Kinetic equilibrium reconstruction of KSTAR plasmas including internal pitch angle profile measurement

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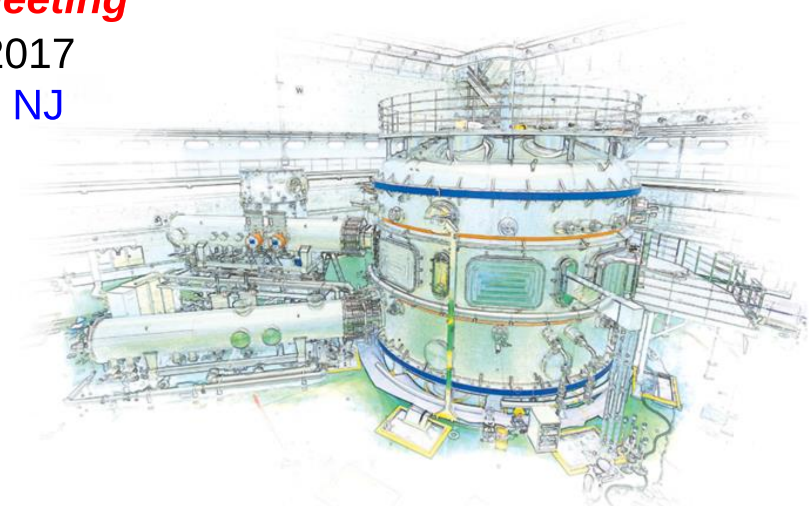
NSTX-U Physics Meeting
November 29th, 2017
PPPL, Princeton, NJ



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National Fusion Research Institute
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Supported by US DOE grant DE-SC0016614

Kinetic equilibrium reconstruction of KSTAR plasmas including internal pitch angle profile has begun

- Motivation

  Requirement for accurate stability analysis and disruption prediction to support continuous operation of high beta KSTAR tokamak plasmas

- Goals

  - Built accurate kinetic equilibrium reconstruction of KSTAR plasmas
  - Provided input for initial plasma stability evaluation[1] and disruption event characterization and forecasting (DECAF)[2]

[1] Y.S. Park, S.A. Sabbagh, J.W. Berkery, et al., Nucl. Fusion **51** (2011) 053001

[2] S.A. Sabbagh, A.C. Sontag, J.M . Bialek, et al., Nucl. Fusion 46 (2006) 635.

Outline

1. Overview of kinetic equilibrium reconstruction
2. KSTAR diagnostics and model for kinetic equilibrium reconstructions
3. Reconstructed profiles and plasma parameters in various KSTAR operation regimes
4. Initial determination of ideal MHD stability
5. Collaborative improvement of equilibrium diagnostics

Kinetic equilibrium reconstruction approach methodically improves accuracy

- Philosophy

  Use best model

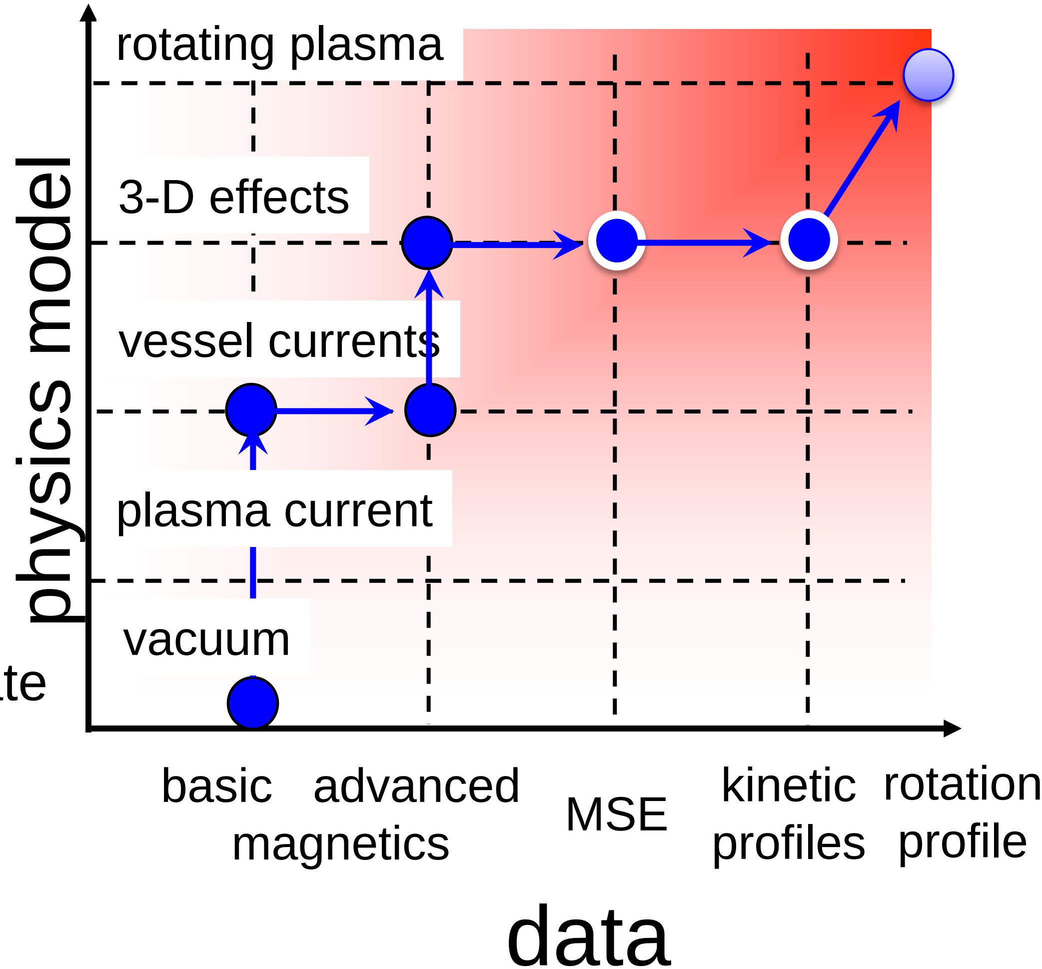
  - for a given physics model/data set, reliably fit all data within error
  - improved model/data set reduces artificial constraint

  Provide rapid reconstruction

  - between-shots capability
  - find constraint set for a given (model/data) pair

  Progress to create more accurate equilibria

  - more complete physics
  - more complete data
  - less artificial constraints
  - suitable for stability calculations



Y.S. Park, et al., Nucl. Fus. **51** (2011) 053001

EFIT* provides a flexible equilibrium reconstruction

- Solve for (1) poloidal flux, ψ, and (2) toroidal current, J_t
  - that satisfy the GS equation: $\Delta^*\psi = -\mu_0 R J_t(\psi)$, where

    $\Delta^*\psi = R^2\nabla\bullet(\nabla\psi/R^2)$; $J_t = Rp'(\psi) + \mu_0 ff'(\psi)/(4\pi^2 R)$; $f(\psi) = RB_t$; $' \equiv \partial/\partial\psi$
  - that provide a least-squares fit to a set of constraints
- Typical constraints for fit
  - Diagnostic data - response from plasma and external coils
    - magnetic (flux loops, I_p, coils, diamagnetic loop, stabilizing plates)
    - P_e from Thomson scattering
    - T_i , V_ϕ from charge exchange recomb. spectroscopy (CES)
    - field pitch angle from motional Stark effect data (MSE)

*L. Lao, et al., Nucl. Fusion **25** (1985) 1611
S. Sabbagh, et al, Nucl. Fusion **41** (2001) 1601

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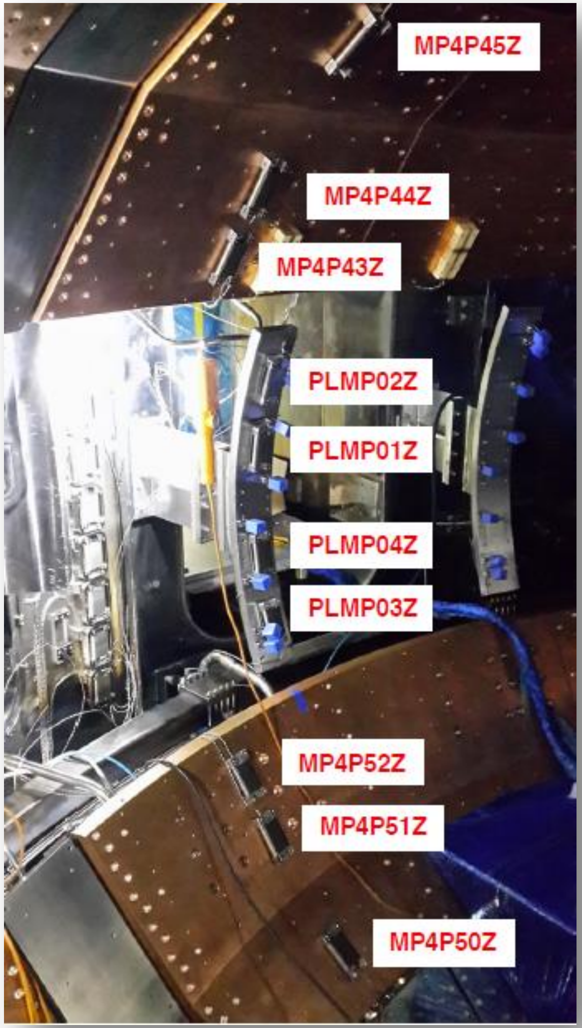
KSTAR magnetic diagnostics provide constraints for equilibrium reconstruction (1)

