

The Effect of Synergy Between Divertor Geometry and Drifts on Divertor Power Dissipation in the DIII-D Small Angle Slot Divertor

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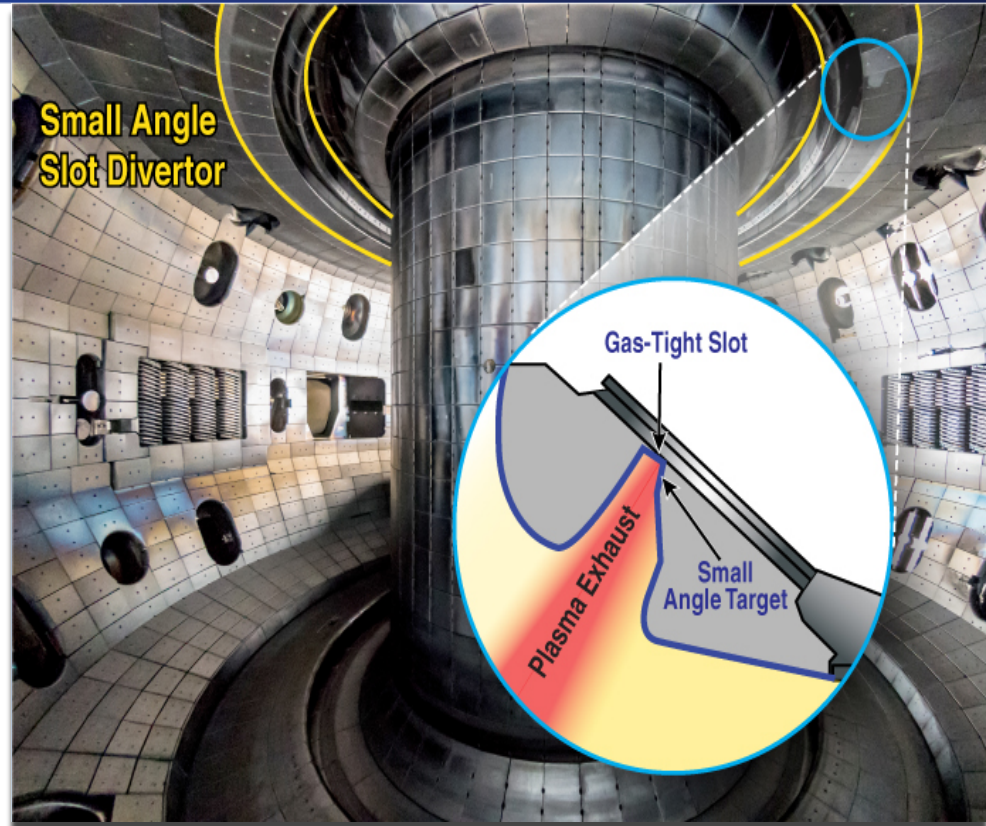
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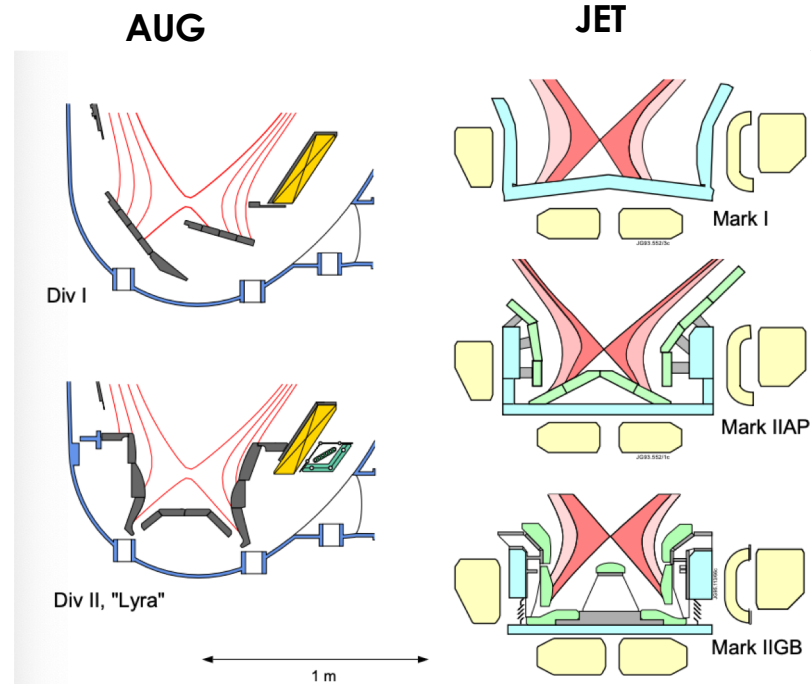
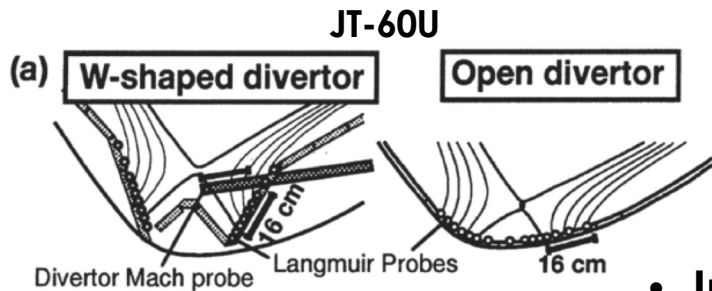
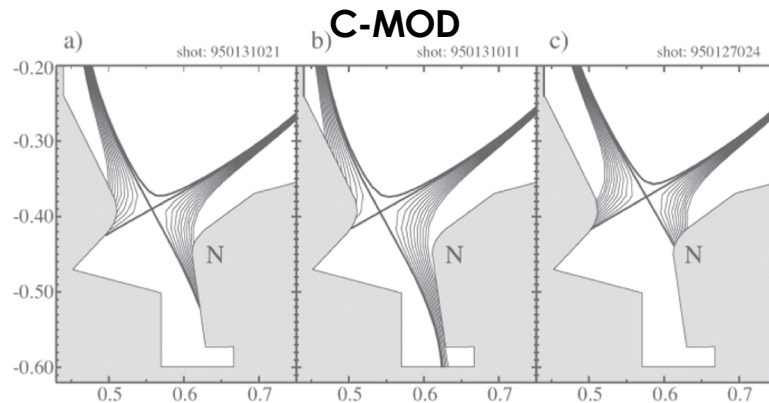
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EX-7/927

Optimizing divertor geometry is a promising way to explore the boundary solution critically for future fusion reactors

- Boundary/PMI will be a critical issue for next-step devices
 - Control of divertor and wall heat and particle load is needed



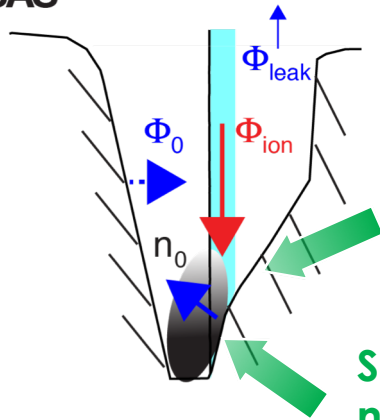
- Increasing divertor closure enhances the divertor neutral trapping and divertor recycling
 - Facilitate the achievement of divertor detachment

