Equilibrium, Stability, RWM control, and ELM Mitigation in KSTAR

S.A. Sabbagh[1], O.N. Katsuro-Hopkins[1],T. Evans[2], J.M. Bialek[1], H.K. Park[3], J.G. Bak[4], J. Chung[4], S.H. Hahn[4], J.Y. Kim[4], M. Kwon[4], G.S. Lee[4], S.G. Lee[4], L.L. Lao[2], S.W. Yoon[4], K.-I. You[4],

[1]Department of Applied Physics, Columbia University, New York, NY, USA
[2]General Atomics, San Diego, CA, USA
[3]POSTECH, Pohang, Korea
[4]Korea Basic Science Institute, Daejeon, Korea

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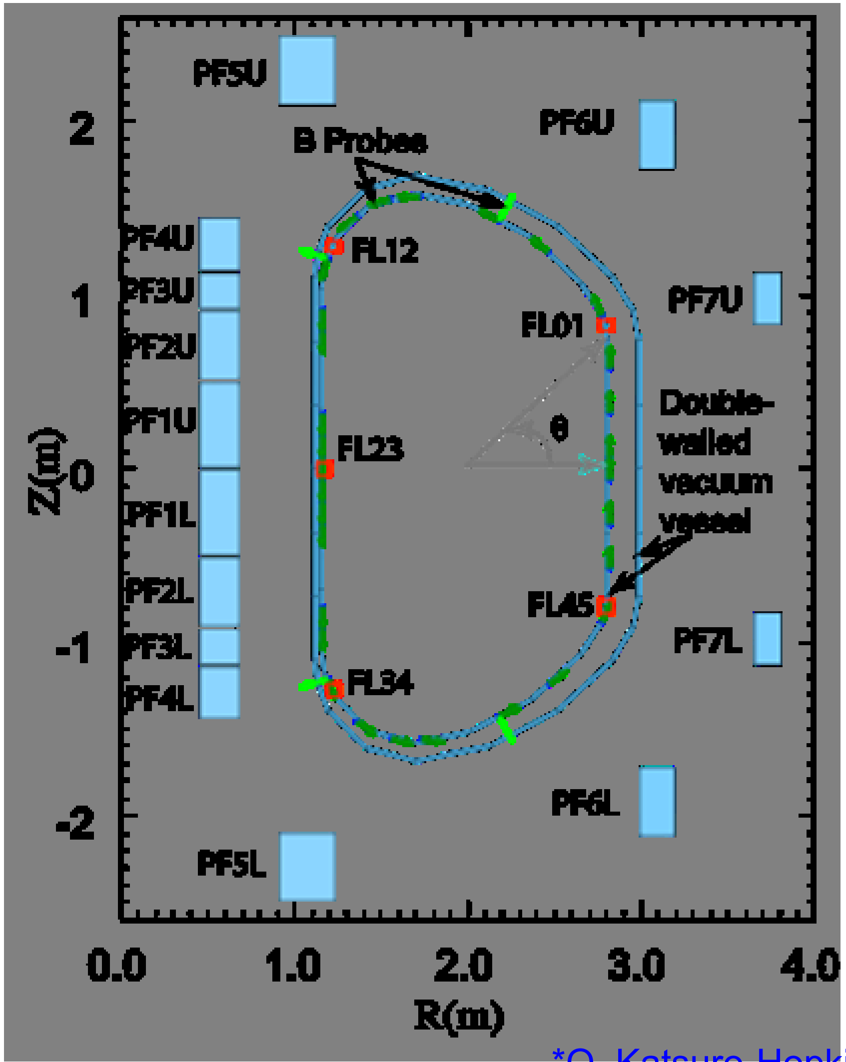
Equilibrium, stability, and IVCC control study supports KSTAR stabilization system and physics research

- Overview
  - Determine optimal stable operating regimes in KSTAR; similar to studies performed for DIII-D, NSTX
  - Determine KSTAR mode control system capabilities and potential for improvements

- Outline
  - Equilibrium model and first plasma reconstructions
  - High beta equilibria theoretical analysis
  - Theoretically stable operational space
  - IVCC performance for RWM control
  - IVCC use for ELM mitigation – set-up and status

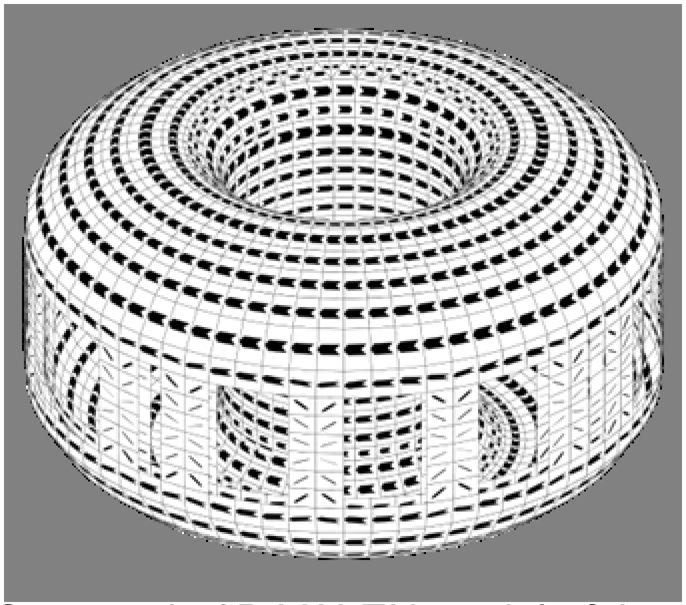
KSTAR configuration and diagnostics for EFIT first plasma equilibrium reconstructions*



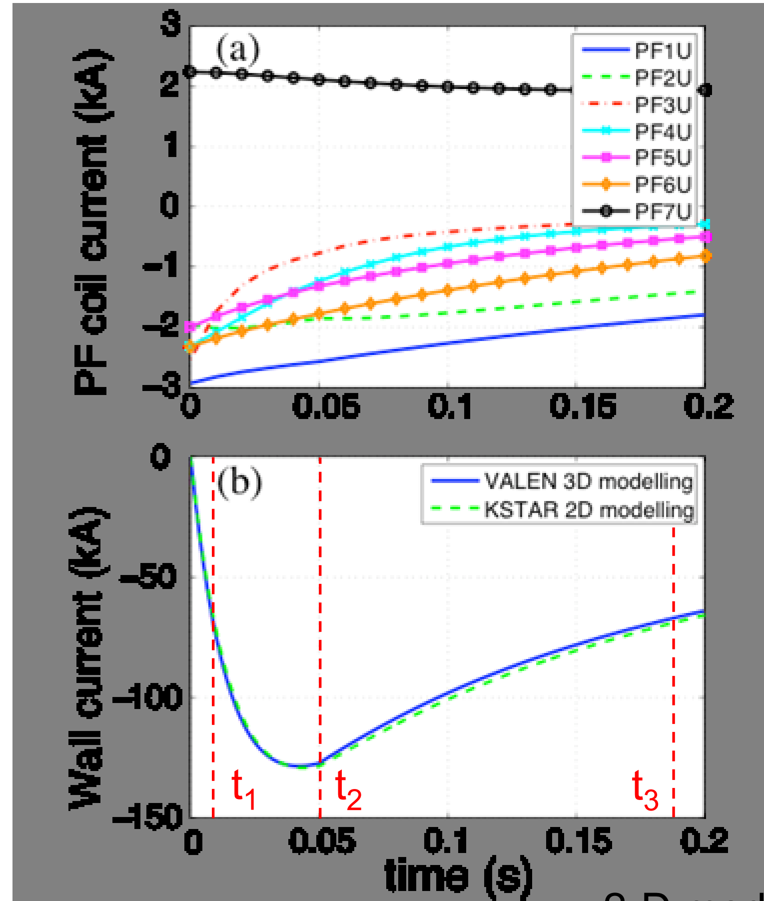
- Data from KSTAR design drawings including
  - 14 PF coil currents,
  - 5 flux loop voltages,
  - 28 magnetic probes,
  - Rogowski coil
  - 28 current carrying segments defining inner and outer vacuum vessel
- Data read directly from KSTAR MDSplus database
  - Includes corrected magnetic probe data (RDATA tree) by S.G. Lee, et al.

