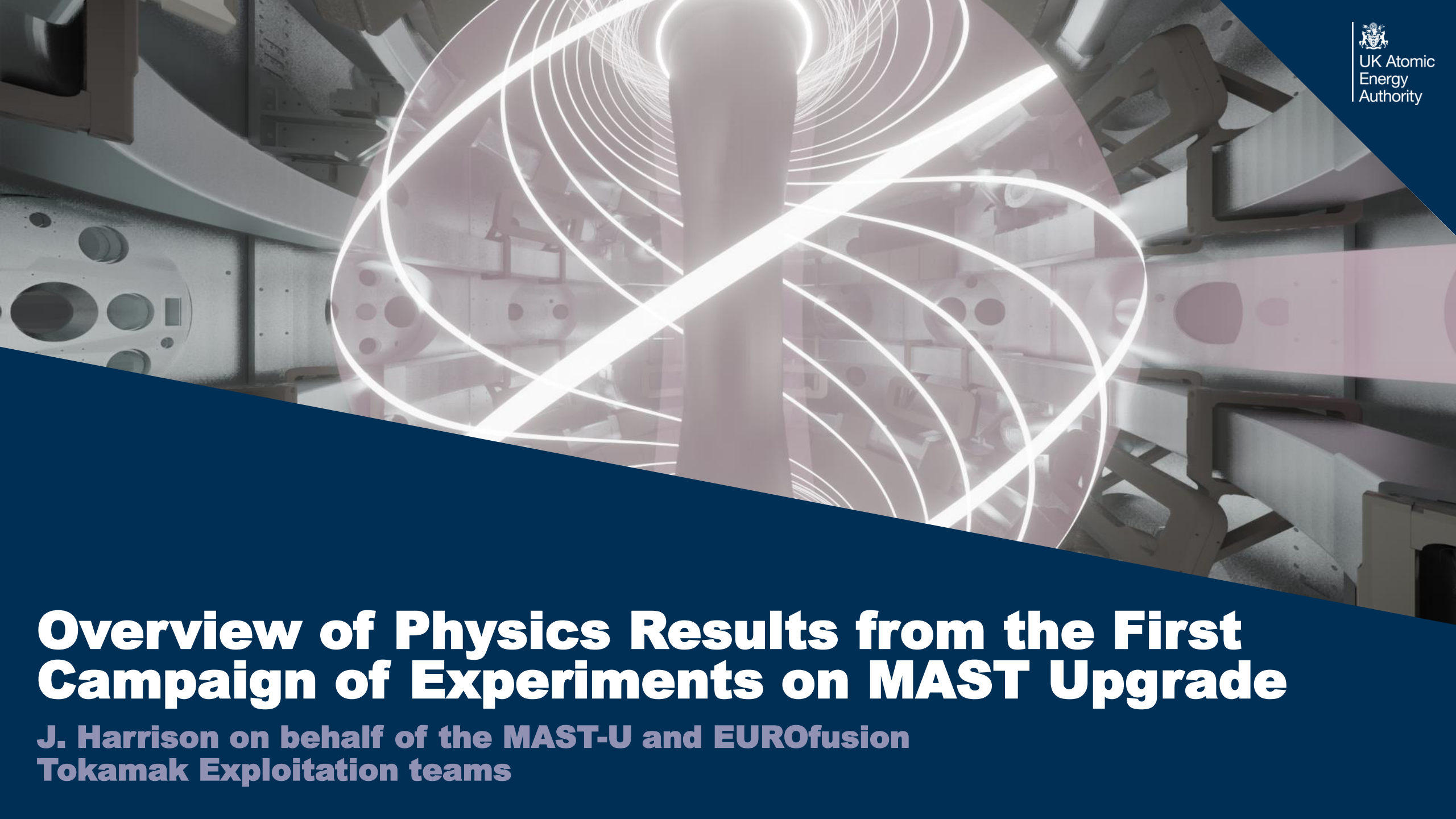




Overview of Physics Results from the First Campaign of Experiments on MAST Upgrade

J. Harrison on behalf of the MAST-U and EUROfusion Tokamak Exploitation teams

Thank you to collaborating institutes



... and contributors to the MAST-U programme

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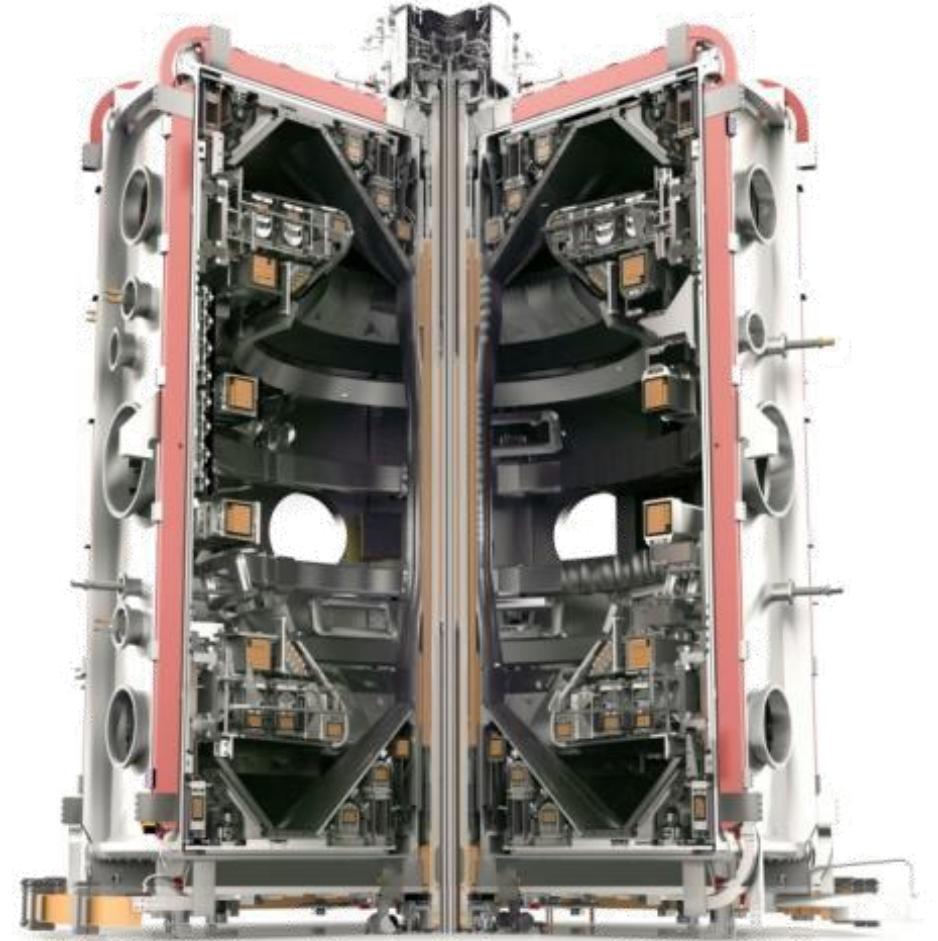
27 Commonwealth Fusion Systems, Cambridge, MA, USA

28 Centre for Advanced Instrumentation, Durham University, South Road, Durham, DH1 3LE, United Kingdom

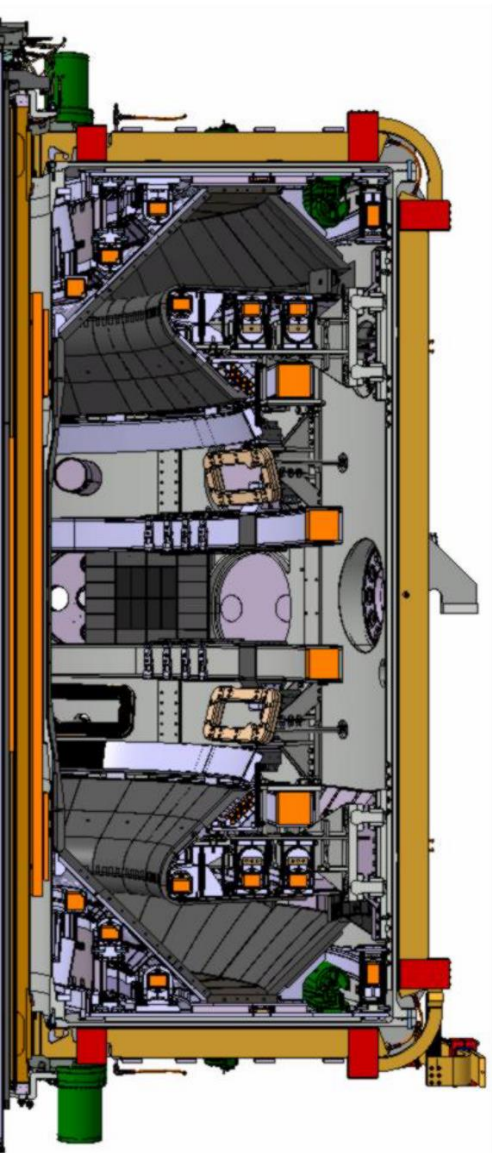
29 Forschungszentrum Jülich GmbH, Institut für Energie und Klimaforschung, Jülich, Germany

30 DIFFER - Dutch Institute for Fundamental Energy Research, De Zaaie 20, 5612 AJ Eindhoven, the Netherlands

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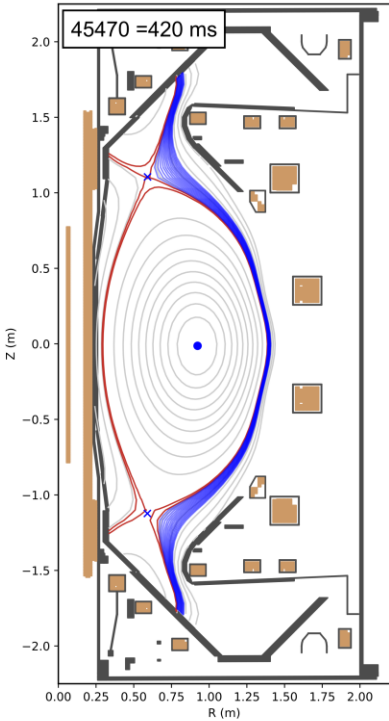
Introduction to MAST Upgrade



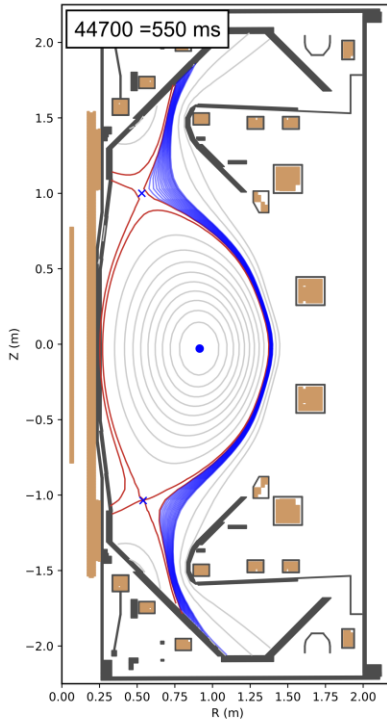
Parameter	1 st Campaign (2021)	2 nd Campaign (2022)
R / a (m)	0.7 / 0.5	0.7 / 0.5
Divertor PFC material	Carbon (graphite)	Carbon (graphite)
B _φ (T at 0.8m)	0.65	0.72
Max I _p (MA)	0.75	1.0
Max κ	2.2	> 2.2
Max δ	0.6	0.6
Divertor geometry	Closed, unpumped	Closed
Max. NBI heating power & duration	3.5 MW for up to 1s	4.2 MW for up to 2s
Ohmic Heating	0.2-1MW	0.2-1MW
NBI geometry	1x on axis, 1x off axis	1x on axis, 1x off axis
Fuelling	Gas	Gas, pellets

Introduction to MAST Upgrade

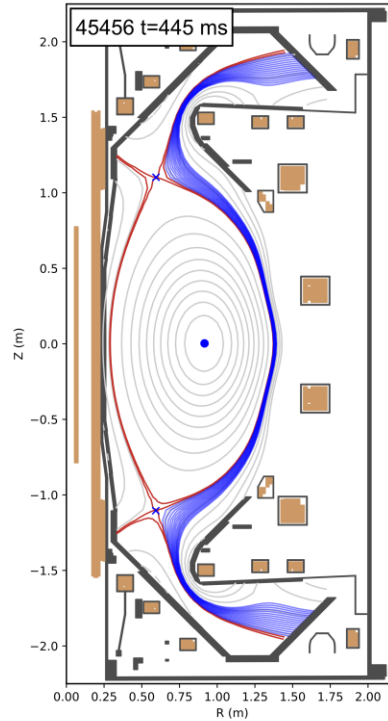
Double null
Conventional divertor



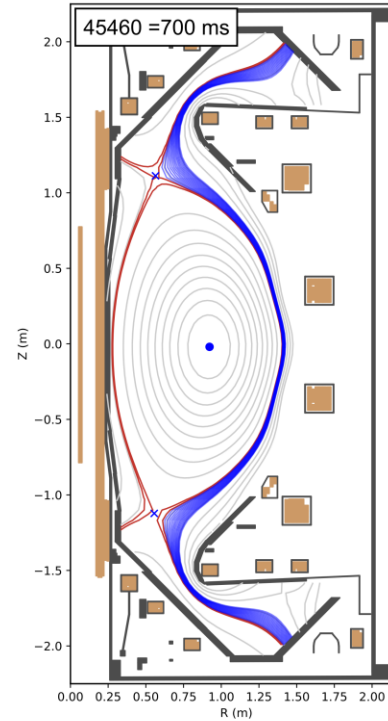
Double null
X-divertor



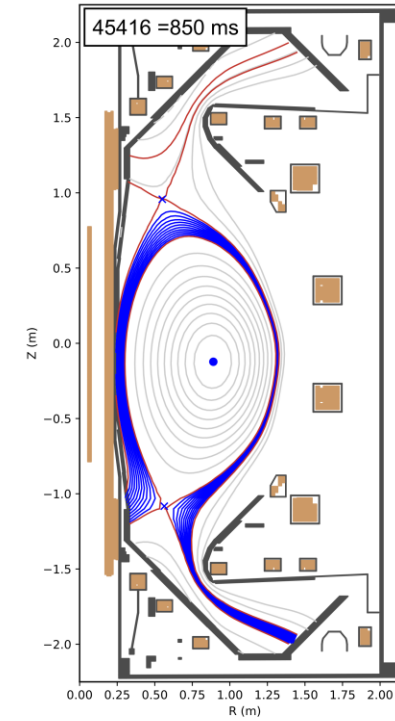
Double null
Super-X divertor



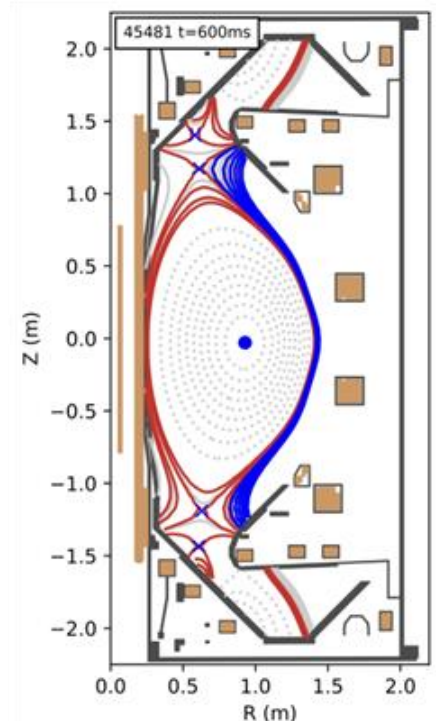
Double null
Extended leg divertor



Disconnected double null
Extended leg divertor



Up-down symmetric
snowflake plus divertor



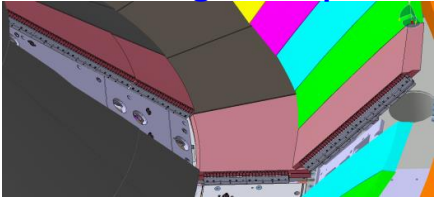
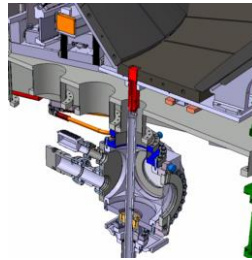
*Allows for assessment of **power sharing** between divertors and impact of **divertor configuration** on heat flux to test their **viability** for future reactors*