- KSTAR magnetics
  - Flux loops (45)
  - Magnetic probe(105)
  - Plasma currents(1)
  - Coil currents(18)
  - Voltage loops(5)
  - Vessel current group (12)

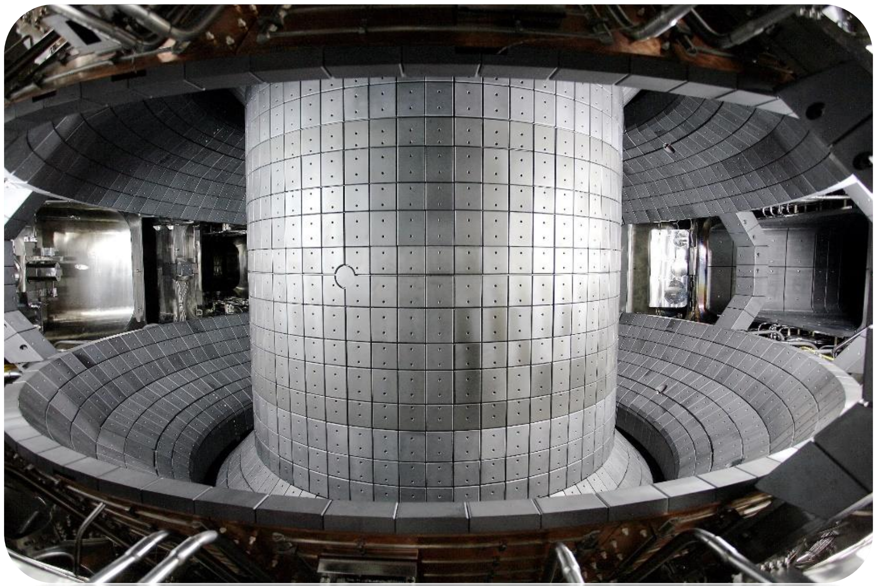


S.A. Sabbagh, et al., Nucl. Fus. **41** (2001) 1601

Y.S. Park, et al., Nucl. Fus. **51** (2011) 053001

KSTAR magnetic diagnostics provide constraints for equilibrium reconstruction (2)

Interior of KSTAR vessel



- **Copper passive plates**
- **In-vessel control coils(IVCC)**

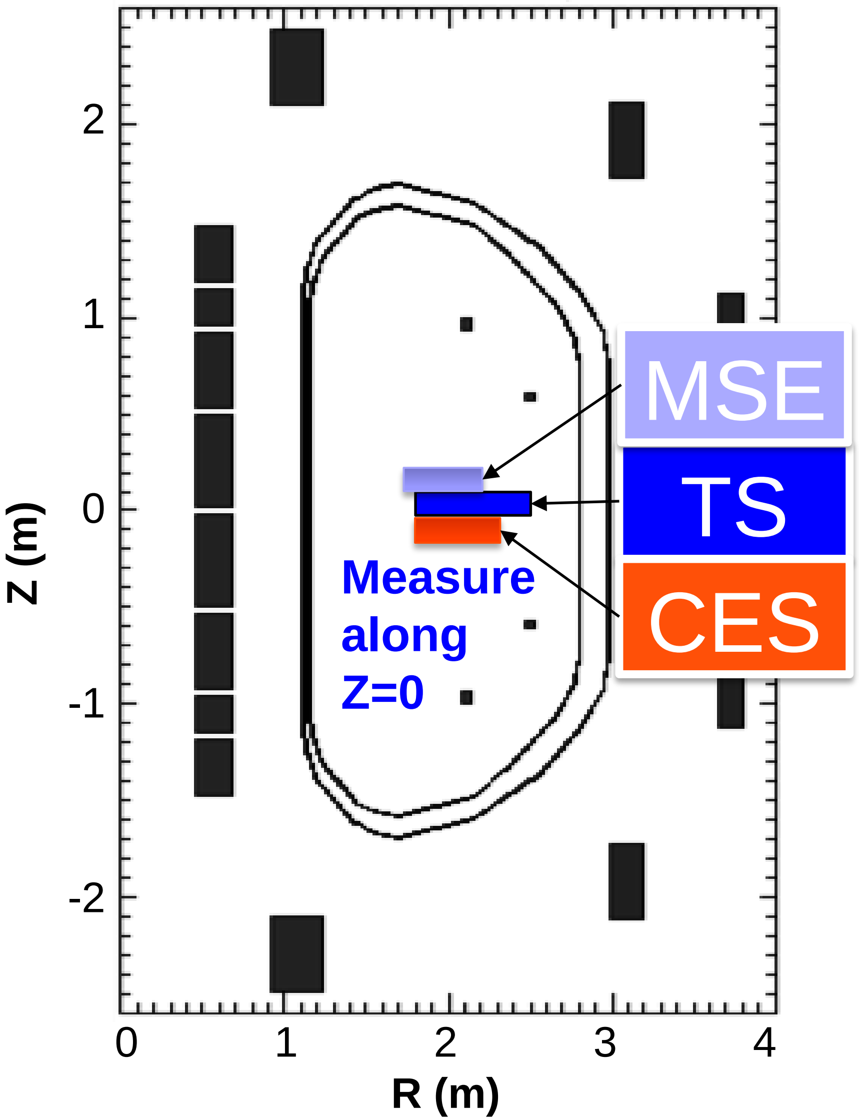
S.A. Sabbagh, et al., Nucl. Fus. **41** (2001) 1601

Y.S. Park, et al., Nucl. Fus. **51** (2011) 053001

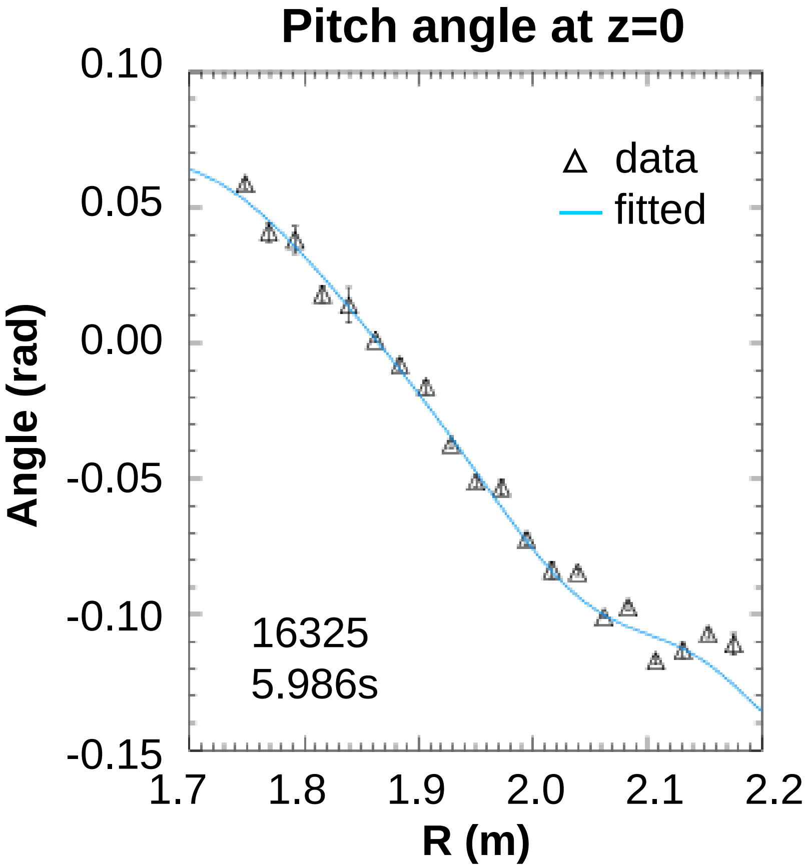
- Vessel currents required
  - Total vessel currents and plasma current
  - Vessel / plates broken into 12 groups (poloidally)
  - Wall currents determined by local loop voltage data (5 loops)
  - Vessel element resistances matched against independent model of vacuum field shots
- Stabilizing plates / divertor plates currents are modelled

