Review of the results from the strongly shaped plasma experiments

Gustavo Paganini Canal[1,2]

on behalf of

R. Maingi[3], T.H. Osborne[1], M.G. Bell[3], R.E. Bell[3], D.P. Boyle[3], J.M. Canik[4], A. Diallo[3], R. Kaita[3], S.M. Kaye[3], H.W. Kugel[3], B.P. LeBlanc[3], S.A. Sabbagh[5], C.H. Skinner[3], V.A. Soukhanoviskii[6], N.M. Ferraro[3], M. Coury[3], F. Scotti[6], W. Guttenfelder[3], D.R. Mikkelsen[3], G.J. Kramer[3] and the NSTX-U Team

[1]General Atomics, San Diego, CA

[2]Oak Ridge Associated Universities, Oak Ridge, TN

[3]Princeton Plasma Physics Laboratory, Princeton, NJ

[4]Oak Ridge National Laboratory, Oak Ridge, TN

[5]Columbia University, New York, NY

[6]Lawrence Livermore National Laboratory, Livermore, CA

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

NSTX-U

Outline: Review of the results from the strongly shaped plasma experiments

- Overview of the strongly shaped plasma experiment
- The effect of Lithium on recycling, edge kinetic profiles and transport
- The effect of Lithium on the plasma microstability
- The effect of Lithium and NBI power on the plasma macrostability
- Summary

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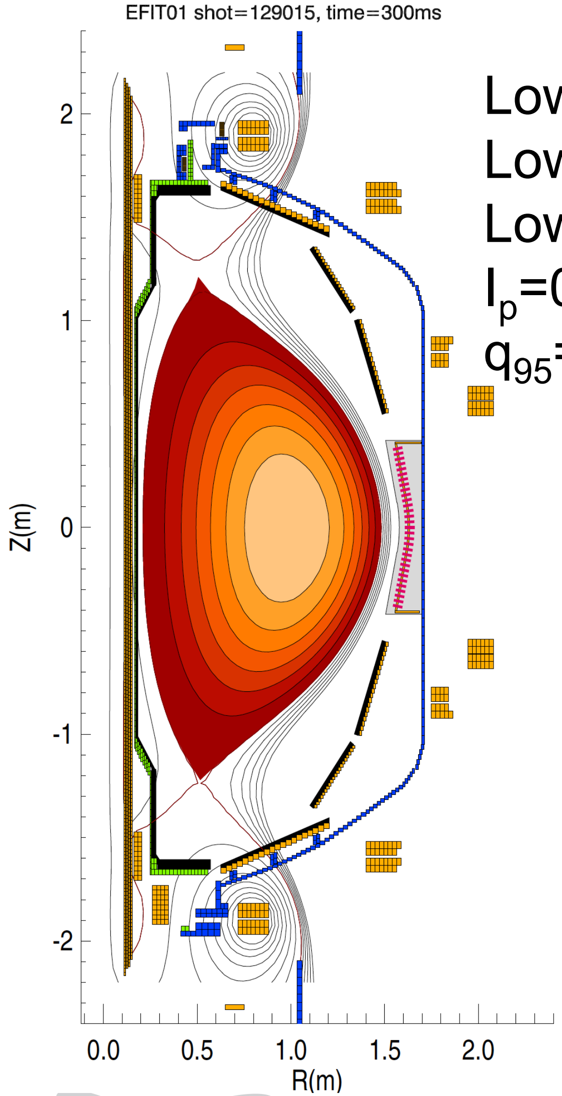
Motivation: Plasma shaping is expected to enhance even more performance in discharges with Lithium conditioning

- **Many devices (TFTR, CDX-U, TJ-II, EAST, FTU and NSTX) have reported performance improvements (confinement and edge stability) with Lithium conditioning**
  - Experiments performed mostly with "weaker" plasma boundary shape than typical in NSTX ($\delta \sim 0.46$, $\kappa \sim 1.8$ and low squareness)

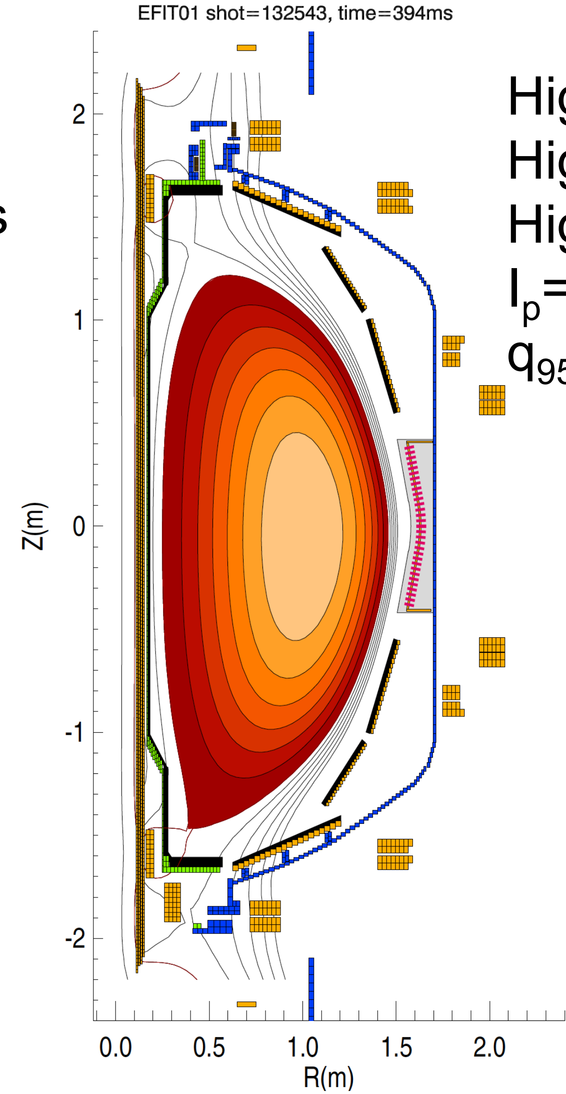
- **Experiments on NSTX have shown that strongly shaped plasmas exhibit improved performance compared to weakly shaped plasmas**
  - Highly shaped plasmas were chosen as the baseline configuration for NSTX-U ($\delta \sim 0.6$-0.7, $\kappa \sim 2.2$ and high squareness)