Leonard PPCF 2018; Asakura JNM 1997; Lipschultz FST 2007; Kallenbach NF 2009; Loarte PPCF 2001

SAS is motivated to enhance power dissipation through concentrating particles to high heat flux regions with advanced target shaping

SAS: Small-angle-slot divertor

SAS



Progressive slot opening toward far-SOL: reflects neutrals into the near-SOL extending dissipation across target

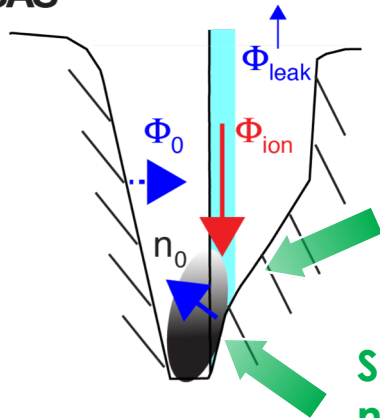
Small target angle in near-SOL: directs recycling neutrals to the strike point, enhance dissipation

Guo NF 2017; Sang PPCF; Guo NF 2019

However, divertor drift flows could alter divertor recycling and significantly affect the divertor behaviors

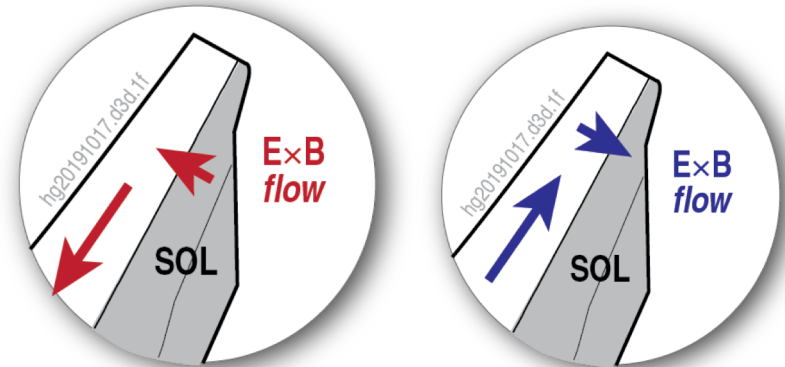
SAS: Small-angle-slot divertor

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Progressive slot opening toward far-SOL: reflects neutrals into the near-SOL extending dissipation across target

Small target angle in near-SOL: directs recycling neutrals to the strike point, initiating detachment



➤ Strong divertor $E \times B$ drift flow in H-mode plasmas

- $E_r \sim 3\nabla T_e \sim 3T_e/\lambda_{qf_x}$
- $E_\theta \sim f(\nabla_{//}T_e, \nabla_{//}P_e, J)$

• Poloidal drift flow comparable with recycling flow: $E_r/B \sim C_s B_\theta/B$

Radial drift flow comparable or dominant than diffusion flow at dissipative divertor

Guo NF 2017; Sang PPCF; Guo NF 2019

Jaervinen NME 2019; Boedo PoP 2000; Chankin JNM 1997

However, divertor drift flows could alter divertor recycling and significantly affect the divertor behaviors

SAS: Small-angle-slot divertor

SAS



Progressive slot opening



- The interplay between divertor drift flows and geometry plays important roles on the divertor dissipation
 - Drift could offset the geometrical effects to either enhance or reduce divertor dissipations
 - Geometry+drift change the trajectory of divertor dissipation

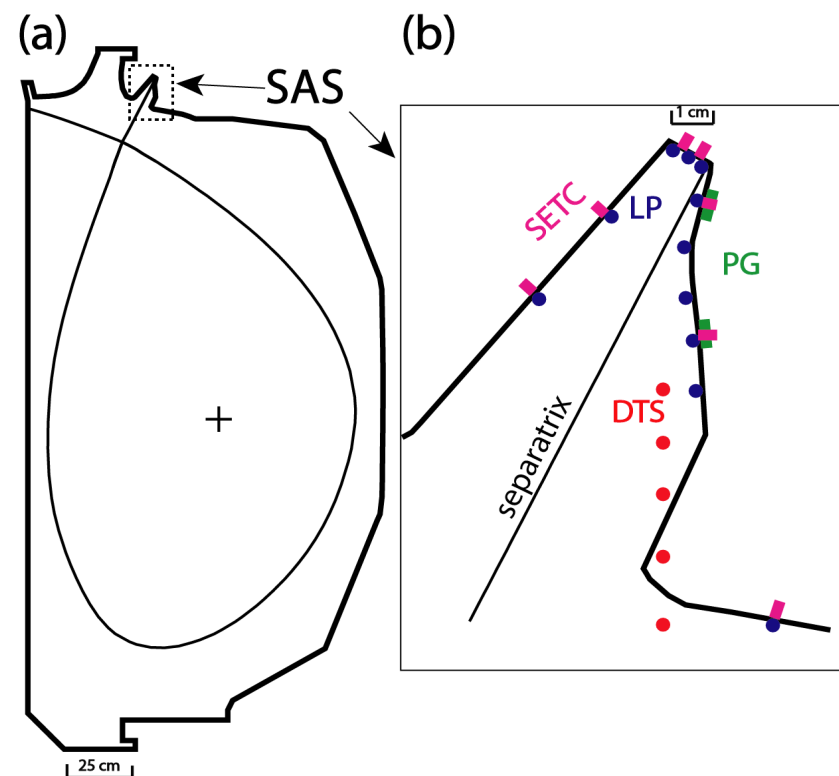
$$L_{\theta}^{-1}(V_{\parallel}/V_e, V_{\parallel}/V_e, J)$$

- Poloidal drift flow comparable with recycling flow: $E_r/B \sim C_s B_{\theta}/B$
- Radial drift flow comparable or dominant than diffusion flow at dissipative divertor

Guo NF 2017; Sang PPCF; Guo NF 2019

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A compact small-angle-slot divertor was installed in DIII-D as a testbed for exploration of divertor solutions

