



The image shows a 3D architectural rendering of a large, modern building with a curved facade and a glass-enclosed staircase. In the center of the building, a large, glowing pink and orange cylindrical structure is visible, representing the STEP divertor concept design. The building is surrounded by green trees and a paved area.

Physics drivers of the STEP divertor concept design

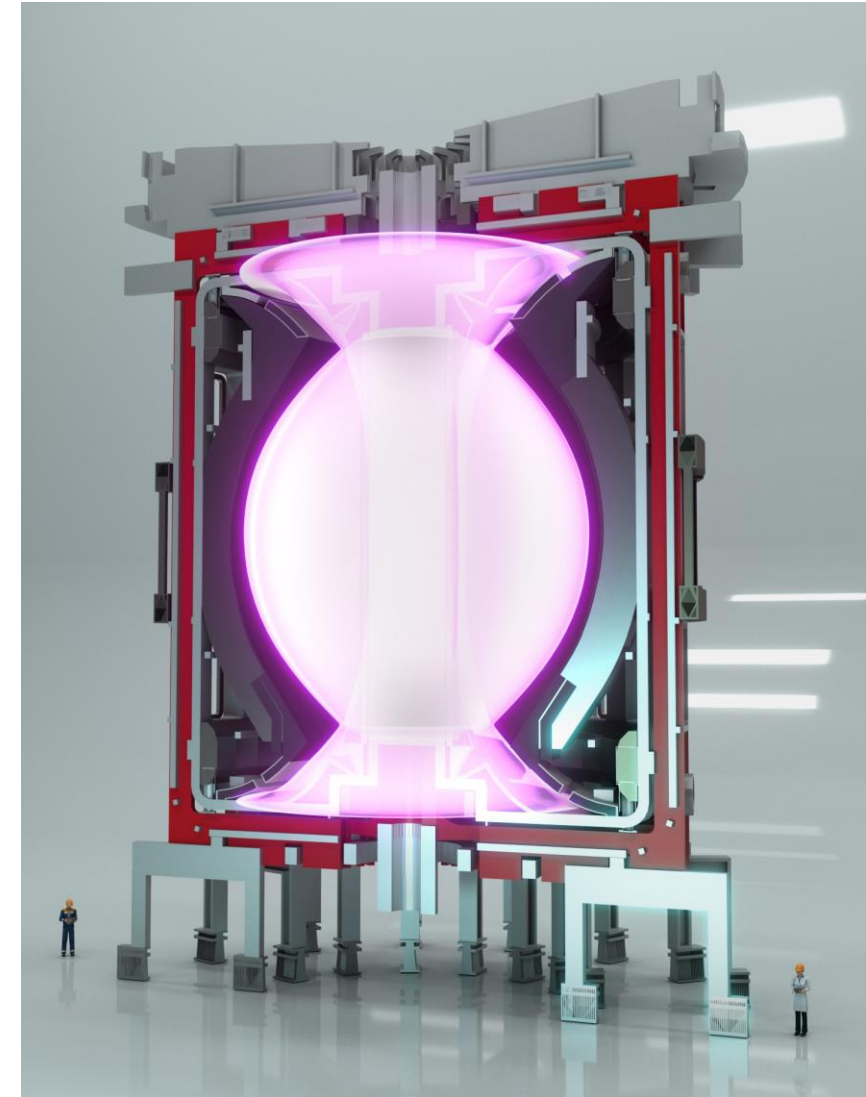
S. Henderson, S. L. Newton, R. T. Osawa, D. Moulton, J. Harrison, L. Xiang, F. Militello, M. Kryjak, C. Cowley, B. Lipschultz, B. Dudson, C. Ridgers, A. Hudoba, G. Voss, G. Cunningham, S. Kahn, A. Tarazona, T. Hebrard, B. Chuilon, A. Barth, S. Wang, J. Farrington, H. Meyer and the STEP team

STEP baseline power exhaust scenario

STEP is a UKAEA programme that will demonstrate the ability to generate net electricity from fusion. It will also determine how the plant will be maintained through its operational life and prove the potential for the plant to produce its own fuel.

Example operational point

Major radius [m]	3.6
Minor radius [m]	2.0
Toroidal field [T]	3.2
Plasma current [MA]	21
Fusion power [GW]	1.76
Auxiliary power [MW]	150
Core radiated power fraction	0.7
Loss power [MW]	485
Seeded impurity	Ar + Xe
Power crossing separatrix [MW]	150
Primary divertor design	Double null
Secondary divertor design (inboard)	X-divertor
Secondary divertor design (outboard)	Extended leg (super-X)



Primary divertor design (SN vs. DN)

Unmitigated power load on divertor surface calculated as

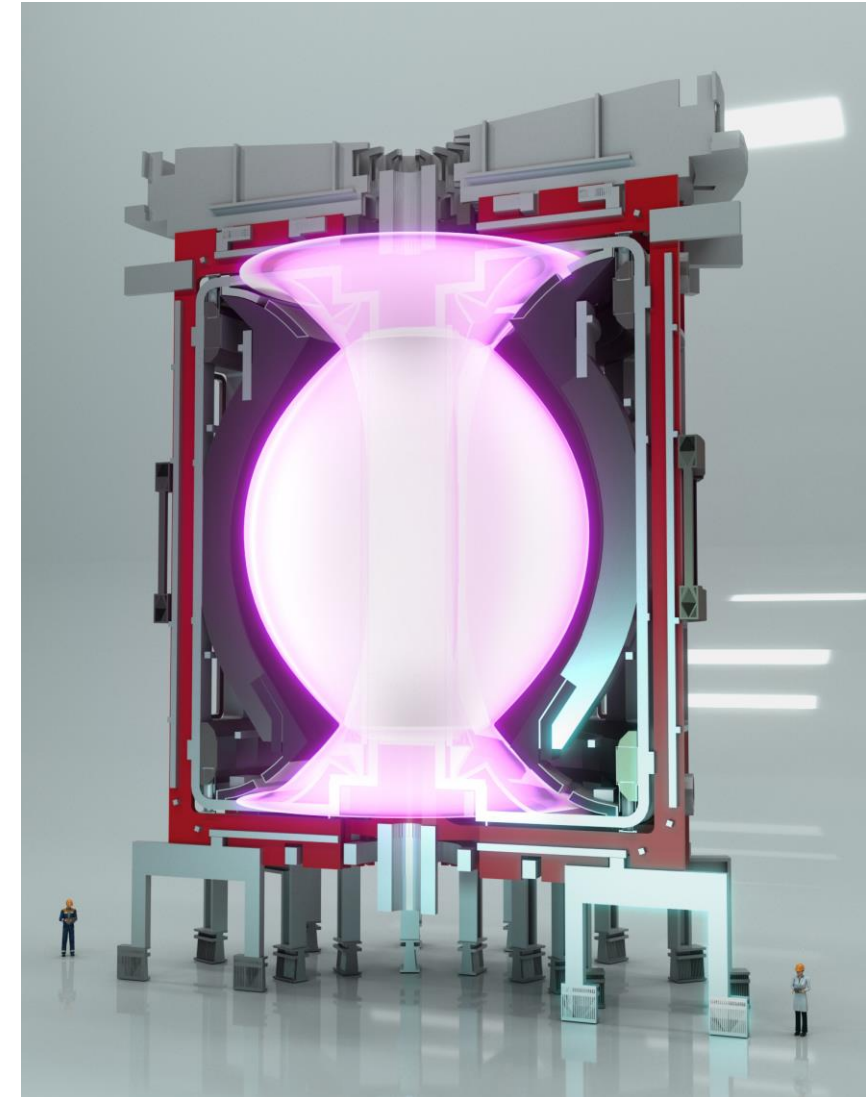
$$q_{surf}^{div} = \frac{P_{SOL}}{A_{wetted}} = \frac{P_{sep} f_{SOL}}{2\pi \lambda_q^{mid} B_{\theta}^{mid} w_f} \frac{R_0}{R^{div} R^{mid}} B_0 \sin \alpha_{inc}$$