*O. Katsuro-Hopkins, et al., IAEA FEC 2008 paper TH/P9-1; submitted to NF

Good agreement between 2D and 3D VALEN modeling total vacuum vessel current evolution for Start up Scenario 1



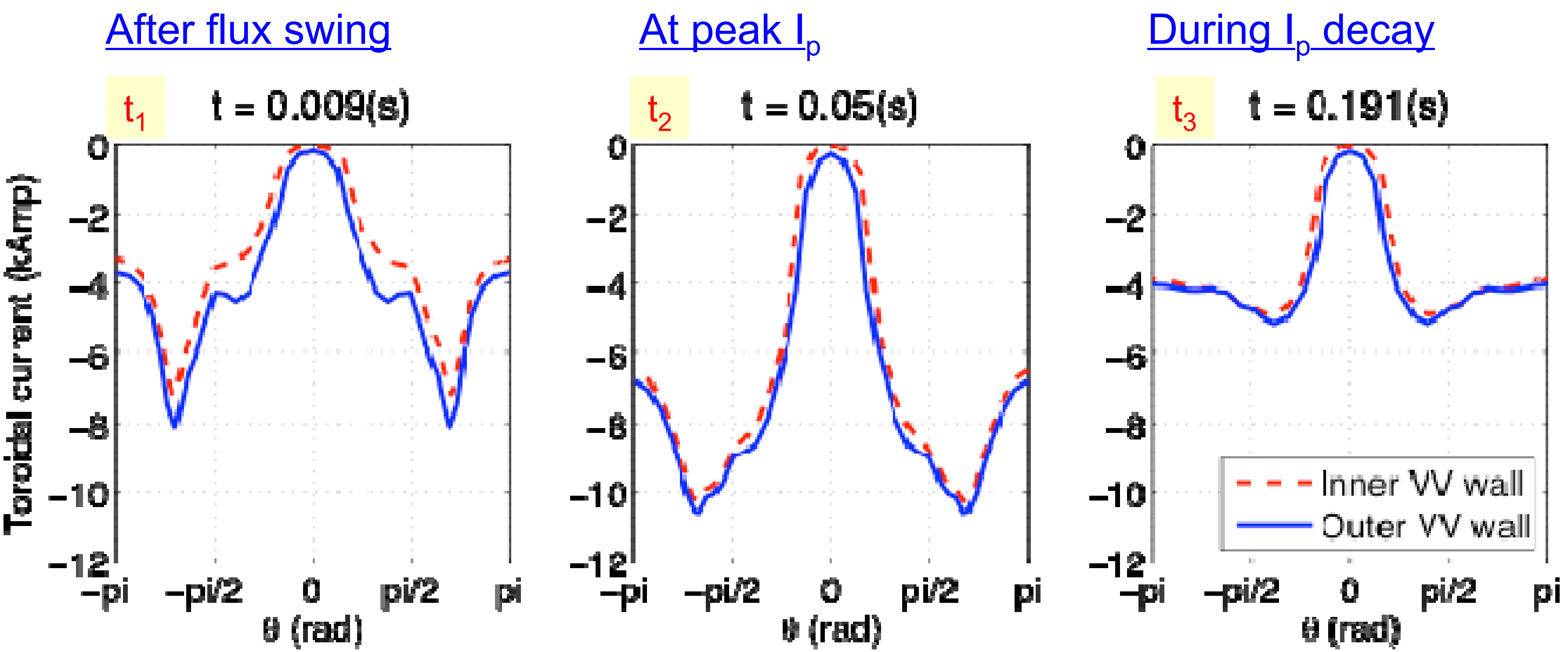
Currents in 3D VALEN model of the KSTAR double-walled vacuum vessel



2-D modeling
S.W. Yoon

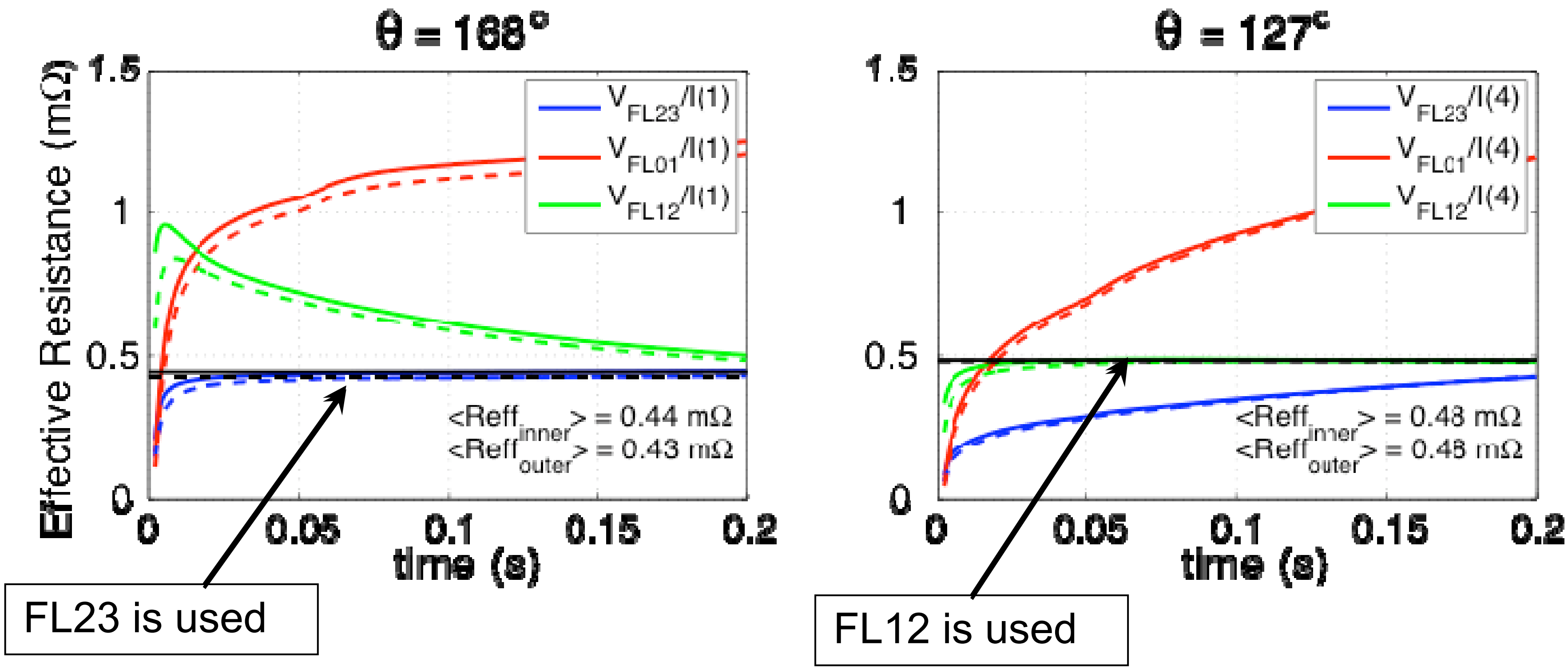
- Reference startup scenario with field null at low *R ~ 1.6 m*
- Total wall current peak value of -128 kA reached at time 0.04 s

VALEN modeling provides poloidal distribution of toroidal current on inner/outer vacuum vessel (VV) walls



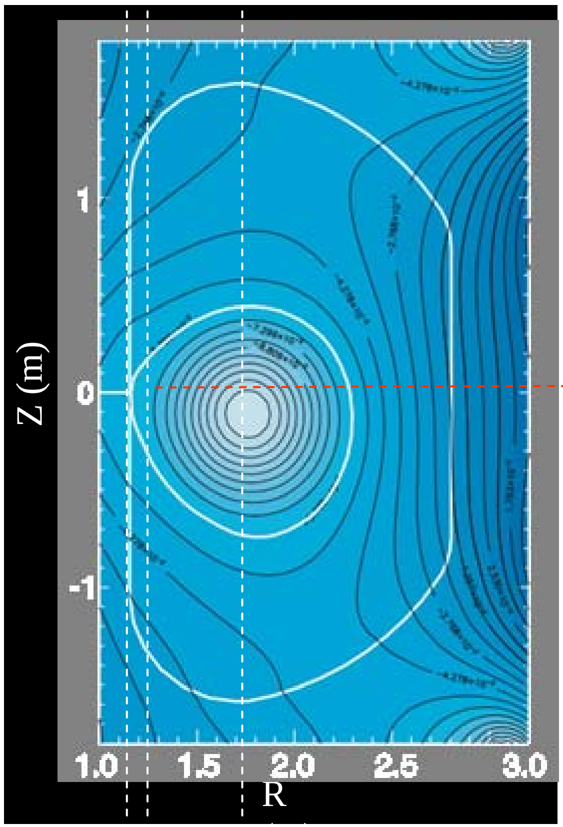
- Near-zero current corresponds to the port penetration region (θ = 0)
- Maximum current at the lowest resistance path around torus (θ ≅ ±125°)
- Used to compute effective resistance calculation for EFIT reconstruction

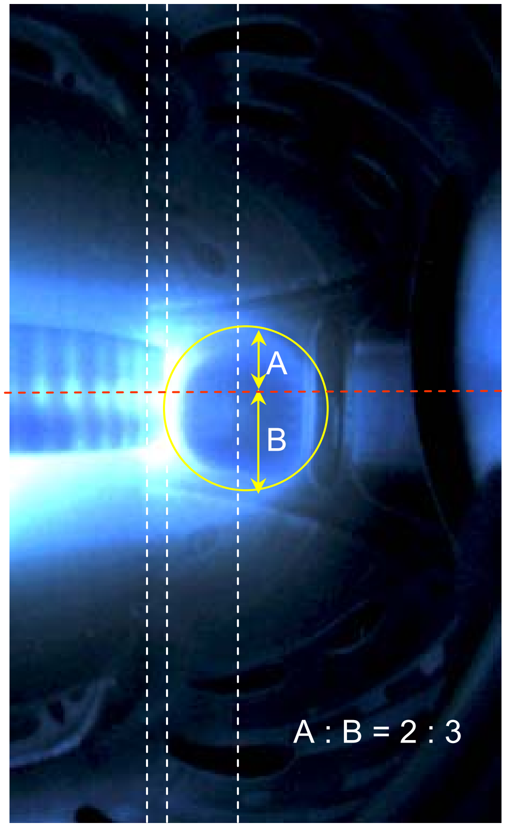
Effective resistance calculated in VALEN an important step for EFIT equilibrium reconstruction

