Power and particle sharing in double null outer divertors

Jonathan H. Yu[1]

B. Grierson[1], J. Guterl[1], A.W. Leonard[1], R. Maurizio[1], A. McLean[2], X. Ma[1], M. Shafer[3], D.B. Weisberg[1]

1 General Atomics, San Diego, CA, USA
2 Lawrence Livermore National Laboratory, Livermore, CA, USA
3 Oak Ridge National Laboratory, Oak Ridge, TN, USA

yujh@fusion.gat.com

Presented at the
IAEA Technical Meeting on Divertor Concepts

November 7-10, 2022

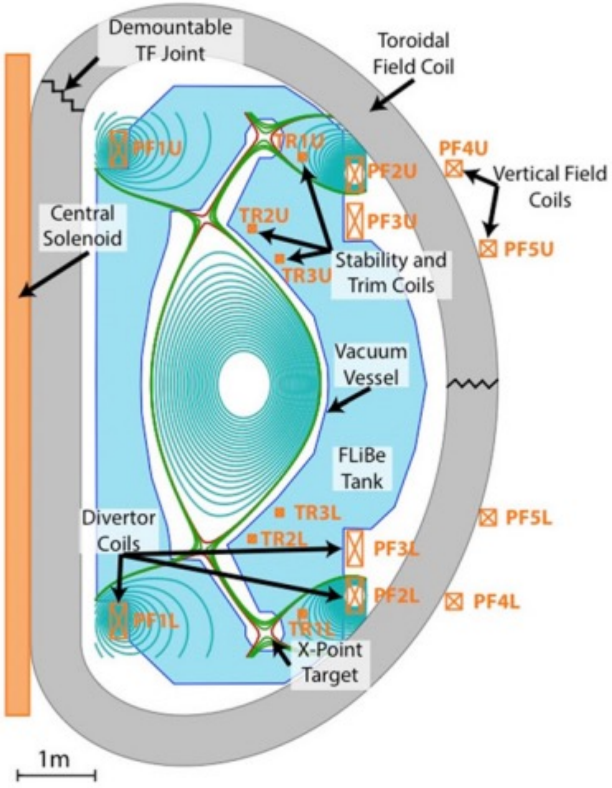
DN has potential advantages and drawbacks for future high performance tokamaks

- **DN advantages**
  – More efficient fueling and better energy confinement (Petrie PSI 2014)
  – Power sharing among two outer divertors
  – Allows strong plasma shaping for core/pedestal performance
- **Drawbacks of DN**
  – Reduced volume for core plasma
  – Challenge to control magnetic balance near DN → consequences for power sharing

Motivation: Need to predict where power and particles go for successful reactor operation

What drives up-down asymmetry of power and particle flows?

DN reactor concepts: UWMAK-I, CIT, ARIES designs, BPX, FIRE, K-DEMO, STEP, ARC



ARC, Kuang FED 2018

Outline

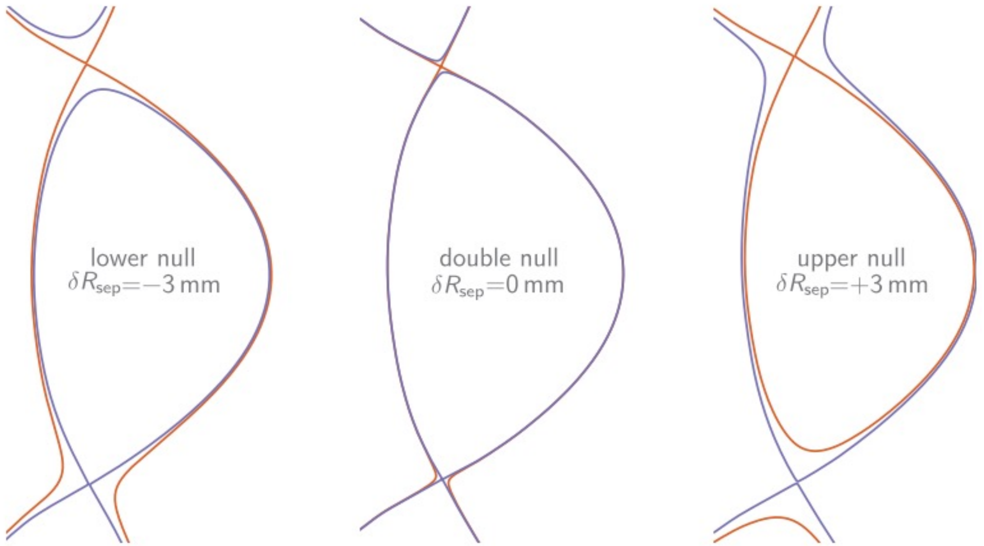
- Up-down symmetry breaking (2D)
  - Magnetic imbalance
  - Particle drifts
  - Pumping or gas injection in only one divertor
  - Asymmetry of divertor wall geometry
- SOLPS-ITER modeling of DIII-D and a conceptual high-field compact tokamak
- Modeling challenges

Any symmetry-breaking effect leads to power sharing imbalance

- **Large (factor of ~<10*) in-out asymmetry of heat and particle fluxes**
  LFS ballooning transport + inner and outer SOLs magnetically disconnected

Causes of up-down asymmetries ← this talk

- **Magnetic imbalance (dRsep ≠ 0)**
- **Drifts:** inherent symmetry-breaking
  - **B** x ∇B
  - **E** x **B**, poloidal and radial
- **Pumping or gas injection in only one divertor**
- **Asymmetry of divertor wall geometries**
- **Asymmetry of magnetic shapes ← not discussed here**



Brunner et al., NF 2018

Different divertor conditions → feedback on SOL flows and exacerbate the asymmetry

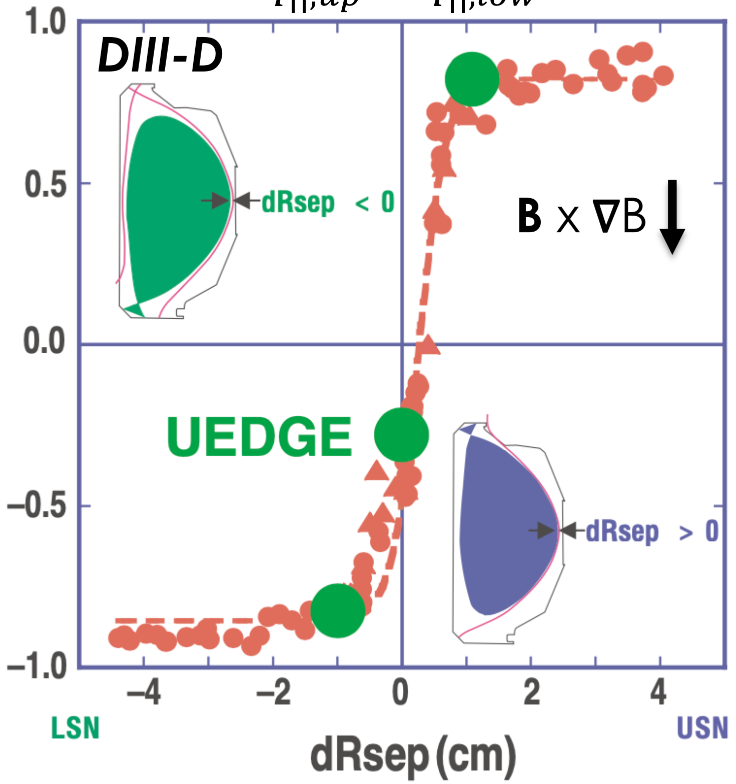
*Owens JNM 1980 (PDX)
*Petrie JNM 2001 (DIII-D)

Magnetic balance and drifts are fundamental drivers of up-down power sharing

- Up-down power sharing is strong function of **magnetic balance**
- However, at balanced DN (dRsep = 0), power sharing is skewed toward divertor in **ion Bx∇B drift direction**
- Perfect power sharing required upper SN magnetic bias of ~1 λ_q to compensate downward drift effect

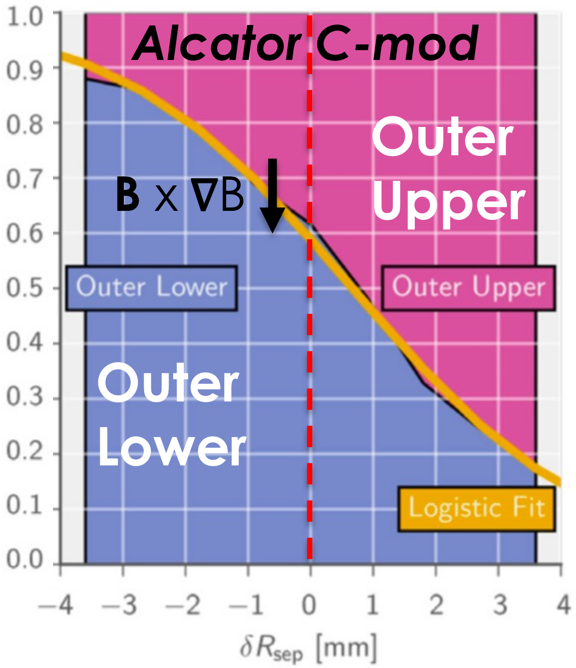
Difference in peak heat fluxes to outer divertors