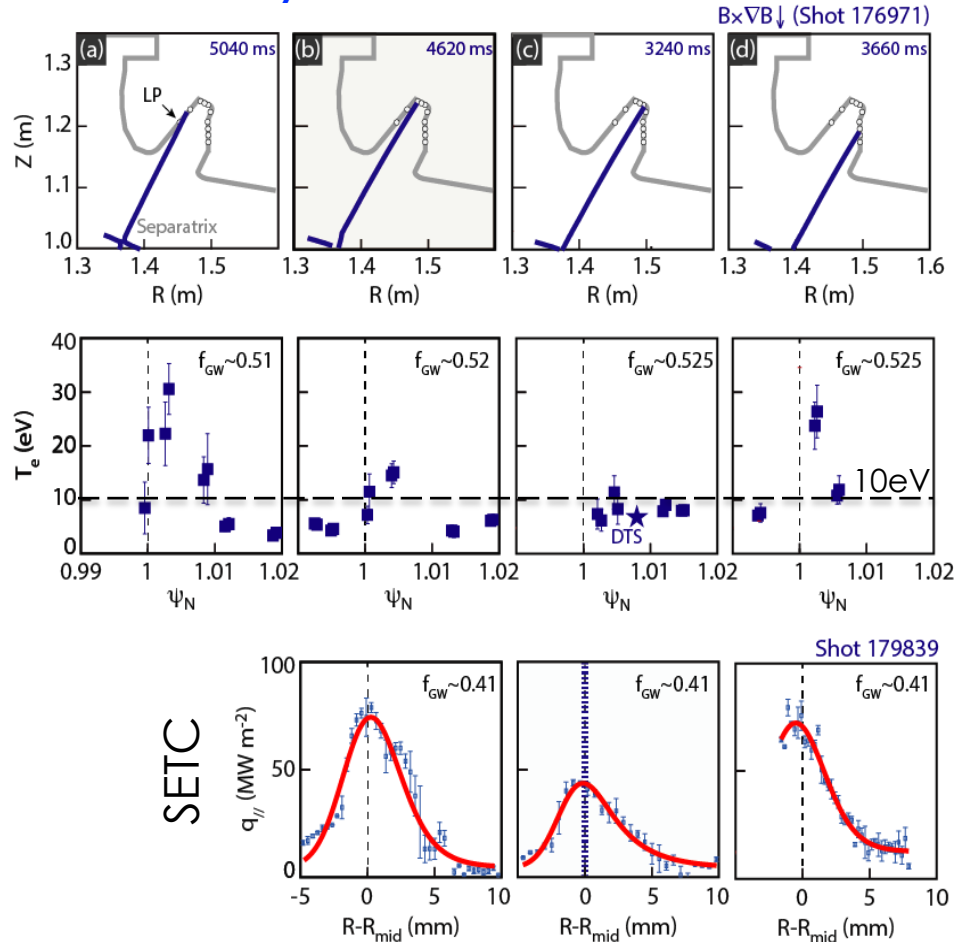


Watkins NME 2019; RSI 2020; Shafer NME 2019;
Ren RSI 2020; Guo NF 2019; Moser APS 2020

- Small tile changes → compact SAS
- Systematical divertor diagnostics suite
 - LP, DTS, PG, SETC
- Main experimental approaches
 - 4MW, 1MA H-mode plasmas
 - Changing/sweeping the strike point
 - Density ramping up for detachment
 - Reversing B_T to change divertor drift flow for studying drift effects
- SOLPS-ITER simulations with full drifts for Experiment-model validation and further detailed physics study

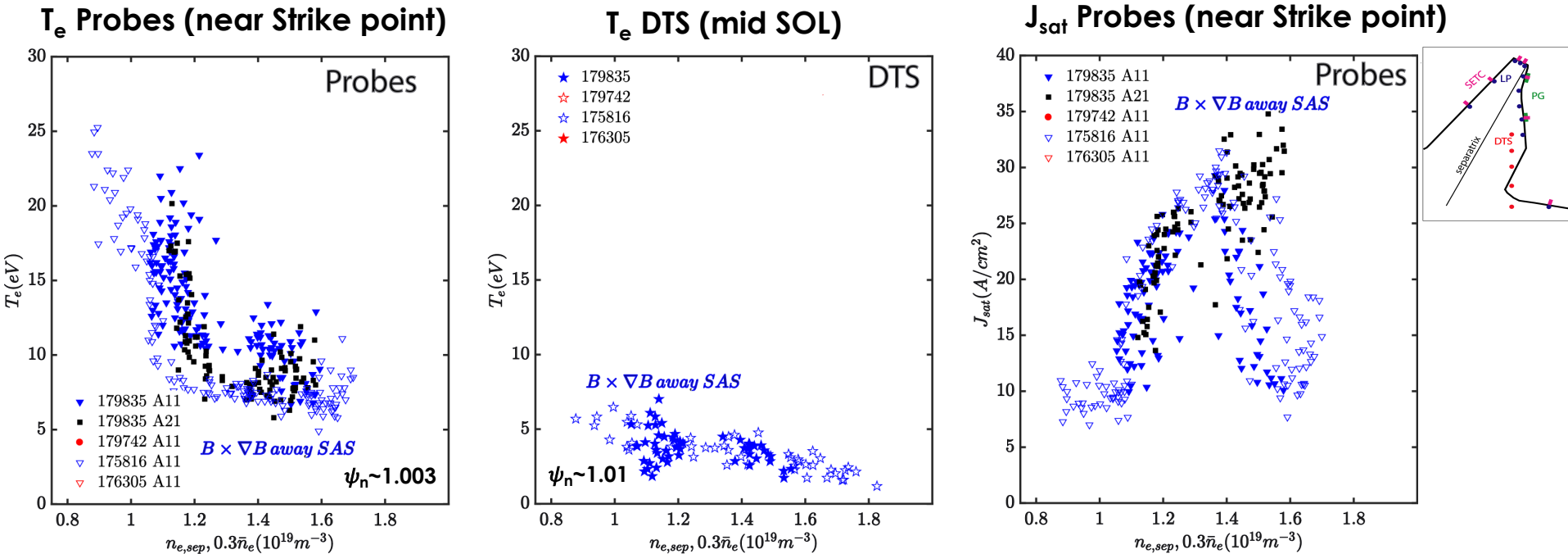
Optimal strike point location at outer corner with low T_e and heat flux was identified in experiment

$B \times \nabla B$ away from SAS



- **Strike point sweeps at fixed density**
- **When SP @ outer corner, flat and low $T_e \sim 10\text{eV}$ across divertor target**
 - Desired for material erosion control
- **Also low heat flux measured by both LP and SETC**
 - Same for another B_T direction
- **3x higher T_e and 2x higher heat flux when SP at slanted target**
 - Geometry effects
 - Neutral less concentrated at peak heat flux region

With Ion $B \times \nabla B$ Drift away Xpt, low T_e is achieved at low main plasma densities



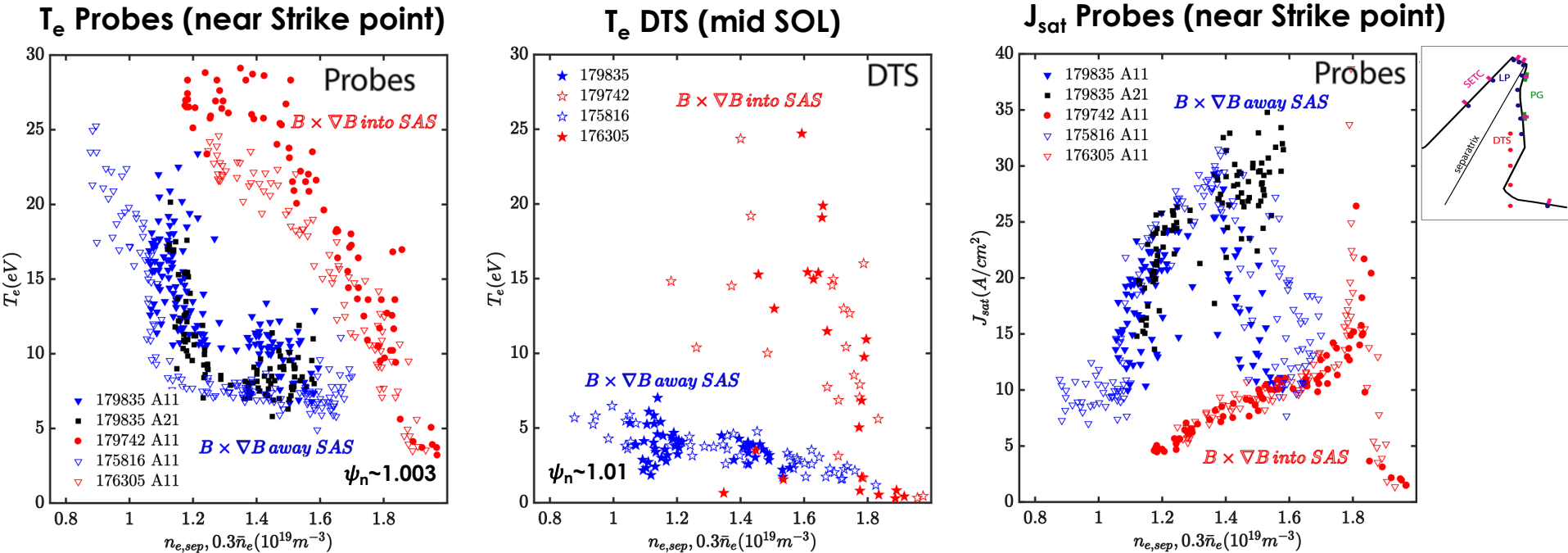
➤ Low $T_e < 10$ eV for both near strike point and mid SOL measurements

