Overview of the MAST Upgrade Physics Programme: Testing novel concepts at low aspect ratio to inform future devices

UK Atomic Energy Authority

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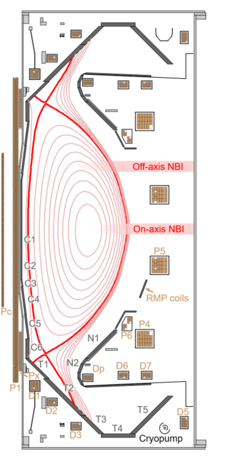
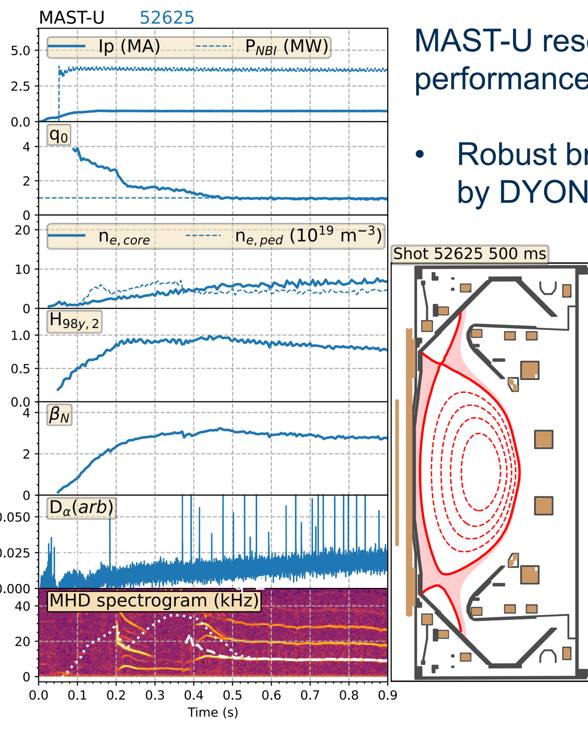
MAST-U Capabilities



Parameter	Design Value	Achieved
R/a (m)	0.7 / 0.5	0.7 / 0.5
Bϕ (0.8 m)	Maximum 0.8 T	0.72 T
Ip (MA)	2.0	1.0
$T_{e,core}$ $T_{i,core}$	2.0 keV, 3.0 keV	
Elongation (κ)	2.5	2.5
Triangularity (δ)	0.6	-0.3 →0.6
Max. NBI power	2.5 MW on-axis 2.5 MW off-axis	2.0 MW on-axis 2.0 MW off-axis
Pulse length (s)	5	1.2

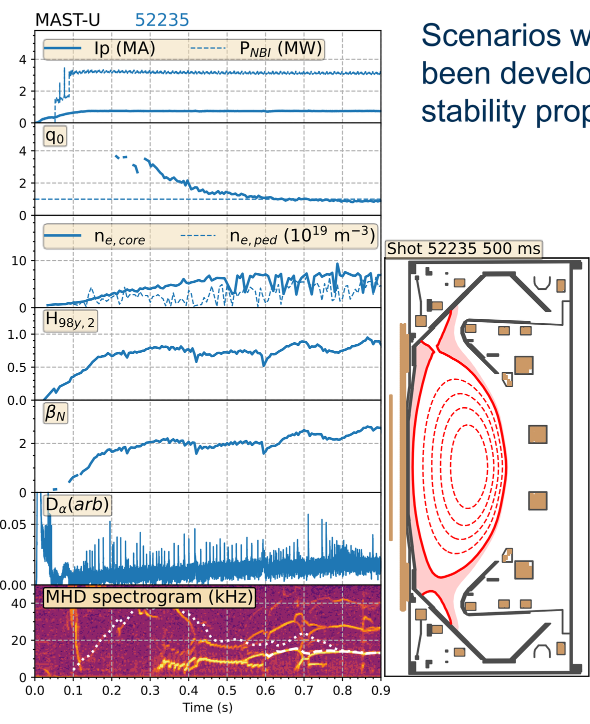
Robust, high performance plasma scenarios have been developed



MAST-U research is underpinned by high-performance, reproducible plasma scenarios

