KSTAR experimental results toward solving burning plasma issues

Jong-Gu Kwak and KSTAR teams

National Fusion Research Institute, Yusong, Daejeon, Korea

Aim of the nuclear fusion research is to realize the fusion reactor for solving energy problem in the world and ITER would be the big milestone for proving the scientific and engineering feasibility of nuclear fusion at burning plasma state. Moreover, the study on the reactor requires operation of the machine to be simple as well as producing high efficient fusion reaction which is to be in cost effective. In this regards, KSTAR has been looking forward to demonstrating the high performance long pulse discharge using highly advanced physics concept and steady state compatible superconducting magnets.[1] By highly elaborating engineering effort to operation of the superconducting machine based on the design concept of AT physics, KSTAR has shown the very outstanding experimental results which would impact on the design of the future reactor. While demonstrating the pulse-length of more than 40 sec H-mode flat-top in 2014 characterizing uniqueness of superconducting machine and achieving high beta(b_N~4) above no-wall limit transiently by optimal I_p/B_T and with P_{ext} ~ 3 MW, KSTAR has also been exploring various means to achieve and sustain steady-state, ELM-suppressed/mitigated H-modes using versatile in-vessel control coils (IVCC), ECCD/ECH, and/or SMBI. The 40s sustaining time corresponds to more than 20 times of current diffusion time that is sufficient time to provide the current profile control by changing hardware of ECH actuator mirror mechanically. KSTAR also showed that the level of the intrinsic error field of the machine is very low and it is suggested that KSTAR may not need any error field correction coil to realize ITER baseline scenario.

In particular, taking advantage of the versatile 3-rows of IVCC which has similar structure as ITER, KSTAR accomplished both n=1 and n=2 RMP-driven, ELM-crash suppressed regimes that lasted up to 5 sec. The demonstration of n=1 ELM suppression was one of the unique results in world-wide tokamak researches. The suppression window in the safety factor q95 has also been extended from 6.5 to 3.9 depending on the coil configuration and the existence of multiple integer operational window of q95 for n=1 RMP ELM suppression indicating the strong impact of resonant component on the ELM suppression. Significant progress has been also made on the investigation of the underlying mechanism on RMP suppression using measurements of pedestal fluctuations and modeling of plasma response. In particular, recent success for longer ELM suppression using mid-coil only application opens the very promising possibility of RMP ELM suppression applicable to the burning plasma where the high neutron and thermal heat flux inside the vacuum vessel requires very careful design of in-vessel components such as coil in terms of material selection and neutron shielding because it should make the design to be simple as much as possible and avoid many engineering issue of manufacturing and installing coils inside the vessel.

For steady state operation, tokamak requires the plasma current drive non-inductively. In advanced scenarios with $q_{95} \geq 8.5$, the plasma current was lowered to 300-400 kA to increase the fraction of non-inductive current drive by increasing β_p . considering auxiliary heating power limitation of present KSTAR resources. The plasma performance was increased after the transition but suddenly collapsed. However, the plasma quickly recovered from this event and the plasma performance was increased again even further up to β_N of 3.0, β_p of 3.5, H_{89} of 2.0, and H_{98} of 1.7. An interpretive ASTRA simulations reveal that the plasma current is driven non-inductively more than 100%. The toroidal magnetic field strength was 2 T. By adjusting plasma control scheme and adding fast radial plasma controller in 2015 campaign, it is expected that longer pulse would be possible. To support external off-axis current drive knob, the new innovative high efficiency current drive, so called helicon CD is developed. The helicon CD is known to have a high efficiency CD on the high density plasma so that if it is successfully validated on KSTAR, it would supplement LHCD in KSTAR. Figure 2(a) showed the installed mockup TWA(Travelling Wave Antenna) at KSTAR and 2(b) showed s-parameter measurement for the antenna. The working frequency is 500 MHz. For sustaining burning plasma, it is necessary to keep fusion output constantly and it is recognized to sustain the burning plasma condition by adjusting input gas. However, if the plasma wall is saturated and recycling is very high, the density control is very difficult in neutral beam dominated heating machine with graphite wall. So it is very important to see how long is the fuel retention at graphite wall in superconducting tokamak in addition to nuclear safety issue from fuel(tritium) accumulation.

