Investigation of Plasma Rotation Alteration and MHD Stability in the Expanded H-mode Operation of KSTAR

Y.S. Park¹, S.A. Sabbagh¹, J.M. Bialek¹, J.W. Berkery¹, J.G. Bak², S.G. Lee², W.H. Ko², Y.M. Jeon², J.K. Park³, S. Hahn², J. Kim², J.-W. Ahn⁴, S.W. Yoon², K.-I. You², K.D. Lee², G.S. Yun⁵, H.K. Park⁵, Y.S. Bae², W.-C. Kim², Y.K. Oh², J.G. Kwak²

¹Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA
²National Fusion Research Institute, Daejeon, Korea
³Princeton Plasma Physics Laboratory, Princeton, NJ, USA
⁴Oak Ridge National Laboratory, Oak Ridge, TN, USA
⁵Pohang University of Science and Technology, Pohang, Korea

E-mail contact of main author: ypark@pppl.gov

Abstract. As a key supporting device for ITER, an important goal for KSTAR is to produce physics understanding of MHD instabilities at long pulse with steady-state profiles, at high normalized beta, and over a wide range of plasma rotation profiles. An advance from initial H-mode operation is a significant increase in plasma stored energy and normalized beta, with $W_{\text{tot}} = 340$ kJ, $\beta_N = 1.9$, which is 75% of the level required to reach the computed ideal $n = 1$ no-wall stability limit. Rotating MHD modes are first observed in the device with perturbations having tearing rather than ideal parity. Modes with $m/n = 3/2$ are triggered during the H-mode phase but are relatively weak and do not substantially reduce $W_{\text{tot}}$. In contrast, 2/1 modes to date only onset when both the confinement and plasma rotation profiles are lowered after H-L back-transition. Subsequent 2/1 mode locking creates a repetitive collapse of $\beta_N$ by more than 50%. A correlation between the 2/1 mode amplitude and local rotation shear from an X-ray imaging crystal spectrometer suggests that the rotation shear at the mode rational surface is stabilizing, and additionally, modes appear to onset only below a certain rotation shear threshold. As a method to access the ITER-relevant low plasma rotation regime, plasma rotation alteration by $n = 1, 2$ applied fields and associated neoclassical toroidal viscosity induced torque is presently investigated. The net rotation profile change measured by a charge exchange recombination diagnostic shows initial evidence of non-resonant rotation damping by the $n = 1, 2$ applied field configurations. Computation of active RWM control using the VALEN code examines control performance using present device sensors, including off-axis saddle loops and midplane locked mode sensors. The locked mode sensors are found to be strongly affected by the mode and control coil-induced vessel current. Power and bandwidth requirements for RWM stabilization are also calculated.

1. Introduction

The Korea Superconducting Tokamak Advanced Research, KSTAR, [1] has been successfully operated since 2008 and is expanding its capability to reach advanced tokamak operation to long pulses of hundreds of seconds, exceeding steady-state physics research timescales. As the plasma stored energy increases toward computed stability boundaries [2], physics challenges include the onset of major MHD instabilities that place operational limits on the device and stabilizing them in a unique machine environment with steady-state plasma profiles. Investigating the instability dependence on key variables such as plasma rotation, collisionality, and aspect ratio at long pulse yields a valuable cross-machine comparison to existing devices and further extrapolation to ITER. Unique capabilities of the device include the non-axisymmetric in-vessel control coil set (IVCC) and long pulse allows advanced physics studies of non-resonant neoclassical toroidal viscosity (NTV) physics, which can provide an actuator to access ITER-relevant low plasma rotation with mono-directed NBI.

Along with the previous effort on equilibrium reconstruction and global MHD stabilization projections [2-3], the present work continues to examine the present expanded high normalized beta H-mode equilibrium operating space by reconstruction of the most
recent experimental equilibria. Instability characteristics in the expanded operational space, and the influence of varied plasma rotation are investigated. Computation of active RWM control examines control performance using present device sensors and resulting power and bandwidth requirements. Analysis of initial observations of plasma rotation profile alteration by applied \( n = 1 \) and \( 2 \) non-axisymmetric fields is also discussed.

