Simulations to explore the TQ-onset phase of natural disruptions in DIII-D

In DIII-D natural disruptions, such as those caused by locked-modes, a large increase in electron density and a significant spike in radiated power are seen, from which a significant influx of carbon from the divertor and deuterium from the first wall can be inferred [1]. This influx is as important to the thermal-quench (TQ) phase of the disruption as the presence of large islands or stochasticity in the edge which initiated the event. The NIMROD code is used to perform MHD simulations in which the magnetic configuration is initialized with 3/1, 5/2, and 2/1 tearing-like perturbations, producing an initially stochastic edge adjacent to a large 2/1 island. The growth-phase (and corresponding relevant physics) of these islands is neglected, but, a source of carbon localized near the outer divertor strike point is added to explore the relative importance of various effects as the TQ is triggered. Without the carbon source, the edge stochastic region eventually overlaps with the 2/1 island and triggers an inward cascade of flux-surface destruction, but the inclusion of the carbon initiates this process much earlier, as carbon radiation causes the cold-front to extend into the q=2 island earlier. Following on these numerical experiments will be attempts to match more closely parameters from specific natural disruptions on DIII-D and then to combine mitigation models with natural disruption scenarios.

[1] E.M. Hollmann, et al., J. Nucl. Mater. **390-391** (2009) 597.

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Sherwood Fusion Theory Conference

4-6 April 2022

What elements are needed to simulate the TQ-onset phase of a locked-mode disruption?

Do not want to:

Simulate the instability growth phase

That's whole other can of worms...

✗

Do want to:

Include all necessary physics to model from initial loss of edge confinement to end of TQ

Large seeded magnetic perturbations ✓

Source of carbon from divertor ✓

Source of D from walls **NEXT**

Appearance of multiple locked modes is seen to be important to the TQ-onset in DIII-D

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Fast and pervasive heat transport induced by multiple locked modes in DIII-D

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- EF penetration leads to born-locked modes in the edge that can easily overlap to produce stochasticity
- Multiple LMs have a greater effect than sum of isolated LMs

Direct measurements of internal structures of born-locked modes and the key role in triggering tokamak disruptions

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- Large LM can slow rotation and lead to EF penetration and higher order edge LMs
- After long quast-stationary phase (~300 ms), TQ onset is correlated with overlap of 2/1, 3/1 islands

Some order of magnitude estimates for C/D sources are taken from...

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Experiments to measure hydrogen release from graphite walls during disruptions in DIII-D

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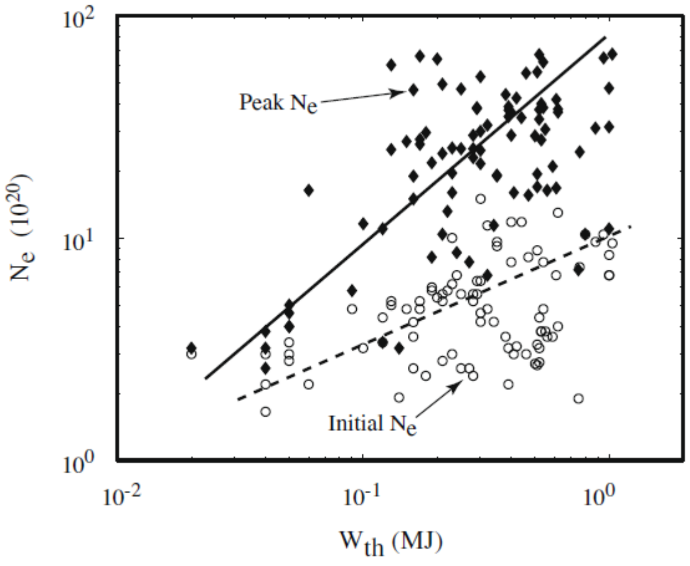

Fig. 2. Initial and peak plasma electron number during natural disruptions as a function of initial plasma thermal energy W_{th}.