- But not deep detachment and not strong molecular recombination

➤ J_{sat} rollover occurs higher density

- J_{sat} rollover $\rightarrow$ particle and momentum loss

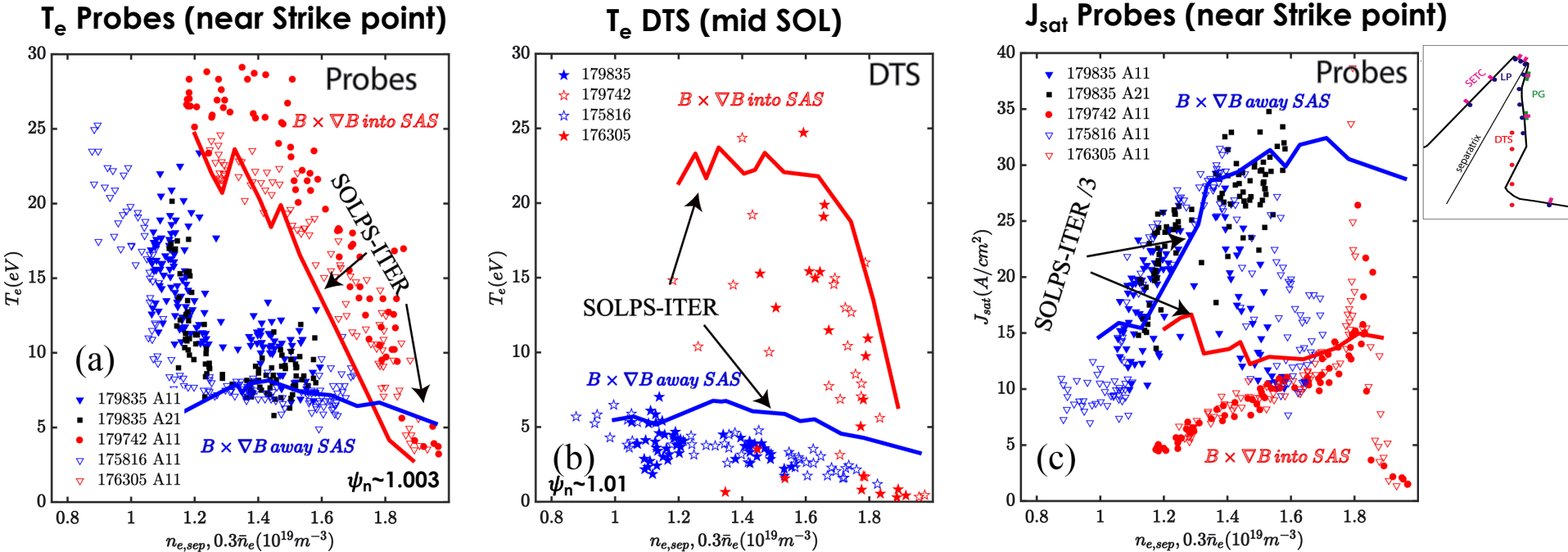
However, **Ion $B \times \nabla B$ Drift toward Xpt** offsets geometric effects $\rightarrow$ Requiring higher density to achieve low T_e



➤ **Divertor plasma remains hot near the SP throughout SOL until detachment onset at high density, ($n_{e,sep} \sim 1.75 \times 10^{19} m^{-3}$)**

- Different T_e -transition density from that at open divertor: $\sim 10\%$ between different B_T
- Strong detachment with low $T_e < 5 eV$ and low J_{sat} can be achieved

SOLPS-ITER simulations with full drifts reproduces the similar trends in experiments

