Kinetic Equilibrium Reconstruction and Stability Analysis of KSTAR Plasmas Supporting Disruption Event Characterization and Forecasting

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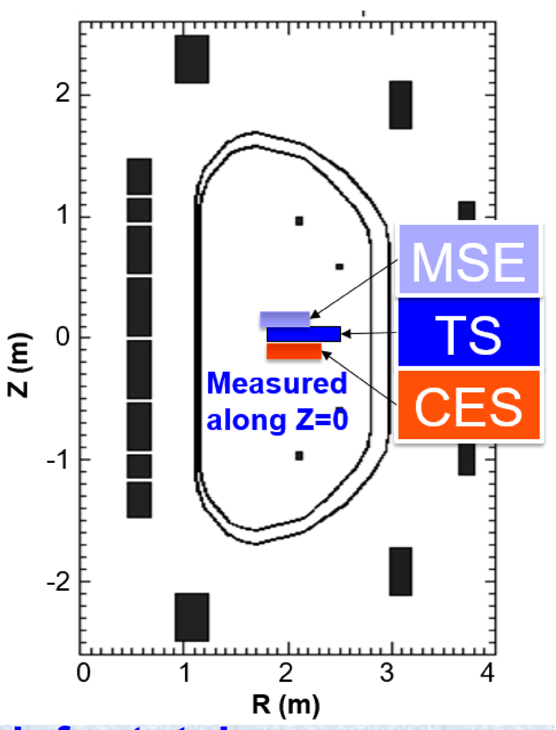
Disruption prediction and avoidance research first requires accurate equilibrium and stability analyses

- Motivation: Disruption prediction and avoidance is
  - Required to sustain long pulse, high performance plasmas
  - Critical for ITER and next-step tokamaks
- Outline
  - Kinetic equilibrium reconstruction approach, results, implications
    - Kinetic equilibrium provide greater profile details than magnetics-only cases
    - MSE data indicates regions of weak / strong shear
  - Validation with CCD images, IRTV, and MHD activities
    - Reverse shear in center correlated with increased β_n and MHD activity
  - Ideal and resistive stability analysis
    - Stability calculation shows sensitivities to pressure profile and q profile
  - Summary / next steps

Kinetic equilibrium reconstruction

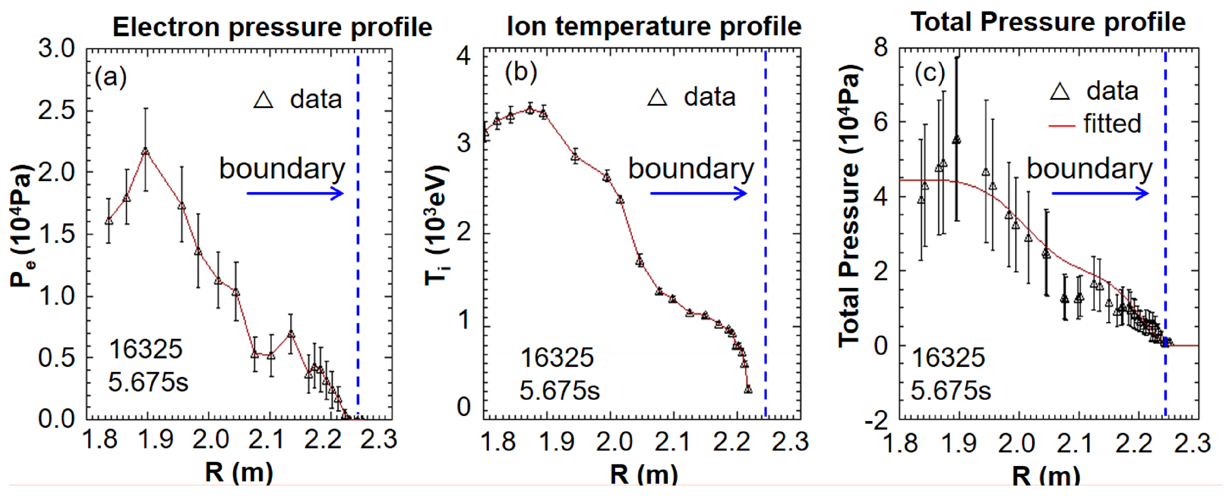
Kinetic data supplements magnetics input for KSTAR kinetic equilibrium reconstructions

- Motional Stark Effect (MSE)
  - MSE (up to 25 channels) measuring plasma magnetic field pitch angle
- Thomson scattering (TS)
  - TS 27 channels
  - Electron density & temperature (N_e, T_e)
- Charge exchange spectroscopy (CES)
  - CES 32 channels
  - Ion Temperature (T_i)