C from walls similar to initial plasma inventory, D from walls 10x higher

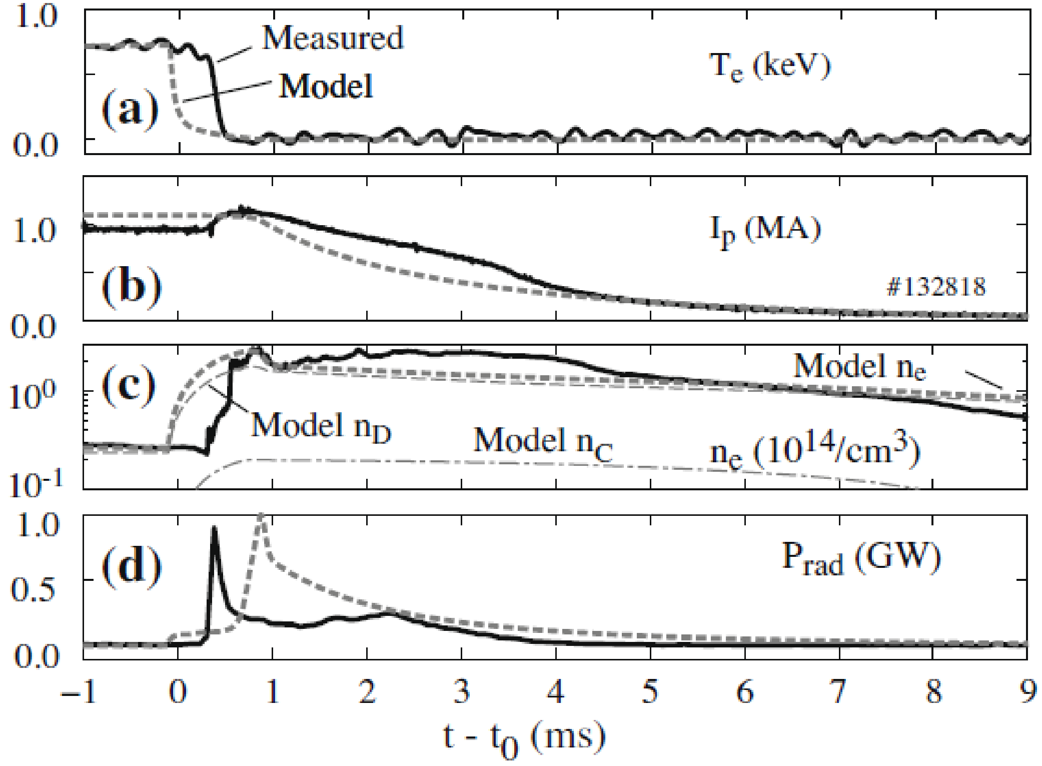

Fig. 3. Time traces of a natural disruption (solid lines) and 0D modeling (dashed lines) for (a) average electron temperature T_e, (b) plasma current I_p, (c) average electron density n_e (including modeled deuterium and carbon ion densities n_D and n_C), and (d) radiated power P_{rad}.

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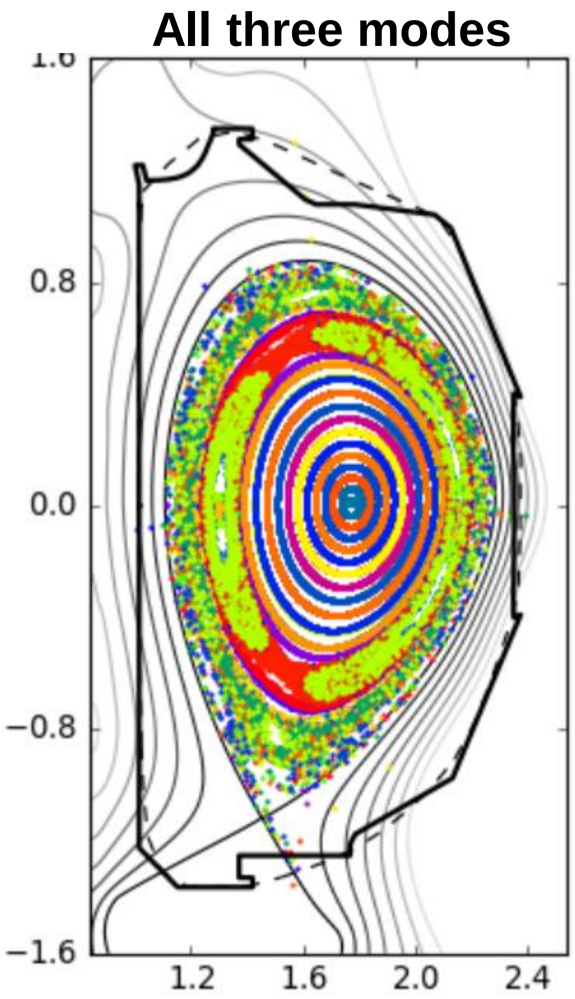
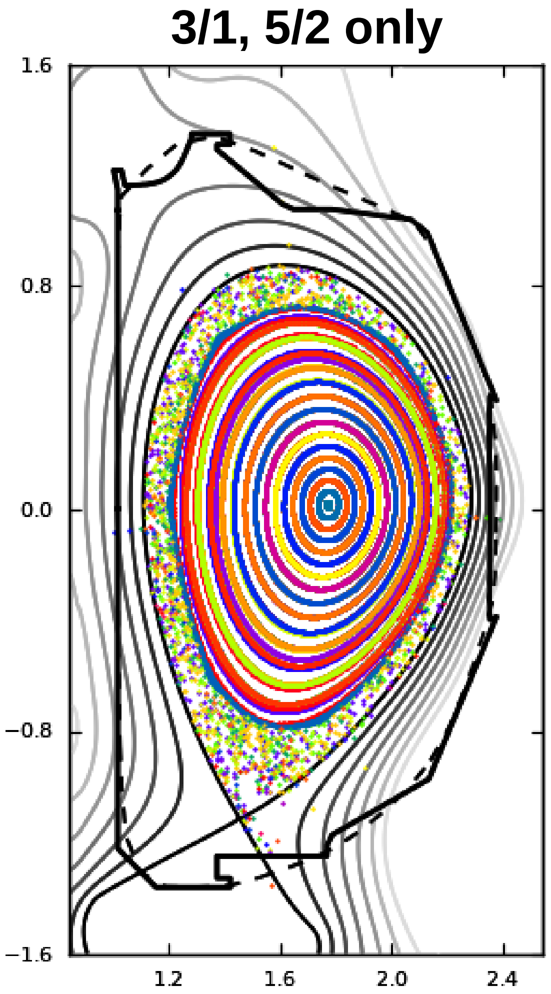
Simulations initiated with only 3D perturbations (no impurity sources)

Beginning with 3/1, 5/2, and 2/1 tearing-like perturbations in a LSN configuration