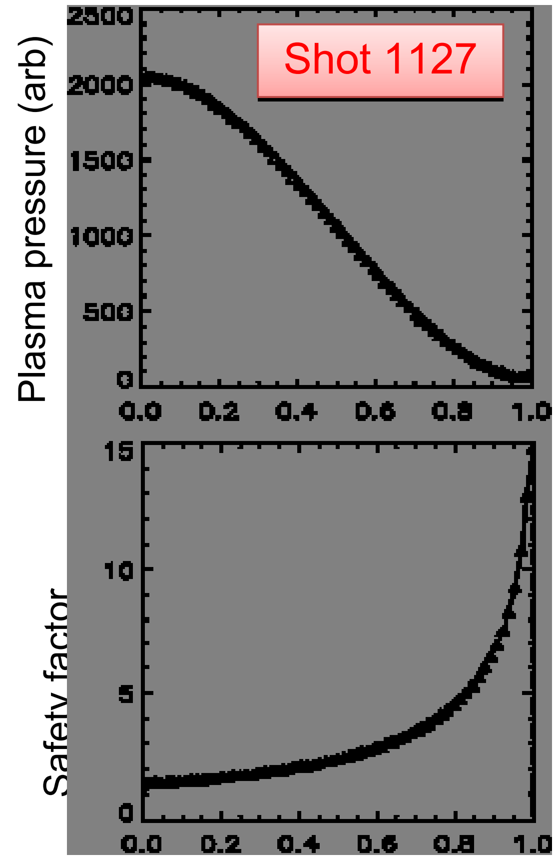


- Effective resistance for inner (solid line) and outer (dashed line) vacuum vessel walls at different poloidal location θ of the wall elements
- $R_{eff;i} = V_{loop;i}/I_i$ (for each wall segment)

In first plasmas reconstructed, vertical and radial position well matches the fast camera image







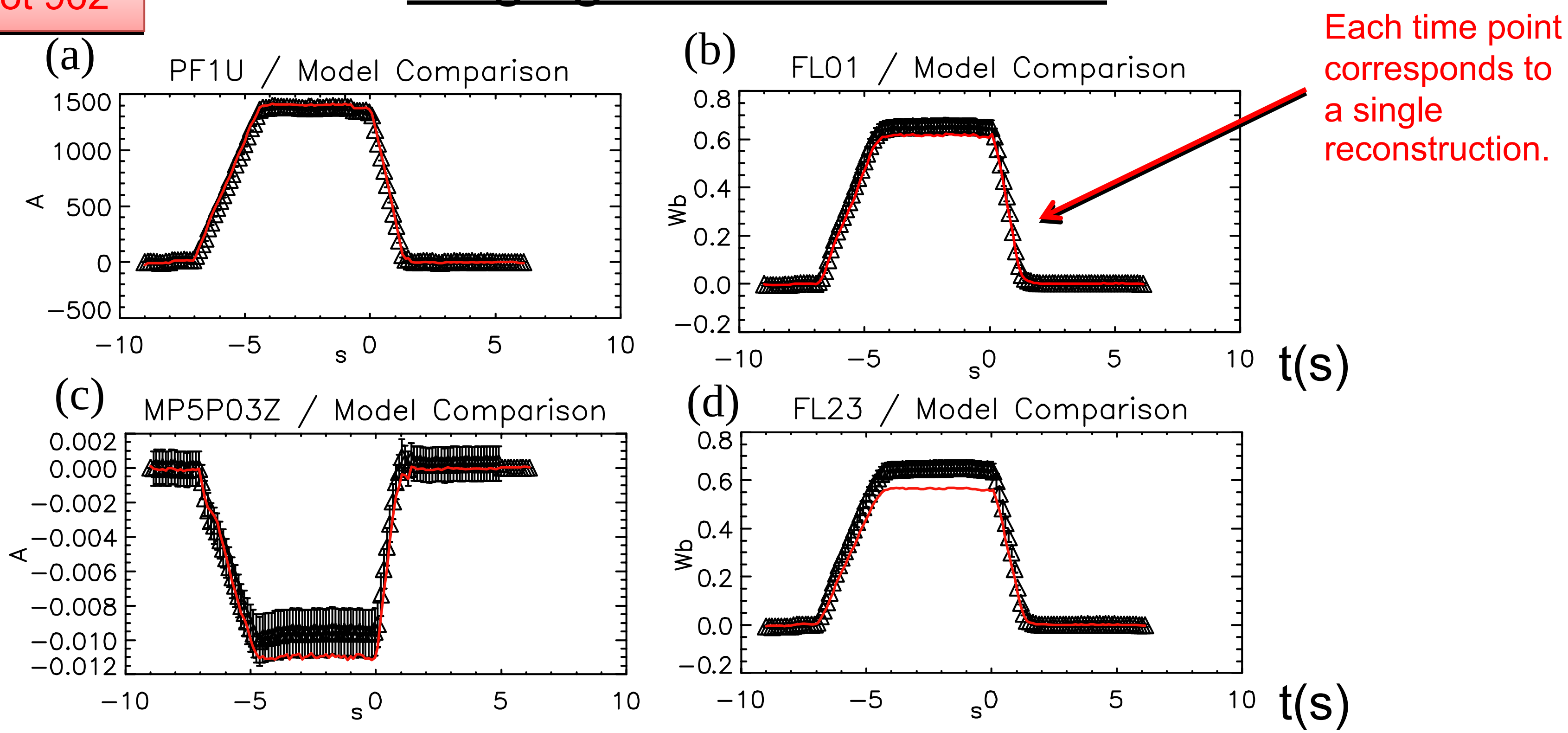
t=0.545s case (frame#133, 543.1 ms)

a: R=1.16m (vessel wall);
b: R=1.26m (inboard limiter);
c: R=1.7m (ECH pre-ionization resonance layer).

- The plasma center shifted about 10 cm below the midplane
- Significant wall current - on the order of plasma current
  - reconstructed $I_{p\text{-wall}}$ = 70 kA
  - reconstructed $I_{p\text{-comp}}$ = 93kA
  - measured $I_{p\text{-meas}}$ = 95 kA

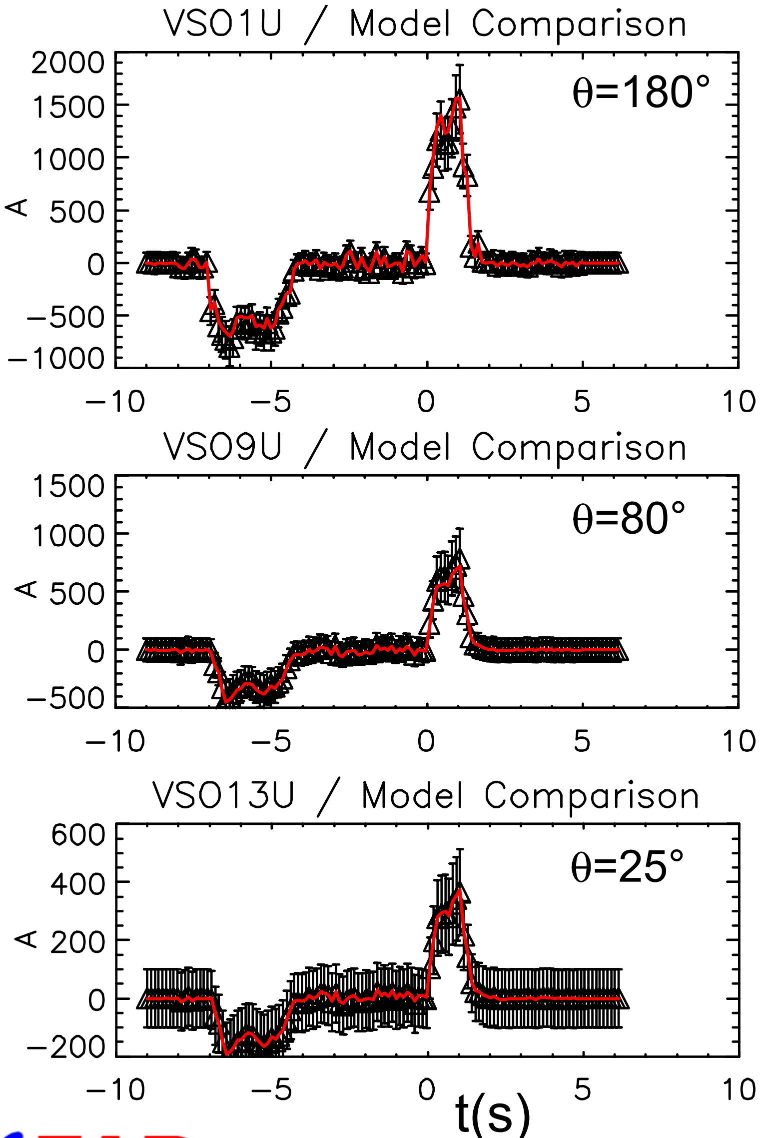
EFIT results typically match within the error with total χ^2 ranging from <100 to ~500

Shot 962



- Here, χ^2 ranges from 40 to 115
- Good match of the modeled and measured PF coil currents
- Flux loop FL01 on outboard side has better agreement then FL23 on inboard side
  - Possibly due to paramagnetic Incoloy material used in some of the poloidal and toroidal field coils (not yet modeled)
- For initial analysis, magnetic probes given largest relative errors (5-10%)

Representative subset of vessel segments currents match the estimates to low tolerance



