Extension of operational boundary of high-beta long-pulse operation at KSTAR*

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Abstract: For the realization of the fusion reactor, solving issues for high beta steady-state operation is one of the essential research topics for the present superconducting tokamaks and in this regard, KSTAR has been focusing on maximizing performance and increasing pulse length addressing scientific and technical issues. Typically, previous study on high beta operation has been focusing on advanced scenario in relatively short pulse discharge at KSTAR and partial success has been reported. However, it must be stressed that it is also essential to verify compatibility of developed high beta scenario to long-pulse and stable long-pulse operation is possible only with reduced level of performance compared with that of the short-pulse. In this work, the results of recent experimental approaches in long-pulse operation are presented focusing respectively on high βp, high beta poloidal. For high βp experiments, conditions of the maximum βp are investigated mainly by parametric scans of toroidal magnetic field (B_T=1.2-2.0 T) and neutral beam injection power (3-5MW). The achieved βp is above 3 with I_p=0.6 MA, B_T=1.2 T and P_Ext ~ 5 MW and it is found to be limited by m/n=2/1 tearing mode and is sensitive on the internal inductance and safety factor. For high βp experiments, conditions of the maximum βp is investigated mainly by parametric scans of plasma current (I_p=0.4-0.7 MA) and also neutral beam injection power (3-5MW). The achieved βp is also above 3 with I_p=0.4 MA, B_T=2.9 T and P_Ext ~ 6 MW and it is found to be limited by heating power and there is no indication of MHD activities. In addition, high βp discharge is due to high bootstrap fraction, closed to the state of fully non-inductive current drive. However, pulse length is limited to 12 second by excessive heat-load on the protection limiters which is turned out mainly due to NBI prompt loss. Finally, several attempt for current profile tailoring will be addressed developing an internal transport barrier and reversed q-profile using counter neutral beam injection.

1. Introduction

For the realization of the fusion reactor, solving issues for high beta steady-state operation is one of the essential research topics for the present superconducting tokamaks and, in this regard KSTAR [1-3], has been focusing on maximizing performance and extending pulse length addressing scientific and technical issues in long-pulse high-beta operation. Typically, previous study on high beta operation has been focusing on advanced scenario in relatively short pulse discharge at KSTAR and partial success has been reported [4]. However, it must be emphasized that it is also essential to verify compatibility of the developed high beta scenario to the steady-state operation and in the previous study, stable long-pulse operation is possible only with reduced level of beta compared with that of the short-pulse.

In this work, the results of recent experimental approaches in long-pulse relevant operation are presented focusing specific scenario respectively on high beta normalized (βn) and high poloidal beta (βp) while the limiting factors for higher beta and longer pulse-length will be discussed for each scenarios. Figure 1 shows general dependence of the plasma beta on both plasma current and toroidal magnetic field which is calculated with zero dimensional power balance model with fixed level (~ 10 MW) of external heating and plasma shape at KSTAR conditions. In this work, as guided by the
figure, to maximize for normalized $\beta_N$, toroidal magnetic field ($B_T$) is the critical parameter to be scanned and therefore $B_T$ is reduced up to 1.2 T to reach maximum $\beta_N$ and the dependence of the onset of tearing modes is investigated in terms of internal inductance and safety factor. As for the high $\beta_p$ attempt, the plasma current ($I_p$) is the main parameter and $I_p$ is scanned up to 0.4 MA to reach maximum $\beta_p$. In parallel, for high $\beta_p$ discharges, the bootstrap fraction is also important parameter to be investigated with respect to steady-state operation and capability for fully non-inductive discharge is also addressed. Finally, implementations of additional high operational scenarios, such as internal transport barrier (ITB) formation and reverse shear (RS), are presented focusing on the plasma current profile control capability using early heating and counter neutral beam current drive.