- Robust breakdown and ramp-up informed by DYON and CREATE-BD modelling
- Early neutral beam injection to maintain an elevated monotonic q profile avoids internal reconnection events
- Thermal confinement large in agreement with ITER scaling, gradually degraded by 2/1 mode

Operation at higher elongation enables sustainment of elevated q profiles

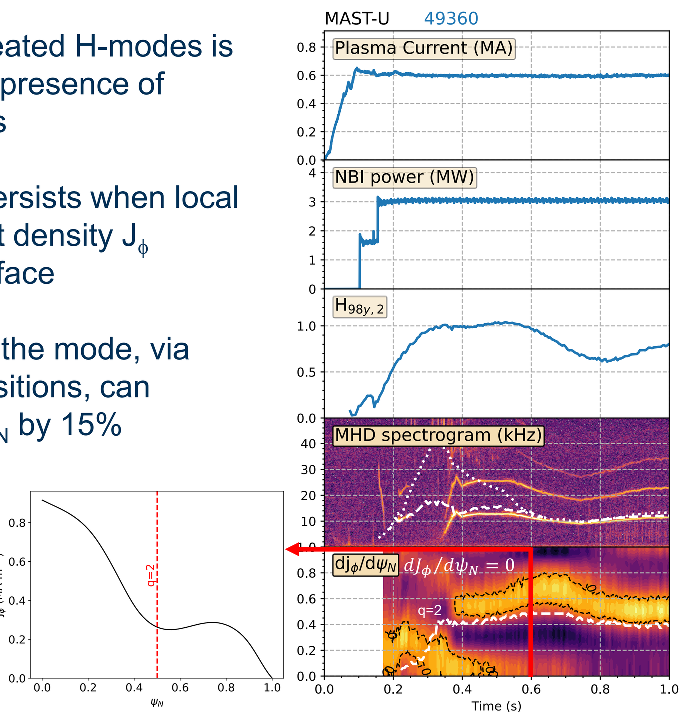


Scenarios with elevated q profiles have been developed to study confinement and stability properties

- No limiter phase to improve plasma purity
- Strong shaping (κ~2.5) supports sustainment of an elevated q profile
  - q_0 > 2.0 for 0.4 (0.2s with lower shaping)
- Early heating and L-H transition to maintain low l_i and good vertical stability at high κ
- Relatively high plasma volume (10 m^3 cf 8 m^3) reduces power density and confinement

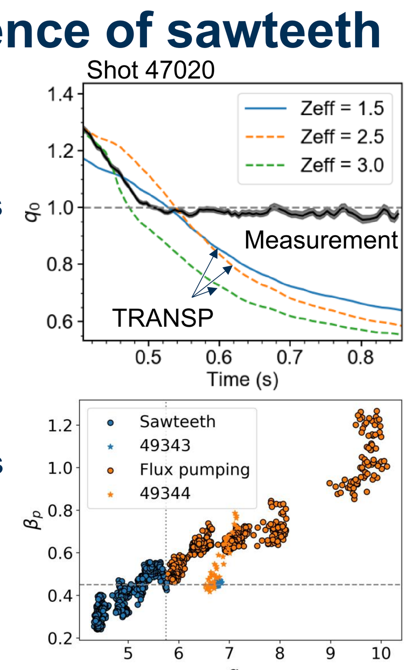
Prevalent performance-limiting instabilities are 2/1 modes

- Performance of NBI heated H-modes is typically limited by the presence of m/n=2/1 tearing modes
- Mode is excited and persists when local minimum in the current density J_ϕ coincides with q=2 surface
- Temporarily disrupting the mode, via vertical kicks, H-L transitions, can temporarily increase β_N by 15%

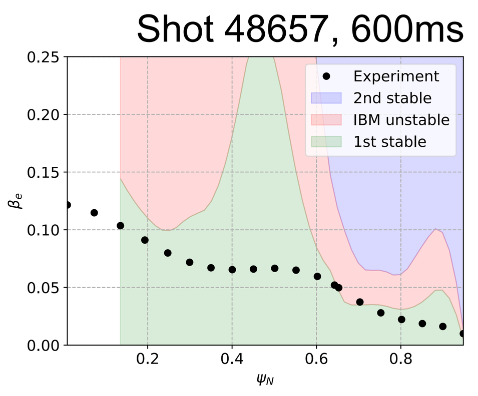


Evidence for flux pumping observed maintaining q_0~1 in the absence of sawteeth

- On-axis safety factor, q_0, is typically above 1 in the absence of sawteeth, indicative of a flux pumping mechanism when on-axis and off-axis neutral beam heating is applied
- Operating space in sawtoothing and flux pumping regimes has been identified
- Rotational coupling between q=1, q=2 surfaces during flux pumping, suggesting differential rotation between them plays a role



