Exploration of new mode of operation for the device beyond the ITER in KSTAR

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Introduction

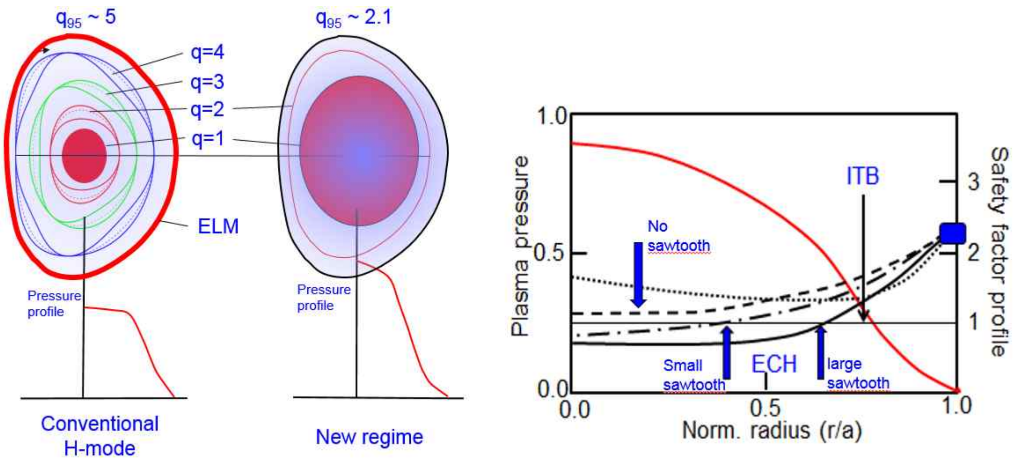
Extensive study result of the H-mode plasmas in tokamak devices enabled to design the current ITER and the projected confinement time of ITER based the scaling should be adequate to achieve the goal of Q~10 (~500MW of fusion power). While the required confinement time may not be an issue, complex internal systems, such as the in-vessel control coils (IVCC), are required to control harmful instabilities (i.e. ELM-crashes) in ITER. However, these complex in-vessel systems can be issues in devices beyond the ITER such as the fusion reactor (DEMO). The KSTAR research focuses on exploration of Internal Transport Barrier (ITB) mode at a low edge safety factor (q_{95}~2) that can minimize the instabilities while the confinement is compatible to the H-mode. If successful, the new mode of operation can replace the H-mode for the DEMO. In the new mode of operation, it is relatively easy to control the remaining instabilities such as sawtooth (1/1 mode). The current profiles can be modified using external current drive system to eliminate the sawtooth entirely or adjust the size of q=1 surface and it can be used for the control of particle exhaust through the sawtooth crash in DEMO. A control of the sawtooth crash time scale, which is critical for the discharges with a low q_{95} operation can be achieved with the moderate ECH power at q=1 surface.

Progress of the fusion research

In the end of 20th century, fusion research demonstrated that the tokamak device achieved the condition close to break-even (Q~1; Q = output power/input power) in three research devices (TFTR, USA, JET, EU and JT-60U, Japan). Here, the output power from full DT experiment was used in TFTR and JET and extrapolation value from DD experiment was used in JT-60U. The successful demonstration of near scientific break-even is finally followed by the ITER project with the goal of Q~10 (~500MW fusion power production). Note that the energy confinement time for ITER is from the extrapolation of the energy confinement scaling, based on H-mode database. ITER may not have any problem in accomplishing the goal of Q~10. However, the goal of DEMO may have to be more than ~1.0 GW so that the electric power production can be close to more than ~500 MW considering conversion efficiency. The size of DEMO can be slightly larger than that of the ITER so that engineering construction is tolerable. Assuming 30% increase in volume compared to ITER, the required energy confinement may be slightly better (~10%) based on the size and performance of the ITER. Here the fusion power is proportional to square of the total plasma energy. Improvements in size and confinement to meet the required fusion power of ~1.0 GW are durable in practice. The next issue is to reduce the complexity of the control systems that are required to suppress the harmful instabilities like Neo-classical Tearing Modes (NTM) and Edge Localized Modes (ELMs) in H-mode plasmas. Note that the control systems on ITER consist of a complex internal IVCC for the ELMs and high power gyrotron systems for NTMs.

