21st joint workshop on electron cyclotron emission (ECE) and electron cyclotron resonance heating (ECRH)

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ITER Organization

Book of Abstracts

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Progress of the EC system for ITER in Japan

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Design of the HE11 mode measurement system for the ITER Gyrotrons

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The installation of the ITER Gyrotrons on the ITER site will start this summer and the tests are scheduled for next year. To transmit Electron Cyclotron (EC) beam minimising the losses, qualified

test and precise alignment are required in the installation of both Gyrotrons and Transmission Lines (TL). Mode purity and suppression of Higher Order Modes (HOMs) are necessary to comply with the required value of at least 95% of HE11 mode at the entrance of the waveguide.
The mode content measurement of the beam exiting the open-ended corrugated waveguides is used to optimize the mirrors' angles inside the Gyrotron Matching Optics Unit (MOU), to get a high purity of the HE11 mode. A precise estimation of the HE11 mode is only possible by measuring the far field of the EC beam, as stated in [1]. Based on far field data and using a phase retrieval technique, we can reconstruct the EC beam produced by the Gyrotrons.
The system setup for HE11 mode measurement is mounted on a linear motorized stage for far field measurement up to 1 m distance and includes a beam target and an infrared (IR) camera. A manual 3-axis stage is used to precisely align the target and the camera. The IR camera measures the beam pattern at different distances to reconstruct the field at the aperture of the corrugated waveguide. For HOMs analysis, we have developed phase retrieval and mode contents codes [2].
Finally, we have designed a beam dump for the EC beam passing through the beam target by using the ray tracing simulation tool ZEMAX. A convex mirror is installed on the beam dump to diffract the EC beam and spread it on a large portion of the inner surface, allowing us to use a low power microwave absorber.
This paper describes the system setup for the HE11 mode measurement, the design of the beam dump and the HOMs analysis, containing the phase retrieval code. Moreover, we will present a benchmark of the proposed HOMs analysis code against existing codes used by the domestic agencies (QST, IAP, KIT, IN-DA and MIT) [3].

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Simulation and reflectivity measurements of the first ITER plasma beam dump material

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Recent progress on the electron cyclotron emission diagnostics development for ITER

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The ITER electron cyclotron emission diagnostic design [1] is progressing and will soon transition into development. The measurement and analysis of the electron cyclotron emission (ECE) is one of the primary diagnostics for measuring the electron temperature (Te) and electron temperature fluctuations (⊠Te) on ITER. Here we describe the current design of that diagnostic. ITER will operate at three axial toroidal magnetic fields of 5.3 T, 2.65 T, and 1.8 T. Operation of the diagnostic at full field is the main interest but critical features of the other emission spectra will be described. EC emission is collected by two very similar optical systems: one will view the plasma radially, and the other will be an oblique view; however, both will measure Te. The oblique view allows detection of the non-thermal distortion in the bulk electron distribution. The two views were designed using Gaussian Beam analysis. In-vacuum calibration sources located in each view, can be switched into each view remotely, allowing measurement of any degradation of in-vessel optics. After the emission leaves the vacuum vessel, it is split into O- and X-mode polarizations and transmitted to the detection instruments (75 - 1000 GHz) via transmission lines. The transmission lines are filled with compressed air/dry N2, a choice which was made to simplify construction and analysis, and to comply with safety requirements in ITER as a nuclear installation. Near the instruments, a switchyard is used to select polarization and view for each of the detection instruments. Only the design for the 220 - 340 GHz radiometer used for 5.3 T operation will be described in detail though the unique features of the other instruments will be described as well. All the components were designed to produce the best possible performance. However, the ITER plasma scenarios have evolved during the diagnostic design process, including operation at 1.8 T. This requires the addition of a 75 - 125 GHz RF front-end plug-in for the radiometers.

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Design of Stray Radiation Sensor for ITER ECE Diagnostic

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The Electron Cyclotron Emission (ECE) diagnostic has a primary role in the measurement of electron temperature profile and electron temperature fluctuations in ITER. This diagnostic shall be exposed to significant power due to unabsorbed Electron Cyclotron Heating (ECH) power in the plasma [1]. The expected stray power loads could be a few watts, and therefore, the protection of millimetre wave components is one of the design challenges of ITER ECE diagnostic. This protection system includes sensors, a band stop notch filter, and a shutter to stop the RF stray radiation from being incident on the sensitive components. The sensors will be positioned along the ECE transmission line, and shall be used for real-time power monitoring of the stray radiation.

Here, we describe a novel design of a sensor for monitoring the stray radiation power. This sensor is a Schottky Diode rectenna, known for high-power and high-speed millimetre wave detection capability [2], [3]. It consists of a 2x2 microstrip patch antenna array, a matching circuit, a diode, and a low pass filter. The antenna array is designed analytically and optimized in CST Microwave Studio, for wide reception angle, high gain, and low side lobe levels. Furthermore, the rectifying circuit is optimized using Agilent Advanced Design System (ADS) software to get better rectification and impedance matching of the signal, thereby improving its detection sensitivity. The ADS simulation results show that the detection sensitivity is about 1000V/W for input power of -30 dBm at 170 GHz, thereby achieving the required performance of the sensor.

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Overview of the Wisconsin HTS Axisymmetric Mirror and the role of ECH

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Design activities of the ECRH system for CFETR

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Electron cyclotron resonance heating (ECRH) system is one of the auxiliary heating mix for China Fusion Engineering Test Reactor (CFETR), which is the proposed next-generation fusion facility in China. The ECRH system will deliver 30 MW of RF power into the plasma at the frequency of 170GHz, the front steering launcher (FSL) is selected as for example to investigate the feasibility with regards to the requirements of physical objectives and the integration design of CFETR. A prototype 2MW system aims to provide technical solutions for long pulse ECRH has been launched in 2019, supported by the Comprehensive Research Facility for Fusion Technology Program (CRAFT) of China. A high power testbench has been built for continuous wave (CW) gyrotron commissioning. A mock-up of multi-beam quasi-optical launcher will be implemented for performance validation. The conceptual design of CFETR ECRH system and the currently design activities are presented in this paper.

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MAST Upgrade Microwave Heating and Current Drive System - Engineering Design Overview

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MAST-Upgrade (MAST-U) is undergoing several enhancements to deliver increased performance and functionality. One such enhancement is the design, development, and implementation of an Electron Bernstein Wave (EBW) Heating and Current Drive (HCD) System. The MAST-U EBW System aims to provide experimental data for model validation, and to provide a greater understanding of EBW physics and its capabilities.
The MAST-U EBW System provides up to 1.8MW of microwave power into the plasma, through a system comprising: high voltage power supplies; gyrotrons; evacuated transmission lines; and a steerable in-vessel launching system. The gyrotrons from Kyoto Fusioneering have a 0.9MW output power capability at the dual frequencies of 28GHz and 34.8GHz, allowing start-up and current drive studies to be carried out at their respective optimum frequencies, with current drive studies targeting the second harmonic.
The in-vessel launching system is designed to provide maximum experimental flexibility. A switching arrangement ex-vessel allows the selection of either on or off axis injection into the plasma via either the mid-plane or upper launcher. Each launch path has two sets of mirrors, with one set steerable for varying the injection angle, aiming for a high positional accuracy and precision. Additionally, for the on-axis launcher, large angular steering ranges allow for both co and counter injection.
Finally, additional diagnostics, termed interceptor plates, are proposed to sit in the path of the first reflection. These will measure the reflected power from the plasma, to both act as an interlock if the reflected power is too high, and provide key information on the coupling efficiency.
This presentation outlines the key objectives of the system, the preliminary system design, and the current status, looking in particular at challenges associated with the chosen frequencies, spatial integration constraints, and the design of the in-vessel launching system.

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Advancing ECH Technology using Multiphysics Modelling

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Electron cyclotron heating (ECH) technology is advancing to meet demands for higher power (>1 MW) and longer pulse lengths (~3600 s). New requirements from heating systems for ITER, the Wisconsin HTS Axisymmetric Mirror (WHAM) experiment, and future systems such as STEP and FPP are leading to more complex ECH designs. Although General Atomics (GA) iterates its designs based on prototyping and testing under high power conditions, Finite Element Analysis (FEA) tools are also an essential step of the design process. FEA software packages such as COMSOL and ANSYS have been used to develop many new designs by providing rapid characterization of hardware performance across a wide range of operating conditions. A new compact RF dummy load was designed to minimize reflected power below 0.5% independent of input polarization. High power testing of the load at DIII-D with 0.8 MW input power demonstrates thermal performance is in agreement with FEA predictions. Extended studies indicate this load design can be modified to accept 1.4 MW steady state input power across multiple frequencies while maintaining acceptable temperatures. A

new split waveguide has been designed using FEA tools for the WHAM experiment underway at the University of Wisconsin, Madison. This component enables the application of a bias voltage across two halves of the waveguide, and allows the injection of microwave power through potentially dangerous electron resonance regions at or near the vessel. New methods for water cooling corrugated waveguides and couplings have also been analyzed using FEA methods. These analyses resulted in the development of cost-effective cooling solutions for large scale ECH systems requiring 1 MW steady state power per transmission line.
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Design of the EC system for DTT

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New developments of megawatt power gyrotrons in Russia

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Construction Status of a 110 GHz, 1 MW Gyrotron with Corrugated Waveguide Output

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Assembly is in progress on a 110 GHz, 1 MW gyrotron with HE11 mode output in corrugated waveguide. This is a significant improvement over conventional gyrotrons with Gaussian mode output. The gyrotron will connect directly to corrugated waveguide transmission lines without a requirement for a mirror optical unit. This results in higher mode purity and reduced RF loss, in addition to a major reduction is system cost and complexity. This presentation will describe the design an update the status of the program.

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1.5 MW CW RF Loads for Gyrotrons

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Abstract attached

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Progress on the Frequency Stabilization of MW-Class 140 GHz Gyrotrons at W7-X with a Phase-Locked Loop

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At Wendelstein 7-X (W7-X), a first proof-of-principle frequency stabilization system for megawatt-class 140 GHz gyrotrons was implemented with an off-the-shelf Phase-Locked Loop (PLL) [1]. To overcome the limitation of this first basic PLL system, a new digital PLL system was implemented, which allows a much more flexible change in operating parameters and can be easily integrated into the W7-X system. The gyrotron output frequency can be controlled with the accelerating voltage, which is applied between the anode and cathode of the gyrotron diode-type Magnetron Injection Gun. For the PLL system, the accelerating voltage is varied through the body voltage power supply [2]. Experiments with the new PLL system were conducted at W7-X with a high-power 140 GHz gyrotron from manufacturer CPI at different pulse lengths (short pulses at 5 ms and long pulses ranging from 5 s to 30 s) and at different operating points.
During the short pulses, the free-running gyrotron frequency drops significantly due to the gyrotron cavity expansion caused by heating and electron beam space charge neutralization. To counter the frequency drop, a change in the body voltage of 5 kV was used during the experiments. The gyrotron frequency was locked within a time shorter than 1 ms and was stabilized for 3 ms after which the frequency drop is too high to be kept stable. For longer pulses, the initial frequency drop ceases after 1 s; however, during the free-running operation, frequency variations in the 1 MHz range still appear afterwards. With the PLL system, the change in body voltage to counter these frequency variations was below 1 kV and the gyrotron frequency could be stabilized after 1 s until the end of the pulse. In the frequency spectrum of the stabilized gyrotron output, a full -20 dB linewidth of

below 20 kHz was measured. Still sidebands arise in the frequency spectrum, the most significant ones appear at harmonics of 3.2 kHz and 135 kHz from the main peak. Those frequencies were also observed in the noise of the cathode power supply and could not be suppressed sufficiently enough by the body power supply. Future investigations will be conducted to reduce the noise of the accelerating voltage.
The new PLL system paves the way for applications that need a stable frequency output of high-power gyrotrons at W7-X, such as Collective Thomson Scattering (CTS) Diagnostic [3] or experiments to directly heat ions with beat waves generated by two gyrotrons operated at a difference frequency equal to the ion cyclotron resonance frequency.

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Higher Off-Axis Electron Cyclotron Current Drive Via 'Top Launch' Approach Demonstrated on the DIII-D Tokamak

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Plasma heating and improvement of lower hybrid current drive efficiency by electron cyclotron waves on EAST

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The electron cyclotron (EC) system on EAST consists of three gyrotrons with a frequency of 140 GHz (second harmonic of the extraordinary mode), each of which is expected to deliver a maximum power of 1.0 MW and be operated at 100-1000 s pulse length. Significant progress in long-pulse operation has been achieved during the 2021 campaign, including the pulse duration of 100 s with EC power injected into plasma of 1.4 MW, and the pulse duration up to 1056 s with EC power of 0.55 MW. High electron temperature (Te > 12 keV) plasma measured by Thomson scattering was

produced with the combination of EC and lower hybrid (LH) waves. It is found that the plasma heating effect depends on the EC power location greatly. As a consequence of the increasment of electron temperature by electron cyclotron resonance heating (ECRH), the lower hybrid current drive (LHCD) effieicny is improved, benefiting for the long-pulse operation. By adjusting the EC power location, the plasma current profile can be modified. The synergy effect between EC and LH current drive was demonstred in steay-state opration on EAST. During this experiment, the LH power was feedback controlled by the magnetic flux consumption with constant plasma current and constant density, which is similar to the previous expetiment on Tore Supra [1]. During the application of 0.55 MW ECCD, the LH power drops by approximately 0.3 MW, at constant loop voltage (Vp = 0 V), plasma current and density. The synergy factor defined as Fsyn = Delta_I / I_EC with Delta_I = I_LH+EC − I_LH, is estimated to be ˜ 2.1.

