UK Atomic Energy Authority

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20th International Spherical Torus Workshop

MAST-U experimental programme: From first plasma to first campaign

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EUROfusion

Research Councils UK Energy For a Low Carbon Future

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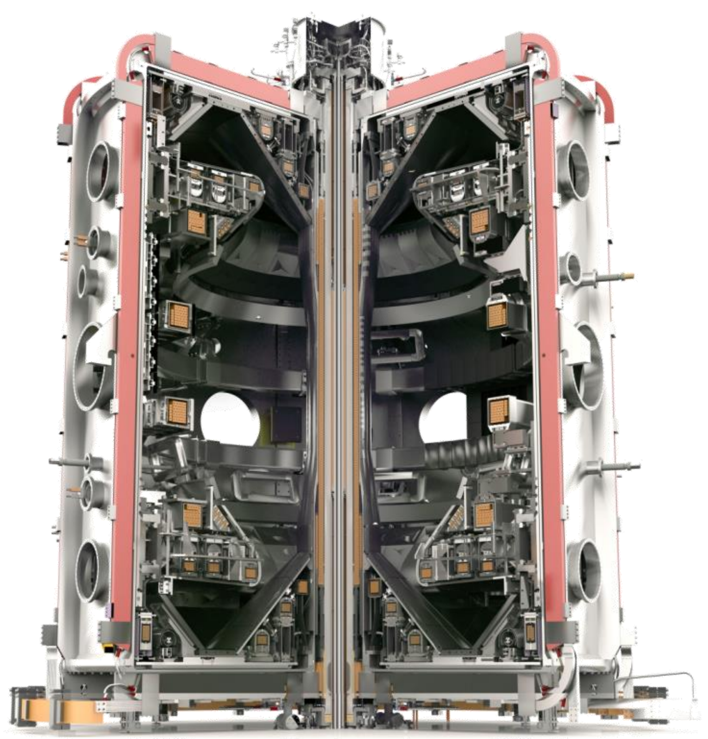
Introduction

MAST Upgrade contributes to 3 primary objectives:

1) Developing novel exhaust concepts
2) Knowledge base for ITER (e.g. understanding and controlling ELMs with 3D fields)
3) Feasibility of spherical tokamak as a future fusion device



One focus of MAST-U is on exhaust physics

- Alternative divertor configurations, specifically the super-X

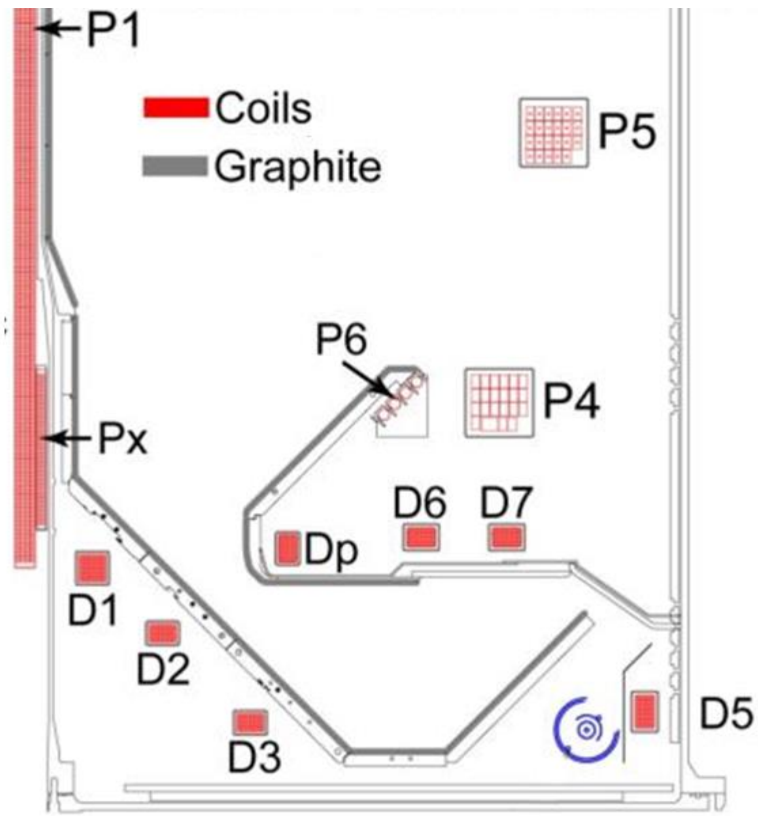
How to we go about generating a plasma for the first time in MAST-U?

How do we produce and control a super-X plasma?

MAST-U capabilities

MAST-U represents a significant change when compared to MAST

- Off axis neutral beam heating
- New coil set
  - Additional coils for control, increased flux swing and toroidal field magnitude
- Gas fuelling



P1	Solenoid for plasma current
P4, P5	Core radial position + shape
P6	Core vertical position
PX, D1, D2, D3	X-point position + divertor leg
DP	X-point position + flux expansion
D5	Super-X leg radius
D6, D7	Super-X flux expansion

MAST-U capabilities

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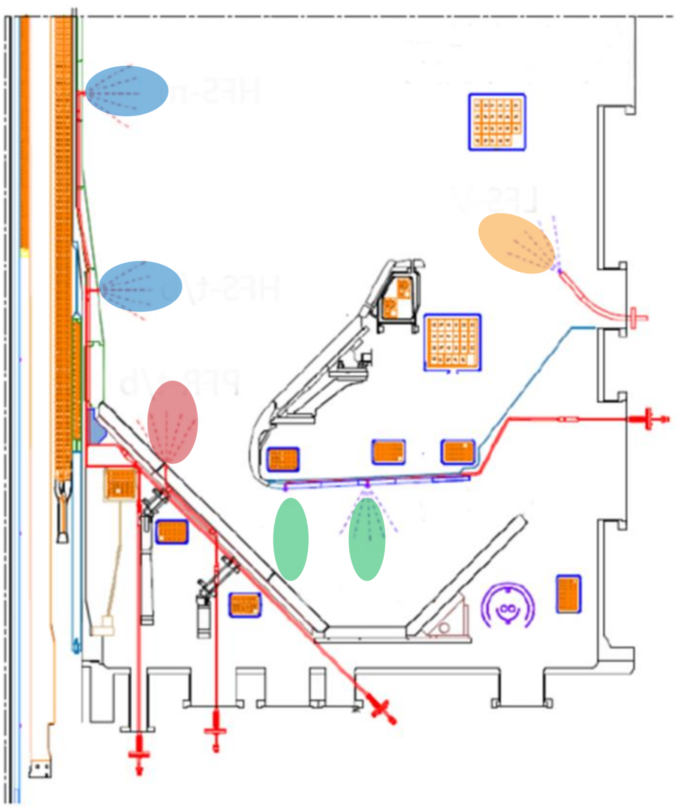


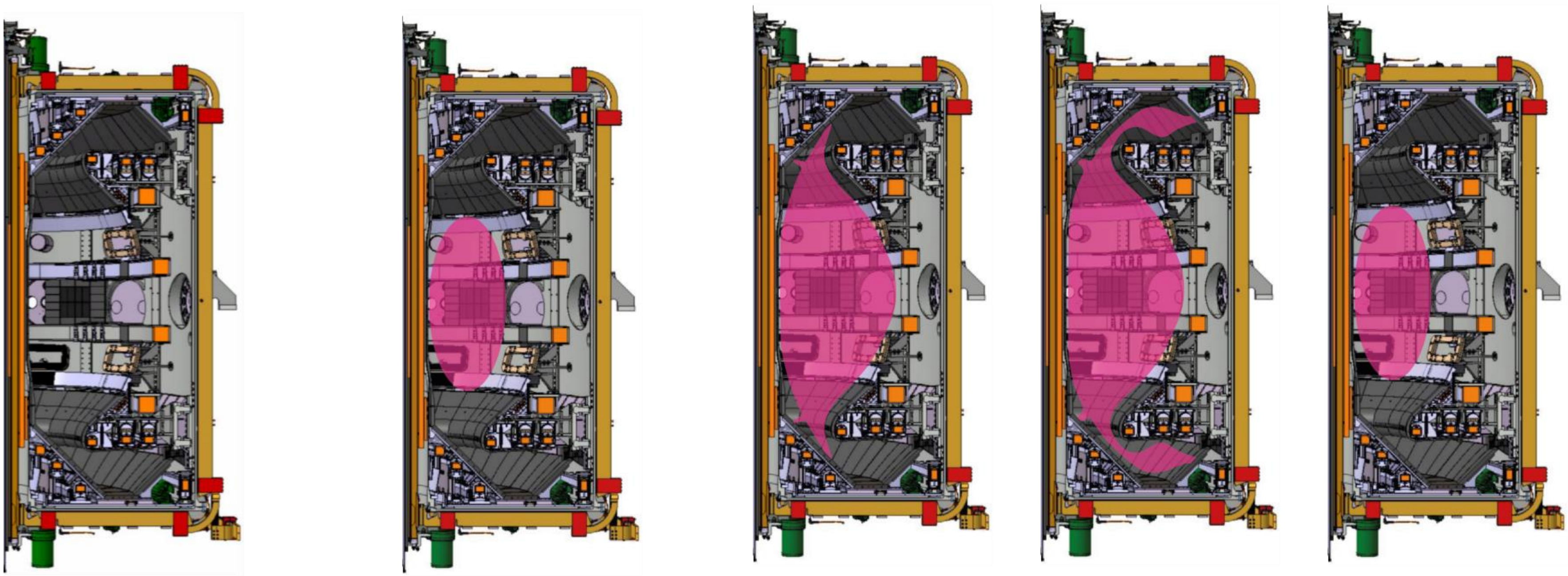
High field side – 12 total valves

Low field side – 4 valves

Private flux region – 6 valves per divertor

Divertor chamber – 24 valves per divertor

MAST-U first plasma



Breakdown | Ramp up | Limiter | Flattop | Ramp down

Conventional | Super-X

Breakdown

Unique features of MAST-U;

