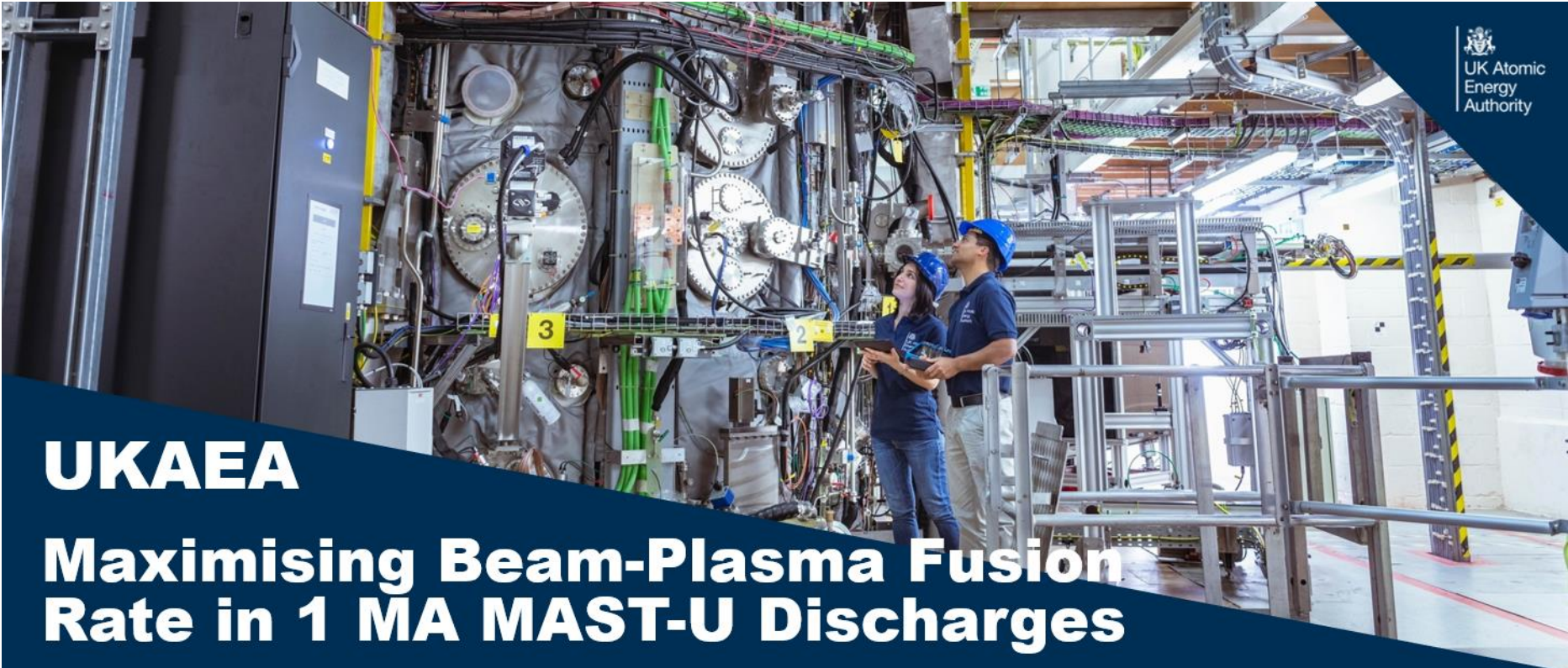




UKAEA

Maximising Beam-Plasma Fusion Rate in 1 MA MAST-U Discharges

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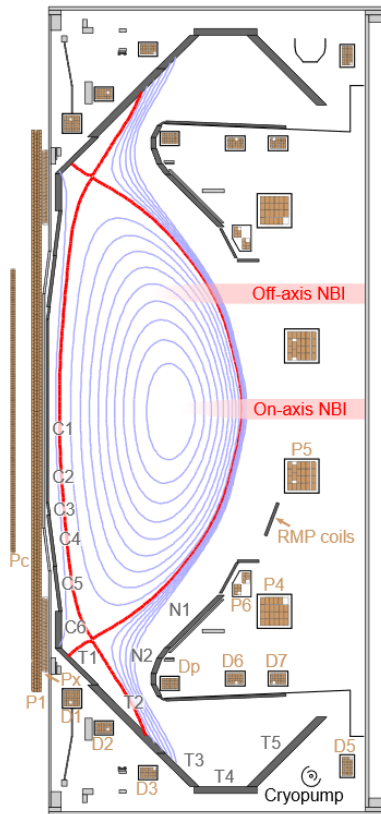
Introduction

- In the past, MAST was prone to **Alfvénic instabilities: Alfvén eigenmodes (AEs), chirping modes, and fishbones** excited by the NBI pressure gradient ∇P_α
- Due to **low magnetic fields, $B_T \sim 0.4 - 0.5$ T**, in MAST, Alfvén velocity $V_A \sim B / \rho^{1/2}$ was low and the **beam was super-Alfvénic** passing through the resonance $V_{||b} = V_A$
- The free energy source ∇P_α **excited Alfvén waves via resonant interaction and caused radial re-distribution of energetic beam** if the wave amplitude $\delta B / B_0$ was high
- The neutron yield on MAST was coming from **beam-plasma D-D fusion**. It was found [1] that having **two NBI on-axis** gave **not much higher neutron yield than with single NBI**. Instead, amplitudes of fishbones and chirping modes increased
- Mitigation of AE-induced fast-ion redistribution in MAST was then investigated and **off-axis geometry for the 2nd beam was proposed for MAST-U design** [2]

[1] M. Turnyanskiy et al 2013 Nucl. Fusion 53 053016

[2] D. Keeling et al 2015 Nucl. Fusion 55 013021

The MAST Upgrade has now on-axis NBI and off-axis NBI



Parameter	Achieved Values
R / a (m)	0.8 / 0.5 ~ 1.6
Max B_ϕ (T at 0.8m)	0.72
Max I_p (MA)	1.0
Max elongation	2.5
Max triangularity	0.6
Injected NBI power (MW)	3.6 for 1s
NBI geometry	1x on-axis ($Z = 0.0\text{m}$, $R_{\text{tan}} = 0.71\text{m}$) 1x off-axis ($Z = 0.65\text{m}$, $R_{\text{tan}} = 0.8\text{m}$)
Particle pumping	~25 m ³ /s from lower cryopump
Fuelling locations	High-field side, low-field side, private flux region, divertor chamber
Divertor configurations	Variable, including conventional, Super-X, X-point target, snowflake, X-divertor
Max T_e , T_i (keV)	2.0, 3.0
Max v_ϕ (km/s)	~150
Max β_N	~4.2
Impurity species	C, He (intrinsic), CD ₄ , N ₂ (extrinsic)
Non-axisymmetric fields	Ex-vessel EFCCs (n=1, n=2) In-vessel RMP coils (n=1, n=2, with upper and lower coils, n=4 with lower row)

The idea of mutual AE “drive absorption” of two fast ion profiles with opposite dP/dr (including off-axis NNBI in ITER)

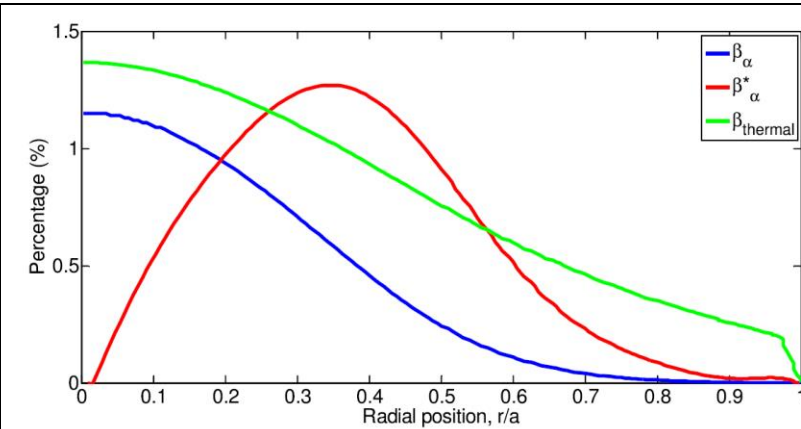


FIG. 3. Profiles of β_α (%), normalised gradient of alpha-particle pressure $\beta_\alpha^* = -ad\beta_\alpha/dr$ and thermal plasma β in the 15MA ITER baseline scenario considered versus normalized radius.