Introduction to MAST Upgrade

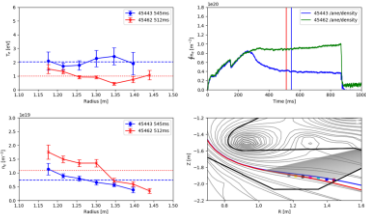
Divertor diagnostics

850 Langmuir probes

Divertor
Science
Facility

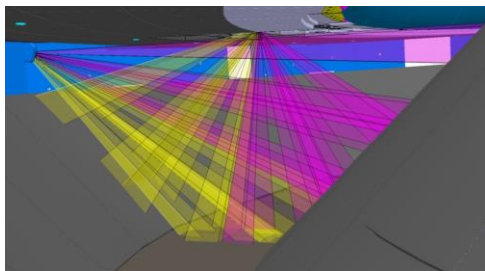


Divertor Thomson
scattering



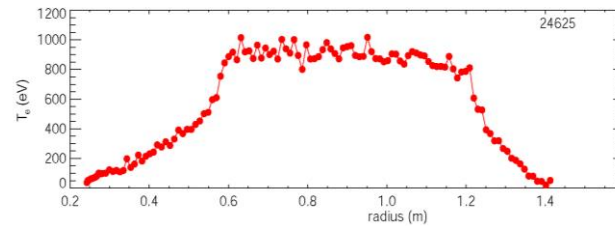
IR & visible imaging,
spectroscopy + VUV

Foil Bolometers

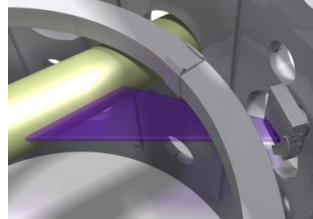


Core & edge diagnostics

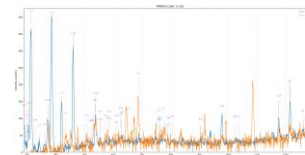
130 pt Thomson



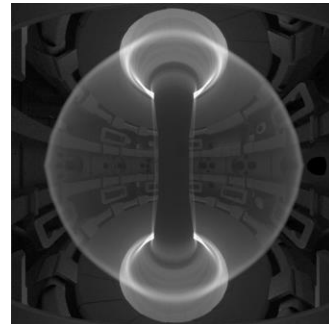
Charge-exchange, MSE, BES



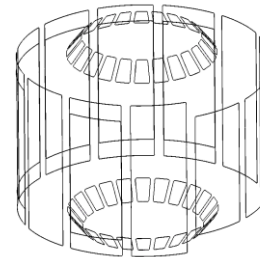
Core SPRED
spectrometer



Visible imaging



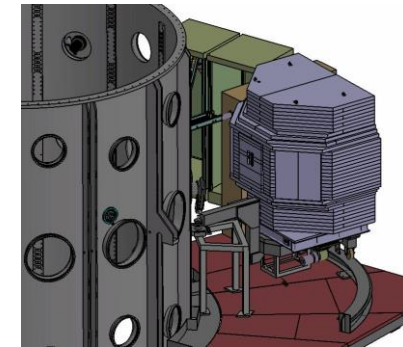
2x Doppler backscattering



Magnetics

Fast particle diagnostics

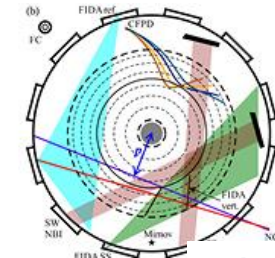
Neutron camera
(Uni. Uppsala)



Fast ion loss detector
(Uni. Seville)

SSNPA, proton detector

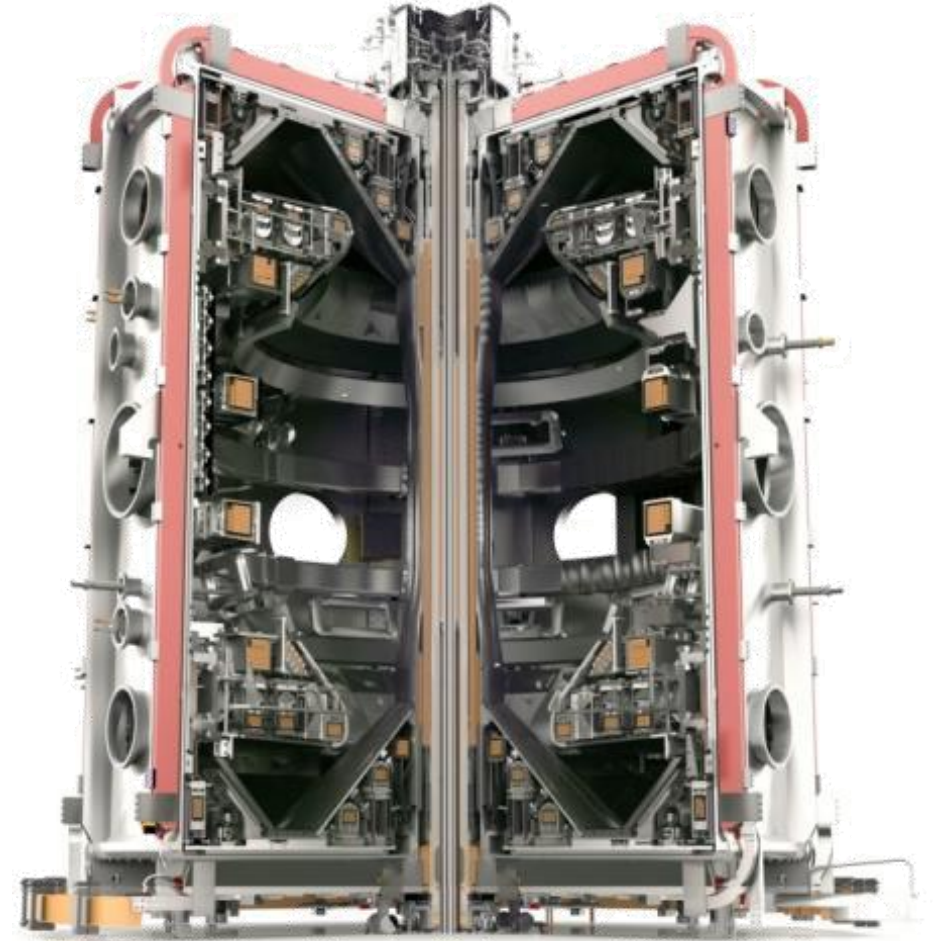
Fast Ion D_α



UPPSALA
UNIVERSITET



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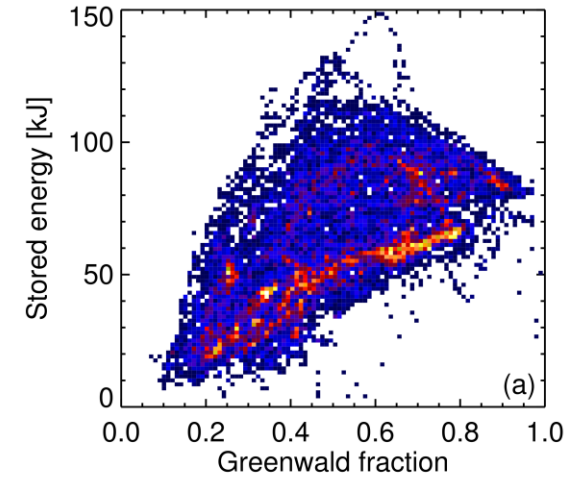
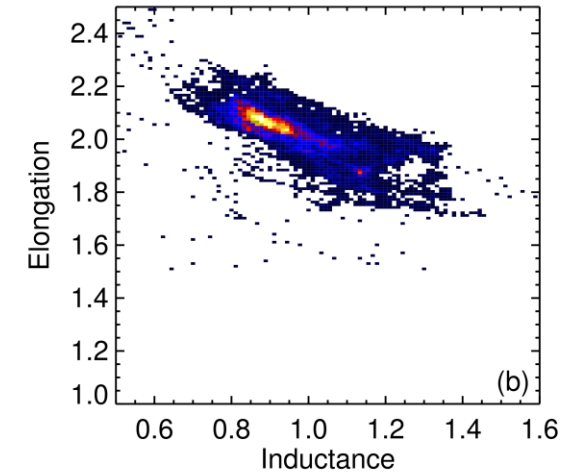
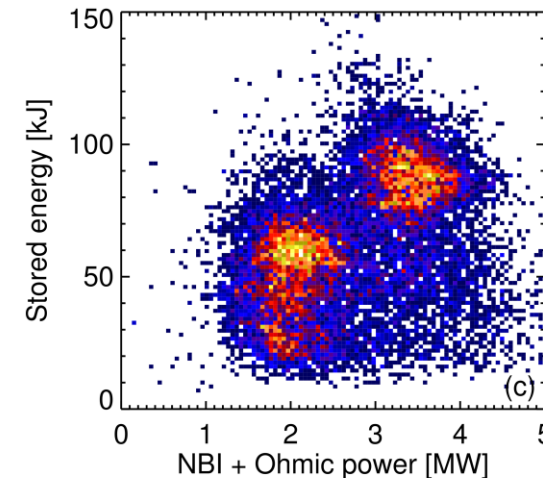
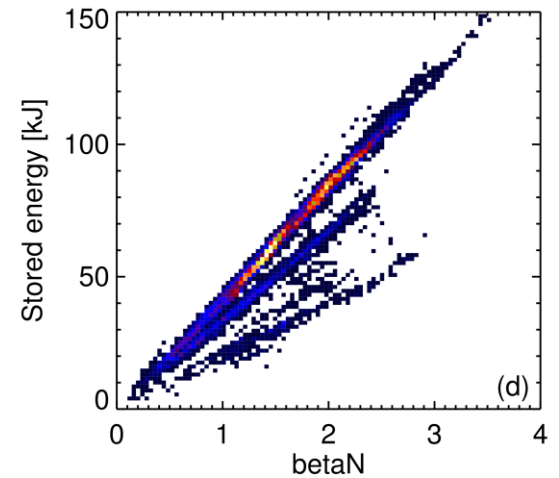