$$\frac{q_{||,up} - q_{||,low}}{q_{||,up} + q_{||,low}}$$



At dRsep=0, ~2x larger peak $q_{||}$ in lower divertor

Fraction of total power flux

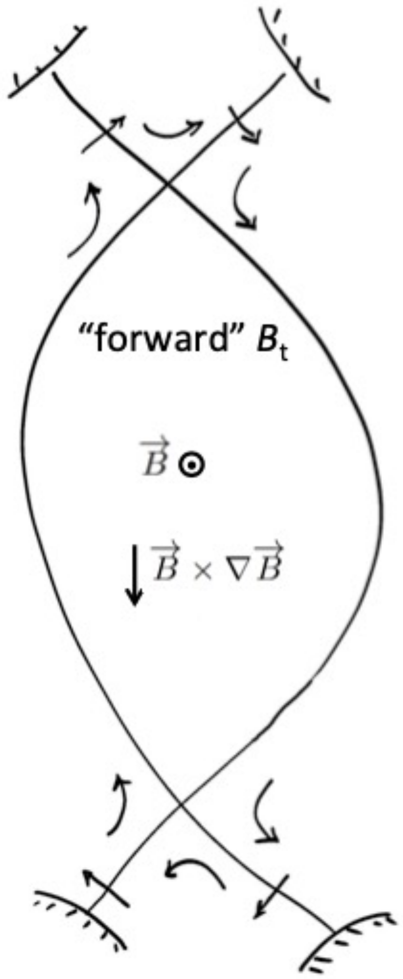


At drSep=0, 60:40 split toward lower divertor

Petrie et al., JNM 2001
Porter et al., IAEA 2003
Brunner et al., NF 2018

Divertor ExB drifts are inherently asymmetric, both in-out and up-down

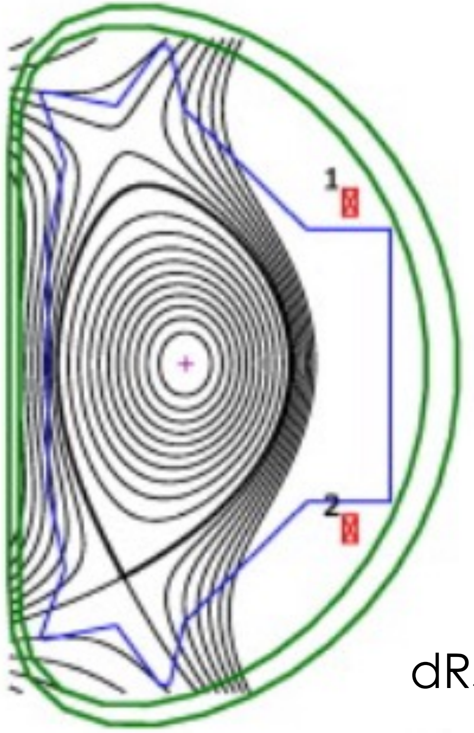
- Ion Bx∇B **out** of divertor:
  - ExB moves particles from **inboard to outboard**
- Ion Bx∇B **into** divertor:
  - ExB moves particles from **outboard to inboard**
- **Drifts redistribute particles and affect:**
  - Particle balance
  - Core fueling
  - Detachment onset
  - Pumping throughput
  - Impurity leakage into core



Meier CPP 2018

Ion flux asymmetry is driven by ExB drifts

- **Before injection, ion flux asymmetric**
- **D_2 injection reduces ion flux in upper divertor everywhere, and shifts ion flux to far SOL in lower divertor**

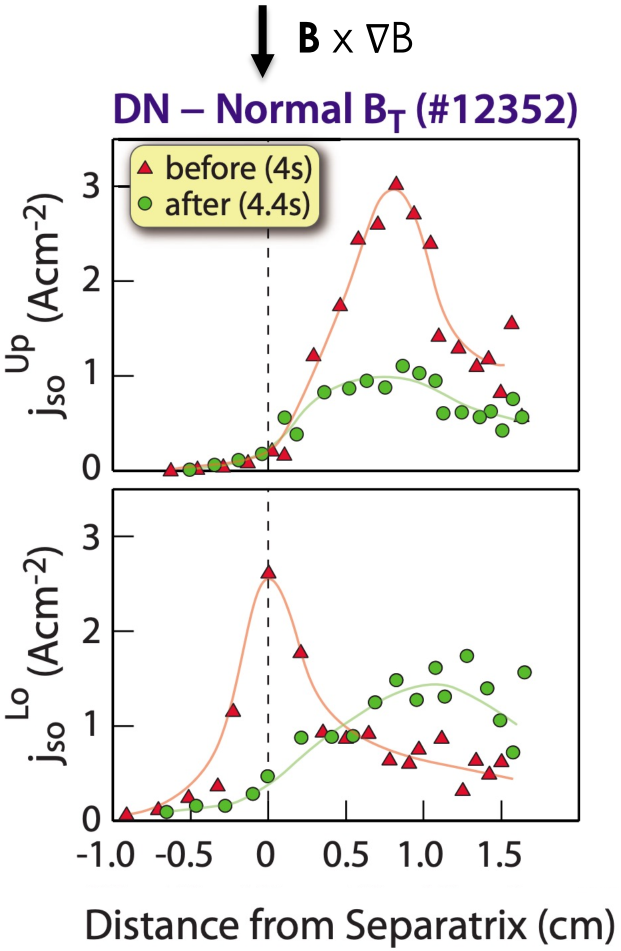


dRsep ~ 0

J_{sat} before and after D_2 injection

Upper

Lower



ExB pushes particles outward

Ion flux in upper divertor peaks in far SOL

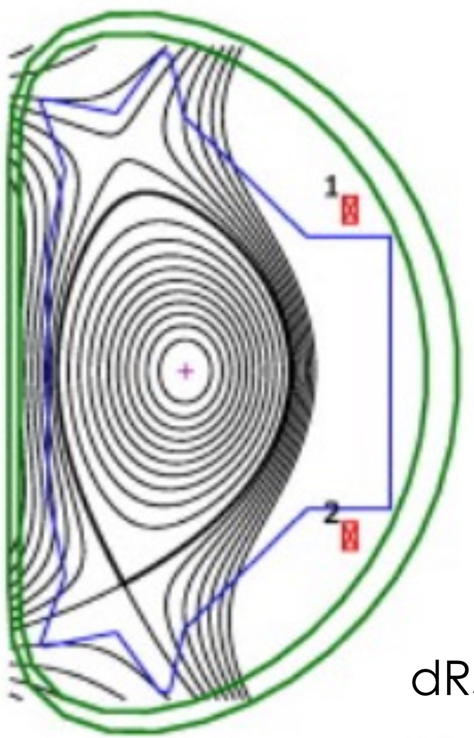
ExB pushes particles inward

Ion flux in lower divertor peaks at separatrix

EAST, Wang PoP 2011

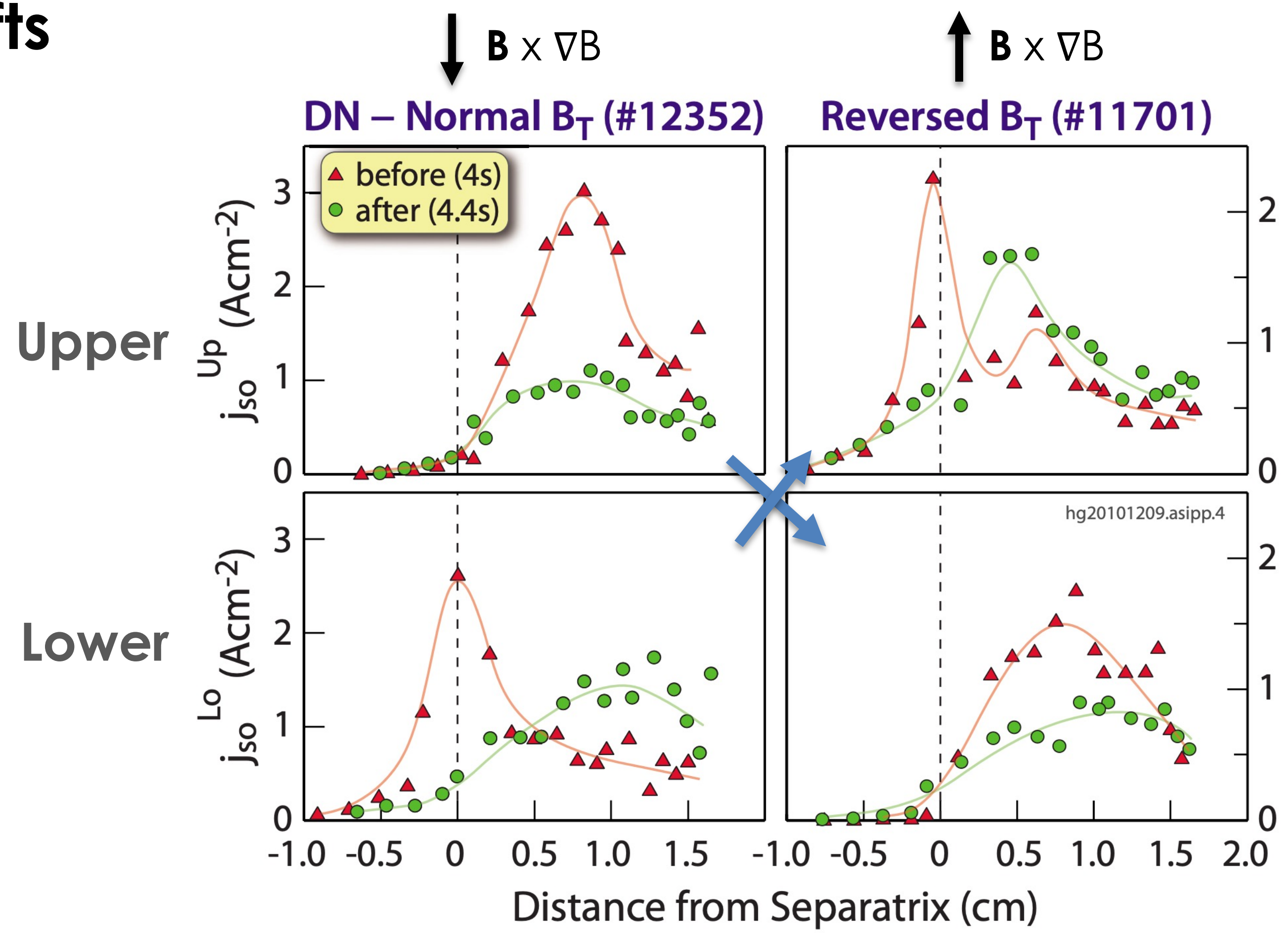
Reversing B_T flips the ion flux asymmetry

