OVERVIEW OF KSTAR RESULTS IN PHASE-I OPERATION

H.L. Yang,[a)*] J.G. Kwak,[a)] Y.K. Oh,[a)] K.R. Park,[a)] W.C. Kim,[a)] S.G. Lee,[a)] J.Y. Kim,[a)] Y.S. Bae,[a)] Y.M. Park,[a)] H.K. Kim,[a)] Y. Chu,[a)] M.K. Park,[a)] J.S. Kim,[a)] S.R. In,[b)] S.H. Joung,[b)] W.H. Choe,[c)] H.K. Park,[d)] Y.S. Hwang,[e)] Y.S. Na,[e)] J.G. Park,[f)] J.W. Ahn,[g)] Y.S. Park[i)], M. Kwon,[a)] J.A. Leuer,[h)] N.W. Eidietis,[h)] A.W. Hyatt,[h)] M. Walker, [h)] Y. Gorelov,[h)] J. Lohr,[h)] D. Mueller,[f)] L.R. Grisham,[f)] S.A. Sabbagh,[i)] K. Watanabe,[j)] T. Inoue,[j)] K. Sakamoto,[j)] Y. Oda,[j)] K. Kajiwara,[j)] R. Ellis,[f)] J. Hosea,[f)] L. Delpech,[k)] T.T.Hoang,[k)] X. Litaudon,[k)] W. Namkung,[d)] M.H. Cho,[d)] and KSTAR team

a) National Fusion Research Institute, 113 Gwahangno, Yusung-Gu, Daejeon, 305-333, Korea
b) Korea Atomic Energy Research Insititute, Daeduk-Daero 989-111, Yuseong-gu, Daejeon, 305-353, Korea
c) Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon, 305-701, Korea
d) Pohang Univ. of Science and Technology, 77 Cheongam-ro, Nam-gu, Pohang, Gyungbuk, 790-784, Korea
e) Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, 151-742, Korea
f) Princeton Plasma Physics Lab., P.O. Box 451 Princetorn, NJ 08543-0451, USA
g) Oak Ridge National Lab., 1 Bethal Valley Rd, OakRidge, TN37831, USA
h) General Atomics, 3550 General Atomics Court, San Diego, CA 92121, USA
i) Columbia Univ., James Forrestal Campus (EWA 244), P.O. Box 451, Princeton, NJ 08543, USA
j) Japan Atomic Energy Agency, 801-1 Mukoyama, Naka-city, Ibaraki-ken, 311-0193, Japan
k) CEA, IFRM,13108 Saint-Paul-Lez-Durance, France

e-mail: hlyang @nfri.re.kr

The KSTAR (Korea Superconducting Tokamak Advanced Research) pursued to develop key technologies for superconducting tokamak operation and to contribute to a few research items for ITER relevant issues. As a result, the KSTAR achieved highly confined mode (H-mode) in 2010 campaign and successfully demonstrated suppression of Edge Localized Mode (ELM) using n=1 Resonant Magnetic Perturbation (RMP) coils. The KSTAR is also initiating machine performance based on the designed machine parameters. The plasma current we achieved was 1 MA, and longest plasma pulse length has been extended to 10 s. In spite of limited heating power to 3.5 MW, several key actuators satisfactorily supported to implement a few scientific researches such as ELM control. On the basis of big progress in both the plasma performance and the experimental results, the KSTAR operation will explore key scientific and technical research issues under steady state operation condition in phase-2 operation.

I. INTRODUCTION

The Korea Superconducting Tokamak Advanced Research (KSTAR) is a superconducting (SC) tokamak which has been designed and constructed to establish a scientific and technological basis for an attractive fusion reactor.[1] Table I summarized the major parameters of the KSTAR and ITER devices. As a succeeding step of the device construction after the declaration of 1st plasma in middle of 2008,[2] a new KSTAR operation project that is categorized by four operation stages has been launched from start of 2008.

The 1st stage of the KSTAR operation starts from 2008 and finishes by end of 2012. In this period, main goal of the KSTAR operation is planned to establish key technologies for superconducting (SC) tokamak operation. The KSTAR in phase-I operation is also aimed to explore a few experiments that are related to ITER relevant issues, through utilization of unique characteristics of the KSTAR device.[3] As a result, the KSTAR operation achieved 1 MA in plasma current. In addition, the KSTAR also achieved H-mode for 5 s and the Edge Localized Mode (ELM) was successfully suppressed through n=1 mode of Resonant Magnetic Perturbation (RMP) control in 2011 KSTAR campaign.

TABLE I. Design Parameters of KSTAR and ITER

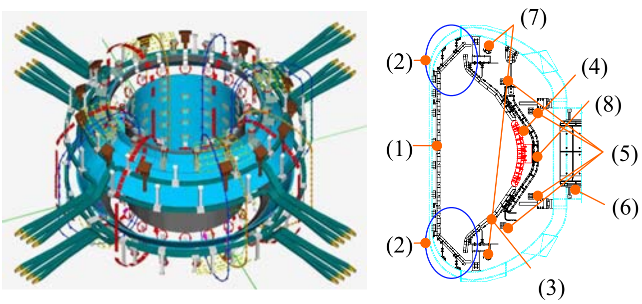
Parameters	KSTAR	ITER
Toroidal field, B0 [T]	3.5	5.3
Plasma current, Ip [MA]	2.0	15(17)
Pulse length [s]	300	400
Normalized beta	5.0	1.8(2.5)
Plasma shape	DN, SN	SN
Major radius, R0 [m]	1.8	6.2
Minor radius, a [m]	0.5	2.0
Elongation,	2.0	1.7
Triangularity,	0.8	0.33
Plasma volume [m3]	17.8	830
Plasma fuel	H, D	H, D, T
Superconductor	Nb_3Sn, NbTi	Nb_3Sn, NbTi
Auxiliary heating /CD [MW]	28	73(110)

In this paper, highlighted results we achieved during phase-I operation will be summarized with brief explanations on both the progress in machine and the plasma performance. In addition, long term operation plan of the KSTAR will be also briefly addressed.