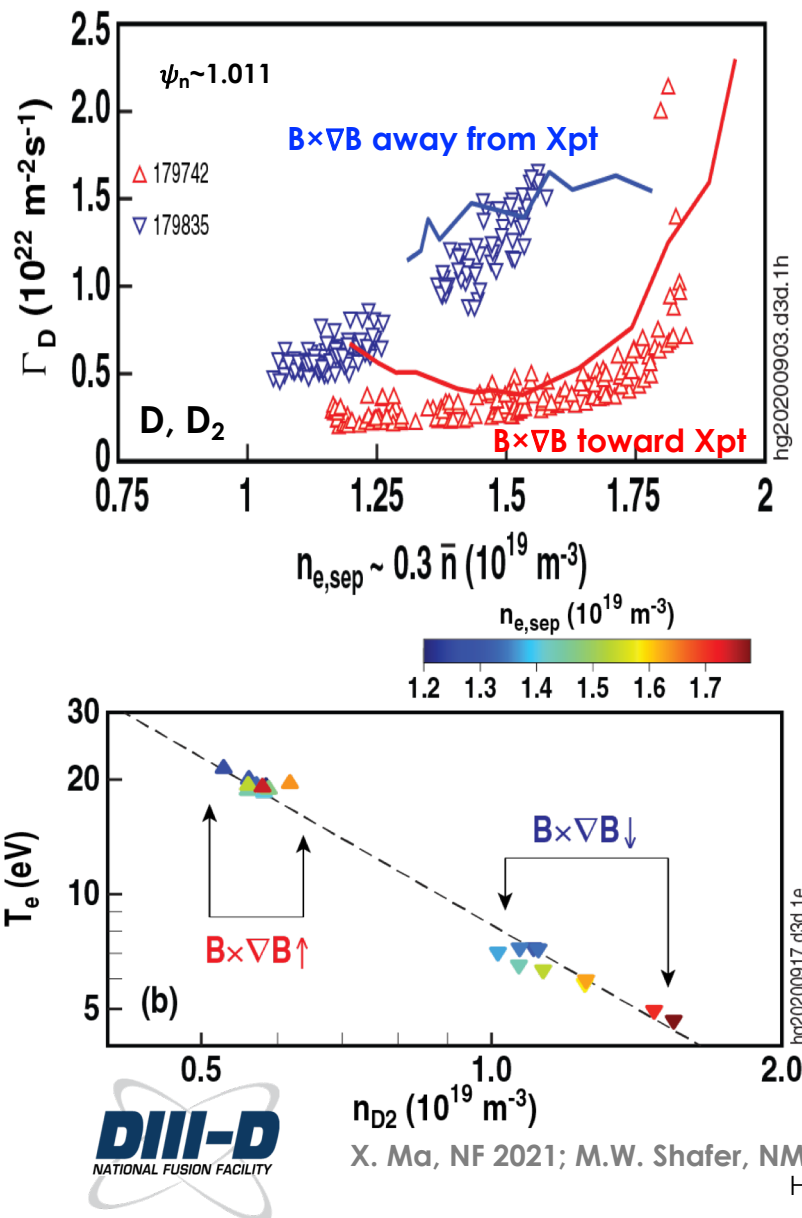


➤ Assuming $n_{e,sep} \sim 0.3 n_e$, for matching the experiment and simulations

➤ SOLPS simulations with drifts overestimates the particle flux by 3x

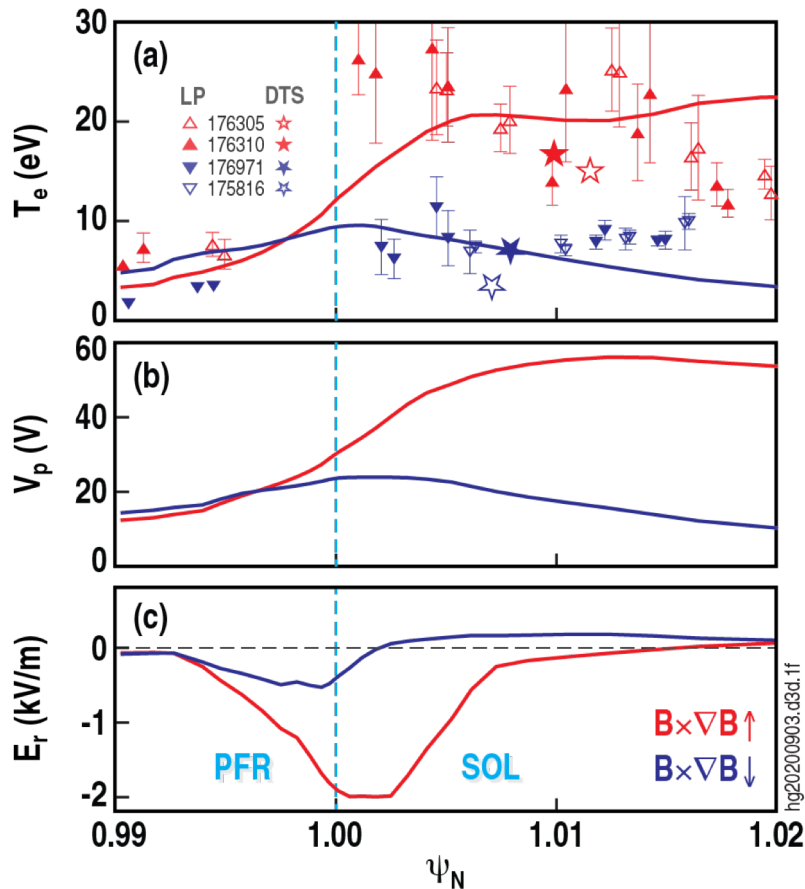
- May relate to -- constant divertor transport $D\&\chi$, radiation shortfall
- Recent simulations with matched profiles shows similar behavior and better agreement

Divertor conditions are consistent with neutral behavior, with quantitatively consistent simulations and experiments



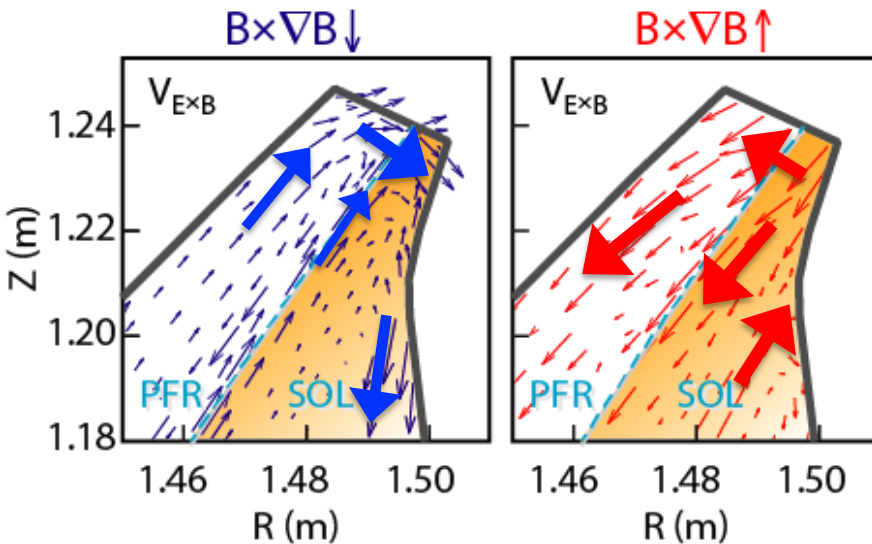
- **Neutral flux in the SOL for the other B_T is much (2X) smaller up to deep detachment**
 - Previous modeling without drift shows one order of magnitude higher neutral flux → **significance of drifts**
- **Neutral recycling and behaviors could be strongly affected by the flows and geometry**
 - Found in both experiments and simulations

Simulations suggest strong coupling between the 2-D drift flows and divertor geometry



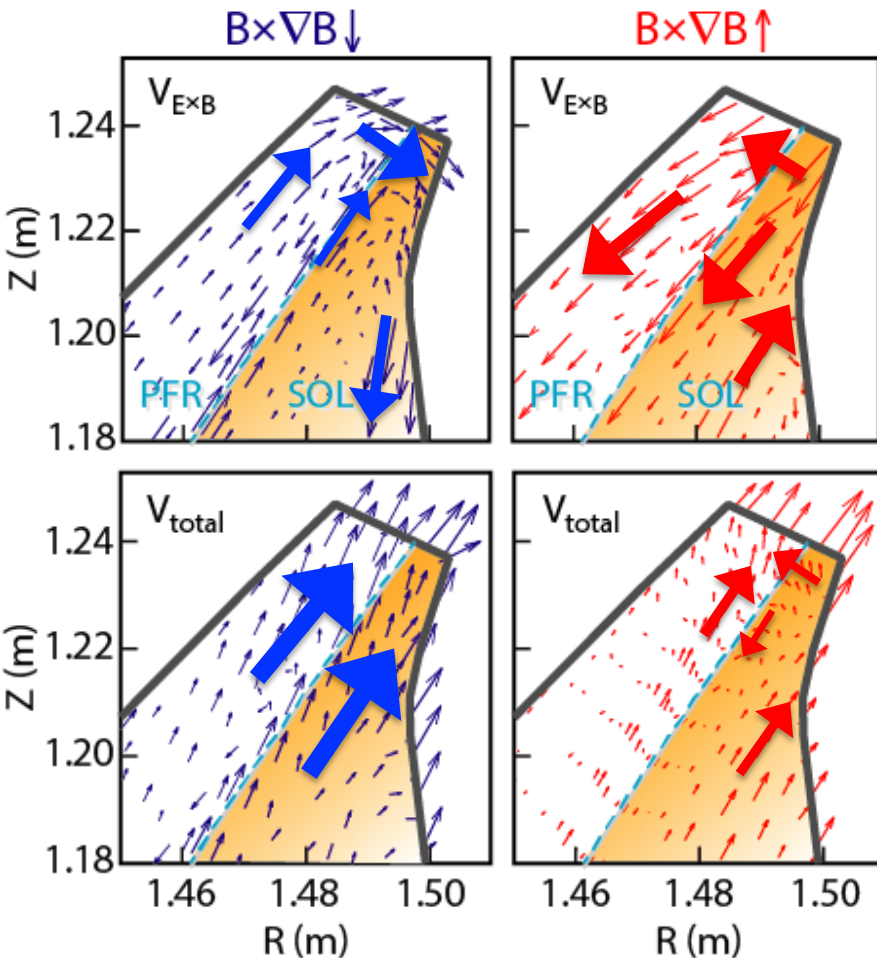
- Simulations show similar profiles features observed in experiments
- **$B \times \nabla B$ away from Xpt: Low and flat T_e**
 - Small T_e radial gradient $\rightarrow$ Small E_r
 - Large T_e parallel gradient $\rightarrow$ Large E_θ
- **$B \times \nabla B$ toward Xpt: High T_e across separatrix**
 - Strong T_e radial gradient $\rightarrow$ Strong E_r
 - Medium T_e parallel gradient $\rightarrow$ Med E_θ

