Japan-Korea Workshop on Physics and Technology of Heating and Current Drive,
Feb. 17-18 (2025), NIFS, Toki city, Japan

"Status of LHD ECH system for next campaign and related topics"

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Electron cyclotron resonance heating (ECRH) plasmas have been crucial in various aspects of plasma physics research and fusion reactor development. They have been widely utilized for plasma start-up, allowing efficient initiation of confined plasmas and for extending plasma operation durations by maintaining stable plasma conditions. Furthermore, ECRH is essential for plasma transport studies, providing valuable insights into energy and particle transport mechanisms, which are key to achieving steady-state operation in future fusion reactors such as those based on the stellarator and tokamak concepts [1, 2]. The ECRH system in Large Helical Device (LHD) has been extensively employed in plasma heating experiments as a conventional heating method and as an advanced high-density heating scheme using perpendicular injection techniques. These methods have been explored to optimize energy absorption and improve plasma confinement properties [3, 4].

For the extension of the existing ECRH system in LHD, preparations are underway for installing a new high-power gyrotron, which is scheduled to be operational starting from the LHD campaign in October 2025. The upgraded ECRH system aims to provide higher power and flexibility for experimental studies.

Beyond its role in plasma heating, the ECRH system has also played a role in plasma diagnostics: collective Thomson scattering diagnostics, which enable the measurement of ion velocity distribution function [5]. Electron cyclotron emission (ECE) diagnostics, including correlation-ECE, have been developed using the ECRH transmission lines for plasma turbulence research. Recent experimental and theoretical investigations have yielded physics results, and ongoing component developments continue to improve these diagnostic techniques' precision and reliability.

In recent years, collaborative research using the LHD-ECRH system has expanded significantly. One notable example is a joint research project conducted with a start-up company, university, and international institute, which focused on developing and testing a 28 GHz gyrotron. This collaboration leveraged the ECRH system for transmission line tests and gyrotron conditioning, contributing to both the enhancement of LHD's experimental capabilities and the broader advancement of gyrotron technology. These efforts align with the overarching goal of improving ECRH systems for future fusion reactors, ensuring efficient and reliable plasma heating and diagnostics.

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"Study of Microwave Transmission Mode Content in KSTAR ECH transmission line from Measured Field Intensity"

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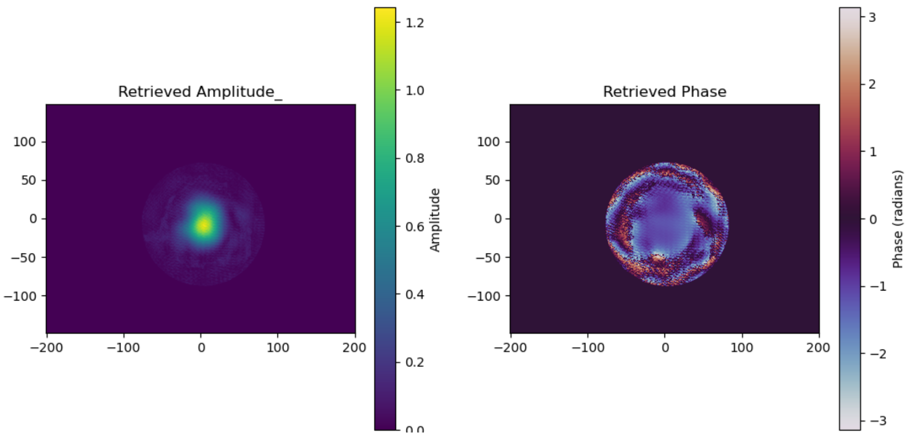
The study of transmission modes of electron cyclotron heating (ECH) transmission lines are very important for the long pulse operation as the gyrotron is located far away from the plasma device [1]. This mode is studied by using phase retrieval method based on intensity pattern. The pattern was measured by taking temperature profile on a paper screen which is placed at different locations and the profile were captured using infrared camera. This retrieval method has been used by several researchers like Yasuhisa Oda for ITER [2], Guoyao Fan for Hl-3 tokamak [3] which uses two set of locations for retrieving the phase and amplitude at the end of waveguide and further calculating the mode content. In the similar way, we have developed our phase retrieval code using three different locations and further calculating the modes. Apart from LP_{01}, LP_{11}(even) LP_{11}(odd), LP_{02}, the other higher order mode content has also been calculated. The below figure shows retrieved amplitude and phase at the output mouth. The others result along with mode content calculations will be discussed in details in the talk.



