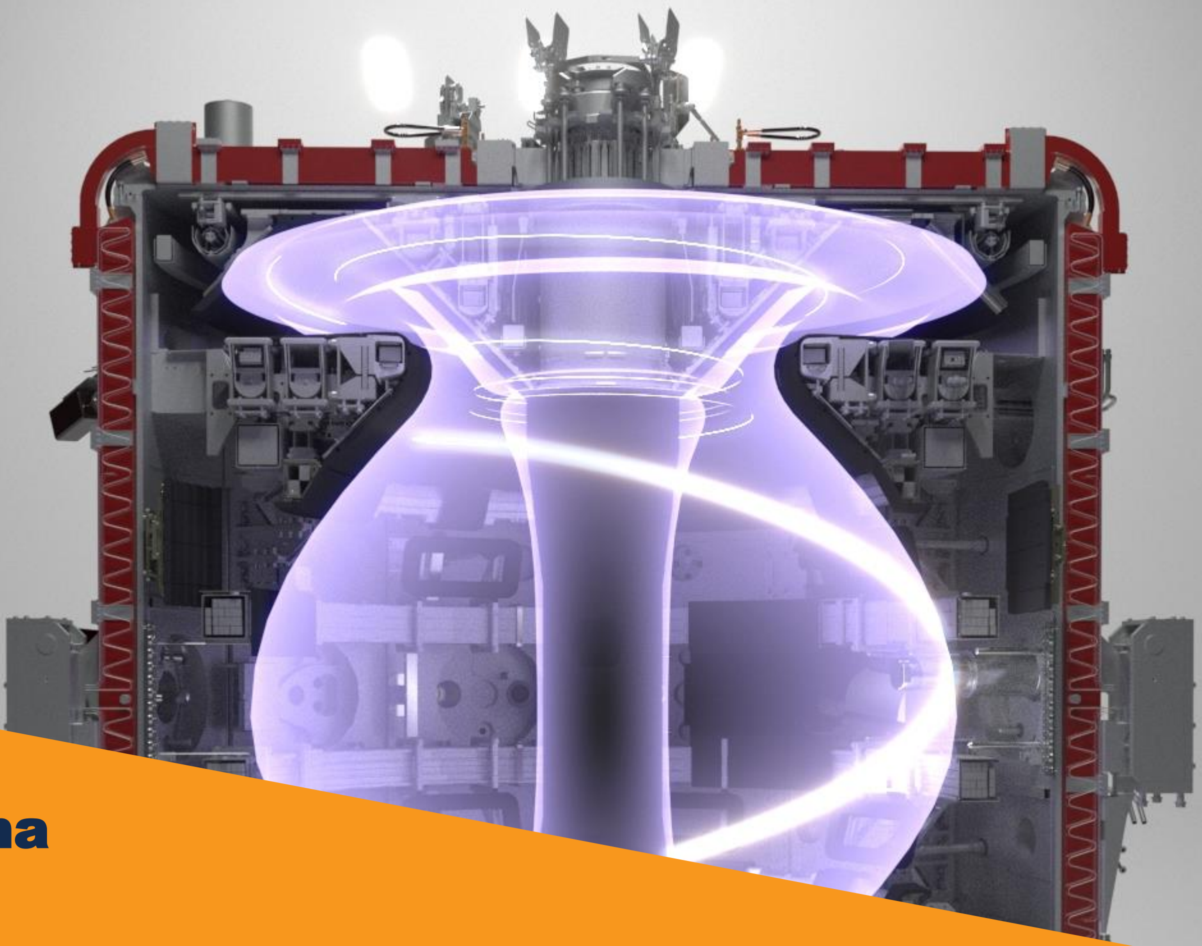

EPS 48th Annual Plasma Physics Conference

Developing understanding of spherical tokamaks with MAST Upgrade

Rory Scannell on behalf of the MAST-U team

This work has been (part-) funded by the EPSRC Energy Programme [grant number EP/W006839/1]

UK Atomic Energy Authority

CCFE
CULHAM CENTRE FOR FUSION ENERGY

Thank you to collaborating institutes

UK Atomic Energy Authority

EUROfusion

CONSORZIO RFX
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Dutch Institute for Fundamental Energy Research

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Durham University

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Lodestar Research Corporation

Kyoto University Founded 1897

東京大学
The University of Tokyo

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IFS

PPPL
Princeton Plasma Physics Laboratory

Imperial College London

Manchester 1824
The University of Manchester

University of Strathclyde Glasgow

Florida International University, Miami, 1965

The University of California, UCLA

The University of California, Irvine

Lawrence Livermore National Laboratory

CCFE
Culham Centre for Fusion Energy

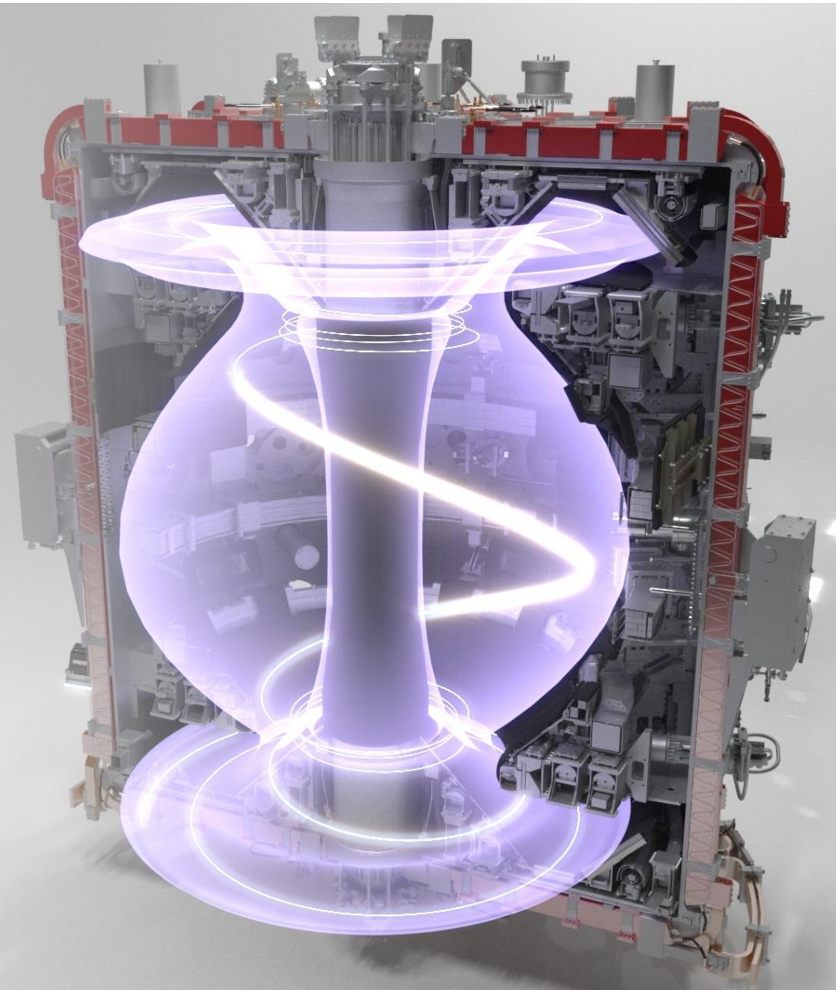
UK Atomic Energy Authority

Introduction to MAST Upgrade

Developing high performance plasmas

Exploring plasma exhaust

Plans for the second campaign



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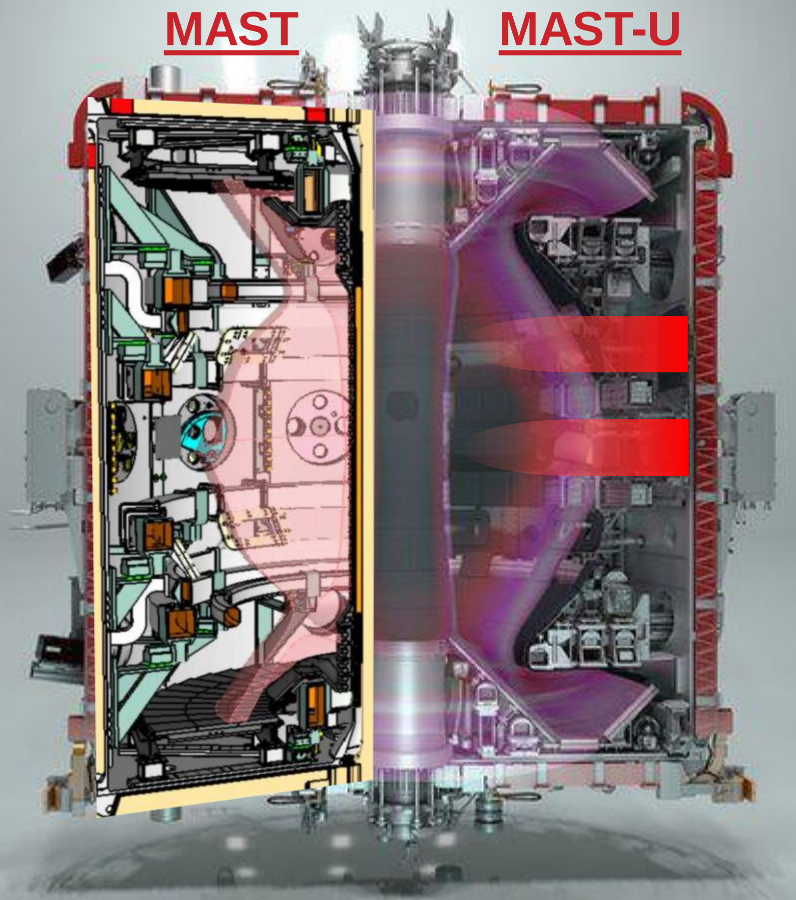
MAST Upgrade is a substantial advance on MAST



New solenoid to increase I_p and pulse duration (0.7s → 5.0s)

