Transport and stability analyses supporting disruption prediction in high beta KSTAR plasmas*

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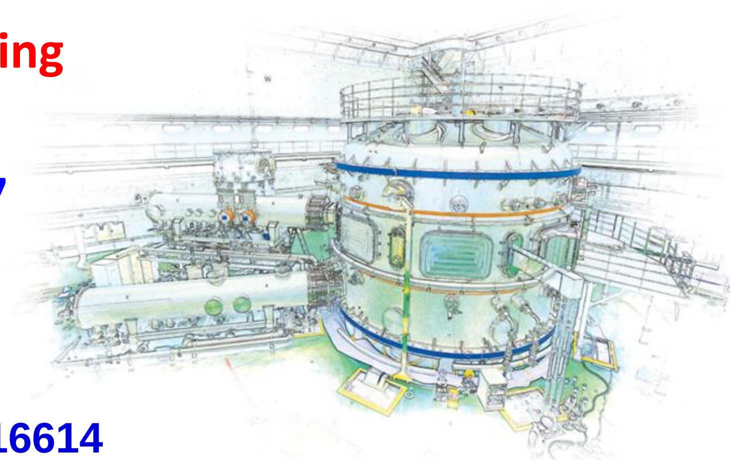
National Fusion Research Institute

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

NSTX-U Physics meeting

29 November 2017

PPPL



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Motivation : Sustain high-β operating regime for efficient fusion production

- Targeting sustained **high β_N advanced tokamak operation** at reduced internal inductance (l_i) above ideal MHD limits

⟶ Avoid **MHD instability**

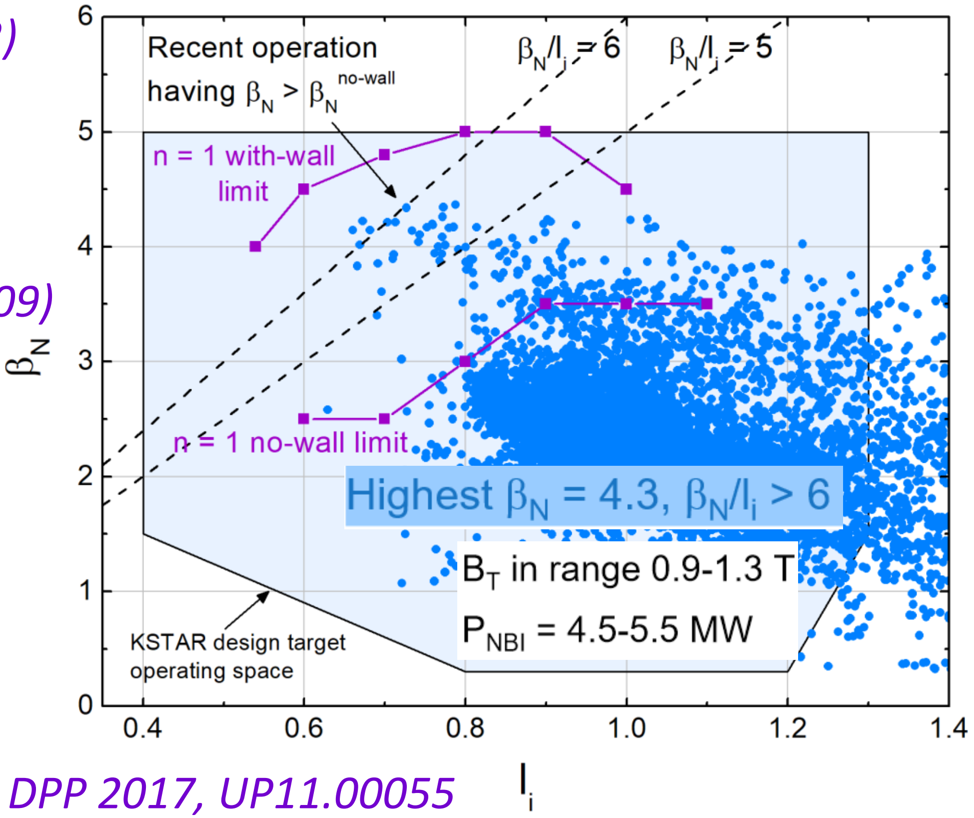
*S.A. Sabbagh et al., Phys. Plasmas **9** 2085 (2002)*
*Y.S. Park et al., Phys. Plasmas **21** 012513 (2014)*

⟶ **High non-inductive current fraction** (f_{NI}) for sustainment

*I. Voitsekhivitch et al., Nucl. Fus. **49** 055026 (2009)*

- Stability analysis essential for **disruption event characterization and prediction** using **DECAF** code

J.W. Berkery et al., APS DPP 2017, CP11.00093



Y.S. Park et al., APS DPP 2017, UP11.00055

Outline : Transport, equilibrium and stability analysis of high-β KSTAR shots

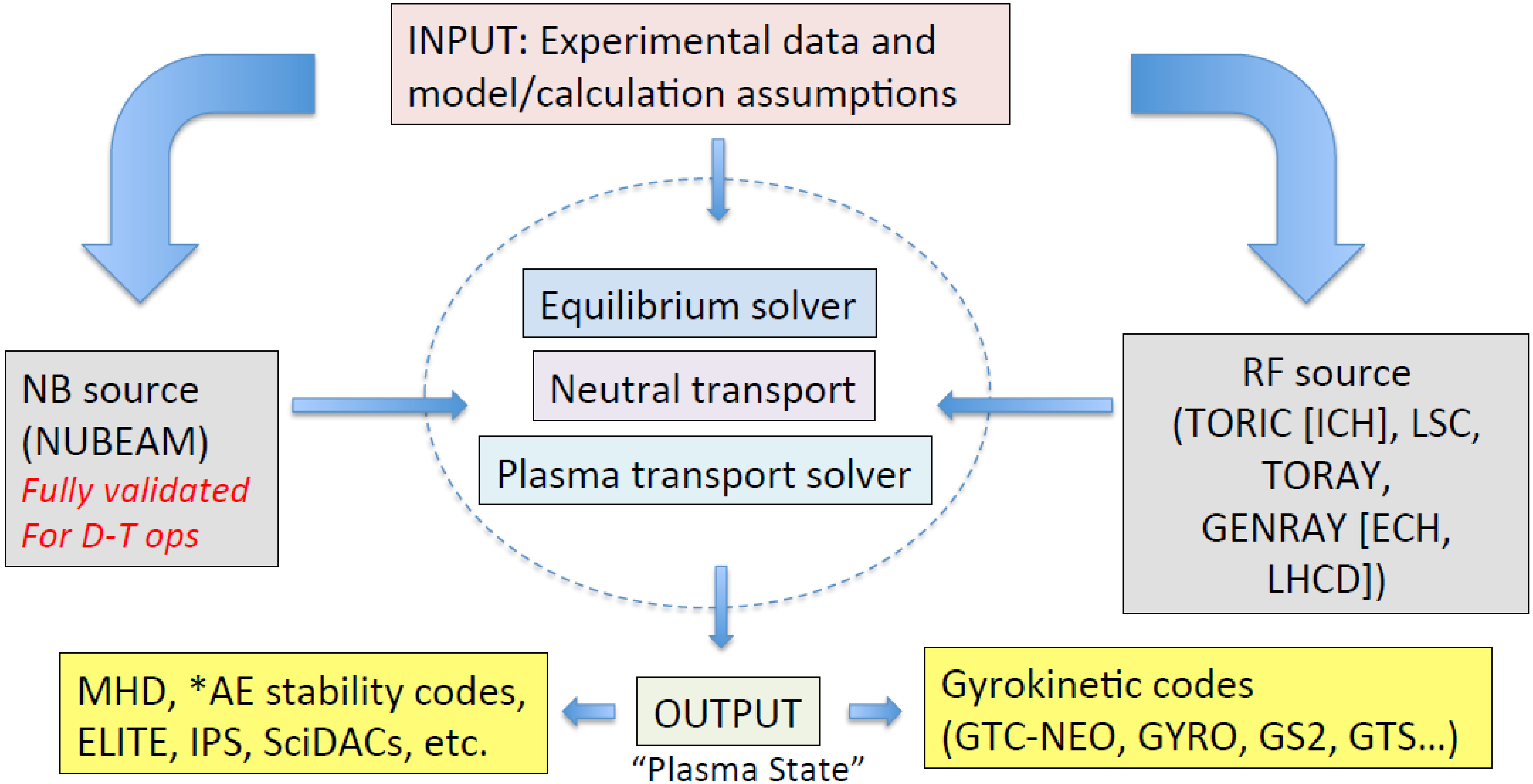
- Interpretive TRANSP analysis *TRANSP : See http://transpweb.pppl.gov*
  - Equilibrium from EFIT (e.g. kinetic EFIT)
    Y. Jiang et al., APS DPP 2017, UP11.00056 ***& following talk***
  - KSTAR experimental data as inputs (N_e, T_e, T_i, ω_φ, …)

  → **Non-inductive current** fraction (f_{NI}) and profiles computed

  → Effects on plasma stability

- MHD mode **stability analysis** :
  - Global mode ideal MHD analysis kink, ballooning, RWM) : DCON
    A.H. Glasser, Phys. Plasmas ***23*** *072505 (2016)*
  - Resistive mode stability analysis: Resistive DCON
    A.H. Glasser et al., Phys. Plasmas ***23*** *112506 (2016)*
  - Kinetic resistive wall mode (RWM) stability analysis: MISK
    J. Berkery et al., Nucl. Fusion ***55*** *123007 (2015); B. Hu et al., Phys. Plasmas* ***12*** *057301 (2005)*

TRANSP : Time dependent 1.5D tool for interpretive/predictive analysis

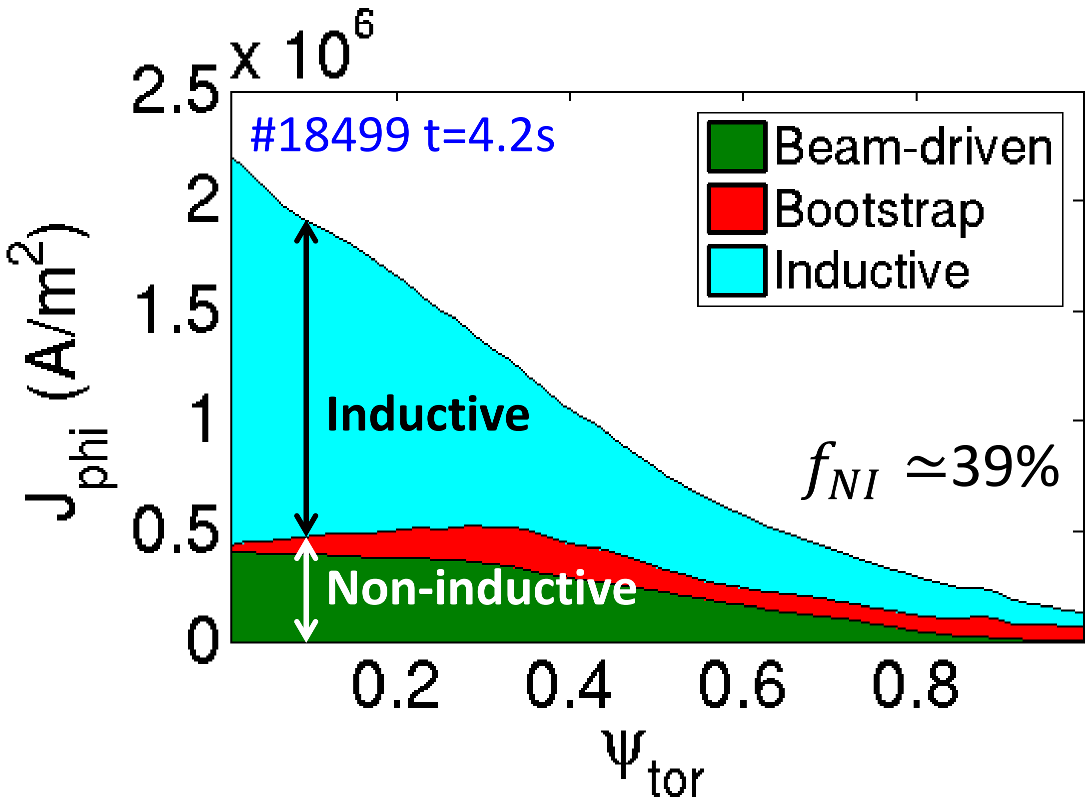


Output of TRANSP (Plasma State File) is standardized for simplifying input to other computationally intensive codes