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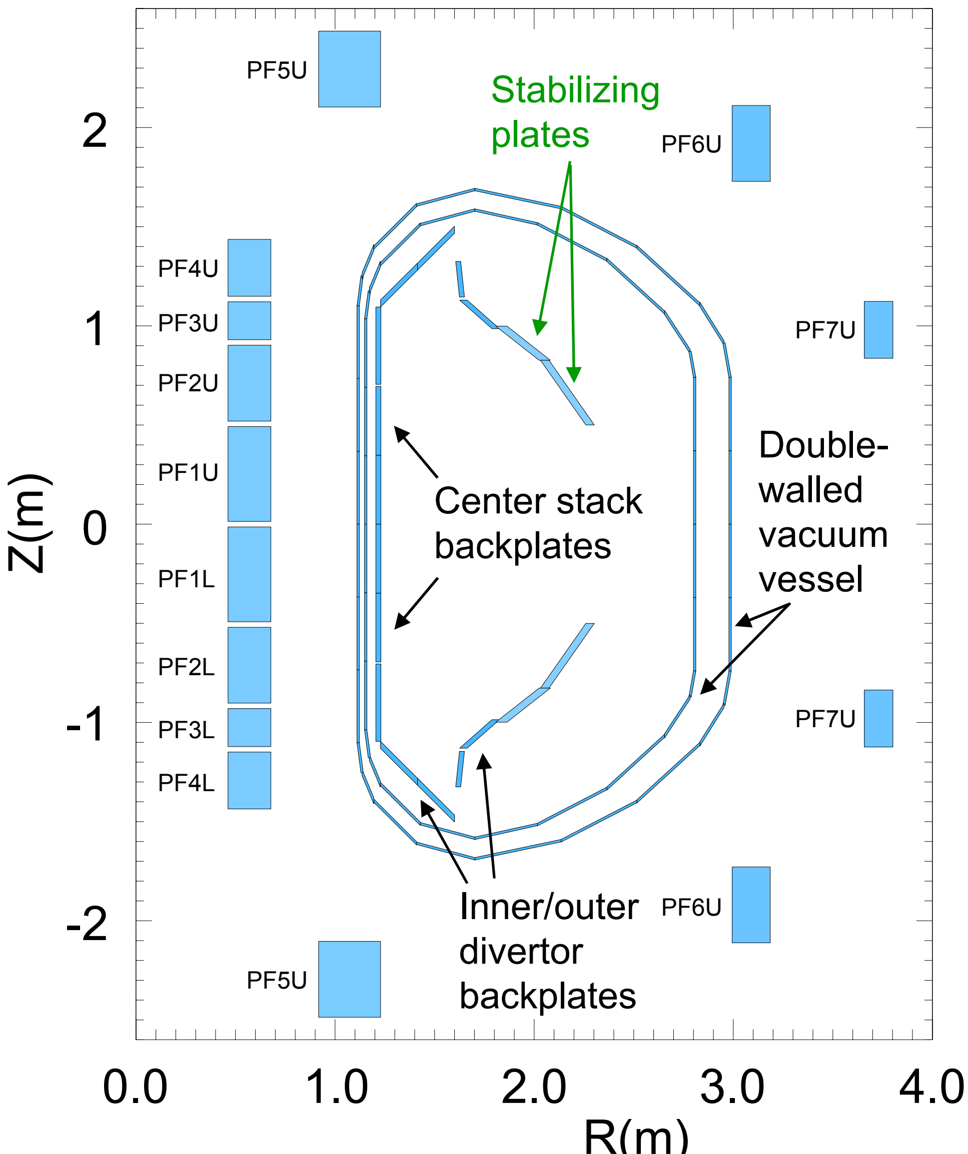
- Current in vessel segments for vacuum field reconstruction using effective resistance
- A large relative error of 30% is assigned to the vessel segment currents to allow variation in reconstruction

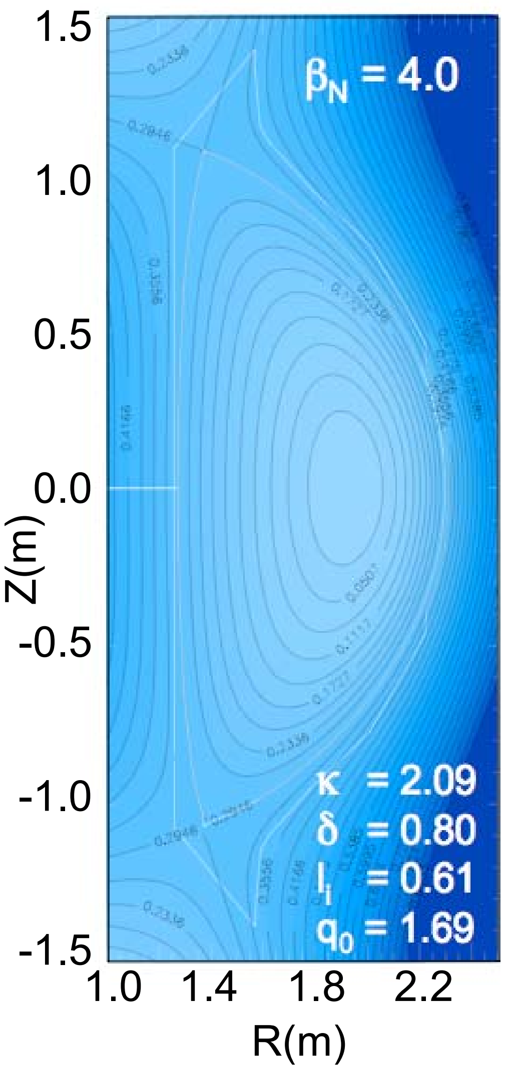
KSTAR configuration used for theoretical equilibria

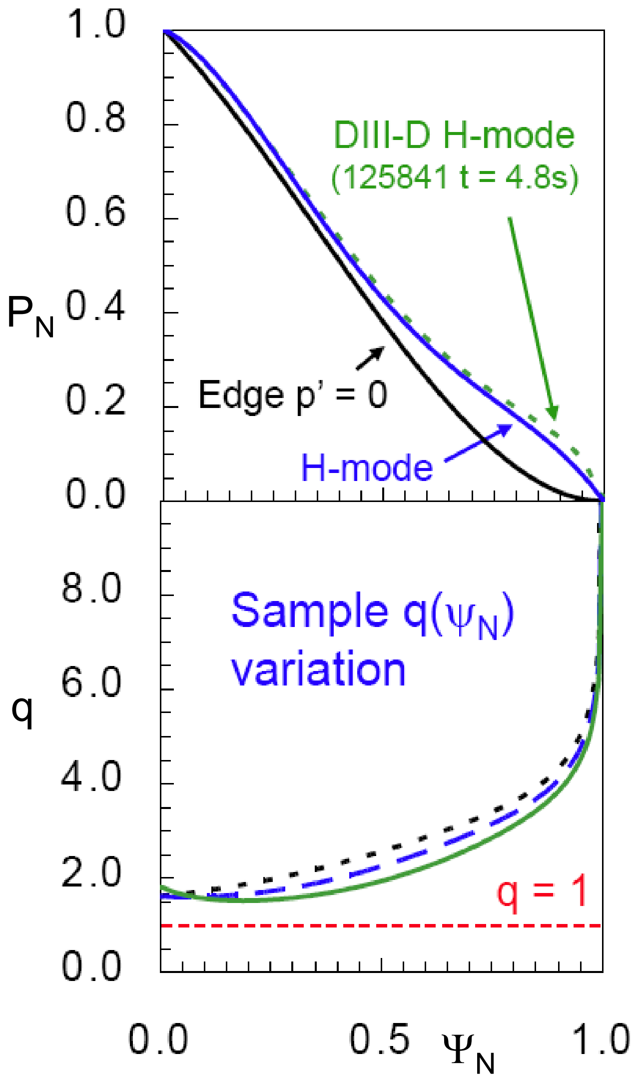


- Theoretical high β equilibria
  - Available to KSTAR research team for further analysis
    - EMAIL request to: sabbagh@pppl.gov
  - EFIT green table directly useable by rtEFIT for real-time plasma control
- Passive stabilizers / vacuum vessel included
  - Important for startup studies; reconstructions during events that change edge current (e.g. ELMs)

Equilibrium variations produced to scan (l_i,β_N)