New mode of operation in KSTAR

Korean fusion energy development plan consists of KSTAR, participation in ITER project and DEMO program. Since nuclear licence and related technology can be transferred from the ITER program, there are few subjects that should be developed to make the DEMO more attractive. They are improved first wall material, efficient divertor, simpler control systems for the harmful instabilities, if the H-mode is adapted. The KSTAR will be used to study these subjects for DEMO program. Here, a new mode of operation, which can minimize the harmful instabilities, will be explored while maintaining the global confinement comparable to that of the H-mode. Since the harmful instabilities are largely driven by either high edge pedestal (i.e. ELMs) or free energy near the rational surfaces (at q=n, where n is an integer) with a high q_{95} as illustrated in Fig. 1(a), where m and n are poloidal and toroidal mode number, respectively. The MHD modes with higher m numbers can be avoided if the edge safety factor (q_{95}) can be set at around ~2 while avoiding the global kink instability [1] as illustrated in Fig. 1(a). The remaining instabilities can be sawtooth (m/n=1/1) at q=1 and weak 3/2 mode. For NTM (2/1 mode) instability, if removal of the rational surface (q=2) inside the plasma is not feasible, the discharge with high core confinement and low pedestal (low free energy) with the q=2 surface at the edge can be introduced as shown in Fig.1 (b). Here, it is known that the ITB mode has a high core confinement and low edge pedestal as demonstrated in the "supershot" in TFTR [2] and QH mode DIII-D [3]. The ITB mode can automatically avoid the ELM instability due to low pedestal at the edge. Next step is to maintain the discharge stable at the edge q_{95} ~2 while sustaining the core confinement. Then the remaining major instability will be sawtooth instability.

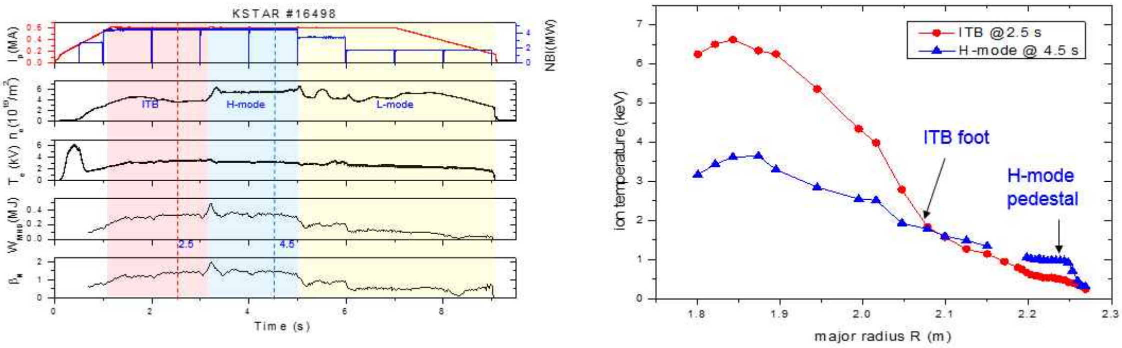


(a) (b)

Fig. 1. (a) Potential instabilities in a H-mode discharge with high q_{95} and high pedestal is compared with the reduced number of instabilities in a discharge with low q_{95} and low pedestal. (b) The size of the q=1 surface can be controlled with ECH or completely eliminated. Here ITB mode can be combined with low q_{95} so that the ELM is eliminated

The sawtooth instability which is confined within the q=1 surface is no harm for the confinement as long as the q=1 surface is small as shown as red colour in the core in Fig. 1(a) . However, size of the q=1 will be increased as the edge q value is lowered as demonstrated in Fig. 1(b). Then the energy released during short crash time which is magnetic reconnection time, can lead to disruption. Luckly the crash time scale of the sawtooth instability can be slowed up to two order of magnitude when the ECH power is illuminated on the q=1 surface. Using the off-axis current drive source, it is possible to control even the size of the q=1 surface or eliminated as illustrated in Fig.1 (b). Control of the size of the q=1 surface, and crash time, allows to use the sawtooth instability for particle exhaust required for the fusion reactor.

In KSTAR experiment, three different modes (ITB, H-mode, and L-mode) are obtained in one discharge as illustrated in Fig. 2(a). The stored energy of the ITB mode is quite comparable to that of the H-mode. In Fig. 2(b), ion temperature profiles for H-mode and ITB mode are compared and notably high core confinement and low edge pedestal of ITB mode were observed as shown in Fig. 2(b). Loss of H-mode pedestal in ITB mode may implicates a reduction of bootstrap current. However, broadening of the ITB region with the core heating profile (in case of DEMO, α-particle) can be used to optimize the useful bootstrap current. Currently, long and stable operation of the discharge with low q95 ~2 is progressing and will be combined with the ITB mode.



(a) (b)

Fig. 2. (a) In one discharge, three different modes of operation (ITB mode, H-mode and L-mode) are demonstrated. Note that the stored energy of the ITB mode is comparable to that of the H-mode (b) Ion temperature profile of the ITB mode (red) and H-mode (blue) are compared each other. Note the high pedestal in H-mode profile as there is no pedestal in ITB mode.

Summary

The success of ITER may warrant a construction of DEMO for electric power demonstration. The complex internal control systems required for instabilities control in H-mode operation in ITER may not be possible in DEMO. In KSTAR, a scenario of stable ITB mode with a low edge q is explored as an alternative of the H-mode for the devices beyond ITER. Here, the stability boundary of the new mode and a path to optimize the ITB boundary for optimum bootstrap current are discussed. The required control tools for the remaining instabilities like sawtooth are also addressed. This includes control of the crash time of sawtooth instability with ECH and size of the q=1 surface with the off-axis current drive system. The sawtooth instability can be used for particle exhaust and confinement control. This work is supported by the NRF of Korea under Contract No. NRF-2014M1A7A1A03029881 and NRF-2014M1A7A1A03029865.

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