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

by
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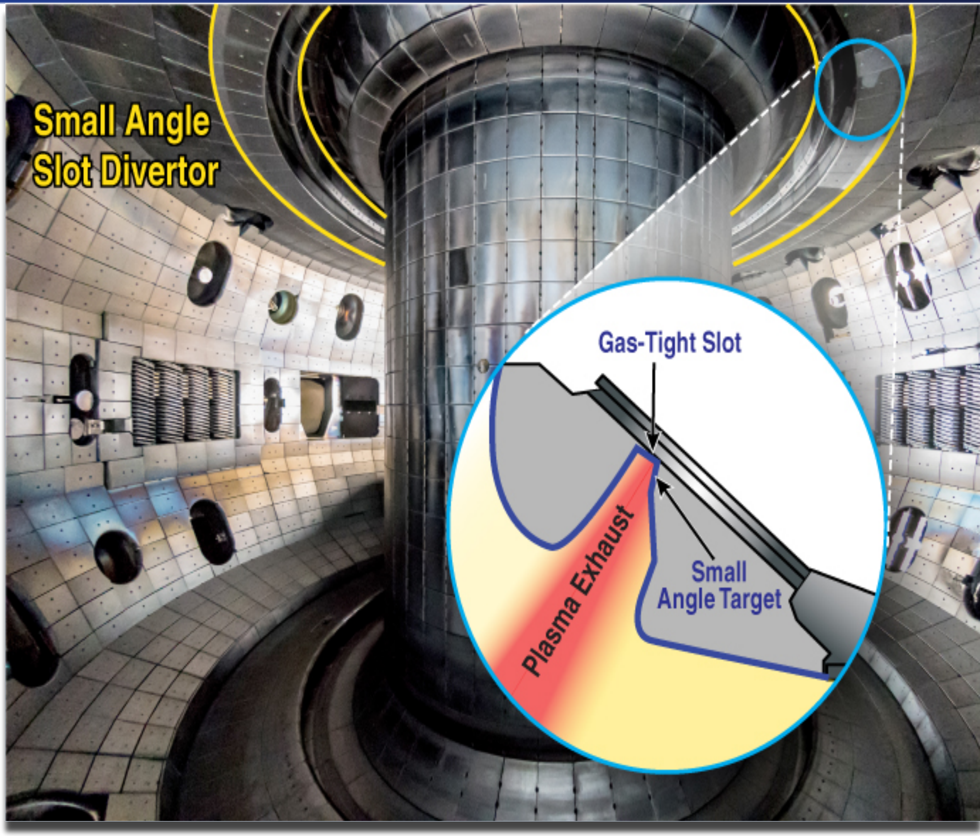

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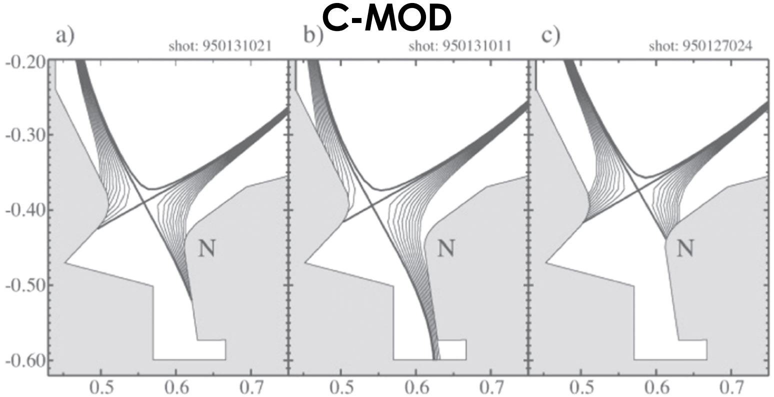
Optimizing divertor geometry is a promising way to explore the boundary solution critically for future fusion reactors

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

C-MOD



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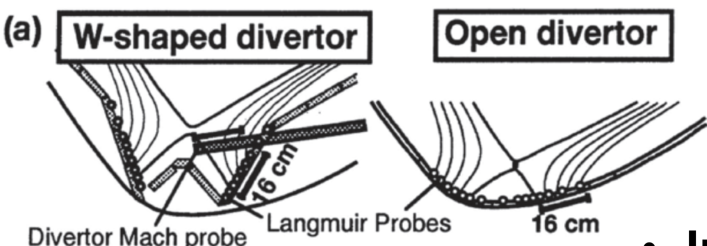

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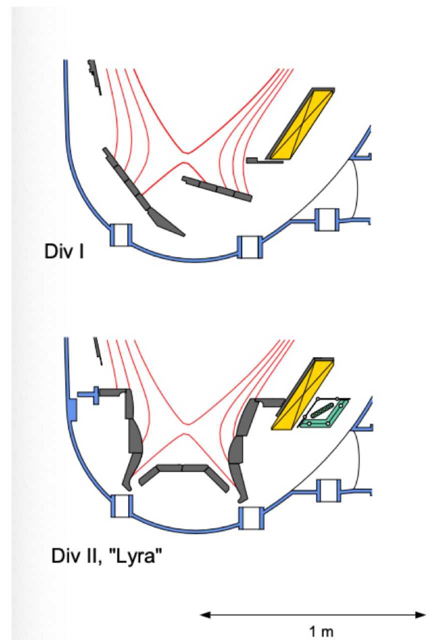

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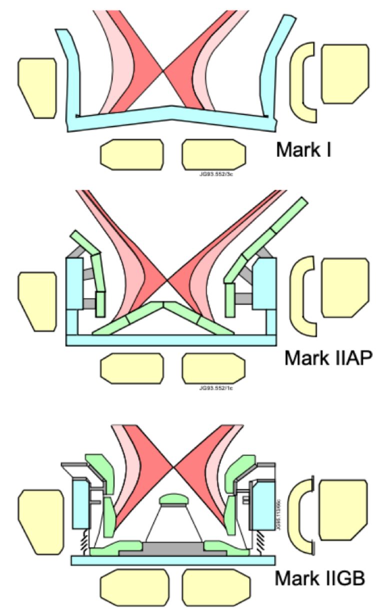

- **Increasing divertor closure enhances the divertor neutral trapping and divertor recycling**
  - **Facilitate the achievement of divertor detachment**

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

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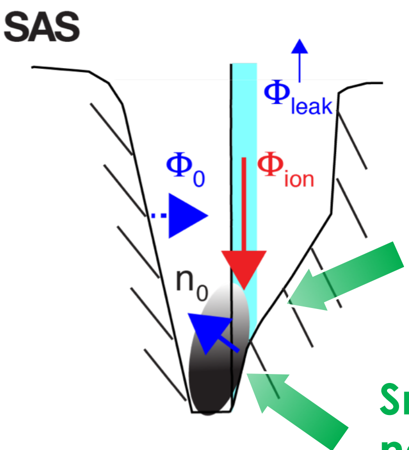
SAS is motivated to enhance power dissipation through concentrating particles to high heat flux regions with advanced target shaping