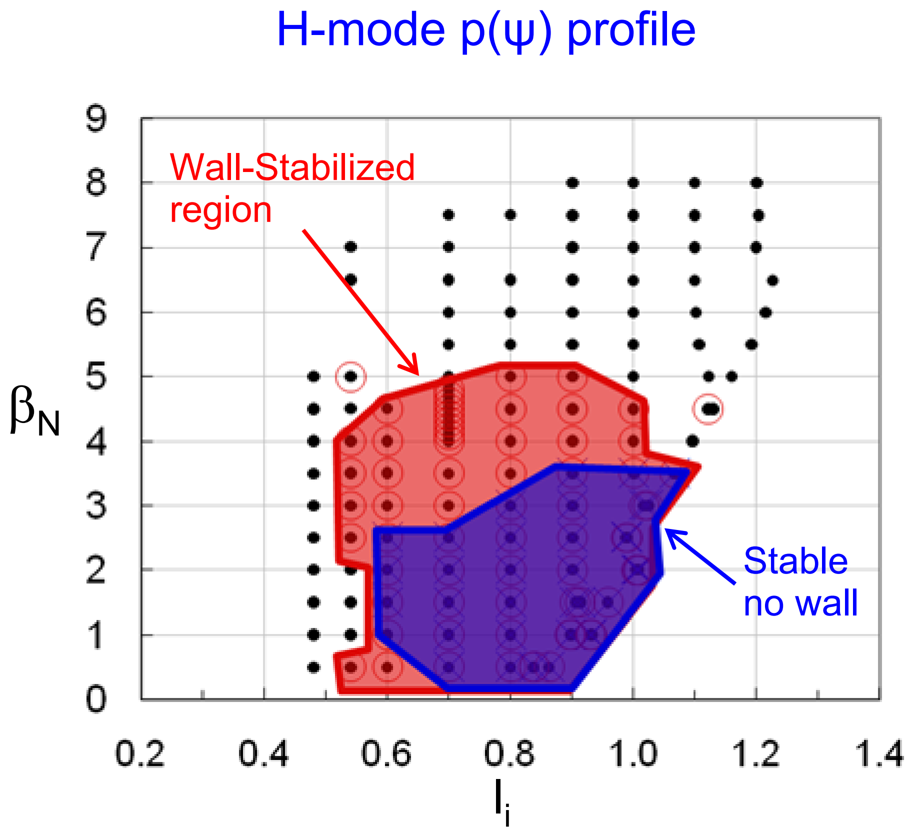
Equilibrium β_N scan, B_t=3.5 T, I_p=2.0 MA

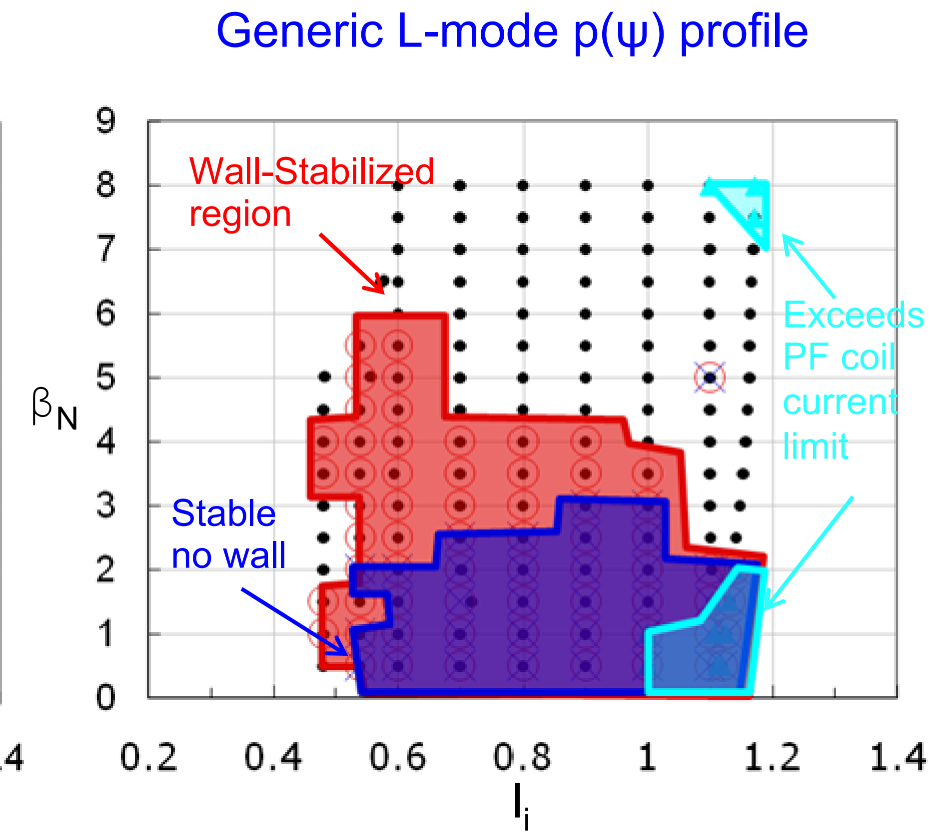




- Boundary shape
  - Free-boundary equilibria with high shaping κ~2,δ~0.8
  - Shaping coil currents constrained to machine limits
- Pressure profile
  - Generic "L-mode", edge p'=0
  - H-mode, modeled from DIII-D
- q profile
  - Monotonic to mild shear reversal with q_0>1 and (q_0-q_{min})<1
- Variations in (l_i,β_n) produced
  - $0.5 \le l_i \le 1.2$; $0.5 \le \beta_n \le 8.0$

Ideal n=1 stability: conducting wall allows significant passive stabilization

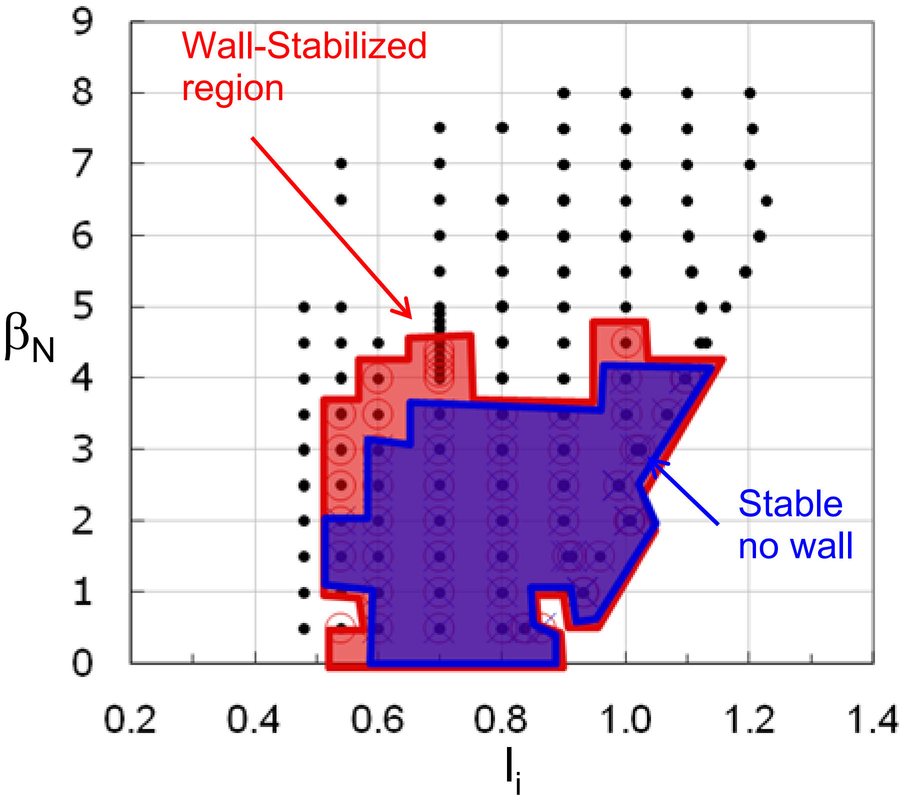




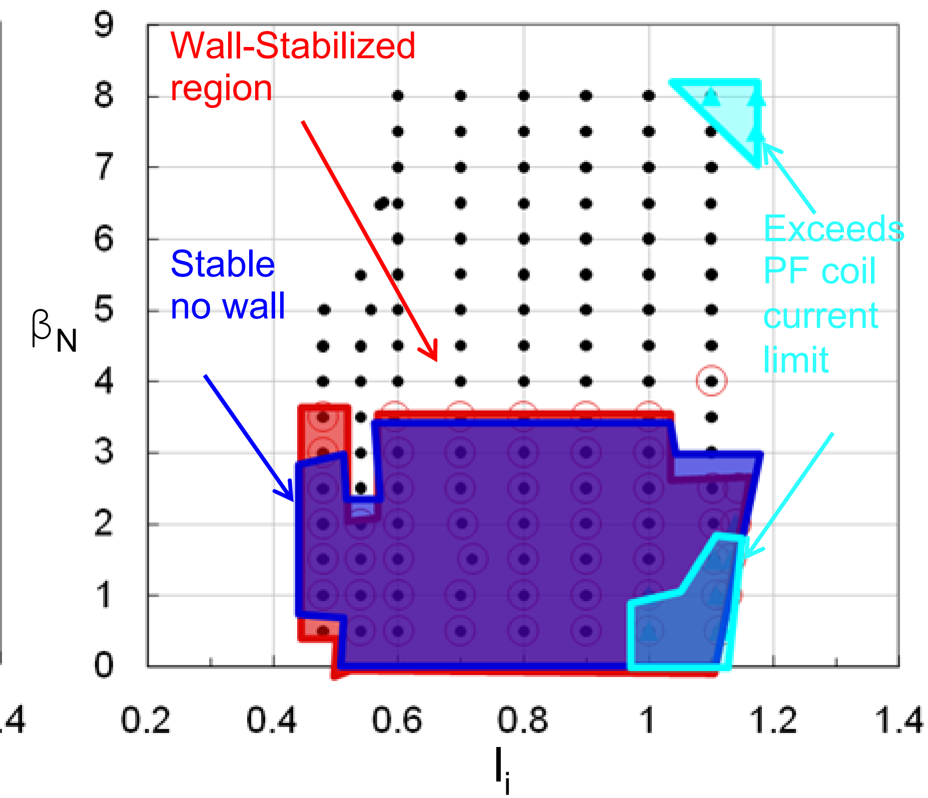
- Wall-stabilized β_n is a factor of two greater then for equilibrium without wall at l_i ~ 0.7