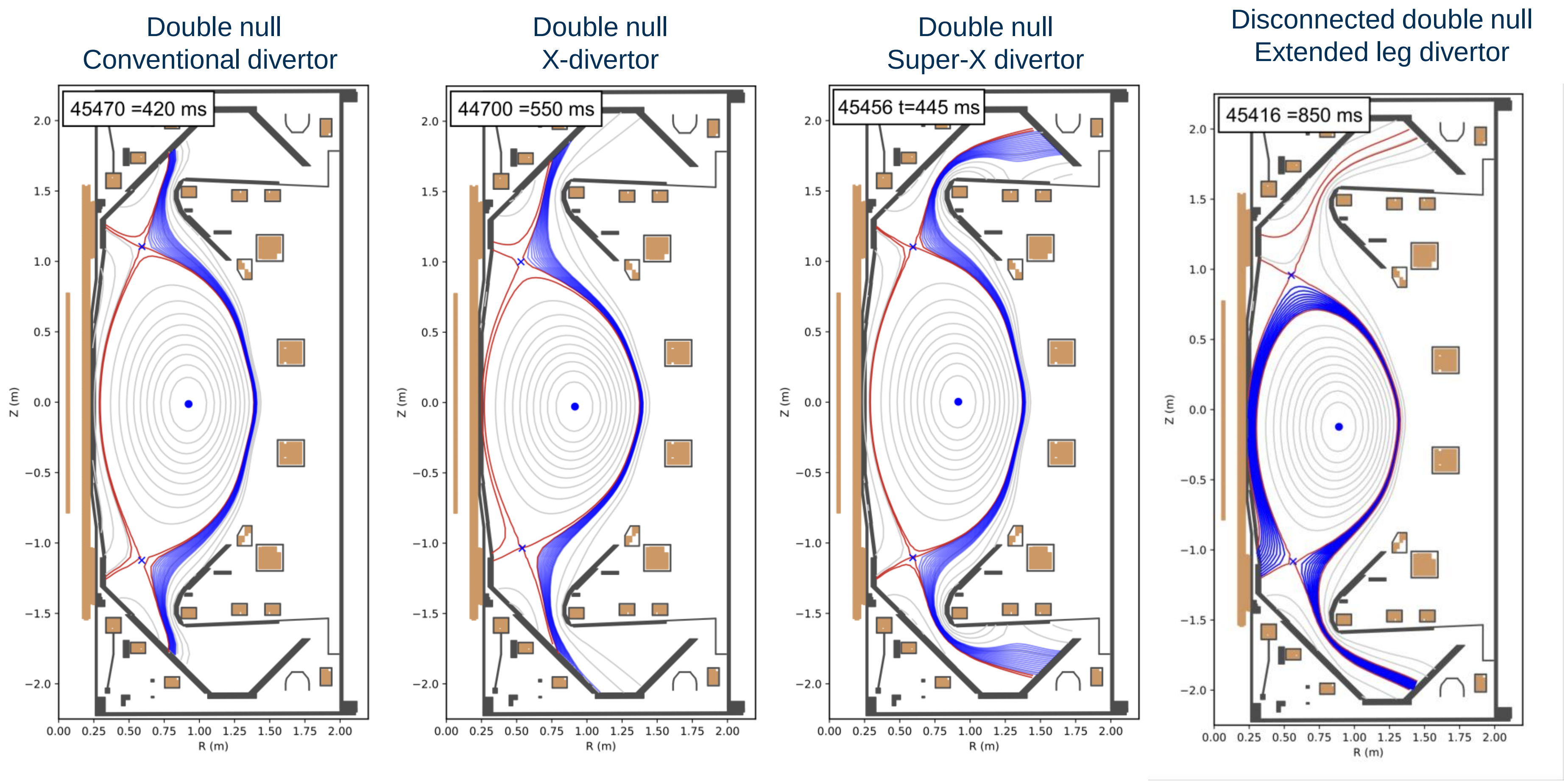
Increased toroidal field (0.5 → 0.8T at 0.8m) for improved confinement

19 new poloidal field coils for improved shaping capabilities

On and off-axis neutral beam heating 2.5 MW for improved q-profile control

Closed divertors with Super-X capability for improved power handling

Flexibility in magnetic geometry



*Allows for assessment of **power sharing** between divertors and impact of **divertor configuration** on heat flux to test their **viability for future reactors***

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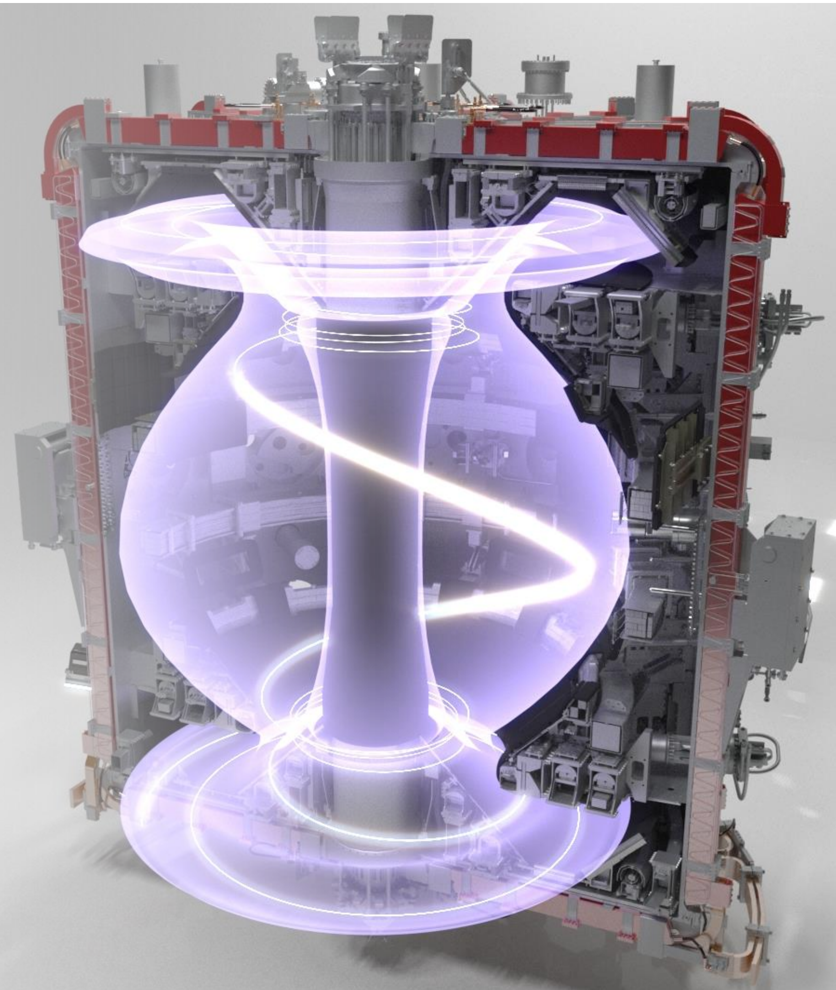


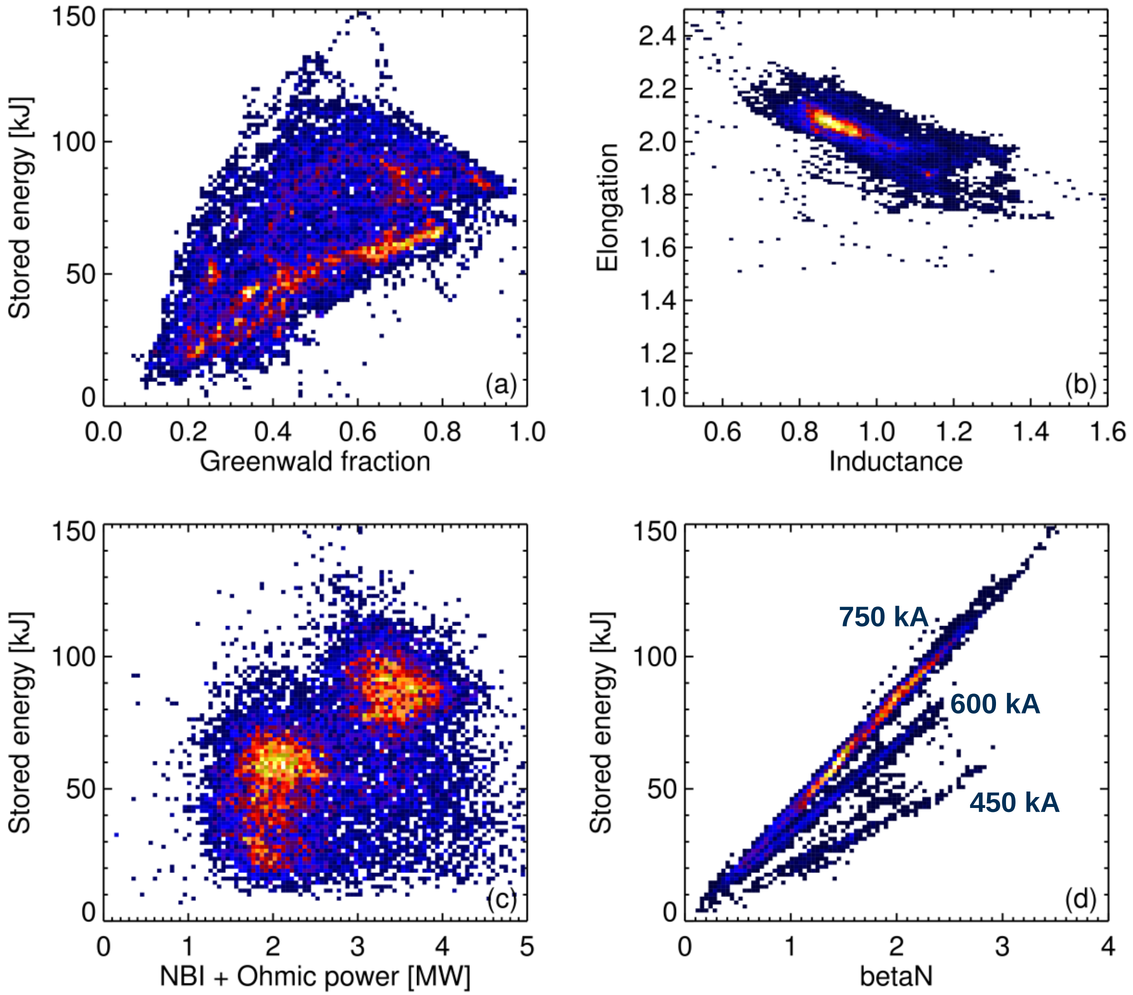
MAST-U plasma operating space

Established conventional and super-X divertor up to 750 kA in L- and H- mode. Good one-beam and two-beam NBI operation with power ~3 MW

Covered a wide parameter space

- ❑ Up to Greenwald limit ($I_P/\pi a^2$)
- ❑ Elongation up to ~2.2 and inductance ~0.7
- ❑ Confinement time ~40 – 50 ms
- ❑ Normalised beta ($\beta/I_P/aB_T$) < 3

Scenario development will continue in 2nd campaign, but the excellent progress so far was only possible after development of various control algorithms



