Recent Advances in the Long Pulse Heating and Current Drive System for KSTAR

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Abstract. The heating and current-drive systems of KSTAR tokamak have been developed to support long pulse, high β, advanced tokamak physics experiments. Key technologies relevant for high power and long-pulse operation are under development. Substantial progresses have been made in areas such as ion source, RF launchers, tuning components and high power supplies and they will make the advanced tokamak operation of the KSTAR be obtainable and maintained for long-pulse operating condition.

1. Introduction

The objectives of the KSTAR tokamak include the advanced tokamak research in a high performance regime and a steady-state operation for a tokamak fusion reactor [1]. The construction of the KSTAR tokamak will be completed by the end of 2007. The baseline heating and current-drive systems [2] of KSTAR tokamak consist of tangential NBI (beam energy < 120 keV, 8 MW), ion cyclotron waves (frequency range of 25-60 MHz, 6 MW), lower hybrid waves (frequency of 5.0 GHz, 1.5 MW), and electron cyclotron waves (frequency of 84 GHz, 0.5 MW). The control functions such as current and pressure profile for advanced tokamak research derives from the use of multiple heating technologies.

Two NBI systems are planned to be installed in the KSATR tokamak to provide ion heating, current-drive, core fueling, profile controls for pressure and current density, and diagnostic requirements. The deuterium beam power per a beam line is 8 MW with an energy of 120 keV. All components such as long-pulse ion source, beamline components, and power supplies have been developed, and they are being tested at the KAERI (Korea Atomic Energy Research Institute) NB test stand.

The role of the ICRF system is providing functions of heating and on-axis/off-axis current-drive over a range of magnetic fields with the frequency range of 25 - 60 MHz. It will deliver 6 MW of RF power to plasma with long-pulse length operation capability up to 300 seconds. For a long pulse, high power transmission, key ICRF components such as a water-cooled, high power density (~ 10 MW/m^2) antenna, a vacuum feedthrough, and the tuning and matching components for slow/fast matching have been developed. High voltage characteristics and long-pulse operation capability are investigated in KAERI RF test stand. Test results show that they have high voltage stand-off characteristics with the peak voltage over 30 kV and they can be used for long-pulse operation.

The ECH system will be used for the pre-ionization to reduce the loop voltage for the breakdown. In the first plasma, the ECH heating will be the second harmonic heating. The gyrotron system consisting of a CPI 84 GHz, 500 kW gyrotron, and the power supplies is under development. The short pulse test of the gyrotron is performed using the 20 μs pulse modulator. The full power test of the gyrotron at the KSTAR site will be done in 2005 using the dummy-load. The launcher composing of two mirrors is under fabrication. The ECH system will be upgraded to the 1 MW ECCD system for MHD stability control and improved core transport.

The LHCD system will provide ability to control and shape the plasma current profile for the advanced tokamak physics experiments. The RF source is four 500 kW, 5.0 GHz klystrons. The frequency of 5.0 GHz is chosen mainly for the higher density limit of the KSTAR tokamak. The launcher and the grill are designed to provide capability to dynamically vary the wave number, $N_{||}$, in the range of 1.3 to 4 in order to support flexible off-axis current profile control.

This paper presents the status of these activities, with focus on the progresses in areas such as ion source, RF launchers, tuning components and high power supplies.

2. Neutral Beam Injection System

Prototypes of all the beam line components for the KSTAR NBI system have been fabricated to test long-pulse length (300 seconds) operation capability, and a test stand has been set up in KAERI. They are being tested in the test stand by high power beams extracted from the developed ion source. The ion source has been fabricated to modify the LPIS bucket source from slit aperture grids to circular ones. Figure 1 shows beam extraction results with the prototype ion source. A beam of 75 kV and 22 A during 5 second is the best result during recent experiments. New grids are being made with new design to get better beam parameters. Typical beam operation parameters in a recent beam extraction experiments are shown in Fig. 2. An OMA system is used in estimating the quality of the extracted beams by the values of ion ratio and beam divergence. The calculated ion ratios are 41.1%, 18.2% and 39.7 % for H^+, H_2^+ and H_3^+ respectively, and beam divergences are 1.45°, 1.70° and 1.68° for a full energy, a half energy and a third energy ion respectively. We expect H^+ ratio will increase by increasing the beam energy, and the beam divergences will decrease with new grids applied to the ion source.