- **This experiment aimed to take advantage of the improvements in performance caused by plasma shaping to improve even more the performance of discharges with Lithium conditioning**

Motivation: Plasma shaping is expected to enhance even more performance in discharges with Lithium conditioning



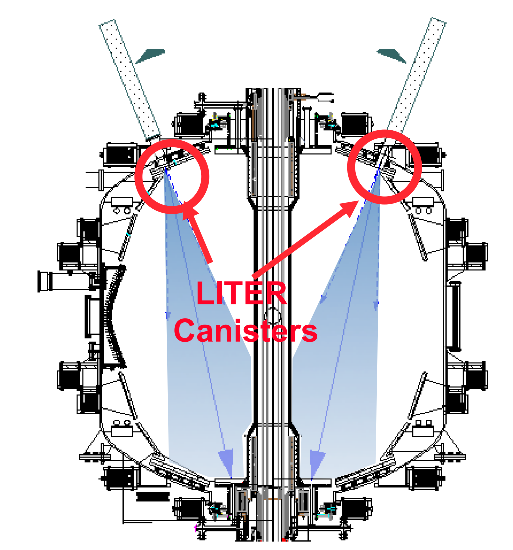
Low δ (0.46)
Low κ (1.8)
Low squareness
I_p=0.8 MA,
q_{95}=7.6

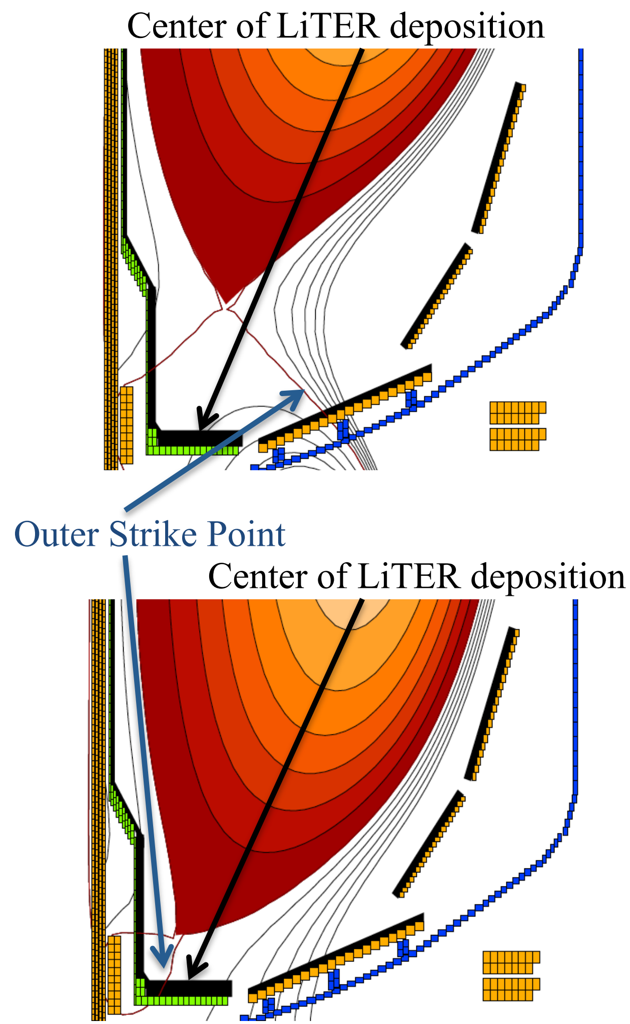


High δ (0.6)
High κ (2.2)
High squareness
I_p=1 MA
q_{95}=8.2

Center of LiTER deposition was very near (far from) outer strike point in strongly (weakly) shaped plasmas

- **Distance between outer strike point and center of LiTER deposition in weakly and strongly shaped plasmas are different**
  - Difference in geometry is expected to have stronger impact on lower divertor measurements





R. Maingi et al., *J. Nucl. Mater.* **463** (2015) 1186

Several discharges were used to identify global β-limit and increase statistics

- **Reference discharges (without Lithium) were carried out for a range of NBI power prior to the introduction of Lithium in this experiment**
  - Global β-limit was found to be about $\beta_N \sim 6$ for the strongly shaped plasmas ($\beta_N \sim 5$ for weakly shaped)

- **The amount of Lithium evaporated into NSTX (Lithium dose) before each discharge ranged from 120 to 570 mg**
  - 7 discharges with average Lithium dose equal to 150 mg
  - 8 discharges with average Lithium dose equal to 250 mg
  - 11 discharges with average Lithium dose equal to 450 mg
  - 9 discharges with average Lithium dose equal to 550 mg

- **The dose of Lithium was decreased during this scan**
  - No signs of hysteresis were observed

- **Improvements is confinement with increasing Lithium dose could lead to global β-limit**
  - NBI power was modestly reduced with increased Lithium dose