2. Development of high $\beta_N$ plasmas

For high $\beta_N$ experiments, conditions of the maximum $\beta_N$ is investigated at typical H-mode discharges mainly by parametric scans of toroidal magnetic field ($B_T=1.4-2.0$ T) and neutral beam injection power ($P_{NBI}=3-5$ MW) with the given plasma current ($I_p\sim0.6$ MA) and the typical plasma shape. Typically for long-pulse operation, the achieved $\beta_N$ is about 2.5 with $I_p=0.6$ MA, $B_T=1.4$T and $P_{NBI}\sim5$ MW at the edge safety factor ($q_{95}$) of 3.4 and it is sustained more than 10 seconds without disruption. However, when
\( \beta_N \) is increased close to 3 using \( P_{\text{NBI}} = 5 \) MW with the safety factor \((q_{95})\) of 3.4, it is found that high \( \beta_N \) phase is limited by \( m/n = 2/1 \) tearing mode (TM) as shown in Fig. 2. The onset of tearing is sensitive on the internal inductance \((l_i)\) which is changing relatively longer time scale of a few seconds, i.e., current diffusion time scale in the discharge. For a lower \( l_i \) (~0.8), discharge with a higher \( q_{95} \) (~ 5), similar \( m/n = 2/1 \) TM is triggered at somewhat lower \( \beta_N \sim 2.4 \). However, though it degrades confinement somewhat, it does not lead to a disruption and onset of \( n=1 \) TM is delayed after additional NBI heating until \( l_i \) is decreased to 0.8. Besides the disruptive events by \( n=1 \) TM (>2.5) discharges, in discharges with typical \( l_i \), more benign \( m/n = 3/2 \) TMs are also unstable when \( \beta_N \) is above 2 and it affects the global confinement degradation of roughly 20%. To check the effect of effect of \( l_i \), a further discharge is conducted with an elevated \( l_i \sim 1.0 \) by tailoring heating sequence (Figure 3.). In this discharge, the plasma current was initially maintained at a higher level of 470 kA and then was lowered to 430 kA at \( B_T = 1.2 \) T for better equilibrium control at the earlier phase of the discharge, resulting in somewhat lower \( q_{95} \) around 4 compared to the target \( q_{95} \) of 4.5 chosen for higher plasma stability. The time-averaged \( \beta_N \) and plasma stored energy during this period are 3.3 and 270 kJ, respectively. The high \( \beta_N \) phase was limited by the onset of a 2/1 tearing mode around \( t = 4.3 \) s in the discharge. Finally, motivated by the previous study, the effect of \( q_{95} \) is also investigated with raising up \( I_p \) up to 0.8 MA at fixed \( B_T = 1.4 \) T targeting \( q_{95} \sim 2.25 \). To test the effect of \( q_{95} \), further decrease of \( q_{95} \) is also studied. One of expected benefits in extremely low \( q_{95} \) operation is inherent removal of performance limiting MHD modes by pushing dangerous rational surfaces \((\text{e.g.,} \ 2/1 \text{ and } 3/2 \text{ surfaces})\) toward safe region \((\text{i.e.,} \ \text{the region with small pressure gradient})\) [5]. Figure 1 depicts the characteristics of MHD instabilities during \( q_{95} \) scan in low \( q_{95} \) operation of KSTAR. As depicted in figures 1d) and 1e), toroidal mode number \( n \) of dominant MHD instability shifted from low \( n \) to high \( n \) along with decreasing \( q_{95} \); i.e., shift from \( n=1 \) to \( n=4 \). In addition, this process is repeated again in reversed order with increasing \( q_{95} \) confirming the \( q_{95} \) dependence.

3. Optimization of high \( \beta_p \) plasmas

The high-\( \beta_p \) scenario with a certain reduced the plasma current is an very promising scenario for the high performance long pulse discharge in KSTAR near term due to the limited heating and current drive power.
However, the main disadvantage of this scenario in KSTAR is turned out to be an increase of the bad orbit loss of the fast ion by the larger drift. It causes the overheating of plasma facing component by the fast ion loss striking the edge surface of the outer poloidal limiter, hence the early termination of the long-pulse steady-state plasma discharge by the protection interlock.

