UNIVERSITY of York

Using variations in divertor magnetic topology and geometry to optimize divertor detachment

- Need for more and quicker divertor design guidance/analysis
- Using ‘experiments’ in SOLPS to quantify the effect of divertor design characteristics on control of divertor detachment onset
  - Strike point angle
  - Baffling
  - Total flux expansion
- Implications for improving the design process

B. Lipschultz[1], A. Fil[1,2], B. Dudson[1], D. Moulton[2], O. Myatra[1], K. Verhaegh[1,2,3] and the TCV team[3]

Most of the thoughts presented are based on the paper – A. Fil et al., ‘Separating the roles of magnetic topology and neutral trapping in modifying the detachment threshold in TCV’, submitted to Plasma Phys. & Contr. Fusion.

[1]University of York, UK, [2]CCFE, UK, [3]TCV team

CCFE CULHAM CENTRE FOR FUSION ENERGY

Reactor divertor design process

1. The core plasma conditions are set based on reactor goals
   - (Q, B, current, aspect ratio,..)
   - Magnetic flux equilibrium developed
2. Space allocated to the divertor based on the coil size
3. Run SOL/divertor fluid codes to determine whether the divertor performs ‘adequately’
   - Close the loop on the reactor design both with engineering and core plasma performance

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Bottleneck for optimzation

Are there ways to enhance the feedback between divertor design, engineering and core characteristics?

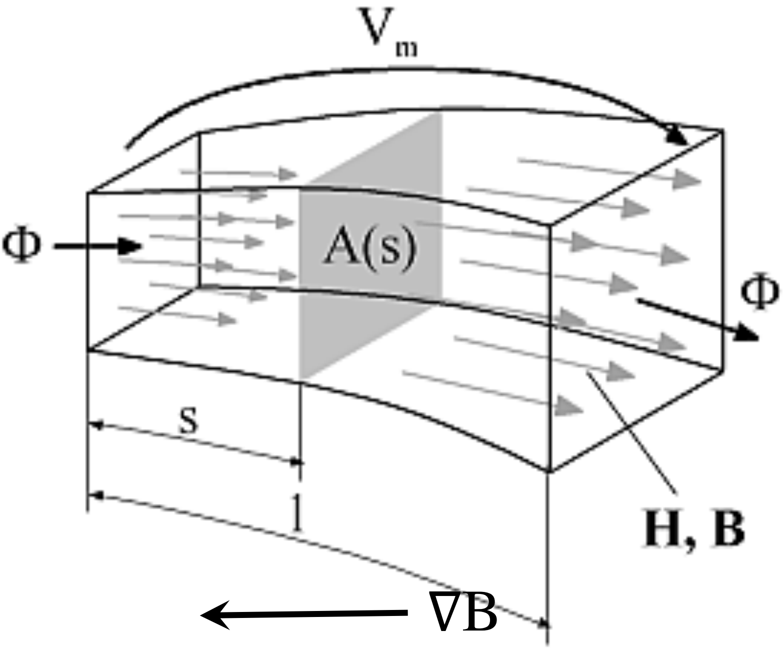
- Are there more ways to enhance the feedback between divertor design and core characteristics?
  - Can simpler (than SOLPS) calculations be properly used?
  - Can one more quickly determine the core operational space compatible with detachment?
  - Can we be quantitative about how those divertor characteristics control detachment access and its characteristics?
    - We have addressed this question through a SOLPS study of TCV detachment threshold in upstream density, $n_{u,d}$

Reminder – what is total flux expansion

- Increase target strike point radius, R_t
  - $|B_t|$, drops. Area of flux tube increases
  - The heat flux parallel to B, $q_{||,t}$ drops

$$B \cdot A_{fluxtube} = const$$

Flux tube area increases as total B drops



$$q_{\parallel} \cdot A_{fluxtube} = const$$

$$\Rightarrow q_{\parallel} \propto |B| \sim \frac{1}{R}$$

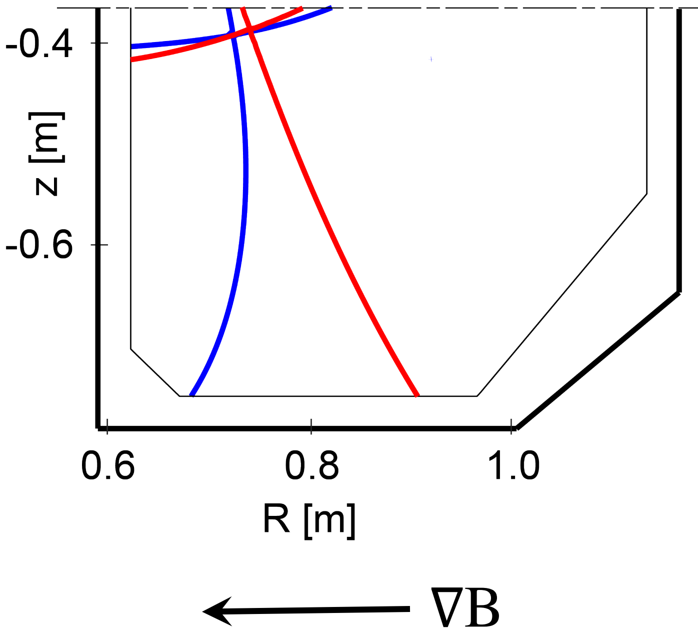
Not a new effect! Already in SOL/Div codes

Simple effect of total flux expansion predicted to lower the detachment threshold

- Increase target strike point radius, R_t
  - $|B_t|$, drops. Area of flux tube increases
  - The heat flux parallel to B, $q_{||,t}$, drops
  - lowering the detachment threshold in upstream density, $n_{u,d}$

$$n_{u,d} \propto \frac{1}{\left|B_x\right| / \left|B_{tar}\right|} \frac{P_{SOL}^{5/7}}{L^{2/7}} \sim \frac{R_x}{R_t} \frac{P_{SOL}^{5/7}}{L^{2/7}}$$ *

Total flux expansion

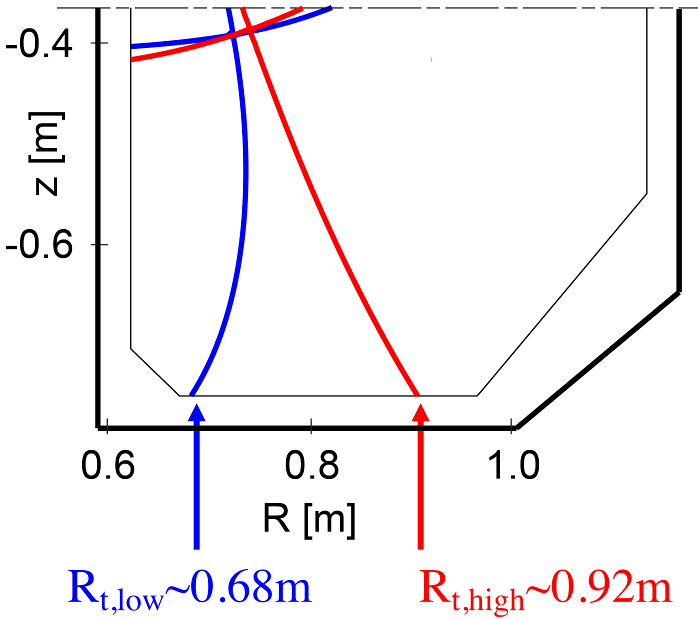


*M. Kotschenreuther et al., Nucl. Fus. **50** (2010) 035003, TW Petrie et al, J. Nucl. Mat. **438**(2013) S166, B. Lipschultz et al., Nucl. Fus. **56** (2016) 056007, D. Moulton et al., PPCF 59 (2017) 065011

Prediction of the effect of total flux expansion for TCV

- Predict the radio of detachment thresholds for the low and high target radius, R_t:

$$D_{predicted} \equiv \frac{n_{u,d}^{R_{t,high}}}{n_{u,d}^{R_{t,low}}} \sim \frac{R_{t,low}}{R_{t,high}} = \frac{0.68}{0.92} = 0.76$$