In conventional aspect-ratio tokamaks, $R_0 \approx R^{div} \approx R^{mid}$

For STs, this assumption is not valid and the inboard divertor power load is a major issue, $R^{div} \approx R^{mid} \approx R_0 \pm a_{minor}$

Assuming $w_f = 1$, $\lambda_q^{mid} = 2\text{mm}$, $f_{SOL}^{inner} = 0.33$, $f_{SOL}^{outer} = 0.66$, $P_{sep} = 150\text{MW}$, $\alpha_{inc} = 2^\circ$

Unmitigated loads (MWm ⁻²)	Inner divertor	Outer divertor
DEMO single null	45.6	91.3
STEP single null	480.7	78.5
STEP double null	173.0	56.5



Power balance

Conventional tokamak experiments indicate power sharing

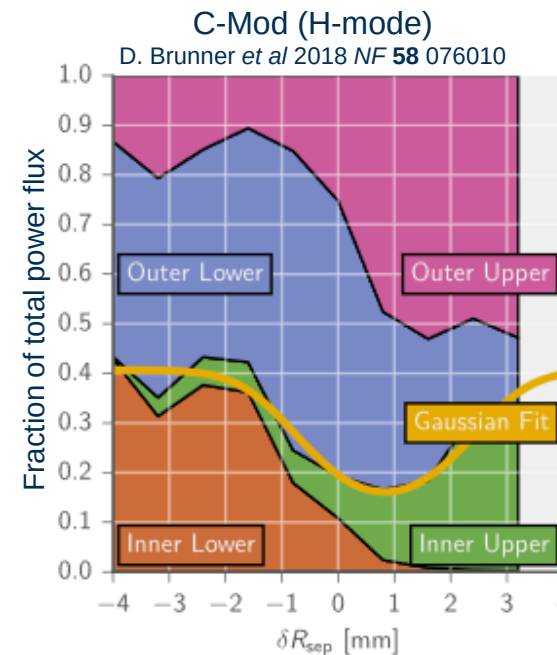
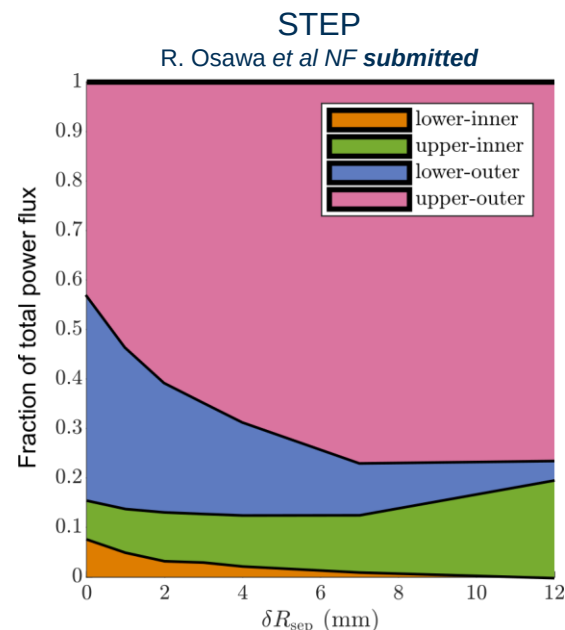
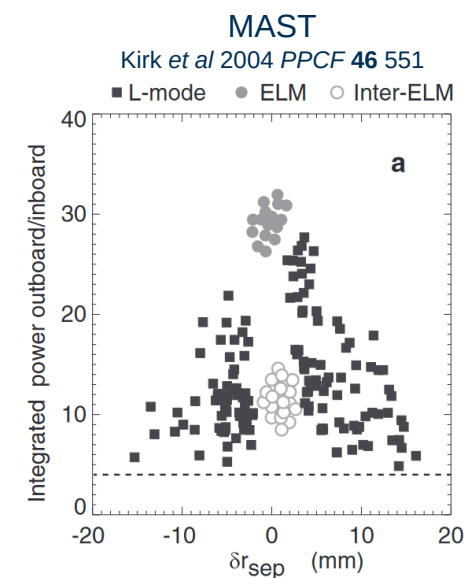
- **Up-down** : around 60 : 40
- **In-out** : around 1 : 4 - **SN** around 1 : 2

STEP SOLPS-ITER simulations (without drifts) shows only ~30% rise of *total* inboard power fraction in SN

Fundamental differences between spherical and conventional tokamaks thought to be caused by:

- **total flux compression** from outer midplane to inner divertor
- **parallel current** in the primary SOL

Benefits of double null may not be as strong as found in conventional tokamaks, but still enough (>x2 reduction in power loads) to motivate design choice



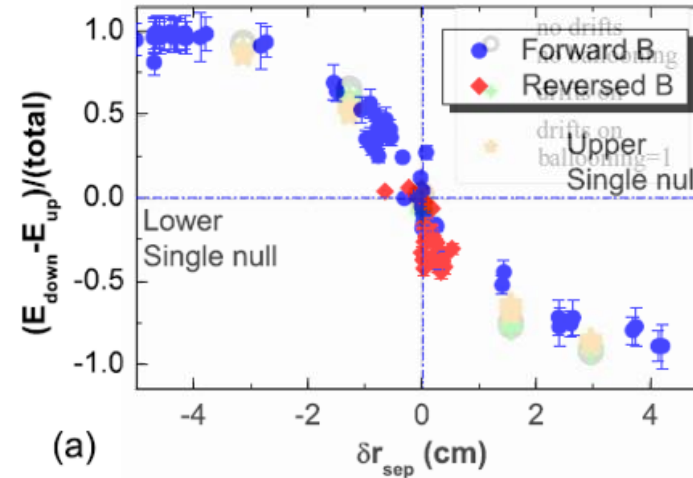
Potential impact of drifts

Assessment of power balance in MAST to guide STEP expectations

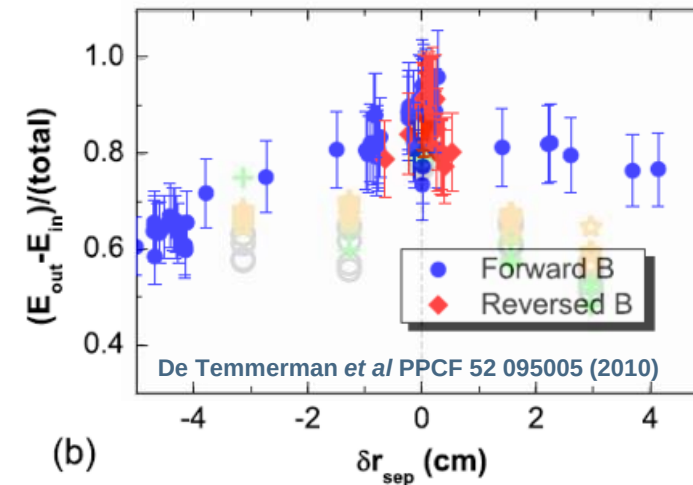
- Up/down balance reproduced in simulations without drifts
- Drifts have marginal impact in general, but may be significant at higher power
- Ballooning transport improves agreement between in/out sharing

