Book of abstracts

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Electron Cyclotron Resonance Heating (ECRH)

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Recent progress of the applications of ECRH/ECCD and the supportive technologies in the LHD

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In the recent experimental campaign of the LHD (Feb.~Aug. 2017), three 77GHz/~1MW/ 5s and two 154GHz/~1MW/5s triode CPD gyorotrons were mainly operated for electron cyclotron resonance heating (ECRH). (Two of 77GHz gyrotorons gave out during this experimental campaign because of the air leak from the sub-window and the leak of the cooling water from a piping joint at the exit of the gyrotoron cavity.) Operations of a real-time checking system of the actual launching direction with a visualized image, a real-time control system of the incident wave polarization, a stray wave monitor with use of a millimeter wave absorber, and a modified interlock system with use of cRIO were newly started. There was no long pulse operation for minutes. ECRH was mainly operated in short pulse (~2sec) experiments in the 3 minutes experimental sequence. In addition, the 3 minutes and 30 seconds sequence was adopted for the Helium ECRH discharge for ~36 seconds with ~0.77MW total (0.2~0.3MW each) input power to reduce the hydrogen/deuterium supply from the vacuum vessel wall so as to realize a peaked density profile that is suitable for the neutral beam (NB) deposition in the central are of the plasma. After this procedure the highest ion temperature (10keV) of the LHD was achieved with the optimized NB and carbon pellets injections.

Recently, effects of electron cyclotron current drive (ECCD) on plasma performances have been studied with various approaches with use of four horizontal antennas which allow wide ranges of the toroidal and vertical launching angles. For example, various types of the electron temperature profile in the core region were observed for similar power deposition with co and counter ECCD. Changes of the characteristics of the turbulent transport and/or MHD instabilities with change of the rotational transform (inverse of the safety factor) by ECCD might explain those variations. The direct oblique launching of the fundamental extraordinary (X) wave from the high field side with use of a horizontal antenna was performed for the first time. Heating efficiency up to 70% was obtained in the under-dense region with optimizing the launching angle. Up to 80% of the plasma cutoff density, increase of the electron temperature was observed. ECRH by the X wave and/or the electron Bernstein wave are possible mechanisms.

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The 8 MW dual-frequency ECRH system of ASDEX Upgrade

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The upgraded ECRH system of ASDEX Upgrade is approaching its completion. All 8 units will start plasma operation this year. They are all operational for 10 s at 140 GHz (1 MW) and 105 GHz (0.8 MW). The increase in EC power has driven concern on EC-driven in-vessel damages, which led to new concepts of passive protective in-vessel structures.

This contribution reports on system performance as well as on technological advances in subsystems and loads. In parallel the system is used for the development of true multi-frequency windows (i.e. not only for the Fabry-Perot resonances) and for the study on ohmic losses of mitre-bend polarisers, which may vary by a factor of two for different settings yielding the same final polarisation.

The major task of the system is of course to supply ECRH and ECCD to the tokamak in close real-time connection with the discharge control system. As a major goal, we will discuss the variety of current profiles achieved so far with half of the system (+NBCD) and sketch the plans for the extensions of these studies using the full system.

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Tests of Advanced RF Off-axis Current Drive Techniques on DIII-D*

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The establishment of reactor-relevant radiofrequency heating and current drive techniques is a focus of work on DIII-D in the next five-year period. This presentation gives an overview of the planned work in the areas of (1) nearly vertically launched ECCD[1], (2) 'helicon' (whistlers or fast waves in the lower hybrid range of frequencies) current drive[2], and (3) high-field-side-launch (HFS) lower hybrid (slow wave) current drive[3]. Each of these techniques addresses the need for efficient off-axis current drive for a steady-state tokamak reactor to supplement the bootstrap current and to provide current profile control. Nearly vertically launched ECCD allows interaction with higher energy electrons and thereby significantly improved current drive efficiency compared with conventional low-field-side launch. A proof-of-principle experiment with a fixed launcher at the top of the DIII-D vacuum vessel powered by existing gyrotrons will be carried out in the near future at the ~1 MW coupled power level. If the predicted improvement in current drive efficiency of up to a factor of 2 is experimentally proven, a more flexible steerable launcher would be installed later in the five-year period. Details are discussed in the contribution by X. Chen. Current drive by fast waves in the lower hybrid range of frequencies is predicted for DIII-D to be significantly more efficient than either off-axis neutral beam current drive available on DIII-D or conventional ECCD in high-density, high electron-beta regimes. A ~1 MW proof-of-principle experiment using helicons at 476 MHz (generated with a single klystron) launched with a novel 'comb-line' traveling wave antenna with 30 elements will be performed on DIII-D starting in 2019. A low-power test with a 12-element prototype comb-line was carried out in 2016; the measured plasma loading in the relevant plasma regimes is sufficient to project to ~75% coupling efficiency to the plasma core with the 30-element high-power version[4]. The 1 MW experiments will assess non-linear effects on coupling and absorption and verify the predicted current drive efficiency. The HFS LHCD experiments will use a 2 MW source at 4.6 GHz and a compact waveguide grill to be installed on the centerpost of the DIII-D device to test, for the first time, the advantages of HFS LHCD. These advantages include substantially improved wave accessibility, current drive efficiency and reduced launcher plasma/materials interaction. The combination of HFS LHCD and nearly vertical launch ECCD may be expected to yield significant synergy in some regimes, since both waves interact with very energetic electrons in overlapping regions of velocity and configuration space.

