Exploring pathways to reactor-relevant integrated scenarios in MAST-U through targeted trade-offs in plasma shape, stability, and density control

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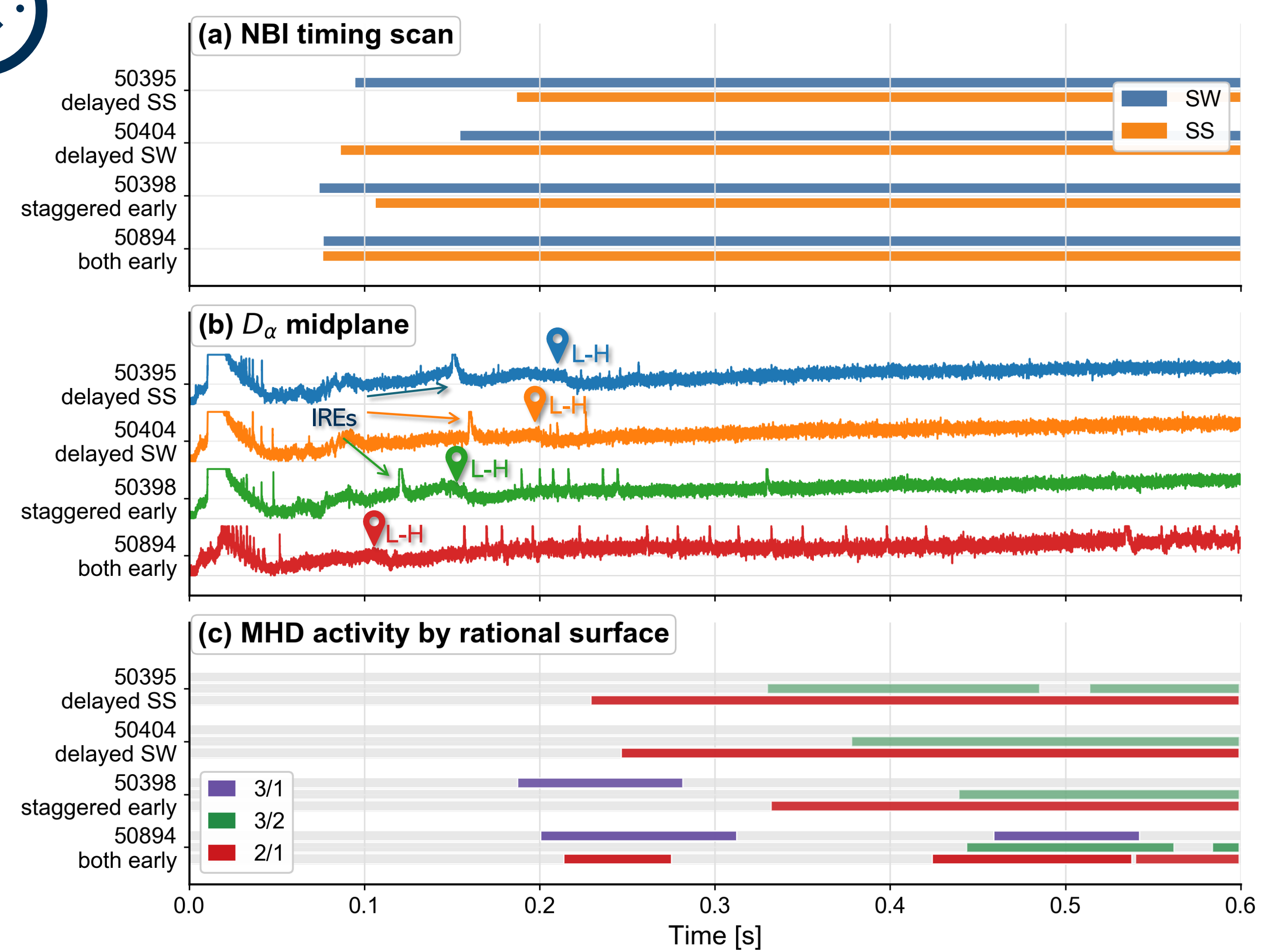
INTRODUCTION

Past high-performance scenarios on MAST-U [1] used delayed on-axis and early off-axis beam injection. A 2/1 mode shortly after the L-H transition strongly degrades confinement. IREs before the L-H transition also hindered robustness.

AIM

Develop a robust scenario closer to reactor-relevant plasma conditions, with high plasma shaping, good confinement with high β_N and β_e, and with routine use of advanced divertor configurations with detached divertors.