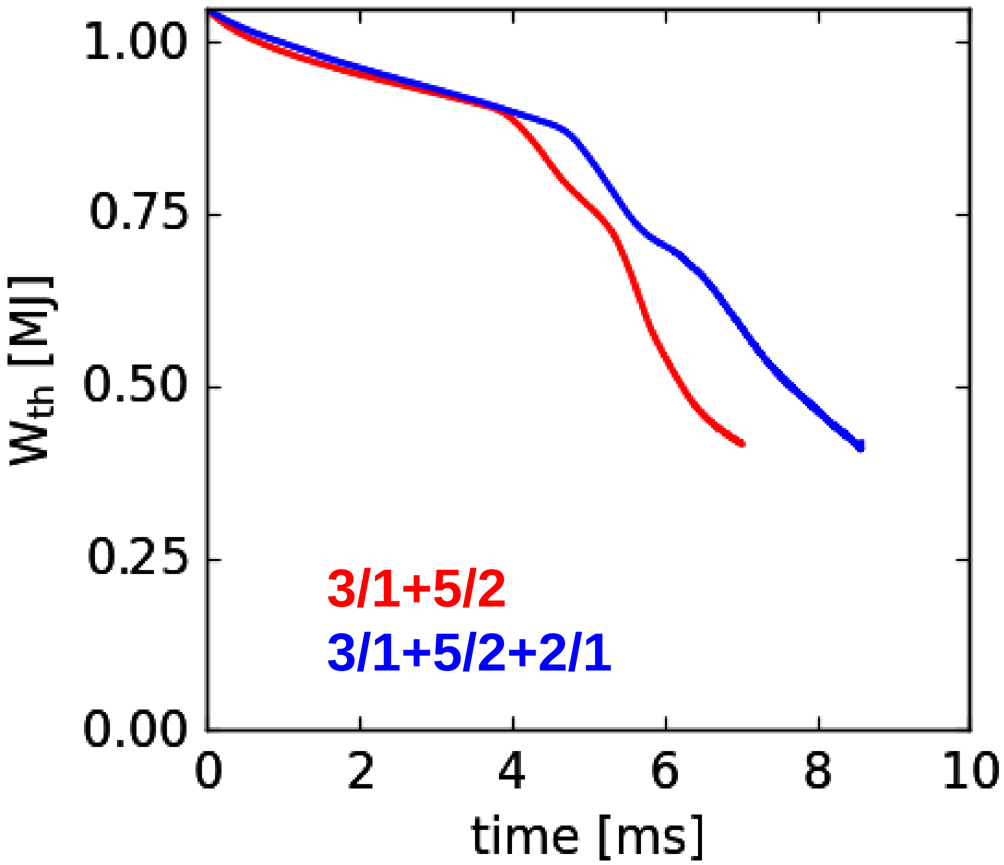


Initial condition combines a stochastic edge region and a large, but separate 2/1 island

Some cases have only the 3/1 and 5/3 perturbations but no 2/1 island

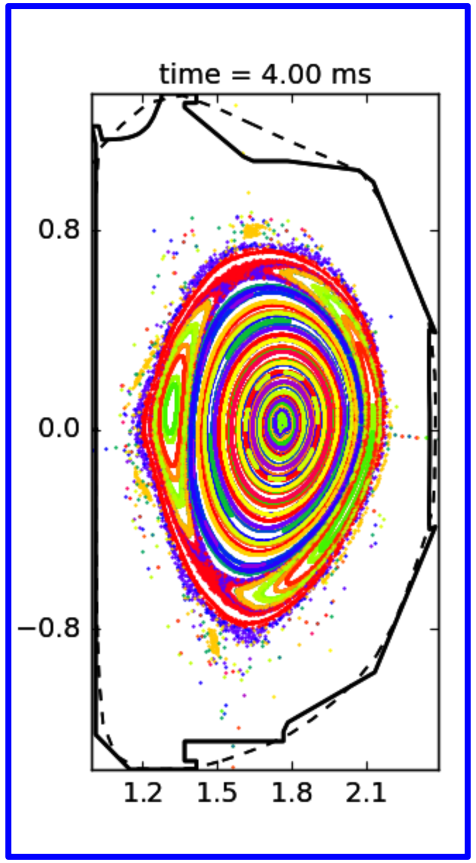
NB: This initial condition will not be the same as a non-linearly saturated state

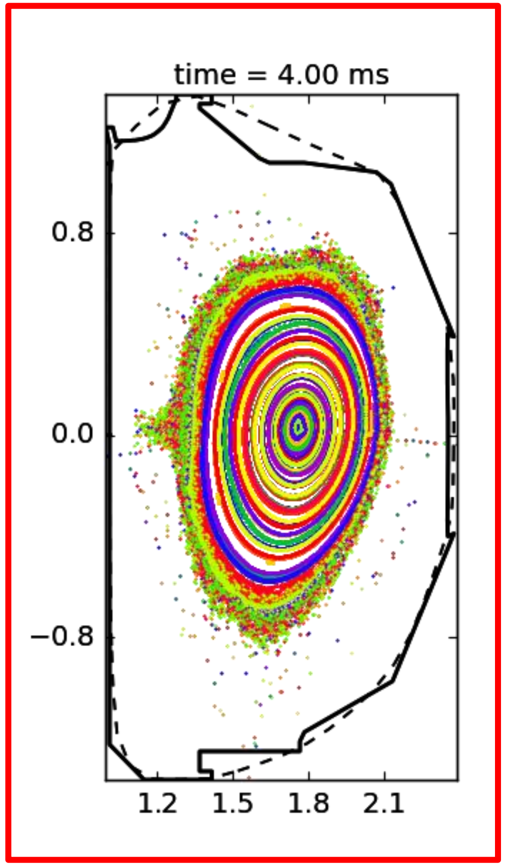
Without 2/1 island, TQ onset caused by stochastic edge happens earlier



By midway through loss of W_{th}, central Te has not dropped appreciably in either case