- **Reversing B_T isolates effect of drifts and causes nearly up-down symmetric flip of J_{sat} profiles**



dRsep ~ 0

J_{sat} before and after D_2 injection

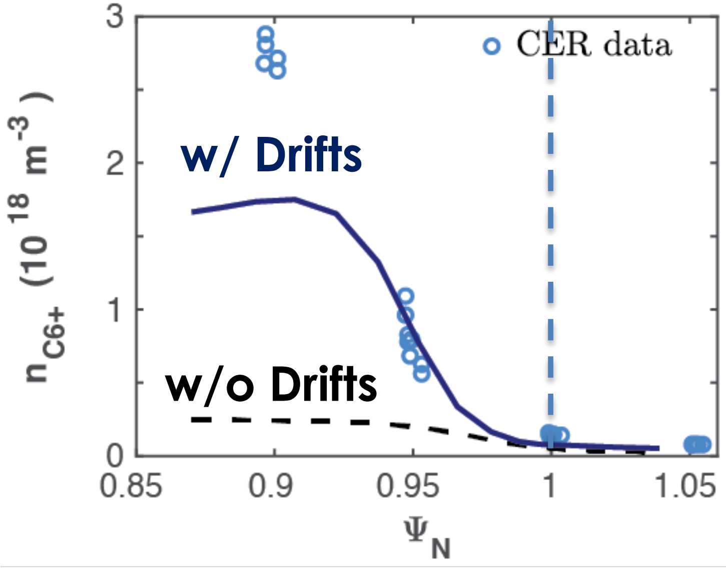


EAST, Wang PoP 2011

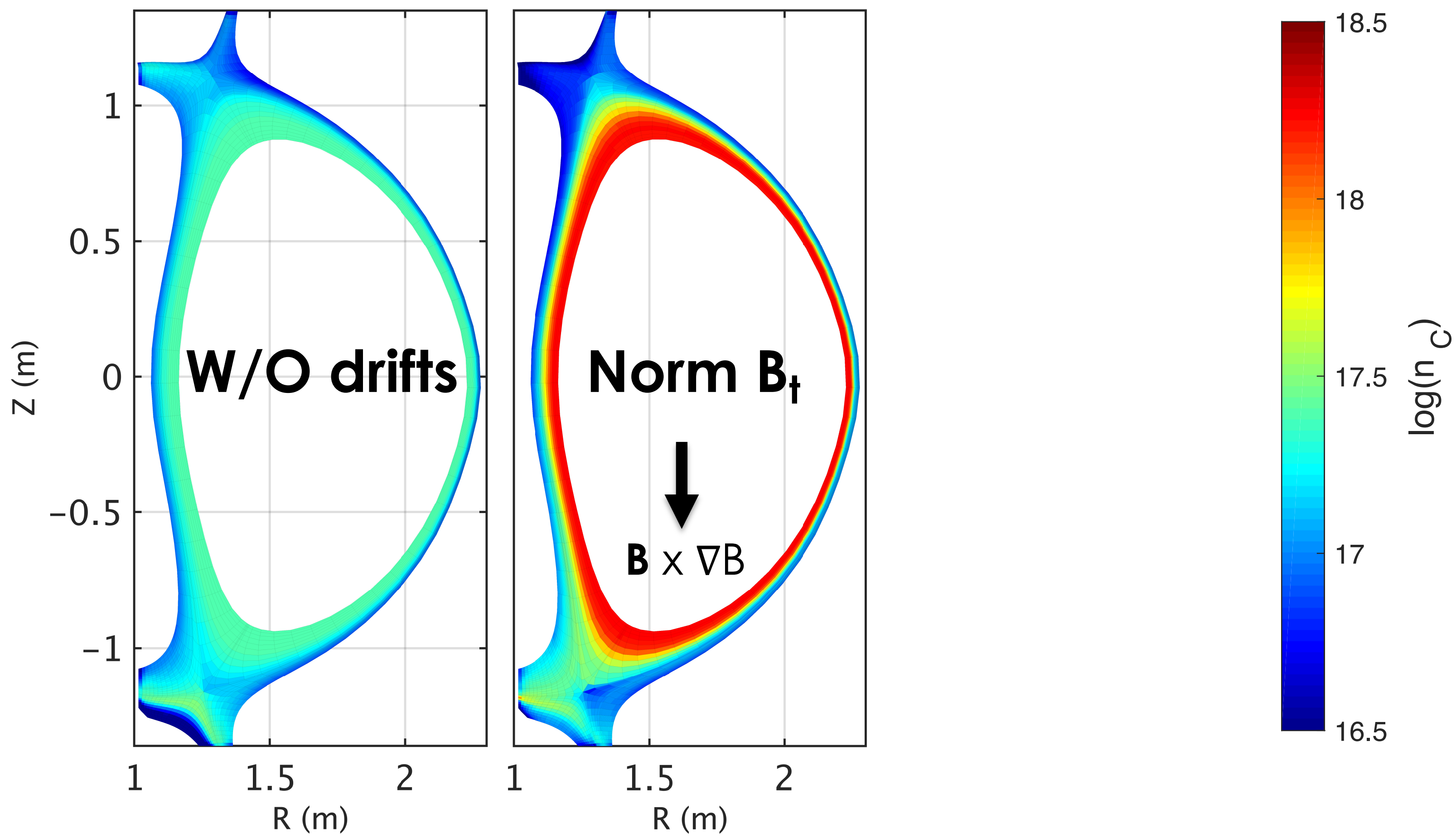
SOLPS-ITER simulations show that drifts strongly affect impurities inside the separatrix, and cause asymmetry in divertors

- **With normal B_T, carbon increases in core and accumulates in the lower inner divertor**

C6+ Upstream Density



Total Carbon Density Distribution in DN



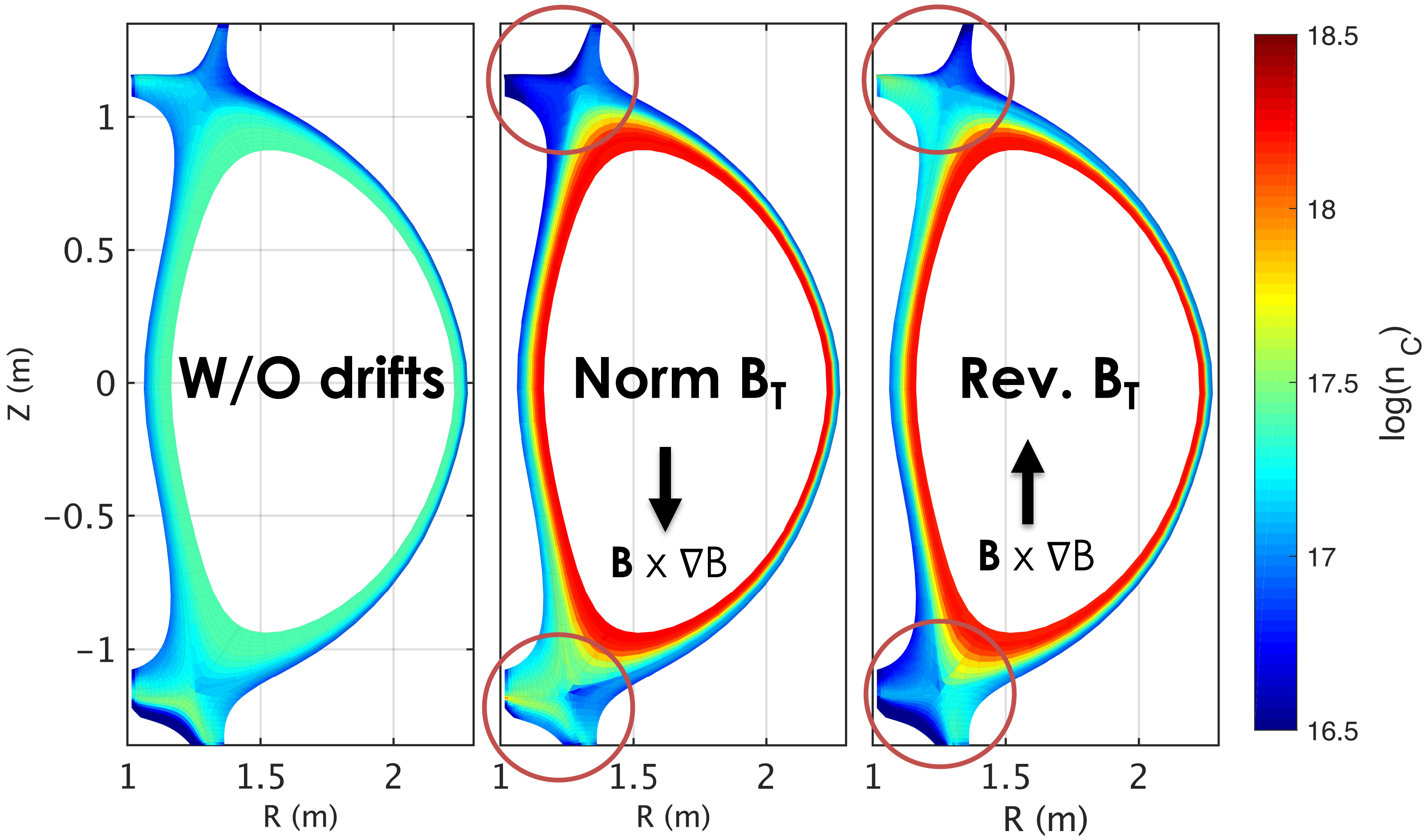
dRsep = -2 mm

DIII-D, X. Ma APS 2022

SOLPS-ITER simulations show that drifts strongly affect impurities inside the separatrix, and cause asymmetry in divertors

- **With normal B_T, carbon increases in core and accumulates in the lower inner divertor**
- **With reversed B_T, more carbon in the lower outer divertor and upper inner divertor**