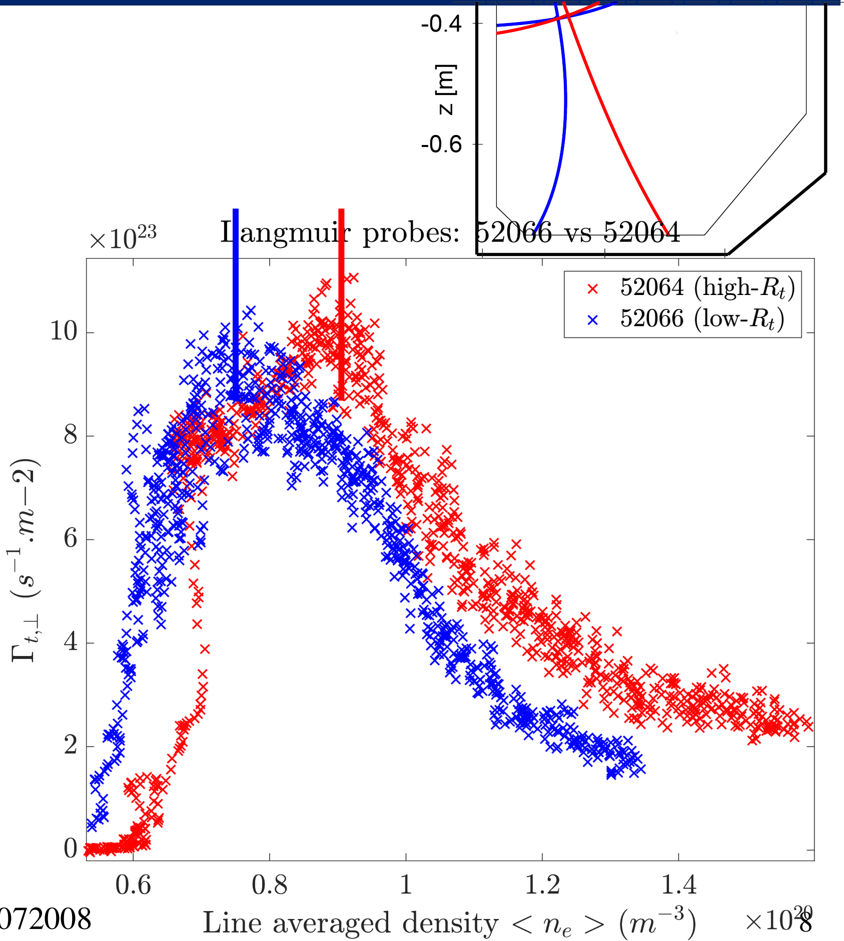


Experiments contradict simple predictions for total flux expansion

- TCV experiments[1] studying just the upstream density detachment threshold, $n_{u,d}$, contradict the simple scaling.

$$D_{predicted} \equiv \frac{n_{u,d}^{R_{t,high}}}{n_{u,d}^{R_{t,low}}} \sim \frac{R_{t,low}}{R_{t,high}} = \frac{0.68}{0.92} = 0.76$$

$$D_{measured} \equiv \frac{\overline{n}_{e,d}^{R_{t,high}}}{\overline{n}_{e,d}^{R_{t,high}}} \sim 1.2^*$$



*Difficult to obtain $n_{u,d}$

[1]C. Theiler et al, Nucl. Fusion 57 (2017) 072008

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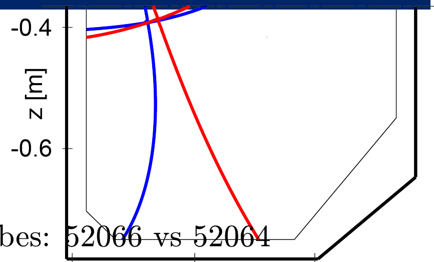
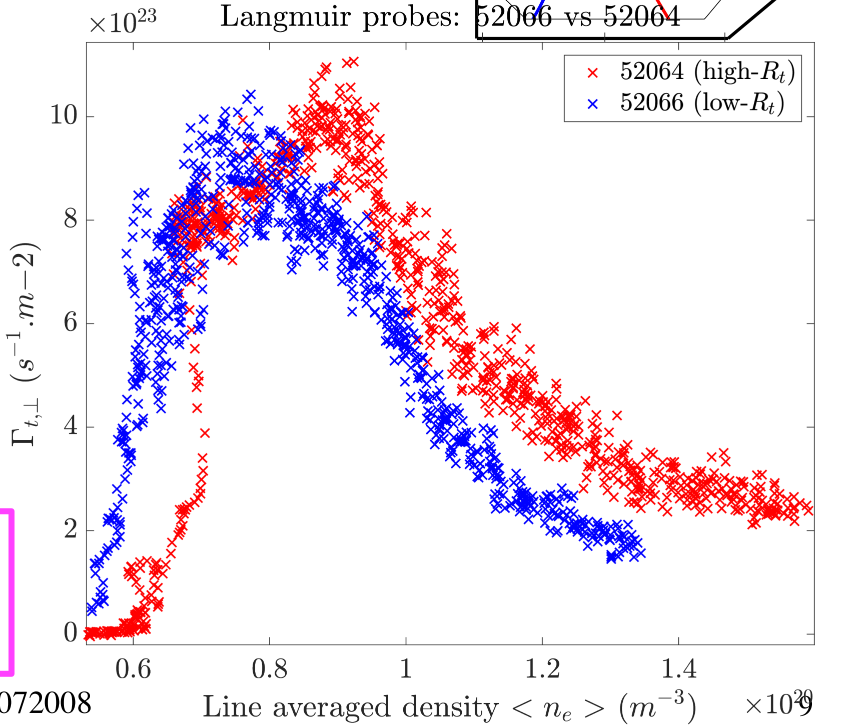
- What leads to this difference between simple prediction and measurement?

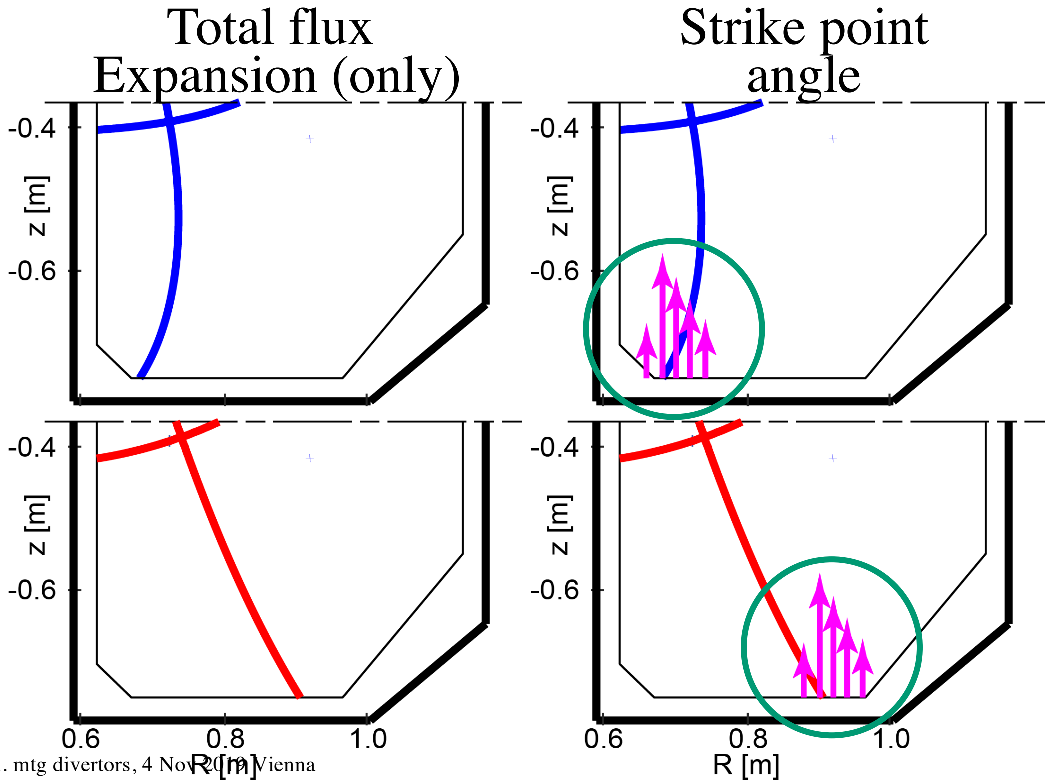




[1]C. Theiler et al, Nucl. Fusion 57 (2017) 072008

Strike point angle is another important divertor characteristic and is different for low- and high R_t in TCV

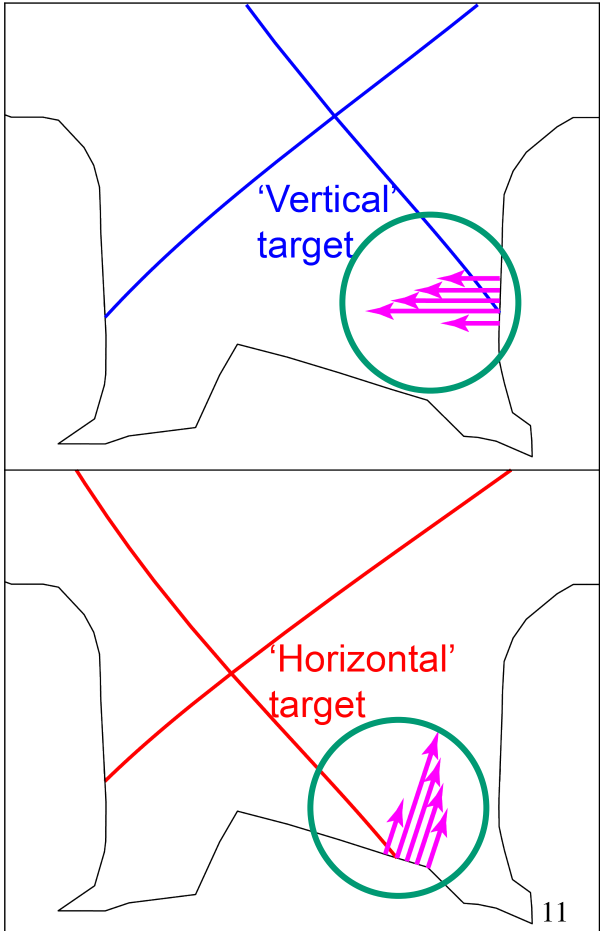
- Recycled neutrals are launched towards different parts of the divertor plasma for low- and high-R_t