Simulations suggest strong coupling between the 2-D drift flows and divertor geometry



- Simulations show similar profile features observed in experiments
- $B \times \nabla B$ away from Xpt: Low and flat T_e
 - Small T_e radial gradient $\rightarrow$ Small E_r
 - Large T_e parallel gradient $\rightarrow$ Large E_θ
 - PFR $E_r \times B$ moves particles to outer div.
 - Radial $E_\theta \times B$ moves particles towards SOL
 - $\rightarrow$ High flux and low T_e
- $B \times \nabla B$ toward Xpt: High T_e across separatrix
 - Strong T_e radial gradient $\rightarrow$ Strong E_r
 - Medium T_e parallel gradient $\rightarrow$ Med E_θ
 - $E_r \times B$ moves particles away from SOL
 - $E_\theta \times B$ moves particles from SOL to PFR
 - $\rightarrow$ Low flux and high T_e
- Both are positive feedbacks driving divertor plasma away or closer to detachment

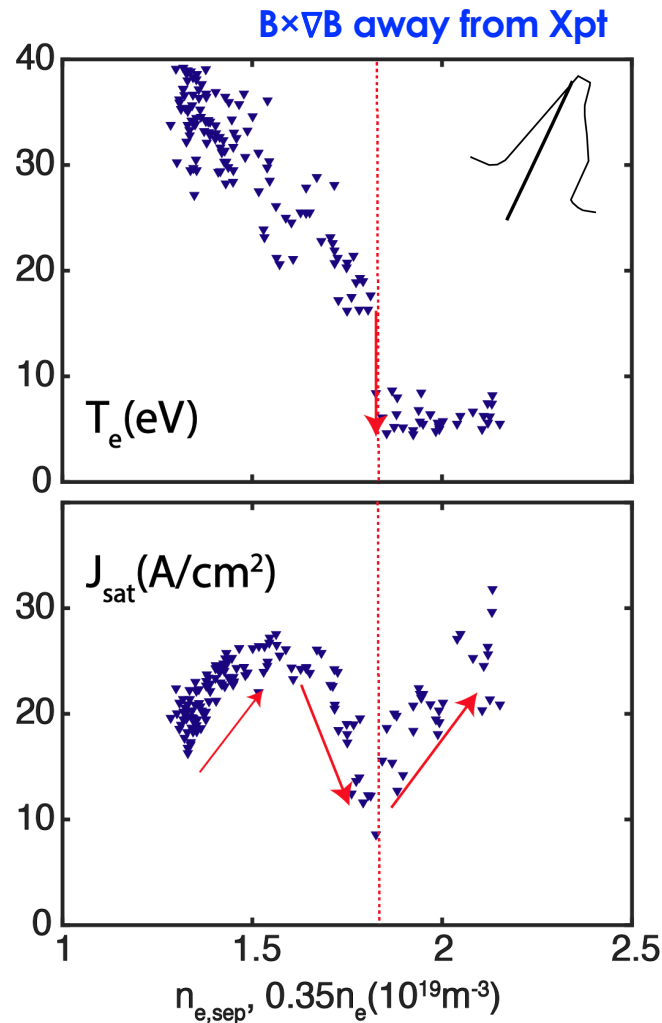
Simulations suggest comparable amplitude between drift flows and main plasma flow



X. Ma, NF 2021

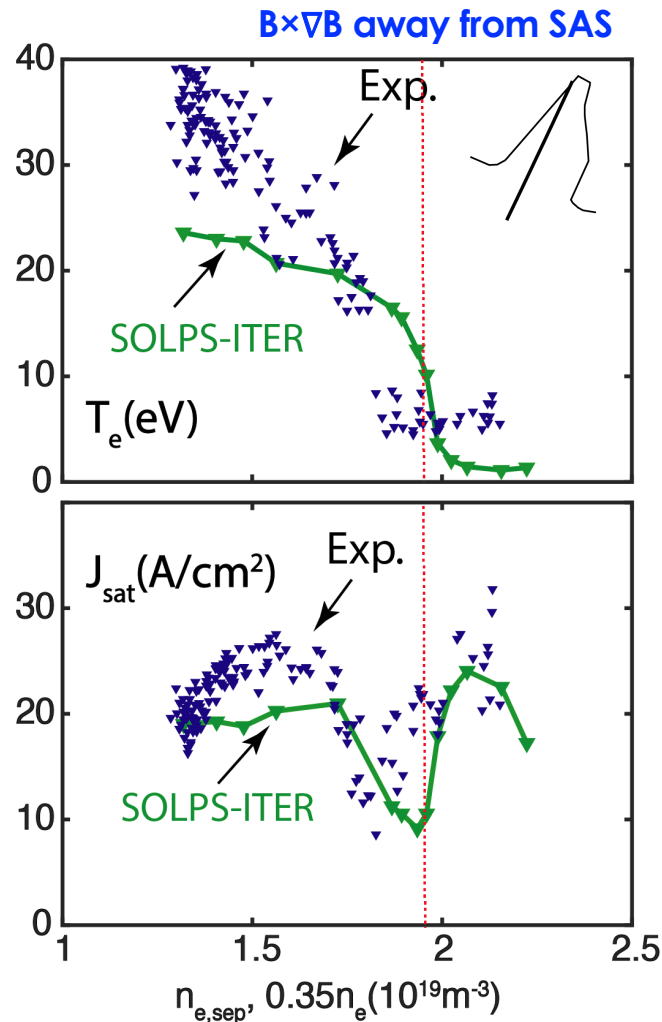
- Total flow V_{total} includes drift flow, poloidal projection of parallel flow, diffusion flows
- $B \times \nabla B$ away from Xpt: Low and flat T_e
 - ExB drift flow same direction as main plasma flow $\rightarrow$ larger total flow
- $B \times \nabla B$ toward Xpt: High T_e across separatrix
 - ExB drift flow opposite direction as main plasma flow $\rightarrow$ weaker total flow
 - Even reversal near the strike point
 - $E_r/B \sim C_s B_\theta/B$