SAS: Small-angle-slot divertor



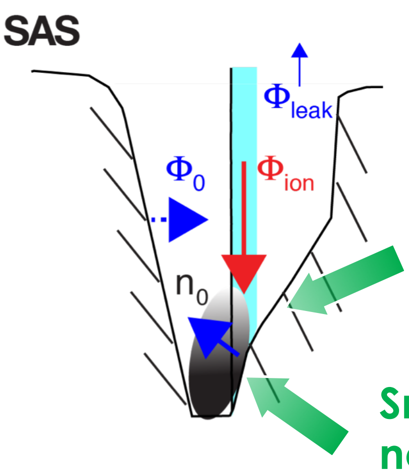
Progressive slot opening toward far-SOL: reflects neutrals into the near-SOL extending dissipation across target

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

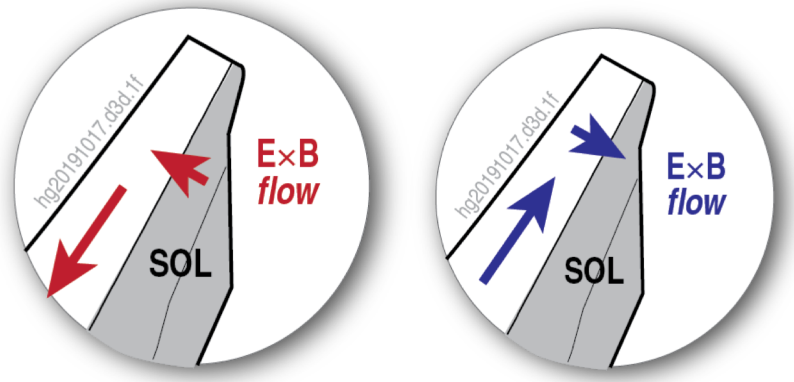
SAS: Small-angle-slot divertor



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

Guo NF 2017; Sang PPCF; Guo NF 2019
Jaervinen NME 2019; Boedo PoP 2000; Chankin JNM 1997



- **Strong divertor E×B drift flow in H-mode plasmas**
  - $E_r \sim 3\nabla T_e \sim 3T_e/\lambda_q f_x$
  - $E_\theta \sim f(\nabla_{//}T_e, \nabla_{//}P_e, J)$
- **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**

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

SAS: Small-angle-slot divertor

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**

- $E_\theta \sim f(\nabla_{//}T_e, \nabla_{//}P_e, J)$

- Poloidal drift flow comparable with recycling flow: $E_r/B \sim C_s B_\theta/B$
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Guo NF 2017; Sang PPCF; Guo NF 2019
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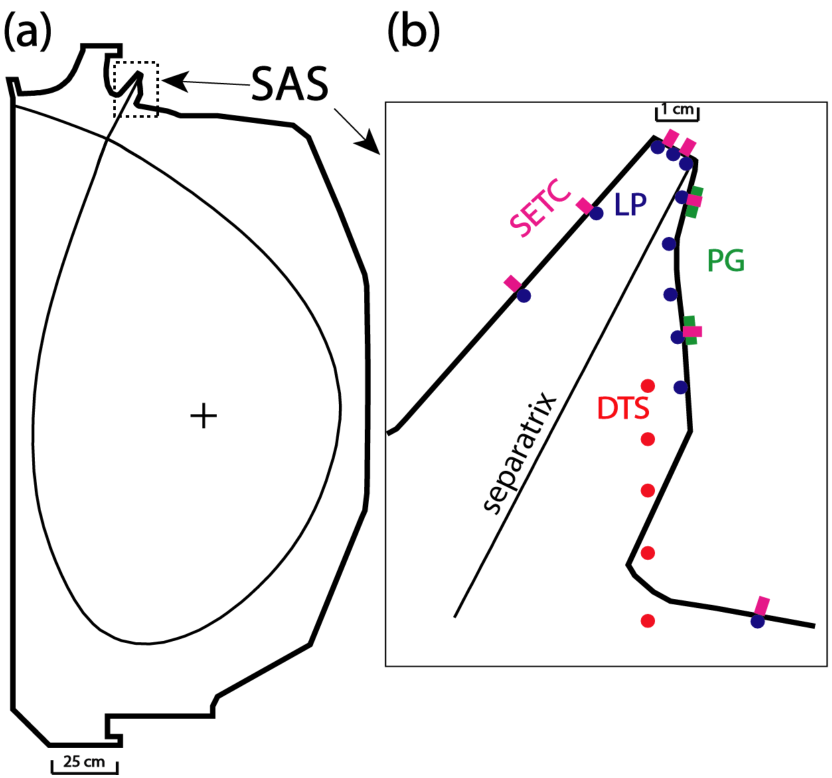
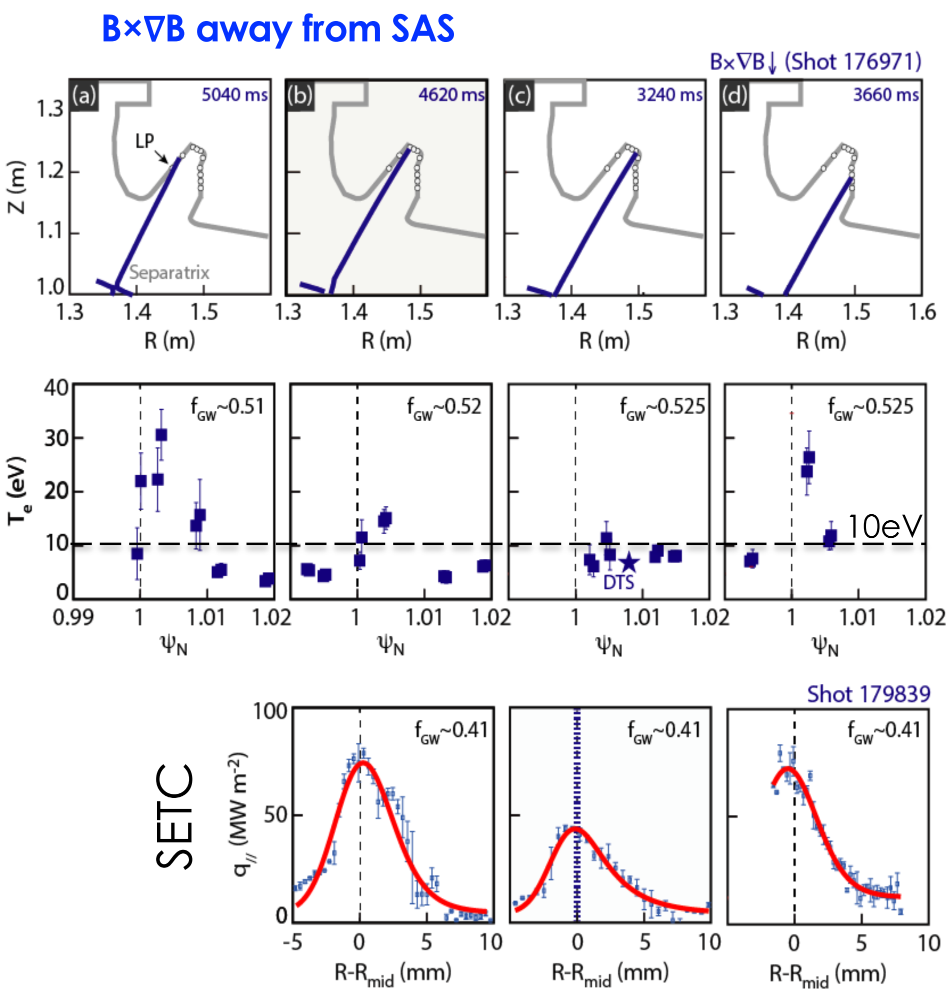
A compact small-angle-slot divertor was installed in DIII-D as a testbed for exploration of divertor solutions



