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Reaching high beta operation in MAST-U (Part I of II)

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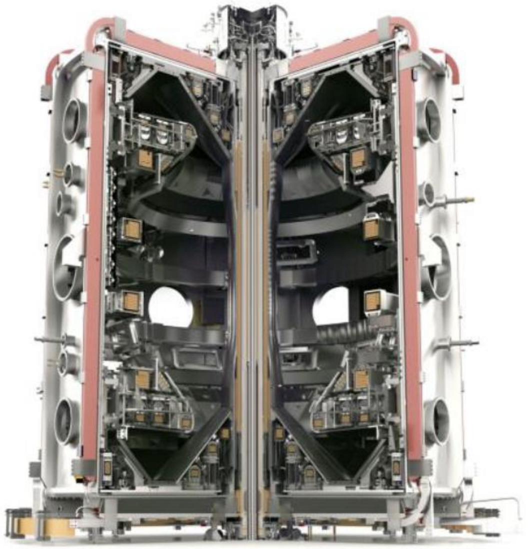
NSTX-U Physics Meeting
(via Zoom)
PPPL
5 February 2024



V3.0

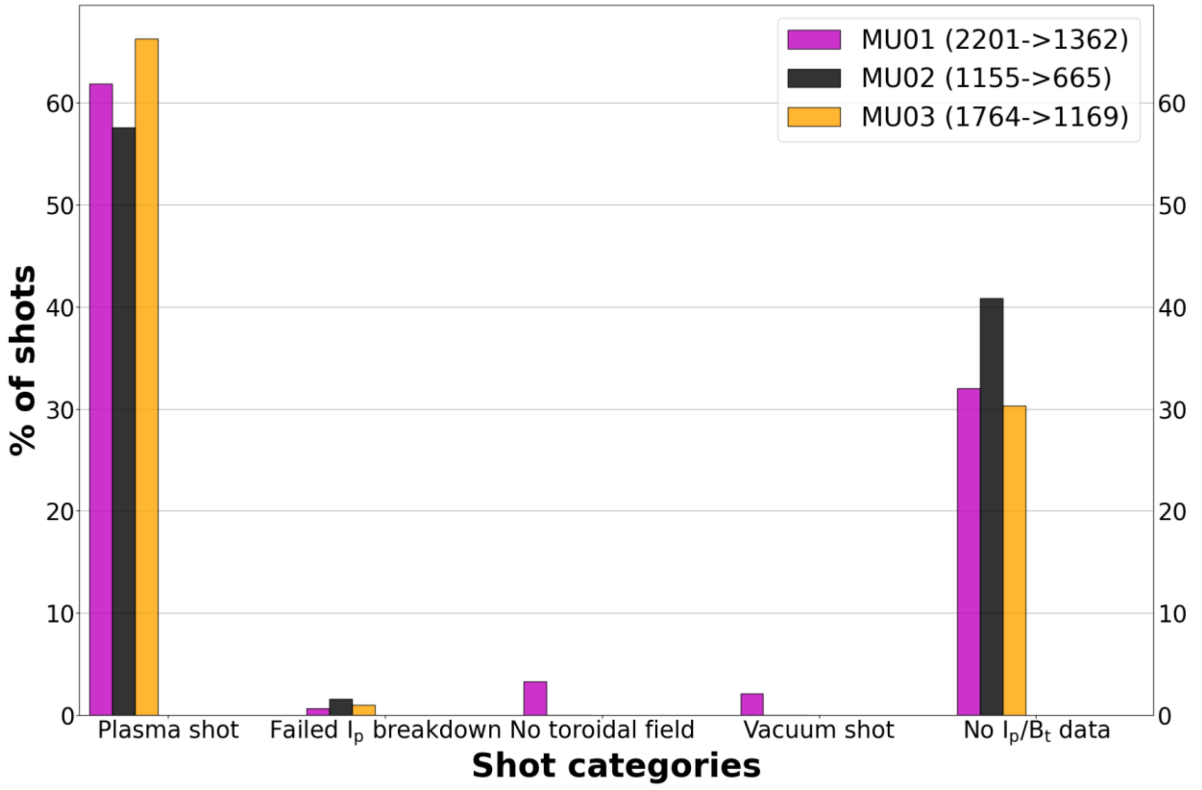
Supported by US DOE grant DE-SC0018623

MAST-U campaign thrust experiment MU03-THR-02 successful in producing sustained high β plasmas

- Goals
  - Produce sustained high performance determined by objective figures of merit (β, β_N, β_p, W_{tot}, τ_E)
  - Produce full understanding of limiting stability physics using unparalleled MAST-U diagnostic set
  - Make connection between operational space produced and that of ST Pilot Plant visions
- Highlights
  - High β_N plasmas created, initial experiments (MU02-THR-02) establishing high $\beta_N > 3$, eliminating IREs in during Ip ramp-up, mode locking at lower range of β_N, and establishing VDE limits
  - Rotating MHD modes mitigated and mode locking completely avoided at elongation ~ 2.3
  - Decrease in l_i observed with all else constant indicating n = 1 core dynamo / flux pumping (Part II)
  - Shafranov shift stabilization with extreme shift of toroidal rotation peak mitigating mode locking
- Part II of this presentation will address further results / physics details of the latest plasma run (about 1.5 weeks ago)

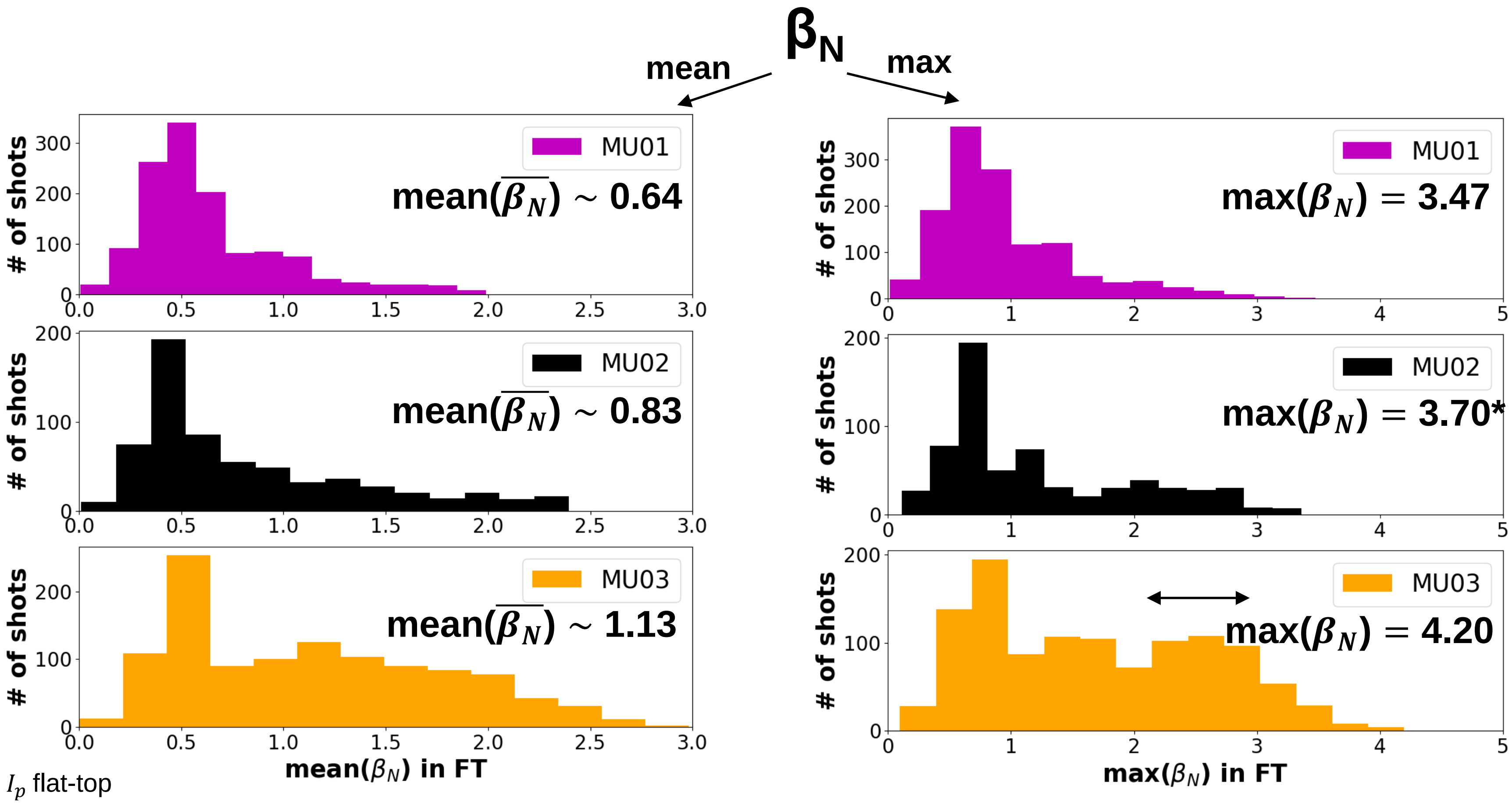
DECAF shows about 3200 plasma shots achieved during the first three MAST-U run campaigns

	MU01	MU02	MU03
Shot range	43313 -> 45513	46020 -> 47174	47712 -> 49475
Total shots	2201	1155	1764
Plasma shots	1362	665	1169



- Plasma shots categorized by DECAF
  - Nearly all plots / analysis shown in this talk created with DECAF
- The MAST-U MU03 run campaign completed at the end of January 2024
  - Some results about 1.5 weeks old (reserved for Part II of this talk)

Plasma β has progressively increased in MAST-U



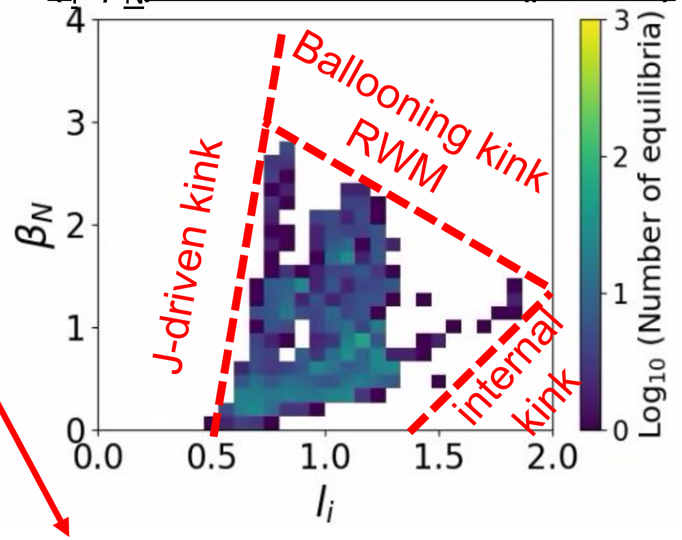
FT = I_p flat-top

- Plasma β (β_p, β_t, β_N) progressively increased in MU01 ➔ MU02 ➔ MU03
- *IAEA FEC record β_N for MAST-U run in our 2nd year experiment MU02-MHD-02
  - Transiently during programmed I_p reduction testing VDE limits

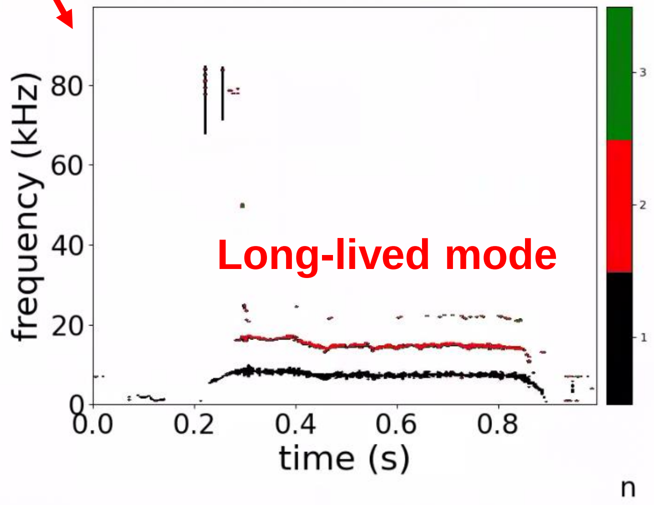
MU02-MHD-02 broadly examining the conditions for stability of key modes that create beta-limiting operational limits

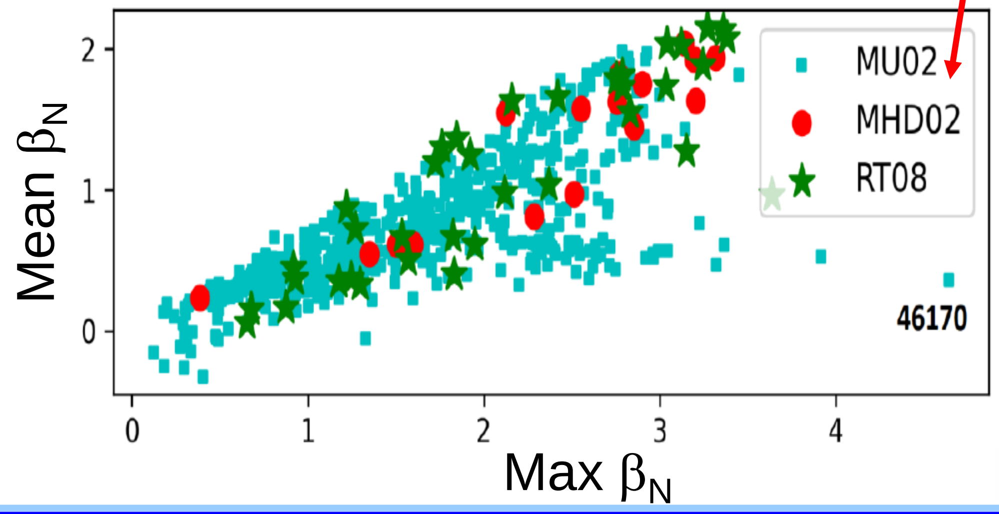
- **Overall goal**
  - Investigate key beta-limiting MHD to determine β_N and other limits, and curtail or eliminate such modes to reach maximum β_N, β_p, β
- **Approaches follow techniques used in NSTX**
  - Very good progress, yet only 2 of 6 steps completed; VDE limits found
  - IREs (leading to uncertain J profile) eliminated during I_p ramp, flat top
  - "Tearing mode" not yet seen; long-lived mode (LLM) is dominant
  - Some information for low, constant I_p target (step 4) from XP RT08

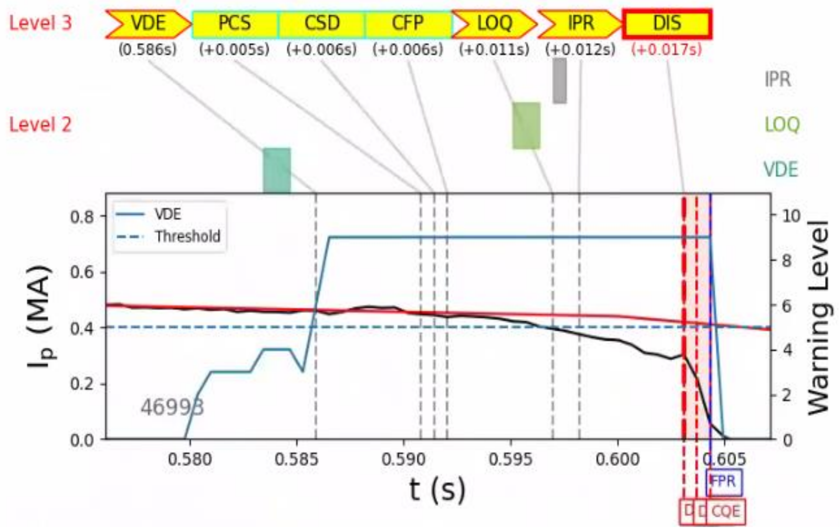
(l_i, β_N) State Occurrence (pre-XP)