1. NBI TIMING SCAN

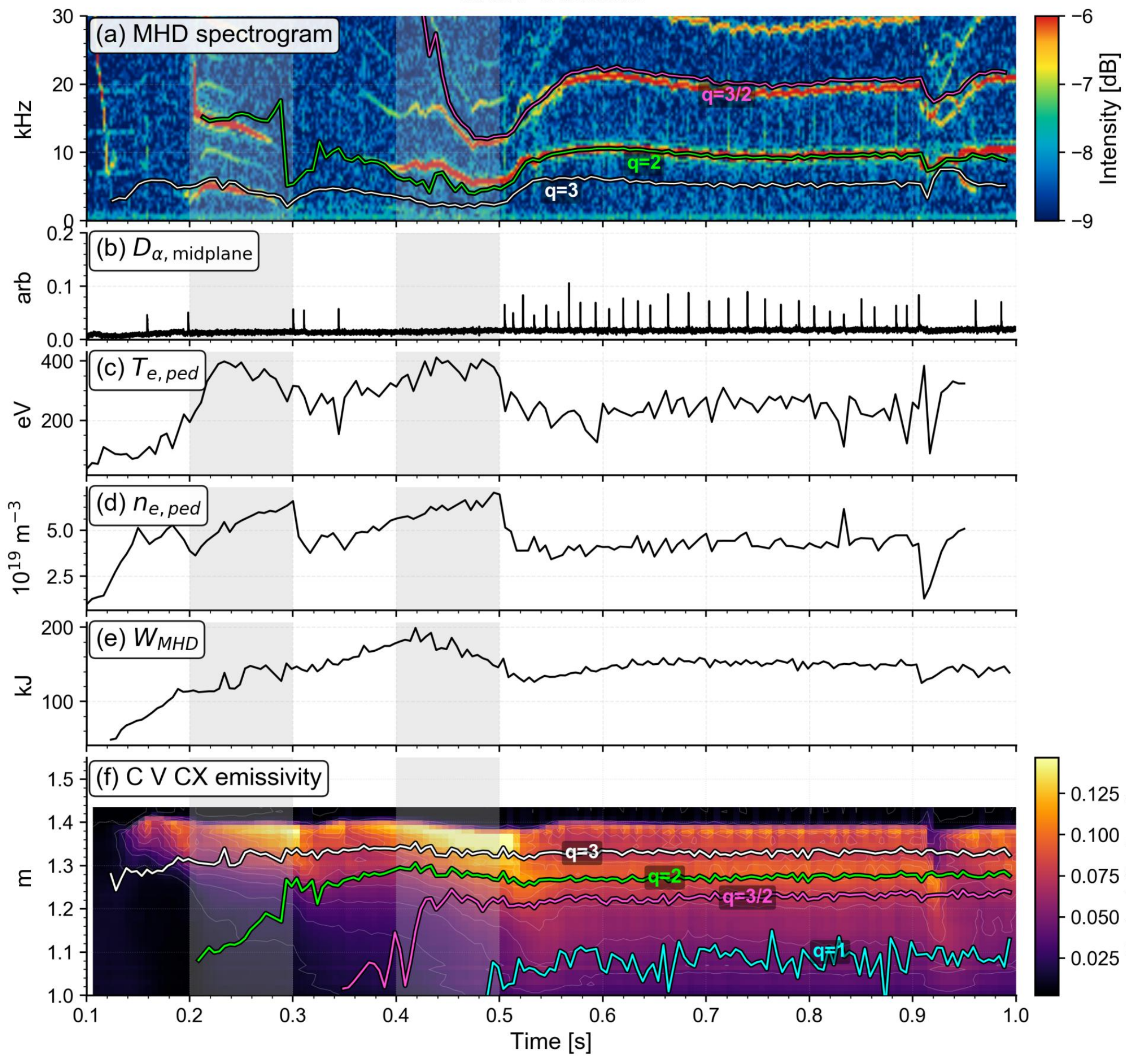


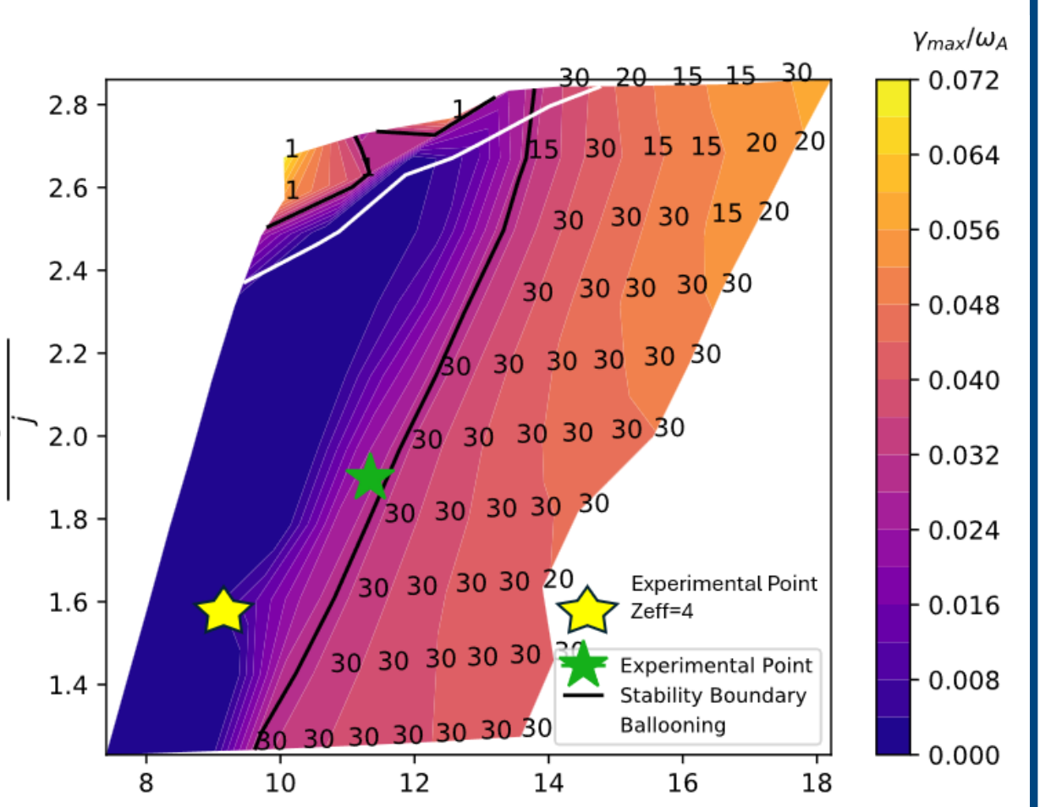
KEY MESSAGES

- **Delayed on-axis beam (SS) least favourable trajectory:** latest L-H and the earliest 2/1 onset
- **Delayed off-axis beam (SW) modest improvement:** L-H earlier and 2/1 onset later
- **Earlier staggered beams further improvement:** earlier L-H and delayed 2/1 onset
- **Both beams early best overall:** mitigates the IRE and results in the latest 2/1 onset
- Precisely timed, delayed NBIs have been used in other programmes to produce hybrid scenarios
- Early beams introduce an early 3/1 mode causing impurity accumulation near the pedestal

Takeaway: Earlier NBI heating improves the access trajectory into H-mode and delays 2/1 mode onset by keeping q_{min} higher for longer, but the best early-heating cases introduce an early 3/1 mode phase and requires pedestal-stability follow-up