II. EVOLUTION OF KEY ACTUATORS

II.A. In-Vessel Components

As shown in Fig. 1 and described in detail in the previous paper,[4] the KSTAR plasma facing components (PFCs) comprises inboard limiter, divertor, passive stabilizer, poloidal limiter, and NB protection armors.



(1) Inboard Limiter, (2) Divertor(DN, 20 s), (3) Passive Stabi lizer, (4) Poloidal Limiter, (5) In-vessel Control Coil, (6) NB Armor, (7) In-vessel Cryo-pump, (8) Mechanical Brides for Passive Stabilizer

Fig. 1. Configuration of KSTAR In-Vessel Components

Major upgrade of PFC system has been launched in middle of 2009, and all the components were installed in the vacuum vessel in 2010. According to engineering design, divertor and NB armors are to be covered with Carbon Fiber Composite (CFC) tiles. However, all of the PFCs are covered with graphite tiles in phase-I operation under consideration of low heat loads (< 1 MW/m^2). The In-Vessel Control Coil (IVCC) was developed to form 4 circular coils for plasma position control and 12 picture frame coils for MHD instability control.[5] More recently, the IVCC was used for non-axisymmetric magnetic perturbation in suppression of edge localized mode (ELM). After two-years engineering design,[6] the IVCC was fabricated and installed in 2010 as shown in (a) of Fig. 2. The IVCC system has been successfully operated in vertical control for highly elongated plasma production in 2010 campaign. The maximum current of each copper conductor was limited to 5 kA (30 kA-turns) at 20 Hz of step waveforms in 2010, and the current was increased to 7.5 kA (45 kA-turns) in 2011. Besides commissioning on the IVC part, the picture frame coils have been also tested with 2 kA current per turn (4 kA-turns) in 2011 for ELM suppression. The power supplies for resonant magnetic field perturbation (RMP) were upgraded to have 4 kA of current rating for 2012 campaign. To enhance plasma performance by exhausting impurities in the plasma, the in-vessel cryopump (IVCP) has been installed backside of the outboard diervtor plates as shown in (7) of Fig. 1. The IVCP consists of three layers of concentric pipes. The total area of 1.01 m^2 in the cryo-pump is cooled by two-phase liquid helium to 4.44 K with inlet pressure of 1.24 bars. The outer and inner thermal shields surrounding the cryo-surface are cooled down to 77 K by liquid nitrogen, and are surrounded by a particle shield. Pumping speed is estimated to be larger than 25,000 liters/s for deuterium per each cryo-pump. The cryo-pump was designed to be cooled down within 20 minutes to cryogenic temperature (12 K), and the cryo-surface is warmed to 100 K within 3 minutes and holds the temperature during regeneration period. The cryo-surface is cooled down again to cryogenic temperature within 5 minutes for a next shot. All the related tests in 2010 showed that the IVCP satisfactorily works. However, the IVCP operation is expected to come in phase-II operation after construction of the liquid helium supply system.

The KSTAR in-vessel components have been continuously upgraded since 2009, and successfully provided an essential circumstance and actuators for several key experiments in phase-I operation. Especially, the versatile KSTAR IVCC system played an important role in both shape control by IVC coils and ELM suppression experiments at highly elongated ELMy H-modes by using the RMP coils. Figure 2 shows the construction sequence of the complicated KSTAR in-vessel components. However, PFCs (especially divertor) should be majorly upgraded for steady state operation.

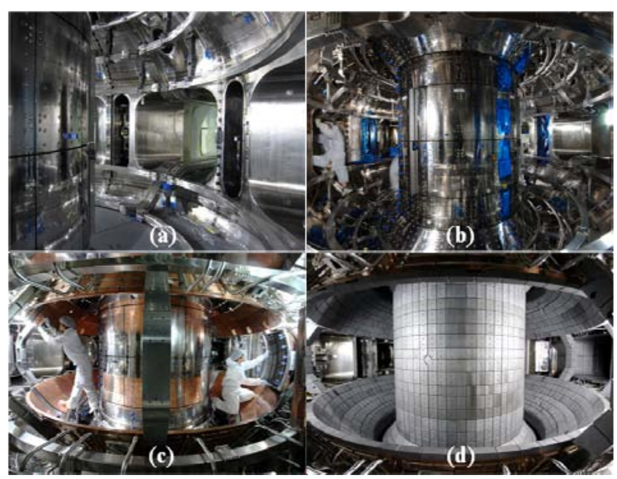


Fig. 2. The KSTAR in-vessel components were installed from the IVCC (a), limiters and divertor (b), passive stabilizer (c) and PFC tiles (d) in turn

II.B. Heating and Current Drive System

II.B.1. Neutral Beam Injection (NBI) System

The NBI system is a mandatory component for both heating and current drive experiments in the KSTAR. Therefore, huge efforts have been paid for development of the NBI system from start of the KSTAR project. As detail explanations are described in a reference paper,[7] first commissioning of the KSTAR NBI which uses positive ion was completed prior to the 2010 KSTAR campaign. The beam chamber was constructed to accommodate three beam-lines from three ion sources. In the construction phase, the beam-line components were installed for the first beam-line associated with the first ion source. The first ion source consists of the plasma source chamber developed by JAEA in the framework of the KO-JA fusion collaboration, which was combined with an accelerator developed by KAERI. Both the source chamber and the accelerator are shown in Fig. 3.