S. Kaye et al., TUG meeting 2015

High non-inductive current fraction required for long pulse, high-β plasmas

- I(Non-inductive) = I(Beam-driven) + I(Bootstrap)
- KSTAR plasmas can have high non-inductive current fraction (f_{NI}>70%)



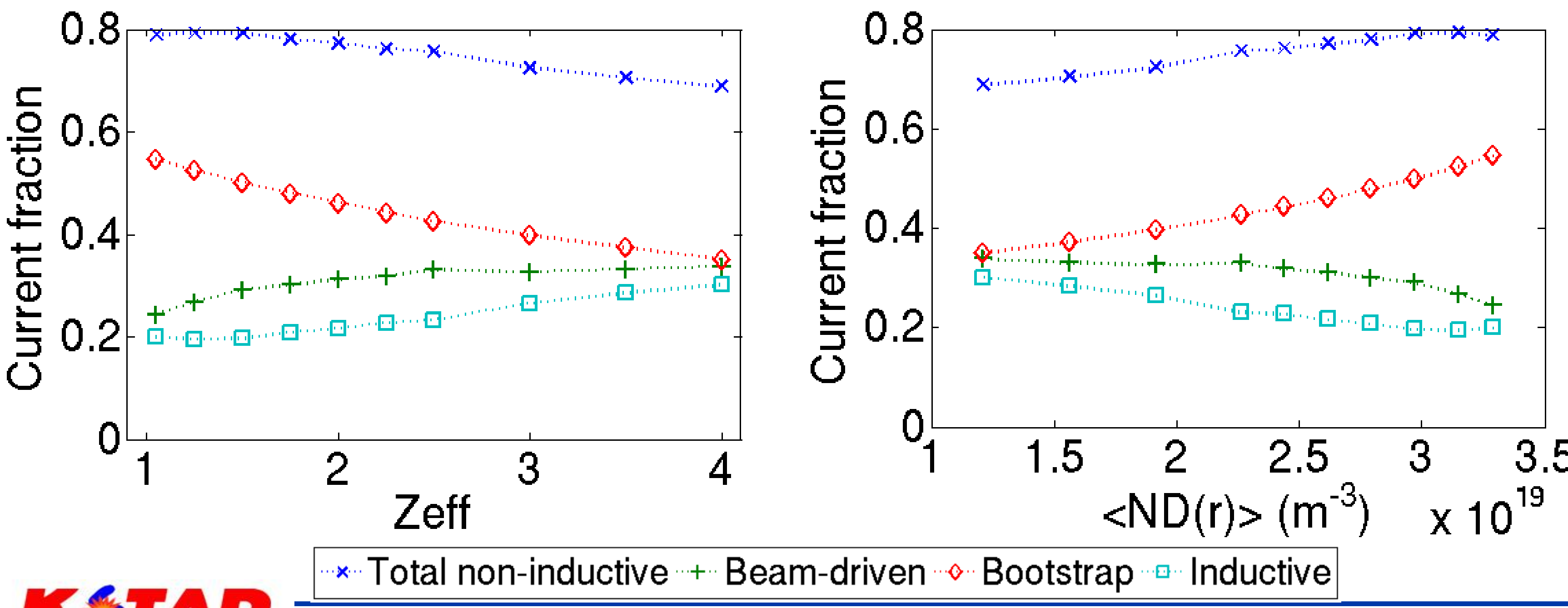
- Need to examine dependence on plasma quantities (N_e, T_i, β_p,…)

KSTAR plasma with low non-inductive fraction for comparison

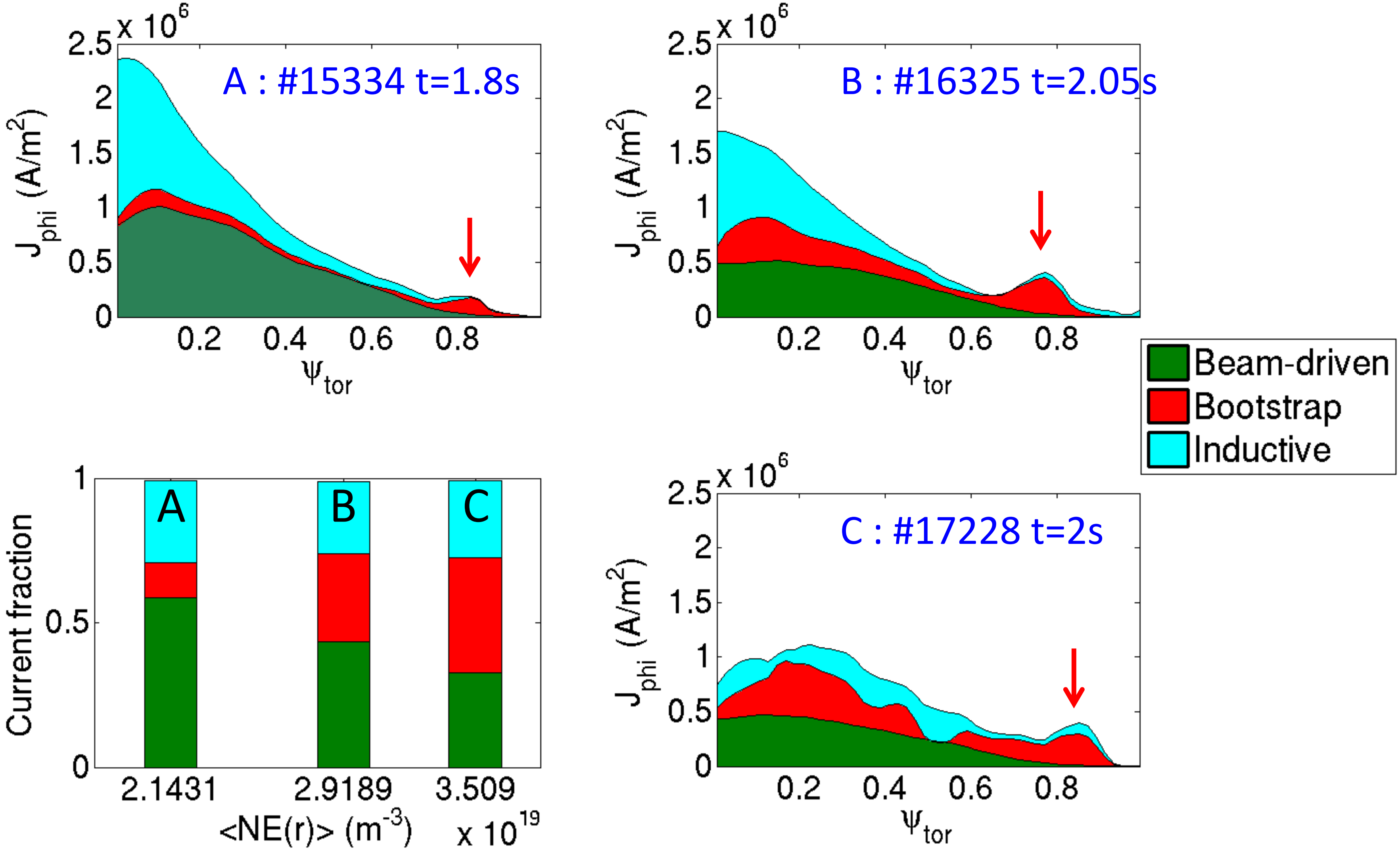
High non-inductive plasmas not sensitive to Z_{eff} variation

- Interpretive TRANSP with KSTAR #17228 t=2s measurements
  - Z_{eff} measurement not available → Z_{eff} profile set constant
- Scan on Z_{eff} alters ion density variation
  - As Z_{eff} increases (N_D decreases) :

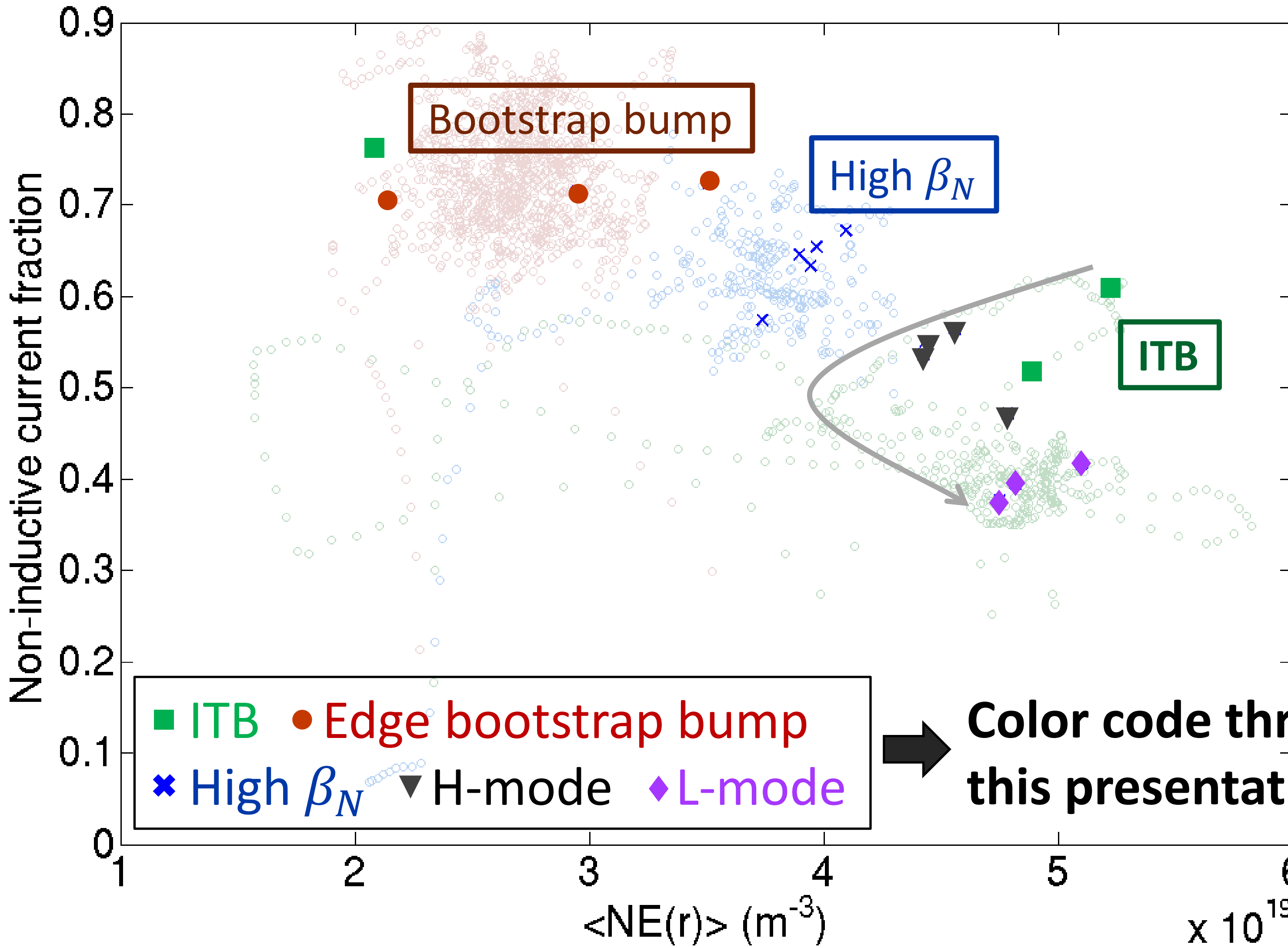
→ Beam driven current ↑, Bootstrap current ↓