(a) (b)

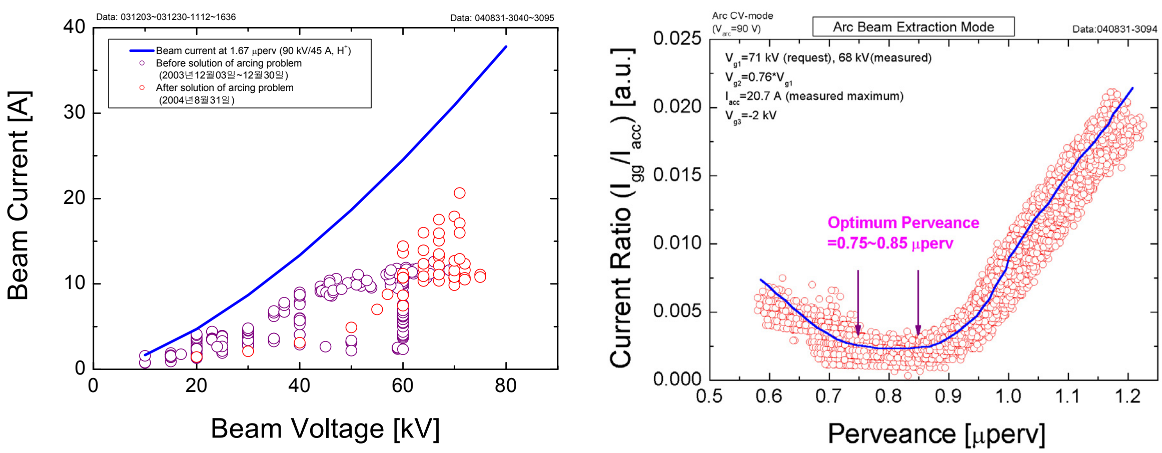

Fig. 1. Achieved parameters with the ion source, (a) voltage and currents (blue line is the objected value) and (b) perveance curve made by 7.7 mm circular aperture grids

The beam line components consist of neutralizer, bending magnet, ion dump, calorimeter, and cryosorption pump. Hypervapotron was used in the calorimeter as a cooling unit, and swirl tube was used in the ion dumps. They are all designed to have sufficient thermal capability corresponding to the maximum heat load of 1 kW/cm^2 for the long-pulse operation. By comparing the test results between the two cooling elements, the final one will be determined for the KSTAR NBI system. Full power test for these components are planned next year when enough beam power is ready. A cryosorption pumping system, which is composed of 4 cylindrical sorption panels and 4 electric coolers, has been developed for the test stand. Hydrogen pumping is effective when the panel temperature decreases less than 20 K. A pumping speed of 1.0 x 10^5 *l*/sec per a panel has been achieved after cooling time of 7 hours. A voltage breaker, which will be used for mechanical connection and electrical isolation between NBI chamber and torus, has been developed. Fig. 3 shows the structure of the voltage breaker. A bellows made by SS316L absorbs mechanical stress with spring constants of 10 kgf/mm in axial direction and 350 kgf/mm in transverse direction.