MAST-U Experiments Test Limits of Local Gyrokinetic Models

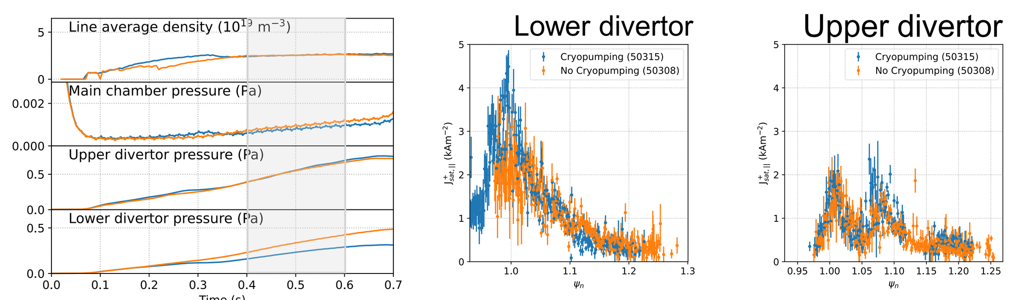


High beta (β_N~4) experiments have accessed a regime where local gyrokinetic simulations exhibit high fluxes and do not saturate

- Threshold to access regime where Maxwell stress is comparable to Reynolds stress
  - Ideal ballooning stability used as a proxy
- MAST-U can access this regime due to high flow shear
  - Gyrokinetic simulations predict high fluxes when flow shear is omitted

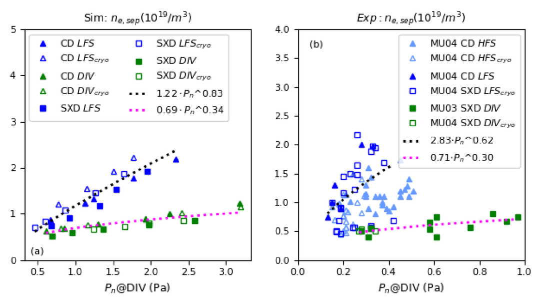
Impact of cryopumping is localised to the lower divertor chamber

- Up to 50% reduction in lower divertor neutral pressure, main chamber and upper divertor are unaffected
- Hotter, less detached divertor conditions in the lower divertor



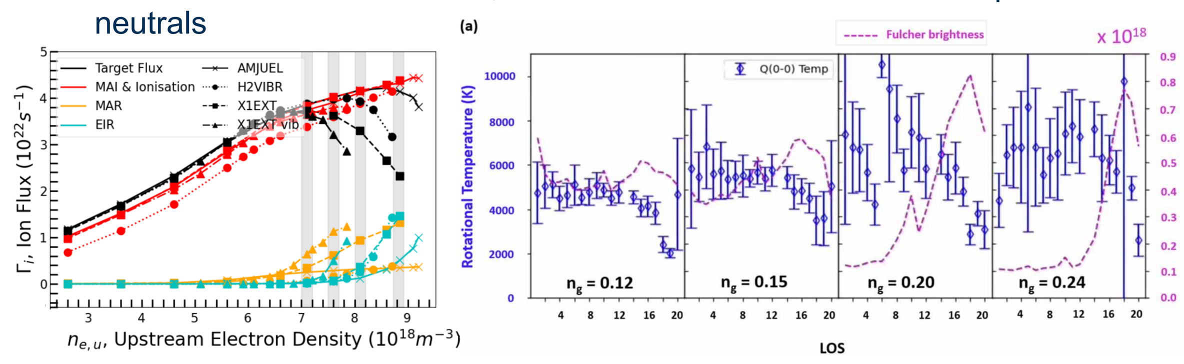
Fuelling location significantly affects the separatrix density