Ideal n=2 stability has higher no-wall & lower with-wall limits than n=1

H-mode p(ψ) profile



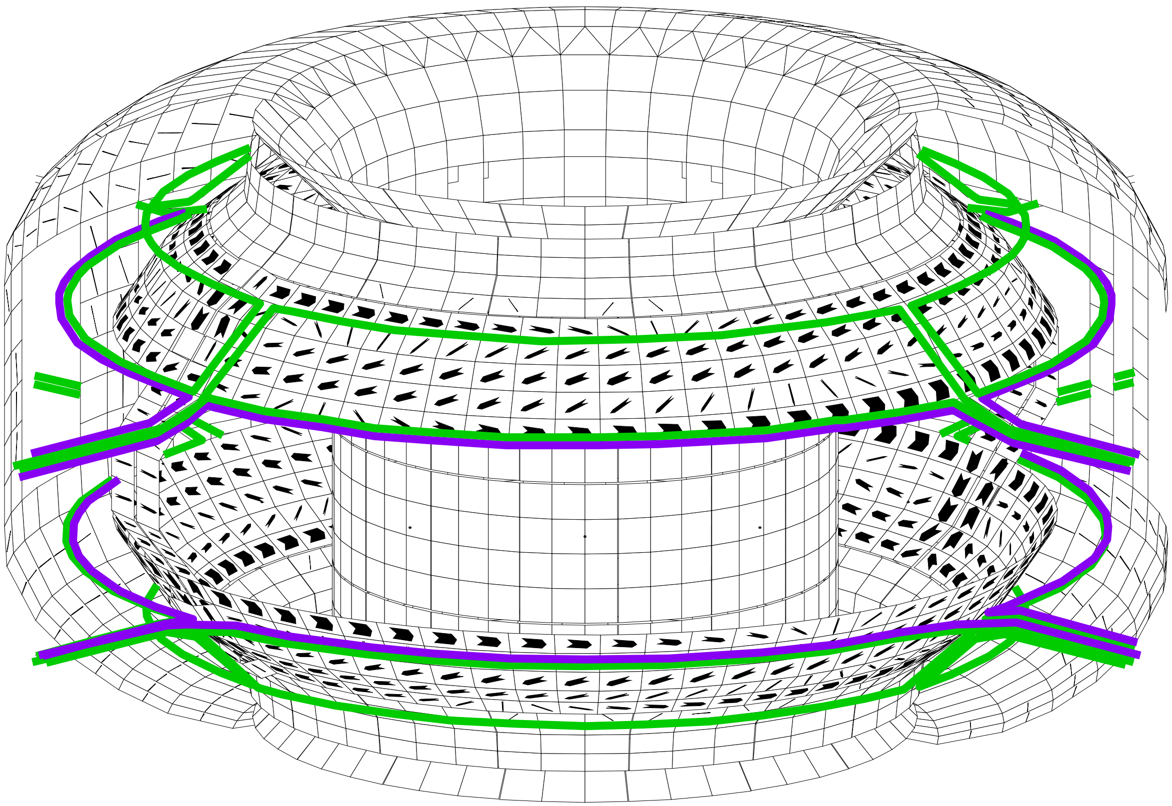
Generic L-mode p(ψ) profile



- Narrow wall stabilized range in β_n for n = 2 - an issue for experiment?
- n > 1 (including n = 2) RWM spectrum observed in NSTX
  (Sabbagh, et al., Nucl. Fusion **46** (2006) 635.)

Conducting hardware, IVCC set up in VALEN-3D* based on engineering drawings

n = 1 RWM passive stabilization currents

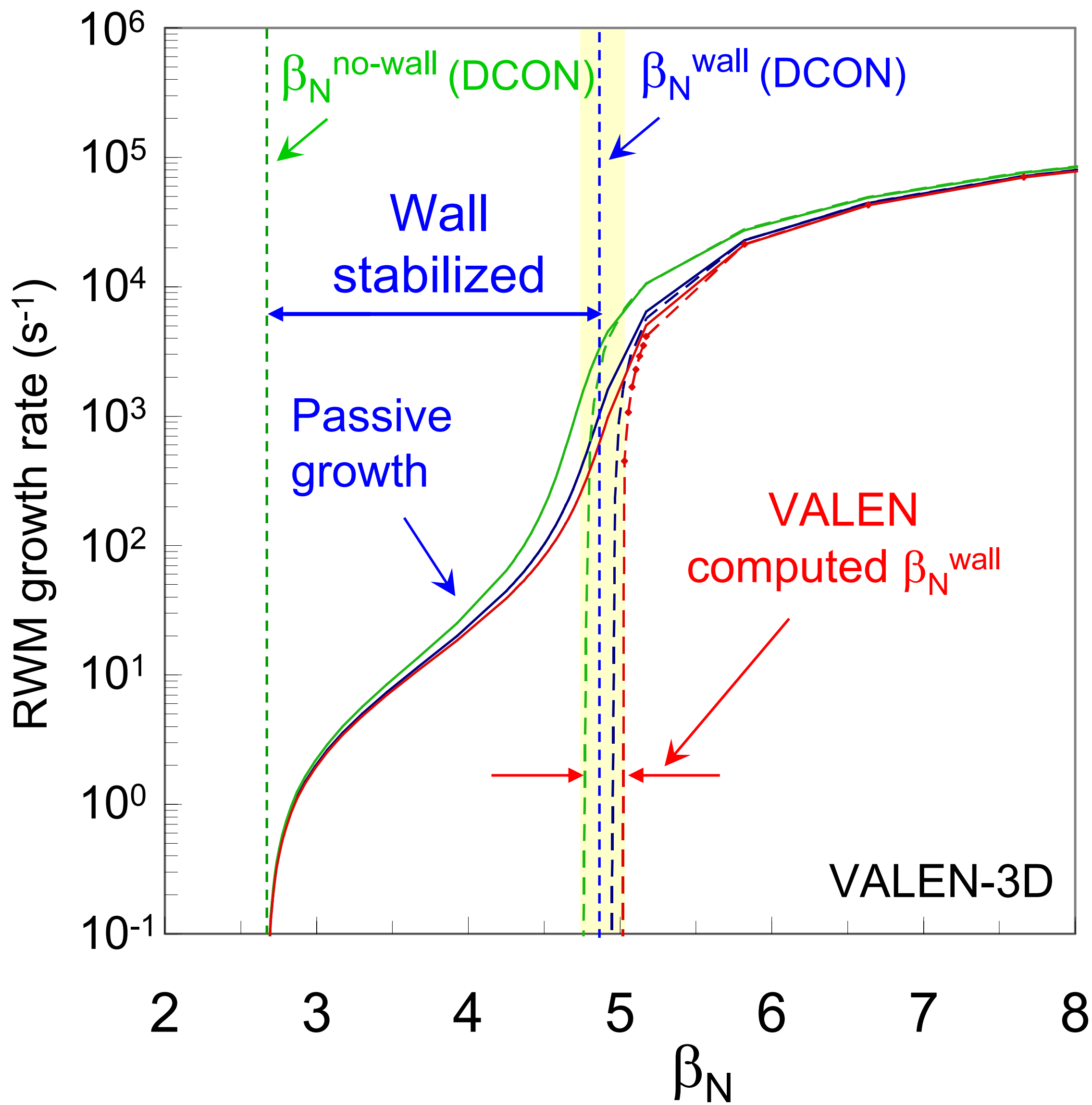


IVCC (RWM) control coils
(upper,middle,lower)

- Conducting hardware modeled
  - Vacuum vessel with actual port structure
  - Center stack backplates
  - Inner and outer divertor backplates
  - Passive stabilizer (PS)
  - PS Current bridge
- Stabilization currents dominant in PS
  - 40 times less resistive than nearby conductors