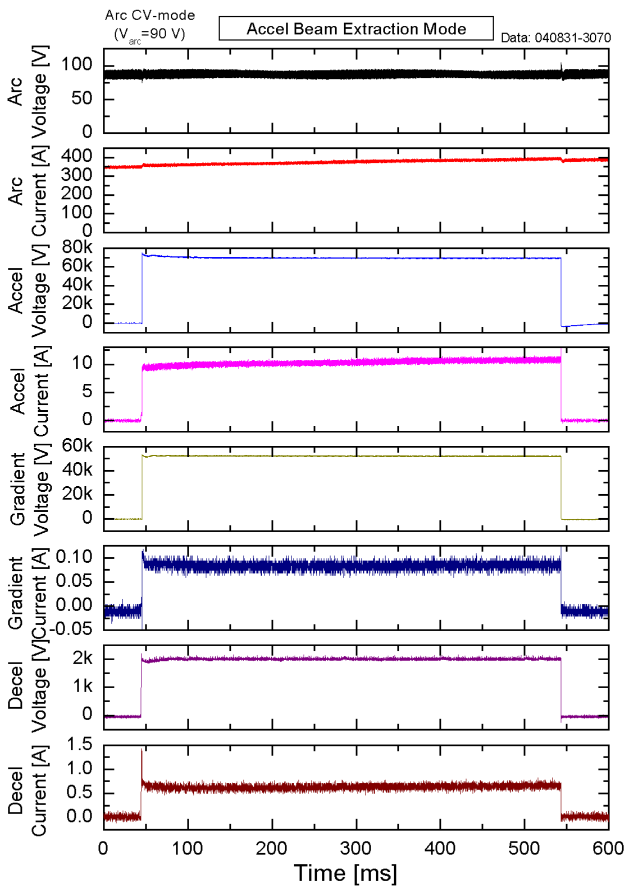

Fig. 2. Typical parameters in a recent beam extraction shot

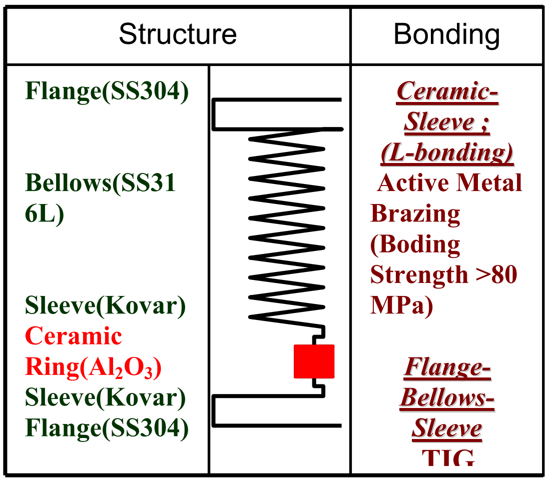

Fig. 3. Structure of 1.2 m dia. voltage breaker

An acceleration power supply for the ion source of KSTAR NBI system also has been developed. The main requirements of this power supply are a maximum current of 70 A and operational voltage of 60 - 120 kV with voltage and current ripples of 2 % peak-to-peak during 320 seconds. The output voltage is controlled by a selection of the number of serially connected nine transformer-rectifiers and forty IGBT chopper modules. The test of the power supplies (P/S) for the ion source, such as filament P/S (20 V, 3200 A), arc P/S (200 V, 1200 A), deceleration P/S (5 kV, 20 A) and acceleration P/S (120 kV, 70 A) have been finished for the long-pulse operation with dummy-load. Full power tests during 300 seconds also have been done with the ion source except for the acceleration P/S. PC based control and monitoring system is being developed in the environment of PXI bus system.

3. ICRF System

ICRF antenna is designed to have four current-straps side by side, each of which is grounded at the center and has a coaxial feed line connected to each end of the current-strap. For long-pulse operation, the antenna has sophisticated cooling channels in the current-strap, Faraday shield, cavity wall and vacuum transmission line for long-pulse operation. A high power density (~ 10 MW/m^2), antenna has been upgraded (Fig. 4) based on the test results for the prototype antenna which was built in 1999 [3]. Major improvements were in coolant passages, material of the Faraday shield, installation mechanism, and sealing material. RF power tests with a water-cooling have been performed at a frequency of 30 MHz to study a long-pulse operation and high voltage stand-off capability. A high voltage test showed a stable operation at a voltage of 42.0 kVp for 5 seconds. In the case of the long-pulse test, Fig. 5 shows that stable operation is possible at a RF voltage of 31.2 kVp for 300 seconds with the maximum temperature of 136 °C, and the VSWR is below 1.55 by using frequency tuning of – 2 kHz.