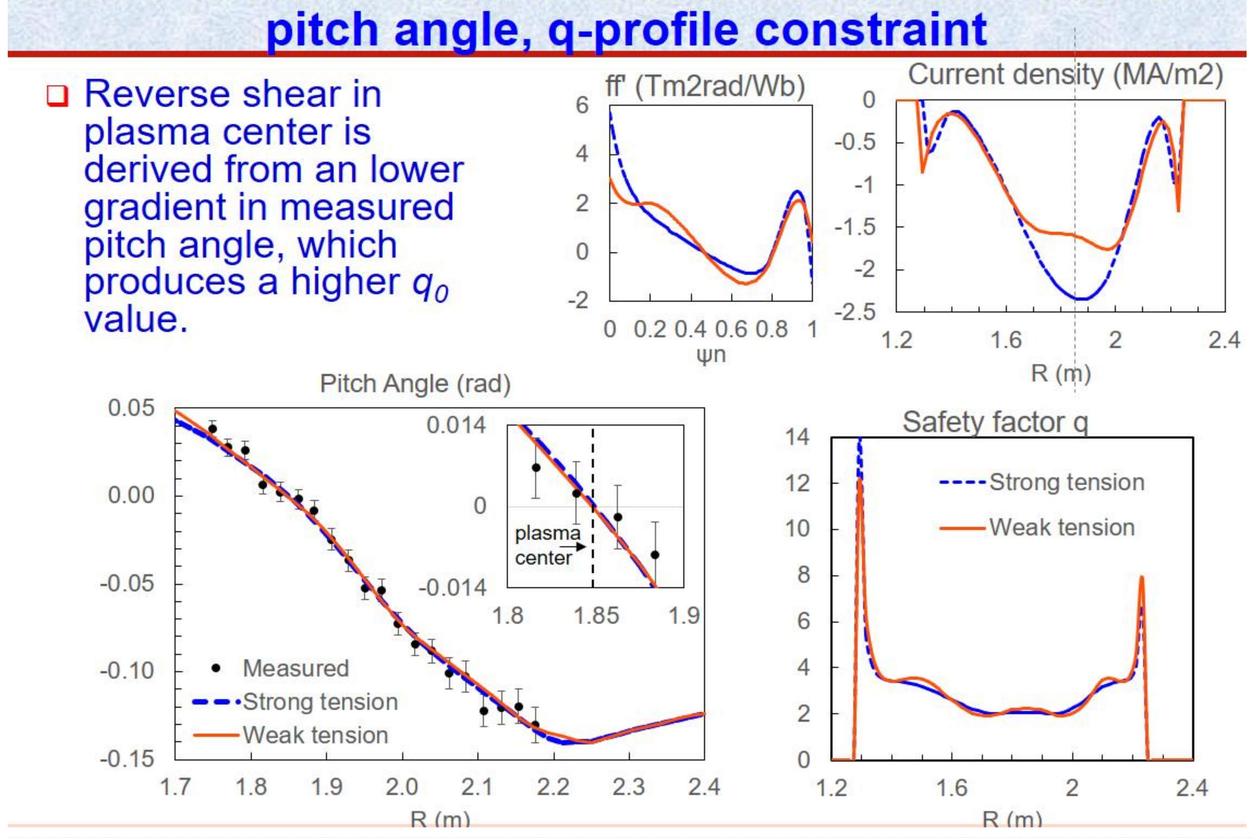
"Partial kinetic" approach for total pressure allows greater flexibility in profile shape

- Electron Pressure $P_e \leftarrow$ 27 Thomson scattering (T_e & N_e), systematic error
- Ion Pressure $P_i \leftarrow$ 32 CES (T_i & N_i estimated from N_e, and estimated Zeff)
- Fast particle pressure P_{fast} "based" on P_e with 100% error bar
- Total pressure $P_{tot} = P_e$ + "P_i" + "P_{fast}" with large total error

