Control of neutral particle fueling and exhaust by plasma edge topology optimization in Wendelstein 7-X and HSX

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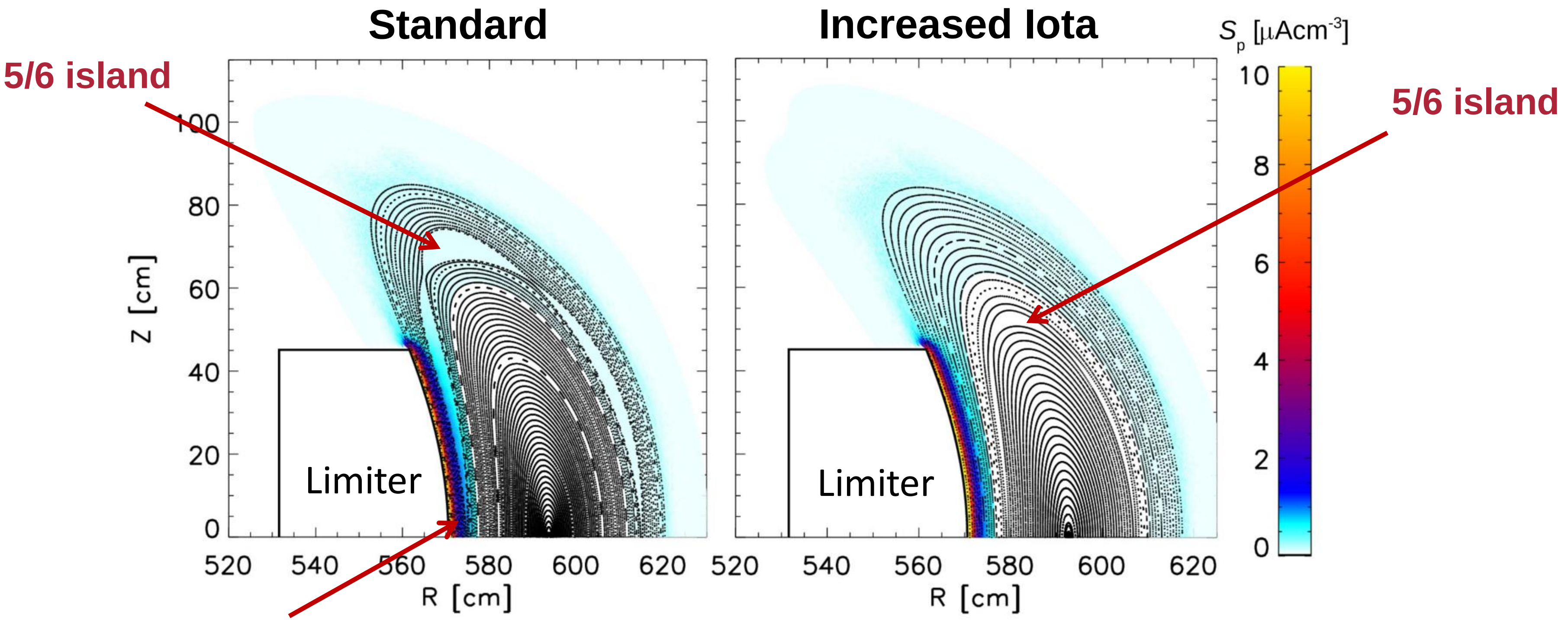
Goal: Investigate role of edge vs. core confinement on particle balance and impurity exhaust



Edge: investigate changes in island position relative to plasma source (ionization) region

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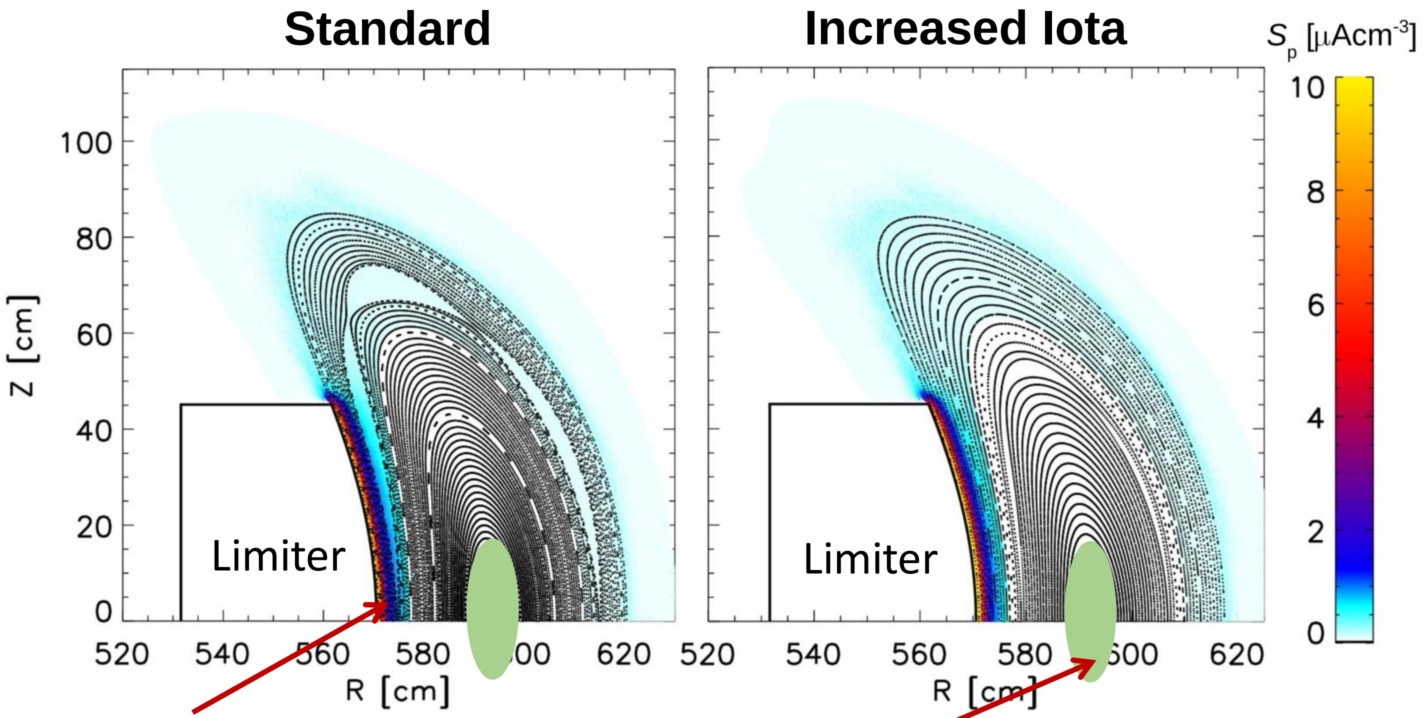

Edge: investigate changes in island position relative to plasma source (ionization) region

Core: do changes in edge topology affect core transport?

Major results

- Edge magnetic topology can be used to control particle confinement/exhaust at W7-X
- Long L_c edge flux bundles in helical SOL confine He and the effect is more prominent in increased iota
- Change in effective ripple at W7-X caused by island movement does not impact core transport
- Experiments at HSX also demonstrate that edge topology changes dominate changes due to effective ripple
- **Edge topology can be optimized without substantially degrading core transport**

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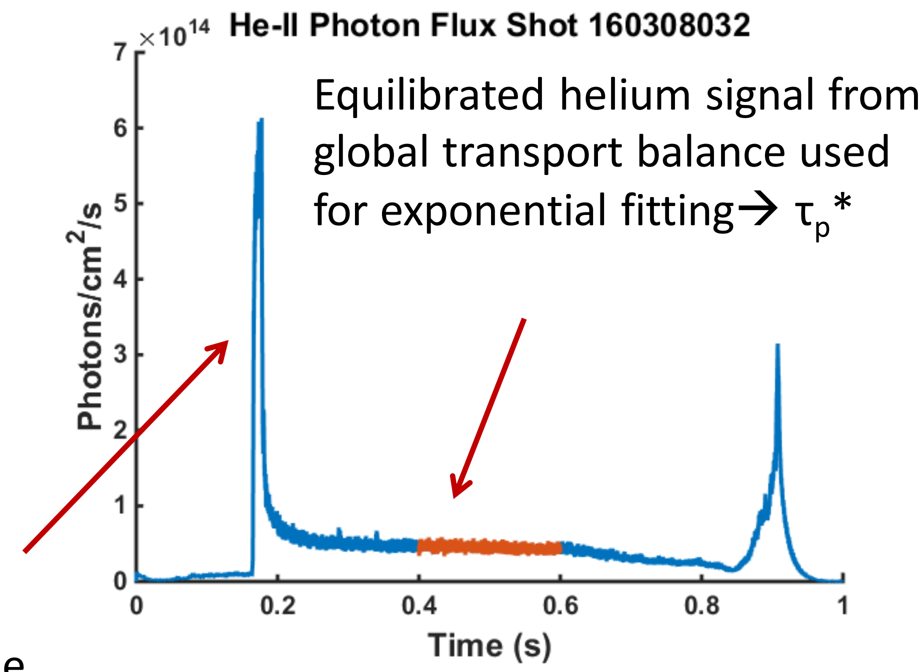
Assess changes in particle confinement by measuring decay of He-I and He-II emission from He injection

- Use fast piezo valve to make short He impurity injection
- Measure He-I and He-II decay and fit exponential to find τ_p* He (characteristic decay time) during steady-state
- τ_p* depends both on particle confinement and edge recycling particle source
    - Fast helium ionization
    - Results not shown, but agree with steady-state trends



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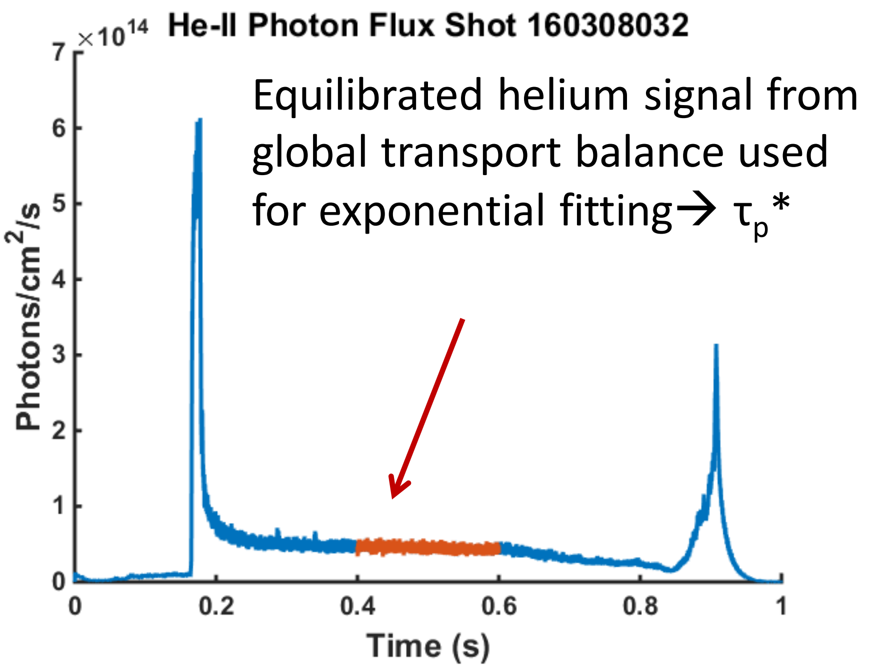
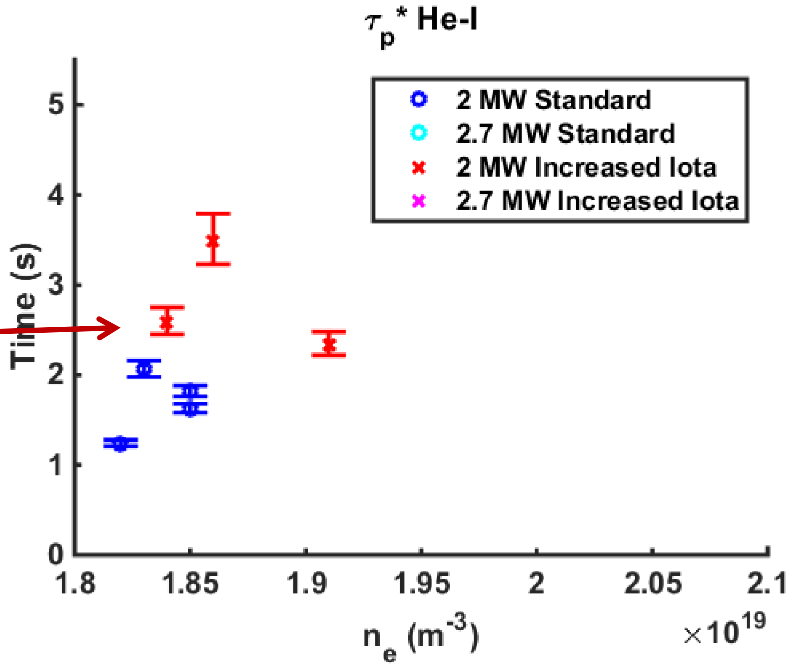
R is the global recycling coefficient, set by wall/limiter conditions

$$\tau_p^* = \frac{\tau_p}{1-R}$$



Effective He-I confinement time increases in increased iota by ~ 50%

Low power



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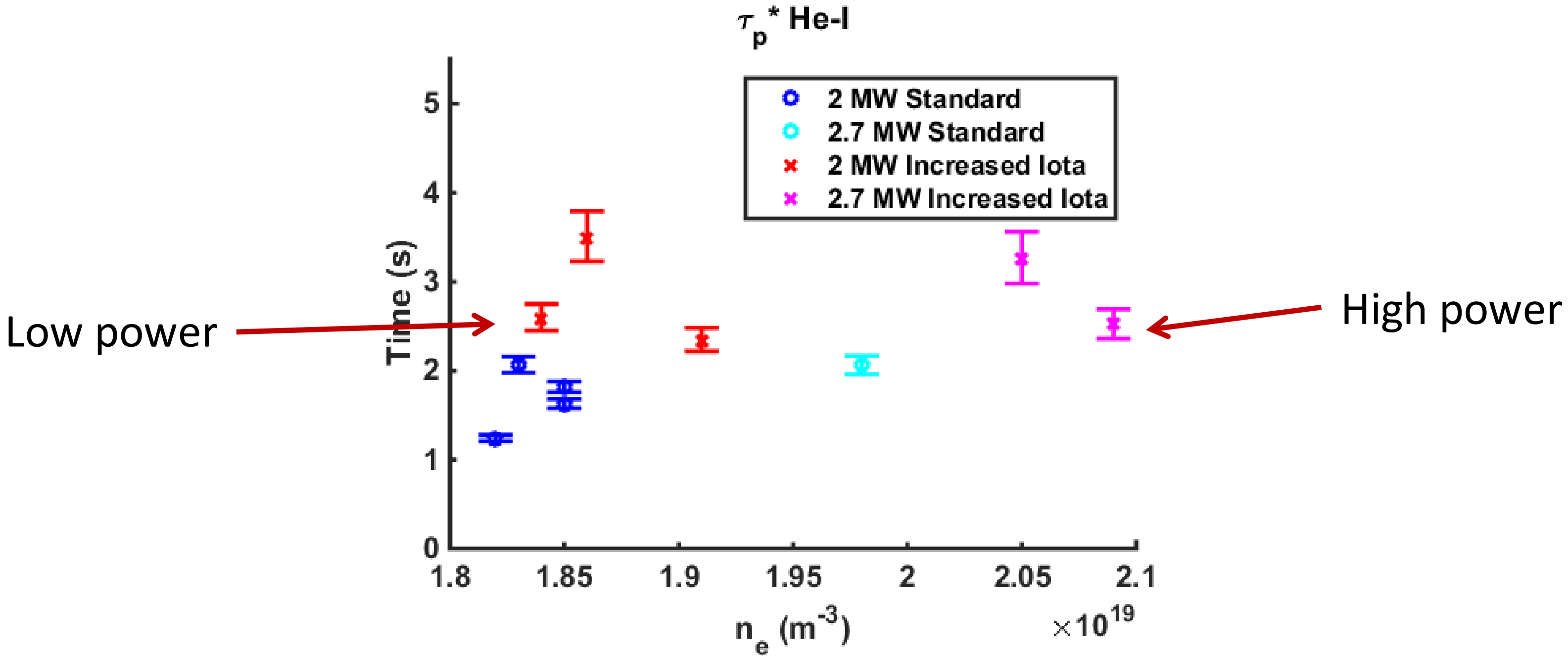

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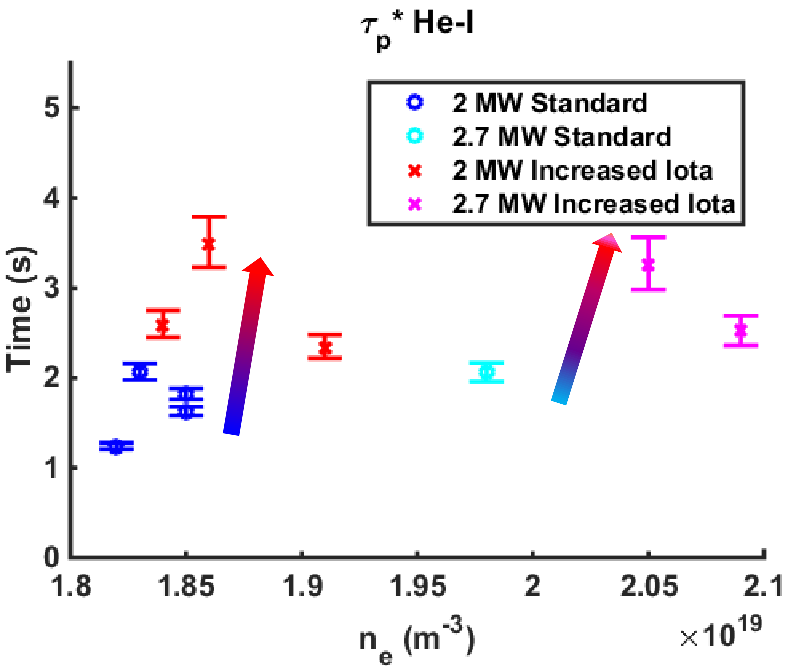
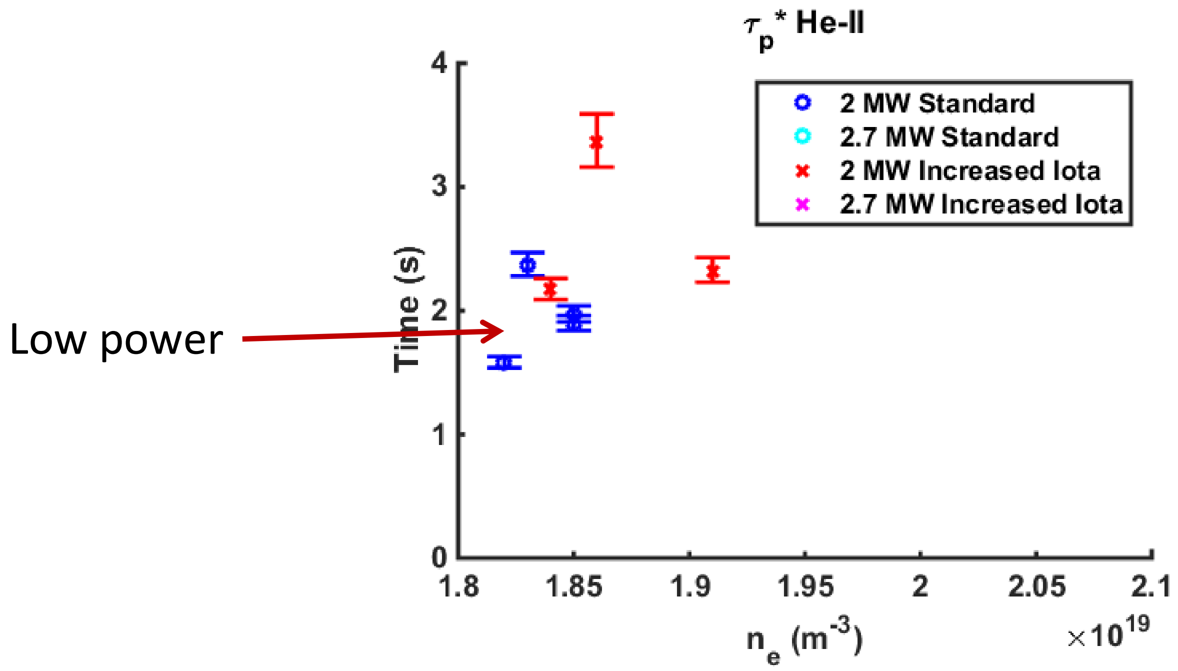