2. DENSITY AND IMPURITY CONTROL





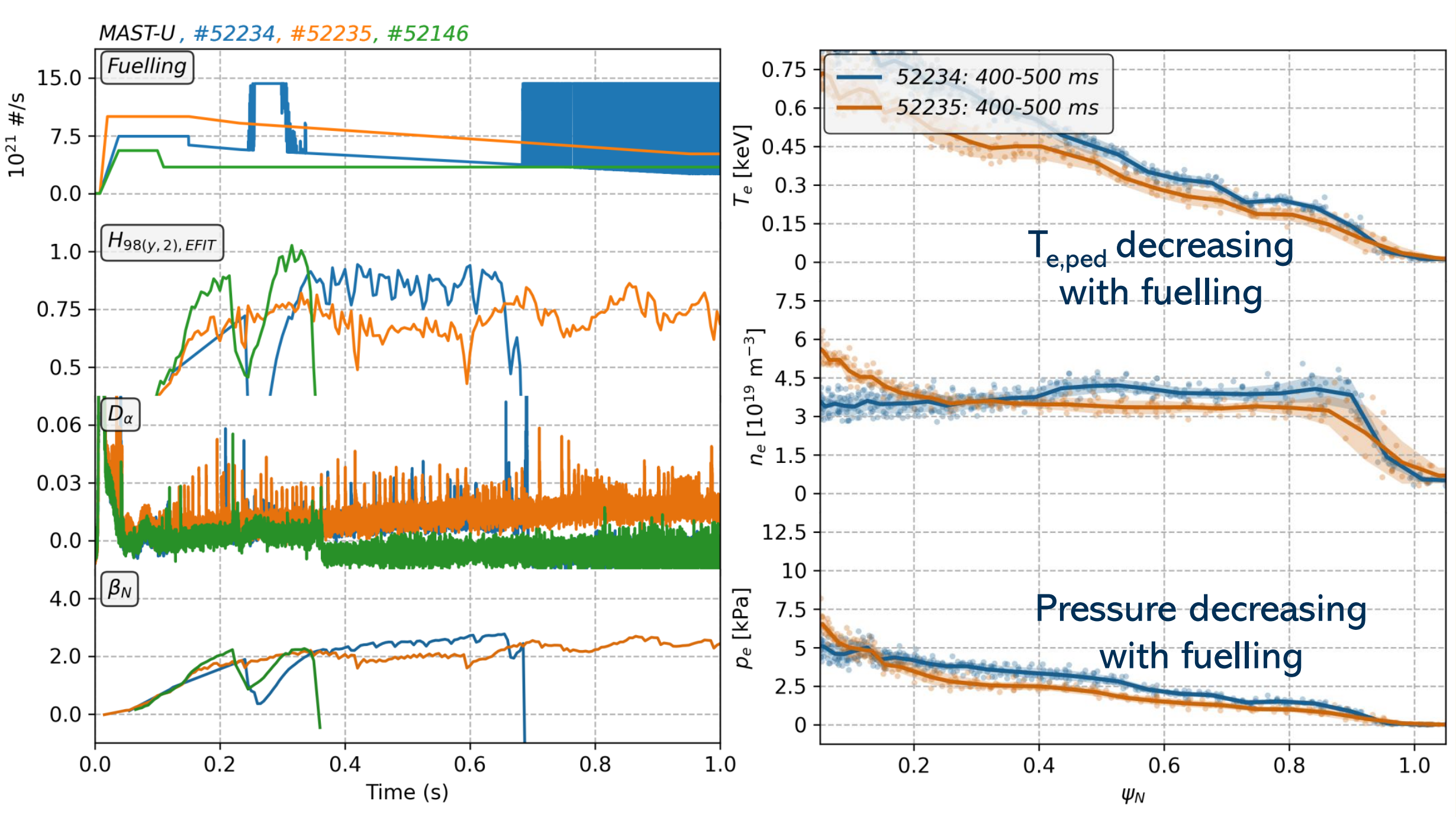
Takeaway: MHD-coupled, impurity-rich pedestal state where ELMs are suppressed, $n_{e,ped}$ and $T_{e,ped}$ rise, but confinement degrades. Priority is to prevent the impurity and density accumulation

KEY MESSAGES

- **Magnetic island near pedestal**: produces high C V emission, consistent with impurity accumulation
- **ELM-free phase**: Rise in pedestal density and temperature often coincides with an ELM-stable phase
- **Stability analysis:** shows increased Zeff moves point away from the P-B stability boundary
- **Confinement degradation**: Despite higher pedestal temperature, stored energy typically falls