Need further assessment of single null H-modes in spherical tokamaks

MAST L-mode measurements

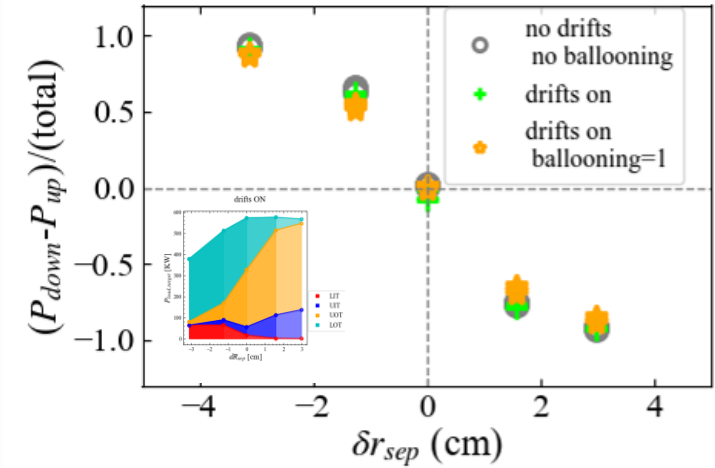
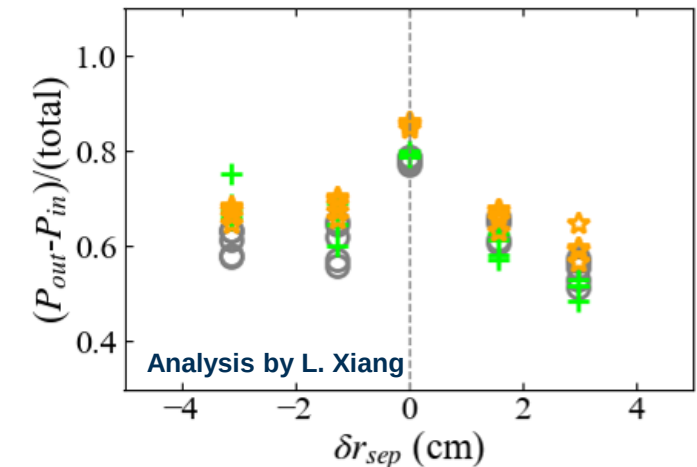


(a)



(b)

MAST L-mode SOLPS-ITER



Oscillating double null

Summarise double / single null options as three categories:

1. Single null

- Inner divertor receives ~20% of power
- Outer divertor receives ~80% of power

POTENTIAL SCENARIO

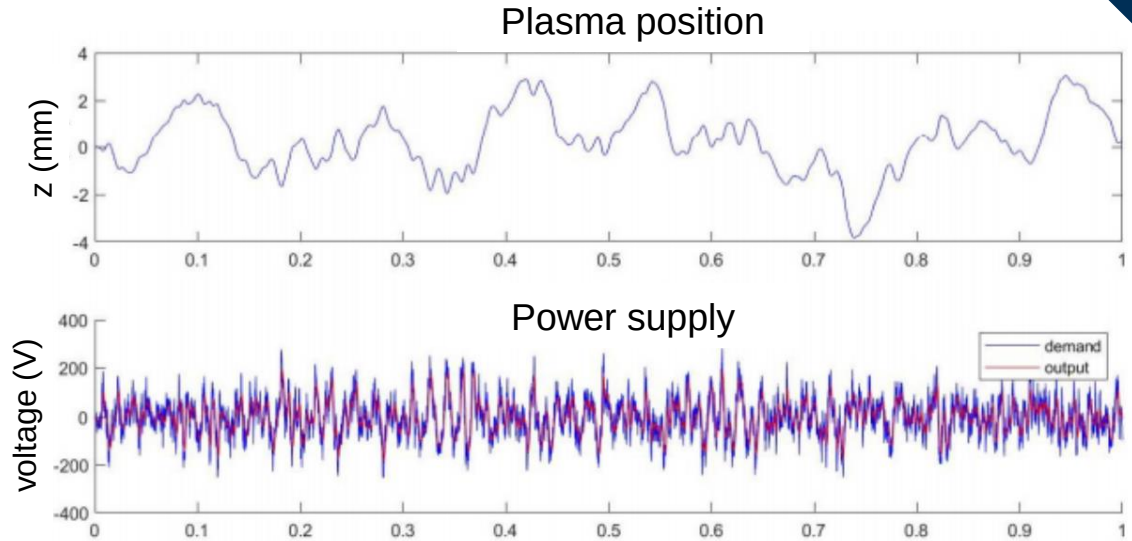
2. Oscillating double null, full power alternating between upper and lower divertor

- Control oscillation frequency to avoid excessive divertor life reduction through fatigue
- Transient/steady state response to be investigated

BEST CASE SCENARIO

3. Well controlled double null, good balancing and small oscillations around optimal position

- Oscillation frequency less important
- Inner divertors receive significantly less than half of the single null power on average



Example : noise on requested amplifier voltage results in variation of plasma centroid vertical position
– *figure only for illustration*

Power supplies will play a significant role, but quality of measurements will also determine how good a balancing can be achieved

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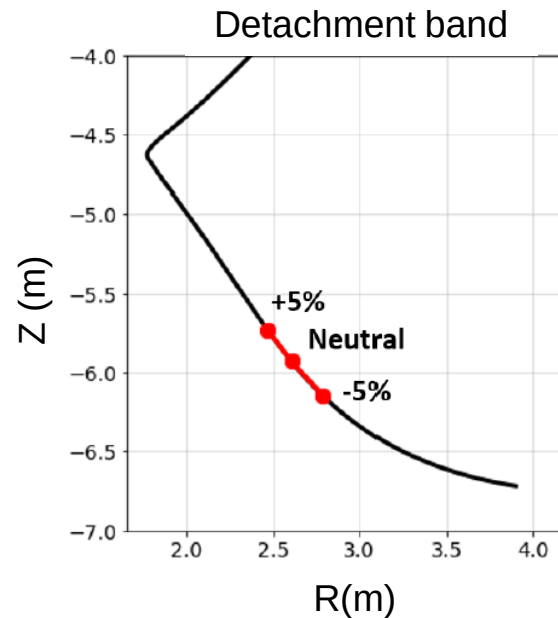
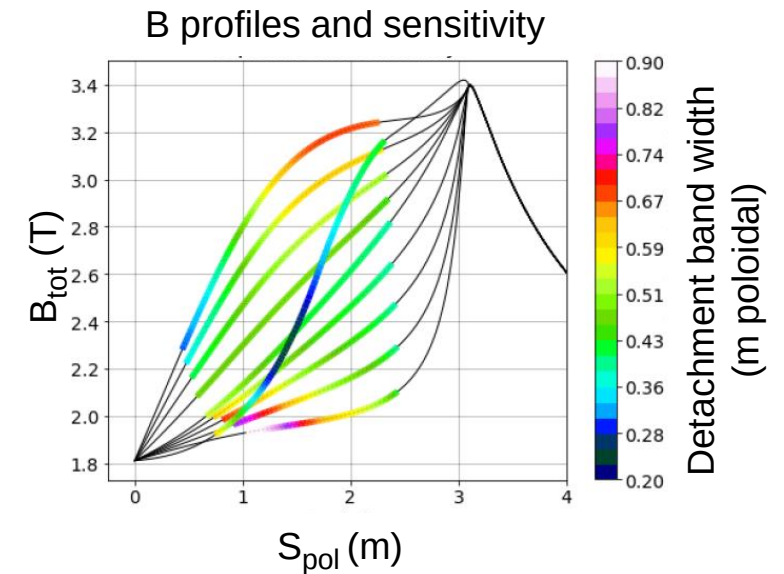
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The DLS model [1] allows us to optimise the detachment window to minimise front movement during power or density perturbations and therefore reduce demand on a detachment control system



