The Role of Drifts and Radiating Species in Detached Divertor Operation at DIII-D

A.G. McLean[1]

with S.L. Allen[1], T. Abrams[3], J.A. Boedo[5], I. Bykov[5], A. Briesemeister[2], J. Canik[2], R. Ding[6], D. Elder[4], D. Eldon[7], M. Fenstermacher[1], M. Groth[8], H.Y. Guo[3], J. Guterl[3], D.N. Hill[3], A. Jarvinen[1], E. Kolemen[7], C. Lasnier[1], A.W. Leonard[3], M. Makowski[1], B. Meyer[1], A.L. Moser[3], T.H. Osborne[3], T.W. Petrie[3], G.D. Porter[1], T. Rognlien[1], D. Rudakov[5], C. Samuell[1], C. Sang[6], P.C. Stangeby[4], D. Thomas[3], E. Unterberg[2], H. Wang[2], J. Watkins[9]

[1]LLNL
[2]ORNL
[3]GA
[4]University of Toronto
[5]UCSD
[6]ASIPP
[7]PPPL
[8]Aalto University
[9]SNL

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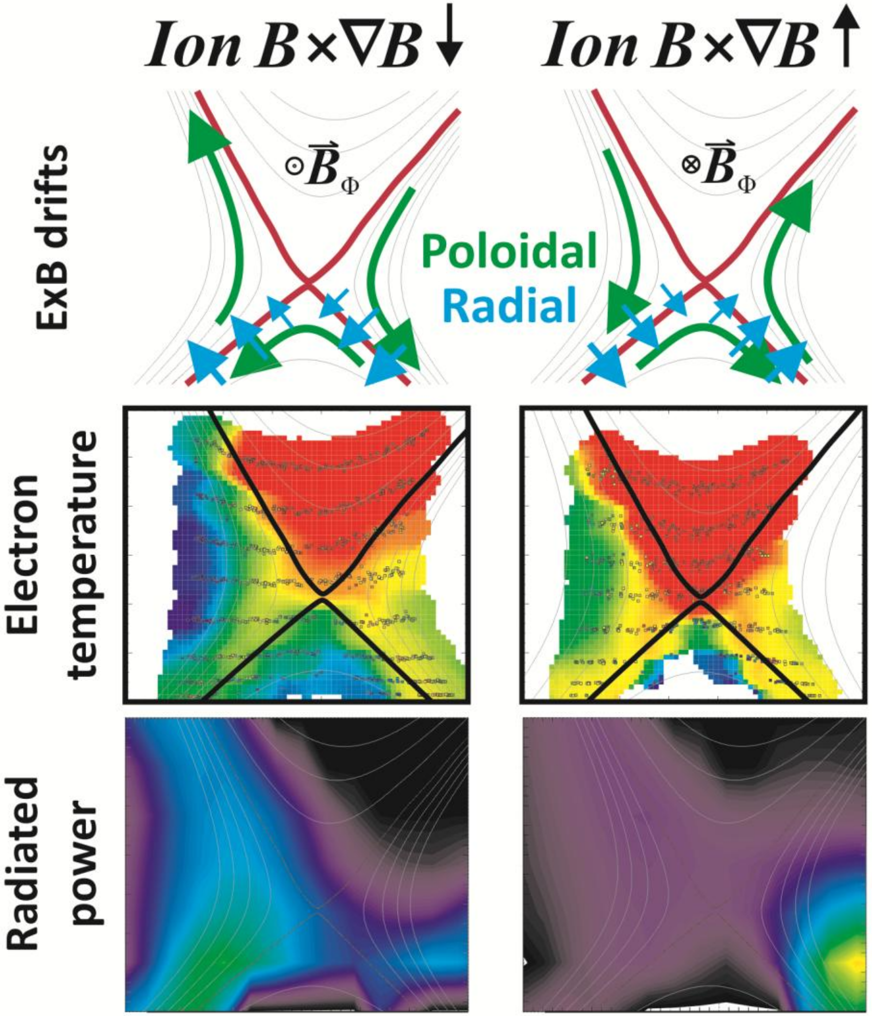
Fusion Energy Sciences

Prediction and Control of Target Heat Load is Critical for Future Devices

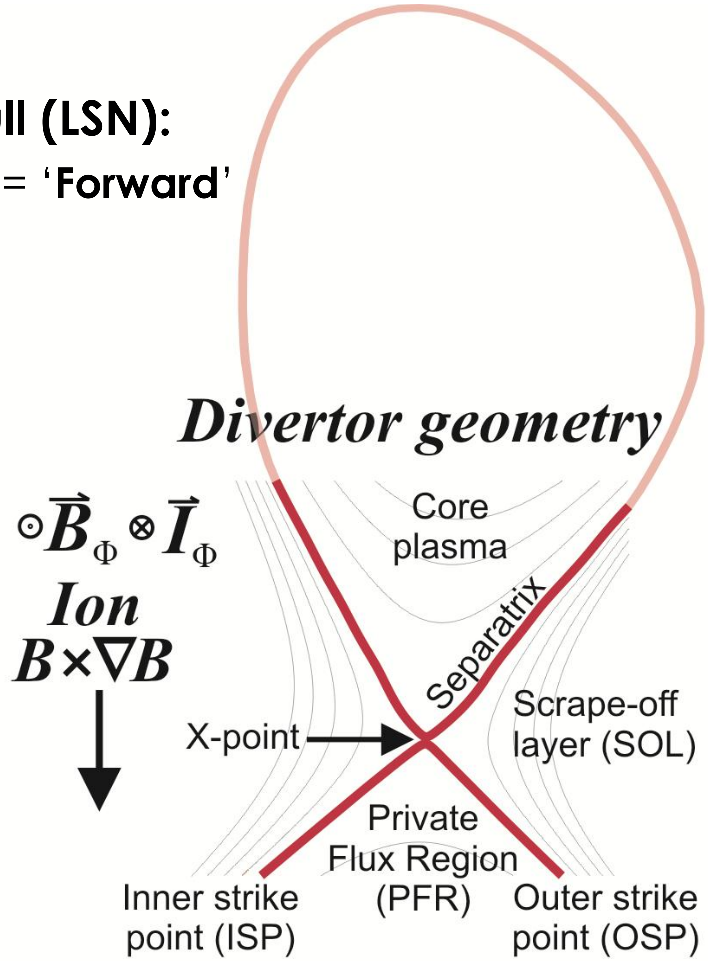
- **Inner/outer target asymmetries**
  - Roles of **E**×**B** drift components
  - Result: Qualitative agreement between experiment and 2D fluid modeling with drifts
- **Detachment onset**
  - 2D measurements with Divertor Thomson scattering (DTS)
  - Result: Rapid transition to a cold outer target with ion B×∇B ↓
- **Radiated power**
  - Universal shortfall when modeling compared to experiment, multiple codes and wall materials
  - Result: No shortfall in He plasma using divertor conditions as input



A.G. McLean, 26th IAEA FEC Kyoto , Japan, October 2016

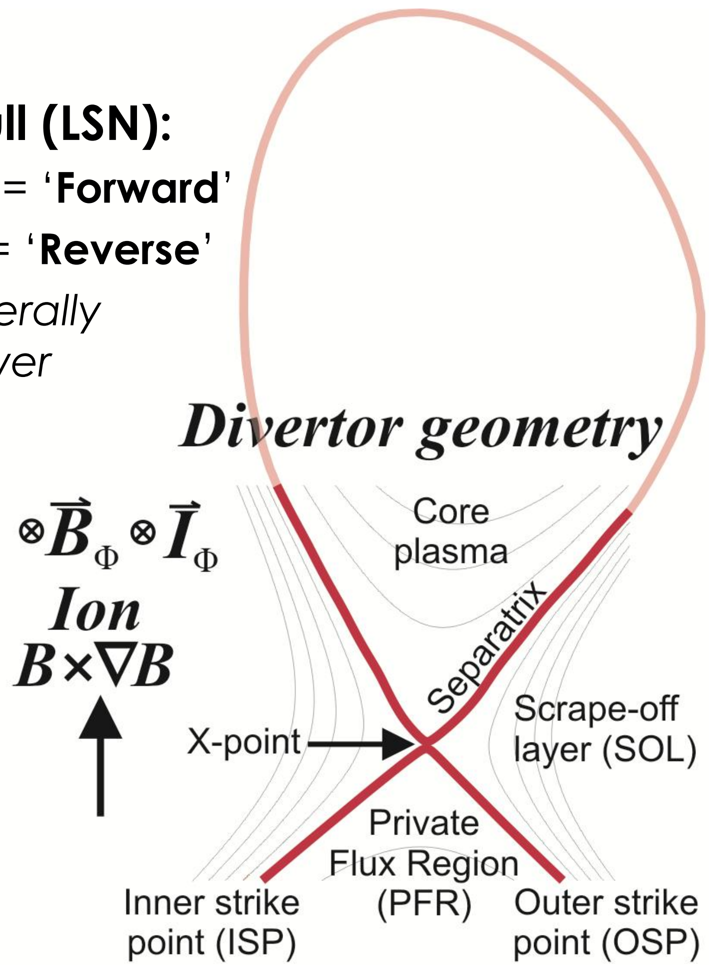
Reversing the Toroidal B Field is Carried Out to Probe the Impact of E×B Drifts in the Divertor

- **Toroidal field convention – lower single null (LSN):**
  - Ion B×∇B direction **down** (into the divertor) = '**Forward**'



Reversing the Toroidal B Field is Carried Out to Probe the Impact of E×B Drifts in the Divertor

- **Toroidal field convention – lower single null (LSN):**
  - Ion B×∇B direction **down** (into the divertor) = '**Forward**'
  - Ion B×∇B direction **up** (out of the divertor) = '**Reverse**'
  - *In fwd B_T, less power to enter H-mode, generally higher confinement for equal injected power*
    - ***'Favorable' direction***



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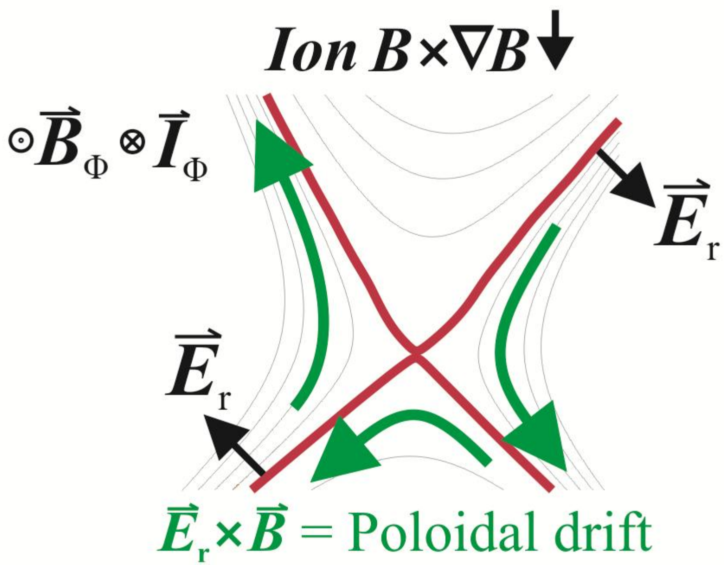
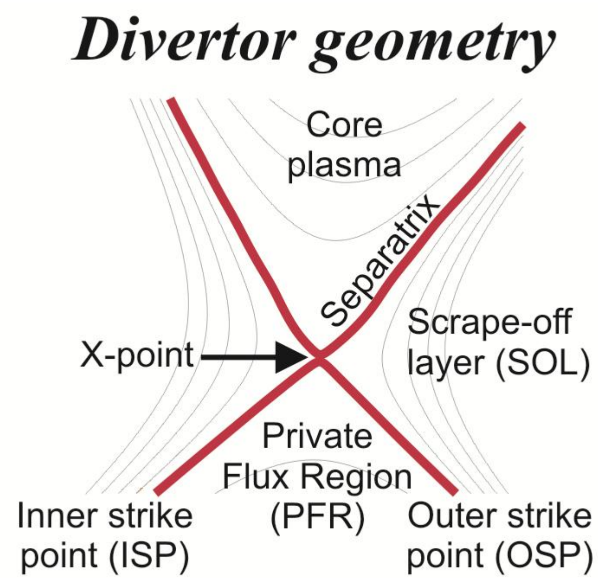
E×B Drifts Can Be Separated Into Two Distinct Components

- **Poloidal E_r×B leads to flow of particles from**
  - *outer to inner* divertor in the PFR with ion B×∇B ↓





E×B Drifts Can Be Separated Into Two Distinct Components

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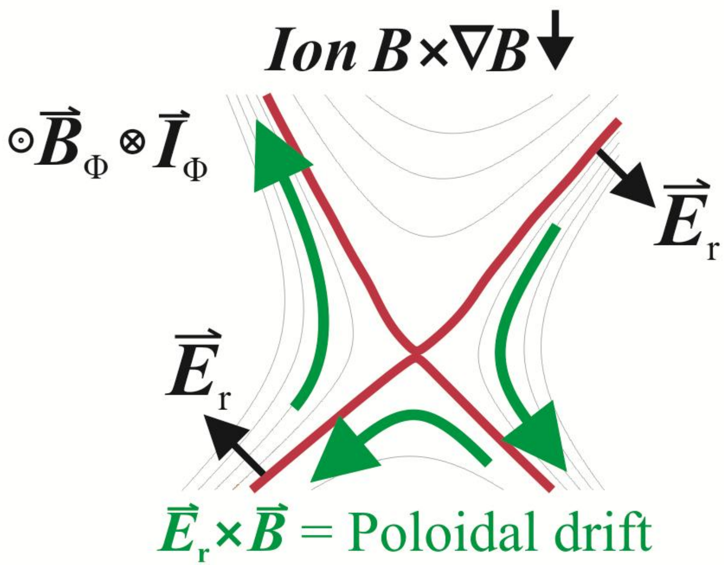
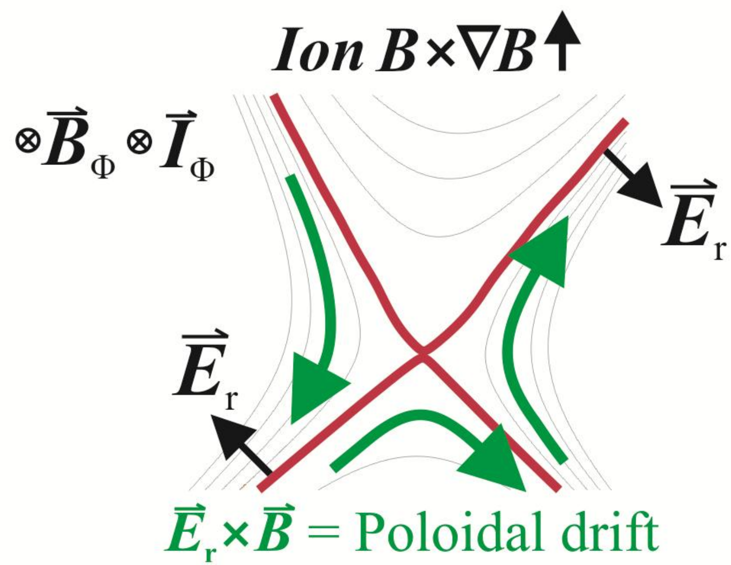
  - *outer to inner* divertor in the PFR with ion B×∇B ↓
  - *inner to outer* divertor in the PFR with ion B×∇B ↑