Bootstrap current fraction increases as electron density increases

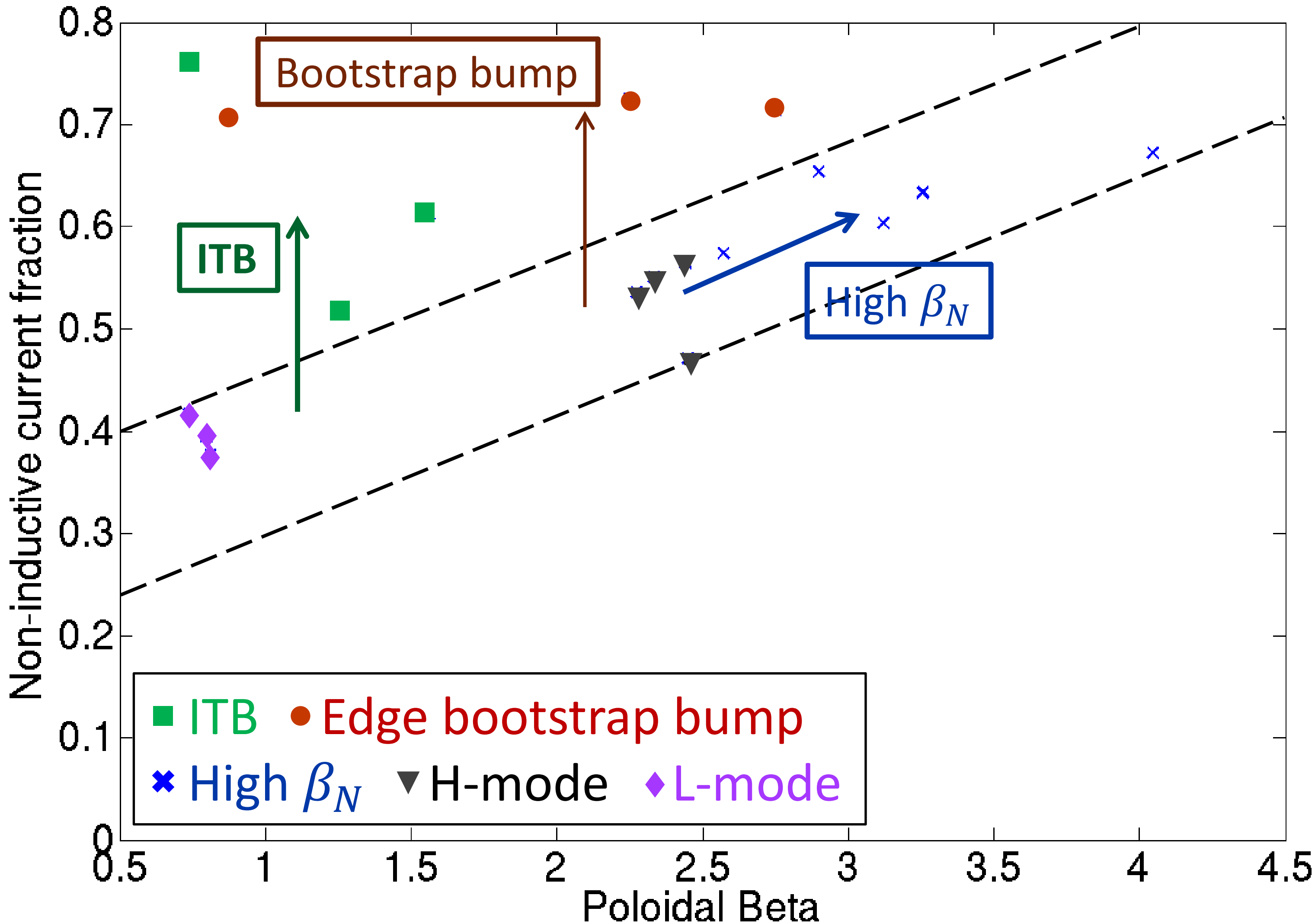


High non-inductive fraction can occur in different KSTAR operational scenarios

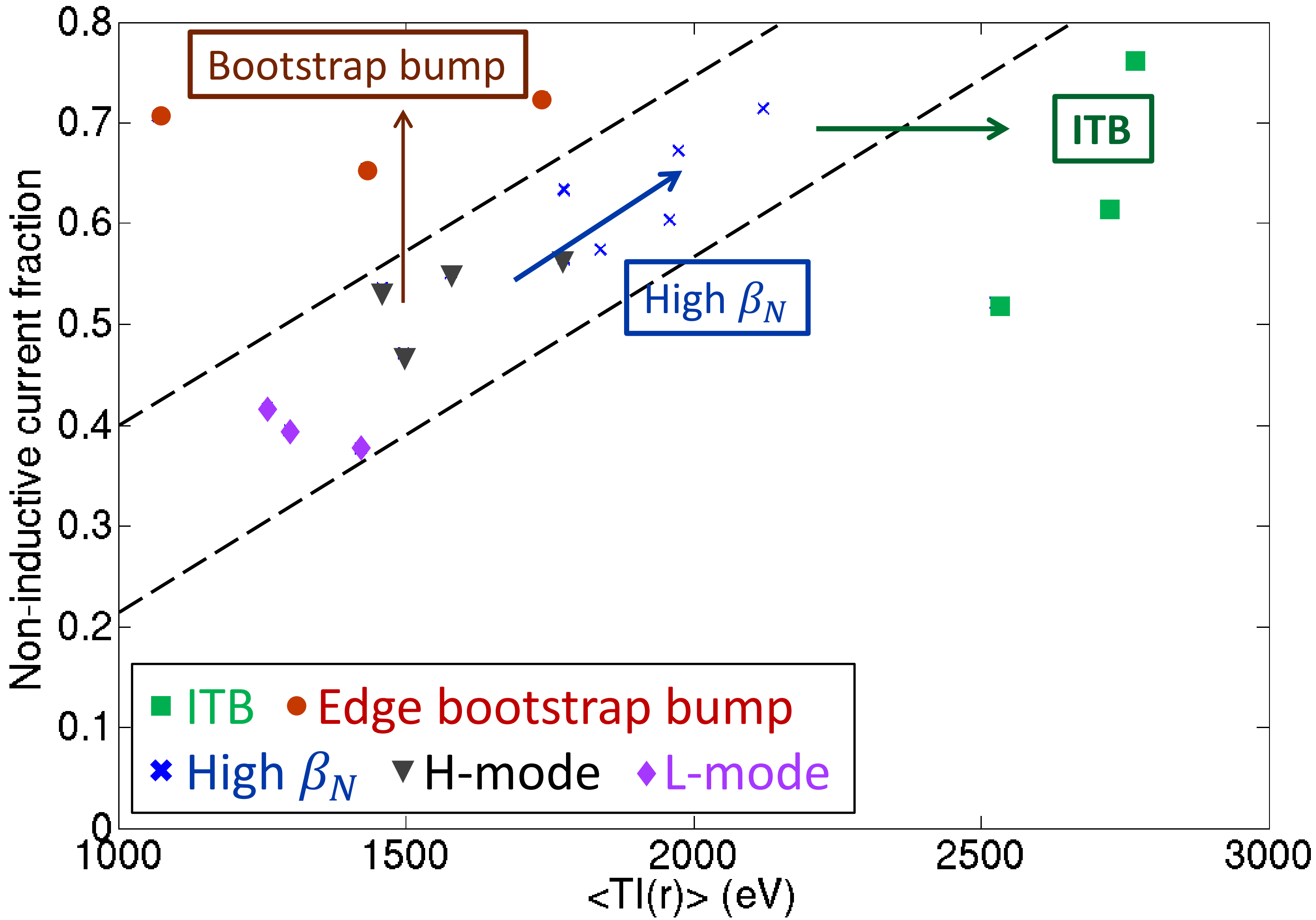


Color code throughout this presentation

Increase of non-inductive current fraction f_{NI} due to increasing β_p, ITB, edge bootstrap current