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ECRH experiments on Tokamaks SST-1 & Aditya-U and ECRH upgradation plan for SST-1

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A 42GHz-500kW ECRH system [1] is used to carry out various experiments related to plasma breakdown and ECR heating on tokamaks SST-1 and Aditya-U. The system has been upgraded with new anode modulator power supply to launch two ECRH pulses to carry out breakdown and heating simultaneously. In SST-1, ECRH system is used routinely for plasma breakdown at fundamental harmonic, approximately 150kW power is launched for 70ms to 150ms duration and consistent plasma start-up is achieved in SST-1. In the recent experiments, second EC pulse is also launched at the plasma flat-top to heat the plasma, some heating signatures are seen but more experiments will be carried out to confirm the plasma heating with ECRH. In Aditya-U tokamak, simultaneous plasma breakdown and heating experiments are carried out successfully [2]. In the first pulse around 100kW power in fundamental O-mode is launched for 70ms duration for the breakdown at low-loop voltage and around 150kW ECRH power for 50ms duration is launched in second EC pulse to heat the plasma. In case of Aditya-U, plasma heating is observed clearly as soft X-ray signal increases sharply with ECRH. In Aditya-U tokamak, deuterium plasma experiments have been carried out and ECRH launched at the flat-top of deuterium plasma current. In deuterium plasma also ECR heating is observed as soft X-ray signal increases with ECH power. For SST-1, ECRH system is being upgraded with another 82.6GHz system, this system would be used to carry out plasma heating and start-up at second harmonic. The 82.6GHz system is already connected with the SST-1 tokamak, the old 82.6GHz-200kW Gyrotron will be upgraded to 400kW system to carry out effective heating experiments on SST-1 at higher ECRH power. The paper would discuss the recent results of ECRH experiments carried out on tokamaks SST-1 & Aditya-U and present the upgradation plan of EC system for SST-1.

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Electron cyclotron heating and current drive systems on DIII-D

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The electron cyclotron heating (ECH) system on DIII-D is currently comprised of four 110-GHz non-depressed collector gyrotrons. All four gyrotrons are expected to inject a total of more than 2.5 MW into the plasma for an administrative limit of 5 s during the upcoming experimental campaign. The history of the ECH system complex on DIII-D will be reviewed and future expansion includes the addition of two more 110-GHz non-depressed collector gyrotrons featuring CuCrZr collectors and one depressed collector gyrotron, all expected to be delivered in 2022.
During a previous experimental campaign, experiments carried out at 110 GHz demonstrated that electron cyclotron current drive (ECCD) in the DIII-D tokamak was almost doubled by using a novel top launch geometry compared with the conventional outside launch ports. Two new top launchers are installed and will be tested in the coming experimental campaign in 2022.
In addition to the electron cyclotron system, two new RF current drive systems are being added to DIII-D. A full scale 2-m long helicon antenna with a 1.2-MW 476-MHz klystron that powers the antenna has been installed and tested with a coupled power of 300 kW.
Another RF system being added is the lower hybrid current drive system that will launch RF from the center post of the tokamak on the high magnetic field side. The lower hybrid current drive will be powered by eight 4.6 -GHz klystrons, each able to deliver 255 kW with first experiments expected to be performed in 2023.
Work supported by US DOE under DE-FC02-04ER54698.

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Triple-Beampath-scenario for O2-heating at Wendelstein 7-X: experience of OP1.2 and final improvements for OP2

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Experiments with reduced single pass absorption at ASDEX Upgrade – instrumentation and applications

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The electron cyclotron resonance heating system (ECRH) at ASDEX Upgrade (AUG) has been extended to eight similar Gyrotrons in total. Each Gyrotron operates at 105 and 140 GHz and is designed for up to 1 MW millimetre wave output power. Experimental topics include conditions with high plasma densities [1], potentially above the X-2 cut-off at 140 GHz. New ECRH heating schemes have been proposed [2] which can cope with the demand, at the cost of reduced single pass absorption, however. In order to routinely use the schemes it was necessary to design reflecting gratings, which significantly increase the second-pass absorption, and install them into the heat shield of AUG's inner column [3]. Four of these gratings consist of tungsten coated graphite, which is a composition of materials, established at AUG for a long time. The other four were manufactured out of P92 steel and a thin tungsten coating was applied, which is a newly developed technique. On the grating surface of the P92 steel, the coating reduces the ohmic reflection losses significantly. For beam position control, all gratings are equipped with thermocouple measurements. The fast response of the thermocouples together with the localized measurement opens the possibility to monitor the beam shape after the first pass through the plasma. For a full beam cross section, however, a large number of plasma experiments is necessary, mainly because of the limited capability to sweep the beam across the measurement position in 2D during the flat-top time of the plasma discharge. Thermocouple measurements have also been used in experiments, which try to quantify the X-3 absorption. This technique relies on the thermal response to a millimetre wave beam in the empty vessel, compared to the thermal response to a partly absorbed beam. Possibilities and limitations of the technique are to be discussed.
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Quantification of X3 absorption for ITER L-mode parameters in ASDEX Upgrade

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Development of ECRH-based methods for assisted discharge recovery: experiment and simulation

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Multipass Absorption of ECH on DIII-D for Polarization/Propagation Tests and High-Density Heating

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The suite of codes to model the electron cyclotron heating (ECH) profile on the DIII-D tokamak has been extended to follow the EC waves (110 GHz, second harmonic) over multiple bounces, allowing quantitative comparisons with experimental measurements in low absorption regimes for a number of purposes. First, the EC wave polarization has been checked by launching the waves radially at the centerpost tiles (see Fig. 1), where the injected X-mode component is absorbed off-axis on the first pass while the injected O-mode component is damped primarily on the second pass (at smaller radius) due to the higher electron temperature and mode scrambling [1]. Second, the injection angle for top launch ECH has been tested by placing the EC resonance so that it grazes the inboard side of the downward propagating beam on the first pass, and grazes the outboard side of the upward propagation beam after it reflects off the floor tiles. This results in a double-peaked deposition profile that can be used to constrain the poloidal launch angle by matching the multipass ray tracing code to the observed BT dependence of the two peaks. Finally, future DIII-D experiments plan to use high density plasmas (above the X-mode cut-off) for pedestal and core-edge integration experiments, and multipass ray tracing is being used to optimize second harmonic O-mode damping (single-pass absorption around 50%) for central electron heating. One option that will be explored is installing polarization-conserving reflection tiles on the centerpost to give two passes of nearly pure O-mode polarization.
Figure 1: Multipass ECH ray tracing for launched O-mode polarization on DIII-D. The carbon tiles are ˜92% reflective at 110 GHz. The modeling takes into account conversion between X-mode and O-mode at each bounce.
Work supported by US DOE under Award Number DE-FC02-04ER54698.
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ECRF stray radiation studies in preparation of the operations of JT-60SA

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For its initial research phase, the JT-60SA tokamak will be equipped with four gyrotrons units delivering up to 3 MW at 110 GHz to the plasma. Together with 6 MW of P-NBI and 10 MW of N-NBI the ECRF power will be used to sustain and control stable operation at high current with a lower single null CFC divertor plasma configuration. The development of the current ramp-up up to full-current operation (5.5 MA) is among the first scientific objectives of this phase. In preparation of this, predictive modelling of the current ramp-up in scenario 2 (type I ELMs, H-mode scenario, BT=2.25 T, q95=3) is being done, based on parameters published in [1]. In this scenario the ECRF power is injected from an early phase of the current ramp. Such modelling provides the Te ad ne profiles giving the opportunity to estimate the expected amount of EC stray radiation during the ramp-up phase when the EC power absorption might be less than 100% and consequently the potential risk of damage of the in-vessel components is higher. The study of the current ramp-up phase complements the analysis of the low absorption scenarios being considered for the design of the EC stray detection system, which is presently based on the adaptation to the JT-60SA parameters of the differential bolometers being developed for ITER. In particular, expected locations and EC stray power loads on PFCs due to shine-through of the EC beams are identified.

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Preliminary conceptual design of the COMPASS Upgrade ECRH heating system

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Tokamak COMPASS Upgrade, a medium-sized device is under the design at the Institute of Plasma Physics in Prague. COMPASS Upgrade will operate with a high magnetic field $B_{\mathrm{T}} = 5$~T, flat top current up to 2 MA with correspondent $n_{GW} = 8.7 \cdot 10^{20}$ m^{-3}. The baseline heating system will be composed of NBI heating system with a power up to 6 MW. To get the ability to heat electrons directly and control the T_i/T_e ratio additional ECRH heating power is required. Two midplane narrow ports are allocated for the core plasma heating launches. One incline port is assigned for the the edge deposition and NTM control launcher.

In the first phase of COMPASS Upgrade operation, the ECRH system will be mainly used for the central plasma heating with a target power $1 - 2$ MW. The system will be gradually extended and it will also serve to achieve advance plasma heating and current drive scenarios.

The ECRH system is foreseen to comprise gyrotrons, of 1 MW power each with a pulse length from 1 to 10 s. The first aim of this study is to determine the best choice of operating frequency. System of multiple options is considered: Dual frequency gyrotrons $105/140$ GHz, 170 GHz gyrotron, and in the future > 200 GHz gyrotron. The choice of the optimal frequency for the plasma discharge depends both on the range of the magnetic field at which COMPASS Upgrade tokamak is expected to operate, and on the physics objectives of the experiment itself. Combination of above mentioned gyrotrons needs to be employed to cover the entire anticipated physics program of COMPASS Upgrade.

Restricted space inside the ports and also inside the tokamak hall precludes the use of separate waveguides and launchers for different frequencies. The transmission line and launcher options are under investigation and the preliminary design, solution, and studies are discussed within this study. A significant proportion of electron heating implies a limitation on the safety of some plasma diagnostics.
The level of stray microwave radiation is evaluated for considered frequencies by the multiresonator model.

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Tolerance analysis of a quasi-optical mode converter for the upgrade of W7-X gyrotrons

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In collaboration with IPP Greifswald, an industrial gyrotron operating at 140 GHz with 1.5 MW RF power for the upgrade of the ECRH system of the W7-X stellarator is under development at KIT. A quasi-optical (q.o.) mode converter has been designed for this 1.5 MW gyrotron, operating in the TE28,10 mode. The q.o. mode converter consists of a mirror-line conical launcher [1] and three mirrors with quasi-quadratic surface contour functions [2]. Launcher and mirrors are optimized using the in-house code TWLDO to provide an RF beam with a high fundamental Gaussian mode content of 99 % at the RF output window and low stray radiation of 1.65 % in the tube. Even though the surface contour of the numerically optimized launcher look quite complex, the wall surface is quite smooth. The perturbations on the wall are in the interval -0.077 mm < ΔR < 0.147 mm. The minimum curvature radii of the perturbed wall surface are 23.2 mm in azimuthal direction (average launcher radius: 24.5+0.004z mm, 0 mm < z < 207 mm) and 159.7 mm in the axial direction, respectively. Generally, the smoother the wall surface the smaller the probability of manufacturing errors.
A copper launcher and a mirror system were fabricated and a low power test facility was built to check the performance of the q.o. mode converter system [3]. The wall surfaces of the fabricated launcher have been measured through the entire length of the launcher at discrete azimuthal angles ($2\pi \cdot n/8$, n = 0,…,7). Comparing the measurement data of the fabricated wall surface to the theoretical values, there is a systematic deviation of the average radius of up to approximately 0.025 mm. The relative contour uncertainty is ±0.01 mm. Nevertheless, the low power measurement results show that the fundamental Gaussian mode content of the RF beam is still as high as 97 % at the position of the output window. In order to check the effect of manufacturing errors, a new launcher wall surface has been reconstructed by interpolating the measurements data of the wall surface at the eight measured azimuthal angles. A model q.o. mode converter containing the reconstructed launcher and three designed mirrors has been analysed. The simulation results show that the fundamental Gaussian mode content and the stray radiation are estimated to be 98.9 % and 1.75 %, respectively. The differences between the simulation and the experimental results might be caused by the mode purity of the low power test facility. It is definitely lower than 100 %. Additionally, the reconstructed launcher wall is somewhat different from the real wall surface, and the fabrication errors of the mirror surfaces are not included in the simulation.

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Radial localization of electron temperature edge pedestal and ELM-like events using ECE measurements at Wendelstein 7-X

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Wendestein 7-X (W7-X) is a high iota, low shear optimized stellarator concerning magnetic field geometry with a scientific objective to attain 30 min of detached steady-state plasmas. The electron cyclotron emission (ECE) at W7-X is measured by a heterodyne radiometer [1] in the spectral range of the X2 emission from 126 to 162 GHz and by a Martin-Puplett interferometer [2] in the spectral range of 100 to 300 GHz along the same line of sight. The 32 channel radiometer has a temporal resolution of the order of μs which enables the measurement of the rapid fluctuations in the electron temperature, T_e, for example, the rapid crashes like edge localized mode (ELM)s possibly caused by the formation of the T_e edge pedestal. With the high-resolution ECE measurements, it is possible to determine the spatial location of ELMs in the plasma.

A magnetic configuration scan [3] was performed at W7-X by varying the rotational transform to analyze the plasma confinement for magnetic configurations with different edge island sizes and locations. Due to the low shear, the separatrix can be shaped by large islands constituting an island divertor. For a few of the magnetic configurations, it was observed with ECE measurements that an edge pedestal develops at the start of the plasma discharge followed by the ELM-like crashes in T_e. This work aims at investigating the changes in the T_e edge gradients for different magnetic configurations with a focus on the identification of the spatial location of the T_e edge pedestal and the ELM-like events with respect to the radial location of rational islands.