Analysis by M. Kryjak

Secondary divertor design – inboard

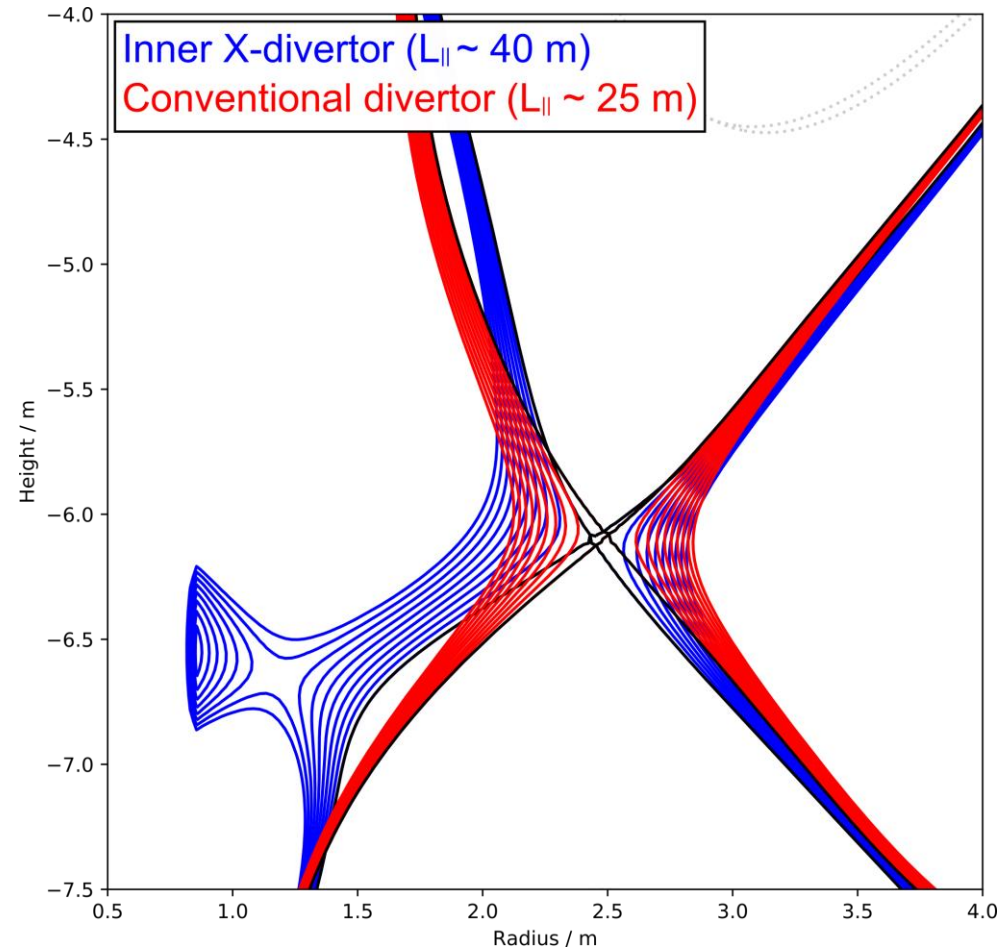
Initial design point : vertical inner target

- significant Ar seeding ($c_{Ar} > 1\%$) required to detach

Alternative baffled inner divertor geometries studied, including geometry *approaching X-divertor*

Inner divertor performance

- Neutral trapping
- Detachment access



Analysis by A. Hudoba

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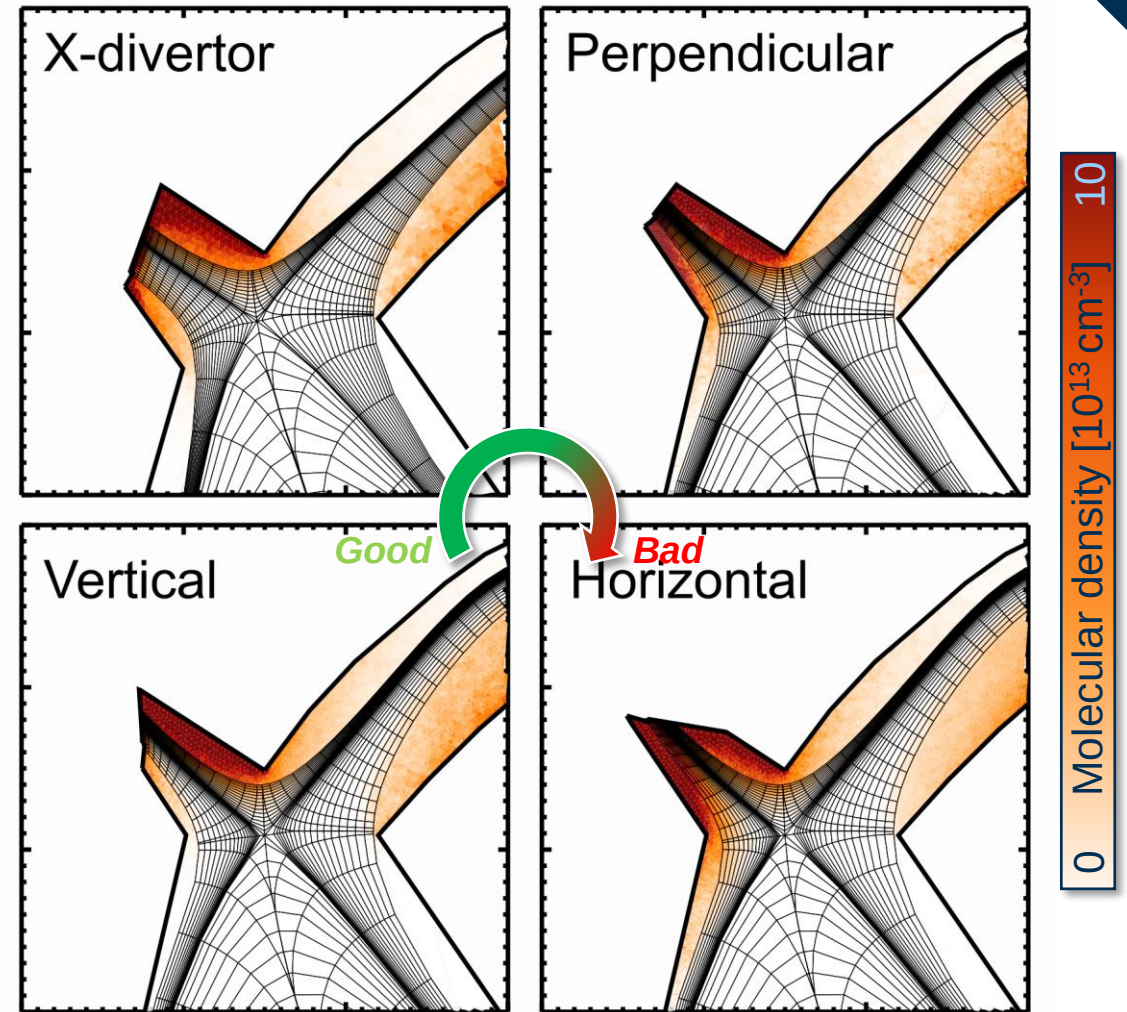
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Inner divertor performance