With regard to the high $\beta_p$ experiments, conditions of the maximum $\beta_p$ are investigated mainly by parametric scans of $I_p=0.4-0.7$ MA and also $P_{\text{NBI}}=3\text{--}5\text{MW}$. The achieved maximum $\beta_p$ is above 3 with lowest $I_p$ of 0.4 MA, $B_T=2.9T$ and $P_{\text{ext}}\sim6\text{MW}$ including 0.7 MW of ECH and up to now, maximum $\beta_p$ is found to be limited by heating power and without indication of MHD activities ($\beta_N\sim2$) due to elevated $q_{95}\sim11$. Upto now, operational rage of high $\beta_p$ scenario at KSTAR is limited within certain level of plasma current ($I_p<0.5$ MA) and $q_{95}>8$. Compared with previous high $\beta_p$ scenarios in JT60U [6] and DIII-D [7], developed high $\beta_p$ scenario at KSTAR is different in core transport characteristics. Previous $\beta_p$ scenario has a weak internal transport barrier but for the above discharge, there is no internal transport barrier in core region and hence the internal inductance is higher ($l_i\sim1.2$). High $\beta_p$ and better confinement are mainly due to the pedestal increase similar to Hybrid scenario [8] and high $l_i$ discharges [9]. High $\beta_p$ scenario provides higher bootstrap fraction ($\sim50\%$ of total $I_p$, which calculated based on the measured pressure profiles) compared with the high $\beta_N$ discharge, closed to the state of fully non-inductive current drive as indicated by PF coils trajectories and loop voltage trace in Figure 4. NUBEAM [10] calculation predicts the NBCD current drive is roughly 0.2 MA which is consistent with bootstrap current calculation. However, though the developed scenario is a good candidate for advanced steady-state operation with fully non-inductive current drive, the sustained pulse length is limited by 12 seconds due to an excessive heat-load on the protection limiters which leads to the safety interlock for PFC temperature ($T_{\text{PFC}}\sim800\text{K}$) rise to shut-down the plasma. According to the NUBEAM calculations of neutral beam fast particles [11], the large orbit loss of NBI fast ions at low $I_p$ operation which is essential for high $\beta_p$ is the main cause of the $T_{\text{PFC}}$ rise and the calculated heat flux pattern is in good agreement with the measured $T_{\text{PFC}}$ distribution (Figure 5a). The dependence of fast ion losses with the plasma current is also experimental verified by the measurement of fast ion loss detector (FILD) [12] which is installed near outside midplane of KSTAR during the $I_p$ scan phase from $I_p=0.35$ to 0.5 MA as shown in figure 5b). Further optimization is also investigated with active cooling of PFC and improving fast ion confinement by plasma density and outer gap control.
Development of current profile control using various heating and plasma scenario

Figure 5. a) fast ion losses calculated on poloidal limiters and the measured temperature rise at the corresponding limiters (Ip=400 kA) b) the measured NBI prompt loss by fast ion loss detectors (FILD) during Ip scan.

4. Development of current profile control using various heating and plasma scenario

The access of the internal transport barrier (ITB) formation [13] is dealt with an important physics issue in the most of tokamaks. Investigation of the ITB formation condition in the KSTAR is also valuable in the point of view although its heating and current drive systems are not fully equipped to see the ITB with H-mode. We have therefore assumed that an early injection of the full NBI power (~ 4.5 MW) during the current ramp-up would give a chance to form an internal barrier if the plasma could stay in the L-mode. To avoid the H-mode transition, we have produced inboard limited plasmas with detaching from the both upper and lower divertors. This was also effective to keep the injected power loss minimum during an on-axis heating. An ITB formation during L-mode has been observed which shows improved core confinement as shown
in the Figure 6. Time trace parameters indicating the plasma performance such as temperatures, the stored energy and the $\beta_N$ are comparable to the H-mode in the discharge. Ion and electron temperature profiles show the barrier clearly in the temperature, and it was sustained for maximum 3.6 s in the dedicated experiment. Reconstruction of the current profile using a measured time-resolved pitch angle is under preparation, and the study of possible MHD activity is followed in this campaign.