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Operational domain for the new 3MW/1000s ECRH System on WEST

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The ECRH system formerly used in Tore Supra is being upgraded to start on WEST in 2023, at a power level of 1 MW and frequency of 105 GHz. Its ultimate 3 MW/1000s capability is expected to enlarge the WEST operational domain by increasing margins with respect to H-mode access, and by providing additional flexibility in terms of achievable scenarios using impurity and/or MHD control. This flexibility is made possible using a modified version of the Tore Supra antenna, based on three external steerable mirrors for controlled power injection [1].
In order to determine an appropriate range of EC wave injection angles for WEST scenarios, the fast and reliable ray-tracing code REMA [2] has been interfaced with the WEST IMAS database. This allows the EC power damping rate to be quickly assessed, as well as deposition profiles to be predicted in realistic plasma conditions. Based on a previous WEST discharge [3] at central magnetic

field $B_0 \sim 3.6$T, central line-integrated density $n_l \sim 4.2 \times 10^{19}\mathrm{m}^{-2}$ and central electron temperature $T_{e0} \sim 3$keV, ray-tracing calculations have been performed. Comprehensive poloidal and toroidal angle scans, as well as variations of B_0, n_l and T_{e0} with respect to the reference parameters have allowed an adequate range of injection angles to be determined for efficient use of ECRH and or ECCD in typical WEST scenarios, and compared with the mechanical limits set by the antenna mechanical characteristics. In order to further characterize the effect of this new power source in WEST scenarios, EC wave deposition and current profiles computed by REMA have been included in integrated simulation codes such as METIS [4]. Using interpretative simulations of well-documented shots as a basis, it has been shown that this additional power source could allow central electron heating to be achieved, potentially alleviating the issue of radiative collapse caused by impurities observed in some situations [3].

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A new 3MW ECRH system at 105 GHz for WEST

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The aim of WEST experiments is to master long plasma pulses (1000 s) and expose ITER-like tungsten tiles to power fluxes up to 10 MW/m2. To increase the margin to reach the H-Mode and to control W-impurities in the plasma, an upgraded ECRH system, with a power capability of 3MW/1000s at a frequency of 105 GHz for a central power absorption, is planned for operation in 2023.
The previous Tore Supra ECRH transmitter was equipped with two 118 GHz gyrotrons, 63.5 mm corrugated HE11 mode waveguides and an antenna with six fixed mirrors and three steering mirrors, all actively cooled. With the modifications of Tore Supra to WEST, simulations at a magnetic field of B0˜3.7T and a central density of ne0˜6.1019 m-3 show that the optimum frequency for a central absorption is 105GHz in the new WEST configuration.
For this purpose, a 105 GHz 1MW gyrotron (TH1511) has been designed at KIT in 2021, based on the technological design of the 140 GHz 1.5 MW gyrotron for W7X (TH1507U). Currently, three industrial gyrotrons are under fabrication at THALES. In the first phase of the project, a part from the gyrotron system, the Tore Supra components are going to be re-installed and re-used whenever is possible.
The design of most of the components such as the High Voltage Power Supply system and the Control system require significant modifications. In parallel an updated corrugated waveguide layout and some modifications of the Tore Supra antenna are under consideration. In 2022, the transformations of the EC transmitter and of the antenna are under way.
This paper will describe the studies performed to adapt the new ECRH system at a 105 GHz frequency to WEST and the status of the modifications necessary to re-start the system in 2023 with a challenging schedule.

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Electron Cyclotron Current Drive Efficiency in the STEP Device

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The UK's Spherical Tokamak for Energy Production (STEP) design program aims at demonstrating the ability to achieve a net electrical gain from fusion reactions in a magnetically confined plasma under reactor relevant conditions. A key aspect for a successful design of a Tokamak reactor is the minimization of the recirculating power needed to maintain plasma operation, dominated by the power required for the auxiliary Heating and Current Drive (H&CD) systems.
After considering all viable H&CD concepts, and assessing multiple aspects like physics applications, technology maturity, ease of maintenance, cost, and grid to plasma efficiency, the STEP program has recently decided to rely uniquely on mm-wave H&CD actuators, namely Electron Cyclotron (EC) and Electron Bernstein Waves (EBW).
This work outlines the studies done so far to assess the H&CD capabilities of EC waves in the burning plasma of different STEP prototype reactor concepts. The modelling of the EC beam propagation, absorption and current drive in the plasma has been performed with the GRAY beam-tracing code [1]. ECCD efficiency has been evaluated in each prototype with extensive scans of the launcher position, toroidal and poloidal launch angles, wave polarization and frequency. The parametric scan allowed to identify the optimal EC beam injection conditions which maximize the CD efficiency, and to verify its robustness against changes of the plasma parameters and its sensitivity to changes of the launch angles.
The normalized CD efficiency ζ_{CD} [2] for the best performing launch conditions at normalized minor radii $\rho < 0.6$ is typically found in the range $0.25 < \zeta_{\mathrm{CD}} < 0.4$, with O-mode absorption at the first or second cyclotron harmonic resonance. Far off-axis, at $\rho > 0.8$, a larger efficiency $\zeta_{\mathrm{CD}} > 0.5$ can be achieved via X-mode absorption at the down-shifted first harmonic resonance and Ohkawa current drive. The ECCD performance during other phases of the plasma discharge, and the trade-off between maximum performance and reliable operation, need careful evaluation before a final choice is made for the optimal EC launch configuration.

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Constraints of ECRH for high-field and high-density tokamak COMPASS-U

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COMPASS Upgrade, a medium-sized tokamak is under design at the Institute of Plasma Physics in Prague [1]. Due to wide range of operation scenarios with toriodal magnetic field up to 5 T and expected high density during H-mode ($I_{\mathrm{p}} = 2\ \mathrm{MA},\ n_{\mathrm{GW}} = 8.7 \cdot 10^{20}\ \mathrm{m}^{-3}$), the design of suitable solution is a challenging task. \\

The ECRH system will be designed to inject the 2 MW of RF power in the initial stage. The main concerns are the cutoff condition on the density and regime of heating (frequency and mode). It is impossible to propose the system which provides the central heating for all the relevant scenarios. The concessions has to be made.

Feasibility studies have been conducted by running numerical simulations with the beam-tracing code TORBEAM [2] and by using scenario predictions from the fast integrate tool METIS [3]. It has shown the possibility to use 140/105 GHz dual tunable frequency system. In scenarios with intermediate magnetic field, the torodial injection angle has to be utilized to shift the resonance layer from high-field side towards the center of the plasma. For the experiments with the lowest magnetic field (≈ 1.25 T) the X3 mode heating is not sufficient due to the low absorption, thus the large shinethrough.

The natural H-mode density was estimated based on scalings from Alcator C-mod [4] and other machines. Given high densities should be avoided for the safety of operation, so plasma current must be reduced. To increase the cutoff density the system will be designed in such a way that it can be upgraded towards 200+ GHz gyrotrons.

Overview of the TORBEAM results for the current drive, NTM suppression and further studies will be provided.

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Development of the Multi-Beam Transmission Line for DTT ECRH system

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The DTT tokamak [1], whose construction is starting in Frascati (Italy), will be equipped with an ECRH system of 16 MW for the first plasma and with a total of 32 gyrotrons (170 GHz, ≥ 1 MW, 100s), organized in 4 clusters of 8 units each in the final design stage. To transmit this large number of power beams from the Gyrotron Hall to the Torus Hall Building a Quasi-Optical (QO) approach has been chosen by a multi-beam transmission line (MBTL) similar to the one installed at W7-X Stellarator. This compact solution, mainly composed of mirrors in "square mirrors configuration" [2] shared by 8 different beams, minimizes the mode conversion losses. Single-beam QOTL is used to connect the gyrotron MOU output to a beam-combiner mirror unit and, after the MBTL, from a beam-splitter mirror unit to the ex-vessel and launchers sections located in the equatorial and upper ports of 4 DTT sectors. A novelty introduced is that the mirrors of the TLs are embodied in a vacuum enclosure to avoid air losses, using metal gaskets to avoid microwave leaks. The TL, designed for up to 1.5 MW per single power beam, will have the total optical path length between 84 m and 138 m from the gyrotrons to the launchers. The main straight section will travel along an elevated corridor ˜10 m above the ground level. The development of the optical design reflects the buildings and neutronic constraints and minimizes overall losses to achieve the target of max 10%.

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Gyrotron anode voltage control in EAST ECRH system

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The diode-type gyrotrons are used in the EAST ECRH system[1]. The anode is one of the main components of the gyrotron[2]. We can control the output power of RF waves by changing the anode voltage. An anode voltage control system was developed based on the ethernet CompactDAQ chassis NI-cDAQ-9185[3]. The anode voltage can be controlled up to 30 kV, and the maximum current is 100 mA. The maximum modulation frequency is 5 kHz at 50% duty cycle.

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Application of a quasioptical code PARADE: modeling of ECRH, ECCD, and ECE diagnostic in toroidal fusion devices

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The newly developed quasioptical ray tracing code named PARADE (PAraxial RAy DEscription) can simulate the quasioptical propagation and absorption of wave beams in inhomogeneous anisotropic media within a reasonable computational resource. The code is based on the Schrödinger-type partial differential equation, that accounts for refraction, diffraction, non-uniform dissipation across the beam, and uniquely, mode-conversion. This Schrödinger-type equation is solved along the reference ray trajectory given by the ray equation. One of the advantage of PARADE is a capability of treating mode-conversion, and another one is a capability to simulate an arbitrary beam profiles with non-uniform dissipation across the beam cross section, whereas most quasioptical codes assume the Gaussian beam profile and uniform dissipation. These advantages were experimentally validated and the results showed good agreements.

Recently, as one of the most anticipated applications of the PARADE code, numerical modeling of the Electron Cyclotron Resonance Heating (ECRH), Current Drive (ECCD), and Emission (ECE) diagnostic in toroidal fusion devices are performed. Quasioptical dissipation of wave power flux by PARADE is directly used for ECRH prediction. An adjoint technique with parallel momentum conservation is applied for ECCD calculation. A radiative transfer model under local thermodynamic equilibrium conditions is applied for ECE evaluation. Weakly relativistic dispersion tensor for arbitrary wave vector and fully relativistic tensor numerically integrated along the resonance curve in momentum space are applied for Hermitian and anti-Hermitian part, respectively, to account for the relativity within a reasonable computational resource. This new application of PARADE is used for EC predictions on the JT-60SA tokamak, and is compared with a multi-ray tracing code conventionally used on there. The broader deposited power and driven current profiles are obtained by introducing diffraction as expected. Furthermore, it is found that non-uniform dissipation makes more broader deposition profile.

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MISTRAL campaign in support of W7-X long pulse operation

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Abstract attached as pdf

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The development of 1 MW ECRH system on J-TEXT

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In 2019, a 105 GHz/500 kW/1 s ECRH system has been established on J-TEXT tokamak to improve plasma parameters and broaden operation range. This system consists of traditional subsystems including a gyrotron from GYCOM, a transmission line based on the corrugated waveguides, and a quasi-optical launcher, where the injection angle of the beam can be adjusted by the steerable mirror integrated in the launcher. Commissioning tests results showed the system could reach at least 450 kW output for 1 s. With this ECRH system, obvious heating effect was observed through various diagnostic signals, the core electron temperature was raised from 0.9 keV to 1.5 keV. Since 2021, another 105 GHz/500 kW/1 s ECRH system has been under development in order to reach 1 MW microwave output in total. The layout of the two 500 kW systems is shown in Fig.1. Based on the established 500 kW ECRH system, physical experiments have been carried out which are related to plasma heating, assisted start up, current drive, plasma disruption, magnetohydrodynamic (MHD) instabilities control, etc. With the developing 500 kW ECRH system, the operation range of J-TEXT will be further extended and more relevant experiments could be carried out.

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Pedestal Stability Impact of edge ECCD and ECH during RMP ELM suppression

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Recent experiments on the DIII-D tokamak show access to edge localized mode (ELM) suppression with resonant magnetic perturbations (RMP) is affected by electron cyclotron heating (ECH) and current drive (ECCD) in the plasma edge region (rho˜0.9-0.95). It is found that application of co-Ip ECCD can lead to the return of edge localized modes (ELMs), while heating the plasma with matching ECH power or counter-Ip ECCD does not lead to termination of ELM suppression. Neither a change in ExB shearing rate profile nor a move of rational surfaces with respect to the pedestal top can explain the effect. With a size of around 1-3% of the stored energy, these ELMs are generally smaller than typical type I-ELMs and display characteristics of a limit cycle oscillation. Using pedestal stability analysis with ELITE [1], it is shown that the plasmas are still located in the deeply stable region of the peeling-ballooning stability map, consistent with the observation that ELMs are grassy rather than of a type-I nature. Furthermore, no significant difference is found between the

suppressed ECH case and the ELMing co-Ip ECCD case within the ELITE code, based on the axisymmetric EFIT equilibrium. Hence, these results are consistent with the hypothesis that during RMP ELM suppression an island is formed on the pedestal top [2,3] and that the co-IP ECCD modulates the island size sufficiently to cause the return of smaller ELMs.

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Fast Scan Fourier Transform Michelson Interferometer System for SST-1 Tokamak

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A fast scan Fourier transform Michelson interferometer system has been installed on SST-1 tokamak. The diagnostic determines electron temperature profile and its evolution by measuring electron cyclotron emissions (ECE) from plasma. This is the first diagnostic on SST-1 to probe higher harmonics of the ECE radiations in 70-500 GHz frequency range. During plasma operation, every 17 ms the system generates an electron temperate profile with a spectral resolution of 3.66 GHz.

The paper addresses different aspects of the diagnostic which have been realized successfully to make Michelson interferometer operational for ECE measurements on SST-1 for the first time. These are - Design and development of wave collection and transport system, In-lab / absolute calibration of the diagnostic & Development and characterization of a new high temperature black body calibration source.

A new wave collection and transport system (WCTS) has been designed and employed to transport signal from SST-1 hall to diagnostics lab. To reduce transmission losses, the layout of transmission line has been done using oversized S-band waveguides and mitre bends in TE01 mode. The design and simulation of the WCTS is done using CST microwave studio. Insertion and return loss determined through simulation in the frequency range 70-170 GHz have been verified with laboratory measurements.