- Large number of poloidal field coils
- Highly flexible for null formation

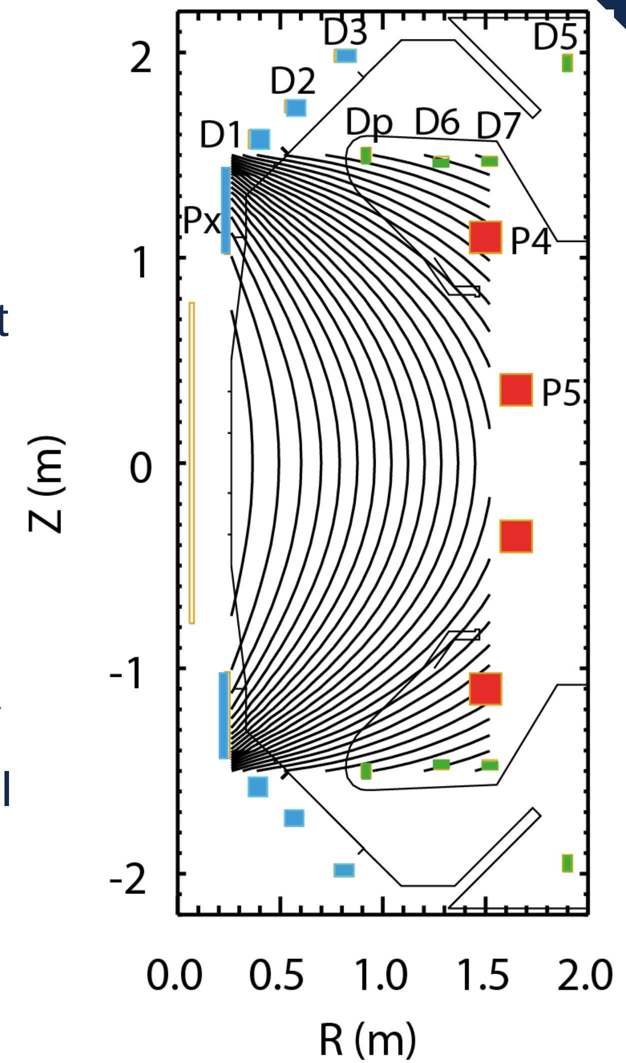
Modelling required to take advantage of the coil set

- Performed in collaboration with PPPL (D. Battaglia et al [1])

Optimise null, loop volts, vertical and radial stability

- Outer most coils (P4/P5) are used for radial control
- Small radius coils (blue); act to extend the solenoid increasing vertical null extent; reduce vertical stability
- Larger radius coils (green); act to produce a large null region, cancelling the solenoid field

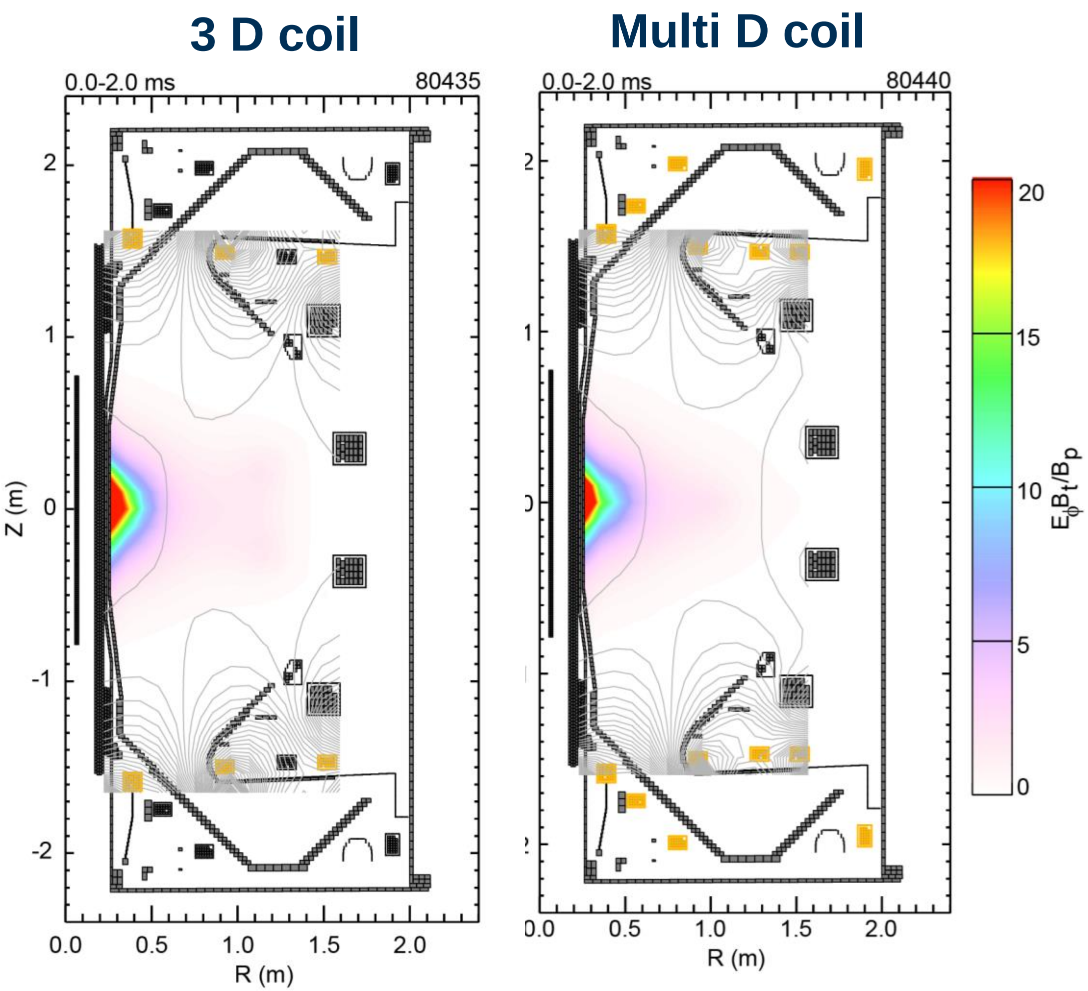
In-vessel filament provides pre-ionisation source



Breakdown

Investigate the use of all the D coils against a limited set, plus solenoid

- Evaluate based on $E_{\phi}B_t/B_p$ > 1 kV/m for breakdown & field evolution at 4 ms (grey)



- Coils coloured yellow are powered
- Similar field structures (slight improvement in multiple coil case)
- Three coil: close to current limits
- Multiple coil: gives more operating space for current
- Sufficient null and electric field in both cases

D Battaglia et al APS 2017

Plasma current ramp up

Once a plasma has been formed, and is fully ionised, the plasma current can be increased

The ramp up determines the current profile in the plasma

- Excessive rates produce MHD activity; slow ramps produce high inductance plasmas

Wish to maintain a broad current profile (low li) as this gives natural elongation

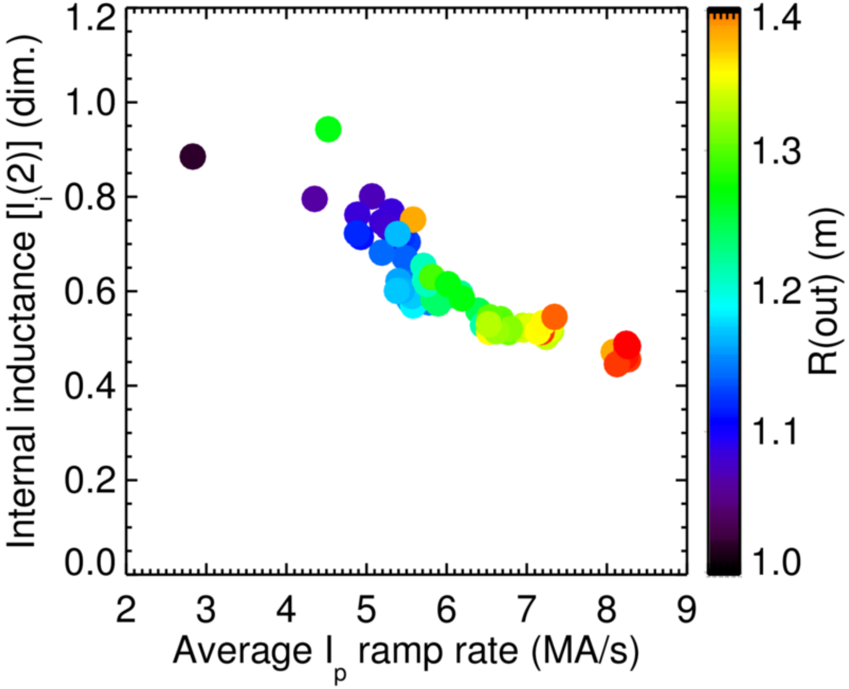
- Minimises poloidal field coil currents