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References

[1] F. POLI *et al.*, *Nucl. Fusion* **53** 013011 (2013)
[2] R. PRATER, *et al., Nucl. Fusion* **54** 083024 (2014)
[3] S.J. WUKITCH, *et al.*, *EPJ Web Conf.*, **157**, 02012, (2017)
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S2: ECH: Operation and Experiment

Heinrich Laqua: Overview of W7-X ECRH Results

Andrew Seltzman: Observation of Electron Bernstein Wave Heating in the RFP

Alexander Borschegovskiy: Optimization of HF-injection at the 2nd harmonic of ECRH on T-10 tokamak in order to obtain high energy content in plasma

Martin Schubert: Beam tracing study for design and operation of two-pass electron cyclotron heating at ASDEX Upgrade

Overview of W7-X ECRH Results

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The stellarator Wendelstein7-X was exclusively heated by ECRH in the operation phase OP1.2a. The ECRH system consists of 10 gyrotrons, with an output power of 0.6-1.0 MW each, a quasi optical transmission line and flexible microwave launcher inside the plasma vessel. The over-all transmission efficiency was estimated to be ~ 94%. The ECRH system is commissioned for 1800 s operation at full power. It already demonstrated all requirements, which are necessary for a high-performance steady state operation at reactor relevant parameters at W7-X. The 140 GHz ECRH uses the second harmonic resonance at 2.5T with an absorbed power of up to 7 MW. Besides the reliable plasma start-up und routine ECRH wall conditioning, stationary discharges up to 30 s have been achieved, which were only limited by the maximum test divertor energy load. Furthermore, the novel remote steering launcher, an important concept for the future fusion reactor, was tested for the first time for plasma heating and current drive. The long discharges were used to demonstrate current control and bootstrap current compensation by ECCD. Localized ECCD strongly changed the rotation transform iota and thus the confinement and stability. In particular by dedicated ECCD strong MHD activity with repetitive central temperature collapse could be driven, which in the worst case lead to a total loss of the plasma confinement. In combination with pellet injection (PI), highest performance with a plasma energy above 1 MJ has been achieved with the X2-mode ECRH at a plasmas density of 0.8 10^{20} m^{-3} and an ion temperature of 3.8 keV, which demonstrates the already good collisional coupling between electrons and ions at that density. Even higher densities have been achieved using the O2-mode combined with PI. Here high-performance plasmas at densities above the X2-cutoff and up to 1.4 10^{20} m^{-3} have been demonstrated, which is already close to the envisaged future steady state high-performance plasma scenario. Achieving efficient plasma heating with the O2 mode requires establishing a sufficiently dense and hot target plasma for the O2 mode to take over. This was accomplished using the X2-mode for the plasma start-up, and then during the initial two seconds of plasma operation the polarization was changed to O2 before the start of pellet fuelling. The O2-mode heating efficiency of > 90% was achieved with the help of individually shaped reflector tiles for the 10 ECRH beams enabling at least 3 passes through the EC-resonance in the plasma center. The reliable and efficient operation was guaranteed by a set of ECRH protective diagnostics, which were specially established for the ECRH requirements. In particular the ECRH stray radiation measurement turned out to be a reliable interlock signal to prohibit ECRH operation with insufficient plasma absorption. Furthermore the position and launch direction of each beam was measured by infrared cameras observing its thermal footprint at the heat shield tiles opposite of the antennas. Finally selected 140 GHz beams was also used as a source for the collective Thomson scattering (CTS), which was also commissioned. Here a local ion temperature measurement was demonstrated.

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Observation of Electron Bernstein Wave Heating in the RFP

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The first observation of RF heating in a reversed field pinch (RFP) using the electron Bernstein wave (EBW) has been demonstrated on Madison Symmetric Torus. Challenging heating environment including an overdense plasma with no high field side, porthole field error, mode conversion in the antenna near field, and a stochastic magnetic field required development of novel techniques to measure heated electrons. Efficient mode conversion of an outboard-launched X mode at 5.5 GHz leads to Doppler-shifted resonant absorption (w = n*w_ce – k||*v||) for a broad range (n=1-7) of harmonics. A spatial distribution of solid targets (limiter and target probe) with diametrically opposed x-ray detectors measures the dynamics of EBW-heated electrons. EBW heating produces a clear supra-thermal electron tail in MST. Radial deposition of the EBW is measured from HXR flux from a radially scanned insertable probe. Deposition location was controllable with |B|. In the thick-shelled MST RFP, the radial accessibility of EBW is limited to r/a > 0.8 (~10cm) by magnetic field error induced by the porthole necessary for the antenna. Experimental measurements show EBW propagation inward through a stochastic magnetic field implying EBW feasibility in spherical and advanced tokamak heating scenarios; accessibility in a thin-shelled RFP with actively controlled saddle coils is likely to be r/a> 0.5 in agreement with ray tracing studies. EBW-heated test electrons are used as a direct probe of edge (r/a > 0.9) radial transport, showing a modest transition from 'standard' to reduced-tearing RFP operation. Electron loss is too fast for collisional effects and implies a large non-collisional radial diffusivity. EBW heating has been demonstrated in reduced magnetic stochasticity plasmas with Beta=15-20%. This material is based upon work supported by the U.S. Department of Energy Office of Science, Office of Fusion Energy Sciences program under Award Number DE-FC02-05ER54814. Work performed at the University of Wisconsin-Madison.

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"Optimization of HF- injection at the 2nd harmonic of ECRH on T-10 tokamak in order to obtain high energy content in plasma"

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Non-traditional scheme of HF-injection has been used in T-10 tokamak for ECRH at the 2nd harmonic of ECR in X-mode. Two HF-launcher systems, with focusing beam, injected power in opposite directions under approximately equals toroidal angles. Input power from each launcher was about the same (Phf =0.85MWt). Btor=2.4T-2.44T provide the central heating.