Effective He-II confinement time increases in increased iota by ~ 20%



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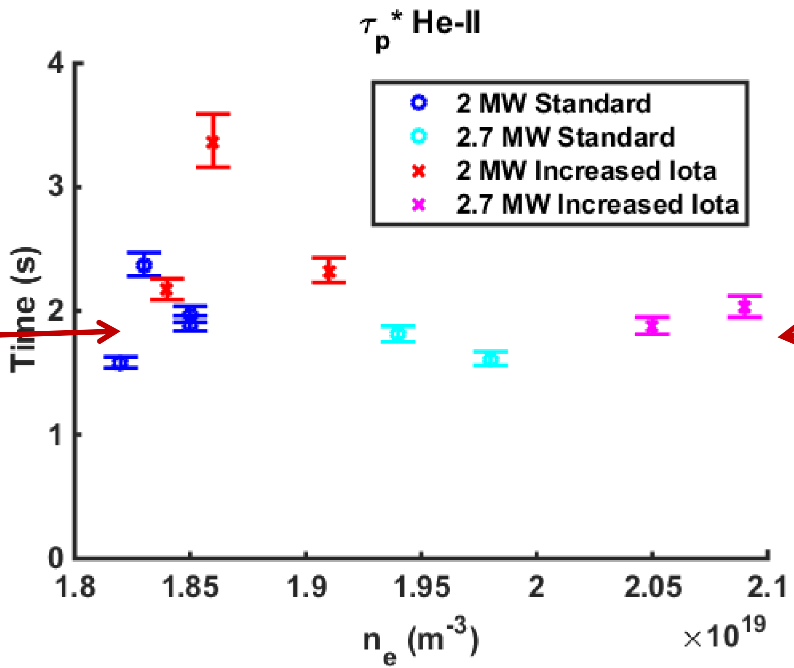
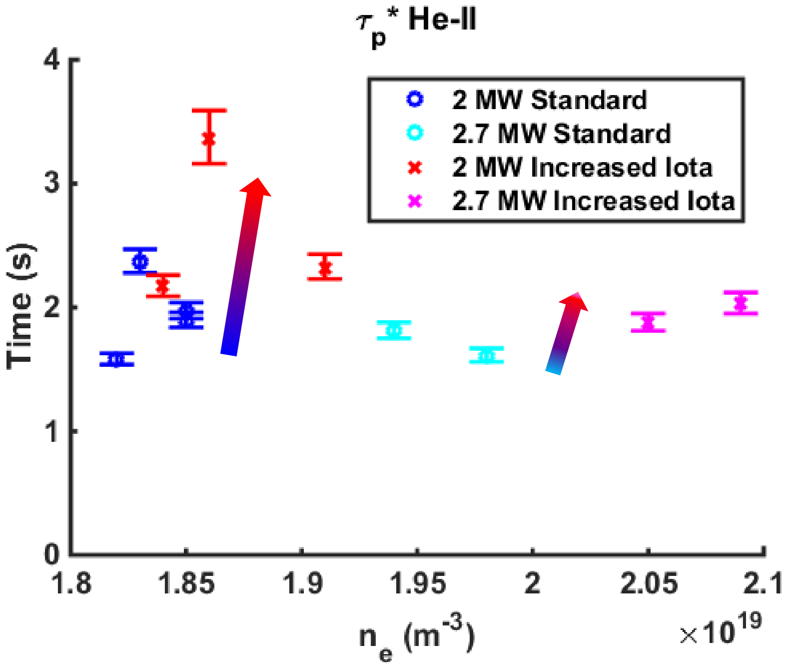


Low power

High power

Effective He-II confinement time increases in increased iota by ~ 20%



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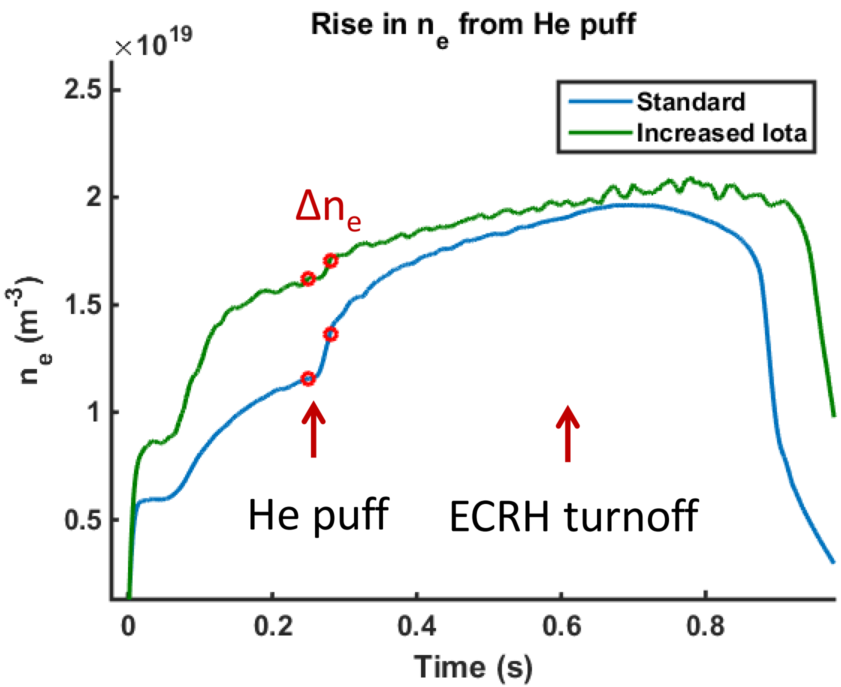
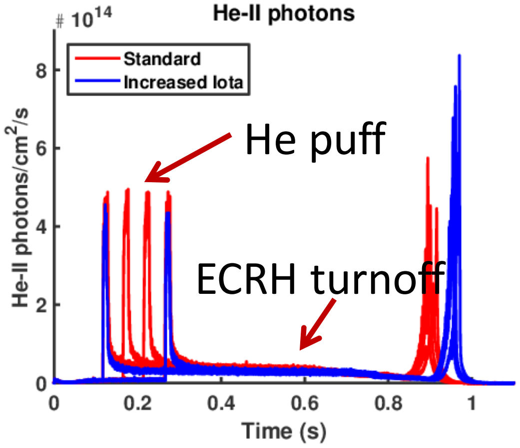
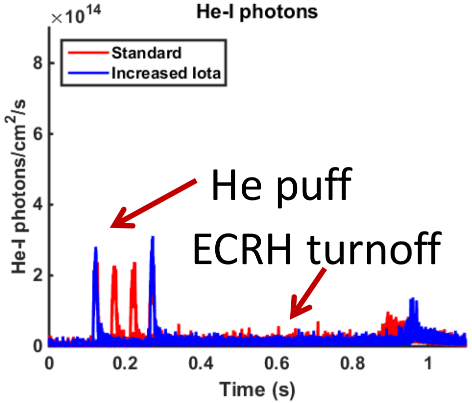
Density evolution provides evidence of reduced fueling in increased iota



- Same number of puffed He particles (1E19)
- Density rise (Δn_e) is a factor of 2 reduced in increased iota
- Evidence for reduced fueling or rapid outward transport
- Where is the helium? In the edge?

Helium emission reduced in increased iota





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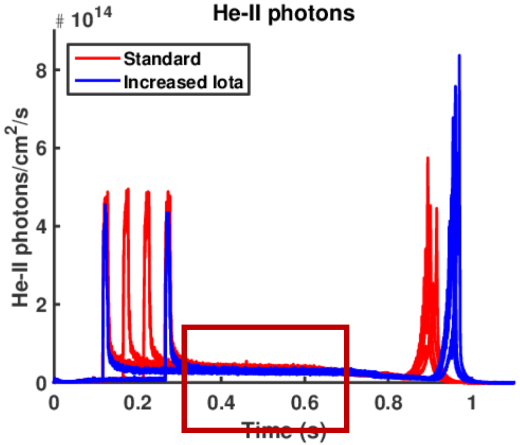

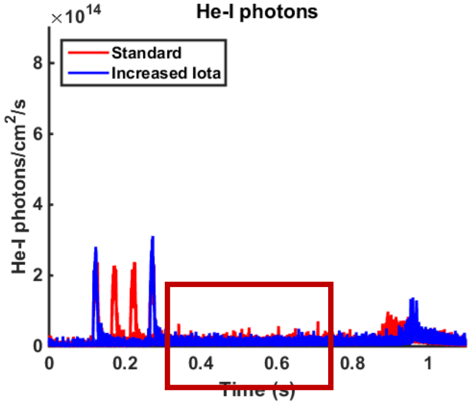

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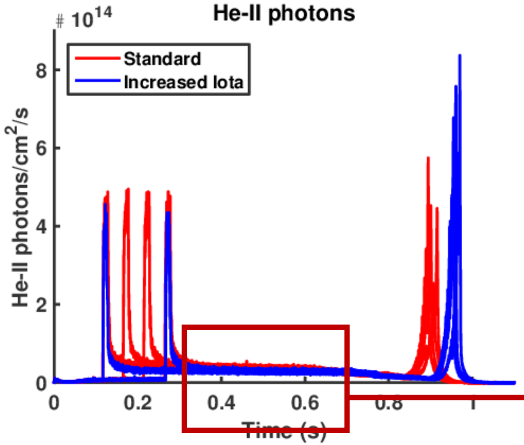
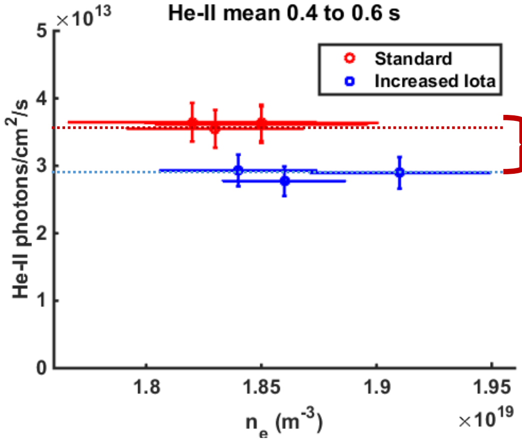
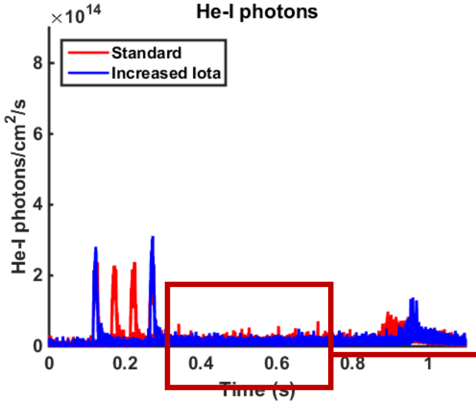




20% reduction in He-II emission in increased iota

Take mean



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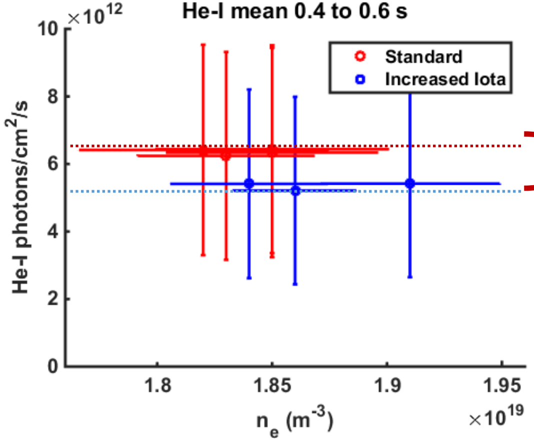
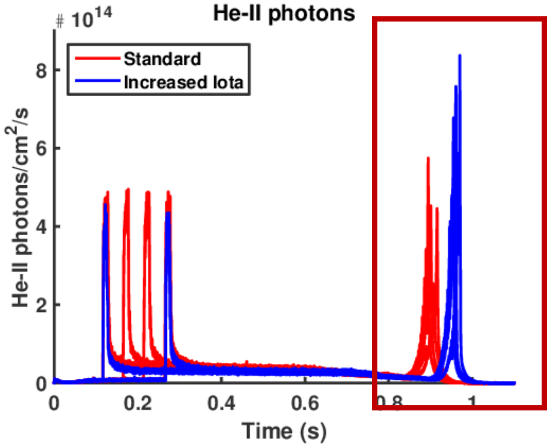
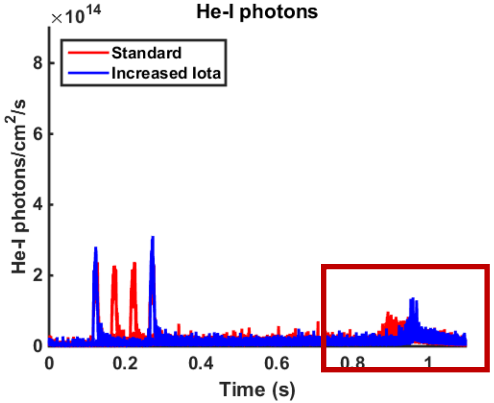


10% reduction in He-I emission in increased iota

After ECRH turnoff, helium emission from recombination is larger in increased iota





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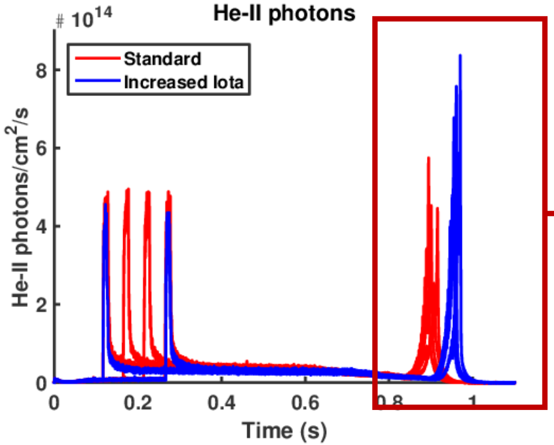
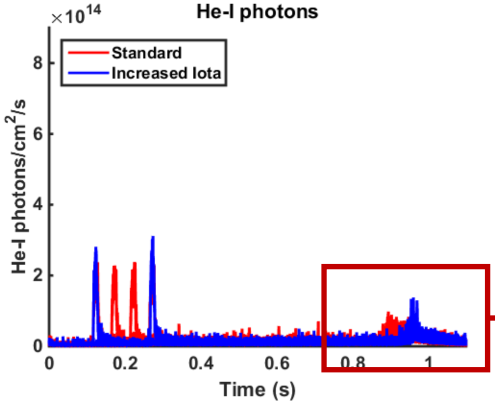
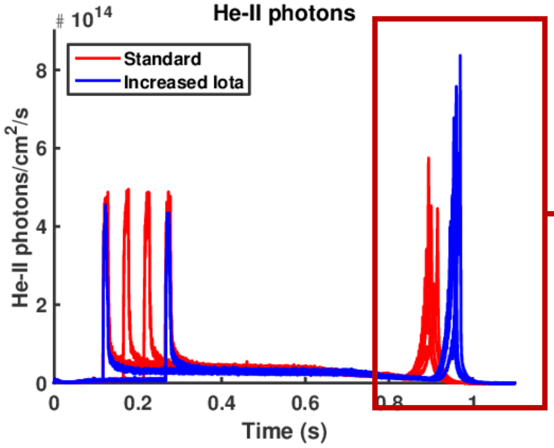


Integrate photons



Max photons (data too noisy to integrate)

After ECRH turnoff, helium emission from recombination is larger in increased iota



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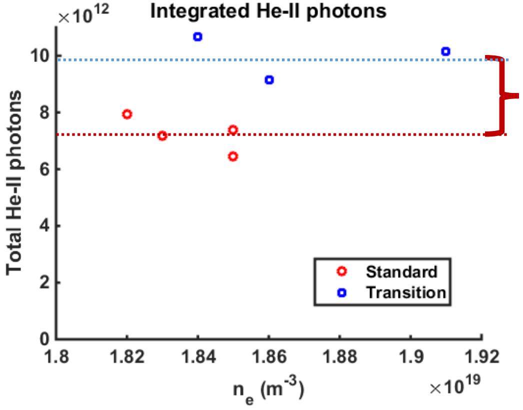
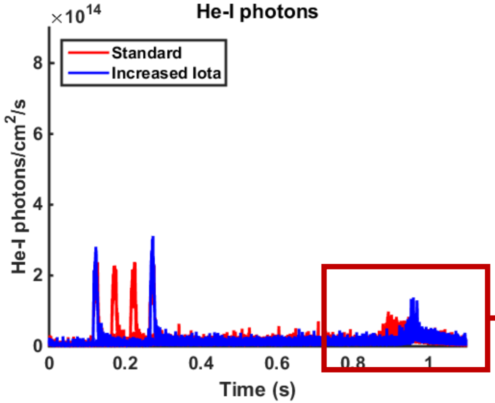


30% increase of He-II emission in increased iota



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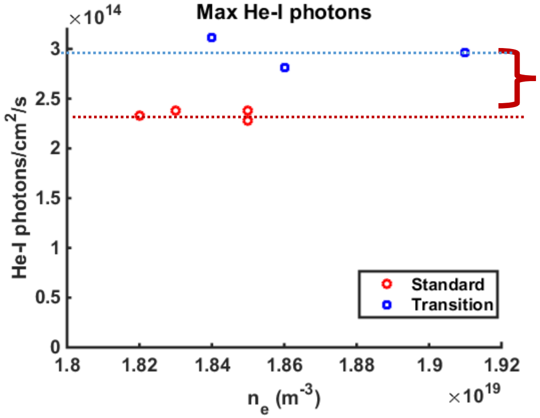
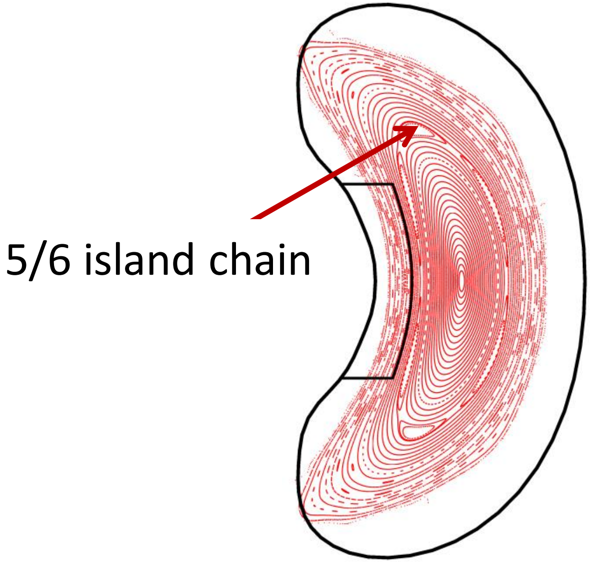


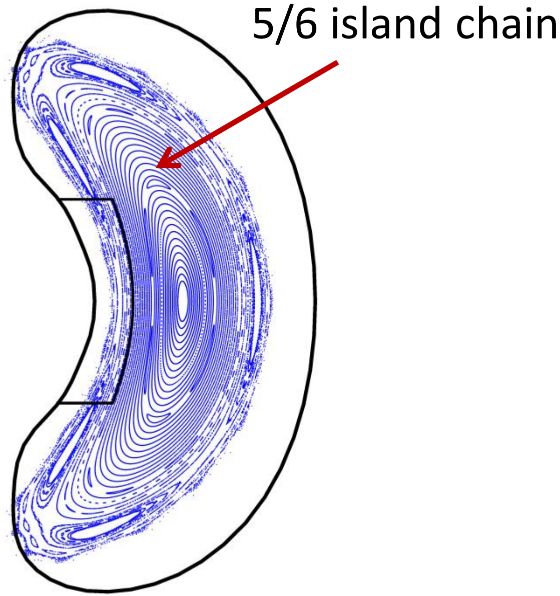
25% increase of He-I emission in increased iota

Systematically transition from standard to increased iota in 6 steps

Iota 0 (Standard)



Iota 12 (Increased Iota)



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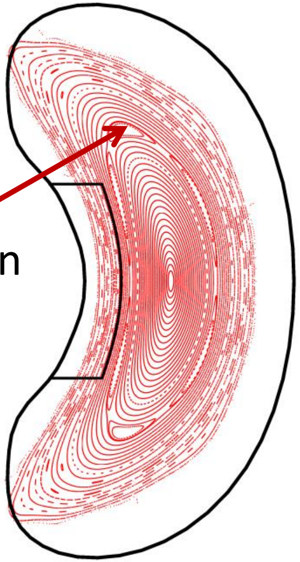
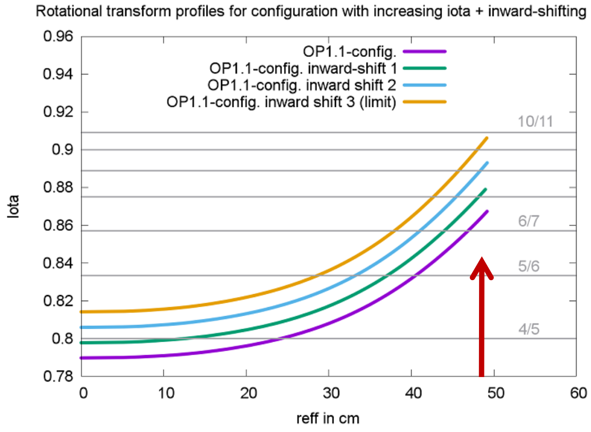