Development of high performance plasmas

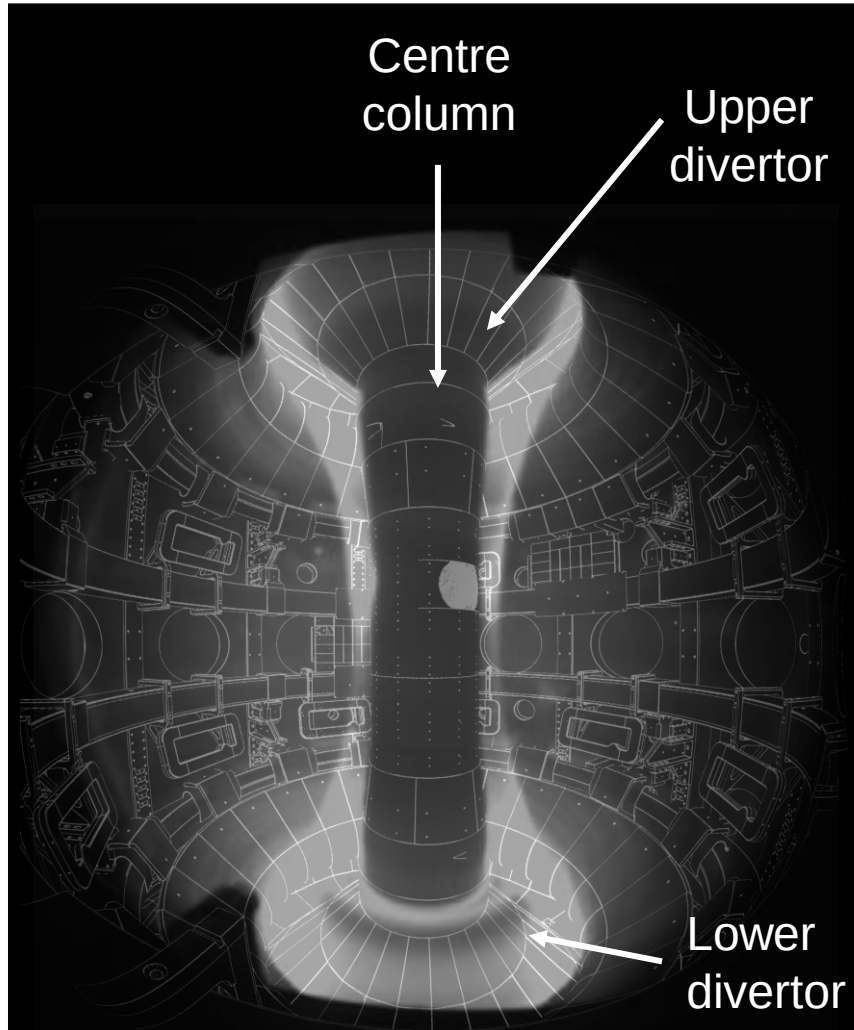
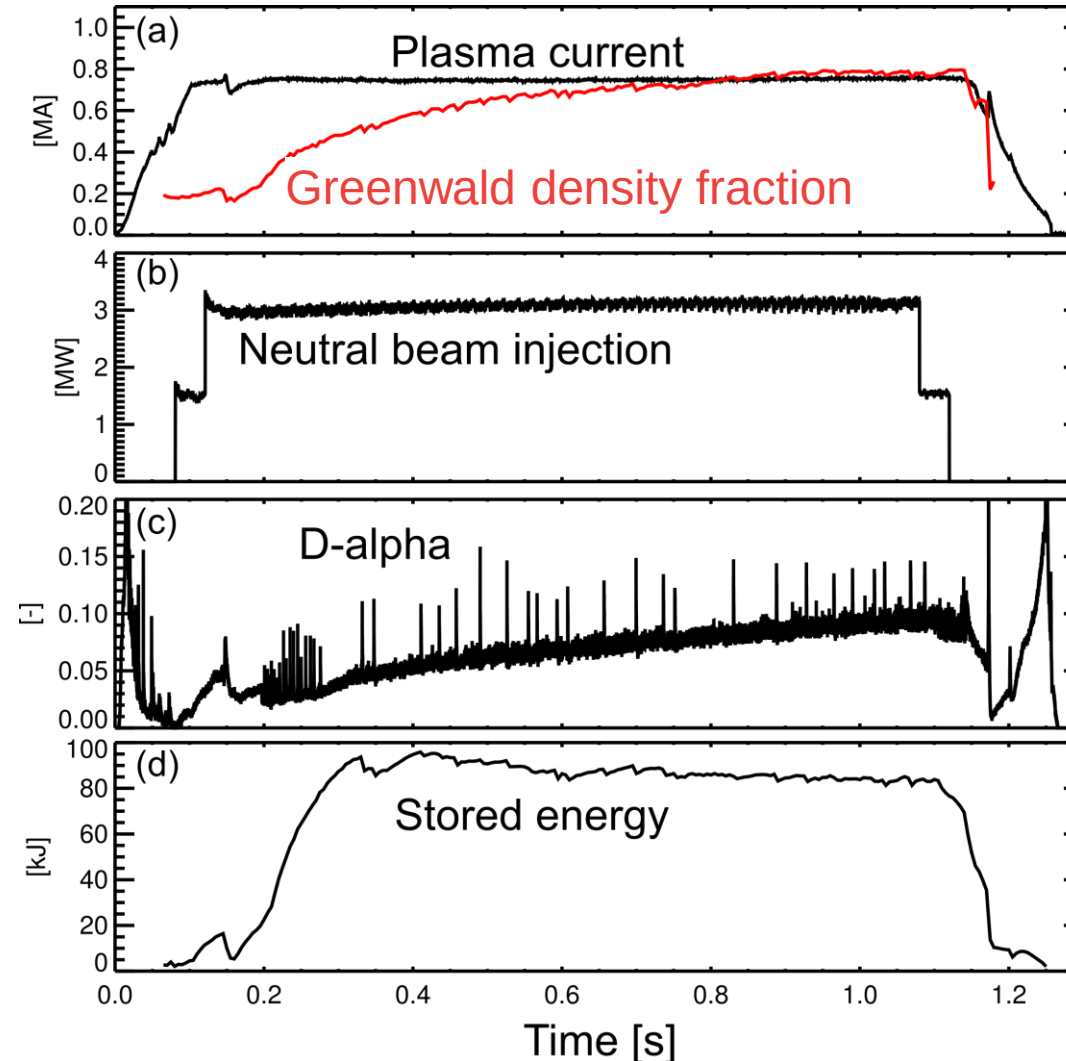
Established conventional and Super-X divertor up to 750 kA in L- and H- mode.
Good one-beam and two-beam NBI operation with power ~ 3 MW

Covered a wide parameter space

- $\overline{n_e}$ up to Greenwald limit
- κ up to ~ 2.2 and $\ell_i(2) \sim 0.7$
- $\tau_E \sim 40 - 50$ ms
- $\beta_N < 3$

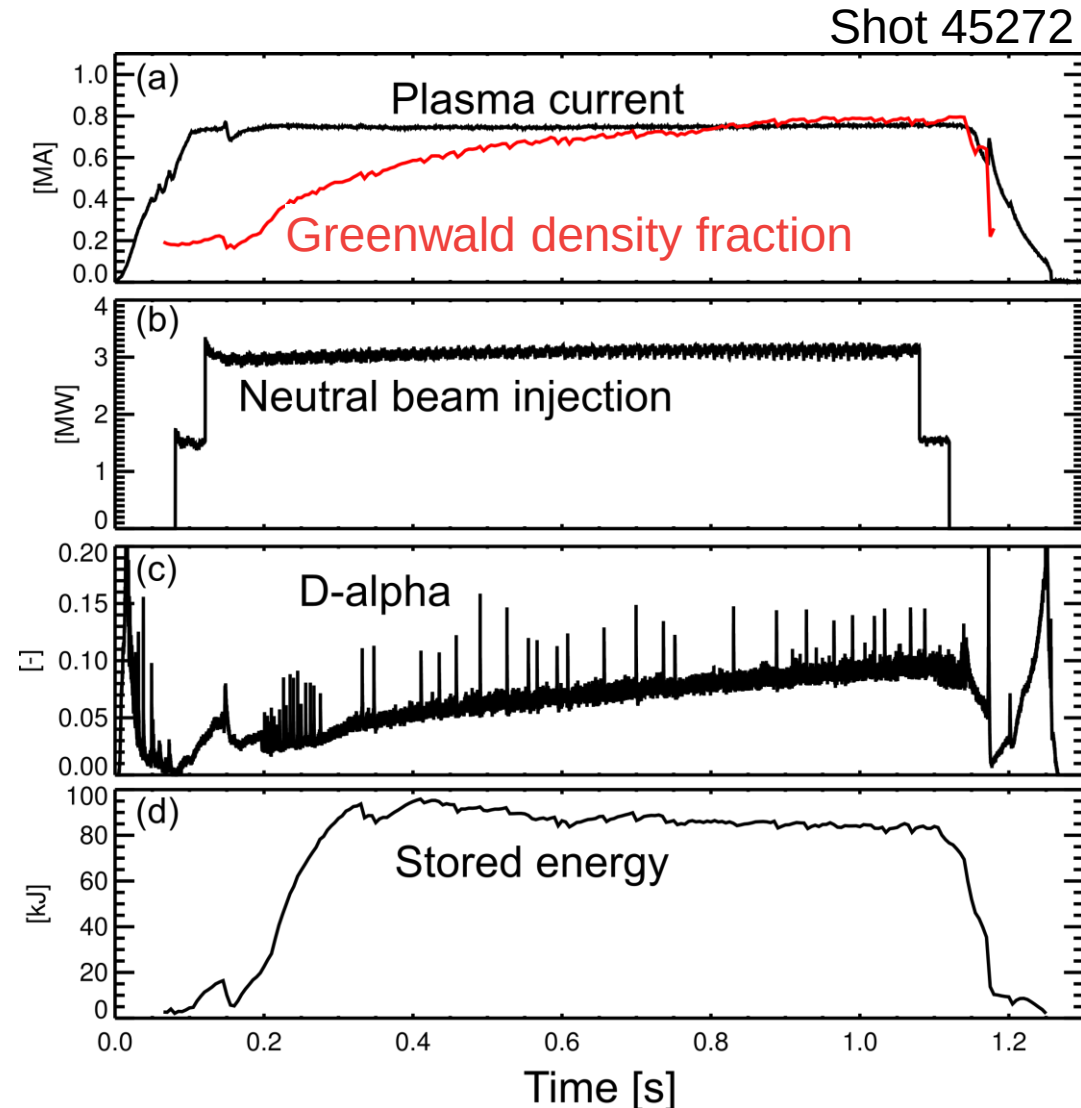


Development of high performance plasmas



Development of high performance plasmas

Frame no. : 0
Current time : -000.1000 s



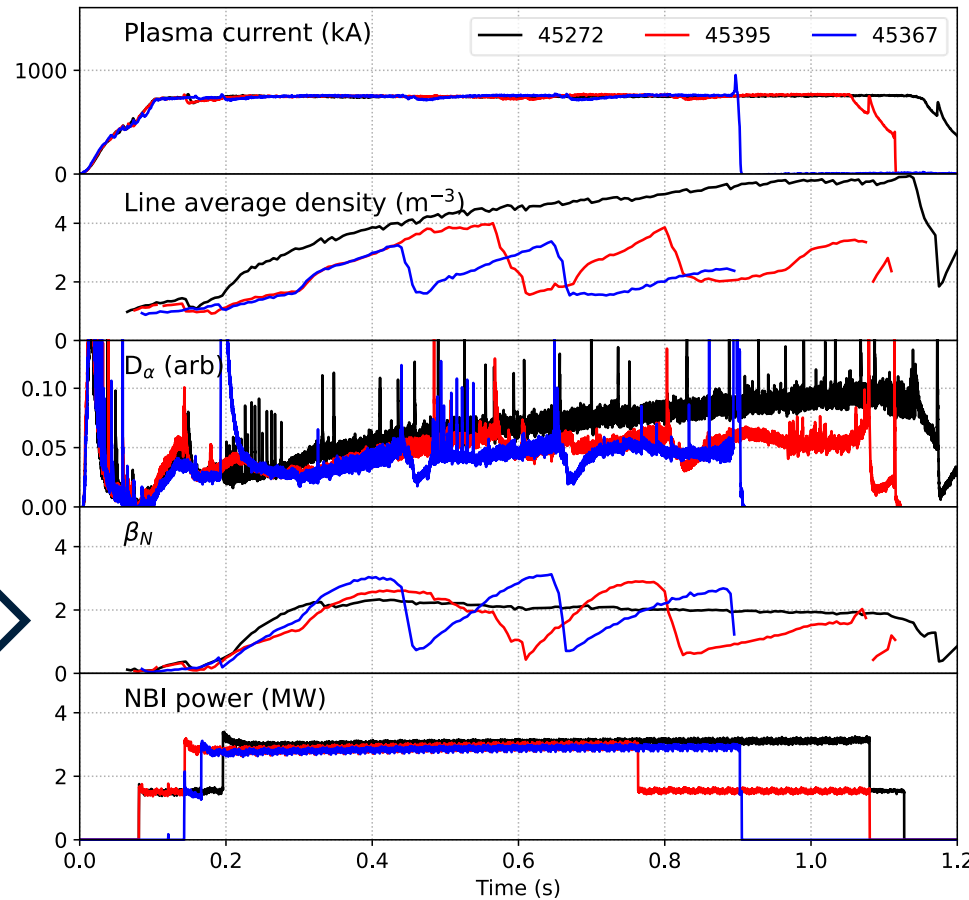
← Two-beams injected for 1 s

← Stable ELMy H-mode scenario

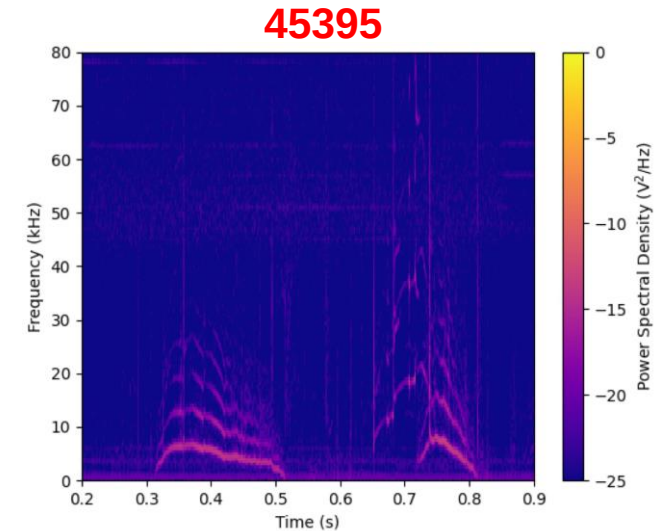
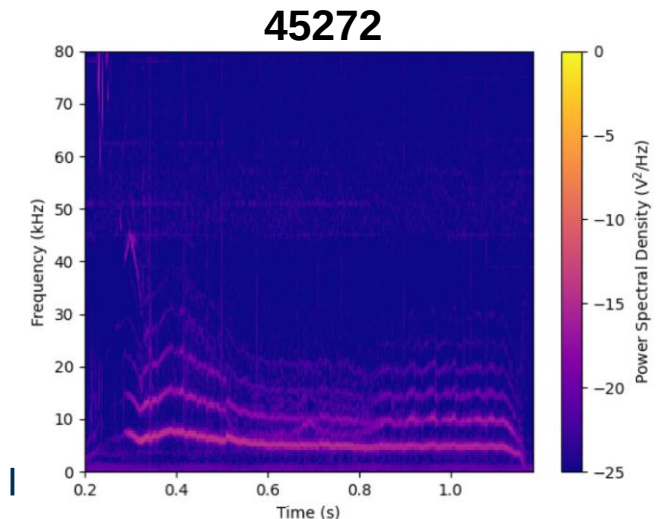
← Core MHD affecting confinement