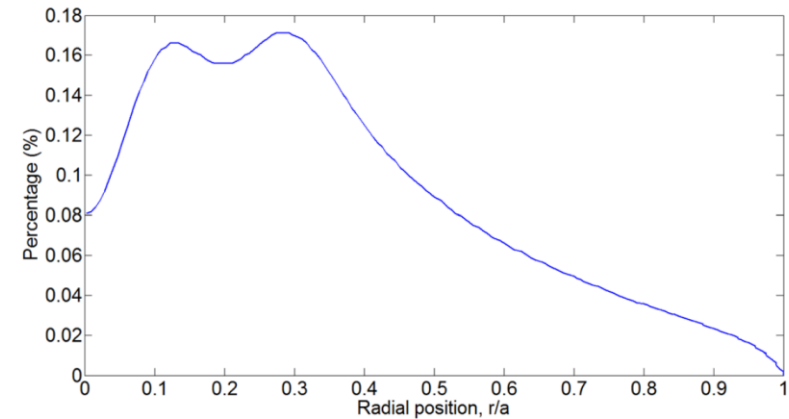
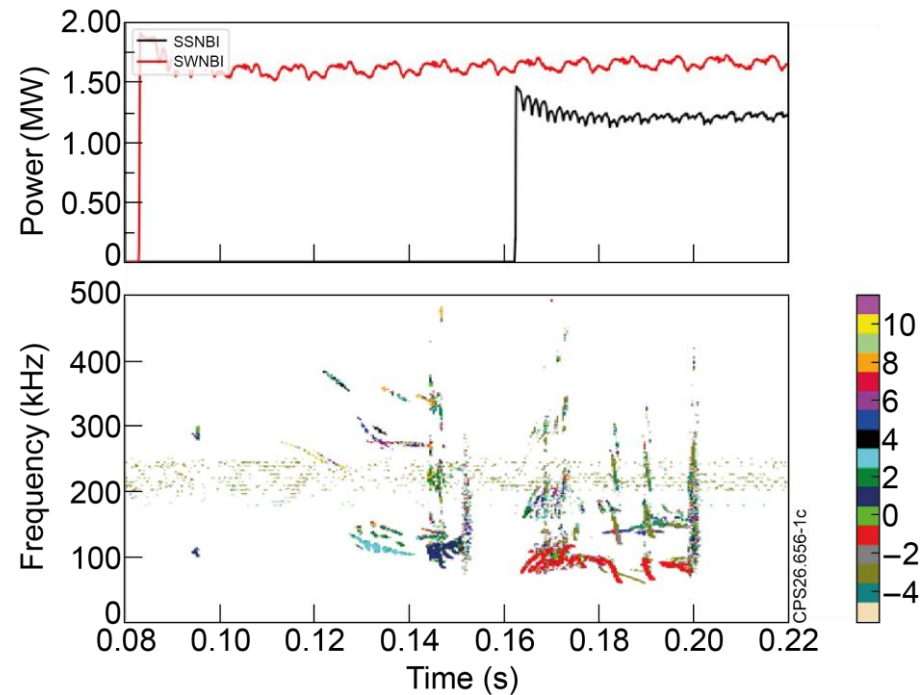


FIG. 4. Profile of β_{beam} (%) in the 15MA ITER baseline scenario considered versus normalized radius.

Employ the damping term $\approx \omega dF/dE < 0$ of fast species 2 slowing-down distribution at TAE position of a drive $\approx -dF/dr > 0$ of species 1. AND vice versa if possible.

Testing this idea on MAST-U with two beams on-axis and off-axis:

MAST-U with two beams at 1 MA test (pulse #49365):



Modes with $n > 0$ driven by off-axis NBI (red trace marked SSNBI) become suppressed when on-axis NBI (black trace marked SWNBI) is applied. Instead, modes with $n < 0$ are excited.

The idea seemingly worked, but **a more accurate balance in NBI power is needed to mutually cancel the beam drives for AEs completely.**

Aims of our MAST-U experiment in 2025-26:

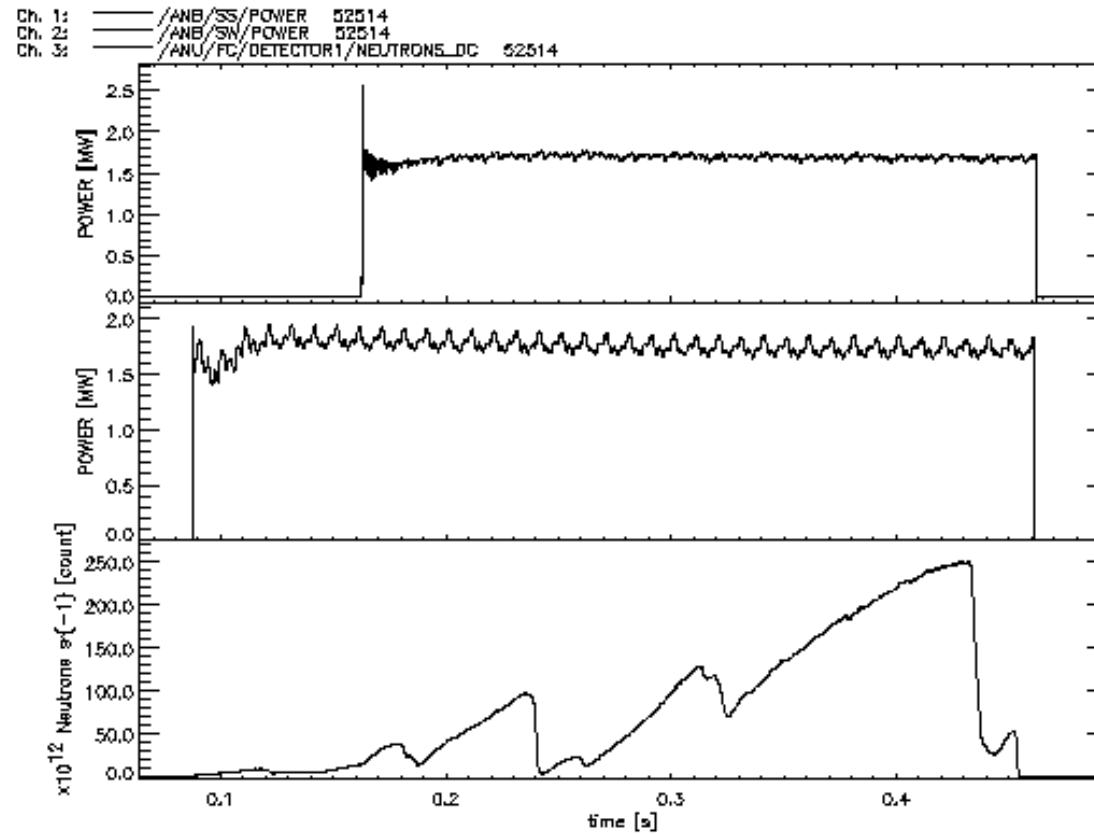
Maximise the beam-plasma D-D fusion performance via suppressing beam-driven fishbones and AEs by combining on-axis and off-axis beams.

Confirm the benefits of the off-axis NBI in reducing the drive of beam-driven instabilities while keeping a good fast ion confinement and achieving high performance plasmas.

Develop a plasma upshift scenario at 1 MA so the off-axis NBI could deliver more neutrons. Use Upper Single Null configuration. The Reference USN pulse #52330 has neutron yield steady at $\sim 1.2 \times 10^{14} \text{ s}^{-1}$.

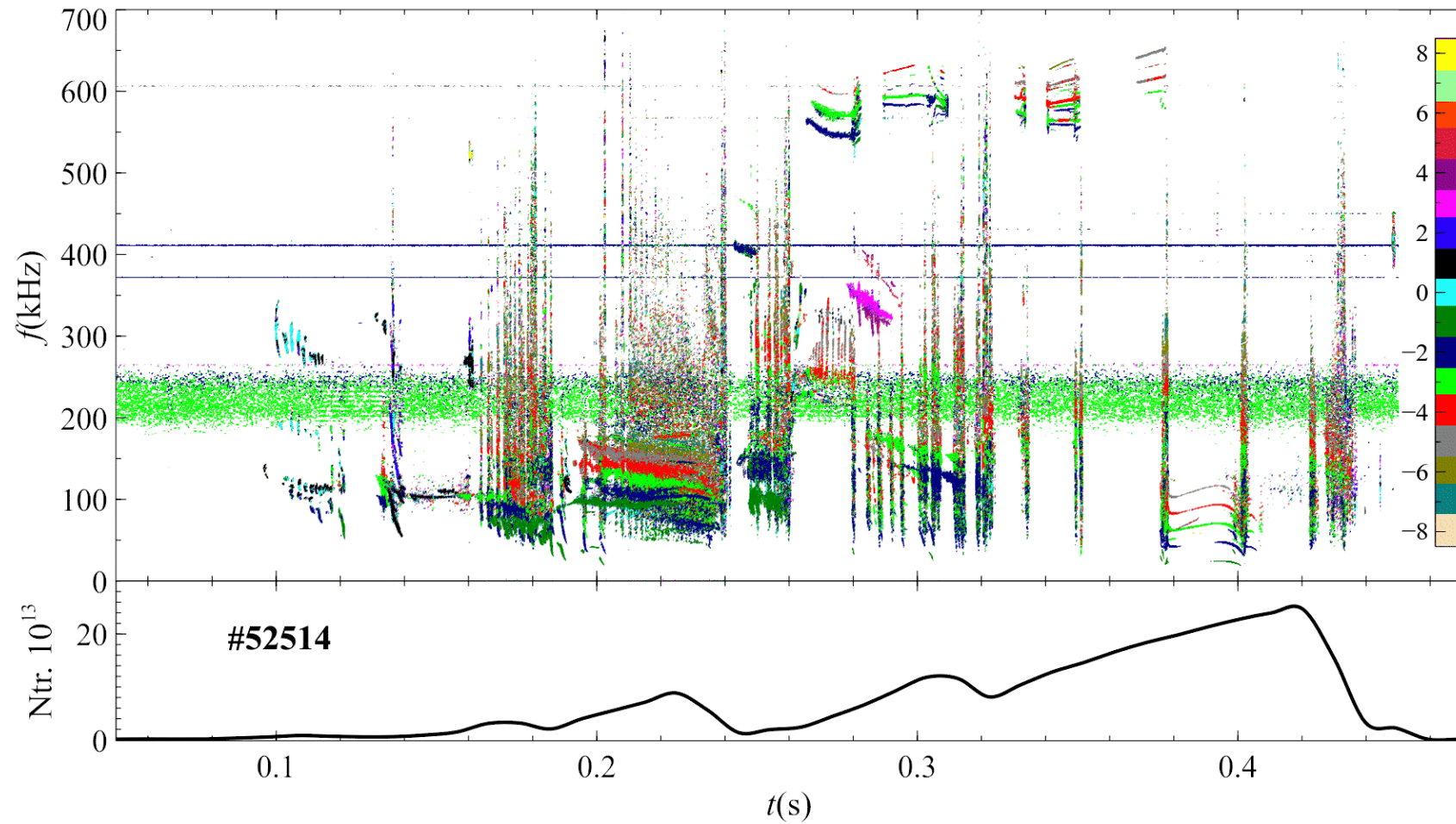
The timing of the beams was taken from the best 1 MA test pulse #49365.