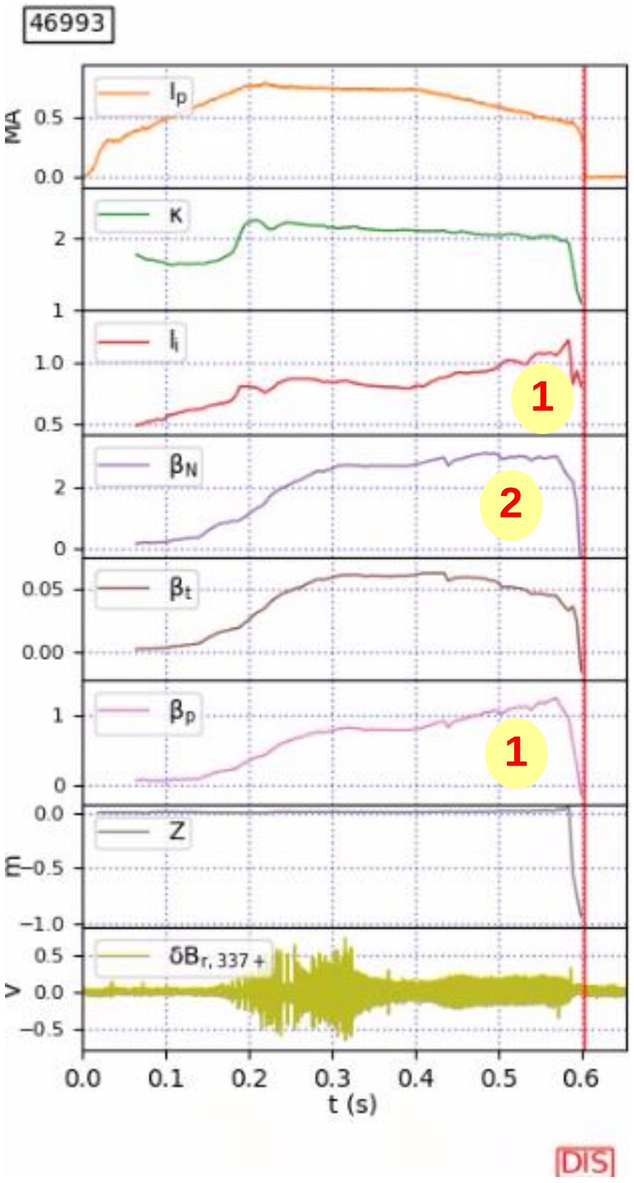
DECAF analysis (physics & tech events)

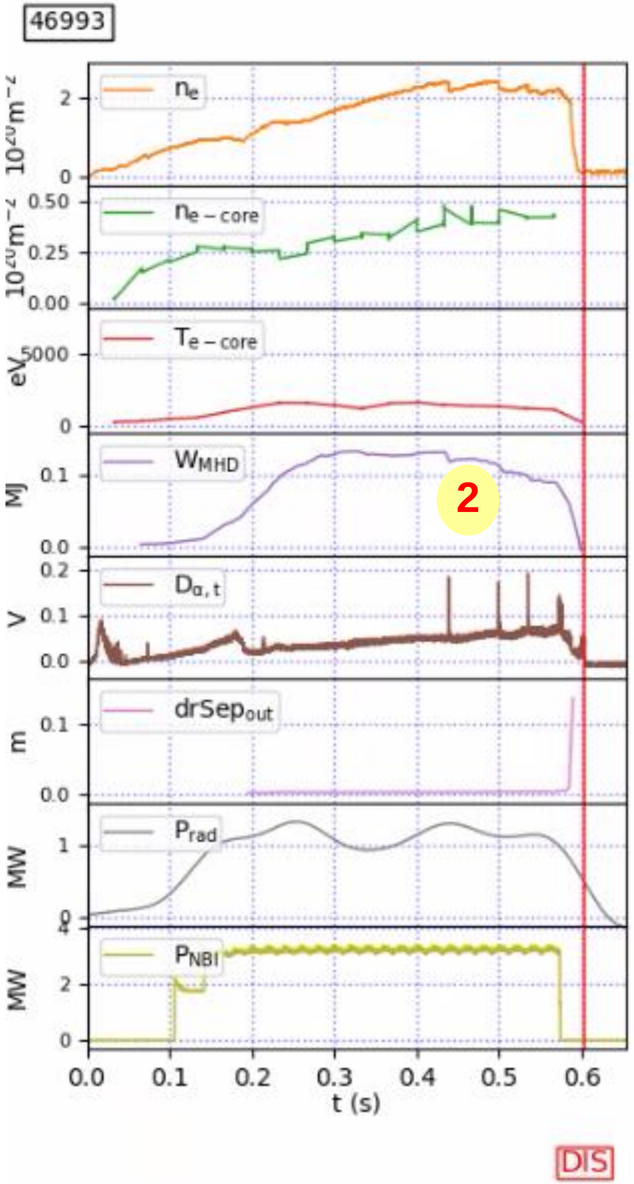






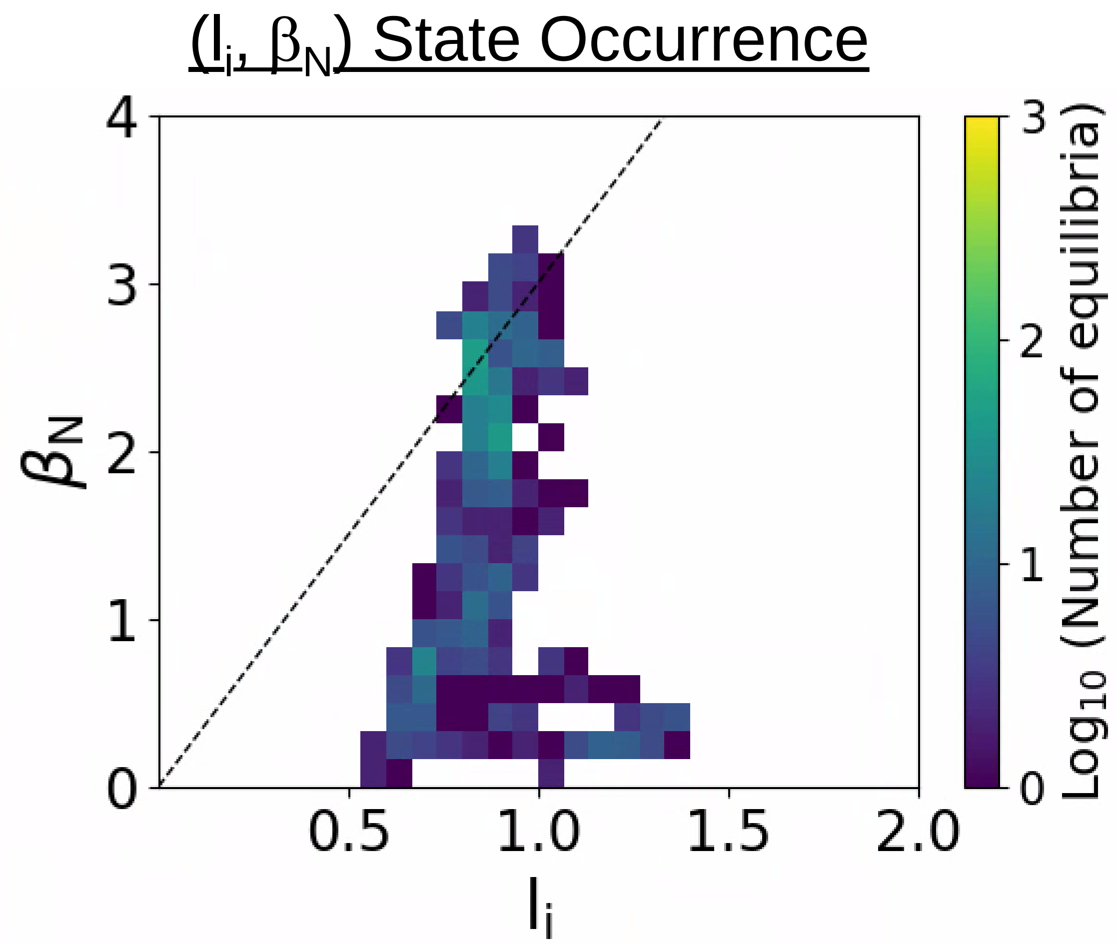
MU02-MHD-02 proceeding as planned – quite successful, with good understanding of the results attained so far with great diagnostics

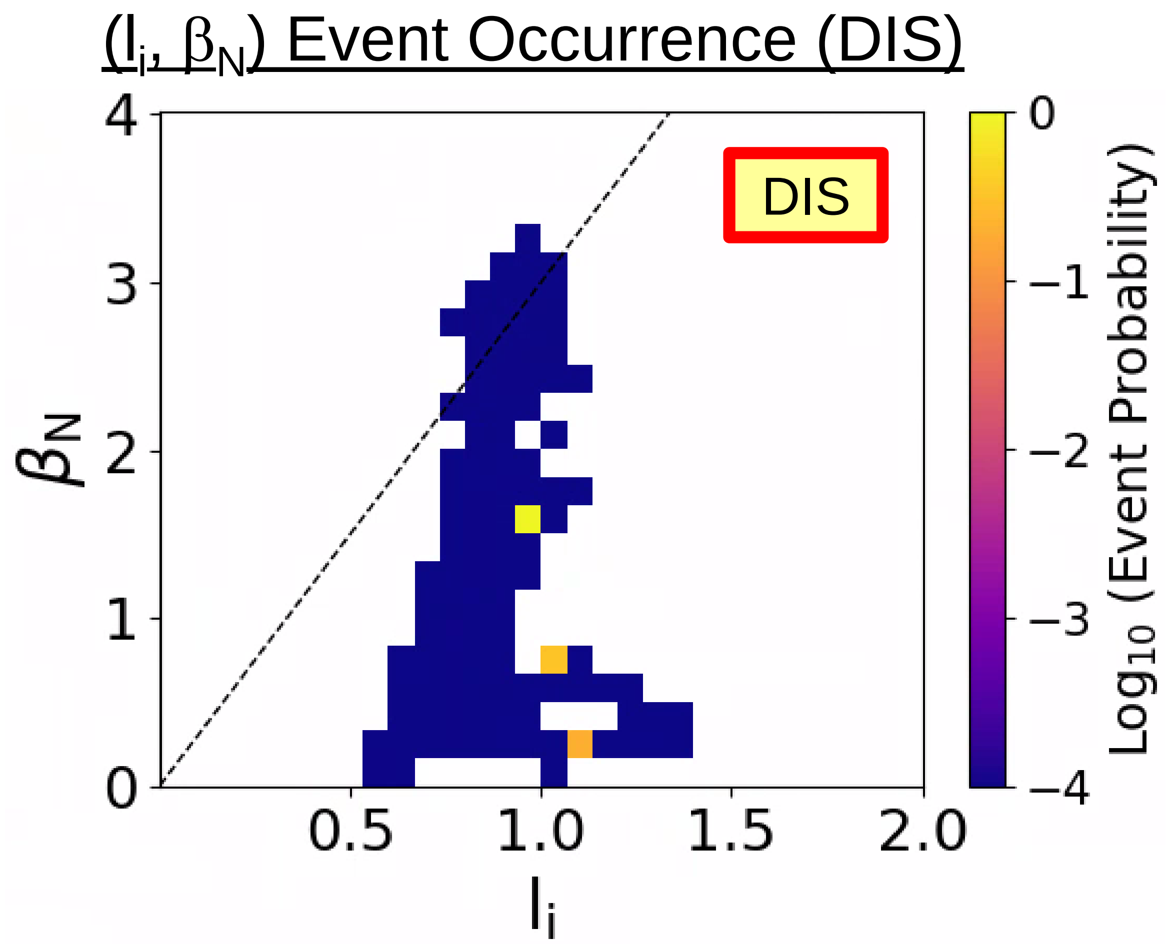




- More to do! Only reached Step 2 (of 6)
  - 18 shots, BUT constraint of 50 ms steps of the NBI during I_p ramp-down development
  - More approaches next 4 steps to affect MHD
  - Burst Thomson shows flat T_e spots (islands)
- Parameter variations as expected
  - 1 The l_i and β_p = 1.3 are still increasing
  - 2 The β_N saturating at ~ 3.3, W_{tot} decreasing
  - The β_p is more than double the base scenario ➔ higher $I_{bootstrap}$
- Related proposals for MU03
  - Expand stability limit tests (more variations) shaping, higher NBI, MHD spectroscopy, etc
    - Expand stability space, inform DECAF analysis

Disruptivity: MU02-MHD-02 continues to show that high β_N operation is basically disruption-free