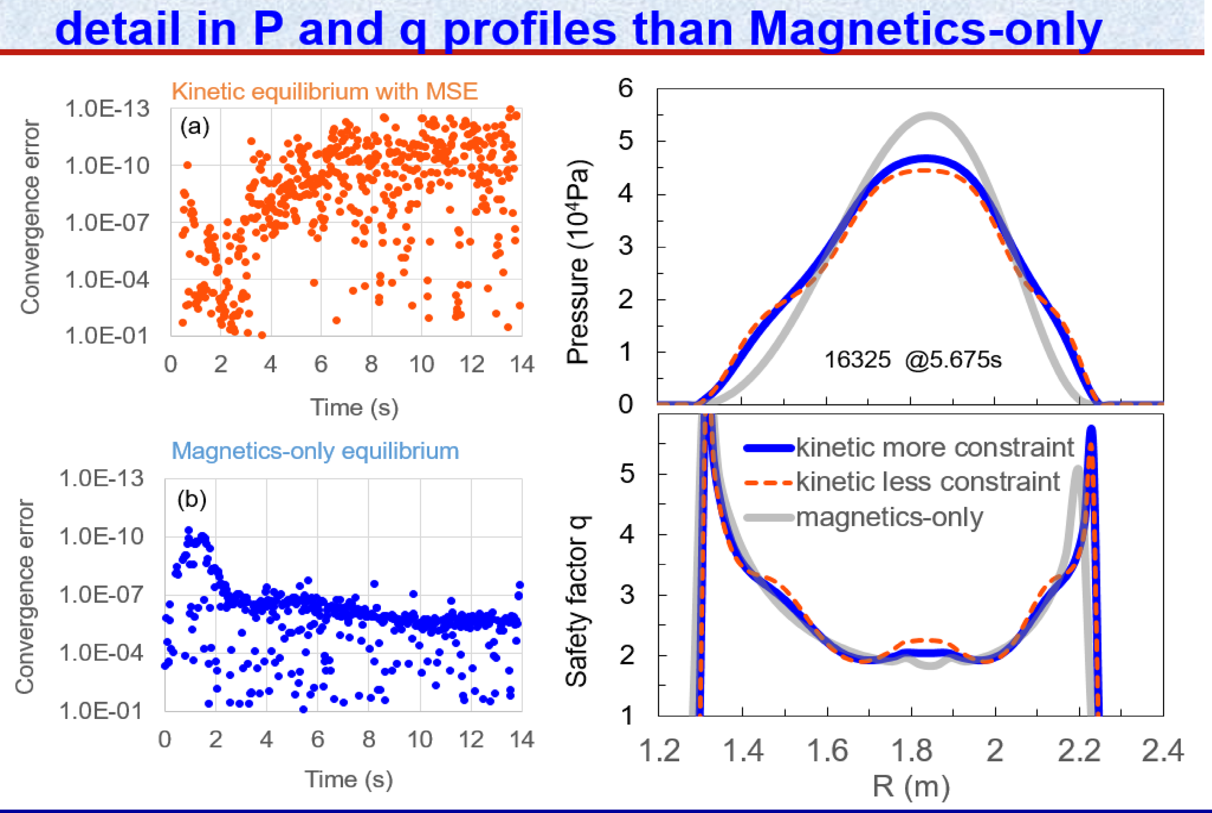


Motional Stark effect (MSE) data provides magnetic pitch angle, q-profile constraint

- Reverse shear in plasma center is derived from an lower gradient in measured pitch angle, which produces a higher q_0 value.



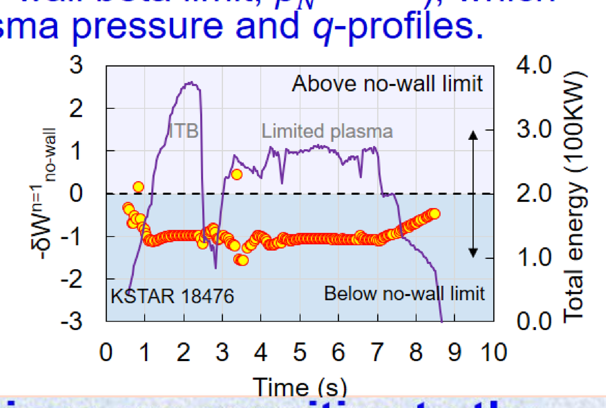
Kinetic equilibrium with MSE produces greater detail in P and q profiles than Magnetics-only



Ideal and resistive stability analysis

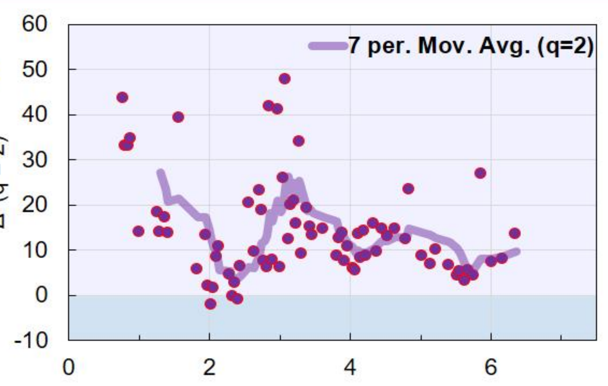
Robust δW evaluation with the reconstructed plasma based on kinetic equilibrium