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"Effect of vertical space of vacuum vessel on formation of closed flux surfaces by ECH"

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In the Low Aspect ratio Torus Experiment (LATE) device, non-inductive startup of spherical Tokamak by electron cyclotron wave (ECW) and/or electron Bernstein wave (EBW) using 2.45 GHz microwaves has been explored, where all the processes including breakdown, plasma current initiation and ramp-up are carried out with EC and/or EB waves.

In such EC startup of Tokamaks, initial closed flux surfaces are generated via a current jump by injecting microwaves into the vacuum vessel with prefilled hydrogen gas under a weak steady vertical field. One possible cause of the current jump is cross-field passing (CFP) electrons, which are a forward energetic part of electrons in the velocity space. Since their orbits take typically elongated banana orbits, the currents carried by CFP electrons could be affected by the vertical space of vacuum vessel. To investigate the dependence on the vertical space of vacuum vessel, movable limiters have been installed in the top and bottom region of LATE, which can vary the aspect ratio of poloidal cross section in the range of Kvv = 1.7 - 2.3 (Kvv is vacuum vessel elongation which is the ratio of vertical length to horizontal one of plasma production region).

The results show that high Kvv is advantageous. With Kvv = 2.3, closed flux surfaces can be formed in a wide range of vertical field decay index and injected microwave power. With Kvv = 1.7, on the other hand, the parameter area in vertical field decay index and microwave power that can make closed flux surfaces become quite small, although the formation of closed flux surfaces is still possible under a sufficient vertical field decay index and microwave power.

"Recent activity in dual frequency (142/208 GHz) gyrotron development and transmission line system"

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A dual-frequency gyrotron is currently under development at UNIST to support future DEMO-relevant and innovative fusion reactors. The target frequencies, 142 GHz and 208 GHz, have been selected based on conceptual design requirements and the availability of existing laboratory resources. The conceptual design study of the gyrotron has been completed, and experimental activities to validate the design are underway. These experiments include testing a mode converter using mode generators for both frequencies, employing a novel alignment technique based on a machine learning algorithm [1]. With the full assembly of a demountable dual-frequency gyrotron, we will present recent experimental results and performance evaluations. Additionally, conceptual design studies on a remotely controlled transmission line and investigations into an OAM (orbital angular momentum) gyrotron will be discussed [2].

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External magnetic field effect and correction coil design for the ITER gyrotrons

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In the ITER electron cyclotron (EC) heating and current driving system, 24 gyrotrons are originally planned to be located in the RF building (B15 south) in order to realize 20 MW long-pulse EC power injection to the ITER vacuum vessel. Additionally, according to a new baseline proposal in 2024, the first wall material is changed from beryllium to tungsten, which requires further reinforcement of the EC system up to 66 MW (80 gyrotrons) to achieve Q=10 plasma operation with managing high Z impurity. Accordingly, additional gyrotron layouts are newly considered in buildings “B15 north” and “B18 (to be build)”. However, since the new layouts are closer to the tokamak, there is a concern that external magnetic field leaked from the tokamak and neighboring gyrotrons will deform internal magnetic field in a gyrotron and thus limit the gyrotron performance. In this study, in order to evaluate such an external field effect, electron orbits in a Japanese ITER gyrotron are numerically traced, and 3 pairs of rectangular correction coils are newly considered around the gyrotron to mitigate external field. The optimum correction coil currents are successfully converged by minimizing the dependence of electron colliding height on the azimuthal angle. After simulating all possible on/off states of individual gyrotron super-conducting magnets, the maximum required coil current is found around 1300 A·Turns, which is smaller than a collector coil current (≥2000 A Turns) already implemented in the gyrotrons and thus considered manufacturable.

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"Non-inductive plasma ramp-up using 8.56 GHz ECH system on QUEST"

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Non-inductive electron cyclotron (EC) plasma current ramp-up experiments have been conducted on the QUEST spherical tokamak [1]. A new 8.56-GHz ECH klystron system with incident-mode selectivity was developed for long-pulse sustainment and effective bulk electron heating [2].

Ray tracing calculations were used to evaluate the power absorption for core plasma heating via the fundamental O-mode and second-harmonic X-mode launched by this system, respectively. For O-mode, EC power was absorbed near a core plasma. For X-mode, a multiple harmonic heating scenario is expected to provide high-efficiency current drive via the fundamental mode and bulk electron heating near the second resonance.