The coupling between drift and geometry could alter the path towards divertor detachment



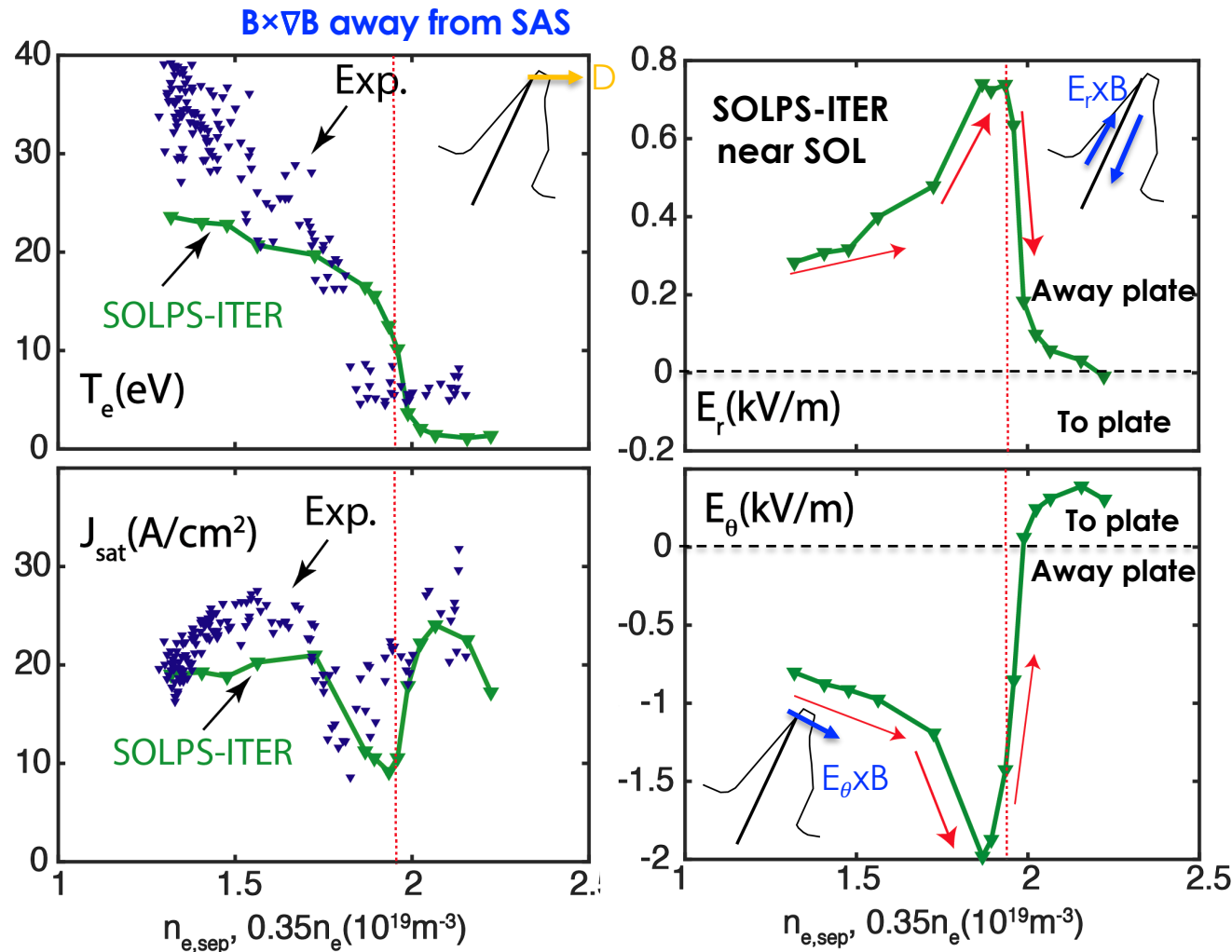
- **T_e -cliff-like transition for $B \times \nabla B$ away from Xpt, for strike point at the slanted target**
 - With open divertor, T_e cliff only found with $B \times \nabla B$ into divertor
- **Inner slant exhibits higher T_e till detachment**
 - Slanted target directs the neutral away the SP
- **Particle flux shows up-down-up trend**
 - J_{sat} dip at high T_e

The coupling between drift and geometry could alter the path towards divertor detachment



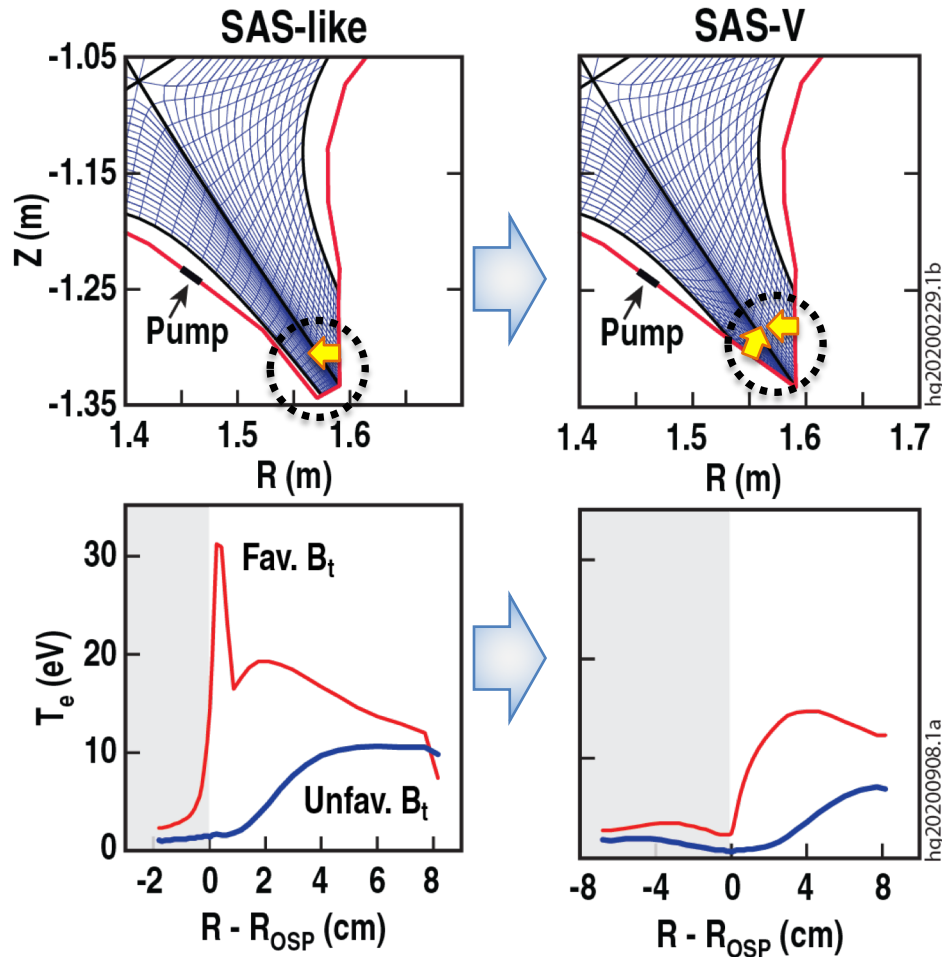
- **T_e -cliff-like transition for $B \times \nabla B$ away from X_{pt} , for strike point at the slanted target**
 - With open divertor, T_e cliff only found with $B \times \nabla B$ into divertor
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 - Slanted target directs the neutral away the SP
- **Particle flux shows up-down-up trend**
 - J_{sat} dip at high T_e
- **SOLPS-ITER simulations reproduce similar trend for both T_e and particle flux**
 - Match upstream profiles but constant div. D, χ
 - Better agreement compared to previous
 - Not fully reproduce T_e -cliff yet