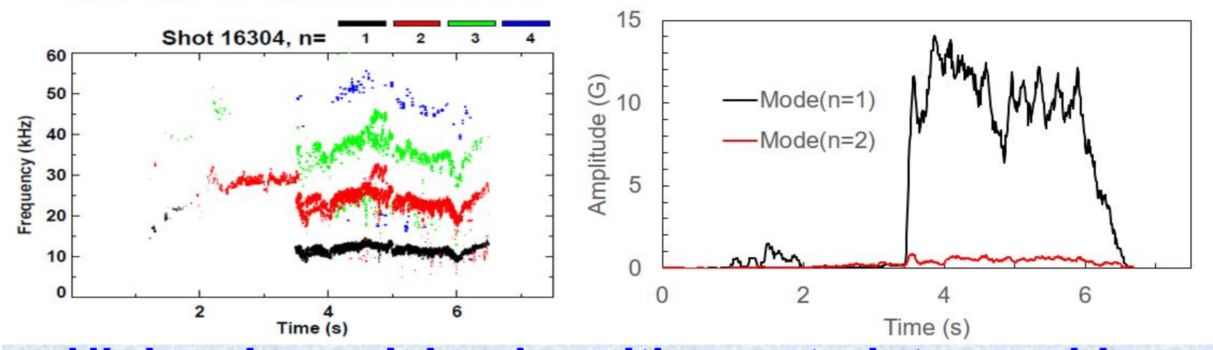
- Present work examines the ability to produce reliable time evolution of stability calculations using experimental data.
- Calculations of global MHD stability limits, such as for toroidal n = 1 kink modes and resistive wall modes (RWM), are needed for disruption characterization and prediction.
- Kinetic equilibria with MSE enable reliable calculation of the global mode stability (e.g. no-wall beta limit, $\beta_N^{no-wall}$), which depends strongly on the plasma pressure and q-profiles.
- Ideal DCON stability calculation of the change in plasma potential energy, δW, can determine whether plasmas are above or below the ideal no-wall beta limit.



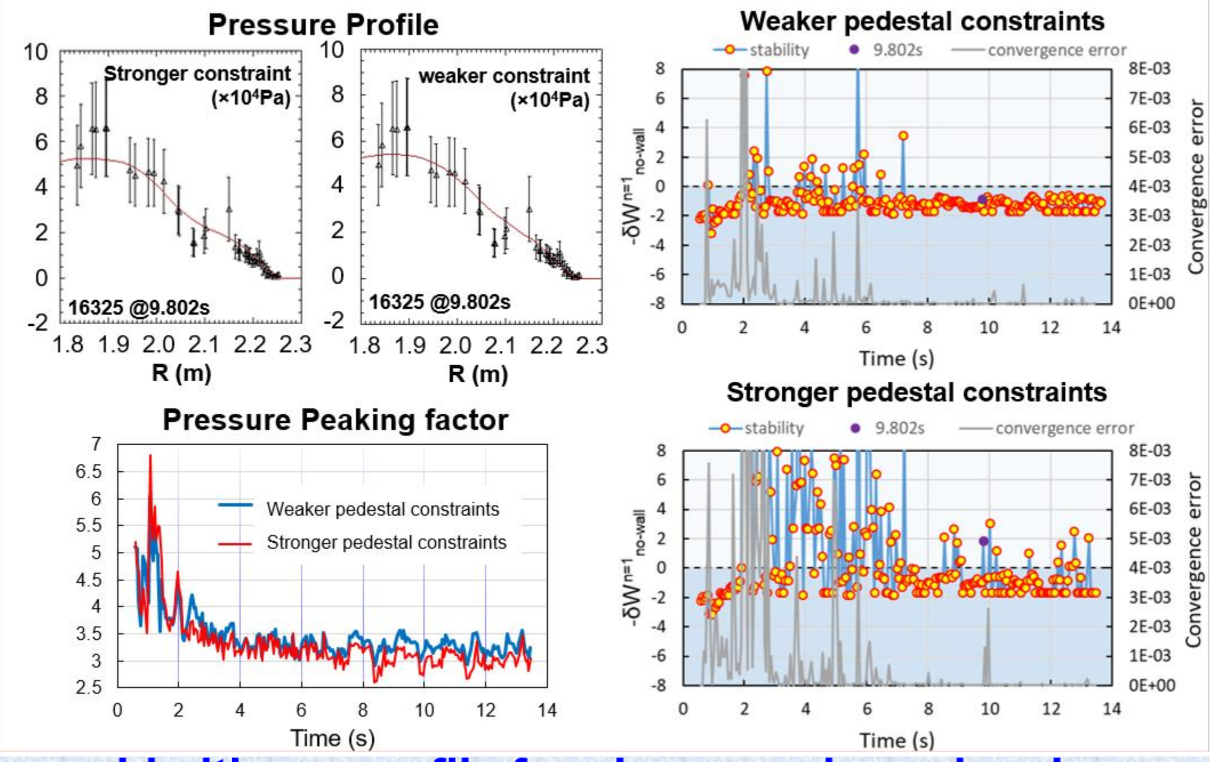
Δ'$_{q=2}$ increase consistent with observed MHD

- Resistive DCON code provides an evaluation of the classical resistive stability index, Δ', for KSTAR
- Computed Δ'$_{q=2}$ stays above the classical resistive stability limit from 1-2s, drops below the limit at 2s, and then increase to 3.4s.