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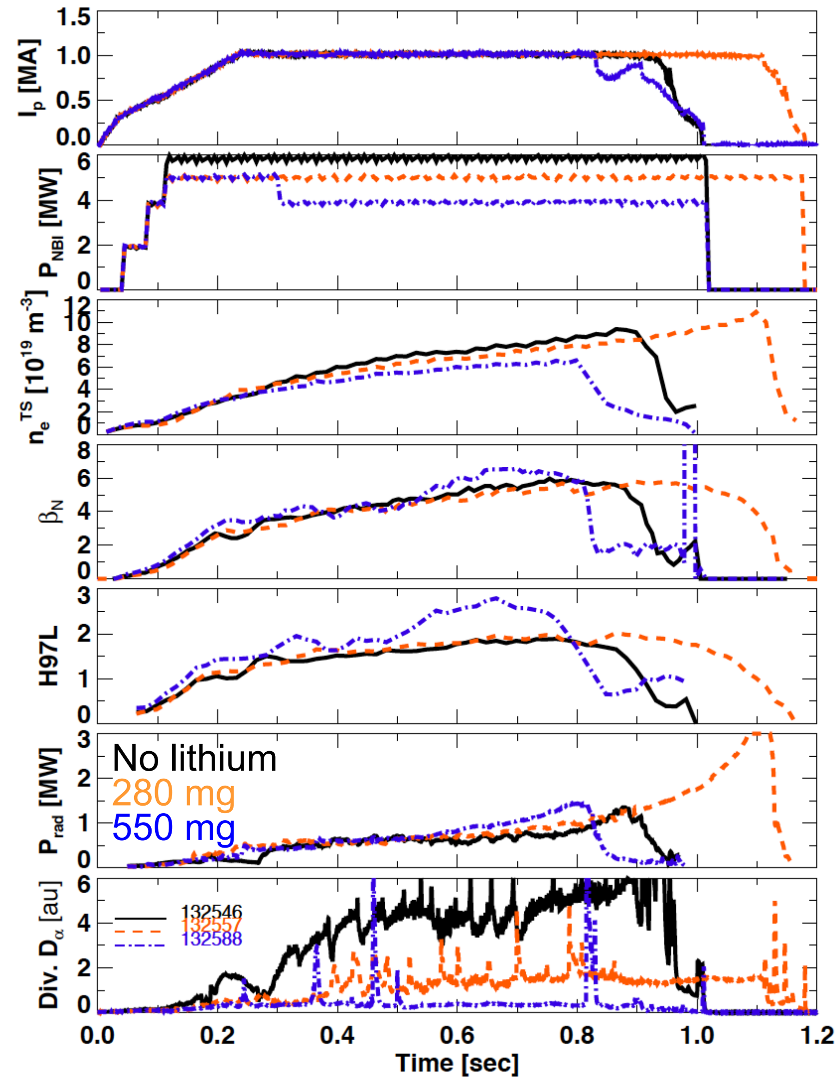
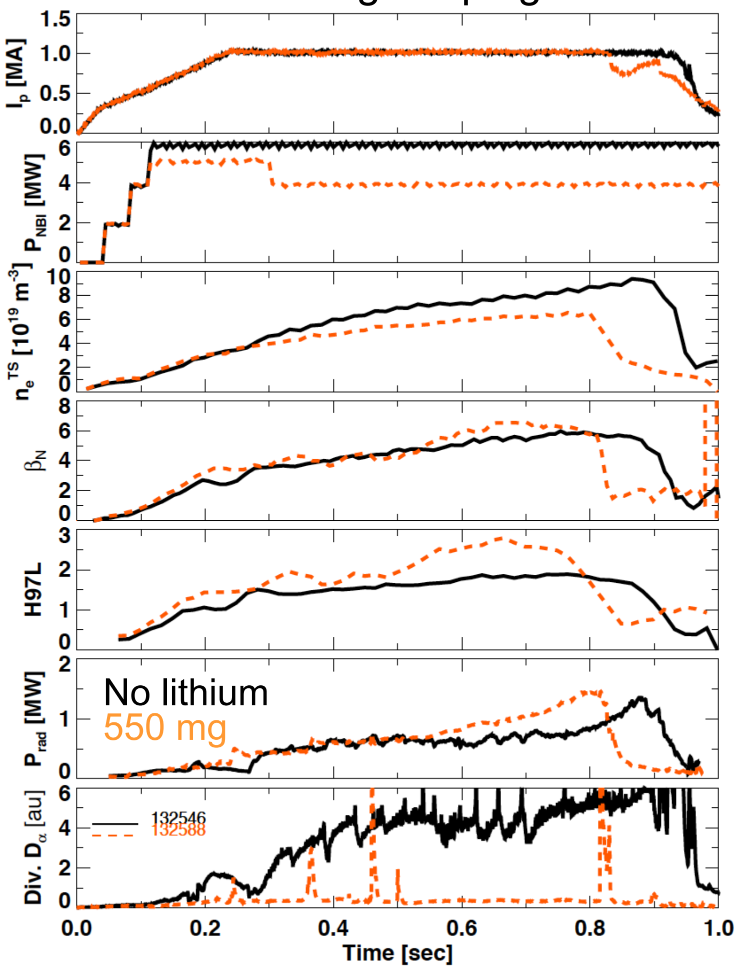
Performance of highly shaped plasmas is improved with increasing Lithium dose

- **Reduced NBI power with increasing Lithium dose**
  - To avoid global β-limit and subsequent minor or major disruption
- **Reduced dn_e/dt**
- **Comparable stored energy (β_N)**
  - Discharge was not optimized for higher Lithium dose case
- **H-factor increased by 50%**
- **Longer ELM-free phases with increasing Lithium dose**
  - Increasing of P_{rad} due to impurity accumulation

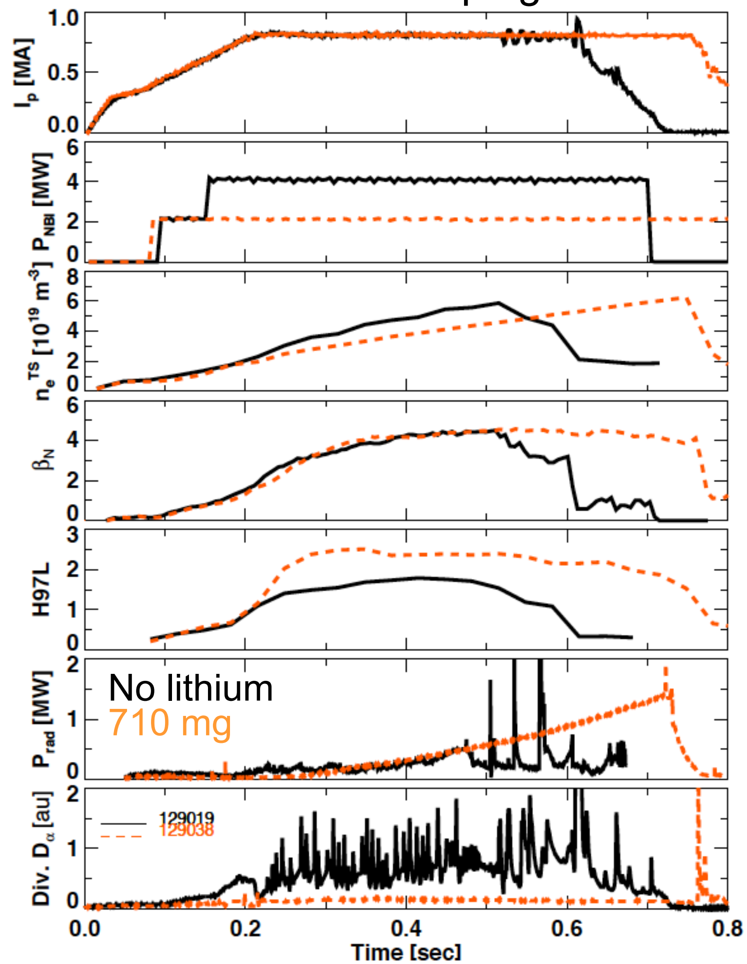


Performance of highly shaped plasmas is improved with increasing Lithium dose (as for weakly shaped plasmas)