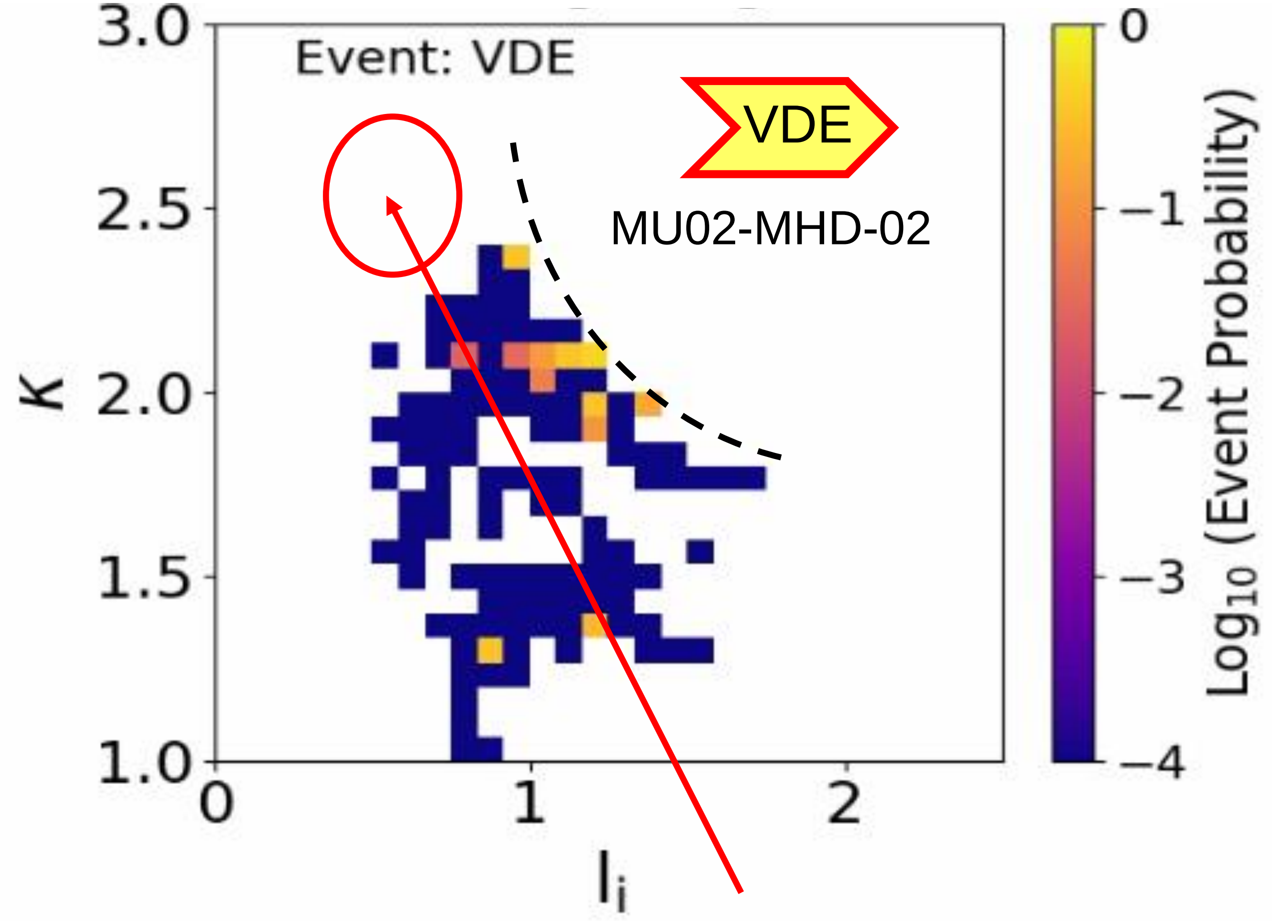




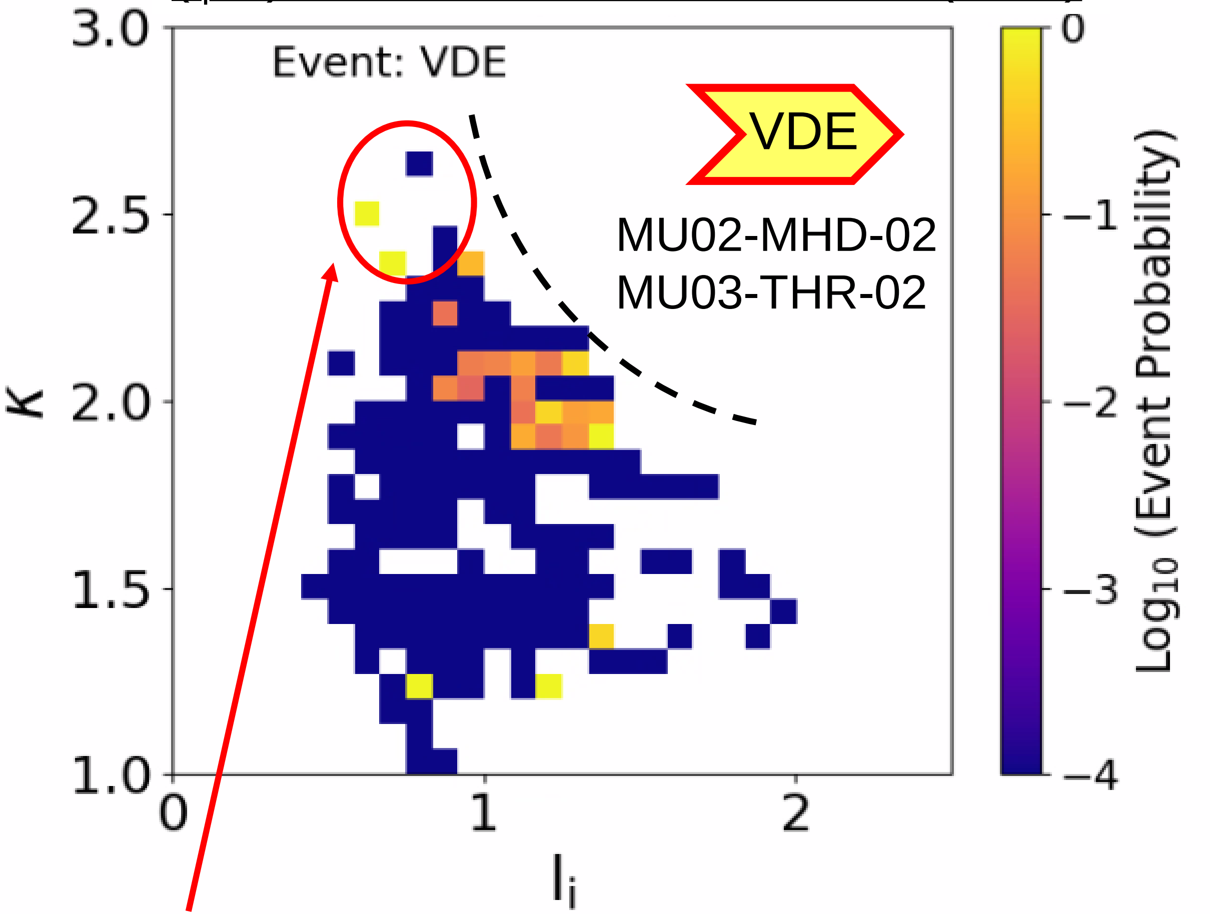
- Large number of equilibria created at high β_N, β_N/l_i; haven't reached limit
- Disruptivity is very low at high β_N, consistent with NSTX, KSTAR, DIII-D

MU03-THR-03 High performance experiment has started operation at increased elongation, steps now being taken to optimize shape

(l_i, κ) DECAF Event Occurrence (VDE)



(l_i, κ) DECAF Event Occurrence (VDE)

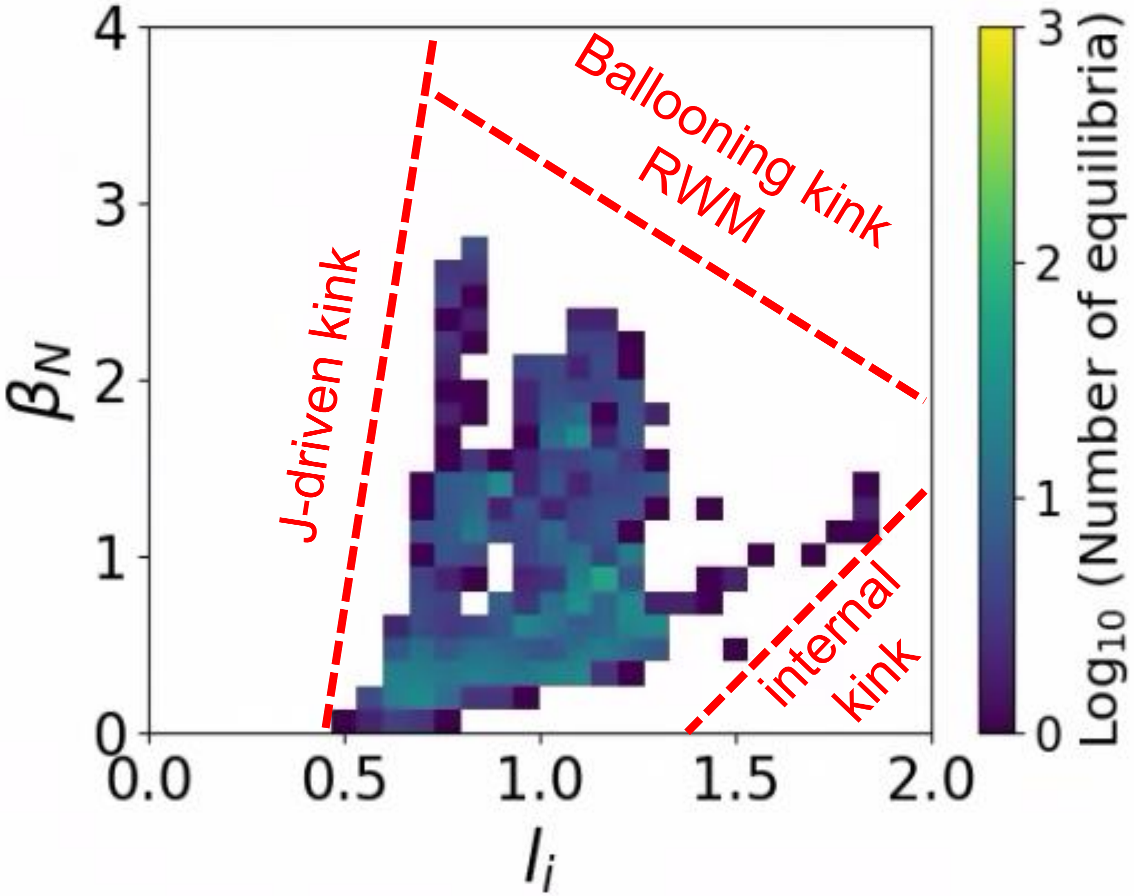


(from EPS 2023: OPERATE HERE! … … we started!

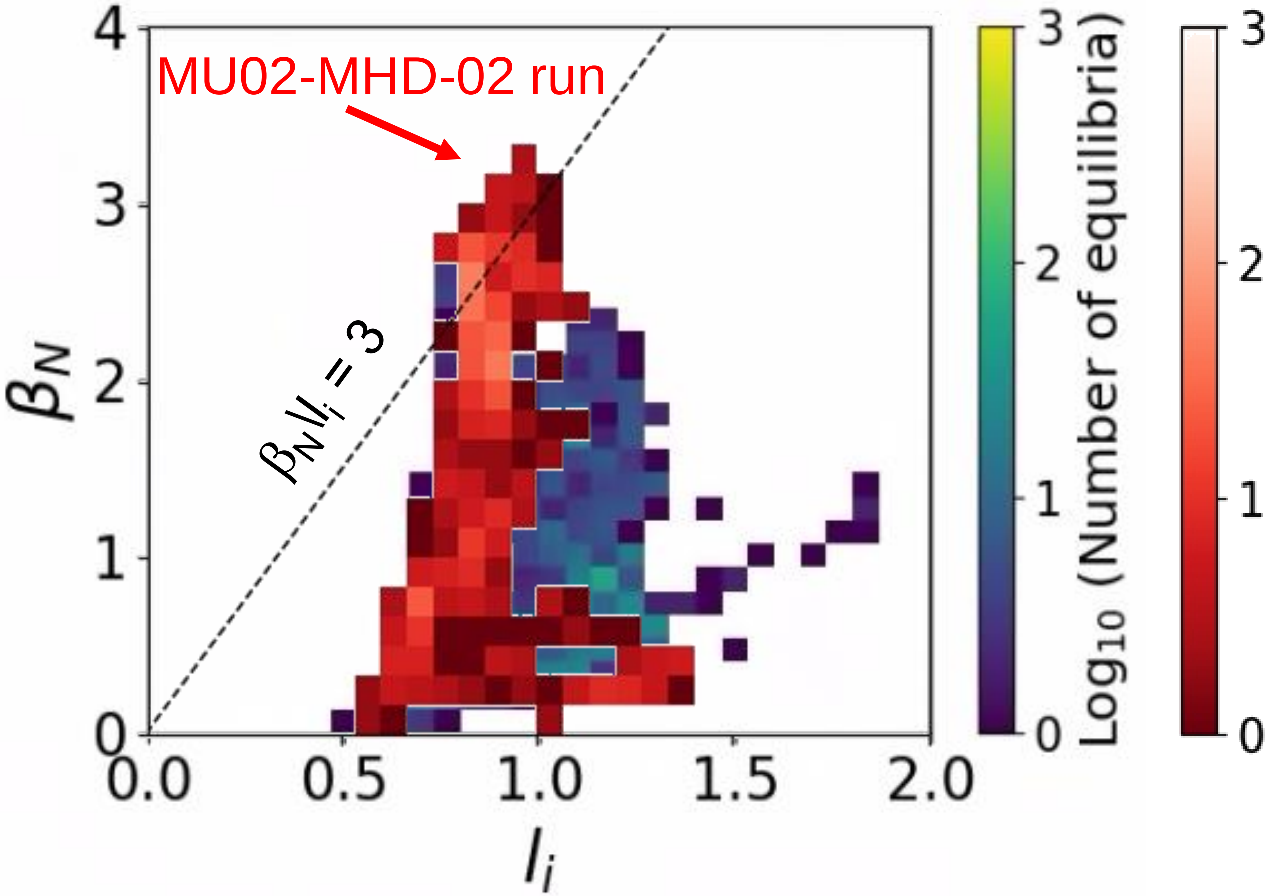
- DECAF VDE Event occurs at high elongation, shows inverse l_i relation as expected

β_N limit: As planned, MU02-MHD-02 expanded MAST-U operation in (l_i, β_N) space

(l_i, β_N) State Occurrence (pre-XP)

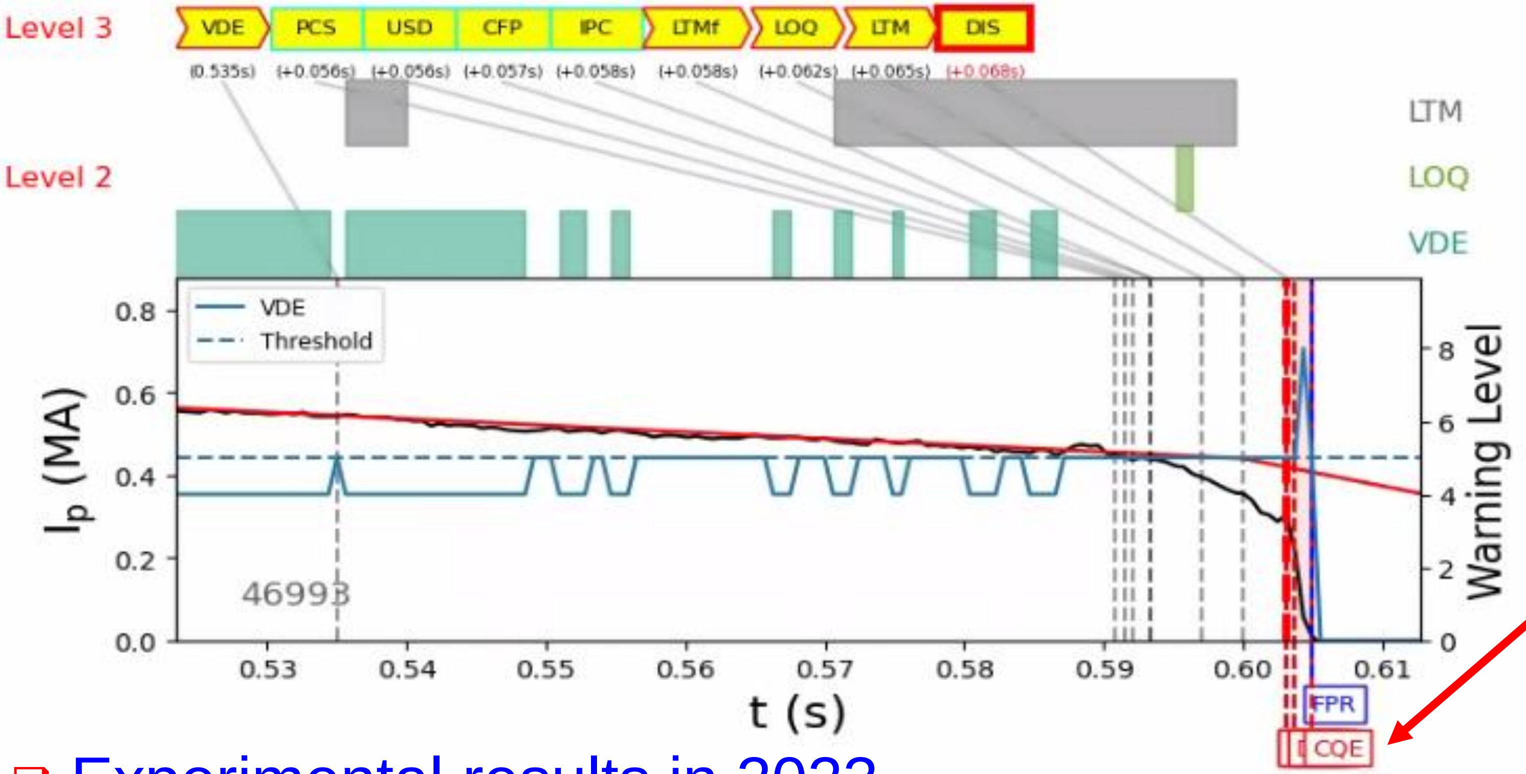


(l_i, β_N) State Occurrence (MHD-02 in red)

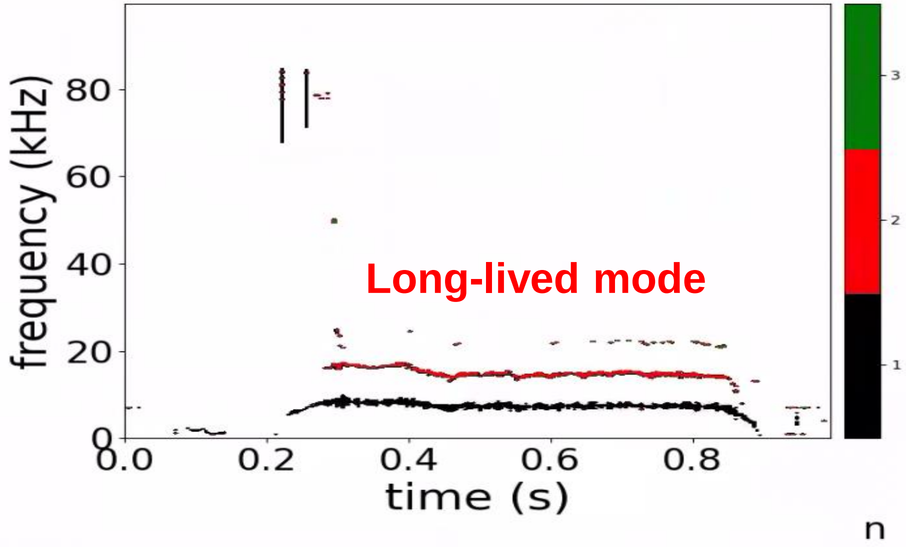


- Lower l_i than general database somewhat surprising, a positive aspect
- Steps 1,2 of experiment successful in raising β_N, move to steps 3 – 6 to go further

MAST-U MU03-THR-02 High Performance Plasma campaign experiment: DECAF used as sole analysis tool to guide