Long lived tearing mode observed in beam heated discharges

Achievable β limited by long-lived $\sim 6\text{kHz}$ mode

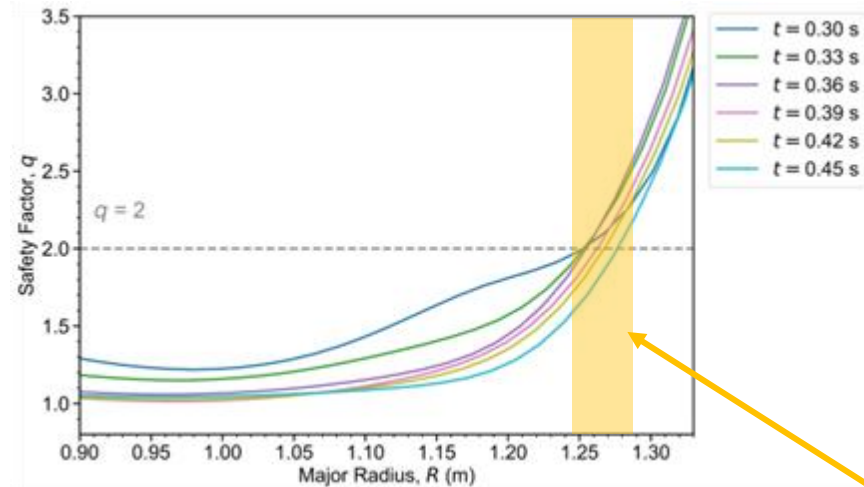


Back-transition to
L-mode if $\beta_N > 3$

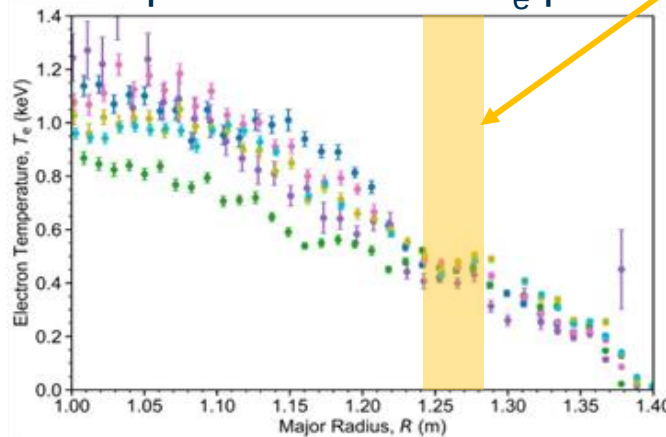


Long lived tearing mode observed in beam heated discharges

q profile from MSE constrained EFIT++

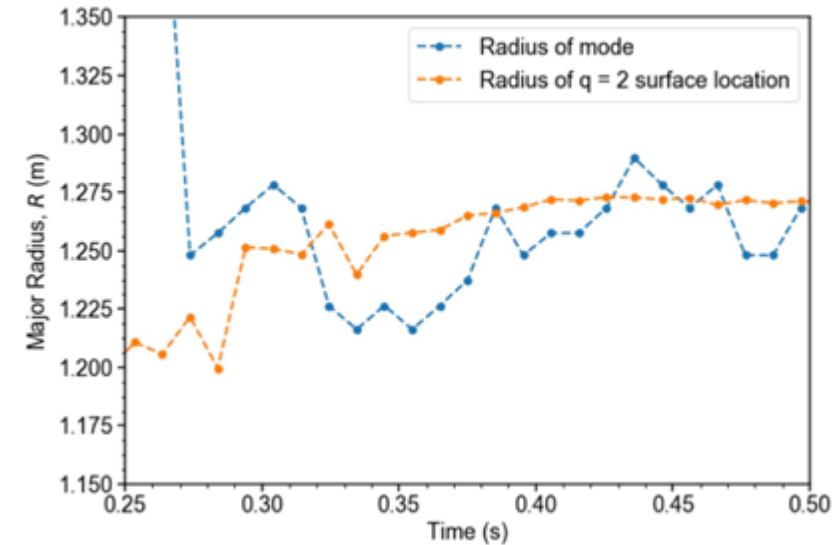


Mid-plane Thomson T_e profile



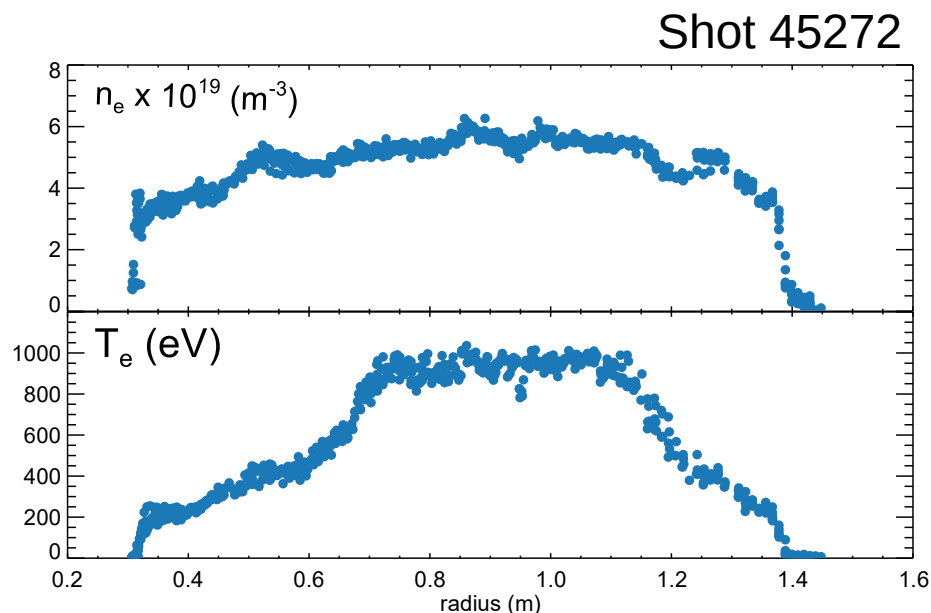
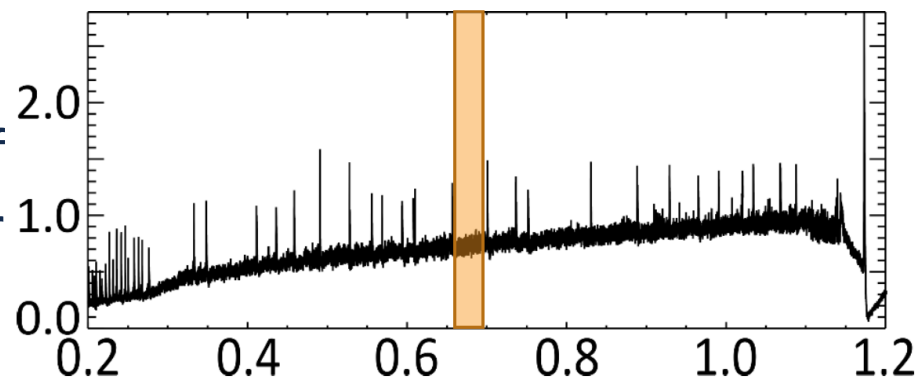
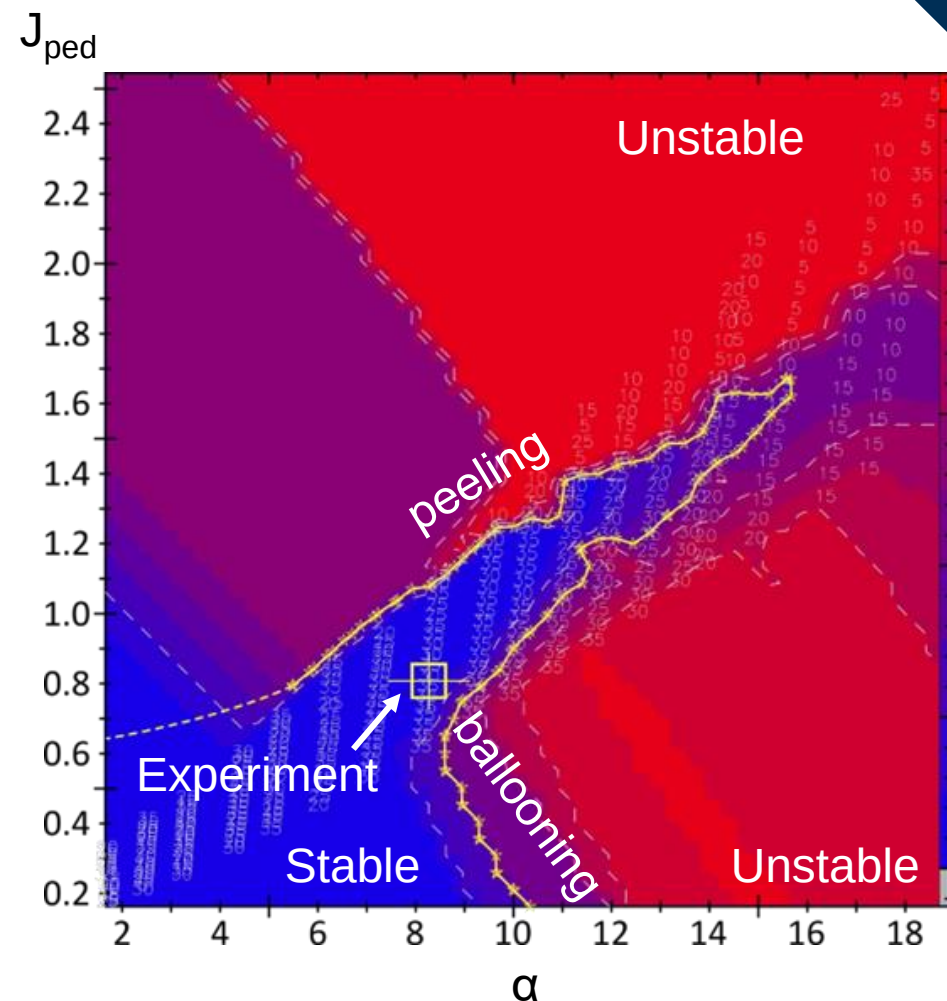
T_e profile flattening around $q = 2$ surface

Mode position consistent with position of 6kHz rotation frequency in core CXRS profiles



Access to peeling limited pedestals

- Compared to old MAST, α is roughly twice as high (steeper pressure gradient).
- Significantly extended region of stability into higher J_{ped} / α values

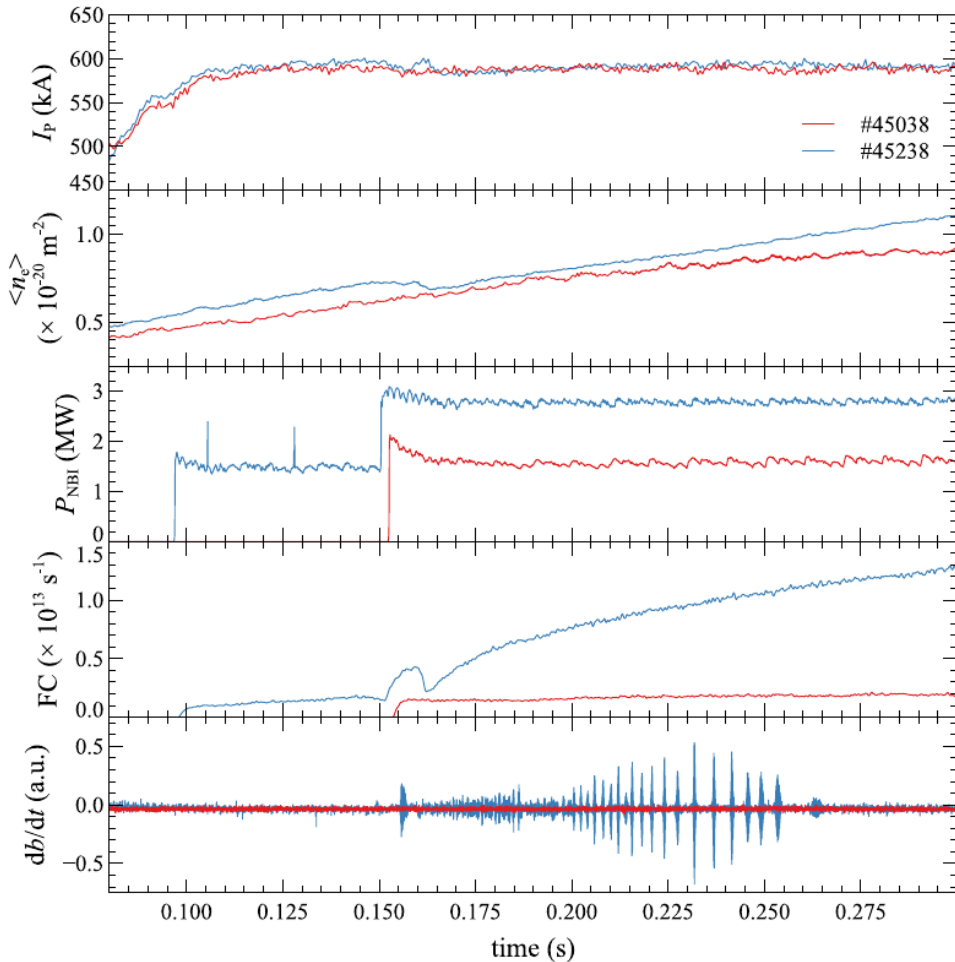
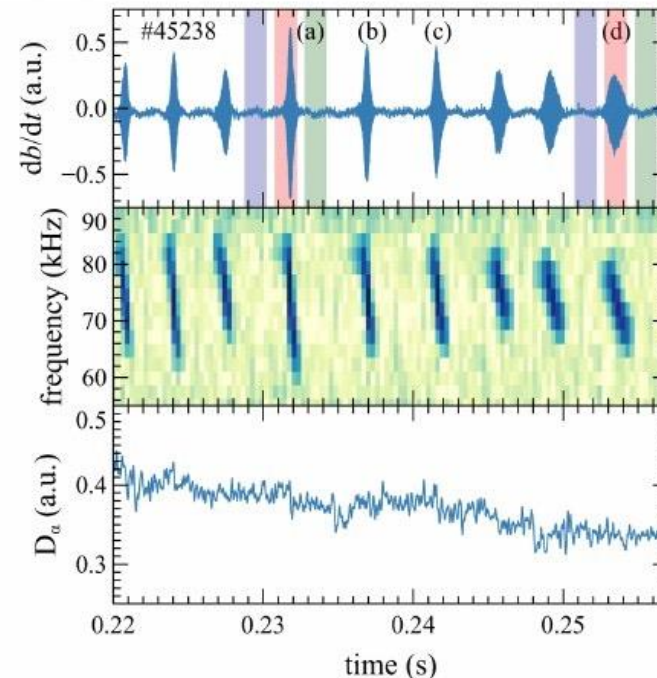
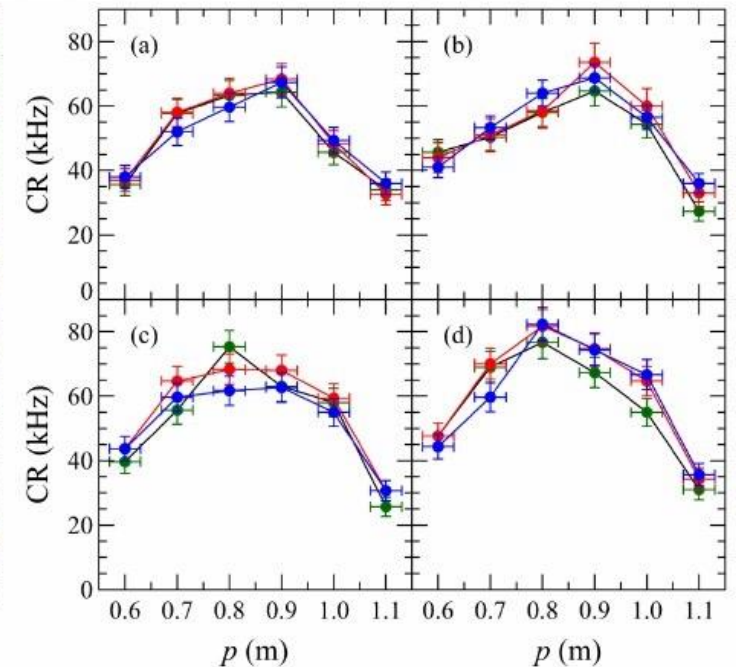