Addition of C-influx may be needed to complete TQ

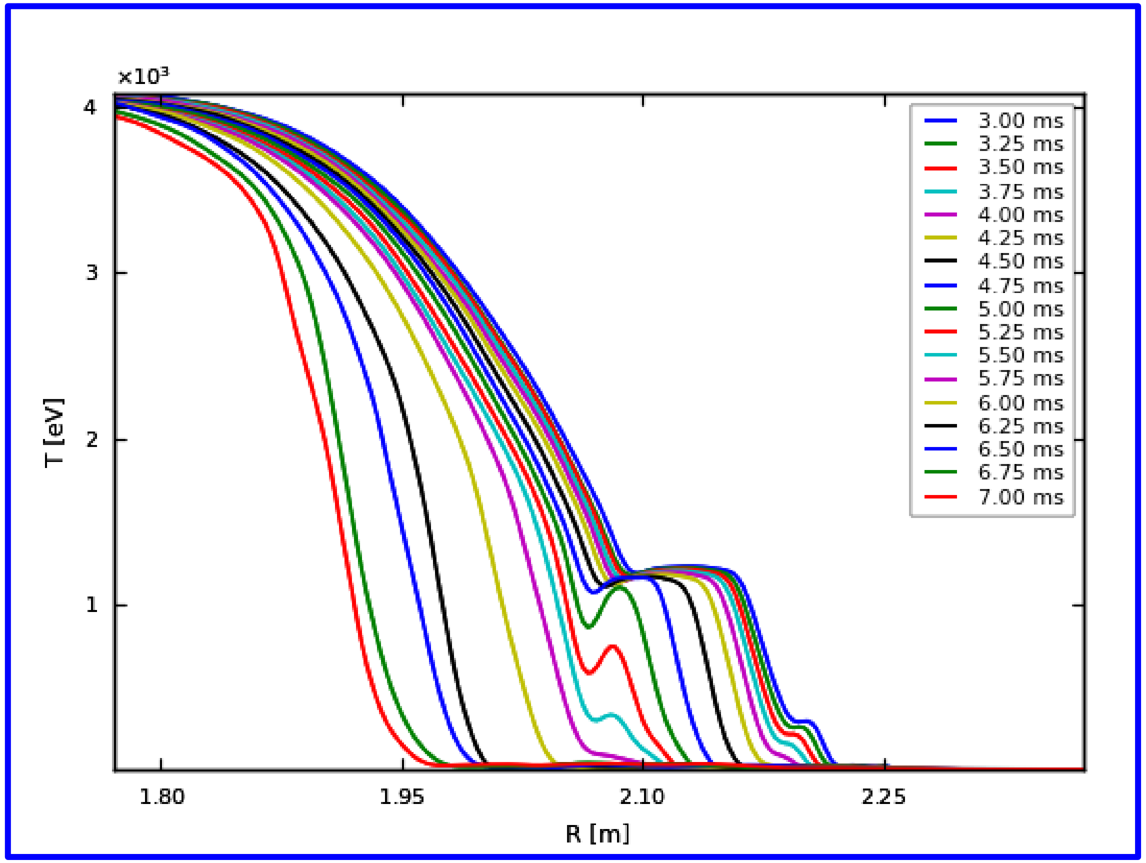




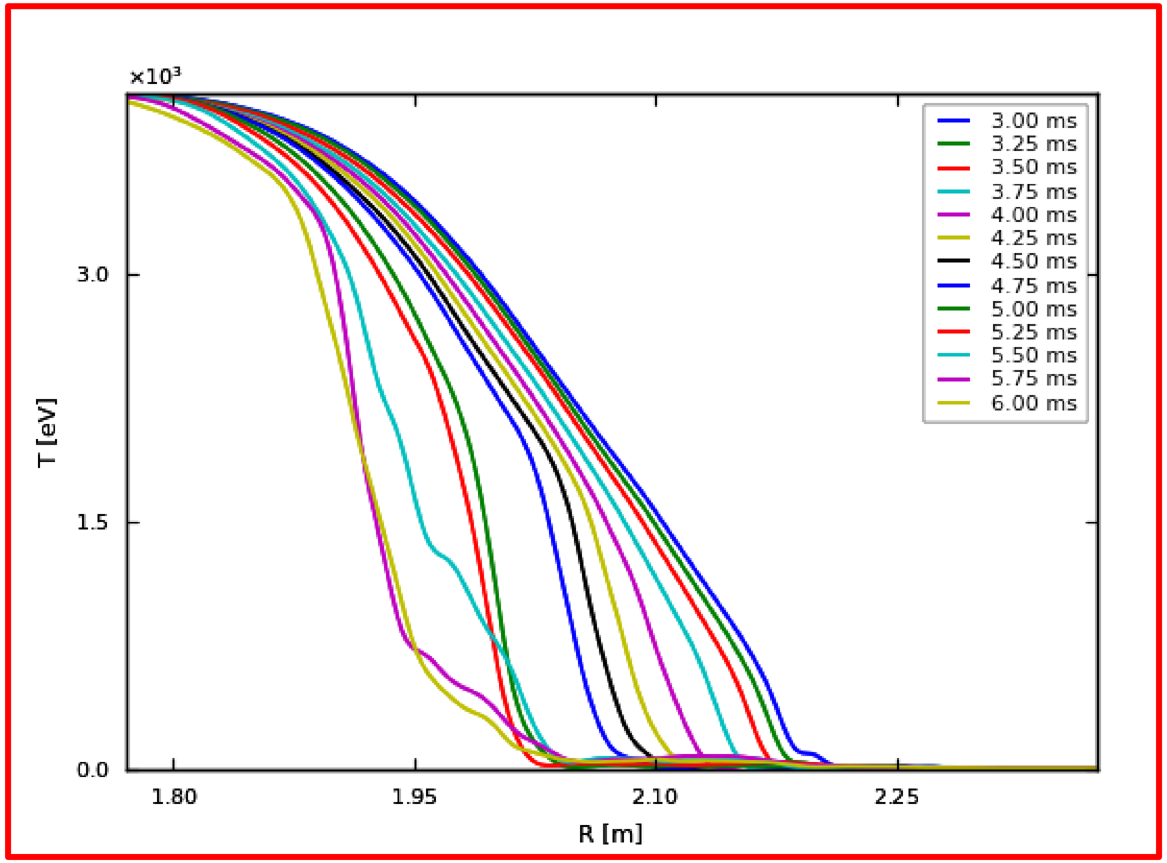
Need to determine if this is phase dependent