A feedthrough which has two alumina (Al_2O_3, 97%) ceramic cylinders and O-ring seal for good mechanical and thermal strength in long-pulse operation was developed [3]. RF test performed at a frequency of 30 MHz shows that the maximum voltage of the standing wave is 28.9 kVp (instantaneously 32.7 kVp), and the pulse length is extended to 300 seconds with a ceramic temperature increase up to 43°. The maximum voltage of the standing wave was limited by the output power of the amplifier and the circuit loss. The tanδ value of the ceramic cylinder was estimated to be 2×10^{-4}, which is a reasonably low value.

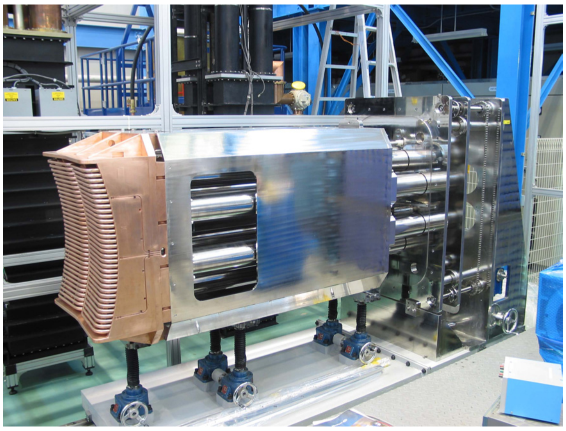

Fig. 4. Fabricated ICRF antenna

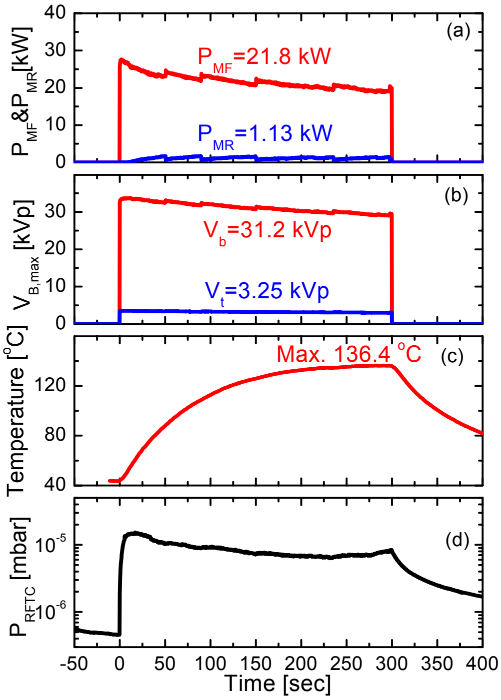

Fig. 5. Time evolution of (a) forward and reflected power, (b) line voltage, (c) cavity temperature, and (d) test chamber pressure, with a water- cooling

Tuners using liquid instead of gas for insulating dielectric medium was developed to solve problems associated with conventional tuners which use sliding contact. They can withstand high RF voltage and liquid level can be changed during high RF voltage without RF breakdown, so it can match slow loading variation. We developed 3 m long, stub tuner and an U-shaped, 5.6 m long, phase shifter made of 9-3/16″ nominal diameter aluminum transmission line. Silicon oil with a relative dielectric constant of 2.74 was used as the insulating dielectric medium. The RF tests show that they have high stand-off voltages (48.75 kVp for the the phase shifter and 43.8 kVp for the stub) for 300 seconds.

In the situation such as H/L mode transitions and ELMs (Edge Localized Modes), the fast tuner which can match the time varying load within milli-second order needs to be developed for long-pulse operation. Feasibility study for a coaxial fast ferrite tuner is under investigation. The electrical length of ferrite loaded transmission line can be changed by controlling ferrite magnetization. For the ferro-magnetic material, ring shaped Al doped YIG (Yttrium Iron Garnet) having saturation magnetization of near 600 Gauss is chosen. VME real-time processor with loading impedance calculated using collected RF voltage and current signals of transmission line controls magnet power supply. With this real-time feature, the tuner can match the time varying load within milli-second order.