The new phenomenon has been found in some shots with W-limiter and the above-mentioned scheme of ECRH. The spontaneous rise of the electron density nearly in the all plasma column occurs simultaneously with the rise of Te in the wide region ($0<r/a<0.8$). We treat it as "global L-H transition" found earlier at JET [1] and in various regimes of JT-60U [2-3] or as "global ITB-event (e.g. see [3] and references therein) simultaneous with usual L-H transition". The value of D-beta falls, the positive value of dW/dt appears and the value of the energy confinement time τE abruptly rises by ~15%. Later on, the value of τE gradually rises along with the density. The absolute value of the electron heat and density fluxes reduces abruptly in the whole plasma column. The accumulation of tungsten and light impurities is absent.

In some of the similar shots clear transition did not occurs and the value of τE rises along with the rise of the density during longer time interval of ECRH/ECCD up to the level reached in the shots with the transition.

References

[1] Neudatchin S V, Cordey J G and Muir D J 20th EPS Conf. on Control. Fus. and Plasma Phys. (Lisboa,) vol. I (Geneva : EPS), p 83 (1993)

[2] Neudatchin S V, Takizuka T et al., Japan J. Appl. Phys. 35 3595 (1996)

[3] Neudatchin S. V., Takizuka T., et al., Plasma Phys. Control. Fusion 44 A383-389 (2002)

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Beam tracing study for design and operation of two-pass electron cyclotron heating at ASDEX Upgrade

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The electron cyclotron resonance heating system (ECRH) at ASDEX Upgrade (AUG) is currently being 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 [1, 2]. Part of the AUG program [3] will focus on experimental conditions, where the plasma density may be above the X-2 cut-off density at 140 GHz. In order to cope with the high density, ECRH will operate in the O-2 mode scheme [4] with potentially incomplete absorption after the first pass. Reflecting gratings [5] installed on the heat shield of AUG's inner column allow for a controlled second pass of the beam's unabsorbed fraction. Thermocouple measurements serve to control the beam position on the grating.
The beam geometry is being finalized for ECRH launchers #1-4, while for the launchers #5-8 it is already set [2,4]. Beam propagation is simulated with the TORBEAM code [6] and previous high density experiments at AUG are used as a database. The geometry is optimized using three criteria: central deposition, high absorption and robustness of the beam dump on the low field side after the second pass.
Other aspects of the simulation are potential changes in the experimental conditions, and of the plasma electron density in particular, such that the properties of the incoming beam deviate from the design values of the reflecting grating. Changes of incoming beam angle, beam width and phase front curvature are possible. The effect on the reflected beam is discussed using simplified models and verified with laboratory measurements. A complementary full-wave simulation of the phase grating mirror, using data from the machining process, is being tested.

References

[1] D. WAGNER, *et al.*, J Inf Milli Terahz **37**, 45-54 (2016)
[2] M. SCHUBERT, *et al.*, EPJ Web of Conferences **157**, 03047 (2017)
[3] A. KALLENBACH, *et al.*, Nucl Fusion **57**, 102015 (2017)
[4] H. HÖHNLE, *et al.*, Nucl Fusion **51**, 083013 (2011)
[5] O. MANGOLD, PhD thesis, Stuttgart University (2009)
[6] E. POLI, *et al.*, Comput Phys Commun **136**, 90 (2001)

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S3: ITER ECRH

Natalia Casal: Status of the ITER Electron Cyclotron Heating & Current Drive System

Ferran Albajar: Metrology techniques for the verification of the alignment of the EU gyrotron prototype for ITER

Zisis Ioannidis: Report of recent experiments with the European 1 MW, 170 GHz CW and SP prototype gyrotrons for ITER

Ken Kajiwara: Progress of the Procurement of the Gyrotron and Development of the ECH/ECCD Launcher for ITER

Status of the ITER Electron Cyclotron Heating & Current Drive System

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The ITER EC H&CD system is to provide 20MW for central heating, current drive, current profile tailoring and control of MHD modes. The system comprises of 12 HV power supply sets, 24 gyrotrons, corresponding transmission lines and 5 launchers. Each of these is in various stages of development from design finalization to completion of the factory acceptance test, with installation of the first power supplies envisioned for 2019. There have been various design modifications over the past few years that include change to a smaller waveguide diameter (50mm) for improved transmission efficiency, modification of the launcher dimensions to comply with new tolerances on the vacuum vessel, and revision of the confinement barriers. In addition, new modifications are being assessed for improved H&CD performance for ITER which include introduction of 1.8T operation (X3), potential power upgrade, global MCNP analysis for improved shielding and simplification of the procurement and installation procedures. This paper aims at providing an overview of the EC system status and introducing the various design changes integrated and under investigation.

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Metrology techniques for the verification of the alignment of the EU gyrotron prototype for ITER

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The EU gyrotron for the ITER Electron Cyclotron (EC) heating system has been developed in coordinated efforts of the EGYC Consortium, Thales ED (TED) and Fusion for Energy (F4E) and under the supervision of ITER Organization Central Team. After the successful verification of the design of the 1MW, 170 GHz hollow cylindrical cavity gyrotron operating at the nominal $TE_{32,9}$ mode with a short pulse gyrotron prototype at KIT, an industrial CW gyrotron prototype has been manufactured by TED and tested at ~0.8 MW of output power and pulse durations of up to 180 s, which is the limit of the HV power supply currently available at KIT. The experiments are being continued at SPC in 2018 to extend further the pulse duration, taking advantage of the existing CW full-power capabilities of the gyrotron test facility recently upgraded for the FALCON project.

The gyrotron cavity interaction is very sensitive to the alignment of the internal mechanical parts of the gyrotron tube with the magnetic field generated by the superconducting magnet within a typical range of 0.2 – 0.5 mm. The control of the tolerances and deformations becomes therefore critical to achieving the target performances. With the EU gyrotron prototype it was possible to adjust the alignment of the gyrotron tube with respect to the magnetic field axis during the installation and commissioning phase. The actual shift and tilt movements were verified using advanced metrology methods such as photogrammetry. In this paper, the alignment control techniques and procedures will be discussed also in view of enhancing the reproducibility of gyrotron performance during series production.