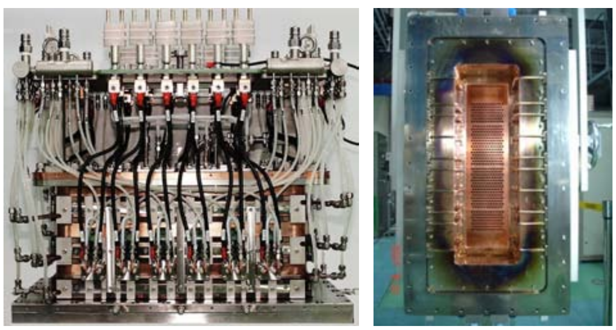


Fig. 3. Source chamber (left), and accelerator (right) of the KSTAR NBI ion source

In 2010 campaign, a deuterium ion beam energy of maximum 12.3 MJ was successfully extracted with 100 kV and 41 A for 3 s pulse duration, which was followed by injection of a MW-deuterium NB injection to the KSTAR plasma. The maximum NB power was estimated to be more than 1.2 MW for beam energy of 90 keV. In 2011, the NB power and the transport efficiency were precisely measured by a calorimetric power measurement system. The transport efficiency is about 78% with the beam perveance in range of 1.25 to 1.3 μ-P. For the first step toward steady-state KSTAR operation, a longer pulse beam extraction was also demonstrated in 2011 and 300-s beam at 80 keV was achieved. The beam extraction was stable in spite of a few breakdowns in the acceleration grids, which has been solved by the sophisticated matching of the power supply control with the beam using HV switching and the fast voltage regulation. In 2011 campaign, H-mode has been remarkably extended through enhanced performance of the NBI system as shown in Fig. 4. Substantial increases of the ion temperature and the toroidal rotation velocity of the plasma were observed during the beam injection. Also, the longest KSTAR plasma discharge was obtained for the total pulse duration of 13.5 s at the plasma current of 600 kA with 11-s long 1.5 MW beam injection at 95 keV.

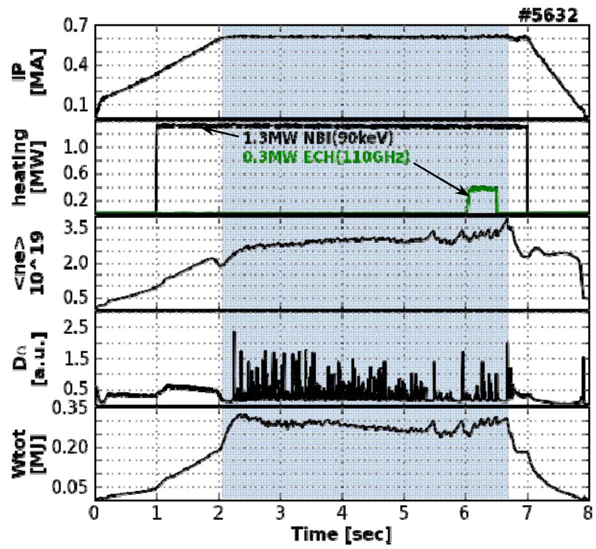


Fig. 4. The beam data in 2010 (a) and major parameters in typical ELMy H-mode and NB injection (b)

For the power upgrade in 2012, the second ion source and associated power supplies are under commissioning. Figure 5 shows the two ion sources that are mounted on the beam box. The second ion source is designed for 2 MW NB power at a maximum beam voltage of 100 kV and an optimum beam perveance of 1.56 μ-P.[8]

Fig. 5. Two ion sources under final commissioning for 2012 campaign (cover of magnetic shield box removed)

II.B.2. ICRF and ECH/ECCD System

As reported in an earlier paper,[4] the ICRF and ECH/ECCD systems contributed the KSTAR operation from early stage of the operation. The ICRF was utilized for Ion Cyclotron Wall Cleaning (ICWC).[9] For fast wave electron heating experiments, the RF frequency was tuned to 30 MHz for 2010 campaign to match the 2.0 T of toroidal magnetic field, which is mainly determined by resonance frequency of 110 GHz ECH-assisted startup system. In spite of successful RF power launch of 0.5 MW in 2010 campaign, the ICRF system has a limit for higher performance due to excessive reflection from the antenna. The ICRF system was modified to utilize all 4-current straps for more power launch reducing the voltage at the antenna using a 2 MW transmitter system in 2011. But the system still showed a few troubles in the resonant loop caused by RF coupling between current straps. Hence, the resonant loop was upgraded by inserting a de-coupler in the resonant loop to isolate the two pairs of current straps to each other.

A 500 kW/110 GHz gyrotron was effectively utilized for ECH-assisted startup, and the remarkable results in ECH-assisted startup using 2nd harmonic[10] in KSTAR are expected to provide a few techniques for start-up with low loop voltage in SC tokamaks. In addition to the ECH-assisted startup system, 170 GHz ECCD is an another important system which is designated for neo-classical tearing mode (NTM) control, saw-teeth mode control as well as electron heating and current drive. The 170 GHz gyrotron was developed by JAEA and delivered to the KSTAR site in 2011. The ECCD launcher was developed through collaboration with PPPL and POSTECH, and the transmission line components and gyrotron power supplies were developed and procured by NFRI and domestic company to complete the 1 MW ECH/ECCD system. The 170 GHz ECH/ECCD system demonstrated EC wave injection to the KSTAR plasma with 600 kW for 10 s pulse length in 2011. The operation regime with maximum output power of the gyrotron was continuously investigated, and more than 800 kW injection with 10 s is planned in 2012 campaign.