Observations of TAEs born by fast particles

Fast ions deposited by both NBIs are super-Alfvénic

- $V_{fi} \sim 2.5 \times 10^6 \text{ m/s} > V_A \sim 1.5 \times 10^6 \text{ m/s (core)}$

Expected central frequency of the toroidicity-induced gap in the shear Alfvén continuum of 80 kHz at the radial location equal to half the minor radius, where TAE's eigenfunctions usually have the largest amplitude



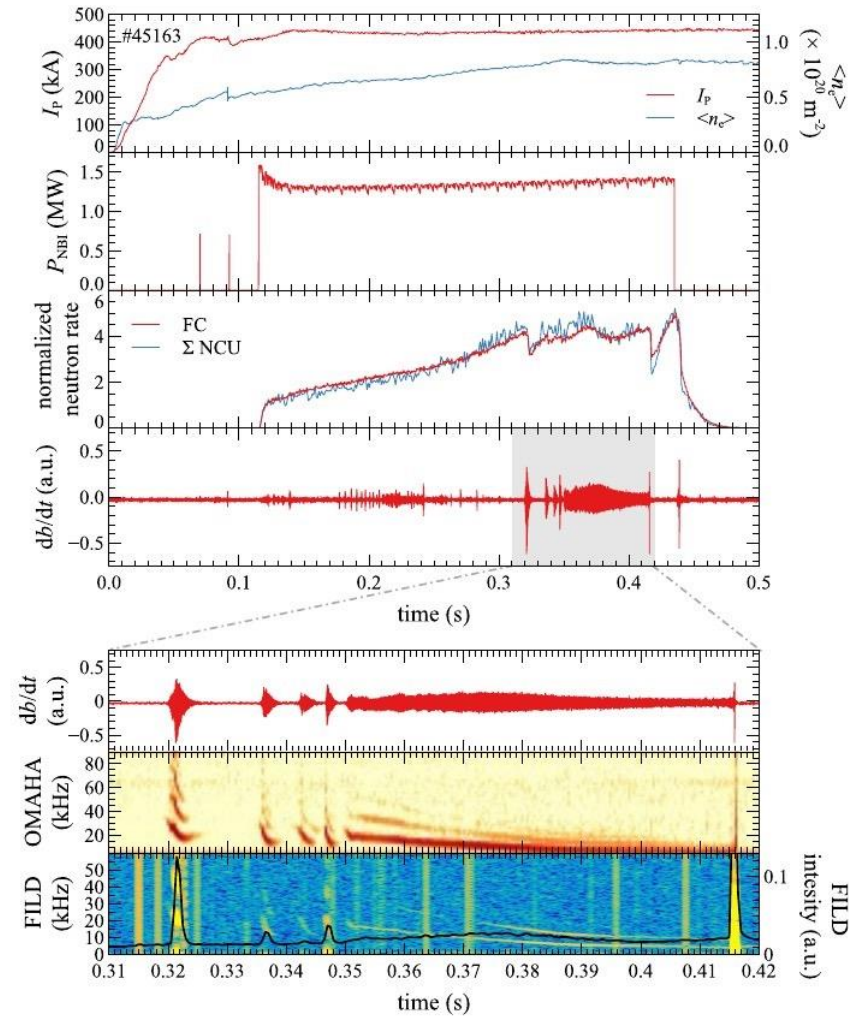
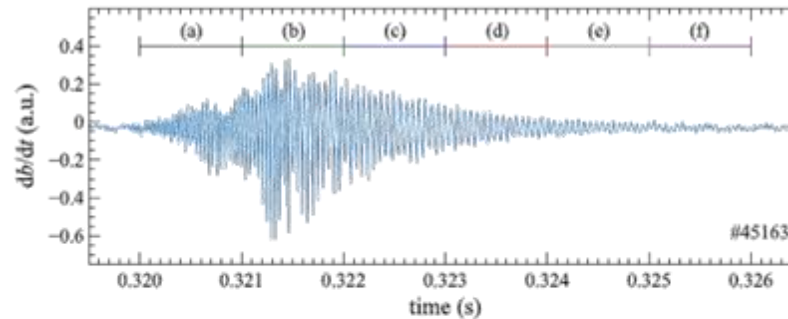
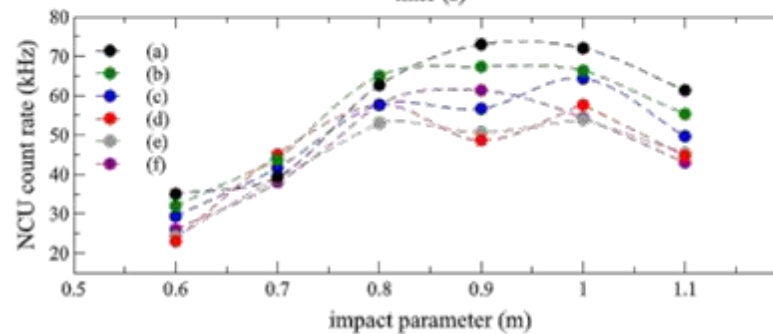
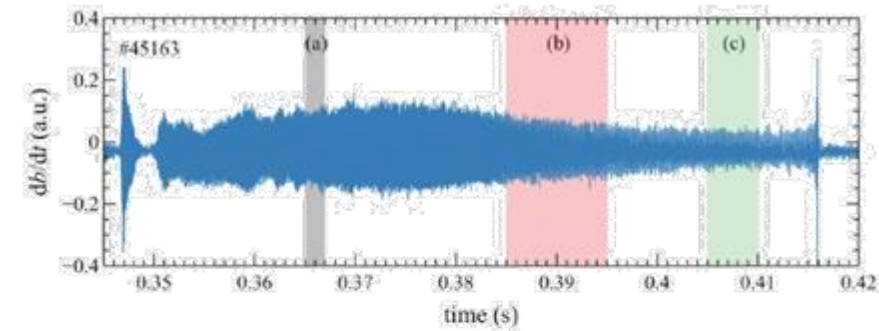
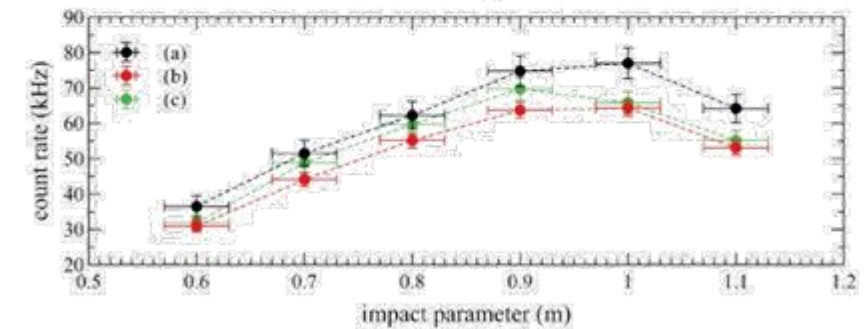
Lack of losses consistent with FILD measurements

Fishbones observed in low current, low density NBI heated plasmas

L-mode plasma, on-axis NBI only

Drop in neutron rate during fishbones due to fast ions

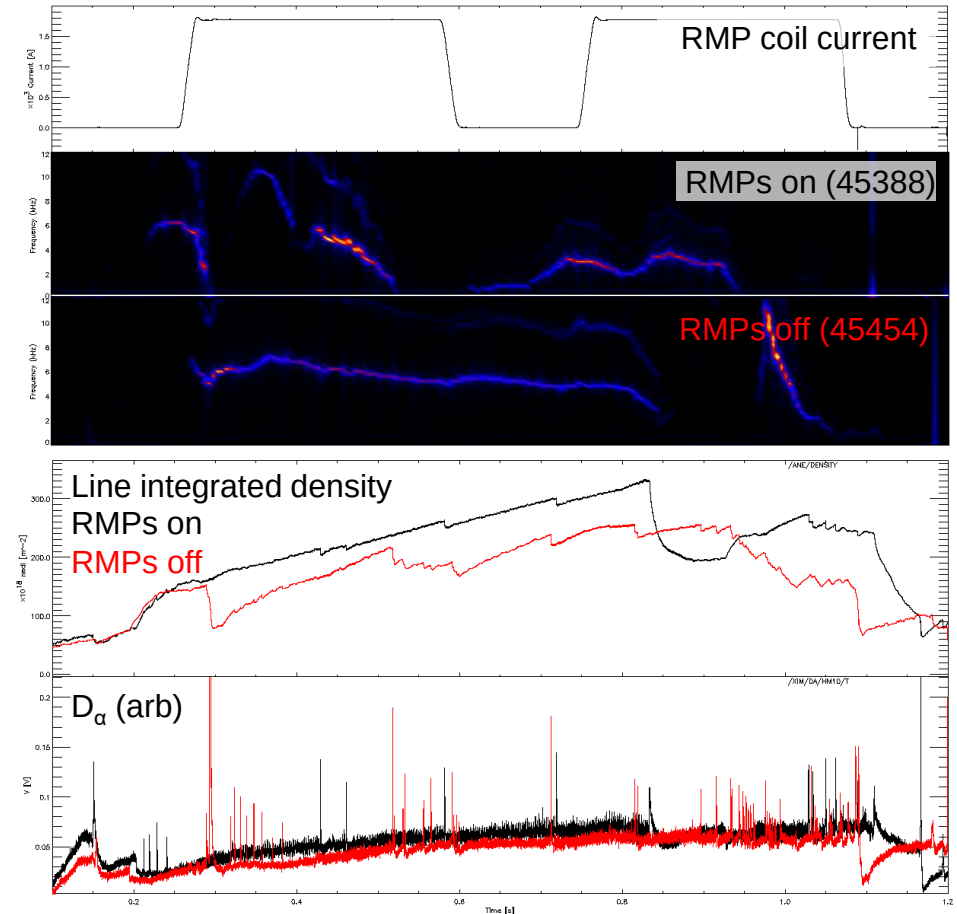
- No drop in core n_e , T_e during the bursts



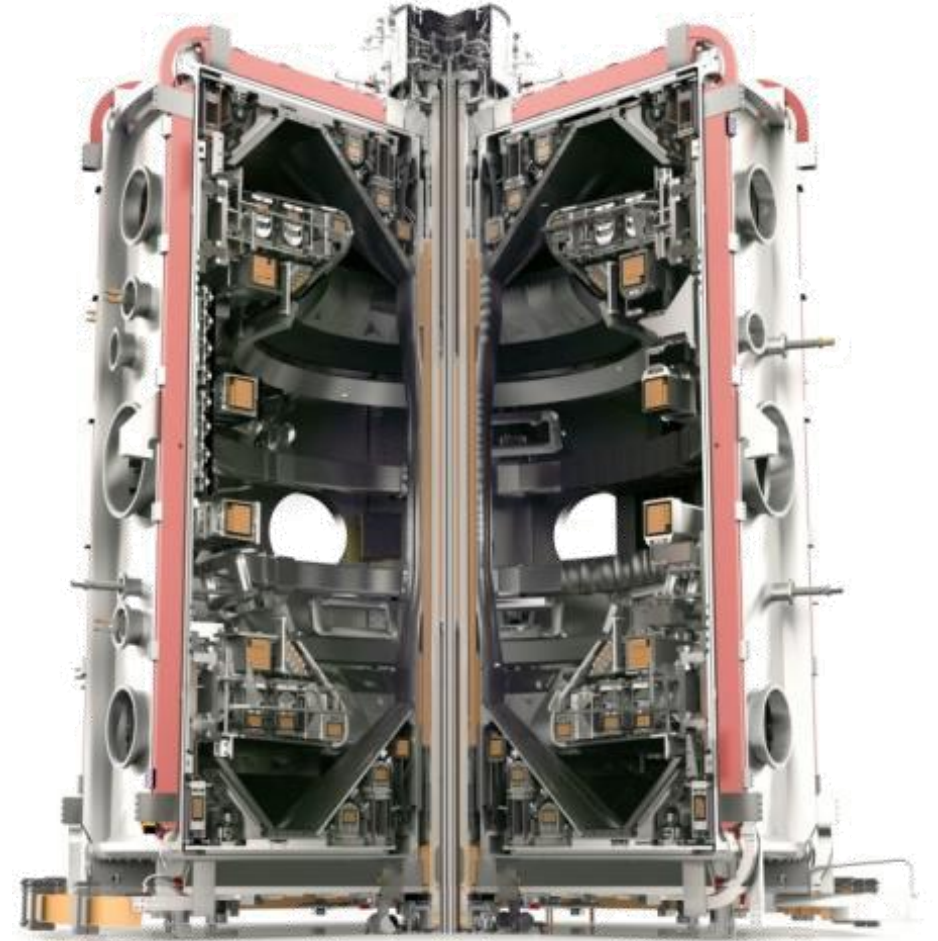
ELM mitigation with RMPs

ELM mitigation achieved with $n=1$ RMPs

- Application of RMPs causes benign 6kHz mode to lock
 - ELM frequency increases (c.f. **shot w/out RMPs**)
 - Density decreases
- Mode accelerates (unlocks) ELM frequency drops when RMPs removed