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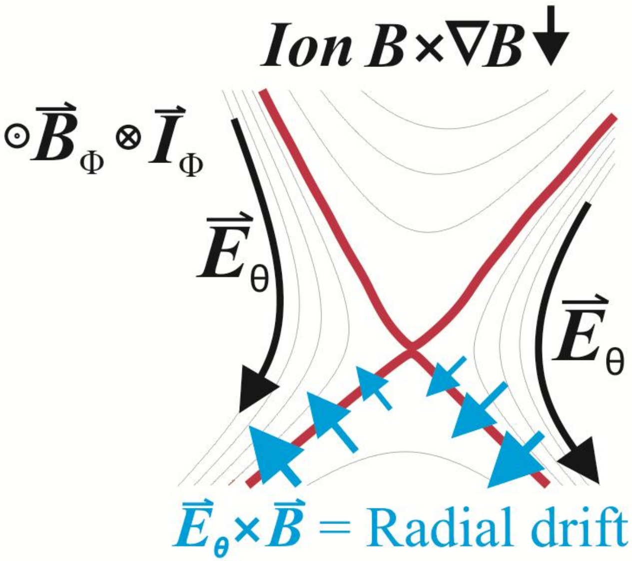
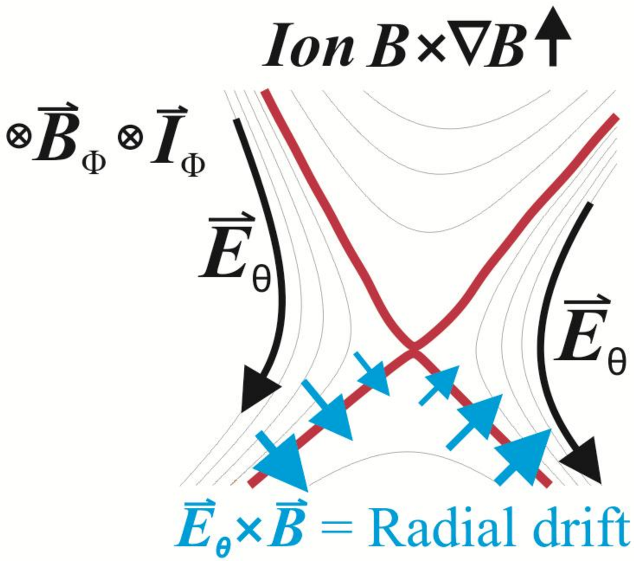
E×B Drifts Can Be Separated Into Two Distinct Components

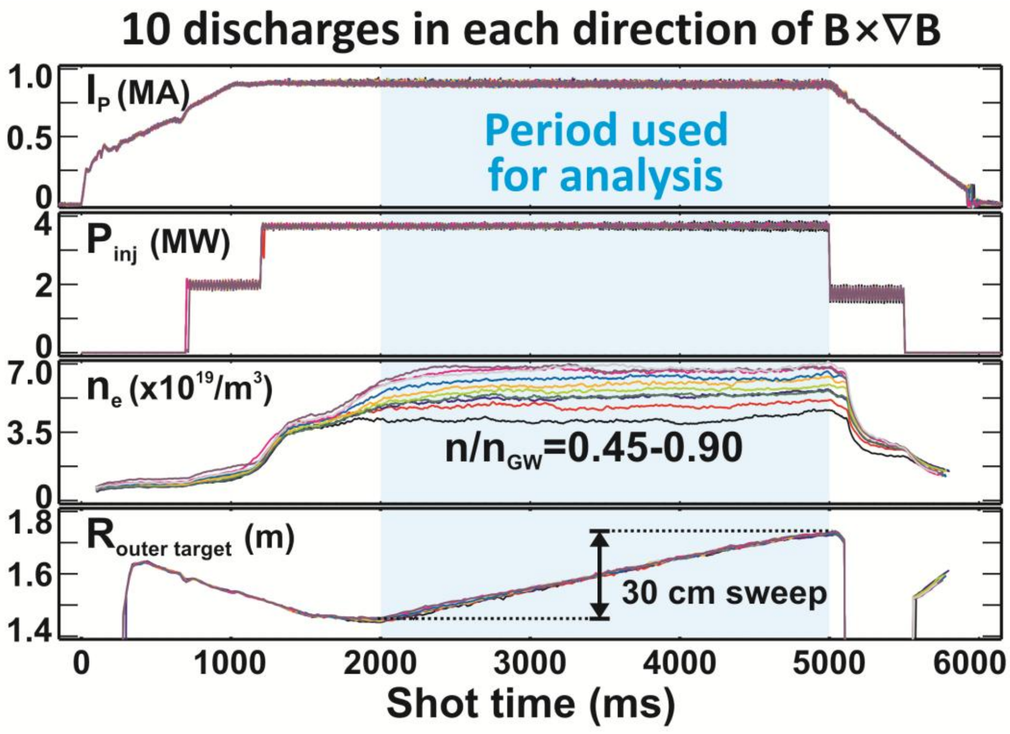
- **Poloidal E_r×B leads to flow of particles from**
  - *outer to inner* divertor in the PFR with ion B×∇B ↓
  - *inner to outer* divertor in the PFR with ion B×∇B ↑
- **Radial E_θ×B carries particles**
  - into/out of the PFR from the outboard side with ion B×∇B ↓
    - Leads to *inward* shifts in radial profiles
  - into/out of the PFR from the inboard side with ion B×∇B ↑
    - Leads to *outward* shifts in radial profiles

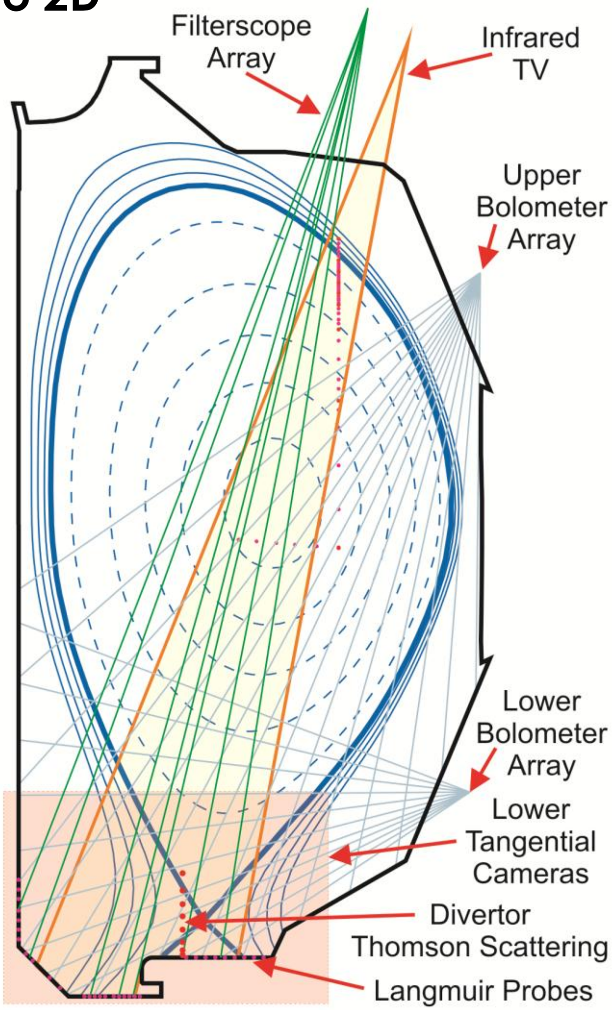




Well Characterized Plasmas are Used to Reveal the Impacts of Drifts

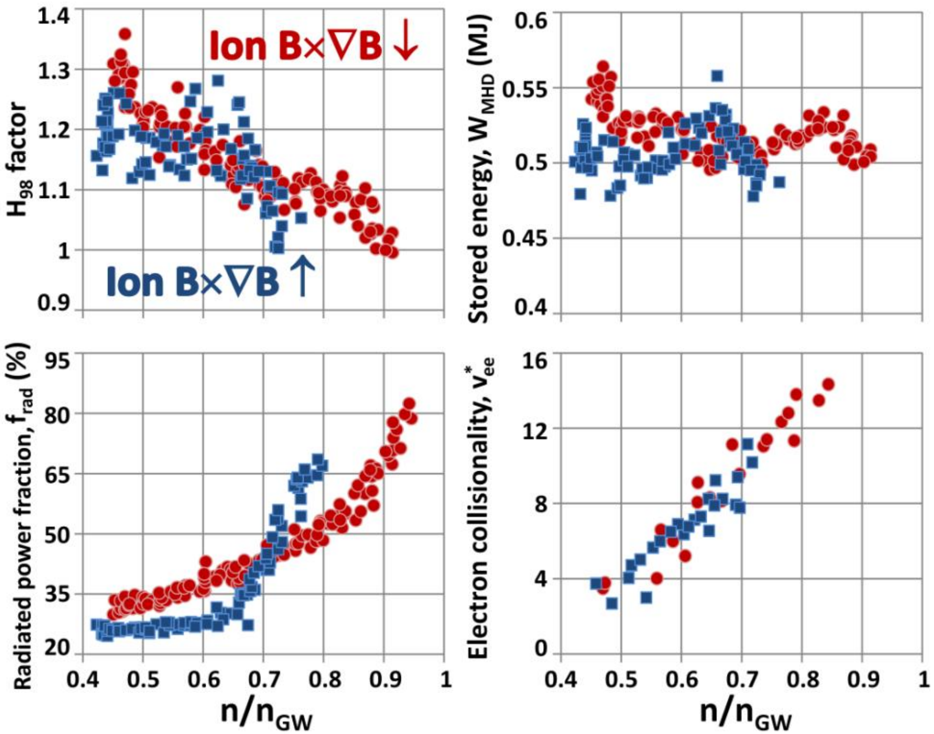
- Increasing steady density step in successive discharges
- Swept X-point across 1D diagnostic arrays to extend to 2D
- Upgraded diagnostics including 2D remapped DTS
- Inter-ELM data analyzed

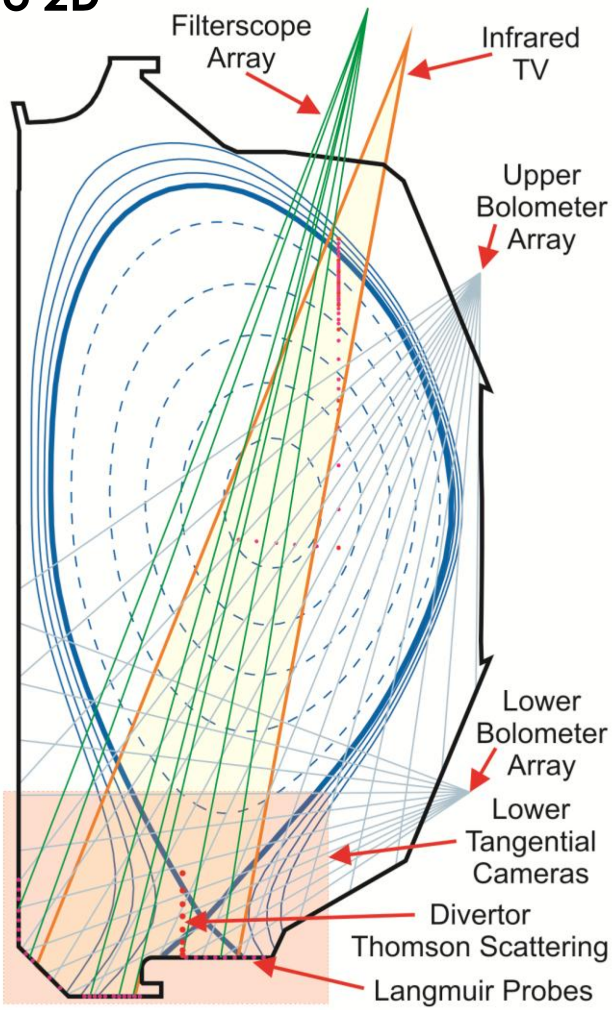




Well Characterized Plasmas With Good Performance are Used to Reveal the Impacts of Drifts

- Increasing steady density step in successive discharges
- Swept X-point across 1D diagnostic arrays to extend to 2D
- Upgraded diagnostics including 2D remapped DTS
- Inter-ELM data analyzed
- H-mode with $H_{98} \geq 1.0$ maintained at all n/n_{GW}





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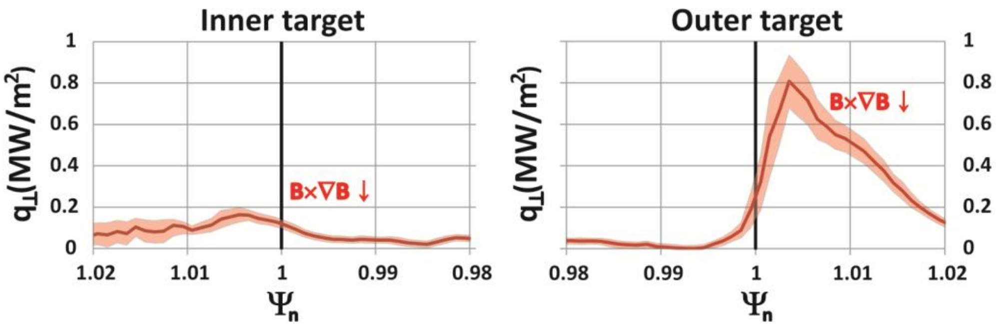
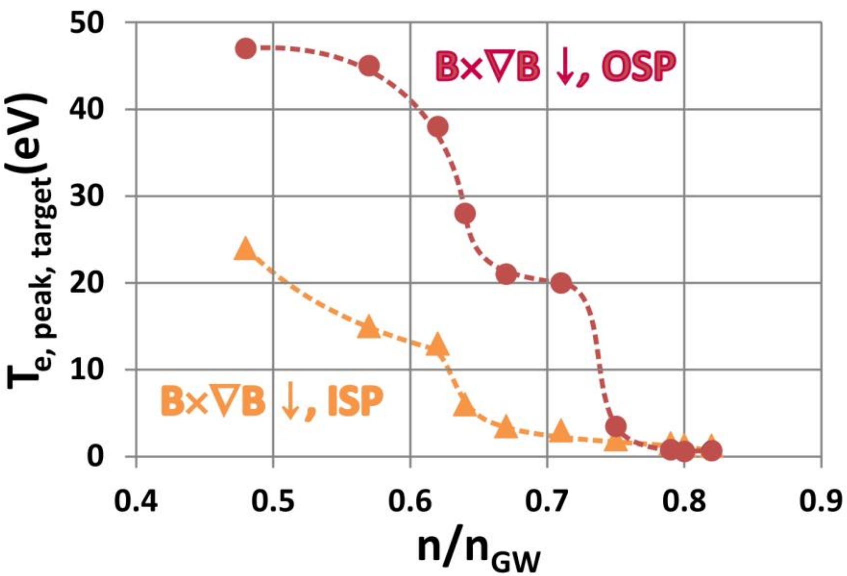
Target Temperature Asymmetry With B×∇B ↓ is Reduced For B×∇B ↑ and Decreases with Increasing Density

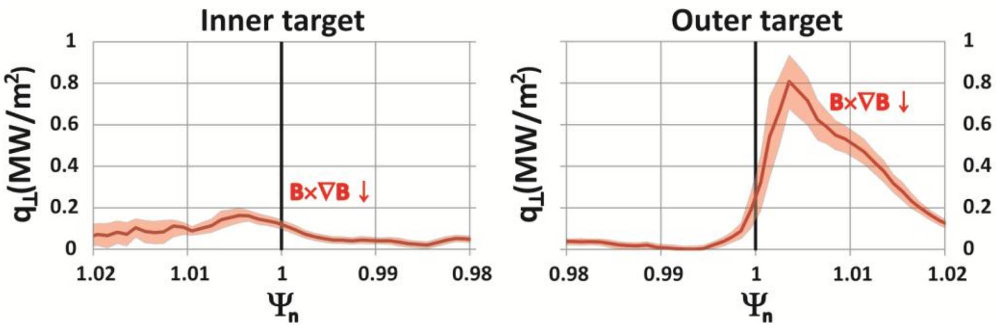
- **Target heat flux higher at outer target with B×∇B ↓**



Target Temperature Asymmetry With B×∇B ↓ is Reduced For B×∇B ↑ and Decreases with Increasing Density

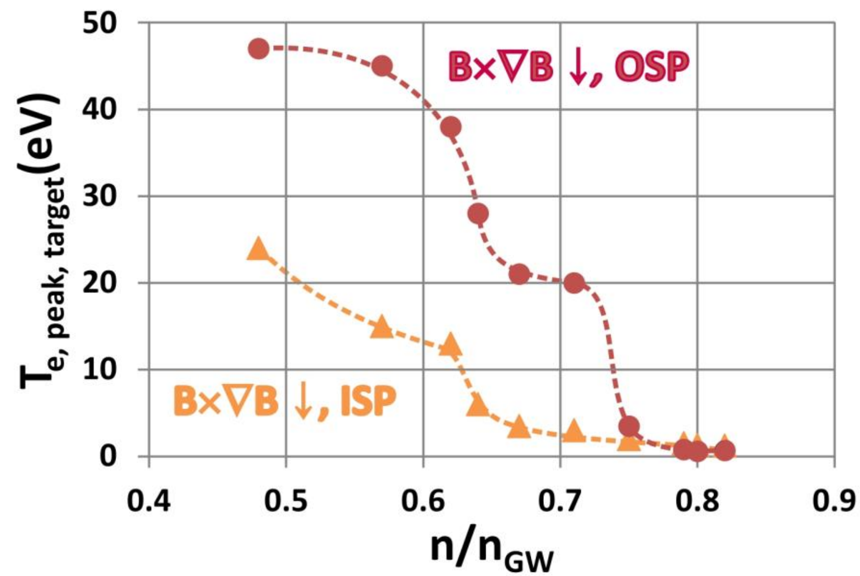
- **Target heat flux higher at outer target with B×∇B ↓**
- **Target T_e higher at the OSP with B×∇B ↓**