Strong shaping



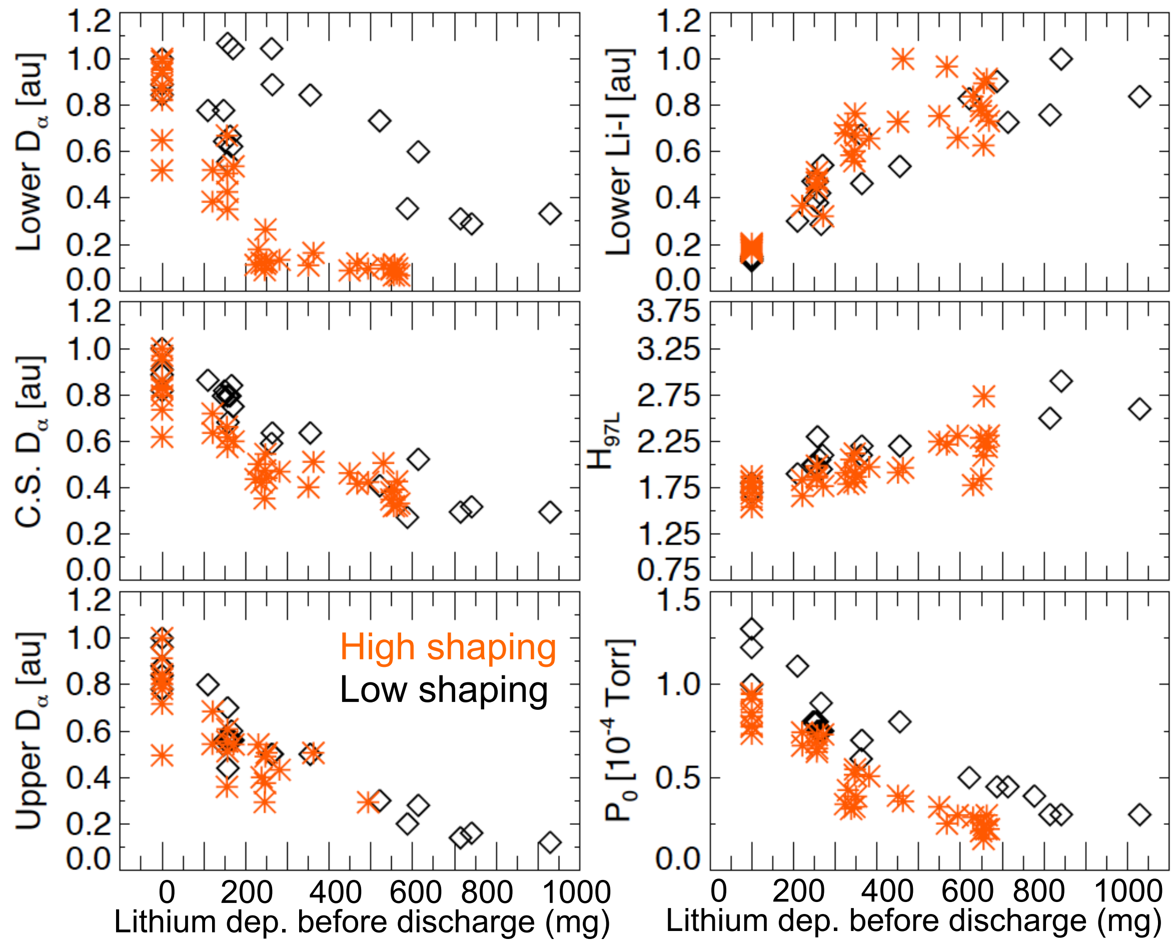
Weak shaping



D_α and neutral pressure decreased, and H97L increased with increasing pre-discharge Lithium evaporation in all data

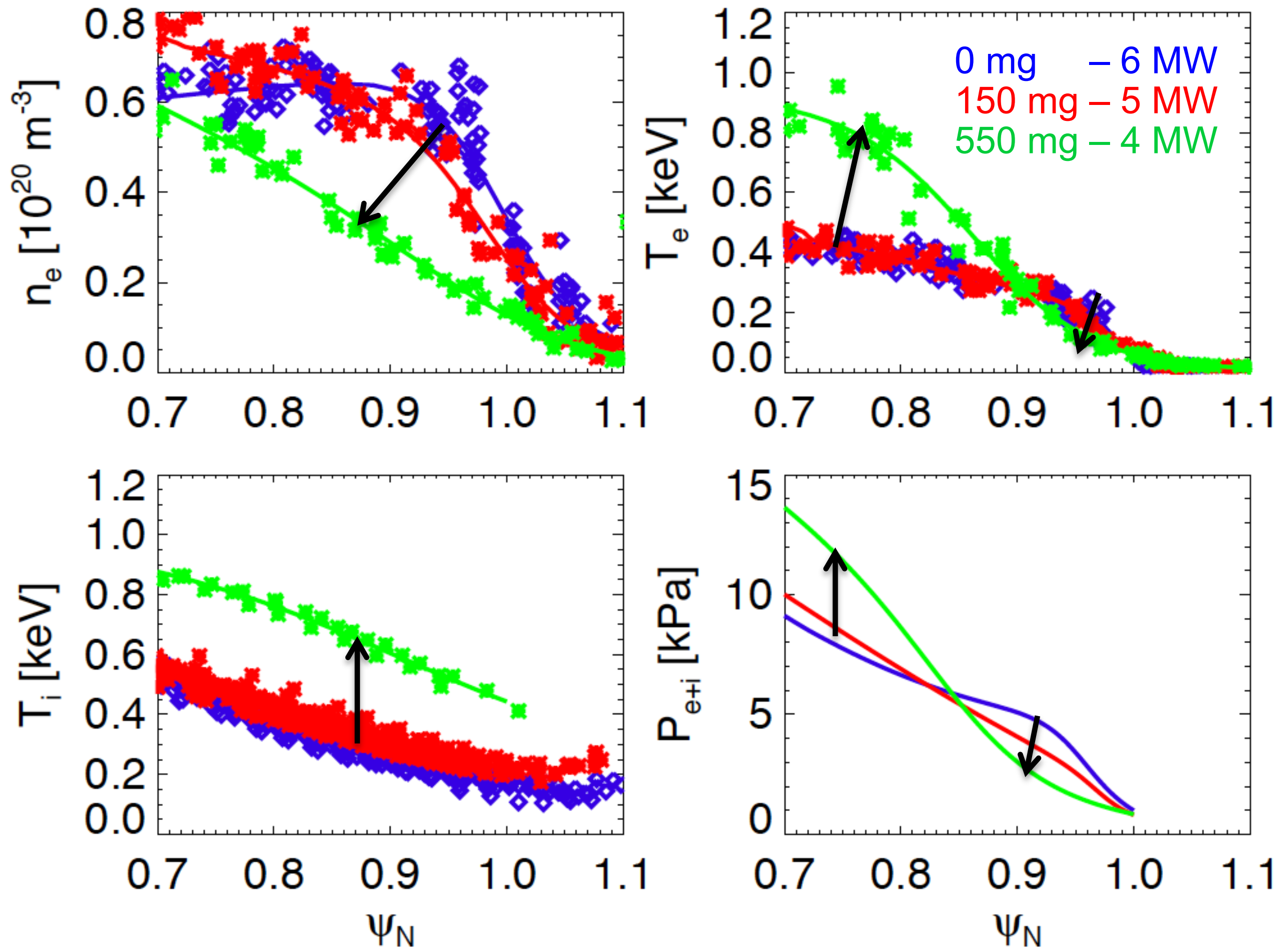
- **Sharp decrease of D_α in the lower divertor for the strongly shaped plasmas followed by a flattening at higher Li doses**
  - Transition from high recycling to sheath limited regime
  - Consistent with expectations from geometrical effects