2. Expanded Equilibrium Operating Space

The EFIT code has been implemented and has reconstructed KSTAR discharges since initial plasma operation in 2008 [2-3]. For reconstruction of 2011 discharges, measurements from a Rogowski coil measuring the plasma current, 14 poloidal field coil currents, 5 flux loop voltage monitors (used to estimate vessel currents), 8 flux loops and 48 magnetic pickup loops were used as constraints. Magnetic non-linearity caused by ferromagnetic materials in coils PF1-PF5 is allowed in the reconstructions and the vessel current model comprises 12 current-carrying groups to represent the poloidal distribution of induced toroidal current taken from 3D time-dependent vacuum field calculations. The reconstructions typically match the measured total vessel current to within 10 kA (peak vessel current \( \sim 150 \) kA) over the discharge lifetime [3-4]. A plasma basis function model constraining the pressure gradient \( p' \) to be a linear function of poloidal flux, \( \psi \), and \( ff' \) to be quadratic in \( \psi \) with zero edge toroidal current is used for reliable reconstruction given the present external magnetic diagnostic set. Here, \( f = RB_T \). The reconstructions match measurements well, and have low total \( \chi^2 < 30 \) and equilibrium convergence error of \( \epsilon = \text{Max} \left( (\psi_{m+1} - \psi_m) / (\psi_0^{m+1} - \psi_1^{m+1}) \right) \sim 10^{-4} \) (here, \( m \) denotes iteration cycle) in current flattop equilibria of more than 300 shots reconstructed in 2011. The \( \chi^2 \) and other equilibrium variables given in the study are the same as defined in reference [3]. The somewhat low \( \chi^2 \) for the given number of measurements indicates that the error bars on some measurements are presently overestimated (the average relative error assumed on magnetic probes is 12%). A slight shift of the plasma below the midplane is found in most of the reconstructions with small negative value of \( dr_{sep} \) from EFIT, defined to be the radial distance between the primary and secondary separatrices mapped to the outer midplane, of approximately -0.5 cm, resulting in an equilibrium configuration close to lower single null.

The H-mode was more stably sustained in 2011 for longer durations up to about 5 s (H-modes were shorter than 2 s in 2010) with operational plasma current and toroidal field similar to the prior campaign, 0.6 MA and 1.6 - 2 T, respectively. In ohmically heated plasmas, 1 MA plasma current and a pulse length longer than 12 s were achieved. The expanded operating regime expressed in stability-relevant parameter space, normalized beta versus internal inductance \( (l_i, \beta_N) \), is shown in Fig. 1a. Progress toward desired operation at lower \( l_i \) and higher \( \beta_N \) in 2011 is shown and compared to data taken up to 2010. Compared to the first diverted H-mode achieved in 2010 with maximum \( \beta_N = 1.3 \), total stored energy, \( W_{tot} = 258 \) kJ, and energy confinement time, \( \tau_E = 148 \) ms [3], equilibria have reached new high values for KSTAR, \( \beta_N = 1.9 \), \( W_{tot} = 340 \) kJ with a corresponding \( \tau_E = 171 \) ms. The maximum \( \beta_N \) was reached at \( B_T \) of 1.6 T. Plasma internal inductance was also reduced to 0.94 from 1.15 at peak \( \beta_N \). The reduced \( l_i \) before the H-mode transition in 2011 compared to previous years helped to sustain lower values to the end of the discharge. Modified plasma shape and position evolution before the plasma becomes diverted may contribute to the change in \( l_i \) evolution by eliminating substantial strike point sweeping on the outer divertor plates in 2010 and also by changing the plasma current evolution due to different neutral beam deposition. The equilibrium enhancement toward higher values of \( \beta_N / l_i > 2 \) in 2011 without substantial increase in auxiliary heating power from 2010 is significant. Enhanced energy confinement due to improved wall conditioning by boronization and a higher bake out temperature.
(increased from 200°C up to 260°C on the carbon tile surface) has allowed this improvement. These results mark substantial progress toward the $n = 1$ ideal no-wall stability limit, computed for KSTAR projected equilibrium targets by the DCON code to be most closely positioned at $\beta_N = 2.5$, $\ell_i = 0.7$ [2]. An operating space plot of plasma elongation versus internal inductance ($\ell_i$, $\kappa$) is shown in Fig. 1b. Internal inductance, which generally inhibits obtainable $\kappa$ under the same magnetic configuration, was lowered in 2011 helping to sustain higher operating $\kappa$ by enhancing vertical stabilization. Although precise plasma shape control is still an important issue in the device, sustained elongation higher than the device design target value of 2.0 was achieved in many equilibria spanning $0.9 < \ell_i < 1.1$. A second neutral beam source, improved machine conditioning, and expected improvements to the H-mode may allow access to the $n = 1$ no-wall stability limit in 2012.