- **Neutral trapping**
- Detachment access

X-divertor geometry appears optimal when also considering low field line incidence angles ($\sim 2^\circ$)
Perpendicular geometry may be required during ramp-up to raise the field line incidence angle



Simulations with $D=1 \times 10^{23}$, fixed Ar fraction 0.5%, $P_{sep}=150 \text{ MW}$

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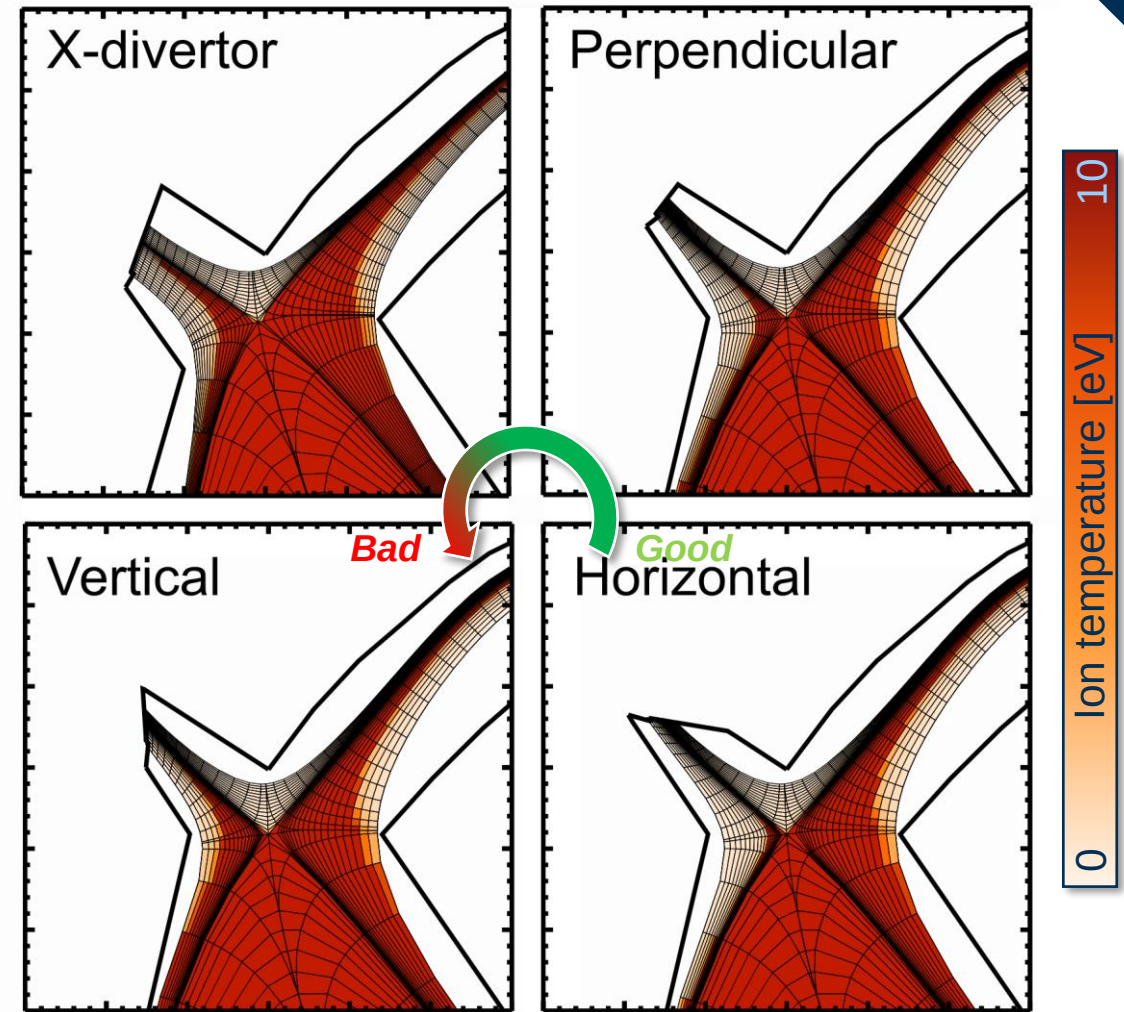
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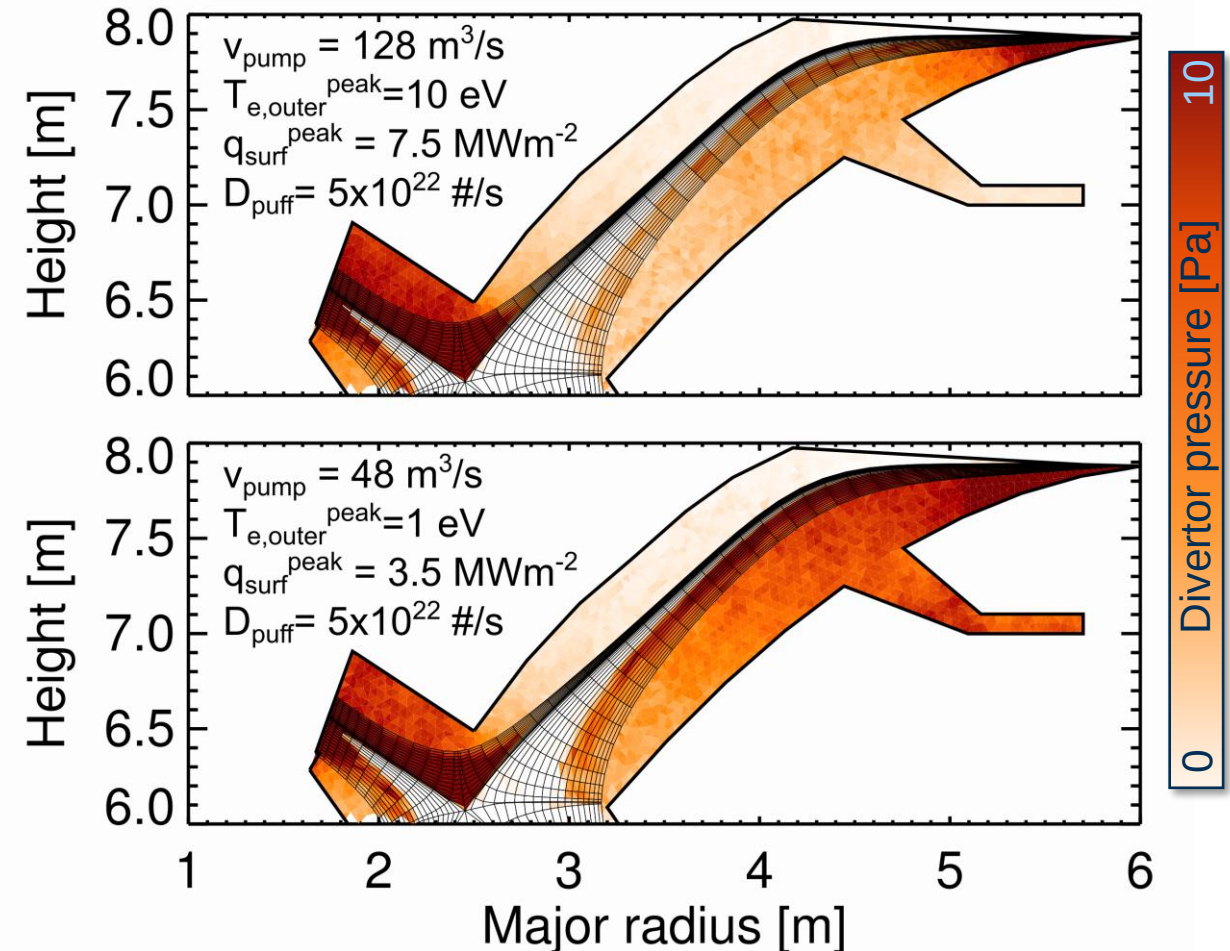
Secondary divertor design – outboard