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Report of recent experiments with the European 1 MW, 170 GHz CW and SP prototype gyrotrons for ITER

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The European 1 MW, 170 GHz industrial CW prototype gyrotron has been designed within EGYC (European GYrotron Consortium) in collaboration with the industrial partner Thales Electron Devices (TED) and under the coordination of Fusion for Energy (F4E). This is a conventional (hollow) cavity gyrotron that is based on the 1 MW, 170 GHz short-pulse (SP) modular gyrotron, which has been designed and manufactured by KIT in collaboration with TED. The SP prototype has been tested in multiple experimental campaigns since 2015 and the nominal cavity mode $TE_{32,9}$ is exited at 170.1 GHz, producing RF power above 1 MW with efficiency 35% (in non-depressed collector operation). The first phase of the experiments with the CW industrial gyrotron was successfully completed at KIT in 2016, verifying most of the ITER specifications. Short pulses (<10ms) deliver RF power higher than 0.9 MW with an electronic efficiency of 26%. The Gaussian mode content of the RF beam is 97%. Pulses with duration of 180 s (limited by the high-voltage power supply at KIT) produce power more than 0.8 MW with 38% efficiency (in depressed collector operation). In this work the achievements with the SP and the CW prototype gyrotrons are summarized.

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Progress of the Procurement of the Gyrotron and Development of the ECH/ECCD Launcher for ITER

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National Institutes for Quantum and Radiological Science and Technology (QST) has a responsibility of procurement of eight gyrotrons and auxiliary systems including the body and anode power supply and Equatorial ECH/ECCD Launcher (EL) for ITER as Japan Domestic Agency of the ITER project. For that purpose wide range of the R&D activities related to the ECH/ECCD system are progressing.

The gyrotron procurement is started and the first two ITER gyrotrons (triode, 170GHz, $TE_{31,11}$, single depressed collector) are manufactured by based on success of the development of 1MW/170 GHz gyrotron. The first one is under conditioning and 200kW/300sec and 1MW/10s were achieved so far. The acceptance test will be conducted with presence of the representative of the ITER Organization. The ITER gyrotron should demonstrate 1MW/300sec/45% electrical efficiency in that test. The designs of the anode/body power supplies are successfully completed. The body power supply is capable of the steady state 40kV/55mA and anode power supply is the +10kV/-20kV bipolar power supply. The anode power supply is developed with 90 series FET device conducting fast on/off switching, which realizes the 5kHz gyrotron beam on/off power modulation by shortening the anode-cathode electrodes of the gyrotron.

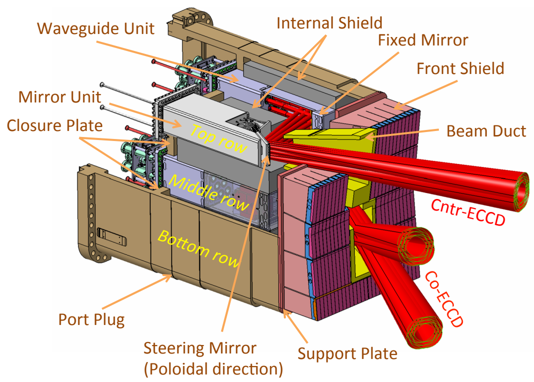

Figure 1: ITER Equatorial Launcher

The steering direction of the EL is changed from toroidal direction to poloidal direction in 2014 in order to enhance the current drive efficiency at $\rho > 0.4$, which gives large impact on the design of EL. As a result, the number of openings of the front shield for RF injection is reduced from three to two by sharing one opening for middle and bottom row as shown in Fig. 1. Note that the top row is for cntr-ECCD and each row has 8 waveguides and two mirrors including one movable steering mirror. The steering mechanism has to be changed due to the change of the steering direction. The same mechanism of the Upper Launcher (UL), which is developed by EU, is adopted for EL. In order to handle the larger mirror of EL compared to UL, the redesign of the steering mechanism is being implemented. The repetitive movement test of the bellows for the steering mirror mechanism is performed at Swiss Plasma Center. The prototype test for manufacturing and testing for internal shield and feed through for waveguide and water pipe is progressing. The inclusion of the ray-tracing code in the optimization iteration process of the curvature of the mirrors and waveguide angles for the poloidal steering launcher are being carried out. The preliminary result shows that the width of current drive profile is reduced from $\Delta\rho = 0.2$ to $\Delta\rho = 0.05$.

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S4: ECH: Gyrotron Development

James Anderson: ECH Technology at General Atomics: Current Status and Future Direction

Grigory Denisov: New Developments of Megawatt Power Gyrotrons in Russia

John Jelonnek: Towards Advanced Fusion Gyrotrons: 2018 Update on Activities within EUROfusion

Fabian Wilde: Measurements of Satellite Mode Activity and Automated Mode Recovery in 140 GHz Wendelstein 7-X Gyrotrons

ECH Technology at General Atomics: Current Status and Future Direction

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Electron Cyclotron Heating (ECH) is a necessary and vital plasma heating mechanism for modern fusion devices. The demand for higher power at longer pulses has placed a new emphasis on modernizing high power microwave technology developed for ECH systems. Transmission line components which have functioned well in the current generation of devices must be improved with new techniques and materials. Active cooling combined with alloys such as Copper Chromium Zirconium (CuCrZr) must be used to handle high heat loads and thermal stress associated with multi-megawatt power. In addition, stringent propagation efficiency and mode purity requirements in transmission lines have resulted in fabrication tolerances that are challenging to meet. Advanced fabrication methods used in other industries are being explored such as E-beam welding, explosion bonding, and additive manufacturing. Inspection techniques are being updated to allow for precision measurements characterizing the long corrugated tubes that make up the transmission lines.