Total Carbon Density Distribution in DN

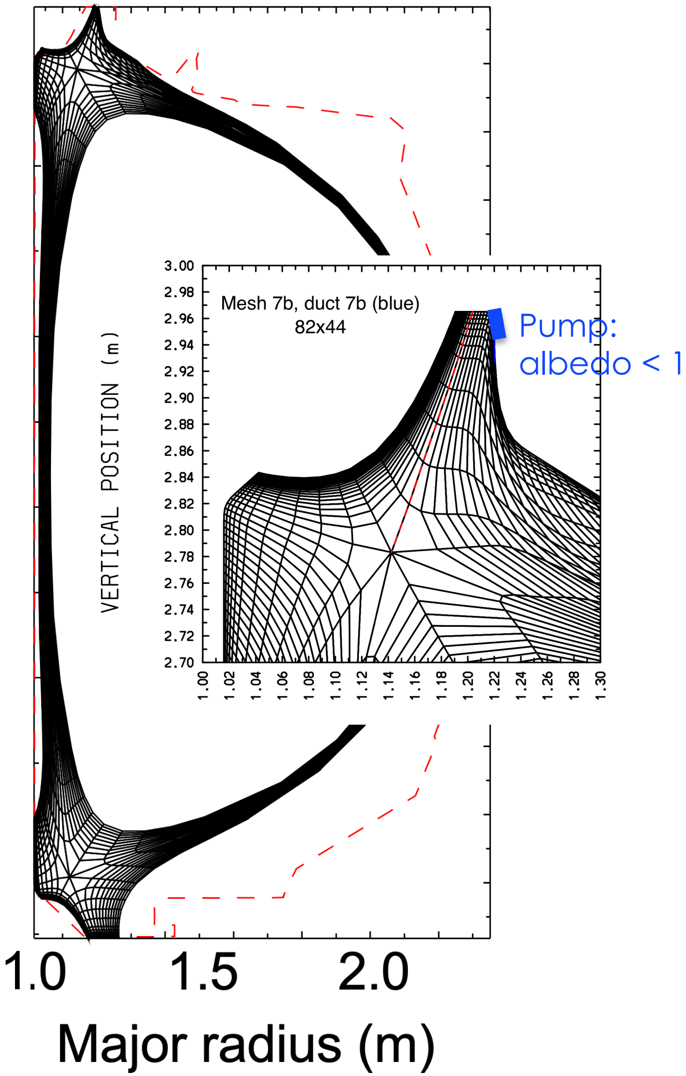


dRsep = -2 mm

DIII-D, X. Ma APS 2022

UEDGE + DEGAS 2 show DN core fueling inside separatrix is dominated by neutrals from lower-inner divertor

Proposed DIII-D upper divertor



T. Rognlien APS 2022

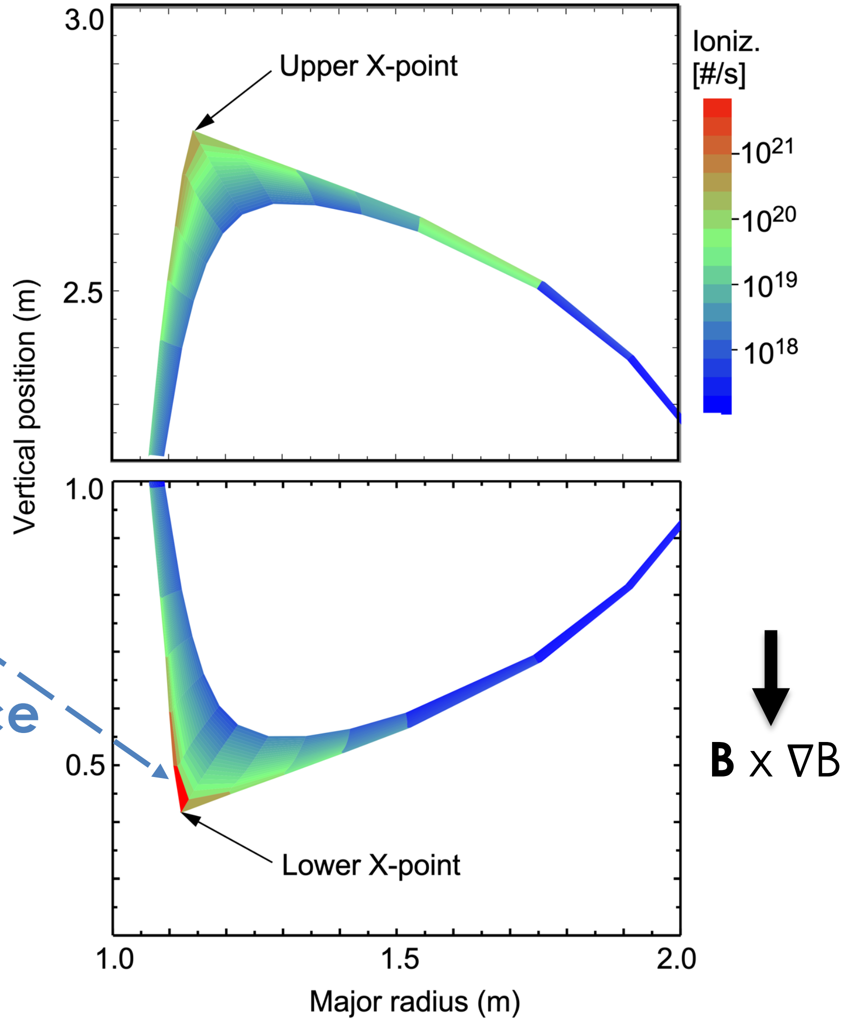
Contribution from each source inside the separatrix (amps):

Upper-inner divertor	**231**
Upper-outer divertor	**57**
Lower-outer divertor	**93**
Lower-inner divertor	**1089**
Gas puff	79

Dominate core source

dRsep = 0
Drifts on

Total core fueling from DEGAS 2

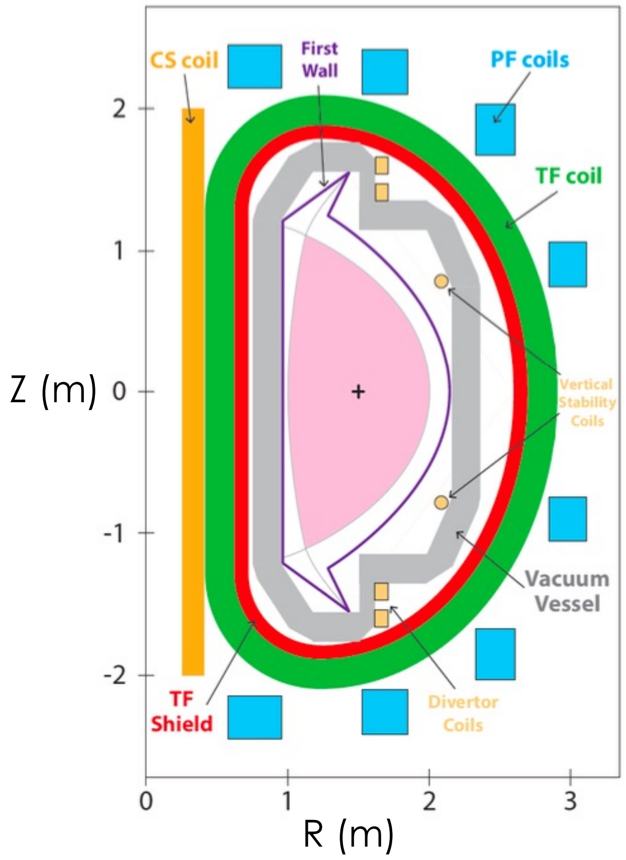


A conceptual high field compact tokamak from an integrated modeling study [1] is used to investigate divertor wall geometries

- **Exhaust and Confinement Integration Tokamak Experiment (EXCITE) [2,3]**
  - Proposed device to achieve steady state burning plasma
  - Power exhaust solution compatible with a fusion pilot plant (FPP)

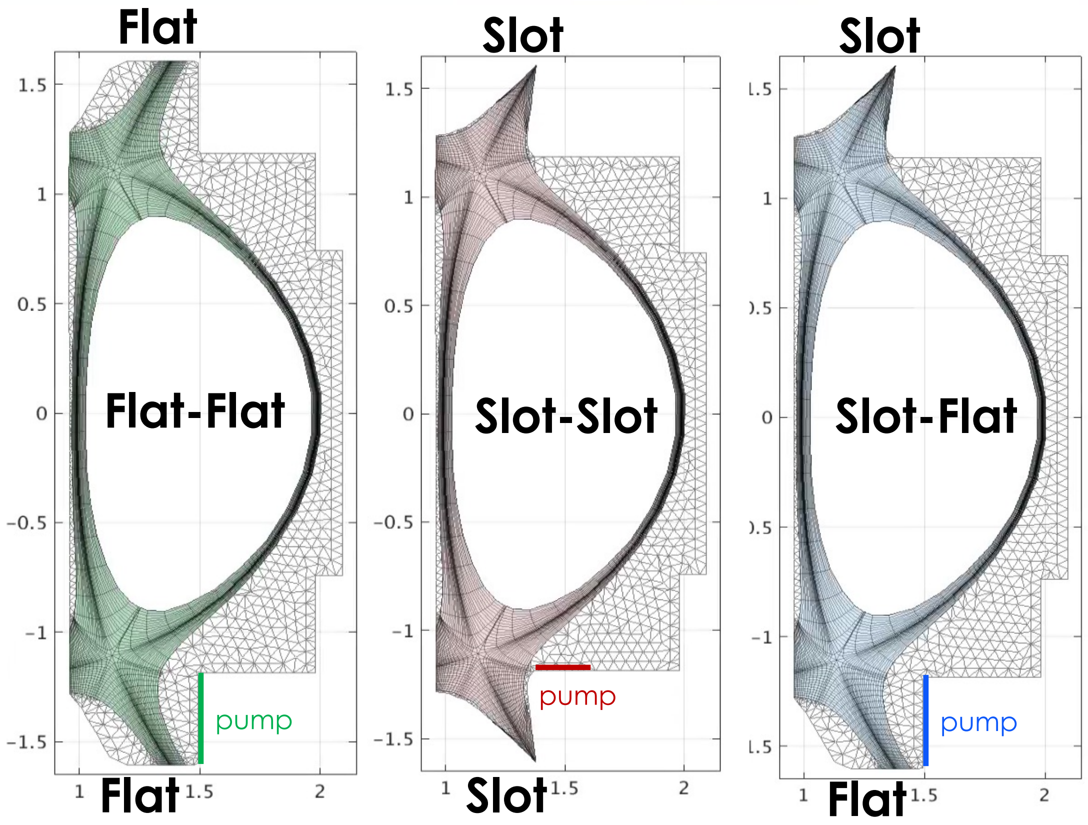
DN parameters used for SOLPS-ITER EXCITE simulations:

Balanced DN magnetic configuration
I_p = 5.0 MA
q_{95} = 3.8
β_N = 2.9
B_T = 6.0 T
R_0 = 1.5 m, A = 3
Power = 4, 20, and 50 MW

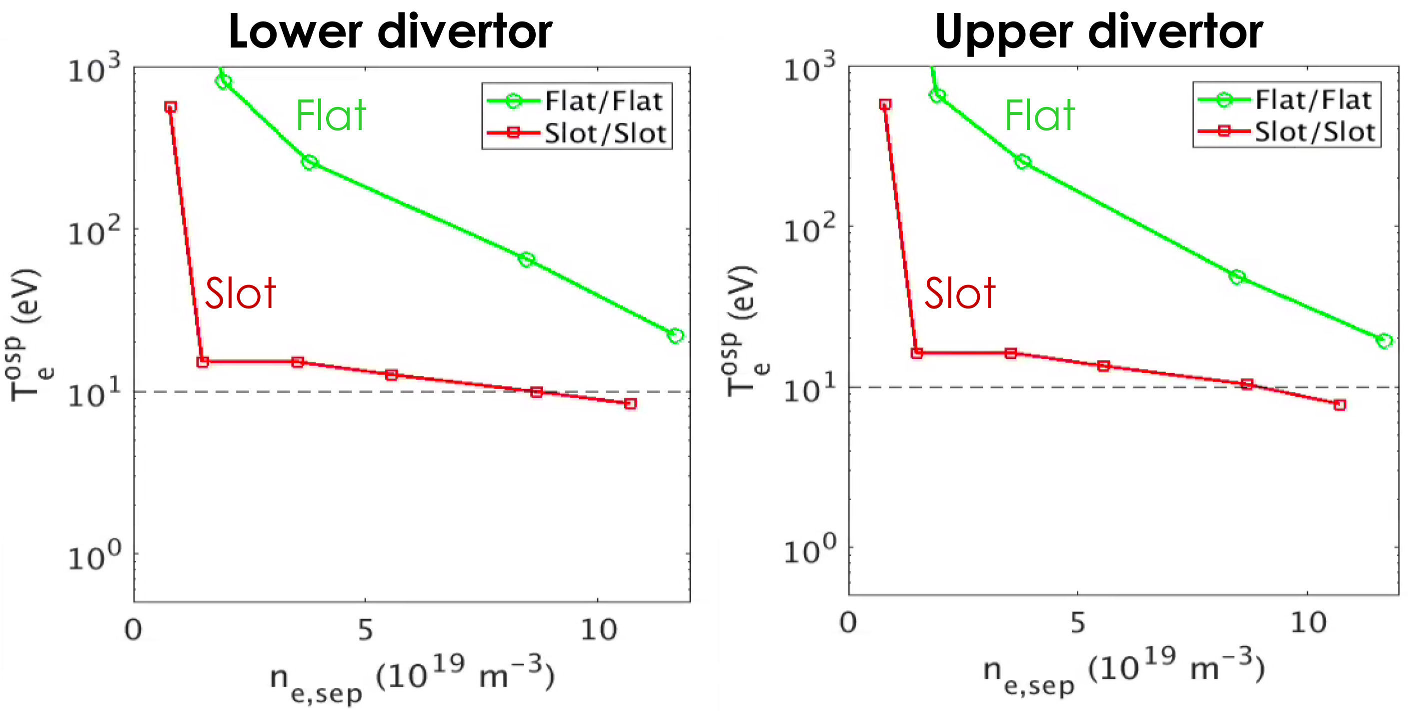


[1] D. Weisberg et al., submitted to FSET 2022
[2] FESAC 2020 Powering the future: Fusion and plasmas
[3] Carry-over of NTUF device recommended by 2020 APS-DPP Community Planning Process

Symmetric divertor geometries have similar plasma conditions



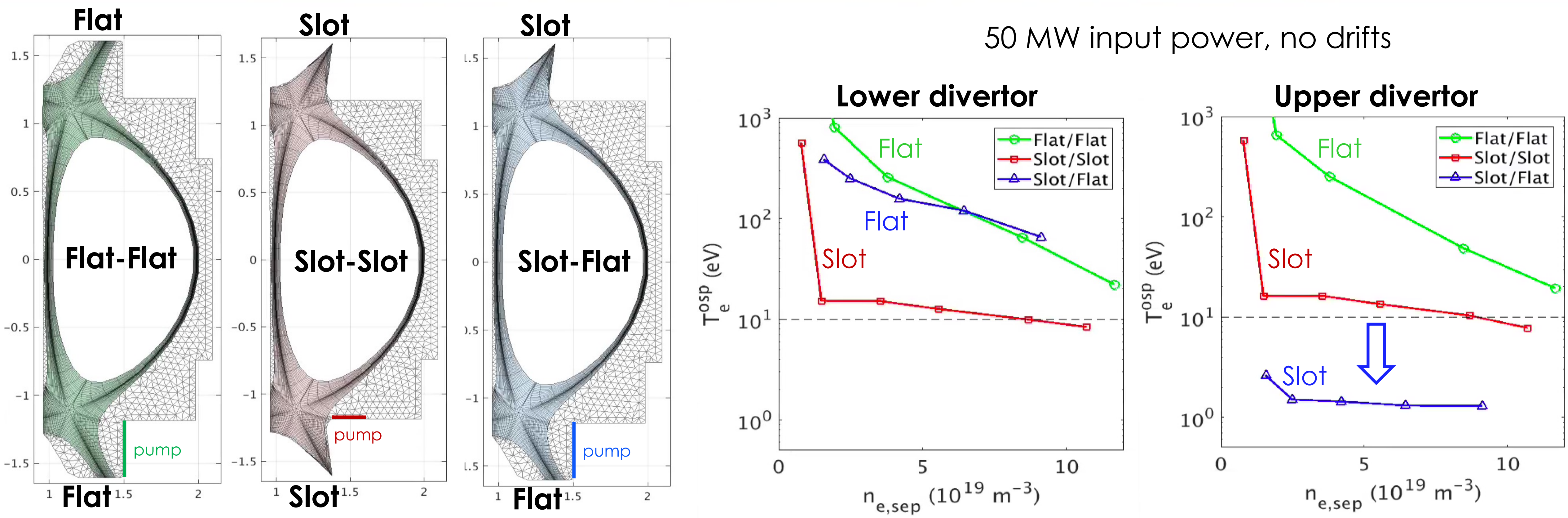
50 MW input power, no drifts



- Higher closure → higher dissipation
- Upper and lower divertors behave similarly when divertors are up-down symmetric

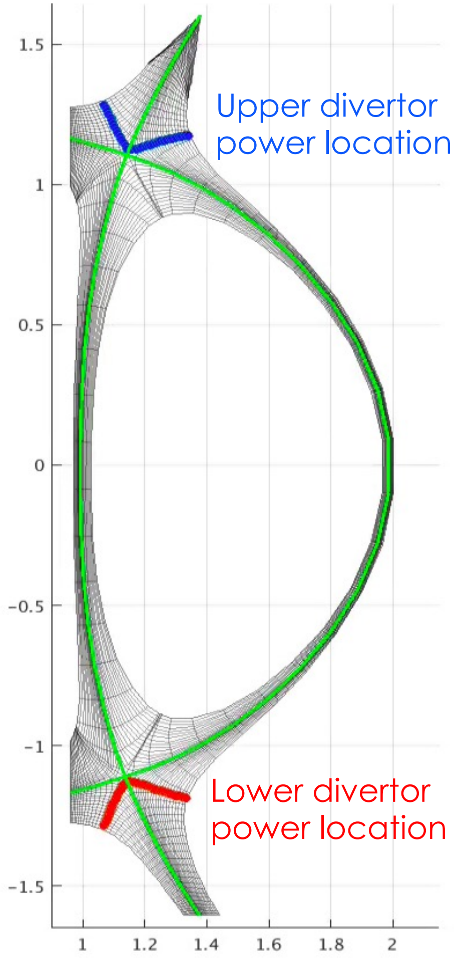
Slot references:

Asymmetric divertors: closed divertor is detached while flat divertor is attached