In-lab and absolute calibration of the diagnostics has been carried out with hot-cold technique [1, 2] in the frequency range 70-500 GHz by periodic switching between the cold source (at 77 K) and room temperature source. Digital signal filtering and coherent averaging of the raw data is done to obtain difference interferograms. The difference interferograms are Fourier transformed and by

using Rayleigh-Jeans law and the sensitivity of the diagnostics is determined [1]. The in-lab and absolute calibration factors have been successfully determined and the presence of water absorption lines was observed at its expected frequencies which deteriorate the signal strength around 556 and 752 GHz. The measured calibration factor has been shown in Figure-1 with significant signal strength up to 1 THz.

To reduce the averaging time and improve the signal to noise ratio during absolute calibration, a new high temperature black body source at 873 K with silicon carbide emitter has been developed with a maximum surface temperature variation of 15 K. Radiation temperature of the calibration source has been measured and radiation losses have been calculated in the entire frequency range. Figure-2 shows the radiation temperature of the high temperature source as a function of frequency. The radiation temperature is found to be about 125 K below the black body physical temperature due to radiation losses.

The results obtained in each section above will be presented and discussed in the paper in detail. The diagnostic is ready for plasma operation during the upcoming SST-1 experimental campaign and will determine electron temperature profile and its evolution with time.

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Synthetic Aperture Microwave Imager (SAMI-2): design, implementation & commissioning at MAST-U

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The second incarnation of the Synthetic Aperture Microwave Imager (SAMI-2) is a tokamak diagnostic operating in the frequency range 20-40 GHz with up to 30 dual-polarisation receiving antennas amd 2 transmitting antennas.
SAMI-2 has two core missions [references to work with the original SAMI]:
(a) imaging spontaneous emission of electron Bernstein waves converted to electromagnetic waves in the plasma edge [1], this being particularly relevant to the forthcoming EBW current drive project on MAST-U;
(b) measuring the magnetic pich angle at a given density [2]: in this second mode of operation, SAMI-2 injects a microwave signal at the plasma and images the Doppler back-scattered signal returned to the diagnostic from the critical density surface. Since turbulence in magnetised plasmas is elongated along magnetic field lines, the largest back-scattered amplitude is oriented perpendicular to the field. Measurements at multiple locations will enable us to deduce the edge current density, which is an important quantity for understanding edge stability.
SAMI-2 represents a bottom-up redesign of the SAMI principle to advance the technique from proof-of-principle to production measurements. Each antenna feeds a RF downconversion PCB that we designed, each with four IQ mixers (for two polarisations and two simultaneous local oscillator frequencies) [3]. The data is then amplified, filtered and digitised via more custom PCBs with control being provided by an off-the-shelf FPGA board. Data is either read into memory on the FPGA board or streamed in real-time over multiple 10 Gb/s network connections.
In this presentation we will describe the technical details of the diagnostic, and its installation and commissioning at MAST-U

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The design of the ECRH system of DTT

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The Divertor Tokamak Test (DTT) facility [1] is under construction in Italy with focus on power and particle exhaust and it will reach the condition of 15 MW/m power flow outwards through the separatrix by coupling up to 45 MW of auxiliary heating power to the plasma. To achieve this goal, the selected heating systems are Electron Cyclotron Resonant Heating (ECRH), Ion Cyclotron Resonant Heating (ICRH) and negative Neutral Beam Injector (NBI). The final power mix (32 MW ECH, 8 MW ICH, 10 MW NBI) will be based mainly on ECH power, exploiting the great advances in the field of the last two decades. The procurement of the first bunch of 16 MW of ECH, based on 1 MW/170 GHz/100 s gyrotrons technology, has already started and will be available for the DTT first plasma. A Quasi Optical (QO) approach has been chosen for the power transmission, as solution for the long distance between Gyrotron Hall and Torus Hall Building, with multi-beam mirrors installed under vacuum to reduce the overall transmission losses below the target of 10%. The power is injected into the tokamak using single-beam independent front-steering launchers, real-time controlled, for different tasks: assisted plasma breakdown, NTM and ST control, EC current drive and main electron heating. A single null configuration has been selected as reference plasma scenario to verify, by the beam tracing code GRAY, the effective flexibility of the EC launcher to fulfil the requirements. The DTT ECH system design, presented here, is based mainly on existing and assessed technologies, although challenging adaptations to the DTT case are considered. The design of an evacuated QO multi-beam requires a detailed evaluation of the stray radiation while a specific control system architecture is needed to manage such a large number of gyrotrons, with the aim to increase the reliability of the system.

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The ECRH-Power Upgrade at the Wendelstein 7-X Stellarator

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The existing ECRH system at W7-X consists of 10 gyrotrons, with output power levels ranging from 0.6 MW up to 1.0 MW each, quasi-optical transmission lines and microwave launchers at the plasma vessel. The overall transmission efficiency of the fundamental Gaussian mode is estimated to be approx. 94 %. The ECRH system is commissioned for a max. pulse length of 1800 s at full power.
Compared to other large fusion experiments, W7-X has a relatively low power-to-volume ratio. However high heating power is particularly necessary for achieving high plasma beta values, where the improved confinement of fast ions, one of the optimization criteria of W7-X, can be examined. In addition, with higher heating power, one expects the achievement of improved confinement regimes, such as the H-mode. It is therefore necessary to expand the ECRH systems in several consecutive steps. It is planned to increase the number of gyrotron positions from 10 to 12 and at the same time to evolve the gyrotron output power in several development steps from 1 MW to nominal 1.5 MW and, finally, up to 2 MW. In a first step, the 11th position was fully equipped and a very first 1.5 MW gyrotron was developed at KIT and manufactured at Thales, France [1]. This 1.5 MW W7-X TH1507U gyrotron is a direct evolution of the 1 MW W7-X TH1507 gyrotron. In the second step, 3 more gyrotrons of the 1.5 MW class are to be ordered, with some of their critical components already designed towards even higher output power. In a final third step, a new 2 MW prototype is to be designed, built and tested. It is to be followed by 3 more 2 MW gyrotrons, so that the ECRH facility will finally be equipped with 3 times 4 gyrotrons each of the 1 MW, 1.5 MW and 2 MW class. At the same time, the transmission lines will also be upgraded for 2 MW operation. Here, the atmospheric transmission was considerably improved by a new powerful air drying system already. Furthermore, the minimum beam waist was enlarged in the critical areas of the new 2 transmission lines to reduce the risk of arcs. A special effort is also made to improve the reliability of the system by the fast control system. For operation at maximum heating power at W7-X, it is also necessary to operate simultaneously with the NBI heating. However, both heating systems must share the same high-voltage supply with 12 modules. Therefore an operation scenario of 2 gyrotrons on one high-voltage module is developed, so that parallel operation of 12 gyrotrons and 4 NBI sources is possible.

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Commissioning of the Gyrotron Test Facility FULGOR - First Results

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Since the mid 80's of the last century KIT is consequently pursuing the goal to develop high power gyrotrons which are widely used as RF source for ECRH and ECCD in fusion devices. KIT is currently establishing a new teststand for gyrotron development. FULGOR (FUsion Long Pulse Gyrotron LabORatory) will allow to test gyrotrons with a performance which is well beyond the state-of-the-art. The HVDCPS (High Voltage Direct Current Power Supply) was manufactured by Ampegon AG, CH, it takes advantage of the Enhanced Pulse Step Modulator technology which allows intermediate tapping points for highly efficient operation of gyrotrons with multi-staged depressed collectors and very low noise levels. The power supply is designed for 10 MW CW operation at 90 kV and 120 A, for short pulse operation (< 5 ms) 130 kV at 120 A is possible. Specific modular units make sure that in case of an arc in the gyrotron the energy is limited to 10 J. The rise time of the pulse is < 50 ⊠s, the modulation frequency is up to 5 kHz. An additional body power supply (BPS) for operation of conventional single-stage depressed collector gyrotrons has been installed. This power supply will deliver an output voltage of up to 50 kV at 100 mA. Future gyrotrons which will be developed for fusion applications will require higher operating frequencies compared to state-of-the-art. This will call superconducting magnets which allow for operation well above 200 GHz. The FULGOR test facility will be equipped with a flexible and extensive diagnostic system which allows the full characterisation of gyrotrons in short pulse and long pulse operation. A new frequency diagnostic system will be built up in the range 170 – 260 GHz, it will include a 18 GHz bandwidth filterbank system with 2 GHz sub-channels and a pulse spectrum analysis system. The cooling system of the facility is capable of handling a power of 10 MW, each secondary cooling channel is equipped with temperature sensors and flow meters to allow calorimetric measurement. Precise temperature sensors and flow meters are installed in the primary cooling circuits to offer exact measurement of the power loading of the different cooling channels in the gyrotron.
First results of gyrotron operation with FULGOR will be reported. In order to verify proper operation of the complete FULGOR teststand a 140 GHz pre-prototype short pulse gyrotron has been used. The basic performance of this gyrotron has been investigated in previous experiments and is reported in [1].

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Development of the diagnostics for electron cyclotron emission measurement on J-TEXT

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Recent developments of ECE radiometer and ECEI for low magnetic field operation on LHD

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ECE diagnostics have been used since the beginning of LHD experiments, and now two new ECE systems, both systems cover in Q-band and V-band, have been installed to meet the demand for information on electron temperature fluctuations in low magnetic field strength experiments.
One is a conventional radiometer. The existing radiometer is optimized for high frequencies, so a new light-collecting (focusing) mirror is installed in the vacuum vessel (as shown in Fig.1), and after quasi-optical transmission, a corrugated waveguide is used to guide the radiometer to a millimeter-wave receiver system located about 5 m away from the LHD main body, where a 32-channel filter bank is used to measure the electron temperature. A system was installed to enable measurement of spatial distribution. The other is an ECE imaging system with an 8 (poloidal) x 8 (radial) x 2-band, 128-channel measurement system with a Local-integrated receiver array [1,2].

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Current status of ECE system on EAST tokamak

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The electron cyclotron emission (ECE) diagnostic on the experimental advanced superconducting tokamak (EAST) has a major upgrade since 2020, when EAST heating system also went through a huge upgrade, including the one NBI system was changed from counter-current to Co-current (moving from port F to port D), and the antenna and the installation port of LHW and ICRF system have also been changed. The quasi-optical (QO) antenna of P port ECE system [1] has been redesigned, the main purpose is to add one oblique ECE view, the angle with respect to perpendicular to the magnetic field is about 10°, which can measure the electron velocity distribution caused by LHW system. The ellipsoidal mirror has also been moved close to the plasma, about 70 cm away from the plasma center, and the poloidal beam waist radius in the plasma has been optimised to be less than 3 cm. The CECE system [2] has also been moved from port G to port C. The frequency coverage of the CECE system has been upgraded to 106-134 GHz by adding one radio frequency (RF) module, also in the intermediate frequency (IF) module, 8 narrow-band filters has been added to improve the space coverage of the system. On port F, a new superheterodyne radiometer with narrow-band filters in IF module has been installed. It consists of eight channels, the radial coverage is about 8 cm, the main purpose of this new system is to study the fine structure of magnetic island.

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Database study of turbulent electron temperature fluctuation measurements at ASDEX Upgrade

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Turbulent transport is generally found to determine energy and particle confinement times in tokamaks. The correlation electron cyclotron emission (CECE) diagnostic installed on the ASDEX Upgrade (AUG) tokamak measures broadband, long-wavelength ($k_\theta \rho_s < 0.3$) electron temperature fluctuations [1], yielding insight into turbulence-driven transport. Analysis of CECE data is well- suited to automation during the steady-state conditions often used for experimental core transport studies. In this work, an automated method for the analysis of CECE data is applied to discharges at AUG. The automated method determines the optimal time windows for CECE analysis during each discharge, evaluates the impact of plasma conditions on measurements, filters the raw data to account for the presence of artifacts stemming from sources including electronics noise, and processes the filtered data into turbulent electron temperature fluctuation amplitudes. For each analysed discharge, the turbulence measurements are paired with dozens of local and global plasma and engineering parameters evaluated during the same time windows and at the same radial locations as the CECE measurements. The resulting experimental turbulence database provides a unique opportunity to search for trends in turbulent electron temperature fluctuation levels over a large range of parameter space and allows for direct comparisons with cutting-edge numerical models of turbulence and transport. In this work, the database is used to study the competing effects of collisionality and gradients on the saturated amplitude of turbulence measured by the CECE diagnostic.

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Non-thermal electron distribution measurement from polarized electron cyclotron emission in the TCV tokamak

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Investigation of Te measurements discrepancies between ECE and Thomson diagnostics in high-performance plasmas in JET

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Accurate and consistent measurements of the electron temperature (Te) profile are paramount for current fusion experiments, like JET, and future devices, such as ITER. In high performance plasmas in JET and TFTR, electron cyclotron emission (ECE) measurements for central Te>5 keV were systematically found to be up to 20% higher than those taken with Thomson scattering (TS) [1, 2]. Conversely, in very high Te plasmas at FTU (Te>10 keV), TS measurements pointed to systematically higher Te values than determined with ECE [3,4]. Such differences in Te measurements could be caused by diagnostic issues (calibration, alignment), but their observation in different machines suggests the presence of an underlying physical reason. A possible cause for this discrepancy could be the presence of a sufficiently large non-Maxwellian feature in the electron energy distribution function (EDF) [5]. In fact, the two diagnostic principles probe different domains of the EDF and the ECE is sensitive to its derivative through the reabsorption term. Such non-Maxwellian features may result from the interaction of the electron population with fast ion tails which, in turn, can be caused by external heating (neutral beam injection, ion cyclotron heating), or fast alpha particles produced by fusion reactions. For recent JET discharges, central Te measurements, relying on LIDAR [6] and the X-mode ECE interferometer [7], both independently and absolutely calibrated, were studied in a large database, including DD, TT, and DT plasmas. Indeed, discrepancies could be observed outside of the experimental uncertainties for a set of high- performance discharges. ECE measurements at high Te were found to be higher or lower than those of LIDAR, depending on the specific plasma scenario. In addition, discrepancies between the peaks of the second and third harmonic ranges of the ECE spectrum, were interpreted as evidence for the presence of non-Maxwellian features, in agreement with previous results [8]. These comparisons seem to suggest that such features can be found in most of the high-performance scenarios selected in this database. The experimental observations are in good agreement with the predictions of an ad-hoc model which calculates ECE emission and absorption by an EDF perturbed with a small non-Maxwellian feature [9]. In addition, more accurate predictions with the SPECE code [10] are presented, showing the effects on the ECE spectra in more detail.