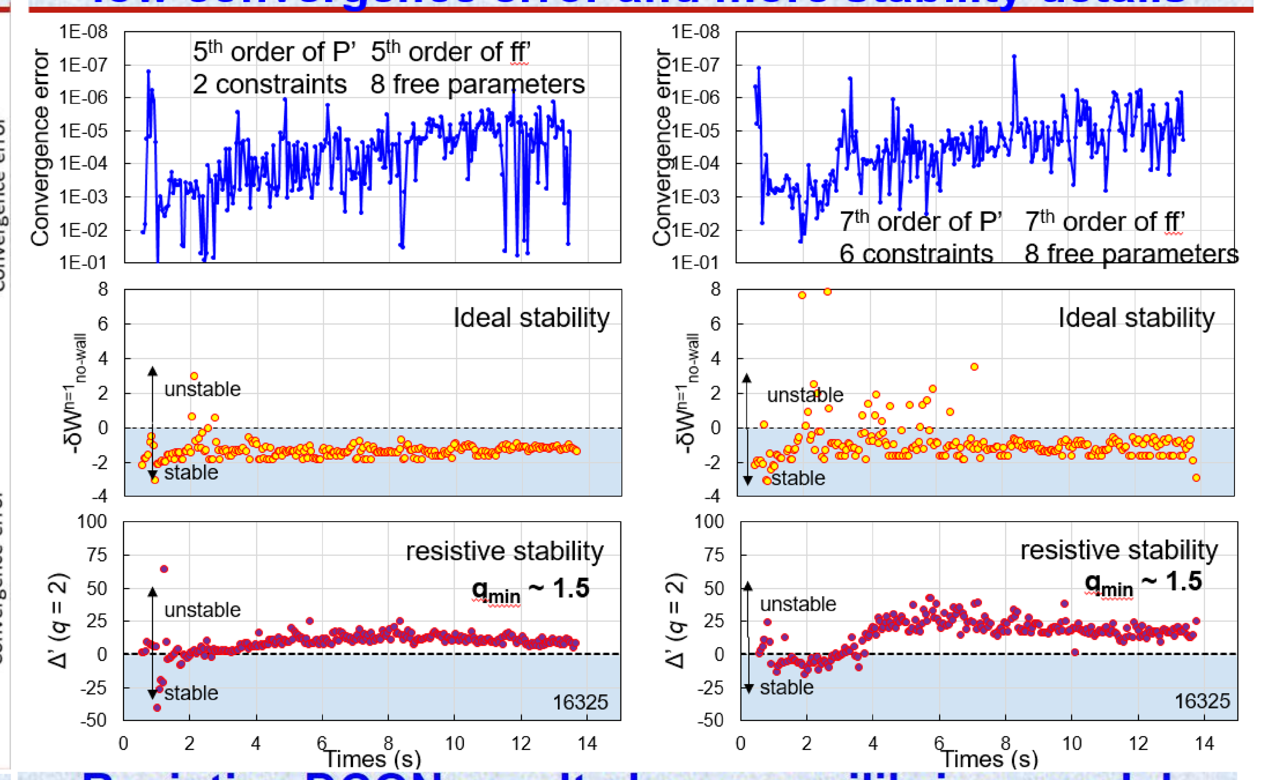




Ideal stability calculations are sensitive to the equilibrium quality and pressure profile