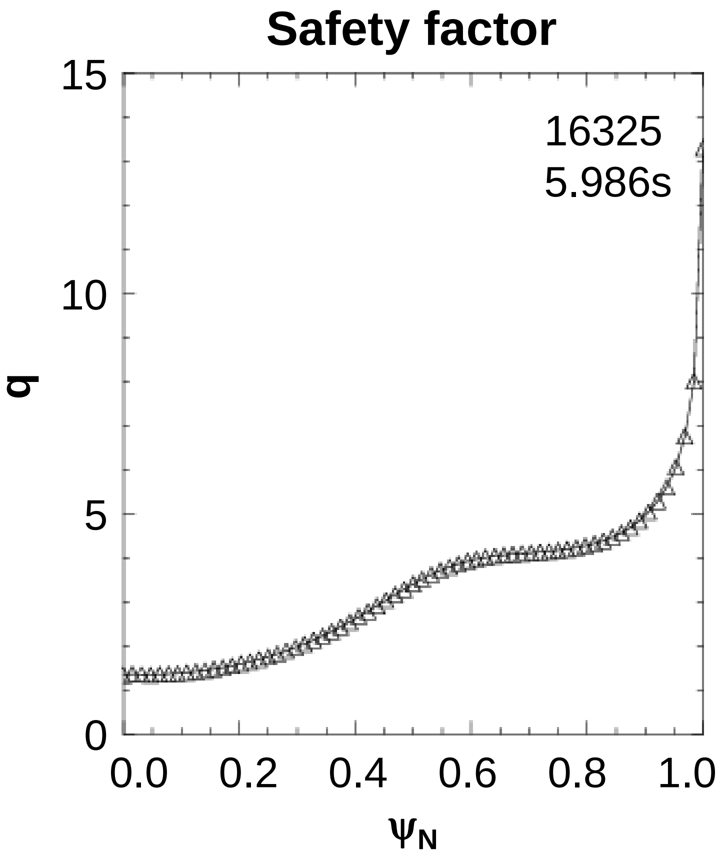
Kinetic data supplements magnetics input for KSTAR kinetic equilibrium reconstructions

- Motional Stark Effect (MSE)
  - MSE 25 channels
  - Plasma magnetic field pitch angle
- Thomson scattering (TS)
  - TS 27 channels
  - Electron Dens. & Temp.(N_e, T_e)
- Charge exchange spectroscopy (CES)
  - CES 32 channels
  - Ion Temp. (T_i)



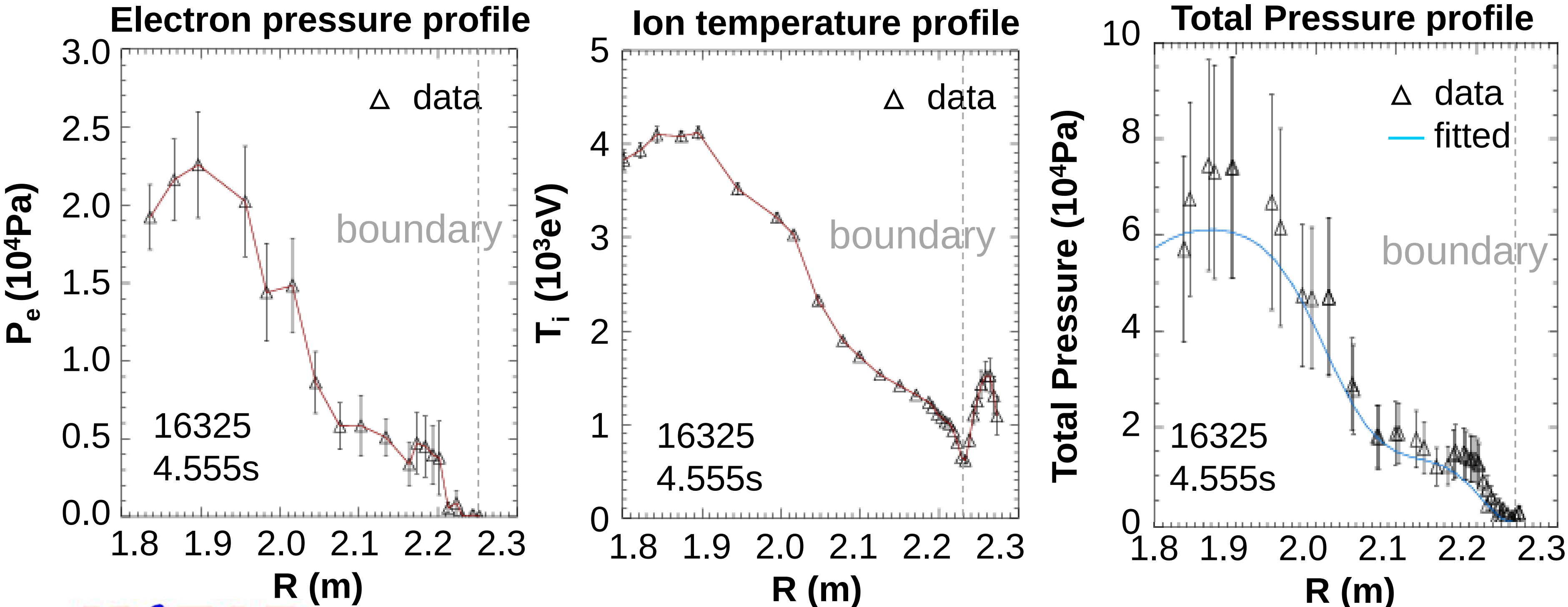
Motional stark effect data provides constraint to improve accuracy of q-profile



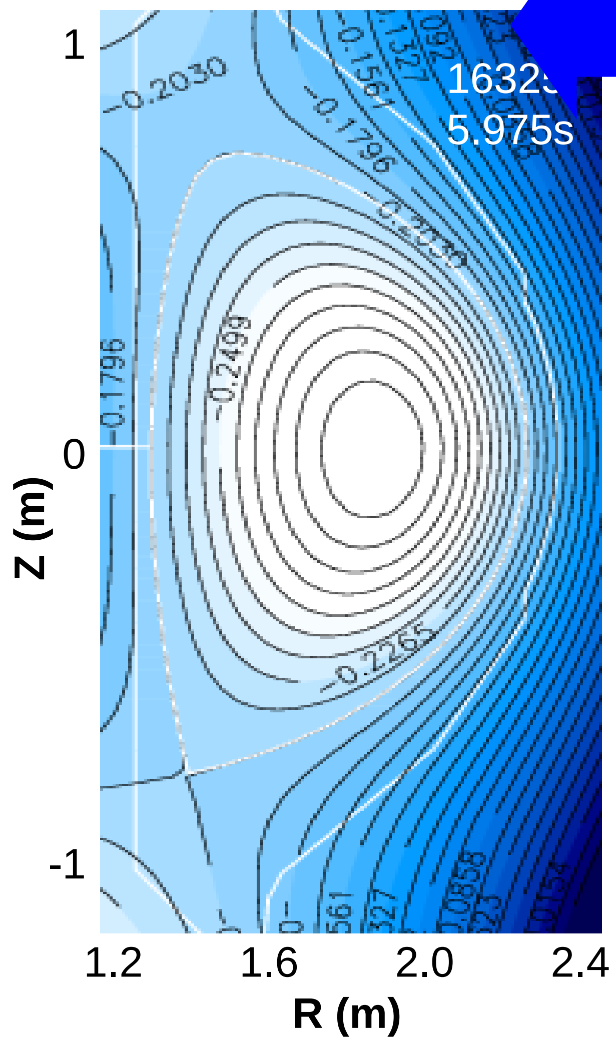


"Partial kinetic" approach for total pressure to allow greater flexibility in profile shape

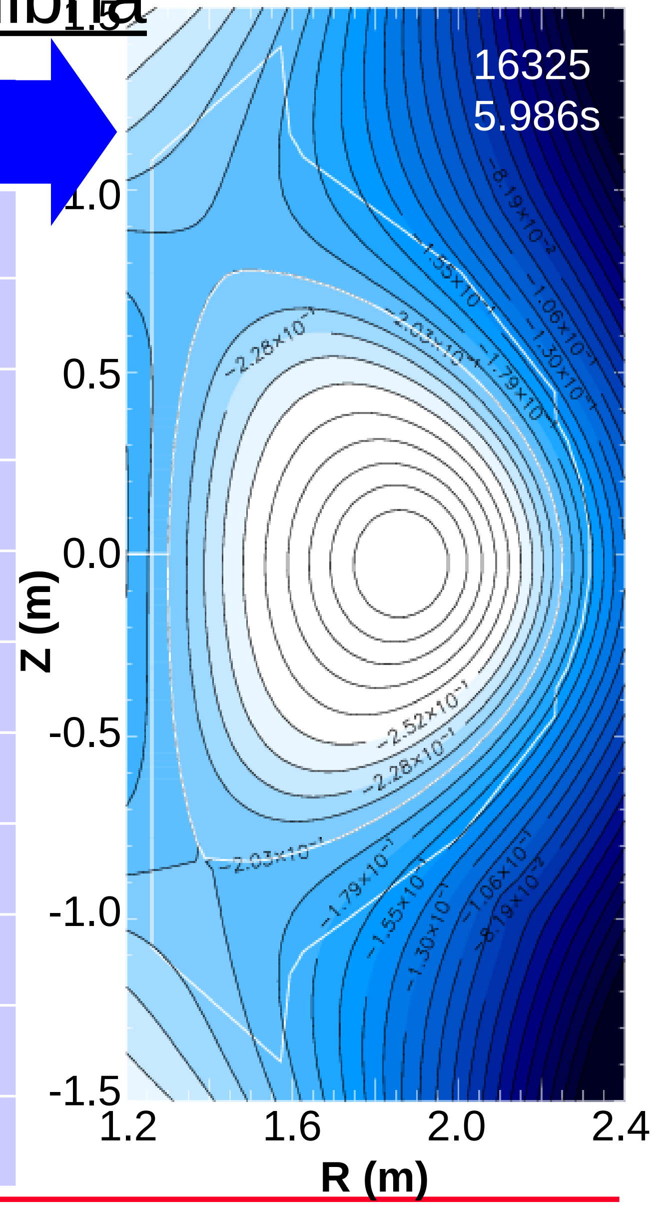
- Electron Pressure $P_e \leftarrow$ 27 Thomson scattering (T_e & N_e)
- Ion Pressure $P_i \leftarrow$ 32 CES (T_i & N_i estimated from N_e)
- Fast particle pressure P_{fast} is based on P_e with 100% error bar
- Total pressure $P_{tot} = P_e$ + "P_i" + "P_{fast}" with large total error