For decades, General Atomics (GA) has produced ECH transmission lines for fusion facilities around the world. GA has developed a series of components to meet the demands for the next generation of fusion device such as ITER, which requires transmission of 1.2 MW of continuous ECH power per line, with 90% propagation efficiency and 95% mode purity [1]. These components include highly robust expansion joints with CuCrZr bellows, long-lasting compact switches with rotating E-beam welded mirror blocks, multi-stage dummy loads, and polarizers designed to withstand formidable heating conditions with minimal surface distortion (Figure 1a) [2]. Stainless steel waveguide sections for launcher sections, which contain the harshest environment in a transmission line, have been analysed, built and tested. Prototypes of these devices have been built and many have been successfully tested under high power conditions at the long-pulse gyrotron test stand at QST's Naka fusion facility [3].

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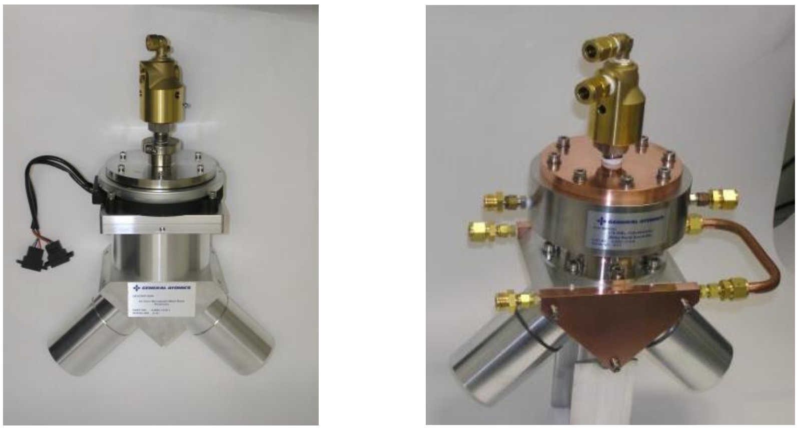
One area of focus for GA's RF component design has been on beam propagation diagnostics. The ability to quickly and accurately monitor power, frequency, and mode purity in a transmission line is crucial for virtually all ECH systems. To address this need, GA has developed high power microwave diagnostics such as an instantaneous power monitor miter bend, a calorimetric-based miter bend (Figure 1b) [4], and a mode monitoring miter bend. A new inline power monitor is also being designed to provide a simple indicator of power in the transmission line.



(a) *(b)*

Figure 1: A polarizer (a), and calorimetric miter bend (b) for 1.5 MW at 170 GHz.

This paper provides an overview of the design, analysis, fabrication, and testing of GA's latest ECH components. Recent tests of water-cooled corrugated waveguide at QST with 300 s gyrotron pulses at 500 kW are presented. New areas of development are also discussed, such the application of additive manufacturing technology towards both low and high power components. Some of the upcoming challenges and future direction for ECH technology are considered.

References

[1] D. Rasmussen, *et al*., JA-EU-US RF Heating Tech. Workshop, Tokyo (2015)
[2] J. Doane, *et al*., Fusion Eng. and Design, **102**, 99-107 (2016)
[3] K. Takahashi, *et al*., JA-EU-US RF Heating Tech. Workshop, Germany (2016)
[4] J. Doane, *et al*., Fusion Eng. and Design, **93**, 1-8 (2015)

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New Developments of Megawatt Power Gyrotrons in Russia

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Gyrotrons for plasma fusion installations usually operate at frequencies 40-170 GHz. Requested output power of the tubes is about 1 MW and pulse duration is between seconds and thousands seconds (depending on plasma machine parameters). In ITER installation there will be 24 of 170 GHz gyrotron systems with 1 MW microwave power each. ITER requirements include also high efficiency of the gyrotrons over 50%, possibility of power modulation with frequency up to 5 kHz, compatibility of the gyrotron complex with ITER control system. In May, 2015 a Russian Prototype of ITER Gyrotron System was completed and its operation was demonstrated. The system includes gyrotron oscillator, liquid-free superconducting magnet, supplementary magnets, several electric power supplies, cooling systems control and protection systems, and other auxiliary units. The gyrotron system shows reliable operation with required parameters. In 2016 fabrication of the first serial gyrotron system was completed. In 2017 the second serial gyrotron system was fabricated and tested. One more 170 GHz ITER gyrotron was delivered for EU team. Megawatt power in very long pulses (300-1000 sec) was also demonstrated with several gyrotrons at 140 GHz frequency for electron-cyclotron systems of EAST (China) and KSTAR (Korea) superconducting tokamaks. Megawatt power gyrotrons with moderate pulse duration from 2 to 10 seconds were developed for TCV, HL-2A, and ASDEX Upgrade tokamaks.

Traditional goals in gyrotron development are the power increase and the frequency increase. Future plasma machines as DEMO claim for EC system higher frequency (comparing with ITER) 230 GHz (170 GHz), module power increase 1.5-2.0 MW (1 MW), efficiency enhancement to value higher 60% (50%), multi-frequency operation in order to avoid wide angle scanning of wave beams in plasma. There are mutual contradictions in these listed requests, for example, the higher frequency and the higher power require bigger gyrotron cavity (higher operating mode) and this affects gyrotron efficiency. Nowadays such a combination of parameters looks unreal – similar case with ITER requirements 25 years ago. Besides power and efficiency increase recently more requirements became more acute in aspects of oscillation spectrum control. As it was mentioned it is considered gyrotron operation at different modes with different frequencies. For one mode operation frequency stabilization is desired and frequency tuning within resonance curve is necessary. Phase and frequency locking is required to make several gyrotrons as coherent oscillators. 250 GHz gyrotron was tested in a pulse mode with power of 300 kW. Results of gyrotron frequency stabilization and oscillator phase locking are encouraging.

