# Operation limits in KSTAR

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## 1. Introduction

The operating space of a tokamak can be generally characterised by Hugill diagram [1] where the boundary is set by runaway electron limit, plasma current limit by low edge *q*-value, Murakami limit determined by power balance [2], and Hugill limit. In particular, the Hugill limit is known to be related with Greenwald limit [3] exhibiting that the most achievable plasma density is proportional to the plasma current. In this study, we investigate the operation window of KSTAR via Hugill diagram by plotting using experimental database collected from year 2011 to 2013 with particular focus on density limits. The low density limit and effects of error field are discussed and the upper density limit in terms of Greenwald density is evaluated.

## 2. Operation window of KSTAR

The operating space of KSTAR is investigated by Hugill diagram which is shown in figure 1 (a) where the data is separated by operational modes; L-mode and H-mode. H-modes exhibits broader operational window compared with L-modes mainly due to their higher heating power. The power dependency of the operation window is documented in figure 1 (b) where the data points include ECRH as well as NBI. As increasing the heating power, extension of the operating space is clearly seen. In terms of the plasma current limit by low edge *q*-value, KSTAR plasmas reach $q^*$ of 2 close to the MHD limit where $q^*$ is the cylindrical kink safety factor, a definition incorporating the effects of non-circular, diverted plasma cross-section. KSTAR has been operated mainly at high edge *q*- regimes so that the low *q*-regime has not been extensively explored yet. The density limits, low density locked mode limit and Greenwald density limit are to be discussed in more detail in the following sections.

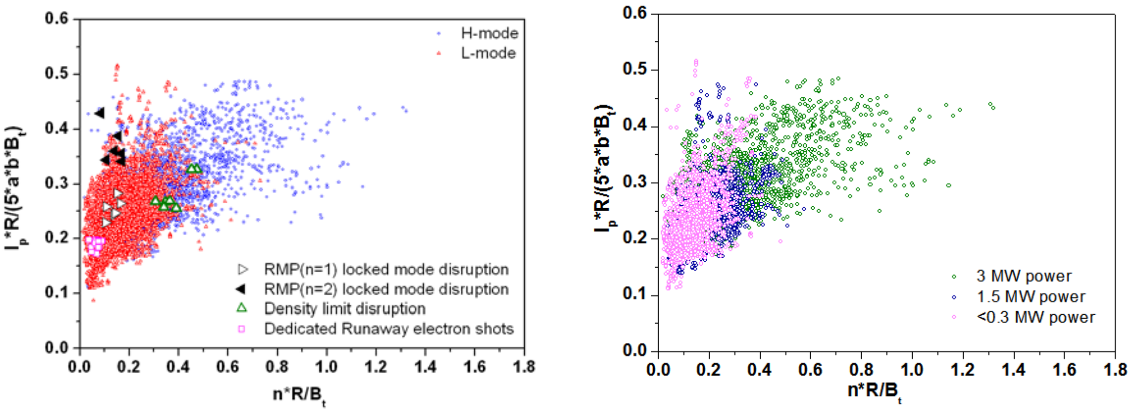


Figure 1 (a) The operating space of KSTAR; Hugill diagram for L-mode and H-mode plasmas. (b) Power dependency of the operating space in KSTAR

## 3. Low density limit and effect of error field in KSTAR

The low density limit is observed to be fairly low as shown in figure 1 and no clear signature of low density locked mode limit in common KSTAR operations. Some dedicated experiments for runaway fast electrons are conducted as presented in figure 1. Although higher amount of runaway electrons is observed, these discharges are sustained stably without disruptions. However, this low density limit is found to rise due to locked mode disruptions as applying resonant magnetic perturbation (RMP) (see the black triangle symbols in figure1). This can be explained in connection with error fields. In DIII-D, it is reported that the locked modes set a low density limit through error fields [4]. The locked modes occurred due to the resonant field errors caused by irregularities of the plasma shaping coils. Large error fields in DIII-D induced a high low density limit but when the irregularities were corrected, the limit of the low density was extended. As shown in figure 2 (a), the boundary set by $q^*D = 72$ due to locked modes where $D = q^* n_e R/B_t$ is the DITE parameter, can be enhanced to the solid line of $D \sim 9$ in DIII-D [4]. In an opposite way to DIII-D, discharges where the error field is increased intentionally by applying RMP are analysed to find out the error field effect on the low density limit in KSTAR. The analysis result shows that when RMP is applied locked modes can occur so that shots are disrupted even though they don't reach the low density limit presented in figure 1 (a). This implies that the low density limit could be altered by the error field induced by RMP. In addition, it is found that $n = 1$ RMP and $n = 2$ RMP exhibit slightly different low density locked mode limits as shown in figure 2 (b). $n = 1$ RMP looks to drive higher low density locked mode limit than $n = 2$ RMP; the Greenwald density fraction of 6% to 16% is observed for $n = 2$ RMP but it is raised to 14% to 21% for *n* = 1 RMP. This is thought to result from the fact that mode locking occurs more easily and frequently for *n* = 1 modes compared with *n* = 2 modes.