5/6 island chain

Iota 2 Iota 4 Iota 8 Iota 10



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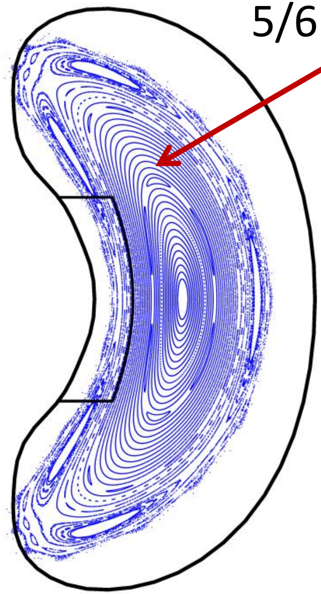
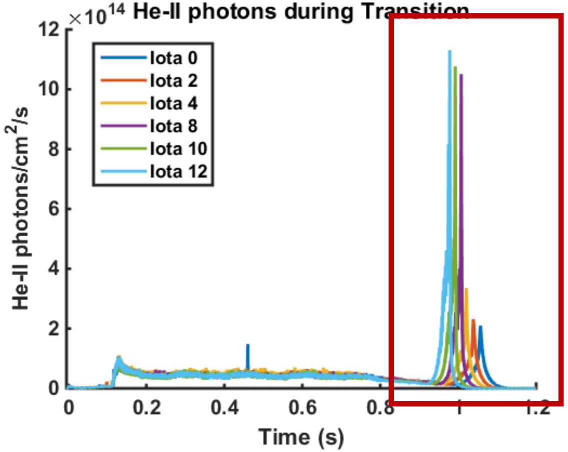
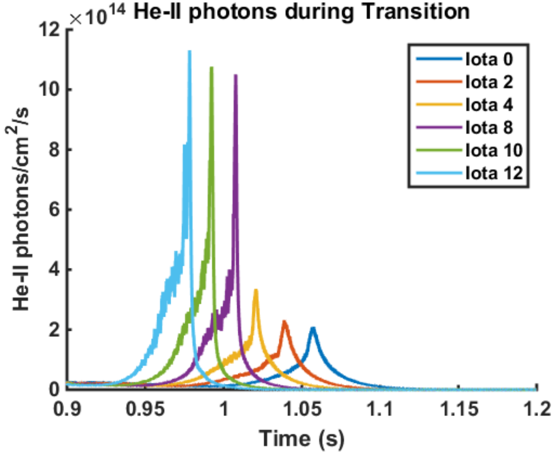


Helium emission after ECRH turnoff increases during iota transition





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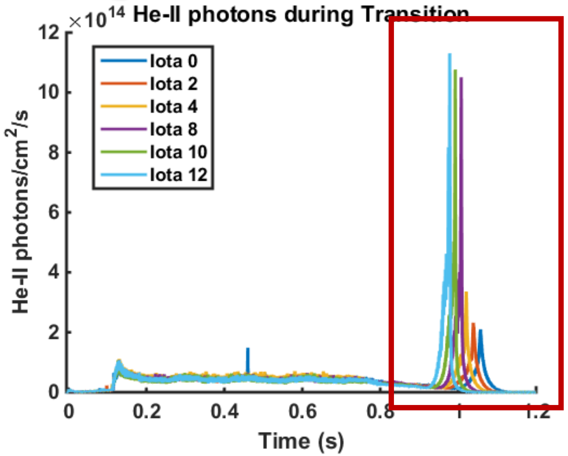

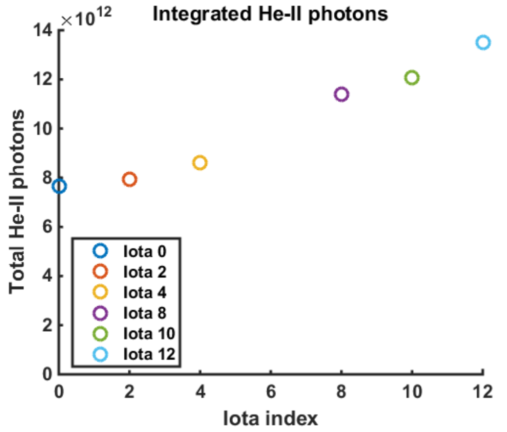

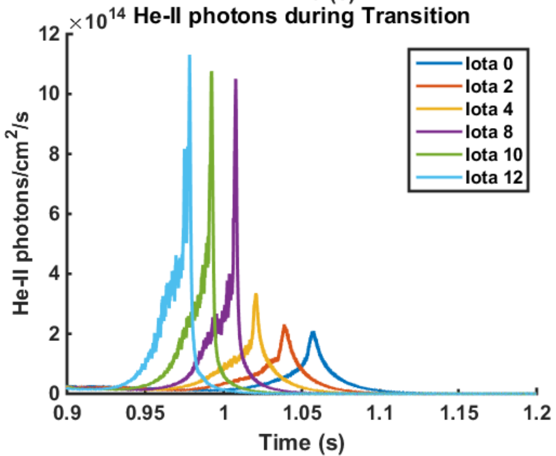

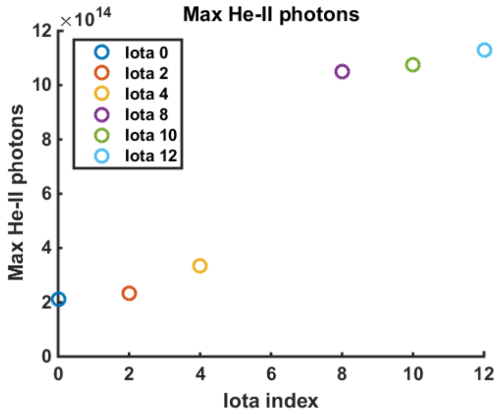

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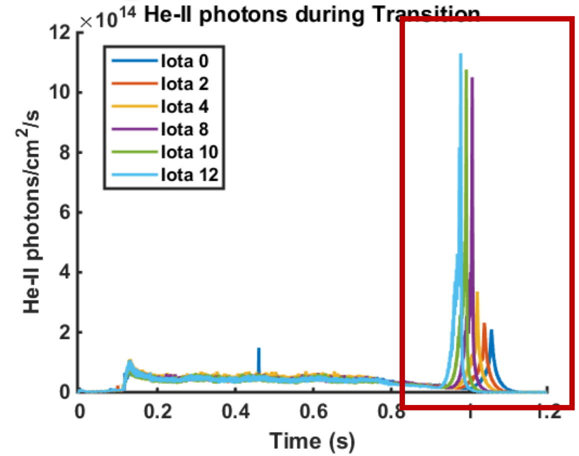
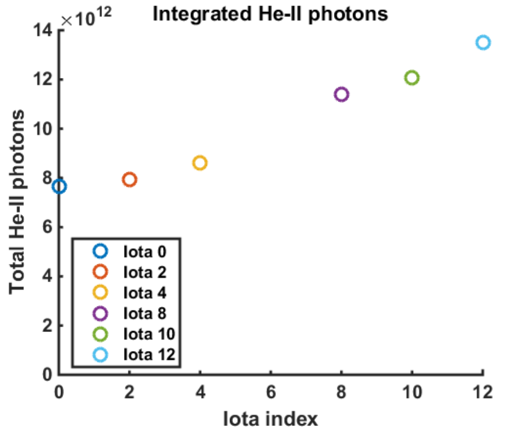
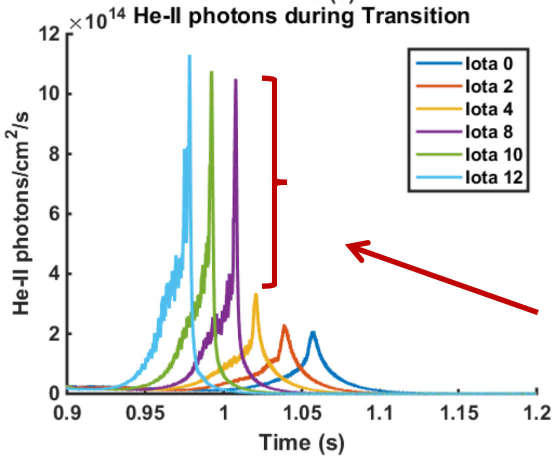
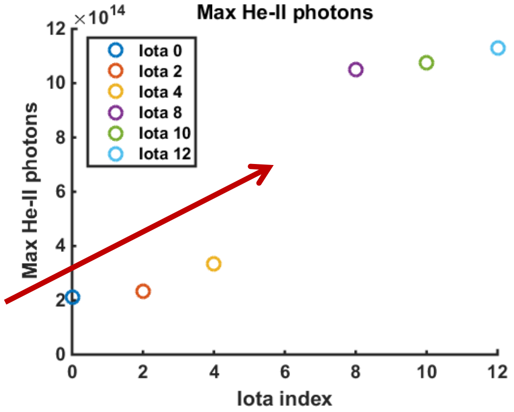




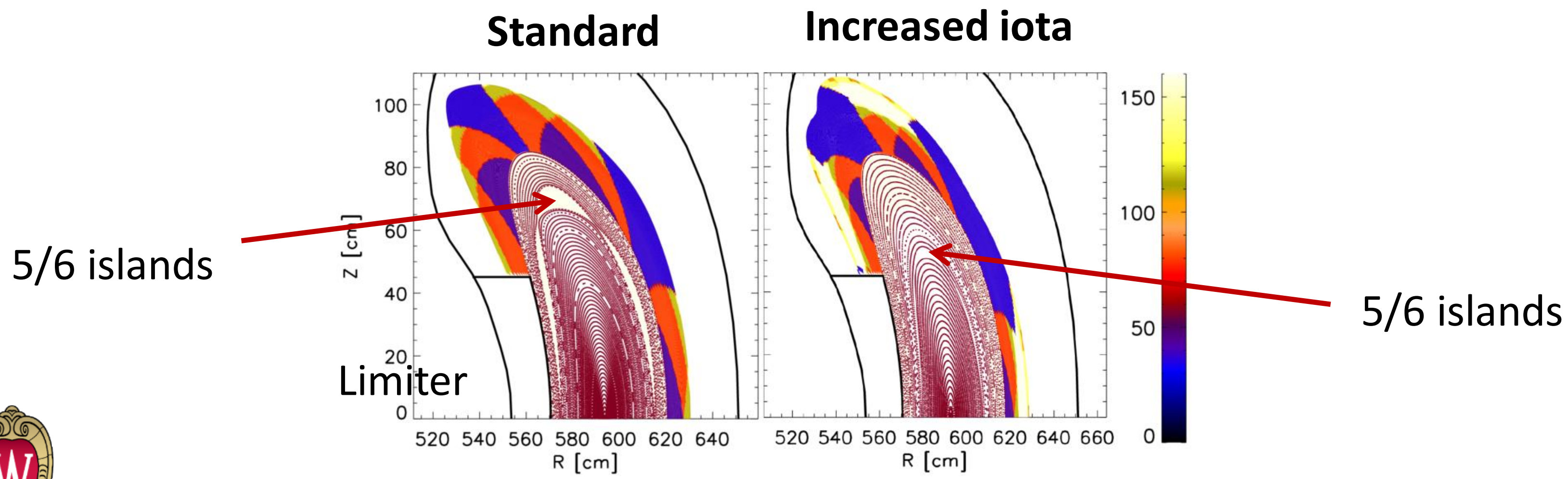


Large jump entry of island into edge?



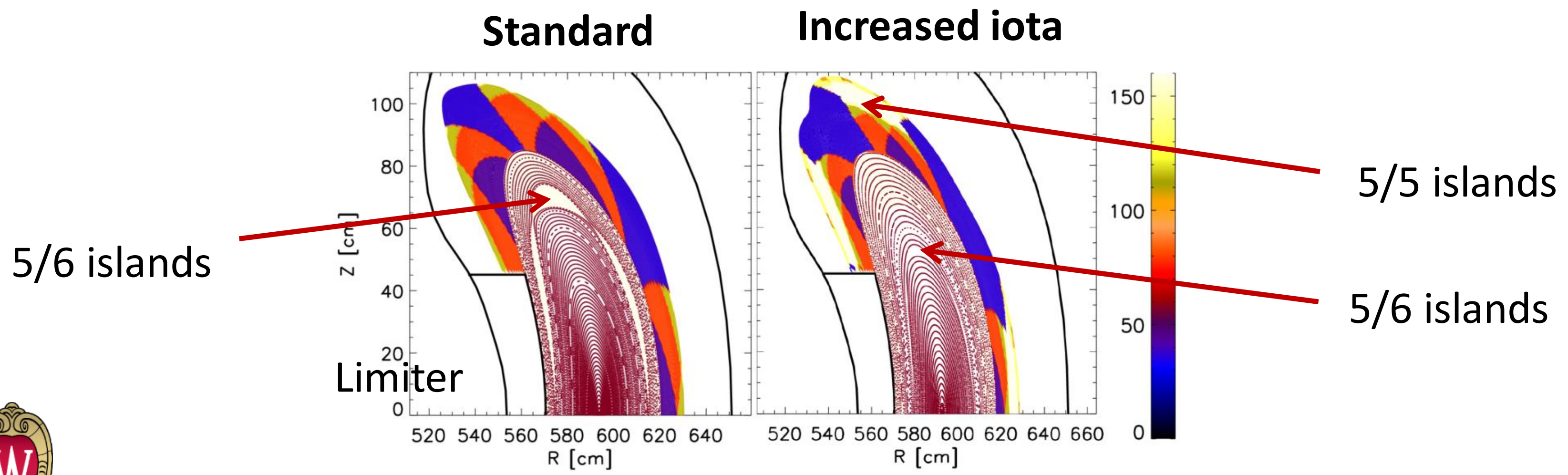
Interior and far SOL topology affected by iota change

- In increased iota, the 5/6 islands are moved inwards out of the source region (i.e. plasma ionization domain)

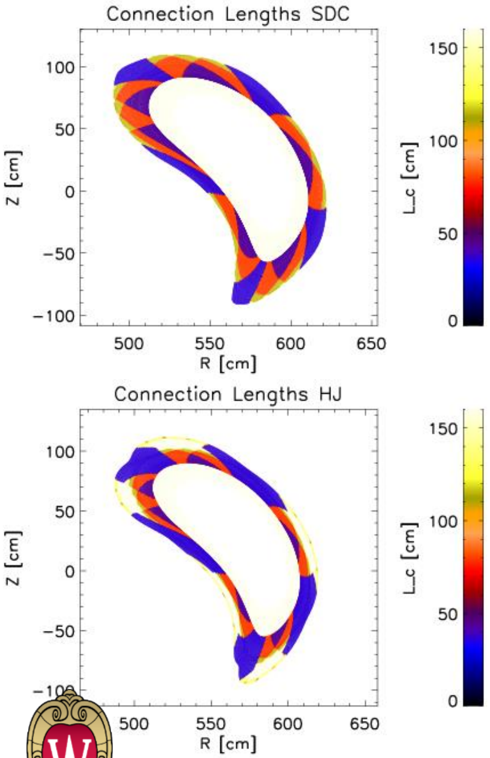


Interior and far SOL topology affected by iota change

- In increased iota, the 5/6 islands are moved inwards out of the source region
- But! The 5/5 islands move into the far SOL



EMC3-EIRENE simulations show that fine changes in magnetic field change He density distribution



See talk F. Effenberg PO4.00007 Wednesday PM

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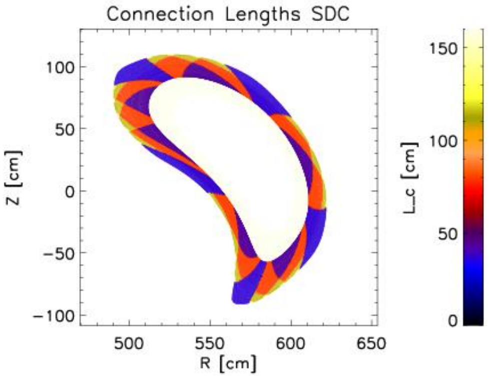
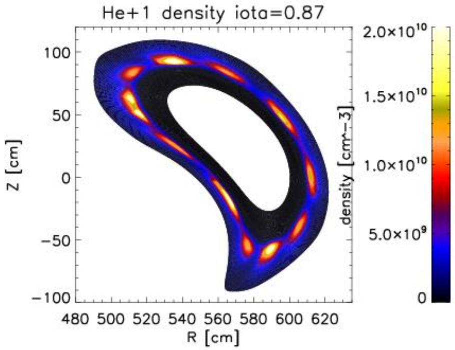
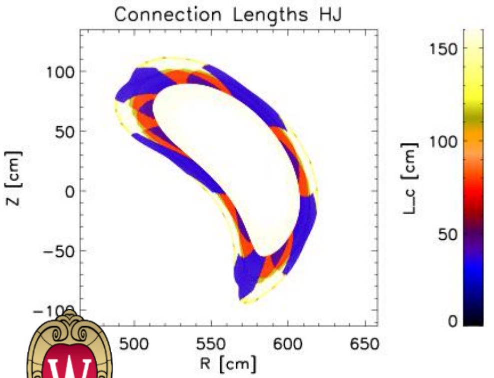
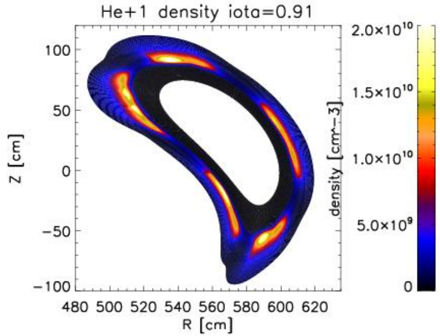


Standard





Increased Iota



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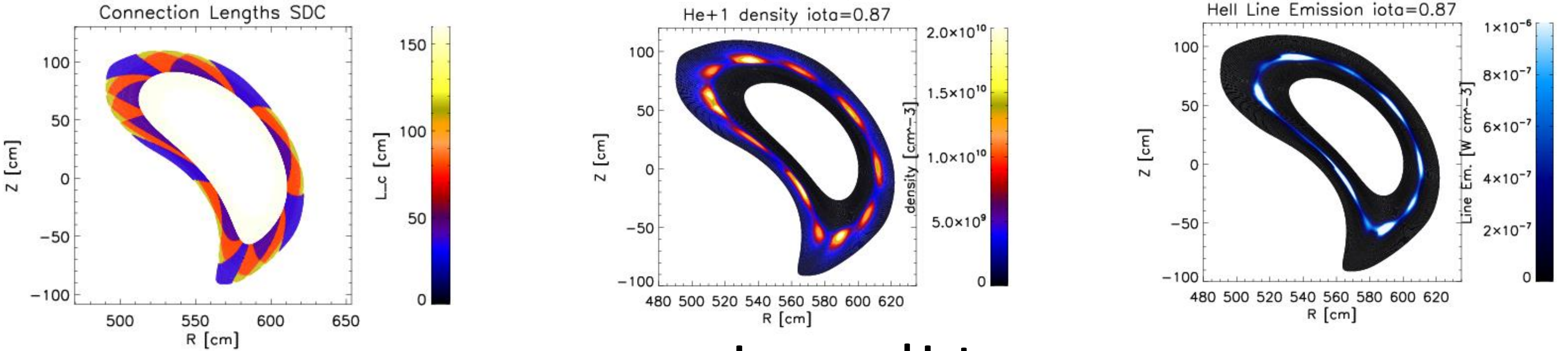

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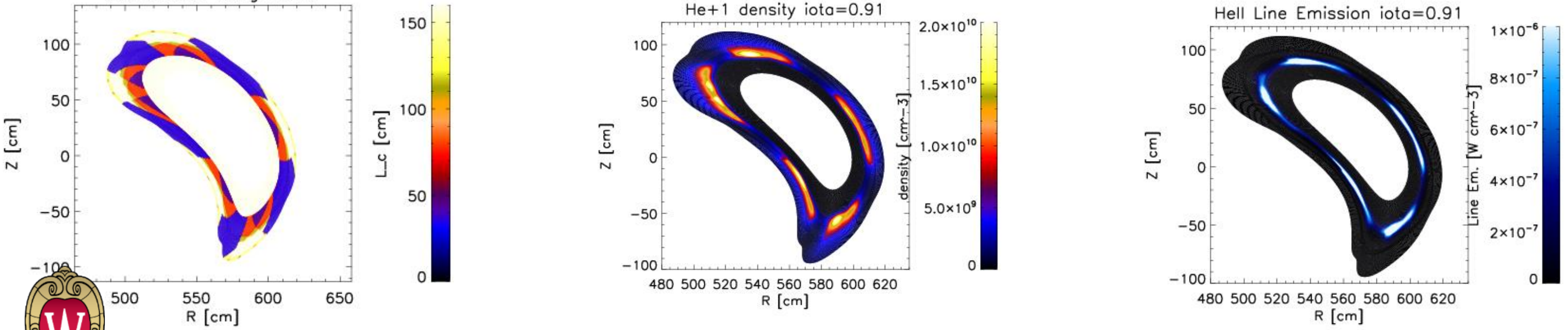

