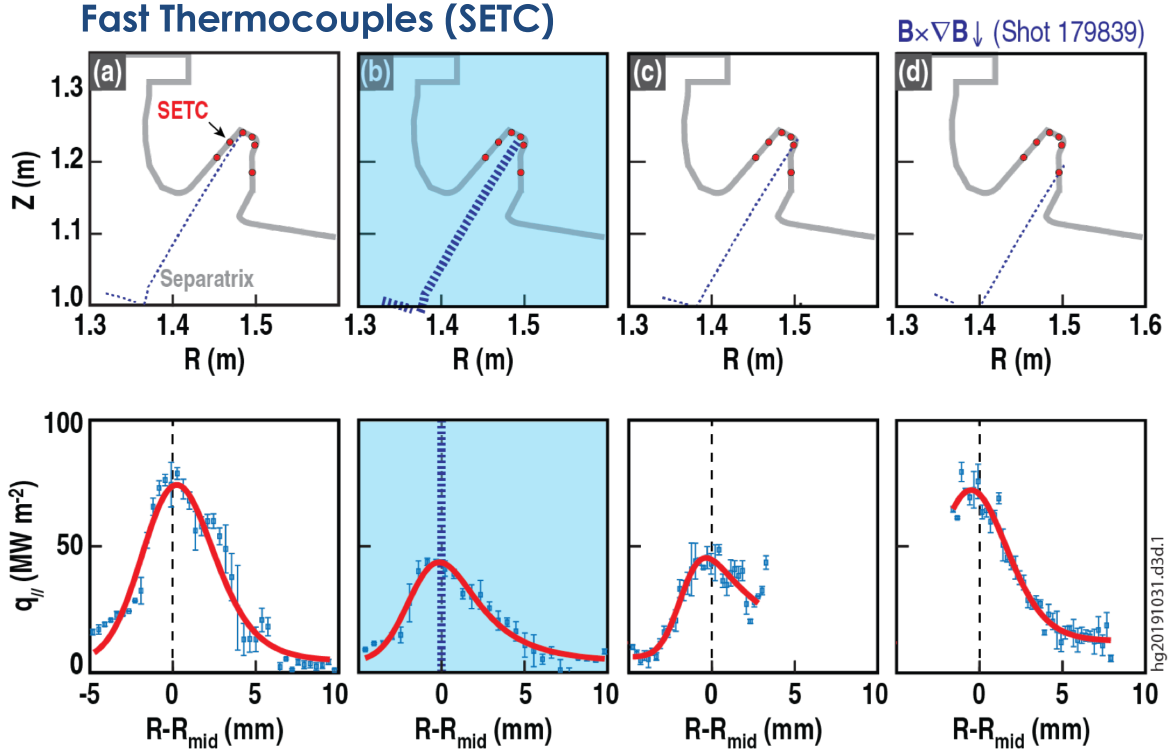
Fast Thermocouples (SETC)



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- **Lower peak $q_{//}$** when strike point is placed near the outer small angle target (Fast thermocouples)

Both divertor closure and target shaping are important for divertor optimization

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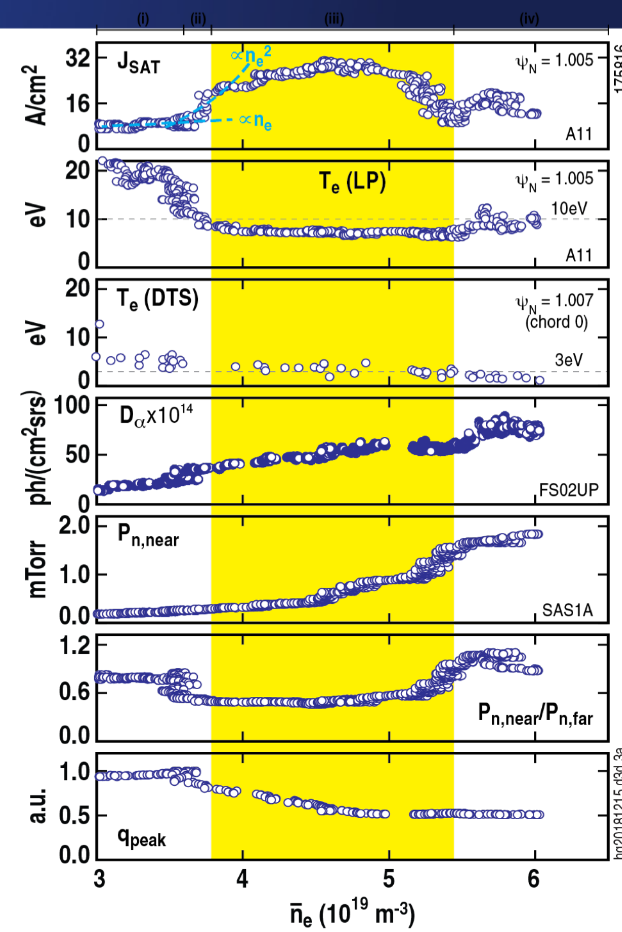
SAS Can Achieve Colder Divertor at Relatively Low Densities with Ion $B\times\nabla B$ Drift Direction away from the Slot