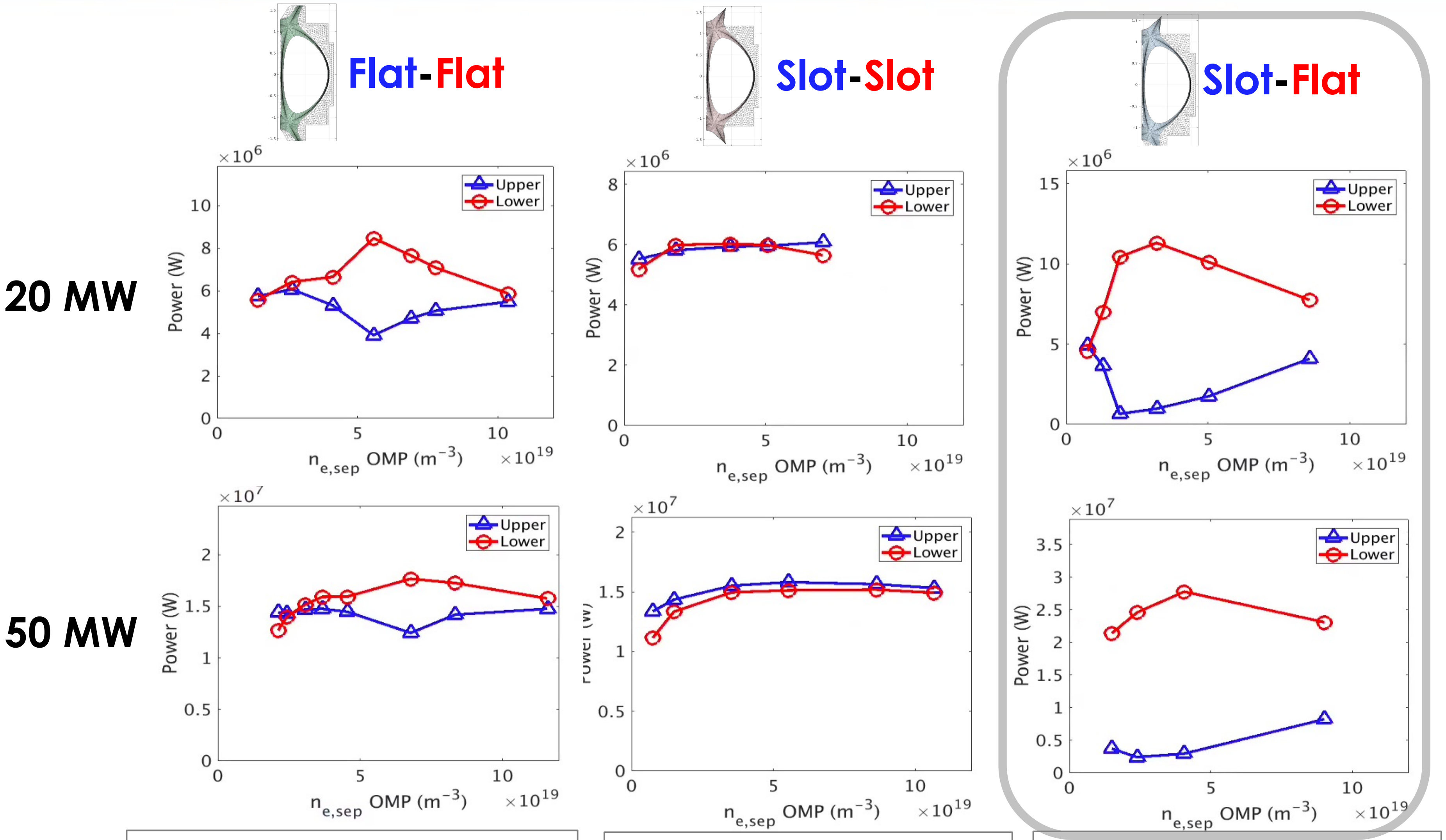


- Higher closure → higher dissipation
- Upper and lower divertors behave similarly when divertors are up-down symmetric
- Slot-Flat: unequal divertor dissipation creates parallel temperature gradient between divertors, which drives **SOL particle and power flow**

Asymmetric divertor conditions lead to power imbalance toward hotter, less dissipative divertor



No drifts

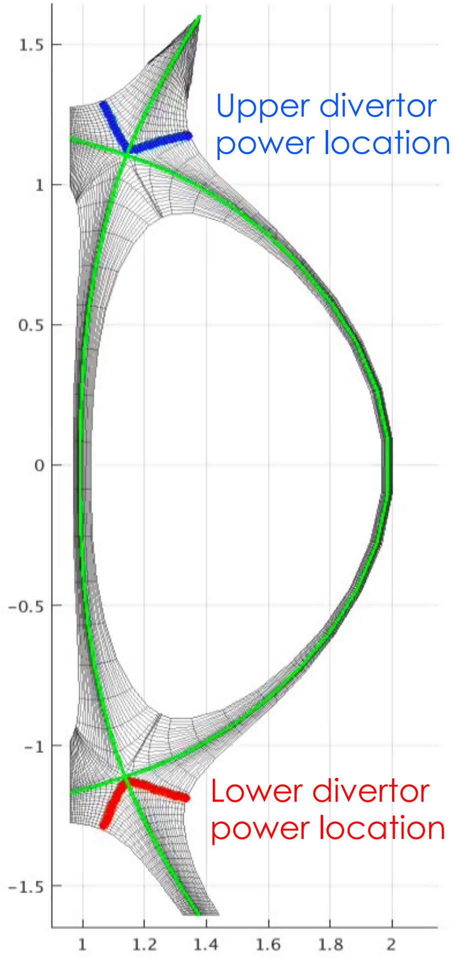


Power sharing asymmetry due to pumping in lower divertor

Power sharing is equal with up-down divertor symmetry and no drifts

<u>Largest power sharing asymmetry</u> due to flow reversal in slot

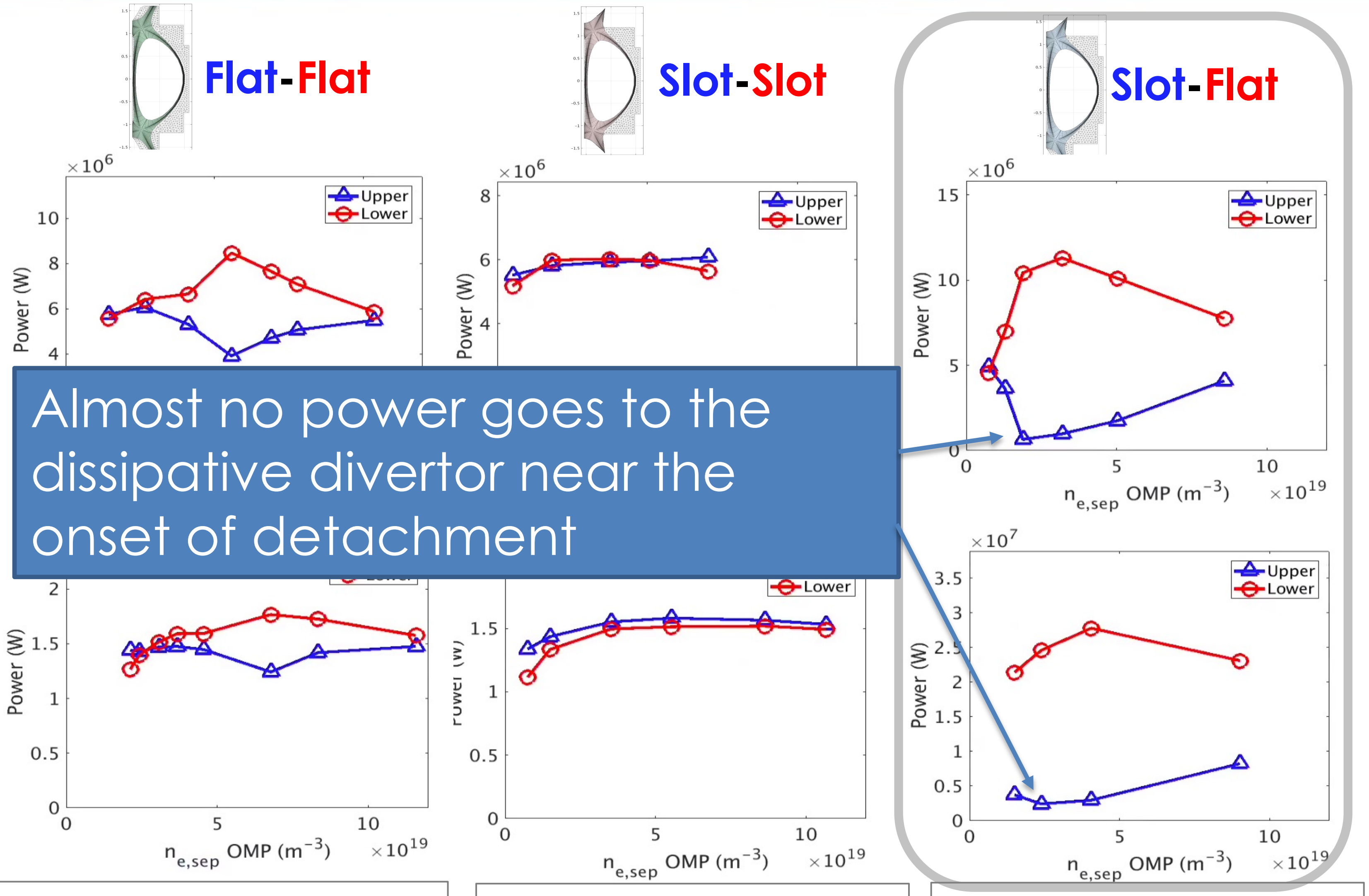
Asymmetric divertor conditions lead to power imbalance toward hotter, less dissipative divertor