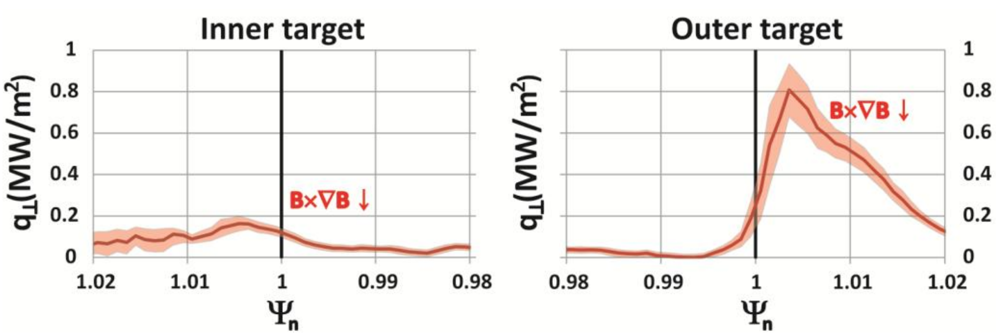


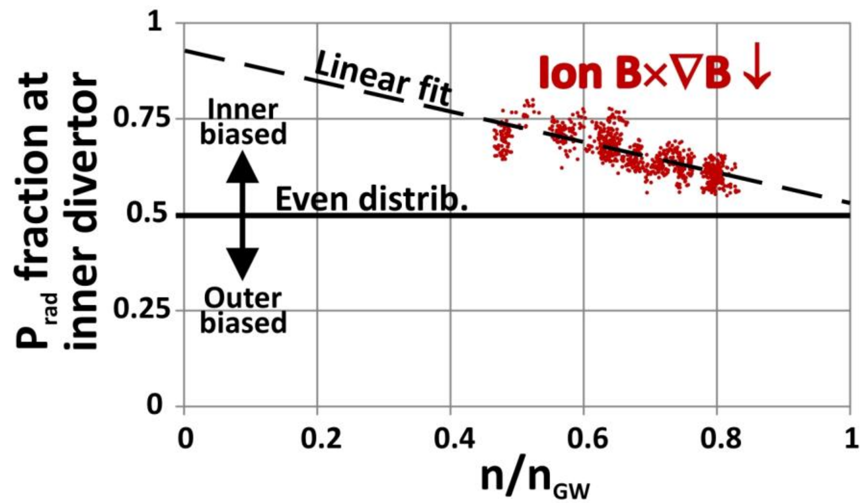


Target Temperature Asymmetry With B×∇B ↓ is Reduced For B×∇B ↑ and Decreases with Increasing Density

- **Target heat flux higher at outer target with B×∇B ↓**
- **Target T_e higher at the OSP with B×∇B ↓**
- **Integrated radiation biased to the inner divertor with B×∇B ↓**
- **Targets show largest asymmetry at lowest density with B×∇B ↓**







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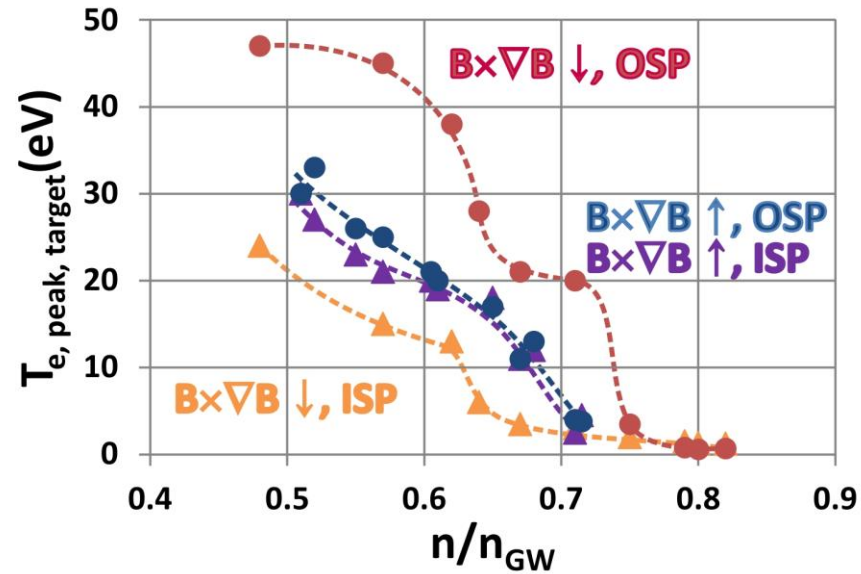
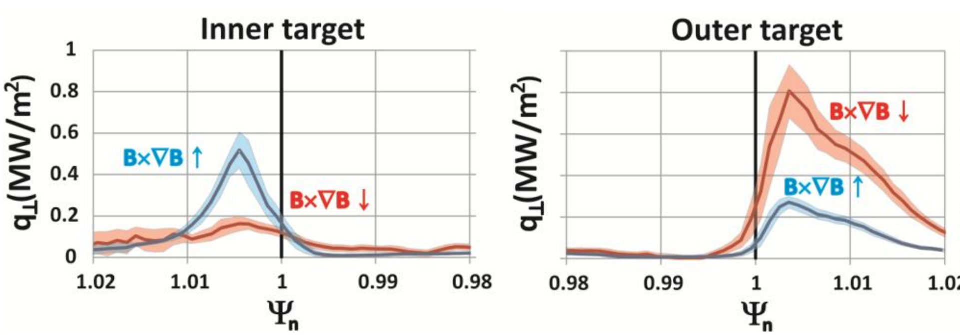
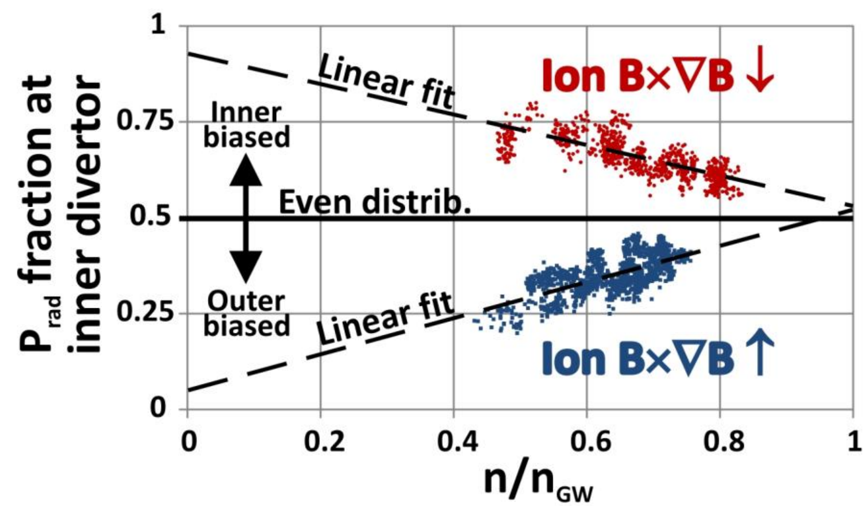
Target Temperature Asymmetry With B×∇B ↓ is Reduced For B×∇B ↑ and Decreases with Increasing Density

- **Target heat flux higher at outer target with B×∇B ↓**
  - Nearly symmetric with B×∇B ↑
- **Target T_e higher at the OSP with B×∇B ↓**
  - Symmetric with B×∇B ↑
- **Integrated radiation biased to the inner divertor with B×∇B ↓**
  - In contrast, mirrored with B×∇B ↑
- **Targets show largest asymmetry at lowest density with B×∇B ↓**







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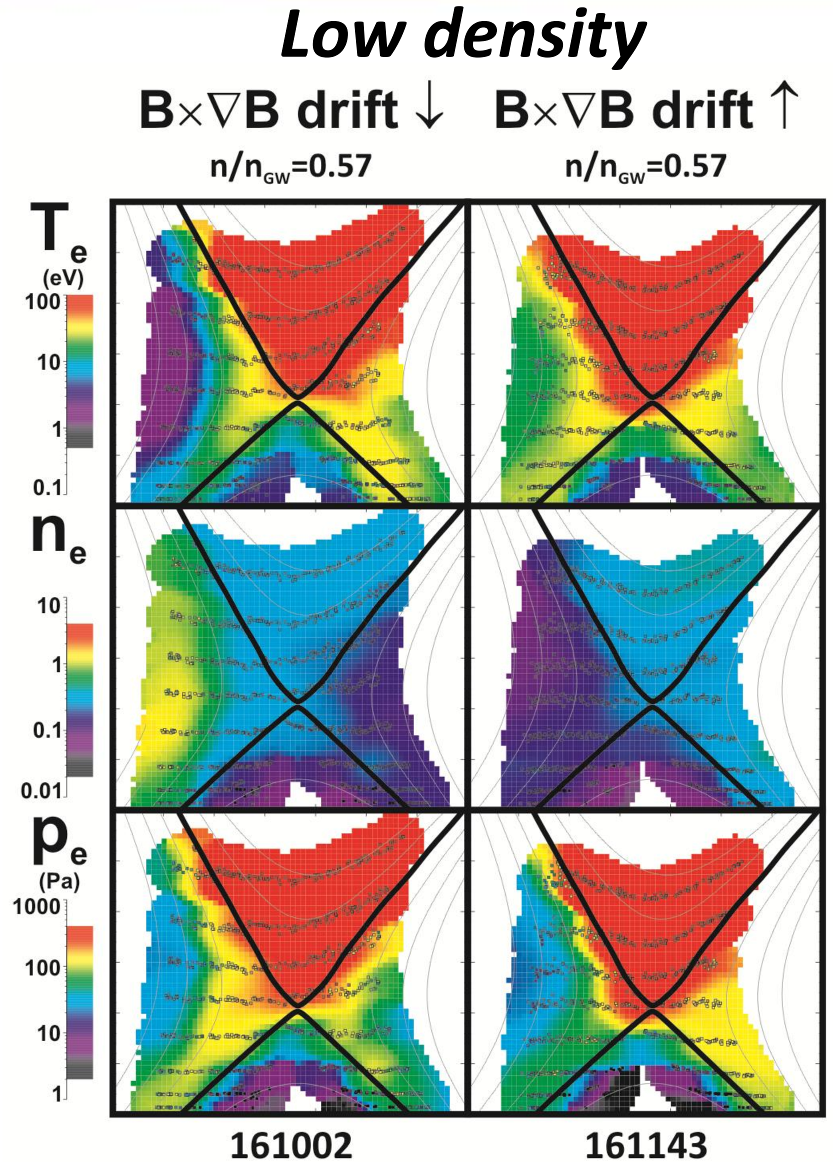
At Low Densities, Drifts are Large and Drive Asymmetries Throughout the Divertor Region

- **Divertor Thomson Scattering (DTS) unique to DIII-D, capable of measurements of $0.5 < T_e < 5$ keV, $1\text{x}10^{18} < n_e < 1\text{x}10^{21}/m^3$**
  - 4 MW H-mode, inter-ELM analysis only
- **Asymmetries in plasma parameters evident with B×∇B ↓, abated asymmetry in B×∇B ↑**
- **Extraordinarily high density throughout inboard SOL region with B×∇B ↓**
  - Confirms measurements made via Stark Broadening at ASDEX (S. Potzel PSI2014)
  - Radial density gradient reversed for B×∇B ↑
- **Pressure higher at the target towards which the poloidal drift in the PFR is directed**
  - As predicted based on particle conservation and poloidal momentum balance (A. Chankin PPCF2015)



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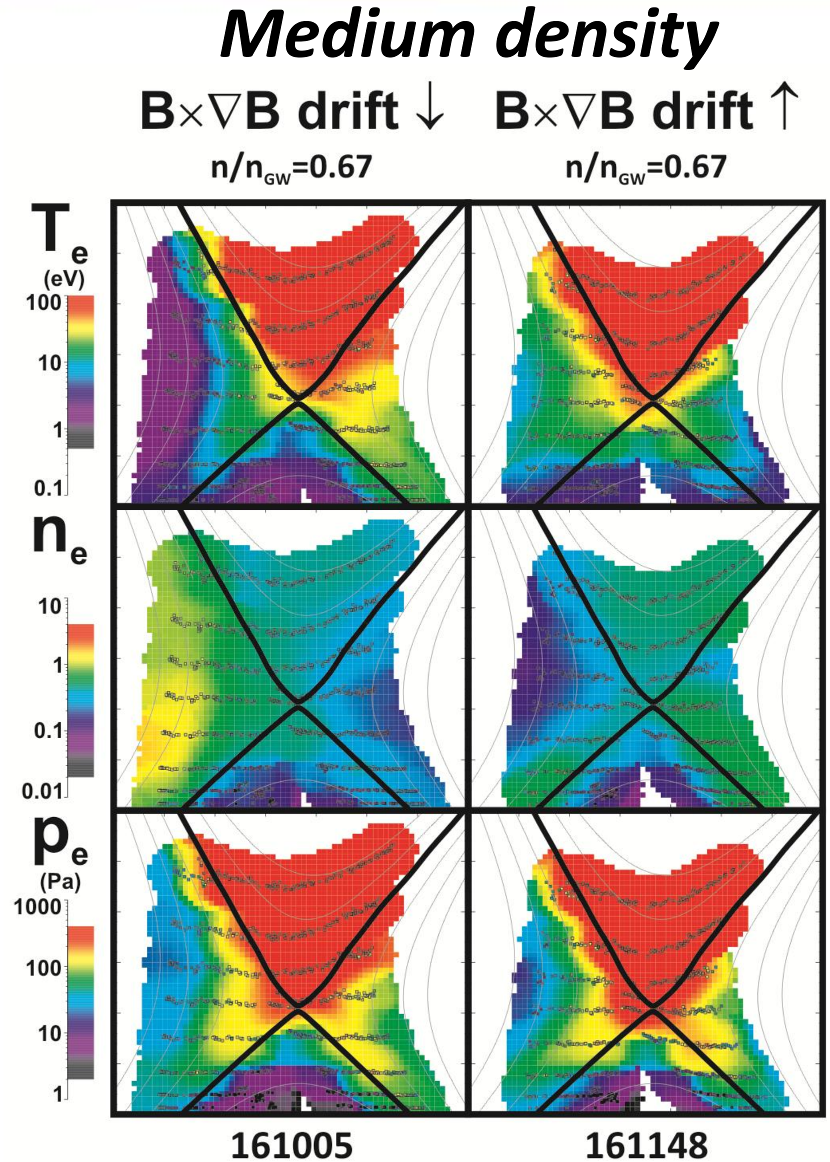
At Medium Densities, Drifts Weaken But Their Impact Remains Observable Upstream of the Targets

- Divertor Thomson Scattering (DTS) unique to DIII-D, capable of measurements of $0.5 < T_e < 5$ keV, $1\times10^{18} < n_e < 1\times10^{21}/m^3$
  - 4 MW H-mode, inter-ELM analysis only

- **Asymmetries in plasma parameters still evident with B×∇B ↓, abated asymmetry in B×∇B ↑**

- **Transition to detachment at higher density shown to minimize the role of drifts at the targets, but not upstream in the legs**



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At the Highest Densities, Impact of Drifts and Asymmetries are Minimal at the Targets