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

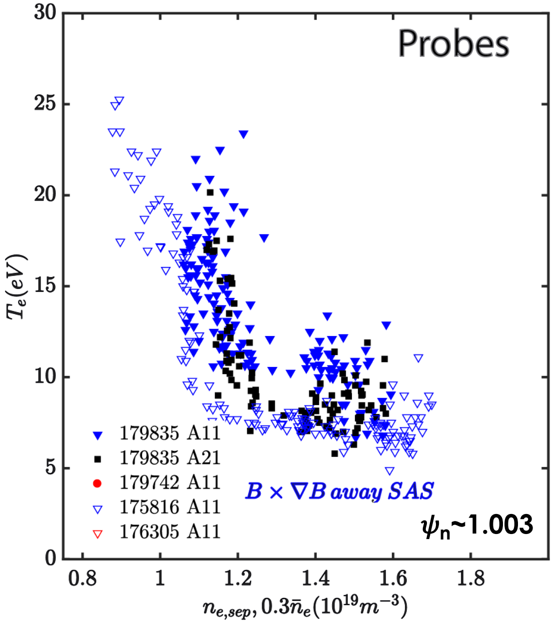


- **Strike point sweeps at fixed density**
- **When SP @ outer corner, flat and low T_e ~10eV across divertor target**
  - Desired for material erosion control
- **Also low heat flux measured by both LP and SETC**
  - Same for another B_T direction
- **3x higher T_e and 2x higher heat flux when SP at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

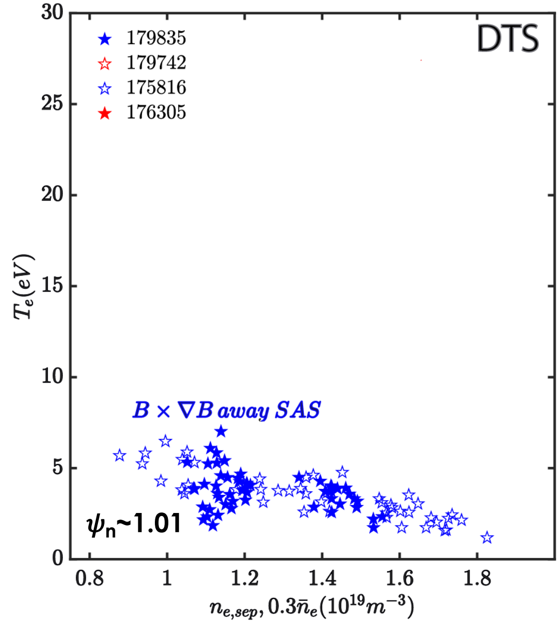
Ren APS 2019; Ren NME 2021; Guo NF 2019

With Ion B×∇B Drift away Xpt, low T_e is achieved at low main plasma densities

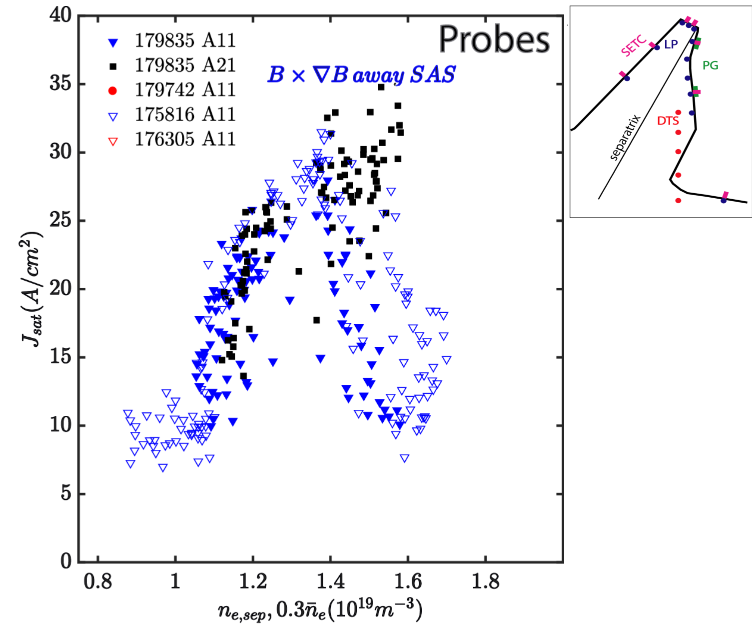
T_e Probes (near Strike point)



T_e DTS (mid SOL)



J_{sat} Probes (near Strike point)



- **Low T_e<10eV 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 → particle and momentum loss

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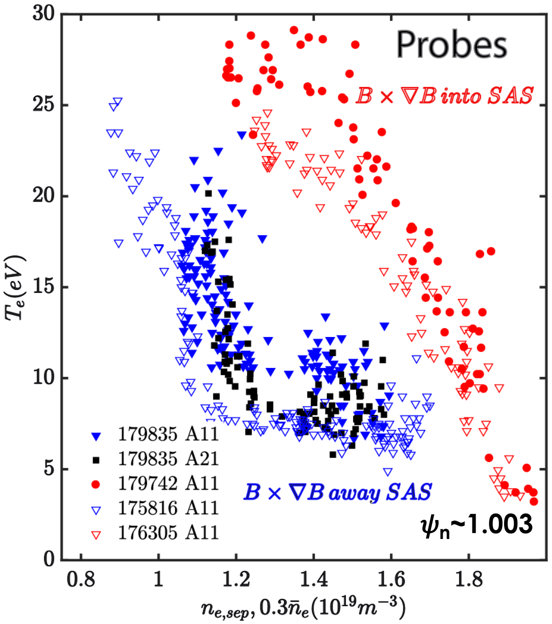
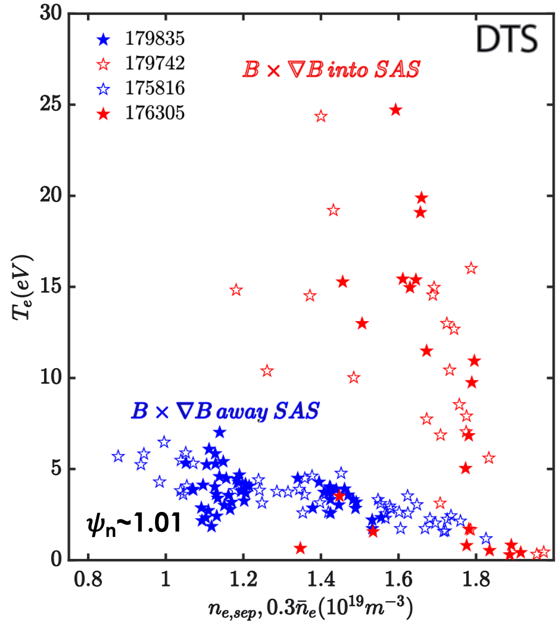
However, Ion B×∇B Drift toward Xpt offsets geometric effects → Requiring higher density to achieve low T_e