Strike point angle to the surface affects the ionization profile

- JET is a good example of the effect of varying strike point angle
  - Recycling neutrals ionize in different plasma regions for ‘vertical target’ and ‘horizontal target’

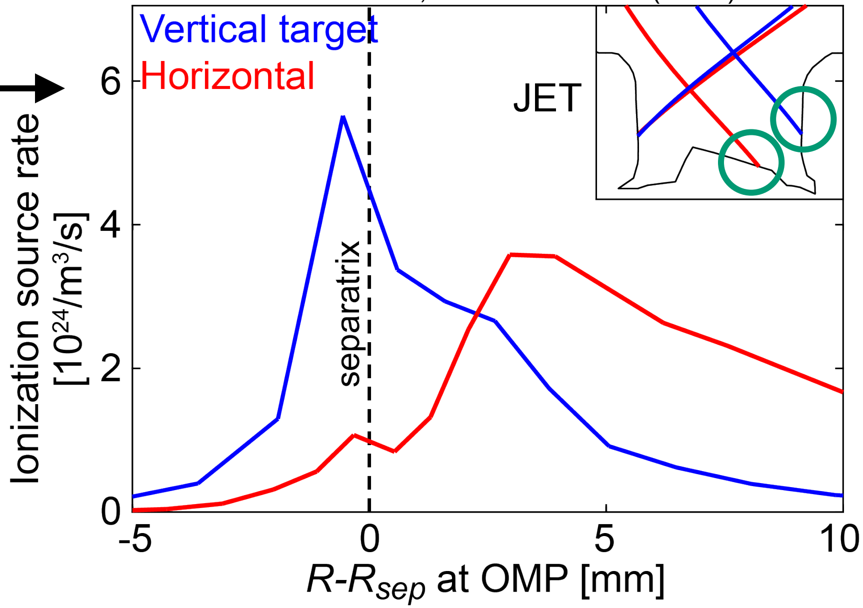
JET



Strike point angle to the surface affects the ionization profile

- EDGE2D-Eirene calculations demonstrate difference in ionization →
  - 'Vertical target'
    - ionization near separatrix
    - increase density; lower temperature
    - **lowers detachment threshold**
  - 'horizontal target'
    - ionization farther from the separatrix

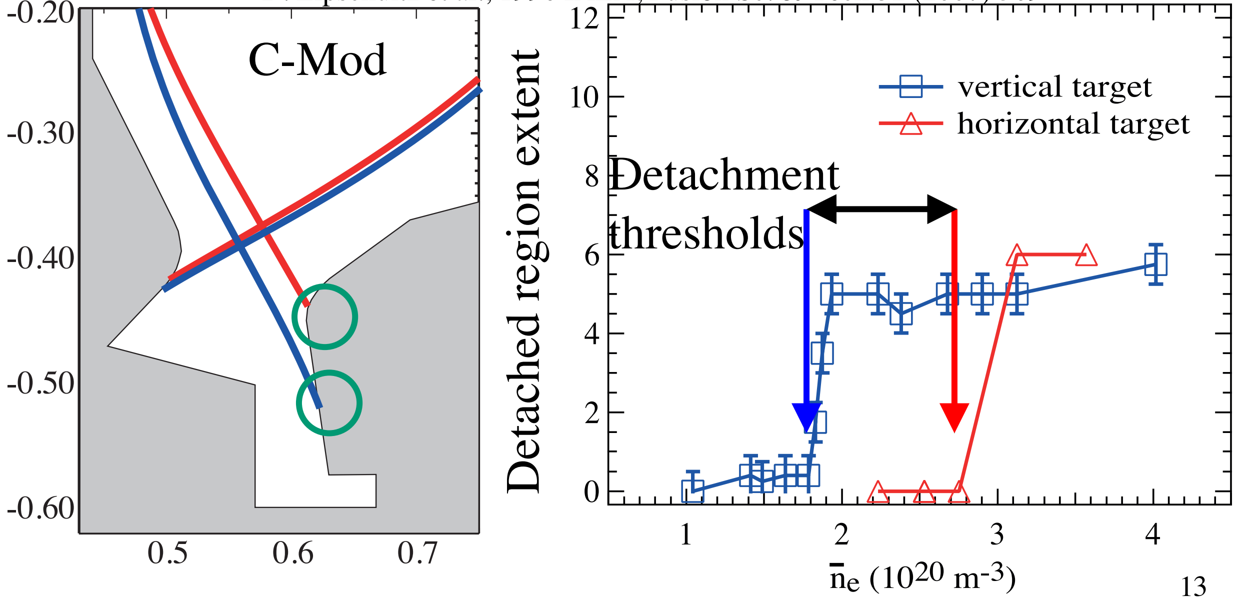
D. Moulton et al., Nucl. Fusion 58 (2018) 096029



The effect of the strike point angle on detachment was realized experimentally, early in divertor studies

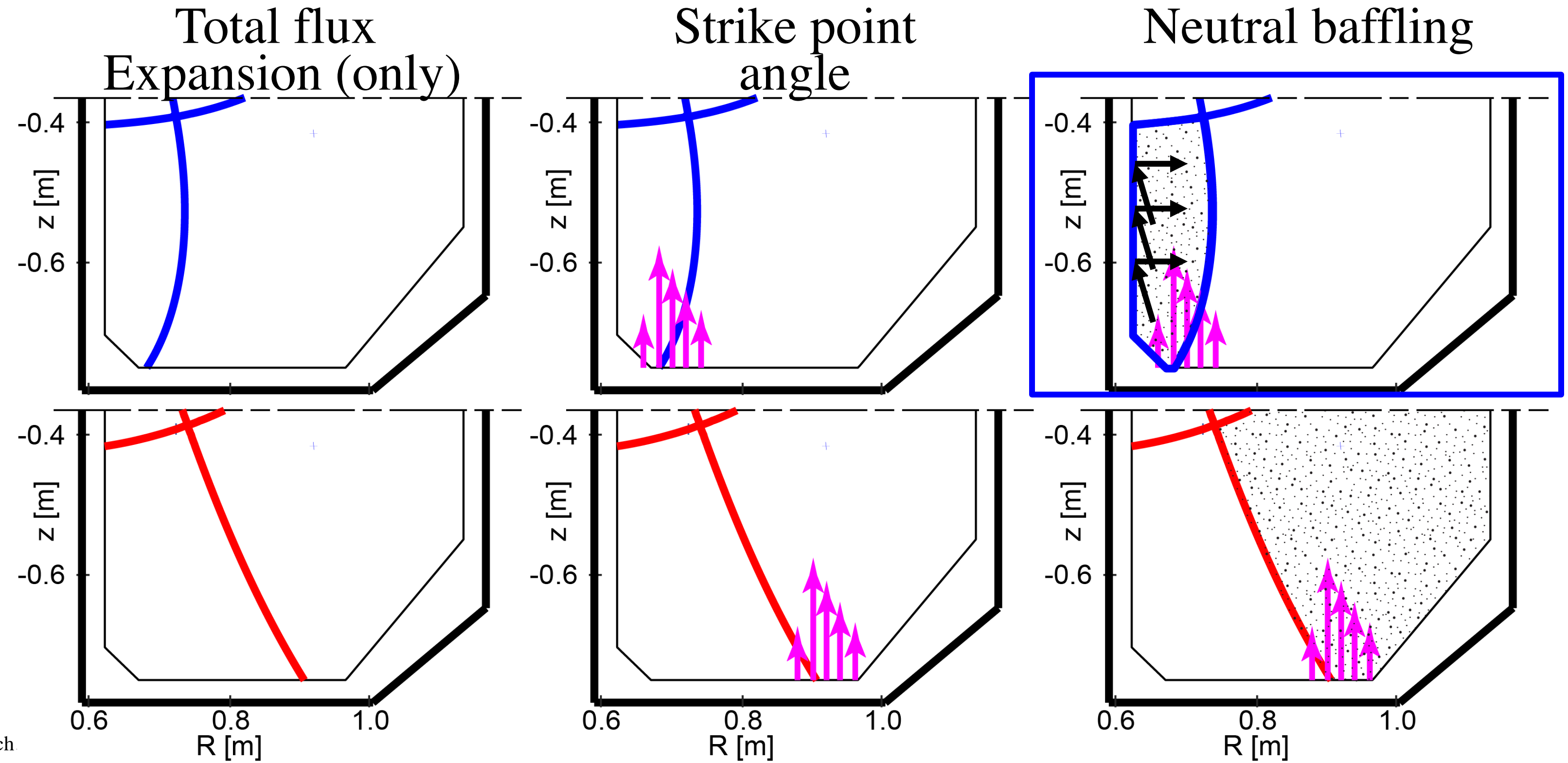
- Experimental comparison:
  - vertical target ~40% lower detachment threshold, n_{ud}
- Most tokamaks moved to the vertical target geometry in the early 2000s