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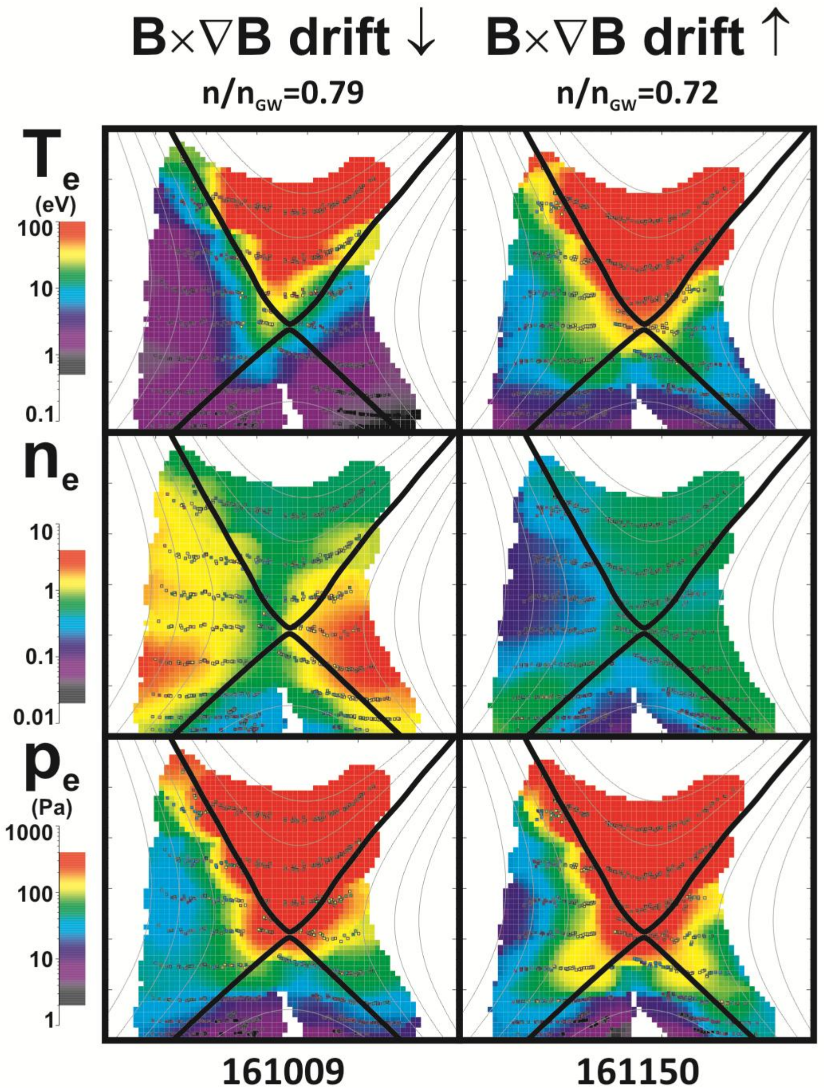
  - 4 MW H-mode, inter-ELM analysis only

- **Plasma parameters symmetrically cold/dense at the targets for both B×∇B ↓ and B×∇B ↑**

- **Sudden transition to cold/detached divertor throughout outer leg region for B×∇B ↓**
  - Smooth transition to detachment at both legs with B×∇B ↑

- **Results confirm earlier theory and modeling that show ExB creates a particle sink in the outer SOL-divertor and a particle source in the inner SOL-divertor for B×∇B ↓**
  - **A. Chankin, Plasma Phys. Cont. Fusion 57 (2015) 095002**

High density

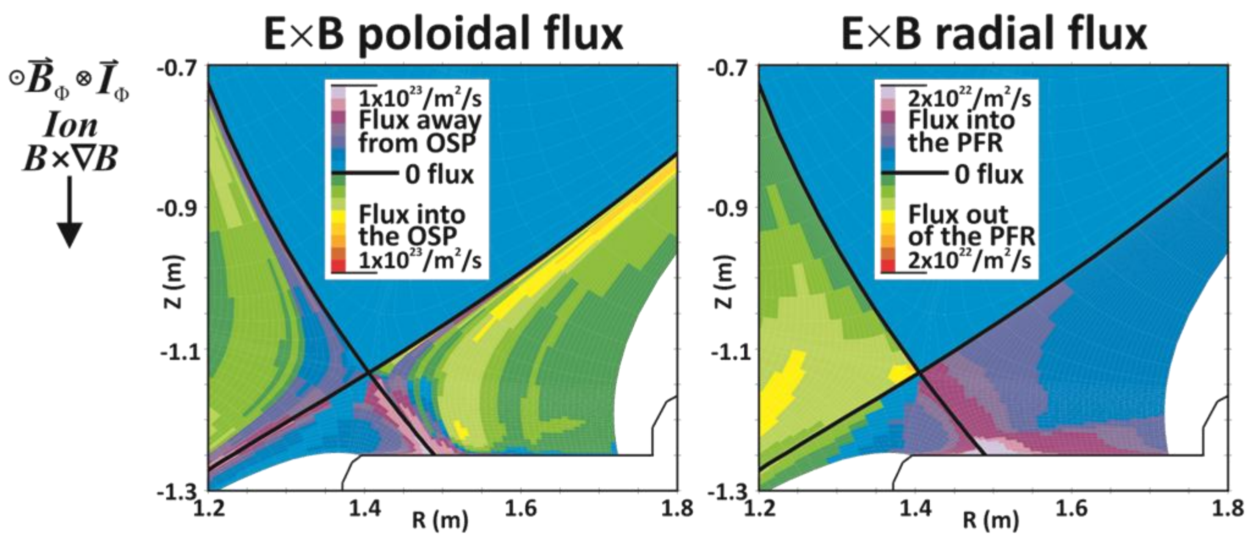


ExB Flow Velocities and Fluxes Calculated Directly From T_e and n_e Measurements Confirm Strong Role of Both Radial and Poloidal Drifts

- **2D ExB drift velocities are calculated from 2D DTS measurements using Ohm's Law for the parallel electric field using OEDGE for gridding and fitting data**
  - Can be done for any plasma (e.g., high power discharges)

- **Spatial derivatives of n_e and T_e used to calculate E, integrated along and across flux tubes to find v_{plasma}, multiplied by local n for particle fluxes**

- **Integrated poloidal and radial fluxes are found to be comparable in attached conditions, as suggested by theory and modeling**



P. Stangeby, PSI2016

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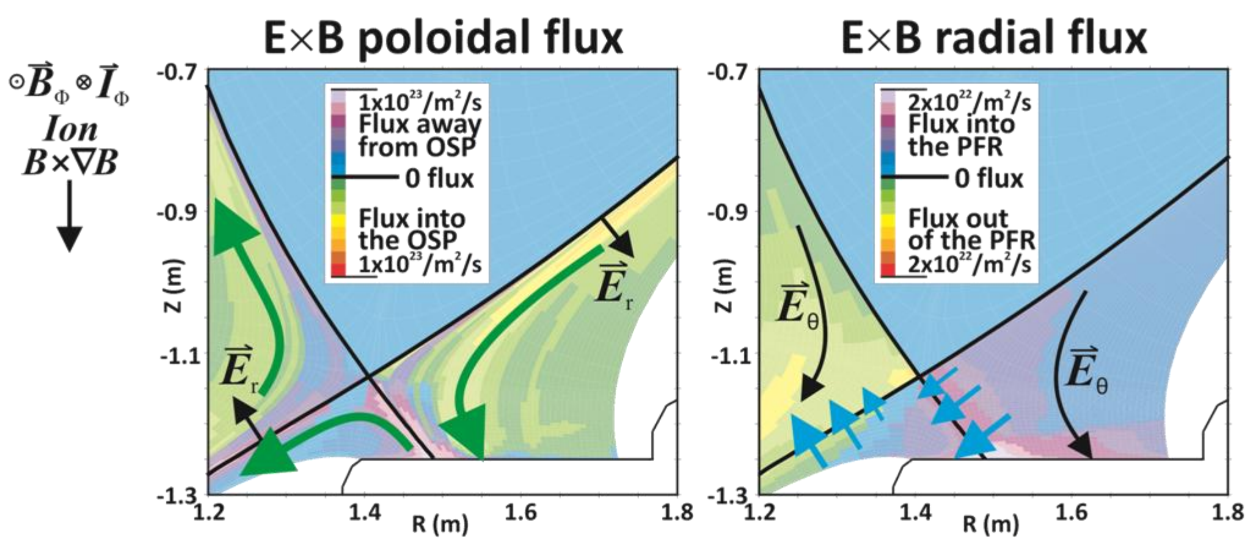
- **Integrated poloidal and radial fluxes are found to be comparable in attached conditions, as suggested by theory and modeling and fluxes match the expected drift pattern**



$\vec{E}_r \times \vec{B}$ = Poloidal drift

$\vec{E}_\vartheta \times \vec{B}$ = Radial drift

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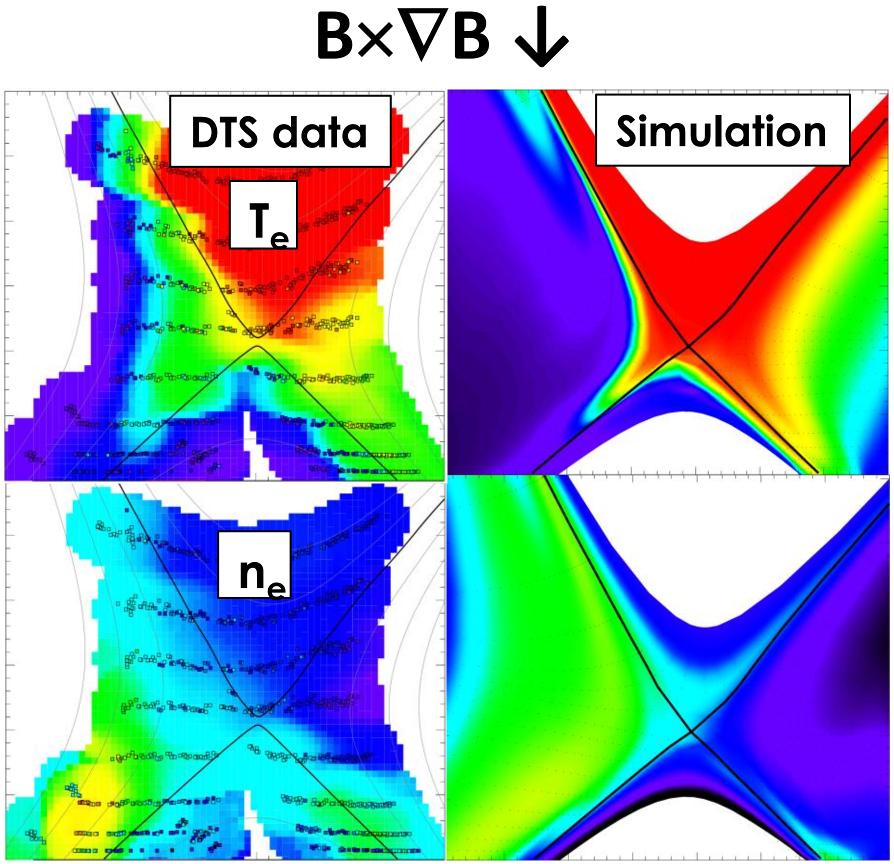
Modeling of DIII-D H-mode With B×∇B ↓ and ↑ Using UEDGE Confirms Relative Roles of Poloidal and Radial E×B on Asymmetries

- **UEDGE fluid model characteristics**
  - H-mode gradients; D=0.15 m^2/s, $\chi_{e,i}$=0.4 m^2/s
  - ***Full drift physics model included***
- **General characteristics in good agreement**
  - In/out radial shift in T_e, opposite direction for n_e
  - Partially attached ISP / well attached OSP
  - Target density peak inboard of the ISP
- ***Confirms strong role of E_θ×B and E_r×B drifts in asymmetry formation throughout the divertor region***



T. Rognlien, PSI2016
A. Järvinen, EPS2016

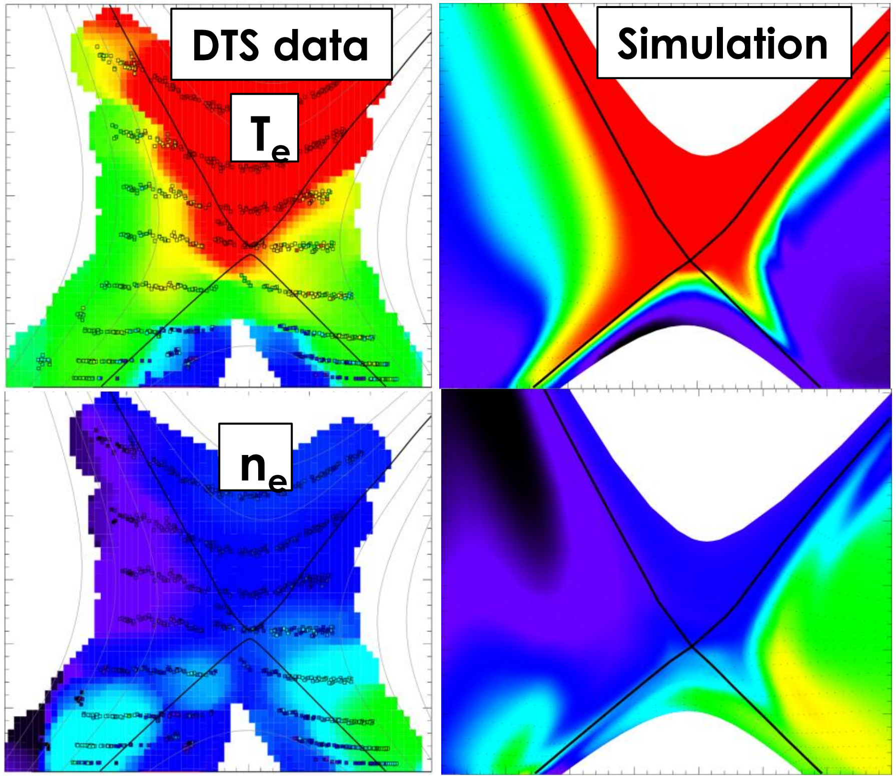
Modeling of DIII-D H-mode With B×∇B ↓ and ↑ Using UEDGE Confirms Relative Roles of Poloidal and Radial E×B on Asymmetries

- **H-mode gradients with drifts with B×∇B ↑ for the first time with UEDGE**

- **Again, general characteristics in good agreement**
  - Improved symmetry in both T_e and n_e
  - Stronger density peak outboard of the OSP
  - *Displacement of peak conditions from target separatrix relative to B×∇B ↑ case confirms role of drifts in target asymmetries*

- **Underscore the importance of including E×B effects in interpretive/ predictive boundary modeling**

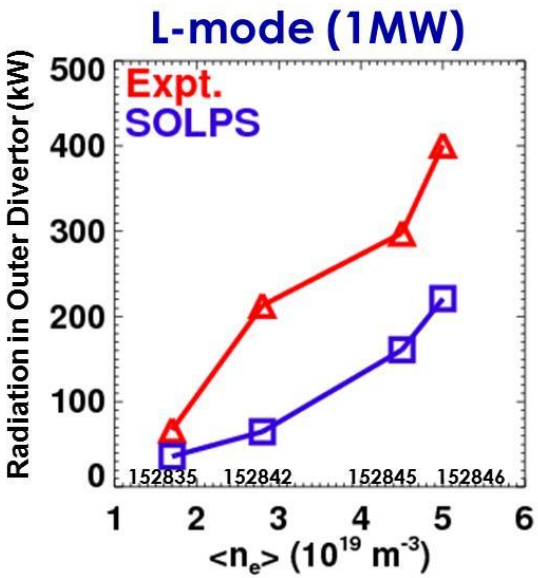
B×∇B ↑

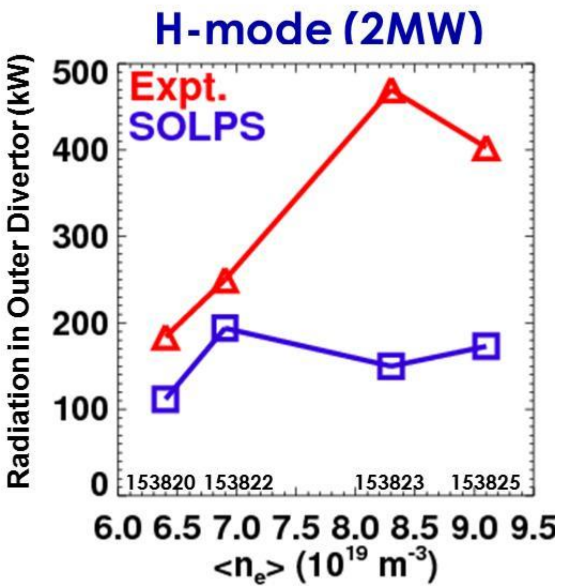


T. Rognlien, PSI2016
A. Järvinen, EPS2016

Matching Divertor Conditions and Eliminating Uncertain Molecular Physics Resolves Radiation "Shortfall"