- **Trends from weakly and strongly shaped plasmas are comparable**
  - Confinement in highly shaped plasmas slightly lower



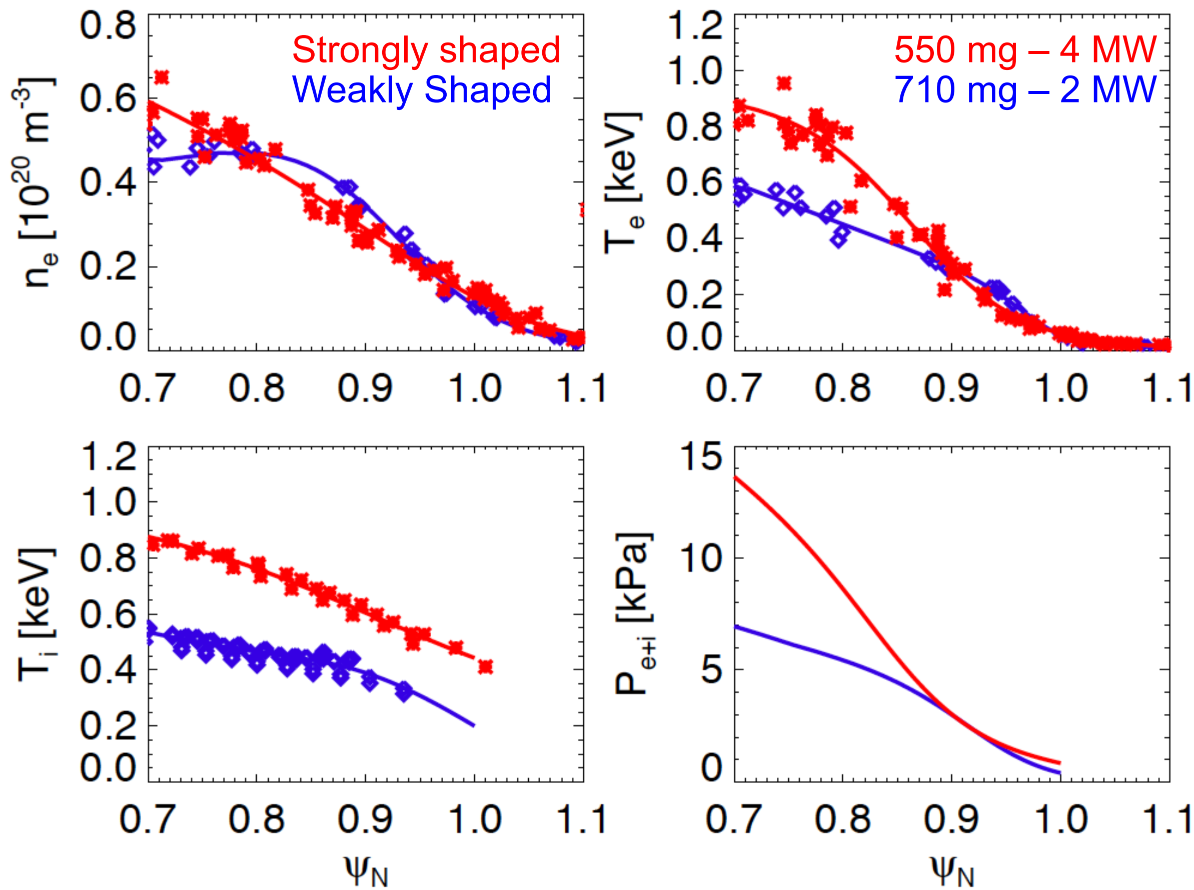
Edge profiles change significantly with increasing Lithium dose in strongly shaped plasmas (as in weakly shaped)

- **Improvement on confinement with Lithium dose could lead to global β-limit**
  - NBI power was reduced with increasing Lithium dose
- **Changes in pressure are expected to improve plasma edge stability**
  - Similar to weakly shaped plasmas



Higher NBI power in strongly shaped discharges leads to high edge temperature and pressure

- **Larger values of q_{95} in highly shaped plasmas allow for**
  - Higher I_P (at the same B_T)
  - Higher NBI power (before reaching global stability limit)
- **The highly shaped plasmas allowed**
  - Larger and stable T_e, T_i and P_{e+i} profiles