Feedback control capabilities

Plasma current control

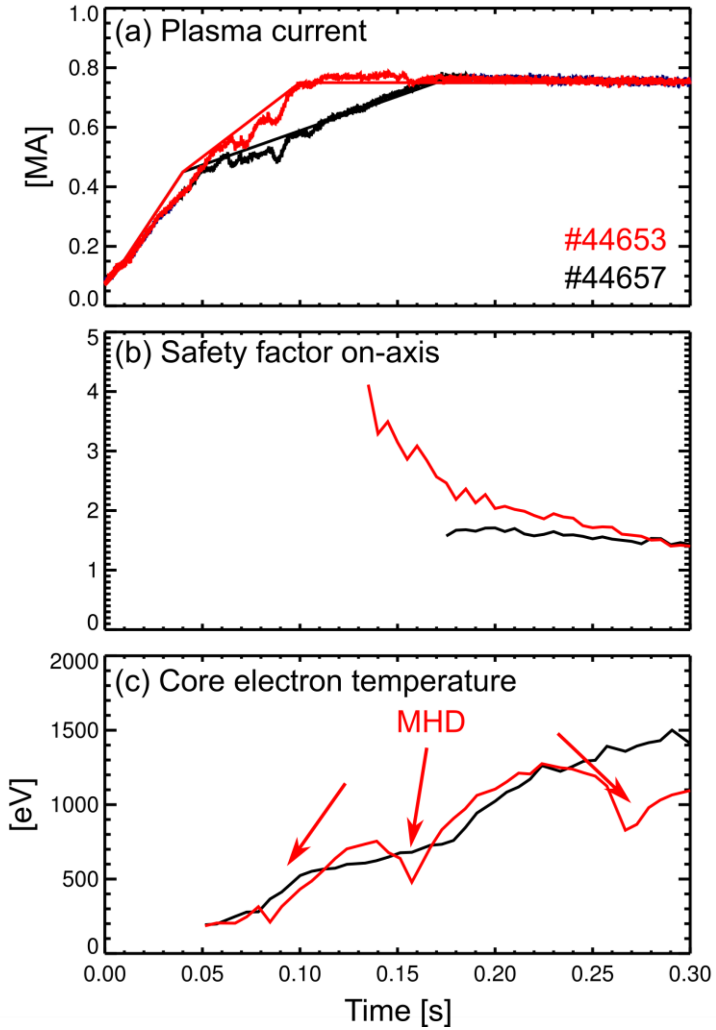
- Hand-over between V_{loop} and current control
- Current ramp rate optimisation

Vertical position control

- Stable double null scenarios achieved
- Facilitates access to H-mode and L-mode

Outer radius control

- Prevents radius expanding during beam injection/gas ramp
- More control schemes to follow in next campaign



Equilibrium reconstruction constrained by Motional Stark effect measurements – S. Gibson

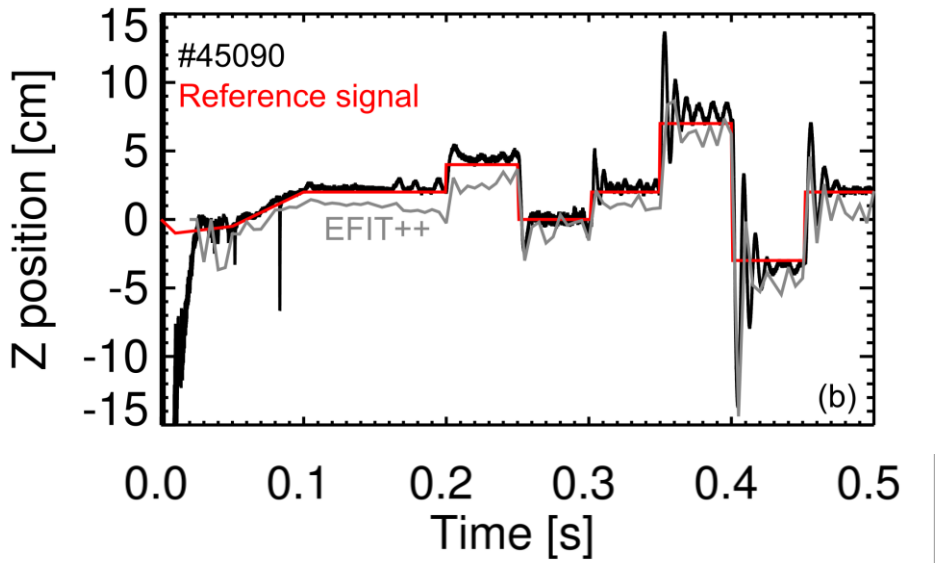
Feedback control capabilities

Plasma current control

- ❑ Hand-over between V_{loop} and current control
- ❑ Current ramp rate optimisation

Vertical position control ➡

- ❑ Stable double null scenarios achieved
- ❑ Facilitates access to H-mode and L-mode



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Feedback control capabilities

UK Atomic Energy Authority

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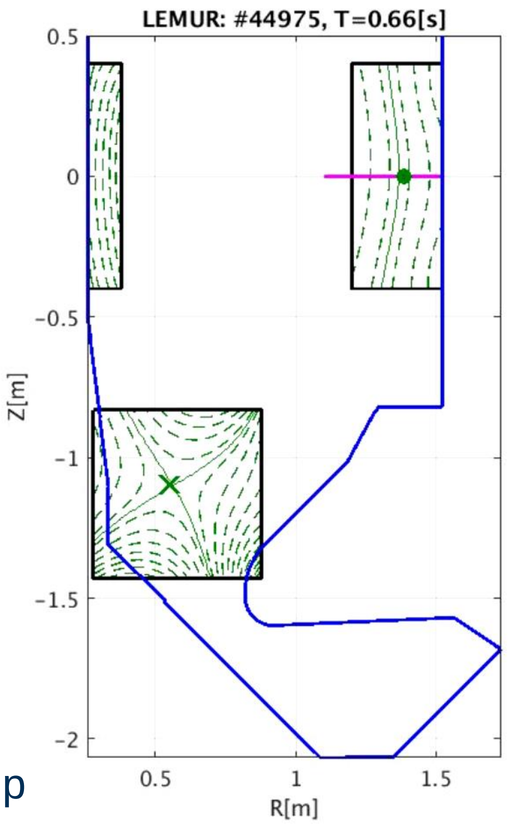

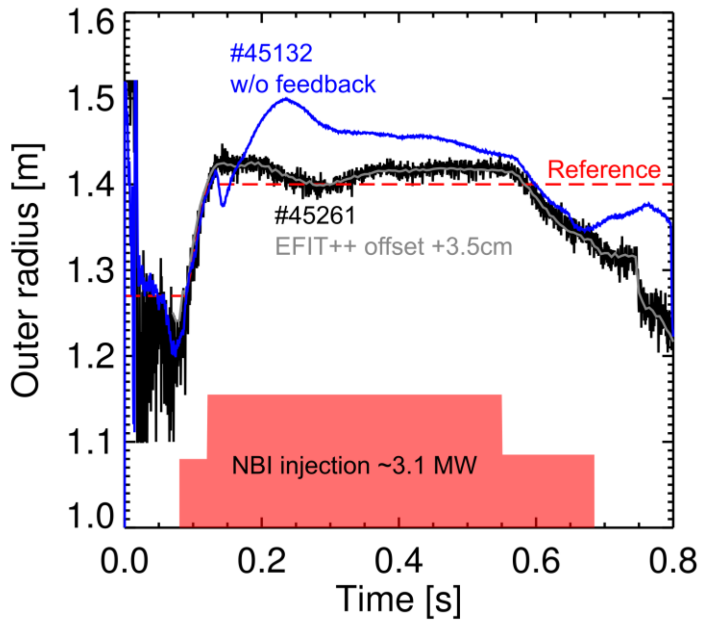

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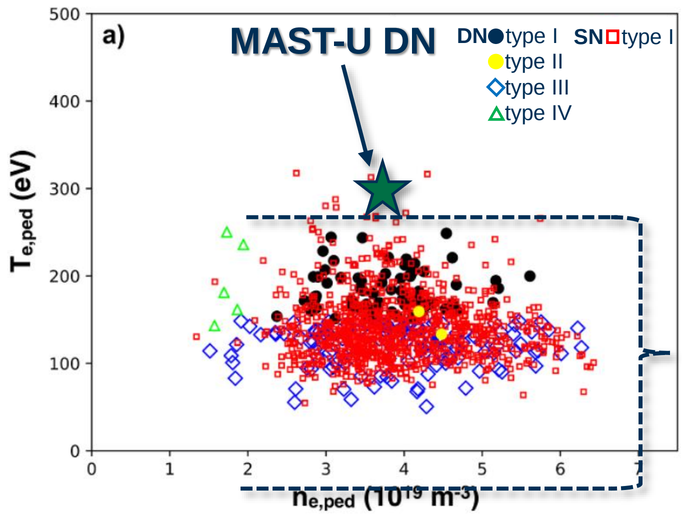
Pedestal temperature

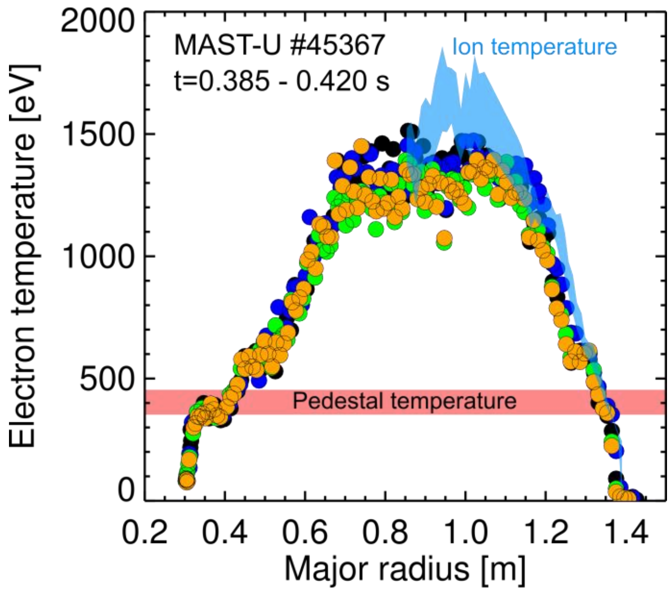
Closed divertors reduce the neutral flux crossing the core plasma boundary, resulting in improved control of the edge density

Achieved hotter temperature pedestals than MAST Upgrade.

New divertor leads to higher edge temperatures and thus access to a new lower collisionality physics regime with higher bootstrap current and improved stability.