- **Matching upstream conditions in fluid modeling leads to a shortfall in divertor radiated power relative to experiment**
- **Common result for DIII-D, JET, ASDEX**
  - Multiple Braginskii fluid codes and wall materials
    - **M. Groth, JNM2011 (UEDGE/DIII-D)**
    - **A. Järvinen, PPCF2016 (EDGE-2D+EIRENE/JET)**
    - **F. Reimold, PSI2016 (SOLPS/ASDEX)**
    - **J. Canik, PSI2016 (SOLPS/DIII-D)**
- **For DIII-D, both SOLPS and UEDGE modeling of D+C plasmas have shown this shortfall**
  - L- and H-mode, all values of n/n_{GW}





J. Canik, PSI2016
J. Canik, APS2016

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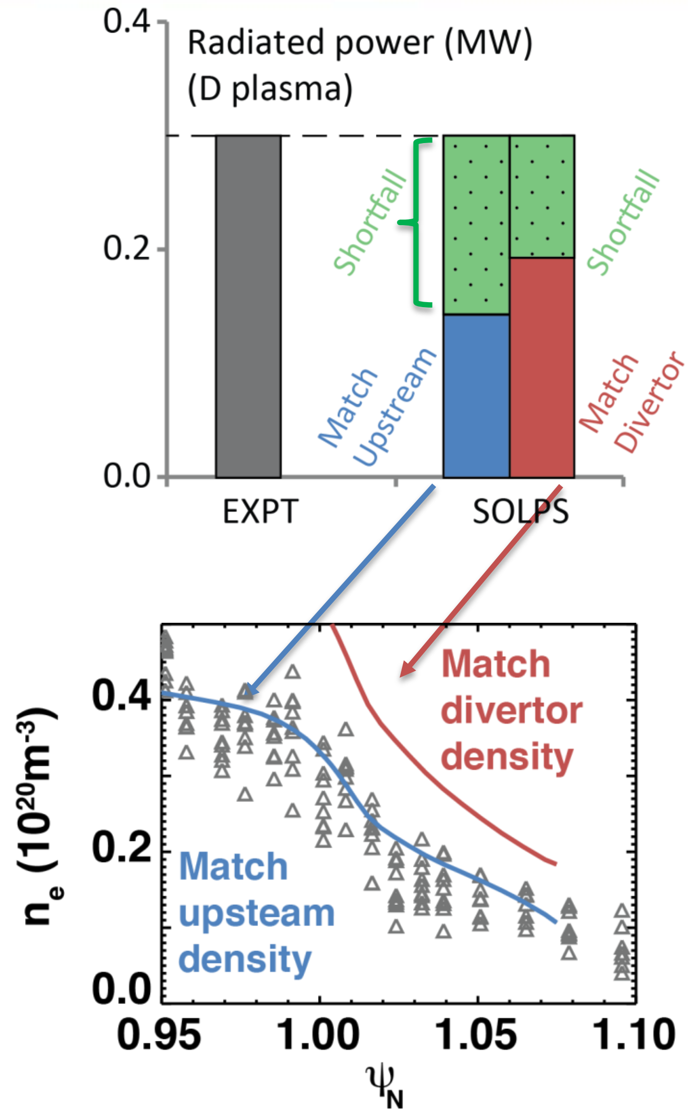
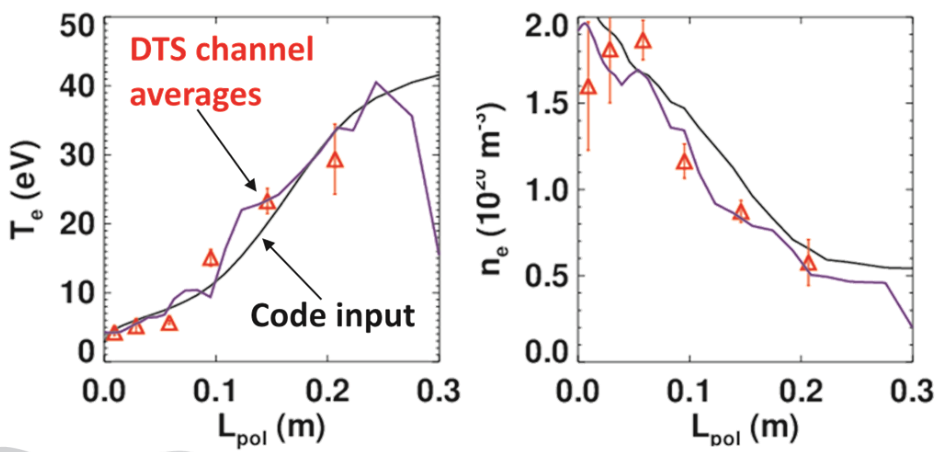
Matching Divertor Conditions and Eliminating Uncertain Molecular Physics Resolves Radiation "Shortfall"

- **However, the shortfall can be reduced using divertor plasma parameters from DTS (2D T_e and n_e) as input**
  - Allow upstream conditions to vary
- **Suggests improvement needed in parallel physics model**
  - Possible ion contribution to pressure/ momentum





J. Canik, APS2016

Matching Divertor Conditions and Eliminating Uncertain Molecular Physics Resolves Radiation "Shortfall"

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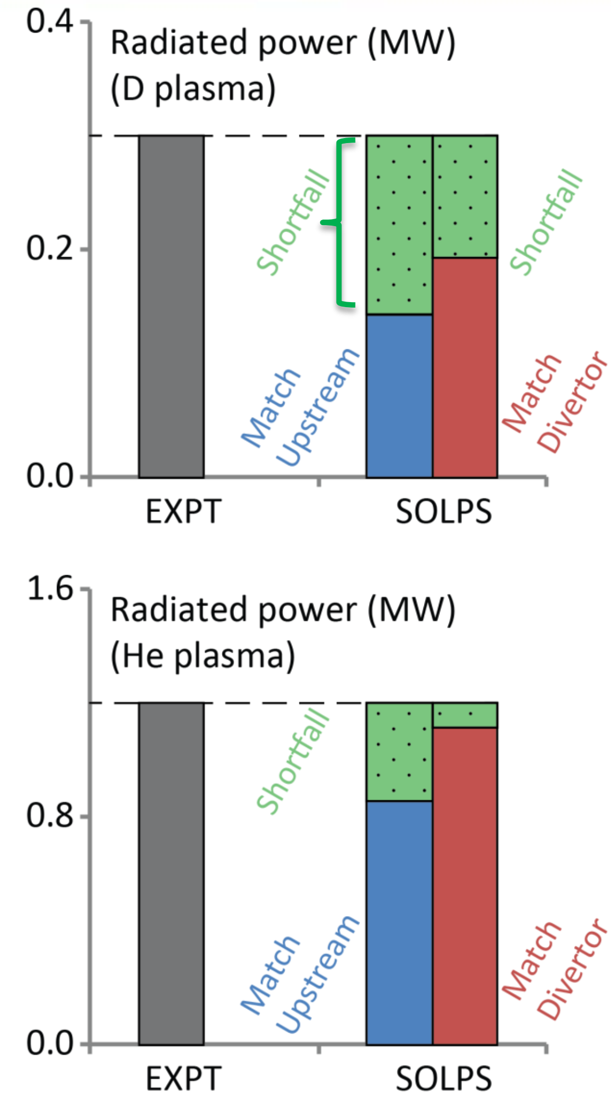
  - Allow upstream conditions to vary
- **Suggests improvement needed in parallel physics model**
  - Possible ion contribution to pressure/momentum
- **Additionally, the P_{rad} shortfall may be eliminated combining this technique with helium plasmas**
  - Removes uncertainty in hydrocarbon atomic/molecular physics
  - Consistent with result of M. Wischmeier, JNM2003 (B2.5-EIRENE/JET He plasma)



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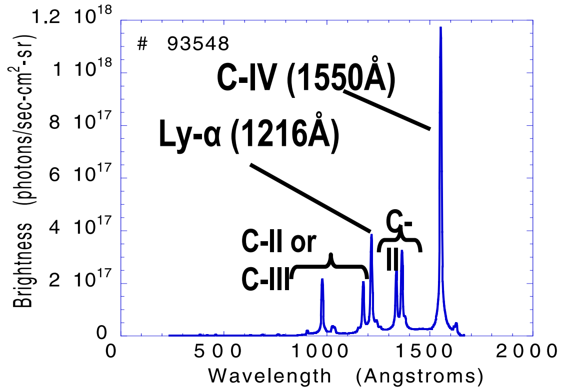
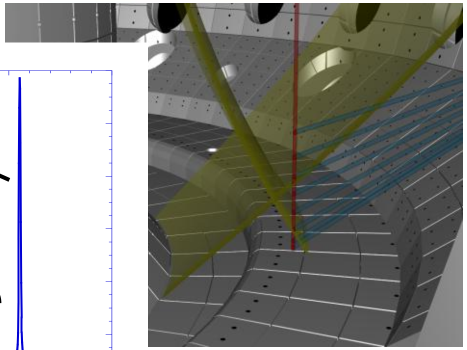
Conclusions: Experiments With B×∇B ↓ and ↑ Provide Direct Evidence that Poloidal and Radial E×B Drifts Strongly Contribute to Target Asymmetries

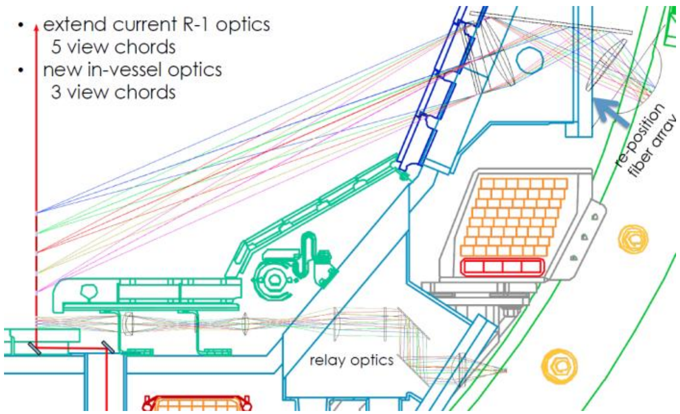
- **Measured 2D divertor plasma parameters are directly interpreted to deduce poloidal and radial components of electric field, potential, and particle fluxes**
- **State-of-the-art fluid modeling in H-mode with a full drift model confirms major plasma characteristics**
  - Implications for heat flux control near a partial detachment operating point
- **A persistent/universal shortfall of radiation found with 2D edge fluid modeling of multiple machines and wall materials is improved using divertor conditions as input**
  - Modeling of He discharges suggests a combination of molecular physics and parallel transport are the cause
- **Comprehensive studies with extensive diagnosis provide valuable physics insight**
  - Demonstrates value of systematic parameter scans, necessity of physics inclusion in modeling

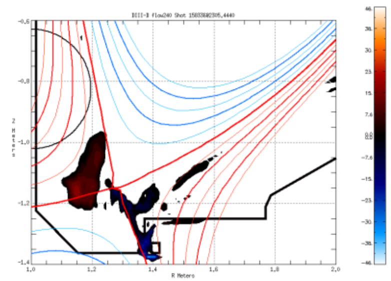
Future Plans in Divertor Science on DIII-D

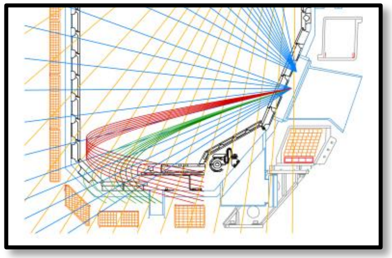
- **Addition of divertor EUV/VUV SPRED for fuel and impurity concentrations**
  - Direct measurement of radiative losses, and component concentrations
  - View coincident with DTS/spectroscopy
- **Divertor Thomson upgrades in progress**
  - Redirection of beam and collection optics to measure in high triangularity
  - Measurement frequency doubled to 100 Hz (2nd laser)
- **Flow interferometry in regular use**
  - CII/CIII/HeII parallel flow field
  - Improved calibration method implemented
- **Planned upgrade for divertor bolometry**
  - Addition of two high resolution fans in the lower divertor







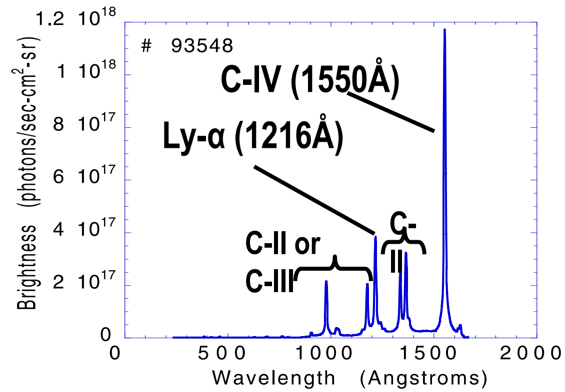


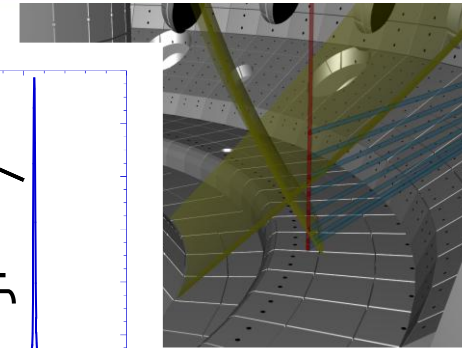


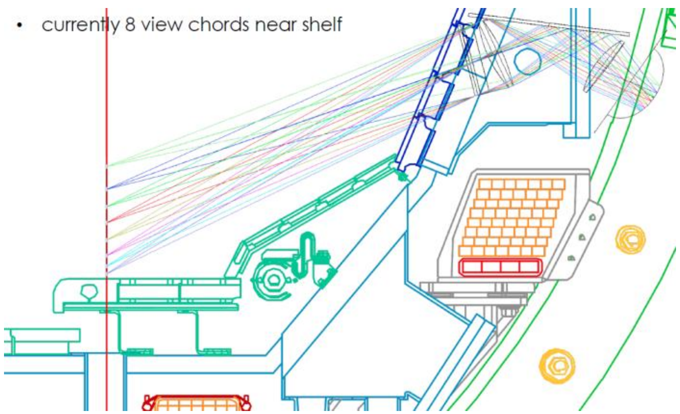
DIII-D NATIONAL FUSION FACILITY

Future Plans in Divertor Science on DIII-D

- **Addition of divertor EUV/VUV SPRED for fuel and impurity concentrations**
  - Direct measurement of radiative losses, and component concentrations
  - View coincident with DTS/spectroscopy
- **Divertor Thomson upgrades in progress**
  - Redirection of beam and collection optics to measure in high triangularity
  - Measurement frequency doubled to 100 Hz (2nd laser)
- **Flow interferometry in regular use**
  - CII/CIII/HeII parallel flow field
  - Improved calibration method implemented
- **Planned upgrade for divertor bolometry**
  - Addition of two high resolution fans in the lower divertor

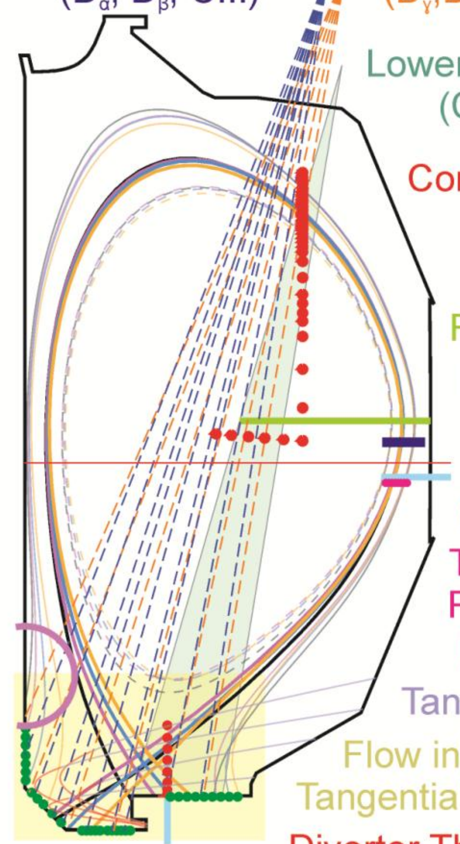






Backup slides

DIII-D includes extensive lower divertor/boundary diagnostic coverage valuable for study of drift impact in attached and detached plasmas