The 250-kW power amplified by the klystron should be divided into four waveguide lines and is transmitted to four vacuum windows to avoid damaging the fragile window. When four waveguide lines are combined, a combined power is efficiently injected into the plasma by appropriately adjusting the phase of the transmitted waves. Following phase adjustment, a transmission efficiency of 98% was achieved for a 10 W/10 ms injection. For a 10 kW/10 s injection, approximately 62% efficiency was obtained, and a non-inductive tokamak plasma was successfully formed.

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Result of ECRH operation in the integrated commissioning phase and upgrade toward the initial research phase on JT-60SA

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During the integrated commissioning phase of JT-60SA, two ECRH systems were operated at 110 GHz with a small-diameter waveguide of 31.75 mm (Unit1) and 82/110/138 GHz with a large-diameter waveguide of 60.3 mm (Unit2) [1,2]. Although the large-diameter waveguide contributes to reduce transmission loss, it potentially has a larger mode conversion loss due to misalignment compared to the small-diameter waveguide. Feasibility in a ~100 m transmission line (TL) is considered to be a large concern but quantitative measurement of TL installation accuracy could not be performed during the installation of TL due to spatial limitations. In order to measure the TL installation accuracy, the transmission efficiency was measured by comparing the power measurement by a dummy load nearby gyrotron and launcher. The results showed that the transmission efficiencies in each system are 66% (Unit1, small-diameter TL) and 79, 84% and 85% (Unit2, large-diameter TL at 82 GHz, 110 GHz and 138 GHz, respectively). The transmission efficiency of the large-diameter waveguide was in good agreement with the calculation assuming 0.9 mrad waveguide tilt connection of averaged over the entire TL. It is small enough not to lose the advantage of large-diameter waveguides. For the evaluation of the transmission characteristic, the output polarization at the end of the TL was measured and compared with the predicted value. The difference is less than 6%, which is equivalent to 0.7% degradation of mode purity in the plasma for three operational frequencies. These results demonstrate the feasibility of large-diameter waveguides at multi-frequencies.

In the plasma experiment during the integrated commissioning phase, ECRH systems were operated in almost all 326 discharge sequences, which suggests the high reliability of the system. During the integrated commissioning, the output power of the gyrotron is increased from 1 MW to 1.5 MW. The availability of the 1.5 MW gyrotron operation for 5 s was confirmed by a dummy load. However, a transmission power of more than 1 MW, which is the design power of the transmission line, had not yet been demonstrated. After the several shots of conditioning, the 1.5 MW (1.3 MW injection power) shots with a duration of 1 s are successful. This result demonstrates the possibility of further increasing the total heating power.

Based on the results of the integrated commissioning phase, four transmission systems were designed for the next initial research phase. Assuming the previously demonstrated installation accuracy of 0.9 mrad, the transmission efficiencies are calculated as 85-90%, which satisfy the design targets. According to the output polarization prediction, the mode purity is expected to be higher than 99% for three operating frequencies of 82/110/138 GHz. Based on this design, procurement of transmission components was initiated, and acceptance testing of the gyrotron power supply and diamond window unit was conducted.

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Status and recent experimental results of KSTAR NBI system

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The KSTAR Neutral Beam Injection (NBI) system plays a crucial role in achieving high-performance, long-pulse plasma operation by providing substantial plasma heating and current drive. It consists of two beamlines, NBI-1 and NBI-2, each equipped with three positive-ion-based ion sources, designed to deliver 2.0 MW of deuterium beam power at an energy of 100 keV. In the 2024 KSTAR campaign, research efforts focused on enhancing the stability and performance of the NBI system while improving real-time control capabilities. Maintenance and optimization of the power and control systems enabled the reliable operation of all six beam sources, ensuring stable plasma experiments. Compared to the previous campaign, an additional 1.5 MW of beam power was simultaneously utilized, significantly contributing to high-performance plasma generation. Furthermore, modifications to the ion source magnetic field configuration increased the fraction of the first energy component, which is expected to enhance plasma heating efficiency. To further advance plasma control in KSTAR, improvements in NBI real-time control performance were implemented. With enhanced operational stability, NBI control operation played a key role in bifurcation studies and MHD avoidance experiments during the 2024 campaign. Additionally, improvements in the PCS-NBI control system enabled the successful commissioning of an NBI feedback control system for β_N. This feedback control system is expected to serve as a foundation for future expansions, leading to the development of surrogate model-based NBI heating and current drive control system. In this presentation, the experimental result of the NBI feedback control system conducted during the 2024 KSTAR campaign will be summarized.