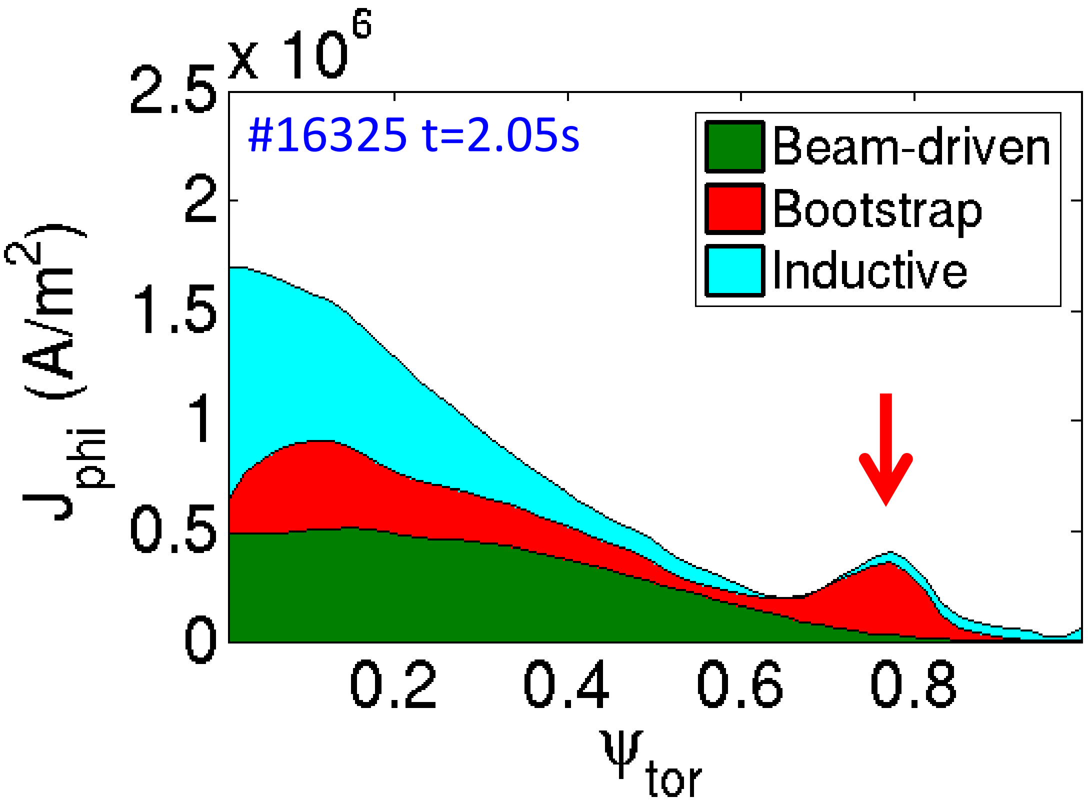


The presence of edge bootstrap in H-mode plasmas significantly increases f_{NI}



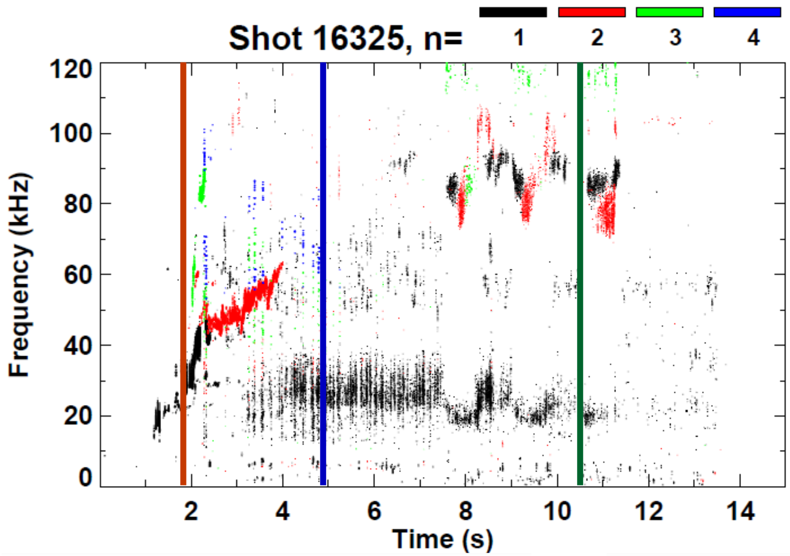
Total non-inductive current fraction f_{NI} increased due to edge 'bootstrap bump'

- Strong bootstrap current fraction in edge region increases significantly f_{NI}



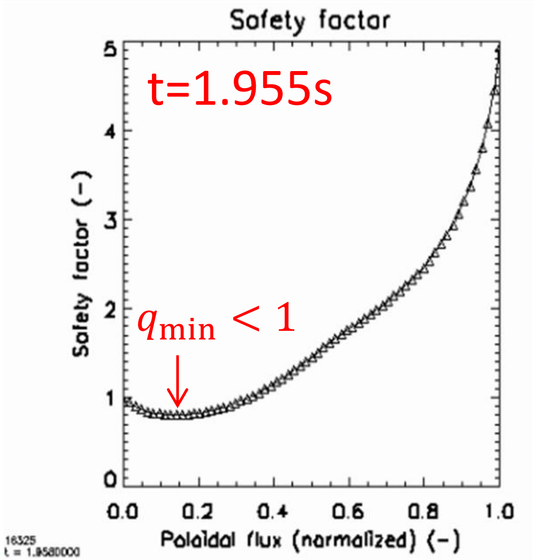
$f_{NI} \simeq 71\%$

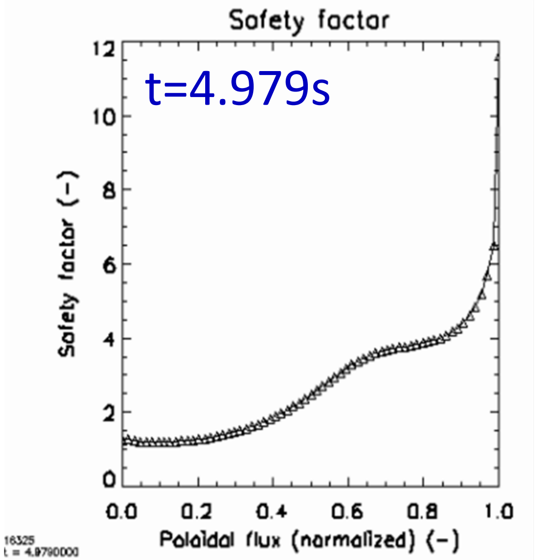
Kinetic EFIT reconstructed low-sheared q-profiles consistent with MHD stability

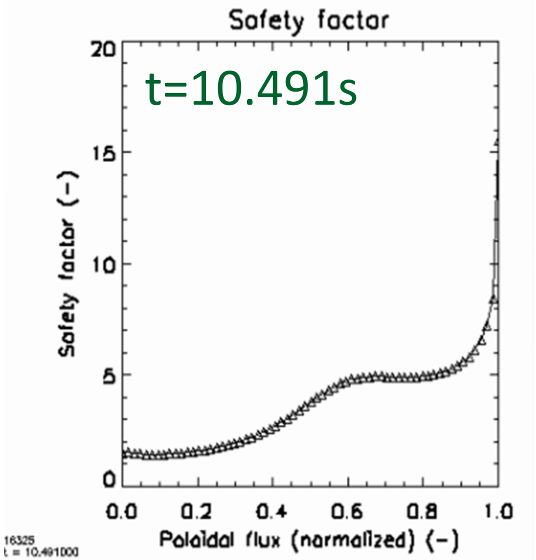


- MHD spectrogram shows $\boldsymbol{n = 1}$ **mode activity** when $\boldsymbol{q_{min} < 1}$
- Low-sheared q-profiles in higher q region

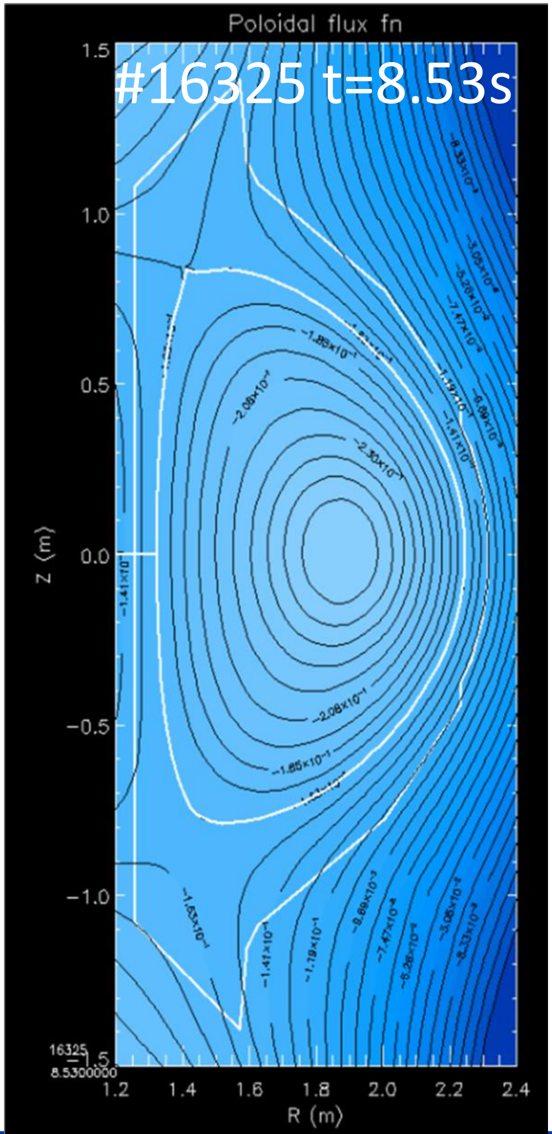
⟶ Plasma is **quiescent** phase



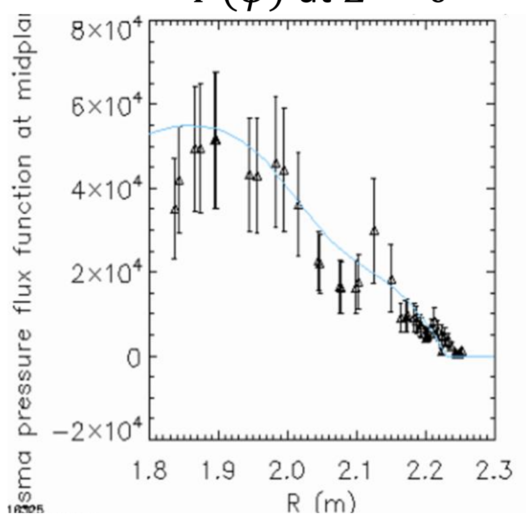




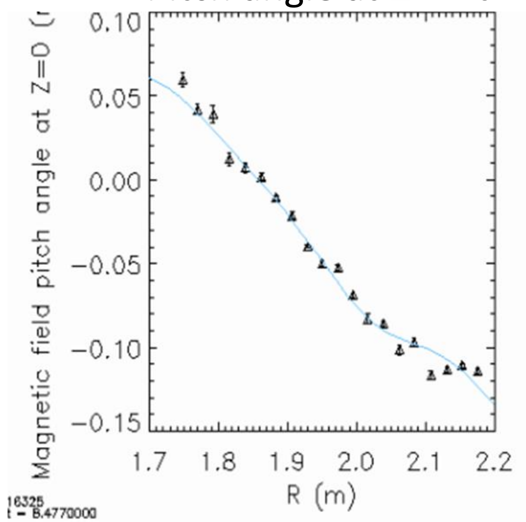
q-profiles are reconstructed from equilibria using magnetic pitch angle measurements