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A model of non-Maxwellian electron distribution for the analysis of ECE in JET discharges

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Discrepancies between electron temperature measurements by Thomson Scattering (TS) and Electron Cyclotron Emission (ECE) have been often observed in high-temperature tokamak plasmas, in particular on TFTR [1], JET [2] and FTU [3]. Such observations, made on different machines, by different types of instruments, using different calibration methods, are too ubiquitous to be ascribed to instrumental effects; they rather call for explanations based on physics phenomena. The hypothesis that the discrepancy could be associated to non-Maxwellian bulk electron distributions has been put forward in the past [4,5] and appears as a plausible explanation in the case of a plasma heated by EC waves, as FTU [3]. For TFTR and JET, electron heating rather takes place because of the interaction of the electron distribution either with a fast ion tail driven by Neutral Beam Injection and/or Ion Cyclotron Resonance Heating, or by energetic alpha particles produced by fusion reactions in a D-T plasma. Two mechanisms are known to produce small bipolar distortions of the electron distribution in the presence of energetic ions: collisional relaxation [6] or Landau damping of Kinetic Alfvén Waves, as observed in the Magnetosheath [7,8].
Recent experiments performed in JET at high level of plasma heating, in preparation of, and during the D-T campaign have shown again TS-ECE discrepancies on an extensive database [9]. ECE is observed to be higher or lower than TS, depending on the plasma scenario. Moreover, ECE measured by a Martin-Puplett interferometer on a broad frequency range displays differences between 2nd and 3rd harmonics, which, at high temperatures (> 4 keV) and high densities are expected to yield the same radiation temperature. In order to perform a systematic analysis of this effect, a simple model of bipolar distortion of the electron distribution function has been developed, allowing analytic calculation of the EC emission and absorption coefficients. Extensive comparisons of the modelled ECE spectra at both the 2nd and the 3rd harmonic with experimental measurements provide a compelling confirmation of bulk electron distribution distortions around 1-2 times the electron thermal velocity and prove useful for a first level of analysis of this effect.

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Measurement on electron temperature fluctuation in LHD using correlation ECE technique

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Investigation on plasma turbulence and micro-instabilities is believed to be essential for understanding the "anomalous" transport phenomenon and improving confinement techniques on plasma. The correlation-electron cyclotron emission (C-ECE) technique, typically cross-correlates two ECE channels that contain identical temperature fluctuation information and individual thermal noise signal. The C-ECE system resolves turbulent temperature fluctuations embedded in the random thermal noise, which may give information about turbulence and micro-instabilities [1].
A C-ECE system on the large helical device (LHD) at the National Institute for Fusion Science (NIFS) measures emission at 74-79.6 GHz using the spectral decorrelation method. The C-ECE system uses a receiver for a collective Thomson scattering diagnostic in the LHD [2]. The C-ECE receiver system shares the RF stage and is divided into a filter bank system consisting of 32 band-pass filters and a fast digitizer system (NI PXIe-5186) at 12.5 GHz sampling rate in the intermediate frequency (IF) stage. Both systems allow measurement frequencies of 0.5-5.6 GHz in the IF stage. The fast digitizer system is flexible on bandwidth and a time resolution for frequency channels [3]. However, this system encounters a long computational time and allows simultaneous processing on only two channels due to the enormous data volume engaged in the analysis.
In this work, initial experimental results on the temperature fluctuation spectra in LHD are obtained by the C-ECE system with a coherency-based analysis method [4]. The coherence spectra is corrected by removing the bias error presented in coherence calculation process. An MHD mode at 5 kHz is excited from the onset of neutral beam injection in a magnetic probe and a coherence spectrum a from two C-ECE receiver systems. According to Figure 1, the coherence spectra spectrum attained from the fast digitizer system give the˜0.6 coherence of˜ 0.6 and a small statistical error level (˜7%) for the observed mode at 5 kHz. The result on temperature fluctuation is computed from the bias removed coherence spectrum and gives a ˜3% level in the frequency range (0 - 400 kHz), which is above the sensitivity limit (˜ 0.9%). Further work will be performed to investigate drift wave turbulence activities and to reconstruct the radial profile of the temperature fluctuation in LHD using the C-ECE receiver systems.

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Bayesian inference of electron cyclotron emission radiometer calibration by changing the magnetic field

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Changing the toroidal magnetic field is one of the relative calibration method to obtain the relative calibration coefficients of electron cyclotron emission radiometers (ECE). At the meanwhile, for the HL-2A, there is a Thomson scattering diagnostic system, which can get the accurate electron temperature (Te). By cross comparison with Thomson scattering Te of the center channel, the absolute Te profile can be obtained by ECE. In general, magnetic field calibration method is a simple and handy way to obtain the calibration coefficients that just need two similar shot but a difference of 1.35% on the magnetic field and has been utilized on HL-2A for many years. For this method, the assumption is that the Te profiles is consistent. It means a little different between the two Te profiles like vertical and horizontal plasma displacements will cause prominent calibration error. In order to reduce the calibration error, displacement, Te perturbation of core region and magnetic field changes analysis has been done. Result shows that 3.7% magnetic field difference can improve the accuracy of calibration. In the meantime, Bayesian inference has been utilized to further improve the accuracy of calibration and get the most probable calibration coefficients and the confidence interval. As shown of Bayesian inference result, it's little different with the mean value of the original data, the coefficients of the area outside the core is confident and the biggest uncertainty is from the core region but which is acceptable.

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Collective Thomson scattering at Wendelstein 7-X: achieved results and glance into the future

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Electron temperature fluctuation levels of quasi-coherent mode across the plasma radius

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The ECRH heated EDA regime at ASDEX Upgrade is an ELM-free regime with good energy confinement properties [1]. As a consequence of high ECRH power, the rotation profiles are hollow, similar to observations in some L-mode plasmas [2], and ELMs are replaced by a quasi-coherent mode regulating the transport and keeping the pedestal stable against large type-I ELMs. Alongside quasi-coherent modes, magnetic measurements show harmonic signature with n = 1 having a similar frequency to quasi-coherent mode. Peculiar to EDA H-modes is that in some core ECE channels, a mode appears with the same frequency as the quasi-coherent mode at the edge.
In this work, we explore the features of the edge quasi-coherent mode and its signature in the core. The relative temperature fluctuation levels across the pedestal are assessed via the Correlation Electron Cyclotron Emission (CECE) instrument [3] covering the region of ρpol = [0.85–1]. The fluctuation levels associated with the quasi-coherent mode remain constant across the pedestal but change for different electron temperatures and temperature gradients. The coupling between the quasi-coherent mode and the harmonic mode is discussed.
The radiation transport forward model supports the interpretation of the core ECE measurement, ECRad [4], with included refraction and realistic ECE geometry. We use a 2D electron temperature and density grid as input parameters, featuring an edge mode of high toroidal mode number. The synthetic ECE signal in the core is refracted by the strong edge modulation but the amplitude is of the order of magnitude lower than in the experiment. Hence, the refraction alone can not fully explain the mode in the core ECE channels.
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Electron temperature fluctuation measurements with Correlation Electron Cyclotron Emission in L-mode and I-mode plasmas at ASDEX Upgrade

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The I-mode confinement regime is a promising operational scenario for future fusion reactors because it features high energy confinement without high particle confinement [1]. The nature of the edge and pedestal turbulence in I-mode plasmas is still under investigation, and open questions exist about the role of the turbulence in determining the transport of I-mode. The edge Weakly Coherent Mode (WCM) appears in the I-mode pedestal and may play a role in transport. In this work we explore electron temperature (T_e) fluctuations in the plasma outer core and pedestal ($\rho_{pol} = 0.85-1.0$) using a 24-channel high radial resolution Correlation Electron Cyclotron Emission (CECE) radiometer [2]. CECE measurements provide turbulence information including the T_e fluctuation amplitude, turbulent spectra, and radial localization of turbulent features. With CECE measurements we show that the WCM is localized in the pedestal region in both L-mode and I-mode and is measured in optically thick plasmas with a T_e temperature fluctuation amplitude of 2.3-4.2%. Broadband drift wave turbulence is measured in the outer core with a Te fluctuation amplitude of <1%. The quality of the confinement of the discharge phases is found to be independent of the presence of the WCM. The quality of the confinement does correlate with changes in outer core ($\rho_{pol} < 0.95$) T_e fluctuation amplitude

A second CECE system recently installed at AUG allowed for non-standard fluctuation measurements during L-mode and I-mode experiments. The second CECE system was toroidally separated from the primary system, allowing measurements of the long-range toroidal correlation of the WCM indicating its low toroidal mode number. A reflectometer sharing a line of sight with the second CECE system enabled density-temperature cross-phase (α_{nT}) measurements [3]. The WCM α_{nT} changes between L-mode and I-mode $-171°$ to $-143°$ as the T_e gradient steepens.

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Propagation properties of electron cyclotron wave with helical wavefront in magnetized plasma

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Numerical investigations of the O-X mode conversion process in MAST Upgrade

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Electron Bernstein waves (EBWs) allow to couple energy to plasmas whose electron density exceeds the cut-off density of the injected microwave [1]. EBWs are electrostatic waves that have no high-density cut-off and are very well absorbed at the electron cyclotron resonance (ECR) and its harmonics, even at low electron temperatures (in contrast to conventional heating of O- or X-mode at harmonics of the ECR [2]). Furthermore, EBWs can very efficiently drive toroidal net currents [3], which is of particular importance in spherical tokamaks like MAST Upgrade [4], due to the necessity of non-inductive current drive in these type of devices.

The electrostatic EBWs can be coupled to injected electromagnetic waves via a two step mode conversion process: an injected O-mode couples to an X-mode at the cut-off layer, propagates then outwards and couples to EBWs in the vicinity of the upper-hybrid resonance layer. The overall efficiency of this process is strongly determined by the O-X coupling process, which itself depends on the injection angle of the O-mode with respect to the background magnetic field at the conversion layer.

In this work we present numerical studies of the O-X coupling efficiency in the MAST Upgrade geometry. Different codes have been used (2D and 3D finite-difference time-domain codes and a code using a Fourier method in the plane normal to the density gradient) to elaborate the importance of microwave beam geometry and plasma density fluctuations on conversion efficiency. Scenarios with low and high confinement have been investigated illustrating the effect of a varying density gradient length on the sensitivity of the O-X conversion efficiency against angular mismatch. High efficiencies on the order of 90 % were found making this microwave heating scheme an attractive candidate for MAST Upgrade.

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Two-dimensional kinetic full wave analysis of O-X-B mode conversion in tokamak plasmas

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see attached PDF file

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Evaluation of the O-X mode conversion rate of the finite width wave in two dimensional systems

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For ECRH in the "over-dense" region where the electron density is more than the cutoff density, the electrostatic electron Bernstein wave (EBW) should be excited via the mode conversion process from the slow X (SX) mode at the upper hybrid resonance (UHR). Waves launched from the low magnetic field side transmit the evanescent region to couple with the SX mode. The previous linear mode conversion theory [1] gives the transmission rate from the incident O-mode to the SX-mode i.e. the O-X mode conversion rate T_{OX} with assuming the plane wave propagation. However, in the real experiment, electromagnetic waves are launched with a finite width from the waveguide antenna, quasi-optical antenna, and so on. The wave optical full wave analysis is required to analyze the characteristics of the mode conversion process with taking into account the beam broadening.
We evaluate T_{OX} numerically for finite width waves in two dimensional systems with using TASK/WF2D code. The cold dielectric tensor is used for solving the Maxwell equation by finite element method and the resonance absorption model in the cold plasma is adopted. The uniform magnetic field where the cyclotron frequency normalized by the wave frequency Ω_e/ω is 0.4, and the linear density profile whose scale length normalized by the vacuum wavelength L_n/λ_0 is 7.5 are adopted. For each case of the propagation angle θ, the incident Gaussian like beams is focused at the plasma cutoff. Two cases of the beam waist size normalized by the vacuum wavelength w_0/λ_0 =3.48 and 1.59 are calculated. We found that T_{OX} is less than one at the optimum propagation angle which the previous linear theory indicates. On the other hand, T_{OX} is more than that given by the linear theory when the propagation angle deviates from the optimum. For the case of narrower beam waist size, these tendencies are enhanced.