The evolution of particle flux strongly correlates with the dynamics of divertor drift flows near target plate

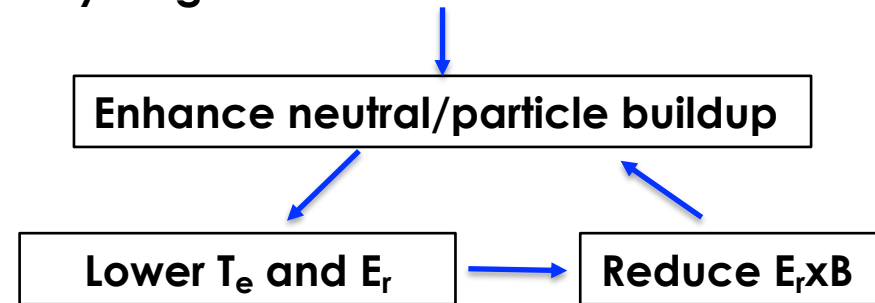


- Drift is amplified by strong gradient between slant and slot
- J_{sat} dip correlates to peak drift flows
- 50% J_{sat} change confirms the equal importance of drift flow and main flow
- Reduction or reversal of drift flows $\rightarrow$ particle accumulations at SP $\rightarrow T_e$ -cliff-like reduction

Implications: optimize the target shaping to manipulate ExB drifts to improve detachment for both B_T directions

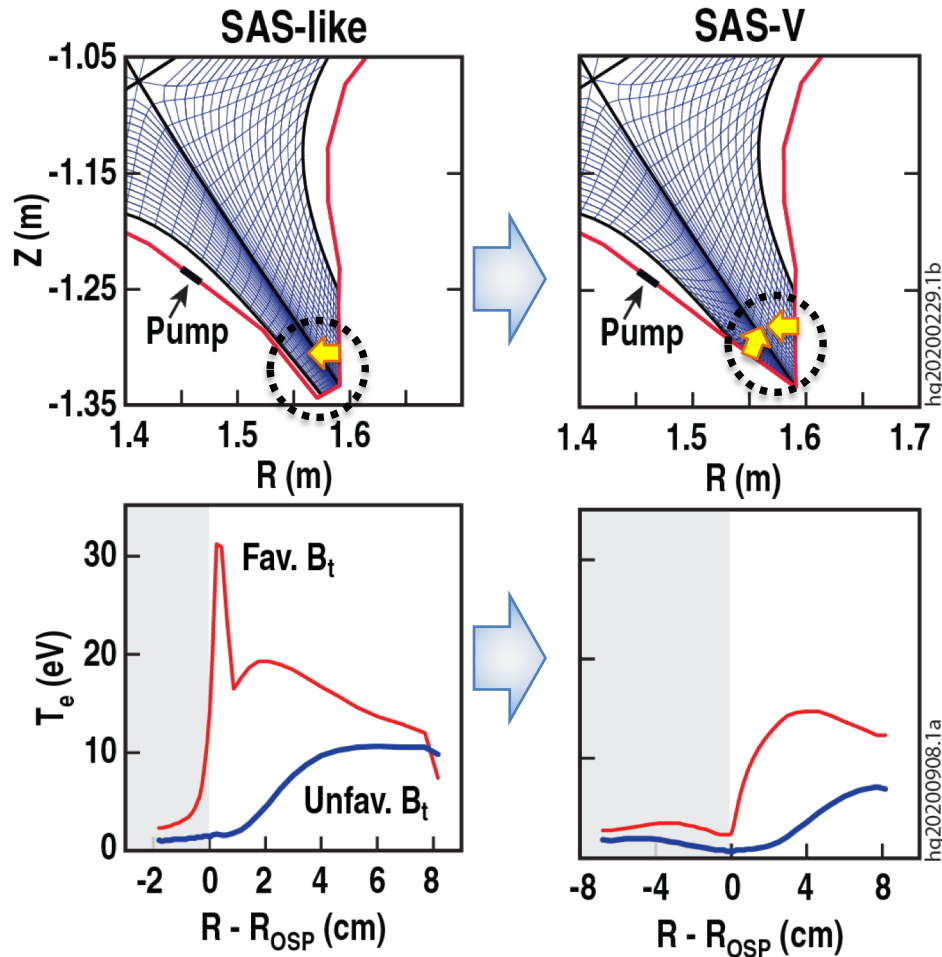


- SAS-V: Slanted surface in the PFR directs recycling flux towards the common SOL



- SAS-V: Low T_e in both B_T directions

DIII-D plans to test SAS-V concept to further investigate the interplay between drifts and geometry



- SAS-V: Slanted surface in the PFR directs recycling flux towards the common SOL

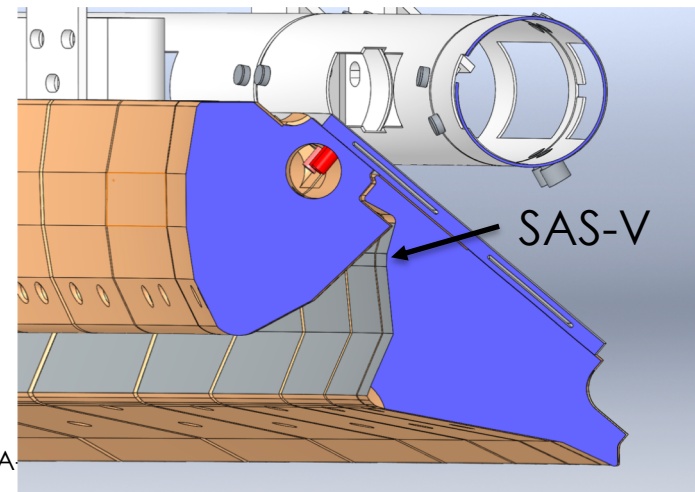
Enhance neutral/particle buildup

Lower T_e and E_r

Reduce $E_r \times B$

- SAS-V: Low T_e in both B_t directions

- DIII-D SAS-V: Further model validation, impurity transport in closed divertor, core-edge integration



Summary

- **DIII-D SAS divertor provides a good opportunity for model validation and exploration of divertor solution**
- **The interplay between divertor drift flows and geometry plays important roles on the divertor dissipation**
 - Drift offsets the geometry effects to either enhance or reduce the anticipated geometric effects
 - Geometry+drift alters the trajectory of divertor dissipation
- **The coupling between drift and geometry needs to be taken seriously into account in future divertor design, in particular for fusion reactors**
 - High power and high current in reactors may strongly enhance divertor drift flows

Thank you for your attentions!!

