UK Atomic Energy Authority

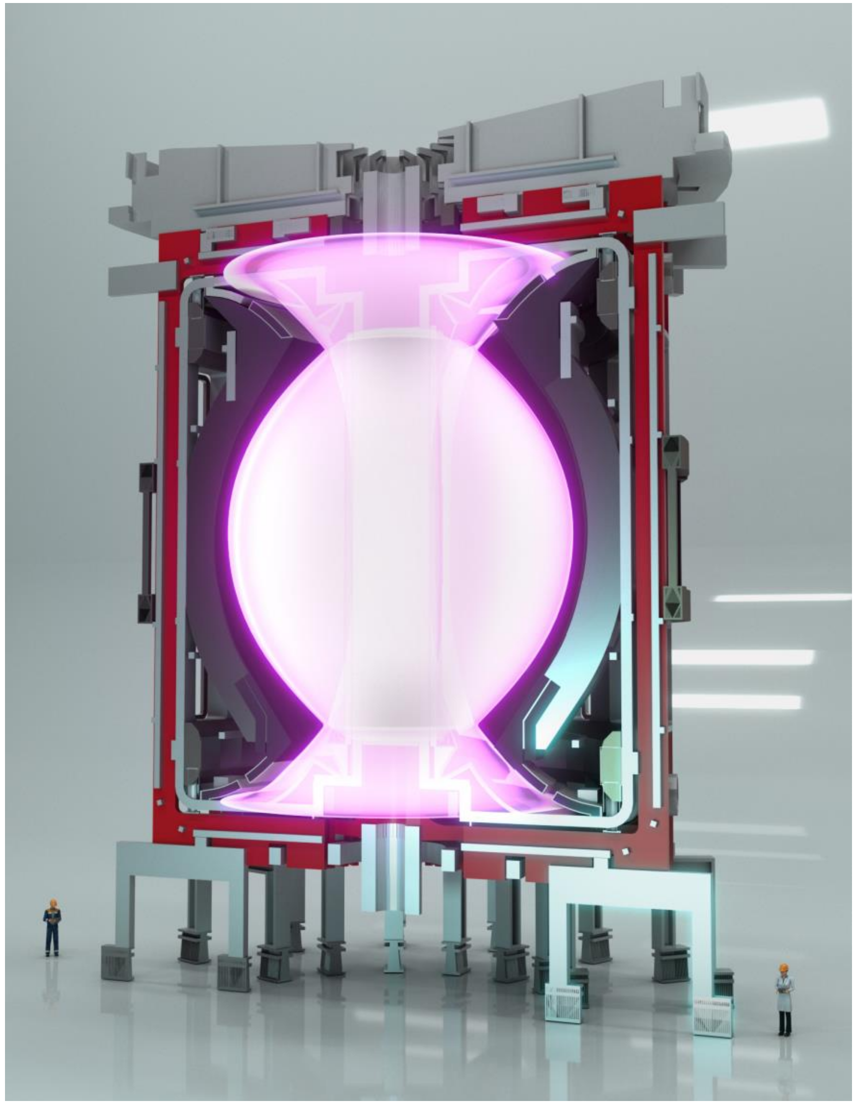
Physics drivers of the STEP divertor concept design

S. L. Newton, S. Henderson, 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

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.

*** All parameters subject to change**	
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
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

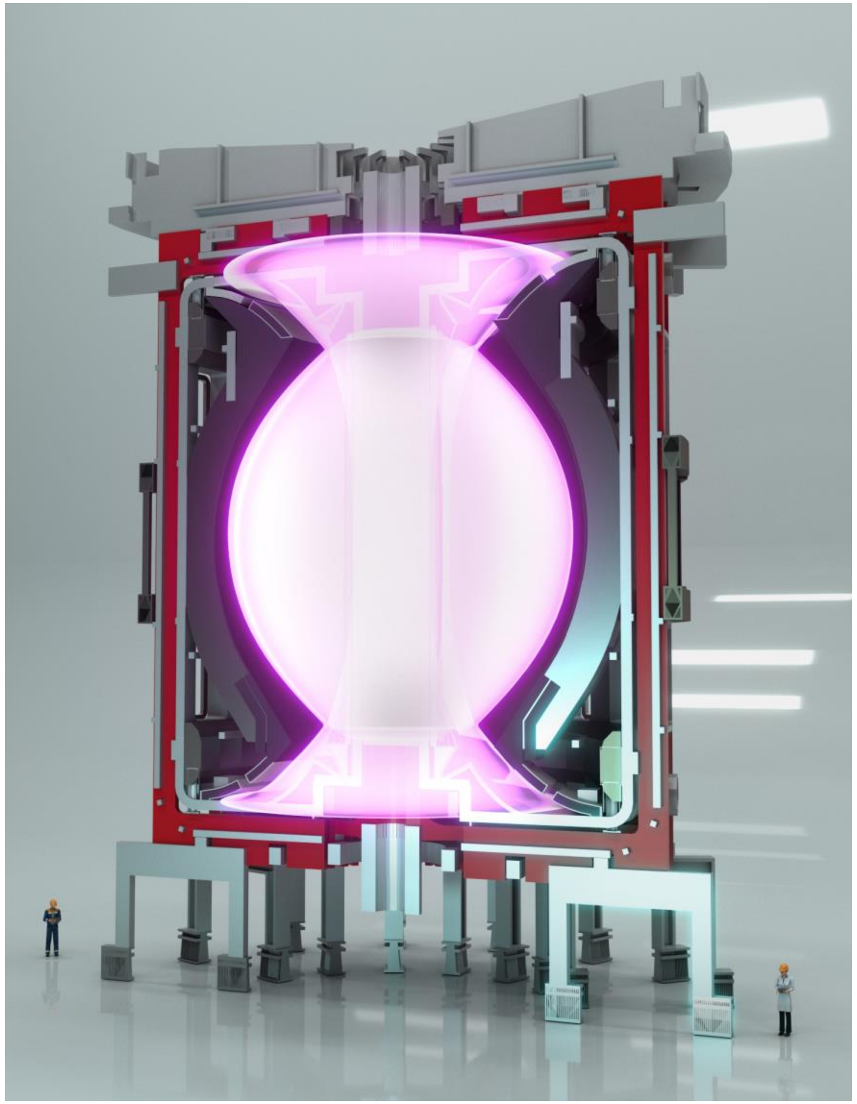
$$q_{surf}^{div} = \frac{P_{SOL}}{A_{wetted}} = \frac{P_{sep} f_{SOL}}{2\pi \lambda_q^{mid} B_\theta^{mid} w_f} \frac{R_0}{R^{div} R^{mid}} B_0 \sin \alpha_{inc}$$