- Fuelling impact on upstream density primarily impacted by fuelling location rather than divertor configuration or cryopump
- SOLPS simulations recover the trend but significantly overestimate divertor neutral pressures compared to experiment



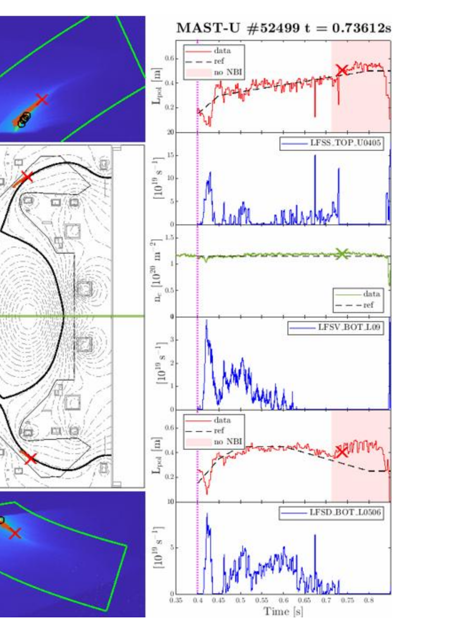
Plasma-Molecule Interactions Influence Divertor Detachment

- Inclusion of vibrationally rates of plasma-neutral interactions can reduce the predicted detachment threshold by SOLPS-ITER by ~20% in MAST-U conditions
- Elevated D_2 rotational temperature is observed as the outer divertors detach on MAST-U and TCV, indicates momentum transfer from plasma to neutrals



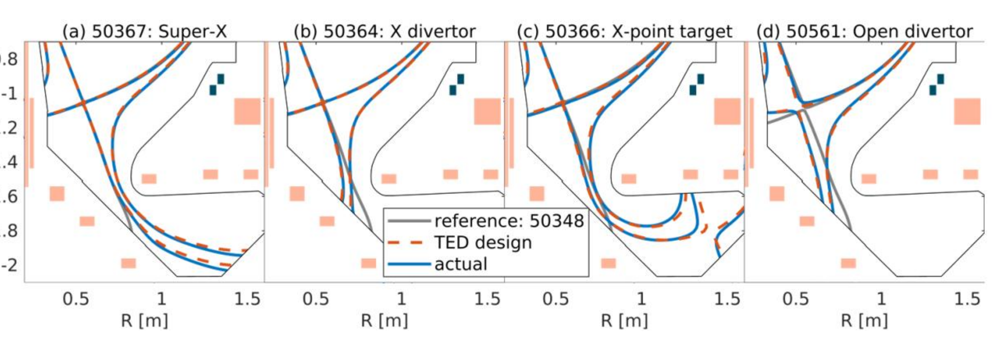
Tightly Baffled Divertors Enable Independent Detachment Control

- Applying detachment control to upper and lower divertors enables their detachment state to be varied independently with D_2 fuelling in NBI heated L-mode experiments
- Control of the density of the plasma core can be performed independently of detachment state of both divertors