Persistence of 2/1 island evident in evolution of temperature profile

3/1+5/2+2/1



3/1+5/2



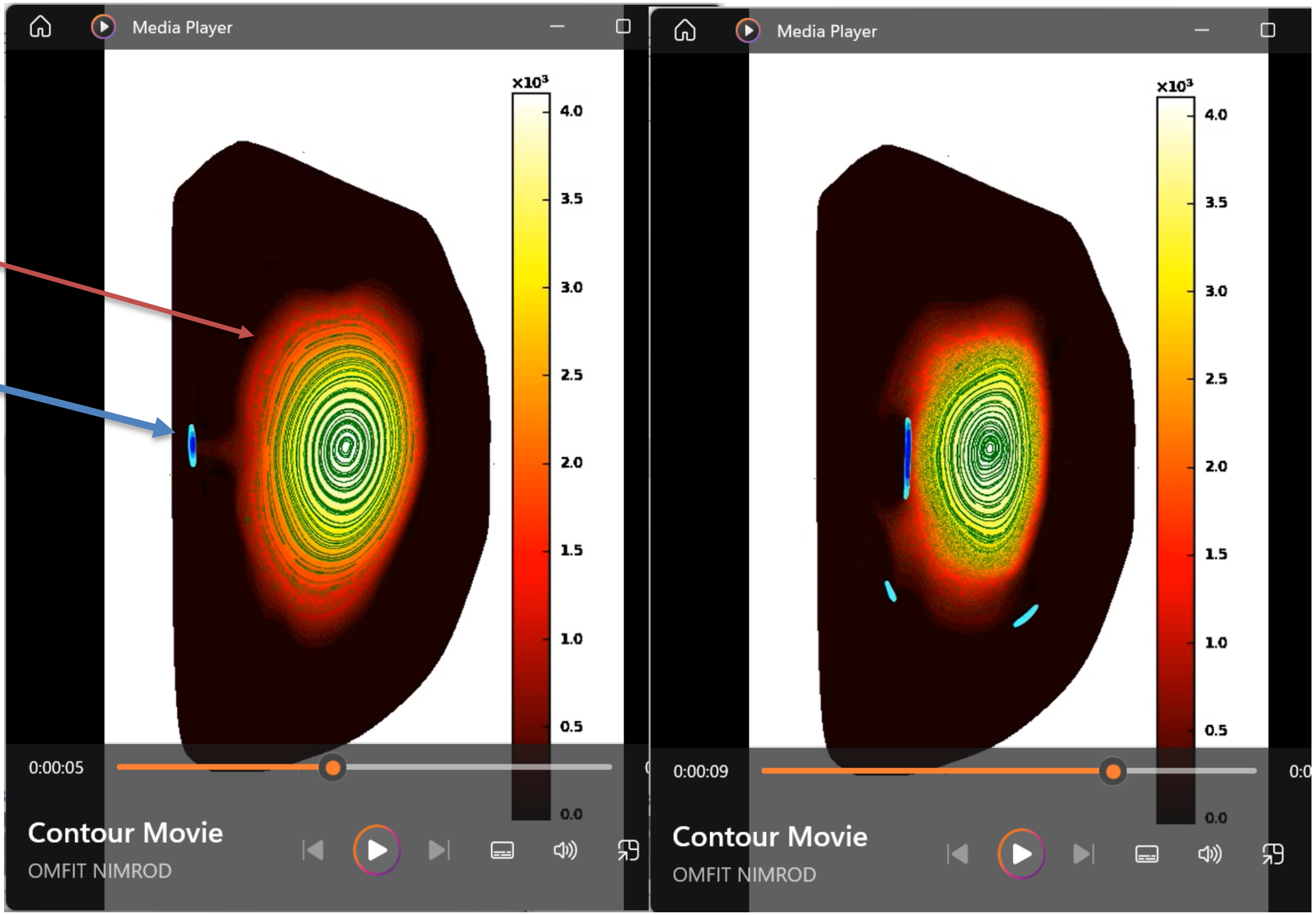
TQ-onset begins with narrow finger of heat flux (with 3/1 symmetry)

3/1 + 5/2 only:

Temperature contours

Peak current density

Watch the video



https://www.youtube.com/shorts/32gj-2TgIsY

V. Izzo

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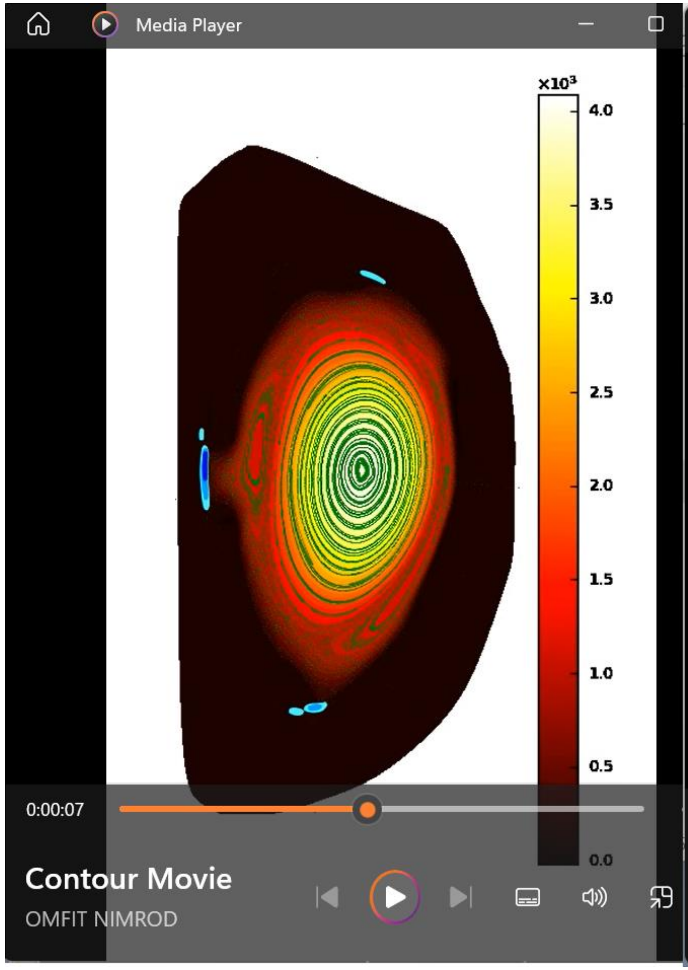
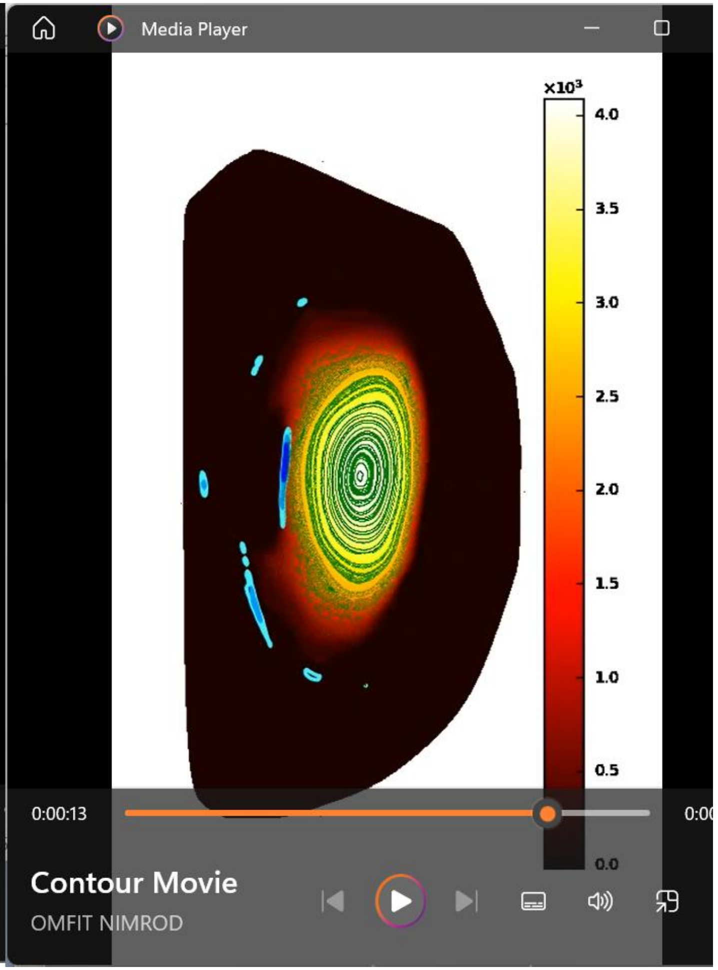
