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

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

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

presented at the

KO-US Bilateral Collaboration Meeting

April 15\textsuperscript{th} – 16th, 2009
General Atomics
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

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

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

2-D modeling
S.W. Yoon
VALLEN modeling provides poloidal distribution of toroidal current on inner/outer vacuum vessel (VV) walls

- Near-zero current corresponds to the port penetration region ($\theta = 0$)
- Maximum current at the lowest resistance path around torus ($\theta \cong \pm 125^\circ$)
- 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 $\theta$ of the wall elements

- $R_{\text{eff};i} = V_{\text{loop};i}/I_i$ (for each wall segment)
In first plasmas reconstructed, vertical and radial position well matches the fast camera image

- 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 $I_{p\text{-comp}} = 93$ kA
  - measured $I_{p\text{-meas}} = 95$ kA

Shot 1127

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

- A : B = 2 : 3

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

Z (m)

Plasma pressure (arb)

Safety factor

Poloidal flux normalized
EFIT results typically match within the error with total $\chi^2$ ranging from <100 to ~500

- Here, $\chi^2$ 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

- 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 $\beta$ 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 \((l_i, \beta_N)\)

**Equilibrium \(\beta_N\) scan, \(B_t = 3.5\ T, l_p = 2.0\ MA\)**

- **Boundary shape**
  - Free-boundary equilibria with high shaping \(\kappa \sim 2, \delta \sim 0.8\)
  - 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 \((q_0 - q_{\text{min}}) < 1\)

- **Variations in \((l_i, \beta_N)\) produced**
  - \(0.5 \leq l_i \leq 1.2; 0.5 \leq \beta_N \leq 8.0\)
Ideal n=1 stability: conducting wall allows significant passive stabilization

• Wall-stabilized $\beta_n$ is a factor of two greater then for equilibrium without wall at $l_i \sim 0.7$
Ideal $n=2$ stability has higher no-wall & lower with-wall limits than $n=1$

- Narrow wall stabilized range in $\beta_n$ 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

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

\[ n = 1 \text{ RWM passive stabilization currents} \]

IVCC (RWM) control coils

(upper, middle, lower)

VALEN 3-D code reproduces $n = 1$ DCON $\beta_N^{\text{wall}}$ limit

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

- Active $n = 1$ RWM stabilization capability with $C_\beta > 98$
  - Optimal ability for mode stabilization
  - Midplane IVCC used with proportional gain

- Equilibrium $\beta_N$ scan with $I_i = 0.7$, H-mode pressure profile

- Computed $\beta_N$ limits
  - $\beta_N^{\text{no-wall}} = 2.56$
  - $\beta_N^{\text{wall}} = 4.76$

$$C_\beta \equiv \frac{(\beta_N - \beta_N^{\text{no-wall}})}{(\beta_N^{\text{wall}} - \beta_N^{\text{no-wall}})}$$
Noise on RWM sensors sets control system power

- **Gaussian white noise**
  - \( \sim 1.5 \)G 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

<table>
<thead>
<tr>
<th></th>
<th>White noise (1.6 – 2.0G RMS)</th>
<th>NSTX 120047 ΔB_p sensors (RMS values)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(I_{IVCC}(A))</td>
<td>(V_{IVCC}(V))</td>
</tr>
<tr>
<td></td>
<td>(RMS values)</td>
<td></td>
</tr>
<tr>
<td>Unloaded IVCC</td>
<td>30</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>41</td>
<td>2.0</td>
</tr>
<tr>
<td>Fast IVCC circuit</td>
<td>20.9</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>28.3</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>80%</td>
<td></td>
</tr>
</tbody>
</table>

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

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

White noise (1.6-2.0G RMS)

(RMS values)

<table>
<thead>
<tr>
<th>$C_\beta$</th>
<th>$I_{IVCC}(A)$</th>
<th>$V_{IVCC}(V)$</th>
<th>$P_{IVCC}(W)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80%</td>
<td>3%</td>
<td>50%</td>
<td>47%</td>
</tr>
<tr>
<td>95%</td>
<td>15%</td>
<td>51%</td>
<td>58%</td>
</tr>
</tbody>
</table>

Unloaded IVCC
L=10$\mu$H
R=0.86mOhm
L/R=12.8ms

FAST IVCC circuit
L=13$\mu$H
R=13.2mOhm
L/R=1.0ms

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

- 3-D field
  - Odd parity
  - Upper/lower coils 4kA
  - Center coil 1 kA

- Equilibrium
  - $B_t = -3.5$ T
  - $I_p = 2$ MA
  - $I_i = 0.70$
  - $\beta_N = 4.0$
  - H-mode p profile

### Contours of 3-D field magnitude

- Poloidal angle
- Toroidal angle (deg)

KSTAR equil. 900001.07040
KSTAR n = 2 IVCC configuration – Chirikov profile shows value approaching 1 at $\psi_N = 0.85$

- Chirikov (island overlap) criterion
  - $> 1$ at $\psi_N = 0.85$
  - 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
  - $I_i = 0.70$
  - $\beta_N = 4.0$
  - 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 $\beta_N$ 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 $\beta_N/\beta_N^{\text{no-wall}} = 2$ at highest $\beta_n$
  - 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