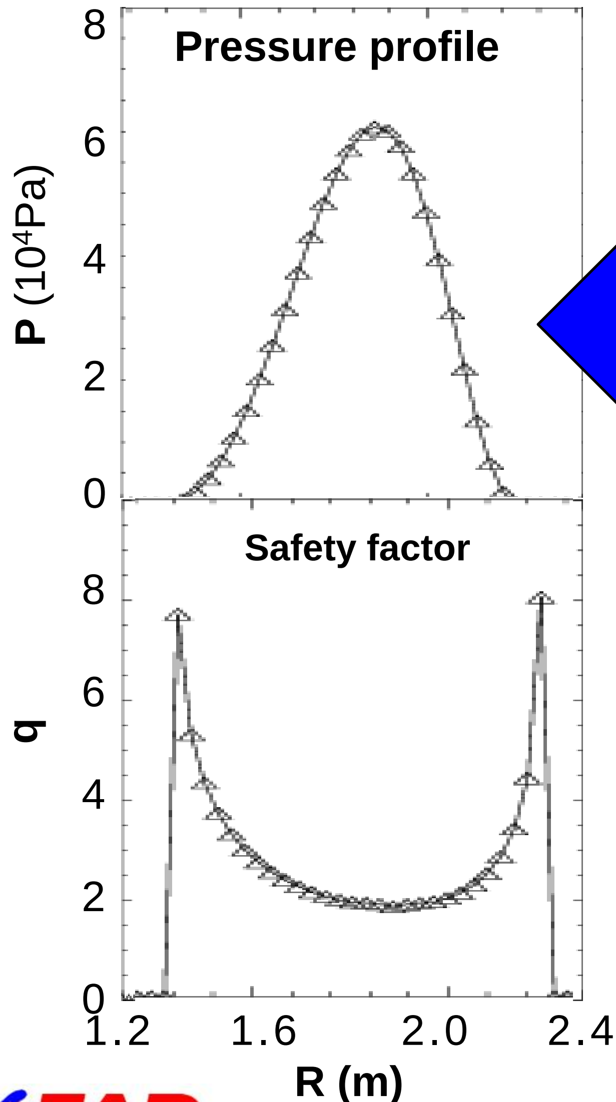
Kinetic equilibria has similar global parameters to magnetic-only equilibria



Magnetic only	Global Para.	Kinetic +MSE
223.9	χ^2	202.4
1.87	R_{axis}(m)	1.861
-0.026	Z_{axis}(m)	-0.07
1.704	elong	1.682
0.578	δ_u	0.540
0.578	δ_L	0.801
1.066	β_T	0.854
1.948	β_p	1.855
2.054	β_n	1.925
0.914	li	1.045
5.95	q_{95}	6.39



Kinetic equilibrium reconstruction with MSE produces substantial detail in P and q profiles

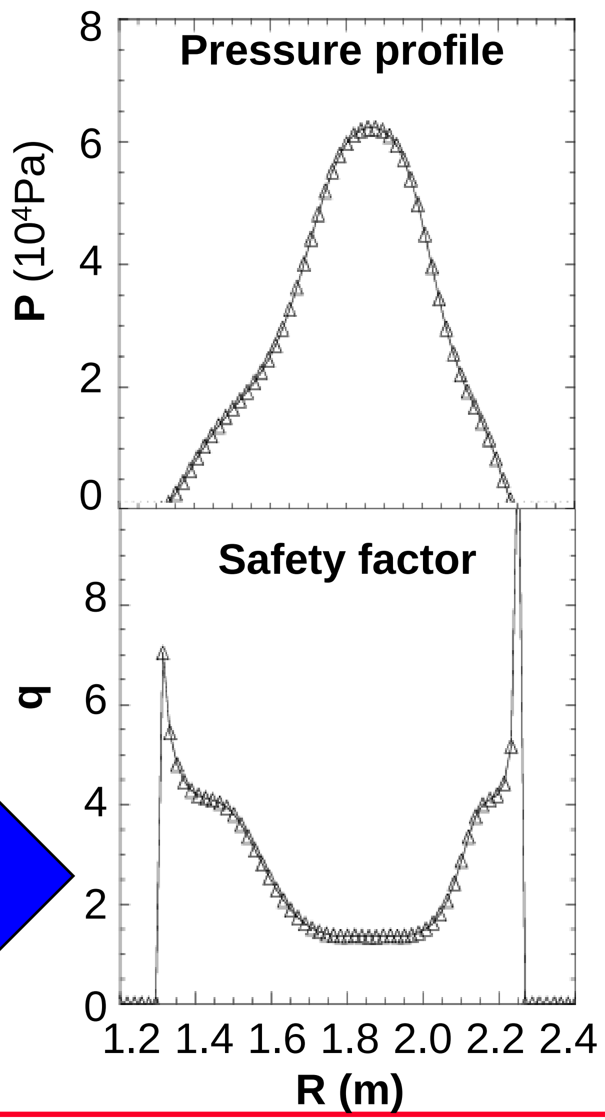


Magnetic only

16325 5.975s

16325 5.986s

Kinetic + MSE



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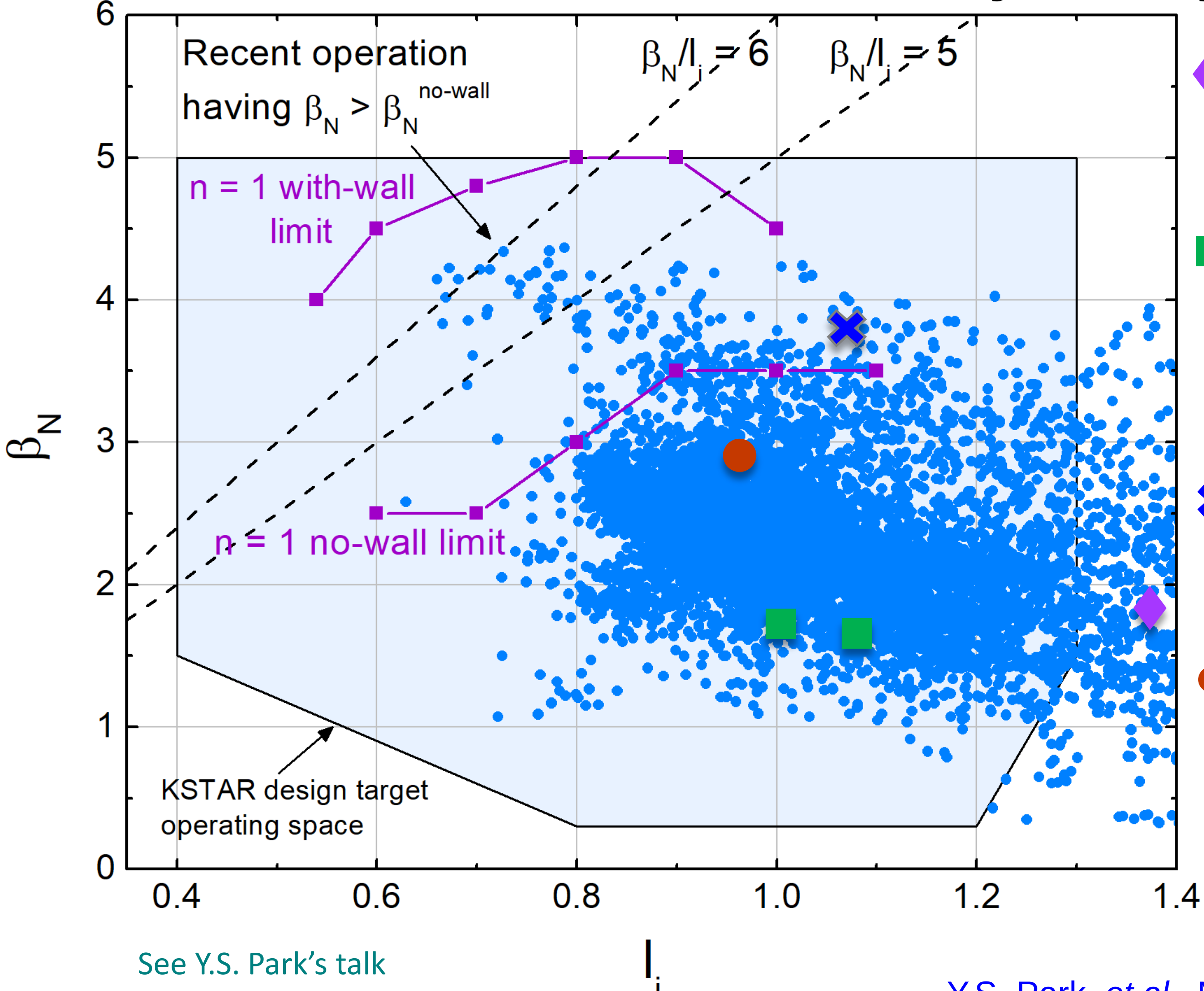
Initial kinetic equilibrium w/ MSE are required for accurate stability analysis