II.B.3. LHCD System

A 5 GHz LHCD system has been developed for past several years[11] and an initial 0.5 MW with 2 seconds pulse length LHCD system is ready for 2012 campaign. The prototype klystron, which was specified by POSTECH, and was fabricated by Toshiba in Japan, was tested at KSTAR site in early start of 2010. The power output we achieved was more than 460 kW for 20-s, and 300 kW for 800-s. The launcher of the LHCD system for 2012 campaign is a fully active waveguide grill with an array of 8 waveguides in column and 4 waveguides in row based on the 4-way splitter without active water cooling. Each waveguide channel of the splitter was welded, and a ceramic vacuum window is mounted on each input waveguide of the splitter for vacuum isolation. Figure 6 shows the LH launcher installed in vacuum vessel.

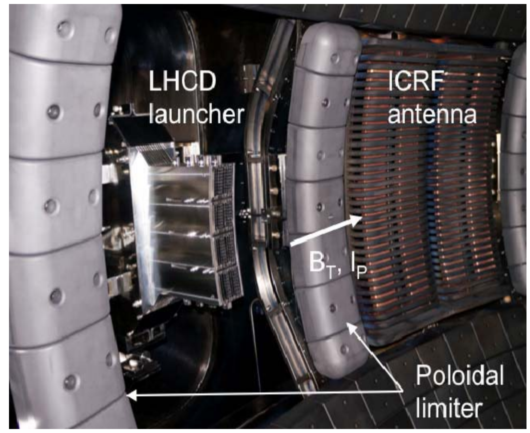


Fig. 6. An initial LH launcher in the vacuum vessel

II.C. Diagnostics

As shown in Table II, Many advanced diagnostic systems as well as basic measurement systems have been developed in collaboration with domestic and international collaborators.[12]

TABLE II. Status and plan (2012) of KSTAR Diagnostics

Installed	Planed in 2012
Magnetic diagnostics Edge probe sensors Recip. Langmuir Probe Visible TV (3 sets) mm-Interferometer D-alpha Monitor Visible Spectrometer Visible Filterscope Hard X-ray Neutron detector ECE & ECEI XICS X-ray Pinhole Camera Soft X-ray Array Resistive Bolometer Ellipsometry / Deposition Fast-ion loss detector Infrared TV CES Coherence Image NPA Thomson Scattering Reflectometer	Divertor IR TV BES MIR 2nd ECEI Imaging Bolometer VUV Survey Spectrometer FIR Interferometer

After early stage of phase-I operation in which most diagnostics are related to the basic diagnostics including magnetic diagnostics (MD), a few advanced diagnostic systems such as charge exchange spectroscopy (CES), X-ray imaging crystal spectrometers (XICS), ECE imaging (ECEi), and Thomson scattering system have been developed to study edge and pedestal physics.

The CES system was dedicated to measure the profiles of ion temperature and rotation velocity from the

CVI line spectra, which started in operation from 2010 in accordance with first operation of the NBI. The profiles of both parameters mentioned above are obtained from spatially resolved line broadening and shift of the CVI 5290.5 Å (n = 8 – 7) line after charge exchange process between injected neutral particles and carbon ions. Two XICS systems, which can record temporally and spatially resolved spectra of helium-like Ar, successfully demonstrated a good capability for the measurement of the profiles of temperature and toroidal rotation velocity in the 2010 campaign. The XICS has been applied to pure Ohmic plasmas as well as to plasmas with ECRH, ICRF, and NBI heating sources. More recently, performance in the time resolution improved to 10 ms using a Pilatus detector.

An ECEi system, which was installed on a mid-plane port during the 2010 campaign, drastically extended the functions of the 1-D ECE radiometer into 2-D local T_e measurements for advanced researches on the dynamics of MHD instabilities in both core and edge regions. The ECEi system is an array of multi-radiometers optically imaged onto the poloidal cross section of the plasma. Key feature of the system is to be characterized as follows: dual detector arrays for simultaneous measurements in high-field and low-field side, high spatial and temporal resolution (~2 cm for spatial and 2 s for temporal), large viewing area (vertical coverage= 40~90 cm and total radial coverage ~30 cm), 3), and 4) fine T_e resolution of ~ 2%. These capabilities enabled 2-D visualization of complex core and edge instabilities during the 2010 campaign. One of the important diagnostic systems for measurement of the electron temperature and density profile is Thomson scattering system. For this purpose, the Thomson scattering system have been developed from start of the phase-I operation, and was installed in 2010. Among various components of the the system, NFRI and domestic company developed a collection lens system, a laser beam dump, a data acquisition system, utility systems, and so forth. Major components of the system are a commercial Nd:YAG Laser (1065 nm, 2 J, 10 Hz) and 17 polychromators, and a bundle of 1.8-mm × 3.5-mm optical fibers. A tungsten halogen lamp was used for the wavelength calibration as well as Rayleigh scattering with N_2 gas for absolute density calibration. A laser with 5 J at 100 Hz, which was developed for ITER divertor Thomson system by JAEA, was also delivered to the KSTAR site and is now under system commissioning for the KSTAR experiments in 2012.