MAST experience;

- Optimise Ip ramp rate
- Increase outer plasma radius

MAST-U;

- Adjust initial gas fuelling
- Early divertor formation
- Early beam heating



Plasma simulation

Initial control of MAST-U plasmas will be via feed forward

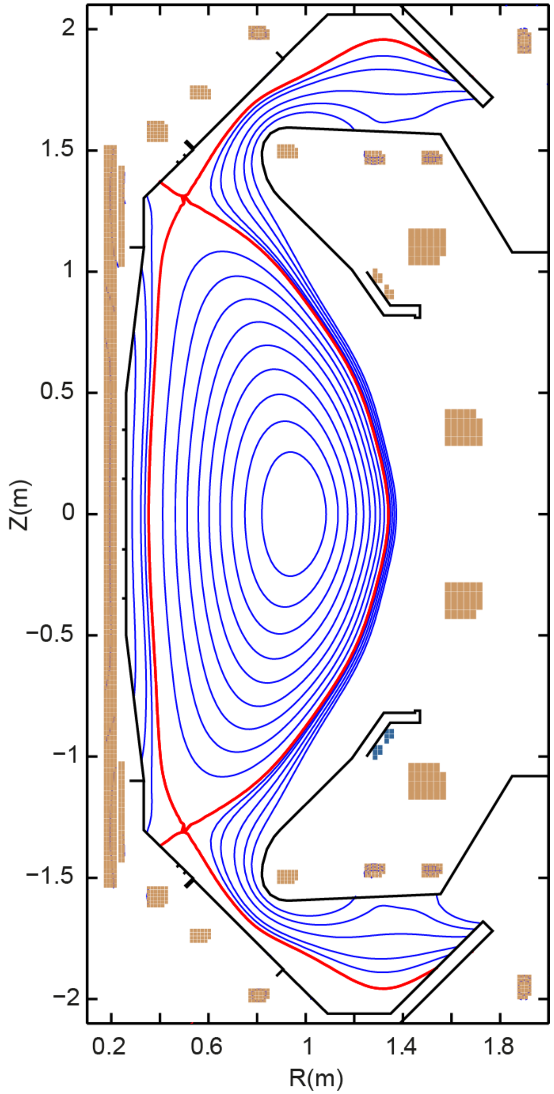
- Coil currents are pre-programmed to give a certain shape of evolution

Use a free boundary equilibrium solver to generate a confined plasma, with the MAST-U coil set (FIESTA)

- Understand what currents are required and which coils can be used for control

Take key parameters from a MAST pulse;

- Plasma current and solenoid swing
- Current profiles
- Generate individual equilibria that show the discharge evolution
    - Aim for a scan in the outer target radius



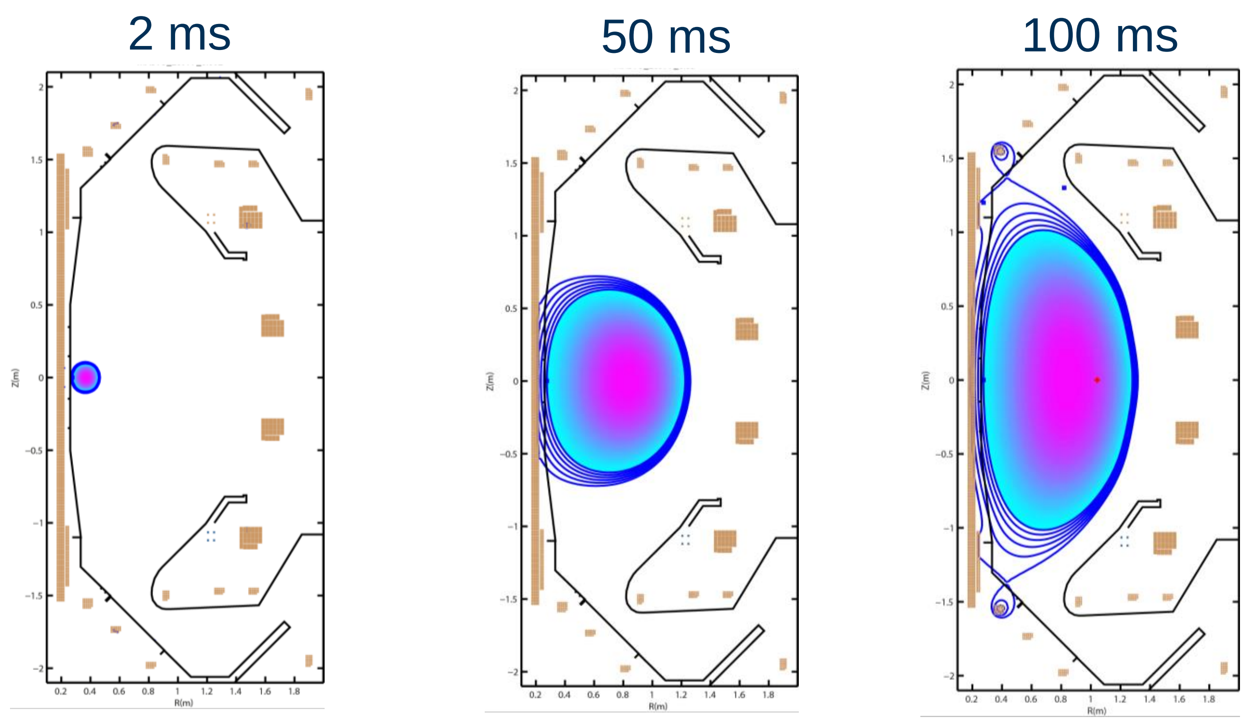
Plasma simulation

Plasma current ramp up phase

- Provide radial control with the P4 and P5 coils
- Waveforms follow on from those used in breakdown

Follow MAST technique of increasing the radius during the current ramp

- Initially, confining a 10 kA plasma, rising up to 600 kA at 100 ms



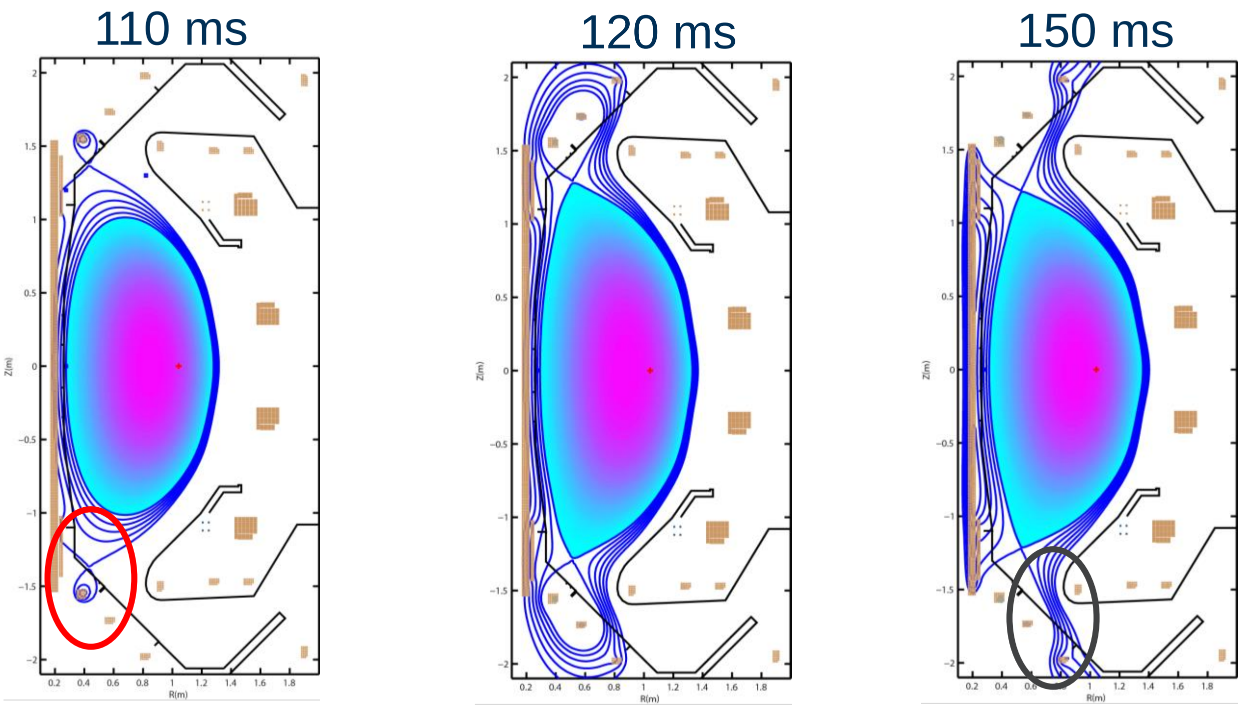
Plasma simulation

Plasma limited on the centre column in this example during ramp up

Conventional divertor formation

At a suitable elongation, aim to divert the plasma

- D1, D2 and Px coils can be driven up to form a conventional divertor shape
- Control of divertor leg position and nose flux expansion: D2, D3, Dp