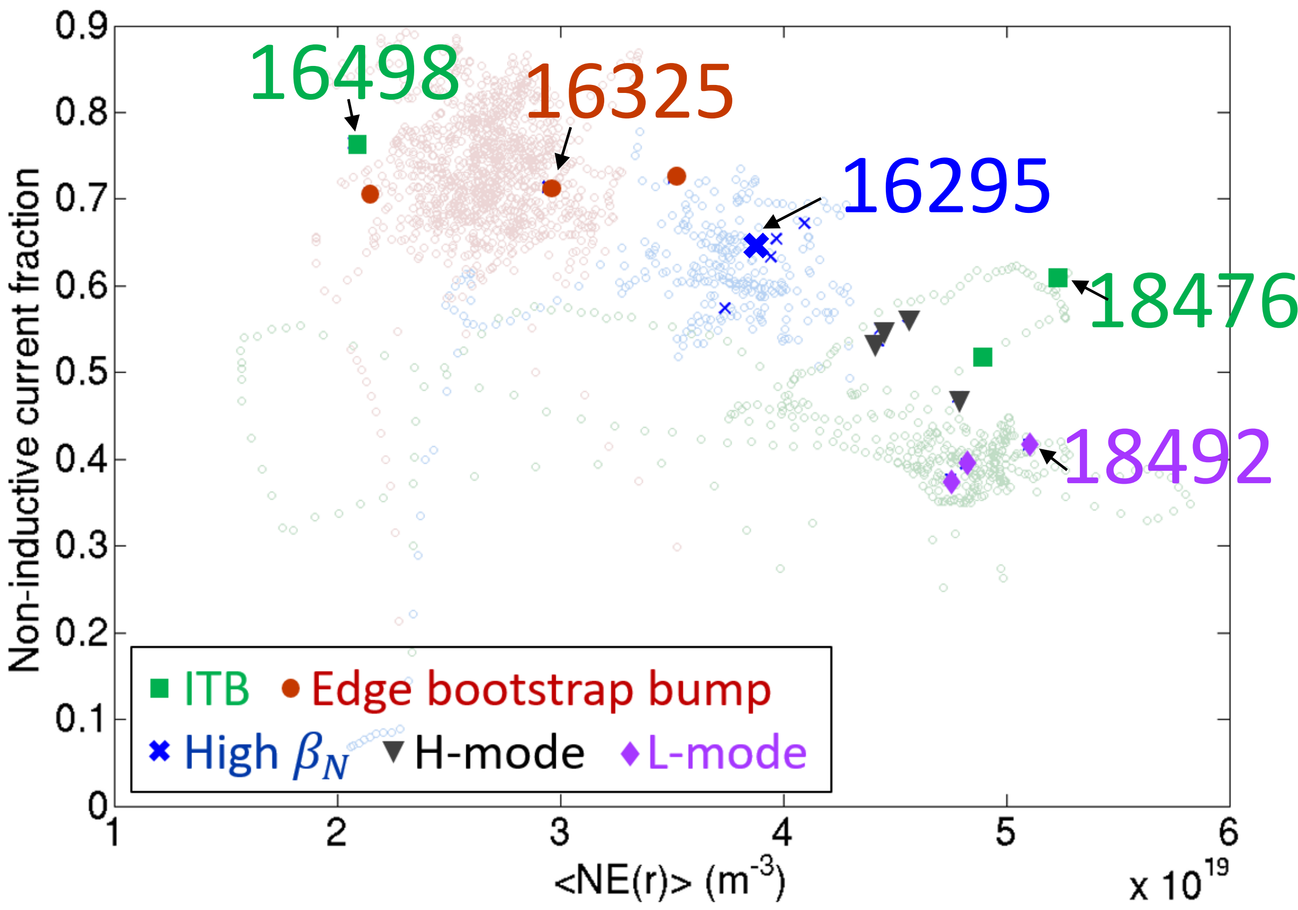
- 18492
  - L-mode
- 18476 & 16498
  - Internal Transport Barrier **(ITB)**
- 16295
  - High $\boldsymbol{\beta_n}$ mode
- 16325
  - High $\boldsymbol{\beta_p}$ mode
  - Edge bootstrap bump

See Y.S. Park's talk

Y.S. Park, *et al.*, Nucl. Fusion **53** (2013) 083029

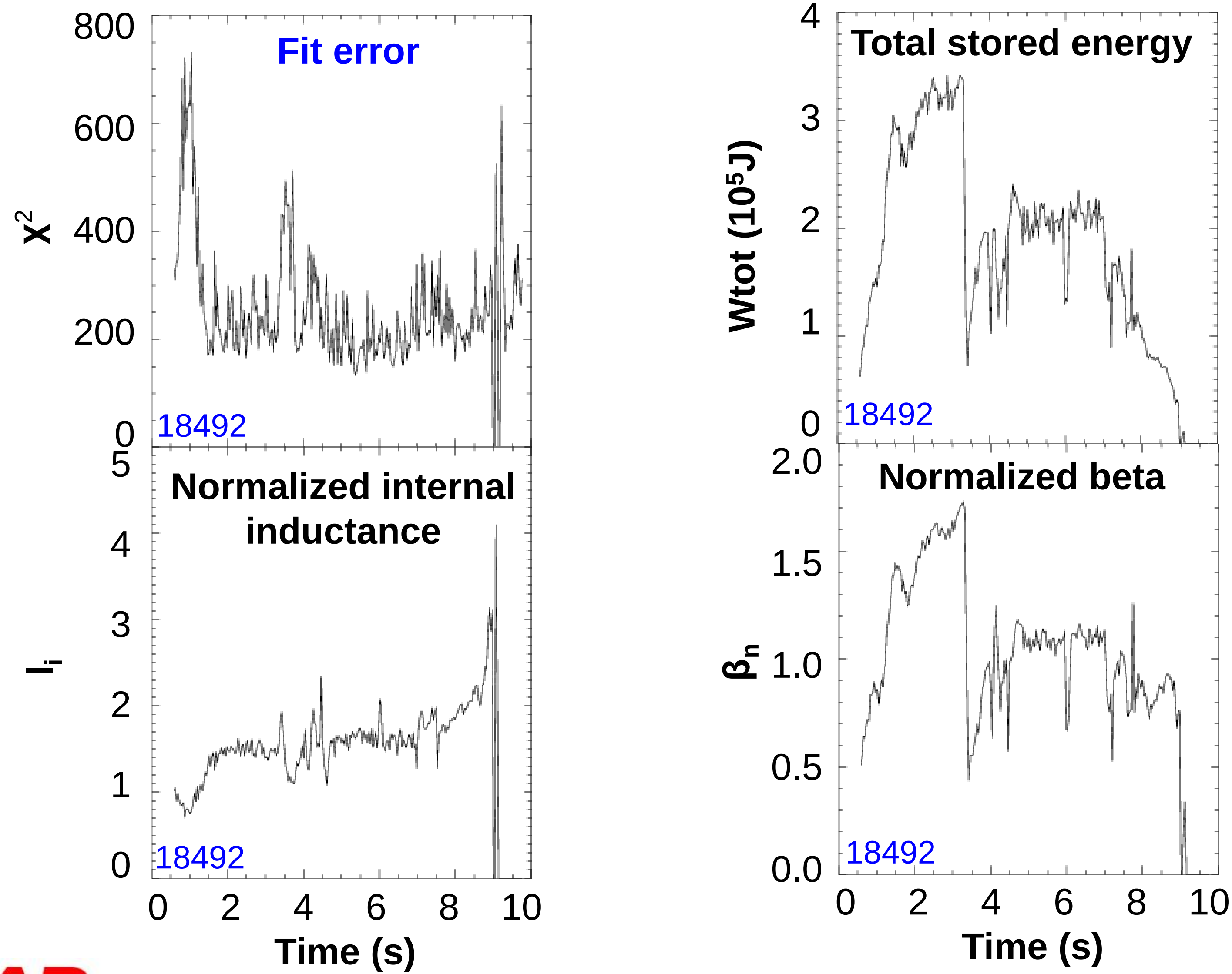
Kinetic reconstructions were performed on plasmas with high-non-inductive fraction