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

For STs the inboard divertor power load is a major issue

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

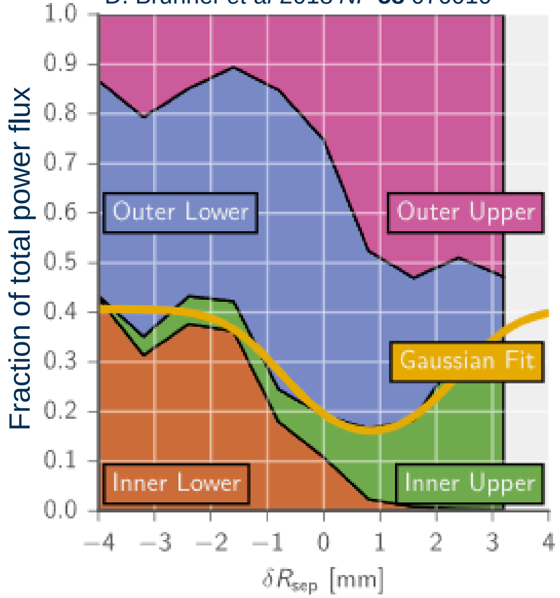
Fundamental differences between spherical and conventional tokamaks thought to be caused by:

- ***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

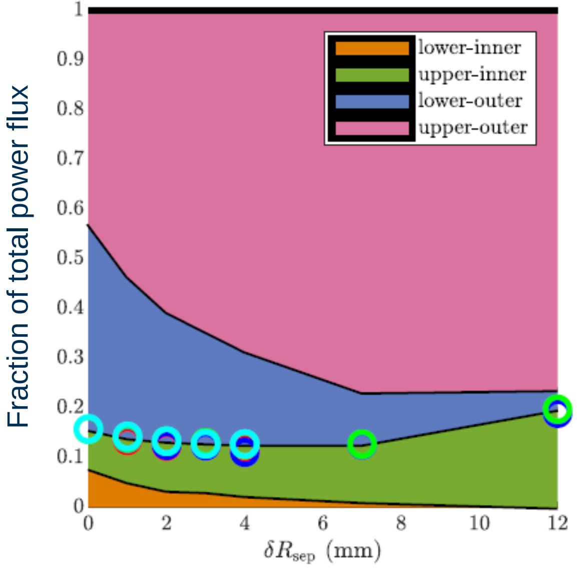
C-Mod (H-mode)

D. Brunner *et al* 2018 *NF* **58** 076010



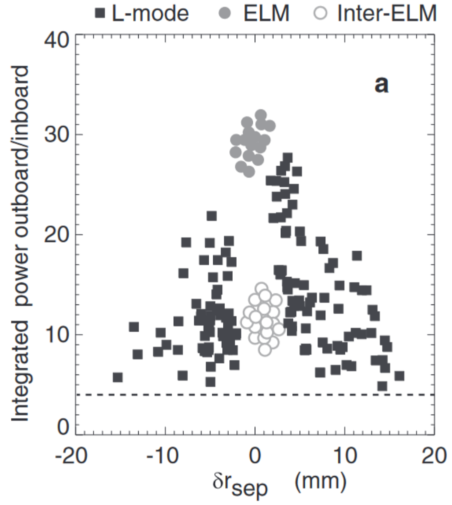
STEP

R. Osawa *et al* *NF* ***submitted***



MAST

Kirk *et al* 2004 *PPCF* **46** 551



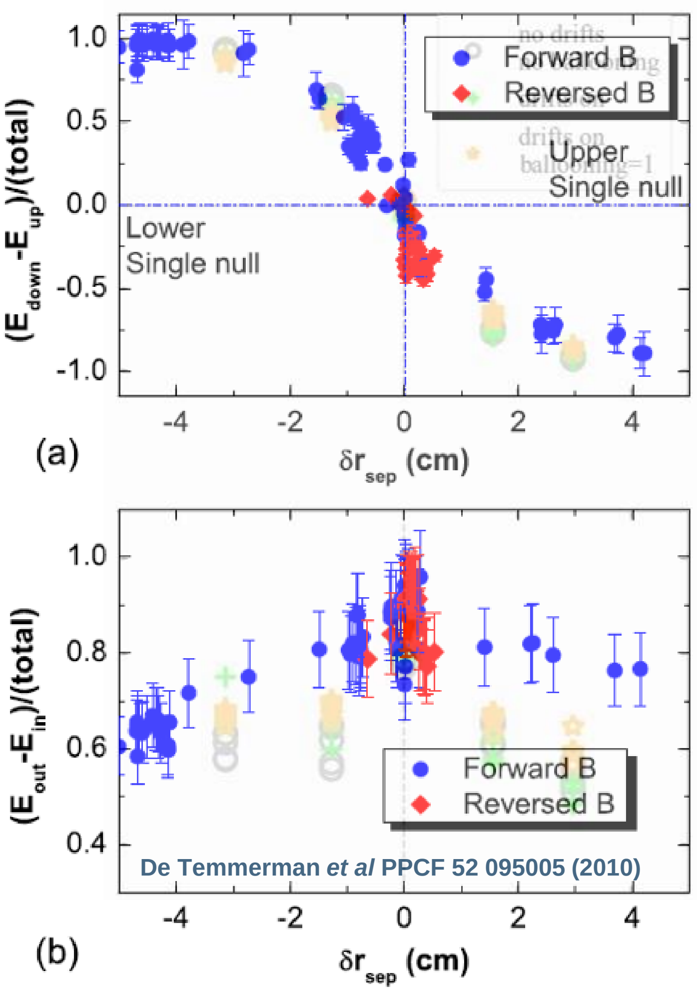
Potential impact of drifts

Assessment of power balance in MAST to guide STEP predictions

- 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

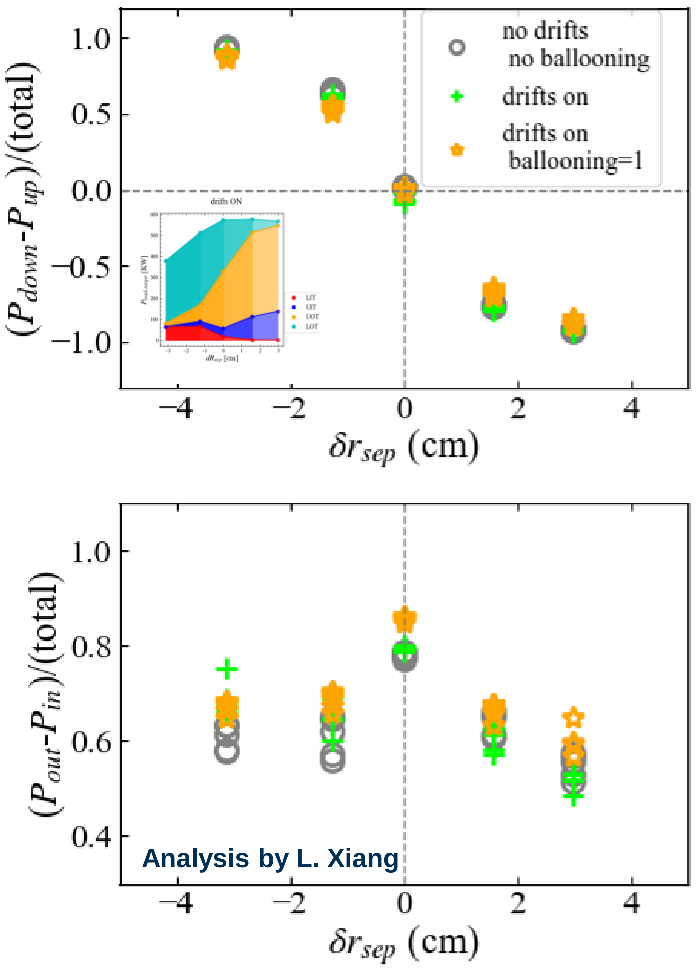
Need further assessment of single null H-modes in spherical tokamaks