III. RESULTS OF MACHINE OPERATION

III.A. Vacuum and Wall Conditioning

The vacuum conditioning for the vacuum vessel and the cryostat has been successfully achieved without any severe troubleshoots since the 1st plasma. The nominal base pressures of the vacuum vessel was lower than 5×10^{-5} Pa before wall conditioning, and the base pressure of the cryostat at room temperature was 1×10^{-4} Pa. According to full installation of the plasma facing components (PFCs), the effective surface area inside the vacuum vessel increased from 11 m^2 to 54 m^2 in 2010. As a result, it was important to apply baking process to reduce the hydrogen retention and water molecules. The KSTAR baking system comprises water baking for the vacuum vessel using double walled configuration, jacket heater baking for the pumping duct, and baking system for PFCs tiles through circulation of hot nitrogen gases. The nominal baking temperature on the PFCs was 280 ℃ for 24 ~ 36 h with simultaneous baking of vacuum vessel to 130 ℃. During (or after) baking process, glow discharge cleaning (GDC) using Helium and D_2 was routinely performed. Owing to intensive baking operation, the out-gassing rate per unit area in the vacuum vessel was significantly reduced. Beside the baking and GDC process, the wall conditioning system also contains boronization system which nominally uses carborane vapor ($C_2B_{10}H_{12}$). The boronization system consists of a carborane evaporator, an injection tube, and toroidal ring on which four holes are perforated. The evaporated carborane vapor is fed into the toroidal ring through the injection tube, and finally injected through these holes for homogenous coating on the wall.

The leak rate of He in the cryostat at cryogenic temperature is most important point to be monitored for safe operation of superconducting (SC) magnets. The He leak rate due to the cold leak increased campaign by campaign. However, the He leak rate showed a tendency of saturation around 3.3×10^{-6} Pa·m^3/s in 2011 campaign. In that case, the vacuum pressure is around 5×10^{-6} Pa, which is substantially lower than the allowable pressure (1×10^{-3} Pa). After leak test during cool down, the PF coil and structure circuit was believed to be a major source of the cold leak. Although the pressure is much lower than the upper pressure limit, continuous investigations to localize the leak points will be paid for repair in the near future.

III.B. Operation Result of SC Magnet System

III.B.1. TF and PF Magnet System

The SC magnet system of the KSTAR is composed of 16 toroidal field (TF) coils and 14 poloidal field (PF) coils that were made of Nb_3Sn (all TF and 5 pairs of PF coils) and NbTi (two pairs of large PF coils). The TF magnet system was successfully charged up to its current rating (35 kA) and produced 3.5 T at the center of the vacuum vessel. The temperature increment of the TF magnet during operation coil was less than 0.2 K and in the temperature margin was kept more than 4 K. The maximum mechanical stress was measured to be 152 MPa, which is substantially lower than the criteria of 500 MPa. Typically, the TF magnet is charged to operational current for 8 hours during KSTAR operation period. The result confirmed that the TF system safely operated without any severe problems. On the other hand, operation characteristics of the PF magnets revealed several issues to be solved in the future. In case of abnormal loss in the plasma control, the plasma current abruptly decreased in the middle of the discharge (shot #3305) and the plasma control system (PCS) made a command to rapidly change the PF current to recover the plasma current level. In this case, PF1 current increased rapidly with 20 kA/s of ramping rate and temperature reached 10.79 K with the temperature margin of 3.39 K. In spite of the uncontrolled accident, the coil system was remained stable without a quench, which clearly proved the advantage of Nb_3Sn strand. This abnormal event was spontaneously solved by reducing the allowable maximum voltage and current ramp rate commands from the PCS and the AC loss heat has been successfully controlled through the phase-I operation period.

III.B.2. SC Current Feeder System

The current feeder system (CFS) for the KSTAR SC magnets is composed of the current leads and the SC bus-lines. The current leads are vapor-cooled type overloaded brass lead, and the bus-lines are made of NbTi strand. Since successful operation in the 1st plasma campaign, the CFS has been upgraded twice in the phase-I operation. The bus-lines for PF3, PF4, PF5, PF6 coils have been upgraded with the additional installation of 4 current leads and 4 CICCs of busline to match magnet power supply (MPS) to enhance capability in shape control in 2010. After final upgrade of the bus-lines, the joint resistance, which was one of the remaining issues, was measured to be less than 2.5 nΩ in average value satisfying the design criterion of 5 nΩ. Another issue was to keep cryogenic stability of the busline. Therefore, flow direction of SHe for the bus-lines and magnets was optimized not to meet inlet and outlet to avoid heat exchange at the joint part. From this point of view, the helium supply lines for the lower and upper PF1 coils, which are electrically connected in series, was separated from the series connection after the fourth campaign.[13]

IV. PLASMA EXPERIMENTS

IV.A. Start up Experiments

As the successful shot rate until 2009 campaign remained less than 21.5%, which mainly stemmed from failure of the startup, various efforts have been paid to investigate the major factor of the failures in the startup. One of the most important clues we found was Incoloy effect that distorted magnetic field configuration inside vacuum vessel. From the point view of magnetic field distortion, it should be distinguished from effects to the magnetic diagnostics. Magnetic distortion described in this paper does not mean effects on the magnetic probes but mean distortion of the external magnetic fields. Incoloy 908 is a weak ferromagnetic material and was used in cable in conduit conductor (CICC) jacket of the TF and PF coils except PF6 and PF7 due to better compatibilities in thermal expansion coefficient to Nb_3Sn. Magnetic field distortion is particularly fatal to the start-up phase because the plasma current is sensitive to external magnetic fields.