Smith et al. 2022 PPCF **64** 045024

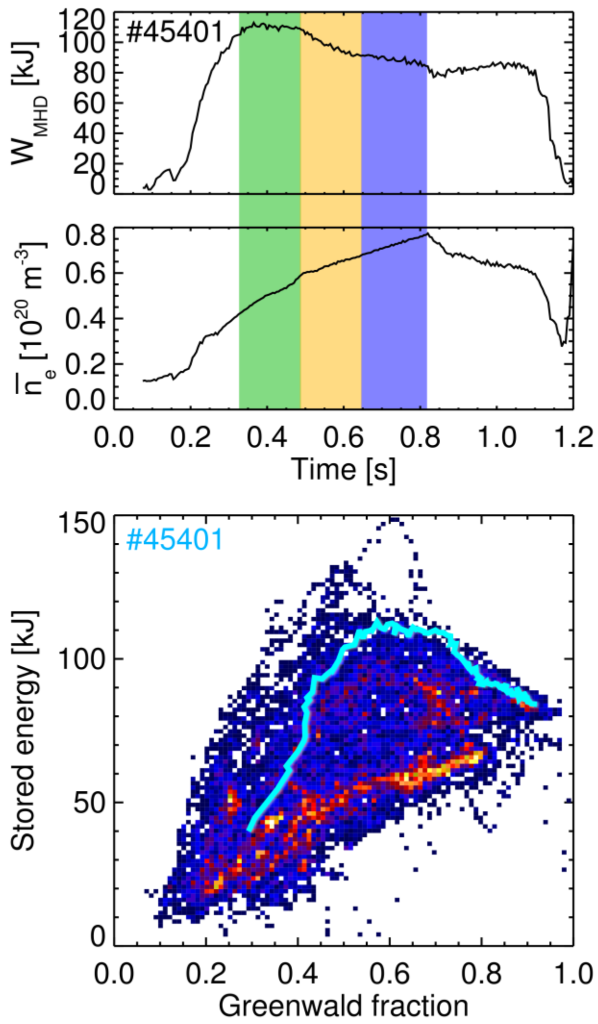


H-mode density limit

It is a major research area to obtain good core confinement throughout the operational space. In H-mode scenarios, a degradation of core performance is typically found when approaching the Greenwald limit

Peak stored energy (and therefore core confinement) found when operating at Greenwald density fractions ~ 0.6

Qualitatively similar density limit behaviour as observed on ASDEX Upgrade – a conventional tokamak with fully tungsten wall



Good confinement

Degrading H-mode

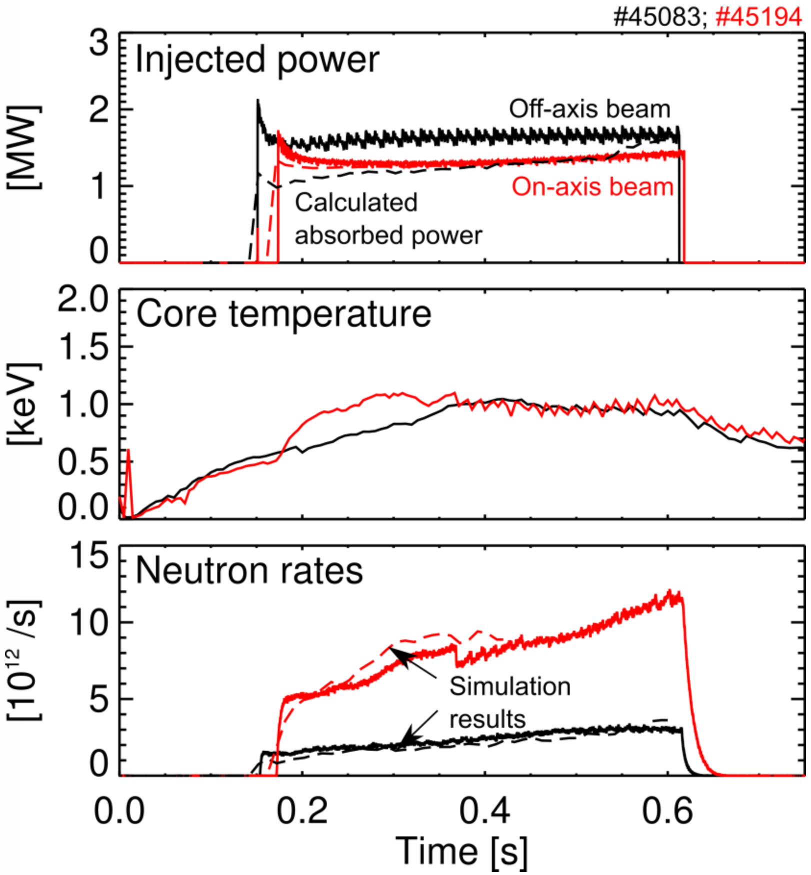
Transition to L-mode

Characterising off-axis beam performance

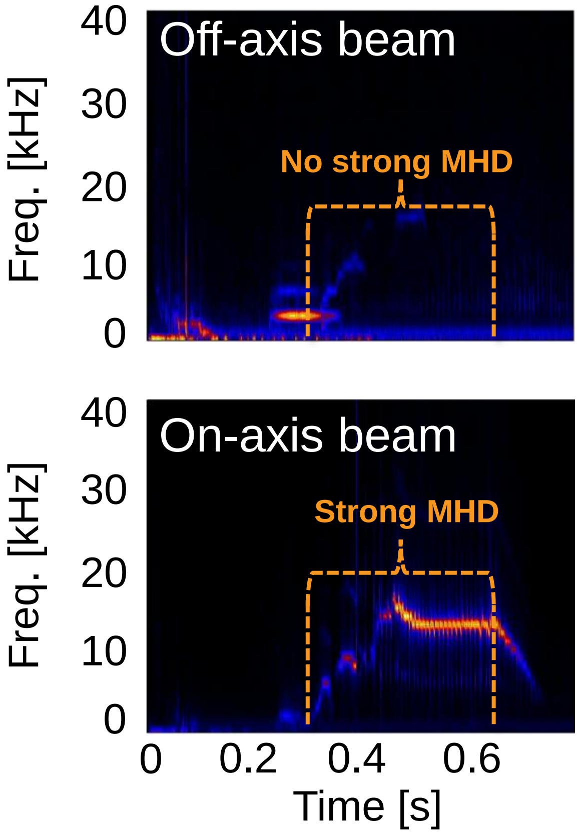
Reliable operation with both on-axis and off-axis neutral beam injection, injecting up to ~3 MW of power

No fast ion driven MHD instabilities (e.g. long lived mode) found with off-axis heating

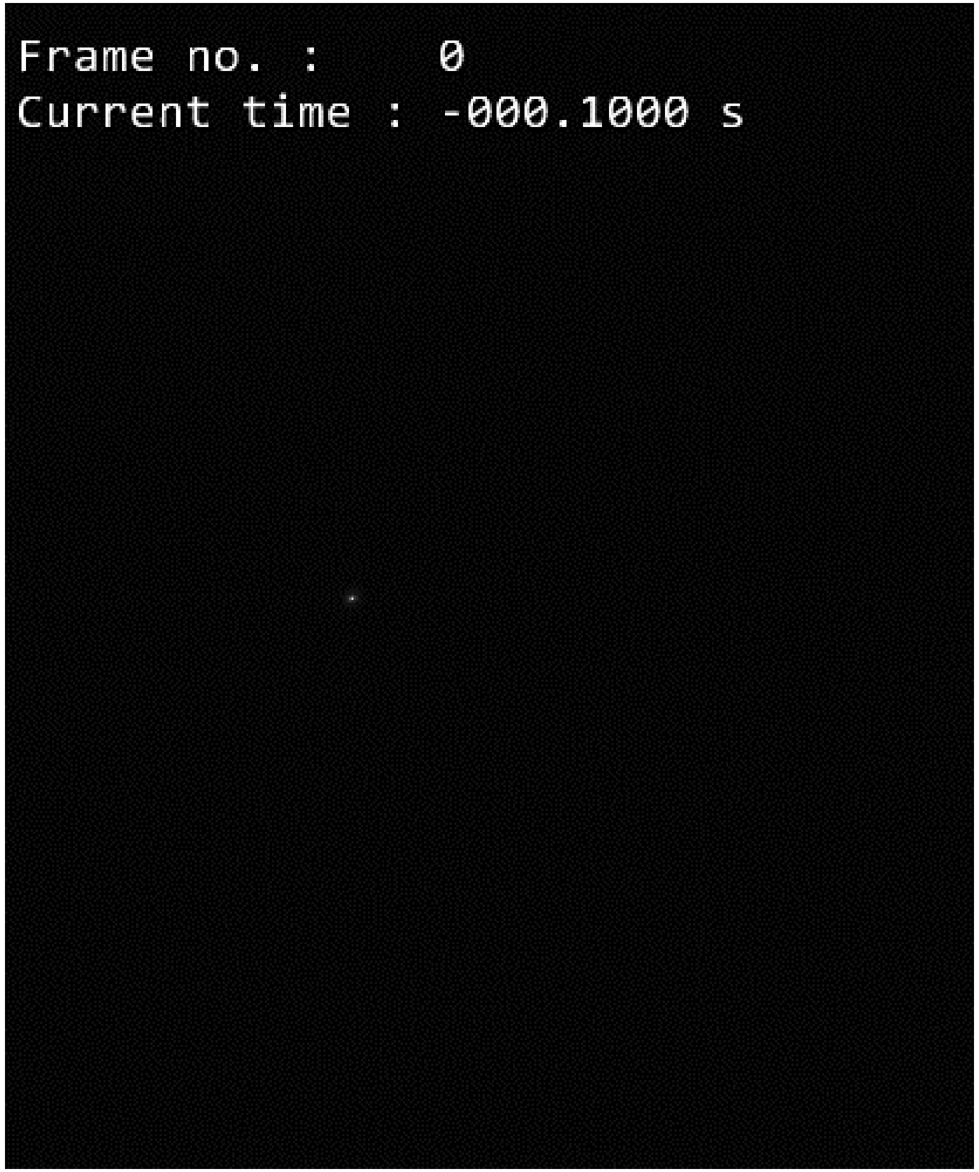
Scenario development to higher plasma current and elongation should improve fast ion confinement time