MAST L-mode measurements



De Temmerman *et al* PPCF 52 095005 (2010)

MAST L-mode SOLPS-ITER



Analysis by L. Xiang

Oscillating double null

Summarise double / single null options as three categories:

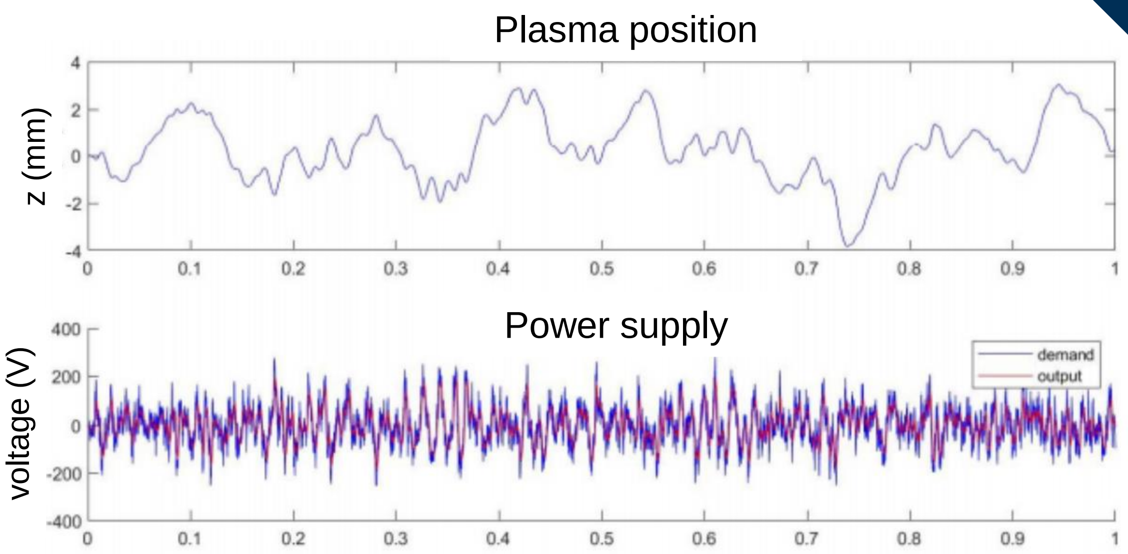
1. **Single null**
    - Inner divertor receives ~20% of power
    - Outer divertor receives ~80% of power

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


Plasma position

Power supply

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 ultimately determine how good a balancing can be achieved

Detachment window

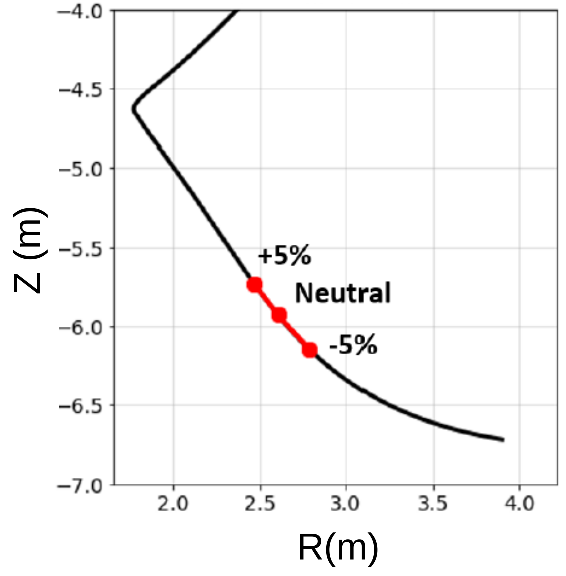
Detachment Sensitivity Location (DLS) model by Lipschultz *et al* [Nucl Fus **46** 056007 (2016)] gives basis for optimising equilibrium and exhaust operating point

Aim to find magnetic field profile along leg minimising front movement during power and density perturbations

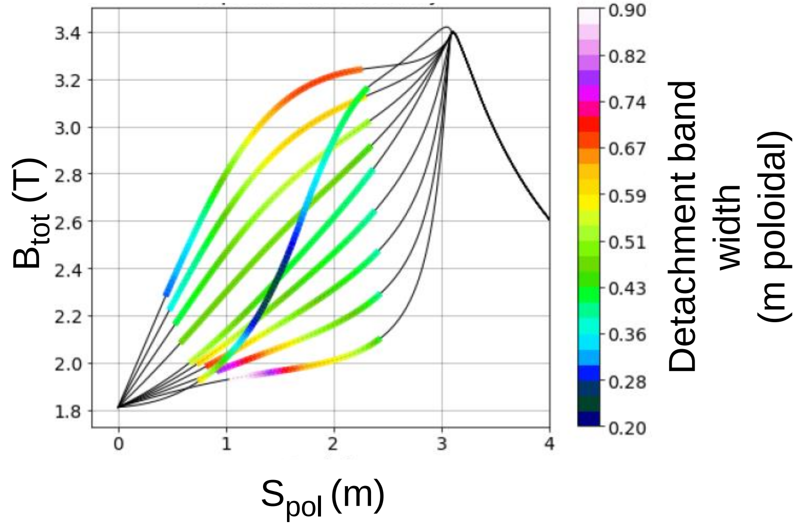
- Front location less sensitive to fluctuations in regions of highest magnetic field gradient along poloidal distance
- Code can be integrated into coil set divertor optimisation

Ultimate goal is to find operating point that reduces the demand on a detachment control system