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Full wave simulation based on weakly relativistic Vlasov-Maxwell system for electron cyclotron wave in magnetized plasmas

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The relativistic dielectric tensor is necessary to model wave propagation and absorption in high-temperature magnetized plasmas. In fusion plasmas, electron cyclotron resonance heating (ECH) requires ray-tracing calculations to evaluate a heating location and a heating efficiency in plasmas. In this study, for a non-uniform medium, a full-wave approach is applied to simulating the propagation and absorption of EC waves in combination with the weakly relativistic dielectric tensor [1]. A finite element method is adopted for the full-wave approach.
The background medium is set to the electron density of 2×10^{19} m^{-3} and electron temperature of

5.76 keV in a two-dimensional rectangular area of 65 mm × 50 mm. An EC wave with a Gaussian profile starts from the left boundary of the area and propagates as an O-mode in the increasing magnetic field B_z. We confirmed that an EC wave decays across the EC resonance layer in Figure 1. To characterize the wave absorption on the electron temperature, the absorption efficiency ($|S_0|$-$|S_{out}|$)/$|S_0|$ is evaluated from the line integral of the Poynting vector |S| of electromagnetic waves, where the subscripts 0 and out indicate the locations at the input and the opposite boundaries, respectively. The absorption efficiency increases up to 100%, as the electron temperature increases from 0 to more than 20 keV. In another situation, when a density cutoff exists in the area, EC waves reflect at the cutoff layer. This demonstration attains insight into the behaviour of electromagnetic waves in weakly relativistic plasmas.

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Radiation pressure of electron cyclotron waves on cylindrical filaments

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Broadening estimation of the ECRH deposition profile using perturbative experiments

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Parametric Dependence of Microwave Beam Broadening by Plasma Turbulence

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See attached abstract for full details.
To inject power for heating or current drive, the RF beams must traverse the turbulent layer of plasma at the edge of the tokamak. In this layer, the density fluctuation level can reach 100 % of the background density, and the plasma fluctuates on length scales similar to that of the wavelength used for power injection. These density fluctuations scatter incident microwaves, resulting in an overall broadening of the beams which can significantly impact the efficiency of the device. We are

therefore seeking to develop a predictive capability of this broadening for current and future tokamaks.
We simulated a microwave beam propagating through a turbulent layer of plasma using the 2D full-wave cold plasma code EMIT-2D. We conducted a series of pairwise parameter scans to determine whether the dependence on each parameter is separable from the others. The parameters we considered were background plasma density, fluctuation amplitude, turbulence correlation lengths in the radial and poloidal direction, thickness of the turbulence layer, and microwave beam waist. We found two pairs of parameters that are not separable: the radial and poloidal correlations lengths, and the fluctuation level and background density. All other dependencies are separable. With this data, we aim to develop an empirical formula, making predictions of the effect possible in microseconds of processing time, instead of the hours required for full-wave simulation.

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Parametric analysis of spectral intensity of electron cyclotron radiation coming out of plasma in ITER

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Electron cyclotron (EC) radiation in ITER due to high electron temperature and high magnetic field besides its important role in power loss balance [1, 2], will be a source of additional thermal and electromagnetic loads for microwave and optical diagnostics [3]. EC radiation from the plasma dominates over the nominal stray radiation from electron cyclotron resonance heating (ECRH) and current drive (ECCD) microwave power sources in high performance discharges of ITER operation and therefore its implication for diagnostics must be investigated [3]. This is especially important for mm-wave diagnostics in ITER such as microwave reflectometers, and Collective Thomson scattering system, whose transmission lines allow, in principle, additional measurements of EC radiation spectra [4]. Although the working frequency range for these diagnostics is significantly lower than the operational frequency for ITER ECRH system (˜ 170 GHz), their antennas and waveguide can receive the entire emission spectrum at frequencies above 12 GHz. Electromagnetic loads strongly depend on the spectral distribution of the EC radiation emerging from the plasma to the first wall and areas behind blankets and in port plugs, where there is usually less heat sink presented.
Here we report on calculations with the CYNEQ code [5, 6] of the spectral intensity of EC radiation coming out of plasma for typical scenarios of ITER operation and various values of surface-averaged reflectivity of the first wall. It is shown that for high values of surface-averaged reflectivity of the first wall (Rw = 0.9), the energy flux density may attain the values of ˜ 100 kW/mˆ2, and its spectral distribution is located mainly in the range 500-1500 GHz.

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First measurements of WEST ECEI diagnostic

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First measurements of WEST ECEI diagnostic

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Electron Cyclotron Emission imaging (ECEI) diagnostic system is a unique tool for visualizing the magnetohydrodynamic (MHD) or turbulent instabilities [1]. For WEST tokamak, teams from Korean universities UNIST and POSTECH and IRFM have collaboratively developed an ECEI diagnostic system that can withstand the accessibility and thermal constraints of the WEST tokamak [2]. The diagnostic is made of:
- two in-vessels mirrors. They focus and redirect the ECE beam toward the man-access flange
- a compact optical enclosure. The optical components are vertically aligned to take advantage of the height of Tore Supra equatorial and fit in the limited space between [3].
- three cubicles in the basement. They house the video modules and the acquisition system
The diagnostic was installed and aligned in 2019. Unsuccessful vacuum qualification of the large vacuum window prevented plasma measurements, but we were able to validate the diagnostic system and perform acquisitions to evaluate the noise level. Analysis of the C4 and C5 campaign data showed that the diagnostic was plagued by large parasitic signals and high level noise.
During the last shutdown, the diagnostic was modified to improve the cubicle shielding: an isolator transformer was installed; the 24 cables linking the optical enclosure to the cubicles are now connected on a connector panel fixed on the cubicle top to reduce the ground loop impact. We also successfully tested the vacuum window assembled with a polymer joint.
The diagnostic was realigned at the end of the shutdown and the ECEI flange with the vacuum window was bolted on the tokamak vessel. The commissioning of the C6 campaign should start in May and we are looking forward for the first ECEI signals on plasma.

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Electron cyclotron heating assisted start-up in J-TEXT

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Electron cyclotron heating (ECH) breakdown and burn-through assist has been adopted to make the ITER start-up, which uses a low toroidal electric field of about 0.3 V/m, more robust. Related studies have been carried out on many fusion machines such as DIII-D, JT-60U, JET, Tore Supra and EAST. However, the required ECH power to ensure an effective breakdown assist at ITER is not yet clear. Experiment was also performed in J-TEXT to determine the minimum ECH requirements to assist breakdown and develop a better physics description of the process. The breakdown loop voltage for a successful shot was reduced from 34 to 3.7 V (corresponding to 0.56 V/m) by 300 kW ECH with X2-mode polarization, as shown in figure 1. The critical power for successful discharge is about 200 kW. When ECH power is higher, there seems to be strong plasma-wall interaction. The effect of different loop voltage and ECH time on start-up was also studied. Extremely low breakdown voltage leads to a higher toroidal field later when putting a capacity to continue discharging in J-TEXT. The earlier shutdown of ECH caused a failed discharge.

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Refinement of the EC stray radiation estimates for ITER

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The ITER ECRH&CD system is composed by 24 gyrotrons at 170 GHz that will deliver 20 MW at the plasma. Up to 6.7 MW will be injected in the empty vacuum vessel at the beginning of each plasma discharge to provide the gas breakdown. In that phase and when the plasma absorption is non ideal a certain level of EC non-absorbed power, usually addressed as stray radiation, will be present. The EC stray radiation interaction with ITER first wall and diagnostics has been described in a preliminary work (Gandini et al., 19th Topical Conference on Radio Frequency Power in Plasmas). A more refined assessment is here described, following update of the diffuse stray radiation model and update of the launchers optics parameters. The optical design of the EC equatorial launcher has been entirely redesigned to optimise the power deposition and minimise interaction with the launcher structures. The updated parameters for the 24 launched beams are now available and have been used to estimate the interaction of the beams to be used for the breakdown phase with the tokamak structures. The preliminary stray radiation model described every opening of the tokamak as a “black” hole, that is a perfect power sink. Refining this crude description using for some of the aperture a “grey” hole model provided a better agreement with benchmarks from other alternative models. Examples of stray radiation estimates performed for various ITER structures, systems and diagnostics are discussed.

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Characterization of Electron Cyclotron Wall Conditioning Plasma in ASDEX Upgrade

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ITER envisages Electron Cyclotron Wall Condition (ECWC) after DMS events, to assist fueling changes and for tritium inventory control in its operational campaigns during which the toroidal magnetic field is continuously present. In PFPO-1, ECWC will operate mostly at the second harmonic X2 ECH wave polarization from upper and equatorial launchers. The here presented experiments in ASDEX Upgrade with full tungsten plasma facing components characterize ECWC discharges with X2 waves launched horizontally from the equatorial ports. The characterization of the deuterium plasmas is based on experimental inputs such as interferometry, in-vessel pressure measurements and poloidal field maps obtained from the measured coil currents, as well as advanced tomographic methods using filtered cameras at the hydrogen Balmer lines. TOMATOR-1D simulations and CTS radiometer spectra complement the findings.
Analysis shows that densities below the R cut-off are be obtained with significant levels of stray radiation. This radiation includes waves at half of the gyrotron frequency due to PDI effects occuring at 2nd harmonic UHR at the LFS of the resonance. Wave refraction at higher densities may be avoided by using optimal poloidal field pattern. Such pattern, along with the location of the ECH resonance, determines as well the strongest surface interaction areas for the charged particles. Directing plasma flux to inner wall surfaces by the field maps, and same for the inner divertor apron, is less effective due to magnetic mirror effects and outward convective flows. This may make ECWC less attractive for fuel recovery from deposits at the inner divertor. The uniform conditioning by an intense flux of low energy atoms produced at the ECH absorption layer may however be effective for main chamber conditioning after DMS events.

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A survey of the ECE bursting phenomenon in the DIII-D tokamak*

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ECE bursting is a phenomenon in tokamaks where very intense bursts of microwave power are observed at electron cyclotron emission frequencies. The bursts have a narrow frequency width, ˜2-4 GHz, and are generally short lived pulses, ˜2 μs, but are very intense, sometimes as high as milliwatt level, which is much higher than the thermal ECE level of 100's of nanowatts. Since a general observation is that these bursts are more commonly observed in low collisionality, high electron beta plasmas, they are expected to be more prevalent in next step devices where they could strongly affect the microwave diagnostics there. Recent papers have proposed explanations of certain types of ECE bursting, in terms of electron acceleration during edge MHD instabilities [1] or parametric decay instabilities during ECH discharges [2]. A survey of the bursting types in DIII D plasmas shows some agreement with the theory predictions, particularly for the most common type of bursting, that associated with ELMs in low-density H mode discharges. However, some defy explanation, for example the very regular bursts associated with the edge harmonic oscillation (EHO) in QH-mode shots, which exhibit an unusual frequency up-shift from the ECE resonance frequency at the oscillation location. Bursts associated with ELMs, sawteeth, the EHO and other MHD instabilities are discussed and categorized. While the most virulent bursting occurs during ECH discharges, ECH injection is not a necessary condition; however, low collisionality, which is often associated with ECH, does appear to be required.

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ECH and ECCD modelling studies for DTT

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The new Divertor Tokamak Test facility (DTT [1]), aimed to perform studies regarding power exhaust and divertor load and currently under construction, will be provided with a mix of additional heating systems. The Electron Cyclotron Resonance Heating (ECRH) system is foreseen to accomplish several tasks: plasma heating, MHD control and non-inductive current drive (CD) for transformer assistance and current profile tailoring. To this purpose, two types of launcher have been proposed, for different wave injection geometries, equipped by steering mirror systems which allow EC absorption over a broad range of plasma locations. Considering the reference DTT Single Null full power scenario (B=6 T) [2], central plasma heating requires 10-20 MW of EC power, with injection frequency of 170 GHz.
In order to investigate and to optimize launchers performances for the foreseen EC tasks, the beam-tracing code GRAY [3] has been used to perform a comprehensive study regarding the propagation, absorption and current drive of the EC beams on the main reference DTT scenario. A range of beam injection positions and angles around the values foreseen by the actual EC launchers design have been tested to reach ECH&ECCD optimization and to evaluate the launchers capability to fulfil its main tasks. Optimal poloidal and toroidal injection angles and relative steering ranges have been identified for the best localization and trade-off between maximum CD and narrow driven current profile width required for efficient MHD control.
In order to explore the EC launchers flexibility, the capability of properly working also in presence of edge density fluctuations induced by pellets injection has been investigated. Significant effects of beam refraction and deviation are seen for a density variation dne,max>6 1019 m-3. Large angle adjustments (5o-20o) can be required to maintain off-axis ECCD at a fixed location, while the plasma core is foreseen to be marginally reachable during large pellet injection. The requirements for real-time control of the injected beam polarization, due to changes either in the steering angles or in the magnetic configuration at the plasma boundary, were also assessed given the importance of optimal coupling to Ordinary mode when operating at the first harmonic resonance.
As future work, the analysis is going to be focused on the dynamical phases of the DTT scenarios.
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Physics Studies for assessment of requirement of Displacement Compensation System for ITER ECE Diagnostic

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The Electron Cyclotron Emission (ECE) diagnostic has the key function of measuring the core electron temperature profile and electron temperature fluctuation, from the intensity of electron cyclotron radiation emitted from the plasma along the major radius. Other roles of this diagnostic include the measurement of plasma energy, radiated power, runaway electron behaviour, edge electron temperature profile, and measurement of the ELM temperature transient. The ECE diagnostic consists of three main systems: (1) front-end optics, which collects the radiation from the plasma, (2) transmission lines including polarizer splitter unit, which transports the ordinary and extraordinary ECE emission modes separately from the front-end and distributes it to the instrumentation, and (3) detection and analysis instrumentation which is housed at a distance from the tokamak, in the diagnostics building [1].
With its high electron temperatures and harsh environment, ITER presents various challenges for the diagnostic system. One of the most insidious is the misalignment between the in-vessel front-end optics and the ex-vessel transmission line which is caused by vibration of the vacuum vessel due to plasma phenomena including vertical displacement events. Since the electron temperature is inferred from the intensity of the ECE, transient misalignment may lead to poor accuracy in this critical measurement. These displacements are expected to be ˜ 15 mm in vertical (z) and horizontal (x) directions, and ˜ 5 mm in the toroidal (y) direction. It is important to minimize the effect of these displacements, so that the system maintains alignment during operation, and reliable temperature information is attained. Our objective is to first study the coupling losses due to imperfect coupling of Gaussian beams owing to port plug displacements. These studies will serve as the basis to assess the requirement of the displacement compensation system. In this paper, different types of Gaussian beam misalignments are discussed and the power loss due to coupling of offset beams is estimated analytically. Measurements are done to determine the power loss due to coupling of offset beams experimentally. The measured value for coupling loss is ˜2.9 dB at 130 GHz, which is quite high, and it is therefore concluded that a system is needed to compensate for the displacements. This conclusion is supported by performance analysis which simulates the effect of displacements on ECE measurements. Comparison to the ITER requirements for the ECE diagnostic yields the acceptable limits on displacements.