References

[1] G.G.Denisov. New trends in gyrotron development, 2017, EPJ Web of Conferences, Volume 149, Pages 01001, https://doi.org/10.1051/epjconf/201714901001

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Towards Advanced Fusion Gyrotrons: 2018 Update on Activities within EUROfusion

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During the ongoing pre-concept design phase (2014 - 2020) for DEMO the activities within EUROfusion WPHCD EC Gyrotron R&D are focusing on options for a near-term DEMOnstration fusion power plant (DEMO), and, at the same time, on long term even more advanced options towards a future Fusion Power Plant, such as flexi-DEMO [1-4]. The near-term target for DEMO is set to pulsed operation, using an EC system operating at 170 GHz and 204 GHz. It benefits from the ITER experience (EC H&CD frequency at 170 GHz). The long term target aims for steady-state operation and might require EC CD frequencies significantly above 200 GHz (e.g. up to 238 GHz). Common targets are an RF power at a single gyrotron output of min. 2 MW and a total gyrotron efficiency higher than 60 %. Another approach under investigation is to go for a fast (in seconds) frequency tuning in steps of around 2 - 3 GHz for plasma stability control. Part of the latter work is a significant investment into advanced Brewster-angle CVD-diamond window technology. Multi-purpose operation at two different alternative frequencies in leaps of about 30 - 40 GHz (e.g. 136/170/204/238 GHz) is considered. Regarding operation at multi-megawatt power levels the focus is on the coaxial-cavity gyrotron technology and advanced technologies of related key components (e.g. improved magnetron injection gun and novel cooling technologies). Different promising concepts for multi-stage depressed collectors (MSDC) are under investigation. Advancing the simulation and test tools complements the research and development work.
Significant investments into FULGOR, the new multi-megawatt long-pulse gyrotron test stand at KIT, will support that research work within EUROfusion.

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This presentation will provide a summary on the present status of the ongoing research and development within EUROfusion and additional supporting work at KIT.

Acknowledgement

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References

[1] M. Q. Tran et al., 26th IAEA-FEC, Kyoto, Japan, 2016.
[2] G. Federici et al., Fusion Engineering and Design, Vol. 109-111, 2016, https://doi.org/10.1016/j.fusengdes.2015.11.050.
[3] G. Federici et al., 13th ISFNT, Kyoto, Japan, 2017.
[4] H. Zohm et al., Nucl. Fusion, Vol. 57, 2017, doi: 10.1088/1741-4326/aa739e.

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Measurements of Satellite Mode Activity and Automated Mode Recovery in 140 GHz Wendelstein 7-X Gyrotrons

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Wendelstein 7-X (W7-X) uses ten 140 GHz gyrotrons for electron cyclotron resonance heating (ECRH). Approaching the practical maximum output power limit causes the excitation of unwanted parasitic and satellite modes which often results in a loss of the nominal operating mode. Therefore the gyrotrons are operated with individual safety margins at significantly reduced output powers to prevent a possible mode loss during operation. The power of those unwanted parasitic and satellite modes is converted to stray radiation which might be used as a precursor for mode loss indicating a potentially unstable operation state of the gyrotron. A dedicated diagnostic and control system could help to mitigate mode losses and to reduce necessary safety margins in operation which would increase the maximum useable output power.

This work evaluates the feasibility of a fast gyrotron controller with a real-time satellite mode activity feedback as a mode-loss precursor and an automated mode recovery. The increased stray radiation of the satellite modes $TE_{27,8}$ (137.3 GHz) and $TE_{29,8}$ (142.5 GHz) was identified as a possible mode-loss precursor.

A measurement setup with five RF detectors attached to a resonator is used to measure the activity of both satellite modes at various working points and output powers. Stacked dielectric discs in an overmoded waveguide were used to realize a satellite mode bandpass filter. For comparison another conventional measurement setup using four open-ended WR6 waveguides as pickups in combination with a triple hybrid ring as power combiner, a 136 GHz high pass and a 140 GHz notch filter was tested.

The automatic mode recovery using the hysteretic gyrotron behaviour was already demonstrated in a previous experiment. A mode recovery algorithm is being implemented and tested on a field-programmable gate array (FPGA).

The status of the diagnostic and control system will be presented.

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S5: ECH Components

Handong Xu: Recent progress of the development of a long pulse 140GHz ECRH system on EAST

Alexander Zach: In-situ real-time monitoring of spurious modes in HE11 transmission lines using multi-hole couplers in miter bends

Torsten Stange: Commissioning and first plasma operation of two remote steering launchers at Wendelstein 7-X

Burkhard Plaum: Development of reflection gratings for advanced ECRH scenarios

Recent progress of the development of a long pulse 140GHz ECRH system on EAST*

Handong Xu [1], Xiaojie Wang[1], Jian Zhang [1], Fukun Liu [1], Yiyun Huang [1], Jiafang Shan [1], Weiye Xu [1], Miaohui Li [1], J.Lohr[2], Y.A.Gorelov[2], J.P.Anderson[2], Dajun Wu [1], Huaichuan Hu [1], Yong Yang [1], Jianqiang Feng[1], Yunying Tang [1], Bo Li [1], Yang Zhang [1], Wendong Ma [1], Zege Wu [1], Jian Wang [1], Liyuan Zhang [1], Fei Guo [1], Haozhang Sun [1], Xinsheng Yan[1] and EAST Team

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A long pulse ECRH system with a goal of 4MW 100~1000s has been developed to meet the requirement of steady-state operation on EAST [1]. The system has been planned since 2011. The general preliminary design of the system was completed in 2012, and all sub-systems have been under development since 2012. The system is mainly composed of four 140GHz gyrotron systems, 4 ITER-like transmission lines, 4 independent channel launchers and corresponding power supplies, water cooling, control & interlock system etc. Each gyrotron is expected to deliver a maximum power of 1MW and be operated at 100s~1000s pulse lengths. Gycom gyrotrons are employed in the No.1 and No.3 systems, CPI gyrotrons are used in the No.2 and No.4 systems.