Current design point : tightly baffled extended outer leg

Additional poloidal flux expansion *i.e.* *super-X* under investigation

Outer divertor performance

- While the inner divertor is detached in these simulations, the outer divertor remains attached
- Various optimisation options are available and currently under investigation
 - Lowering pump speed
 - Increase total flux expansion
 - Gas puff location



Impurity enrichment

Well baffled horizontal outer divertor target

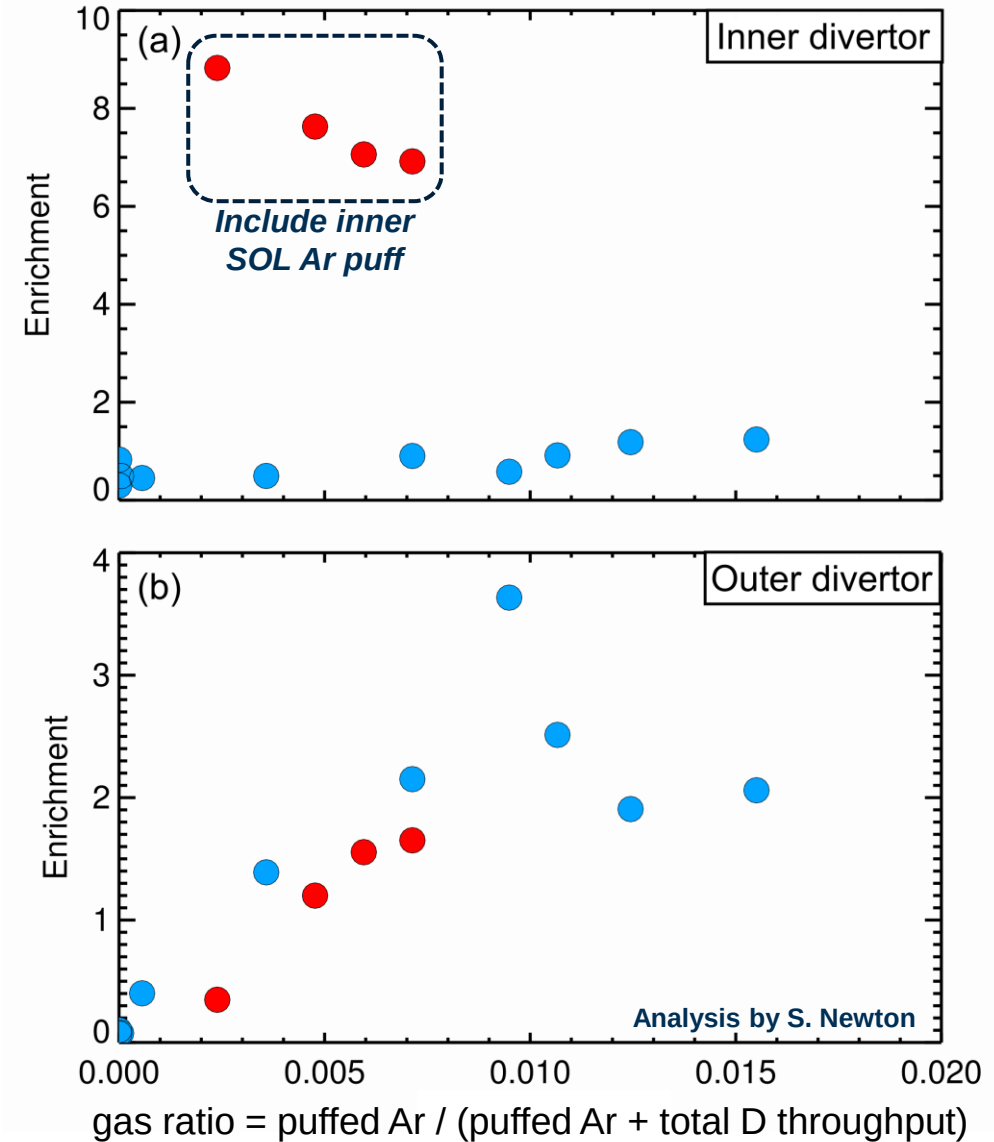
- enrichment increases with increasing Ar seeding

Baffled inner divertor target

- negligible enrichment
- Significant improvement of enrichment by puffing directly into divertor

$enrichment = X \text{ volume averaged over divertor SOL} /$
 $X \text{ volume averaged over 8 midplane cells inside separatrix}$

$$X = \left(n_{Ar} + \sum_{z=1}^{18} n_{Ar,z+} \right) / (n_D + n_i)$$



Integrated exhaust optimisation

Free boundary equilibrium exploration with FIESTA

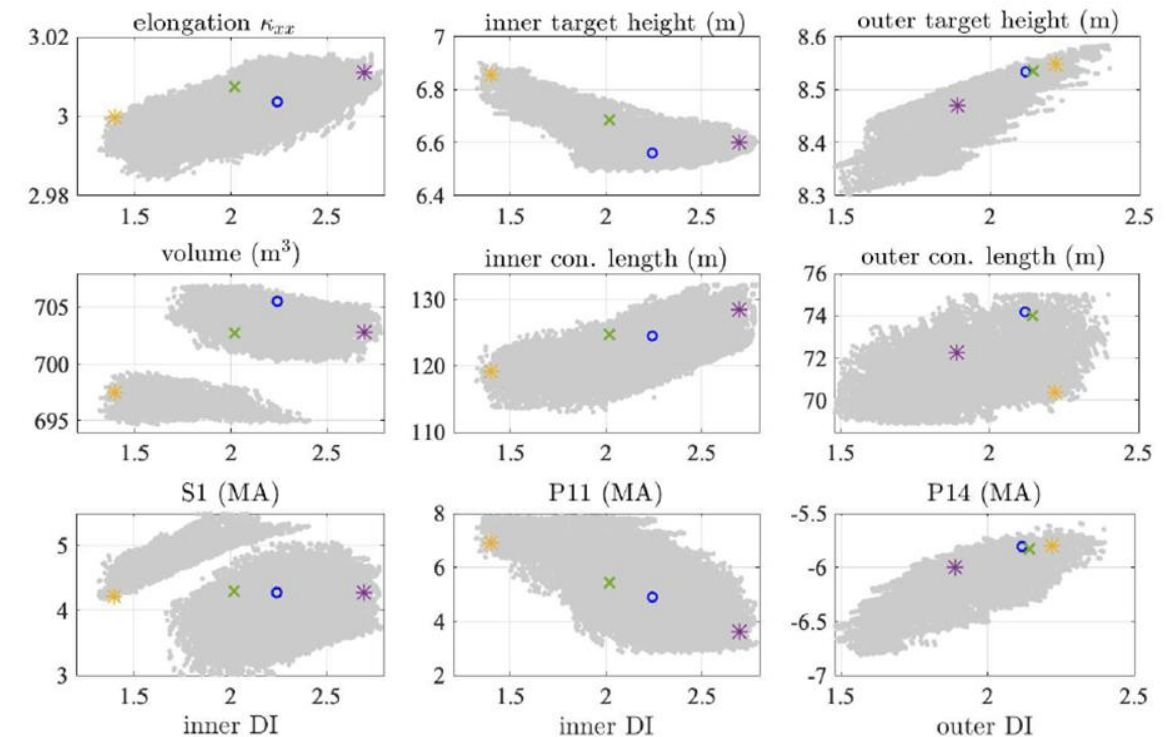
- Identify trends and trade-offs in design space
- Scan parameters varying weights of constraints defining
 1. **Spatial integration and engineering limits**
e.g. PF coil size, position and maximum currents
 2. **Core plasma scenario**
Operational constraints e.g. q_0 from JETTO
 3. **Divertor performance**
Connection length, target incidence angle, divertor index locating flux expansion