B. Lipschultz et al., 1996 IAEA, Fusion Sc. & Tech **51** (2007) 369



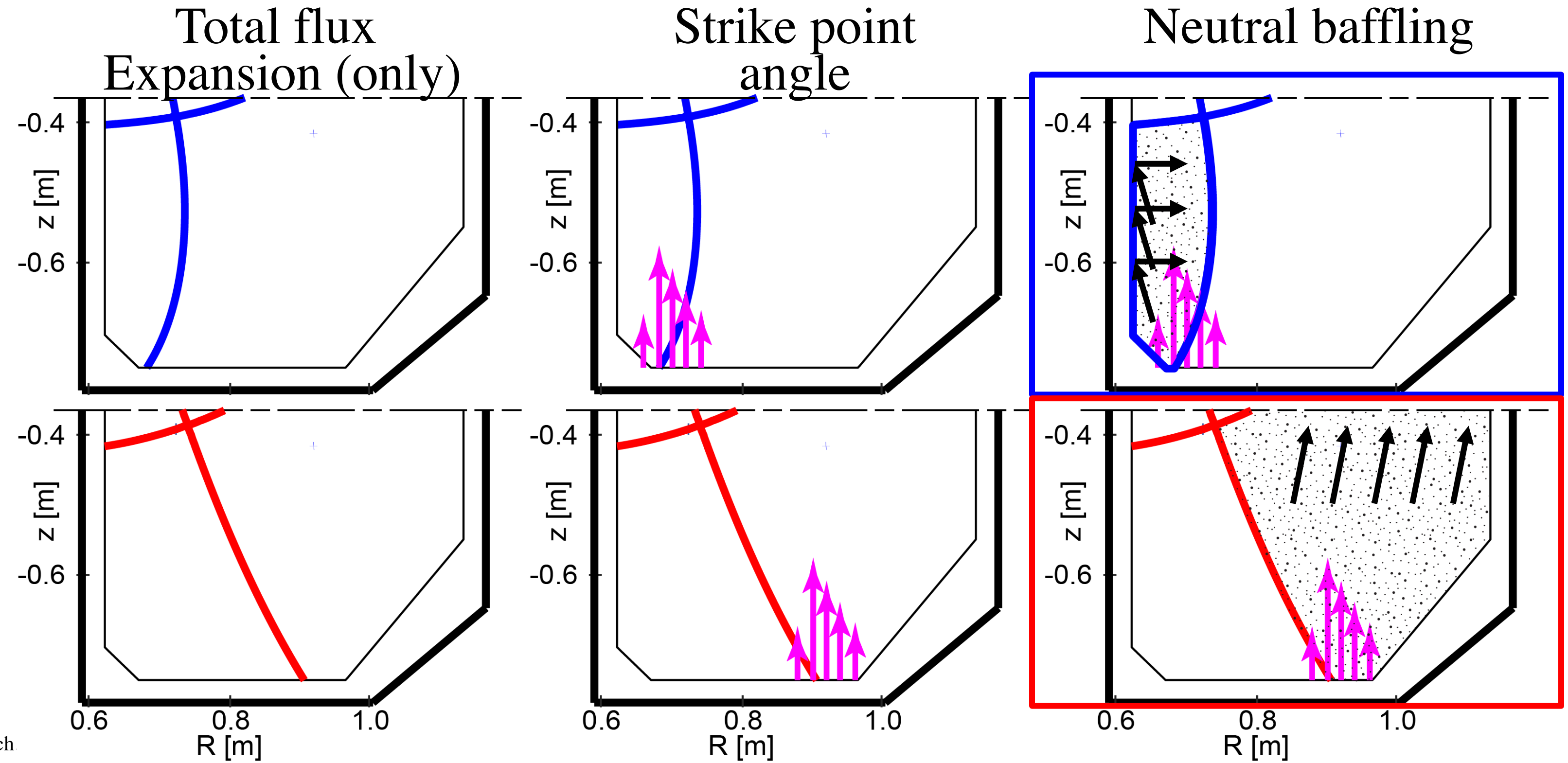
Baffle geometry also has a strong role in determining the detachment threshold

- Low R_t divertor traps neutrals between inner wall, inner and outer separatrices



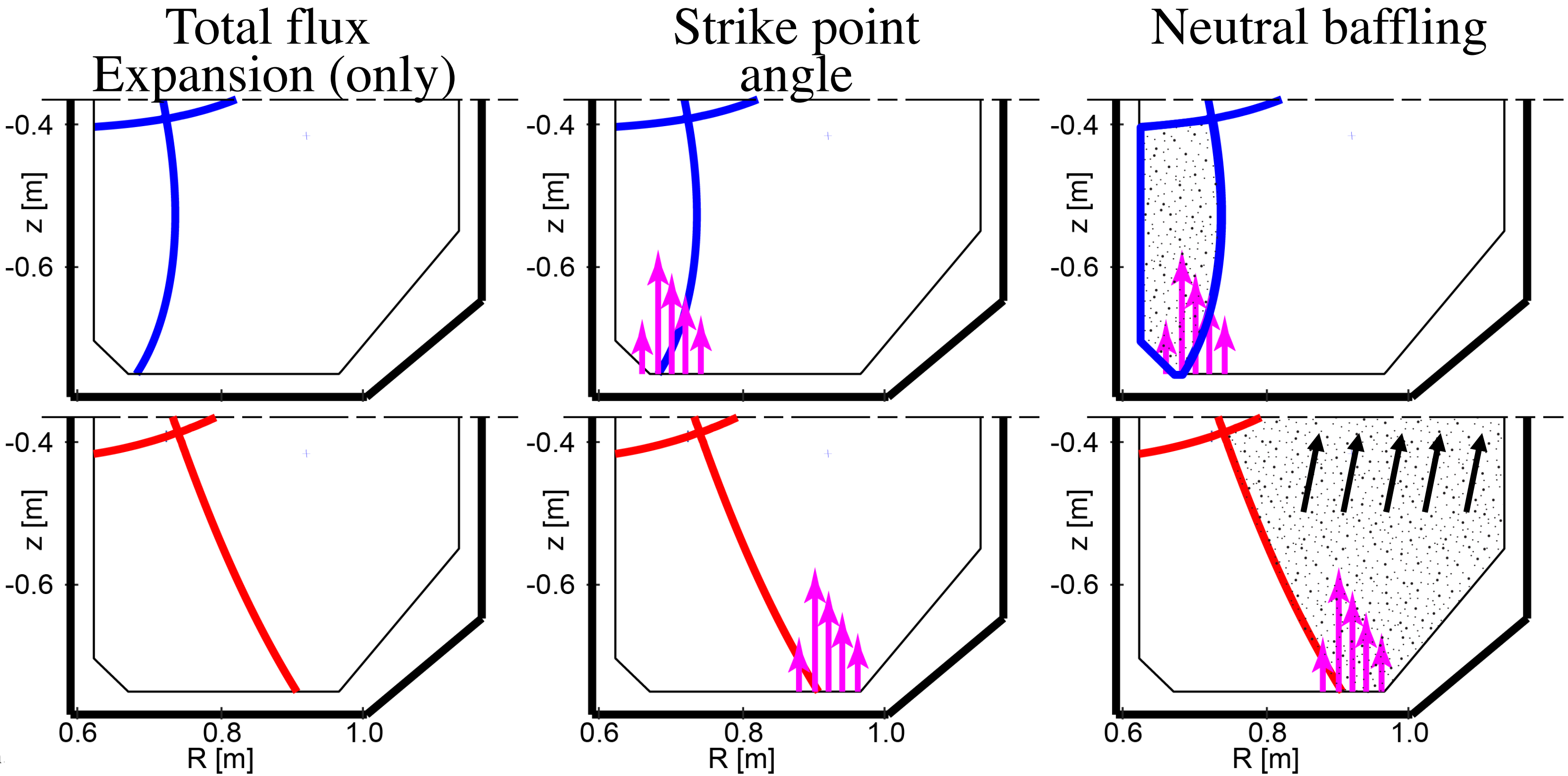
Neutral trapping in the divertor favors low target R

- Low R_t divertor traps neutrals between inner wall, inner and outer separatrices
- Neutrals in the high R_t configuration **easily escape the divertor**



All three divertor design choices affect the detachment threshold

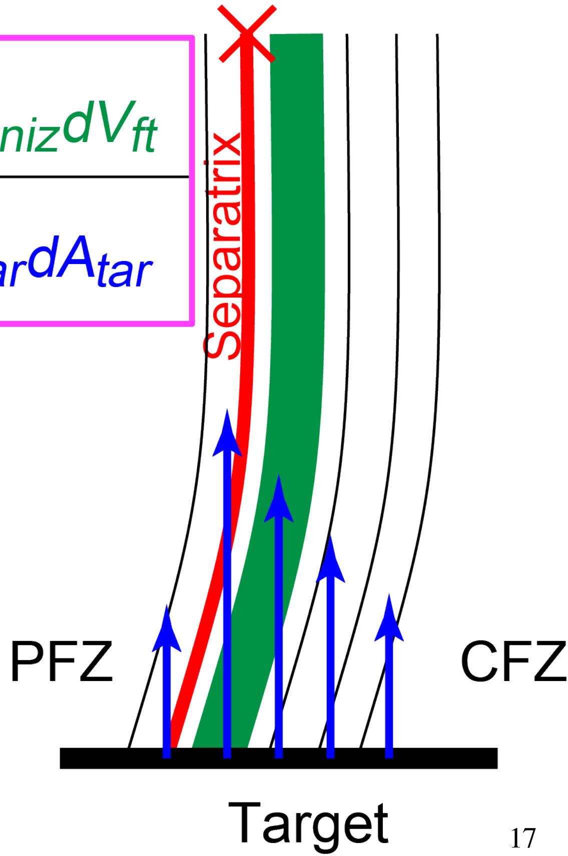
- Total flux expansion lowers $n_{u,d}$ for the high-R_t
- Strike point angle and neutral baffling lower $n_{u,d}$ for the low-R_t