Detachment band



B profiles and sensitivity



Analysis by *M. Kryjak*

Secondary divertor design – inboard

Initial design point : vertical inner target

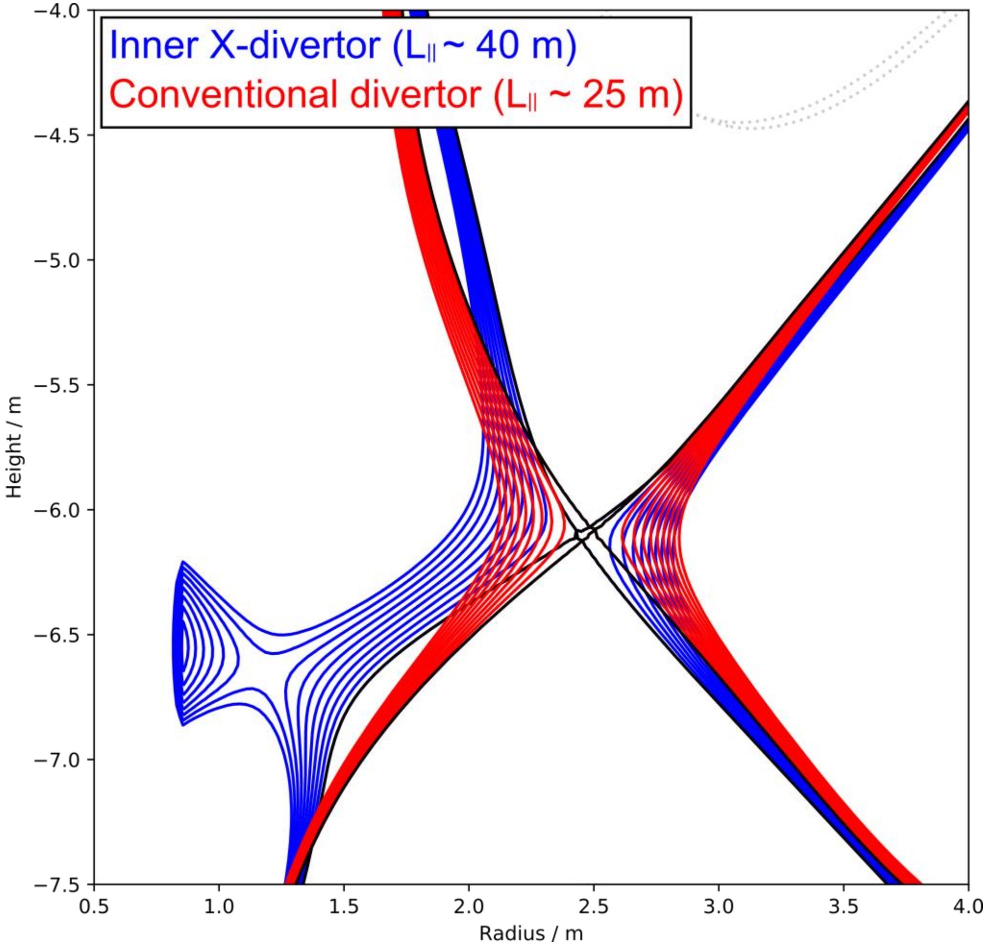
- significant Ar seeding (c_{Ar}>1%) required to achieve pronounced detachment

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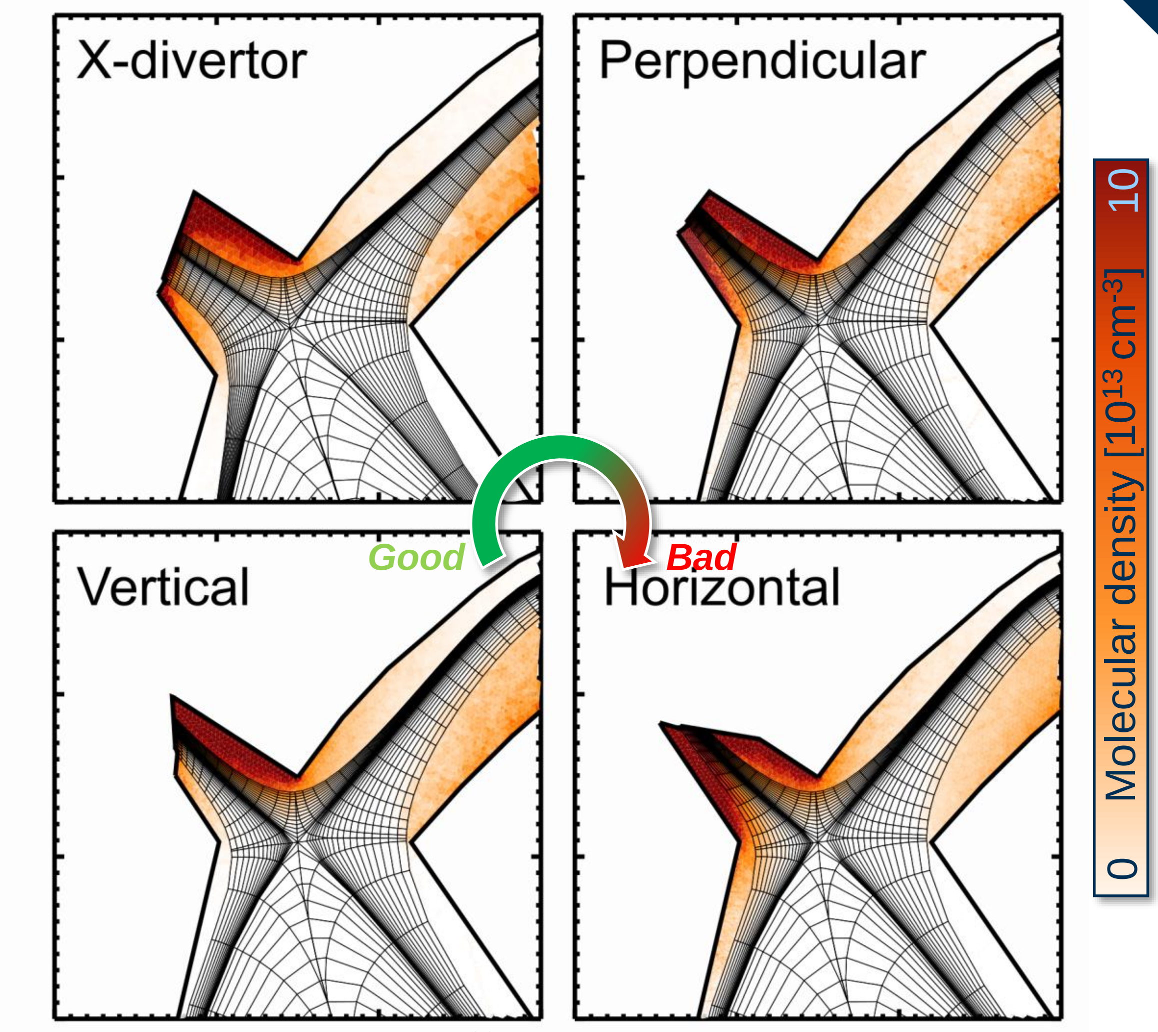
X-divertor geometry appears optimal when also considering low field line incidence angles (~2°) Perpendicular geometry may be required during ramp-up to raise the field line incidence angle