With 2/1 island, TQ onset is very similar but appears delayed due to island interaction

3/1 + 5/2 + large 2/1 island:

Watch the video





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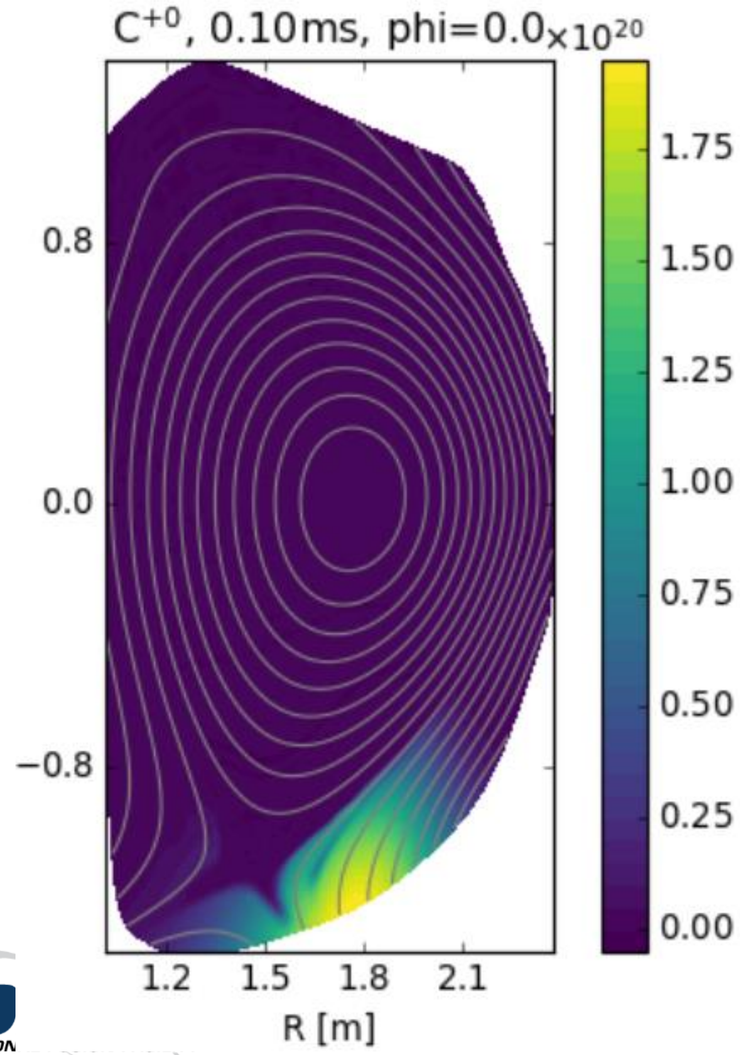
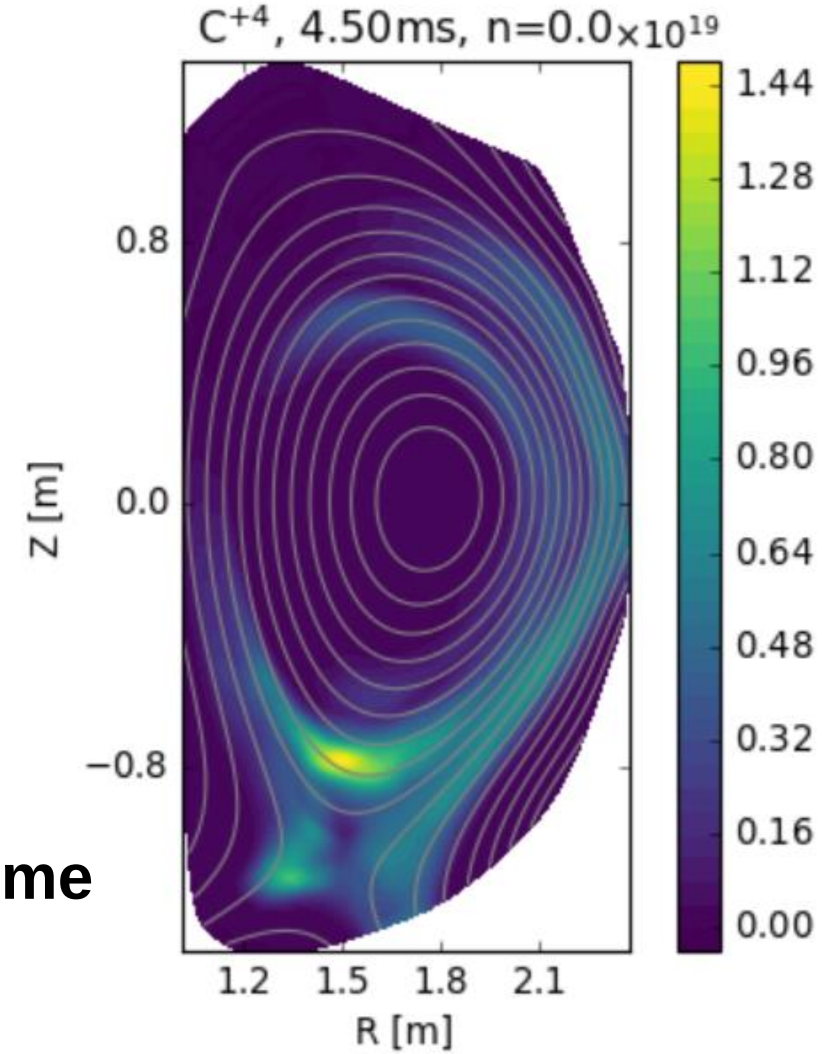
Inclusion of carbon source from the divertor