Define ‘neutral trapping’ to aid in comparing various effects

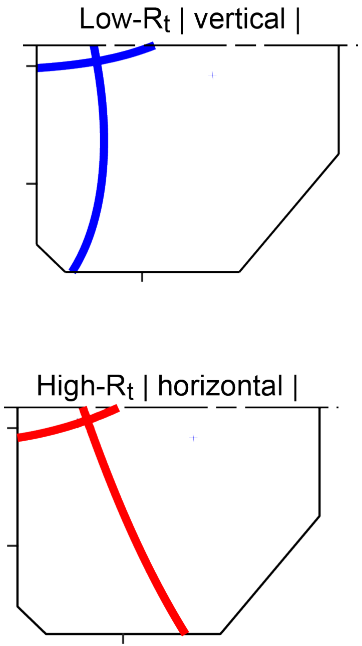
- We quantify the relative contributions of strike point angle and neutral baffling on the detachment threshold
  - η_{RI} is the fraction of the **total** divertor ionization source that occurs in a flux tube near the separatrix
  - We make this ‘measurement’ for TCV SOLPS cases

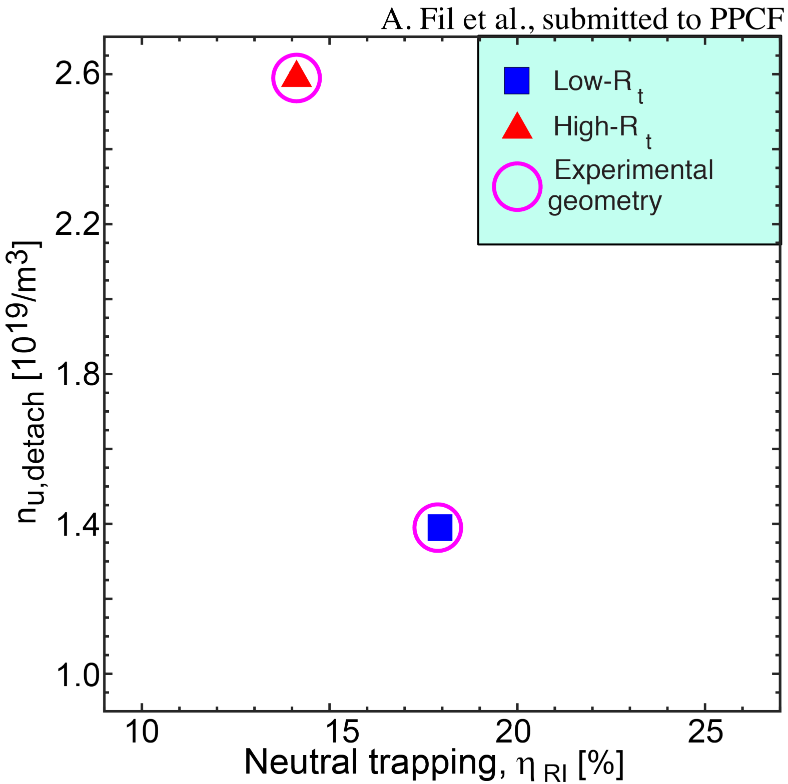
$$\eta_{RI} \equiv \frac{\int S_{ioniz} dV_{ft}}{\int \Gamma_{tar} dA_{tar}}$$



As expected – an anti-correlation between $n_{u,d}$ and η_{RI}

- Detachment threshold $n_{u,d}$ appears sensitive to η_{RI}



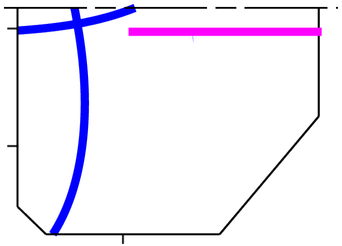


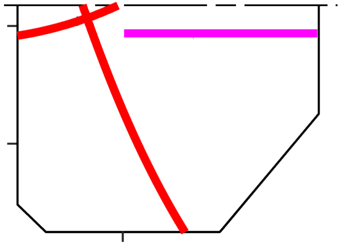
$$D_{predicted} \sim 0.76$$

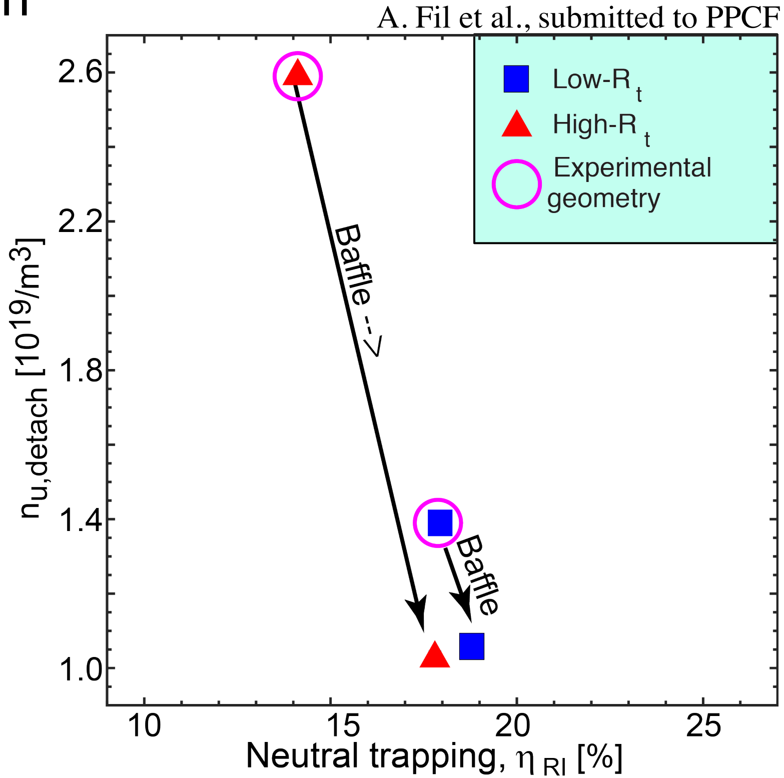
$$D_{code} = \frac{n_{u,d}^{R_{t,high}}}{n_{u,d}^{R_{t,low}}} \sim 1.86$$

The baffle strongly strongly affects detachment threshold for high-R_t case

- Similar neutral confinement for high- & low-Rt; better match to total flux expansion prediction







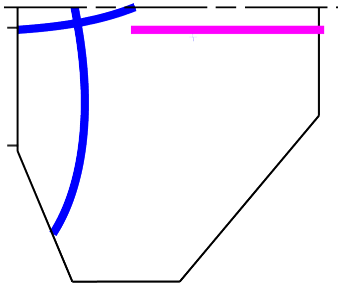
$$D_{predicted} \sim 0.76$$

$$D_{code} \equiv \frac{n_{u,d}^{R_{t,high}}}{n_{u,d}^{R_{t,low}}} \sim 1$$

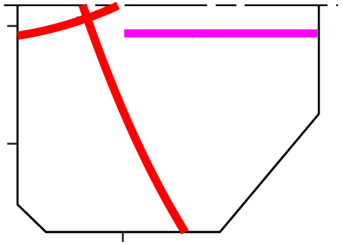
Having baffling AND strike point angle the same for low- and high-R_t: isolate total flux expansion effect

- Match predictions for total flux expansion!
- What else can we learn?