The first 1 MA record neutron pulse with two beams #52514

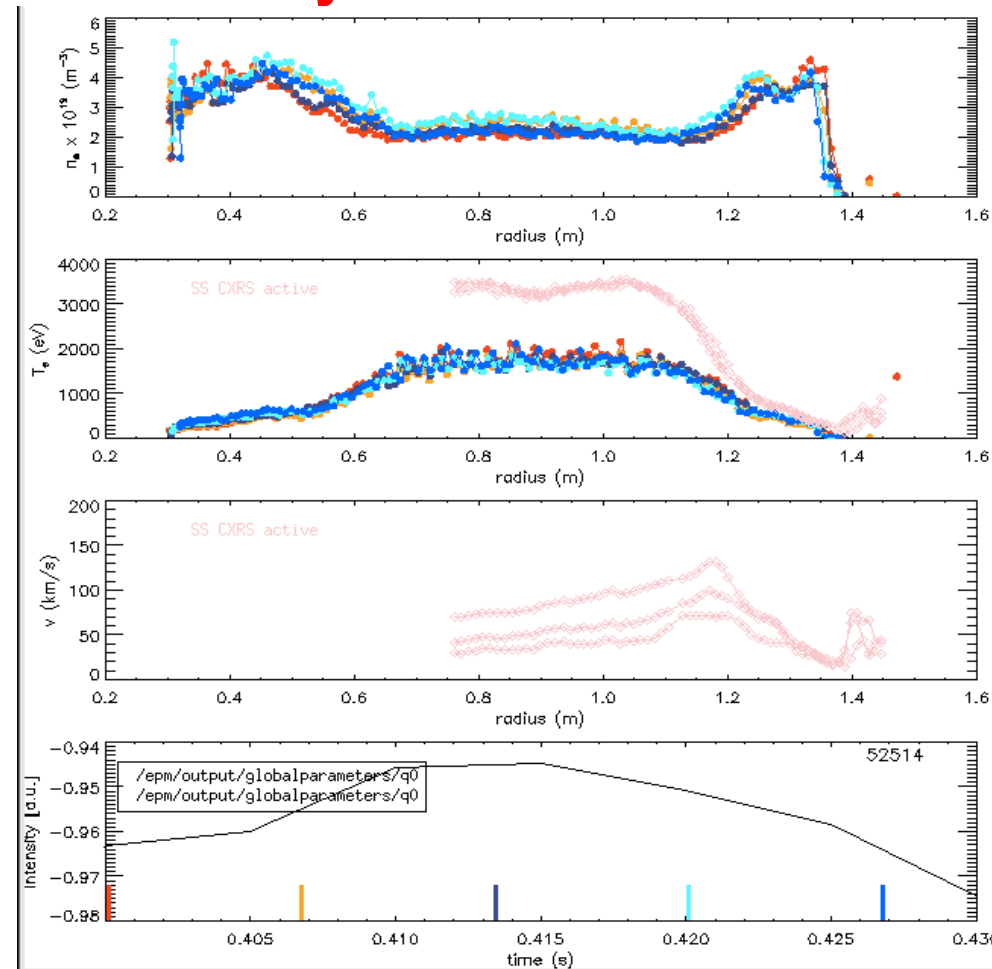


From Top to Bottom: on-axis NBI power waveform; off-axis NBI power waveform; the measured D-D neutron rate up to $2.5 \times 10^{14} \text{ s}^{-1}$.

AEs are seen BEFORE 0.32 s. Then, a time window free of AEs appeared and neutron rate increased. The sawtooth-like MHD events are IREs, and the vertical stripes seen after 0.32 ms are ELMs.



High ion plasma temperatures were achieved, ~ 3.5 keV, while electron density remained low in the centre:

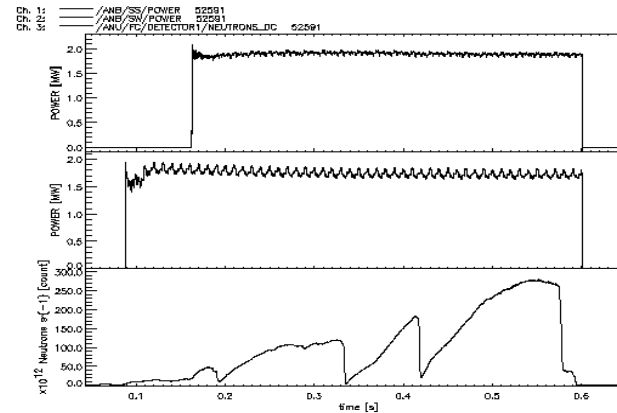


The Continuation Session Followed then:

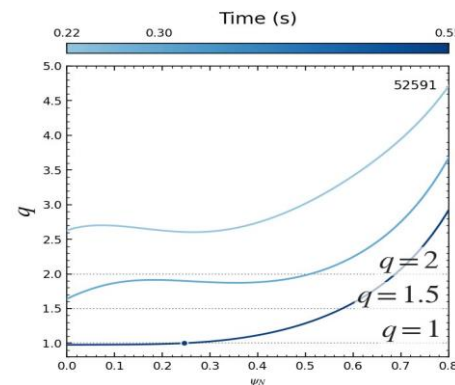
- 1) We now take #52514 as our new Reference BUT increased **NBI energy to 69keV to make MSE available**. The fuelling was exactly like in #52514.
- 2) The first pulse with 2 beams, **#52591, achieved a new record in neutron yield, $2.8 \times 10^{14} \text{ s}^{-1}$** .
- 3) The **upshift of the plasma to 4.1 cm in #52593 has delivered a somewhat higher neutron yield, $3.03 \times 10^{14} \text{ s}^{-1}$** .

In all cases the high neutron rates were achieved **during no-AE time windows** at the end of the discharges

