Fast ion loss by resonant magnetic perturbation in KSTAR

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Resonant magnetic perturbation (RMP) is utilized for ELM mitigation/suppression in KSTAR. However, it has been found through the modeling and the experiments that RMP for the ELM control can affect the fast ion confinement. Recent numerical simulations have shown that the beam ion loss in the presence of non-axisymmetric magnetic perturbation (or resonant magnetic perturbation) is enhanced at the toroidally localized positions [1,2] depending on the perturbation field configuration. In 2011 experiment in KSTAR, fast ion loss at the FILD (fast-ion loss detector) position was enhanced during n=1 / +90° phasing RMP application [3], and it has been found on ASDEX-Upgrade that loss rate of the fast ion was up to 6 times higher than the NBI prompt loss [4]. However in 2012, it has been ever found that almost suppressed during RMP phase with same coil current configuration at the same FILD location in KSTAR [5]. In addition, in 2013 experiment in KSTAR, non-axisymmetric fast ion loss behavior according to the perturbed radial B–field (B_r) direction and has been shown. In this paper, fast ion loss behaviors during RMP induced mode-locking will be presented. In addition, Fast-ion orbit simulation results from the modified LORBIT codes under the KSTAR RMP experimental conditions will be presented.

A scintillator based fast ion loss detector (FILD) [3] to study fast ion loss mechanism in KSTAR. Figure 1 shows #9093 shot with RMP. In this case, the perturbed radial B–field by the n=1 RMP is toward to outboard side and fast ion loss rate from FILD CCD camera and PMT arrays are increase by factor of 2 (during H-mode, yellow colored region) and even 1 order higher (locked mode, red region) compare to pre-RMP phase (green region). This experimental result raises the significant caution on the RMP-induced

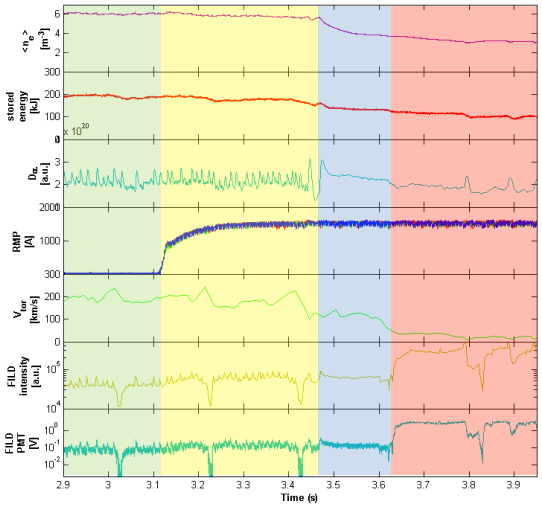

Figure 1. 4 different fast ion loss characteristics: pre-RMP region (shaded with green), ELMy RMP region (yellow), L-mode RMP region (blue) and RMP locked mode region (red).

fast-ion loss, especially in case of RMP-induced mode locking. Furthermore, asymmetric localized fast ion loss by the B_r perturbation should be clarified. In order to understand the fast ion loss characteristics and mechanism, the conventional Lorentz orbit (LORBIT) code [6] has been modified through addition of the three-dimensional calculation routine to deal with the perturbed vacuum magnetic field . In addition, operators for collision and pitch-angle scattering have been added to obtain the realistic loss fraction of the beam ions [7]. The modified LORBIT code is also capable to calculate fast-ion loss on the three-dimensional KSTAR vacuum vessel geometry. NUBEAM code provides the ionization profiles of injected beams. KSTAR have 2 NBI beam lines and well aligned to tangential direction. Initial beam energy is 90keV and the initial pitch-angle angle ($\Lambda = \arccos(v_{||}/v)$) of the ionized fast particle ranges between 0˚ and 60˚ (peak of the pitch-angle distribution is at 40˚). The LORBIT simulation was performed under the vacuum field during n=1 RMP induced locked mode (#9093, red region in figure 1). Since the plasma rotation is decreased almost to zero, the screening effect of perturbation field is negligible. Full gyration orbits of 200,000 particles have been followed for 1msec in the axisymmetric field (no RMP) and three-dimensional field (RMP application). Since the ion collision rate is about 1.5kHz for parameters used for LORBIT code, pitch-angle scattering has minimum effect. The LORBIT code simulation results shows that most of lost ion hit three poloidal limiters and lower passive plates even in three-dimensional field. (Fig. 2) It is because; poloidal limiters are placed at certain toroidal angles, 145˚, 170˚ and 190˚. Therefore although the fast ion