Rapid structure prototyping

- Peak power loading (Kallenbach model)
- Wall radiation loading (CHERAB/2P model)

Family of equilibria (grey) approaching inner X-divertor configuration 

control parameters vs divertor indices



Analysis by A. Hudoba

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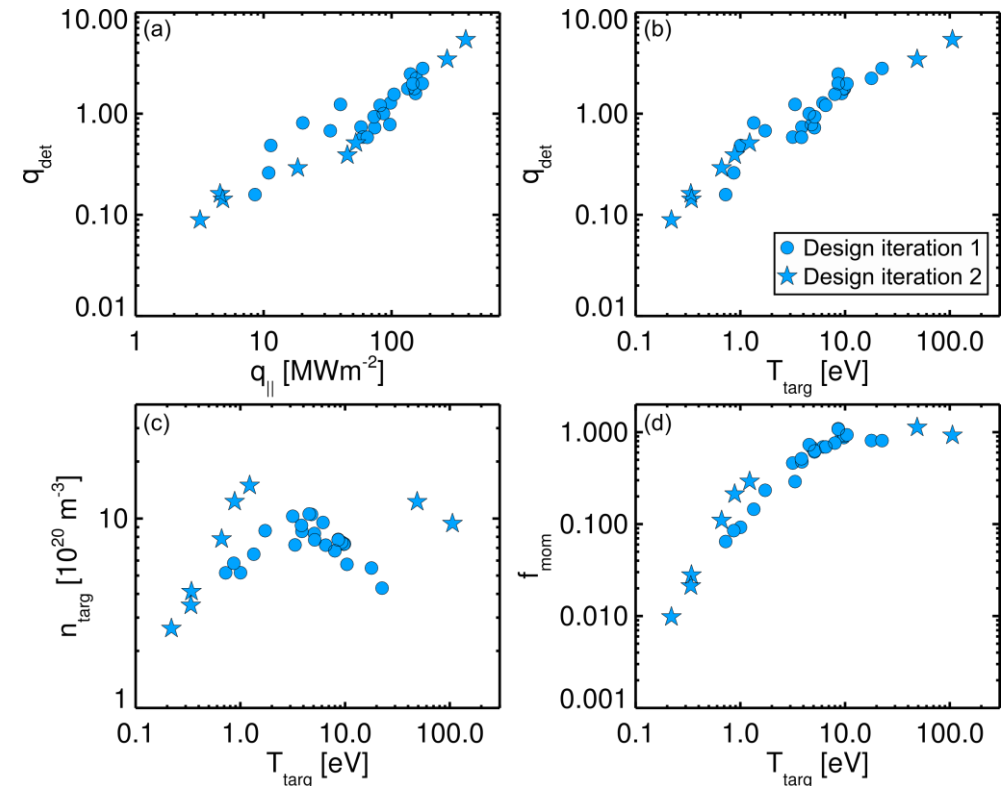
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Simple analytical equation predicting detachment point [1]

$$q_{det} \cong 1.3 \frac{P_{SOL}}{R_{div}} \frac{5 \text{ mm}}{\lambda_{int}} \left(\frac{R_{div}}{1.65} \right)^{-0.11} ((1 + f_Z c_Z) p_{div})^{-1}$$

$$q_{||}|_{q_{det}=1} \approx 0.03 n_{e,sep} (T_{e,sep} + T_{i,sep}) \approx 60 \text{ MWm}^{-2}$$

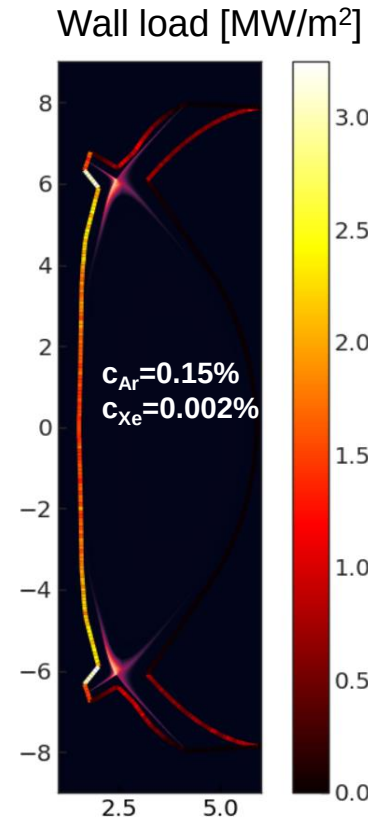
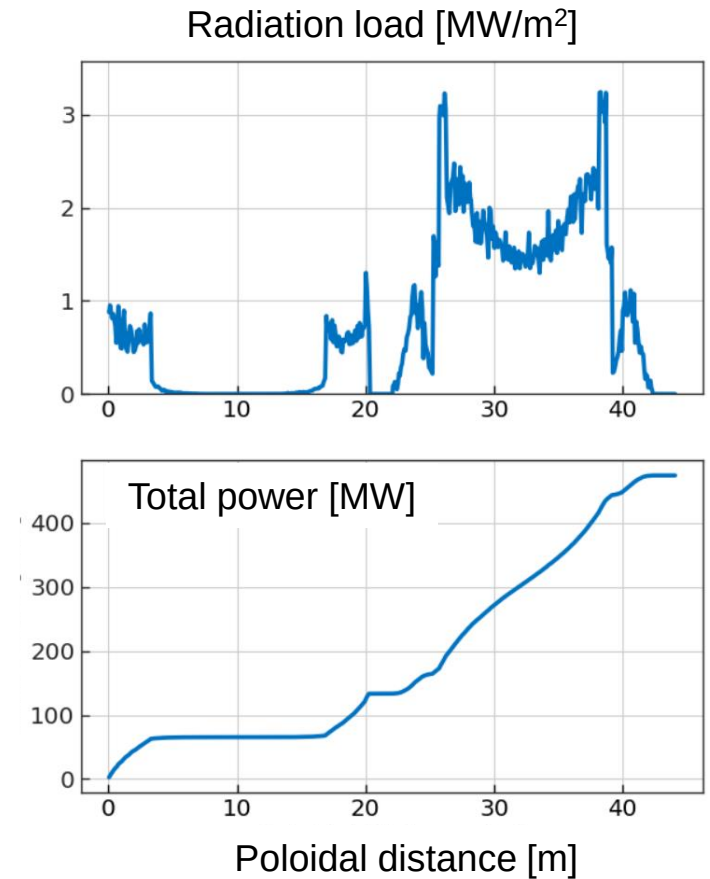
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Analysis by D. Vaccaro