- **Improved 2D profiles of T_e, n_e, e-pressure from DTS**
- **Upstream profiles from core Thomson scattering, reciprocating (RCP), charge-exchange (CER), reflectometry**
- **Target particle flux from Langmuir probe array (LP) and visible cameras (DiMES TV)**
- **Heat flux from IR TV (floor view, and periscope IRTV with full poloidal view)**
- **Line emission profiles from PMT and visible divertor spectrometer arrays, tangential-viewing cameras (1D and 2D)**
- **Toroidal impurity flows measured with interferometric cameras and tangential-viewing spectroscopy (1D and 2D)**
- **Bolometer total radiation**
- **Neutral pressure measured with ASDEX ionization gauges in divertor and outer midplane**

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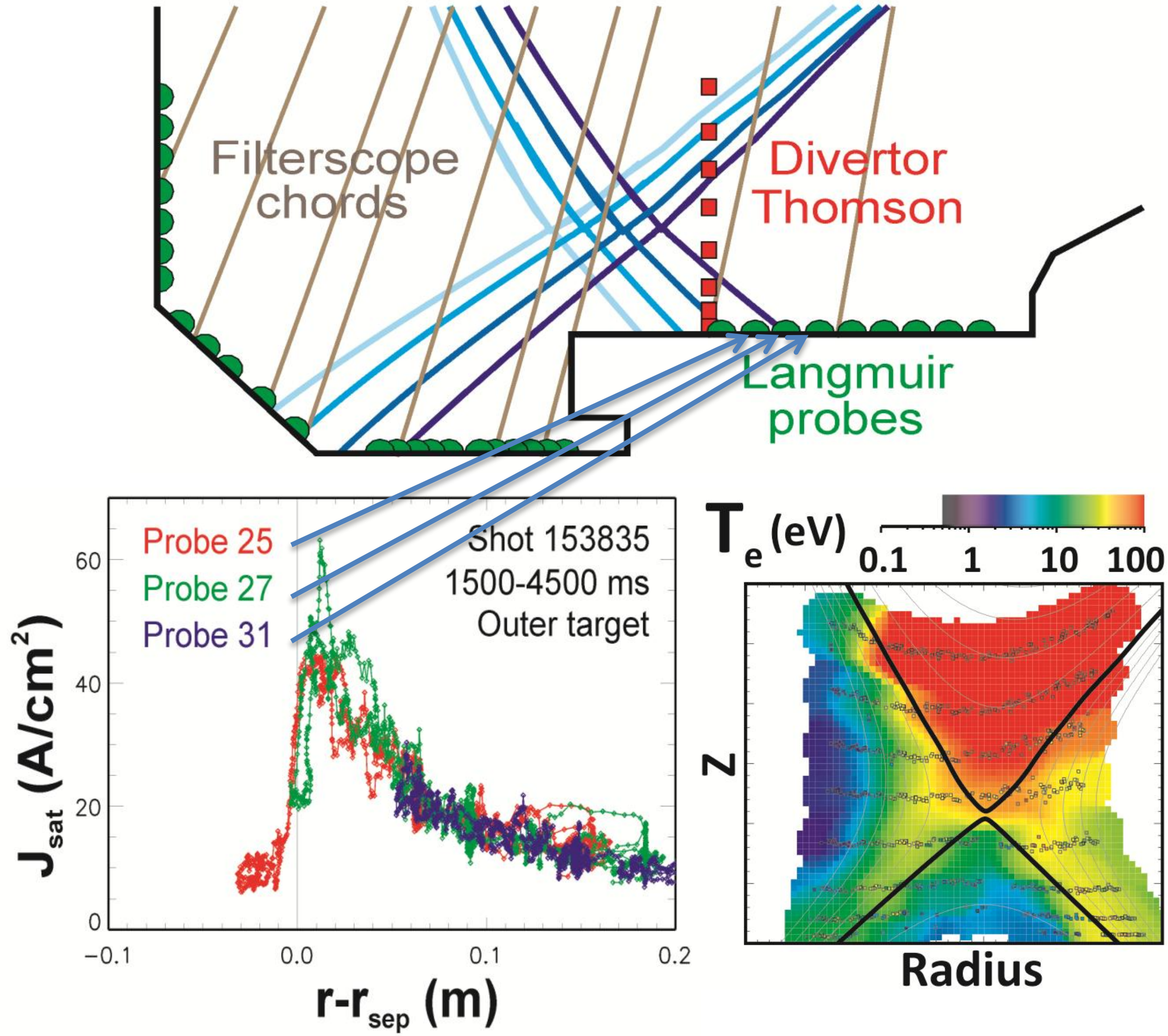
Strike Point Sweeping With Constant Divertor Conditions is Used to Extend 1D Measurements To 2D

- **DIII-D employs an open lower divertor, graphite first-wall tiles, and frequent conditioning**
- **Measurement of continuity in divertor conditions verified with mapped data from**
  - Langmuir probes
  - Multichannel spectroscopy
  - Heat flux profiles
- **Each step in the sweep used to reconstruct a 2D DTS profile**



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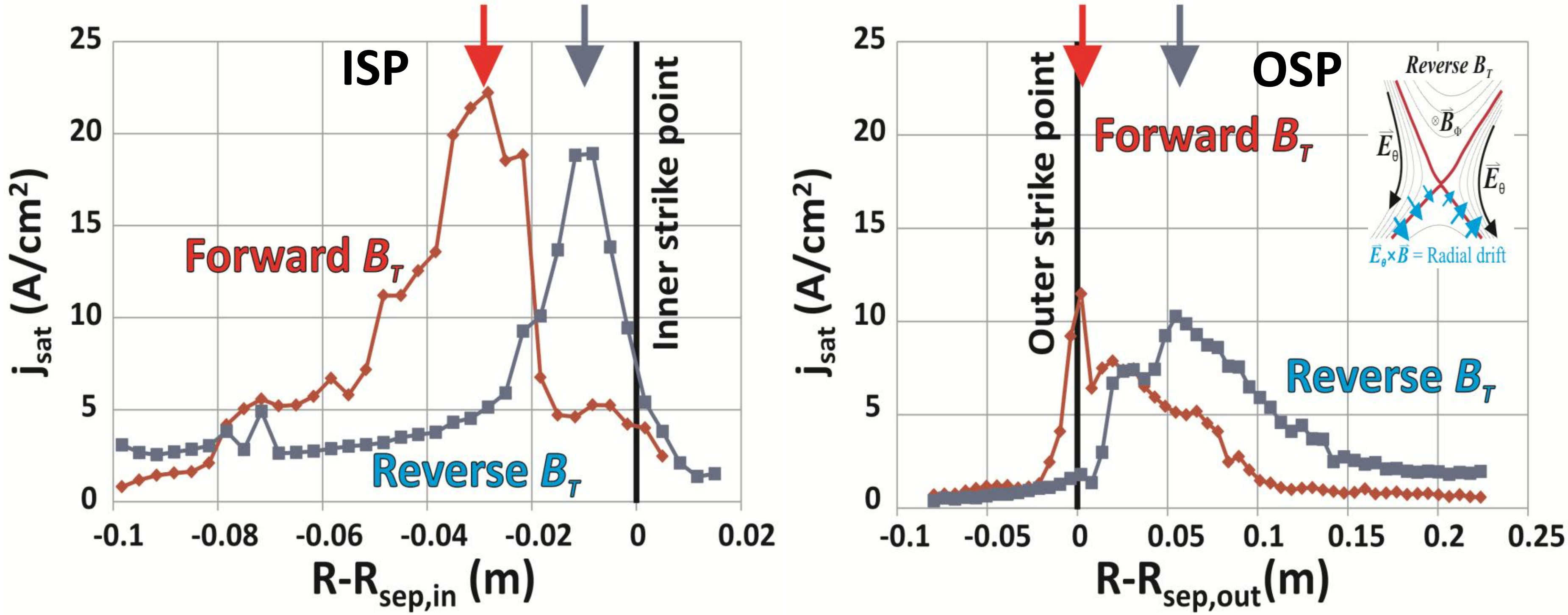
Langmuir Probes Demonstrate Shifts of j_{sat} and Plasma Potential as the B Field Reverses which Reduce as Density Increases

- **J_{sat} profiles shifted inward in forward B_T relative to reverse consistent with radial E×B drift direction**
- **Smallest shift when poloidal temperature gradient is the least ($E_\theta \propto dT/ds$)**
  - Simultaneous drop in plasma potential measured by the probes

Low density, n/n_{GW}=0.6



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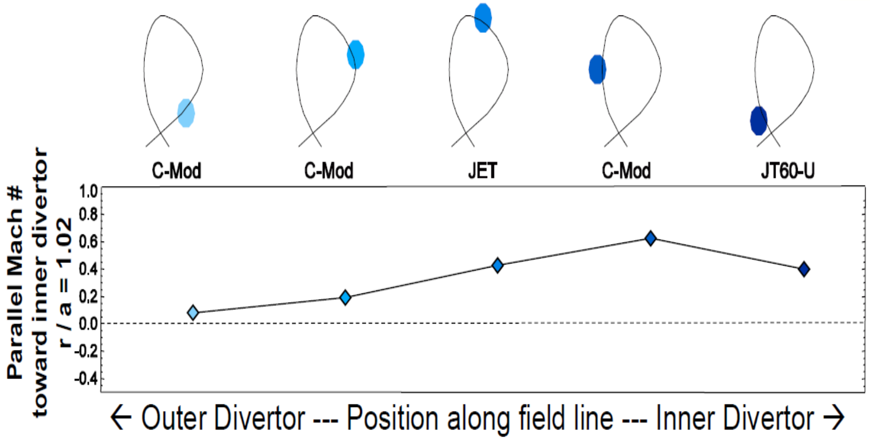
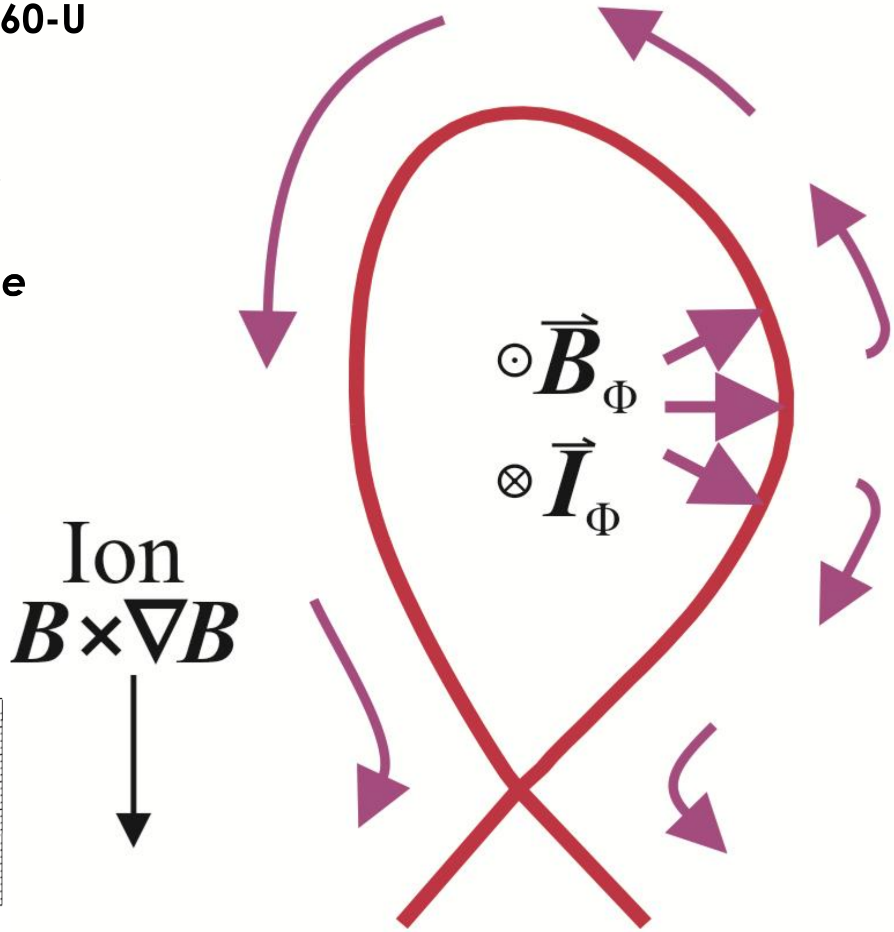
Strong ballooning-like parallel transport from the outboard midplane drives parallel flow around the SOL

- **Dominant cause of Mach~0.5 flow observed in plasma crown and HFS of C-Mod, JET, JT60-U and DIII-D**
  - *Smick, Nucl. Fusion 53 (2013) 023001.*
  - *Stangeby, J. Nucl. Mater. 415 (2011) S278.*
- $\nabla \cdot V_\theta + \nabla \cdot V_r = 0$
- ***Stagnation point near outboard midplane***
- ***Flow direction not dependent on B***



Smick and LaBombard, PSI2010



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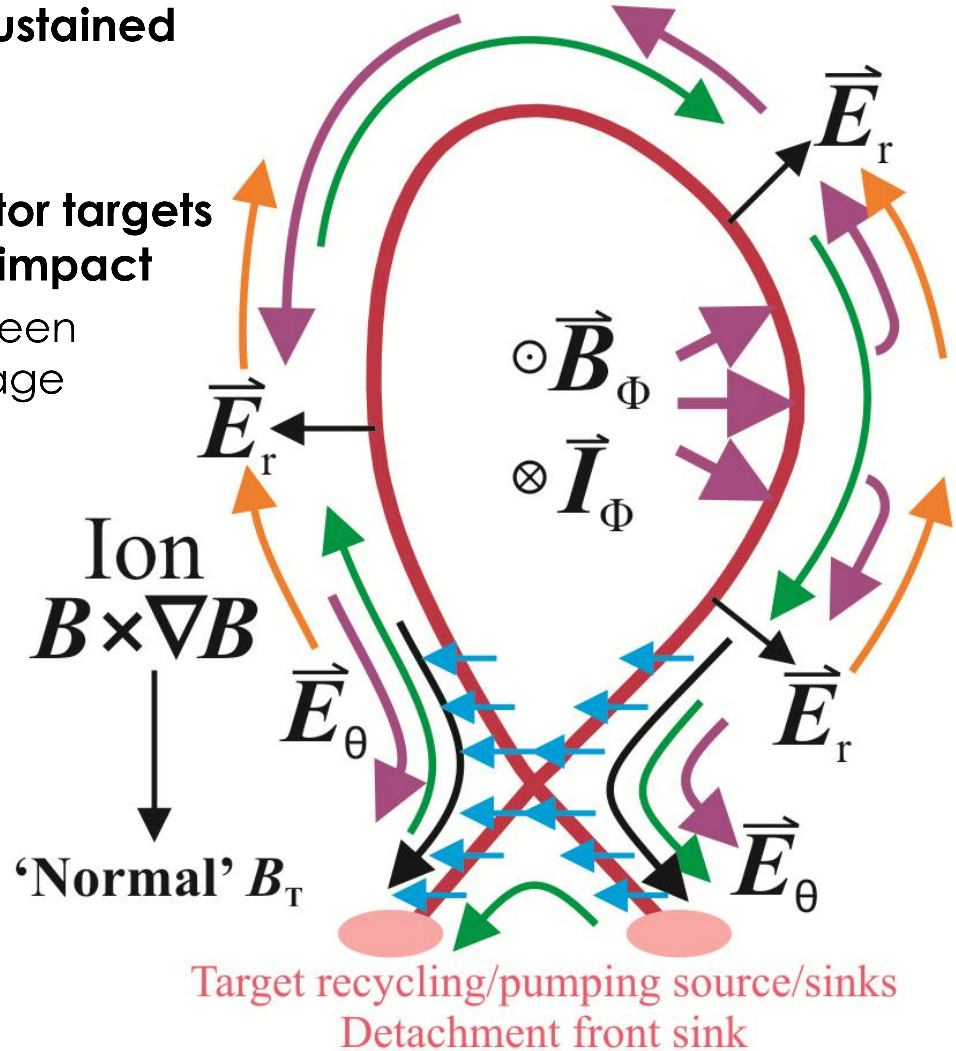
Together, transport (parallel) and drift-driven (perpendicular) forces lead to a complex picture of particle/power flows around a tokamak