- Non-inductive fraction :
  - Beam-driven
  - Bootstrap
- Non-inductive fraction is very important for stable high beta steady state operation

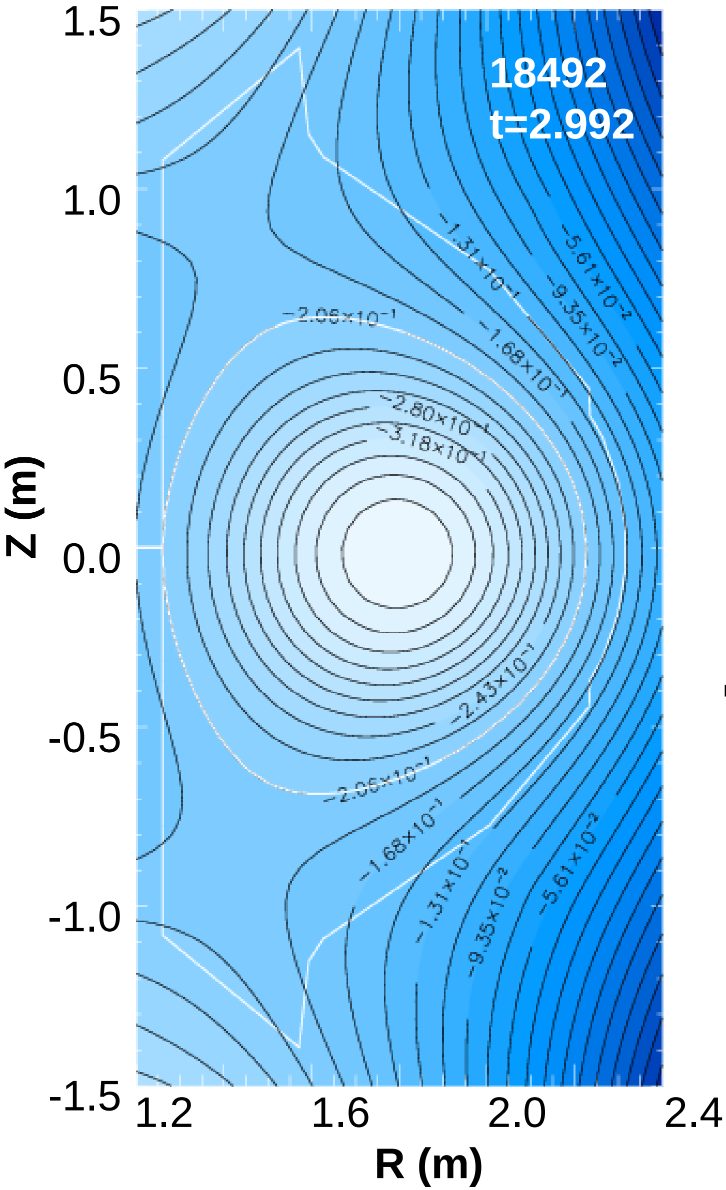


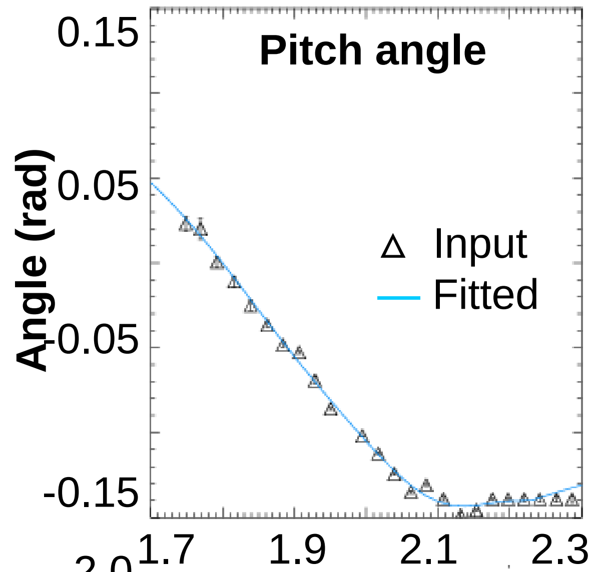
See J.H. Ahn's talk

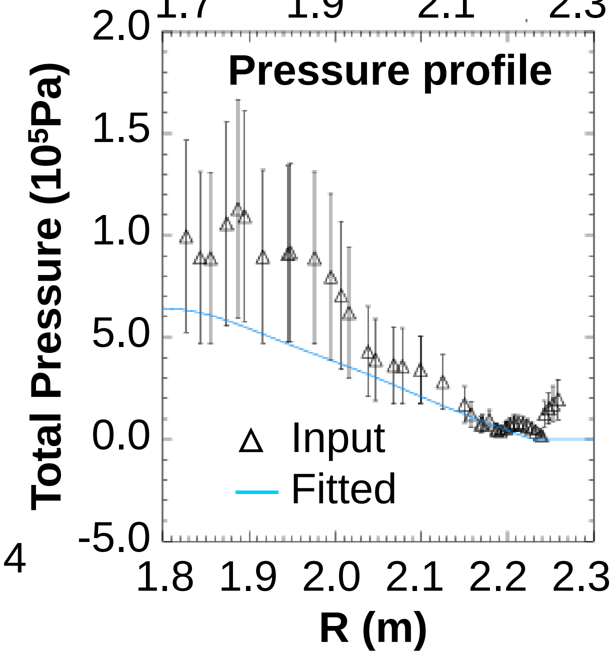
Good convergence in KSTAR kinetic equilibrium reconstruction for L-mode



High consistency with field pitch angle





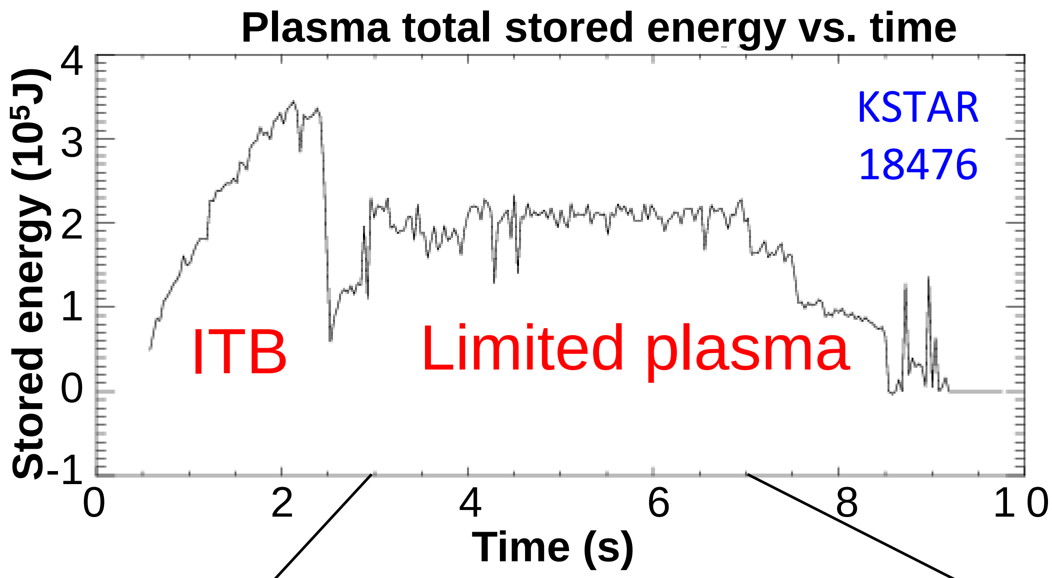


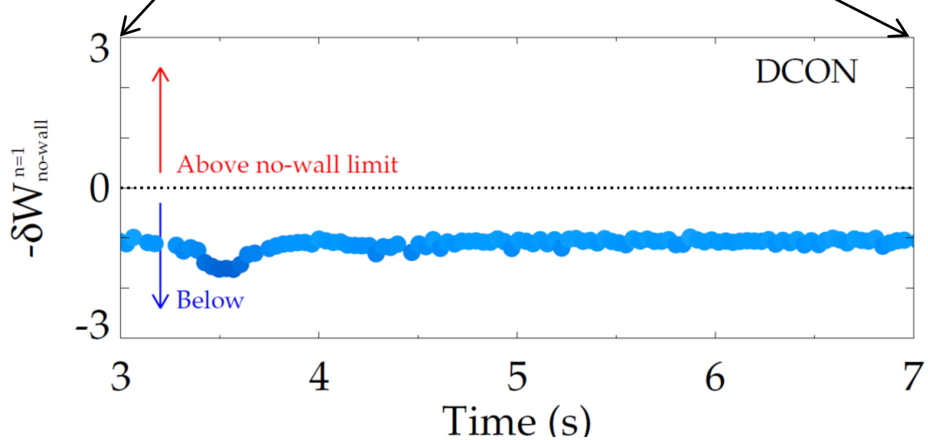
χ^2	207.9
R_{axis}(m)	1.80
Z_{axis}(m)	-0.17
elong	1.374
δ_u	0.232
δ_L	0.271
β_T	0.779
β_p	1.302
β_n	1.693
li	1.392
q_{95}	4.814