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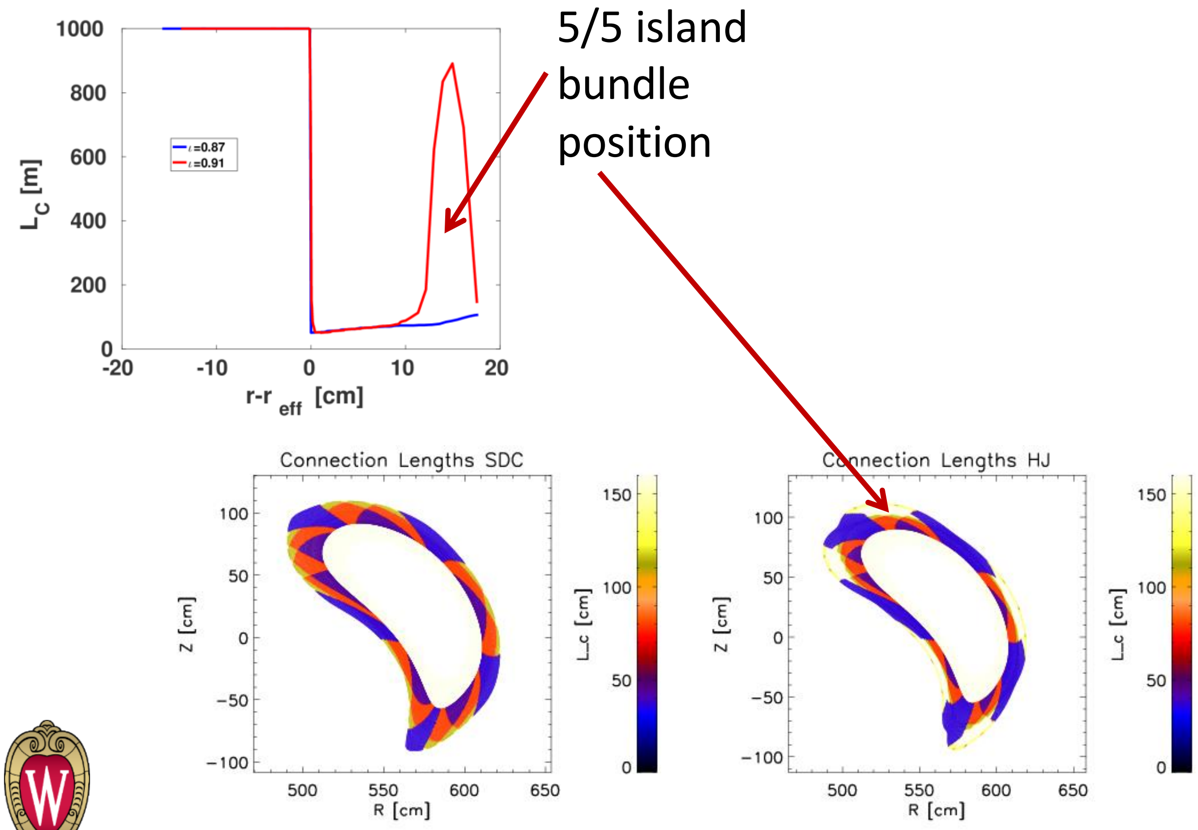

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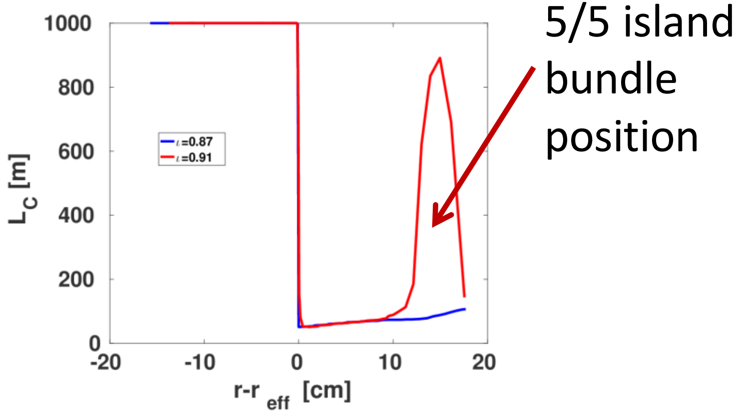
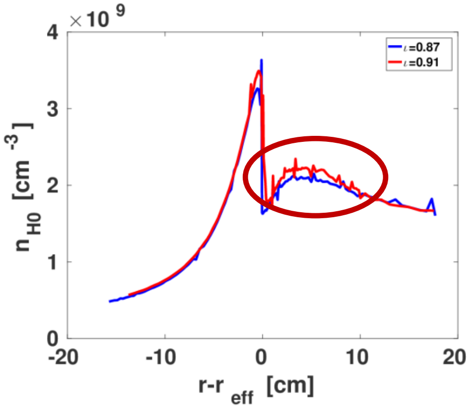
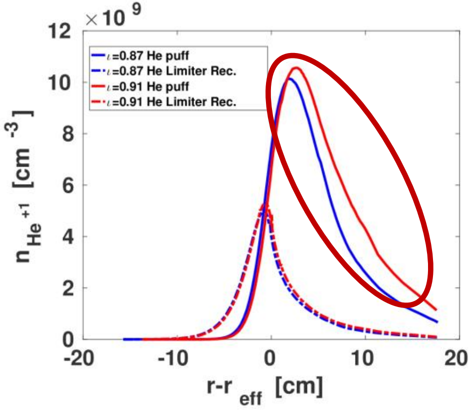
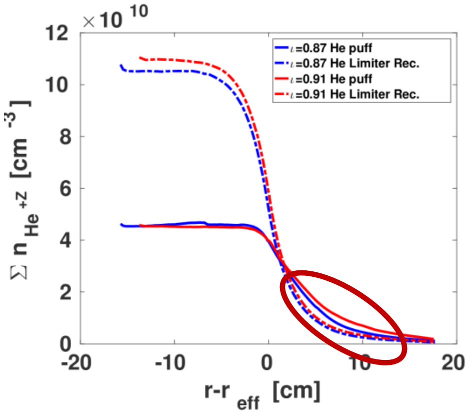


- **EMC3-EIRENE calculations indicate that neutral He density and He-I density is shifted slightly radially outward in increased iota**







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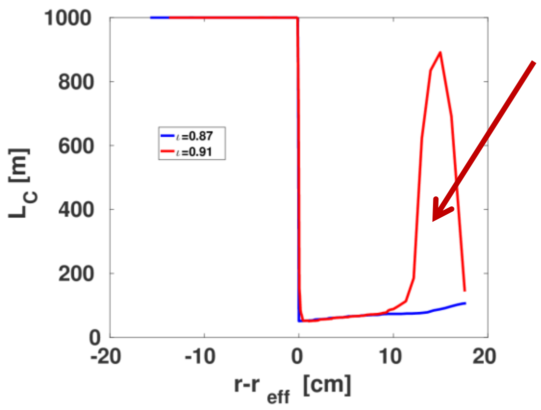
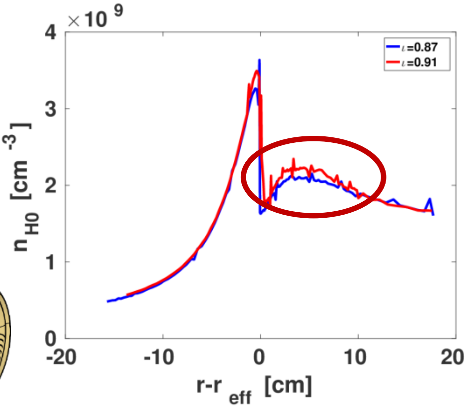
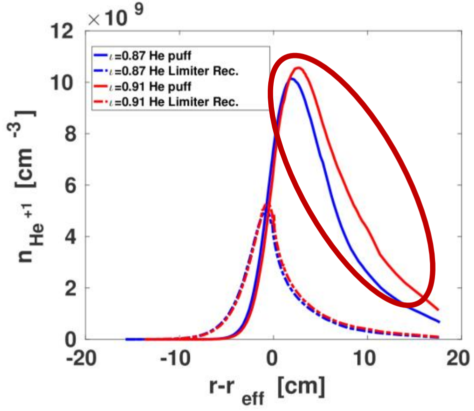
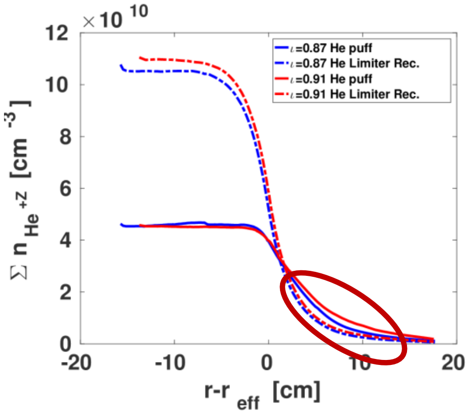


5/5 island bundle position

- **EMC3-EIRENE calculations indicate that neutral He density and He-I density is shifted slightly radially outward in increased iota**
- These small changes don't fully explain experimental findings
- Will continue to be examined in future work (boundary conditions, as-built magnetic field structure, etc.)







Major results

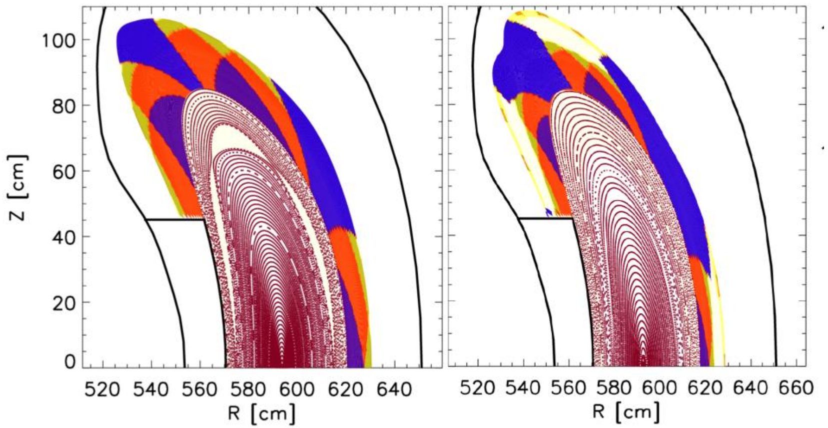
- Edge magnetic topology can be used to control particle confinement/exhaust at W7-X
- Long L_c edge flux bundles in helical SOL confine He and the effect is more prominent in increased iota
- Change in effective ripple at W7-X caused by island movement does not impact core transport
- Experiments at HSX also demonstrate that edge topology changes dominate changes due to effective ripple
- **Edge topology can be optimized without substantially degrading core transport**

At W7-X, by moving islands inward, also changed effective ripple → does not affect core confinement

- In the long mean free path regime, stellarator neoclassical transport may depend on the effective ripple, ε_{eff}
- ε_{eff} is a factor of 2 larger in the increased iota configuration

- Islands inside LCFS
- Small helical ripple

- Islands inside LCFS
- Moderate helical ripple



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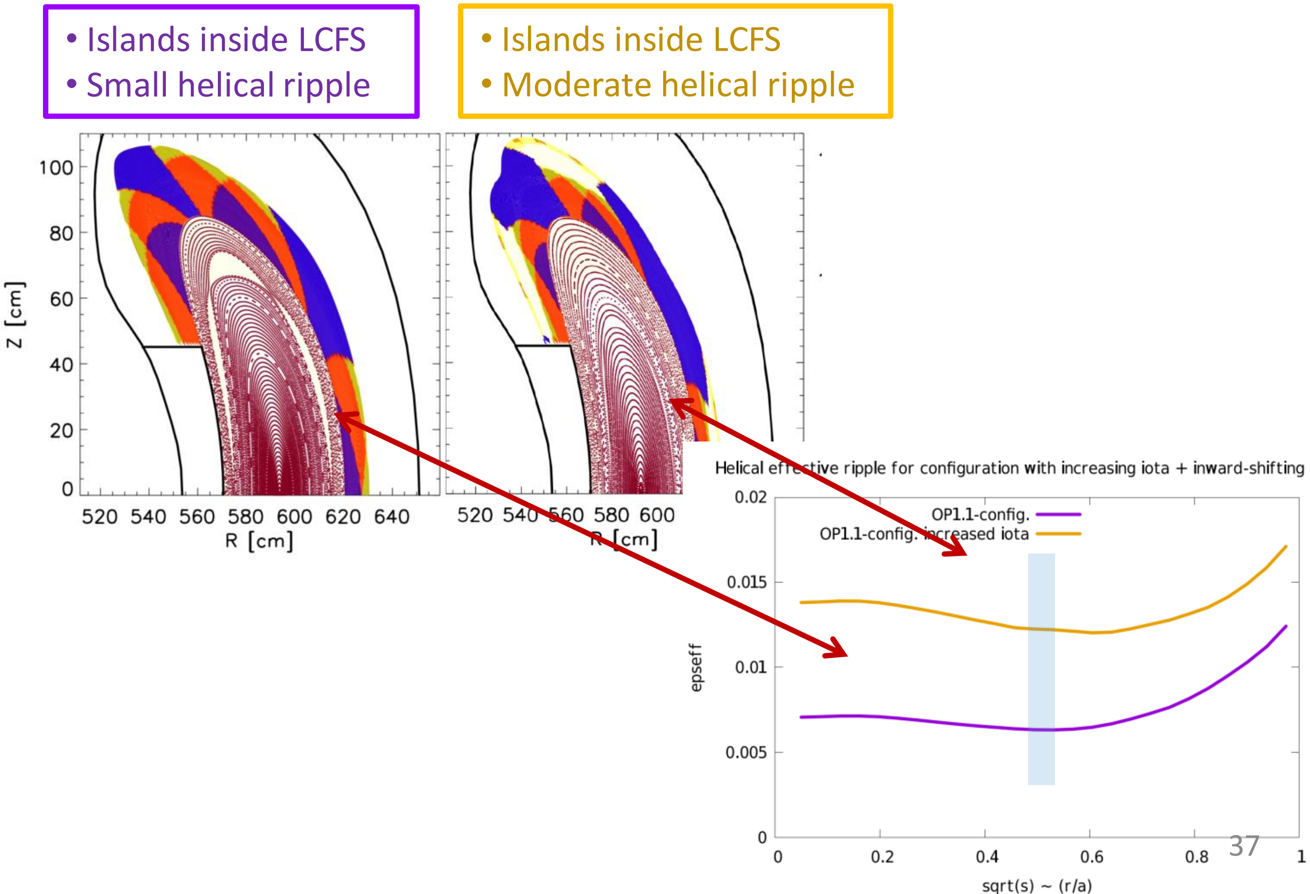

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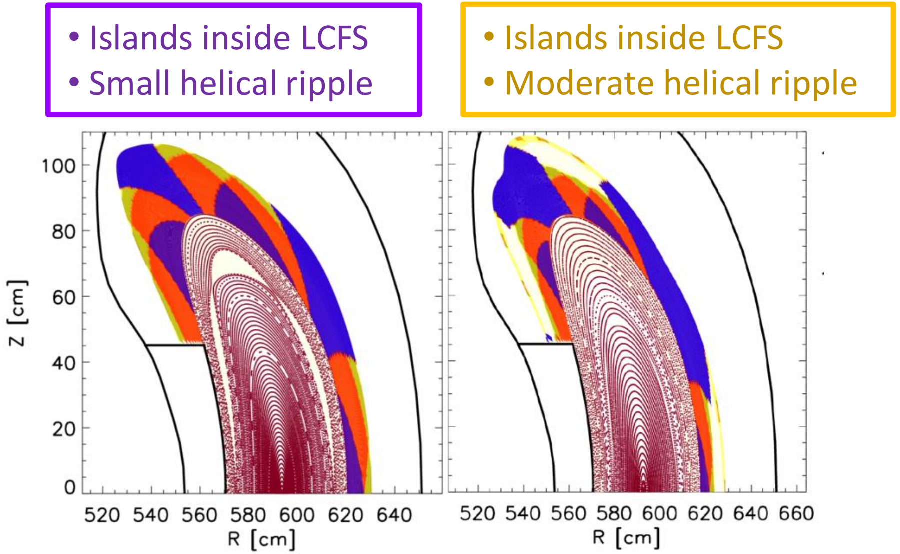

- **However, both measurements (N. Pablant) and modeling (M. Landreman) have shown that there is a positive E_r in the core**
- **In this regime, ε_{eff} should have a small contribution**
- **Supported by measurements from many diagnostics that show no substantial changes**

Major results

- Edge magnetic topology can be used to control particle confinement/exhaust at W7-X
- Long L_c edge flux bundles in helical SOL confine He and the effect is more prominent in increased iota
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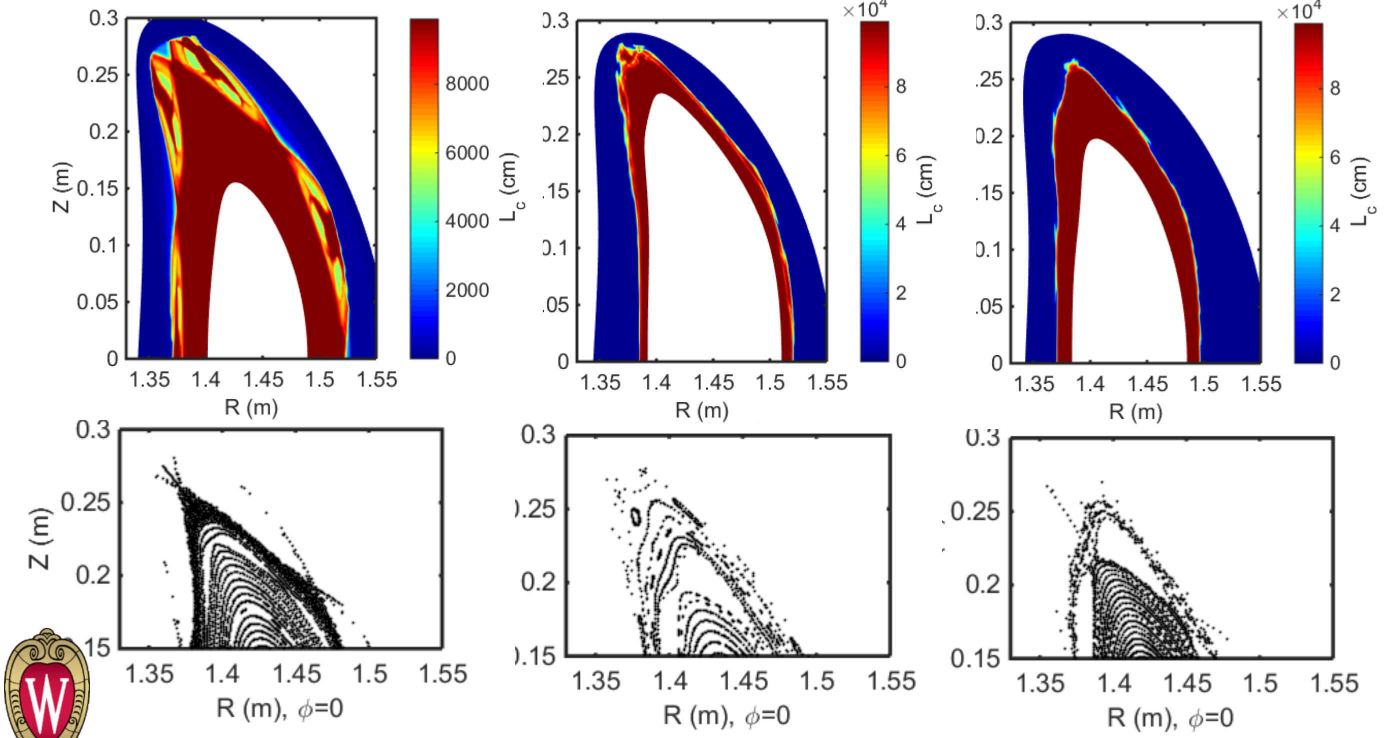
HSX can compare core and edge transport by separately varying ripple and island position

- Islands in edge
- Small helical ripple

- Islands inside LCFS
- Small helical ripple

- Islands inside LCFS
- Large helical ripple



HSX can compare core and edge transport by separately varying ripple and island position

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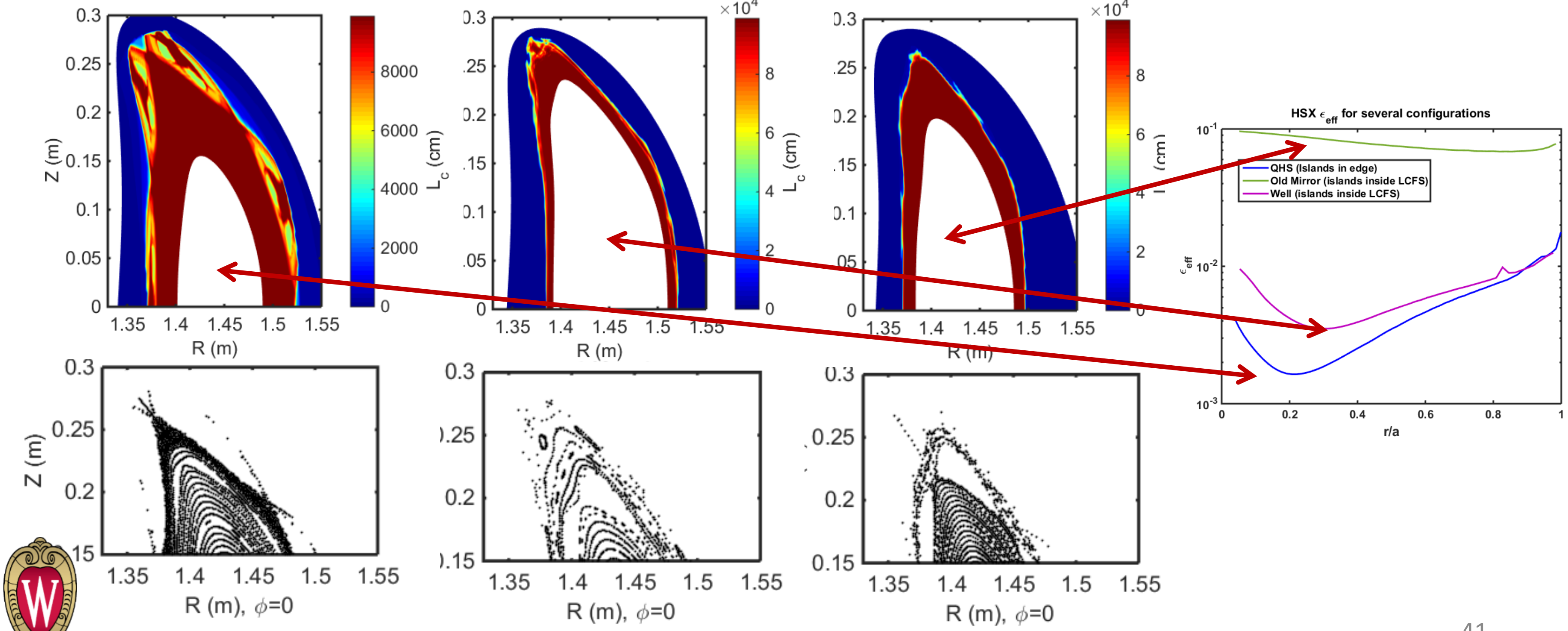