- DECAF technical events
  - Example: USD (uncontrolled shut down)
  - Critical for physical understanding!
  - Criteria typically hard to find
- Disruption “interval”
  - Disruption is more than just a single time point, has sub-events



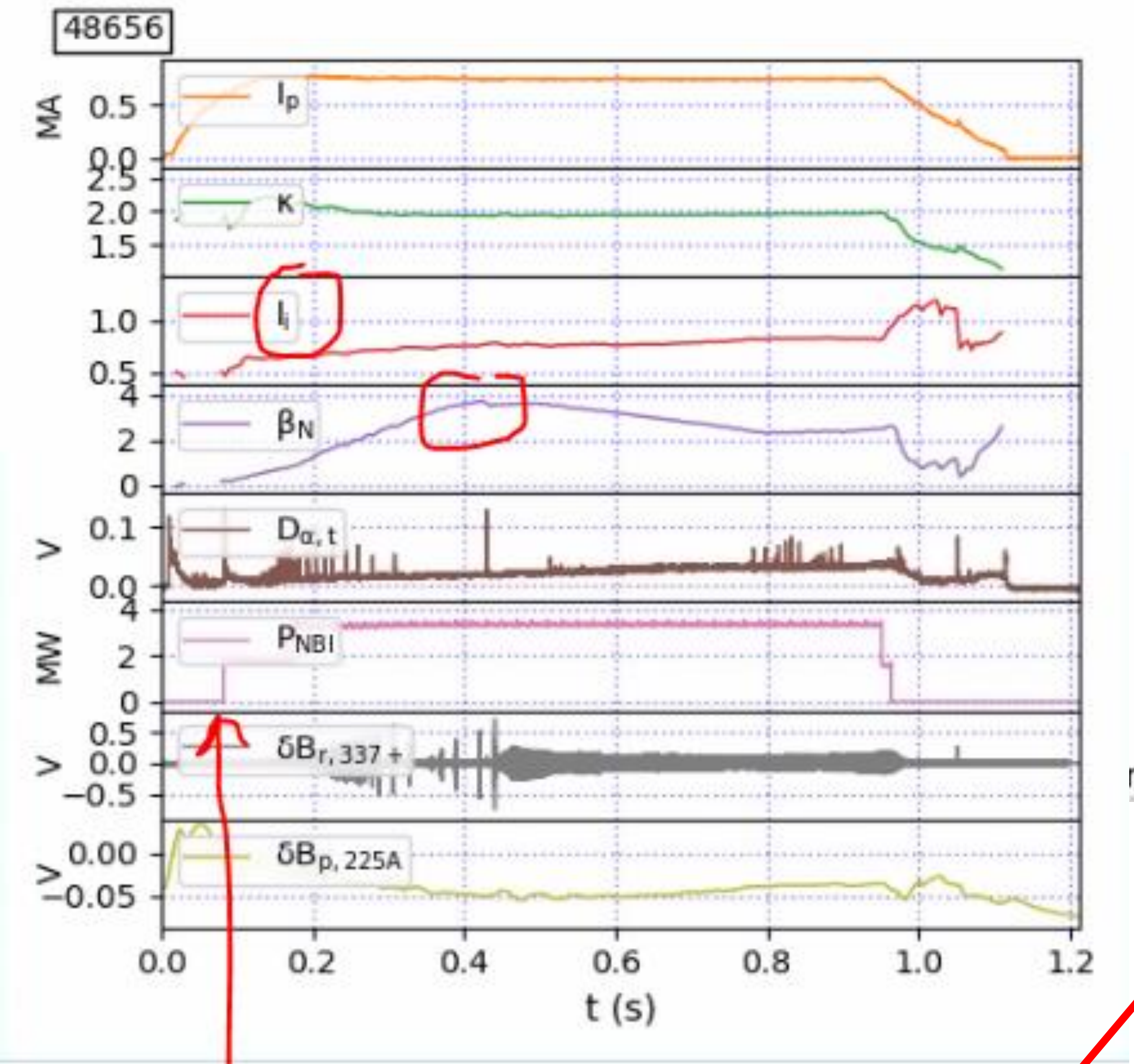
- Experimental results in 2023
  - Record MAST-U β_N = 3.7 produced (8/8/23); more to come!
  - IREs eliminated during I_p ramp, flat top
  - Long-lived mode (LLM) dominant (aim to eliminate it!)
  - VDE limits investigated for coming shape optimization

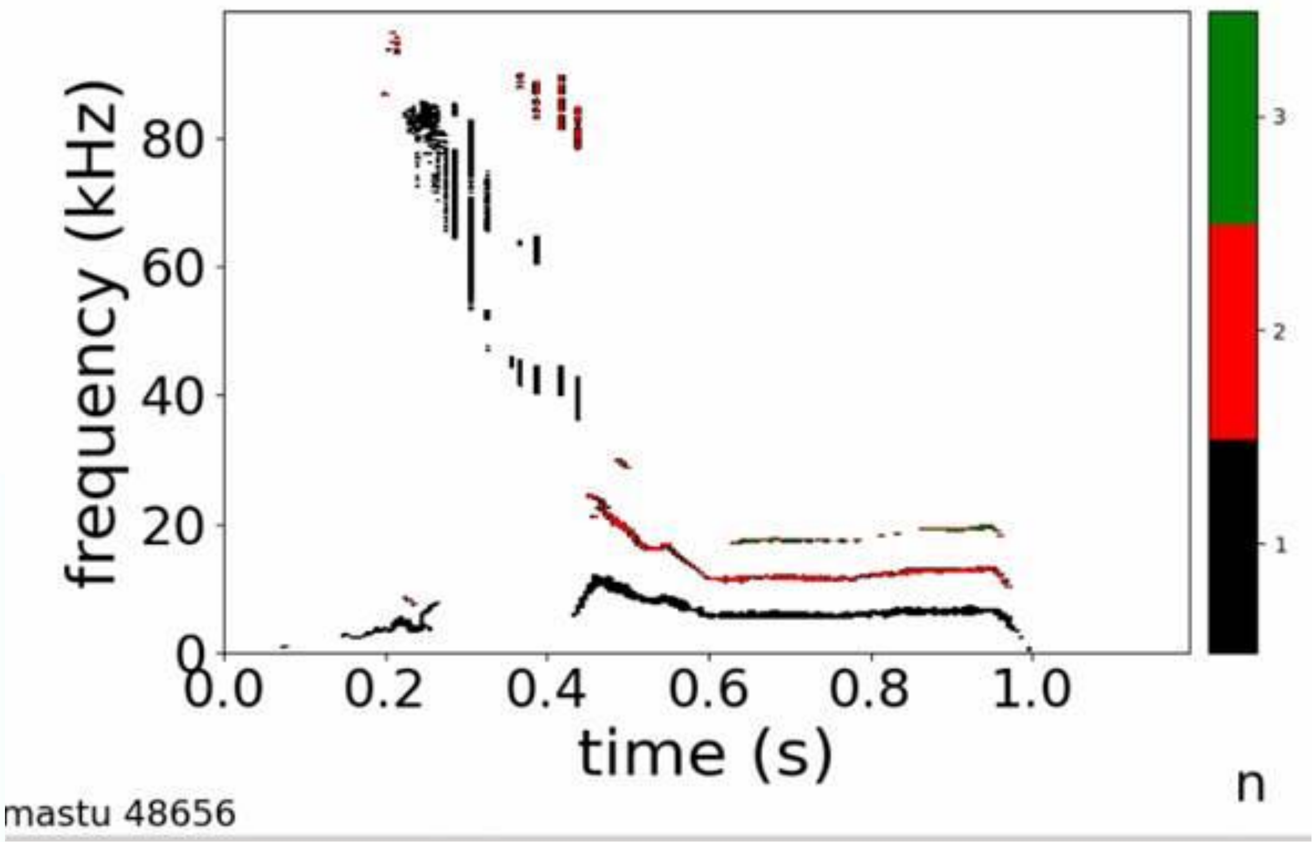
MU03-THR-02 aims to logically combine elements to produce maximum performance in MAST-U with physics understanding

- Goals
  - Produce sustained high performance determined by objective figures of merit (β, β_N, β_p, W_{tot}, τ_E)
  - Produce full understanding of limiting stability physics using unparalleled MAST-U diagnostic set
  - Make connection between operational space produced and that of ST Pilot Plant visions

- Strawman Approach (70 shots, run at different times in MU03 campaign)
  1. EARLY STAGE: Complete and expand the MU02-MHD-02 plan to maximize β, β_N, β_p
     - techniques also aim to reduce / eliminate the LLM – the remaining impediment to high performance
  2. MIDDLE STAGE: Fully expand performance enhancement and operational space approaches
     - Expand boundary shape, q profile variation; piggyback aspects of experiments (e.g. controlled ramp-down)
     - Expand operational space to maximum I_p ~ 1.0 MA and W_{tot}, compare q, mode activity to lower I_p operation
     - Fully diagnose plasma, including use of MHD spectroscopy
  3. LATE STAGE:
     - Combine the most successful scenario development elements to produce maximum performance
     - Fully determine the physics of performance limiting MHD, with connection to Pilot Plant relevant q, β_N, etc.

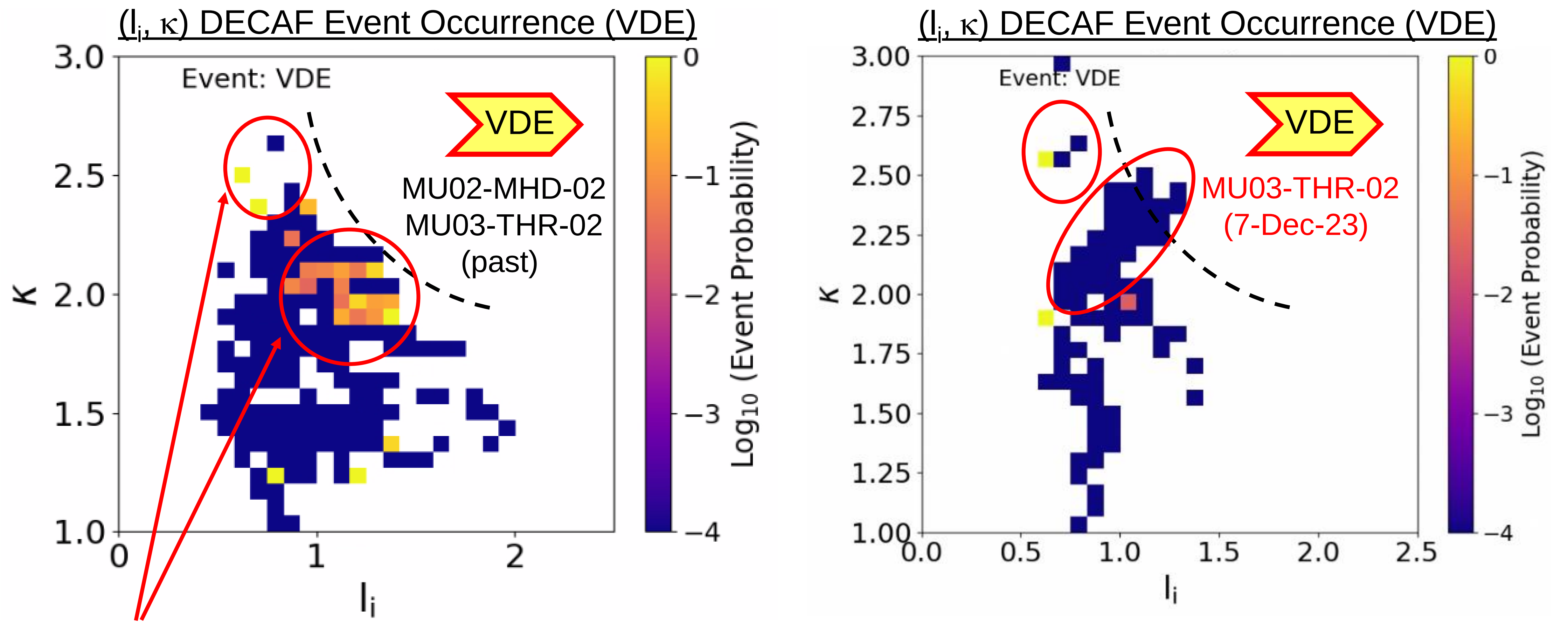
Long-lived mode with "clean" spectrogram produced in recent MU03 plasma with improved control considered for THR-02





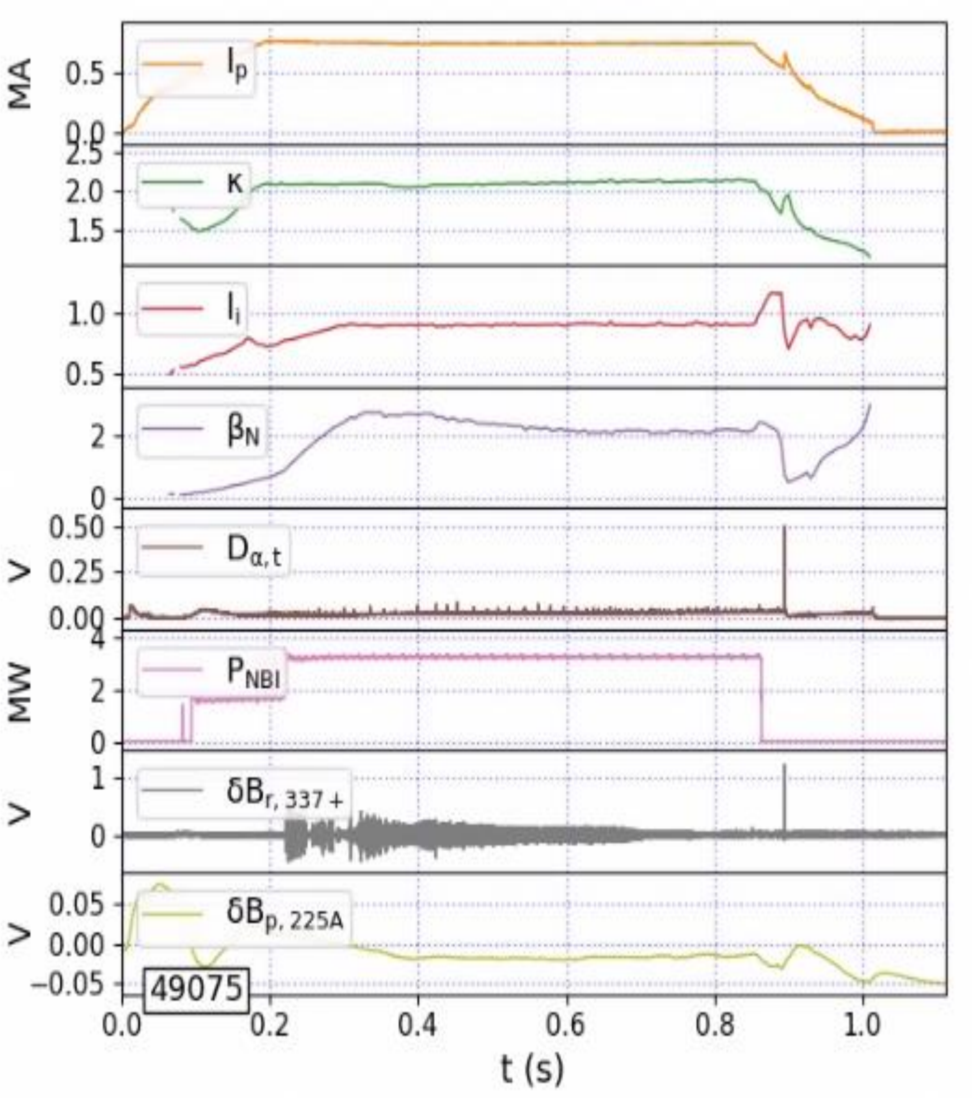
- Early NBI produces broad density and current profile (low l_i ~ 0.8) at peak β_N
- Reduce LLM by increased elongation