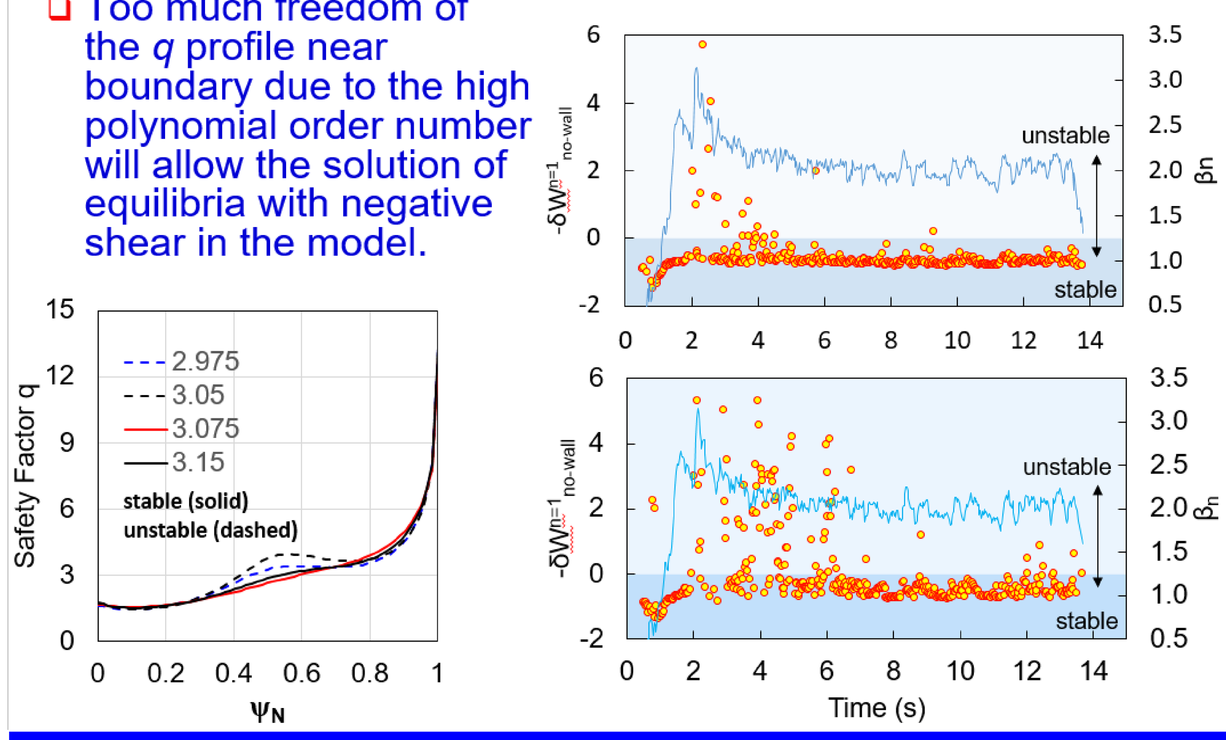


High polynomial order with constraints provides low convergence error and more stability details



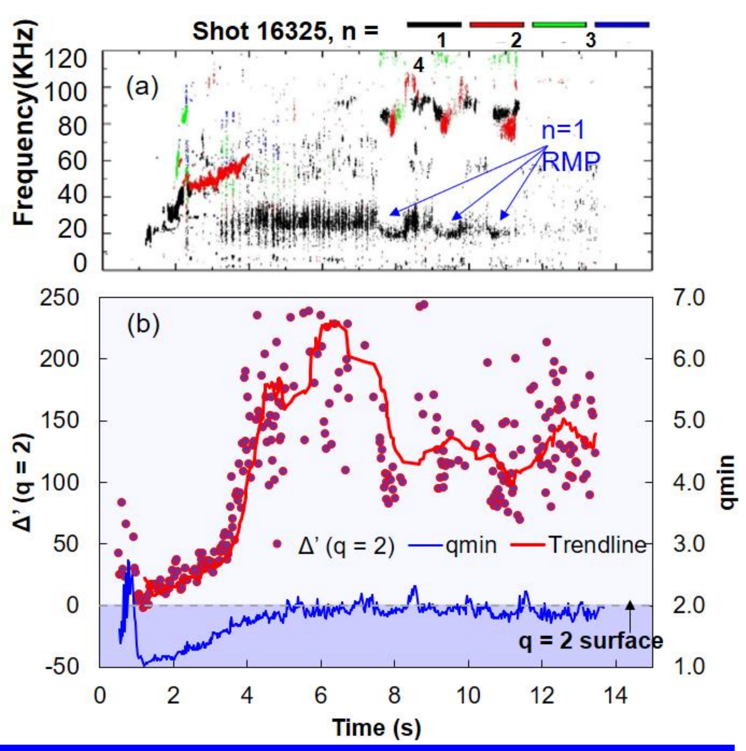
Limiting q profile freedom near boundary in equilibrium model to reduce the δW evaluation noise

- Too much freedom of the q profile near boundary due to the high polynomial order number will allow the solution of equilibria with negative shear in the model.