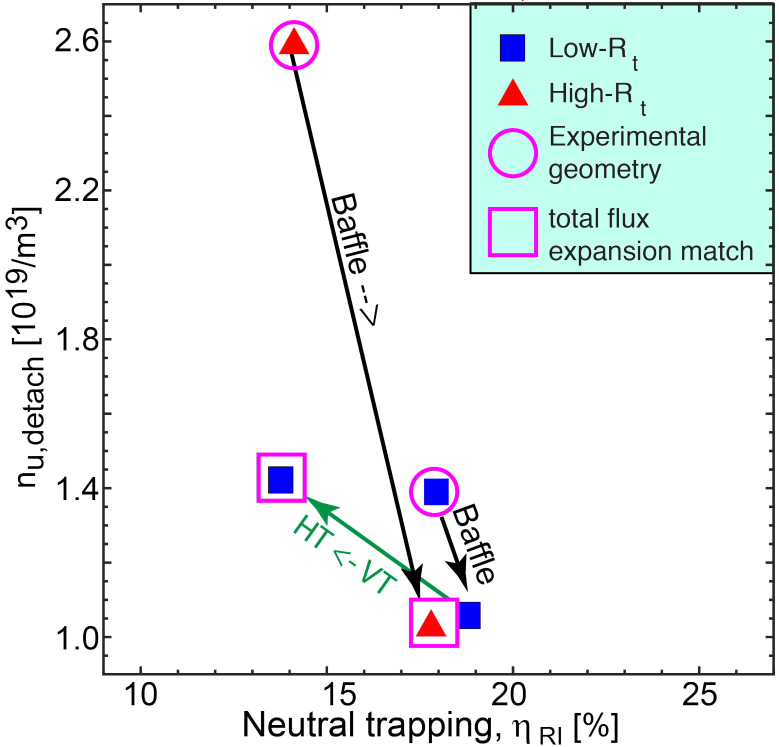
Low-R_t | horizontal | baffled



High-R_t | horizontal | baffled



A. Fil et al., submitted to PPCF



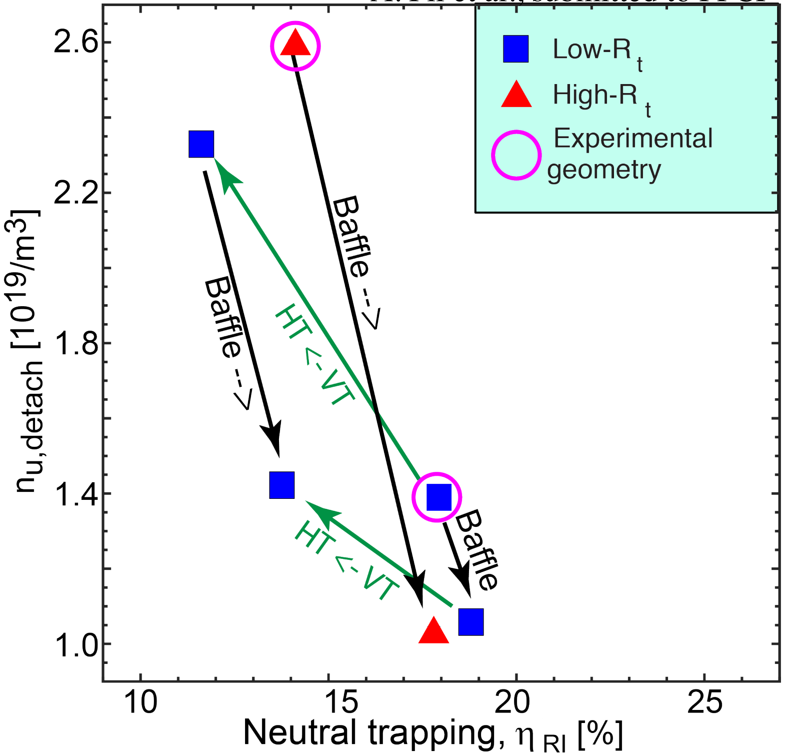
$$D_{predicted} \sim 0.76$$

$$D_{code} \equiv \frac{n_{u,d}^{R_{t,high}}}{n_{u,d}^{R_{t,low}}} \sim 0.74$$

Contrasting the effect of neutral baffle vs strike point angle

- Baffle (confining recycling neutrals)
  - Raises neutral density across the entire divertor, raising density and ionization costs, accelerating detachment
  - Small effect on η_{RI} but large on $n_{u,d}$
- Strike point angle of ‘vertical target’
  - Raises neutral density and ionization costs on a focussed region
  - Larger effect on η_{RI}, similar for $n_{u,d}$

A. Fil et al., submitted to PPCF

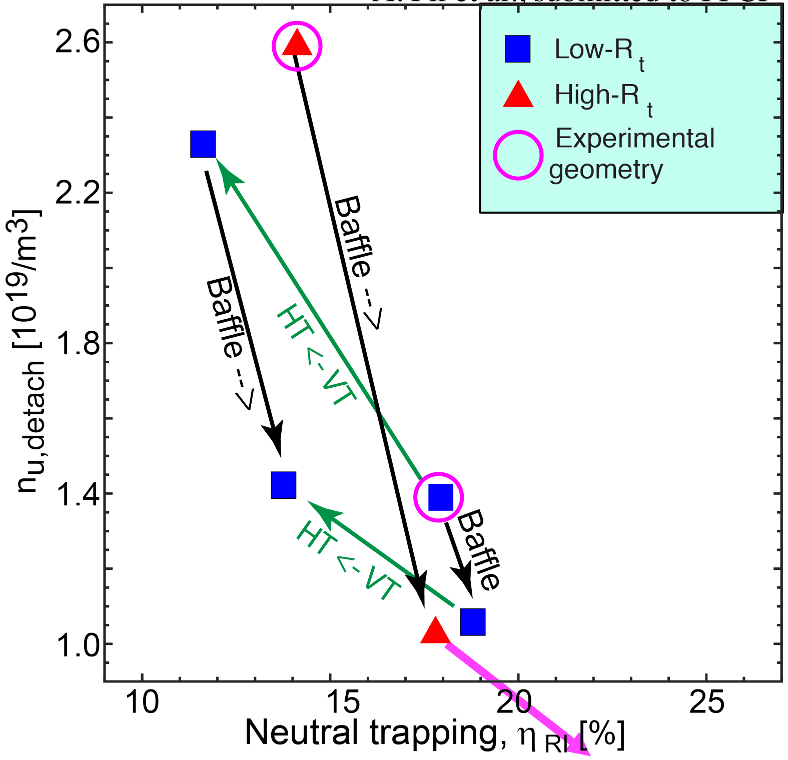


Contrasting the effect of neutral baffle vs strike point angle

- We expect adding vertical target to high-R_t to reduce $n_{u,d}$ and raise η_{RI}

- Caveat – This analysis presented here is for TCV conditions, far from a reactor
  - However, strike point angle and neutral baffling enhancements are recognized in studies of ITER, C-Mod and AUG
  - The total flux expansion effect is straightforward and already in codes.

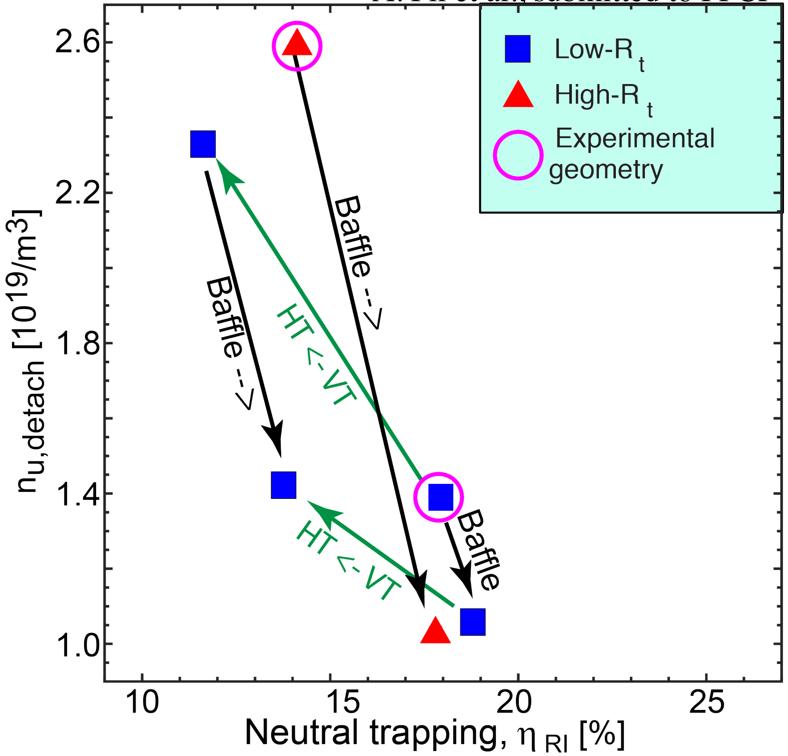
A. Fil et al., submitted to PPCF



Contrasting the effect of neutral baffle vs strike point angle

- Results indicate the the effect of total flux expansion is occurring but may be hidden by neutrals effects
  - It is ‘additive’, or ‘subtractive’ in this case, so an independent effect

A. Fil et al., submitted to PPCF



Other implications of this study for divertor design

- These results can be generalized using the Lengyel radiation formulation to include two other 'control' variables[1] – impurity concentration, C_z, *and* P_{SOL}:

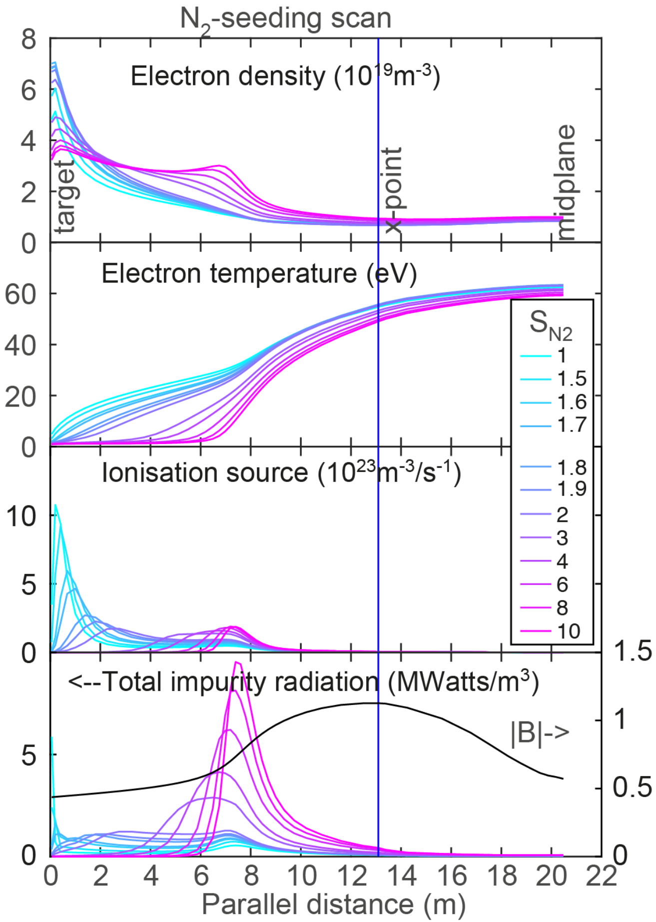
$$\left[\frac{n_u C_Z^{1/2}}{P_{SOL}^{5/7}}\right]_{detach} \propto \frac{|B_{tar}|}{|B_x|} f(L, z_x / L)$$