3. Characteristics of Observed MHD Instabilities

Rotating MHD modes are observed with perturbations having tearing rather than ideal parity. Modes with poloidal/toroidal mode number $m/n = 3/2$ and 2/1 were destabilized in different operating regimes as shown in Fig. 1a. Modes with $m/n = 3/2$ onset at lower $\ell_i$ than modes with $m/n = 2/1$ in the range $0.5 < \beta_N < 1.0$. In the analysis, the $m$ structure is identified by a 2D ECE imaging diagnostic [5] and an $n$ structure determined by phase analysis of a toroidal Mirnov probe array. The 3/2 modes are triggered during the ELMy H-mode phase with $B_T = 1.6$-1.8 T but are relatively weak and do not substantially reduce $W_{tot}$. The core ECE data shows that 3/2 mode onsets are well synchronized with large sawtooth crashes. The modes are mostly absent in H-mode operation with $B_T = 2.0$ T and higher $\beta_N > 1.0$ as sawteeth are eliminated at increased stored energy most likely due to higher central $q$ at higher temperature. The existence of a triggering event suggests that the 3/2 mode is close to being neoclassically unstable where small island stabilization physics requires a finite seed island for mode onset. In contrast and surprisingly,

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2/1 modes to date have not onset in H-mode. The modes only onset when both the stored energy and plasma rotation are lowered after an H-L back-transition in $B_T = 2$ T discharges. The equilibrium $q_{95}$ is also lowered before mode onset (due to equilibrium shape reduction) with onset values ranging from 4.3 to 6.2 ($4.9 < q_{95} < 6.4$ for 3/2 modes) and the mode evolves as $q_{95}$ mostly increases as shown in Fig. 2. The 2/1 modes are first born very slowly rotating with rotation frequency at onset lower than 4 kHz (20-30 kHz for 3/2 modes) and quickly reach peak amplitude (mode saturated) and persist for less than a second. Unlike the 3/2 modes, no preceding MHD activity has been observed in the 2/1 onset and subsequent 2/1 mode locking creates a repetitive collapse of $\beta_N$ by more than 50%. Note that the mode onset values shown in Fig. 2 are evaluated at full saturation when the mode reaches an initial peak amplitude, although the 3/2 mode amplitude couldn’t be reliably estimated due to a limited Mirnov bandwidth which inhibited further analysis.

Figure 3a shows the 2/1 mode amplitude versus mode rotation frequency for several discharges having low variation of $q_{95}$ during the mode evolution period (thus having small expected change in mode rational surface location). The mode frequency, which can be an approximate measure of a local plasma rotation around the mode rational surface, increases as plasma rotation recovers after the back-transition, and the mode decays away with increasing mode rotation. Plasma rotation from an X-ray imaging crystal spectrometer (XICS) [6] during the mode period also shows a very consistent behavior. Plasma rotation shear is known to have a stabilizing effect on tearing stability [7-8], and a correlation is also found in KSTAR. Figure 3b shows the 2/1 amplitude versus rotation shear measured by vertical XICS chord pairs straddling the mode rational surface. The result suggests that the mode amplitude tends to be reduced with strong rotation shear and additionally (not shown in figure), the mode is more likely to trigger at rotation shear weaker than about -670 krad/s/m. Accordingly, strong rotation shear is found to make mode onset more difficult and requires higher onset beta. The scatter in the data might be due to an offset in XICS data or a small variation in distance between the pickup coils and $q = 2$ rational surface. Weakened rotation shear could increase coupling between the mode and other MHD seeding events but this is unlikely in this case since the present 2/1 modes are the only significant MHD activity measured. Thus the rotation shear is thought to directly impact tearing stability by making $\Delta'$ less stable or to modify other small island stabilizing physics as is consistent with existing theories and observations in other devices. As the plasma rotation and rotation shear are linearly correlated, the effects of rotation and rotation shear on tearing stability are not conclusively decoupled in the present experiment.

Many of the 2/1 modes trigger in shots with $n = 1$ non-axisymmetric static fields from the
IVCCs. One possibility is that under significantly lowered plasma rotation after the back-transition, applied field shielding by induced image currents at the rational surface can be reduced, potentially providing a small resonant seed island for 2/1 onset. However, the mode triggers even if the applied field is absent, and in the case with the field applied, the mode doesn't trigger at the highest level of applied field during the L-mode, but mostly onsets when the applied field is almost fully decayed or even after the field is turned off. In addition, the onset doesn't strongly depend on varied applied $n = 1$ fields with different poloidal parity which generate different resonant pitch alignment. Hence the most important variable correlated with 2/1 onset seems to be a significant rotation collapse viable only through the back-transition. Rotation reduction enhanced by the applied field could make the plasma more susceptible to 2/1 onset, or its combined impact with potentially lower collisionality (as the applied field lowers the density) might also contribute since the neoclassical pressure destabilization is relevant at lower collisionality. Quantitative estimation of tearing stability and associated neoclassical effects will require implementation of planned diagnostics such as motional Stark effect to measure internal field line pitch.