"Negative Ion Production Characteristics of Two-Region Arc Plasma (TRAP) Ion Source"

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At the Korea Atomic Energy Research Institute, a novel Two Region Arc Plasma (TRAP) ion source is under development for negative hydrogen neutral beam injection (NBI) systems in fusion applications. A key advantage of this design is its ability to confine primary electrons emitted from the filament exclusively within the driver region, thereby eliminating the need for external filter magnets. In this configuration, the ratio of primary electrons to low-energy electrons in the driver and extraction regions can be precisely controlled by adjusting discharge parameters such as filament position, filament current, arc voltage, and gas pressure. This parameter tuning creates optimal conditions for negative ion production, especially within the extraction region. This study systematically investigates the effect of these parameters on negative ion generation. A diagnostic system, based on laser-induced photo-detachment combined with Langmuir probe measurements, was developed to evaluate the negative ion density. Experimental results demonstrate that, with optimized discharge conditions, a high density of negative ions can be achieved in the extraction region without relying on an external magnetic filter. This presentation will detail the diagnostic approach and discuss comprehensive experimental results

"Oscillation of negative ion beamlet and effect on beam focusing for negative-NBI"

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Direct effect of RF electric field was identified with RF perturbation experiment on FA negative ion source. We found (1) the beamlet width and beamlet axis position oscillate with RF frequency, (2) the amplitude of beamlet width is proportional to RF electric field and to the gradient of the perveance curve d<wx>/dPerv. We also discuss about how to suppress the oscillation of the beamlet in RF negative ion sources.

"Study of Beam Trajectory in KSTAR Neutral Beam Injector using Beamlet-Based Model"

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The KSTAR Neutral Beam Injection (NBI) system utilized to achieve high-performance, long-pulse plasma operation by providing substantial plasma heating and current drive. During the beam transmission, the high-energetic NB generates thermal loads due to collisions with transmission line components and is influenced by external conditions such as magnetic field. To study the impact of external conditions on the beam trajectory and enhance transmission efficiency under various KSTAR operation conditions, a 'beamlet-based trajectory calculation model' was developed. Measurement data on beam species and divergence angles, obtained using Doppler-shift spectroscopy, were used as inputs for this beamlet-based model. Additionally, the accuracy and reliability of the model were validated by comparing its results with the measurement data from the transmission line components using the calorimetric method. Using this model, neutral beam loss rates within the beamline were evaluated for various beam divergence angles. Furthermore, a study on beam loss based on the beam trajectory was conducted under conditions where a large amount of PF coil current was present, such as during long-pulse operation and high I_p experiments.

"Hybrid simulation of Alfvén Eigenmodes due to multiple fast ions in the Large Helical Device "

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In the magnetic confinement fusion devices, there are multiple fast ion species such as fusion product α-particles and fast deuterons produced by neutral beam injection (NBI). These fast ions may induce instabilities such as Alfvén Eigenmodes (AEs) which enhance fast-ion transport and losses. The study of fast ion driven instabilities is one of the important topics for fusion reactor.

To clarify the relationship between instabilities and fast ion transport in the multiple fast ion species plasma, experiments with the combined injection of hydrogen and deuterium beams were conducted in the Large Helical Device (LHD). The AE bursts caused by the fast protons and fast deuterons were observed in the experiments [1].

In the plasma with multiple fast ion species, a complex synergetic effect of multiple fast ion species may arise on the instabilities and fast ion transport, because the interaction with the instabilities may differ for different species. For example, one fast ion species may drive an instability while another species may stabilize it. The stabilizing fast ion species may be transported by the instability driven by another fast ion species. Computer simulation is a useful tool for investigating the synergetic effect. A hybrid simulation code for nonlinear MHD and energetic particle dynamics, MEGA, can investigate AE instabilities including the fast ion source, collisions, and losses [2,3].

In this study, simulations of the LHD experiments with the fast protons and fast deuterons are performed using MEGA code where NBI, collisions, and fast ion losses are taken into account. In the MEGA simulations, AE modes with frequencies that are consistent with those observed in the LHD experiment [1] could be reproduced. The additional AEs were destabilized by multiple fast ion redistributions, and then, the loss rates of both fast proton and fast deuteron significantly increased.