- **Net poloidal rotation in the SOL gives rise to ion parallel Pfirsch-Schlüter flows sustained by up-down pressure asymmetry**

- **Ionization-driven flows at the divertor targets can additionally have large scale impact**
  - Flow reversal and coupling between divertor legs due to neutral leakage

- **Flows caused by ∇B and centrifugal drifts, related to gradients of *p/e*BR, are relatively small**
  - Pressure near equilibrium
  - Scale as 1/major radius compared to ExB which scales as 1/plasma scale length (L_p<<R)
  - Small variations in geometric volume factor R



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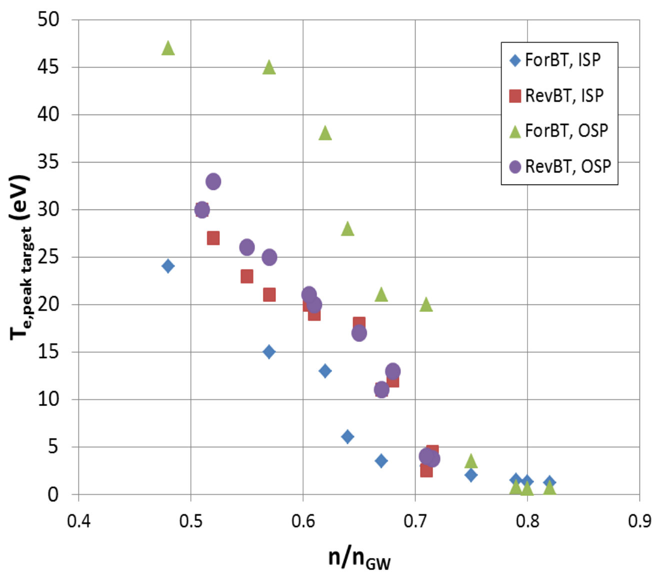
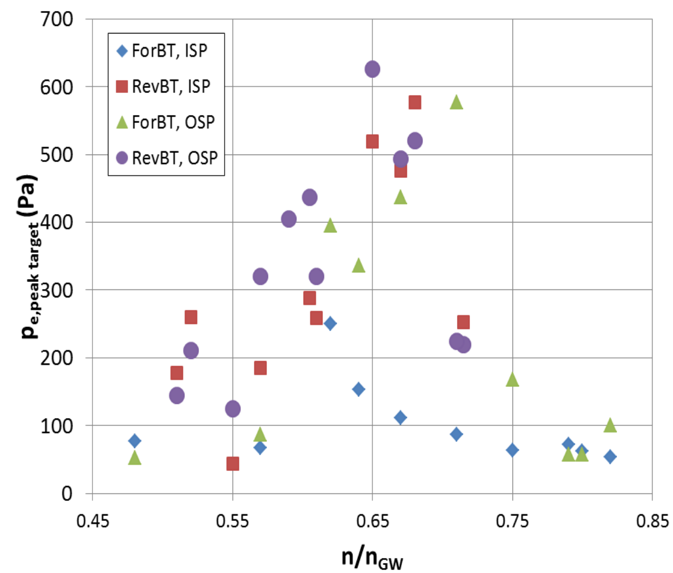
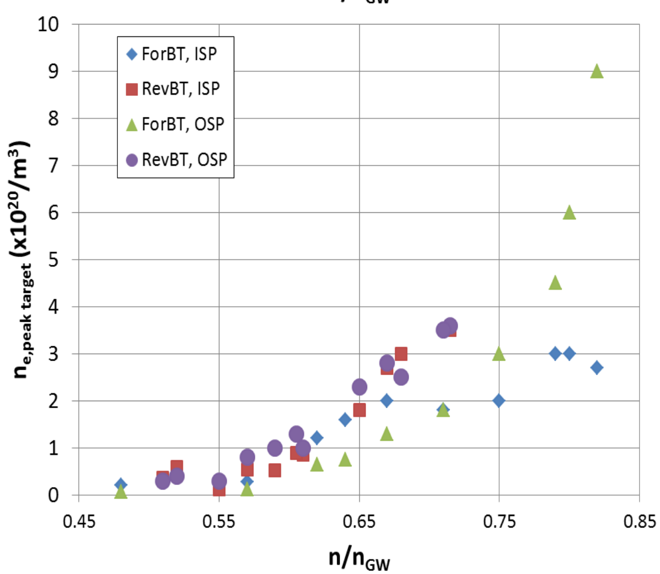
Peak plasma conditions at the outer target, forward vs reverse B_T



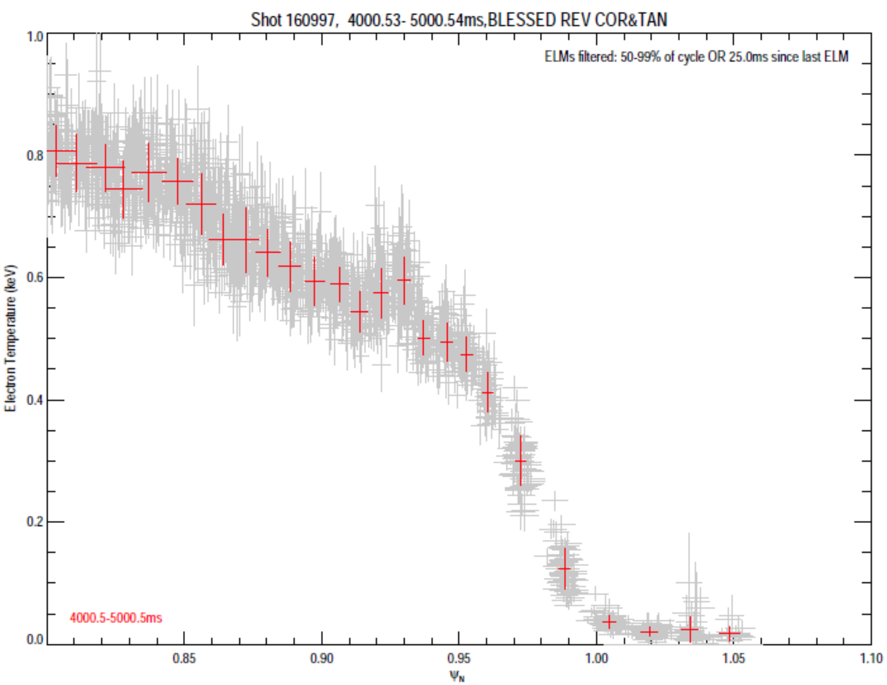




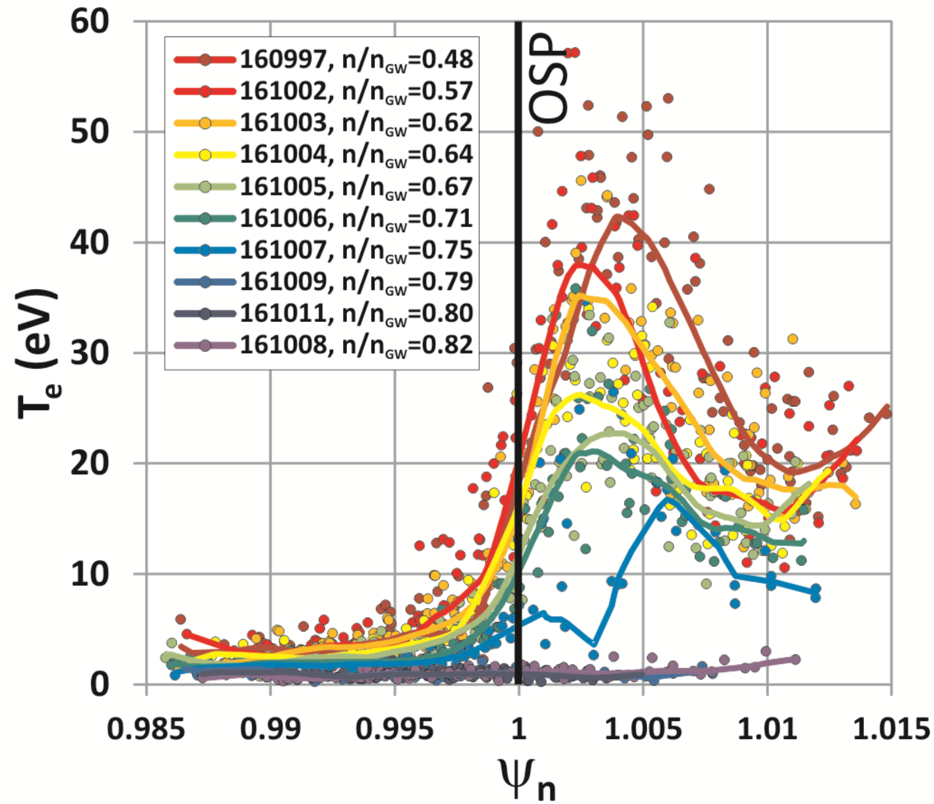
- **T_e cliff in fwdB_T associated with ~10X drop in p_e (n/nGW=0.72-0.78)**
  - Largest fraction of drop in p_e occurs when T_e drops from 4 to 1 eV, not ~20 to 4 eV
- **OSP detached in revB_T does not have unusual drop in p_e**
- **Symmetry in revB_T ISP/OSP peak values apparent compared to fwdB_T**

Raw Thomson data shows the influence of fluctuations captured by the system

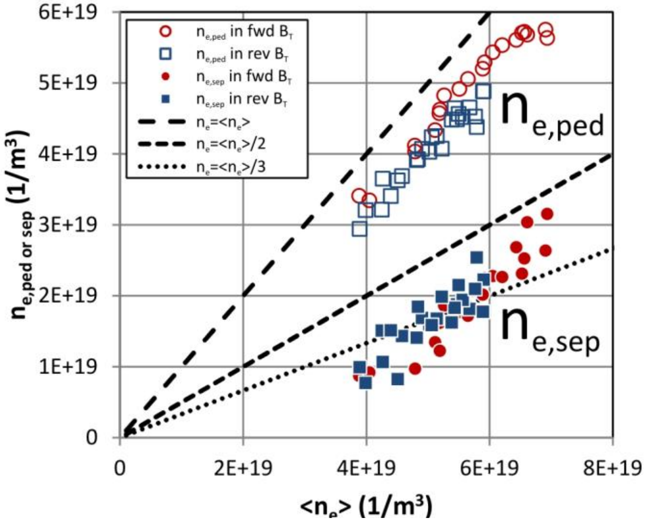
Core/pedestal system

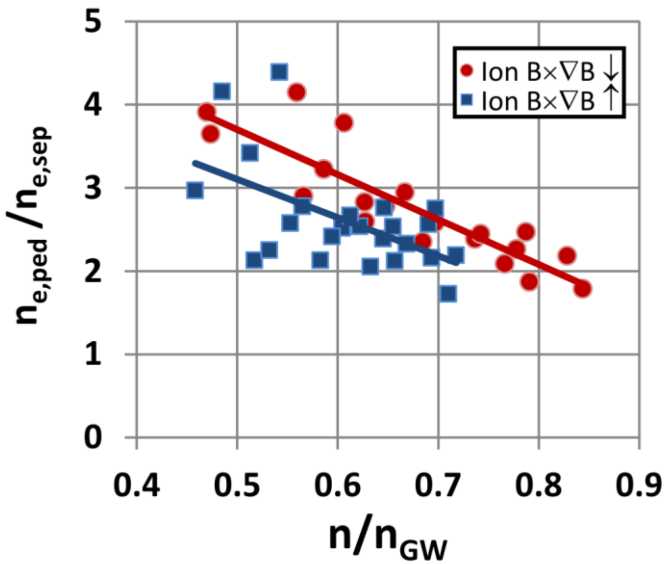


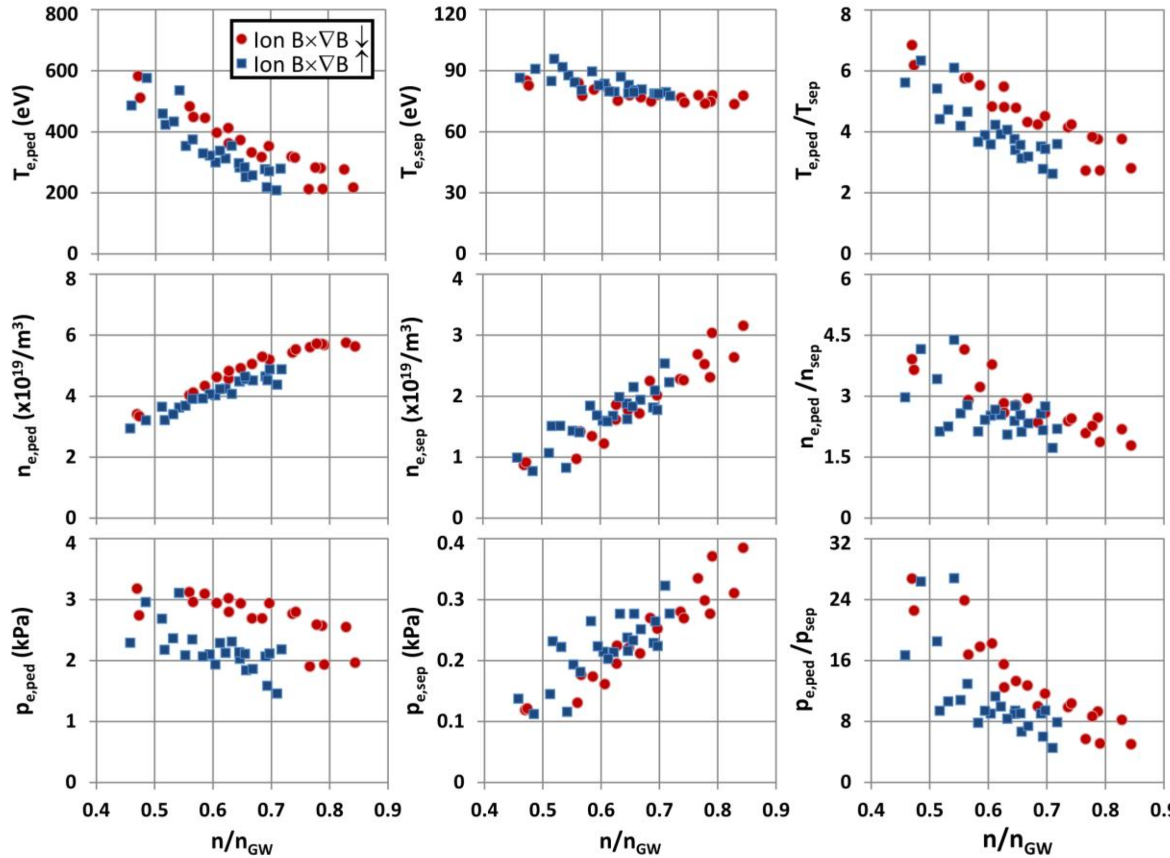
Divertor system



Upstream/pedestal profiles demonstrate minor but systematic differences between fwd/rev Bt through the transition to detachment