4. Rotation Profile Alteration by Non-axisymmetric Applied Fields

Non-resonant alteration of plasma rotation by non-axisymmetric magnetic fields is an important tool for rotation control in mono-directed NBI heated tokamak plasmas, and to study the underlying neoclassical toroidal viscosity (NTV) physics [9] such as its collisionality dependence and steady-state behavior, including offset rotation. Rotation influence on macroscopic MHD stability is another key physics study. Initial success in non-resonant alteration of the plasma rotation profile is shown in Fig. 4, which illustrates variation of the plasma toroidal rotation profile during H-mode operation using separately $n = 1$, and $n = 2$ applied fields generated by the IVCC. Plasma boundary movement was properly compensated in the calculation of the rotation profile change measured by a charge exchange recombination diagnostic (CES) [10]. The rotation profiles are translated to a corresponding EFIT normalized flux grid and differenced. The current rise time in the IVCC circuit that applies the braking field is relatively slow (on the order of momentum confinement time), so to separate the effect of the braking field the rotation damping rate in a comparable discharge with no applied $n > 0$ field is subtracted to evaluate the rotation profile damping rates due to the applied $n > 0$ field. Cases utilizing an $n = 1$ field configuration show higher damping than $n = 2$ and both show rotation profile alteration similar to non-resonant damping observed in NSTX in which the damping scales linearly with the plasma rotation [11-12]. Analysis of

![FIG. 4. (a) Comparison of rotation profile change by (a) $n = 1$ applied field configuration in the H-mode rotation profile and (b) $n = 2$ configuration. Shown are the measured rotation profiles (blue and red) and the calculated net rotation damping rates due to the non-axisymmetric field alone (green).](image-url)
existing data using ECE and magnetic diagnostics shows that tearing modes leading to resonant rotation damping are absent in these cases. The $n = 1$ applied fields also do not exhibit mode locking at rotation levels reduced significantly below the Fitzpatrick locking criterion [13], an additional characteristic consistent with non-resonant rotation damping.

5. RWM Active Feedback Physics Design

![Image](image.png)

**FIG. 5.** (a) KSTAR locked mode (LM) and saddle-loop (SL) sensors with middle IVCCs in the VALEN-3D model. (b) B-normal distribution of the unstable $n = 1$ eigenfunction used in the calculation.

Initial computations of active RWM feedback using the VALEN code [14] with idealized sensors measuring poloidal field perturbations ($B_p$ sensors) showed that the $n = 1$ mode can be stabilized up to $\beta_N = 4.8$, corresponding to $C_\beta = 99\%$ of the $n = 1$ ideal with-wall limit (displayed in blue in Fig. 6a and Fig. 7a), via control fields produced by the middle-IVCC with minimum control power of 0.83 kW for an ideal control system [3]. Here, $C_\beta = (\beta_N - \beta_{N_{\text{no-wall}}}) / (\beta_{N_{\text{wall}}} - \beta_{N_{\text{no-wall}}})$. In the present analysis, an expanded set of sensors presently installed on the device are included in the VALEN model to determine an optimal sensor configuration for future active $n = 1$ control. The four (90° toroidally separated) midplane locked mode (LM) sensors and 40 (10 poloidal positions for the same four toroidal positions of the LM sensors) off-midplane saddle loop (SL) sensors are included and the geometry of these sensor sets are shown in Fig. 5, along with the 4 middle-IVCCs and the KSTAR conducting structure. The LM and SL sensors are all single-turn loops mounted on the inner vacuum vessel surface which can measure radial and poloidal components of the RWM, respectively. The circuit parameters for each middle-IVCC quadrant, $L = 44 \mu H$, $R = 3.66 \Omega$ with $L/R = 12$ msec, and a single $n = 1$ unstable eigenfunction from DCON ($l_i = 0.7$ and $\beta_N = 5.0$ projected KSTAR equilibrium with H-mode pressure profile) are used.