Plasma simulation

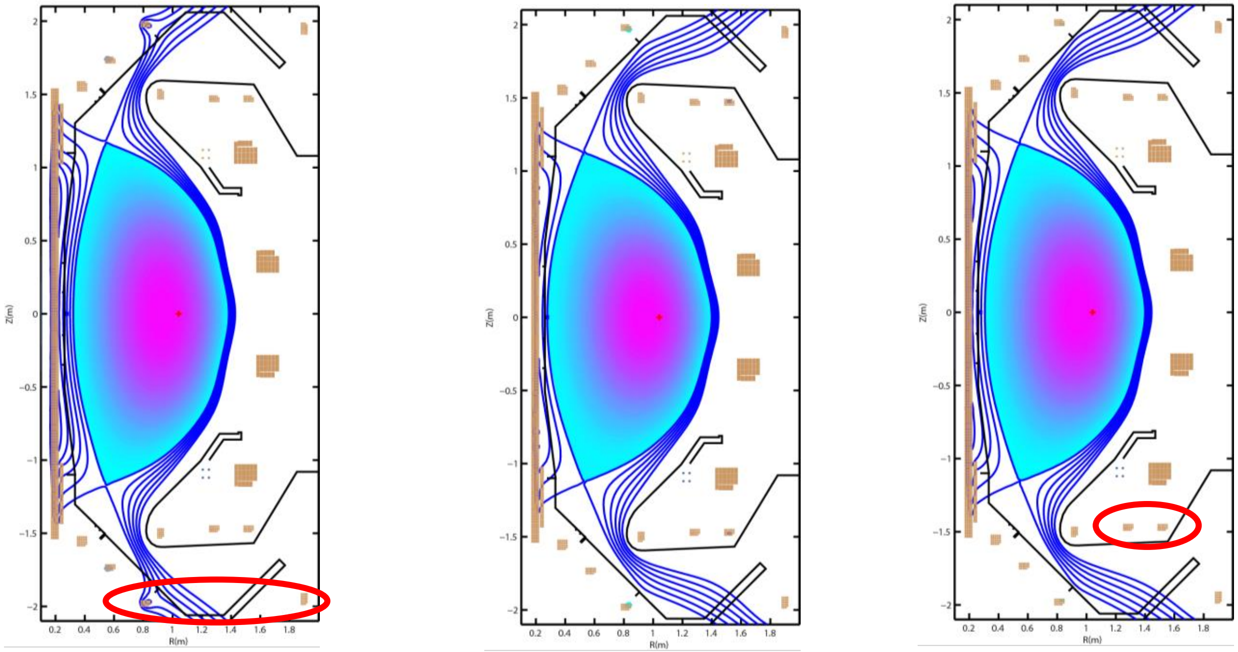
Super-X divertor formation

- Increase conventional strike point radius with D3
- Drive D5 up to move the strike point out across the horizontal tile to T5

Subsequently, the shape can be refined;

- D5: strike point position
- D6/D7: Super-X chamber flux expansion

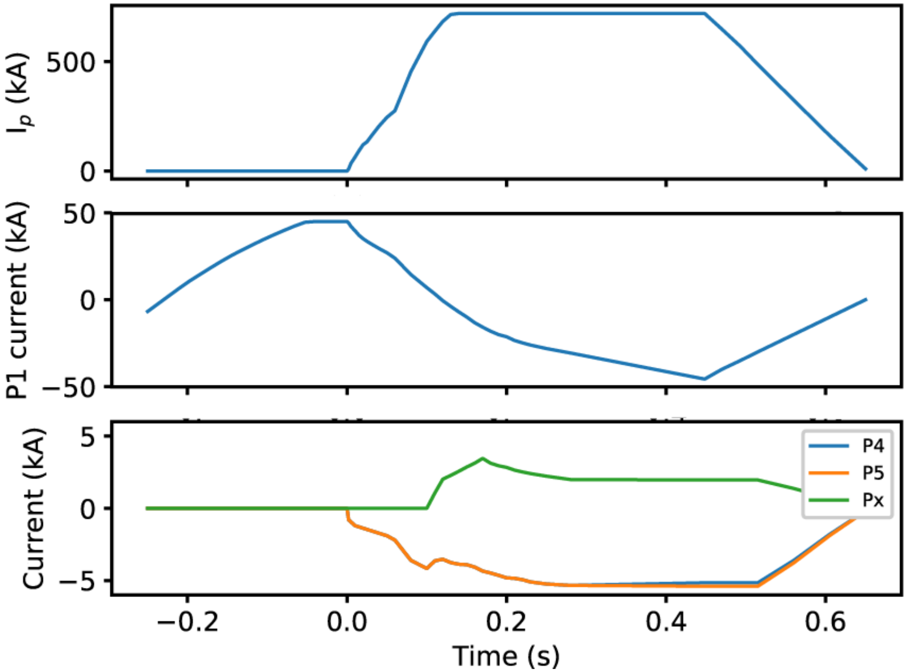
180 ms | 220 ms | 280 ms

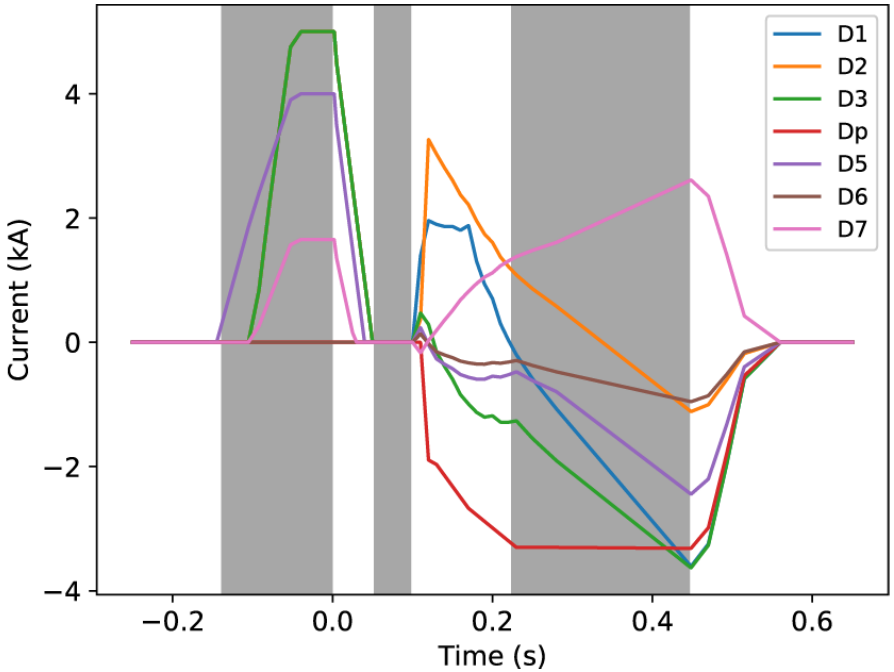


Plasma simulation

Modelled discharge has several phases, each with different coils used

- Premagnetisation, breakdown, limiter, divertor, super-X, ramp down





Plasma shape control

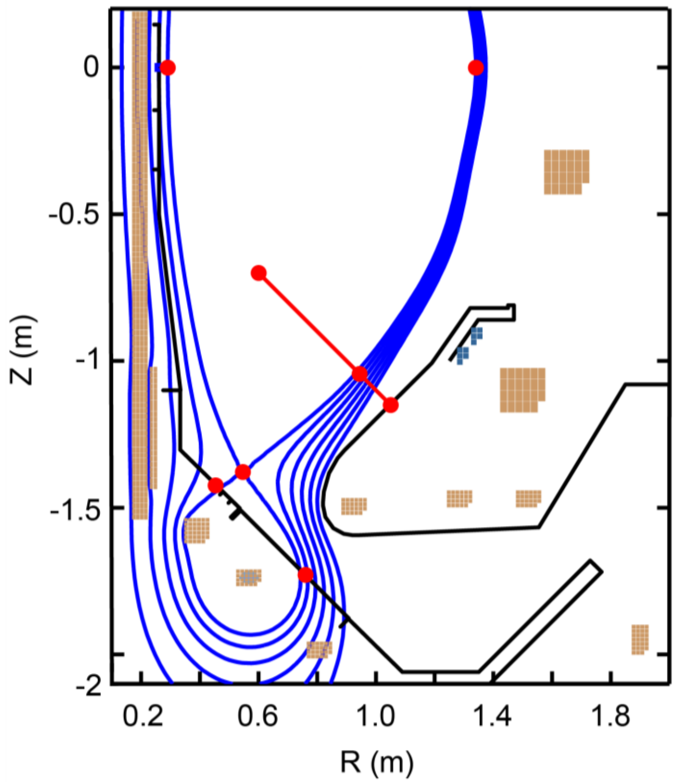
Aim to have automated, fed back plasma control