- **Low Recycling Regime**:
  $T_e \gtrsim 20$ eV, $J_{sat} \propto \bar{n}_e$.

- **High Recycling/Dissipative Regime**:
  T_e drops below 10 eV, $J_{sat} \propto \bar{n}_e^2$.

- **Detachment Onset:**
  J_{sat} increases with $\bar{n}_e$ less strongly than quadratically

- **Complete Detachment:**
  involves volume recombination near target at very low T_e



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SAS Appears to Detach at Lower Density Than Matched Open LSN or Moderately Closed USN Divertors with Ion $B \times \nabla B$ Drift away from X-Point

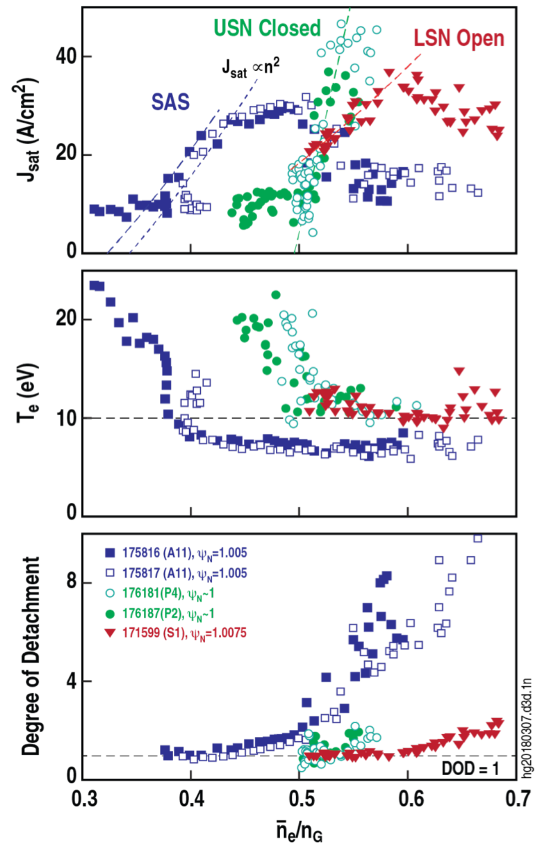
- **SAS: Onset of detachment with Degree of Detachment, DOD > 1, at $\bar{n}_e/n_G$ ~ 0.4 well before rollover-particle-detachment (peaking of J_{sat})**

$$DOD \equiv \frac{J_{sat}^{HRR}}{J_{sat}^{measured}}, \quad J_{sat}^{HRR*} = C\bar{n}_e^2$$

- **LSN/USN: Achieve cold divertor with low T_e < 10 eV near rollover at much higher densities, quickly followed by X-point MARFE**

SAS facilitates H-mode operation with colder divertor for B × ∇B away from the X-point as used for Advanced Tokamaks