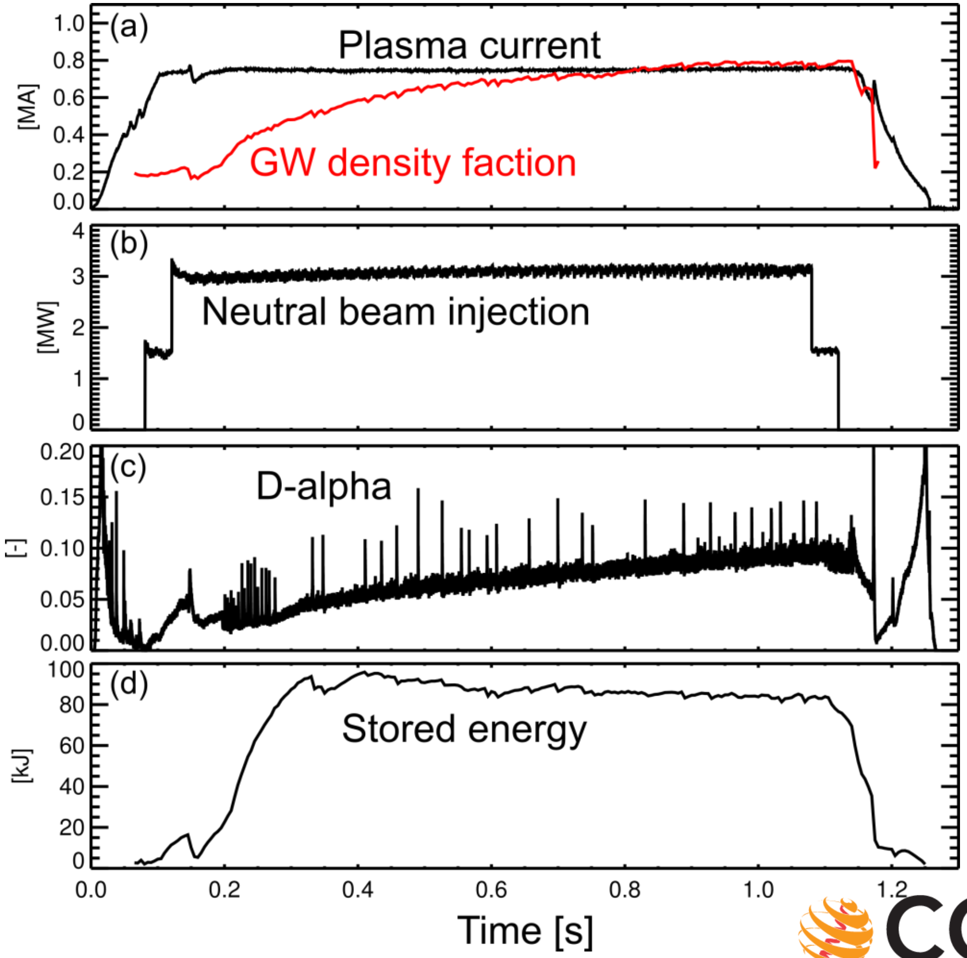
Spectrogram of Mirnov data



Highest performance stable scenario



- ✓ Two-beams injected for 1 s
- ✓ Stable ELMy H-mode scenario
- ✓ Relatively high β_N~2.2



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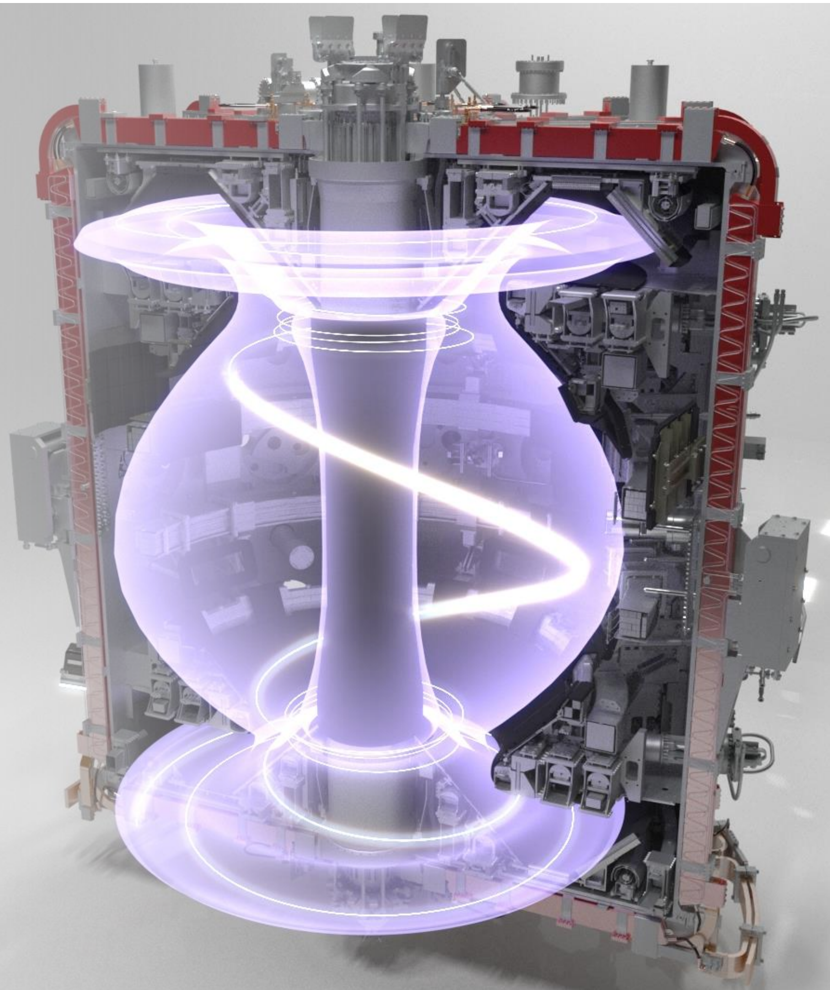
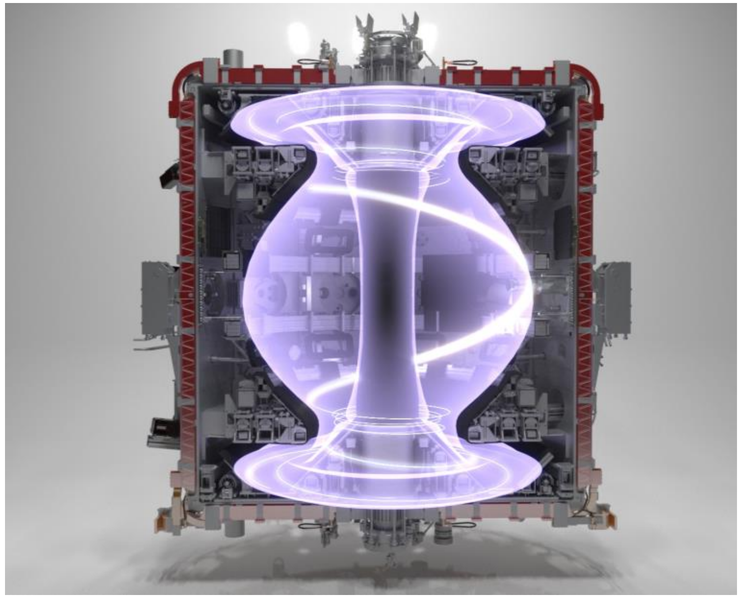
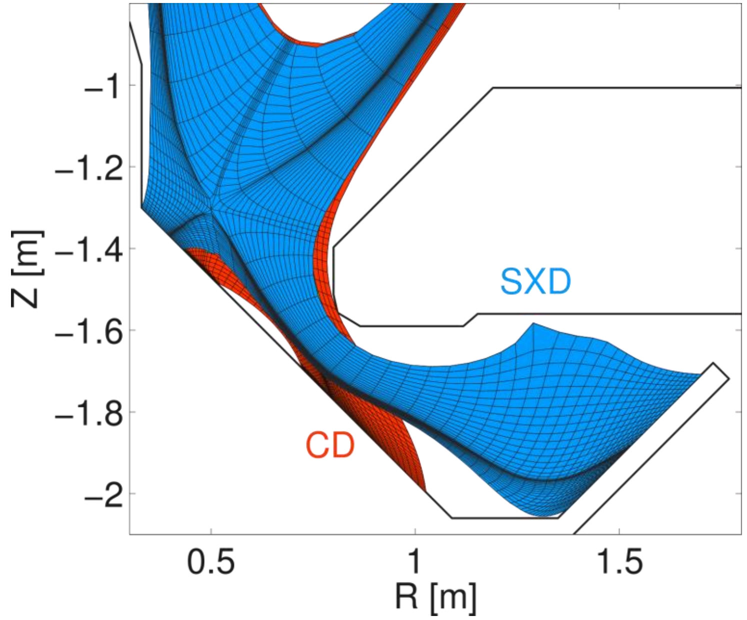
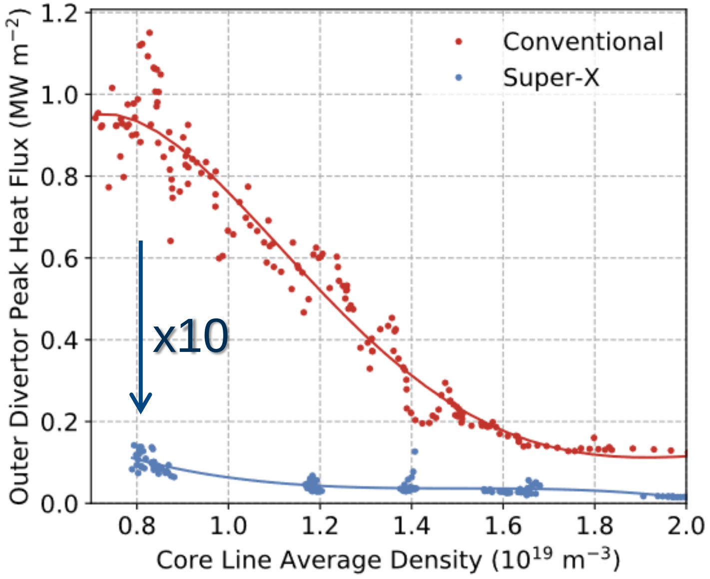


Reduced Divertor Heat Flux in the Super-X







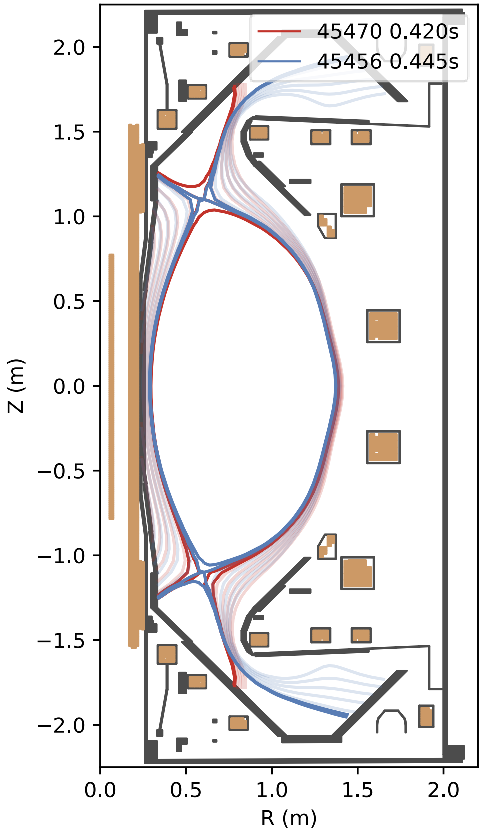
Reduced q_{surf}^{div} through both the unique geometry and enhanced volumetric losses (f_{leg}) along the field lines.