In thermo-nuclear tokamak discharge, plasma current and its resulting field strongly govern the characteristics of physics phenomena such as intrinsic torque direction. Thus it is highly beneficial to conduct comparative experiments by changing plasma current direction with fixing other parameters. In addition, by switching plasma current direction, we could easily implement counter injection of neutral beams (NBs), which are utilized as main workhorse of current drive and external torque in modern fusion devices.

![Figure 7](image)

**Figure 7.** Reversed $I_p$ discharge with counter NB current drive (NBCD). a) plasma current $I_p$, b) NBI heating power, c) loop voltage, magnetic flux, and electric power, d) $D_\alpha$ signal as an indicator of H-mode, and e) safety factor $q$ profile at timing of vertical dashed line.

However, for reversed Ip operation, KSTAR cannot use blip resistors which provide almost half amount of total loop voltage during plasma start-up phase. In order to overcome the handicap of low loop voltage start-up, we adopt ECH-assisted start-up with trapped particle configuration [14]. With using the mentioned technique, 500 kA level of reversed Ip H-mode discharge was stably demonstrated and weakly reversed shear discharge was steadily sustained with 3.4 MW level of counter NBCD as shown in figure 7. Here, hollow current profile is formed by the combination of counter NBCD and externally driven inductive current in the middle of plasma current flat-top. Note that the requirement of inductive current needs to be increased for compensating the portion of counter NBCD. It means that we may sustain/alter various current profiles by changing the amount of NBCD and plasma current level. It is beneficial especially for physics studies in super-conducting tokamaks, for instance KSTAR, since superconducting tokamak has a limitation in fast ramp-up of plasma current. The fast ramp-up of plasma current is typical method used in normal-conducting tokamaks for implementing hollow current profile and reversed shear discharge for advanced
operation. In future, we will study the dependencies of plasma current direction with including counter NBCD effect in order to reveal the underlying physics mechanism in various fields such as intrinsic torque and NTV physics.

5. Conclusion

The recent effort of extension of operational boundary at KSTAR is addressed focusing on high beta long-pulse scenario in this work. Firstly, high $\beta_N$ scenario is developed tuning toroidal magnetic field, plasma current, safety factor and internal inductance. As a result, high $\beta_N (>3 )$ discharge is obtained without a onset of tearing mode (TM) sustained more than 3 second which is larger than current diffusion time. Onset characteristic of TM is also investigated up to very low $q_{95} \sim 2$ and TMs with lower toroidal mode number are suppressed though high n TM is more unstable.

Secondly, as a good target for long-pulse steady-state operation, $\beta_p$ discharge is developed tuning up optimal plasma current for high confinement factor and bootstrap current. As a result, a close to fully non-inductive high $\beta_p$ discharge is obtained at relatively low plasma current and higher safety factor. It is demonstrated that the developed mode can be sustained for steady-state without any MHD event but due to the high heat-flux to poloidal limiter, the pulse length is limited to 12 second up to now and further optimization is also investigated with active cooling of PFC and improving fast ion confinement by plasma density and outer gap control.

Finally, other possibility for high beta long-pulse scenario is investigated focusing on the present capability of current profile control. An early heating of neutral beam injection with L-mode edge leads to an internal transport barrier both in electron and ion thermal channels and could last several seconds without strong MHD crash. Also, a first reverse shear discharge at KSTAR is developed using counter neutral beam current drive in reverse plasma current operation extending operational boundary of KSTAR toward long-pulse steady-state discharge.

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Reference