- First step: Identify what coils manipulate a given shape parameter
- Second step: Real time reconstruction to provide variable to feedback on

Control points

- Inner radius (R(in))
- Outer radius (R(out))
- Outer strike point (RoutL)
- Inner strike point (RinL)
- X point (RlowX, ZlowX)
- Nose gap (Ng)

Determine which coils allow the control of each of these points



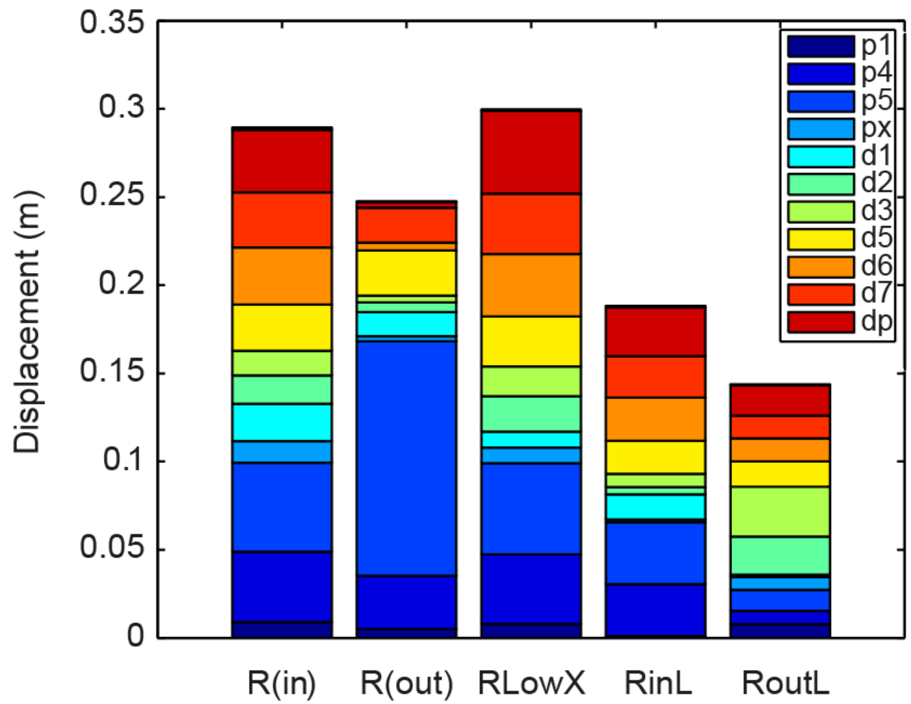
Plasma shape control

To understand the use of the coils in MAST-U

- Take an equilibrium, add a fixed amount of current in each coil individually
- Determine the effect on each of the control points
    - How much does it move for a given amount of current in a given coil?

Result

A given coil affects all control points



Calculate the rate a control point changes for a given coil

- Get rate, M, for all coils, I, for each control point, P

$$MI = P$$

- Inverse of M; gives current in each coil for a specific change in only one parameter

This defines a virtual circuit

Plasma shape control

Use the virtual circuit to control the outer leg location

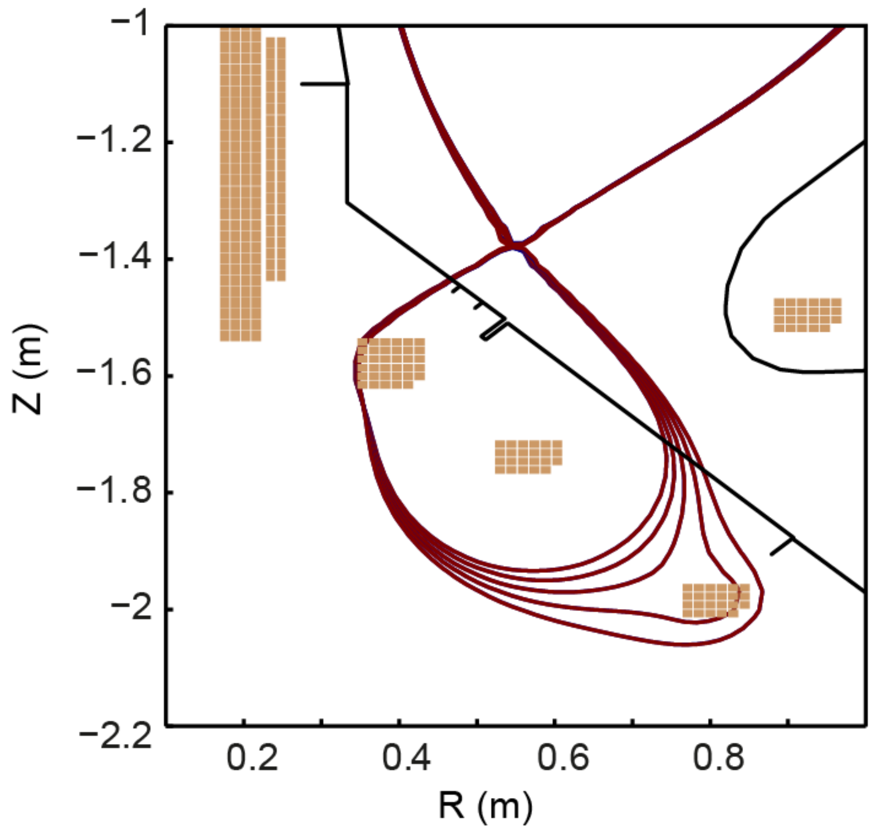
- Request 1 cm steps in the location of the leg

Method produces a scan in the strike point location

- Other control points remain fixed
- Simplified control of the shape compared to individually programming coil current

Composition of the coils in the virtual circuit varies;

- Depends on the equilibrium
- Need to switch between circuits as the shot proceeds



Required plasma parameters

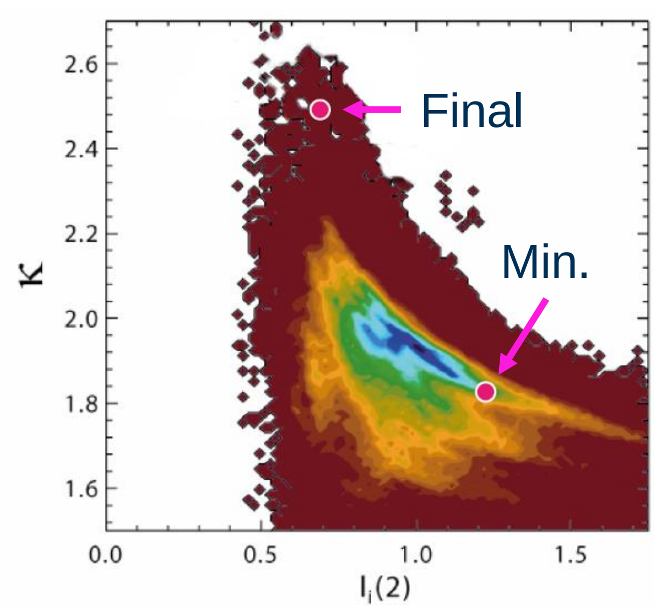
Plasma inductance (l_i) affects elongation (κ) and control of plasma

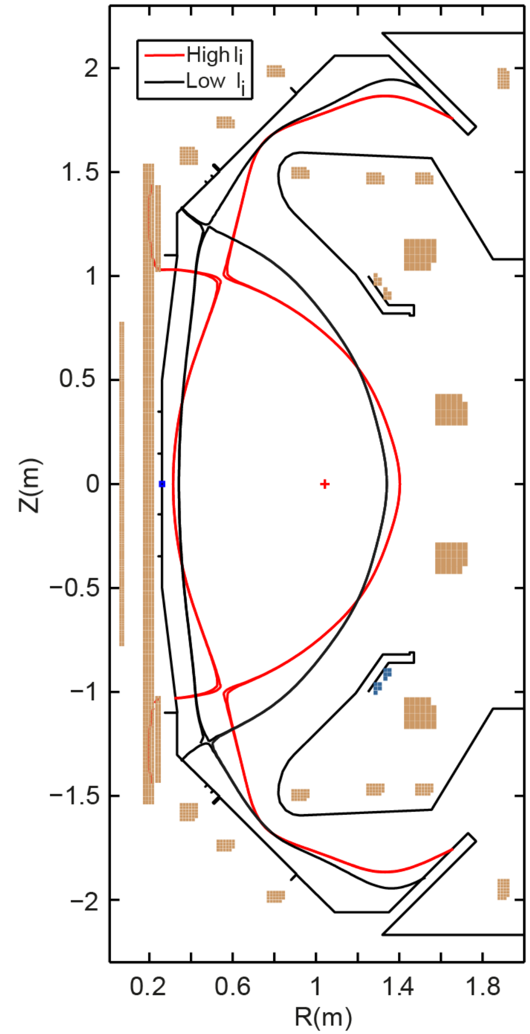
- At what $l_i(2)$ can a Super-X divertor be formed with the available coil current?
- Generate a test case at 700 kA at zero solenoid current