The second 1 MA record neutron pulse with two beams #52591

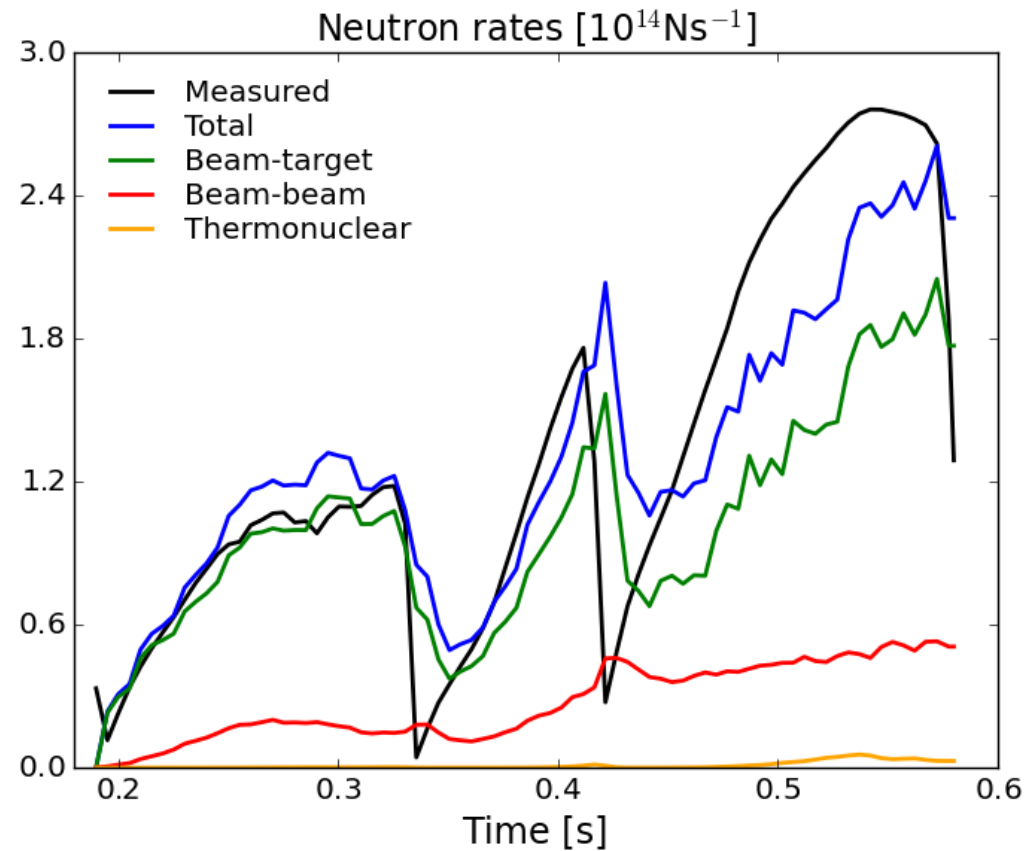


From Top to Bottom: **on-axis NBI power waveform; off-axis NBI power waveform; the measured D-D neutron rate up to $2.8 \times 10^{14} \text{ s}^{-1}$.**

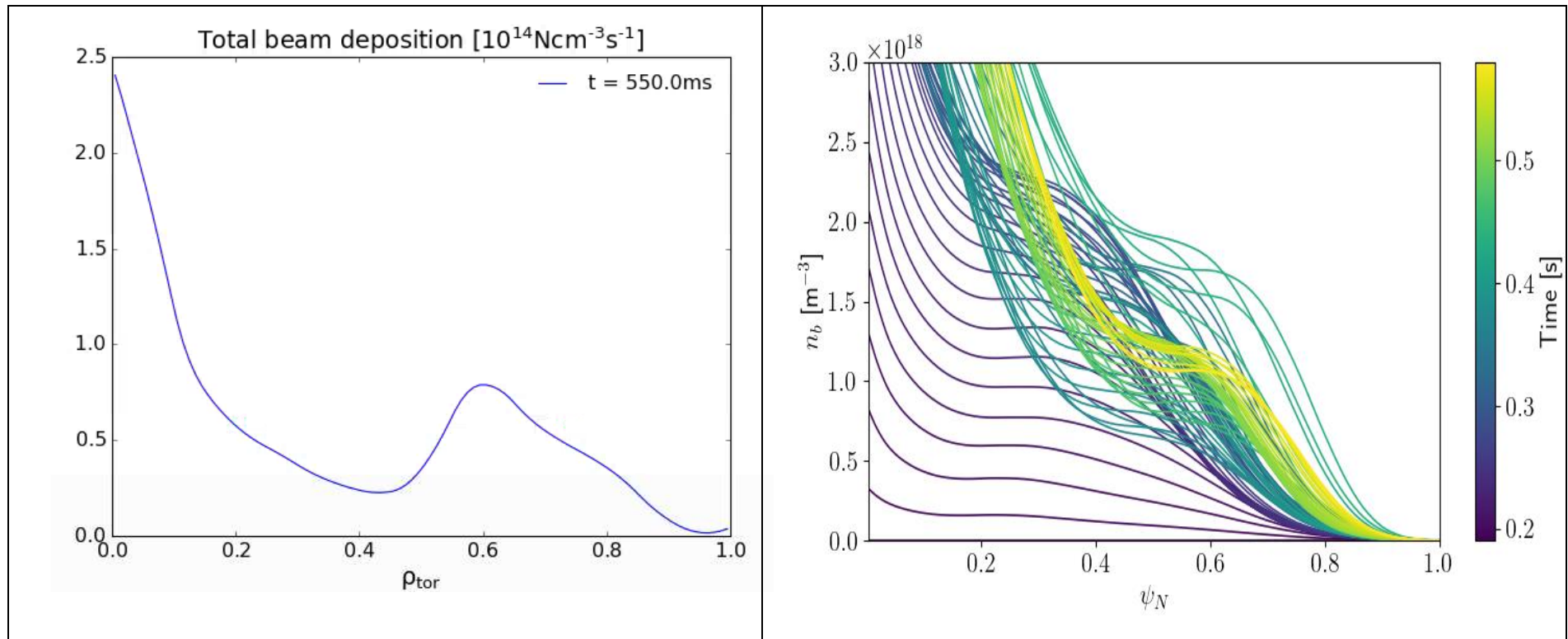


The q-profiles from MSE analyses at 220 ms, 300 ms, and 550 ms.

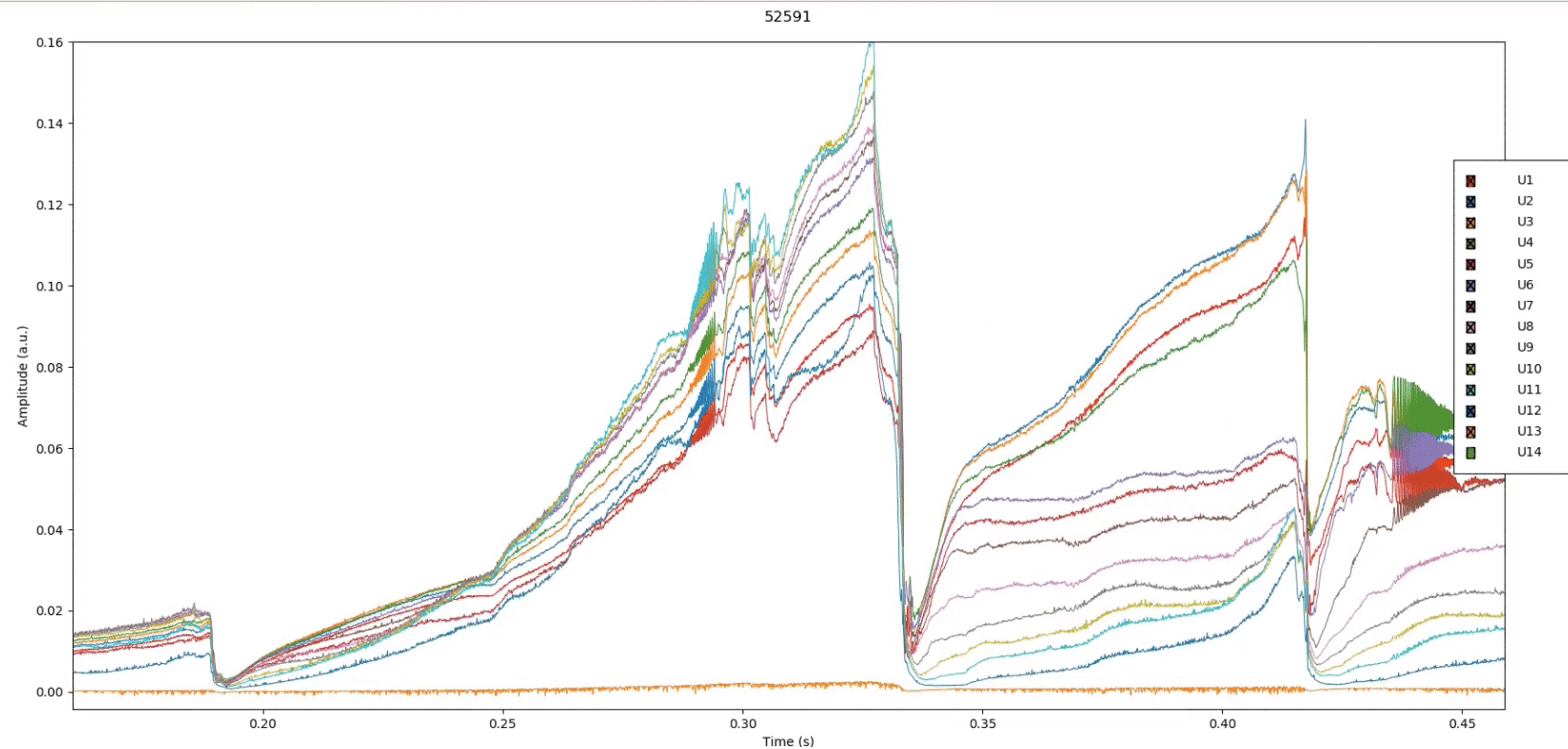
The TRANSP analysis does not show a neutron deficit (C. Olde)