The compensation of the effect of Incoloy is not simple because the additional magnetic field by Incoloy is not uniform in the field-null region. The shot #2068 in the 2009 campaign used a startup scenario which did not compensate the deformed magnetic fields, and the radial gradient of B_z in the shot was too steep near the inboard side. Radial displacements frequently occurred during the start-up when the assumed ramp rate of plasma current was not satisfactorily matched to the pre-programmed trajectory of B_z. Moreover, the feedback control system to prevent the excessive radial displacement was absent in this stage.

After careful investigations on the phenomena described earlier, a compensation scenario of the Incoloy effect was additionally added in the new start-up scenario. The compensated scenario contains re-calculations of magnetic field to form a filed null at center of the vacuum vessel as well as forming an optimum filed index ($0 < dBz/dr < 1.5$) including magnetic field distortion from the Incoloy effect.[14] As a result, the proper profile of B_z was achieved and the radial profile of B_z satisfies the positional stability. The successful shot rate increased up to 74.3% compared with 21.5% in 2009, and pure Ohmic startup without ECH assistance was demonstrated with low loop voltage of 3 V.

IV.B. Plasma Control System

The KSTAR PCS[15] that is based on the DIII-D PCS, uses Linux cluster technology with eight processors at a frequency of 20 kHz. In 2010 and 2011 campaign, the PCS provided a feed-forward D-shape scenario for making quadrupole filed configurations to elongate the plasma during the I_p ramp-up. Combinations of the IVC (internal vertical control) coils which form a circular coil from the IVCC, and the passive stabilizers realized the double–null plasma with elongation of higher than 1.5. A PD controller in the PCS was used to control the fast vertical movement with the IVC and the passive stabilizers, which mitigated the natural vertical growth rate to ~100 rad/s at $\kappa > 1.8$. RZIP control actuators were refined to construct R and Z estimators based on flux loops and magnetic probes in order to control the highly elongated plasmas (κ ≥ 1.5). Vertical position estimator was developed using two normal magnetic pickup probes located at the inboard midplane. In 2011 campaign, new implementations of real-time EFIT (rtEFIT) enabled between-shot analyses as well as applications of iso-flux controls for axisymmetric shape control.[16] The result of rtEFIT satisfactorily matched to that of the fast plasma TVs in most L-mode shots. Nevertheless, this system requires more optimization process for better shape reconstructions during the H-mode, electromagnetic contributions by in-vessel conductors, and for minimizing irregular underestimations owing to drifty magnetic probes on the shape parameters for highly elongated plasmas, which resulted in excessive shape control and finally caused crashes of the plasma.

The rtEFIT/isoflux algorithm that was newly upgraded using two independent processes in the system was tested for the circular plasmas at I_p = 500 kA in 2010 campaign. The "isoelong" algorithm, which can handle plasmas with any shape, was applied to keep or increase elongation by the divertor/outboard coils as main actuators. As a result, the algorithm was able to either sustain circular plasmas or to elongate the plasma slowly more than 2 s.

IV.C. H-mode Confinement Experiments

Typical ELMy H-mode discharges were achieved on the KSTAR tokamak with a combined auxiliary heating of NBI and ECRH. The required minimum power is about 1.3 MW at a density of 1.4 × 10^{19} m^{-3} with a highly elongated double-null shape. The poloidal beta increased by factor of two after the L-H transition and the H-mode was sustained for about 1 second.[17] Figure 7 shows the temporal evolution of the several key parameters in the typical H-mode discharge in 2010 (shot #4333). In this discharge, external heating of P_{NBI} = 1.2 ~ 1.3 MW and P_{ECRH} = 0.2 MW were applied from t=0.5 s to t= 2.5 s. After the I_p reached flattop with good shaping with high elongation, the H-mode was accessed at t=1.3 s as was clearly indicated by a sudden increase of the line density and the poloidal beta and also from a strong decrease of the H_α signals. The back H-L transitions were often triggered by poor controllability of plasma shape and therefore a small clearance from the wall and high impurity influxes. A very slow transition time (30~50 ms) and a long dithering phase also indicated that the auxiliary power was near the threshold power. Before the first H-mode access, the first boronization was applied with carborane. The boronization reduced the oxygen level significantly, the estimated Z_{eff} was about two, and there was not much difference of Z_{eff} between L-and H-mode discharges. However, the radiation power is still uncertain due to measurement issues of the bolometer. From an initial analysis on the global confinement, the estimated energy confinement time, both for L-and H-modes, predicts it was 30-50% larger than prediction of the global scaling though its accuracy depends on reliable calculations of the loss power and the diamagnetic energy. Further validation is required with independent diagnostics and modeling efforts.

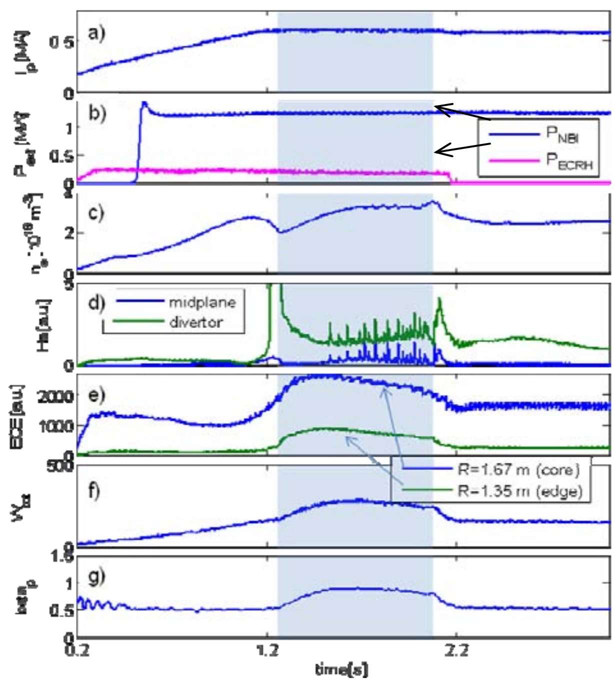


Fig. 7. Time trance of typical H-mode (shot #4333). Plasma current (a), external heating power (b) line integrated density (c), H_α (d), ECE (e), stored energy (f) , and beta-p (g)