Simulations with D=1x10^{23}, fixed Ar fraction 0.5%, P_{sep}=150 MW

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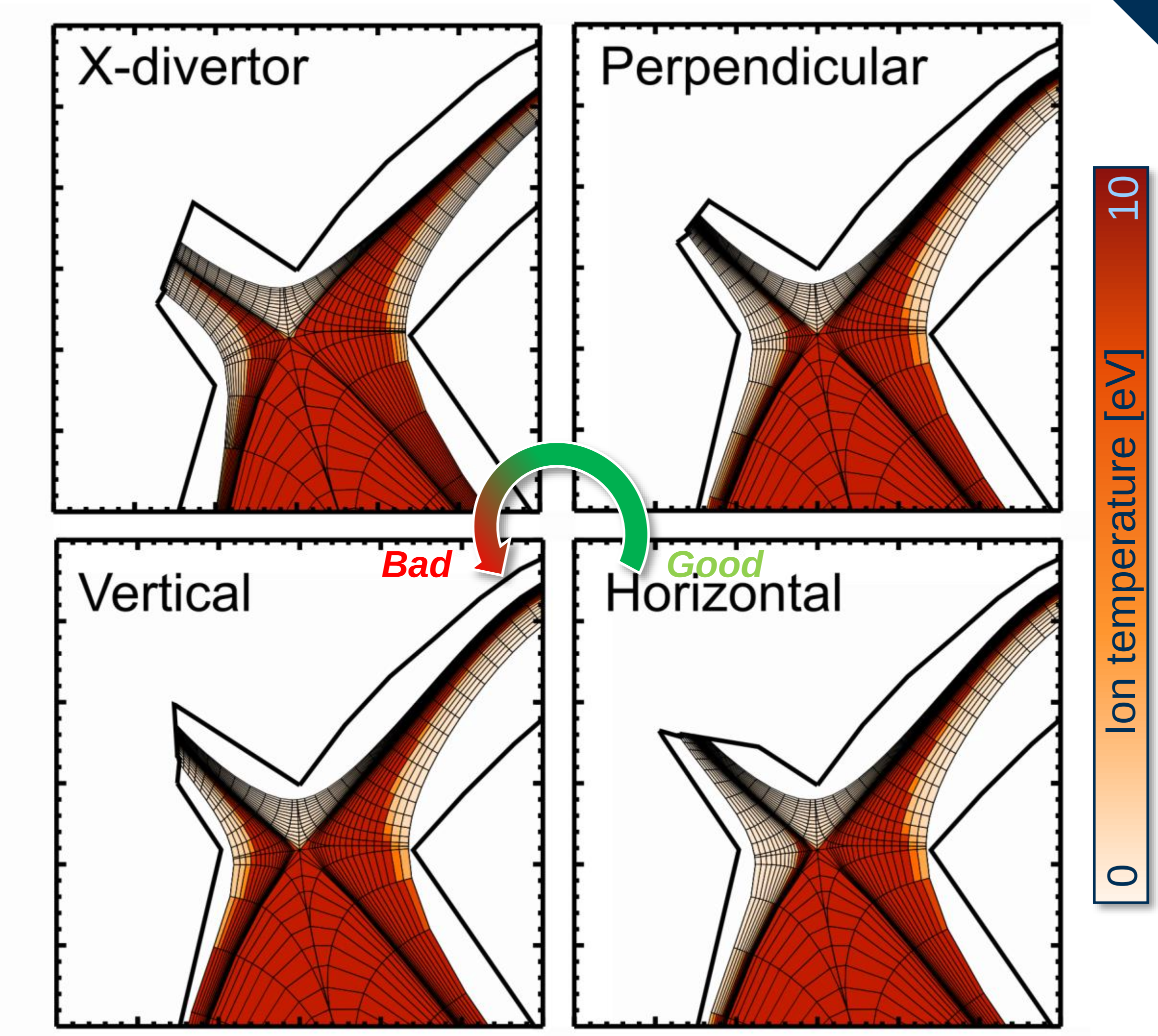