No drifts

20 MW

50 MW



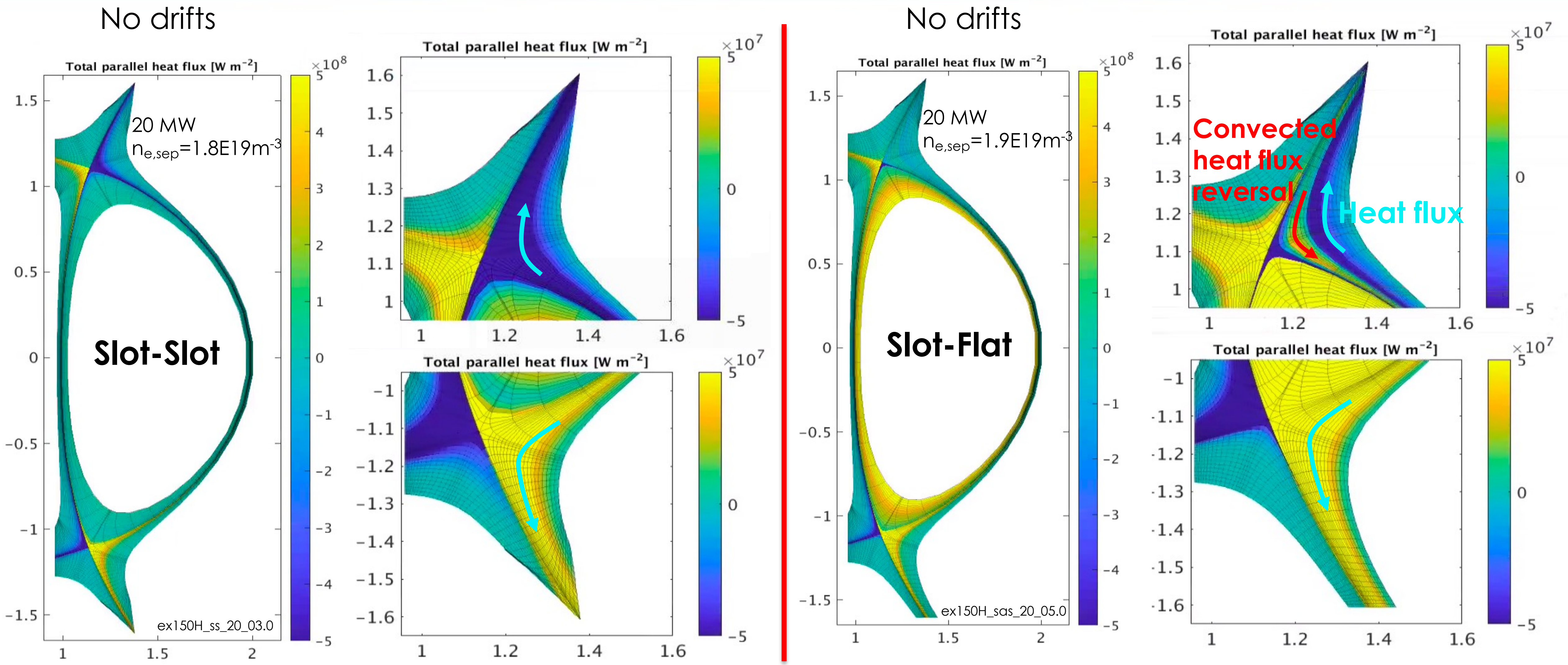
Almost no power goes to the dissipative divertor near the onset of detachment

Power sharing asymmetry due to pumping in lower divertor

Power sharing is equal with up-down divertor symmetry and no drifts

<u>Largest power sharing asymmetry</u> due to flow reversal in slot

Power imbalance is due to convected electron heat flux reversal

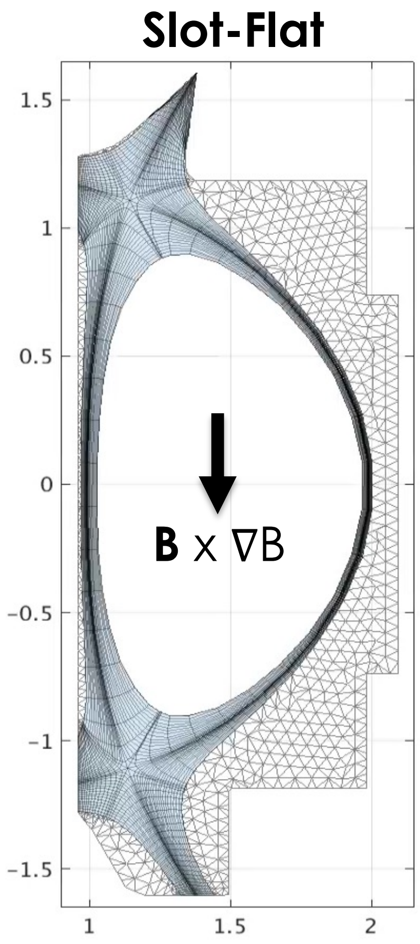


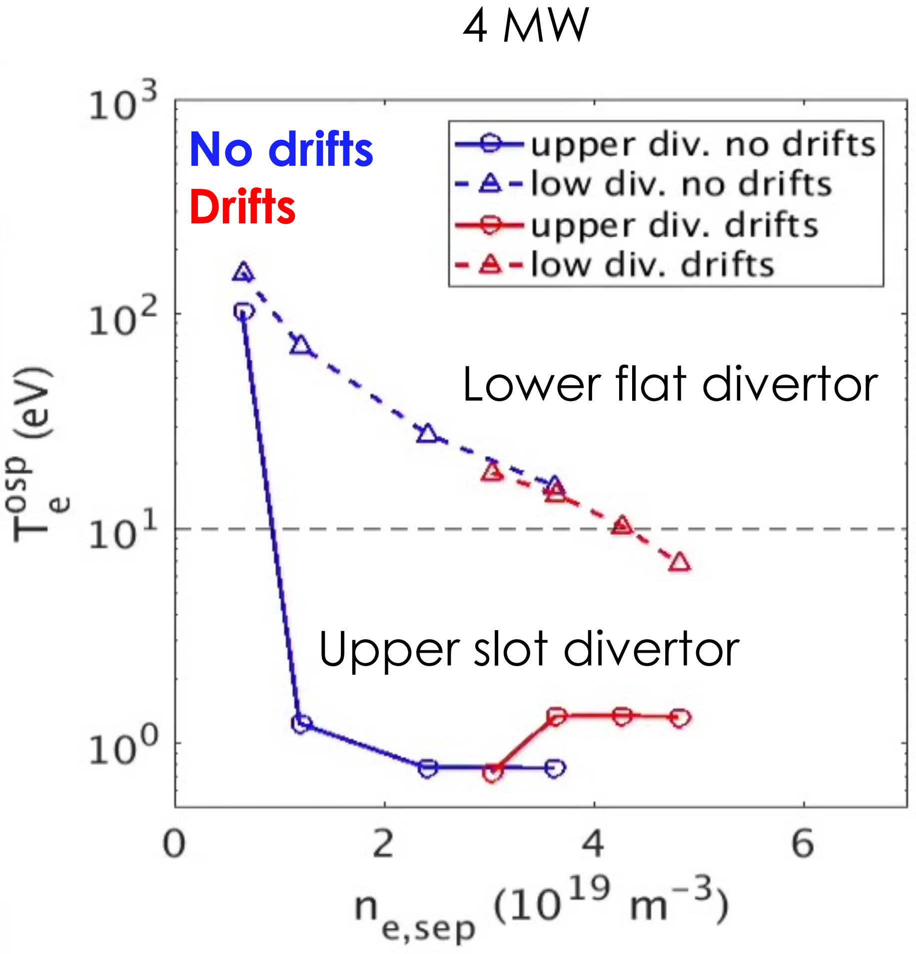
Equal divertor conditions in symmetric divertor configuration

>0: clockwise
<0: counter-clockwise

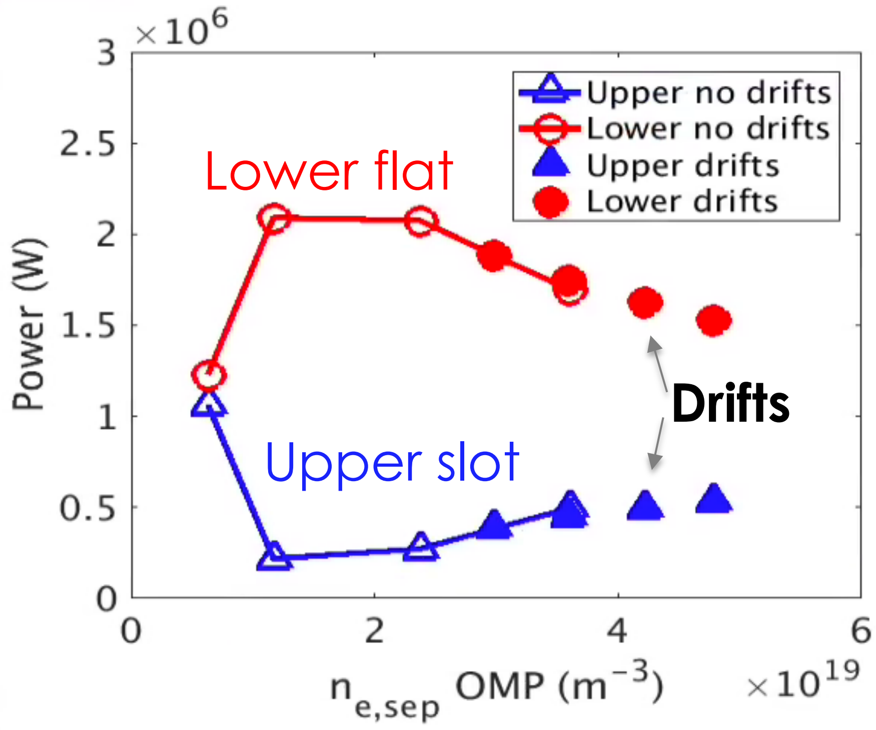
Compression of recycled neutrals, lower Te → thermoelectric current flow reversal

With drifts, slot remains detached with ion B x ∇B out of slot, and heat flux continues to favor the hotter open divertor