- Lower $n_{u,d}$ is equivalent to detaching at higher P_{SOL} or lower C_z

[1]B. Lipschultz et al, Nucl. Fusion **56** (2016) 056007

Other ‘experiments’ in SOLPS* on detachment position control

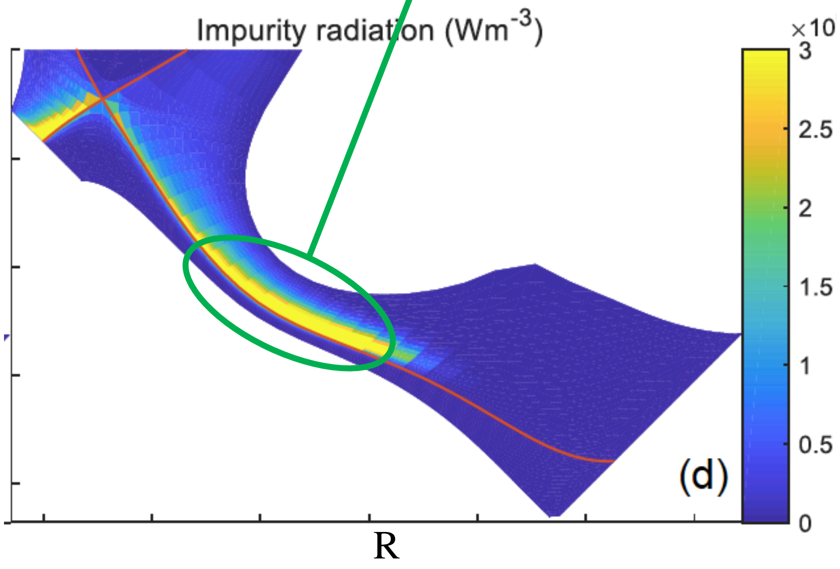
- MAST-U Detachment (seeding):

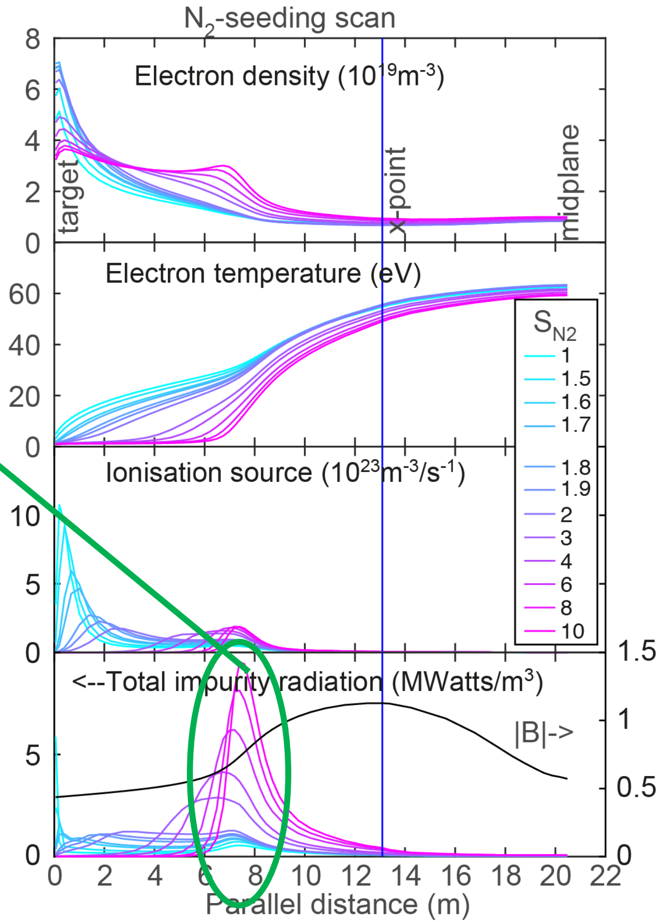


*O. Myatra, MAST-U, PSI18 poster

Other ‘experiments’ in SOLPS* indicate control increases with the magnitude of ∇|B|

- Movement slows down even though seeding rate is strongly increased
- Radiation region ‘stops’ mid-divertor where ∇|B| (really $\nabla|q_{||}|$) large



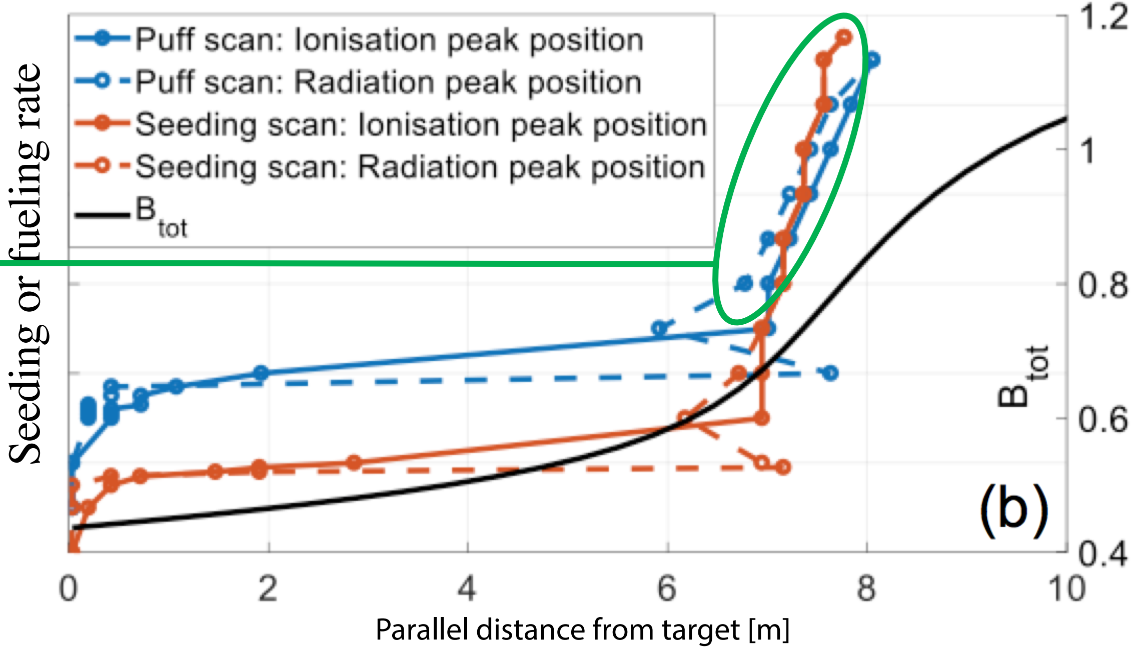


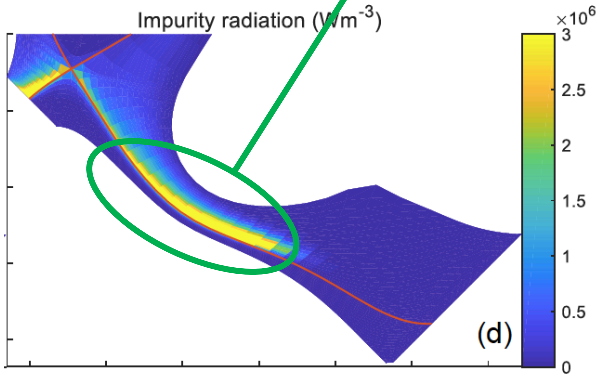
*O. Myatra, MAST-U, PSI18 poster

Strong ∇|B| correlates with 'slowing' front movement*

- Could be ∇|B| (really $\nabla|q_{||}|$) location stabilizing effect[4]