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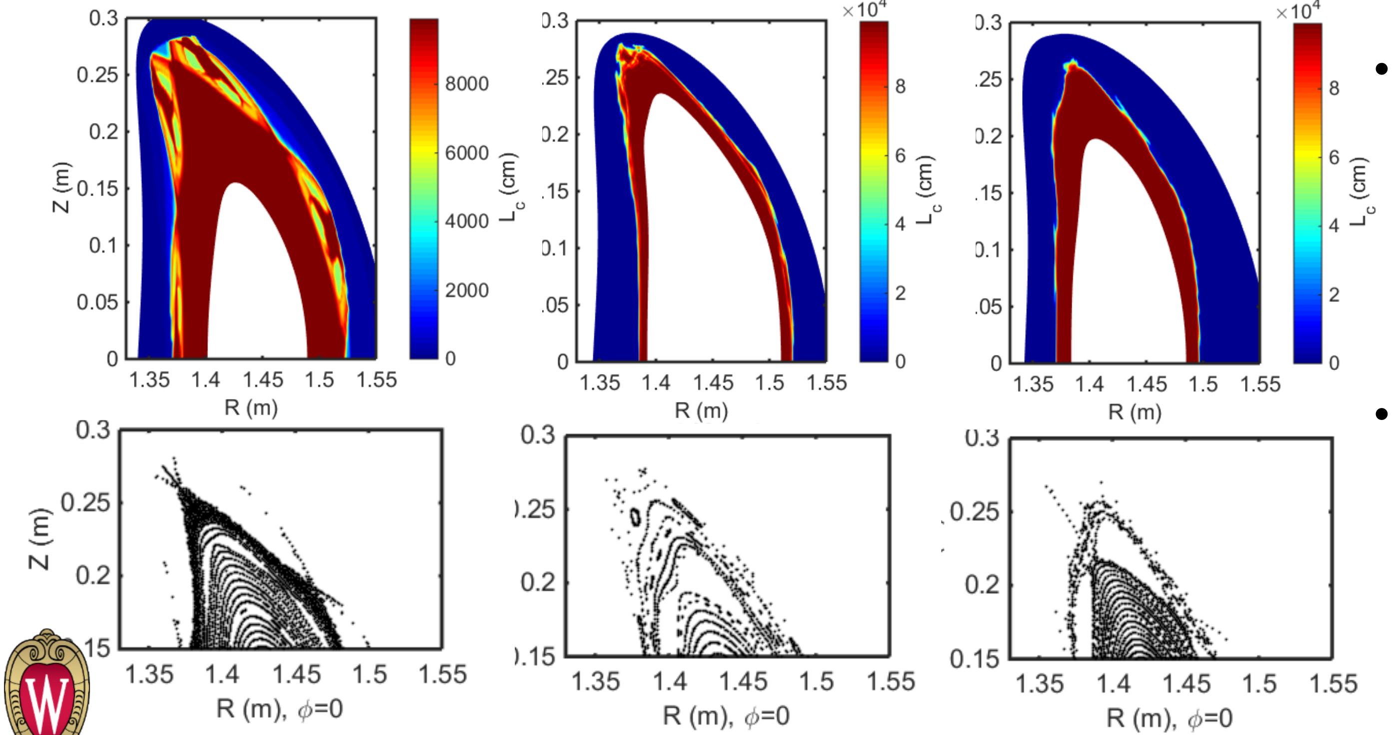
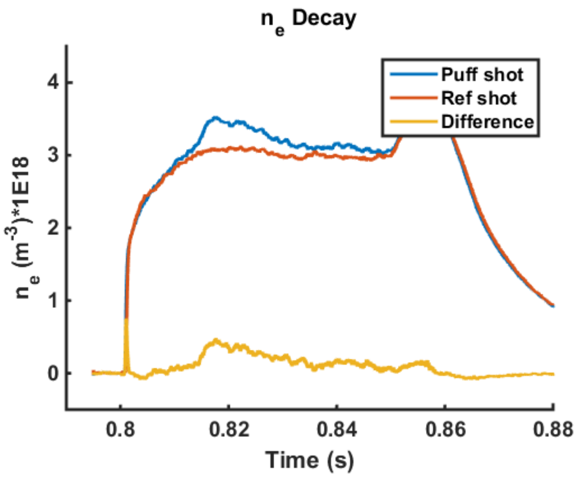


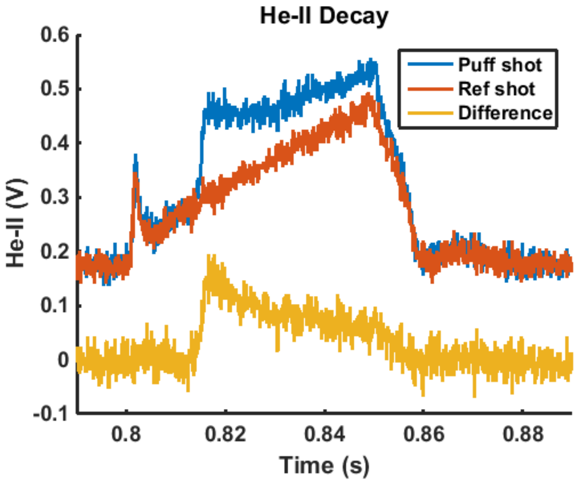
- **Measurements at HSX (S. Kumar) have shown a positive E_r throughout the entire minor radius**
- **In this regime, ε_{eff} should have a small contribution**

Assess changes in particle confinement by measuring decay of n_e and He-II emission

- Short H puff
- Measure decay in line averaged density



- Short He puff
- Measure decay in He-II (468 nm)



- In both cases, subtract signal from reference discharge with no perturbative puff
- Fit exponential to entire decay curve (i.e. no long and short decay like at W7-X due to short plasma duration)

Major results

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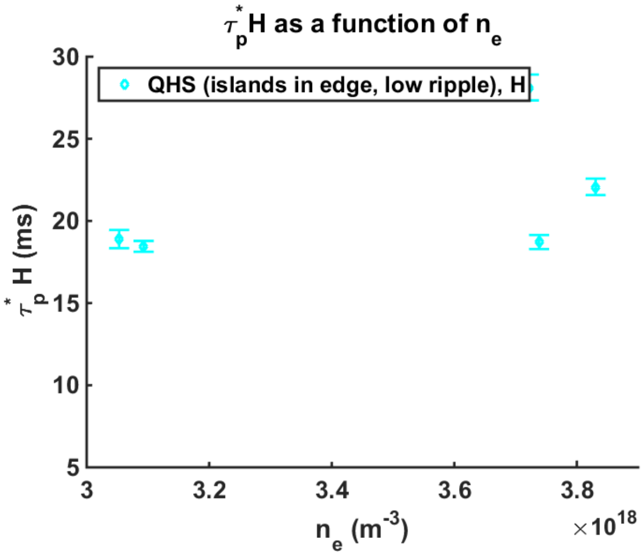
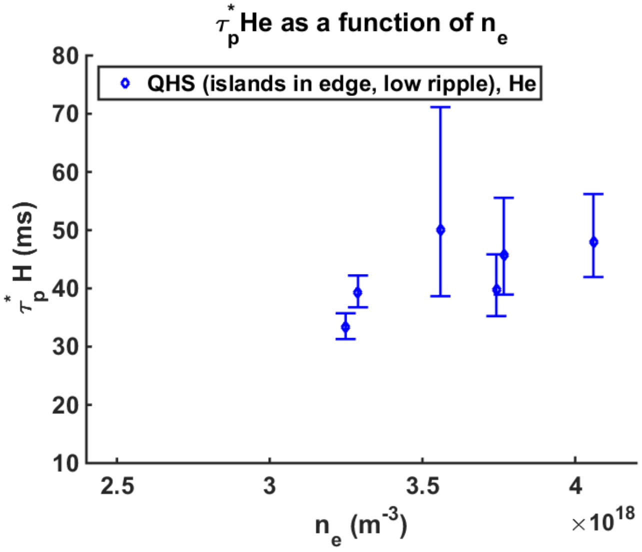
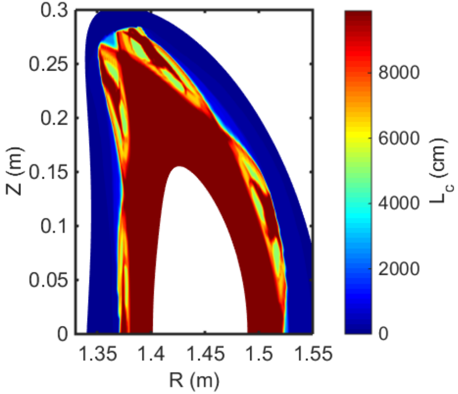
τ_p* H and τ_p* He in islands in edge, low ripple configuration

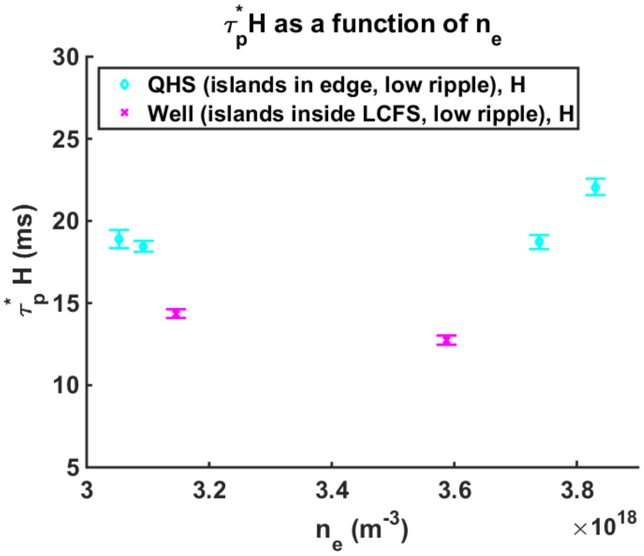


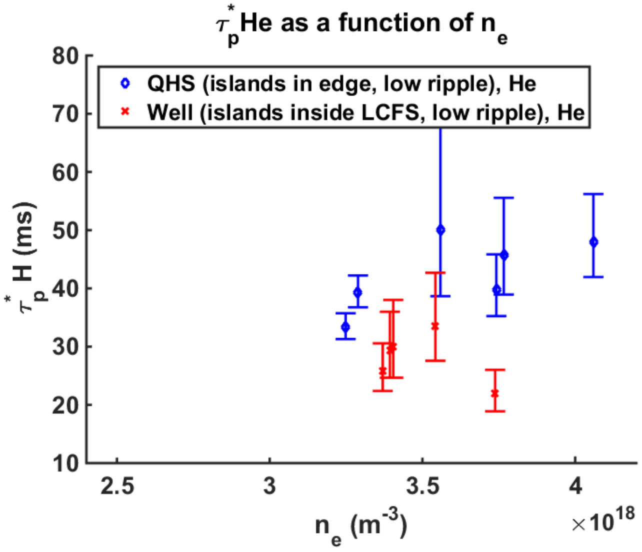


- Islands in edge
- Small helical ripple

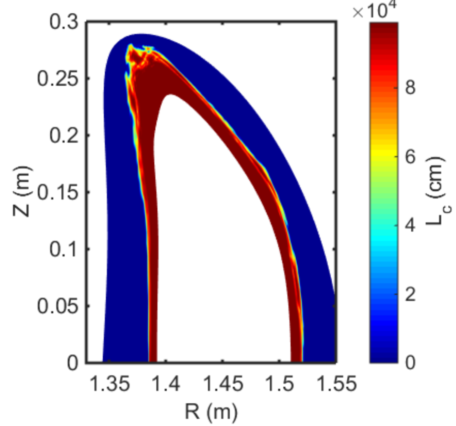


τ_p* H and τ_p* He in islands inside LCFS, low ripple configuration

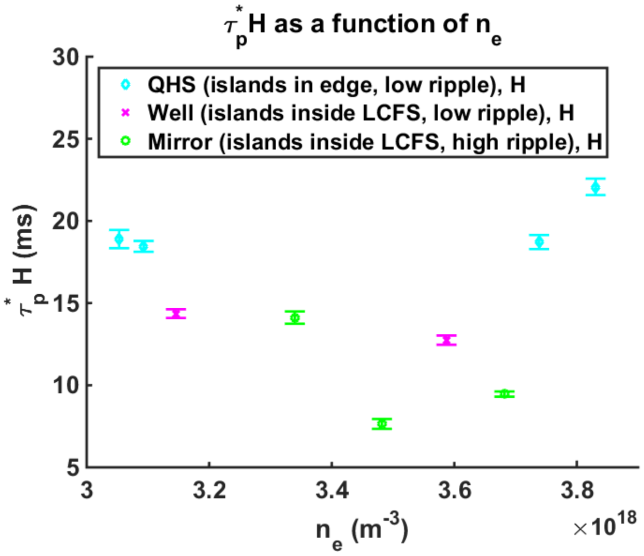


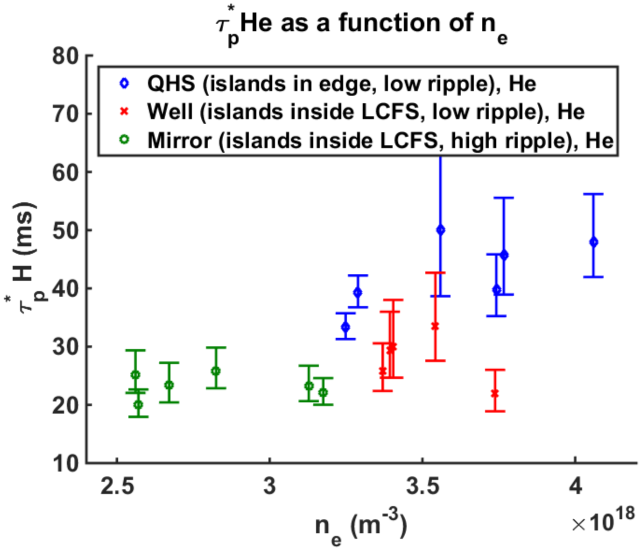


- Islands inside LCFS
- Small helical ripple

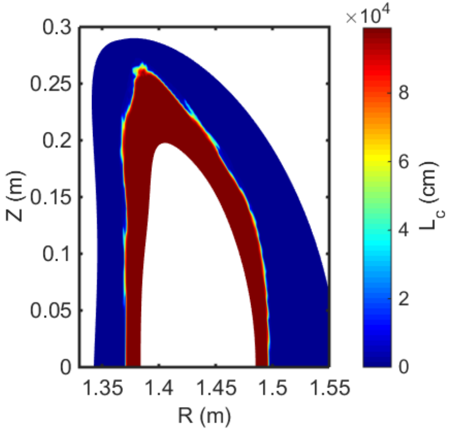


τ_p* H and τ_p* He in islands inside LCFS, high ripple configuration



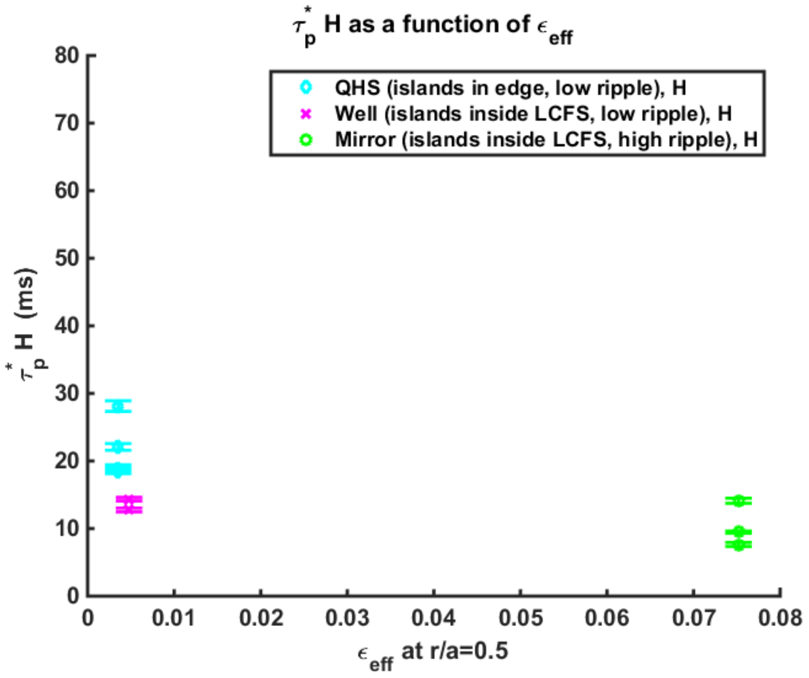


- Islands inside LCFS
- Large helical ripple

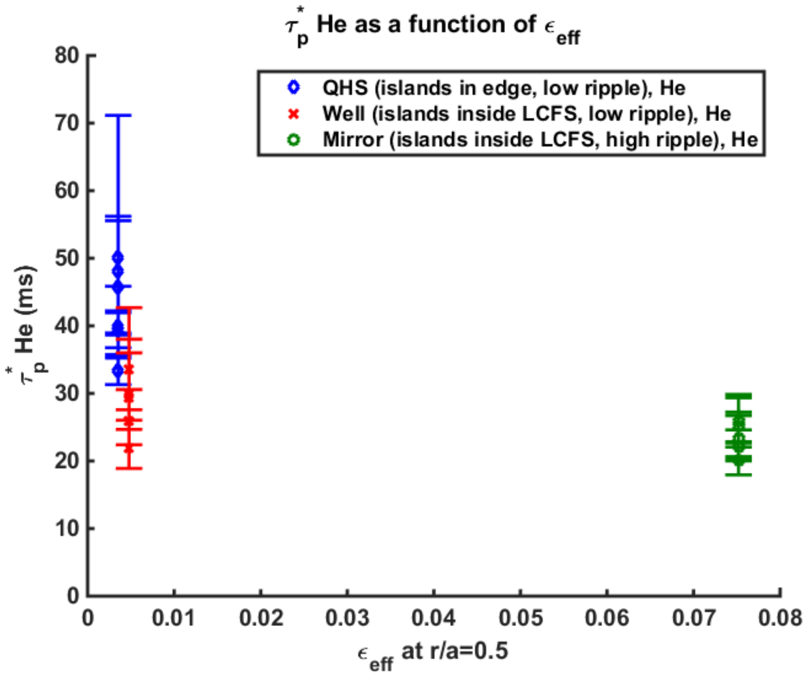


Both τ_p* H and τ_p* He longest in islands in edge, low ripple configuration

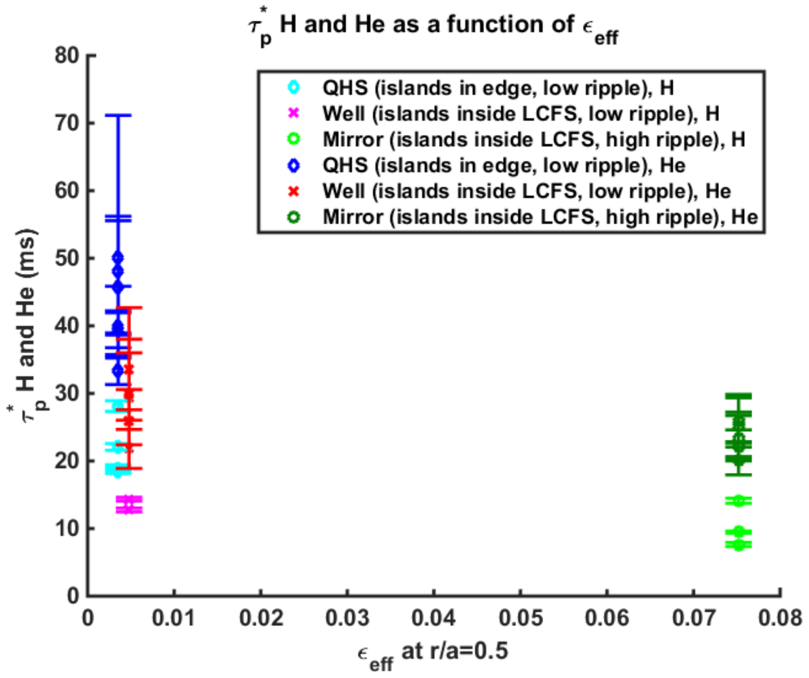
We can examine τ_p* H as a function of effective ripple at r/a=0.5 for each configuration



We can examine τ_p* He as a function of effective ripple at r/a=0.5 for each configuration



We can examine τ_p* H and τ_p* He together to study impact of effective ripple on global particle transport



τ_p* He about a factor of 2 larger than τ_p* H

- **τ_p* H and τ_p* He together imply that the change in edge topology dominates change in core transport**
- Do edge islands improve confinement? → Future work

Summary

- Changes in magnetic topology shown to aid direct control of particle confinement in W7-X and HSX
- W7-X: edge magnetic topology enables trapping of helium, potentially other impurities
- **W7-X and HSX: the edge topology can be changed without substantially impacting core particle transport →** has positive implications for future divertor design
- Outlook: results are promising for good particle and impurity exhaust with island divertor at W7-X

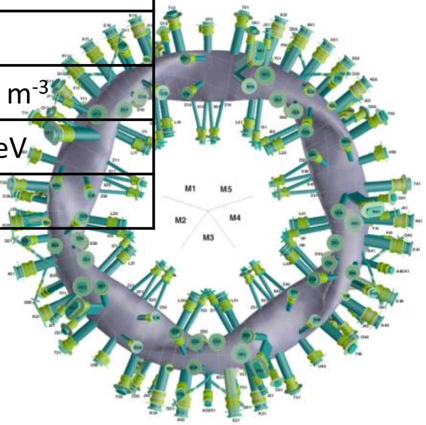
Thank you

Extra slides

W7-X and HSX experimental parameters

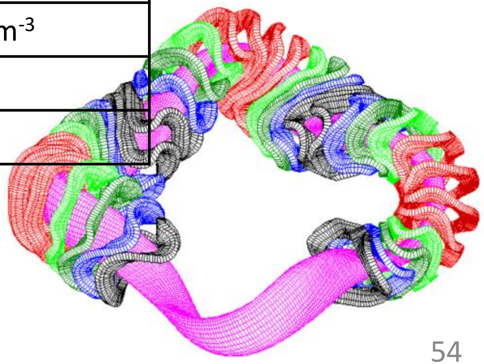
W7-X

T_{plasma}	Up to 6 s
P_{ECRH}	4 MW
R	5.5 m
r	0.53 m
$n_{e,\ core}$	2E19 m^{-3}
λ_{iz,H_2}	1 mm
$T_{e,\ core}$	8 keV
$T_{i,\ core}$	1 keV
$n_{e,\ edge}$	0.5E19 m^{-3}
$T_{e,\ edge}$	10-15 eV
$T_{i,\ edge}$	?