3. FUELLING AND DIVERTOR CLOSURE

More fuelling damps MHD-driven pump-out, but lowers confinement



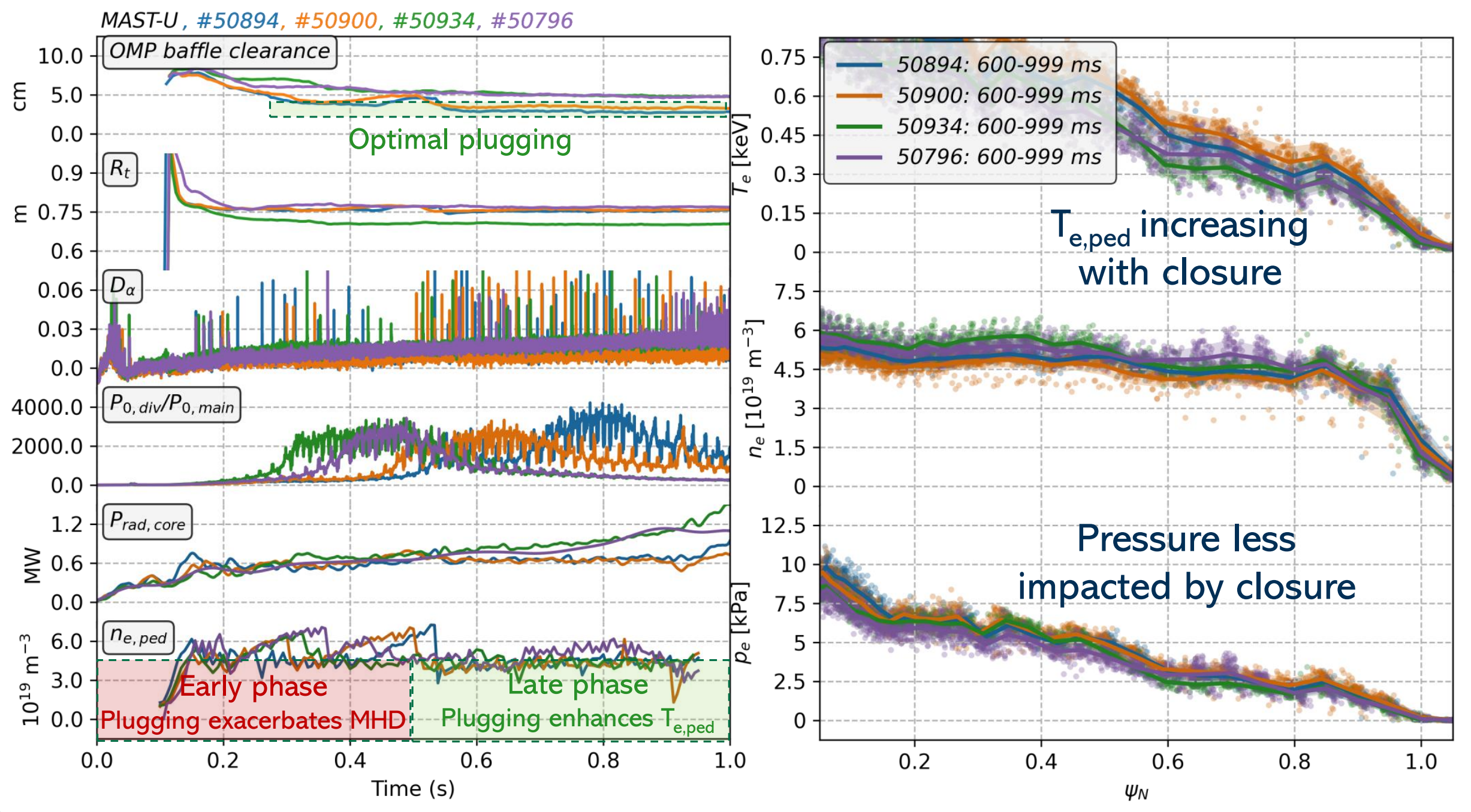
MHD pump-out

IREs and large ELMs can expel density, sometimes improving beam coupling and rotation, but are not reliable operating paths