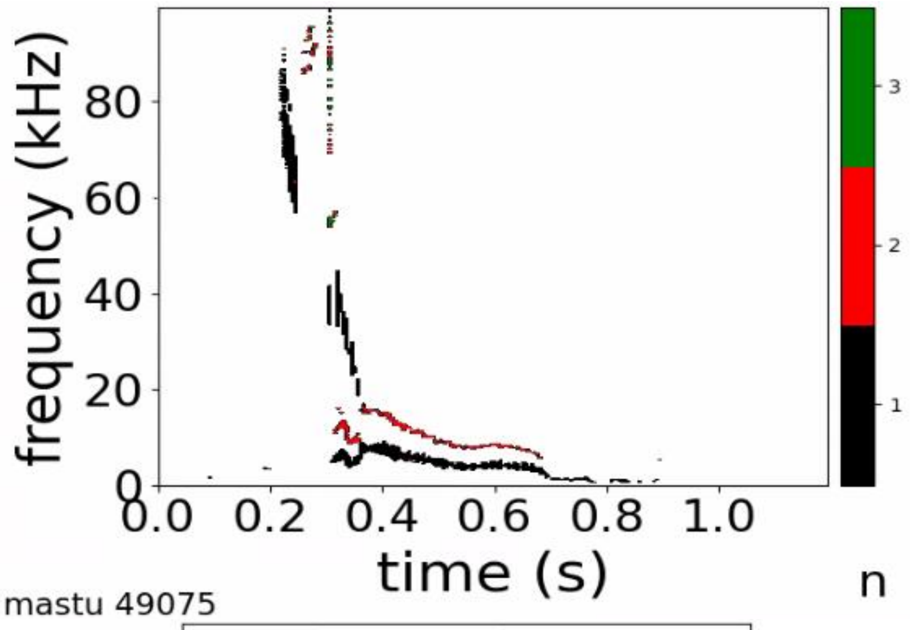
MU03-THR-03 on 7-Dec produced controlled operation at higher elongation, a significant milestone in this experiment

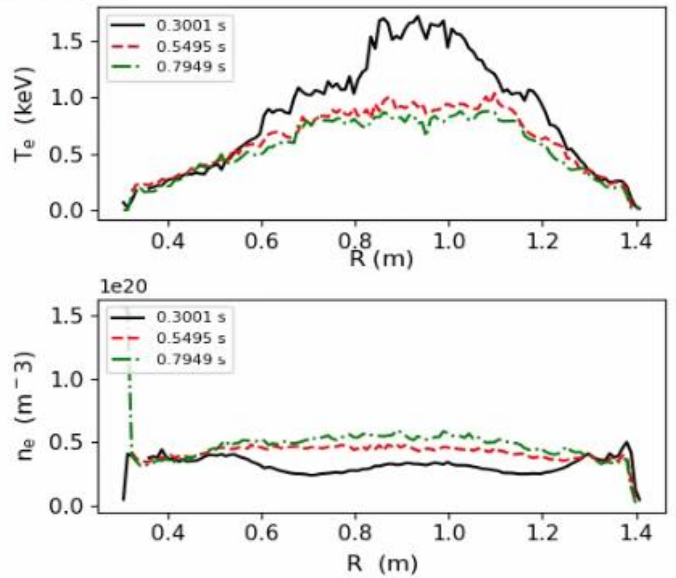


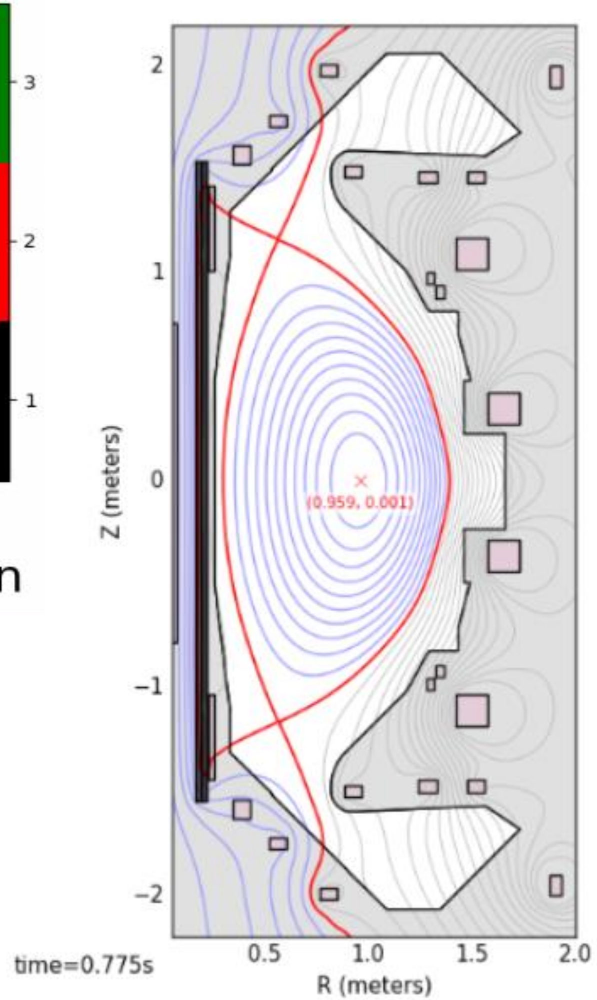
- Past MU03-THR-02 high elongation shots not controlled, high squareness, VDEs
- MU03-THR-02 (7-Dec) high κ scan shots mostly well controlled; almost no VDEs

Elongation 2.05 – 2.15 plasma had well-controlled equilibrium, li < 1, LLM that decreased in time with no LTM disruption



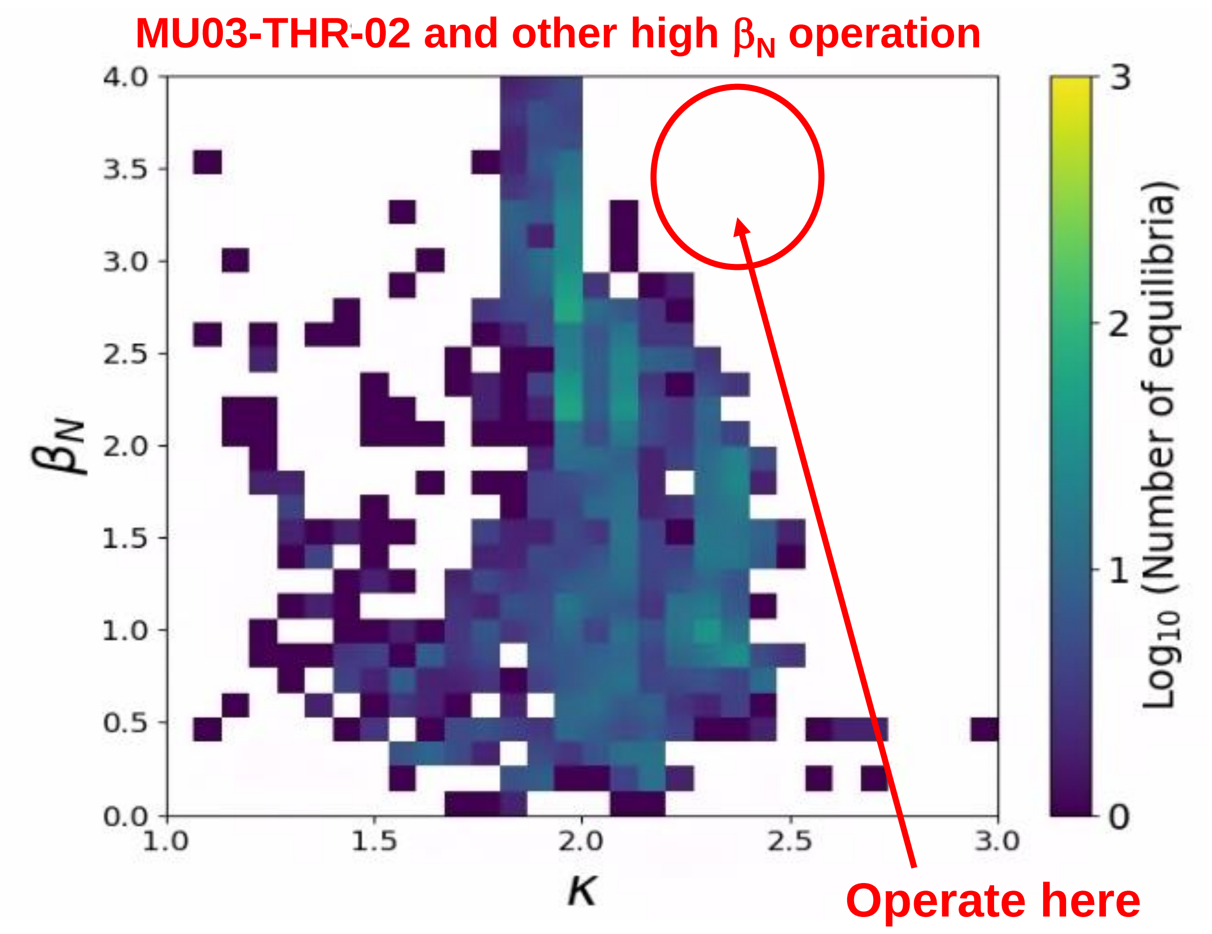


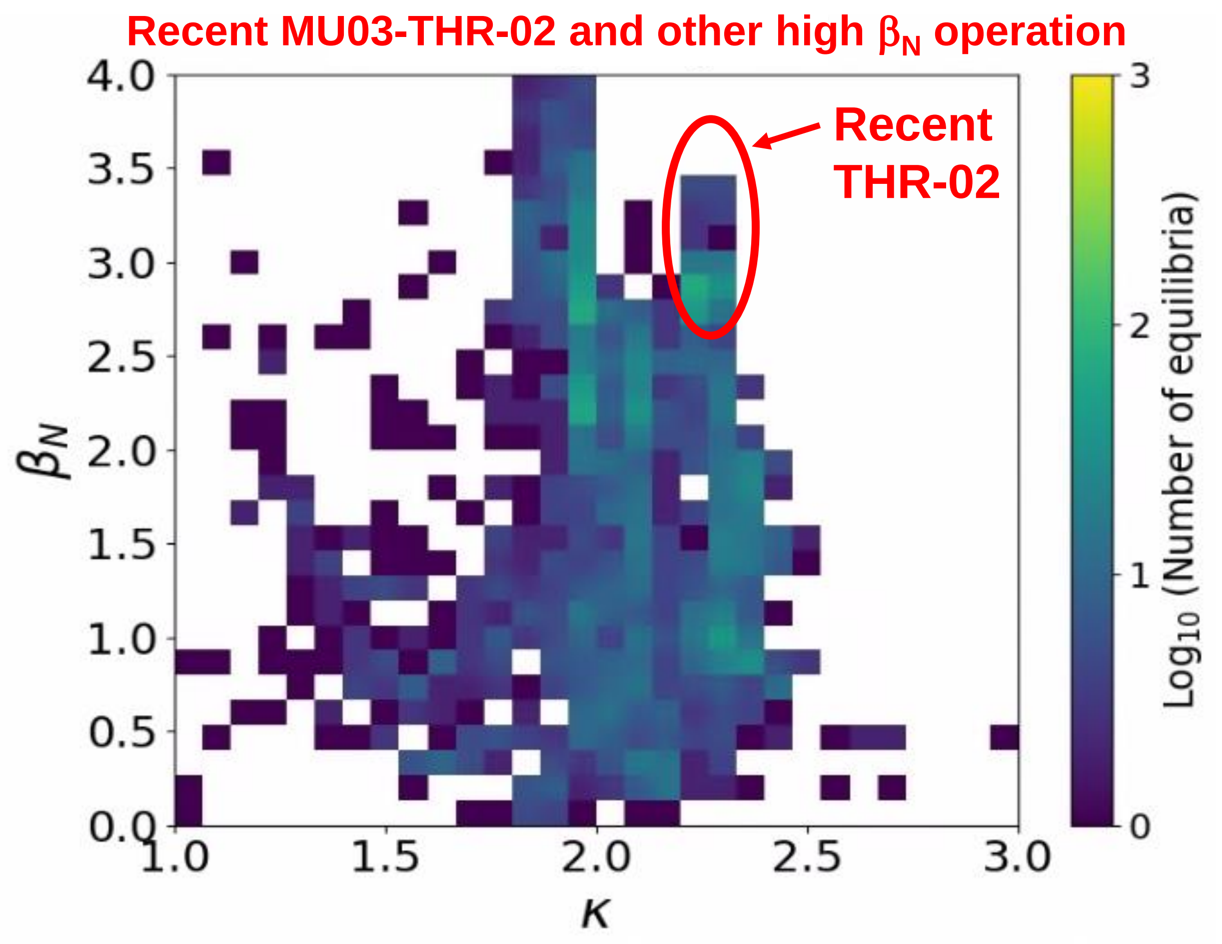




- Broad n_e fills in, T_e broadens

Recent MU03-THR-02 experiment accesses high β_N at increased elongation





- the β_N was observed to roll over strongly at increased elongation
- increased elongation desirable for sustain plasma operation