HSX

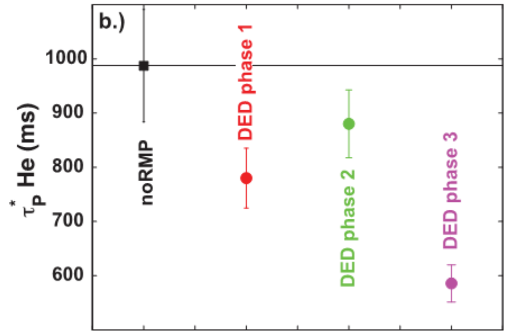
T_{plasma}	50 ms
P_{ECRH}	100 kW
R	1.2 m
r	0.15 m
$n_{e,\ core}$	5E18 m^{-3}
λ_{iz,H_2}	1 cm
$T_{e,\ core}$	2.5 keV
$T_{i,\ core}$	60 eV
$n_{e,\ edge}$	5E17 m^{-3}
$T_{e,\ edge}$	70 eV
$T_{i,\ edge}$	25 eV



Results at TEXTOR and LHD

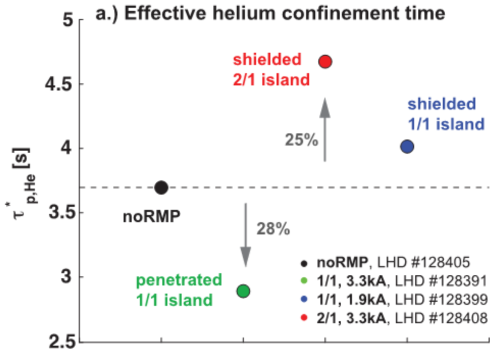
TEXTOR

- Reduction of fueling efficiency
- Increase of level of He in SOL
- Faster decay times (shorter Tp*)



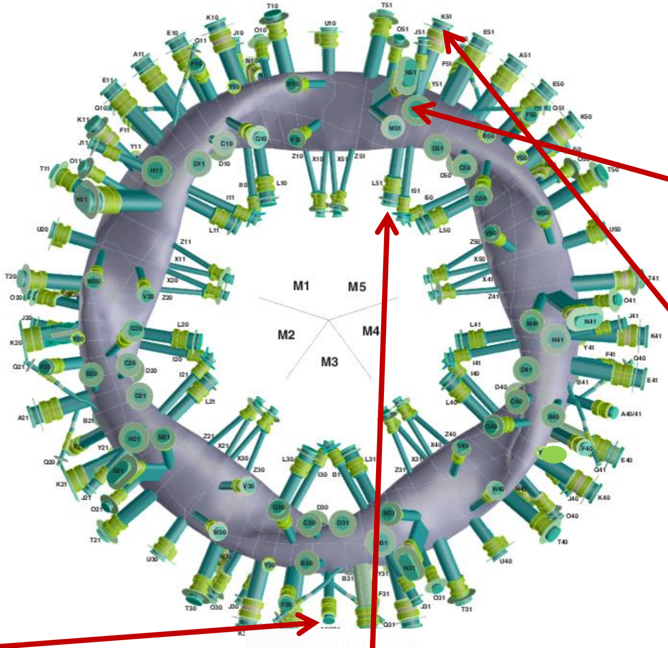
LHD

- Reduction in fueling efficiency
- 10% drop in He-I emission in edge
- Both shorter and longer decay times



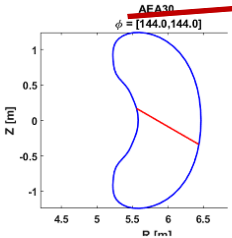
O. Schmitz et al., Nucl. Fusion Vol 56, No 106011, 2016.

Diagnostic and experimental setup at W7-X

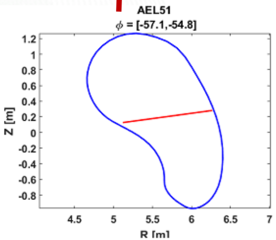


He gas puff

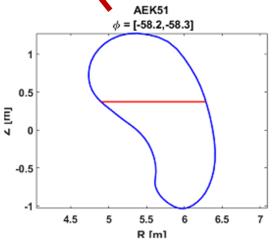
Measure emission using ORNL filterscope diagnostic



A30 He-I (limiter-viewing)



L51 He-I



K51- He-II

Goal: Investigate balance of edge and core transport

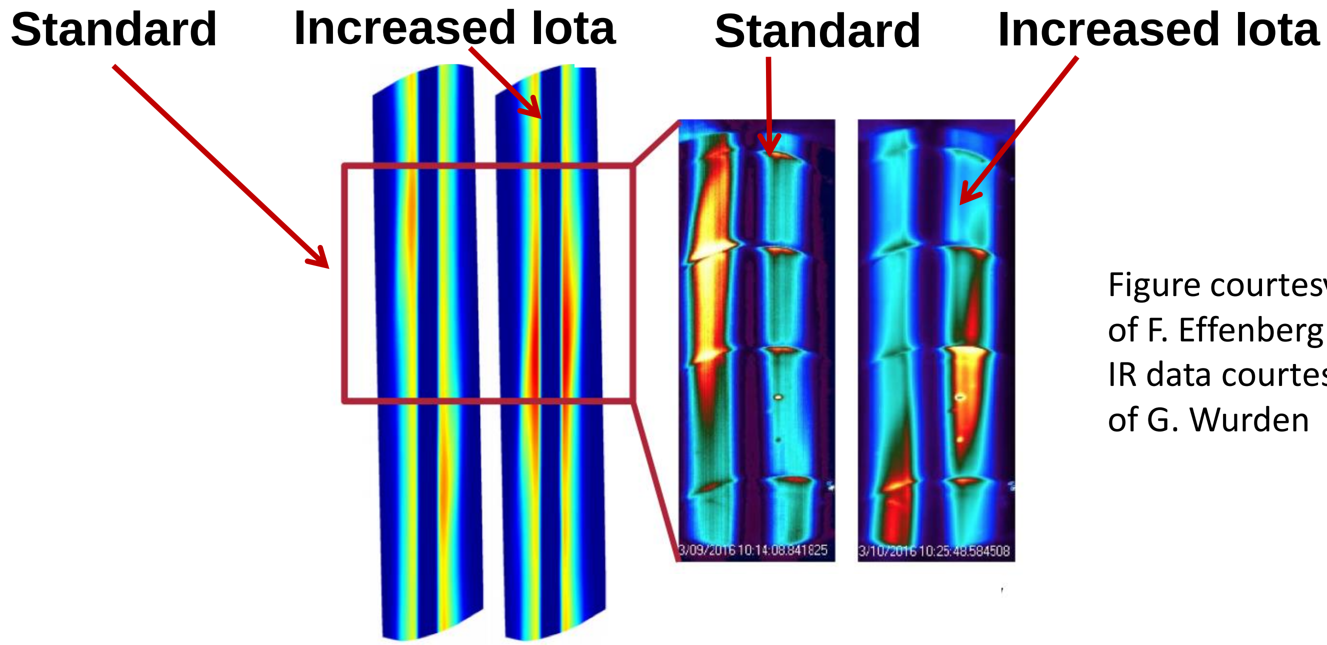
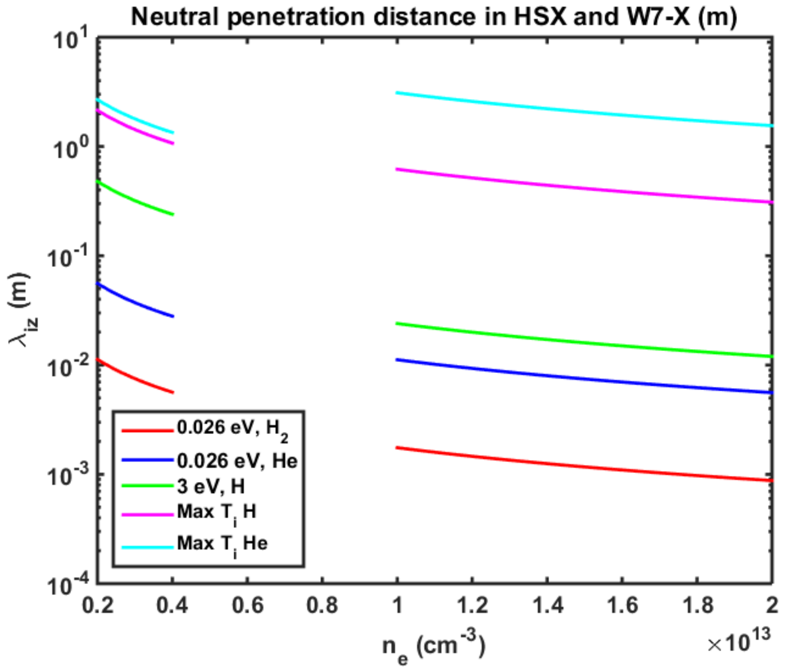


Figure courtesy of F. Effenberg
IR data courtesy of G. Wurden

Edge: investigate changes in island position relative to plasma source (ionization) region

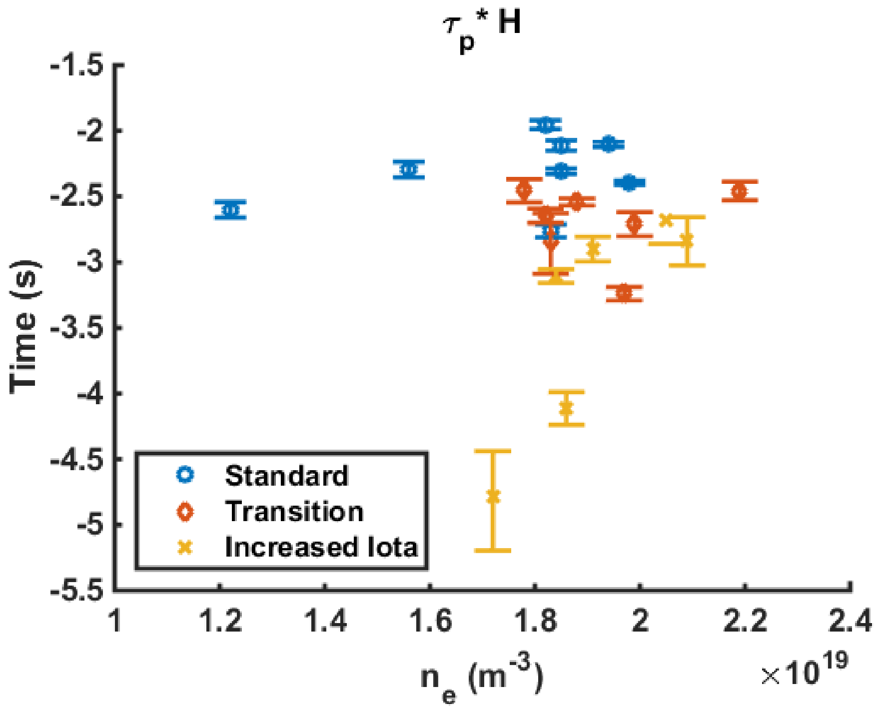
Core: long mean free path regime, role of core transport also explored

Higher densities affect neutral penetration length λ_{iz}



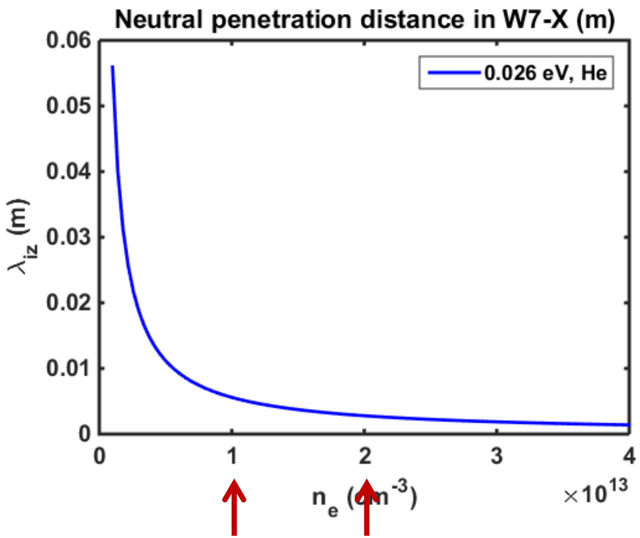
- Neutral penetration lengths can be on the order of the HSX minor radius (15 cm)
- The higher density in W7-X prevents neutrals from penetrating as deeply
- Smaller shifts in island position are required to move it out of the source region
- EMC3-EIRENE calculations needed for more detailed information

Rise in density provides Tp* H



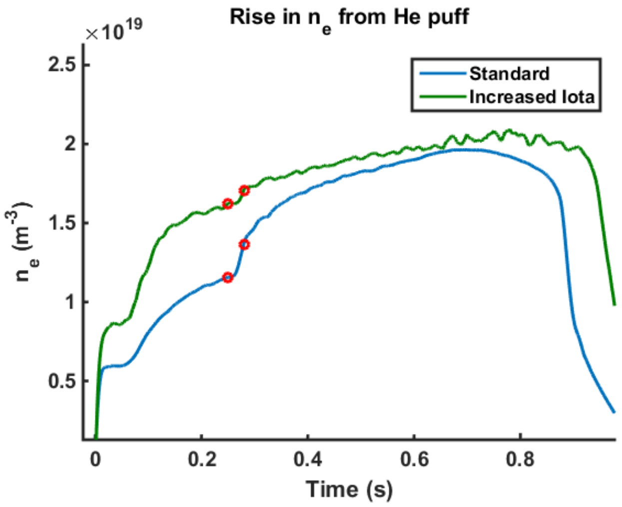
- More negative values → slower density rise
- Less negative values → faster density rise
- Slower density rise may imply a degradation in confinement in increased iota
- This agrees with expected increase in core neoclassical transport

Does change in density prevent He from penetrating?



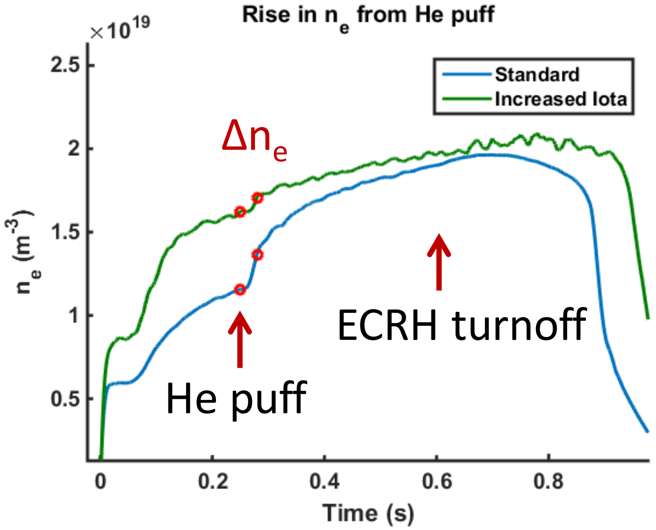
Standard

Increased Iota



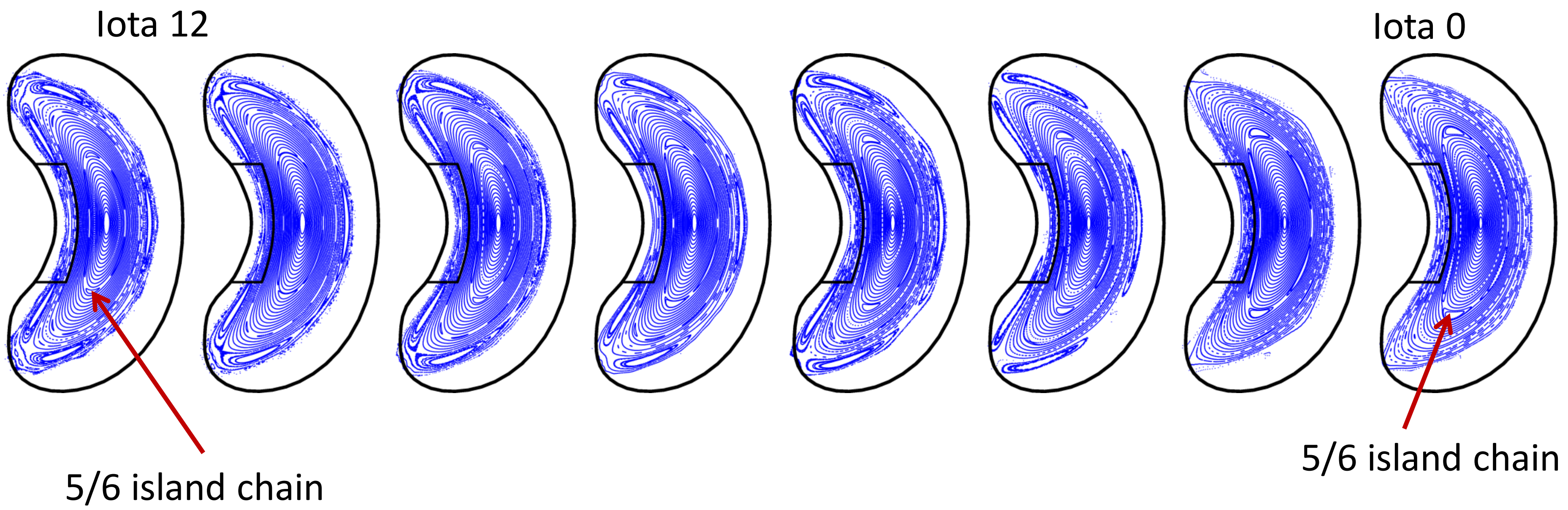
Density evolution provides evidence of reduced fueling and possible enhanced transport in increased iota

- Density rise slower in increased iota
- Could be reduced confinement and/or reduced edge sourcing
- In both cases, over-fueled situation (negative τ_p*)



- Same number of puffed He particles (1E19)
- Density rise (Δn_e) is a factor of 2 reduced in increased iota
- Evidence for reduced fueling or rapid outward transport
- Where is the helium? In the edge?

