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Recent process in KSTAR long pulse operation

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KSTAR has a mission such as achieving a pulse length for more than 300 seconds and achieving a high-performance plasma1. The pulse length of the KSTAR discharge has increased each year gradually. Assigned research on the long pulse operation in KSTAR has been conducted since 2015. The pulse length of 90 seconds is achieved in the 2018 KSTAR experimental campaign.

The high β_P operation mode which helps to be in high fNI is preferred to explore the long pulse discharge. The high β_P operation mode in KSTAR is achieved by optimizing the operating conditions such as the reduction of plasma current and the precise control of the ECCD deposition location. Operating conditions of the long pulse discharge are usually I_P=400-450 kA, B_T=1.8-2.5 T, P_{NBI}=2.0-4.3 MW, and P_{EC}=0.7 MW. Plasma parameters of the long pulse discharge are presented as $n_{e,core}$˜2.5-5.5x10^{19} m^{-3}, $T_{e,core}$˜2.0-6.0 keV, β_P˜1.3-2.7, and V_{loop}≤0.1 V.

The operating limits which do not allow to go the longer pulse are as follows; The first is the heat control on the PFCs. KSTAR has a limited PFC cooling capacity compared with heat sources at present. The temperature on the PFCs is kept rising, especially the poloidal limiter and the divertor, and any steady-state condition of temperature is not observed yet. The second is the significant non-linear drifting signal in the magnetic diagnostics such as Rogowski coil, magnetic probes, and flux loops. If magnetic signals used in the real-time control of plasma shape are suffered from significant non-linear drift during the long pulse discharge, the plasma shape has distorted and deteriorated control accuracy and reliability. The third is the plasma performance degradation for long time scale. KSTAR routinely observes gradual performance degradation in the long pulse discharges.

In the 2018 long pulse experiment, the plasma shape and the operating condition of NBIs have been firstly optimized to reduce the heat on PFCs such as divertor and poloidal limiter, which it is allowed to conduct the longer pulse length. And the real-time EFIT operation utilized for the real-time plasms shape control has been optimized by excluding signals showing the significant non-linear drift. The performance degradation for a long time scale is under investigation and resolving.

Figure 1 shows the overview of the longest discharge #21735, a pulse length of ˜90 seconds, achieved in the 2018 KSTAR experimental campaign. Plasma features are plasma current of 400 kA, toroidal magnetic field strength of 2.44 T, NBI power of 2.8 MW, and ECH power of 0.7 MW. High β_P operation mode is sustained until ˜50 s with high electron temperature reaching ˜6 keV with electron density of ˜2.5x10^{19} m^{-3} and ion temperature of ˜2 keV at the plasma center. After ˜50 s, the plasma performance β_P is degraded and accelerated with the change of the X-point location that is helpful to be the longer pulse length by reducing the burden of PF3 and PF4.

As shown in Fig. 2, the discharge #21735 is suffered from significant non-linear drifting signals in the magnetics due to the hot plasma with the long pulse length. Figure 2(a) shows that plasma shape analyzed with non-linear drift corrected signals is much different from one with un-corrected signals, especially in Rout and RX. Also, the rate of β_P degradation is evaluated to be reduced a little bit when it analyzed with non-linear drift corrected signals. Figure 2(b) shows that the influence of drifting signals in magnetics on the temperature of the poloidal limiter which is a region showing the highest temperature among PFCs in the long pulse discharge at present. By excluding significant drifting signals of the magnetics in the analysis of the real-time EFIT, the plasma shape is relatively controlled further to the real target. Controlled and stable plasma shape in terms of Rout especially leads to stable and low poloidal limiter temperature further.

For the longer pulse discharge in KSTAR, the heat to the poloidal limiter as well as the divertor must be reduced and controlled. KSTAR is upgrading its H&CD with NBI of ˜12MW in 2020 and the divertor material and shape to control the heat load on the plate in 2021. The fast-ion loss driven by the KSTAR NBI system is the leading cause of overheating the poloidal limiter. The correlation between plasma shape and temperature on the poloidal limiter is related to the behavior of fast-ion particles. Ref. 2 discusses that the extended plasma shape to the outward leads the fast-ion loss through a bad orbit loss process. Furthermore, the unintentional change in plasma shape by non-linear drifting signals is likely to cause plasma performance degradation.

The fast-ion loss is also enhanced by MHD activities in the core and transport regions such as NTM and the Alfven mode. The increase of plasma current, i.e., from 400 kA to 600 kA, is expected to reduce the bad orbit loss of the fast ion. However, the temperature growth rate of the poloidal limiter varied little with the increase of plasma current in the KSTAR long pulse experiment. In these discharges, the fast-ion loss due to the enhanced transport by MHD activities is considered more dominical than the fast-ion loss through the bad orbit. The enhancement transport of fast-ion loss was analyzed by using TRANSP and NuBDeC 2. Thus, the presence of MHD activities in the core and transport regions reduces the absorption of the NBI power, which results in the degradation of plasma performance and increases the temperature of the poloidal limiter,

as well as makes worse plasma performance in itself.
At the discharge #21735, PF1-PF4 coils reach their limit of the induced current set to 15 kA. Therefore, additional H&CD and higher plasma performance are required for reducing the burden of PF coils and for conducting the longer pulse length up to over 102 seconds. Based on existing KSTAR long pulse discharges, it is analyzed whether the H&CD upgrade will allow going for the longer pule operation within the operating limits. Mainly we focus on how to control the heat on the PFCs and the significant non-linear drifting magnetic signals. Also, we suggest the practical guidelines to achieve the longer pulse length with the high-performance plasma

Reference
1 Lee, G.S., et al., Nucl. Fusion 40 (2000) 575.
2 Rhee, T., et al., Phys. Plasmas 26 (2019) 112504

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