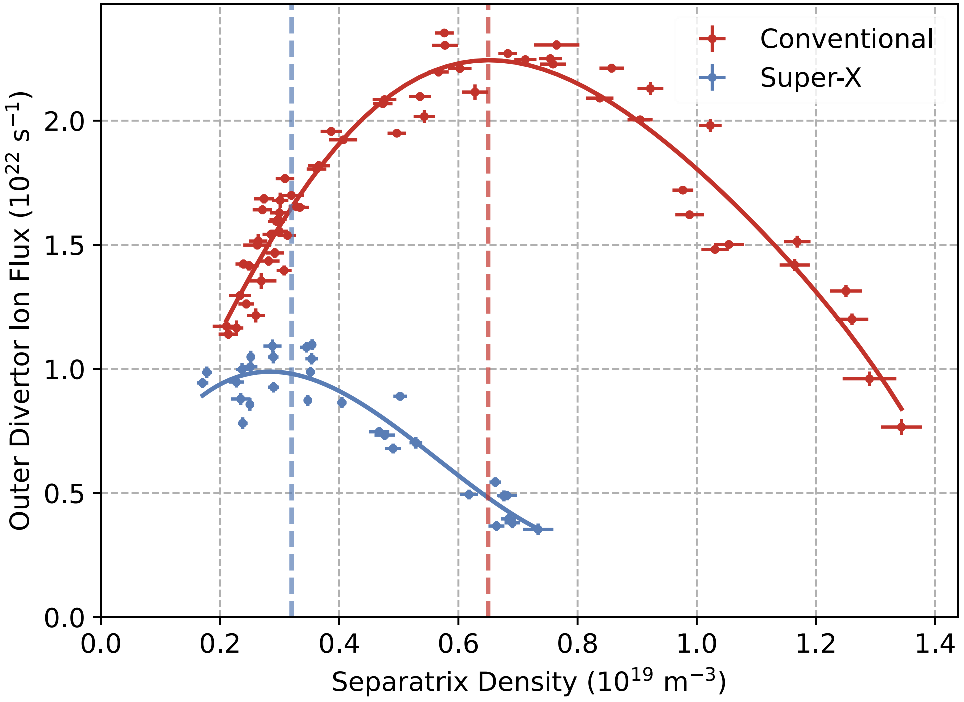
Simulations predict 5-10x difference in heat flux between the CD and SXD configurations

Experimental IR measurements reproduced the simulation results

E Havlíčková *et al* 2015 *PPCF* **57** 115001

Roll over and entry to detachment





As density is increased there is a roll over where flux to the divertor beings to reduce.

Separatrix density threshold for mitigating divertor particle flux x2 lower in Super-X

Confirms theory prediction*
$n_{e,sep,thr} \propto 1/R_{target}$

* B Lipschultz et al Nucl. Fusion 56 056007 (2016)

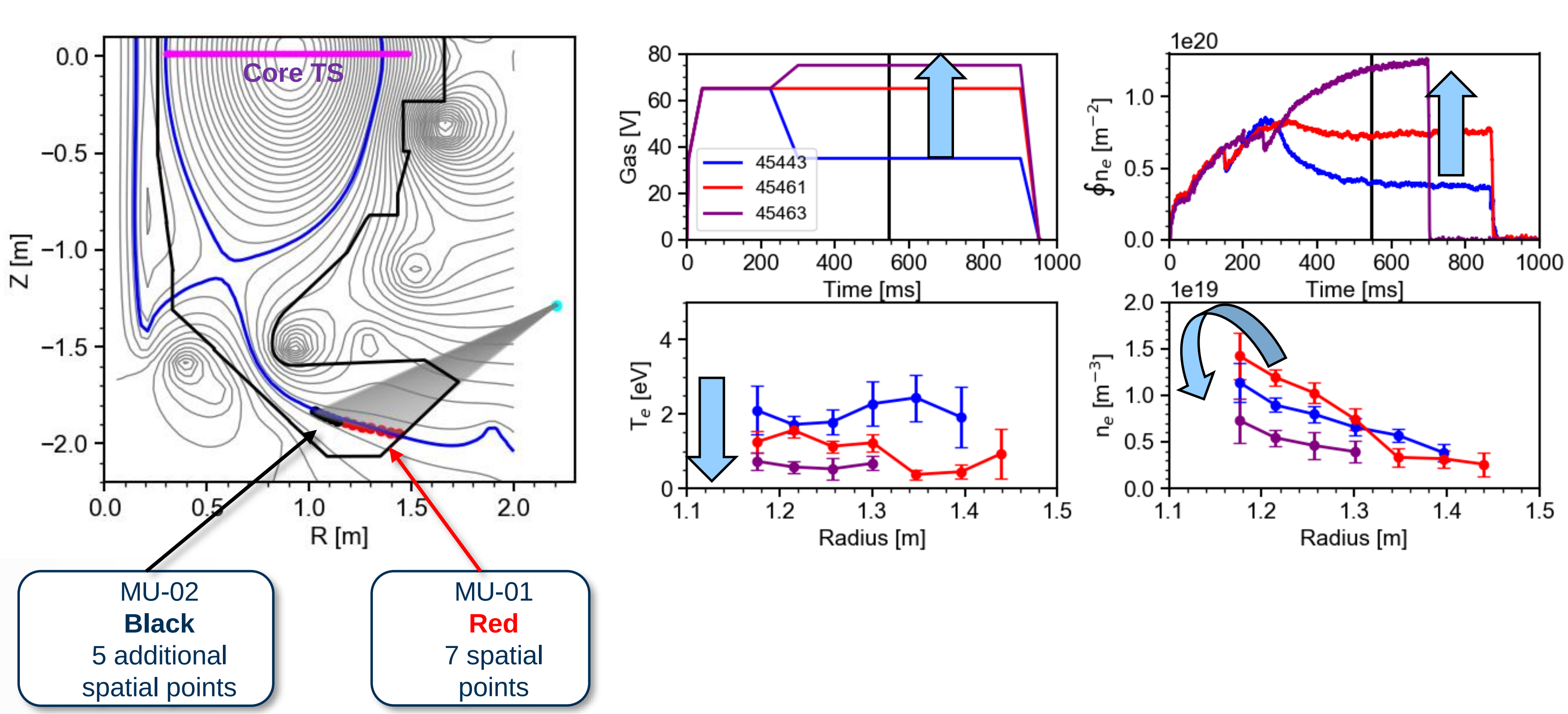
Divertor Thomson scattering

New diagnostic measurements for temperature and density in divertor

45443 **Attached** with highest temperature and reasonable divertor density

45461 **Detachment Onset** with divertor density increasing with a drop in divertor temperature

45463 **Deeply detached** so temperature and density have decreased significantly, especially at the target



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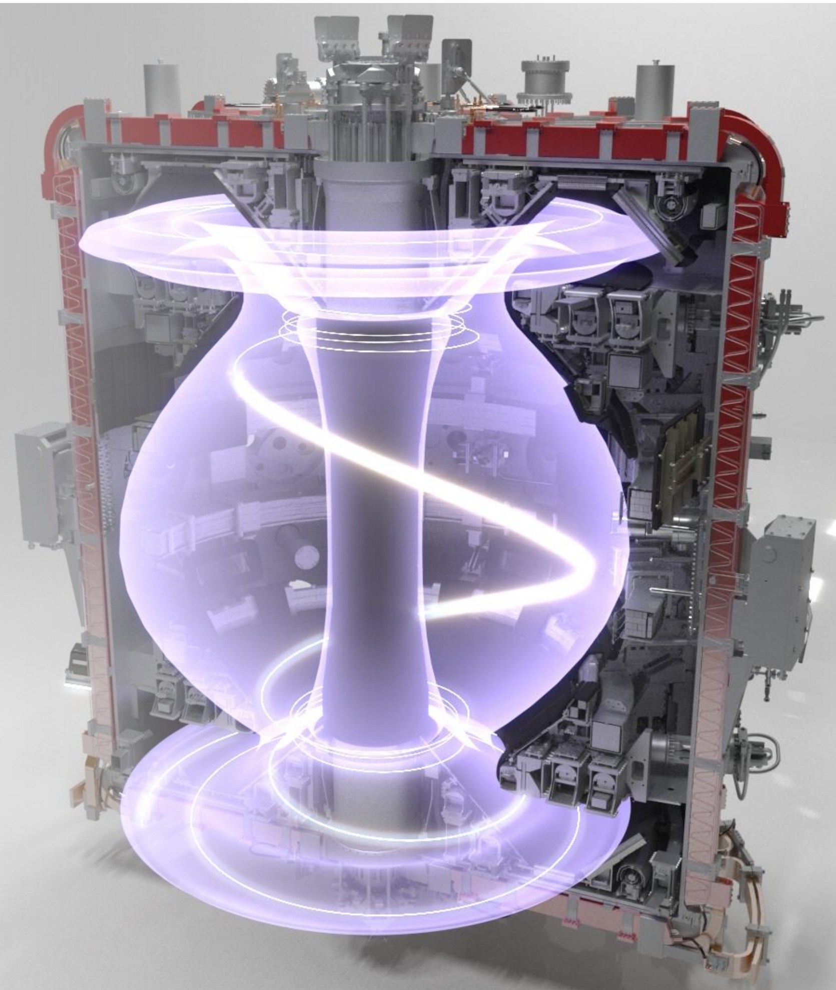