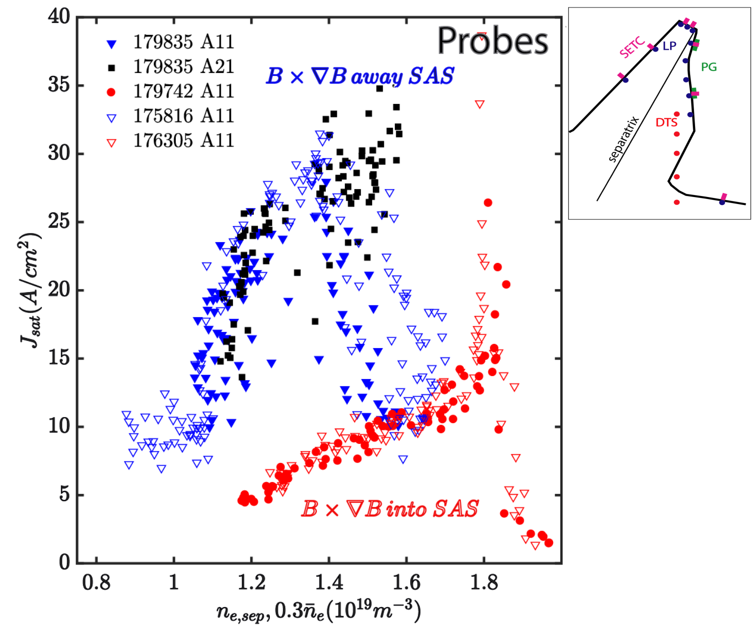
T_e Probes (near Strike point)



T_e DTS (mid SOL)



J_{sat} Probes (near Strike point)



- **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: ~10% between different B_T
  - Strong detachment with low T_e<5eV and low J_{sat} can be achieved

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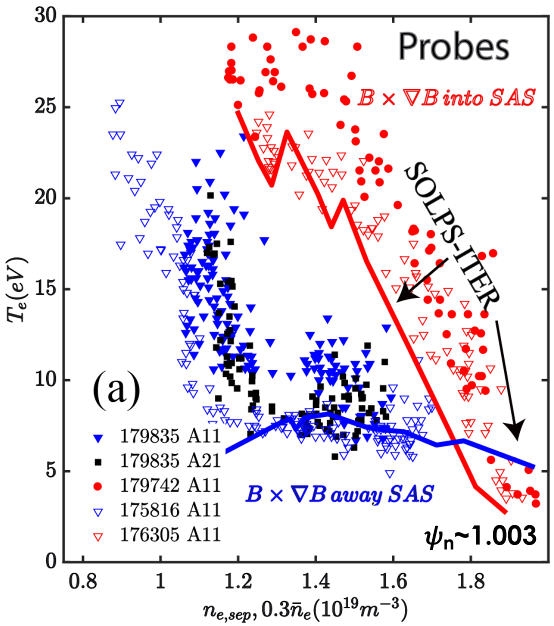
Jaervinen PRL 2018

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

T_e Probes (near Strike point)



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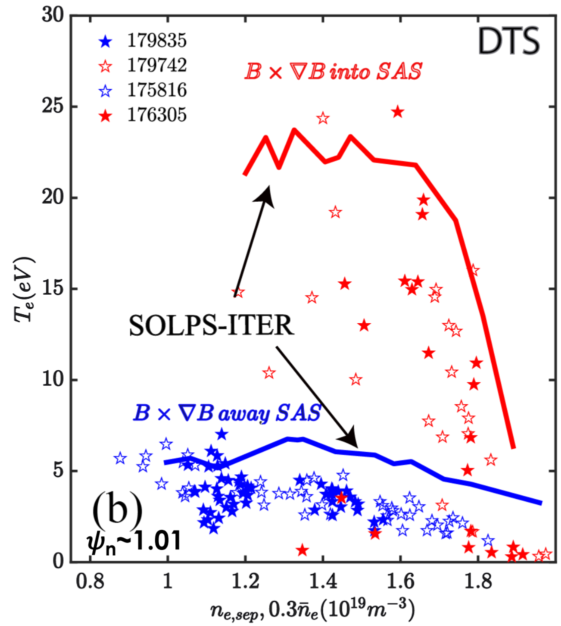
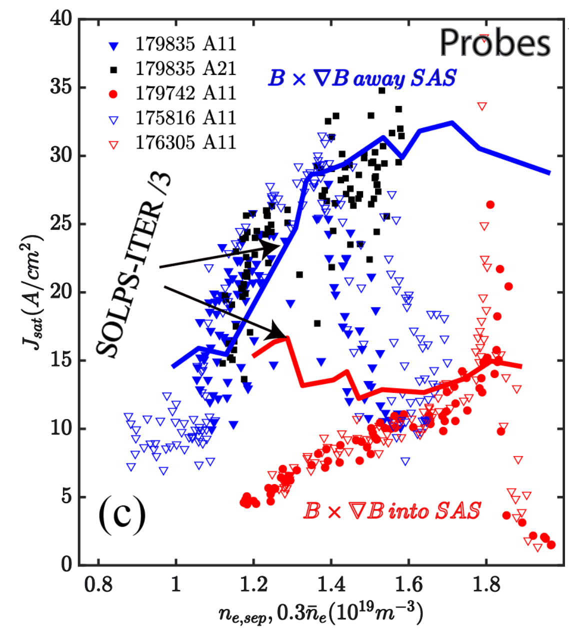
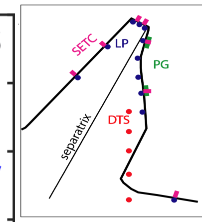


J_{sat} Probes (near Strike point)





- **Assuming n_{esep}~ 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&χ, radiation shortfall
  - Recent simulations with matched profiles shows similar behavior and better agreement