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"Simultaneous Estimation of Edge Plasma Density Profiles and Heating Beam Properties via Bayesian Inference and Gaussian Process Regression in the KSTAR H-BES System"

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In this study, we develop a method for estimating edge plasma density profiles and analyzing beam attenuation using the KSTAR hydrogen beam emission spectroscopy (H-BES) system. The system, comprising 16 radial and 4 poloidal channels with approximately 1 cm spatial resolution, measures Doppler-shifted D-alpha emissions that serve as indicators of local plasma conditions. A collisional radiative model is employed to relate the observed D-alpha intensities to plasma density, with the beam's influence accounted for by incorporating independently measured density and temperature profiles. We model the density profile using a Gaussian process prior and employ Markov Chain Monte Carlo (MCMC) methods to explore the posterior distribution. Beam attenuation, as observed through BES measurements, is used to refine the density estimation further. Importantly, the BES signals enable cross-validation between the inferred density profile and the measured beam attenuation, thereby providing mutual verification of these diagnostic parameters.
An absolute calibration factor is determined by integrating the BES data with edge interferometry measurements. In addition, our approach rigorously quantifies the uncertainties inherent in both the BES light intensity and the calibration process. This integrated treatment of uncertainties, along with the simultaneous analysis of density and beam attenuation, offers a more comprehensive understanding of beam–plasma interaction dynamics. By directly incorporating beam–plasma interactions into the model, our approach facilitates the determination of heating beam properties rather than relying solely on density profile-based estimations. We anticipate that further in-depth research will yield more detailed insights into beam properties during plasma operation.

"Estimation of Electron Cyclotron Plasma Heating Profiles Based on Ray Tracing Simulation Data"

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Efficient plasma heating is a crucial prerequisite for achieving fusion reactions in KSTAR, where the plasma temperature must reach the order of 100 million degrees Celsius. Among various heating mechanisms, electron cyclotron heating (ECH) utilizes the electron cyclotron resonance frequency of RF waves to transfer energy directly to the electrons. However, in practical operation, the actual RF power absorbed by electrons may fall short of theoretical predictions, as evidenced by zero-dimensional (0-D) power efficiency analyses. Additionally, the spatial distribution of absorbed power varies radially within the plasma, necessitating a more detailed one-dimensional (1-D) power profile analysis. Ray tracing simulations [1] serve as an essential tool to model and evaluate these heating profiles, capturing the complex interactions between RF waves and the plasma environment. However, the efficiency of plasma heating and the resultant radial heating profile are governed by multiple environmental parameters, exhibiting highly nonlinear relationships. In this study, we leverage machine learning techniques to establish predictive models for these relationships, aiming to enhance the estimation of radial heating profiles and optimize the performance of ECH systems. Our approach enables accelerated analysis of heating efficiency under various plasma conditions, contributing to the refinement of KSTAR's operational strategies for improved fusion performance.

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Kinetic full wave analysis of electron cyclotron waves using integral form of dielectric tensor

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In order to describe wave optical behavior of electron cyclotron waves, such as excitation by finite-size antennas, wave tunneling over an evanescent layer, and formation of standing waves, full wave analyses in which Maxwell's equation for a given wave frequency is solved as a boundary-value problem are useful and powerful tools in various plasma configurations. Several schemes to include kinetic response of plasmas have been developed based on a local dielectric tensor obtained in a uniform plasma as a function of wave number vector. For a systematic way of kinetic full wave analyses in inhomogeneous plasmas, integral forms of dielectric tensor have been developed. The integral forms are obtained by transforming the velocity integral in a dielectric tensor to the positional integeral by following the particle orbits. Two types of kernel functions, PDKF (plasma dispersion kernel function) and PGKF (plasma gyro kernel function), have been derived. PDKF is for the parallel motion along the magnetic field line with up to the second-order inhomogeneity of the magnetic field strength. PGKF is for the perpendicular gyro motion. The kernel functions are used in the full wave code using the finite element method (FEM). With one-dimensional (1D) model using PDKF, magnetic beach heating near the electron cyclotron resonance is described. With another 1D model using PGKF, the O-X-B mode conversion is analyzed. The O-mode is excited by a wave guide from the low-field-side, mode-converted to the X-mode and reflected, then reflected again near the upper hybrid resonance (UHR) and mode converted to the electron Bernstein waves (EBW), and finally absorbed near the cyclotron resonance. In the presence of very small amount of collision, $\nu/\omega \sim 10^{-5}$, most of the power is absorbed near UHR. Analysis on the poloidal plane including the poloidal magnetic field will be presented with a recently updated 2D FEM code (TASK/WF2D).