Resistive DCON result shows equilibrium model with lowest error produces similar Δ' evolution

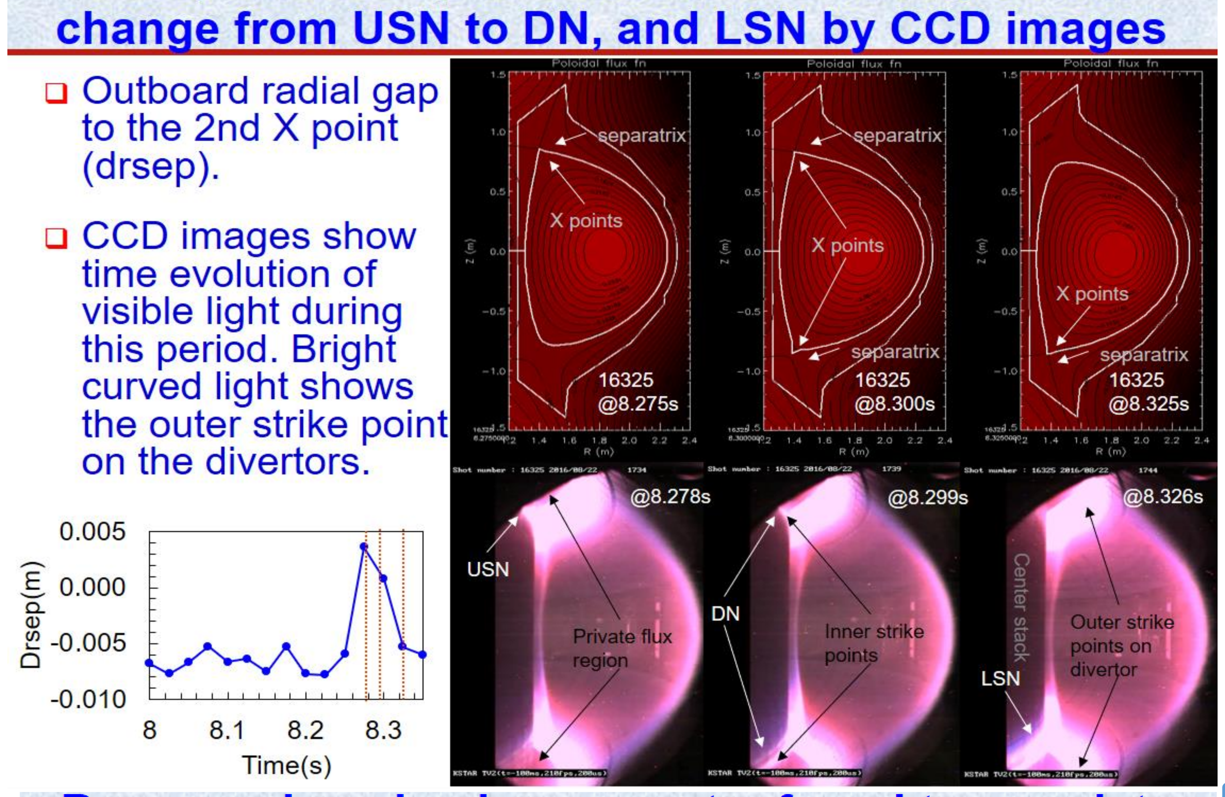
- When the qmin is larger than 2, there is no q = 2 surface,
- Computation of the resistive Δ'$_{q=2}$ outputs values of increasing variation when q_{min} is close to 2 flux surfaces.
- Trendlines (20 pt. moving average) are taken from the results with q_{min} <1.9 to eliminate the influence from the numerical large variation.