Simulations with $D=1x10^{23}$, fixed Ar fraction 0.5%, P_{sep}=150 MW

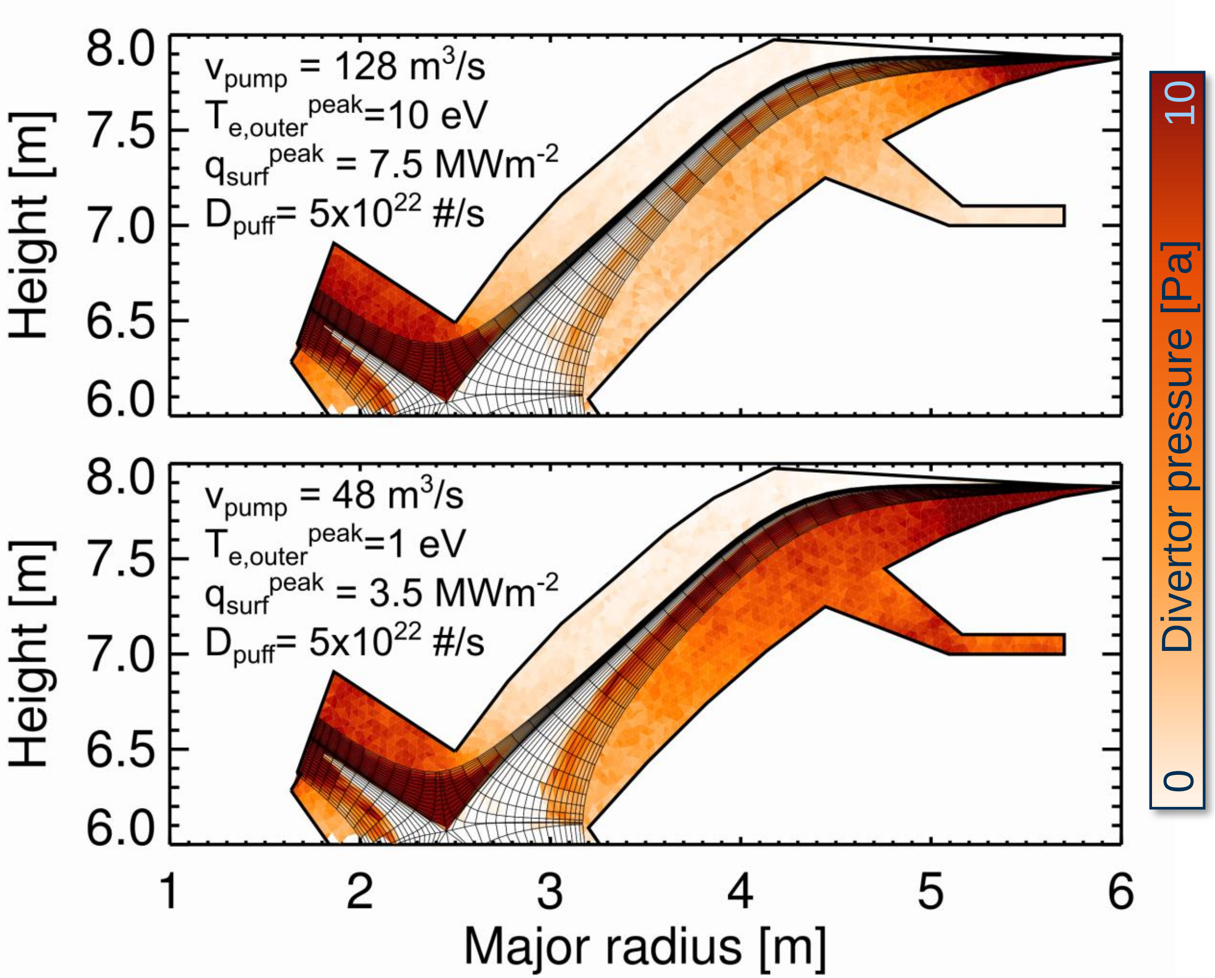
Secondary divertor design – outboard

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 from outer PFR

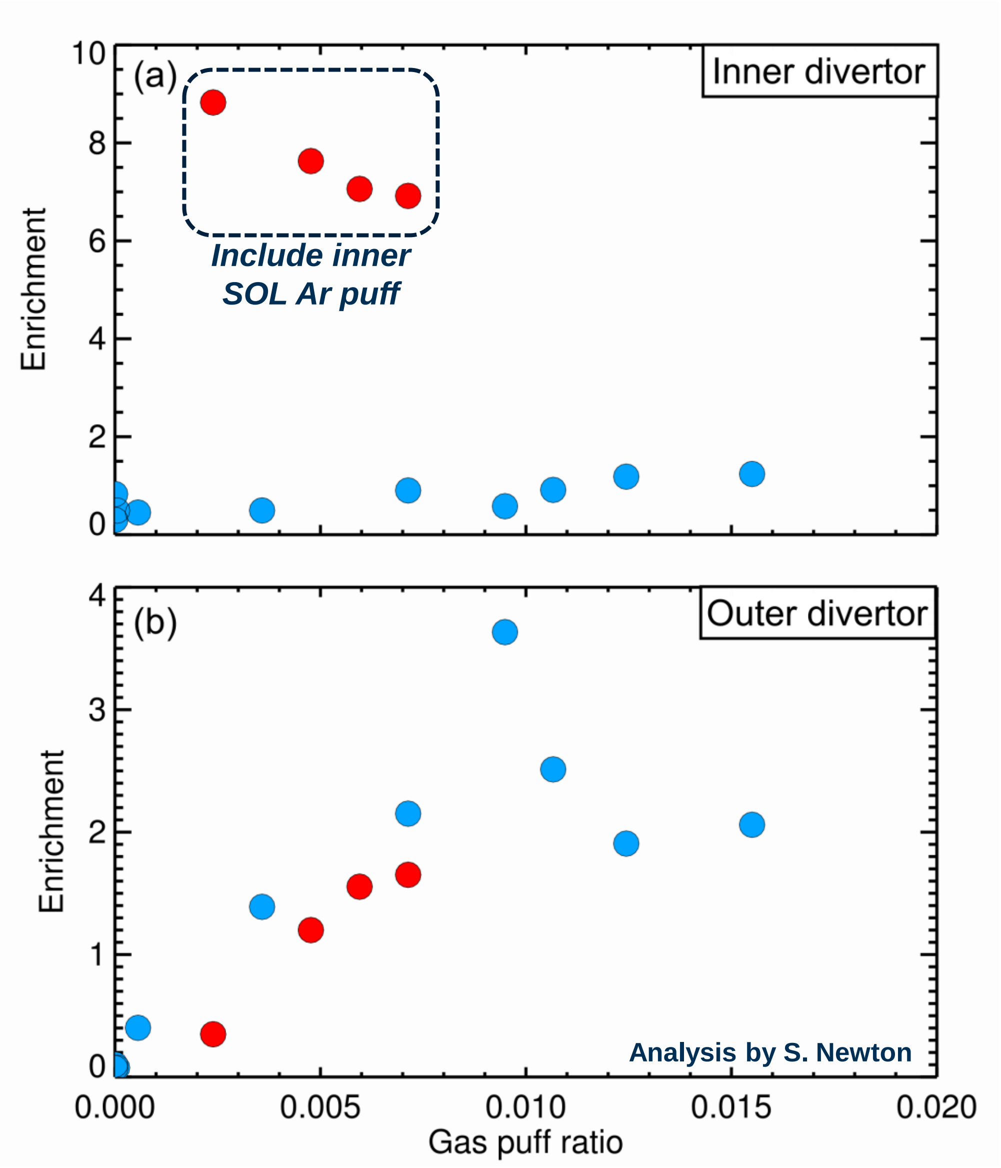
Baffled inner divertor target

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

enrichment = X volume averaged over divertor SOL /
X volume averaged over 8 midplane cells inside separatrix

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

gas puff ratio = puffed Ar / (puffed Ar + total D throughput)



Analysis by S. Newton

Integrated exhaust optimisation

Free boundary equilibrium exploration with FIESTA

- Identify trends and trade-offs in design space
- Scan parameters varying weights of constraints defining

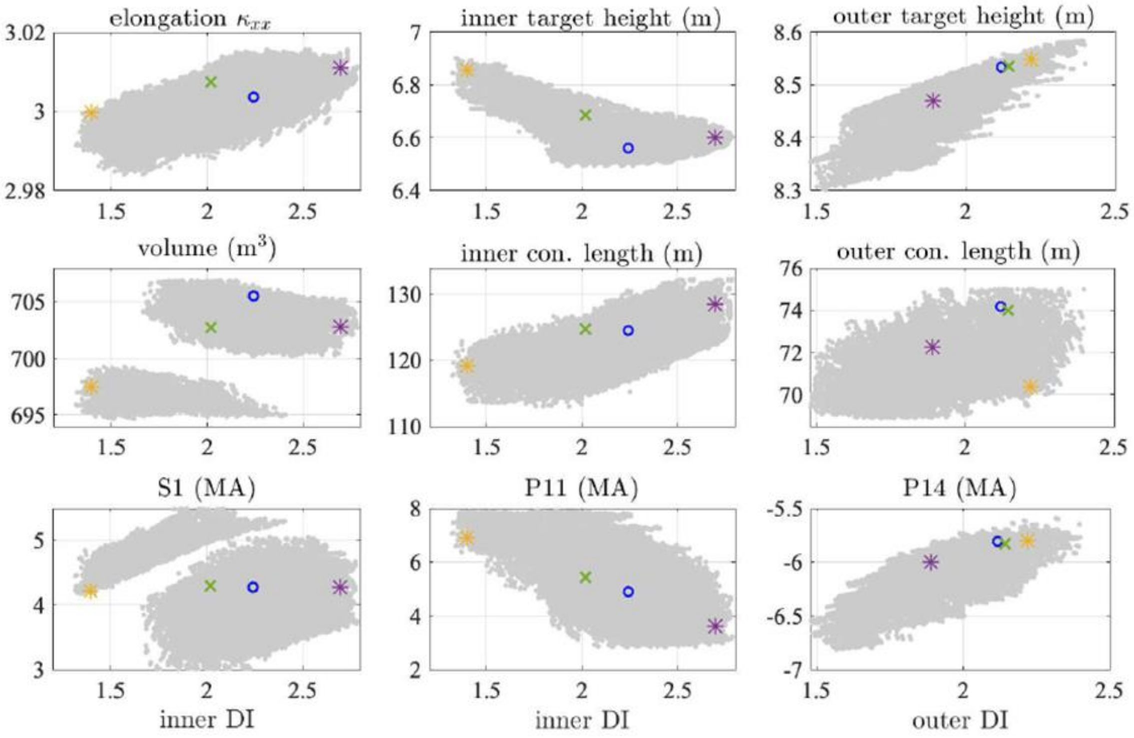
1. **Spatial integration and engineering limits**
   e.g. PF coil size, position and maximum currents
2. **Core plasma scenario**
   Operational constraints e.g. q_0 from JETTO
3. **Divertor performance**
   Connection length, target incidence angle, divertor index locating flux expansion