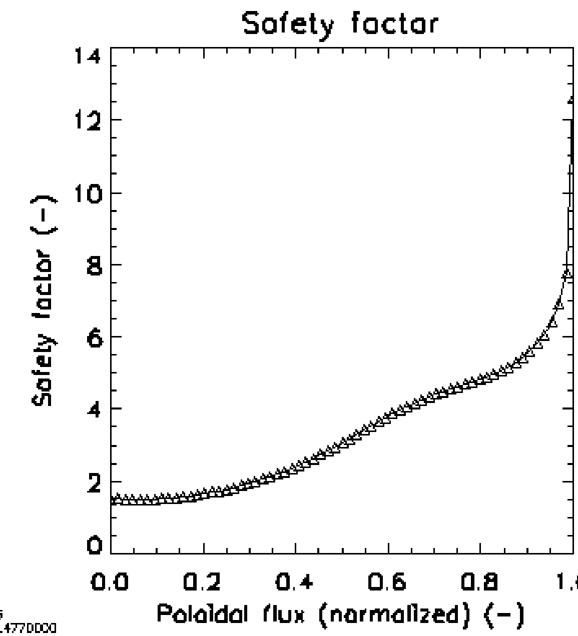


$P(\psi)$ at $Z = 0$



Pitch angle at $Z = 0$

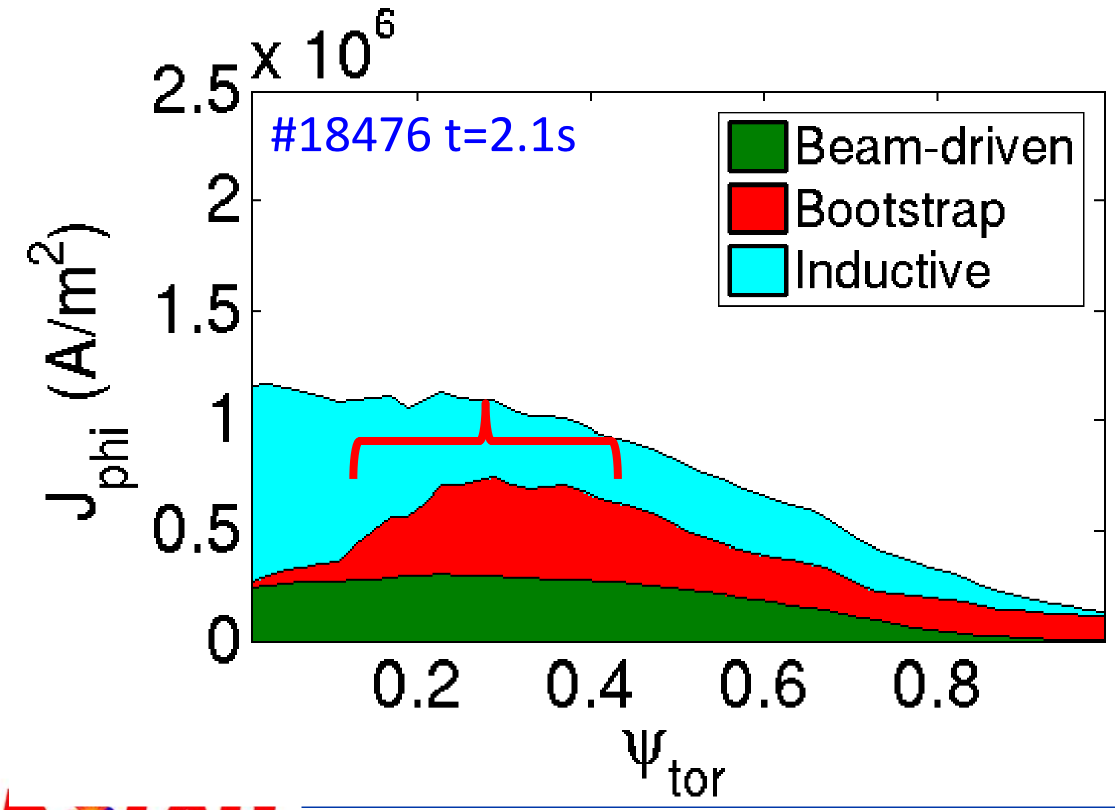




Y. Jiang et al., APS DPP 2017, UP11.00056 ***& next talk***

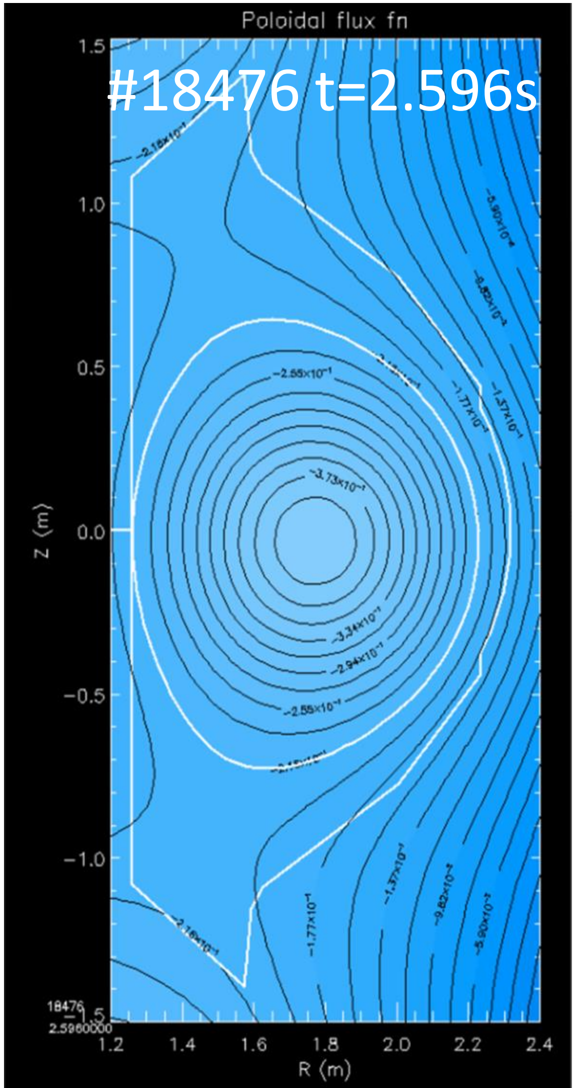
Total non-inductive current fraction f_{NI} increased by core bootstrap current due to ITB

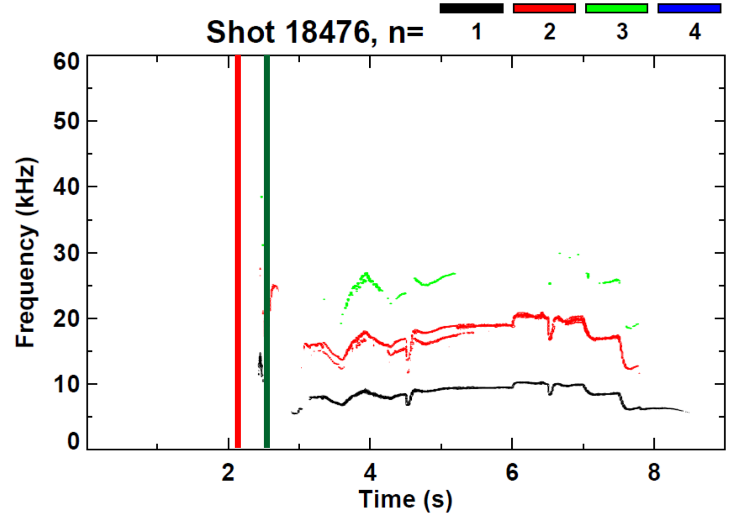
- Stronger core bootstrap current fraction compared to H-mode

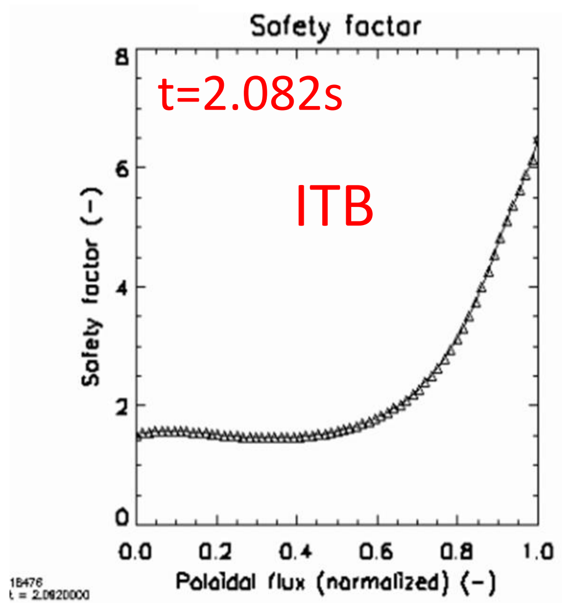


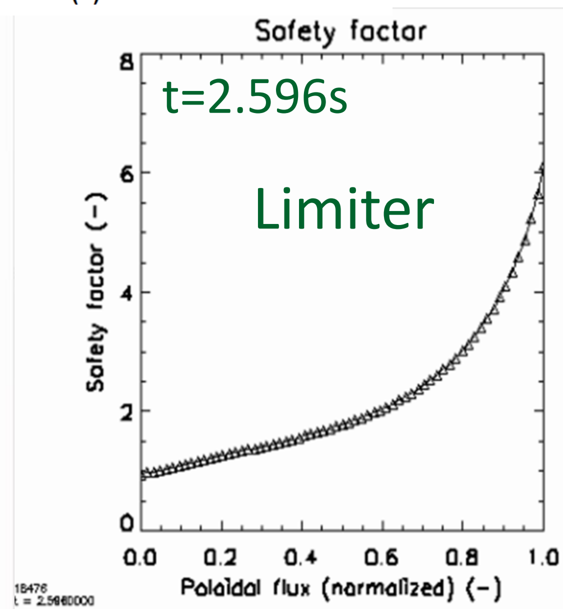
$f_{NI} \simeq 61\%$

q-profiles of ITB / limiter plasmas have significant differences









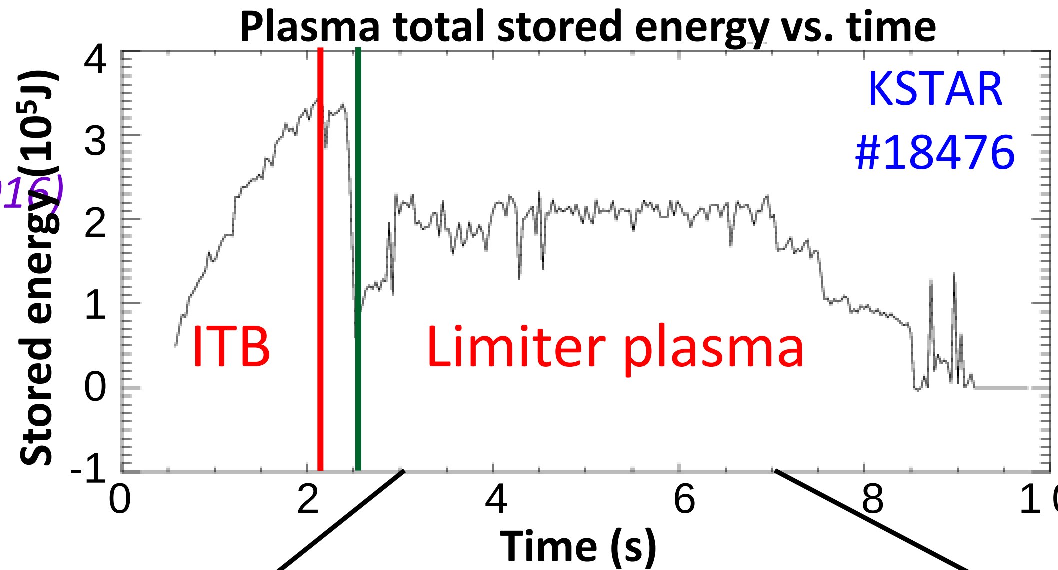
Ideal global stability analysis of new KSTAR kinetic equilibria examined with ideal DCON