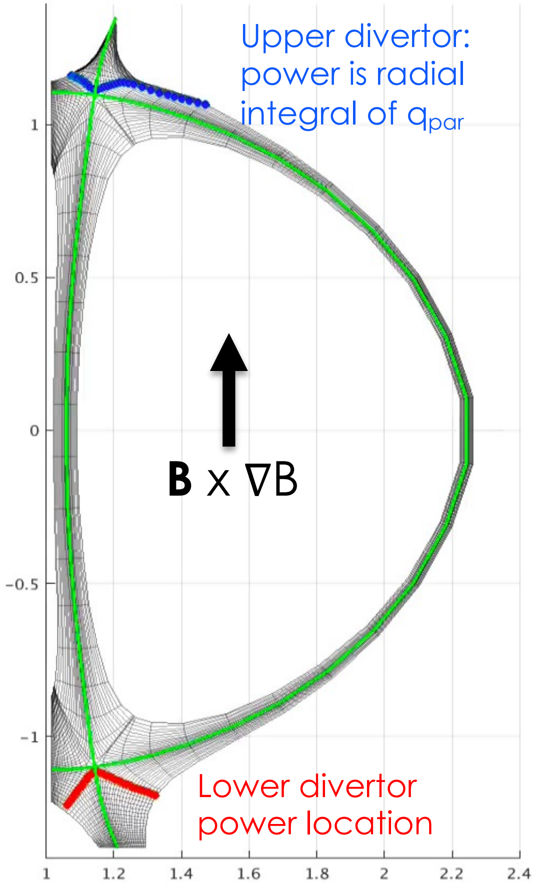


Power flows mainly to lower divertor with grad B drift out of slot



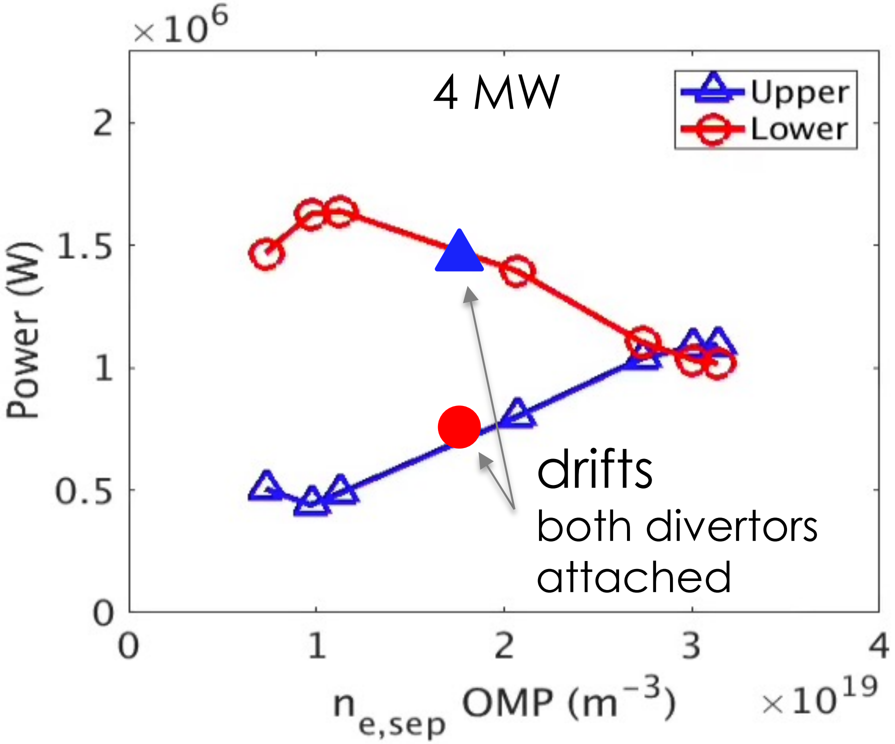
However, reversing B_T causes slot to attach (similar to lower divertor), flow reversal stops, and drifts dominate the asymmetry

Reversed B_T



dRsep = 0

Power flowing into
upper slot and lower flat divertors



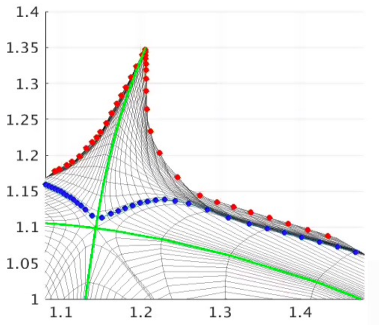
Slot is no longer detached with this drift direction

More power goes to slot in ion **B** x ∇B direction than to lower divertor

When both divertors are attached, power sharing is driven by drifts rather than divertor shape asymmetry.

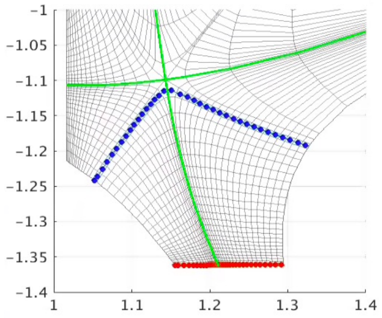
Drifts can overcome the baffling asymmetry

Slot

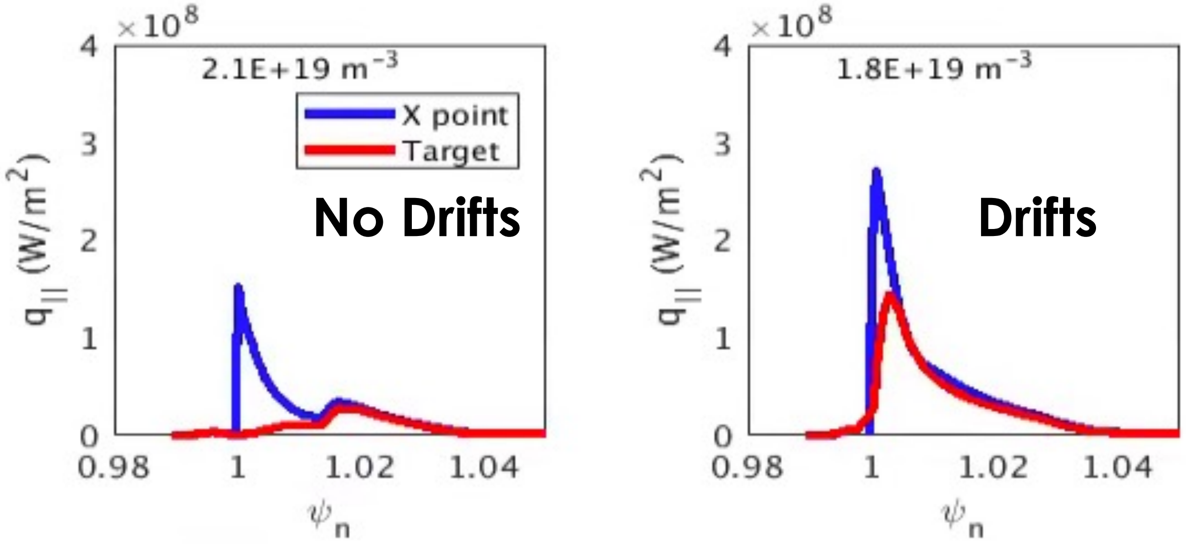


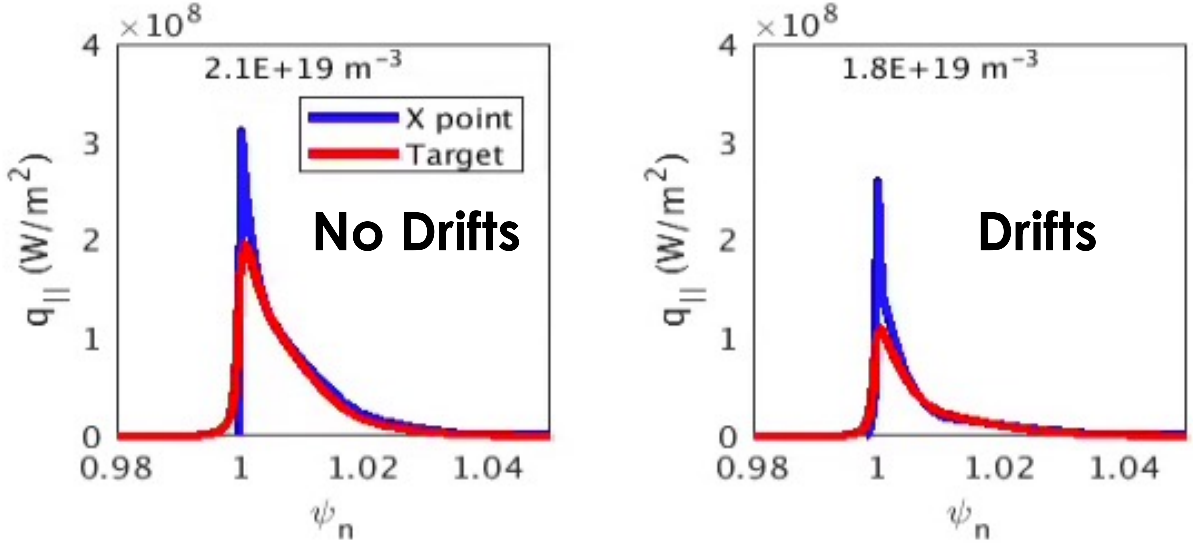
B x ∇B ↑

Lower divertor



4 MW, SAS-2





With ion grad B drift into slot, ExB drives particles to PFR → dissipation in slot reduces and both divertors become attached.

Peak heat fluxes to both divertors are ~equal.

Summary and Conclusions

- Sources of asymmetries interact
- Thermoelectric current exacerbates power sharing asymmetry by driving electron heat flux to hotter divertor
- Implications for DN operation and divertor design:
  - To achieve desired up-down power sharing, operational controls needed to compensate for inherent drift asymmetries
  - Knobs: magnetic balance, impurity or fuel injection, pumping
  - For example, can use dRsep to compensate for drifts
- Need to quantify asymmetry contributions from each source
- Most issues discussed here also apply to SN in-out asymmetry

2D boundary modeling challenges

- **Difficult to converge simulations, in particular with drifts**
  - Can we establish a criteria for the necessity of drifts, analogous to Knudsen number for kinetic vs fluid neutrals?
- **Limitation in speed of solution (>~4 weeks for drift convergence with SOLPS-ITER)**
  - Challenge to explore broad range of divertor designs
  - Can fluid neutrals be used, and then solution refined with kinetic neutrals?
  - Machine learning: Sven Wiesen's talk 🙂
- **Ability to converge depends on trajectory through parameter space**
  - Starting point matters
  - Convergence is highly dependent on experience and perseverance of modeler
  - E.g., when attempting higher power with drifts:
    - No convergence possible when starting from a high power no-drift case
    - Need to start from a converged solution of a lower power drift case
  - See Ben Dudson's work on automation and acceleration 🙂
- **Scaling of solution speed with power, boundary conditions, etc.**