Systematically transition from standard to increased iota in 6 steps



Figures courtesy F. Effenberg

Differences between ideal and as-built coils

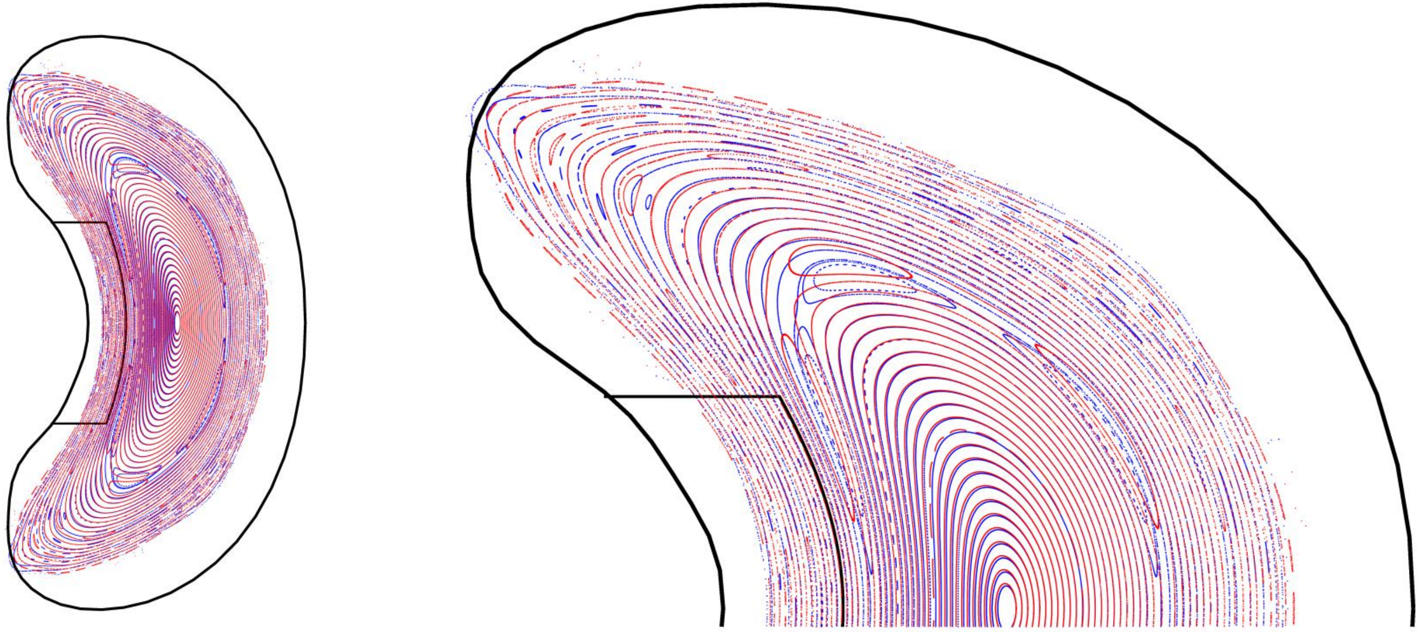
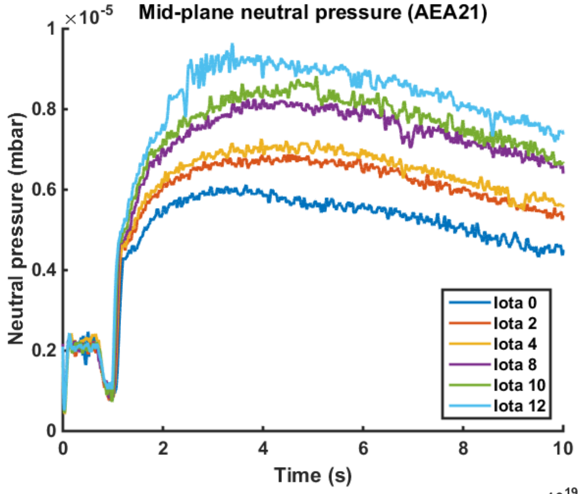
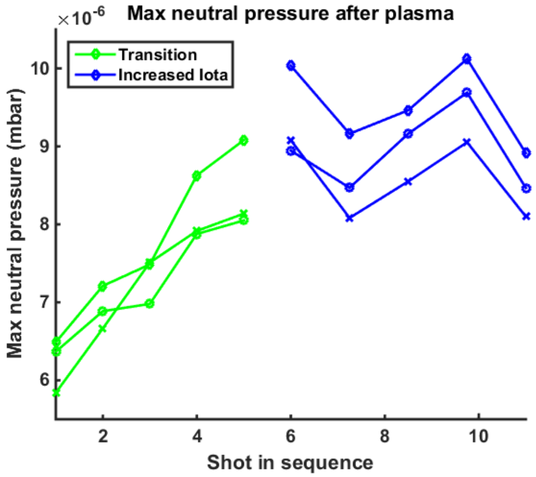
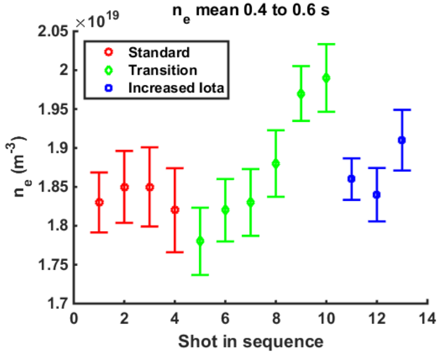


Figure courtesy F. Effenberg

Neutral pressure rises during transition

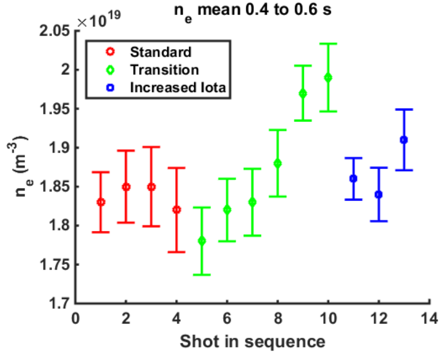


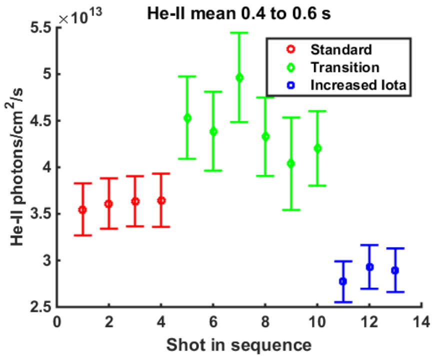


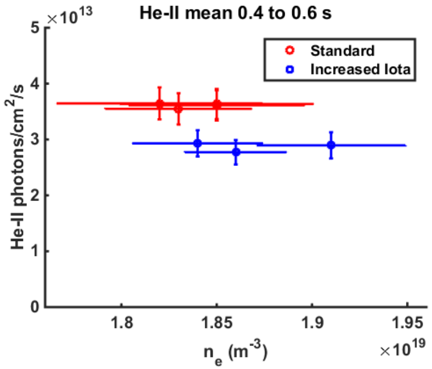


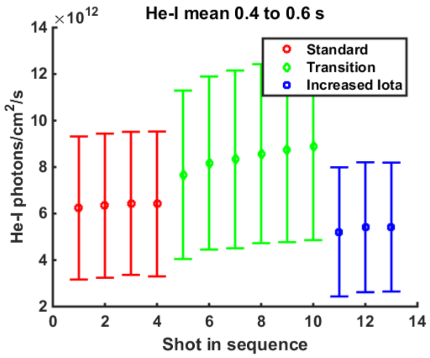
But density is also rising

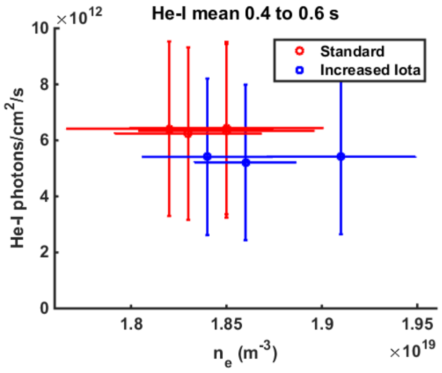
Density, He-I, He-II during transition



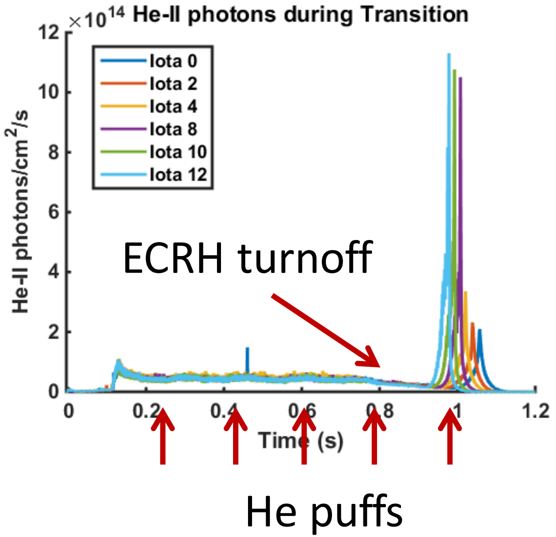


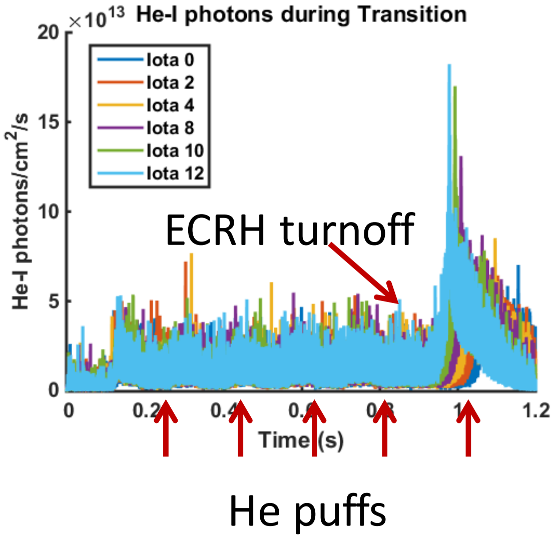




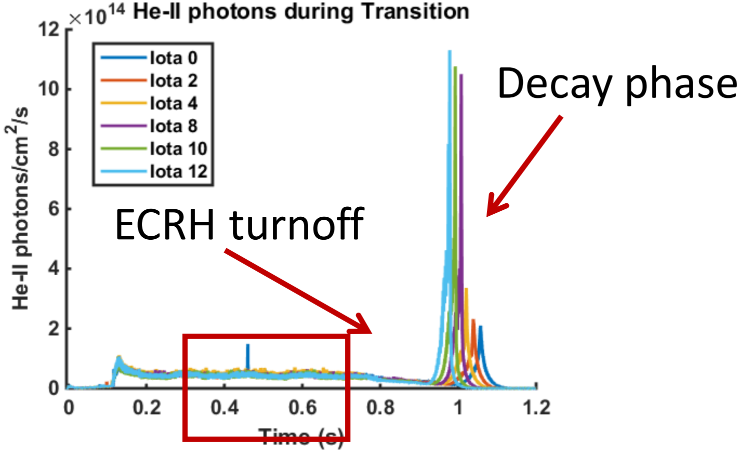


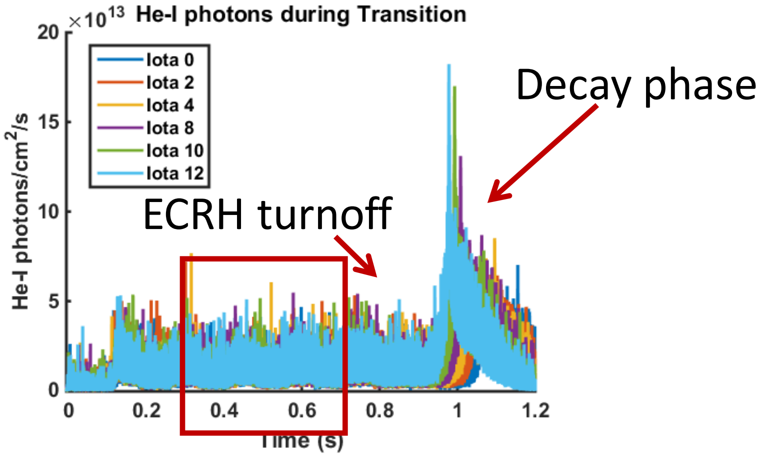
He-I and He-II emission remain relatively constant during transition



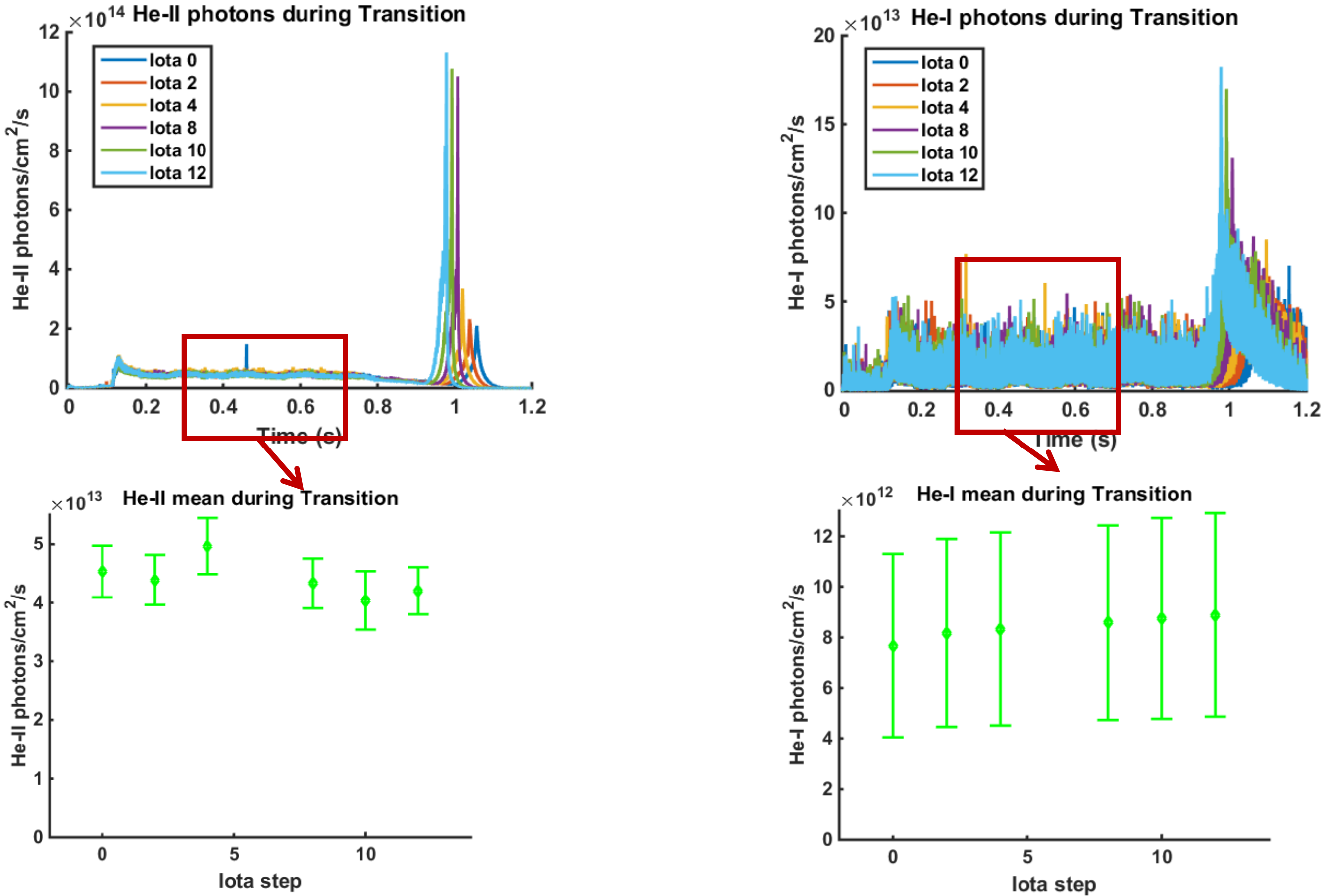


He-I and He-II emission remain relatively constant during transition

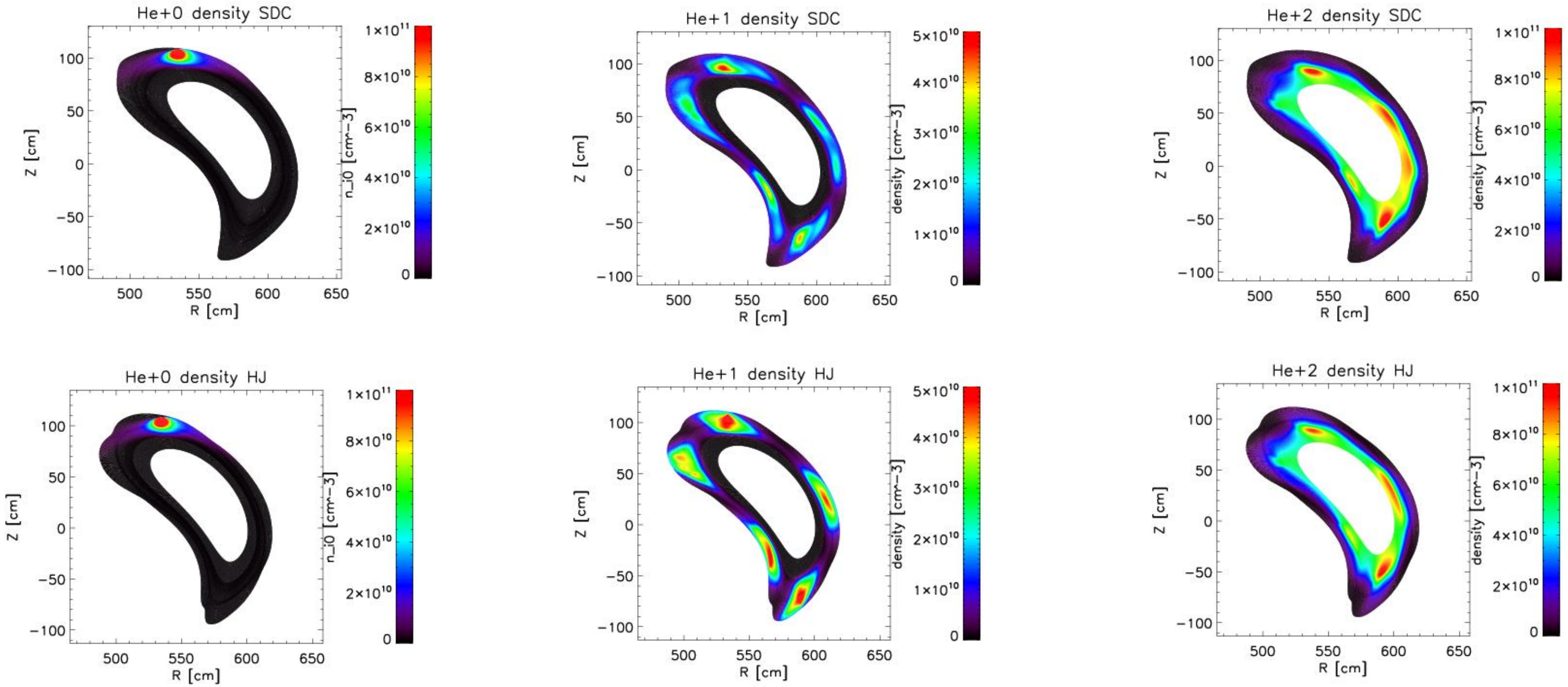




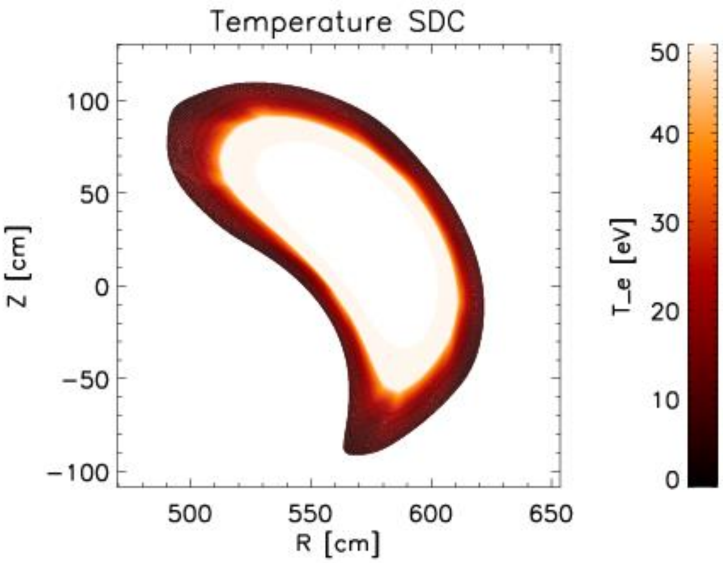
He-I and He-II emission remain relatively constant during transition

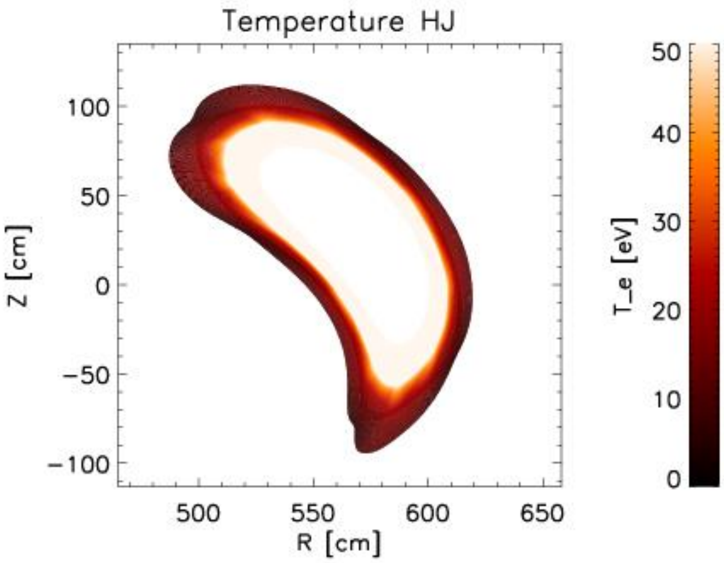


He density from EMC3-EIRENE



EMC3-EIRENE temperature



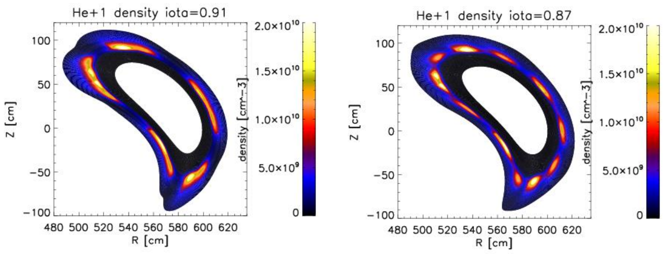


He-I ionization energy → 25 eV
He-II ionization energy → 55 eV

EMC3-EIRENE calculations courtesy of F. Effenberg

Full particle balance required for τ_p

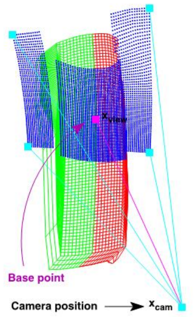
Numerical particle balance in EMC3-EIRENE



- Numerical particle balance performed
- EMC3-EIRENE calculations indicate that for H, confinement is degraded by 15% from Standard to Increased Iota

See I. Waters poster NP10.00029 Wednesday AM

Experimental particle balance



[1]

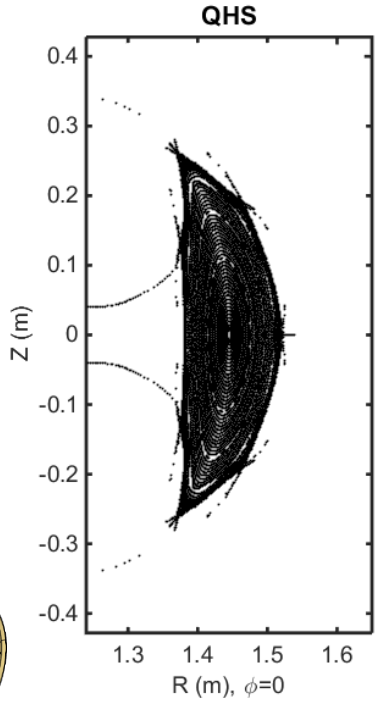
- Spectroscopic measurements obtained
- How to infer limiter particle flux using these measurements?