In 2011 campaign, the H-mode discharges were remarkably improved through enhanced NB power (~1.5 MW) and control capabilities. As a result, the H-mode discharges sustained for 5-s with accompanying various types of edge localized mode which will be described later. Power scan experiments revealed that there exists a critical electron density where power threshold for L-H transition is minimum and it is about 0.9 MW for a line-averaged density of ~2.0 × 10^{19} /m^3 as shown in Fig. 8.

IV.D. ELM Control Experiments

The KSTAR H-mode plasmas exhibited three distinctive types of ELMs: 1) large type-I ELMs with relatively low ELM frequency (f_{ELM}=10-50Hz) and good confinement ($H_{98(y,2)}$=0.9-1), 2) smaller, possibly type-III, ELMs with high ELM frequency (f_{ELM}=50-250Hz) and poorer confinement ($H_{98(y,2)}$=0.7-0.8), and 3) a mixed, large and small, ELM regime with good confinement ($H_{98(y,2)\sim 1}$).

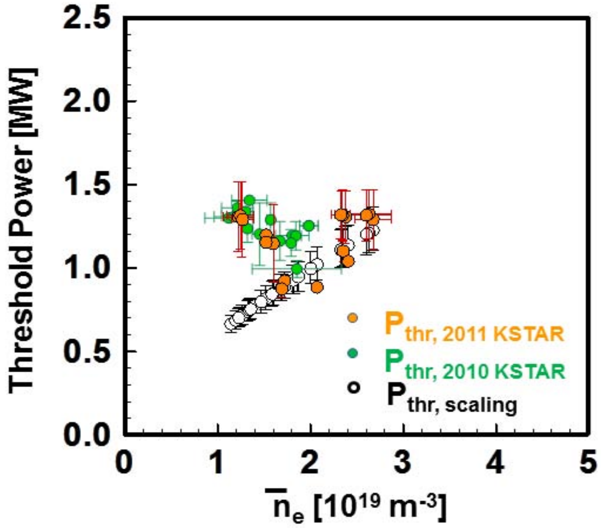


Fig. 8. Threshold power for L-H transition as a function of line-averaged density.

Among these ELM types, the large type-I ELM control is one of the most urgent issues to be solved for lifetime of the PFCs in future reactor devices such as ITER. From this point of view, majorly two methods to control the ELM were implemented in the 2011 campaign such as non-axisymmetric resonant magnetic perturbation (RMP), a supersonic molecular beam injection (SMBI), and the direct electron cyclotron heating in the pedestal region.

AS a result, the ELM was successfully suppressed in KSTAR by applying non-axisymmetric RMPs.[18] Particularly the result is considered to be very interesting achievement by a fact that ELM was successfully suppressed by applying n=1 RMP instead of n=3 RMP, which was reported in DIII-D by applying n=3 RMP and has not been reproduced in other devices until 2011. Figure 9 shows a typical ELM suppressed discharge in comparison with a reference ELMy H-mode discharge.

In initial ELM phase, the line-averaged electron density ($<n_e>$), the total stored energy (W_{tot}), and the toroidal rotation (v_{tor}) decreased by a ~10%. However, most parameters became stationary though there is a slow increase of line-average density in the ELM suppressed phase. Most effective condition for ELM suppression was n=1 at +90 phase angle. Furthermore, by injection of the supersonic molecular beam injection (SMBI) at the gas pressure ~1 MPa in the H-mode pedestal region, the frequency of ELM was increased from about 40 Hz to about 98 Hz and amplitude was decreased for a finite duration period after SMBI.[19]

There is also possibility of ELM control by direct heating or current drive in the pedestal region which will effect on the peeling ballooning stability boundary of the ELM. The main heating schemes are ECH, ECCD, and lower hybrid current drive (LHCD) for the local heating and/or current drive in the narrow width of the pedestal which is typically a few centimeters in the KSTAR discharges. In the 2011 KSTAR campaign, the initial experiments of pedestal ECH/ECCD have been done by using both 170 GHz and 110 GHz ECH systems. The maximum available EC power available is 0.3 MW for 110 GHz and 0.6 MW for 170 GHz, respectively. In KSTAR discharge #6313, after the L-H transition, ECH was injected for the period t=2.6-3.1 s. The ELM frequency increased from about 25 Hz to about 40 Hz during the ECH injection. In addition, the line-averaged electron density decreased and the global toroidal rotation also decreased. However, the stored energy did not change significantly.