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Investigation of the heating characteristics of Electron Bernstein wave via slow X-B mode conversion in LHD

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The electron Bernstein wave (EBW) [1] is an electrostatic mode in magnetized plasmas. The EBW has no limitation of electron density on propagation and the power is absorbed at the electron cyclotron resonance layer. The EBW can also drive plasma current because the wavenumber parallel to the magnetic field $k_{\|}$ can be large. The mode conversion process is essential to excite the EBW at the upper hybrid resonance (UHR) layer. A new antenna system was installed in the Large Helical Device (LHD) to inject 77 GHz ECH perpendicularly to the magnetic field from the outboard side of the vacuum vessel. In some magnetic configurations of the LHD, the ECH can be injected from the high field side (HFS) using this new system. The ECH injection from HFS in two polarization settings exciting O-mode or X-mode selectively was conducted to investigate the heating characteristics of the EBW via slow X-B conversion by comparing the X-mode injection with the O-mode injection. The clear differences in the variation of the electron temperature and plasma stored energy were not observed because the relatively low electron density was needed to set the UHR layer in front of the new antenna. On the other hand, the large variation of the plasma current was confirmed during the X-mode wave injection in spite of $k_{\|} \sim 0$ (Figure 1). The strong emission implying the occurrence

of the parametric decay instability was also observed (Figure 2). These results show signs of EBW excitation.

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High Power mm-wave loss measurements of ITER ex-vessel waveguide component prototypes at the FALCON test facility in Lausanne Switzerland

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Many future Fusion devices will rely heavily, if not solely, on electron cyclotron (EC) heating subsystems to provide bulk heating, instability control (neoclassical tearing mode (NTM) stabilisation), and thermal instability control. Efficient use of the installed heating power (gyrotrons) requires low-loss transmission of the power over 100s of meters since the mm-wave sources need to be installed where the stray magnetic field has a small amplitude. Transmission lines are used to propagate the mm-wave power over this long distance. Quasi-optical techniques (mirrors) are used at W7X and are planned for DTT, for example. Guided components are installed at DIII-D, TCV and elsewhere and are planned at JT60SA and ITER. High power test facilities exist to evaluate the power transmission of assemblies of guided components (transmission lines). The European test facility FALCON was setup by Switzerland and Fusion for Energy (F4E) in Lausanne Switzerland at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in the Swiss Plasma Center (SPC). Operations are funded through a framework contract with F4E. SPC operates the facility. Two ITER-class 170GHz gyrotrons are housed within the facility and used to evaluate the thermal behaviour of components provided by various ITER partners. Loss measurements are presented for miter bends and waveguides of several materials at two different diameters. The results are used to model the expected losses in the ITER ex-vessel waveguides (EW) that are part of the ITER EC launcher (both Upper and Equatorial).
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Future R&D toward Microwave H&CD systems for Commercialised Fusion Reactors

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The requirements of a microwave heating and current drive (mm-wave HCD) system applied to a commercial fusion reactor differ significantly from the present-day systems used for magnetic confinement research devices. The latter require versatile systems that can provide a variety of HCD applications to adapt to changing physics objectives when investigating the optimum plasma scenarios for a future burning reactor. High power sources with steerable launchers at the plasma boundary are a key aspect in exploring the usage of mm-wave HCD. However, extrapolating to a burning fusion reactor, the design criteria need to be re-orientated towards optimising plug-to-plasma efficiency, steady-state operation, longevity, RAMI, cost, etc. The development of the Spherical Tokamak for Energy Production (STEP) HCD system is beginning to bridge this gap toward commercialisation and as a result improvements are being identified for all parts of a future commercialised mm-wave HCD system.
The aim of this presentation is to review the requirements of a fusion power plant ⊠-wave HCD system and then outline R&D tasks required toward satisfying those requirements. The list of tasks includes improvements to the high voltage power supplies, mm-wave sources, transmission system and launchers. The discussion focuses in particular on the STEP requirements – a reactor grade spherical tokamak, aiming to achieve a net power gain back to the grid. STEP has a moderate field (˜3.2T) and a steady state HCD power demand ˜150MW.

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Quantifying electron cyclotron power deposition broadening in DIII-D

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Electron cyclotron (EC) radiation is a powerful tool in fusion devices. Compared to other heating and current drive methods, millimeter EC waves exhibit a particularly localized resonance and a radially narrow power deposition region. Localized deposition allows EC radiation to be used for a wide variety of applications, including (but not limited to) perturbative transport studies, profile control, and MHD control. The exact width and shape of the power deposition profile must be well known for these applications and is typically estimated using forward methods (i.e. beam/ray tracing). However, both experimental and numerical studies have indicated that power deposition profiles may be broader than traditional forward methods indicate and have linked this effect to plasma edge turbulence [1]. This has significant implications for EC applications in future large fusion devices [1]. To help quantify this effect ahead of ITER operation, we aim to measure the ECH power deposition profile in a set of DIII-D discharges and compare that to forward estimations. We use four inverse methods to compute the deposition profile from ECE and Thomson scattering measurements: break-in-slope (BIS) [2], maximum likelihood estimation (MLE) [3], frequency domain least squares (FDLS) [4] and flux fit [5]. We apply these methods to a set of 6 discharges from DIII-D spanning a range of confinement modes (limited and diverted L-mode, H- and QH-mode and negative triangularity) and compare against the established ray-tracing code TORAY [6]. We measure significant broadening across all six discharges: between 1.6 and 6.2 times over the TORAY estimates depending on the discharge and method. Most of the

broadening (i.e. in five out of six discharges) observed is between 1.6 and 3.6 times. We show that this level of broadening in ITER will have serious consequences for the NTM control system.

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Electron Cyclotron Heating Systems and Modeling for the WHAM Device

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A high-k RF scattering diagnostic for measuring binormal wavenumber electron scale turbulence on MAST-U

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Plasma turbulence plays a key role in determining the spatial-temporal evolution of plasmas in astrophysical, geophysical and laboratory contexts. In particular, turbulence on disparate spatial and temporal scales limits the level of confinement achievable in magnetic confinement fusion experiments and therefore limits the viability of sustainable fusion power. MAST-U is a well-equipped experimental facility having instruments to measure ion-scale turbulence and electron scale turbulence at the plasma edge. However, measurement of turbulence at electron scales in the core is problematic, especially in H mode. This gap in measurement capability has provided the motivation to develop a high-k microwave scattering diagnostic for MAST-U. The turbulence is expected to be most significant in the binormal direction with scale ranges expected of order $k_{\perp e}$ ~ 0.1 -> 0.4 (where k_{perp} is the binormal turbulence wavenumber and ρ_e the electron gyroradius) in the confinement region of the core plasma (0.5 < r/a < 1). We therefore propose a binormal high-k scattering diagnostic operating with near-perpendicular incidence to the magnetic field through the scattering region. In this paper, the results of Gaussian wave optics and beam-tracing calculations [1] are presented that demonstrate the predicted spatial and wavenumber resolution of the diagnostic along with the sensitivity of the measurement, assuming a probe beam crossing close to the diameter of the MAST-U vessel in the equatorial mid-plane. The analysis considers the variation of magnetic pitch angle ($\alpha = tan^{-1}(B_\theta/B_\phi)$) as a function of plasma radius and its effect on the instrument selectivity function $F(r)$ as a function of scattering location and $k_\perp \rho_e$. The system we propose will operate in the collective scattering regime governed by the Bragg condition at a frequency close to 350GHz to

maintain adequate $k_\perp \rho_e$ resolution over the range of interest whilst minimising beam refraction and maximising the detected signal to noise ratio. We conducted beam-tracing calculations [1] of the primary and scattered rays for a representative high-beta MAST-U equilibrium (results presented in figure 1). These were computed for the 3 scattering coordinates of 1.0m, 1.14m and 1.24m in major radius. In each case, we defined 4 equally spaced scattered beams up to a maximum scattering angle limited by a proposed 290mm x 250mm elliptical receiving window aperture centred 0.14m below the midplane. For a position midway between the magnetic axis and the pedestal (R_{scatt} = 1.14m) this gives a maximum measurable $k_\perp \rho_e$ of ˜0.33.
Using the $k_\perp$ data for each of the scattered components from the beam tracing simulations, we conducted an analysis of the instrument selectivity function using a methodology similar to that presented by Mazzucato et al. [2, 3]. We obtained a minimum localisation of 0.06m for a $k_\perp \rho_e$ of ˜0.33 at R_{scatt} = 1.14m. Assuming a source power of 100mW, 9dB of detection loss and a detector noise bandwidth of 10MHz this corresponds to a minimum signal to noise power ratio of 16. This can be improved further via narrowing of the detection bandwidth or upgrade of the transmitted power using a vacuum tube source.

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Propagation of electromagnetic paraxial beams in fluctuating fusion plasmas

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The wave kinetic equation [1, 2] has proved a suitable tool to tackle the problem of wave scattering from density fluctuations in fusion plasmas in the high-frequency limit. Its numerical implementation in the Monte Carlo code WKBeam [3] allowed a detailed study of the effects of beam scattering to be expected in ITER [4, 5]. This approach, although more efficient than a direct numerical solution of the wave problem (if this can be afforded at all) is still numerically expensive and does not allow the analysis of the results in terms of simple, physically relevant beam parameters.

In this work, a paraxial expansion of the Wigner function is introduced which allows us to derive phase-space paraxial equations following the example of the paraxial WKB (pWKB) method [6]. Analytic and numerical solutions obtained in simplified cases employing both, the paraxial Wigner function and the standard pWKB, approaches are shown to coincide in the case of no scattering.

In presence of fluctuations, a beam can be represented as an ensemble of solutions of the wave equation, each corresponding to a different realization of the random density field. Such an ensemble is the analogous of a "mixed state" in quantum mechanics, while the single solution obtained with a fixed density is a "pure state" [7]. As the beam propagates through a fluctuating plasma, the paraxial Wigner-function approach captures the decreasing purity of the state, which can be measured by an entropy function defined in analogy to quantum mechanics [8]. Methods for the numerical solution of the paraxial-Wigner-function approach are proposed and benchmarked with solutions obtained through alternative methods in simplified geometries [9].

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Ray tracing calculations for the First Plasma configuration of ITER Electron Cyclotron Heating system

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Abstract of the "Ray tracing calculations for the First Plasma configuration of ITER Electron Cyclotron Heating system" contribution

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Status of the ITER ECRH&CD control system development

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Status of the ITER ECRH&CD control system development

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Progress in the Short-Pulse E×B Drift Two-Stage Depressed Collector Prototype for Gyrotrons

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The plug-in efficiency of Electron-Cyclotron-Resonance-Heating (ECRH) systems of nuclear fusion facilities is important for the performance of existing devices and will become a vital performance

parameter of future facilities that will have installed multiple tens of megawatts of microwave power. Gyrotrons are the sources of any ECRH system. Today, a gyrotron provides 1-2 MW output power at maximum 50 % total gyrotron efficiency with a single stage depressed collector. It is limited, on the one hand, by the efficiency of the interaction between the electron beam and the electromagnetic wave and, on the other hand, by the maximum depression voltage that can be applied to the spent electron beam. To target the latter limitation, Multistage Depressed Collectors (MDC) incorporates multiple depression voltages so that the total gyrotron efficiency can be significantly improved.
The E×B drift concept is considered as the most promising method for the spatial separation of the spent beam electrons with a large spread of rest-energy in a fusion gyrotron [1-2]. In recent years, various designs based on the E×B drift concept have been theoretically investigated at KIT [3-11]. The design approach described in [7, 8, 10, 11] is deemed to be the simplest and most promising concept of a first prototype. This first prototype is specified for short-pulse operation with a pulse length of < 3 ms and a maximum power of 4 MW in the spent electron beam to validate the physical principle of electron separation without the need to implement sophisticated cooling and beam sweeping systems.
Major targets of the mechanical design of the first MDC prototype are compactness and simplicity. The complexity of the collector is increased with the size of the electrodes, the size of ceramics used for high voltage insulation, the size of seals for the vacuum enclosure and the weight of the individual components. Taking all those factors into account, an MDC system is optimized to significantly reduce the manufacturing complexity of the prototype. The mechanical design and the progress in manufacturing of the two-stage depressed collector prototype for the KIT 2 MW 170 GHz coaxial-cavity gyrotron [12] are presented here.

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Calculations for the optical system for the first ITER plasma

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When the first plasma is generated in ITER, the machine will not be fully equipped with all in-vessel components. In particular, the equatorial launcher will not be available the equatorial launcher will

not be available to provide central ECRH-heating. This leaves the upper launcher as the only option for the initial plasma breakdown. In order to direct the microwave to the desired path, which goes horizontally through the resonance layer, a dedicated optical system consisting of in-vessel mirrors and a beam dump is necessary [1], [2]. After an initial design, which required a sophisticated diffraction grating, a new design using just smooth mirrors was suggested [3].
For the simulation of the optical path including the reflections on the focusing mirrors, a physical optics code, which is part of the PROFUSION package, was used. It allows to simulate the reflection on metallic mirrors including higher order effects like mode conversion and cross polarization. Furthermore, the code was extended to calculate the spillover effects due to the limited mirror size. The irregular mirror contour can be provided numerically and the effect of the field truncation can be modeled both on terms of the power density on the vessel wall and the deterioration of the reflected beam. Another tool was developed for tracking the polarisation through the beam path. It allows to determine the direction of the E-field in the upper launcher in order to have the maximum power beam power in X-mode in the resonance layer.
The paper outlines the calculation methods and presents numerical results.
This work was funded by the ITER organization under the service contract No. 43-2080.