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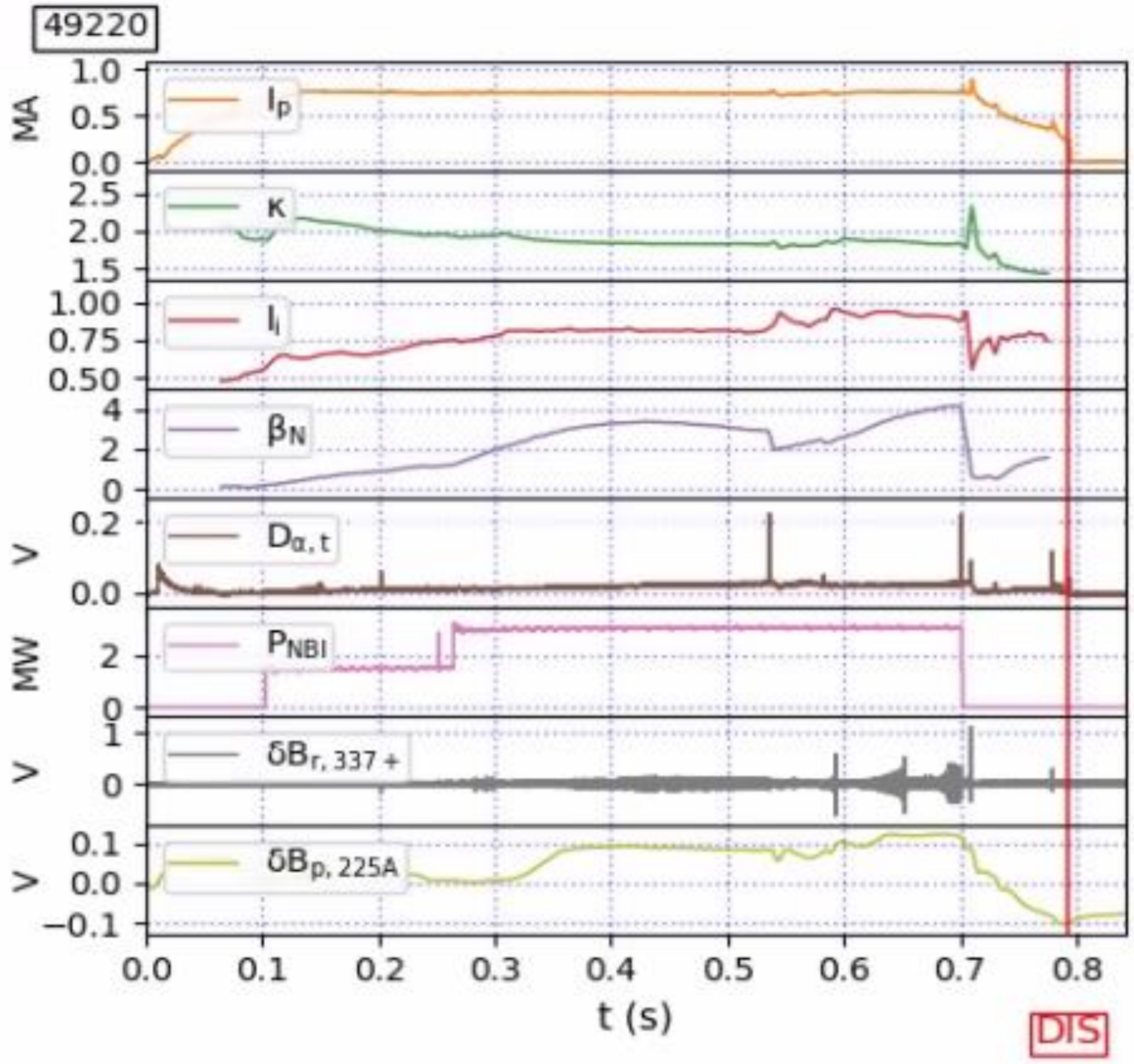
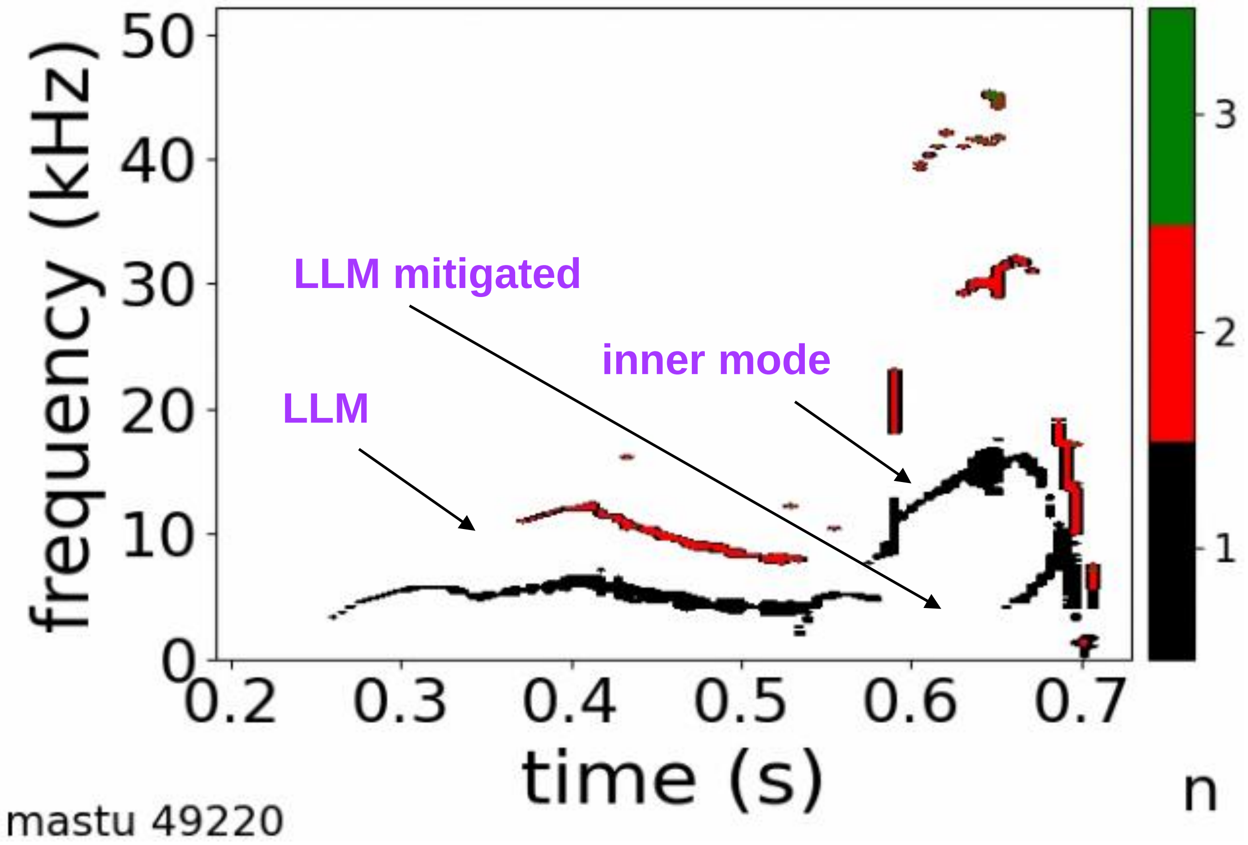
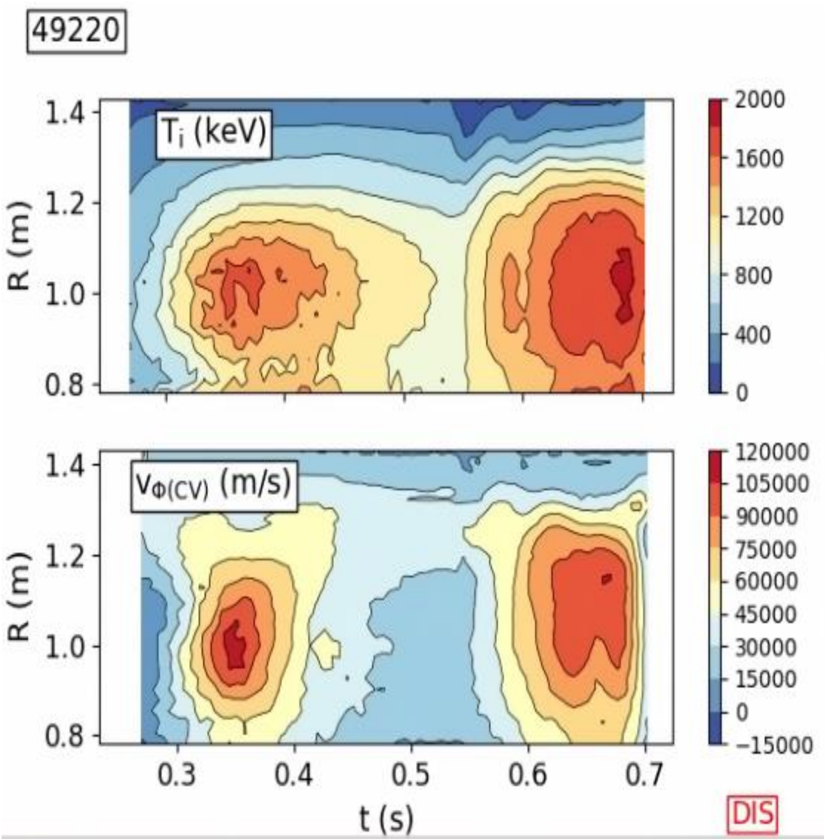
MAST-U MU03 shot 49220 is an excellent illustration of stability physics alterations by rotation and density profile changes

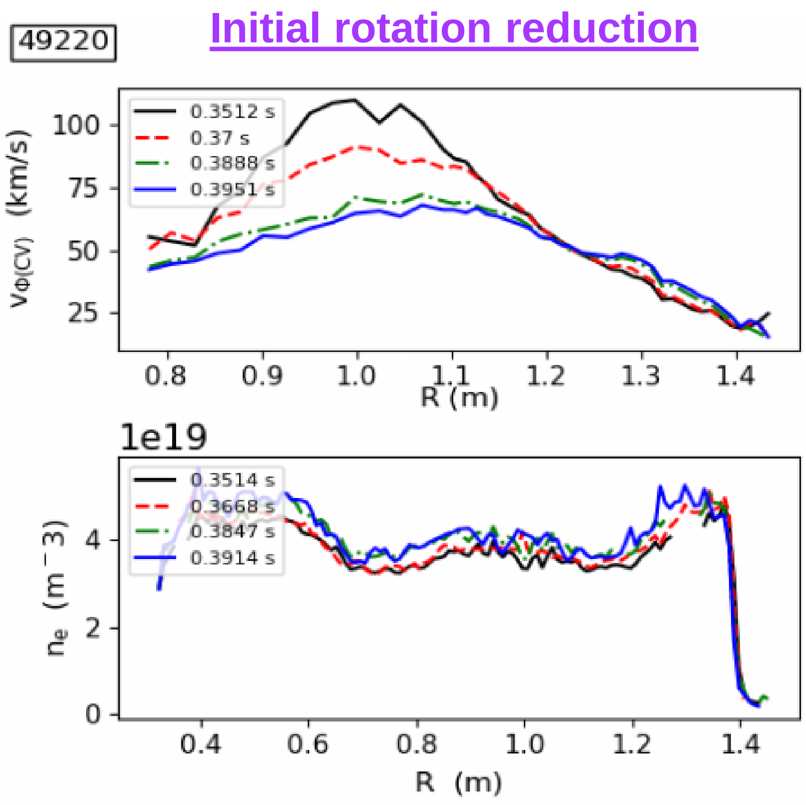


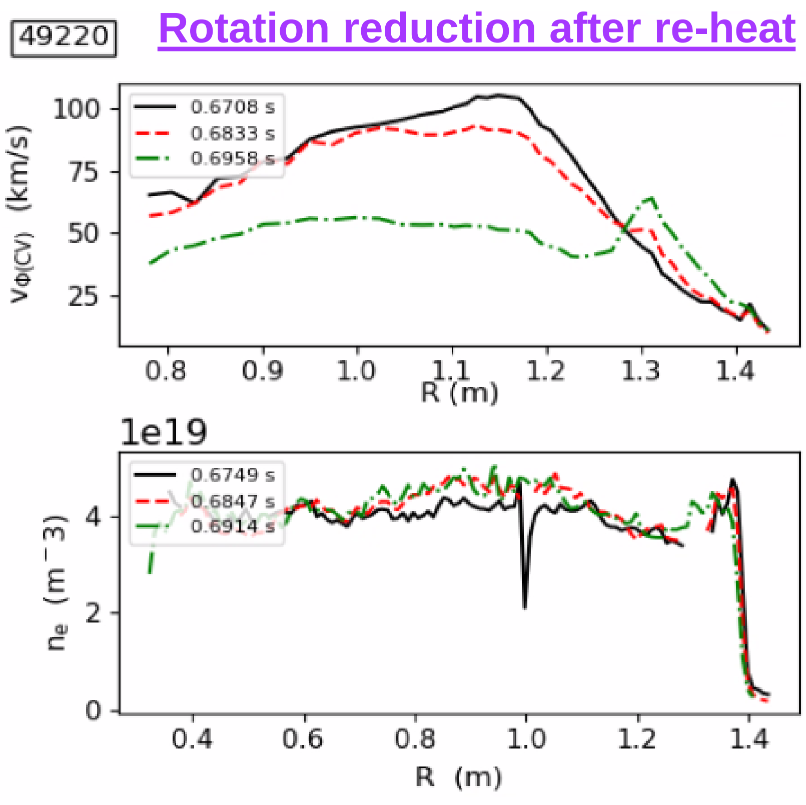


- No early *AE modes (delayed SS NBI)
- LLM stabilizes, core mode appears
- LLM mitigated even though $\kappa < 2$

MAST-U MU03 shot 49220 – toroidal rotation sustained avoiding mode lock

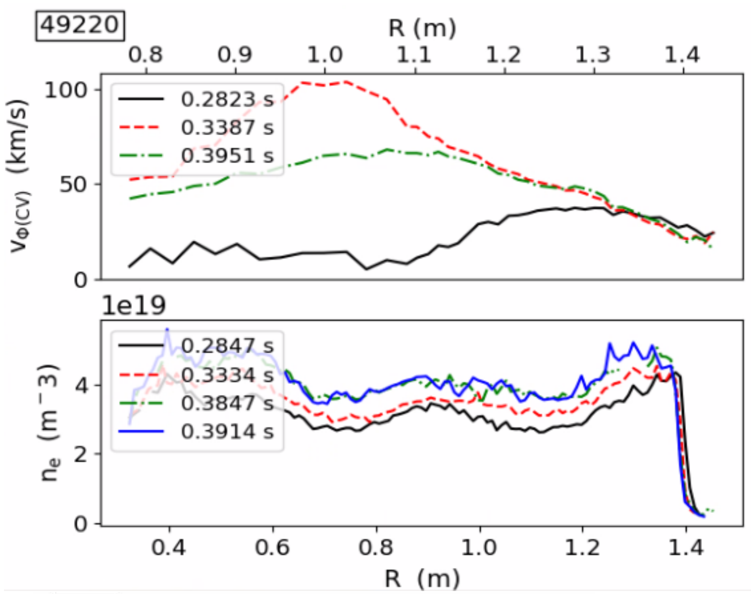


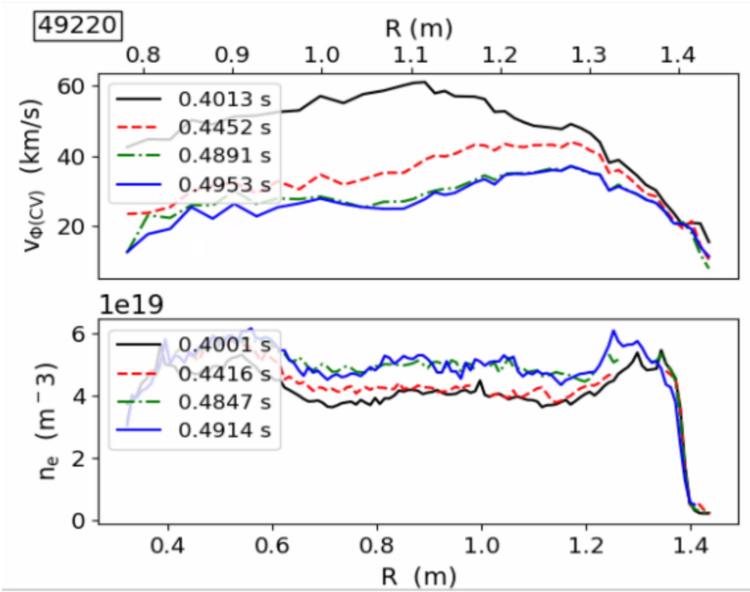


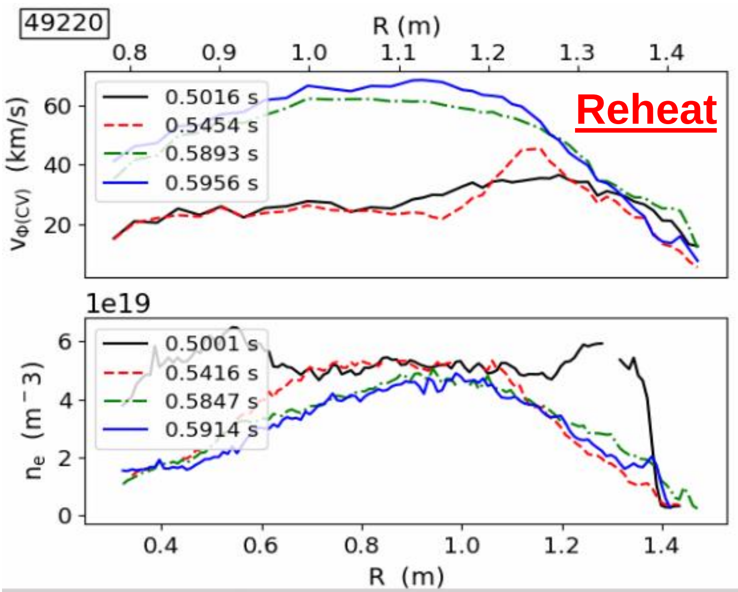


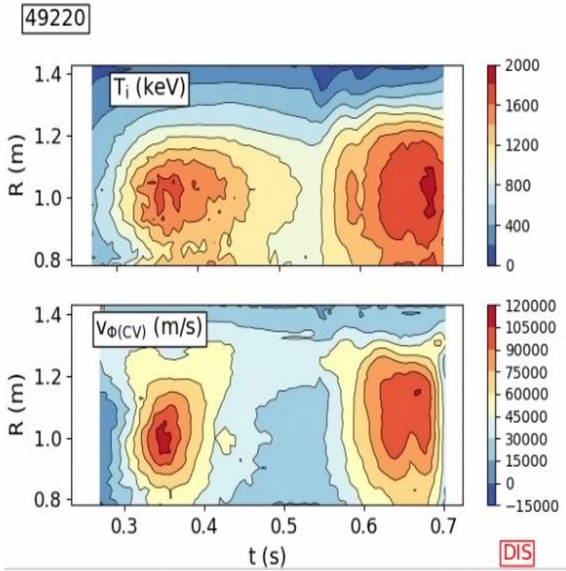
- Density profiles are largely unaffected during faster rotation reduction periods

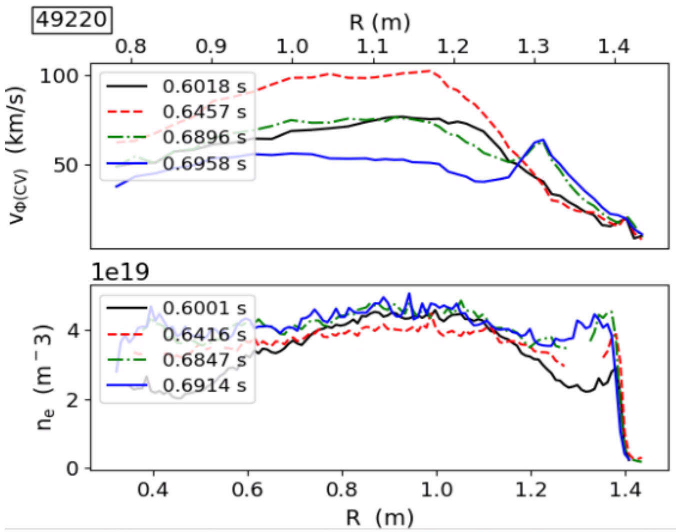
MAST-U MU03 shot 49220 – toroidal rotation increases rapidly after Large ELM, LLM stabilizes; plasma reheats to β_N = 4