Rapid structure prototyping

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

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

control parameters vs divertor indices



Analysis by A. Hudoba

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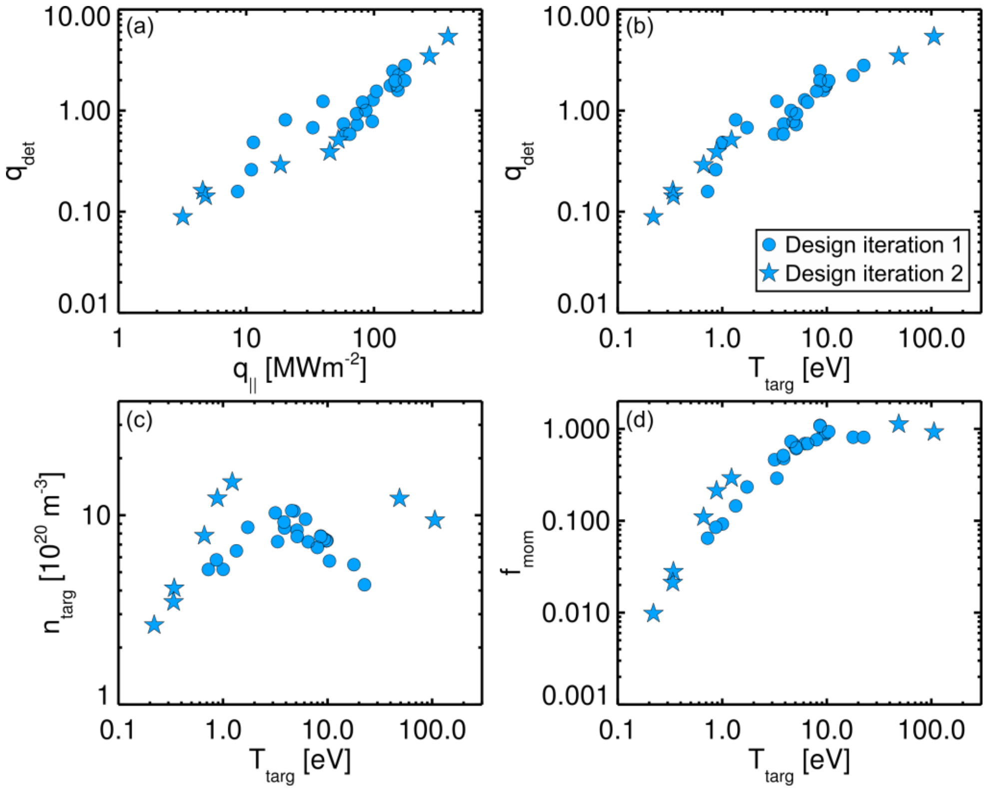

Simple analytical equation predicting detachment point [1]

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

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

[1] Kallenbach *et al* PPCF **58** 045013 (2016)

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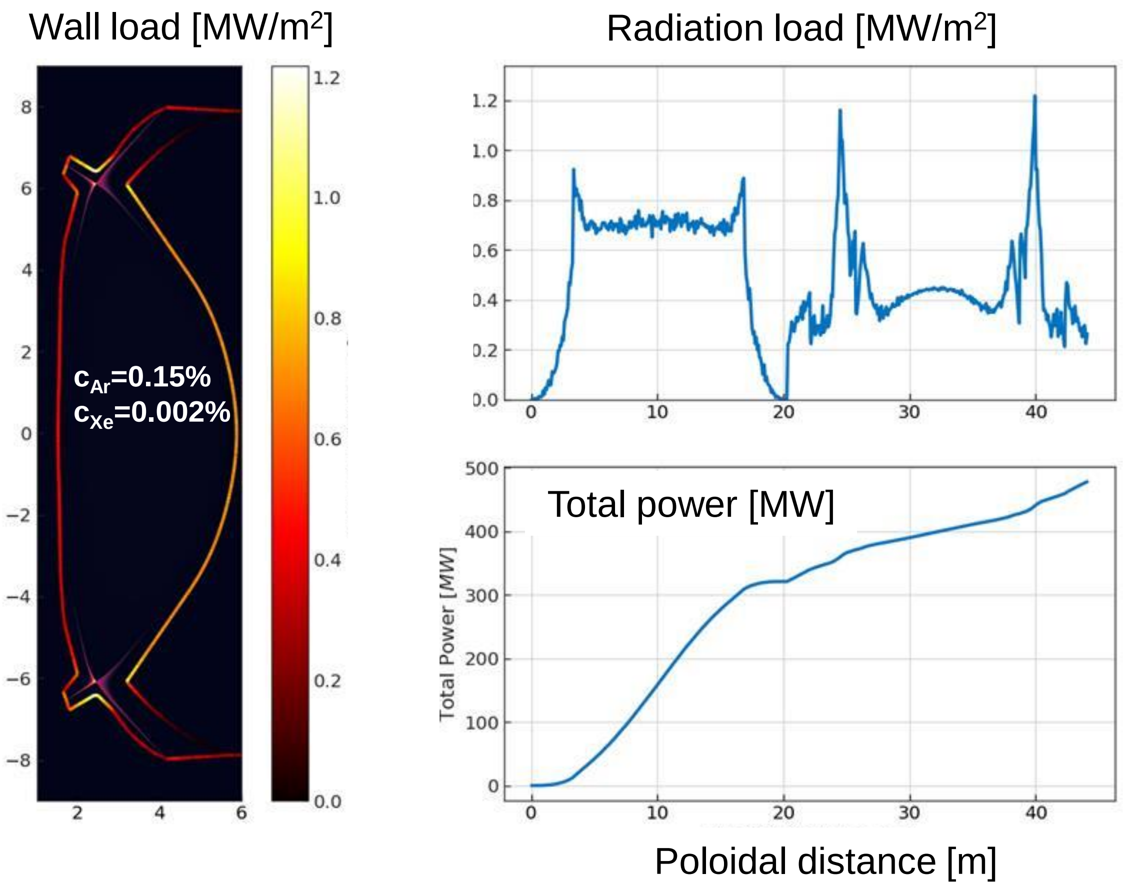