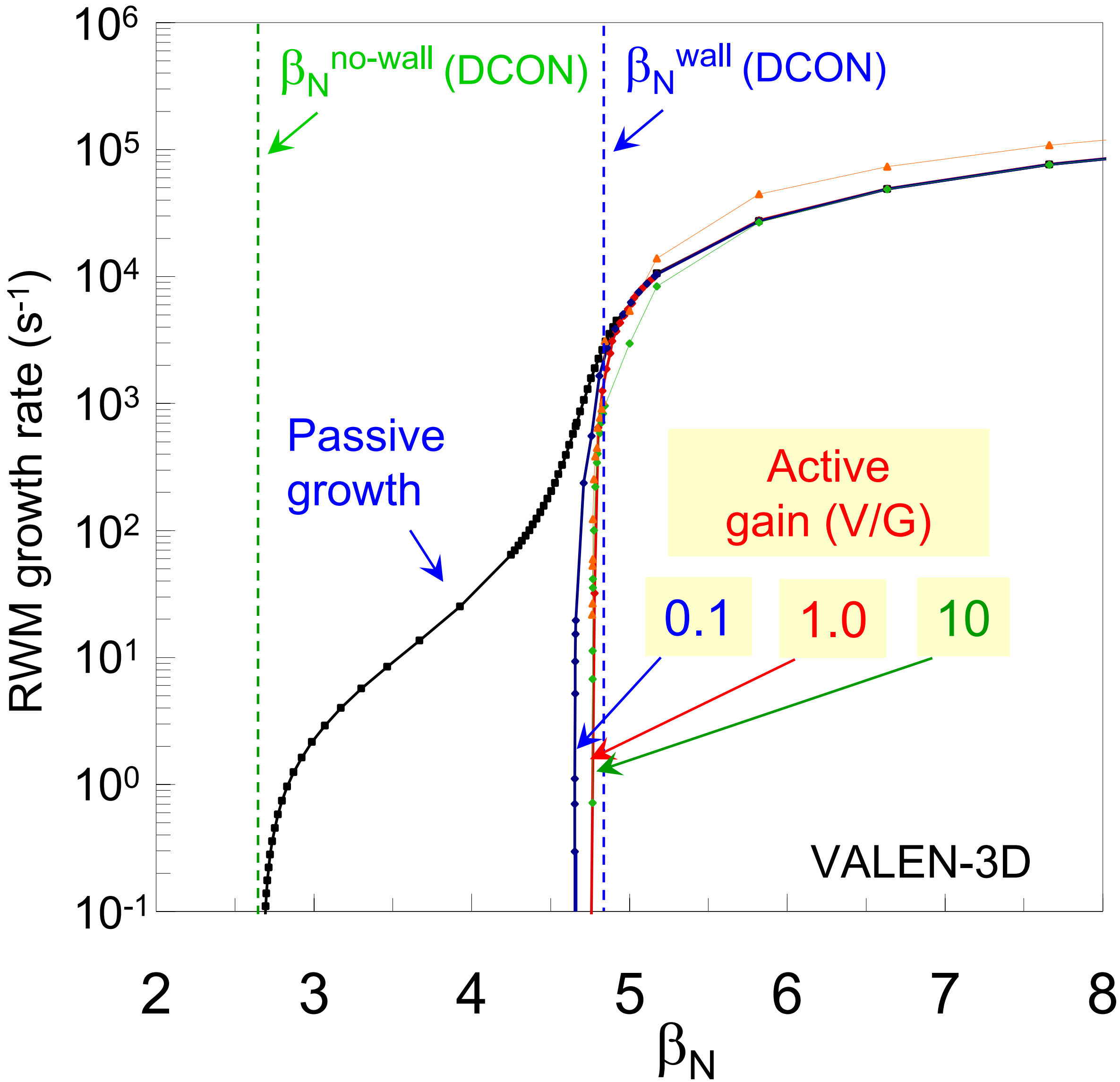
*Bialek J. et al., Phys. Plasmas **8** (2001) 2170.

VALEN 3-D code reproduces n = 1 DCON β_N^{wall} limit



- Important cross-check for VALEN-3D / DCON calibration
- Equilibrium β_N scan with l_i = 0.7, H-mode pressure profile
- DCON n = 1 β_N limits
  - $\beta_N^{no\text{-}wall}$ = 2.6
  - β_N^{wall} = 4.8
- VALEN-3D n = 1 β_N^{wall}
  - 4.77 < β_N^{wall} < 5.0
  - Range generated by various RWM eigenfunctions from equilibria near β_N = 5

IVCC allows active n = 1 RWM stabilization near β_N^{wall}

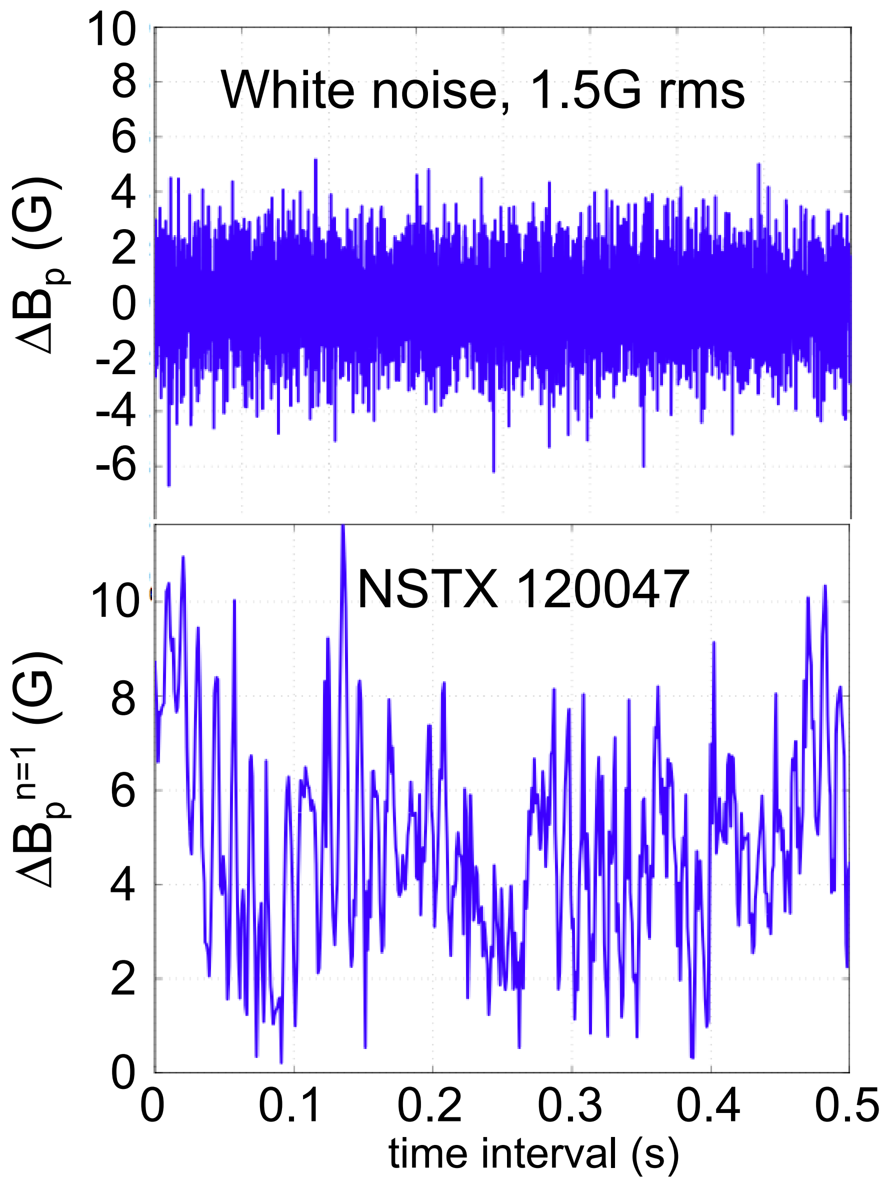


- Active n = 1 RWM stabilization capability with C_β > 98%
  - Optimal ability for mode stabilization
  - Midplane IVCC used with proportional gain
- Equilibrium β_N scan with l_i = 0.7, H-mode pressure profile
- Computed β_N limits
  - $\beta_N^{no\text{-}wall} = 2.56$
  - $\beta_N^{wall} = 4.76$

$$C_\beta \equiv \frac{(\beta_N - \beta_N^{no\text{-}wall})}{(\beta_N^{wall} - \beta_N^{no\text{-}wall})}$$

Noise on RWM sensors sets control system power

- **Gaussian white noise**
  - ~ 1.5G rms, based on noise in DIII-D RWM B_p sensors
  - Minimum estimate of control system power consumption
    - Perfect response to RWM
    - No other coherent modes
- **Experimental sensor input**
  - NSTX B_p sensors during RWM active stabilization
  - Maximum estimate of control system power consumption
    - DC offset from resonant field amplification; stray field from passive plate currents
    - The $\Delta B/B_0$ larger in ST than at higher aspect ratio



Power estimates bracket needs for KSTAR RWM control using proportional gain

Unloaded IVCC
L = 10 μH
R = 0.86 mOhm
L/R = 12.8 ms

(proportional gain controller)

White noise (1.6 – 2.0G RMS) (RMS values) | NSTX 120047 ΔB_p sensors (RMS values)

C_β	I_{IVCC}(A)	V_{IVCC}(V)	P_{IVCC}(W)	I_{IVCC}(A)	V_{IVCC}(V)	P_{IVCC}(W)
80%	30	1.6	45	362	0.7	253
95%	41	2.0	82	430	0.8	307

Fast IVCC circuit
L = 13 μH
R = 13.2 mOhm
L/R = 1.0 ms

(proportional gain controller)

(RMS values) | (RMS values)

C_β	I_{IVCC}(A)	V_{IVCC}(V)	P_{IVCC}(W)	I_{IVCC}(A)	V_{IVCC}(V)	P_{IVCC}(W)
80%	20.9	1.56	30.0	1.9e3	24.9	62e3
95%	28.3	1.78	50.6	9e3	119	1.8e6

- Initial results using advanced linear quadratic Gaussian (LQG) controller yield factor of 2 power reduction for white noise

O.N. Katsuro-Hopkins, et al., *Nucl. Fusion* **47**, 1157 (2007).