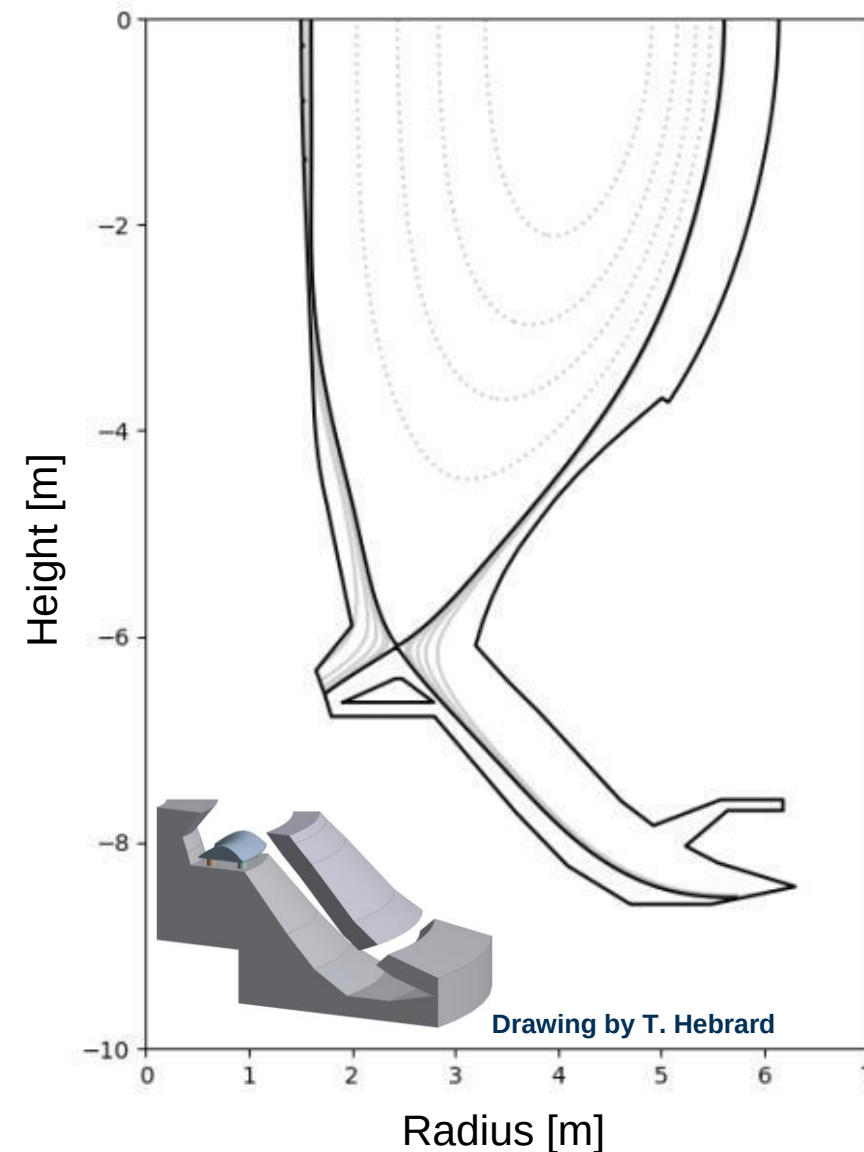
STEP divertor first wall

Following studies of various geometries, the current divertor design has the following features

- Vertical inner divertor target plate, compatible with perpendicular and X-divertor geometries with field line incidence angles of $\sim 2^\circ$
- Pump duct placed in outer divertor, although optimum position still under investigation
- Extended outer divertor ($R_{sp} \sim 6$ m) with field line incidence angle $\sim 4^\circ$
- Dome has been considered to provide pathway for particles to escape inner divertor towards pump duct in outer divertor (assumed 25% transmission)

Main chamber first wall coordinates are still in review, e.g. plasma wall gaps

Optimised free-boundary equilibrium
– A. Hudoba

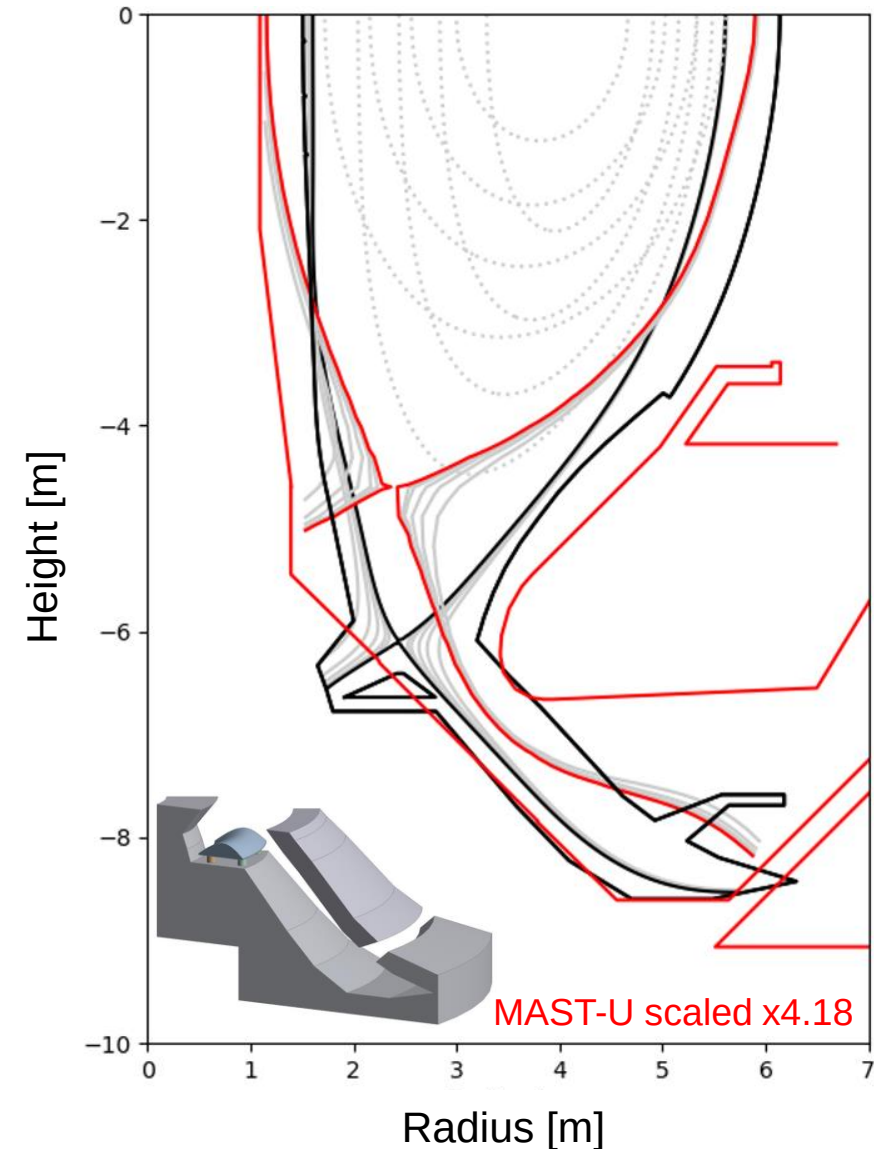


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Comparison with scaled MAST-U first wall design



Summary: STEP divertor concept design

Inner leg exhaust challenge motivates need for double null

- Explore control schemes

Alternative divertors explored for inboard and outboard

- Inboard X-divertor and outboard super-X

Developing integrated modelling processes

- Optimise free boundary equilibrium for divertor performance
- Neutral trapping and detachment access driving inner target design
- Capture behaviour with reduced models