The development of the two Gycom gyrotron systems has been finished. The first short pulse EC wave injection has been demonstrated successfully during the EAST 2015 Spring campaign. In the commissioning and operation towards steady-state operation, 0.4MW 100s has been injected to plasma successfully by using the No.1 system, 4.7keV 102s L mode and 102s H mode plasma have been achieved on EAST with the help of ECRH. Recently, a longest pulse of 0.55MW 1000s has been obtained based on calorimetric dummy load measurements [2] on the No.3 gyrotron.

The No.2 gyrotron also has been installed and partially tested, 500kW 80s has been demonstrated in the dummy load. The remaining No.4 gyrotron will be ready to test in 2018 or 2019. The whole 4MW system will be completed within two years. The 400s fully non-inductive H mode operation would be expected in the next four years in the condition of fully tungsten diverter on EAST.

References

[1] Handong.Xu, *et al.*, Plasma Science and Technology **18**, pp442-pp448 (2016)

[2] Weiye. Xu, *et al.*, Fusion Engineering and Design **113**, pp119-pp125 (2016)

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In-situ real-time monitoring of spurious modes in HE_{11} transmission lines using multi-hole couplers in miter bends

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Transmission of high-power millimeter waves for ECRH is often realised with oversized corrugated circular waveguides. Coupling from the gyrotron source to the waveguide is typically done via matching mirrors in free space. Small alignment errors of the system lead to the excitation of higher-order modes inside the waveguide beside the main transmission mode HE_{11}. Those modes have comparably higher losses and can in worst case result in local fields exceeding the breakdown limit of the medium inside the waveguide.

For alignment control over the whole pulse duration of the gyrotron, a set of hole-array couplers placed into a miter bend mirror probes the field inside the waveguide. The arrays are designed to detect the tracer modes for beam offset and tilt ($LP_{11}^{(e/o)}$) as well as for beam waist mismatch (LP_{02}). In addition, a main mode coupler sensitive mostly for the HE_{11} content is used as a power monitor. By maximizing the signal of the power monitor and minimizing the content of tracer modes, a first-order optimization of the coupling from free space to the waveguide can be achieved. Signal processing of the 140 GHz information is done at kHz range after downmixing, using a frequency shifted part of the power monitor signal.

As the measurement system is placed in a miter bend mirror, it can also be easily installed at various locations along the transmission line to check for possible misalignments of the waveguide connections between miter bends. Simulation and low power experimental results will be shown.

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Commissioning and first plasma operation of two remote steering launchers at Wendelstein 7-X

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The overall goal of the super-conducting stellarator Wendelstein 7-X (W7-X) is to demonstrate the reactor relevance of the stellarator confinement concept. For this reason, W7-X is equipped with a steady state ECRH-system with ten 140 GHz gyrotrons of 1 MW nominal power each to guarantee 30 min operation at reactor relevant plasma parameters [1]. By default, the ten microwave beams are injected by front steering launchers (FSL), which are used in all experimental devices but which are probably not compatible with the extremely harsh environment of a fusion reactor. Therefore, alternative concepts like the remote steering launcher (RSL) [2] without any movable elements in the reactor chamber have been developed as an additional launch scheme for W7-X. Due to multi-mode interference, a squared corrugated waveguide of proper length and width is able to image a single frequency input beam within an angular range of +/-15° with respect to the waveguide axis to the same emission angle at the waveguide output. For 140 GHz at a power level of the order MW, a waveguide width of at least 50 mm leads to 4.6 m overall waveguide length allowing to steer the heating beam within the plasma by a movable mirror far away from the reactor chamber.

Two RSLs have been elaborately produced [2] and installed at W7-X with a toroidal launch angle of 50° relative to the magnetic axis to achieve high current drive efficiency. The toroidal position in the 3D magnetic field structure was chosen in this way, so that the steering capabilities allow selective heating of trapped and passing particles in specific magnetic field configurations foreseen in later operation phases. Furthermore, the steering plane of one RSL-antenna allows an overlap with the receiving antenna of a collective Thomson scattering system, which just started operation.

In preparation for the first plasma operation of the RSLs, the final emission characteristics were measured with high power in the plasma vessel over the whole steering range by use of a PVC-target perpendicular to the waveguide axis at a distance of 1 m to the waveguide aperture. The quality of the beam is excellent and the emission angles are in good agreement with the expected trajectory. The first plasma operation with use of the RSLs started in October 2017 during the second experimental campaign OP1.2a. The pulse time was increased stepwise from 5 ms to finally 5 s with minor problems due to arcing events. An overview of the achieved results during commissioning and plasma operation will be given in this contribution.

References

[1] V. ERCKMANN, *et al.*, Fusion Science and Technology **52**, 291-312 (2007)

[2] W. KASPAREK, *et al.*, EPJ Web of Conferences **87**, 04005 (2015)

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Development of reflection gratings for advanced ECRH scenarios

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When heating fusion plasmas at higher harmonics of the electron cyclotron frequency, the absorption efficiency can be reduced. This leads to a significant transmitted beam power hitting the wall at the high field side (HFS). To protect wall and to use the remaining power, one method is to place a specialized reflector at the HFS, which directs the beam back into the plasma for a second heating pass [1]. The reflector needs to conform to the tiles at the HFS, which are often non-planar. The direction of the reflected beam is chosen such that the absorption of the second heating pass is maximized and the wall area at the LFS, which is hit after the second pass, contains no sensitive components. Additional requirements are a refocusing of the beam and polarization independence of the reflection characteristics. All these conditions can only be fulfilled with a grating. The design process involves the decomposition of the 3D field problem into a series of 2D reflections of plane waves. After the 2D gratings are optimized, the final 3D grating can be synthesized.