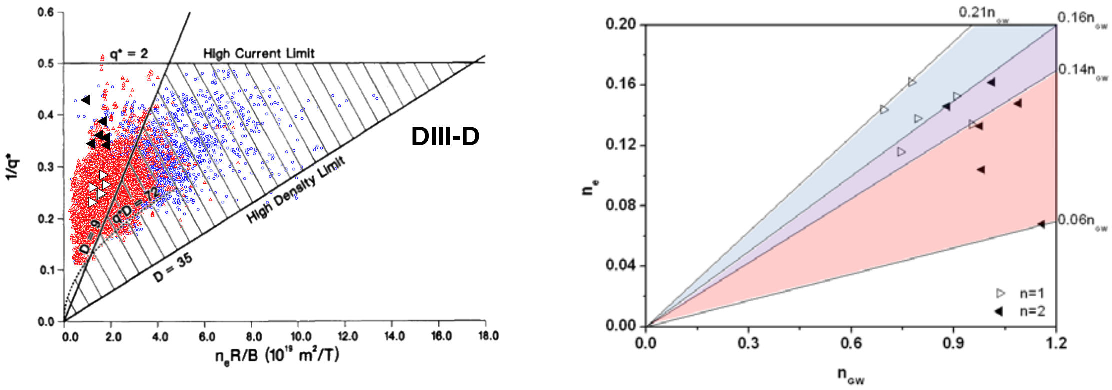


Figure 2. (a) Hugill diagram for DIII-D and KSTAR where the effect of error fields on the low density limit is highlighted. (b) Greenwald density fraction of n = 1 RMP and n = 2 RMP exhibiting different low density locked mode limits in KSTAR.

**4. Greenwald density limits in KSTAR**

Greenwald density fractions are evaluated in KSTAR plasmas. In a Hugill diagram, the lower diagonal boundary is related to Greenwald density limit. Greenwald density limit is defined as $n_{GW} = \frac{I_p}{\pi a^2}$ [5]. To examine Greenwald limit in KSTAR, plot of the line average density versus Greenwald limit of each shot is drawn in figure 3. About 60% and above 100% of Greenwald density is observed for L-mode and H-mode discharges, respectively. In L-mode discharges, this is conjectured as a fuelling limit, the so-called “soft density limit” [5] due to inability of neutrals to penetrate deeply into the plasmas for plasmas with divertor configurations. In H-mode discharges, it is thought that discharges with the density above $1.0n_{GW}$ possibly result from local effects such as peaked density profiles and high triangularity. Edge transport barrier formation in the particle channel is expected to contribute to increase the density level as well. Here, it is noteworthy that while generally successful, Greenwald density limit misses any local or profile dependences and produces results without a clear connection to the underlying physics.

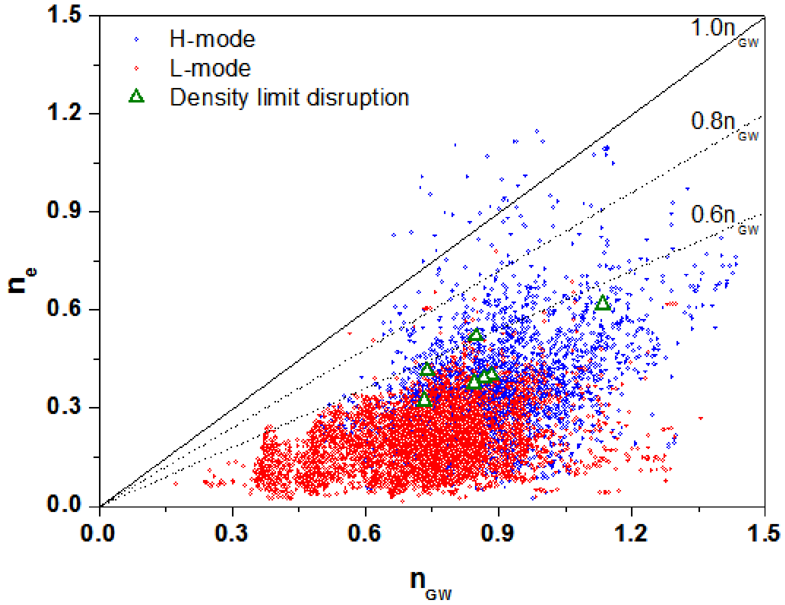


Figure 3. Plot of line average density versus Greenwald density limit in L-mode (red) and H-mode (blue). The solid line indicates 100% of Greenwald density. The green triangles present density limit disruptions due to core impurity accumulation and MARFE.

## 5. Summary and future work

The operation limit of KSTAR is investigated using Hugill diagram with database of year 2011-2013. H-mode discharges show broader operating space compared with L-mode which is due to power dependency. The Hugill diagram exhibits no noticeable low density locked mode limit. This is thought to be as a result of low error fields in KSTAR. It is supported by experimental results with RMP where the low density locked mode boundary appears. A higher low density locked mode limit is observed for $n$ = 1 compared with $n$ = 2 RMP cases. This is thought to result from the fact that mode locking occurs more easily and frequently for $n$ = 1 modes compared with $n$ = 2 modes. The Greenwald density fractions as high density limit are evaluated in KSTAR plasmas. About 60% and above 100% of Greenwald density are observed in L-mode and H-mode discharges, respectively.

## Reference

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