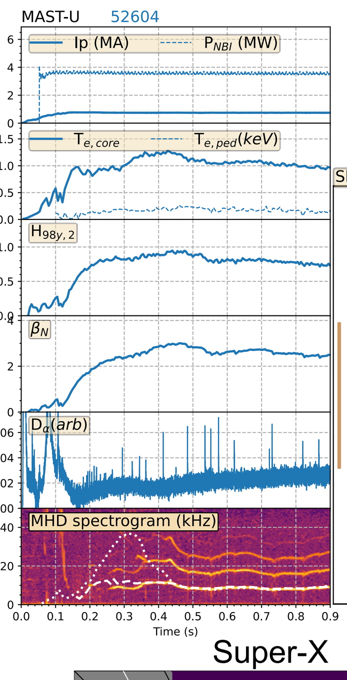


Development of divertor configurations accelerated with Tokamak Exhaust Designer

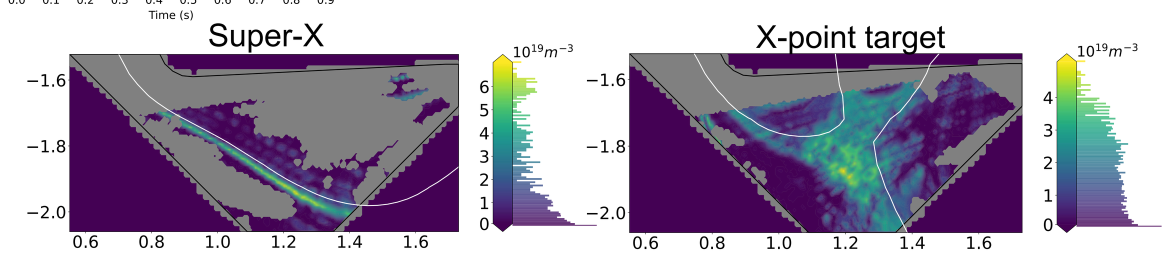
- Exploits spherical harmonics to represent flux from poloidal shaping coils to accelerate calculations
- Enables the development of feedforward and feedback divertor shape controllers
- Linear constraints are easily accommodated to specify the position of the separatrix and null points, flux expansion, etc within machine limits



Core-Edge Integration Observed with X-Point Target Divertor Configuration

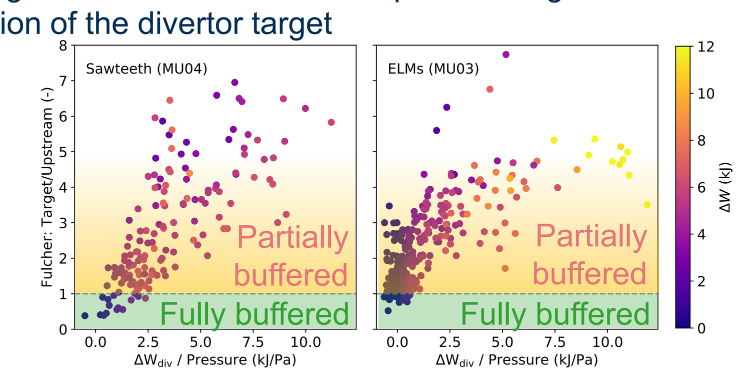


- Modest impact of outer divertor configuration on the edge pedestal or global confinement
- Consistent with a fixed ionisation front position as X-point target is formed, upstream of the secondary nulls
- T_e along outer divertor legs lower in the X-point target (< 1 eV) than in the Super-X configuration (~1-1.5 eV)
- Divertor density profiles inferred from are significantly broader in the X-point target configuration, promoting stronger plasma neutral interactions



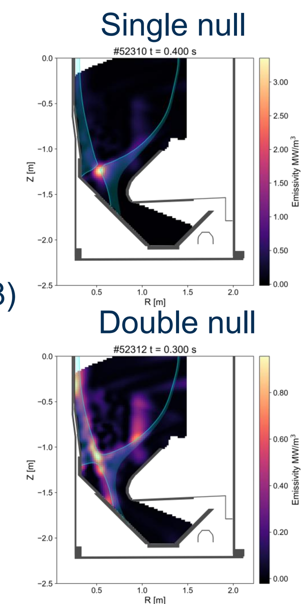
Buffering of transient heat loads observed in the Super-X configuration

- Power loads due to ELMs and sawteeth with < 2 kJ energy can be fully buffered with similar dependence of buffering on divertor neutral pressure
- Partial buffering is observed of transients of up to 5 kJ
- Buffering is more effective in the Super-X configuration due to geometric expansion of the divertor target



X-point radiator established with N_2 seeding for the first time in a spherical tokamak