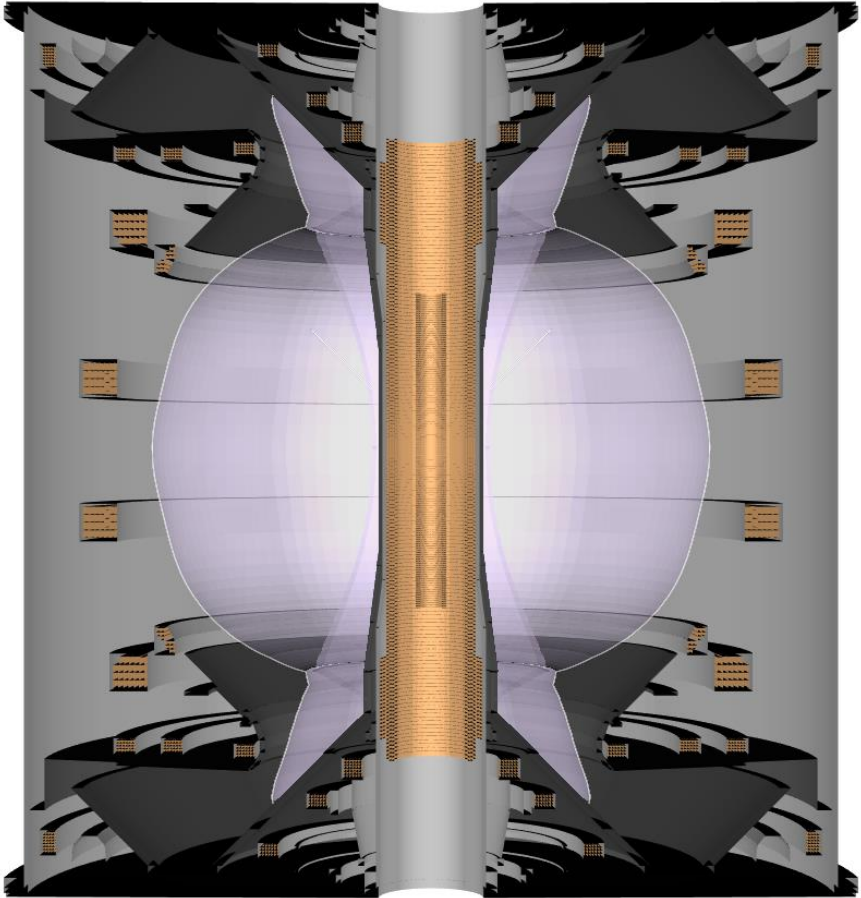


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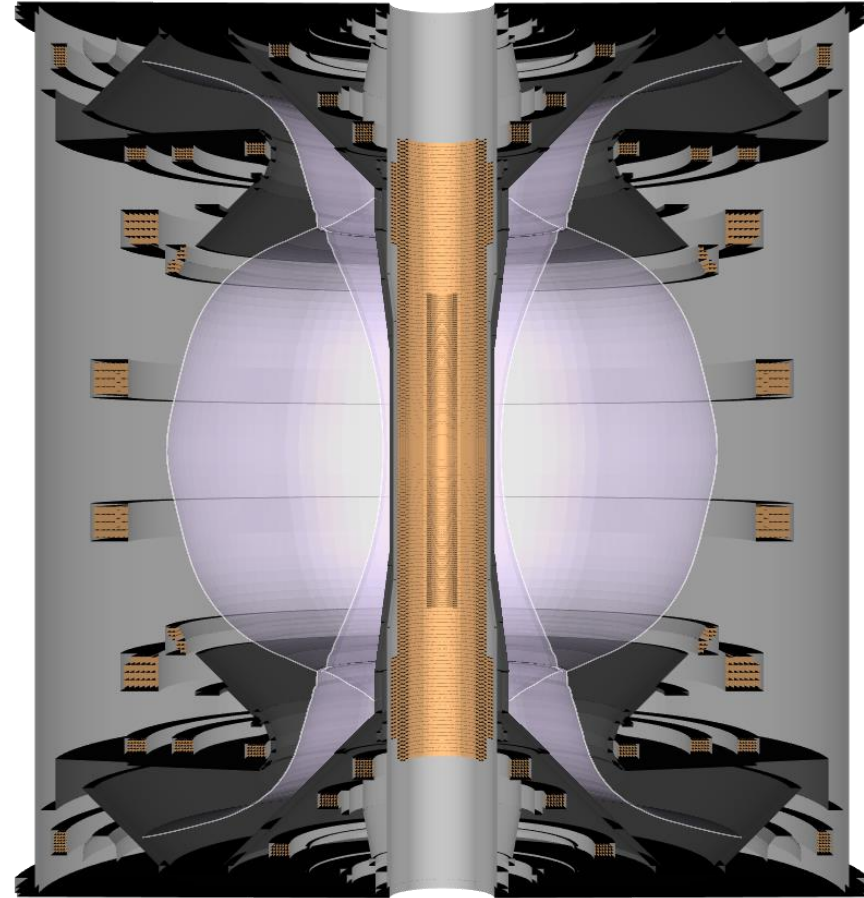


Benefits of the Super-X Divertor Configuration

Conventional



Super-X



Strike point at
higher radius

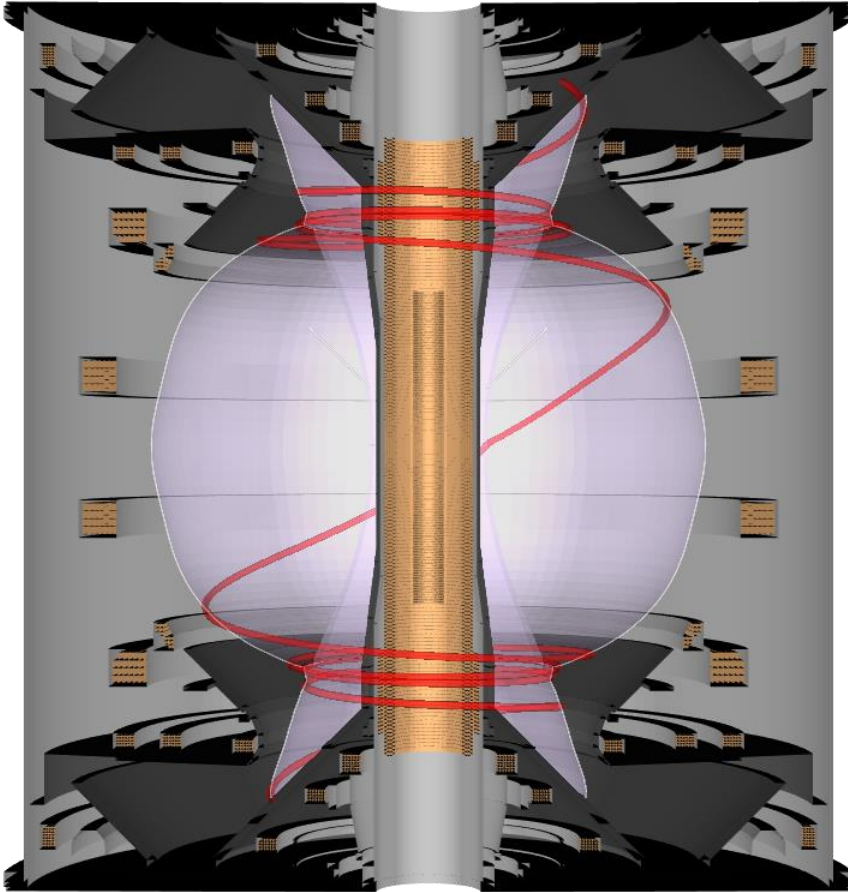


Power deposited
over larger area
(esp. in STs)

**Reduced fluxes to
divertor surfaces**

Benefits of the Super-X Divertor Configuration

Conventional



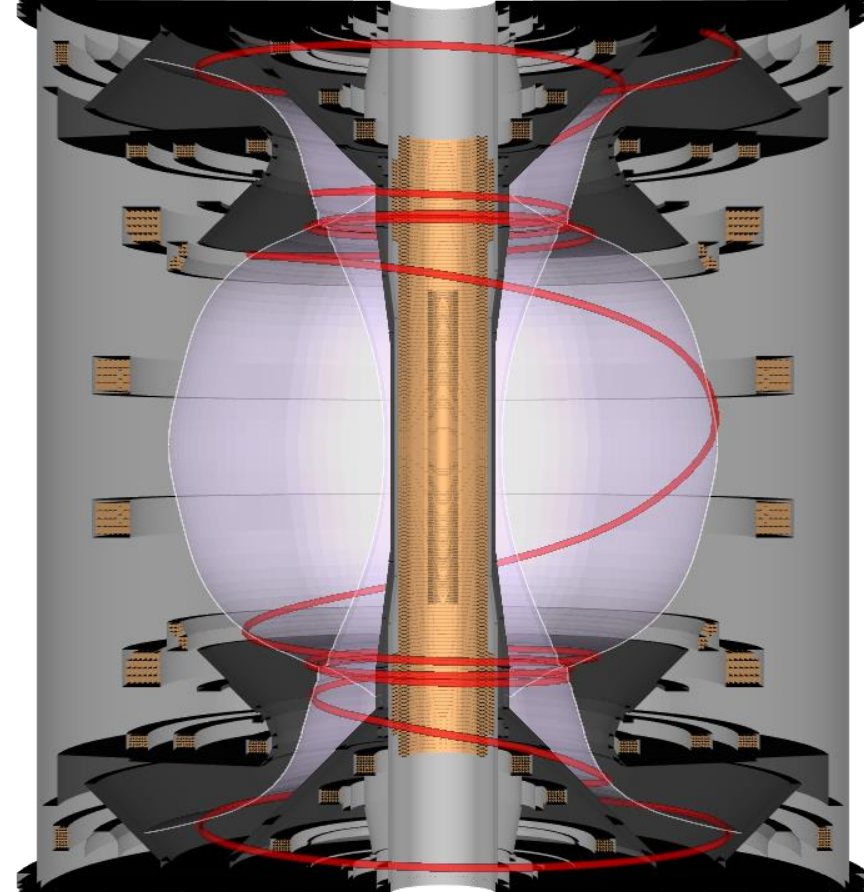
Low poloidal field in
divertor chambers



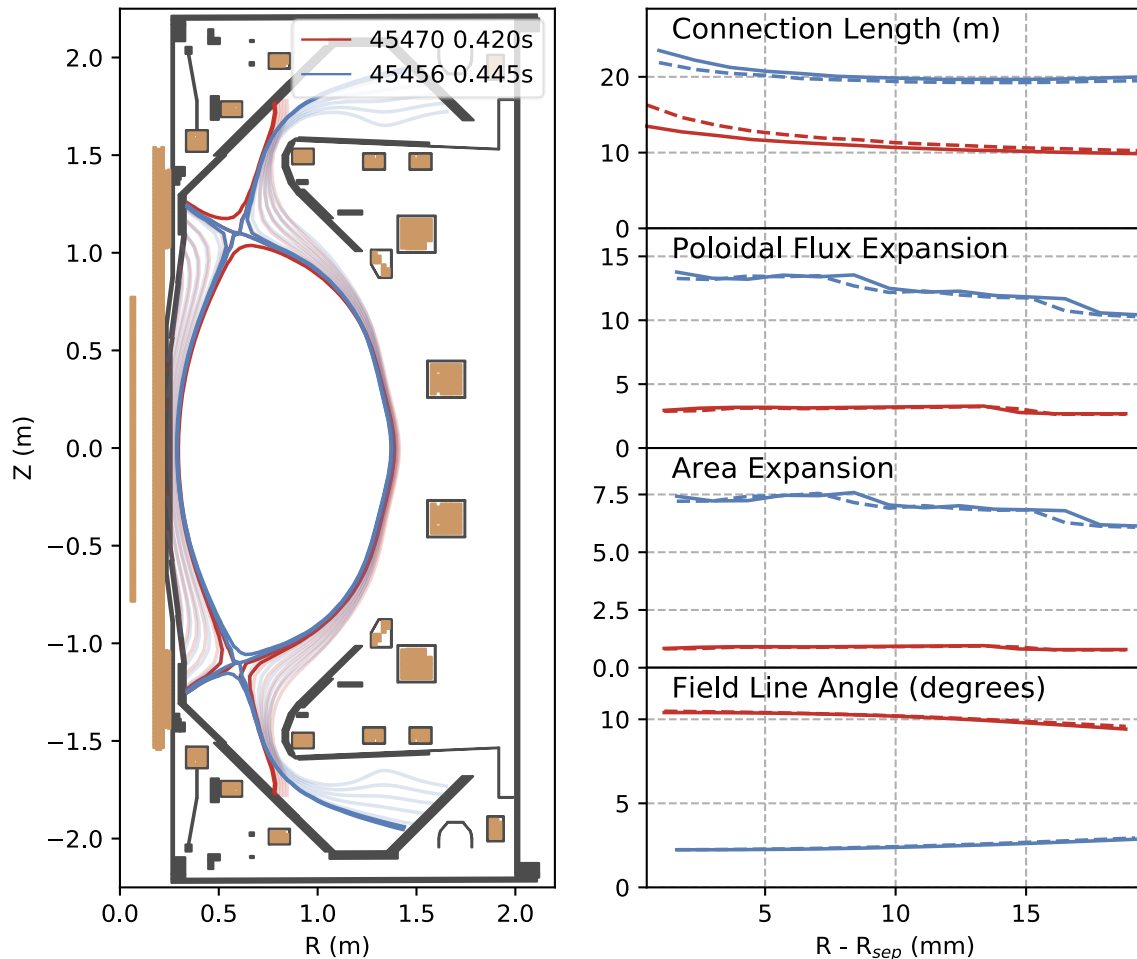
Longer field lines to
the divertor target

Improved access
to detachment

Super-X



Benefits of the Super-X Divertor Configuration

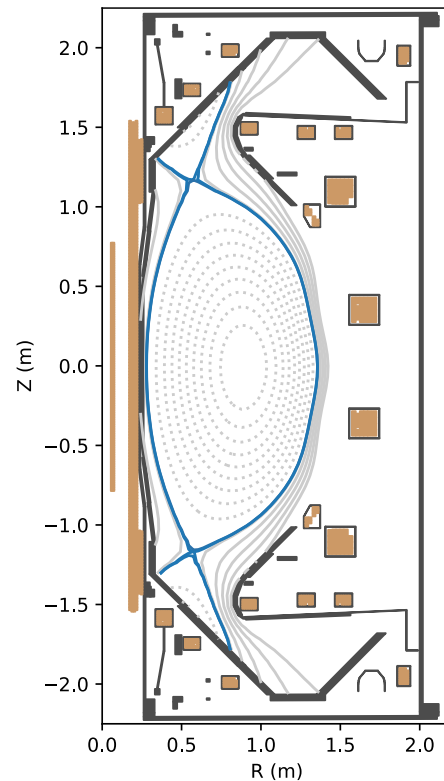
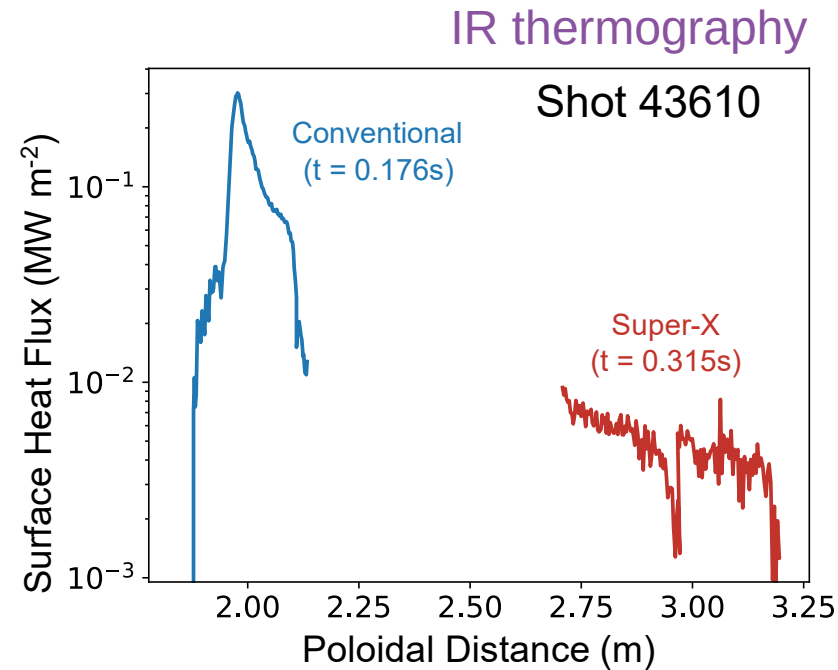
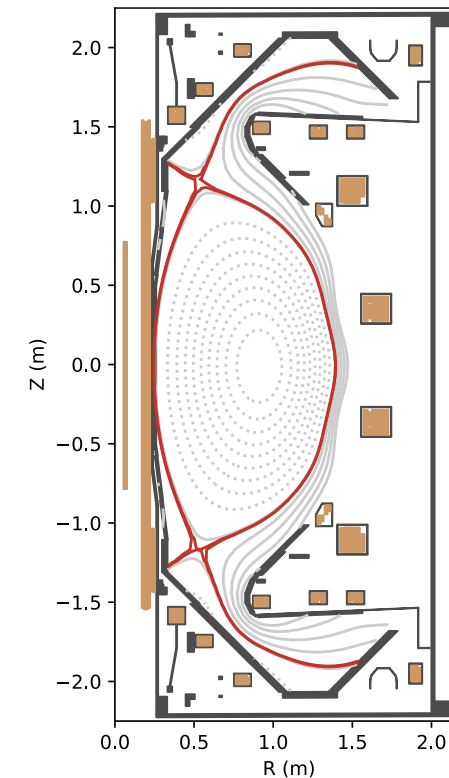