*HRR: High Recycling Regime



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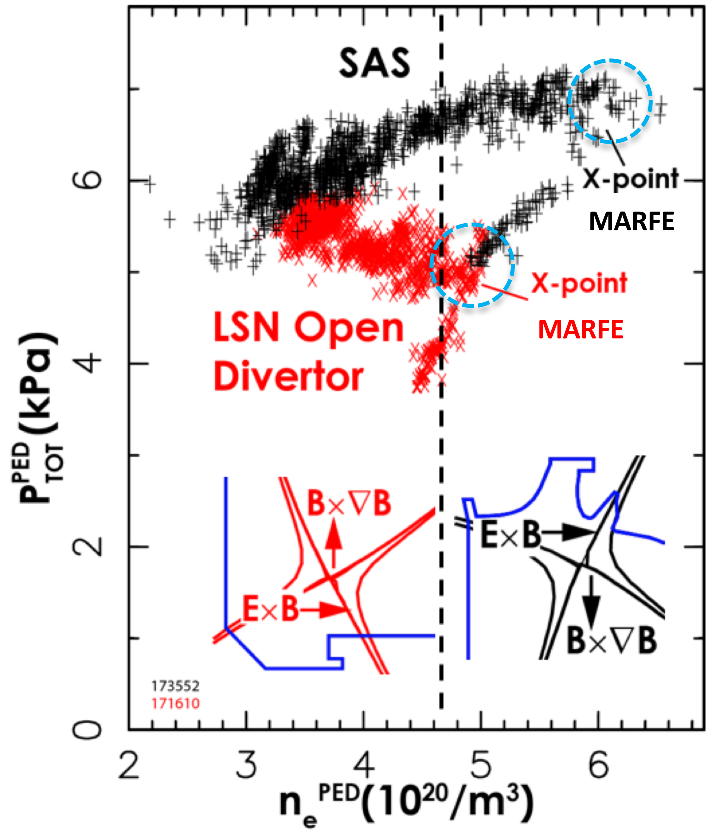
Operation with Ion B×∇*B* Drift away from X-point Significantly Improves Pedestal Performance

- **Pedestal pressure, P_{TOT}^{PED} improves with n_e in SAS but degrades in LSN (Lower Single Null with open divertor)**
- **P_{TOT}^{PED}, typically degrades as density is increased with D_2 puffing**
- **The final pedestal collapse associated with the onset of X-point MARFE occurs at higher pedestal densities.**



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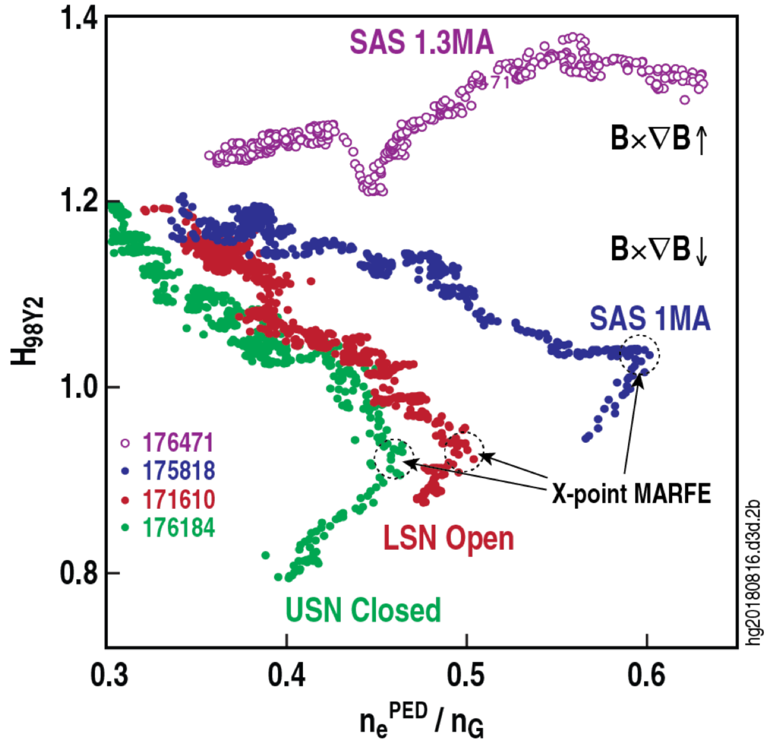
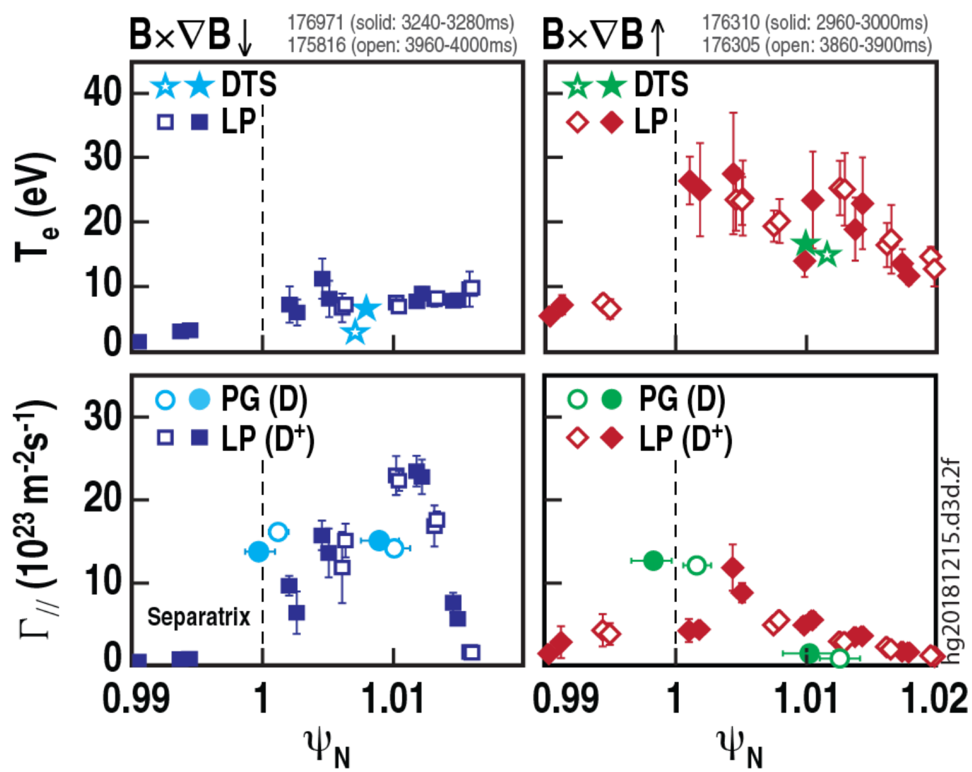
SAS Discharges Show Less Confinement Degradation with Density Increase than More Open Divertor Configurations in DIII-D