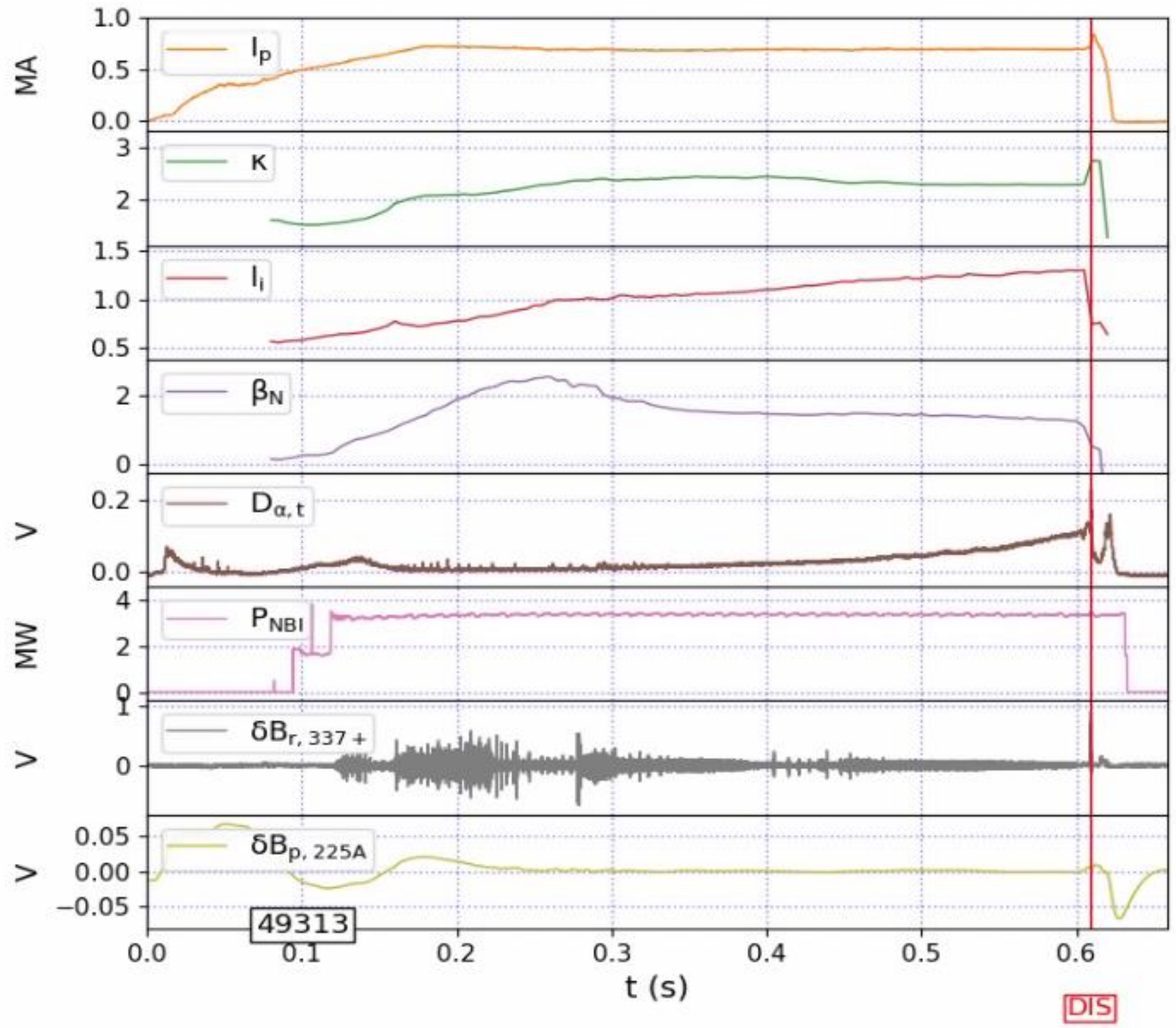


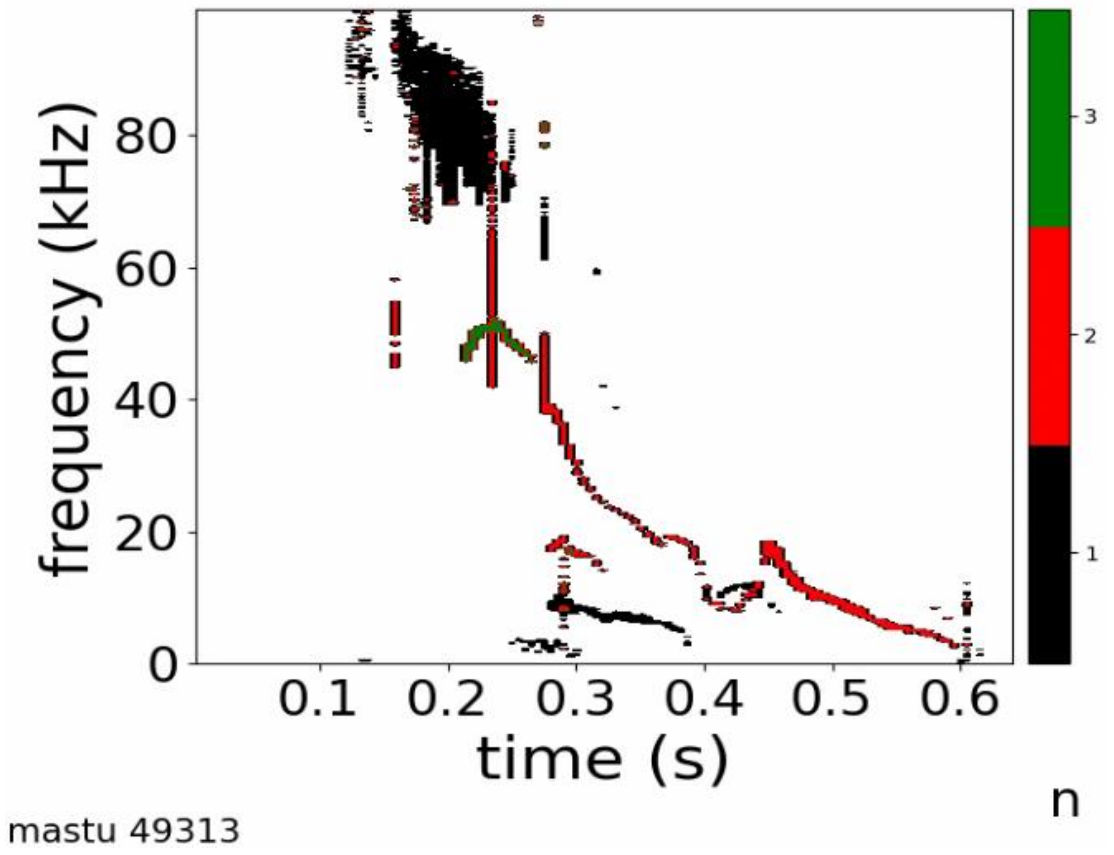




- Large ELM significantly alters density to a far more peaked profile
  - NBI has better core penetration
- Broad rotation profile forms, plasma spins up during reheat
- Reduced density gradient may help stabilize LLM

n = 1 component of LLM stabilized during high elongation





- The β_N still rolls over as n = 2 mode dominates
- Improve this by delaying SS NBI

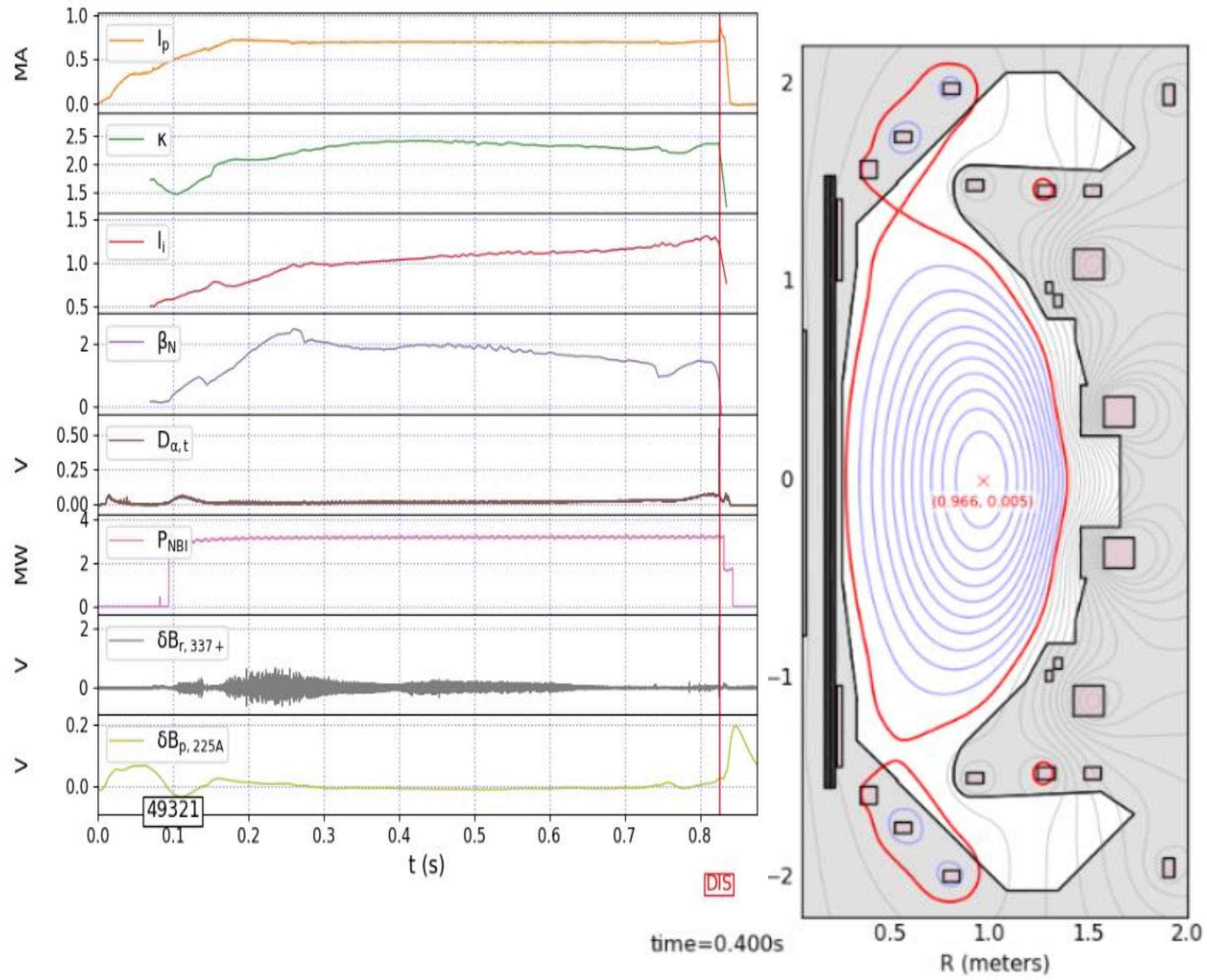
MU03-THR-02 recently affected LLM evolution – now positioned to optimize target and reach new highs in plasma beta

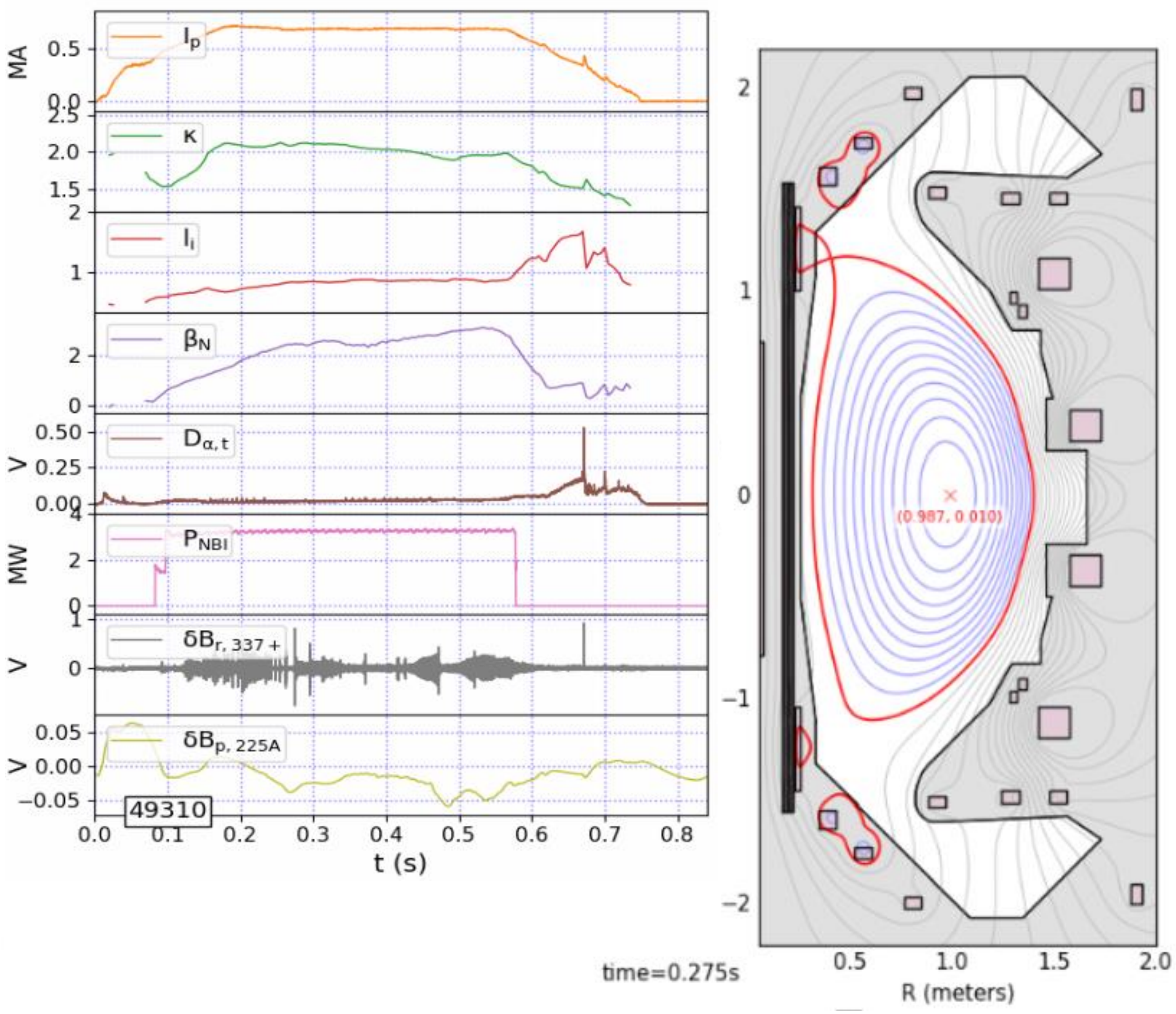
- Robust high elongation targets created starting 7-Dec-23
- B_T reduction successfully run in non-optimized target plasma
- Plasma shape optimization aimed to mitigate/stabilize LLM
  - High elongation period moved earlier
  - Outer strike point moved outward to reduce mode locking
  - Additional target plasma created with lower kappa, low R strike points 15-Jan-24
- Next steps
  - Choose two plasma targets for final optimizations to mitigate/stabilize LLM
    - Will include slight reduction in I_p, SS NBI timing alteration, etc.
  - Reduce B_T in optimized target plasma
  - Conduct MHD spectroscopy measurement to assess RWM stability

Final choice of plasma targets for accessing / sustaining higher beta based on experimental experience to date

- Mode characteristics
  - There are two key rotating n = 1 MHD modes with associated n = 2 (sometimes n = 3)
  - Lower frequency mode appears to be LLM, name the other the “inner” mode
- Mode stability – several variations affect it
  - Plasma shape: can apparently stabilize the inner mode (49313)
  - Plasma rotation: saturate the mode if rotating quickly enough
  - Plasma rotation shear: to avoid mode phase coupling
  - Density profile: (ex: 49220 and similar shots with loss of density pedestal and reheat)
- Key: Plasma elongation / rotation both stabilizing, but can offset one another
- Initial SW with delayed SS NBI application generally superior for MHD stability
- Mode phase coupling must be avoided – leads to certain mode lock and disruption
- Several PCS approaches used during MU03-THR-02. Use the most robust ones.