Final operating scenario; $l_i(2)$ = 0.7; κ = 2.5; 1 MA

- Minimum; $l_i(2)$ = 1.2; κ = 1.8; 700 kA

Compare where these sit in MAST operating space





Vertical stability: f_s=2.2; m_i=1.2

Divertor Configurations in MAST-U

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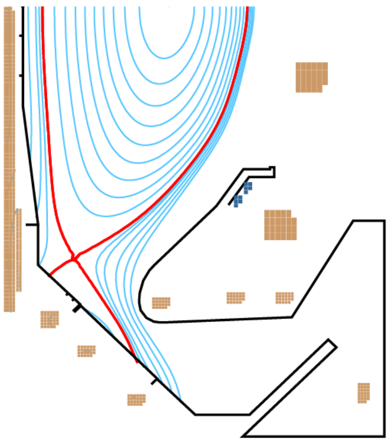
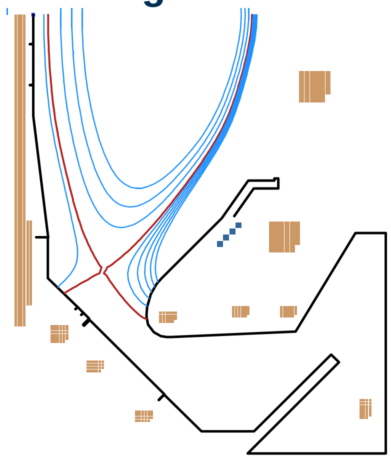
MAST Upgrade has considerable flexibility for studying conventional and alternative divertor configurations

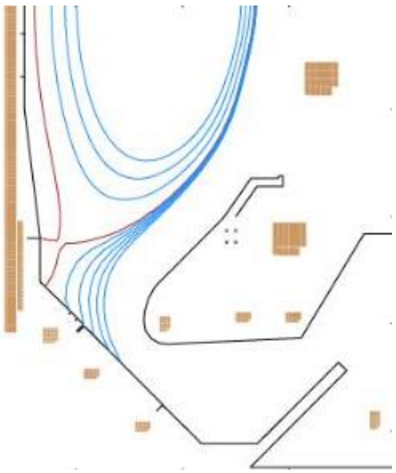
Conventional



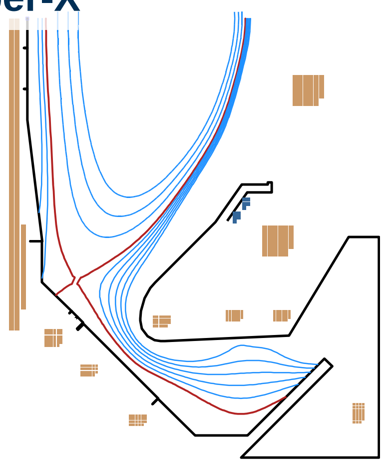
Vertical Target



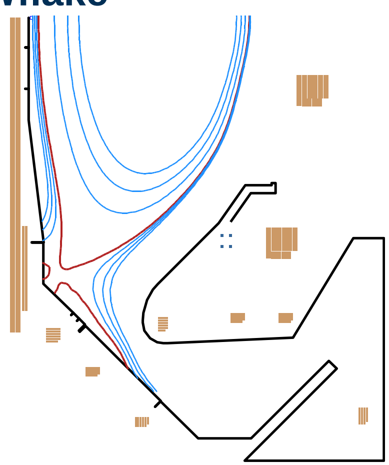
X divertor



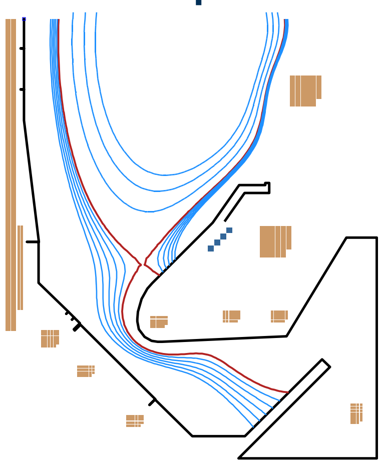
Super-X



Snowflake



Inner Strike Super-X



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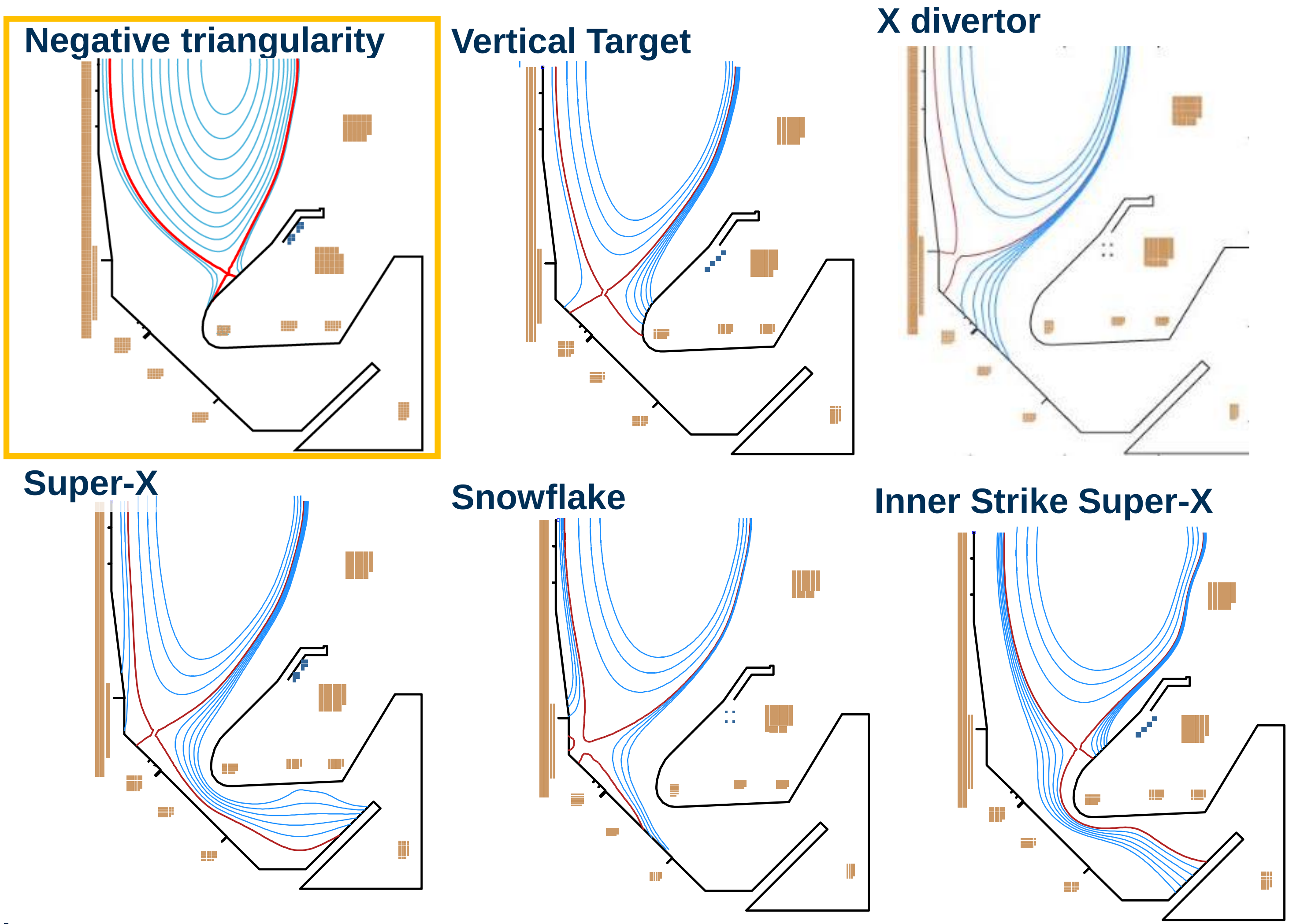
Divertor Configurations in MAST-U

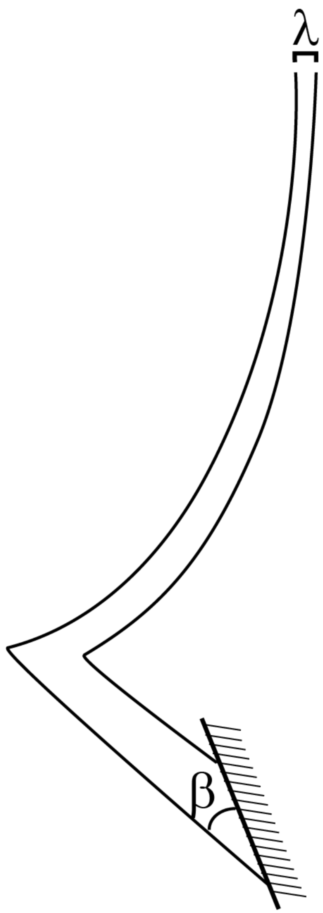
MAST Upgrade has considerable flexibility for studying conventional and alternative divertor configurations