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New modelling capabilities to support ITER EC H&CD System optimization and the preparation of plasma operation

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Abstract for the contribution “New modelling capabilities to support ITER EC H&CD System optimization and the preparation of plasma operation”

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Microwave current drive for STEP and MAST Upgrade

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Overview of ECRH and EBW modelling on ST40

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A dual-frequency electron cyclotron resonance heating (ECRH) system is currently under development on the ST40 spherical tokamak, which will employ two gyrotrons with a maximum output power of 1 MW each at frequencies of 105GHz and 140GHz. In this paper we will present modelling results of ECRH and EBW current drive capabilities in ST40 of both available gyrotrons for various launch configurations and operating frequencies, including methods under consideration for non-inductive plasma start-up.

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Electron Bernstein Wave (EBW) current drive profiles and efficiency for STEP

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The UK's Spherical Tokamak for Energy Production (STEP) reactor design program is now exclusively investigating concepts using microwave-based heating and current drive (HCD) systems. Electron Bernstein Wave (EBW) HCD is a relatively immature technology compared to Electron Cyclotron (EC) HCD but is of interest due to the promise of high current drive efficiency and access to dense plasmas at low magnetic fields where EC is cut off. This presentation will discuss estimated EBW current drive efficiency on STEP.

GENRAY and CQL3D were used to estimate the current drive profiles and normalised current drive efficiency $\zeta_{CD} = \frac{32.7 I_{CD}[A] n_e[10^{20} m^{-3}] R[m]}{P[W] T_e[keV]}$ for several reactor concepts with varying temperature, density, geometry and magnetic field. $\zeta_{CD} > 1.0$ was readily found for $\rho = 0.65{-}0.9$ while $\zeta_{CD} > 0.5$ was found for $\rho \geq 0.5$

The absorption location of the EBW exhibits a large shift away from the cyclotron harmonic due to Doppler broadening of the resonance at finite temperature. Estimations of the shift from these scans

is being used to develop a fast model to support integrated scenario modelling in the neighbourhood of the preferred concept.

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X-I mode for efficient solenoid-free ECCD plasma current start-up for fusion reactor

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I am submitting our abstract. We can give either oral or poster presentations. Thank you!

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Parametric Decay Instabilities during Electron Cyclotron Resonance Heating of Fusion Plasmas, Problems and Possibilities

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Induced microwave scattering in the ITER edge transport barrier at ECRH and possibility of its modeling at ASDEX-Upgrade

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High power electron cyclotron resonance heating (ECRH) is widely used in the current toroidal devices for auxiliary electron heating. The O1-mode ECRH technique is also considered for the local electron heating providing the neoclassical tearing mode control in ITER. Until very recently the propagation and absorption of ordinary microwaves were believed to be well-described by the linear theory and assumed to be predictable in detail. However, as it was shown in [1], in ITER they can suffer from a low threshold induced side-scattering instability in the edge transport barrier. The presence of a large density gradient have a significant impact on the properties of waves in the low hybrid (LH) frequency range, leading to new transparency windows that are absent in the homogeneous plasma [2]. These new modes can be 2D localized along the direction of a plasma inhomogeneity due to the gradient effects and along the magnetic field due to the magnetic ripples. The instability power threshold leading to this 2D localized LH wave excitation appears to be much less than 1 MW. It can be overcome in future O1-mode ECRH experiments at ITER and at DEMO, leading to broadening of the power deposition profile and therefore decreasing the neoclassical tearing mode suppression efficiency. Thus the urgent experimental investigation of this parametric decay instability seems important for the ITER experiment planning. In the present paper we demonstrate

a possibility to investigate the O-mode induced side-scattering instability and its consequences in the CTS and O2-mode ECRH experiments at the ASDEX-Upgrade tokamak. The instability threshold is shown to be well below 0.5 MW. Its dependence on the density gradient in the edge transport barrier, magnetic field ripple and on the scattering angle is studied. The instability growth rate and the frequency spectra produced by it are determined.
The paper was prepared under support of the Russian Science Foundation grant 22-12-00010. References
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Nonlinear degradation of O-X-B in MAST Upgrade

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Spherical tokamaks are often operated in a highly overdense regime, which means that their core is unavailable to ECRH at several of the lowest harmonics. However, a mode coupling scheme known as O-X-B[1] may enable the use of high power microwaves for heating and current drive in such plasmas. The O-X-B scheme couples electromagnetic waves from e.g. a gyrotron to electrostatic waves known as electron Bernstein waves (EBWs) which can propagate without a high density cut-off and are strongly damped at the electron cyclotron resonances. The use of EBWs is considered a key enabling technology at MAST Upgrade which has acquired two 28/34.8 GHz gyrotrons chosen specifically for O-X-B instead of regular ECRH. Although the mode coupling scheme is promising at low power densities[2], a number of nonlinear effects may degrade its performance when unprecedented gyrotron power levels are used for O-X-B operation. Parametric decay instabilities (PDIs) and stochastic electron heating (SEH) are considered likely nonlinear loss mechanisms in upcoming MAST Upgrade EBW experiments. Even though the conversion rate of O-X-B is favorable at low power, it may scale unfavorably with power above a nonlinear threshold.
In this contribution, we investigate PDIs and SEH in the vicinity of the upper hybrid layer where EBWs are excited. The UH layer is of particular interest due in part to the wave amplification that occurs in that part of the plasma. Based on the wave amplification, we estimate a threshold for SEH to set in, causing the gyrating electron motion to be warped and become stochastic by the large amplitude electric field of the EBWs. We also consider the possibility of generating EBW shifted in frequency through PDIs, which may in turn be observed outside the plasma, by considering the PDI selection rules. The results are compared to particle-in-cell simulations, exploring changes in frequency spectra and plasma temperature as the gyrotron power density is varied.
It is found that both nonlinear effects are likely to interfere with O-X-B in MAST Upgrade at the power levels the gyrotrons are able to deliver. Whilst the SEH can cause substantial wave damping to occur in an undesired region of the plasma, some of the frequencies excited by PDIs may possibly still have beneficial properties. In particular, the excitation of ion waves such as lower hybrid waves is possible and characteristic frequencies escaping the plasma could present diagnostic opportunities.

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ITER ECH&CD Control System: architecture, interfaces and status of development

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Advanced ITER ECRH control functions and interface with the Plasma Control System

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Radiation pressure of electron cyclotron waves on cylindrical filaments

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The advantages of using electron cyclotron (EC) waves for heating and for modifying the current profile have been established experimentally in a variety of fusion devices. In ITER, EC waves will be used to mitigate deleterious instabilities and, consequently, enhance plasma confinement. The efficiency and precise location of power deposition in the core can be affected by filamentary structures present in the edge region. These structures scatter EC waves while, simultaneously, being influenced by the radiation pressure.

In order to understand wave scattering by turbulence, we have formulated an analytical model based on the Kirchhoff's tangent plane approximation. The basis of the Kirchhoff's approximation is built upon the theory of physical optics. In this approximation, the scattering of EC waves is determined by wave fields on the tangent surface of turbulence separating two different plasma densities. The Kirchhoff approach not only simplifies the modeling of wave scattering but, more importantly, gives physical insight into several aspects of scattering.

The radiation force on a filament is given by the Maxwell stress tensor. In 1905, Poynting was the first to evaluate and measure the radiation force on an interface separating two different dielectric media \cite{poynting}. For ordinary light propagating in vacuum and incident on a glass surface, Poynting noted that the surface is "pulled" towards the vacuum. In a magnetized cold plasma, there are two independent wave modes. Even if only one of these modes is excited by an RF antenna, a filament will couple power to the other mode - a consequence of electromagnetic boundary conditions \cite{ram}. We determine the radiation force by EC waves on a cylindrical filament aligned along the magnetic field. The results are compared and contrasted with those for RF waves at lower frequencies and with Poynting's seminal observations \cite{valvis}. The radiation force can be large enough to impact

the motion of a filament, leading to an effect that is likely to be observed in experiments. The prospect of utilizing RF waves to modify some aspects of edge turbulence becomes an intriguing possibility.

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Broadening estimation of the ECRH deposition profile using perturbative experiments

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Electron cyclotron resonance heating (ECRH) plays a crucial role in many fusion applications. Examples are plasma heating, the suppression of neo-classical tearing modes (NTMs), sawtooth instability control, start-up (break-down), and profile control. In addition, modulated ECRH plays a crucial role in the study of electron heat transport. For most of these examples, the standard assumption is that the deposition profile is localized as is predicted by standard ray-tracing codes. However, recent work shows that density fluctuations in the plasma edge can scatter the ECRH beam leading to a broadened deposition profile [1]. These can be up to 2 or 3 times wider than predictions based on ray-tracing.

This is a presentation on our recent work on a further analysis of the ECRH-broadening using perturbative experiments. We compare several deposition estimation methods applied to different confinement modes, i.e., limited-, diverted-, negative triangularity L-mode, ELMy H-mode, and QH-mode. For comparison, we have modified the work in [1] to allow for more arbitrary profile shapes [2]. We have compared the result to other well known deposition estimation methods such as break-in-slope, as well as to two newly (in-house) developed methods based on maximum likelihood and closed-form solutions, which also compensate for transport broadening [3,4]. All these methods show a consistent image of broadening compared to the results of ray-tracing code TORAY [5], but also that the amount of broadening heavily depends on the confinement modes. Moreover, the analysis shows that the peak location of the deposition might also be shifted.

The effect the broadening can have on two of the above mentioned applications will be briefly discussed: 1) the increased power needed to suppress NTMs and 2) on the estimation of transport (perturbative and non-perturbative) when the standard assumption of (known) localized deposition is violated [6].

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Triple-Beampath-scenario for O2-heating at Wendelstein 7-X: experience of OP1.2 and final improvements for OP2

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The standard ECRH scenario at the stellarator Wendelstein 7-X (W7-X) as well as many other fusion experiments is X2-heating with 140 GHz, because at fusion relevant plasma parameters an X2-polarized microwave beam is fully absorbed during its first pass through the plasma column. However, W7-X is optimized for the 1/ν-collisionality regime at densities beyond the corresponding X2-cutoff $n_{cut,X2} = 1.210^{20} m^{-3}$. In contrast, the complementary O2-polarization is operable up to densities of $1.810^{20} m^{-3}$, but its absorption coefficient is a magnitude lower compared to X2. In this case, 20-30 % of the input power remains as shine-through beam, which should be re-transmitted through the hot plasma center as often as possible to minimize the overall stray radiation in the plasma vessel. For this reason, each of the 10 ECRH-beams in the operational campaign 1.2 (OP1.2) of W7-X uses a special reflection tile with a holographic microwave grating, which allows any reflection angle in relation to the incident microwave beam. After the second pass, a large polished stainless steel wall panel is used as reflector to finally realize a steady state capable triple-beampath-scenario, which allows to sustain ECRH beyond the X2-cutoff density by O2-heating only. With an input power of about 6 MW, the exclusively O2-heated plasmas were operated at electron densities in range of $n_e = 1.2 - 1.510^{20} m^{-3}$ and temperatures of $T_e = 2 - 3keV$. In general, the measured stray radiation and therefore the plasma absorption was in very good agreement with the calculations of the ray tracing code TRAVIS. For this reason, the code was used to further optimize the individual beam trajectories of the triple-beampath-scenario and the used reflector gratings. The correct polarization matching of the second pass turned out to be the most critical issue for the overall efficiency. For this reason, only 4 of 12 ECRH beams will be used in combination with a holographic grating in the next operational campaign OP2. The other ones will be operated slightly off-axis in combination with a polarization grating, because the current technology of holographic gratings does not allow to freely select the polarization of the reflected beam. Compared to OP1.2, the stray radiation will be reduced by a factor of 2, which corresponds to an overall absorption of about 95 % at central plasma parameters of $T_e = 3keV$ and $n_e = 1.210^{20} m^{-3}$.

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Higher Off-Axis Electron Cyclotron Current Drive Via 'Top Launch' Approach Demonstrated on the DIII-D Tokamak

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For the first time in a tokamak, experiments on DIII-D have measured doubling the off-axis electron cyclotron current drive (ECCD) efficiency of conventional outside launch using a novel top launch geometry, as predicted by quasi-linear Fokker-Planck simulations [1]. Studies of many tokamak reactors have shown that off-axis current drive is a requirement for a steady-state reactor in the Advanced Tokamak (AT) regime [2]; however, sufficiently efficient off-axis current drive technique under these conditions remains a challenge [3]. 'Top launch' ECCD via unique geometry (i.e., launching EC wave with large toroidal angle in a plane nearly parallel to the resonance) is predicted to greatly increase the ECCD efficiency at mid-radius, compared to conventional ECCD. DIII-D experiments using a prototype top launch system with a fixed mirror have tested the main tenets of this technique: 1) unique launch geometry allows selective EC wave damping on higher v|| electrons driving current more efficiently, 2) longer absorption zone compensates for inherently weaker absorption at higher v||. The increased ECCD efficiency agrees with code predictions that include both the effects of longer path length and selective damping. At optimal condition which balances the higher v|| and sufficient absorption, significantly enhanced (doubling) driven current at rho˜0.5 has been demonstrated on DIII-D. Simulations of 'Top launch' ECCD for FNSF, DEMO and CFETR support it as an improved efficiency off-axis current drive technique for future fusion reactors [4-6].
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