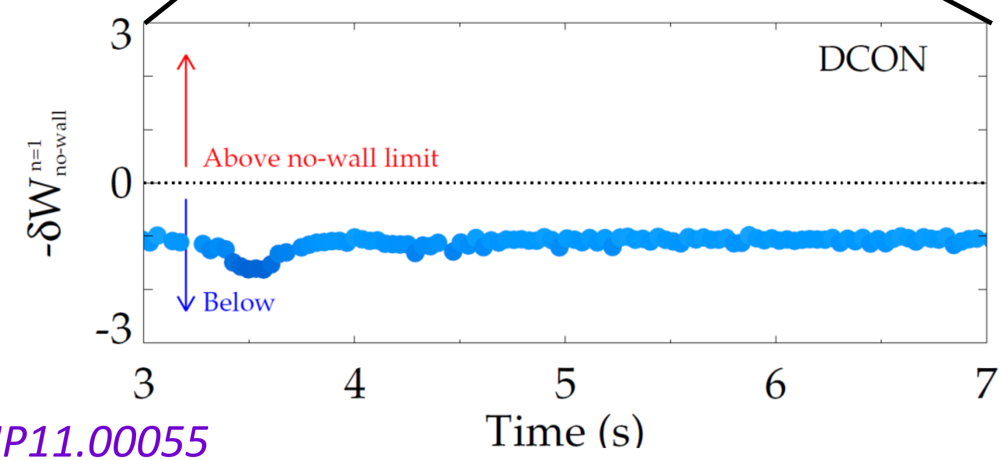
- Ideal δW calculations with DCON

*A.H. Glasser, Phys. Plasmas **23** 072505 (2016)*

→ Indication whether plasmas above or below $n = 1$ no-wall β limit

- **Ideal stability** (below $n = 1$ no-wall limit) during later phase as expected

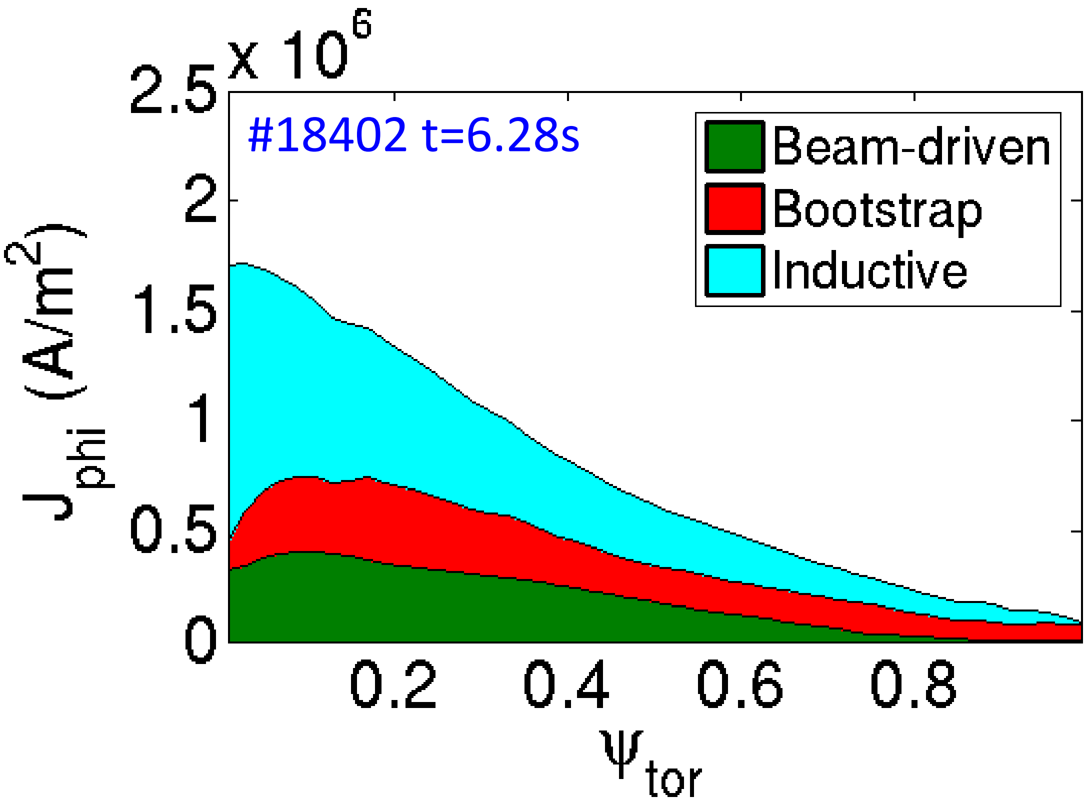




See also : *Y.S. Park et al., APS DPP 2017, UP11.00055*

Increased core bootstrap current in H-mode due to increased ∇P

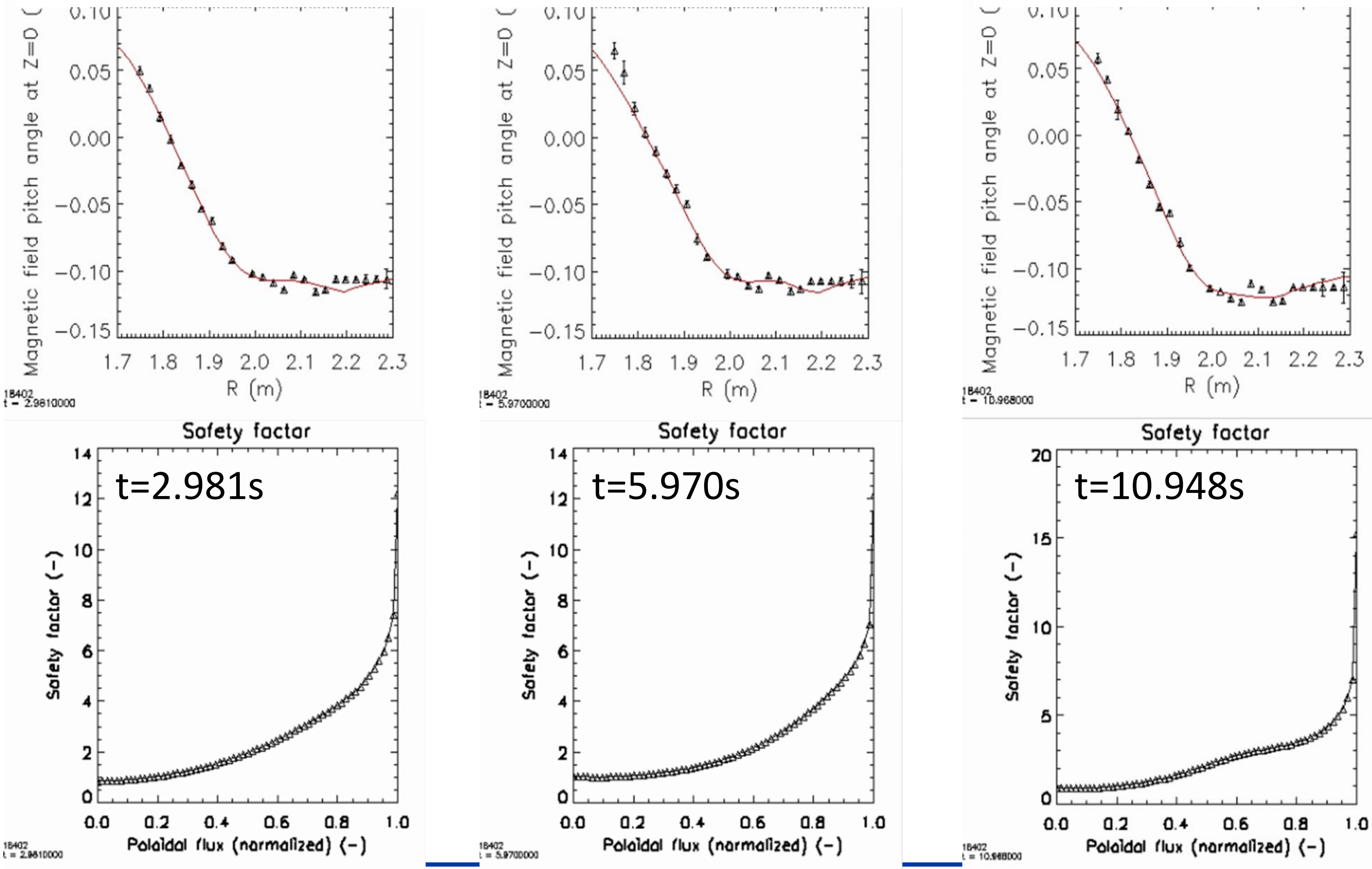
- Stronger bootstrap current fraction in core region compared to L-mode, due to stronger pressure gradient
- Still significant inductive current fraction (especially in the core)



$f_{NI} \simeq 55\%$

q-profiles reconstructed from kinetic equilibria show evolution of magnetic shear

Pitch angle at $Z = 0$ **Pitch angle at $Z = 0$** **Pitch angle at $Z = 0$**



Resistive DCON : a new tool for MHD stability analysis used on KSTAR for the first time

- New resistive DCON code

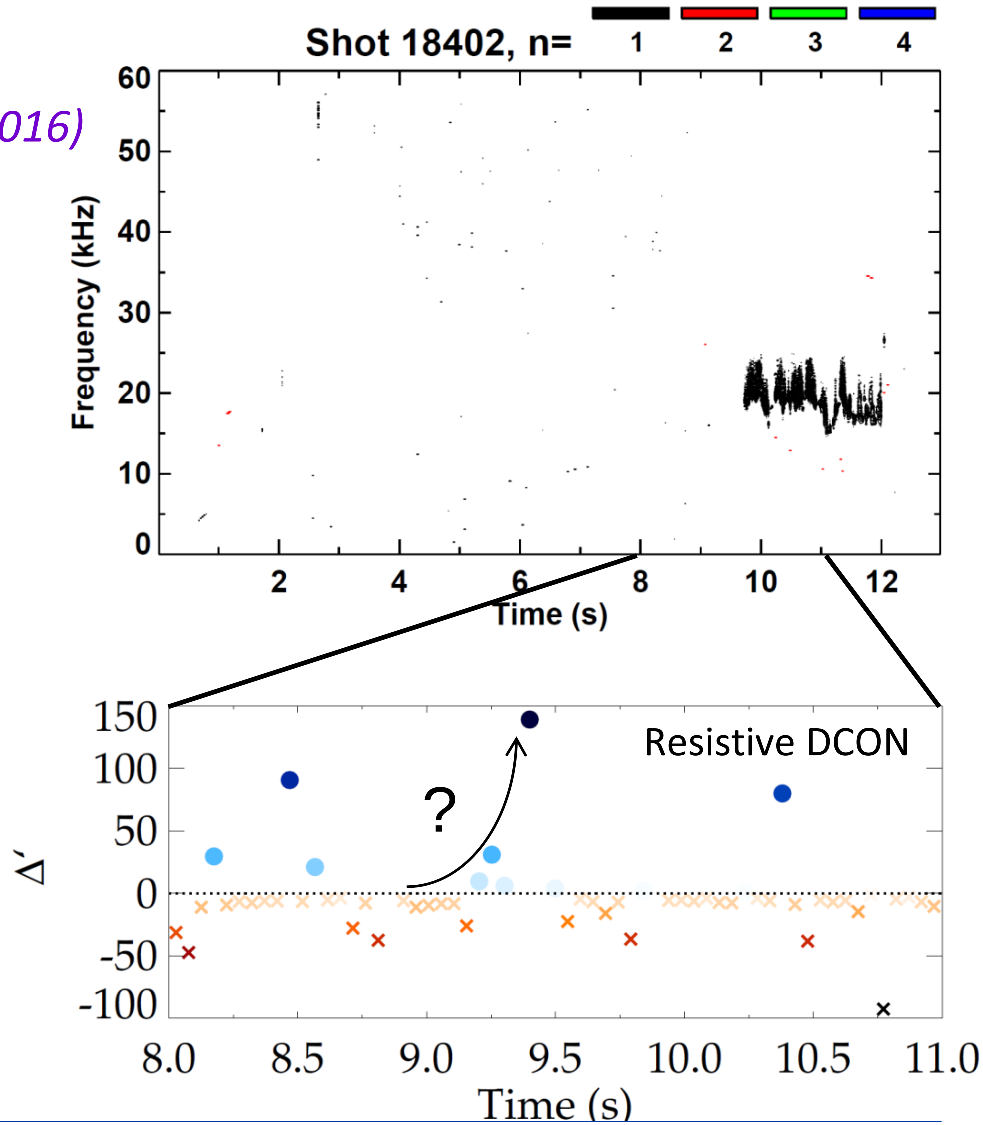
*A.H. Glasser et al., Phys. Plasmas **23** 112506 (2016)*