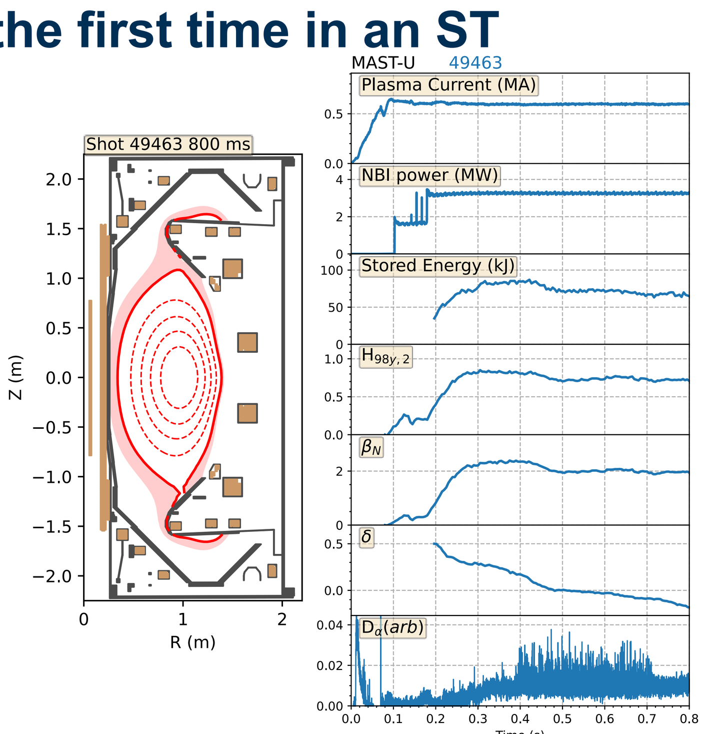
- Radiation localised near the lower X-point in single null, more broadly distributed radiation on the high-field side in double null
- Onset of X-point radiator regime coincides with reduction in energy confinement ($H_{98y,2}$ 1.0 → 0.8)
  - Higher N_2 seeding results in H-L back-transition in single-null or onset of ELM-free pedestal regime in double-null
  - Inner and outer divertor power loads significantly reduced



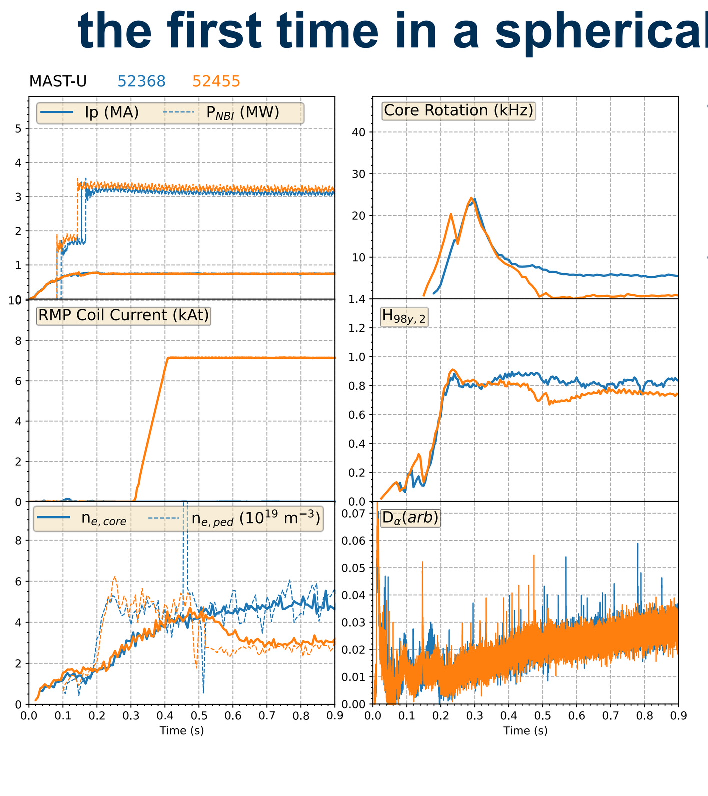
Absence of ELMs observed at negative triangularity for the first time in an ST

Transition from type-III to ELM-free edge has been observed at sufficiently negative triangularity

- First observation in a low aspect ratio tokamak
- Transition to ELM-free regime occurs at δ_{CRIT} ~ -0.06
- Closure of access to region of 2[nd] ballooning stability *precedes* transition to ELM-free edge, unlike TCV, DIII-D



Initial evidence of RMP ELM suppression for the first time in a spherical tokamak



- ELM mitigation with static and rotating n=1 RMPs has been observed in double null
- ELMs suppression with RMPs observed for the first time in a spherical tokamak
  - Observed using RMPs with dominant n=3 component applied to single null plasmas
  - Absence of ELMs accompanied by density pump-out and strong rotation braking
  - Persistence of T_e pedestal shows plasma remains in H mode