4. ECH system

The ECH system is under development using a 84-GHz, 500 kW gyrotron. Because the KSTAR tokamak has the thick vacuum vessel wall, superconducting poloidal field coils, and the accompanying limited current ramp rates, the generated loop voltage may be too low to provide breakdown reliably. Therefore, the ECH system will be used for the pre-ionization to reduce the loop voltage for the breakdown. The pre-ionization has been successfully applied in a variety of tokamaks and is normally used to produce the plasma in contemporary stellarators. The general conclusion of these experiments is that ECH was effective in producing a good plasma which would (a) reduce the startup runaway electrons, (b) reduce the voltage required to start the plasma current, and (c) somewhat reduce the volt-sec expenditure from the transformer needed to establish the plasma. For the KSTAR, the pre-ionization is studied using the 0-dimensional code for many other initial conditions considering the effects of the error field, impurities, and the circuit parameters of the seven pairs of the superconducting poloidal field coils [4]. We studied the pre-ionization effects in both fundamental harmonic resonance and the second harmonic resonance cases because it is expected that the central toroidal magnetic field will be excited to 1.5 T for the first plasma hence the second harmonic resonance for 84 GHz. Fig. 6 (a) shows that the loop voltage of 6 V is enough to start the plasma current with > 100 kW EC-wave for the fundamental harmonic case. Here, the ohmic-drive by the poloidal coils starts at 0.1 second. But in the second harmonic case, we see the time delay of the plasma current ramping as shown in Fig. 6 (b).

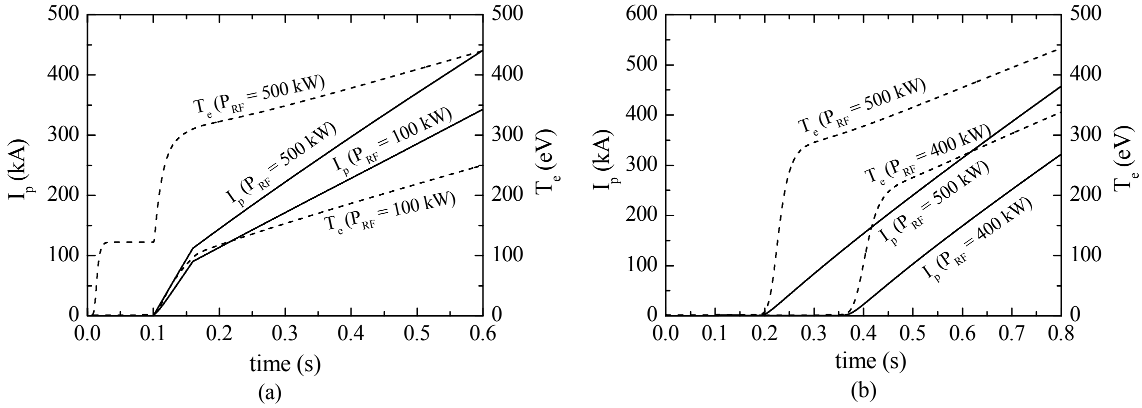

Fig. 6. The plasma current and the electron temperature as a function of time (a) for the fundamental harmonic resonance and (b) second harmonic resonance.

The ECH system is composed of two main parts: the gyrotron system and the transmission line system. The gyrotron system consists of a CPI 84-GHz, 500-kW gyrotron, and the power supplies. Delivering the gyrotron to Pohang Accelerator Laboratory (PAL), the short pulse test of the gyrotron is performed using the 20 μs-pulse modulator. The short pulse test showed the good reliability even in the higher repetition rate, 60 Hz. The transmission line system is mainly composed of the evacuated 31.75-mm corrugated waveguides, a few miter bends, and a launcher. And, two diamond windows will be used for the vacuum isolation. One is located at the output port of the gyrotron, and the other will be located at the transmission line. The launcher is designed in collaboration with Princeton Plasma Physics Laboratory (PPPL) on the basis of DIII-D ECH launcher composing of two mirrors. And it is now under fabrication at PPPL. This two-mirror launcher system will be also used for the ECCD experiment to see the suppression of the neo-classical tearing mode (NTM). The 2-second gyrotron power supplies are now under test with the control system. The full power test of the gyrotron at the KSTAR site will be done in 2005 using the dummy-load. For the automated ECH system operation, a Programmable Logic Controller (PLC) is used. The PLC also has a function of fault and interlock. The schematic layout of the ECH system is shown in Fig. 7.