- **SAS discharge at I_p=1MA, P_{NBI}=4MW shows less degradation than matched LSN open divertor or USN more closed divertor**
- **Confinement collapse at X-point MARFE onset occurs at significantly higher density in SAS discharge**
- **H_{98} <u>improves</u> with density at 1.3 MA, *B*×∇*B* toward SAS**



Operation with Ion B×∇B Drift toward X-point Offsets the Anticipated Geometric Effects of SAS

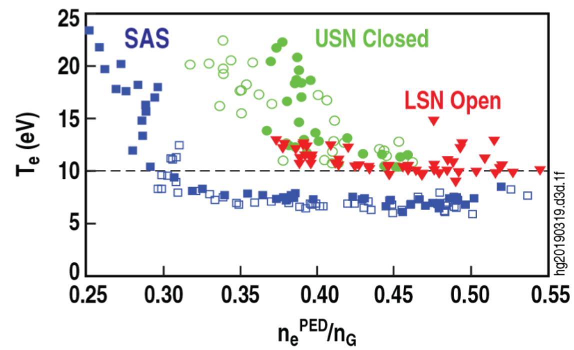
- **B × ∇B away from SAS**:
  - Flat $T_e \lesssim 10\ eV$ across target, when strike point is placed near the outer small angle target
  - Partially detached near separatrix
- **B × ∇B toward SAS:**
  - Significantly higher $T_e \sim 30$ eV, peaked near separatrix
  - Γ_i and Γ_D fluxes also peak near separatrix

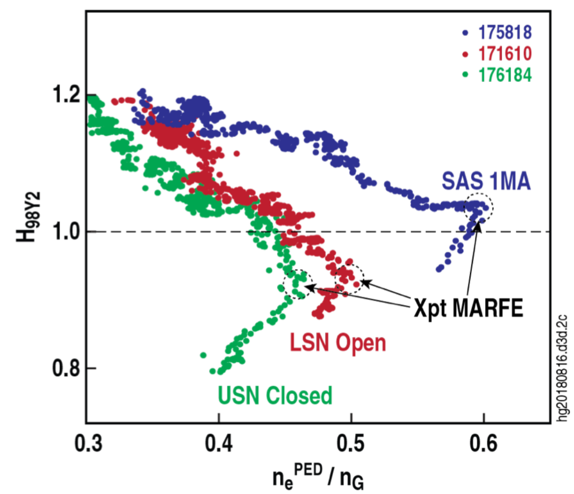


SAS Can Leverage Synergy between Slot Geometry & Drift Effects to Facilitate Integration of High Performance Core w/ Dissipative Divertor

- **SAS demonstrates improved divertor dissipation while maintaining high core performance for ion $B\times\nabla B$ drift away from X-point**
  - *SAS may significantly widen window for AT operation with cold divertor*
- **Initial SOLPS-ITER modeling shows some promising trends consistent with experimental observations**

Pointing to an interesting divertor optimization path to explore that offers potential for future fusion reactors





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