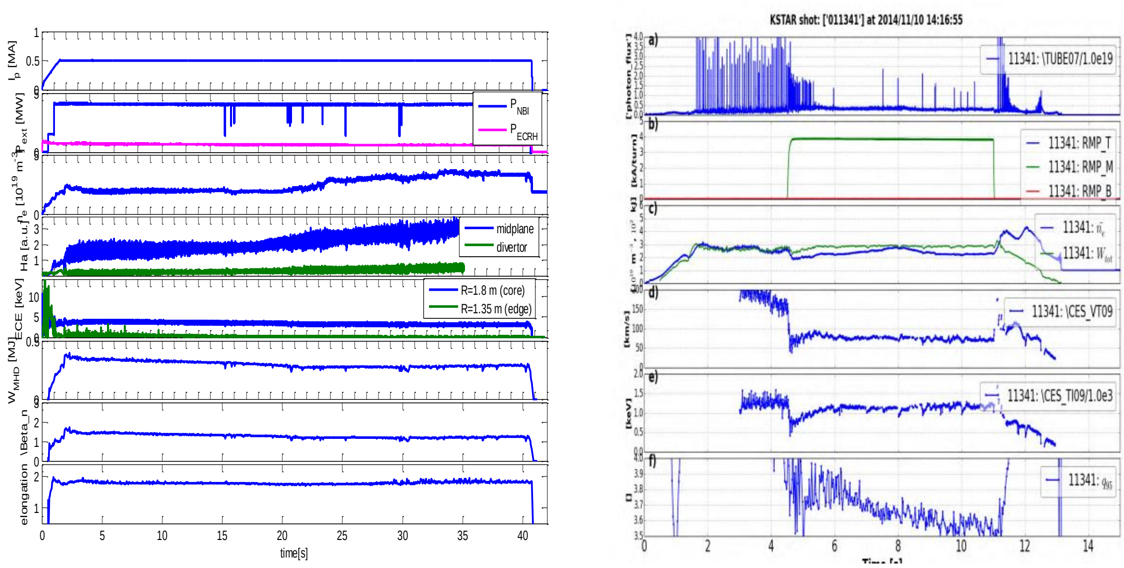
Burning plasma at tokamak condition also requires continuous operation without abnormal event such as disruption because the ejected heat from stored energy in a short time is not acceptable to heat limit of PFC at disruption and subsequent halo-current and runaway electrons induce severe damages on the machine if it is not properly controlled. So forecasting the disruption event or mitigation of heat and runaway electron just after that is one of key research issues for ITER as well as future tokamak fusion reactor. KSTAR has equipped various 2D MHD image diagnostics such as ECEi and IR/bolometer TV to monitor pre-disruption state and thermal quench process. ECEi clearly showed that multiple disruption events happen after the mode locking due to the m/n=2/1 mode growth. In addition, one of KSTAR results showed the possibility of delay of starting point of disruption from the tearing mode by pre-application of NRMP to the plasma so that it enables to save time for the operator to counteract the disruption if not avoidable.[2] n=2 non-resonant field could hinder the growth of n=1 locked mode after locking. Burning plasma requires the plasma current as high as possible to enhance the confinement and this also increase halo-current at disruption event. It is well known that toroidal peaking in halo-currents induces non axisymmetric force on the tokamak vessel and induced the engineering issue for reactor design. Recent KSTAR results suggest that there might be some correlation between intrinsic error field and toroidal peaking of halo currents so that it might be possible to reinforce the vessel structure against the disruption selectively before full power operation. Figure 3(a) and 3(b) showed halo-current distribution on the upper and lower diverter and figure 3(c) showed direction of intrinsic error field on KSTAR.