Plans for second campaign MU02

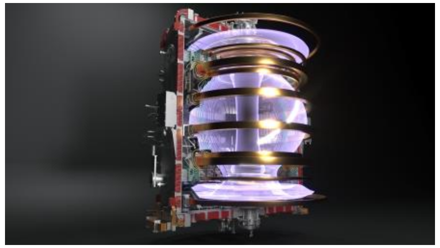
2022 timeline

Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec

Shutdown

Restart

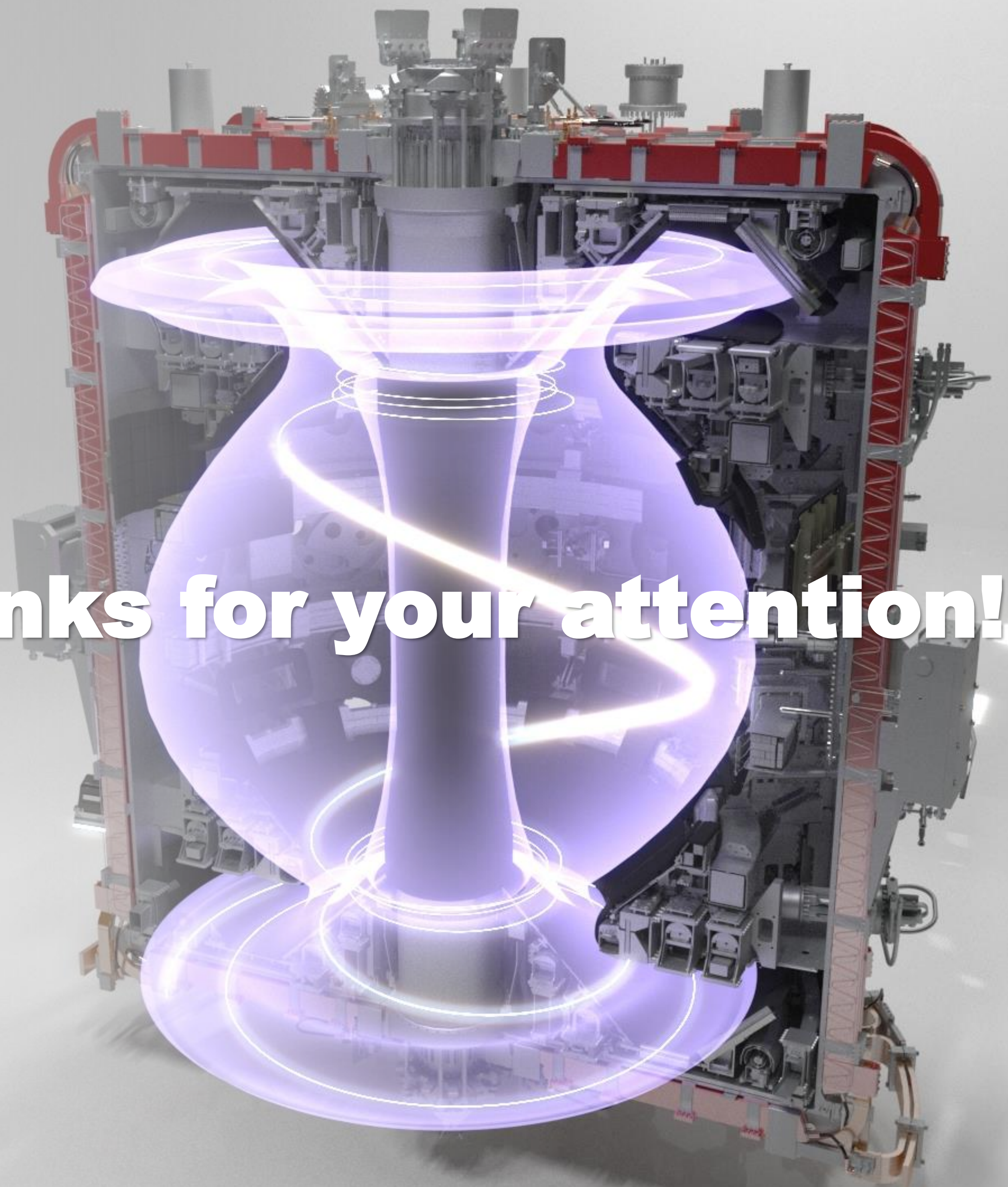
Campaign



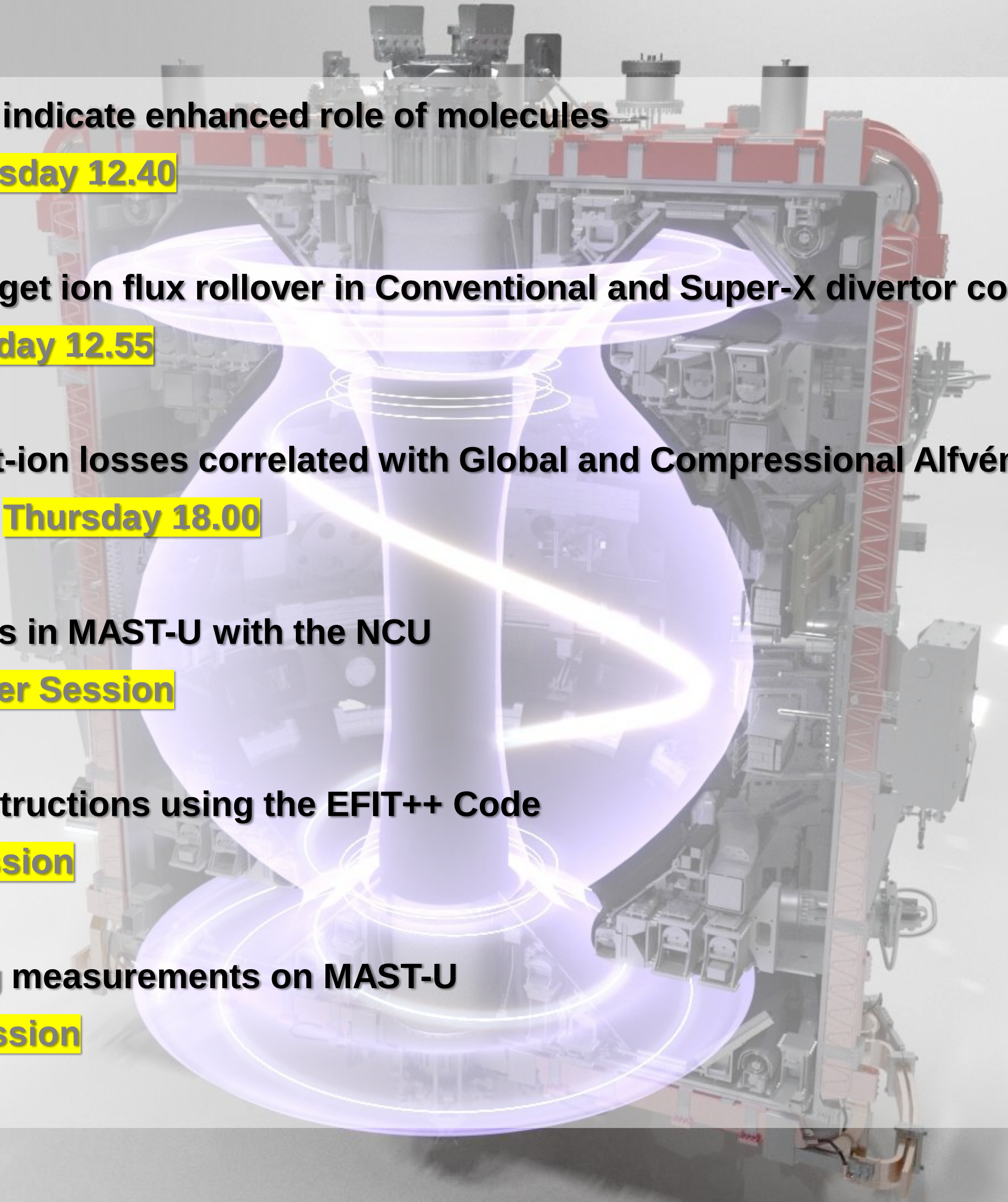
MAST-U capabilities
- Increase toroidal field: 0.65 – 0.72 T
- Increase plasma current: 0.75 – 1 MA
- Max NBI power: 3.5 MW – 4.2 MW for 2 s

Controllers to be developed
- Density control
- Improved shape control
- Detachment front position

Diagnostics
- Proton detector
- Divertor Science Facility RFEA
- Soft X-rays
- Expanded Divertor TS



Thanks for your attention!



First MAST-U detachment results indicate enhanced role of molecules

Kevin Verhaegh Wednesday 12.40

Interpretative modelling of the target ion flux rollover in Conventional and Super-X divertor configurations on MAST Upgrade

David Moulton Wednesday 12.55

Experimental observations of fast-ion losses correlated with Global and Compressional Alfvén Eigenmodes in MAST-U

Juan Rivero-Rodriguez Thursday 18.00

Observations of confined fast ions in MAST-U with the NCU

Marco Cecconello Poster Session

First MAST-U Equilibrium Reconstructions using the EFIT++ Code

Lucy Kogan Poster Session

First divertor Thomson scattering measurements on MAST-U

James Clark Poster Session

Further Information on MAST Upgrade

UK Atomic Energy Authority

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Back up slides

Plans for second campaign MU02

UK Atomic Energy Authority

Ma

Dec

Tokamak Science priorities for MU02

To advance understanding of plasma exhaust and benefits of alternative divertor configurations

i. Explore limits in L-mode and H-mode with attached and detached divertors
ii. Study impact of divertor configuration on access to H-mode, detachment, and core-edge-divertor integration

To broaden the MAST-U operating space and maximise plasma performance

i. Optimising the q-profile, inductance, and NBI heating and current drive to achieve and sustain stable, strongly shaped and high β plasmas
ii. Understand the role of magnetic field and main chamber neutrals on core and pedestal performance

MAST-U capabilitie
- Increase toroidal
- Increase plasma
- Max NBI power: 3

stics
ovements and
nissioning of existing
new diagnostics

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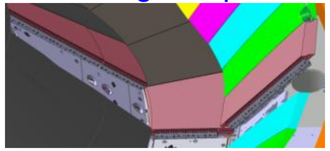
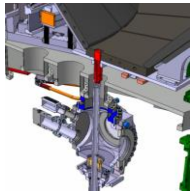
Diagnostics

Divertor diagnostics

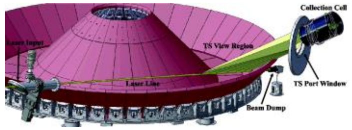
850 Langmuir probes



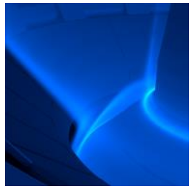
Divertor Science Facility



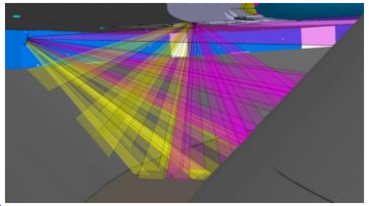
Divertor Thomson scattering



IR & visible imaging, spectroscopy + VUV

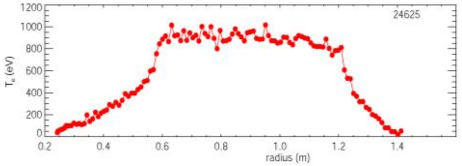


Foil Bolometers

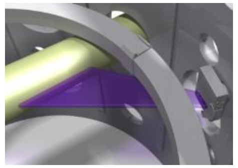


Core & edge diagnostics

130 pt Thomson scattering

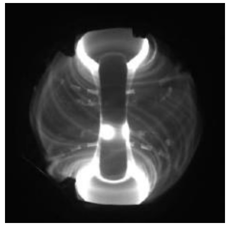


Charge-exchange, MSE, BES

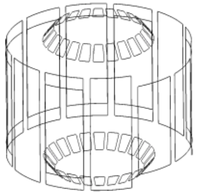


Core SPRED spectrometer

Visible imaging



Magnetic



2x Doppler backscattering

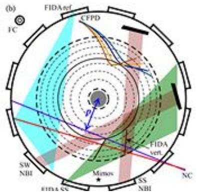
Fast particle diagnostics

Neutron camera

Fast ion loss detector (Uni. Seville)