Validation by CCD, IRTV and MHD activities

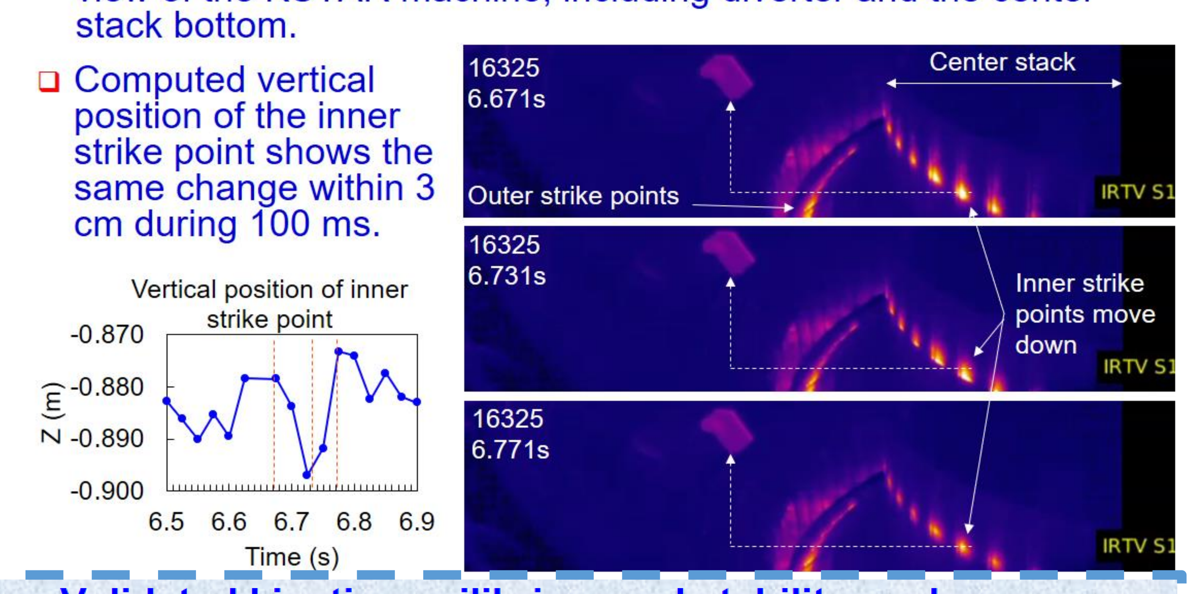
Computed drsep consistent with configuration change from USN to DN, and LSN by CCD images

- Outboard radial gap to the 2nd X point (drsep).
- CCD images show time evolution of visible light during this period. Bright curved light shows the outer strike point on the divertors.



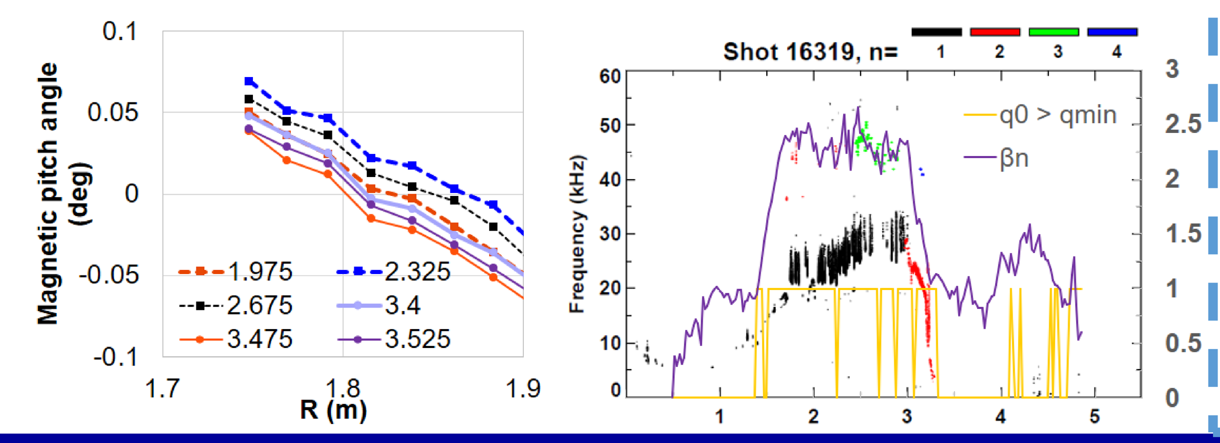
IRTV video shows a clear inner strike point shift consistent with kinetic equilibrium result

- Subsequent IRTV photos illustrate inner strike points on the center stack moving down first, and then moving up. Bright points in the pictures show higher temperatures on lower inside view of the KSTAR machine, including diverter and the center stack bottom.
- Computed vertical position of the inner strike point shows the same change within 3 cm during 100 ms.



Reverse shear in plasma center found to correlate with high β_n and MHD activity for KSTAR discharge

- Lower gradient in pitch angle (square) goes across the 0 deg axis produces reversed shear in the plasma center.
- The kinetic equilibrium shows the reverse shear in plasma center at several time windows (yellow line)
- High β_n (>1) and n = 1 and n = 2 MHD activities with 20-30 KHz frequency are detected during reverse shear window.



Validated kinetic equilibrium and stability analyses are improved for disruption prediction and avoidance research

- Kinetic equilibrium reconstruction with MSE
  - Polynomial and spline basis functions for toroidal current density are studies with KSTAR high performance plasmas.
  - Reversed shear in plasma center correlated with high β_N and MHD activity is needed further work.
- Ideal, and resistive stability analyses
  - Ideal δW and linear Δ' are evaluated with low noise by using present kinetic equilibrium with MSE.
  - Improved equilibria with best convergence error level enables ideal and resistive stability analysis with a determination of result sensitivity.
- Key input for disruption prediction and avoidance research
  - Provides reliable and physics validated equilibrium and stability input for DECAF analysis