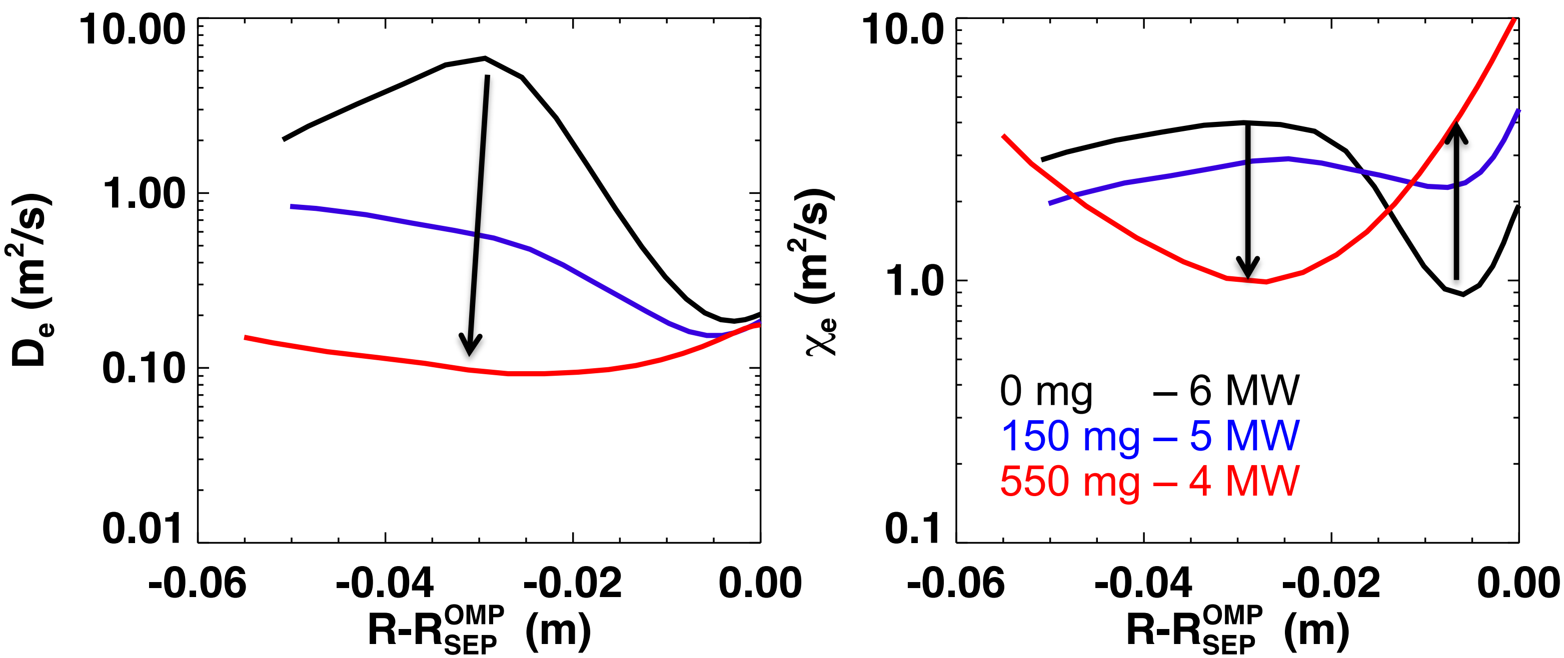


SOLPS was used to assess changes in recycling coefficient and cross-field transport changes with Lithium dose

- **SOLPS was used in interpretative mode to quantify changes in divertor recycling and cross-field transport with Lithium dose**
- **Energy and particle fluxes were specified at the inner simulation boundary based on experimental data**
- **Free parameters were scanned to match measured mid-plane and divertor profiles**
  - Separatrix location adjusted to match $q_{div,peak}$
  - Plate recycling coefficient and radiation were varied to match $D_{\alpha,peak}$
  - No separation between D and v_{pinch}
    - + Diffusivities are "effective" values

SOLPS was used to assess changes in recycling coefficient and cross-field transport changes with Lithium dose

- **The SOLPS simulations show that**
  - A decrease in recycling coefficient from 0.99 to 0.9 is required to explain the observed reduction of D_α with increasing Lithium dose
  - Electron thermal diffusivity is found to:
    - Increased (~ 5x) in the pedestal region
    - Decreased (~ 4x) elsewhere



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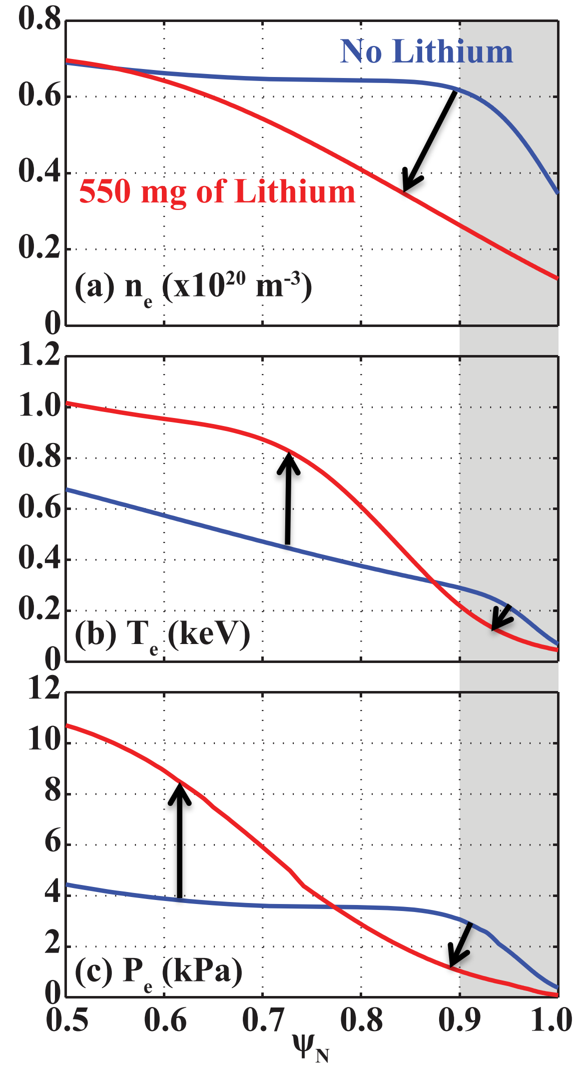
GS2 linear gyrokinetic calculations of microstability in weakly and strongly shaped plasmas do not differ significantly