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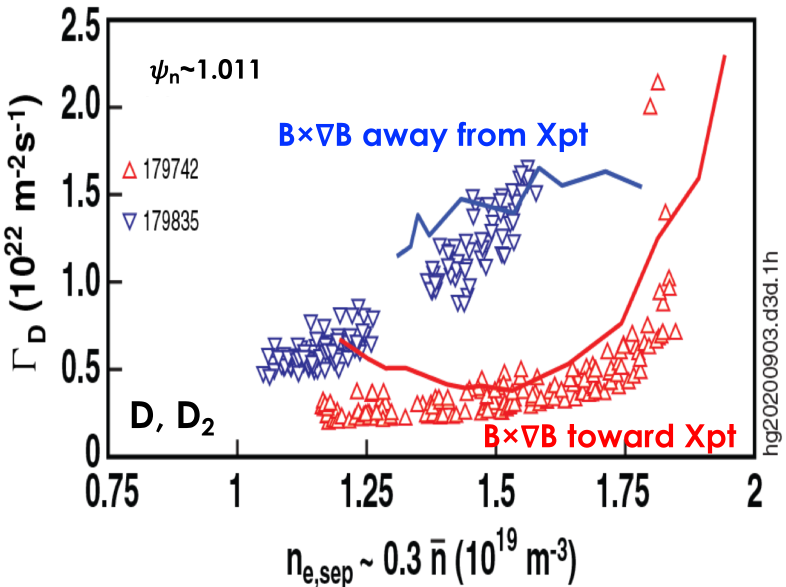
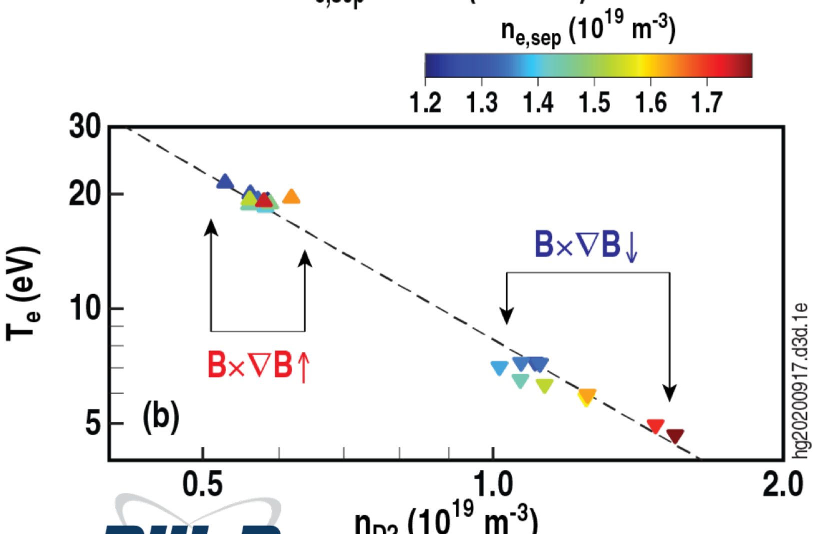
Maurizio, to be submitted to NF

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

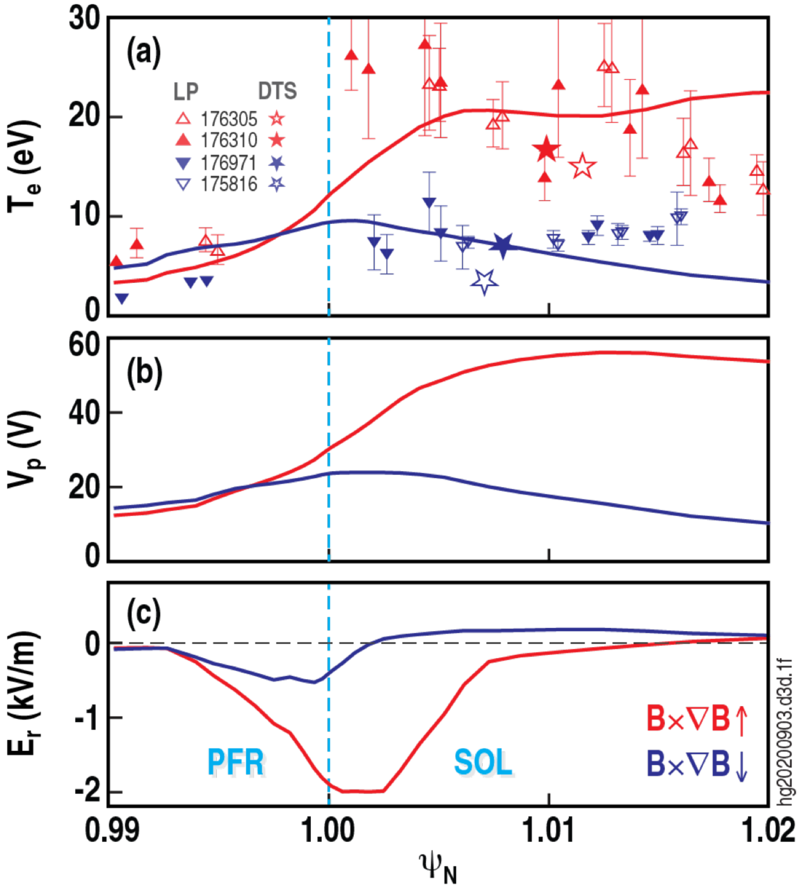




- **Neutral flux in the SOL for the other B_T is much (2X) smaller up to deep detachment**
  - Previous modeling without drift shows one order of magnitude higher neutral flux → significance of drifts
- **Neutral recycling and behaviors could be strongly affected by the flows and geometry**
  - Found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