See H. Frerichs poster TP10.00074 Thursday AM

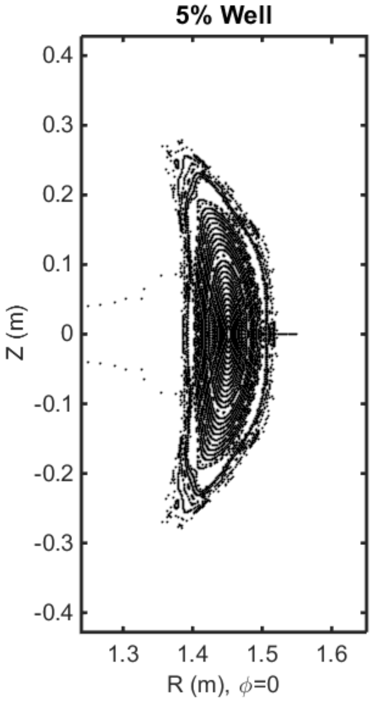
1. Figure reproduced from H. Frerichs et al., Rev. Sci. Instrum. Vol 87, 11D441 (2016).

Can't move islands without also changing effective ripple

- Islands in edge
- Small helical ripple



- Islands inside LCFS
- Small helical ripple



- Islands inside LCFS
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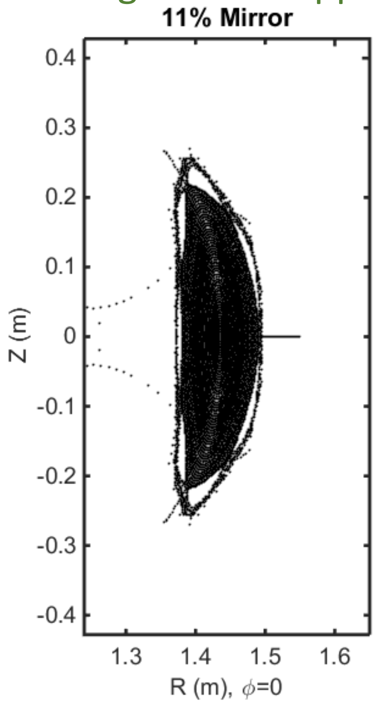


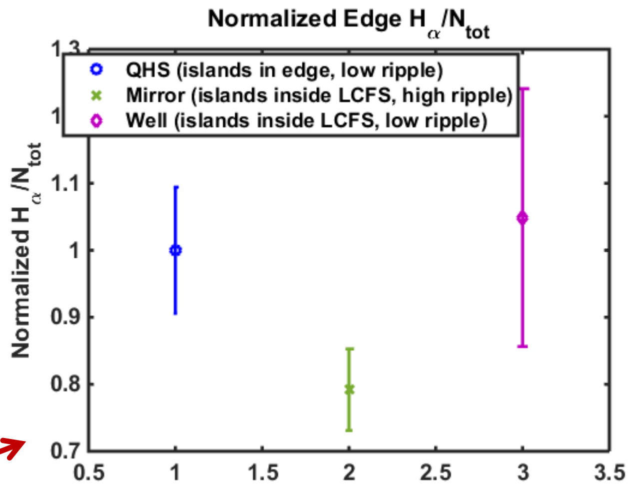
Does global recycling coefficient R change between configurations?

$$\tau_p^* = \frac{\tau_p}{1 - R}$$

τ_p* depends both on global particle confinement time and also on global recycling coefficient, *R*

Normalized a 'recycling-viewing' H-alpha channel to the total number of plasma particles N_{tot}

$$R = \frac{\Gamma_{neutral}}{\Gamma_{ion}} \propto \frac{H_\alpha}{N_{tot}}$$



- Local recycling coefficient proxy changes, but global particle source also changes between configurations
- EMC3-EIRENE can provide additional insight → future work

EMC3-EIRENE shows changes in edge topology affects particle source

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- Small helical ripple

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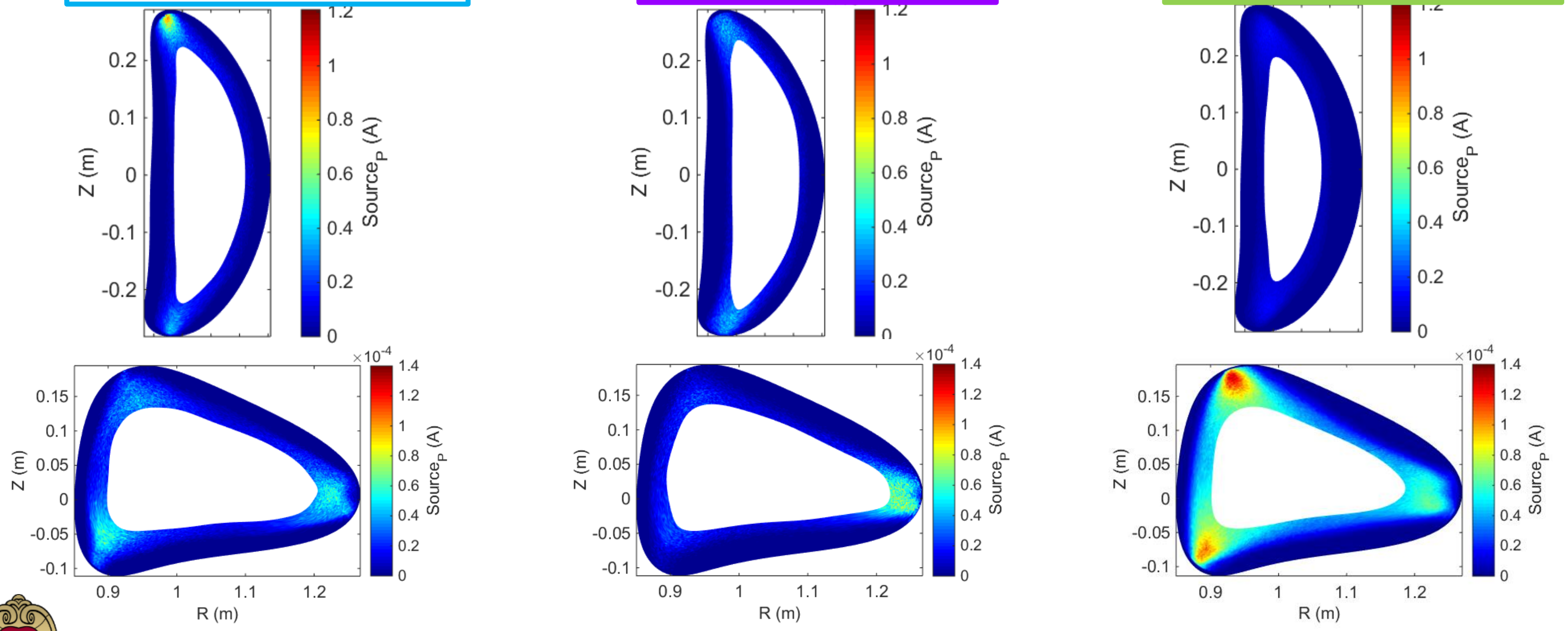
- Large helical ripple



EMC3-EIRENE results courtesy of A. Bader

See A. Bader poster TP10.00070 Thursday AM

EMC3-EIRENE shows changes in edge topology affects particle source

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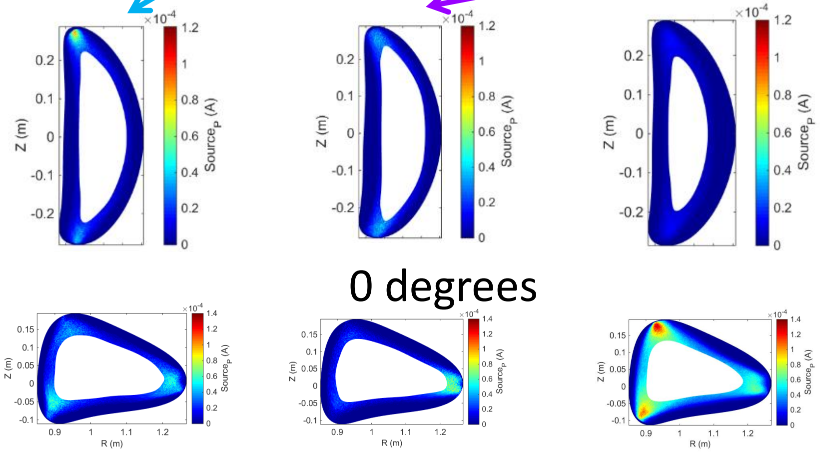
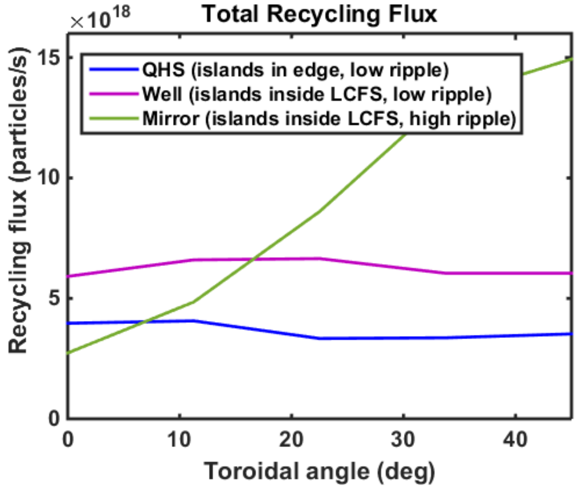


0 degrees

41 degrees



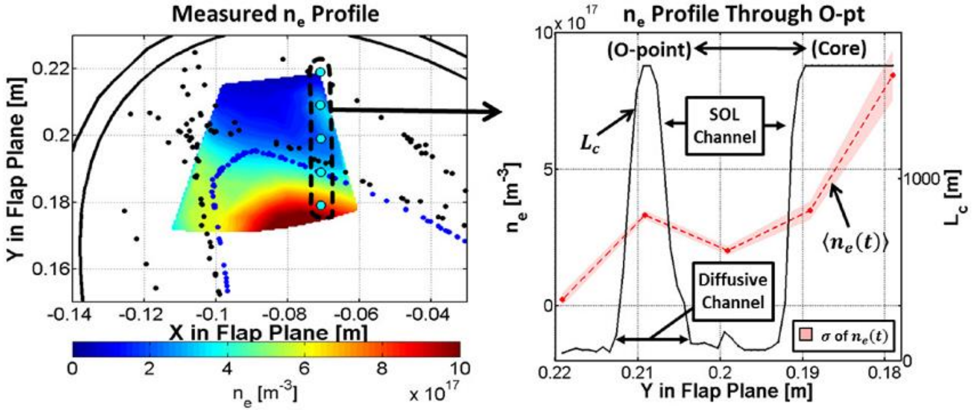
EMC3-EIRENE results courtesy of A. Bader

Numerical particle balance courtesy of I. Waters

See I. Waters poster NP10.00029 Wednesday AM

Particle confinement in islands has been observed in several experiments

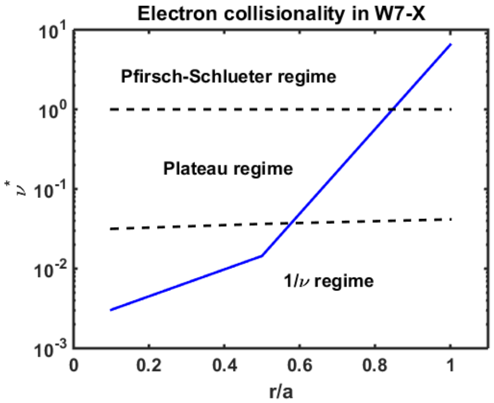
- Snake-like density perturbations in JET in which a fueling pellet caused a long-lived density rise at the q=1 rational surface [1]
- Density peaking in 2/1 island in TEXTOR-94 [2]
- Density peaking in the HSX 8/7 edge island independent of direct gas puff fueling [3]

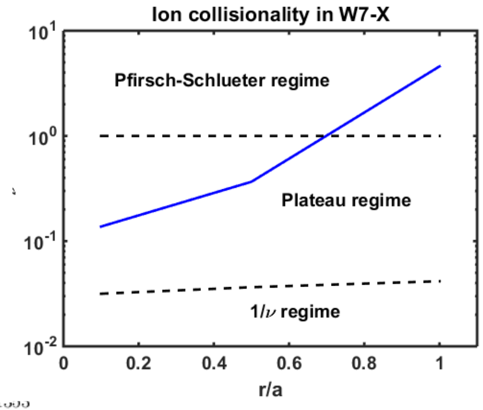


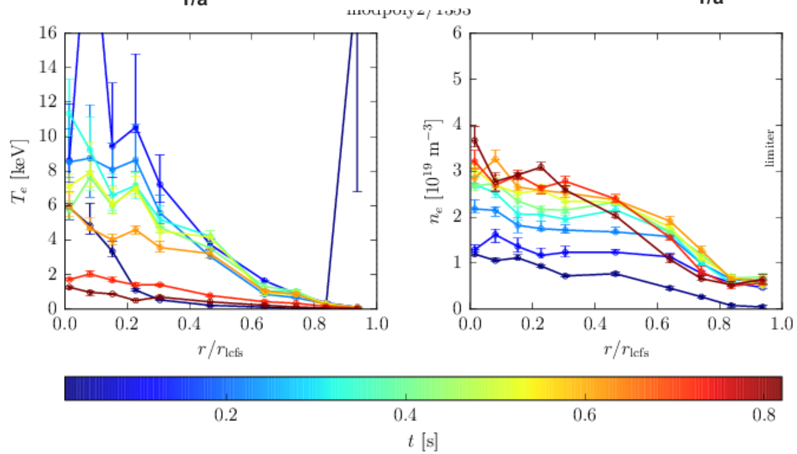
[3]

1. A. Weller et al., PRL, Vol 59, No 20, 1987.
2. P. C. De Vries et al., Nucl. Fusion 37, 1641, 1997.
3. Figure reproduced from A. Akerson et al, PPCF Vol 58, 2016.

W7-X collisionality with Er = 0



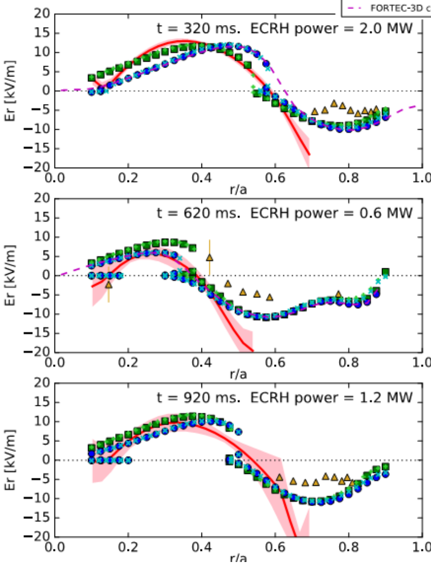




Thomson data and figure courtesy of S. Bozhenkov

Ambipolar Er

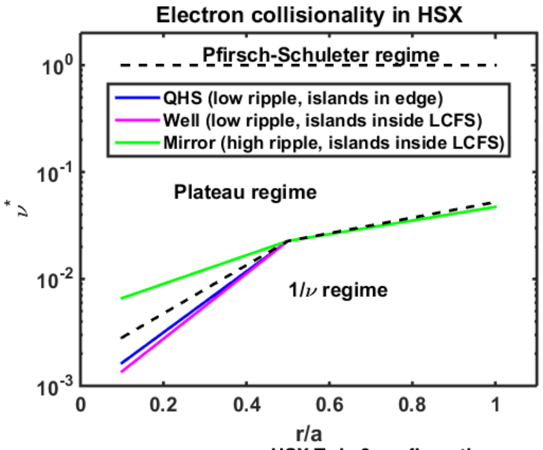
See Pablant invited talk: PI3.4

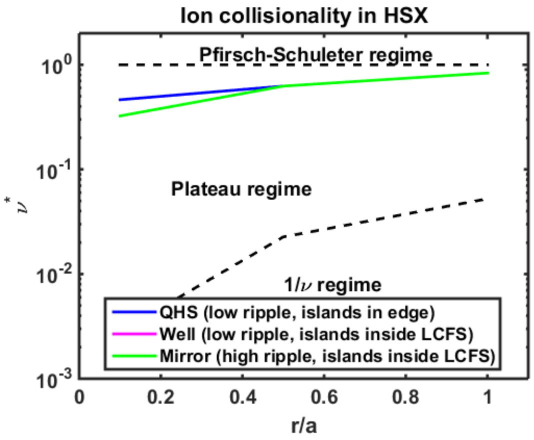


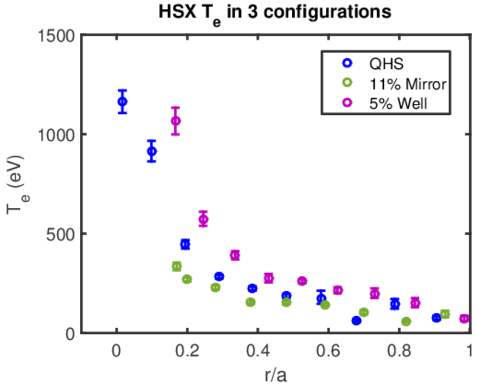
- Neoclassical calculations predict Er>0 in the core, Er<0 in the edge, in agreement with diagnostics. (Core electron root confinement.)
- Radius of Er sign reversal increases with ECRH power. Location of sign reversal agrees very well between measurement & simulation across time.
- Excellent agreement between SFINCS, NTSS, and FORTEC-3D.

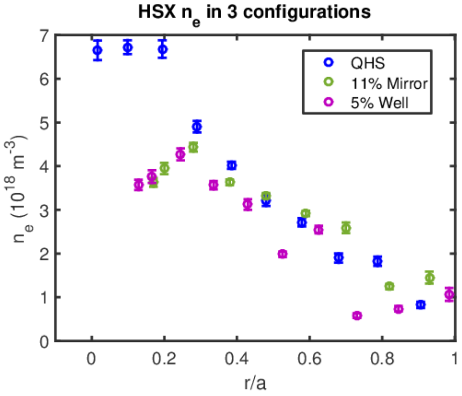
Reproduced from M. Landreman APS 2016 Poster

HSX collisionality with Er = 0









DKES neoclassical calculations for HSX

r/a=0.3

QHS

Mirror

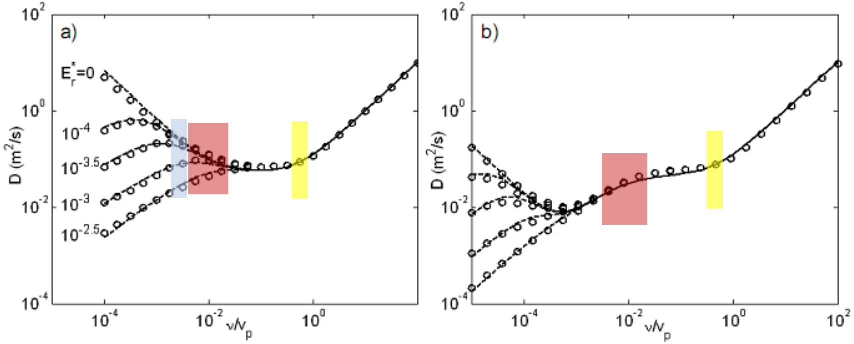


Figure 2.15: Database of DKES results (open circles) and fit to analytic form (lines) for the a) Mirror and b) QHS configurations at r/a=0.3. The values of $E_r^* = E_r/v_p$ are labeled for the Mirror configuration; the QHS values are the same

r/a=0.9

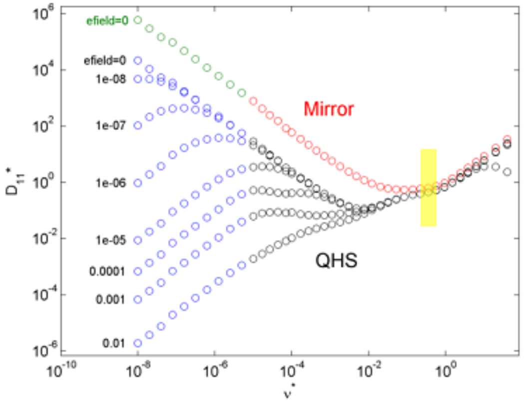


Figure 2.3 DKES particle transport coefficient for different values of E_r for the QHS configuration and a single curve for the Mirror configuration (E_r=0) for comparison. Both surfaces represented are near near r/a=0.9.

1. Reproduced from J. Canik dissertation

2. Reproduced from R. Wilcox dissertation