Ideal stability of new kinetic equilibria is examined by DCON

- DCON stability calculations of ideal δW indicate whether plasmas are above or below the no-wall beta limit

- Analysis of new KSTAR kinetic equilibria indicates ideal stability (below no-wall limit) during later phase (as expected)

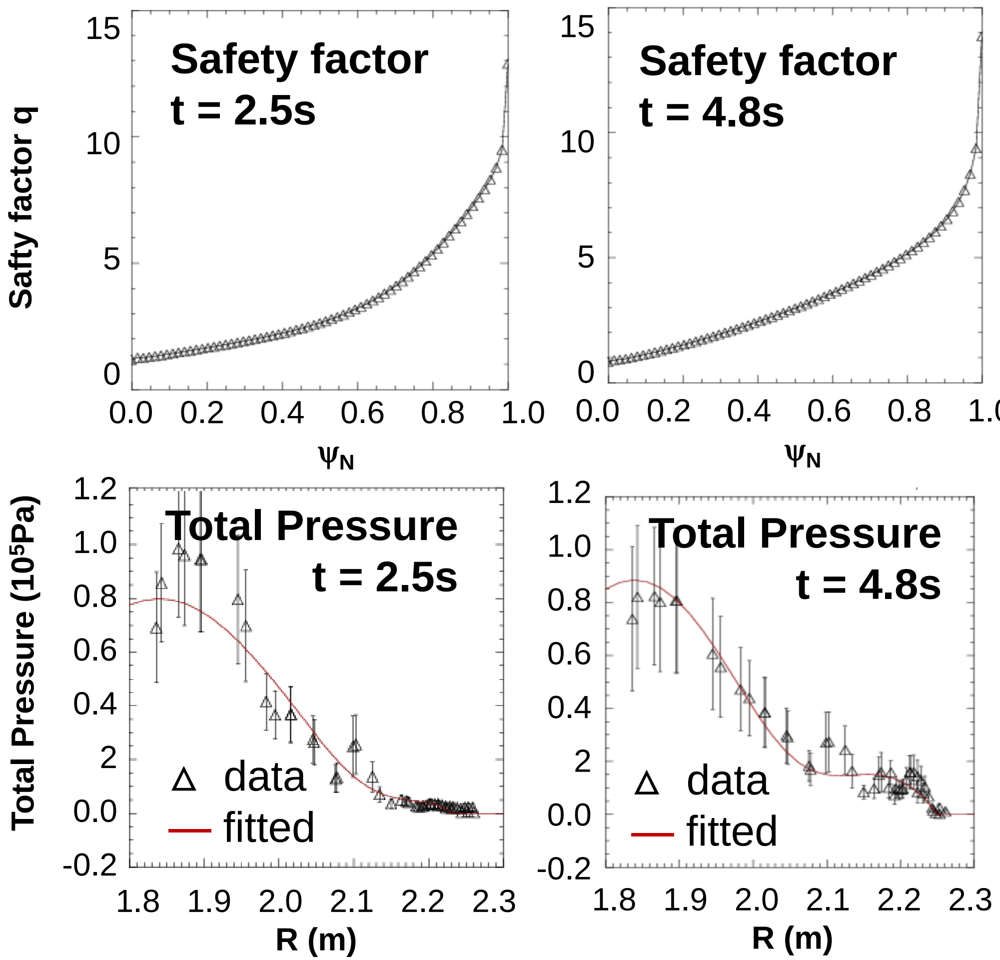


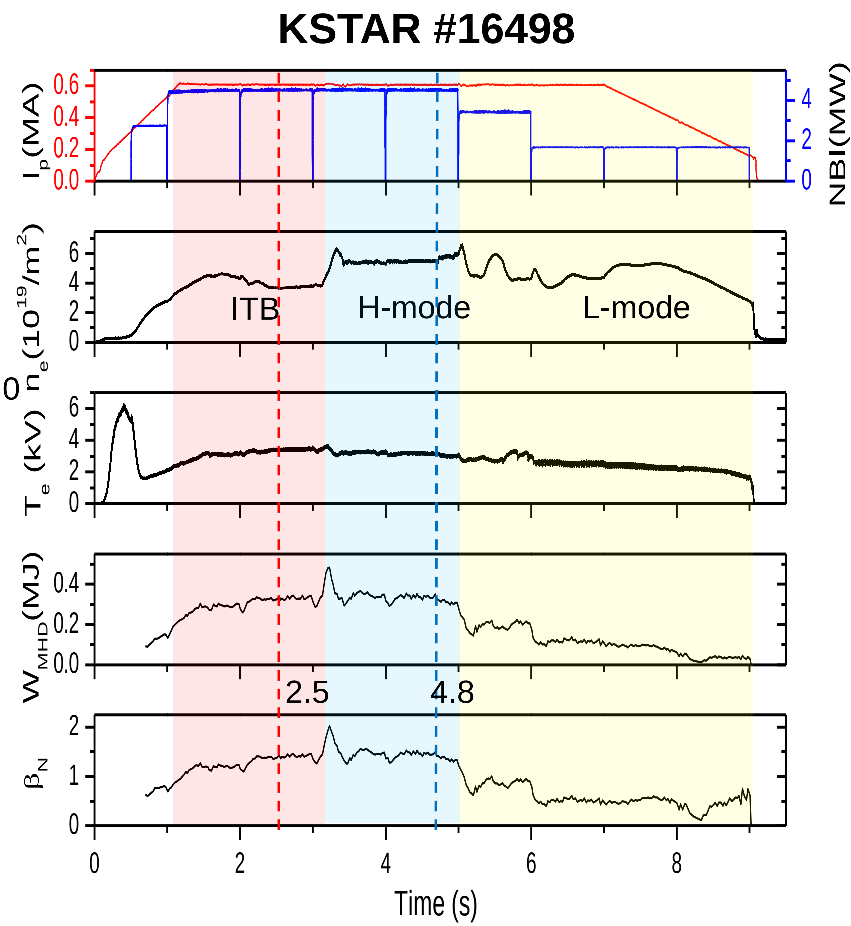


DCON: [A. H. Glasser, Physics of Plasmas 23, 072505 (2016)]

See also Y.S. Park and J.H. Ahn's talk

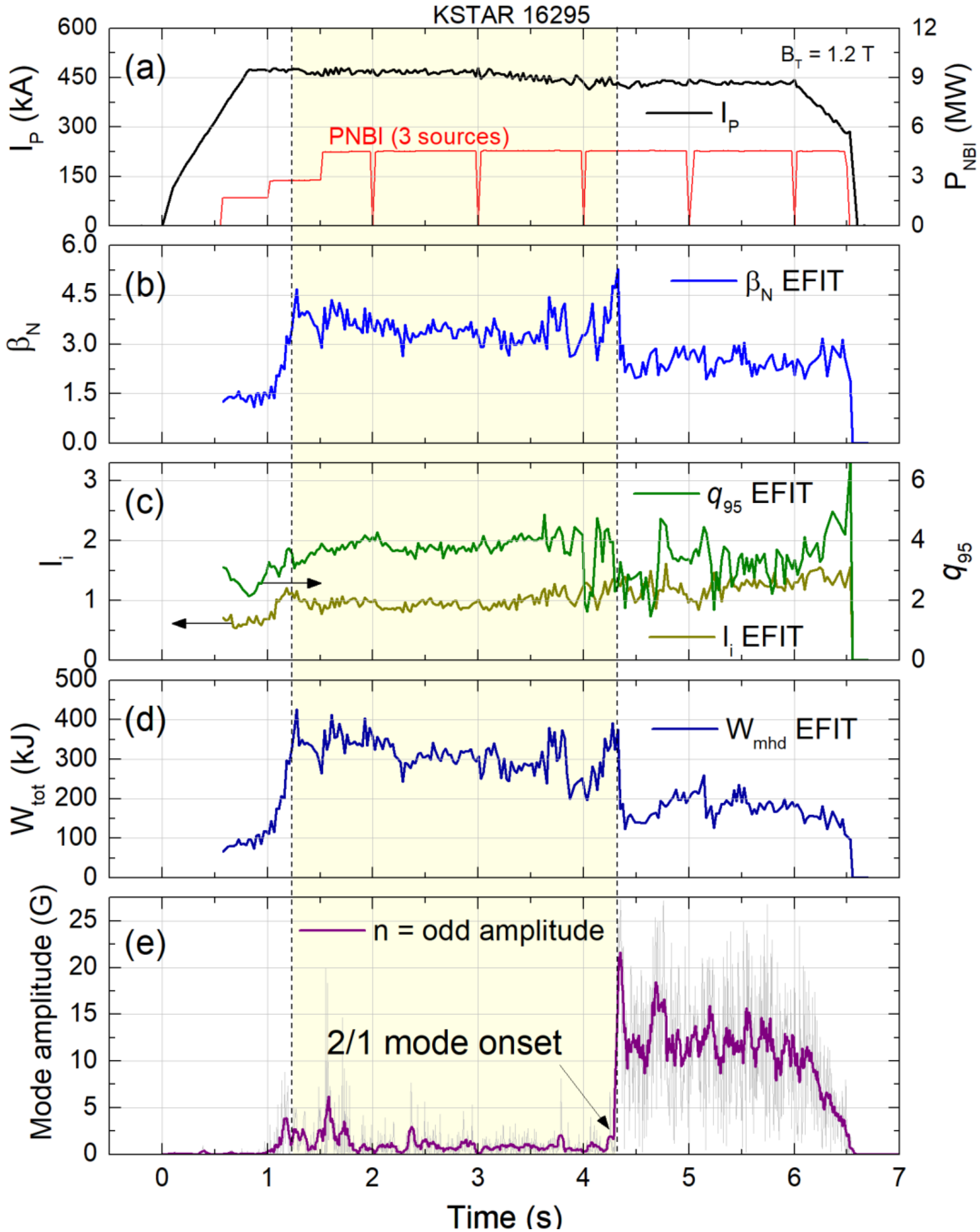
Improvement in confinement is comparable to the H-mode in the discharge