Beam power deposition and beam density evolution from TRANSP

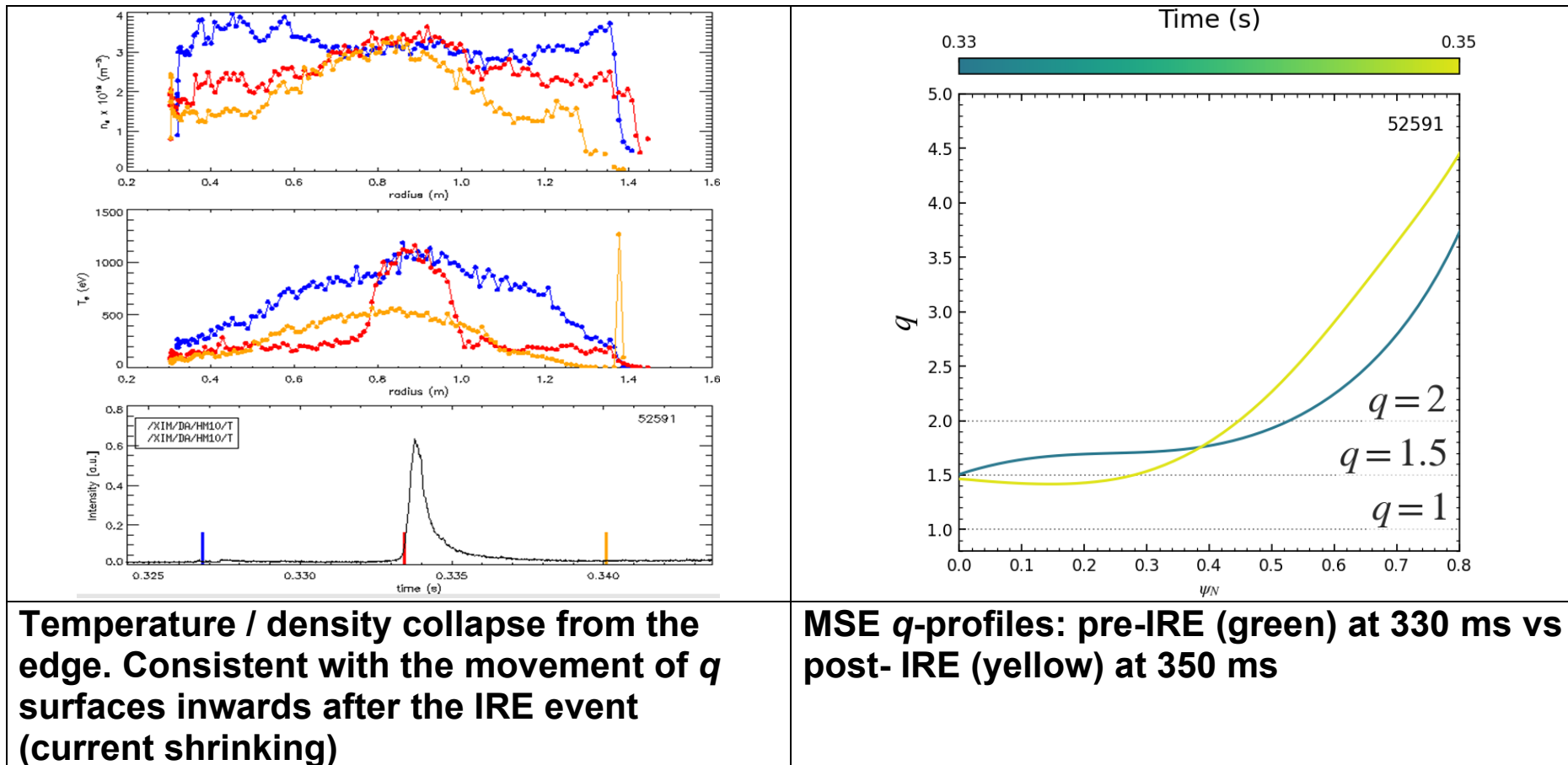


The sawtooth-type oscillations were identified as Internal Reconnection Events (IREs). SXR used for time-resolved IRE:

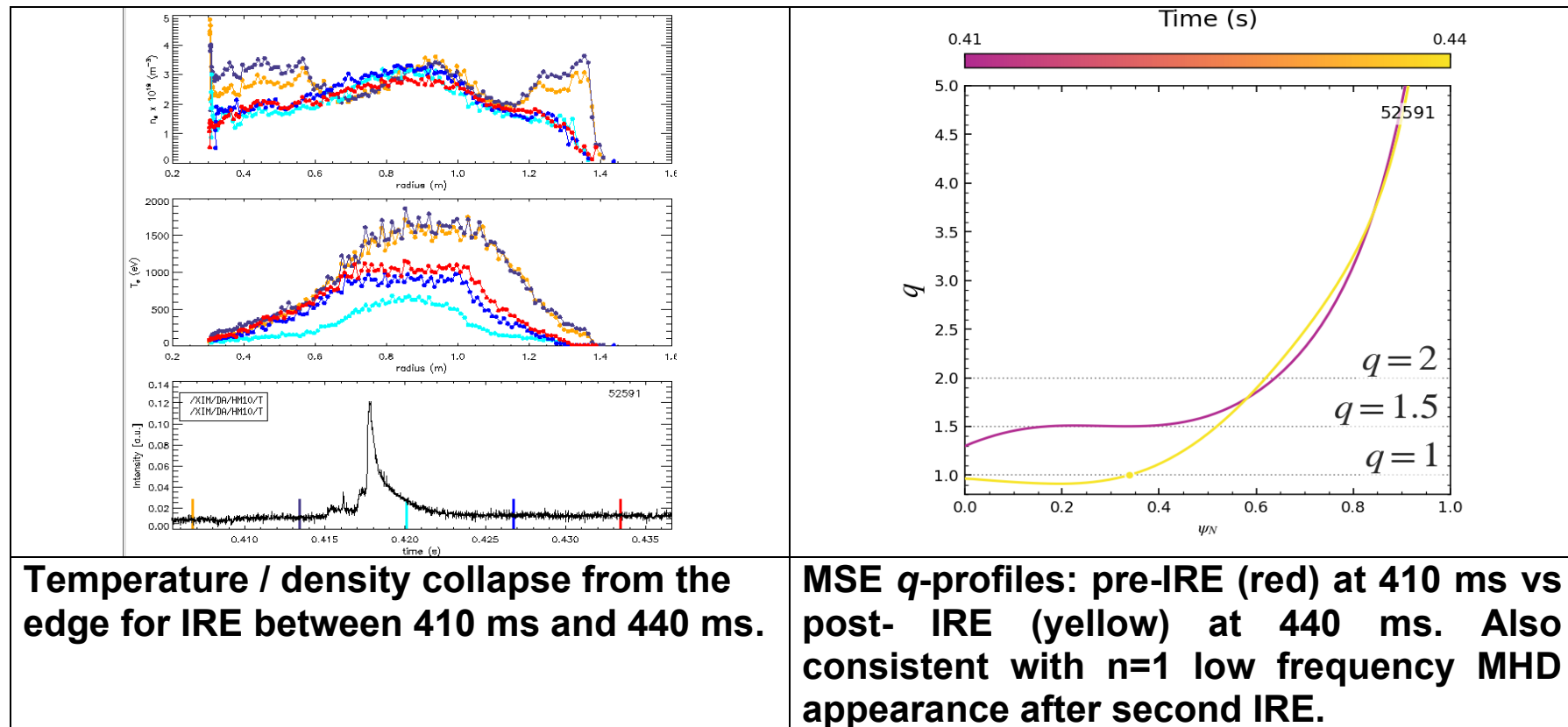


- Although flat top IRE-free scenarios have been developed on MAST before, **their Neutron rates were not high.**