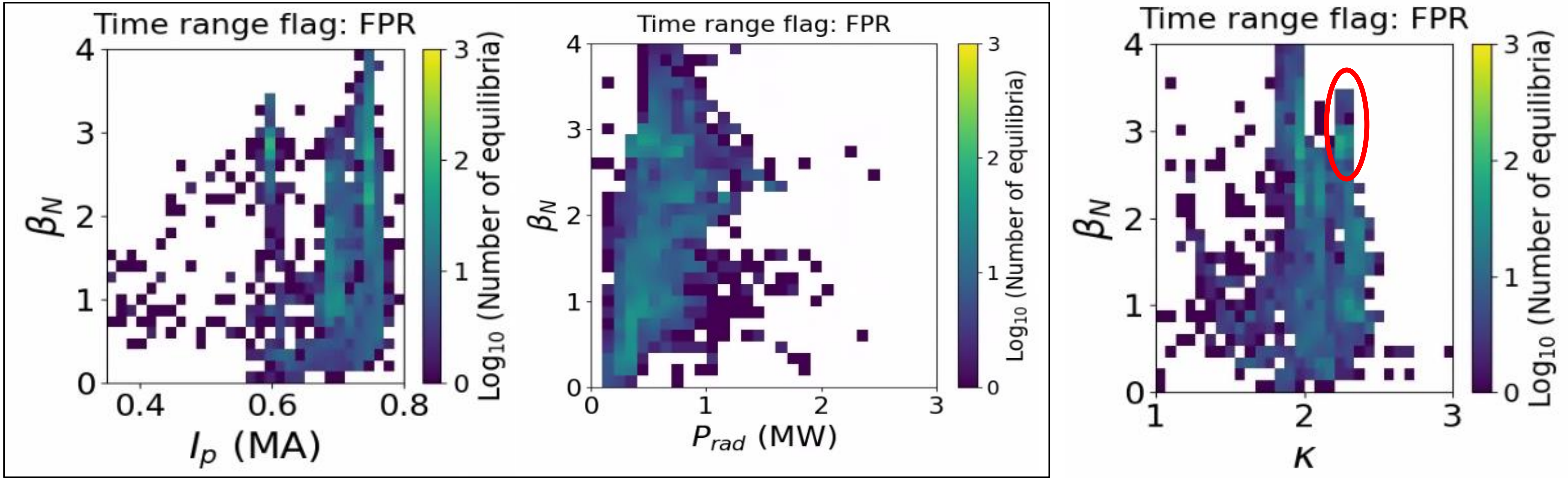
Further optimizations now possible with MU03-THR-02 high kappa, and low kappa high triangularity targets





- Sustained, but β_N rolls w/H-mode n_e profile
- β_N reaches 3.2, not yet optimized

Recent MU03-THR-02 and other high β_N experiments show a dependence of β_N on I_p



- Maximum β_N reached at reduced radiated power
- Increase of elongation > 2.3 lead to increased P_{rad} ➔ increase triangularity
- ➔ Reach sustained high β_N at high elongation, sustained rotation, and low P_{rad}

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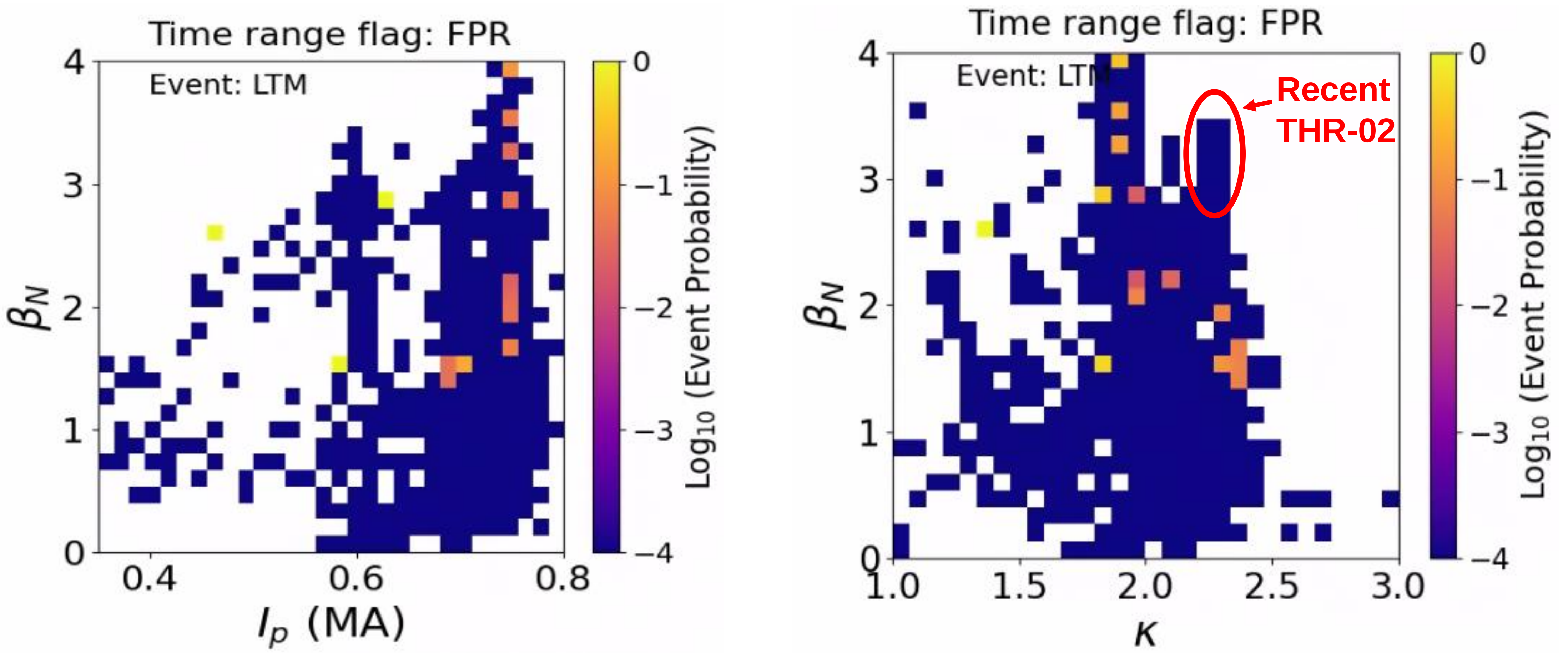
Recent MU03-THR-02 accessed high β_N at high elongation with suffering locked mode disruptions



- High beta operation = 4 (I_p = 0.75 MA) exhibited locked modes / disruptions
- MU03-THR-02 completely avoided mode locking at elongation ~ 2.3

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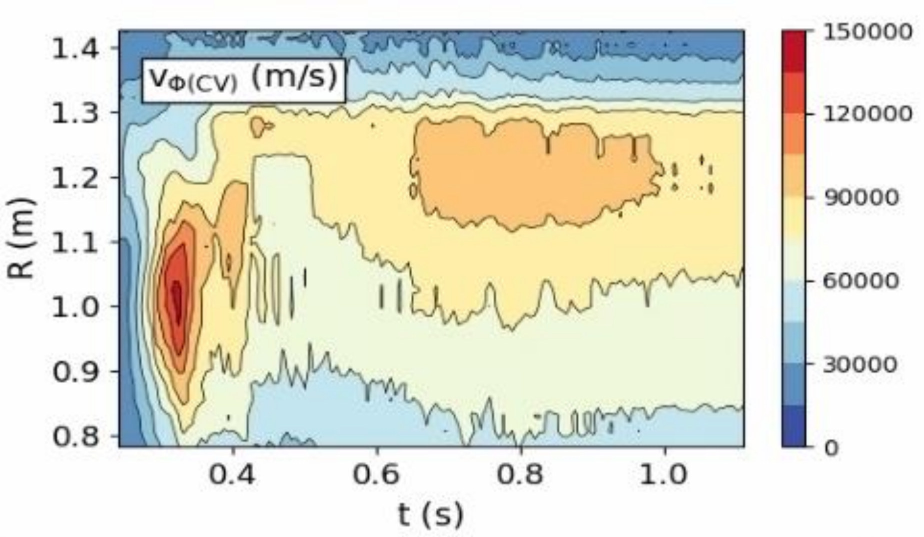
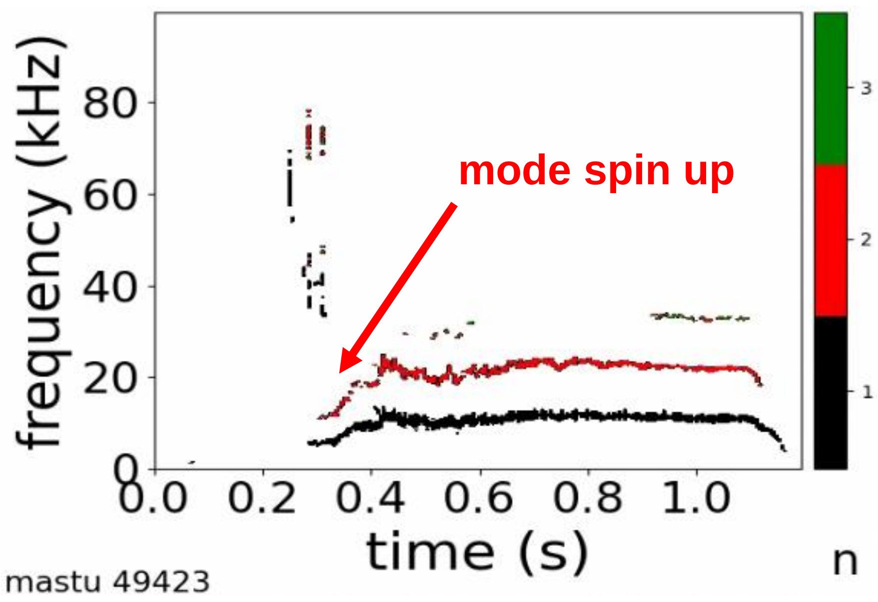
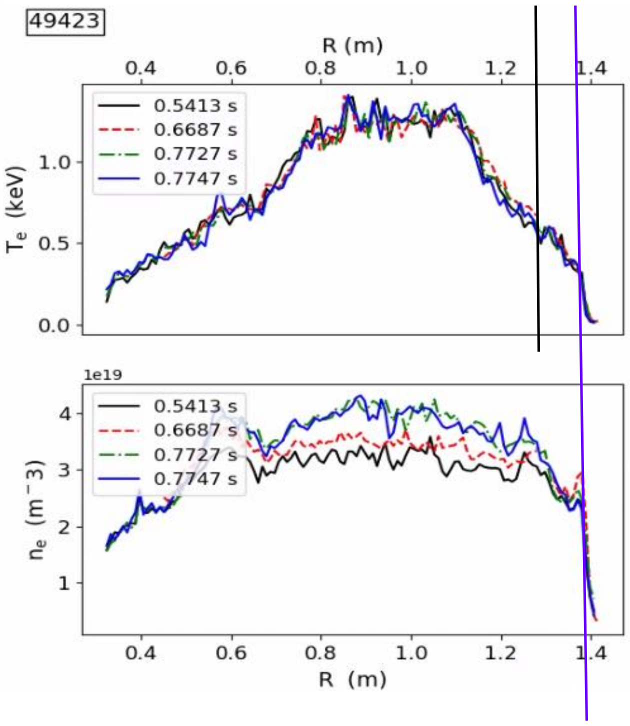
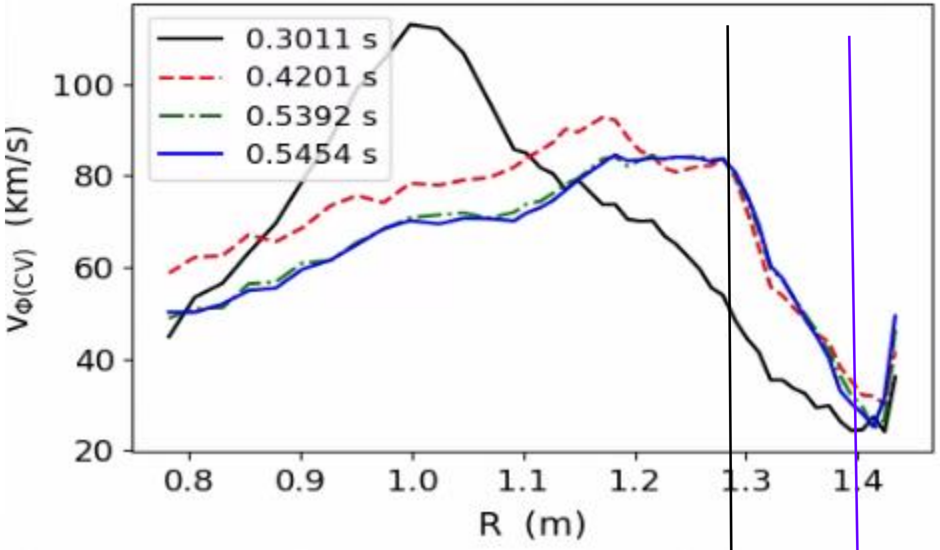
Recent MU03 shot at high elongation has positive characteristics for continued MU03-THR-02 shot evolution

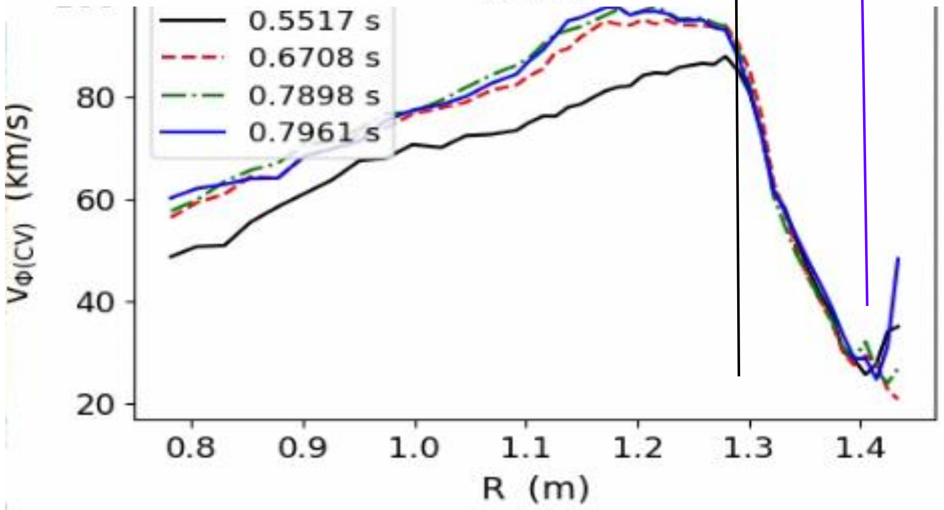




Thomson T_e, n_e profiles







- Extreme shift of toroidal rotation peak avoids mode locking

MAST-U campaign thrust experiment MU03-THR-02 successful in producing sustained high β plasmas

Goals

- Produce sustained high performance determined by objective figures of merit (β, β_N, β_p, W_{tot}, τ_E)
- Produce full understanding of limiting stability physics using unparalleled MAST-U diagnostic set
- Make connection between operational space produced and that of ST Pilot Plant visions

Highlights

- High β_N plasmas created, initial experiments (MU02-THR-02) establishing high $\beta_N > 3$, eliminating IREs in during Ip ramp-up, mode locking at lower range of β_N, and establishing VDE limits
- Rotating MHD modes mitigated and mode locking completely avoided at elongation ~ 2.3
- Decrease in l_i observed with all else constant indicating n = 1 core dynamo / flux pumping (Part II)
- Shafranov shift stabilization with extreme shift of toroidal rotation peak mitigating mode locking

Part II of this presentation will address further results / physics details, including

- MU03-THR-02 sustained plasmas with MHD mode mitigation reaching high β_N, and making this work at I_p = 0.75 MA
- Comparisons to NSTX using DECAF (educational similarities and differences)