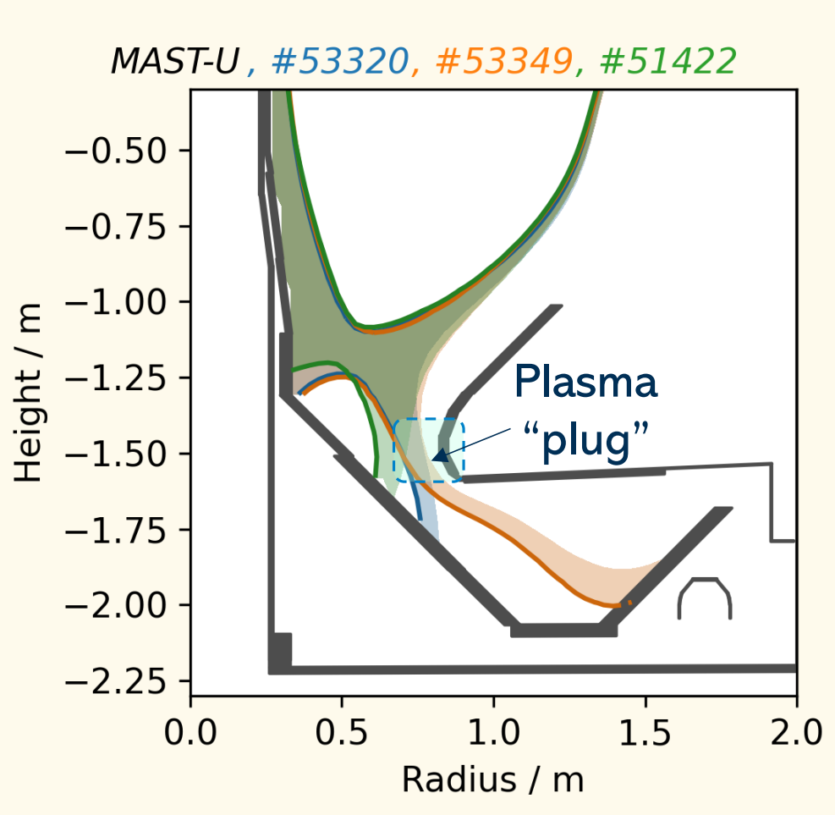
Fuelling actuator

Additional D_2 puffing mitigates IREs, but cools pedestal and lowers confinement

Divertor neutral closure provides a second actuator for MHD and pedestal temperature enhancement



Plasma plugging



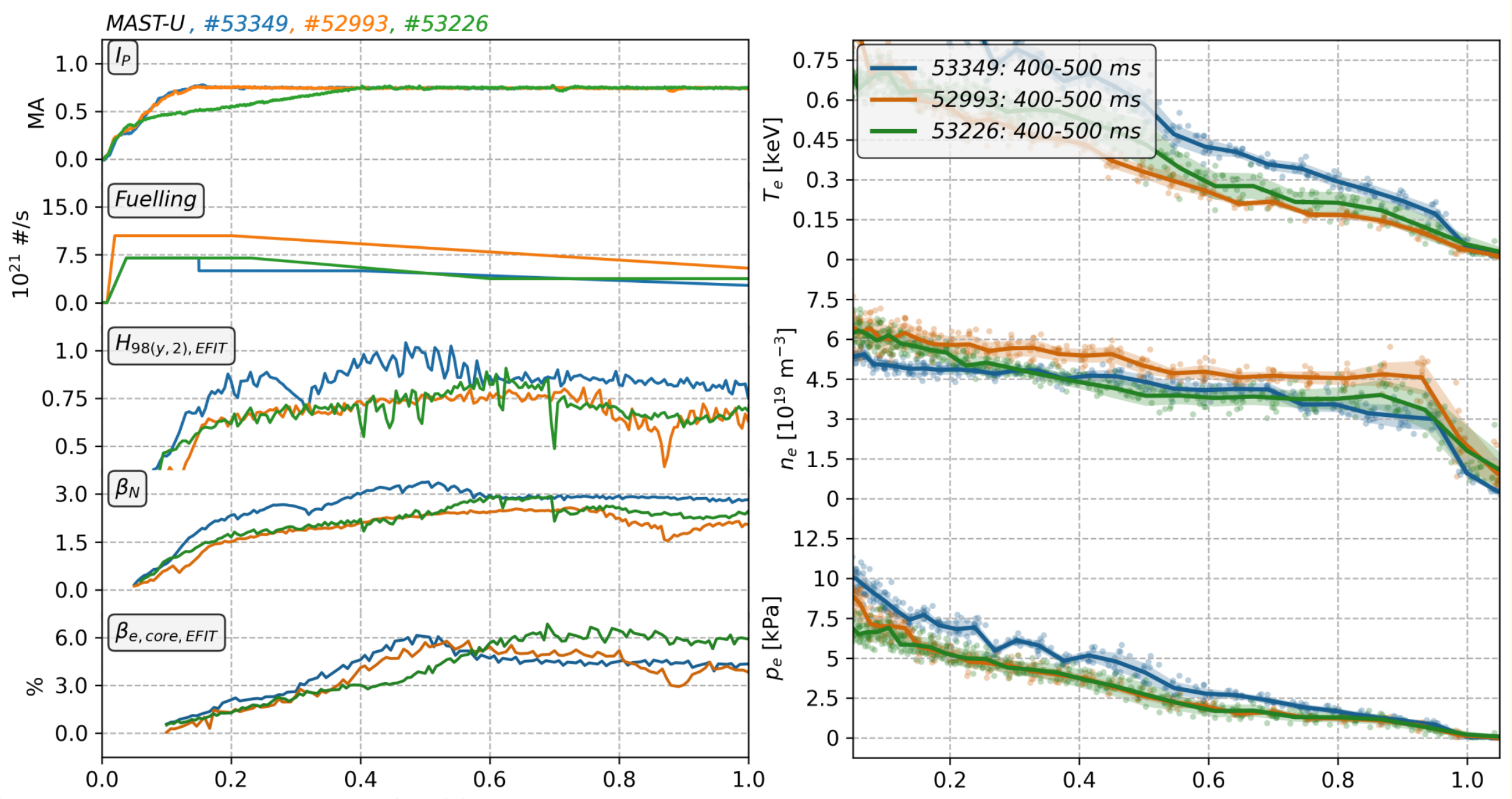
Early plugging worsens MHD
Late plugging enhances $T_{e,ped}$