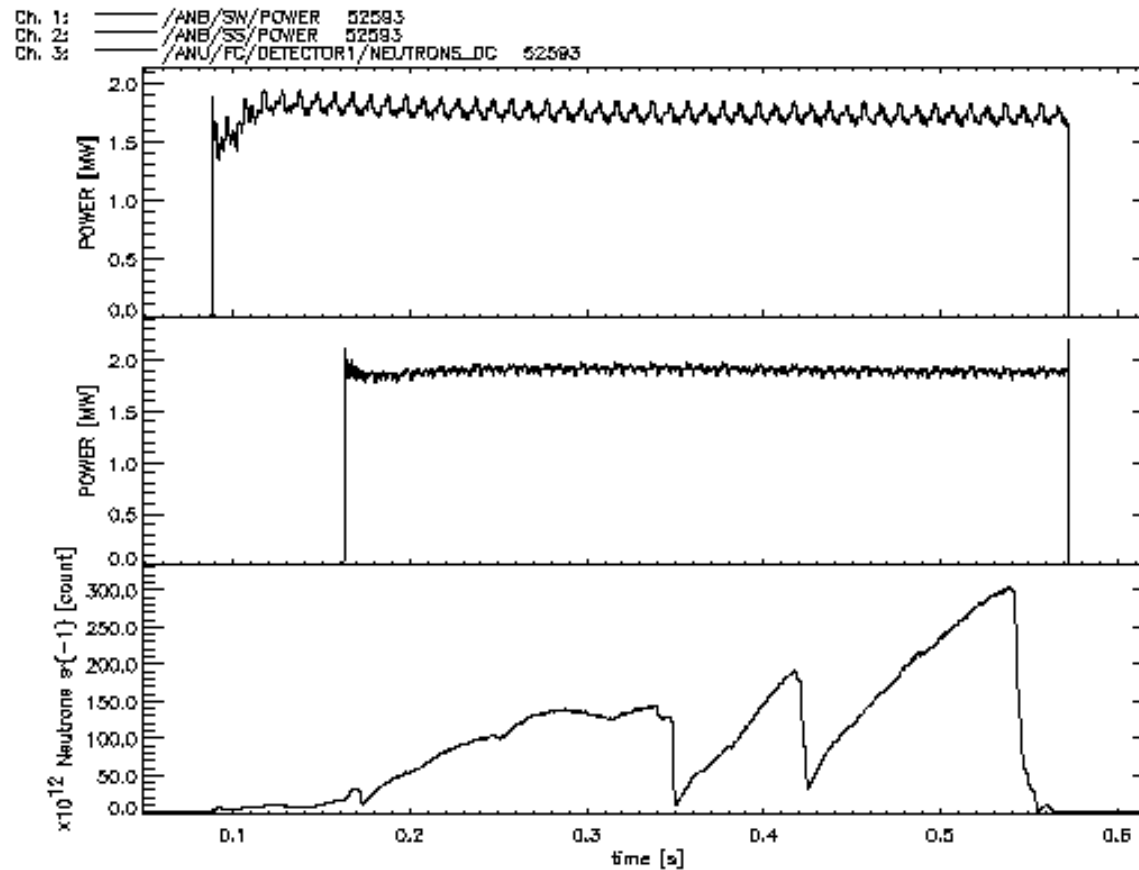
q-profiles from MSE, temperature and density profiles just before and after the IRE at 330 ms in #52591 (S. Blackmore)



Later IRE at ~420 ms in #52591

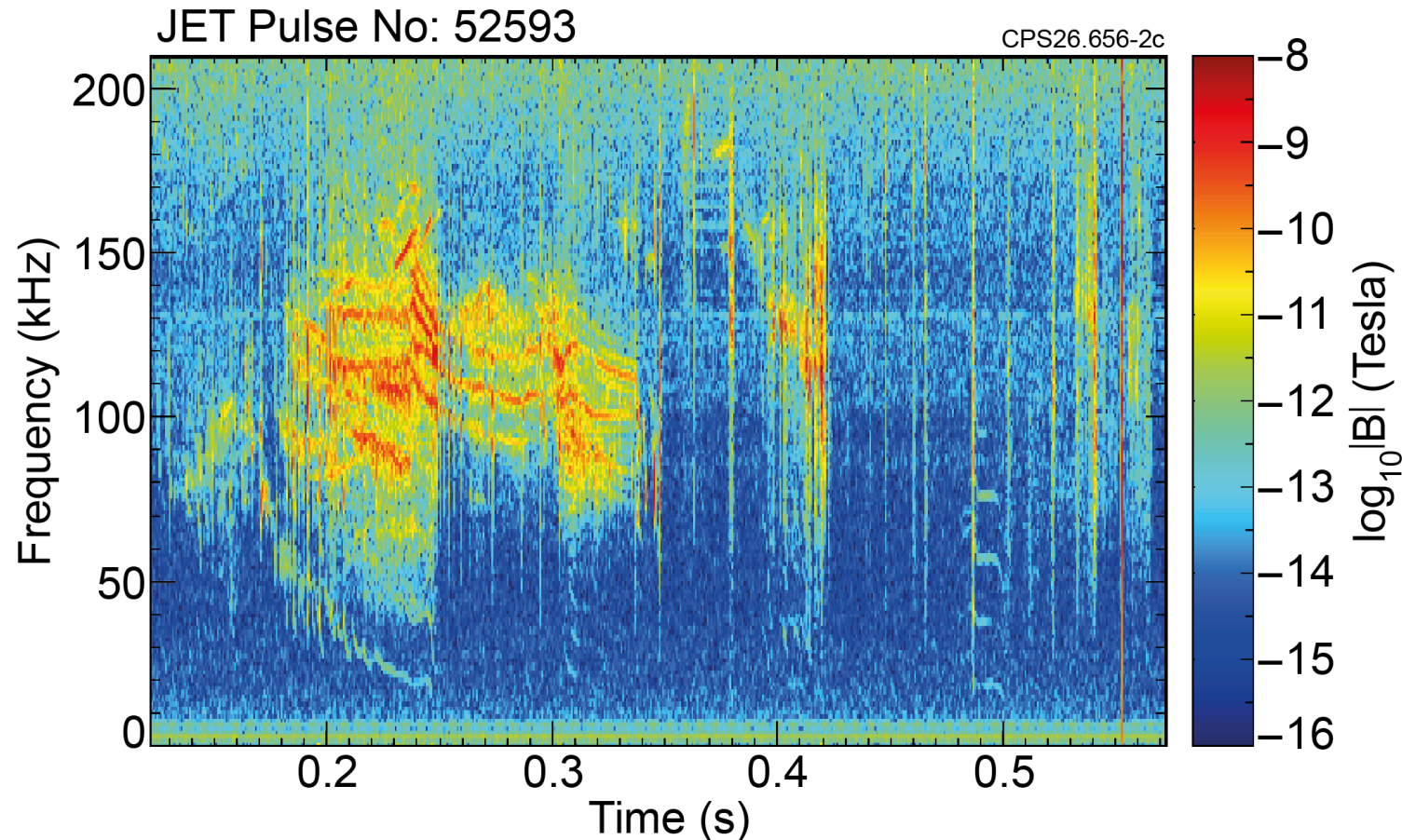


Third 1 MA record neutron upshifted pulse with two beams #52593



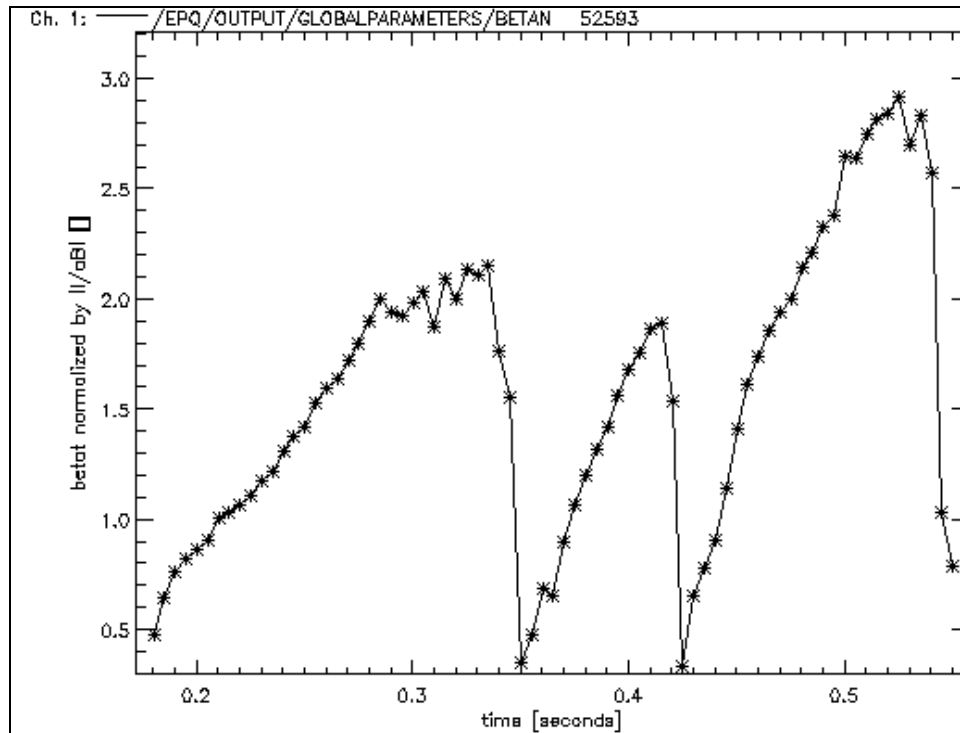
In contrast to #52591 the neutron rate in #52593 still goes up at the end