used to calculate the $q = 2$ Δ' for case with sudden appearance of $n = 1$ mode

  - Positive Δ' would indicate classical instability at $q = 2$

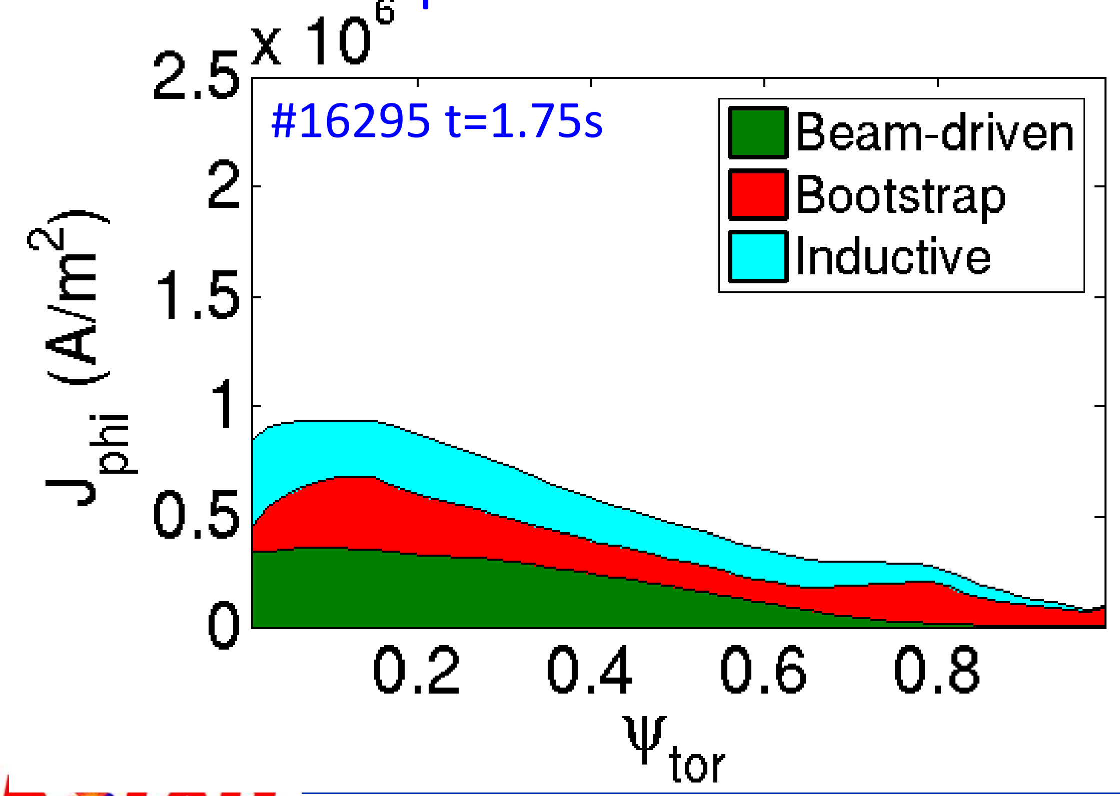
- Calculation shows a near marginal Δ' at $q = 2$ around time of mode onset

  - Requires further analysis



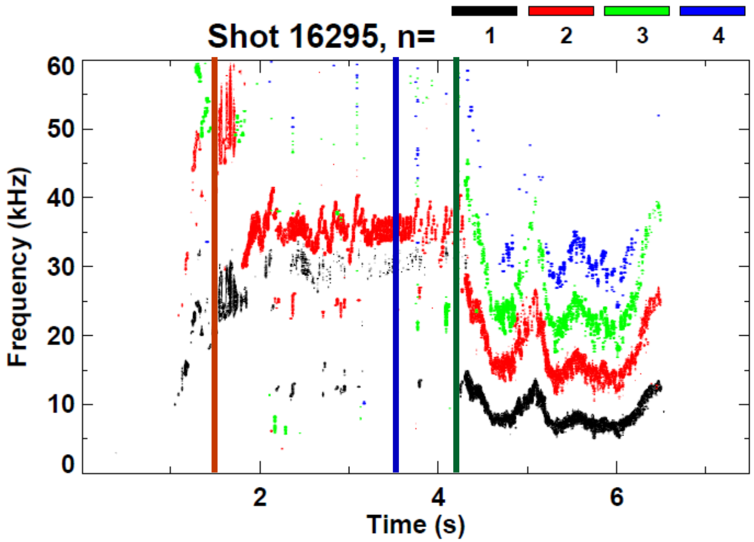
A broad non-inductive current fraction profile in high β_N plasma operation

- Significant and broad bootstrap current fraction compared to L-mode plasmas
- Inductive current fraction significantly decreased compared to L- or H-mode plasmas



$f_{NI} \simeq 67\%$

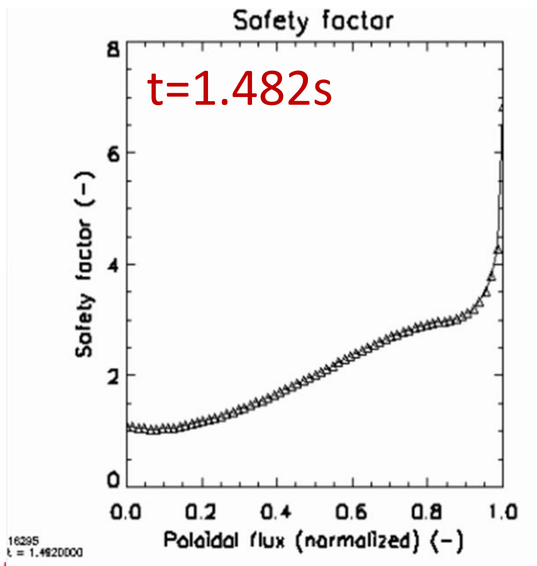
End of high-β_N phase due to onset of $n = 1$ mode

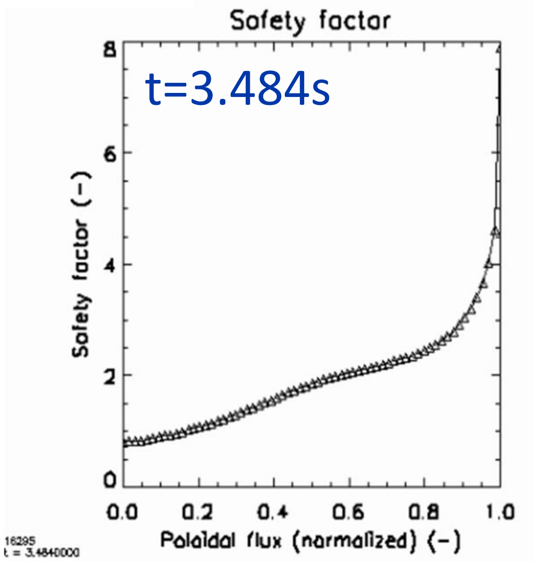


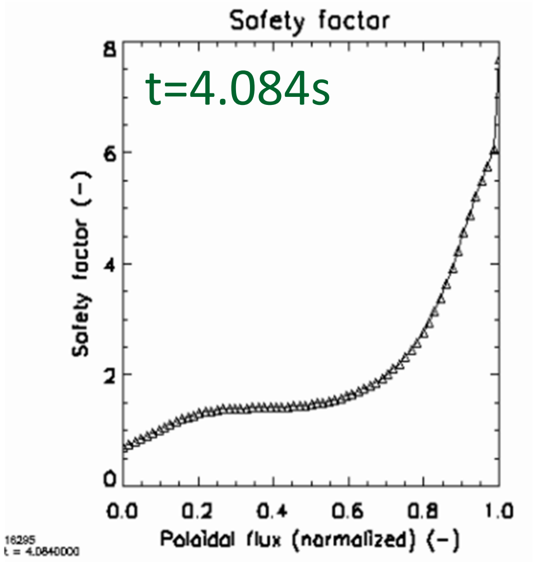
- MHD spectrogram shows onset of $n = 1$ **mode** at t≃4.2s

⟶ End of high-β phase

⟶ Detailed stability analysis shown in *Y.S. Park et al., APS DPP 2017, UP11.00055*







Calculations of kinetic modifications to ideal stability examined with MISK code

$$(\gamma - i\omega_r)\,\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

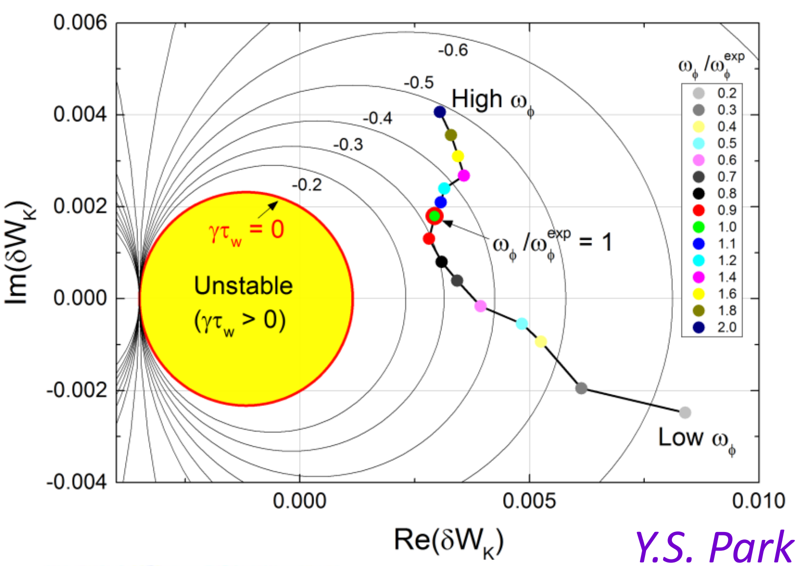
$$\delta W_K \sim \frac{1}{\langle\omega_D\rangle + l\omega_b - i\nu_{\mathrm{eff}} + \omega_E}$$