- **Depositing Lithium increases ∇n for Ψ_N < 0.90**
  - Microtearing modes become weaker
  - Decreased electron heat transport
    - Agrees with observed larger ∇T
- **Depositing Lithium decreases ∇n for Ψ_N > 0.90**
  - ETG modes become stronger
  - Increased electron heat transport
    - Agrees with observed lower T_e
- **Results do not differ significantly from modestly shaped plasma experiments [J.M. Canik NF 2013 and M. Coury PoP 2016]**
  - Shaping the plasma leads to non-conventional mode structures
    - Results are more difficult to interpret



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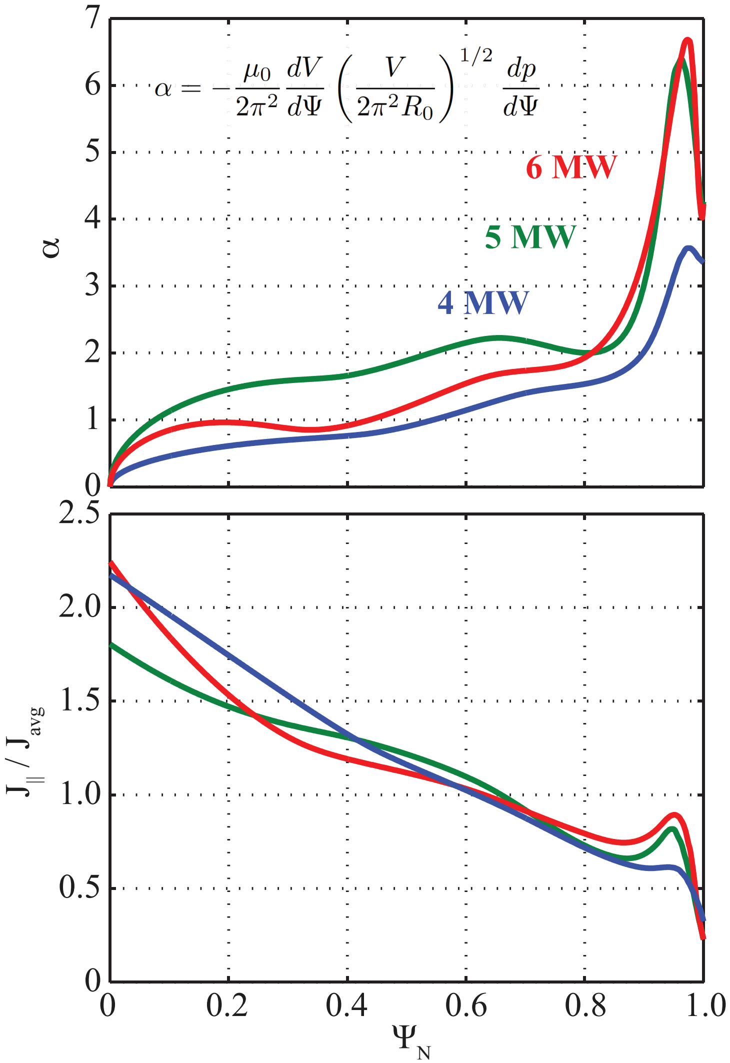
NBI power scan in the reference discharge provides information on main drive of plasma edge instabilities

- **NBI power scan in the reference (no Lithium) discharge was performed to identify β stability limit**

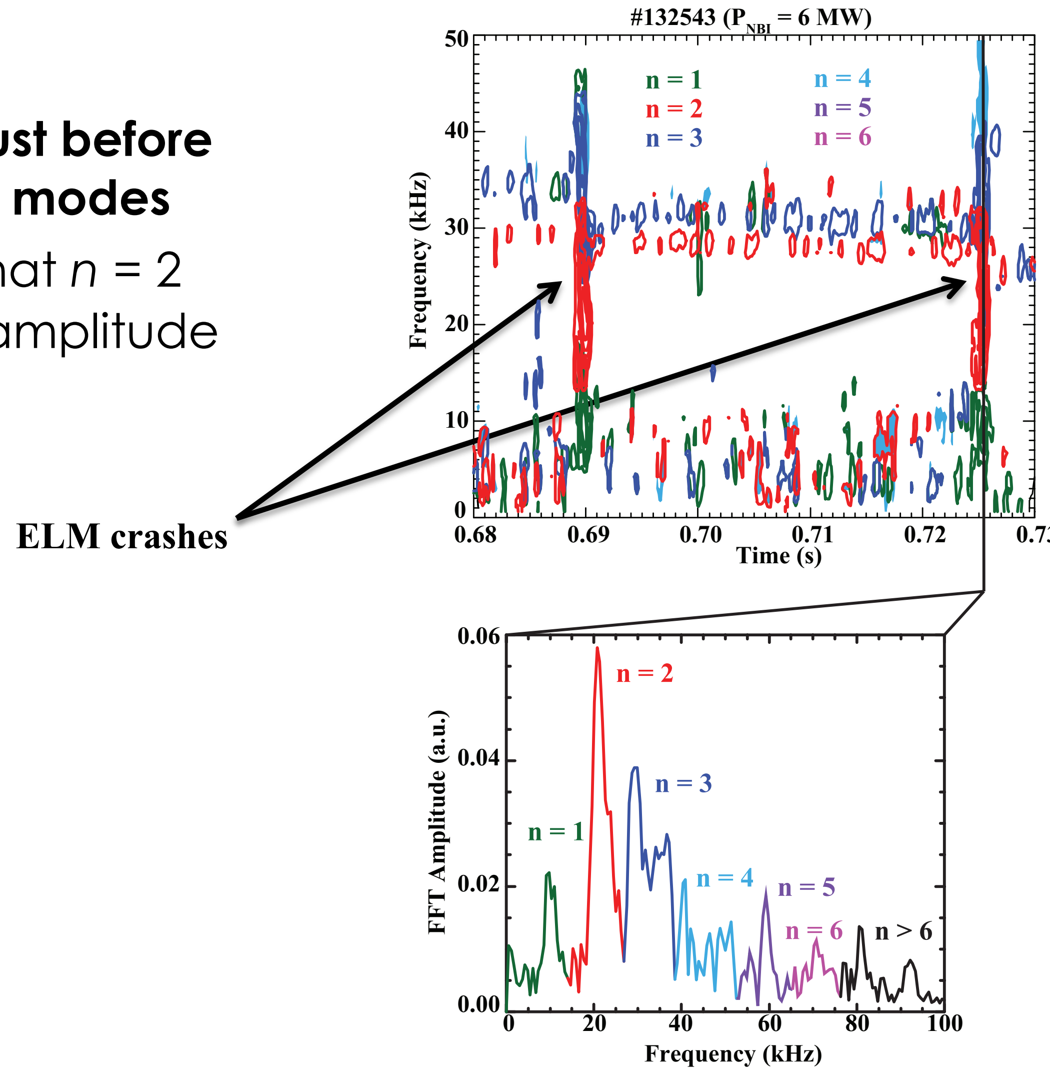
- **Normalized pressure gradient, α, and parallel current density, $J_{||}$, for discharges with 5 and 6 MW of NBI power are comparable**
  - Suggests that both plasmas reach edge stability boundary