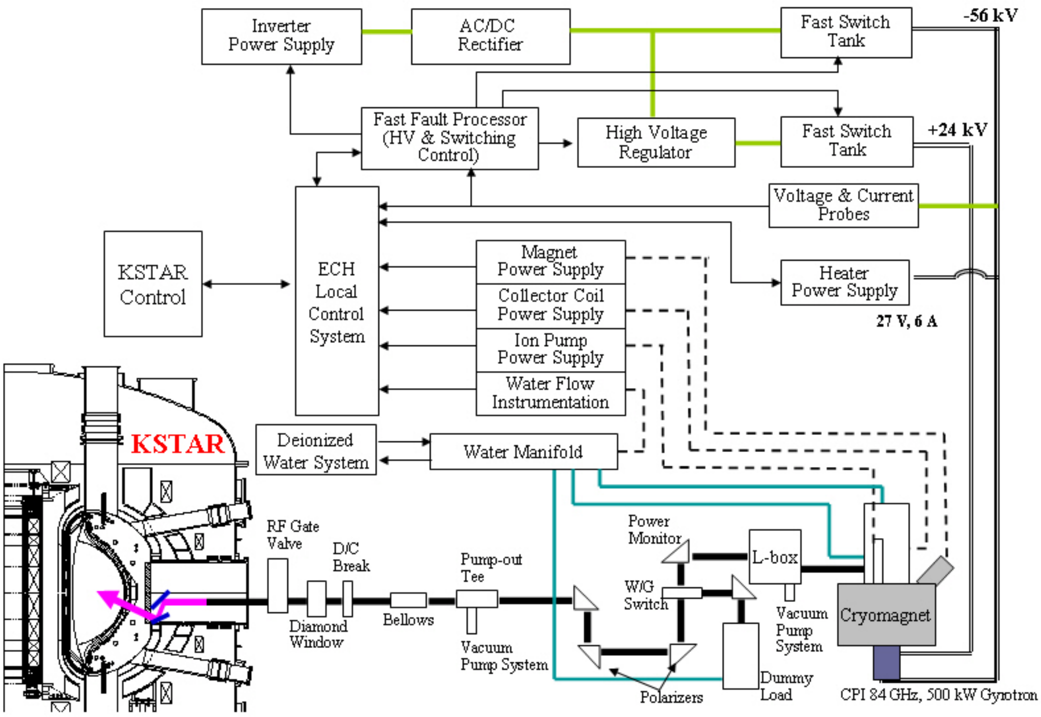

Fig. 7. The schematic layout of the 84 GHz, 500 kW ECH system.

5. LHCD system

The current interest of the LHCD system lies mainly in its ability to control and shape the plasma current profile rather than in its plasma heating capabilities. An unfavorable current profile can cause MHD instabilities like sawteeth, ballooning mode or kink modes capable of ending the discharge violently. The shaping of the current profile can suppress many unstable MHD modes. The off-axis current driven by the LH launcher can create broad or even hollow current profiles required in ‘advanced tokamak’ scenario in ITER thus introducing the negative shear into the poloidal magnetic field inside the half radius. The broad current profile is also suggested to be responsible for the mitigation of the type I ELMs mode (Edge Localized Modes) which is being brought by stepping into the high confinement mode (H-mode), while at the same time could sustain an internal transport barrier (ITB) which is increasing the energy content. Many recent experiments have demonstrated LH alone-sustained ITBs, full non-inductive current-drive with large bootstrap current fraction by LH alone, and the improvement in the coupling to the ITB plasmas. Many of the challenges of the LH wave coupling in L-H transition have been overcome and good coupling have been achieved in many different plasmas by positioning of the LH-launcher and the gas jet into the edge plasma. However, plenty of work still has to be done before it can be used in the reactor e.g. more powerful and efficient power sources. In these points of view, the LH system is expected to provide the major contribution of the advanced tokamak fusion physics experiments with a steady-state operation. Therefore, the KSTAR will also use the LHCD system. The RF source of the KSTAR LHCD system is four 500 kW, 5.0-GHz klystrons. The high power LHCD system in the many other tokamak devices use the lower RF frequency than 5.0 GHz except the FTU tokamak using 8 GHz gyrotron. Note that the ITER will also use 5.0-GHz RF for the LHCD system. The 5.0-GHz RF is chosen mainly for the higher density limit of the KSTAR tokamak.