X. Ma, NF 2021; M.W. Shafer, NME 2019; Stangeby NF 2017; Kallenbach NME 2019; Pitts NME 2019

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



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

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X. Ma, NF 2021

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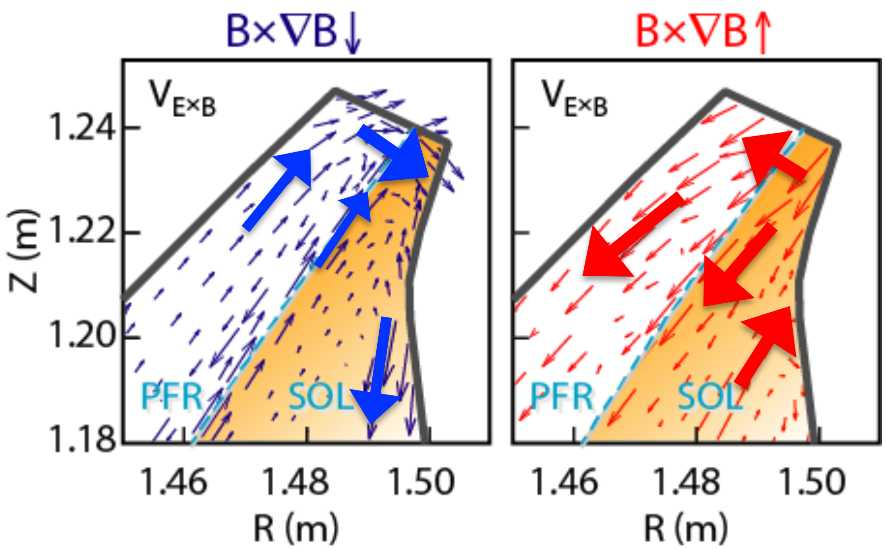
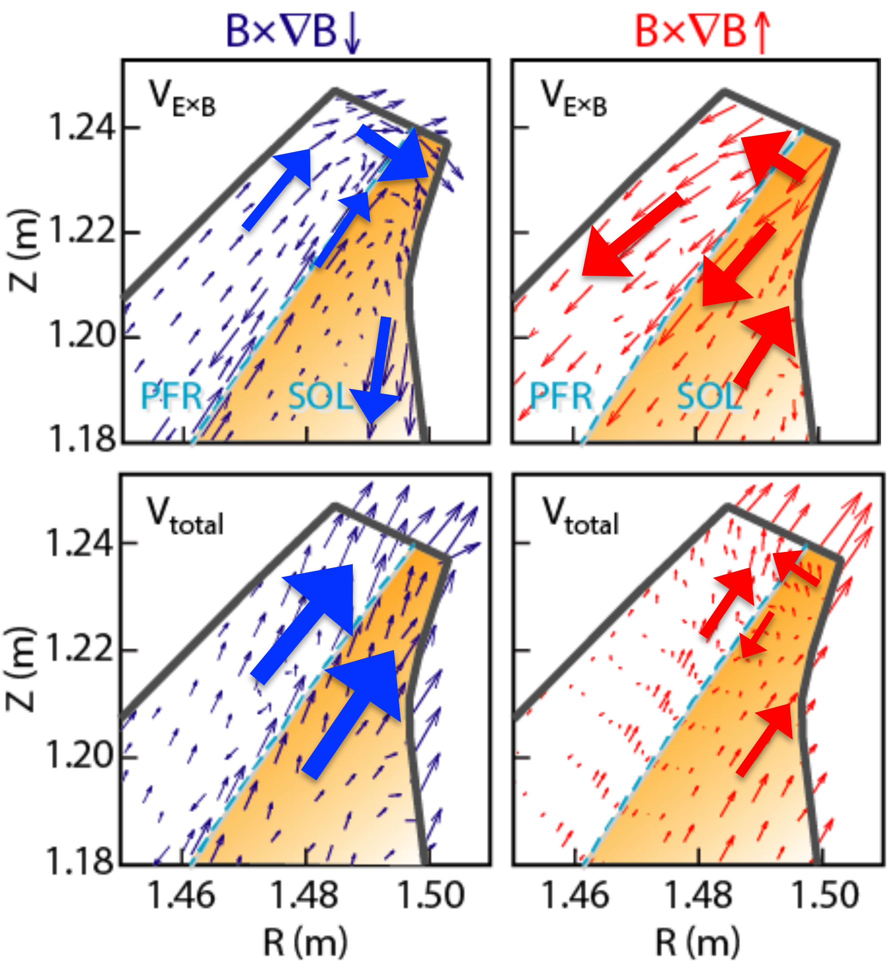


- **Simulations show similar profiles features observed in experiments**
- **B×∇B away from Xpt: Low and flat T_e**
  - Small T_e radial gradient → Small E_r
  - Large T_e parallel gradient → Large E_θ
  - PFR E_rxB moves particles to outer div.
  - Radial E_θxB moves particles towards SOL

  → **High flux and low T_e**
- **B×∇B toward Xpt: High T_e across separatrix**
  - Strong T_e radial gradient → Strong E_r
  - Medium T_e parallel gradient → Med E_θ
  - E_rxB moves particles away from SOL
  - E_θxB moves particles from SOL to PFR

  → **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×∇B away from Xpt: Low and flat T_e**
  - ExB drift flow same direction as main plasma flow → larger total flow
- **B×∇B toward Xpt: High T_e across separatrix**
  - ExB drift flow opposite direction as main plasma flow → weaker total flow
  - Even reversal near the strike point
  - **$E_r/B \sim C_s B_\theta/B$**

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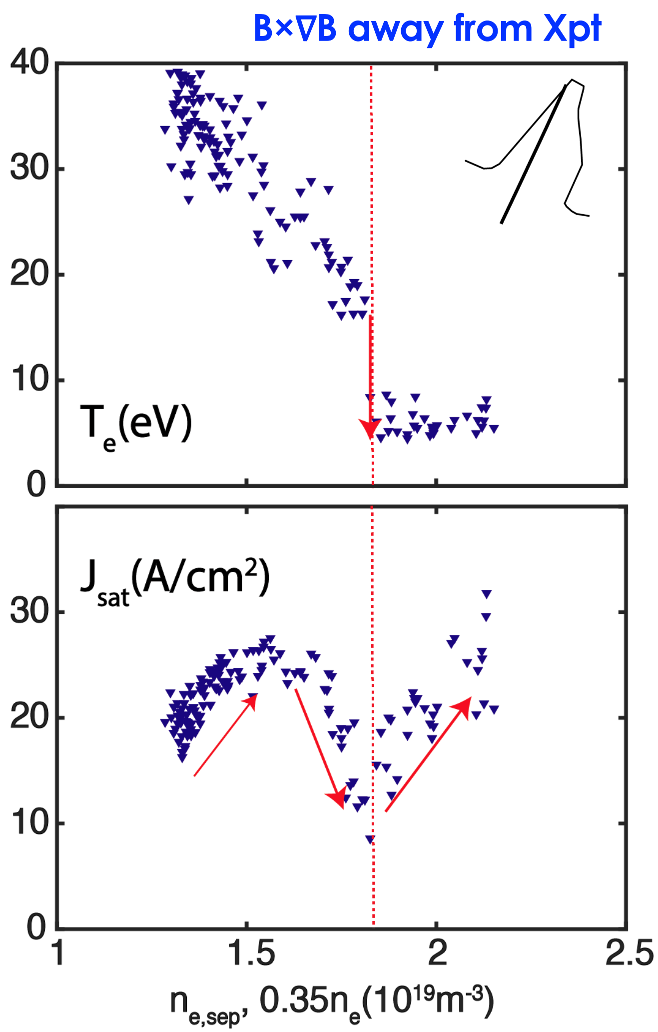
The coupling between drift and geometry could alter the path towards divertor detachment



- **T_e-cliff-like transition for B×∇B away from Xpt, for strike point at the slanted target**
  - With open divertor, T_e cliff only found with B×∇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

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Jaervinen, PRL 2018; NF 2020; NME 2019