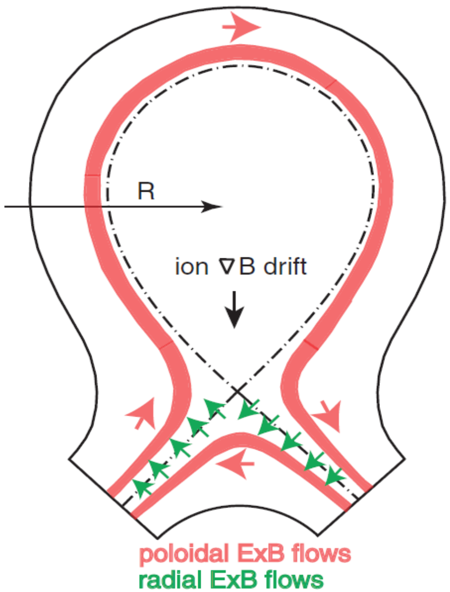


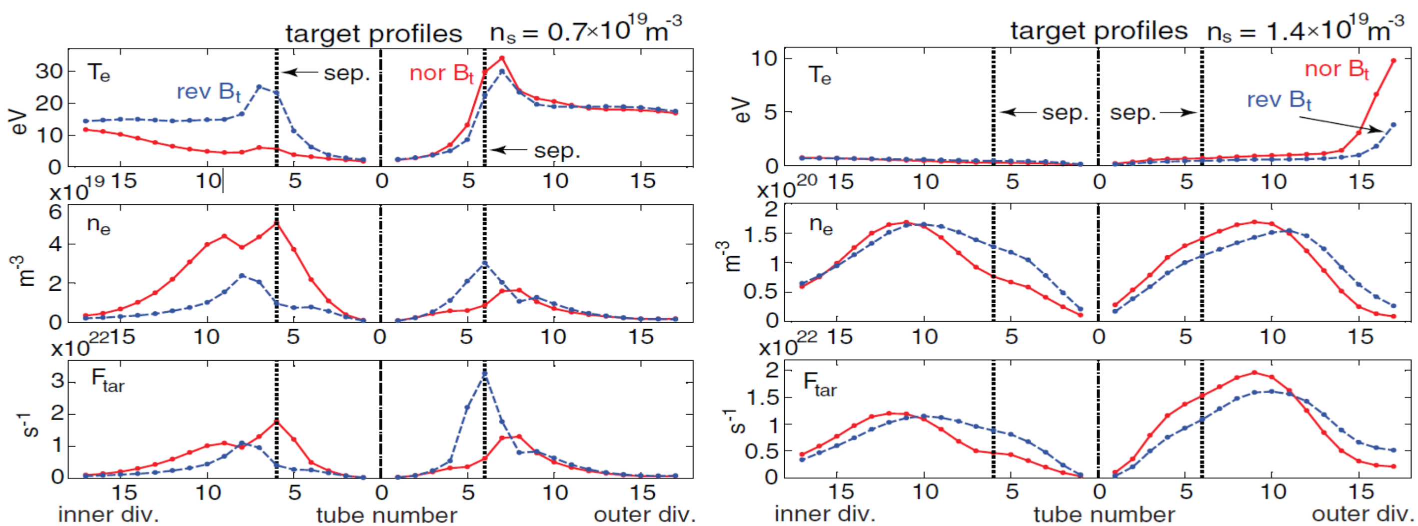




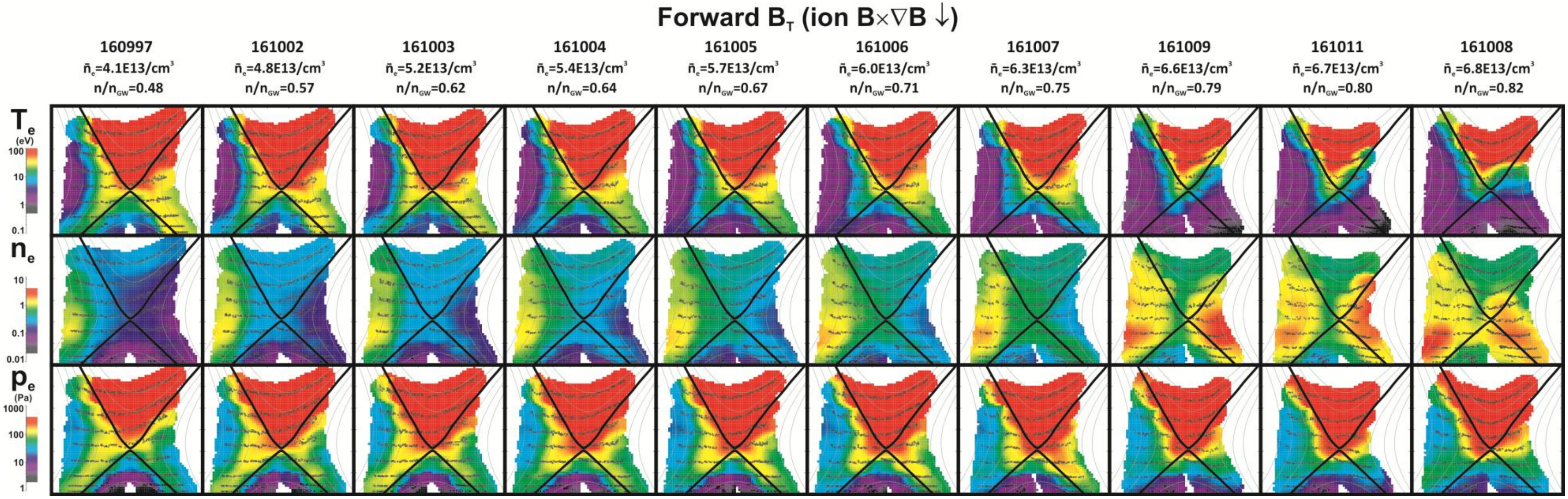
Recent modeling of JET strongly suggest $E_\theta x B_\phi$ radial drift component is dominant prior to detachment onset

- Chankin/Groth JET EDGE2D results
- 2D edge fluid code of L-mode discharges with drifts included predict influence of Bt reversal on divertor and target asymmetries
- Analysis of convective fluxes caused by poloidal and radial ExB drifts
- Crucial role of radial ExB drift in influencing asymmetries
- Opposite to the result expected if poloidal ExB drift was dominant in the divertor





DTS: Forward B_T (B x gradB down)



- 10 step series, n/n_{GW}=0.48 to 0.82
- Both targets attached to ~0.62
- Inner target detaches smoothly from ~0.62 to 0.75
- Outer target detaches suddenly from 0.75 to 0.79 (5% increase in $n_{e,bar}$) – "Te cliff"
- Significant radial n_e gradient; highest at inboard from lowest n_e to n/n_{GW}~0.75
- Jump in p_e throughout divertor at high recycling onset (0.57 to 0.62), slow decrease at inner target, jump down at outer target at point of detachment

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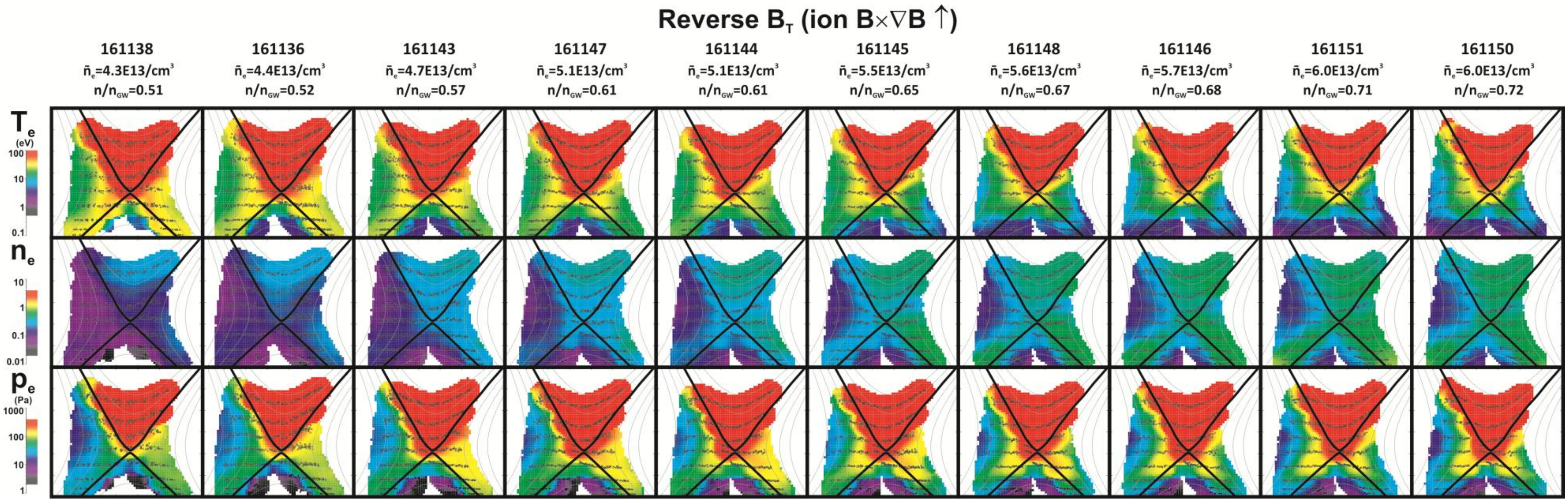
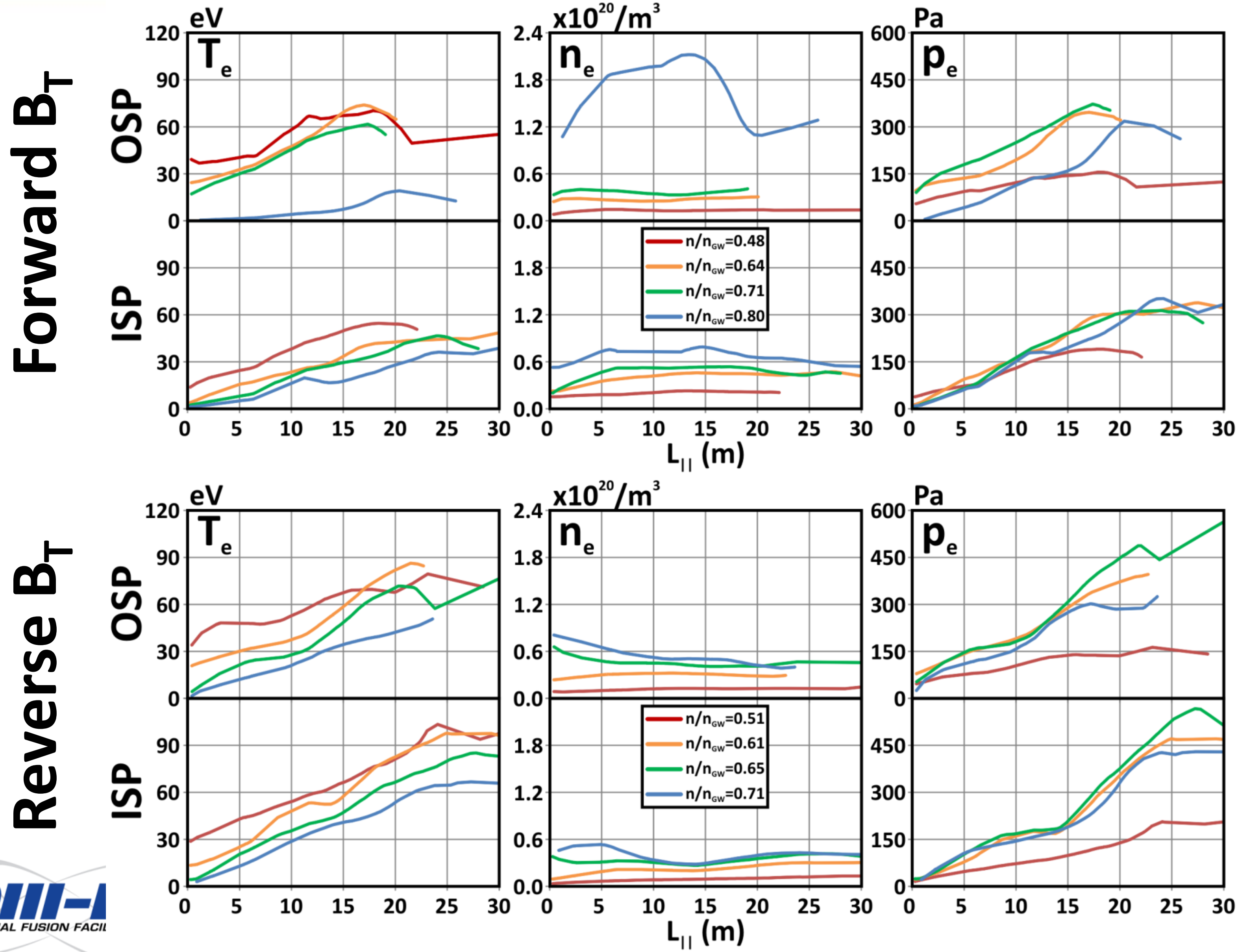
DTS: Reverse B_T (B x gradB up)

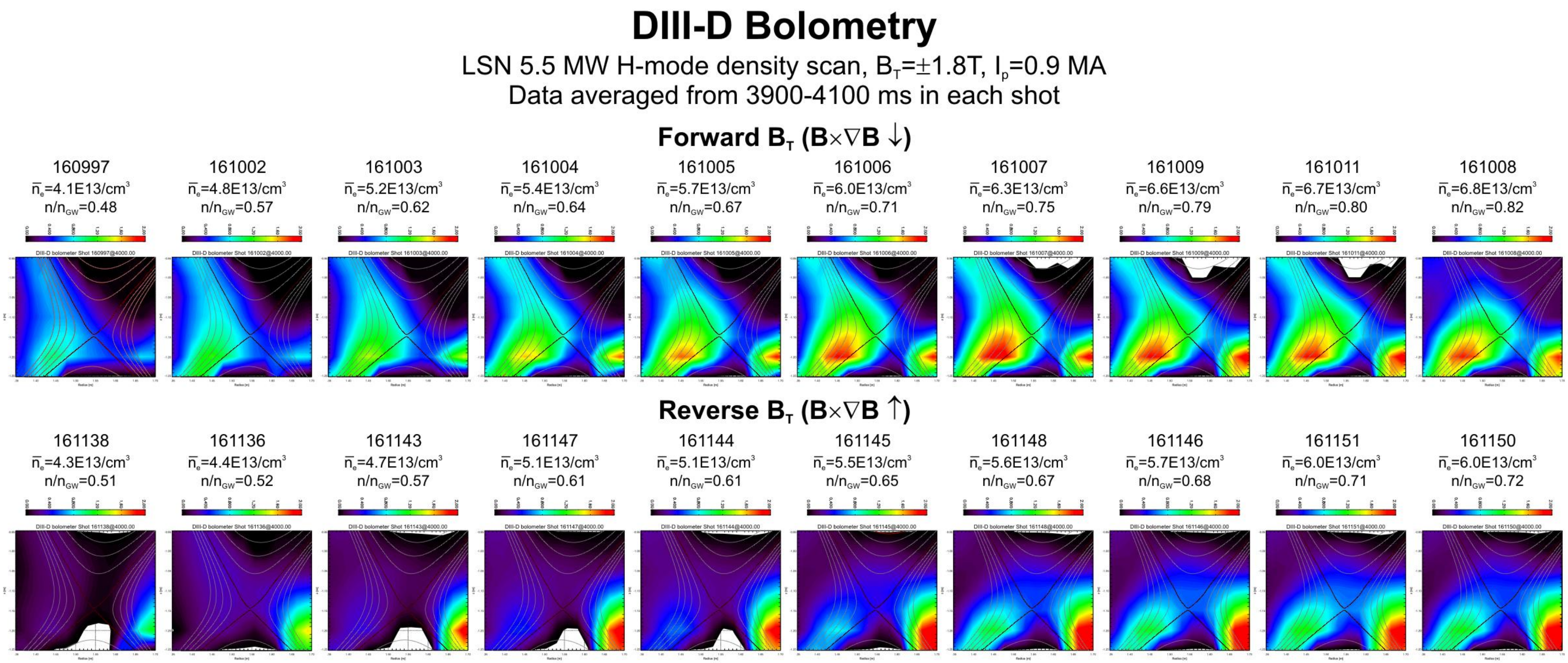


- **10 step series, n/n_{GW}=0.51 to 0.72 (compared to 0.48 to 0.82 in fwdB_T)**
  - Higher density attempts caused plasma to drop out of H-mode in revB_T
- **Both targets attached to ~0.61 (compared to ~0.62 in fwdB_T)**
- **Both targets detach together starting near ~0.65-0.67 (~same as inner target in fwdB_T case)**
- **Smaller ne gradient, but upwards at higher major radius (i.e., wider low field side SOL)**
- **p_e climbs then drops slowly at both targets**

DTS-measured parameters vs. $L_{||}$ demonstrate sudden transition to detachment along the entire OSP leg for fwd B_T



Bolometry



- **Same shots as in DTS series data (forward and reverse B_T)**
- **Inversion of data from 3900-4100 ms (ELM-averaged), both targets on the shelf**

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