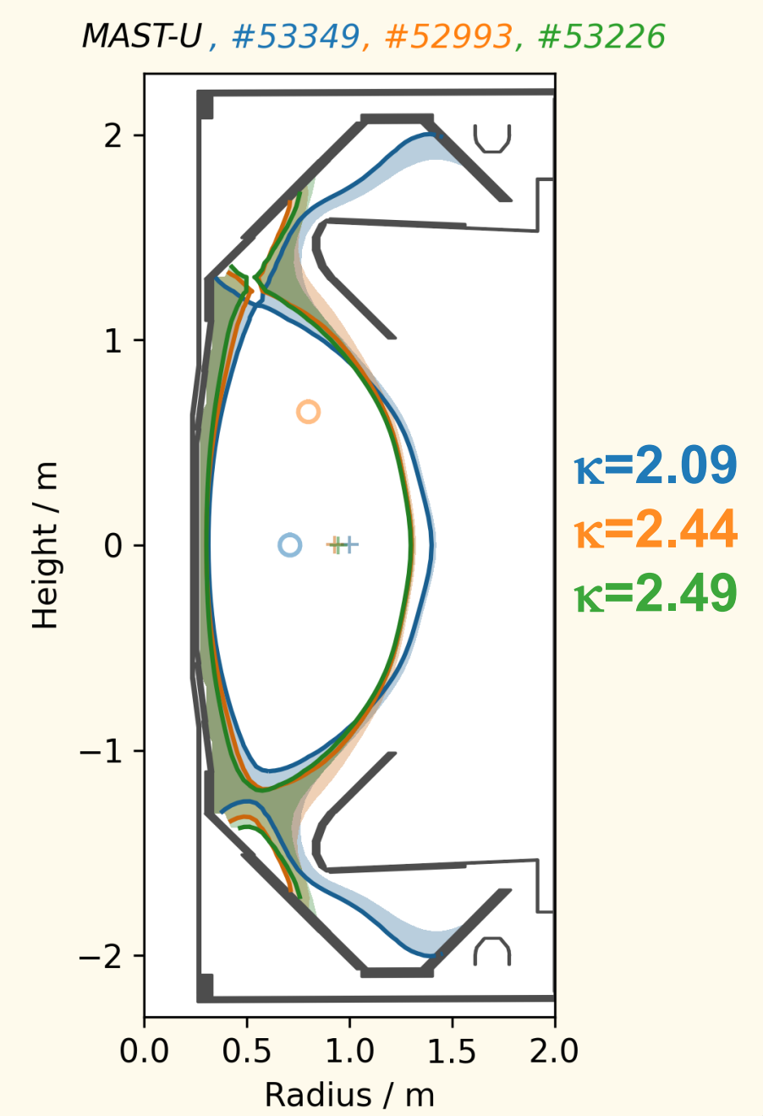
Conventional divertor	SXD geometry	Open divertor
Optimal baffle clearance of ~3-4 cm. At this distance, ELMs can also drive erosion	Reduces sensitivity to baffle clearance, allowing the SOL to be moved further from the baffle	Increases core radiation and reduces pedestal temperature by ~100 eV

Takeaway:
D_2 fuelling and closure are effective actuators but have trade-offs. SXD has most benefit at κ~2