"Observation of non-thermal RF radiations excited during external heating"

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The external heating methods such as ECRH, ICRF heating, and NBI can achieve the velocity population inversion at least for a short time. With the existence of the velocity population inversion, non-thermal radiations are generated as the results of kinetic instabilities. With using of high speed digitizers, various types of precise frequency spectrograms of non-thermal radiations have been observed during the external heating at LHD, and Heliotron-J.

- Harmonic ion cyclotron emissions at the peripheral region originated perpendicular NB [1,2]
- Harmonic ion cyclotron emissions at the peripheral region originated fusion born alpha particles during perpendicular NB when large reconnection events occur [3]
- Lower hybrid frequency and its harmonic frequency ranges accompanied with the sidebands characterized by ion cyclotron frequencies during tangential NB [4]
- Lower hybrid frequency and its harmonic frequency ranges accompanied with the sidebands characterized by ion cyclotron frequencies during perpendicular Helium NB
- Large relativistically shifted emission in harmonic electron cyclotron frequency range during ECRH/ECCD in very low dense plasmas [5]

Non-linear couplings between non-thermally emitted waves that are originated at spatially separated regions are observed. This fact suggests that we should consider the propagation, absorption, and linear and non-linear mode conversion processes as the energy cascade process of energetic particles generated via external heating methods or the nuclear fusion reaction.

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"Non-inductive start-up experiment with various lower-hybrid launch scenarios on TST-2"

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Efficient non-inductive start-up of a spherical tokamak may be achieved by using lower-hybrid waves that have high current drive efficiency. On the TST-2 spherical tokamak, three lower-hybrid launchers are installed at the outer-midplane, top and outer-off-midplane to explore efficient start-up scenarios. Plasma current ramp-up up to 26 kA has been achieved so far, which is about a quarter of the Ohmically driven plasma current. The outer-midplane launch scenario was found to drive current robustly over the course of plasma current ramp-up due to the absorption that relied on the toroidal up-shift of the parallel wavenumber. The top launch scenario was more efficient above certain plasma current due to up-shift of the poloidal wavenumber, and achieved the maximum plasma current on TST-2. However, x-ray radiation measurement indicated there was substantial orbit loss of fast electrons that may be limiting the maximum driven current. The off-midplane launcher was developed to achieve robust current drive as well as minimal fast electron losses. The off-midplane launcher driven plasma had higher electron temperature with modest x-ray radiation compared to the previous two launchers, qualitatively in agreement with the theoretical predictions. The coupled power was limited, however, which limited the driven plasma current. New limiters were installed to reduce antenna-plasma interactions and increase the power handling capability of the off-midplane launcher..

"Development of a Lower Hybrid Fast Wave Antenna and Low Power Coupling in KSTAR Plasmas"

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A traveling wave antenna consisting of a slotted waveguide with corrugated walls has been developed for lower hybrid fast wave (LHFW) experiments in KSTAR plasmas [1]. $n_{\parallel 0}$ increases from 2.1 to 2.6 as the frequency increases from 2.4 GHz to 2.5 GHz. Plasma coupling simulations show that the coupling efficiency reaches nearly 60% and imply that controlling the gap distance to be shorter than $\lambda_g/4$ (~14 mm) is an important factor in fast wave coupling. The slotted waveguide antenna is manufactured from a single copper body, except for its thin slotted front surface, to minimize the RF loss. The vector network analyzer (VNA) measurements are in good agreement with the simulation results. The antenna is successfully installed on KSTAR together with waveguides and vacuum RF windows. Low power coupling experiments using a signal generator are performed to evaluate the coupling efficiency during KSTAR discharges. In this workshop, the design results and experimental efforts to develop the LHFW antenna are reported along with preliminary results on low power coupling in KSTAR plasmas.

References

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Report on the helicon current drive in KSTAR and the expected performance in Korean DEMO reactor

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The plasma current drive has been an essential for the recent achievement of high performance KSTAR discharges. For the effective plasma current drive, near-parallel P-NB and EC has been routine auxiliaries in KSTAR. In addition to these conventional technologies, helicon current drive [1] has been developed to supply efficient off-axis current to the KSTAR plasmas for the development of steady-state high beta plasmas as a DEMO relevant technology. The evidence of the helicon power coupling to the plasma was observed following the increase of injection power through MW level travelling wave antenna. In this presentation, the status and the near-term plan of KSTAR current drive and modelling study of helicon current drive in K-DEMO will be discussed.

References

[1]. S. J. Wang *et al*, Nucl. Fusion, **57**, (2017) 046010