Divertor power loading

Alternative divertors offer a potential solution to the challenge of power exhaust in future devices

Target power load can be determined using the formula below;



$$q_{\perp} = \frac{P_{in}(1 - f_r)}{2\pi\lambda_q R_t f_x N_d}\sin(\beta)$$

To modify the heat flux arriving at the tile;

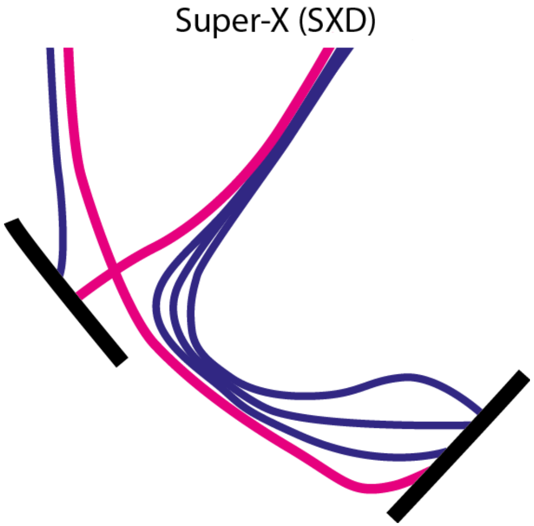
- Increase the flux expansion (f_x): limited by tile shadowing
- Increase the number of divertors (N_d)
- Broaden the scrape off layer (λ_q)
- Increase the target radius
- Raise the fraction of power radiated (f_r)

Super-X divertor physics

Investigate the Super-X divertor (SXD) [1]

SXD aims to reduce the power load arriving at the target

- Increase total flux expansion at large R_t (drops parallel heat flux, increases area)
- Increase the target radius, R_t (increase wetted area)
- Large connection length (greater divertor volume, promotes detachment)
- Divertor closure enhances neutral baffling



$$T_e^t \propto \frac{(q_{\|}^u)^{10/7} \cdot (1 - f_{\mathrm{rad}})^2}{n_u^2 L_{\|}^{4/7}} \frac{R_u^2}{R_t^2}$$

These three effects can reduce the target temperature, promoting detachment

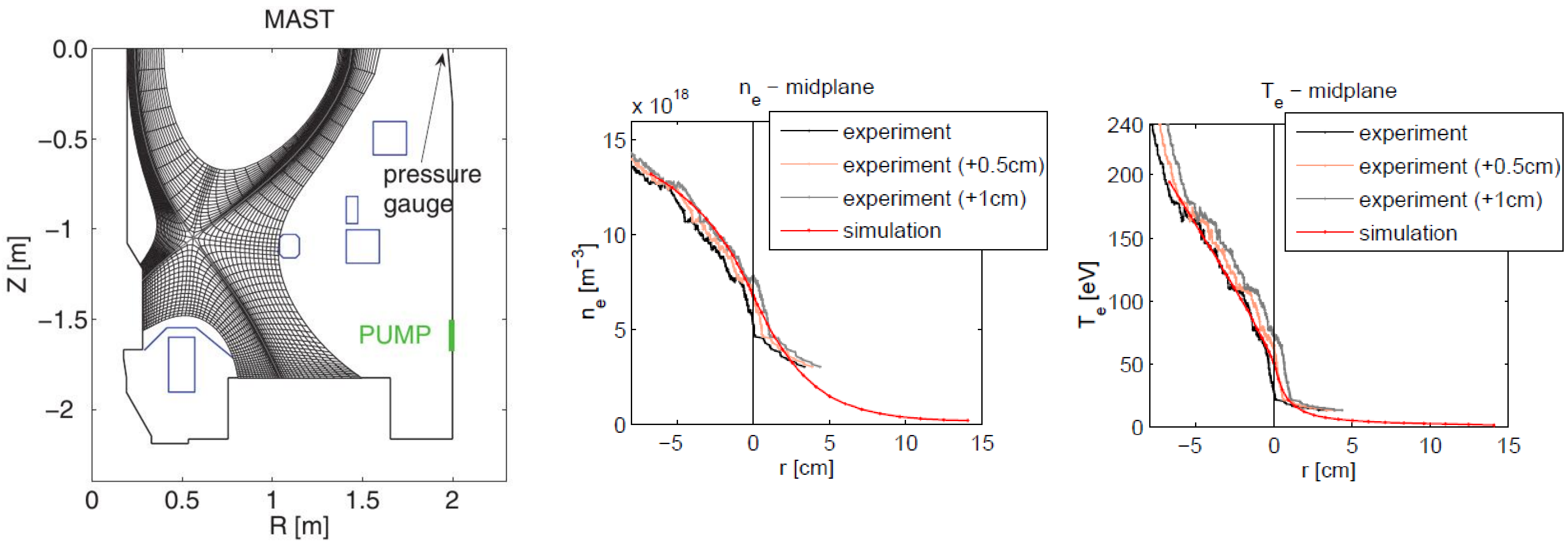
- Detachment: power and particle flux to the target decreases due to losses in the divertor volume

[1] Valanju et al Phys Plasmas 16 (2009) 056110

MAST-U Super-X divertor

SOLPS can be used to model the Super-X divertor

- First benchmark results from MAST before extending to MAST-U



Extract radial transport coefficients that well describe midplane and target data

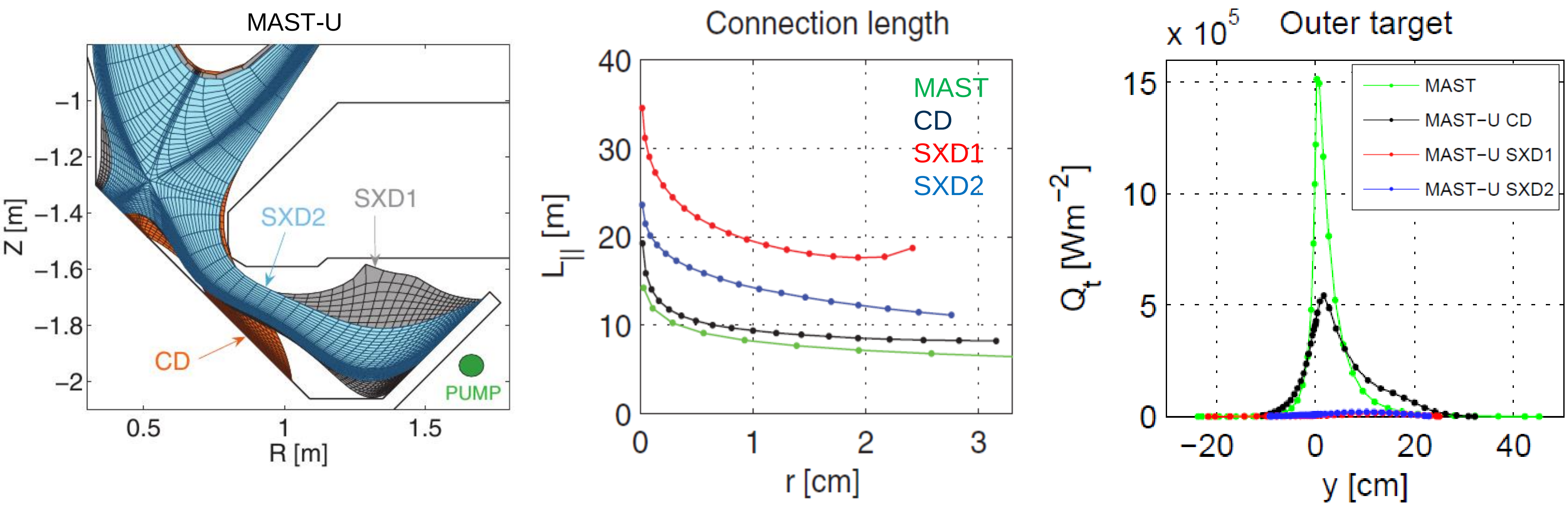
- Then use these to extrapolate to MAST-U

E. Havlíčková et al, PPCF **57** (2015) 115001

MAST-U Super-X divertor

Investigate different magnetic configurations in MAST-U

- Conventional divertor (CD), SXD1 with high flux expansion, SXD2 with low flux expansion



Super-X geometry pushes the target plasma into detachment, reducing the heat flux density and temperature at the target to ~zero.

Attached regime in SXD in L-mode can be achieved if **the heating power** or the **pumping speed** is increased at the same density.