AE activity is observed in this MAST-U discharge BEFORE 0.42 s

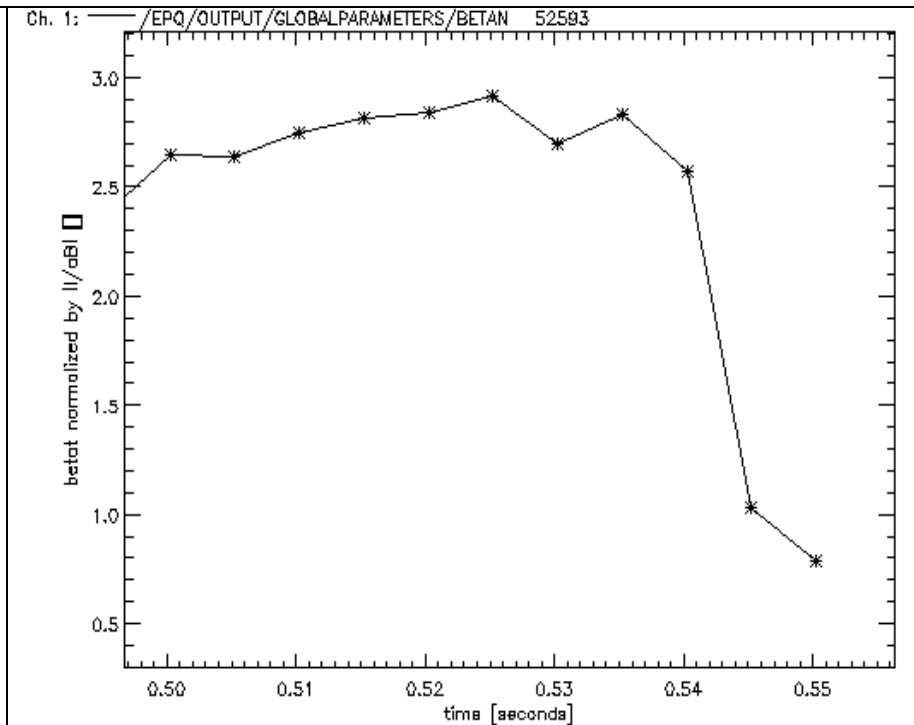


AE-free time window from 0.42 s to 0.55 s allows the build-up of neutron rate to high values

The dynamics of β^N in #52593

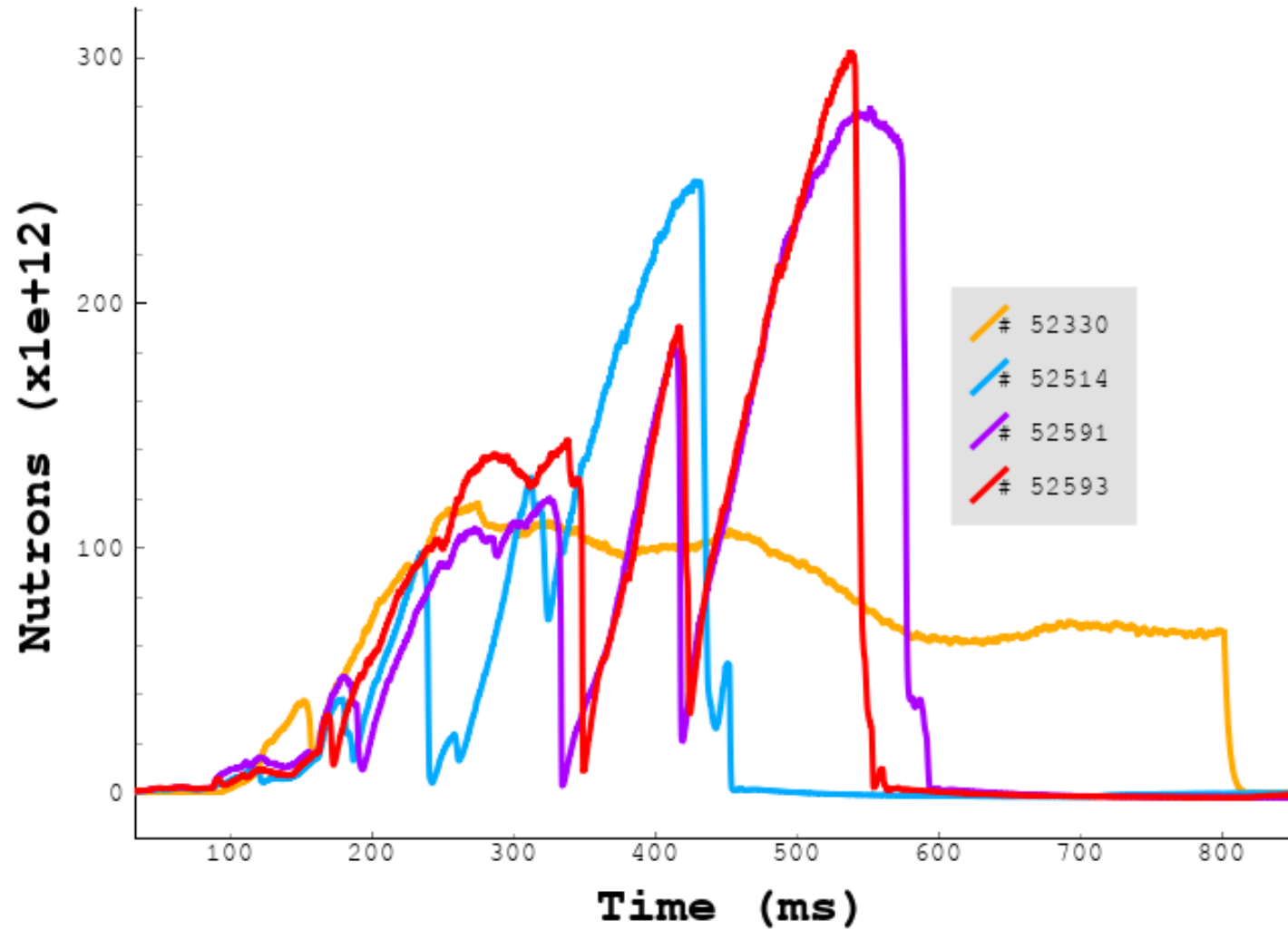


Temporal evolution of β^N in MAST-U discharge #52593

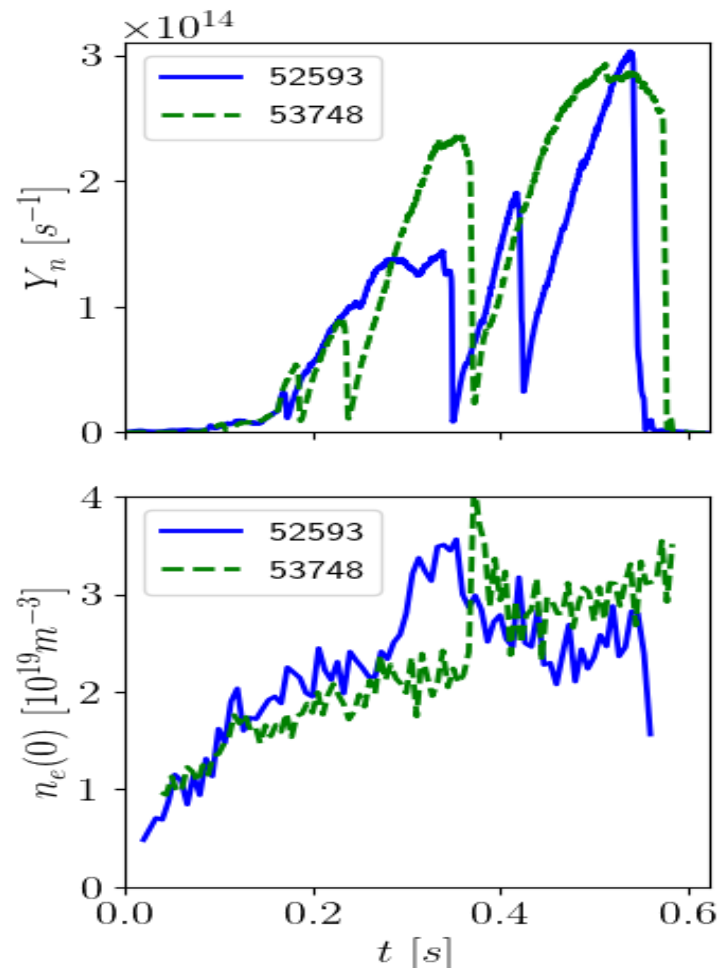


Zoom of β^N around the last MHD event in MAST-U discharge #52593

SUMMARY OF THE NEUTRON RATES IN 2025:



2026: Development of Upper Single Null Plasma Shape Control has led to Longer Time of High Neutron Rates



History of Internal Reconnection Events (IREs)

- The **absence** of current terminated disruptions on STs became of interest in 90's when **START had no disruptions in more than 30000 discharges**;
- Instead, Internal Reconnection Events (IREs) appeared to be common and exhibited properties similar to disruptions: **rapid increase in plasma current, negative spike in loop voltage, increase in elongation, reduction in plasma energy, but without terminating the current**: R. Buttery et al., 1996, Proceed. of 23rd EPS, Kiev, Part I, p.416;
- **IREs on NSTX were found to have the rate of thermal quench ~10 times slower** than in moderate aspect ratio tokamaks: I. Semenov et al., 2003 Phys.of Plasmas 10, p.664;
- Nonlinear MHD modelling of IREs was performed in [N. Mizuguchi et al., Phys. Plasmas 7, 940–949 (2000)] but did not deliver any mitigation scenarios.