MISK Calculations

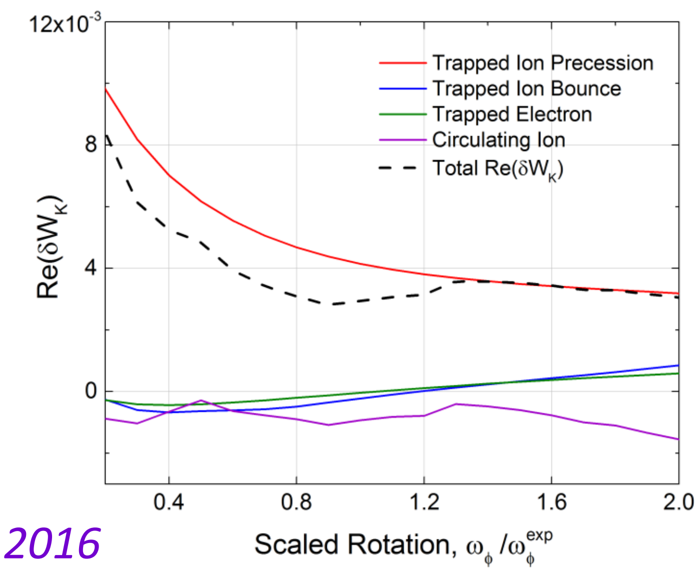
- Benchmarked
- Compared to Experiments

Fluid terms   Kinetic effects: Collisionality   Rotation

MISK kinetic stability calculations for KSTAR with previous magnetics only equilibrium and without energetic particles



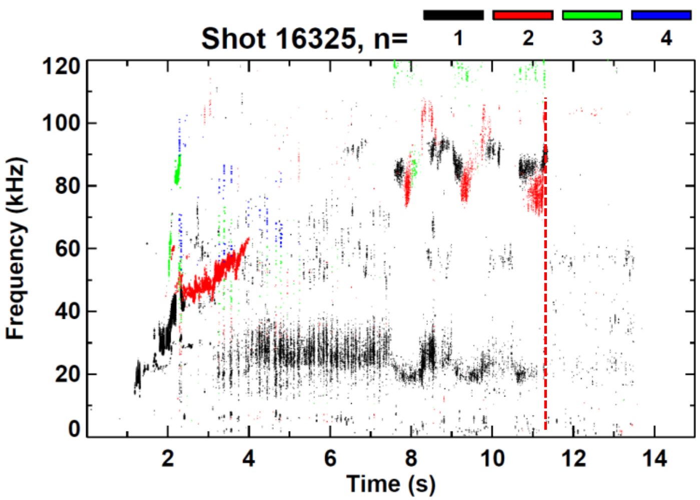
KSTAR
#16295
@2.315s

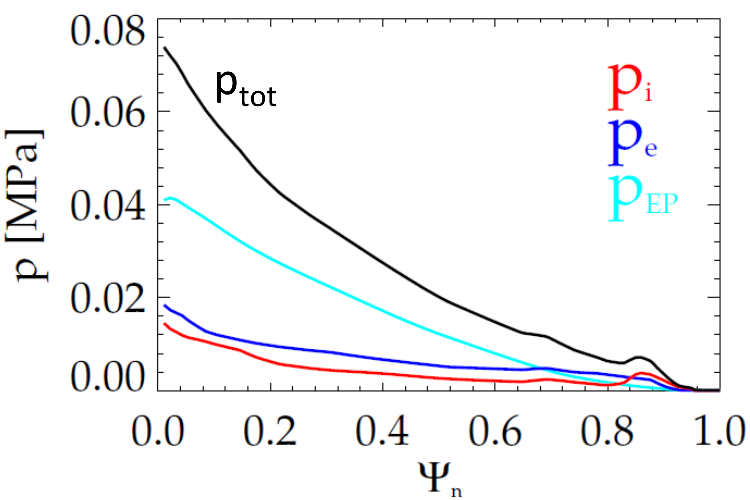


Y.S. Park et al., APS DPP 2016

Kinetic global stability analysis of new KSTAR kinetic equilibria is commencing

KSTAR #16325 @11.975s

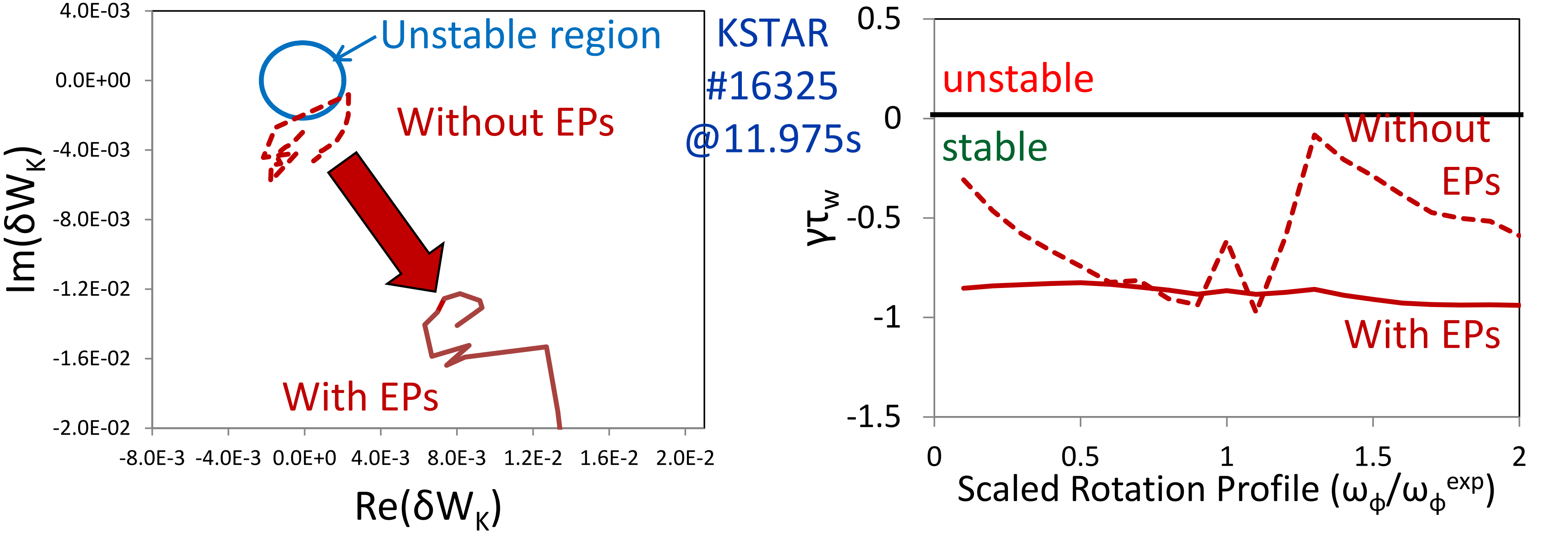




TRANSP analysis of new kinetic KSTAR equilibria gives EP pressure

- KSTAR discharge with high non-inductive fraction, bootstrap current bump, and large energetic particle (EP) fraction
  - Experimental plasma was stable to global MHD modes (RWM), has varying rotating MHD
  - Time point analyzed for global stability was free of MHD activity

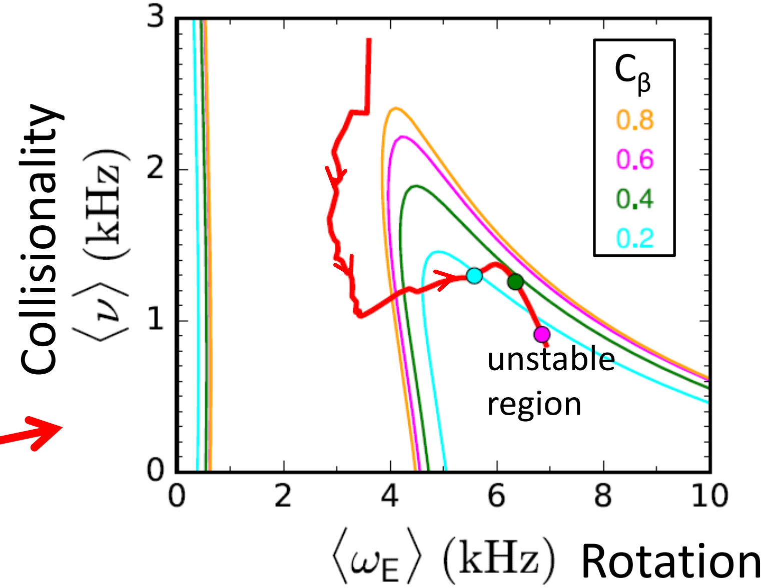
MISK kinetic stability analysis indicates large stabilizing effect of energetic particles



- MISK calculations find the equilibrium is stable to resistive wall modes (consistent with experiment)
  - Close to marginal stability with variation of the experimental rotation profile and without considering energetic particles
  - Energetic particles contribute large stabilizing effect (due to large EP fraction)

Present KSTAR research will now provide input to Disruption Event Characterization And Forecasting (DECAF) code

- DECAF identifies disruption event chains and predicts events in those chains using warning algorithms (including stability models)



  - Global MHD stability models

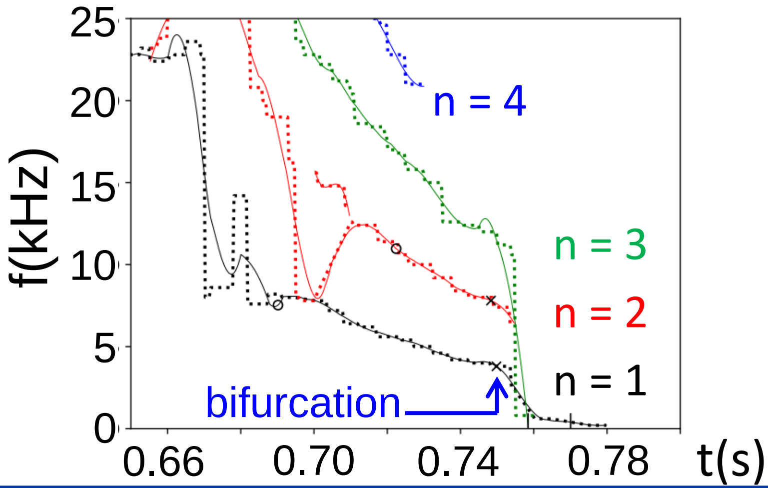
*J.W. Berkery et al., Phys. Plasmas **24** 056103 (2017)*

J.W. Berkery et al., APS DPP 2017, CP11.00093

  - Automated Identification of rotating MHD bifurcation, locking

J.D. Riquezes et al., APS DPP 2017, UP11.00053

  - Prediction of MHD mode onset with resistive DCON



Examination of KSTAR transport and stability supporting disruption prediction and avoidance research has begun

- Interpretive TRANSP analyses show **high non-inductive current fraction** in advanced tokamak KSTAR operation regimes
  - While the **total non-inductive current fraction** is high (**up to 75%** in plasmas examined), the non-inductive profile can vary substantially
- The resultant q profiles in these regimes (verified by kinetic equilibrium reconstruction including MSE) can yield varied stability
  - Interesting flat q shear regions form that may correlate with observed plasma stability, depending on the q level at which they appear
- Continuing analysis provides physics understanding toward attaining stable long pulse, high performance KSTAR operation
  - Aim to optimize stable plasma trajectories to KSTAR design target plasmas
  - Set up predictive TRANSP runs for the 2018 scenarios with 2nd NBI system