SSNPA, proton detector

Fast Ion D_α



e.g. electron temperature & density, radiation, heat flux

e.g. electron temperature & density, ion temperature, q-profile, turbulence

e.g. neutron flux, fast ion density and velocity distribution

Feedback control capabilities

Plasma current control ➡

- Hand-over between V_{loop} and current control
- Current ramp rate optimisation

Vertical position control

- Stable double null scenarios achieved
- Facilitates access to H-mode and L-mode

Outer radius control

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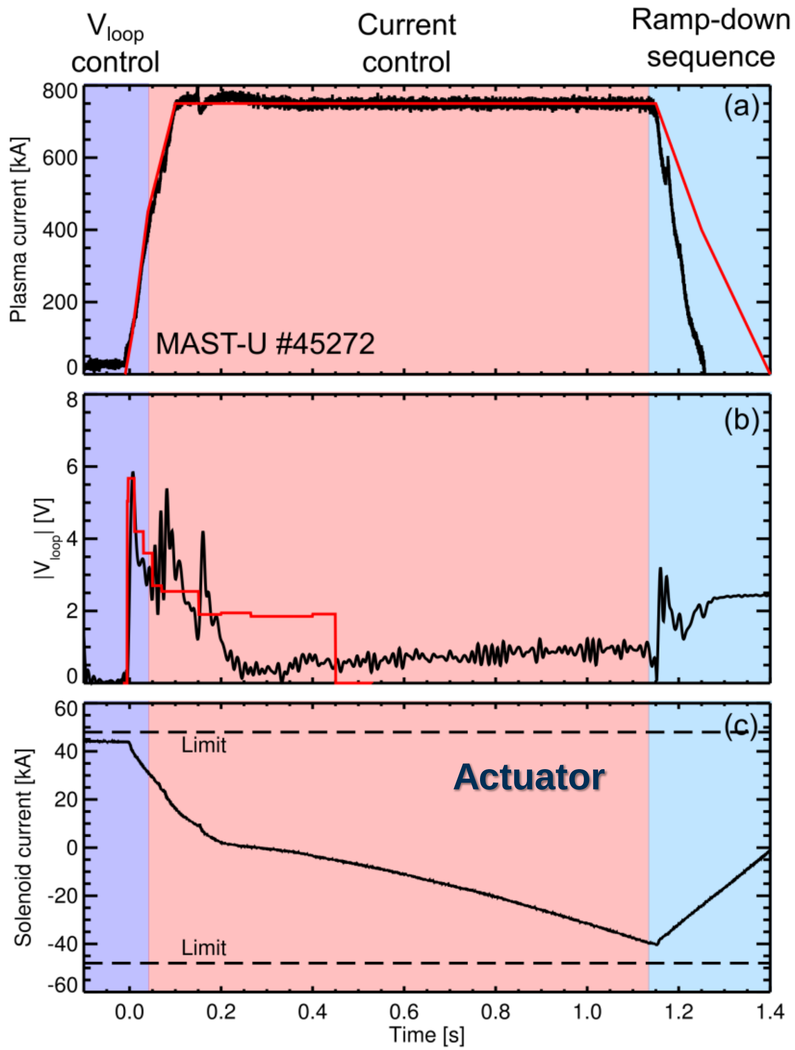
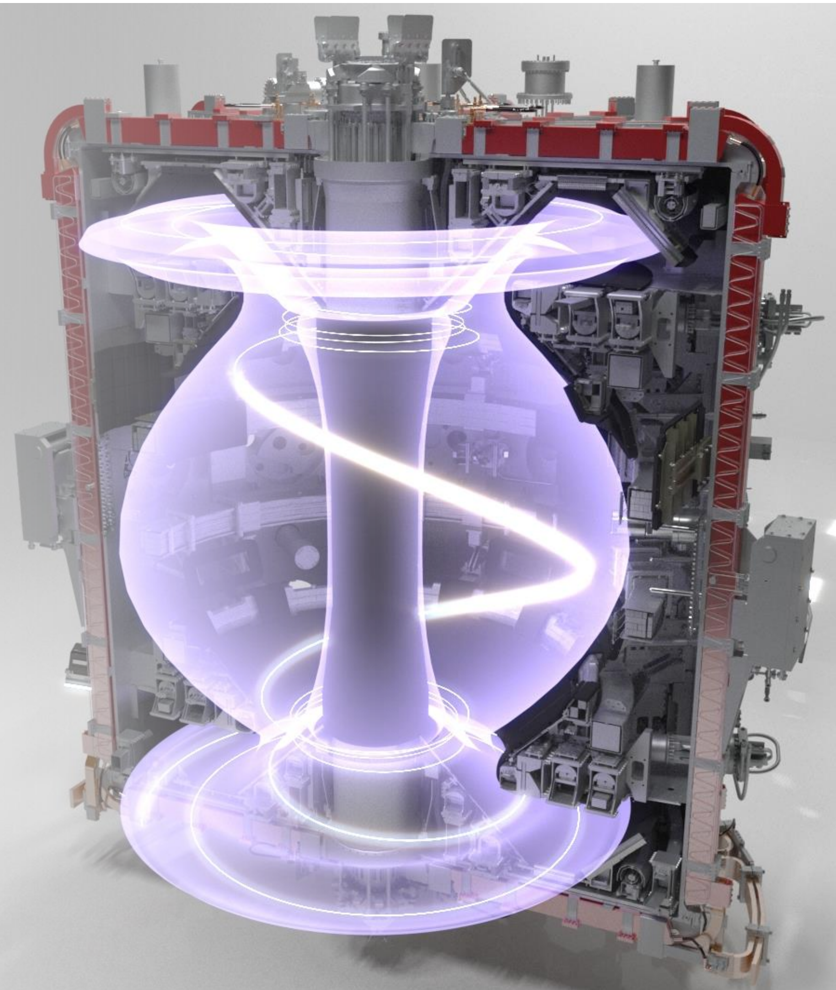


MAST Upgrade Objectives

- Develop understanding of novel exhaust concepts

- Building the knowledge base for ITER

- Assessing the feasibility of the spherical tokamak as a future fusion device (STEP)



Tokamak exhaust challenge

UK Atomic Energy Authority

q_{surf}^{div} ~$10s$ GWm^{-2} in reactors if unmitigated

Material limits typically <10 MWm^{-2}

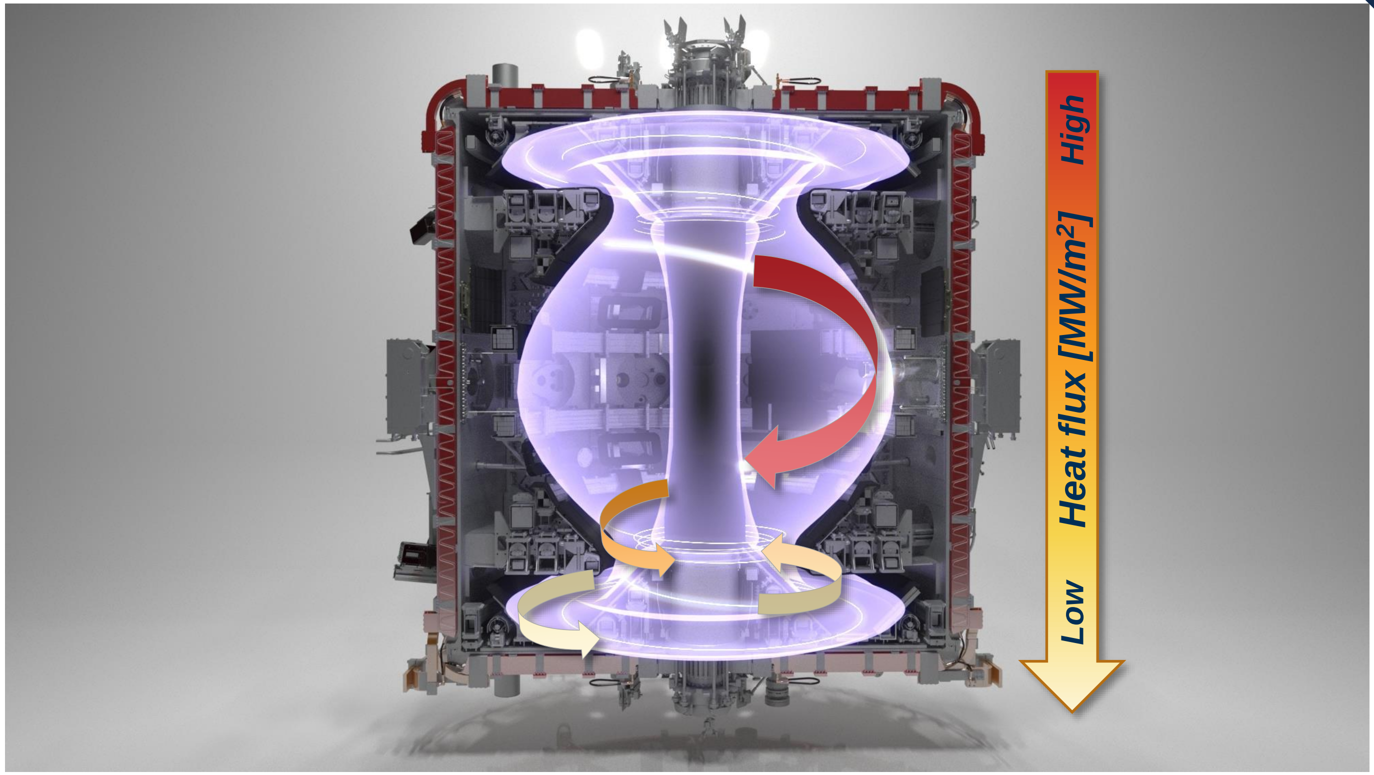
The power crossing the plasma boundary that is deposited on the machine surfaces is

$$P_{sep} = P_{input} - P_{radiation} - {dW}/_{dt} \text{ [MW]}$$

The heat flux travels parallel to the field and at the divertor is given by

$$q_{surf}^{div} = \frac{P_{sep} B_T}{2\pi \lambda_q B_p R} f_{leg} f_{inc} \text{ [MW/m}^2\text{]}$$

Volumetric losses **Tile inclination**



The MAST-U divertor is uniquely designed to reduce q_{surf}^{div} through both the unique geometry and enhanced volumetric losses (f_{leg}) along the field lines.

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