Advanced Linear Quadratic Gaussian (LQG) controller* yield factor of 2 power reduction for white noise

White noise (1.6-2.0G RMS)

(RMS values)

C_β	I_{IVCC}(A)	V_{IVCC}(V)	P_{IVCC}(W)
80%	3%	50%	47%
95%	15%	51%	58%

80%	38%	75%	47%
95%	15%	73%	58%

Unloaded IVCC
L=10μH
R=0.86mOhm
L/R=12.8ms

FAST IVCC circuit
L=13μH
R=13.2mOhm
L/R=1.0ms

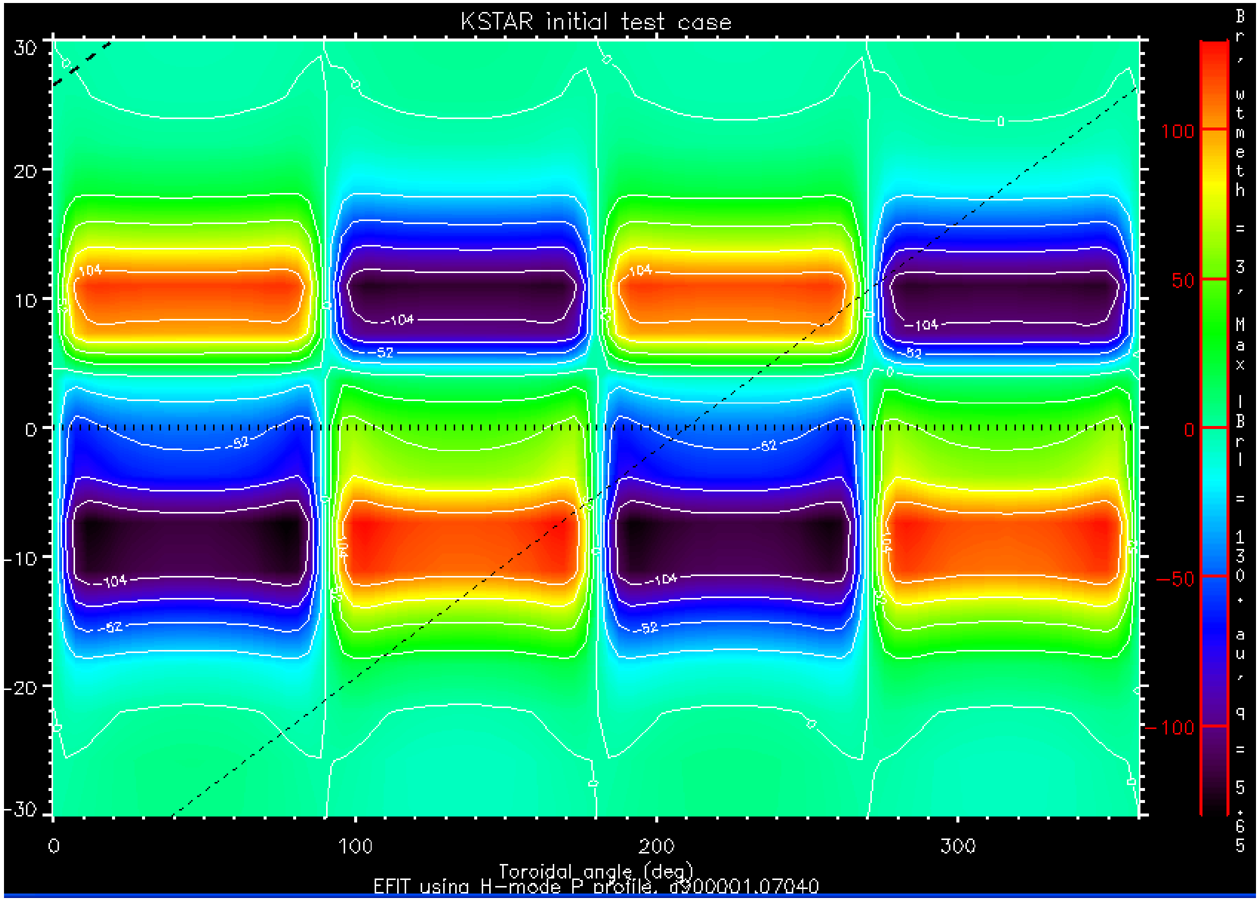
*O.N. Katsuro-Hopkins, et al., *Nucl. Fusion* **47**, 1157 (2007).

IVCC ELM mitigation potential starting to be examined

- Goals
  - Determine performance expectations for present IVCC design
  - Determine possible IVCC modifications for improved ELM mitigation
- Status
  - Collaborative work between Columbia U. collaborators and Todd Evans (GA) recently started to enable TRIP3D code for KSTAR use
  - KSTAR IVCC added to TRIP3D to allow analysis
  - Initial test runs made
    - Tests use theoretical KSTAR high beta equilibria with H-mode profile
  - Next steps include
    - investigation of most favorable IVCC current patterns
    - ELM mitigation robustness vs. equilibrium variations
    - IVCC "upgrades" (e.g. Todd Evans suggests higher-n capability)

KSTAR n = 2 IVCC configuration considered as initial case

Contours of 3-D field magnitude



Poloidal angle

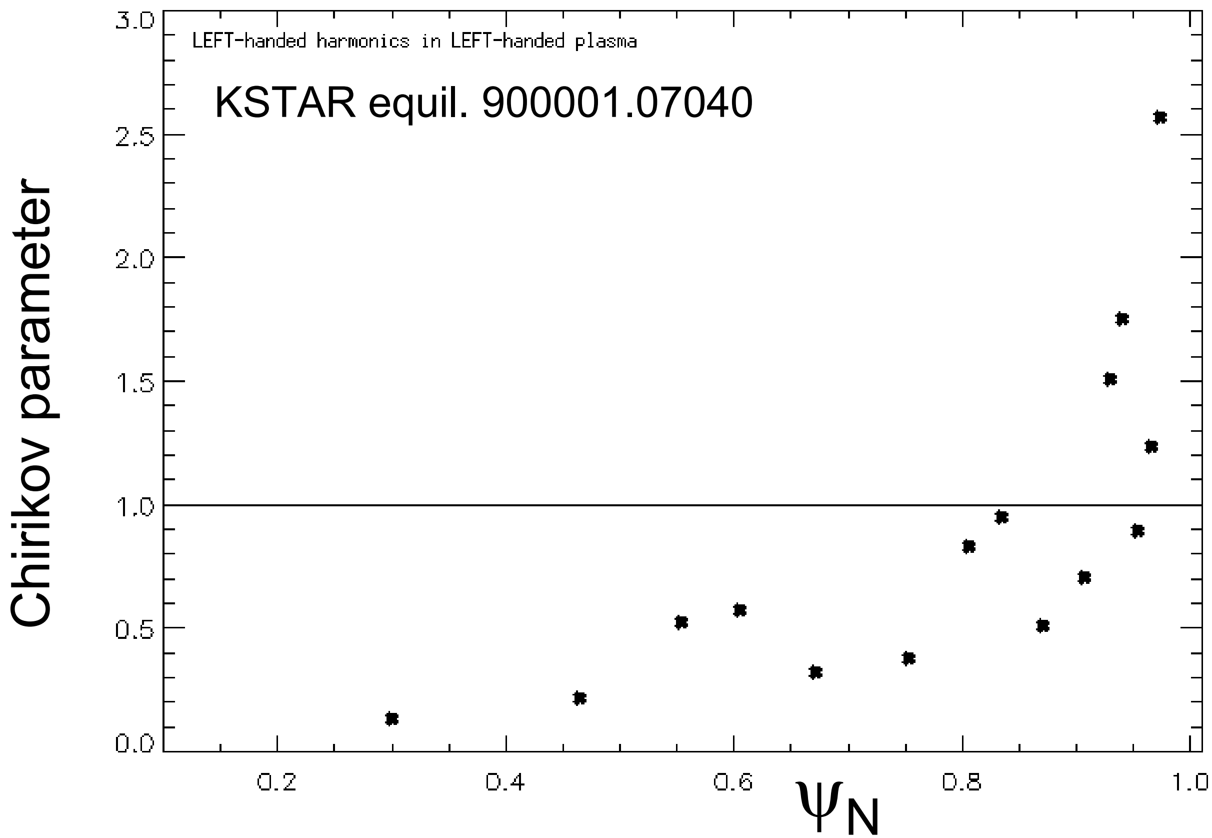
Toroidal angle (deg)

- 3-D field
  - Odd parity
  - Upper/lower coils 4kA
  - center coil 1 kA
- Equilibrium
  - B_t = -3.5 T
  - I_p = 2 MA
  - l_i = 0.70
  - β_N = 4.0
  - H-mode p profile

KSTAR equil. 900001.07040

KSTAR n = 2 IVCC configuration – Chirikov profile shows value approaching 1 at ψ_N = 0.85

Chirikov profile for KSTAR n = 2 configuration



- Chirikov (island overlap) criterion
  - > 1 at ψ_N = 0.85 guidance for ELM mitigation
- 3-D field
  - Odd parity
  - Upper/lower coils 4kA
  - center coil 1 kA
- Equilibrium
  - B_t = -3.5 T
  - I_p = 2 MA
  - l_i = 0.70
  - β_N = 4.0
  - H-mode p profile

- Initial test run: additional modeling needed to compare IVCC spectrum with the DIII-D I-coil spectrum needed for ELM suppression

KSTAR capability of producing long-pulse, high β_N plasmas, and control with IVCC under study

- First plasma equilibria created in KSTAR reconstructed using EFIT including vacuum vessel currents
  - Model refinement (e.g. Incoloy compensation) continues
- Initial vacuum field reconstructions give reasonable matches between measured/computed signals with relatively large error bars
  - Reconstructed plasma vertical and radial position well matches visible light from a fast framing camera
- Large wall-stabilized region to kink/ballooning modes predicted for the device with $\beta_N / \beta_N^{no\text{-}wall} = 2$ at highest β_n
  - Co-directed NBI, passive stabilizers allow kink stabilization
- Active IVCC mode control system can provide effective n = 1 RWM control at reasonable power levels to high $C_\beta > 98\%$
  - With midplane coil alone; use off-midplane coils for plasma rotation, ELM control
- ELM mitigation capability of present IVCC under investigation
  - Potential improvements to present design to be considered