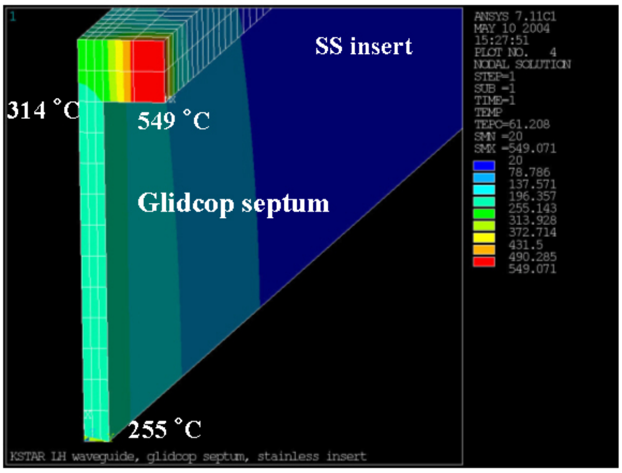

Fig. 8. ANSYS thermal analysis of the single Glidcop septum with top water cooled within 5 mm of front.

The RF power will be delivered through the long transmission lines composed of waveguides and 3-dB dividers from klystrons to the launcher. Due to the high insertion losses in the standard C-band waveguide size WR187, the transmission lines will be the oversized circular waveguides before the network of 3-dB dividers and phase shifters. The LH system shall provide capability to dynamically vary the wave number, $N_{||}$, in the range of 1.4 to 3.6 with a width $\Delta N_{||}$ = 0.54 in order to support flexible off-axis current profile control. The launcher is under design. It is composed of a series of stacked waveguide channels and the grill (front coupler). In previous work, the launcher except grill was basically designed to be composed of two modules that are assembled at upper and lower positions [5]. Each module has 2 rows of 32 waveguide channels hence 8 columns for each klystron. The short dimension of the standard WR187 waveguide is reduced to 0.55 cm by means of E-plane taper before the inputs of upper and lower modules. Each input with the same phase is again divided poloidally into two branches using a one-way 3-dB power splitter. The two vertical outputs will be in the same phase via a fixed-phase shifter. Now, the near steady-state of the KSTAR operation (300 s) presents some new challenges which will require new launcher design features: (a) the better heat removal from the launcher grill, (b) the shielding of the microwave windows from direct line of sight to the plasma, and (c) compact water loads for absorbing power reflected from either grill or plasma interface. The new design work is performed in collaboration with PPPL. Recently, a proper grill design is presented in the US-Korea workshop on the KSTAR workshop [6]. Fig. 8 shows ANSYS thermal analysis result of a fully active Glidcop grill design with water cooled top. The result assures the optimum spectral selection and directivity and the sufficient cooling for steady-state. Considering heat and disruption loads, a Glidcop/SS sandwiched grill would be the best design.

6. Concluding Remarks

Heating and current-drive systems of KSTAR tokamak will be installed in phased manner: NBI system from 2008, ICRF system from 2009, LHCD system from 2010 and ECCD system from 2011. Depending on the operation scenarios of KSTAR experiments, each system will be expanded to provide more power with a pulse length up to 300 seconds.

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