- **Discharge with 4 MW of NBI power has lower α and $J_{||}$, and no ELMs**
  - Profiles evolution are likely limited by edge transport (values are below stability threshold)



Experimental measurements indicate that ELMs are triggered by modes of low toroidal number

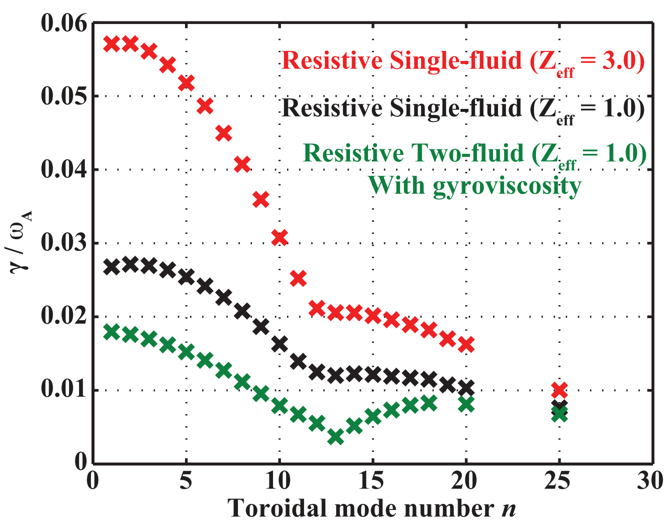
- **Magnetic measurements just before ELM crashes indicate low *n* modes**
  - Measurements show that n = 2 mode has the largest amplitude

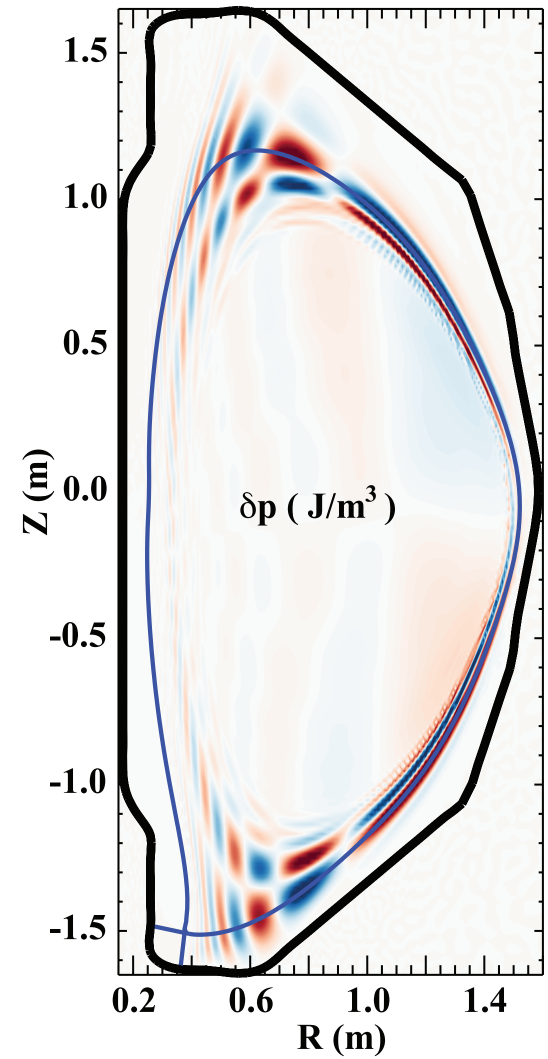


Stability calculations indicate that ELMs are triggered by low *n* resistive modes

- **Ideal MHD calculations (ELITE) indicate that all ideal modes are stable**
  - ELITE runs only for *n* > 5 (use GATO for *n* < 5)

- **Single- and two-fluid resistive MHD calculations (M3D-C[1]) predict unstable resistive modes of low *n***
  - Plasma is close to β-limit (simulation is sensitive to global modes)





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  - ELITE runs only for $n > 5$ (use GATO for $n < 5$)

- **Single- and two-fluid resistive MHD calculations (M3D-C^1) predict unstable resistive modes of low *n***
  - Plasma is close to β-limit (simulation is sensitive to global modes)

Ideal MHD calculations (ELITE) indicate the ideal modes are all stable in the Lithium dose scan experiment

- Resistive MHD calculations (M3D-C^1) are still in progress

Summary: Results provide a baseline expectation on Lithium benefits on NSTX-U, which is optimized for strongly shaped plasmas

- **Increasing Lithium dose in strongly shaped plasmas is observed to**
  - Reduce recycling and neutral pressure
  - Improved energy confinement and edge stability

- **Trends from weakly and strongly shaped plasmas are comparable**
  - Differences might be related to geometrical effects

- **SOLPS modelling shows that**
  - A reduction of the recycling coefficient from 0.99 to 0.9 is required to explain the observed reduction on D_α with increasing Lithium dose
    - + Lithium deposition closer to strike point leads to a transition from high recycling to sheath limited regime
  - The electron transport channel is increased (~5x) in the pedestal region and decreased(~4x) elsewhere
    - + Consistent with GS2 gyrokinetic calculations of microinstabilities

- **Change in edge kinetic profiles are likely the key for observed ELM stabilization**
  - MHD stability calculations indicate that ideal modes are stable and ELMs are triggered by resistive modes of low *n*