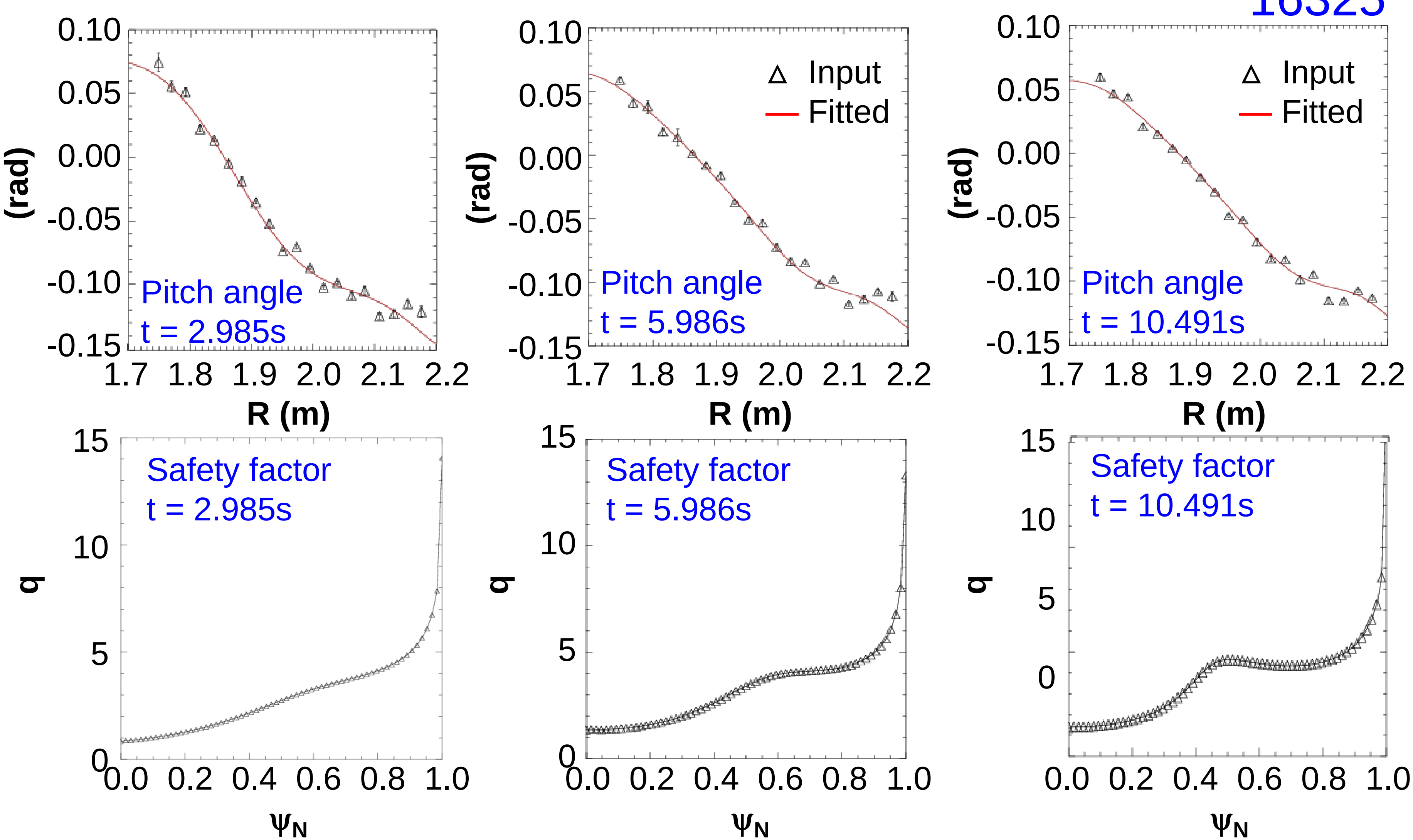
experiment by Jinil Jung

Present kinetic reconstructions will allow more accurate stability determination



Kinetic equilibria with MSE shows evolution of q-profile to low shear at high q

16325



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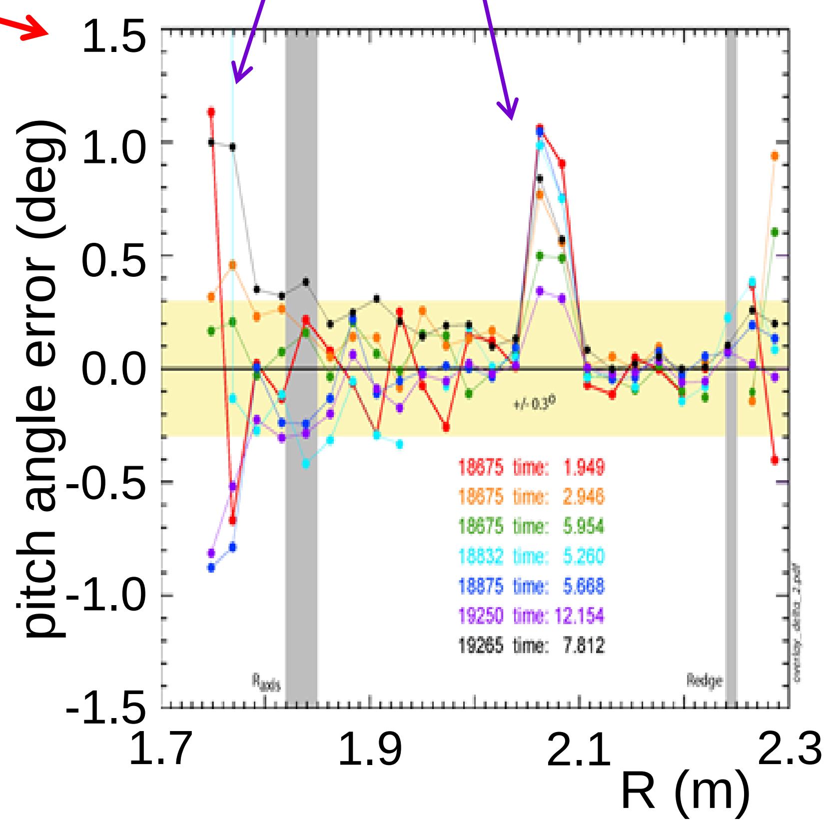
Kinetic reconstructions will continue to improve by Columbia / PPPL / MIT Collaboration

- Transferred 10 channel MSE background light polychrometer from C-Mod to KSTAR (4/2017) (See S.D. Scott poster in 2017 APS DPP meeting)
  - Investigating improvement of MSE measurement by background light subtraction
  - Continued calibration improvements through collaborative investigation
- Collaborative effort to further improve Thomson scattering data
- Continued improvement of kinetic equilibrium reconstructions
  - Activate the completed sensor compensation of 3D IVCC coil currents
  - Improved modeling / planned neural net delivery of fast particle pressure P_{fast}

Pitch angle can be troublesome on some channels due to neglect of background light subtraction



Kinetic equilibrium reconstruction of KSTAR plasmas including MSE data provide critical input for disruption prediction and avoidance research

- Inclusion of key input data
  - Thomson scattering, charge exchange spectroscopy, and allowance for fast particle pressure; motional Stark effect data (25 channels)
  - External magnetics and shaping field currents, vacuum vessel currents, and passive plate currents allowed
- Exploration of operational regimes and new physics
  - Plasmas with high non-inductive fraction display advanced tokamak profiles, including weak/reversed shear
  - Low shear regions found at various levels of q
- Critical input for stability analysis and understanding
  - Continue investigation of weak q shear as possible explanation of tearing mode stability at in higher q vs. lower q regions
  - Provide key input for disruption prediction, active RWM control in 2018