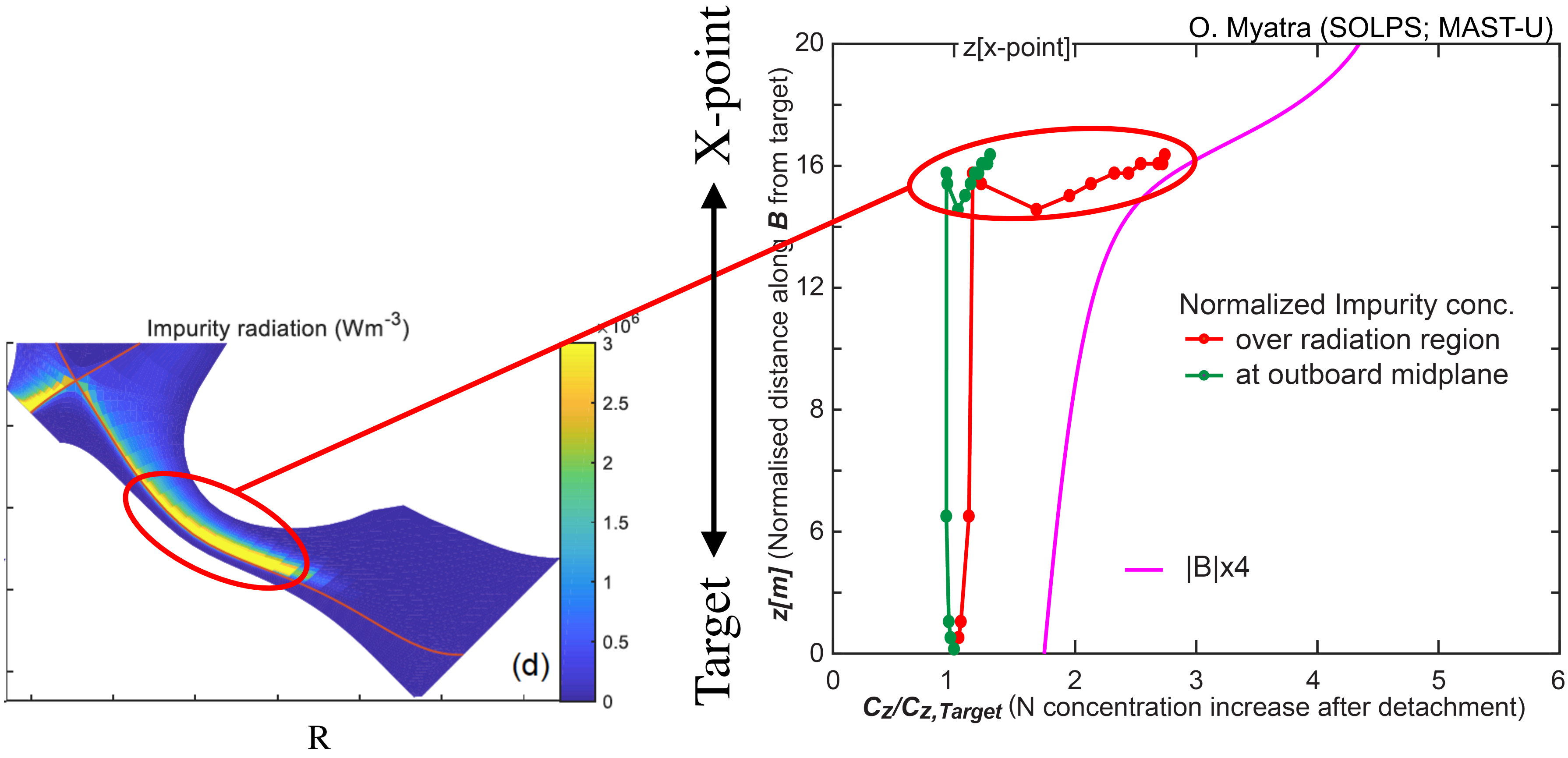
O. Myatra (SOLPS; MAST-U)





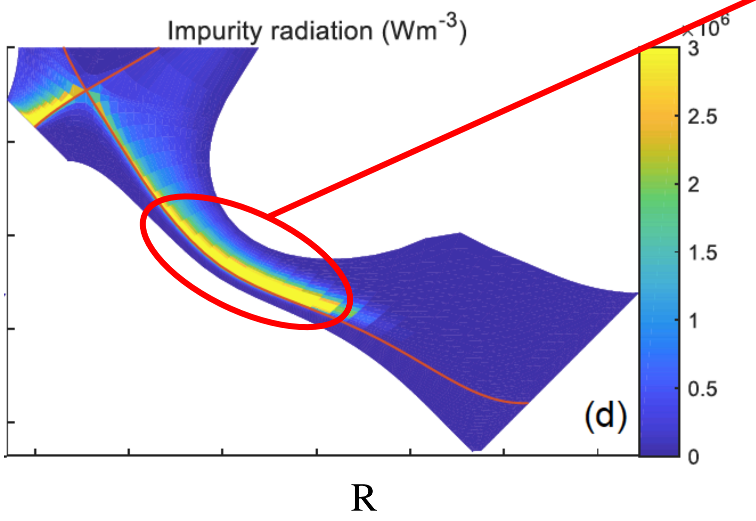
*B. Lipschultz et al, Nucl. Fusion **98** (2016) 056007

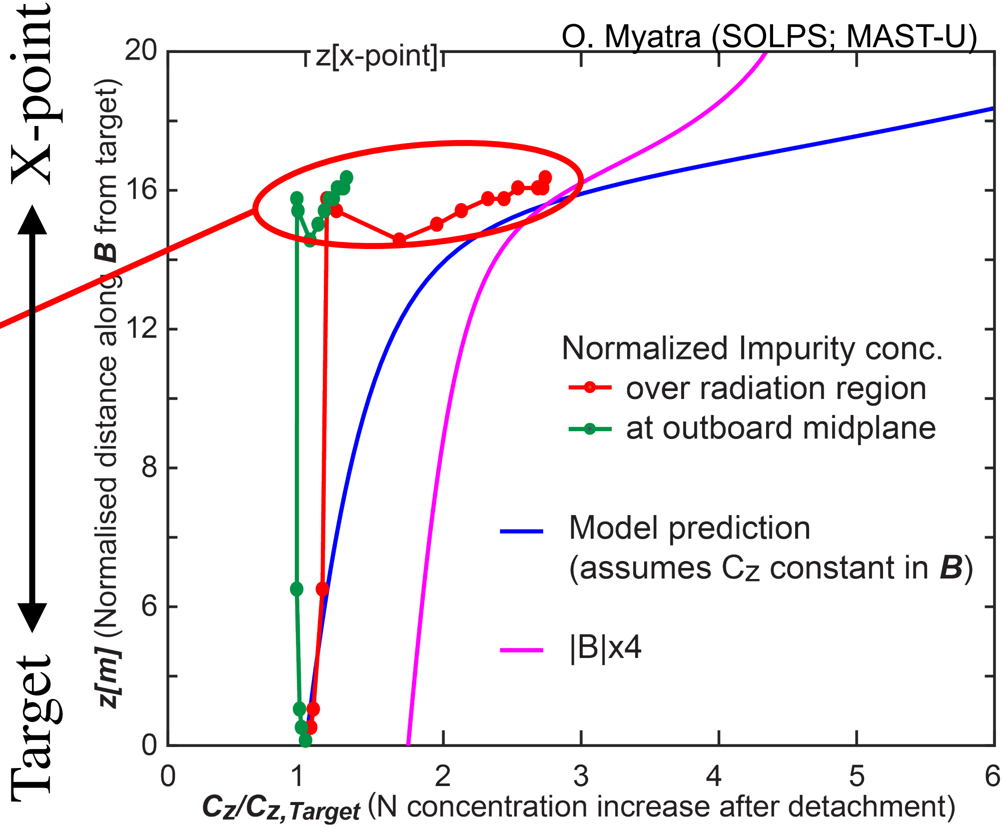
Detachment position vs normalized impurity fraction, $C_z/C_{z,target}$, correlates with position vs |B|



Model prediction[1] of movement fair approximation of SOLPS ‘experimental’ results

- Reasonable agreement with model prediction*
  - Tests with more equilibria needed
  - ∇|B| (∇|$q_{||}$|) could be another ‘tool’ in divertor design





*B. Lipschultz et al, Nucl. Fusion **98** (2016) 056007

Summary - Control of detachment threshold and movement

To optimize minimization of the detachment threshold:

- Divertor designs should enhance baffling & optimize strike point angle
  - If total flux expansion can be accommodated it will
    - Lower $n_{u,d}$ further (and potential to optimize control of location)

Further studies needed:

- A full study over a range of strike point angles would help optimize strike point angle choice over a range of divertor plasma densities and $q_{||}$
- More study is needed of how divertor design choices affect:
  - Divertor impurity confinement (e.g. forces on impurity ions)
  - Detachment control after onset

Backup slides

Model prediction[1] of detachment location movement can be used to compare to SOLPS results

- Useful for predicting general sensitivity of detachment movement, *z*, to changes in one or more control variables, C_x and their derivative dz/dC_x (and detachment thresholds)
  - Many simplifications required for such an analytic model

$$\frac{n_u f_{imp}^{1/2}}{P_{SOL}^{5/7}} \propto \frac{B[z]}{B_x}\left[\frac{(z_x - z)}{3}\left(1 + \left|\frac{B[z]}{B_x}\right| + \left|\frac{B[z]}{B_x}\right|^2\right) + \frac{(L - z_x)}{2}\right]^{2/7}$$

$$\frac{C_{nu} C_{imp}^{1/2}}{C_{PSOL}^{5/7}} \propto A[z]$$

- Initial control variables, C_x - impurity concentration, P_{SOL} and upstream density, n_u
- Movement in z related to
  - magnetic field profile (affects $\nabla|B|$ and $\nabla|q_{||}|$) and z_x/L
  - Variation in control variables, C_x, leads to a different solution and z

[1] B. Lipschultz et al, Nucl. Fusion **98** (2016) 056007