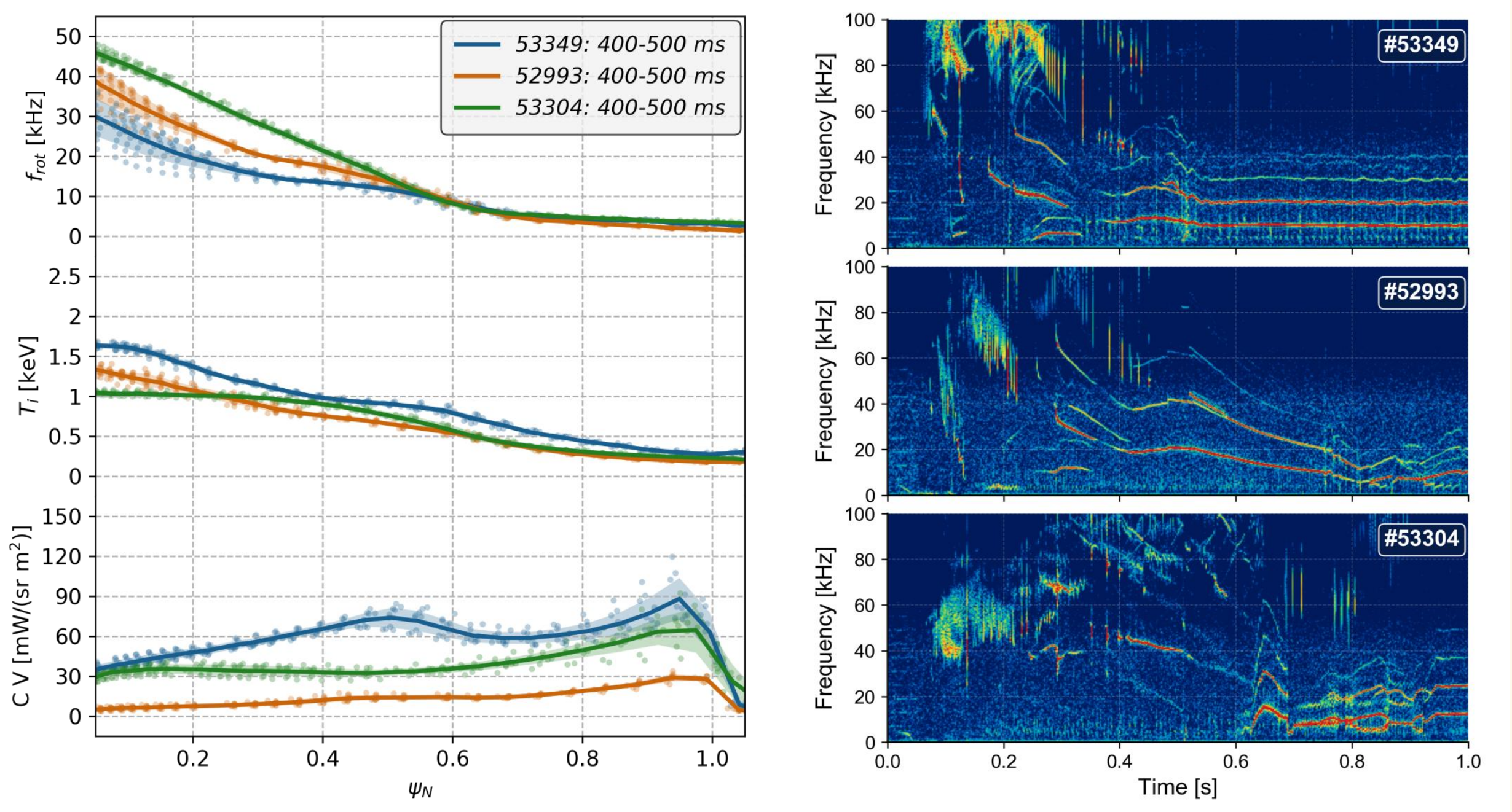
4. PLASMA SHAPING

Higher elongation lowers confinement but improves steady phase high $\beta_{e,core}$





CXRS measurements and spectrogram shows different MHD behaviour at higher elongation



Elongation κ~2.1

H_{98}~1 and β_N~3.2, but degrades after 2/1 onset

Rotation promptly damped after 2/1 onset

Elongation κ~2.5

Worse confinement and β_N but higher steady β_e~5%

Higher frequency MHD

Slower I_P ramp with less fuelling does not recover confinement or β_N

Takeaway: High elongation is not MHD-free, but the MHD is less damaging to the core: modes rotate faster, core rotation is sustained for longer, and $\beta_{e,core}$ remains steady. The penalty is lower confinement, which cannot be explained by the need for higher fuelling since slower ramp-up scenarios with less fuelling did not recover H_{98} or β_N.

KEY TRADE-OFFS

Highest-performance route not set by a single actuator. NBI timing, fuelling, baffle closure and elongation can each improve part of the scenario but also introduce a penalty. The viable operating window is a coupled optimisation, usually focused around MHD stability.

Under present MAST-U capability, the most robust route appears to be **medium elongation, highest toroidal field, early beam heating and active optimisation of the 2/1 MHD phase using fuelling and baffle closure**. Early diverting may further reduce impurity accumulation, but this remains to be tested at medium elongation.

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References

[1] A. Thornton et al 29th IAEA Fusion Energy Conference (FEC 2023)
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