Analysis by D. Vaccaro

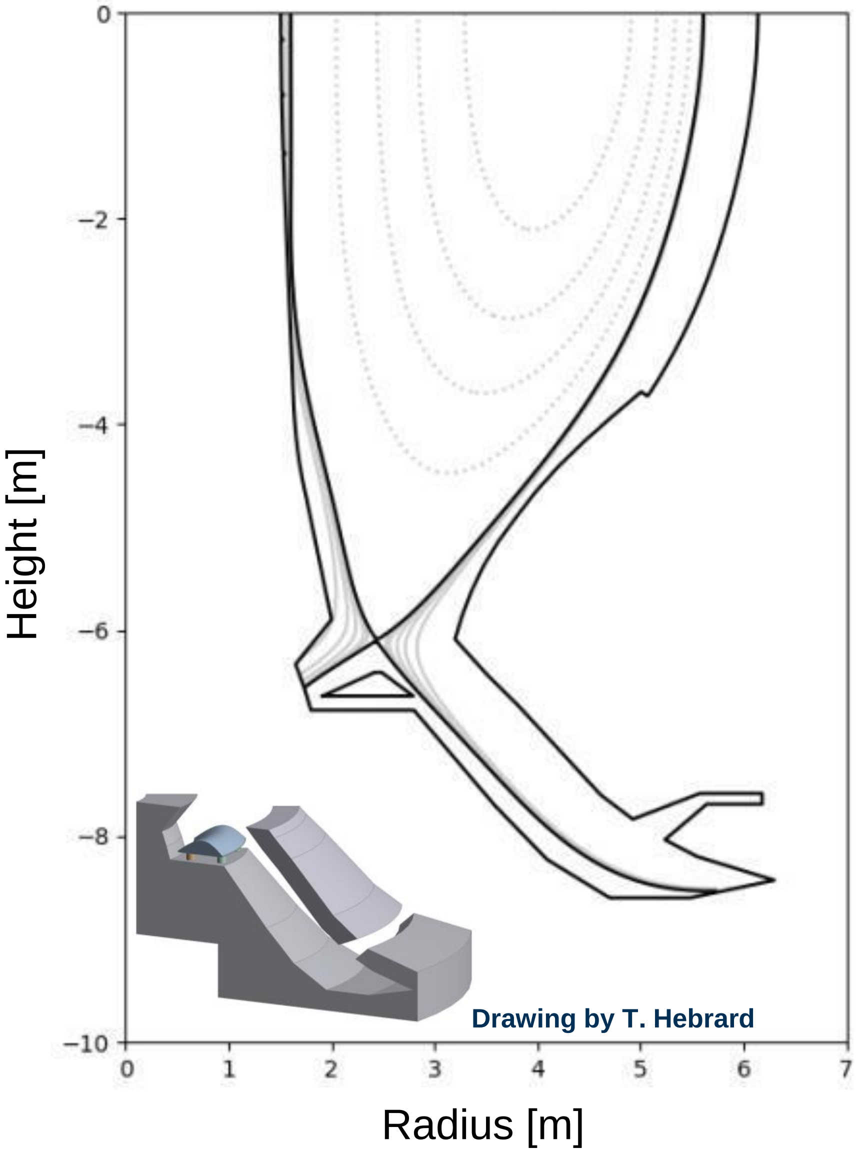
STEP divertor first wall

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 ~2°
- Pump duct placed in outer divertor, although optimum position still under investigation
- Extended outer divertor (R_{sp}~6 m) with field line incidence angle ~4°
- 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



Drawing by T. Hebrard

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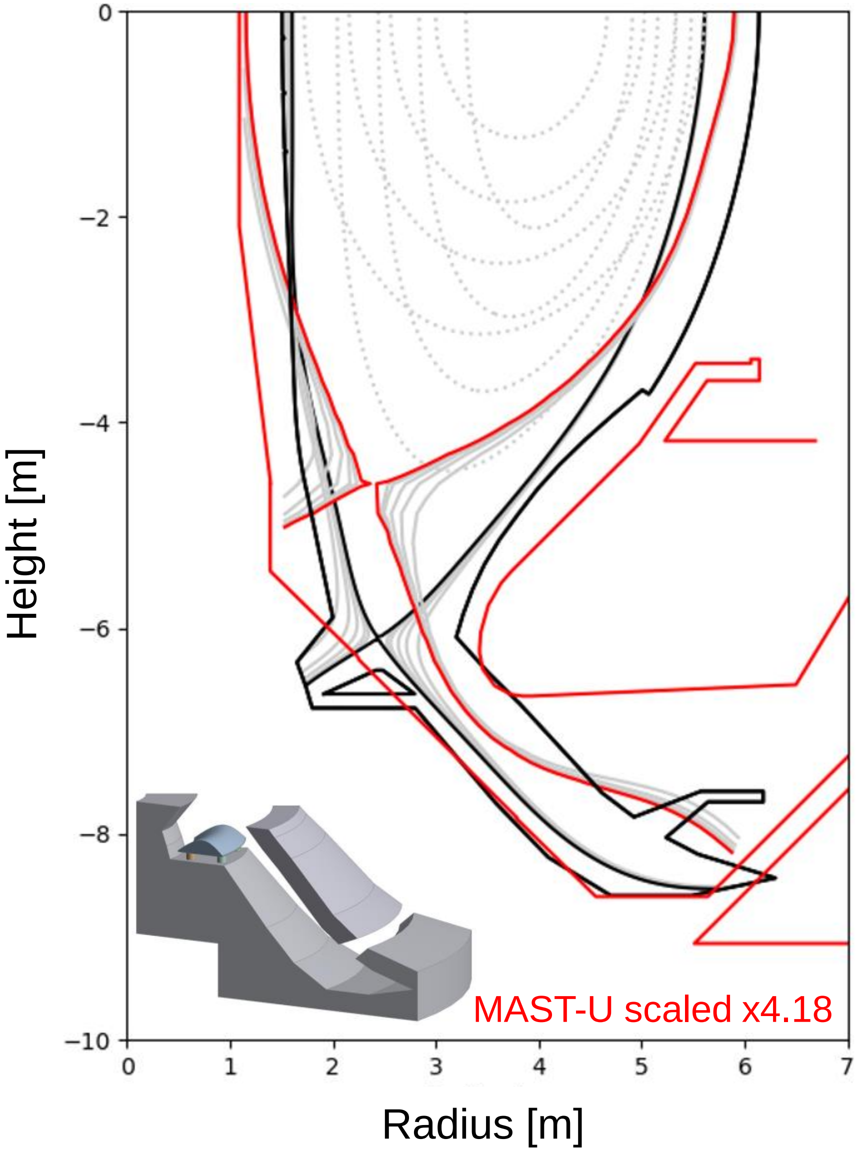
Comparison with scaled MAST-U first wall design



Next steps and gap analysis

Optimising gas flow rates, pumping speeds and He removal

Deciding on exhaust control scheme wrt. to transients

Aid extrapolation with intermediary devices

- Loss power, re-attachment conditions, power fall-off width

No machine has divertor design common to STEP

- Efficiency of pumping, and neutral trapping
- Core performance with compatible exhaust solution

Physics assumptions not well tested/studied in current machines

- Power balance in spherical tokamaks with advanced divertors
- Scaling of detachment threshold with magnetic field and major radius

Modelling deficiencies

- Impact of molecules not well characterised, giving uncertainties in fully detached simulations
- Simplified descriptions of anomalous multi-ion cross-field transport