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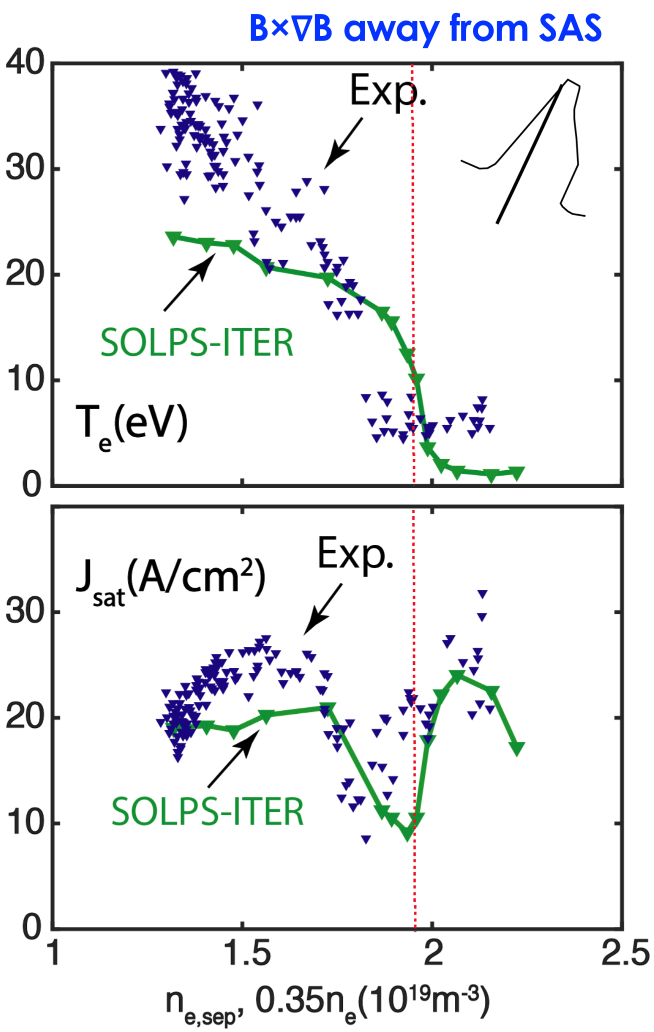

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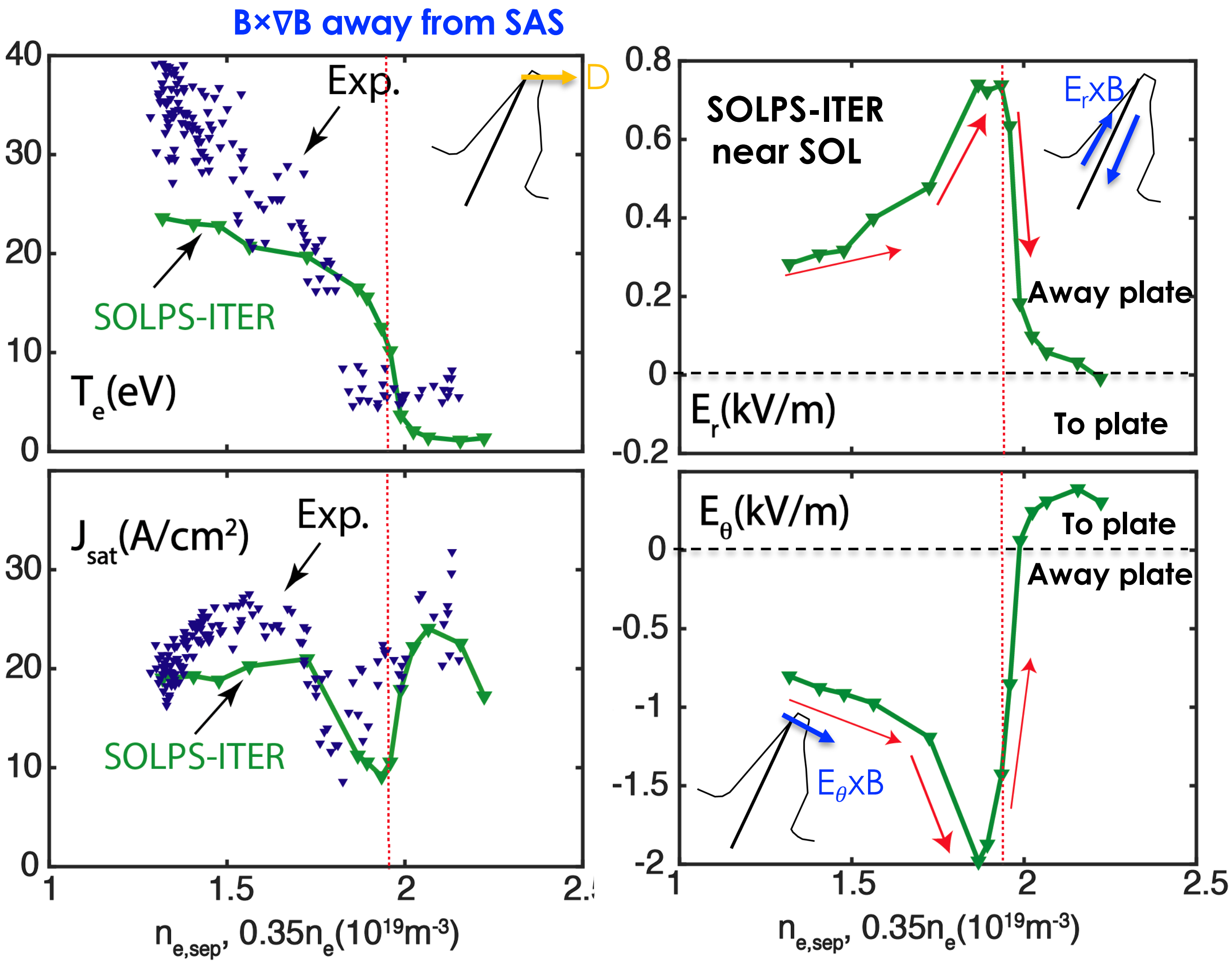
  - Slanted target directs the neutral away the SP
- **Particle flux shows up-down-up trend**
  - J_{sat} dip at high T_e
- **SOLPS-ITER simulations reproduce similar trend for both T_e and particle flux**
  - Match upstream profiles but constant div. D, χ
    - Better agreement compared to previous
  - Not fully reproduce T_e-cliff yet