E. Havlíčková et al, PPCF **57** (2015) 115001

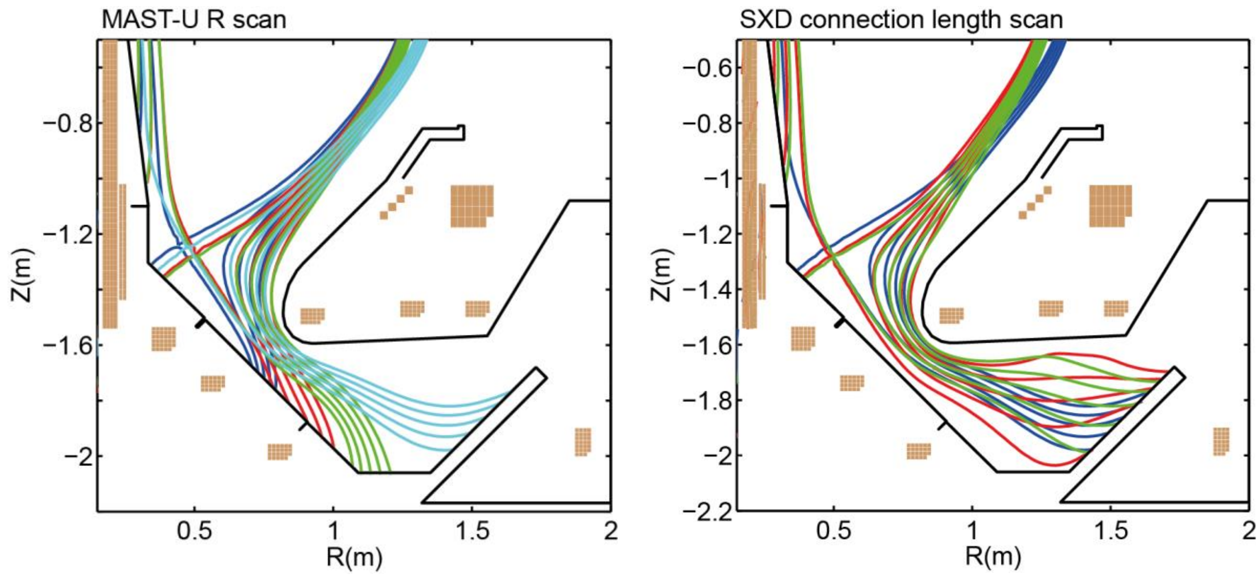
MAST-U assessment of the Super-X divertor

Initial experiments will focus on forming the Super-X divertor

- Make early comparisons between conventional and SXD divertor behaviour
  - Scan target radius and evaluate the heat flux to the tiles
  - Determine the access to detachment and how it varies
  - Investigate the control of the detachment front by varying the poloidal flux expansion

Produce 400 kA plasma first and then extend to higher current

- Higher current decreases λ_q which will affect parallel heat flux

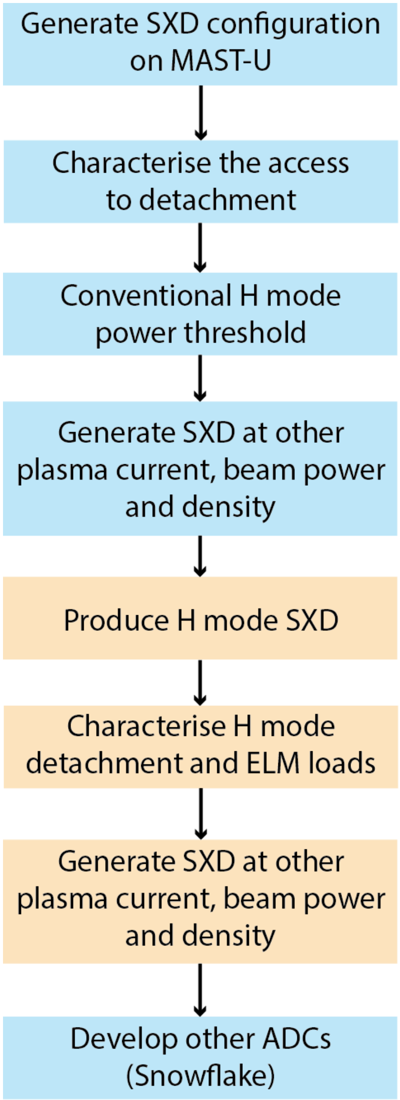


MAST-U assessment of the Super-X divertor

How does the alternative divertor configurations (ADCs) affect the target power load/onset of detachment?

- Operational window (attached/detached, L/H mode, ELM/ELM free)
- Effect of ADCs on the target heat load, scaling with geometry
- Flux expansion in the SXD – comparison with past modelling
- Baffling and effect on core confinement
- SOL width and transport characterisation and multi-machine scaling
- ELM heat loads

Does modelling support the experimental results?



High-Level Goals of Tokamak Science

UK Atomic Energy Authority

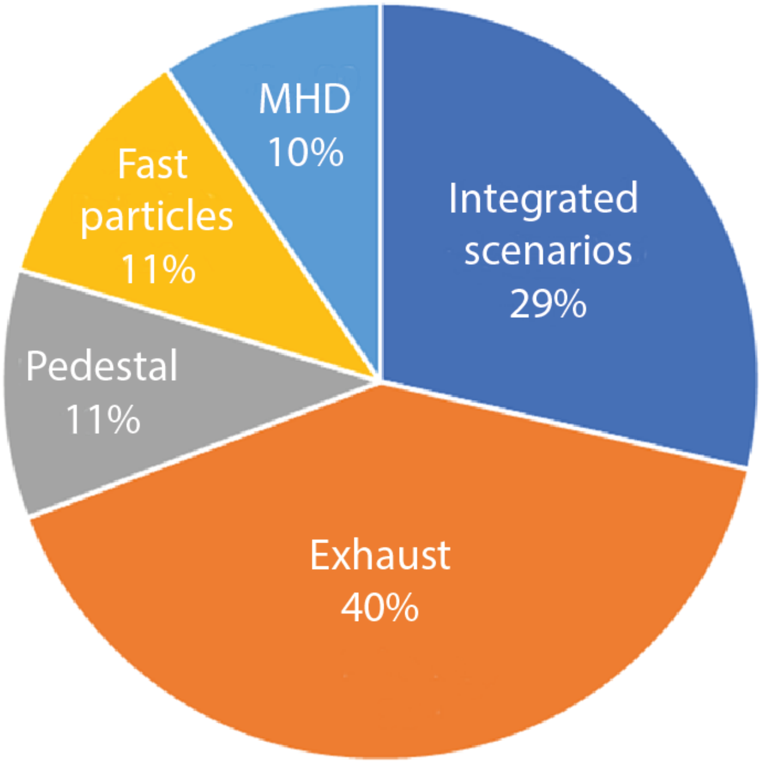
MAST-U restart phase

- Commissioning: 300 shots
- Restart: 600 shots

MAST-U first campaign

- Internal and EUROfusion components
- Total shots: 1600

Shots Allocated by Topic Area



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High-Level Goals for first campaign

UK Atomic Energy Authority

Exhaust Physics

- Understand the effect of divertor magnetic configuration on SOL transport, power and particle losses and loads to divertor PFCs
- Validate the MAST Upgrade design concept, e.g. neutral baffling, power deposition to divertor PFCs
- Study effect of divertor configuration on detachment physics
- Understand divertor detachment and the roles of atomic and molecular physics, magnetic geometry and topology
- Understand the role of filaments on particle and heat deposition to the first wall and divertor.

High-Level Goals for first campaign

UK Atomic Energy Authority

Integrated Scenarios

- Develop scenarios on MAST-U to enable the scientific programme
- Broaden the MAST-U operating space and maximise plasma performance
- Optimise q profile and neutral beam heating (on and off axis)
- Explore operating space (and limits) with attached and detached divertors, in L-mode and H-mode
- Study effect of divertor configuration on transport

Fast Particle Physics

- Compare effect of on and off-axis NBI on fast ion redistribution
- Study redistribution and loss of fast particles and compare to state-of-the-art modelling tools (HALO)
- Study non-linear wave-particle interactions, especially the excitation and damping of TAEs, CAEs in experiments

High-Level Goals for first campaign

UK Atomic Energy Authority

MHD & Pedestal Physics

- Characterise and correct for error fields
- Study the effects of divertor configuration on H-mode access and quality
- Understand role of magnetic field, main chamber neutrals on pedestal performance and ELMs
- Study performance limiting MHD at high β, incl. NTMs, LLMs, RWMs
- Develop a predictive pedestal model and validate against present experiments
- Understand how to mitigate and suppress ELMs using RMPs and explore stationary ELM-free or small ELM regimes

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Summary

Extensive preparations have been made for the start of MAST-U plasmas and first campaign

- Breakdown modelling and recipes prepared for first plasma
- Strategy for initial plasma formation using feedforward control developed
- Techniques for feed back control using virtual circuits generated

Key to the MAST-U programme is the investigation of the Super-X divertor

- Assessment of alternative divertor configurations for power handling, scrape off layer transport and particle fluxes to the target

The MAST-U programme also covers many other key areas of plasma physics

- Pedestal physics, scenario development, fast ion physics, ELM control and mitigation

We look forward to welcoming collaborators to the first experiments on MAST-U

- First plasma: December 2019; First campaign: Summer 2020