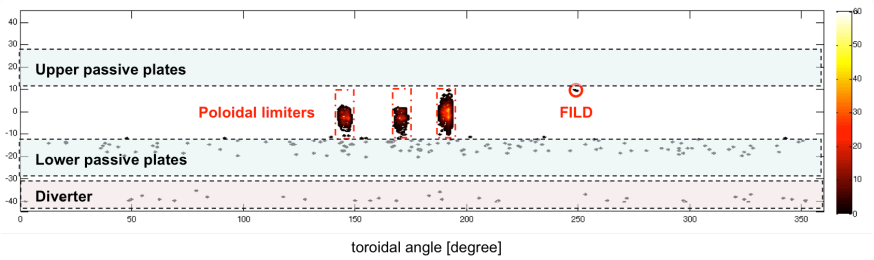

Figure 2. Fast ion loss position calculated by LORBIT code. KSTAR three-dimensional wall is consist of upper and lower passive plates, diverter, three poloidal limiters and FILD-probe. Most of lost ion are concentrated at poloidal limiters. Lost ions by impact on lower passive plates are evenly distributed throughout the all toroidal angle.

orbit is perturbed by the RMP, as long as the fast ion orbit is placed in the non-limiter toroidal angle, the ion is still confined in the plasma until the ion reach the limiters and it appears to be the same for both RMP and non-RMP cases. However, loss fraction of injected ions and pitch-angle distribution are turned out to be quite different. In case of non-RMP plasma, 1.2% of injected ions are lost within 100μs by impacting poloidal limiters and lower passive plates. Meanwhile, 1.5% of the injected ions are lost and it is over 25% of increase compare to non-RMP plasma. In addition, pitch-angle distribution of lost ions for non-RMP plasma is concentrated on 35˚ to 60˚ while 20˚ to 60˚ for RMP plasma, which is more spread out. It implies that when RMP is applied, fast ion with comparably low pitch-angle can be lost easily. B_r direction has an effect on fast ion density profile. At C-port, where the direction of B_r perturbation by RMP is outward, ion orbit density at the edge of the plasma is larger by 50% then the K-port which is separated 180˚ toroidally and the B_r perturbation direction in inward. (Fig. 3) It is due to the symmetry breaking by the RMP and could lead to the localized fast loss. In the core region, it seems fast ion orbits are trapped by m/n=1/1 island and shows more broad profiles compared to non-RMP case.

LORBIT code calculates full gyro-orbit of the beam ions and shows that the most of fast ion loss occurred by impact on the poloidal limiters. Also it describes that fast ion loss is increased by 25% during RMP. Outward B_r perturbation direction increases the fast ion orbit density by 50% compared to inward B_r perturbation case. However, the amount of lost fast ions from the simulation is much smaller compared to the RMP-induced mode-

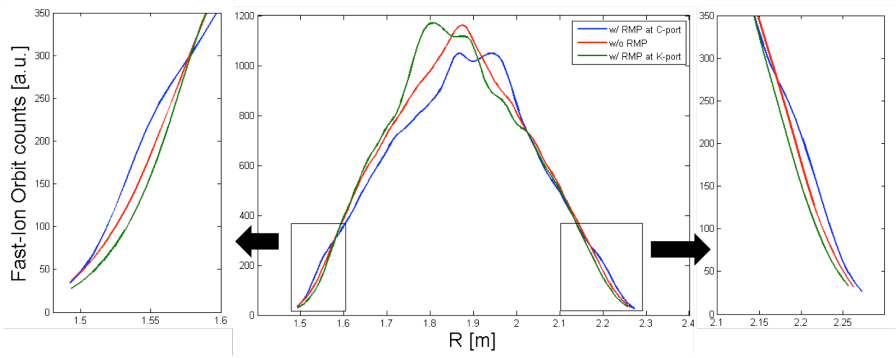

Figure 3. Fast ion orbit density profile in RMP plasma (blue, green) and non-RMP plasma (red). Fast ion orbit density is determined by the direction of perturbed radial B-field.

locking case. For a quantitative study of fast ion loss during RMP-induced mode locking, plasma response in the core region such as 'resonant-field amplification (RFA)' needs to be considered. Also additional fast ion loss detector (FILD-2) at different toroidal position was installed for 2014 KSTAR experimental campaign and will be used to observe asymmetric fast ion loss simultaneously.

In addition to the beam-heating, ICRF heating will significantly increase perpendicular velocity of the fast ions and will increase the population of high pitch-angle tail in the fast ion pitch-angle distribution. Consequently, ICRH heating during RMP application will increase fast ion loss rate since the number of trapped particles (increased pitch-angle) traveling the edge/SOL plasmas can be increased and the orbit width can be increased, too.

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