Conventional and Super-X divertor configurations were compared in ohmic and NBI heated experiments with similar core shaping

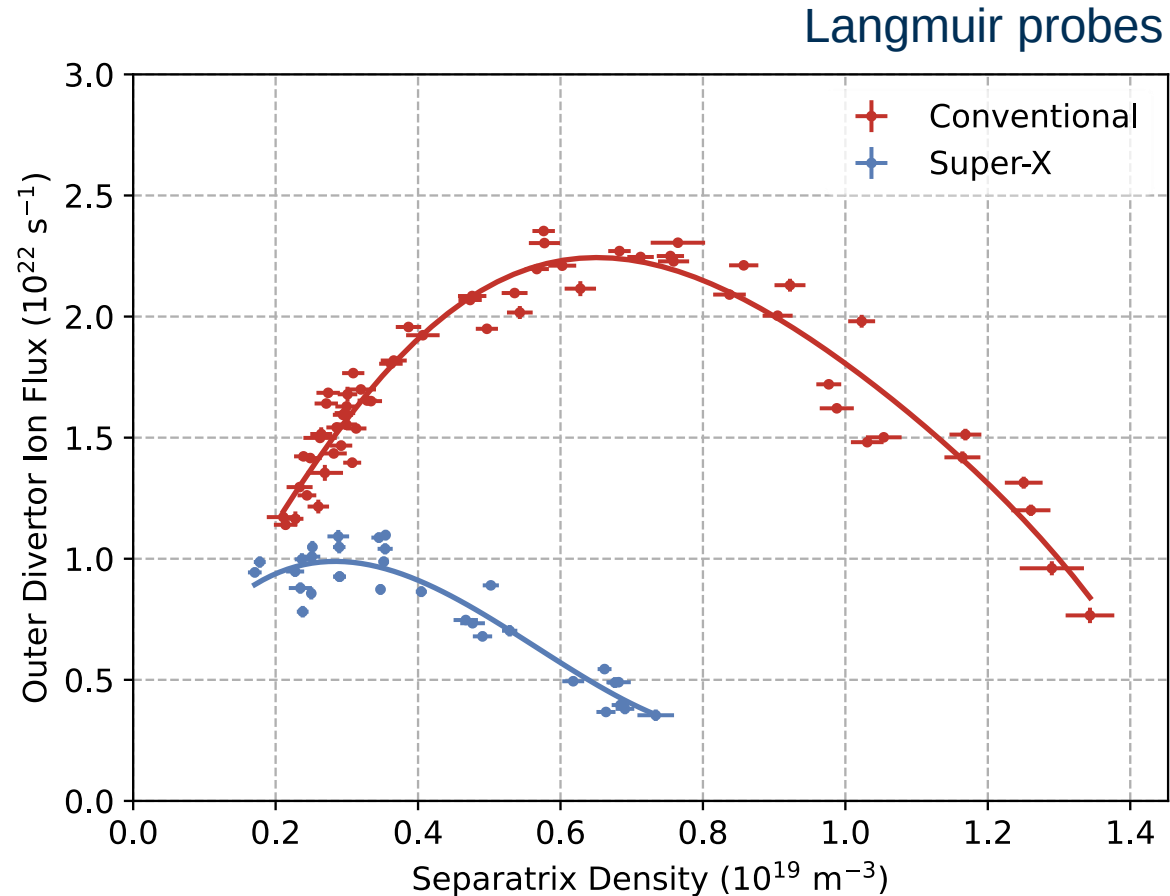
- Both are up-down symmetric and tightly baffled
- Power is deposited over much larger area of the divertor
- Super-X has 2x higher field line length

10x Reduction in Peak Heat Flux in the Super-X Configuration

Significant reduction in divertor power loads also observed in experiments with 3.2MW of NBI heating



2x Reduction in Detachment Threshold



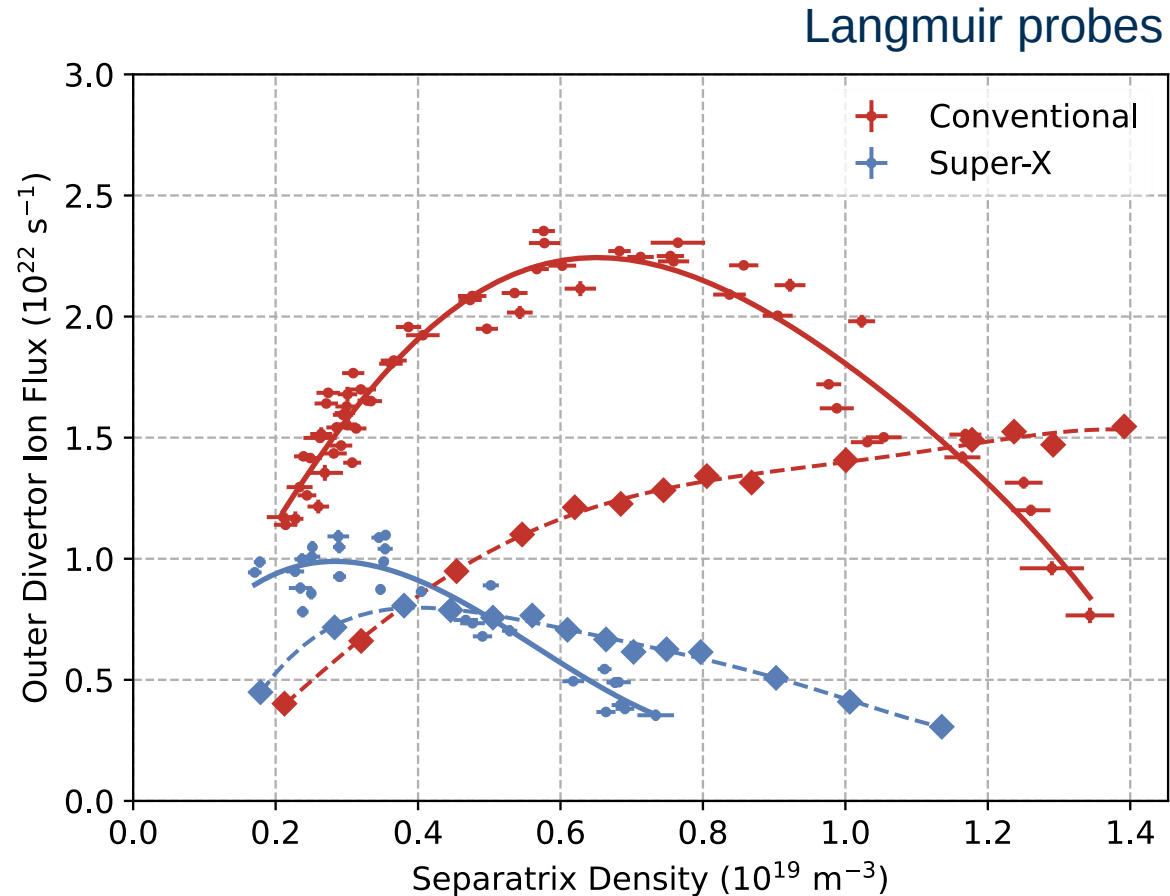
Detachment onset studied in detail in ohmic experiments

Density at the outer mid-plane to detach the outer divertor target factor ~ 2 lower in the Super-X configuration, consistent with analytic modelling*

- $n_{e,sep,thr} \propto \frac{1}{R_{target}}$

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

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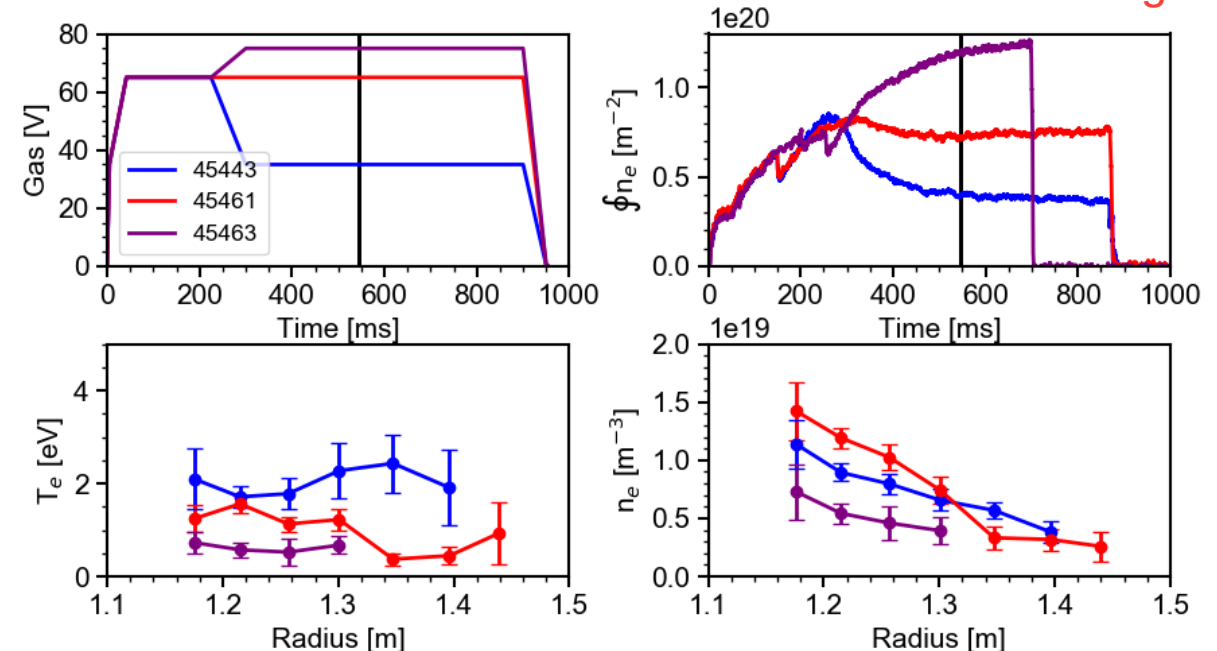
- $n_{e,sep,thr} \propto \frac{1}{R_{target}}$

Detachment in Super-X well reproduced by SOLPS-ITER simulations

Low divertor T_e in Super-X configuration

- Thomson scattering measurements confirm low T_e ($< 3\text{eV}$) across the divertor leg, even at lowest density ($0.1 \times n_{\text{GW}}$)
- Divertor electron density decreases with increasing fuelling & core density
 - Indicative of strongly detached divertors

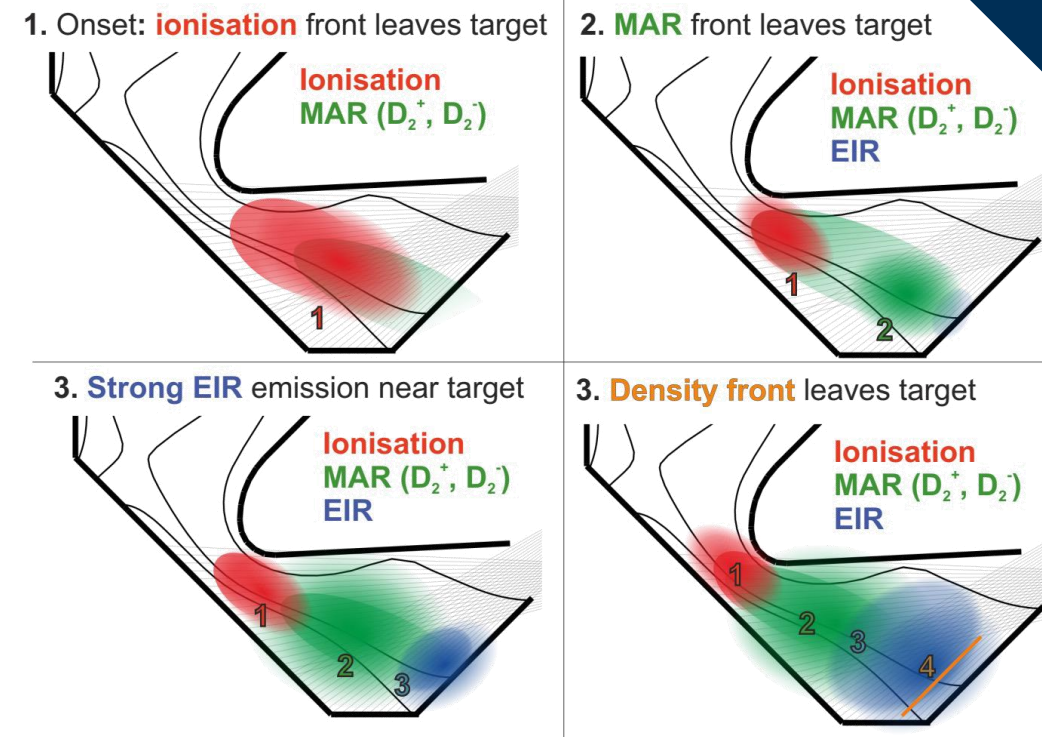
Divertor Thomson Scattering



Spectroscopic Measurements Illustrate Mechanisms Governing Detachment

Super-X detachment (ohmic L-mode):