In summary, KSTAR has successfully extended the operation boundary toward high-performance, long-pulse H-mode (~ 43 Sec at 0.6MA), transiently accessing to high beta (β_N ~ 4) beyond no-wall limit. ELM suppression/mitigation physics study have been prioritized, expanding the operation range of q95 (4 – 6) in n=1 and n=2 and longer suppression (~5s) by using middle coil only in conjunction with long pulse sustainment at superconducting machine and IR TV measurement on the divertor. For in-depth study of disruption, overall process of disruption is visualized and past failures of passive plate is interpreted with observed toroidal asymmetry of Halo current and possibly intrinsic error field

References

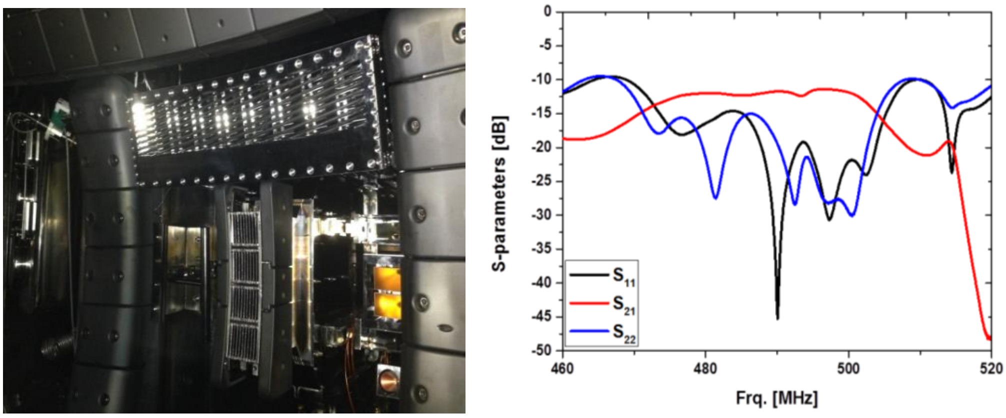
[1] Jong-Gu Kwak el al., “An overview of KSTAR results”, Nuclear Fusion 53(2013)104005

[2] J. Kim el al., PRL submitted (2015)



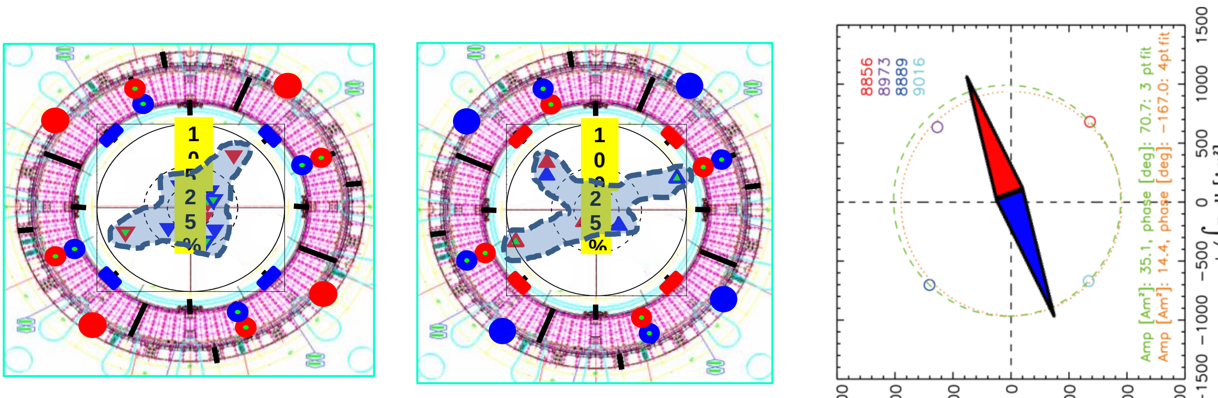
(a) (b)

Fig. 1. the time evolution of long pulse H-mode discharge(a) and typical shot of ELM suppression where the duration time is more than 5s and the middle coil is only used(b)



(a) (b)

Fig. 2. Helicon mockup antenna installed at KSTAR(a) where helicon antenna is positioned above LHCD antenna and measured s-parameter(b)



(a) (b) (c)

Fig. 3. Distribution of halo-current, lower(a) and upper(b) diverter and intrinsic error field(c)