The growth rate calculation using the LM sensors in green in Fig. 6a shows that a limited control performance corresponding to $C_\beta = 16\%$ ($\beta_N$ up to 3.0) with a proportional controller gain, $G_p = 14 \text{ V/G}$ can be achieved. Note that the applied feedback gain and phase are optimally chosen to produce the highest possible $C_\beta$ in the calculations. As the prompt field of the control coils directly opposes the mode field in the LM sensors, and the mutual coupling between sensors and coils is strong, the applied control field should be compensated from the sensors to better detect the mode. The control performance is additionally limited by the presence of the elongated horizontal port penetrations facing the LM sensors. Computations show that control coil-induced vessel currents circulating around the port penetrations can significantly distort the measured $n = 1$ field. Figure 6b shows the amount of circulating...
current around the penetrations on the inner and outer vessel walls during \( n = 1 \) feedback. Theoretically performed ideal compensation of the vessel current shows that the control performance can be increased up to \( C_\beta = 98\% \) from a value of 37\% reached by compensating only the applied control field.

Among the 10 SLs at the toroidal positions shown in Fig. 5, control performance of two up-down sensor pairs, SL05-06 and SL01-10 are examined. The SL01-10 sensors measure about 30\% higher mode field than the SL05-06 which results in higher control performance (23\% higher \( C_\beta \)) as shown in Fig. 7a. Unlike the LM sensors, vessel current near the SL sensors does not significantly limit the control performance, and compensation of the applied control field alone can increase the \( C_\beta \) from 44\% to 86\% for the SL01-10 sensors which is significantly higher than the expected performance by the LM sensors with the same compensation. Power requirements for RWM stabilization are calculated from time domain feedback control using the compensated SL01-10 sensors with a feedback gain 2 V/G. Feedback is started when the growing mode amplitude becomes 10 G and the mode is fully suppressed by the feedback as shown in Fig. 7b. Potential control degradation by shielding of the mode field by nearby conductive passive plates (Fig. 5) when the mode rotates by feedback is found not to be severe. For the idealized case assuming no sensor noise, peak values of the required coil currents and voltages are less than 312 A-turn and 0.6 V/turn for each coil and the total RMS power is estimated as 0.1 kW for the entire middle-IVCC coil set.

![Figure 6](image1)

**FIG. 6.** (a) RWM growth rate vs. \( \beta_N \) with feedback using the LM sensors. The computed feedback improvements expected from external field compensations are shown. (b) Control coil-induced circulating vessel current around the LM sensors during feedback shown in Fig. 7b.

![Figure 7](image2)

**FIG. 7.** (a) RWM growth rate vs. \( \beta_N \) with different SL sensor configurations. (b) RWM amplitude and phase during feedback stabilization using the SL01-10 sensor sets (8 total). (c) Total RMS control power versus white noise level in the SL01-10 sensors.
Figure 7c shows the increase in required control power up to a modest 3.4 kW with increasing sensor noise level. As the SL sensors measure much weaker mode field than the ideal Bp sensors, the feedback allows only a 2 G noise level (compared to 10 G noise level allowed in the case with ideal Bp sensors [3]). At this noise level and above, the mode amplitude cannot be suppressed and sustained below its initial value. Further calculations with faster control coil circuit response times and a suggested new set of future sensors are being made to provide more useful guidance for RWM control design in KSTAR.

6. Conclusions and Discussion

The H-mode operation of KSTAR has been expanded toward higher values of $\beta_n/l_i$ computed by equilibrium reconstructions and is planned to probe the $n = 1$ no-wall stability limit made possible by various improvements in machine capabilities in 2012. Work continues to develop reconstructions including measured internal profile constraints to describe the H-mode profiles with high reliability and for improved evaluation of MHD stability limits. The $m/n = 3/2$ and $2/1$ tearing modes are observed in the device for the first time and their onset conditions and impact on plasma confinement are characterized. It is found that rotation shear at the mode rational surface is well correlated with decreased $2/1$ mode amplitude and higher beta required for mode onset. Expected future H-mode operation may present a different tearing mode behavior at higher beta. Plasma rotation profile alteration by $n = 1$ and 2 applied fields from the IVCCs is analyzed and resulting rotation damping rate profiles from both field configurations are consistent with non-resonant damping, which is also supported by additional evidence. Doubled IVCC current and expected higher ion temperature in 2012 will enable experiments to have stronger non-resonant braking and thus implies more favorable condition to study NTV physics. Progress from the initial projection of global $n = 1$ active control in KSTAR includes expanded calculations using the present device sensors. The midplane locked mode sensors are found to be strongly affected by nearby feedback-induced vessel current, and the off-axis saddle loops with proper compensation of the prompt applied field exhibit higher control performance corresponding to $C_\beta$ of 86%. Successful feedback using existing saddle loop sensors with compensation of the applied field shows that growing modes can be actively stabilized with modest RMS control power. This research was supported by the U.S. Department of Energy under contract DE-FG02-99ER54524.

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