1. **Ionisation** front 'detaches' from target
2. **Plasma molecule interactions (MAR)** 'detach' from target, $T_e < \sim 1\text{eV}$
3. **Electron-ion recombination (EIR)** appears ($T_e < 0.5\text{eV}$, $n_e \sim 10^{19}\text{ m}^{-3}$)
4. **Density front detaches** from target ($T_e \ll 0.5\text{eV}$, $n_e \ll 10^{19}\text{ m}^{-3}$)

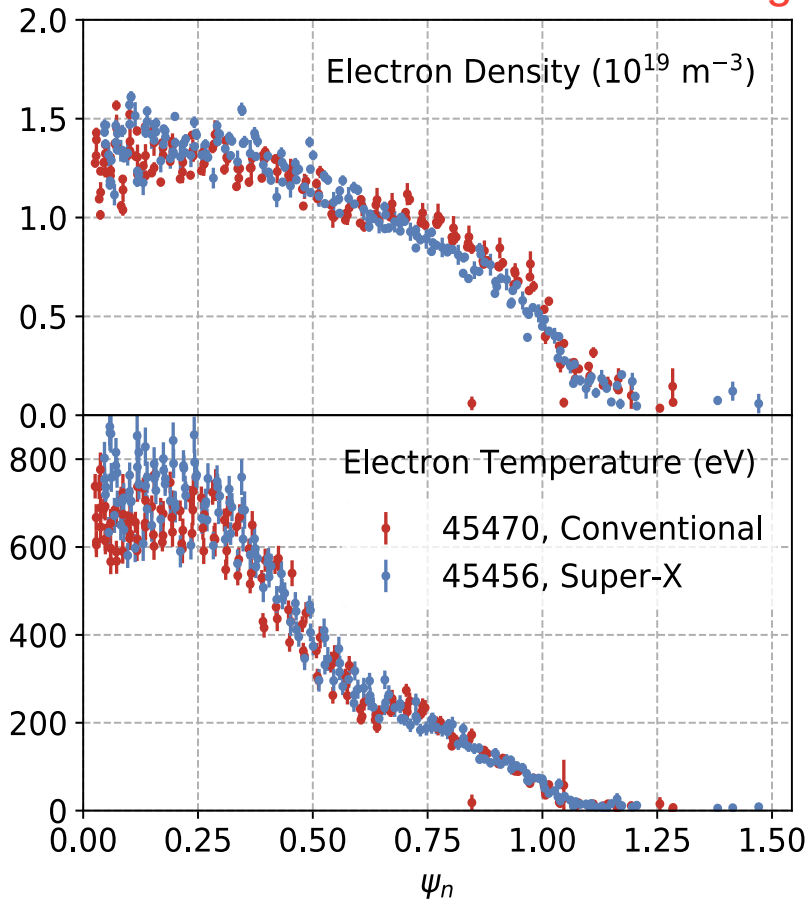


Tightly baffled SXD increases plasma neutral/molecule interaction → **PMR** critical for MAST-U SXD

However, **PMR** not included (properly) in plasma-edge physics codes → future work

No Loss of Confinement with a Detached Super-X Divertor in L-mode

Core Thomson Scattering

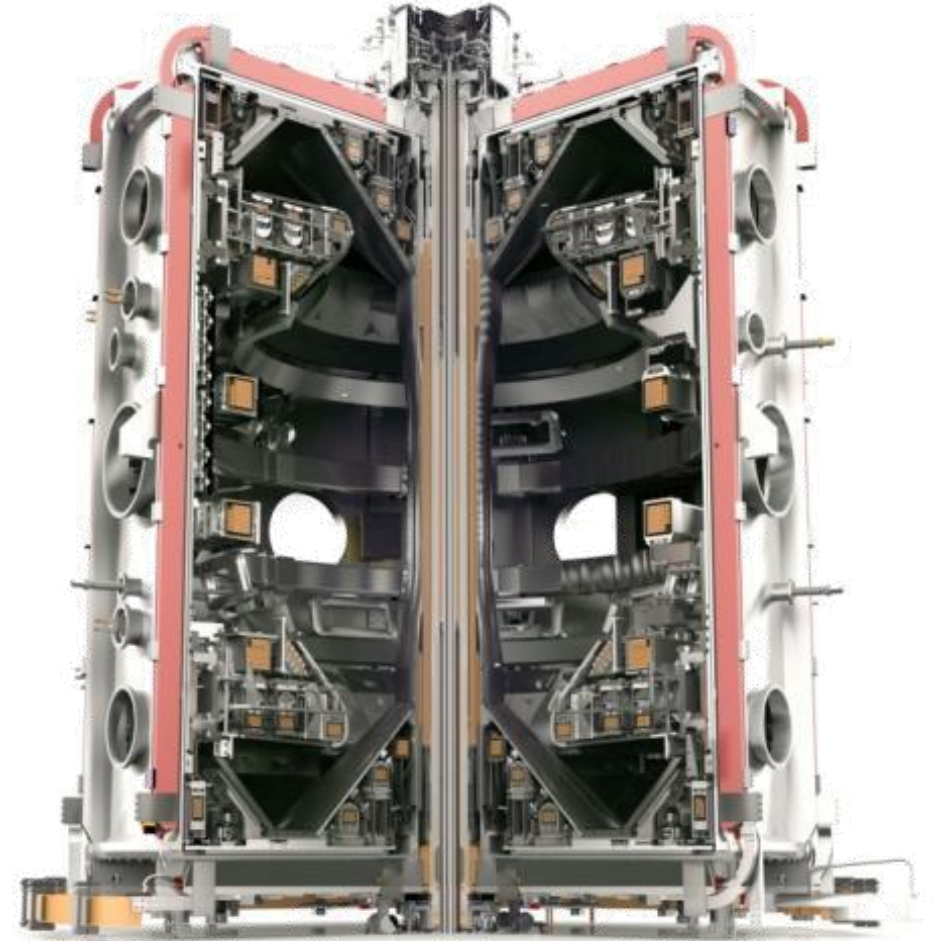


Confinement in the plasma core largely unaffected by the change in divertor configuration when the conventional divertor is attached and Super-X is detached

If conduction transports heat along field lines, would expect T_e at the separatrix to be higher in Super-X

- Interpretive simulations reproduce experiments, suggesting convection plays an important role

1. Introduction to MAST Upgrade
2. Developing high performance plasmas
3. Exploring plasma exhaust
4. Preparations for future campaigns
5. Summary



Preparations for future campaigns

MU02 physics campaign is currently underway

Internal programme divided into 4 topic areas:

- Integrated Scenarios
- Exhaust
- MHD & Pedestal Physics
- Fast Particles, Heating and Current Drive

~1/3rd run time allocated to EUROfusion Tokamak Exploitation experiments

Improved capabilities

Higher TF: 0.65 → 0.72T

Higher I_p : 0.75 → 1.0MA

Higher NBI power: 3.5 → 4.2MW

Improved plasma control

Real-time shape control

Density control

Detachment front position

Improved diagnostics

Fusion proton detector (FIU)

Divertor RFEA

Expanded divertor Thomson

Main chamber & divertor neutral pressure

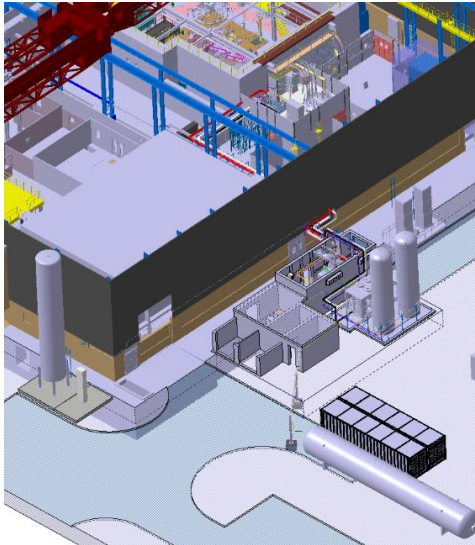
SXR emission

Divertor SPRED, mid-plane reciprocating probe

Preparations for future campaigns

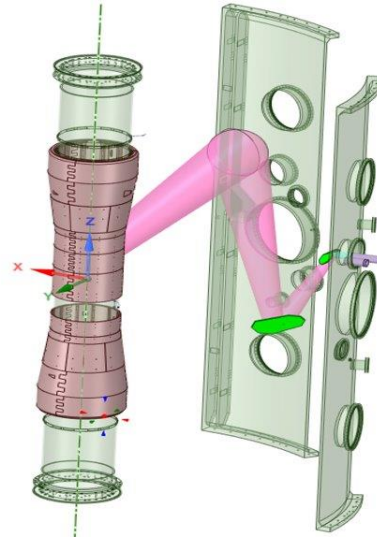
MU03 (2023)

Cryopumping



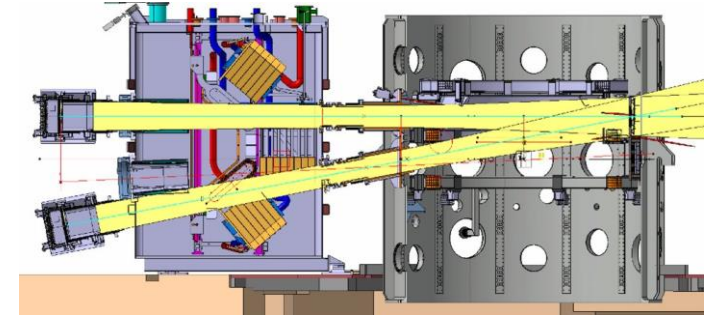
MU04 (2024)

1.6MW EBW Heating
& Current Drive



MU05 (2025)

Additional 5MW NBI heating



Diagnostics upgrades

Preparations for future campaigns

MU03 (2023)

Cryopumping

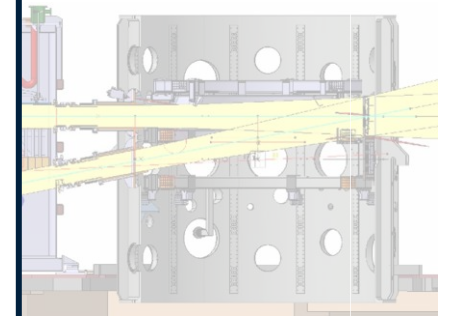
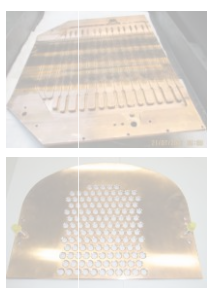


MU04 (2024)



MU05 (2025)

MW NBI heating

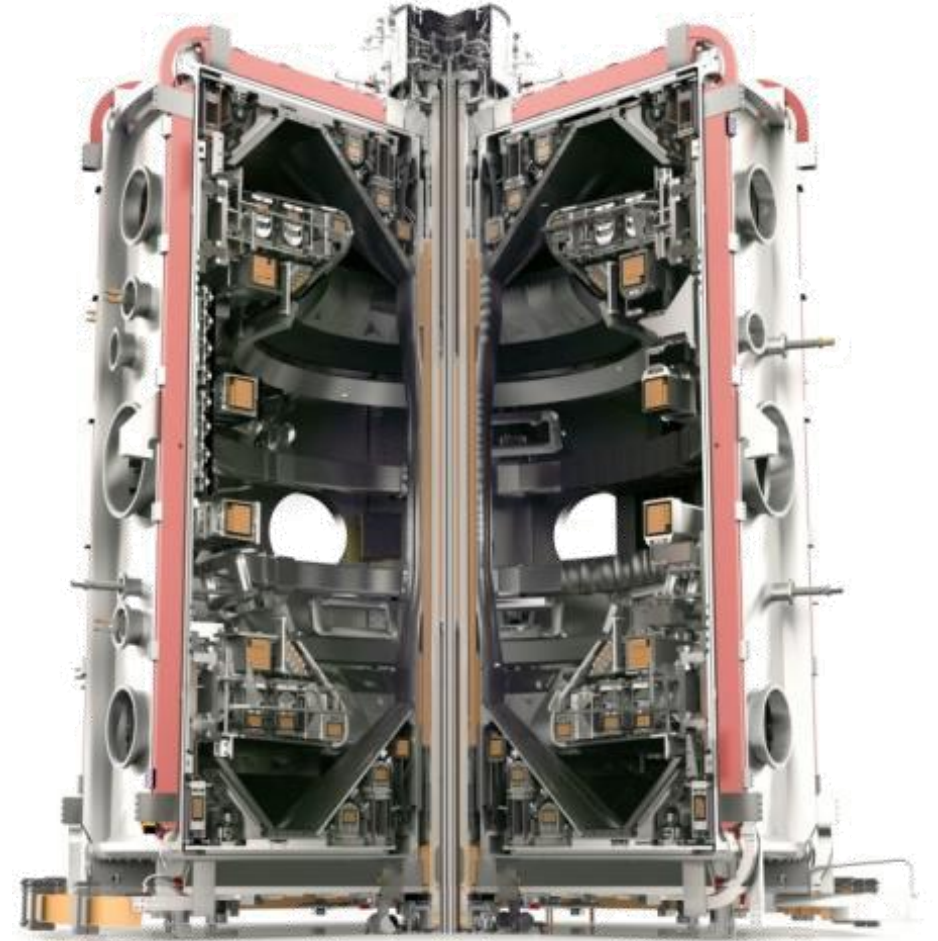


Future campaigns and machine enhancements will concentrate on addressing key physics issues for fusion

- Testing alternative divertors at higher heat flux
- Integration of good stationary core and pedestal confinement with strong dissipation in the divertors
- Heating and current drive

Diagnostics upgrades

1. Introduction to MAST Upgrade
2. Developing high performance plasmas
3. Exploring plasma exhaust
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Summary

Results from the first physics campaign on MAST Upgrade are improving our understanding of key physics issues for STs and future tokamak devices

- Significant reduction in divertor heat flux and detachment threshold observed in the Super-X configuration compared with a conventional divertor
- Achieved high-performance H-mode scenarios
- Achieved pedestals limited by peeling instabilities, potentially aiding access to stationary ELM-free scenarios and Super H-mode
- ELM mitigation has been observed with Resonant Magnetic Perturbations
- Fast particle driven instabilities (TAEs, fishbones) have been excited by on-axis NBI

Future campaigns will have improved heating and current drive, control and diagnostics to enable detailed physics studies in more reactor-relevant regimes