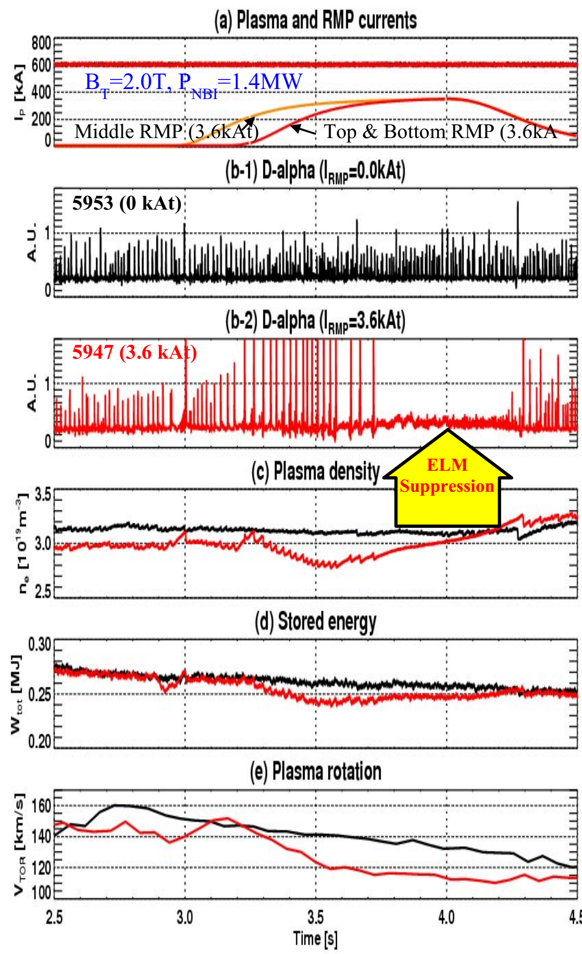


Fig. 9. A representative ELM suppressed RMP discharge in comparison with a reference ELMy H-mode discharge.

IV.E. Exploration on the Machine Specifications

The highlight in 2011 campaign could be categorized by two experimental research goals. The first one was exploring achievement of the machine specifications to demonstrate milestones in KSTAR operation. For the plasma current, the achieved current level was increased year by year as shown in Fig. 10. After successful first plasma in 2008 with the plasma current of 100 kA, the plasma current reached 1 MA in 2011 campaign through upgraded capacity of shaping control, position control, and upgrade of PF coil power supplies.

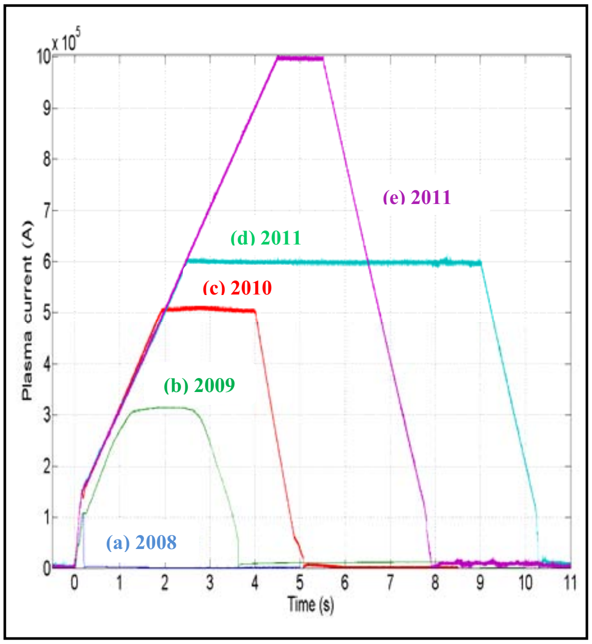


Fig. 10. Evolution of the plasma current in KSTAR: (a) 2008 (first plasma, #794), (b) 2009 (300 kA, #2048), (c) 2010 (500 kA, #3862), (d) 2011 (600 kA, >10 s, #6049), (e) 2011 (1 MA, #6184)

IV.F. Experimental Plan in 2012 Campaign

Main research direction of the 2012 KSTAR campaign is focused on extending operational regime through achievement of controllable H-mode for longer than 10-s at a mega-Ampere level of the plasma current. Upgrade of the key actuators for the goal are also in progress in accordance with hardware requirements. As described earlier, the NBI is under upgrade for additional 2 MW of heating power. 170 GHz ECH/ECCD system will be also optimized to have larger than 0.8 of microwave injection. As an initial stage of preparation for steady state operation in phase-II operation period, new 5 GHz LHCD system will operate for basic study of non-inductive current drive with capacity of 0.3 MW/2-s. Furthermore, enhanced performance in the diagnostic system including Thomson scattering (5J, 100Hz laser), beam emission spectroscopy (BES), MIR, 2nd ECEi system, infrared TV (IRTV) will provide most essential information on the plasma experiments.

V. SUMMARY AND FUTURE PLAN

Key components of the KSTAR has been successfully developed and stably operated for past four years. By the 3D non-axisymmetric picture frame coils from the segmented IVCC, the H-mode plasma confinement and successful ELM mitigation in 2011 campaign was achieved. The TF magnet stably operated with rating current (35 kA) for eight hours with temperature increment within 0.3 K. The plasma start up scenario was optimized by compensating scenario from the Incoloy effect of the SC coils. The plasma current reached 1 MA, and the ELMy H-mode was successfully produced at a plasma current of 0.6 MW.

The KSTAR device will be continuously upgraded to explore the research goals including high performance steady-state confinement which are essential for ITER and future fusion reactors. In the first stage of KSTAR operation from 2008 to 2012, the major goal is aimed to get stable plasma confinement to reach the basic plasma performance which is compatible with that of other present tokamaks. In the second phase, the major goals are to achieve the long pulse H-mode confinement and to explore the controllability of the ELM, disruption, H/L mode, and profile in the SC tokamak. From the third phase, the operation and experiments will be focused on the researches which are essential for high performance reactor operation such as stable operation under the high beta, high non-inductive bootstrap current condition and solving the relevant engineering issues.

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SWIP collaborated in the SMBI experiments. Tore Supra team in France collaborated on development of KSTAR LHCD system.

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