Source of Carbon added near outer divertor strike-point (like MGI sources)



Neutral C early in the simulation

Constant source for first 1 ms of the simulation, then none



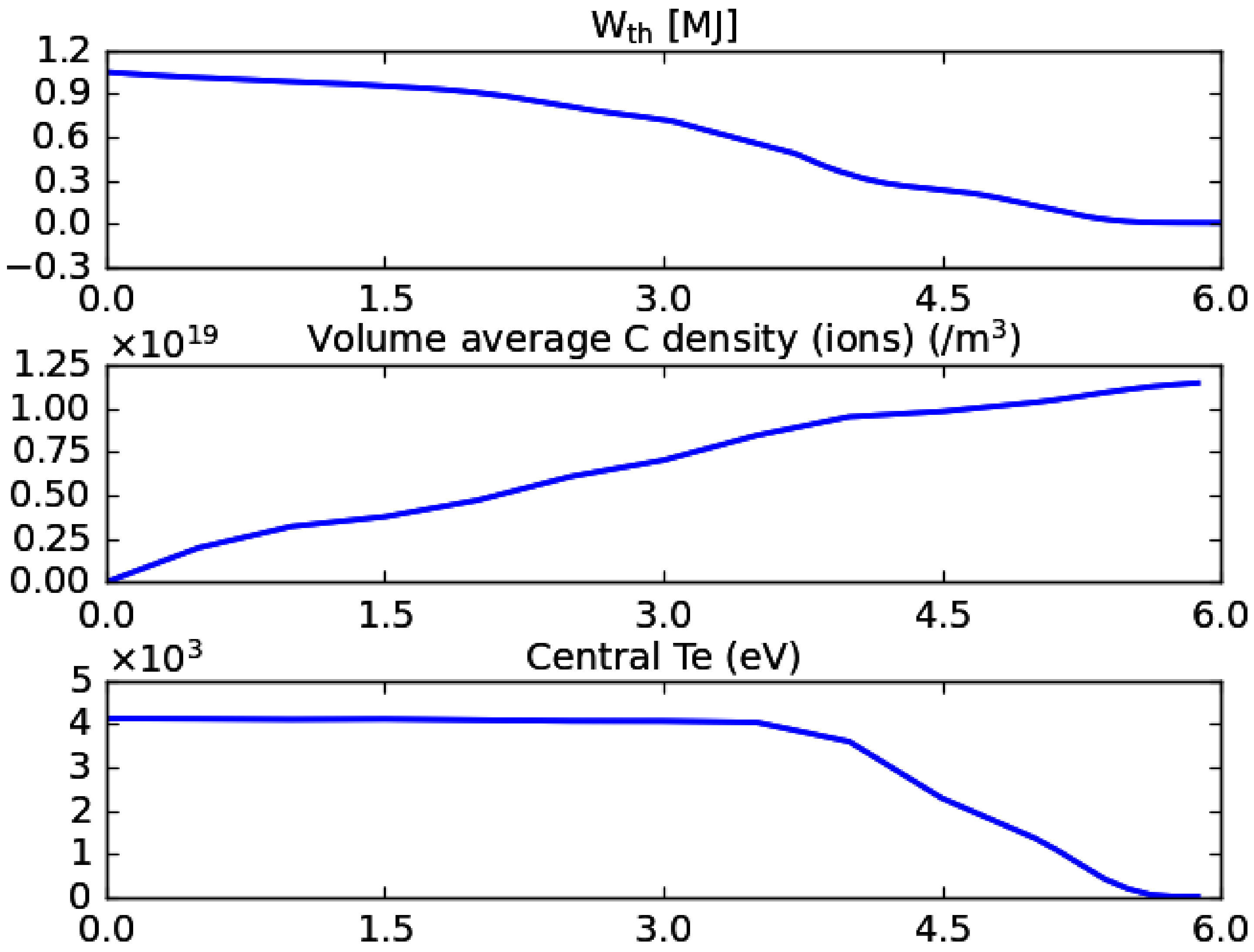
C^{+4} later in time

TQ-onset happens sooner with carbon source

Drop in thermal energy happens slowly over ~5ms

Volume averaged (ionized) carbon is still lower than typical in DIII-D experiments

Complete TQ: Based on central T, TQ time is about 1.5 ms



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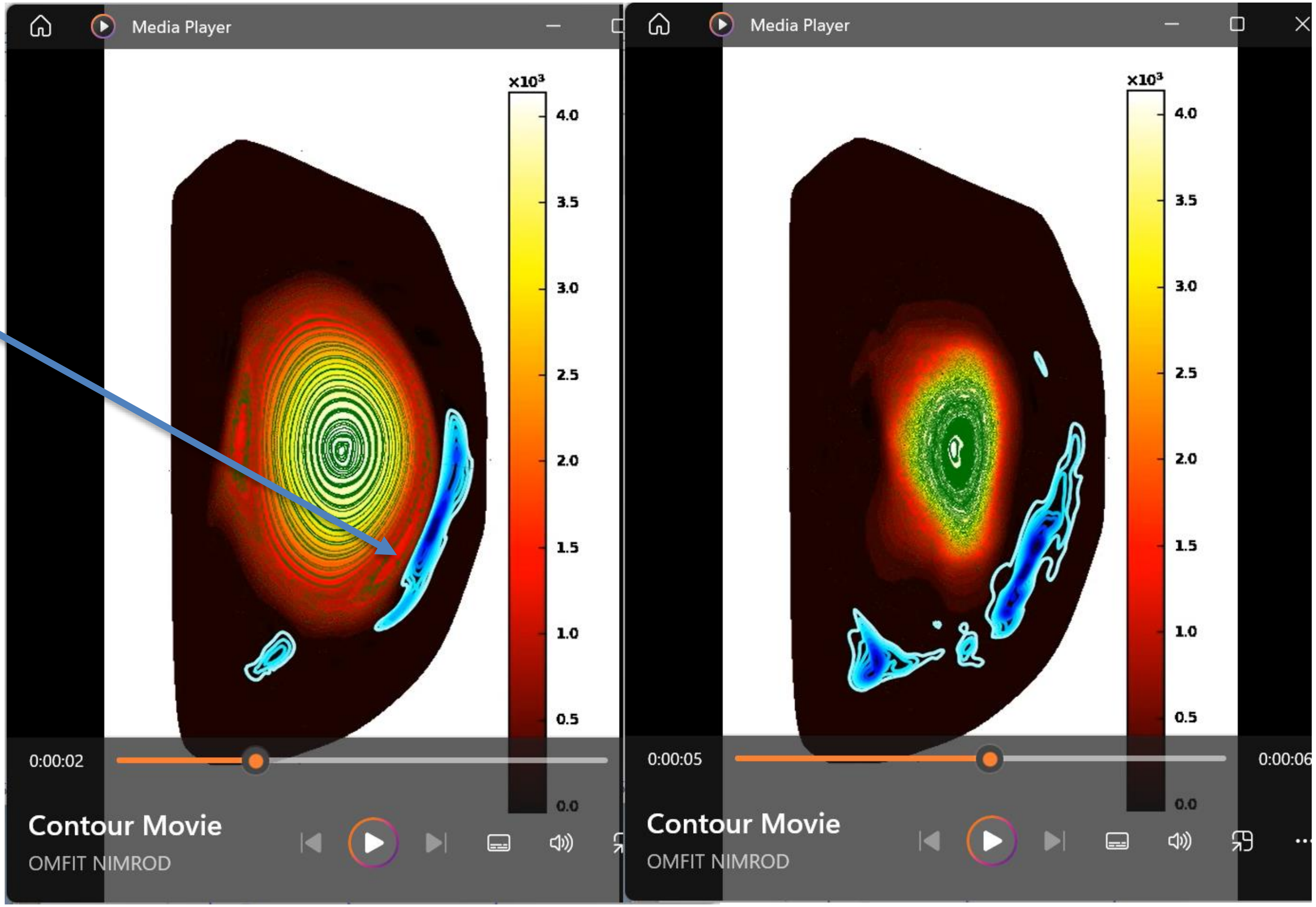
Early phase still shows some similarities to no-carbon simulations

3/1 + 5/2 + large 2/1 island + carbon source:

C^{+4} density contours

Watch the video



https://youtube.com/shorts/IOuiD3bLYBs

Summary

- Status: preliminary modeling to assemble all elements needed to simulate DIII-D natural TQ
- Stochastic edge alone (overlapping 3/1 & 5/2 islands) can trigger a TQ-onset
- With addition of large 2/1 island, TQ-onset is very similar, but island interaction changes timing (may be phase dependent)
- Source of carbon from divertor speeds up TQ-onset. Only case in which a complete TQ was successfully simulated.

Future work

- Vary relative phase, amplitudes of initial perturbations (may consider IWL cases in which these were carefully measured in DIII-D)

- Add deuterium source from walls and examine more closely the rate/timing of deuterium & carbon sources relative to TQ-onset

- Consider inclusion of resistive wall