Jaervinen, PRL 2018; NF 2020; NME 2019

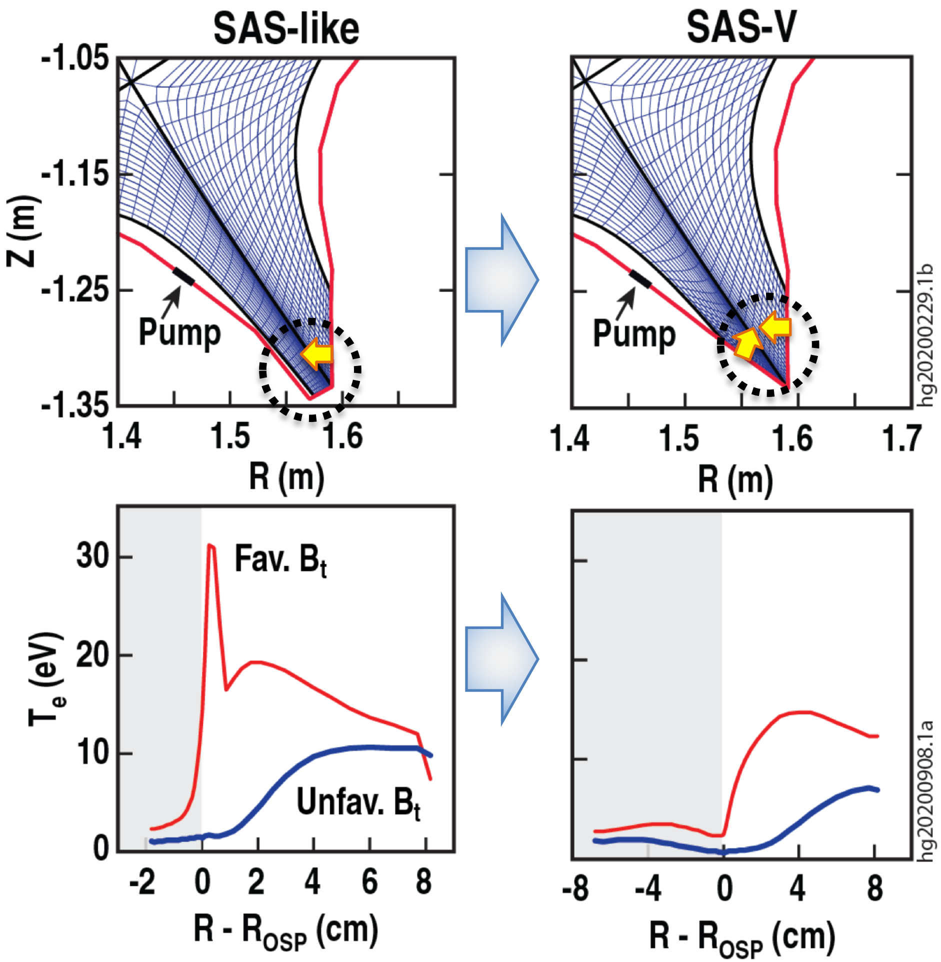
The evolution of particle flux strongly correlates with the dynamics of divertor drift flows near target plate



- 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 → particle accumulations at SP →T_e-cliff-like reduction

Wang, PRL 2020

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

Enhance neutral/particle buildup → Lower T_e and E_r → Reduce E_rxB → Enhance neutral/particle buildup

- SAS-V: Low T_e in both B_T directions

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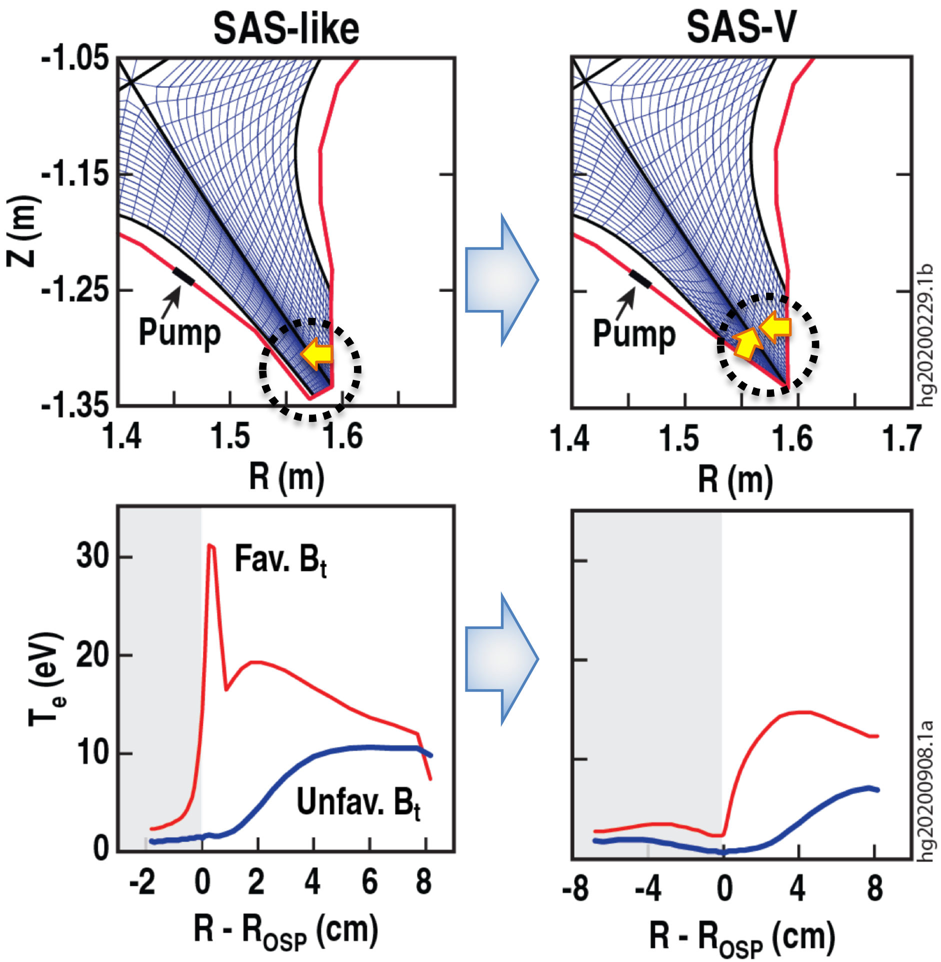
Du NF 2021; Guo APS 2020

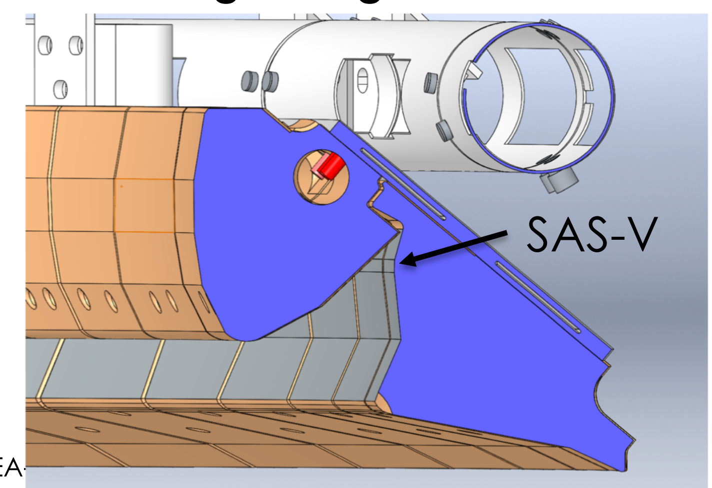
DIII-D plans to test SAS-V concept to further investigate the interplay between drifts and geometry



- **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_rxB** → **Enhance neutral/particle buildup**

- **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**



Du NF 2021; Guo APS 2020

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!!