**Recently, IRE study with neural network was developed for ST-40
(C. Windsor et al., 2026, submitted to Nucl. Fusion).**

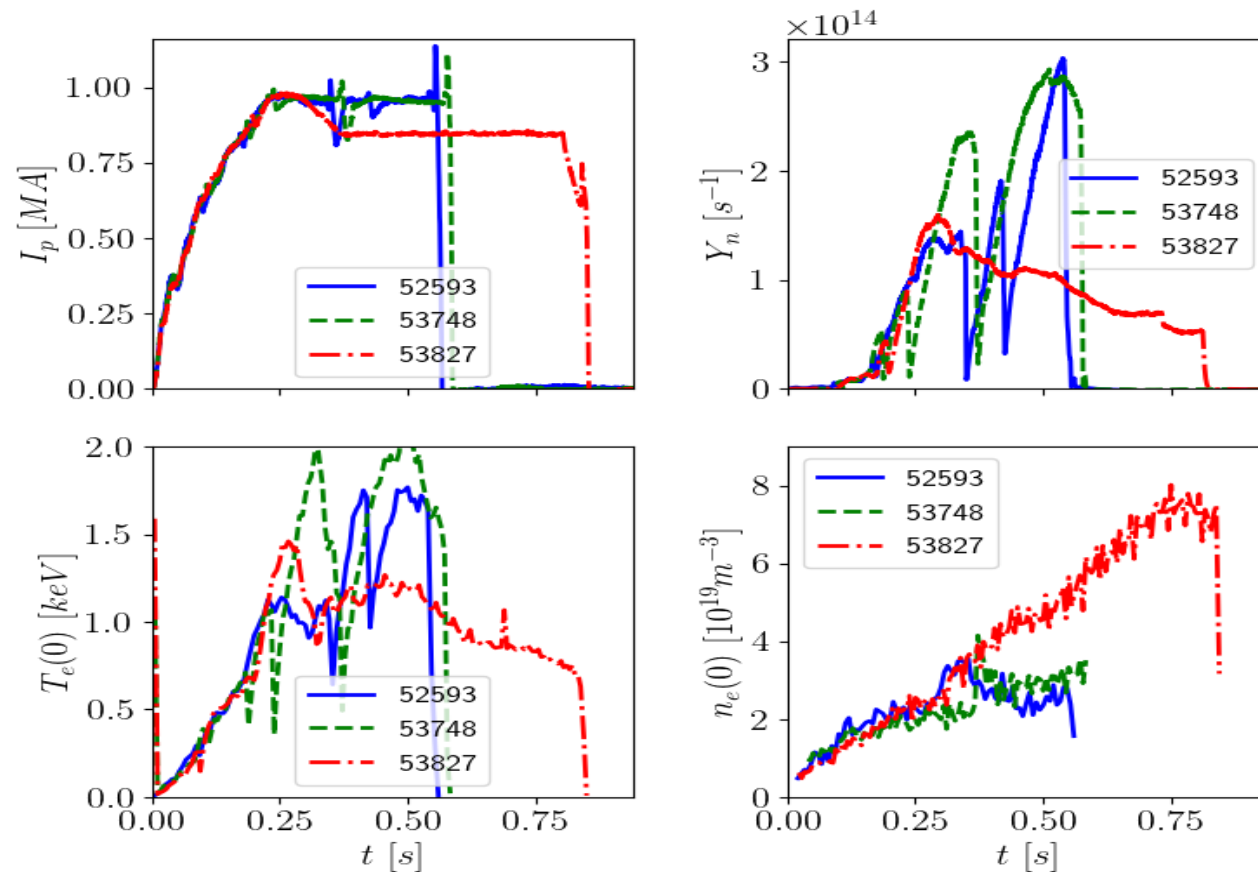
**The main result of this study important for us was:
IRE is less likely at higher q_{95} and β_{pol}**



Our proposal was:

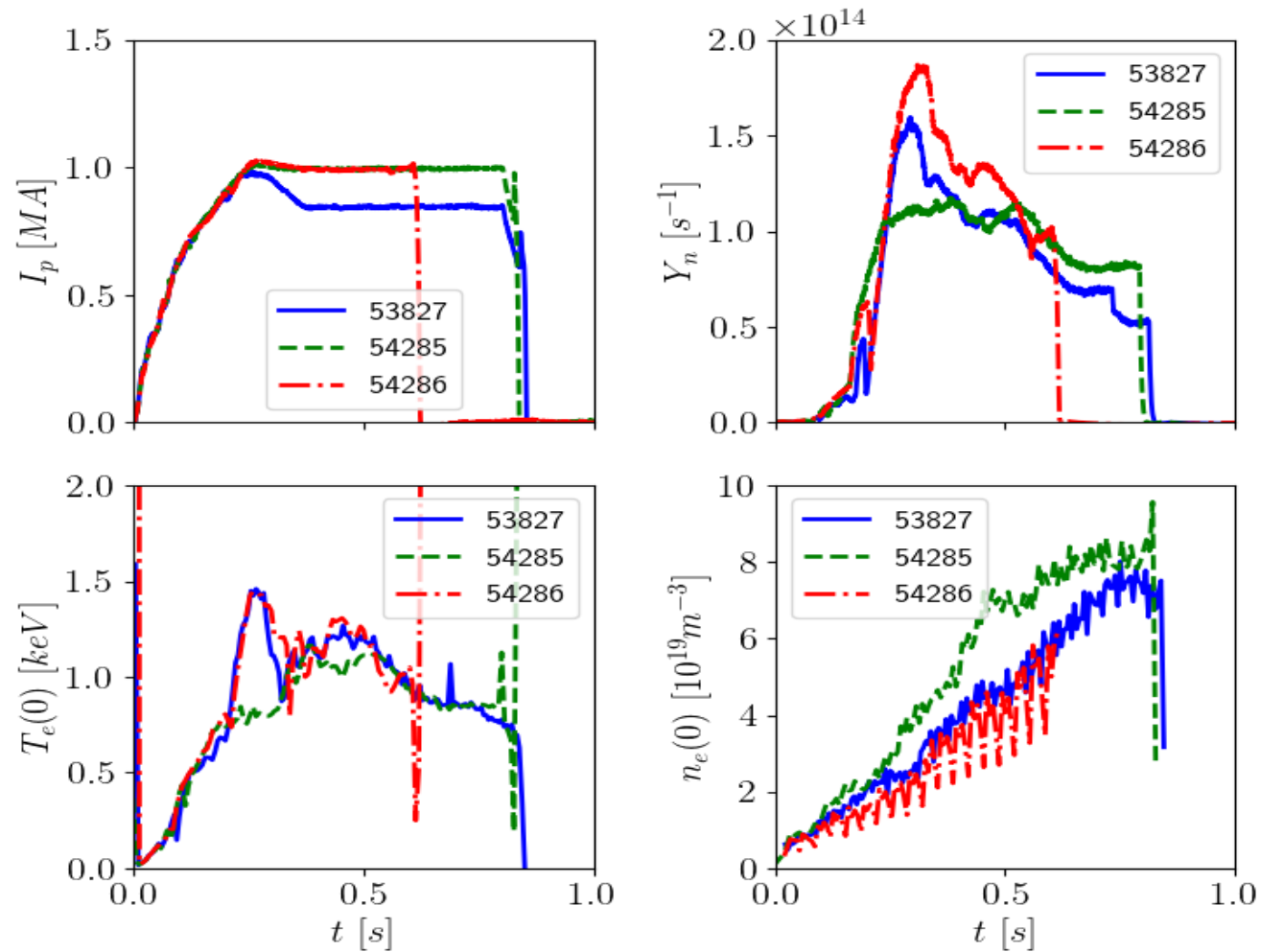
**Decreasing the inductive current just before IRE
could mitigate the IRE (current ramp-down technique)**

Current Ramp-Down for IRE Mitigation: 1MA $\rightarrow$ 850 kA in 80 ms



This technique mitigated IRE successfully!
However, the density control afterwards required a further development.

Controlling n_e by lower fuelling and kicks did not help much so far



CONCLUSIONS:

A scenario was established at **1 MA and two beams on-axis and off-axis**. It is characterized by **absence of beam-driven AEs** at the end of the pulse. High rates of beam-plasma D-D neutrons were achieved because of that. **The current MAST-U record stands at $3.03 \times 10^{14} \text{ s}^{-1}$** .

A robust agreement of the data versus TRANSP and MSE analyses was established. Modelling of beam-driven AEs is in progress.

This scenario has a potential for further development since:

- The trace of the neutron rate in #52593 was still **going up at the time of IRE collapse at the end**;
- We did not explore yet the fuelling and density control;
- We may increase neutron rate by further plasma upshift to ~ 8 cm achieved at 750 kA, but not tested at 1 MA yet. We also can play with ellipticity.

The technique of **mitigating IREs with current ramp-down worked successfully**, but plasma density control requires a further development.