The paper presents the microwave aspects of the design process of reflecting gratings for ASDEX-Upgrade. The recent improvements of the optimization framework are discussed and experimental results are presented.

References

[1] H.Höhnle, *et al*., Investigation of the O2- and X3-mode heating in ASDEX Upgrade, 36th European Physical Society Conference on Plasma Physics, 2009

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S6: Diagnostics: CTS

Søren Bang Korsholm: Design and development of the ITER CTS diagnostic

Dmitry Moseev (M. Stejner): First collective Thomson scattering results from Wendelstein 7-X

Teruo Saito: Developments for collective Thomson scattering equipment with a sub-THz gyrotron in LHD

Stephen Cauffman: Adaption of a Dual-Frequency 104/140 GHz Gyrotron for Operation at 175 GHz

Design and development of the ITER CTS diagnostic

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The Collective Thomson Scattering (CTS) diagnostic will a primary diagnostic for measuring the dynamics of the confined fusion born alpha particles in ITER and will be the only diagnostic for alphas below 1.7 MeV [1]. The probe beam of the CTS diagnostic comes from a 60 GHz 1 MW gyrotron operated in a ~100 Hz modulation sequence. In the plasma, the probing beam will be scattered off fluctuations primarily due to the dynamics of the ions. Seven fixed receiver mirrors will pick up scattered radiation (the CTS signal) from seven measurement volumes along the probe beam covering the cross section of the plasma. The diagnostic is planned to provide a temporal resolution of ~100 ms and a spatial resolution of ~a/4 in the core and ~a/20 near the plasma edge. The front-end quasi-optics will be installed in an equatorial port plug (EPP#12) and a particular challenge will be to pass the probing beam through the fundamental electron cyclotron resonance, which is located in the port plug (R=10.3 m) for the nominal magnetic field $B_T = 5.3$ T. Hence, particular mitigation actions against arcing have to be applied. The status of the design and specific challenges will be discussed.

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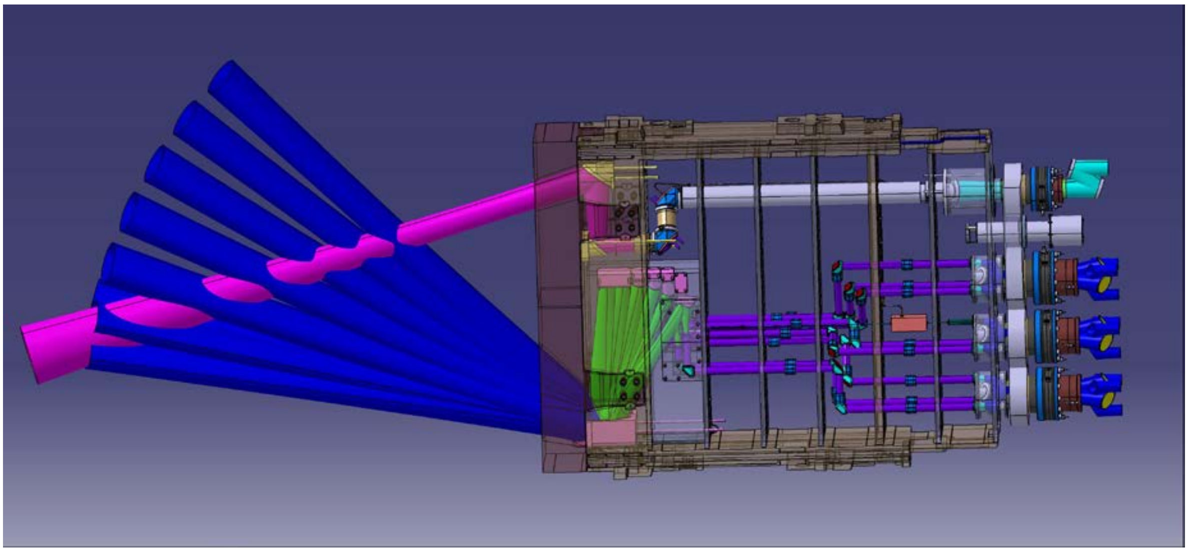

Figure 1: CATIA drawing of the present in-vessel design of the ITER CTS diagnostic.

References

[1] M. Salewski, *et al*., Alpha-particle velocity-space diagnostic in ITER, submitted, (2018)

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First collective Thomson scattering results from Wendelstein 7-X

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In collective Thomson scattering (CTS) measurements, a high-power probe beam is used to scatter off plasma fluctuations to gain information about the ion population. Typically, a dedicated gyrotron is used as source of the probing beam. Examples of information that can be obtained from a CTS diagnostic include 1D projected fast-ion velocity distributions, bulk-ion isotope ratios, temperatures and drift velocities.

On Wendelstein 7X (W7X) a CTS system has been designed which uses the heating gyrotrons as sources of the probe radiation. This concept significantly reduces the cost of the system but increases the requirements on the receiver robustness against stray radiation, and it enhanced the noise levels in the measurements. The technique was pioneered at the ASDEX Upgrade Tokamak and has shown to provide measurements of the ion temperature that are in agreement with measurements based on charge exchange recombination spectroscopy [1].

The probe radiation is delivered by a 700 kW gyrotron operating at 140 GHz. The scattered signal is detected by a receiver system based on a highly sensitive heterodyne radiometer. Notch filters are used to block the radiation from all gyrotrons at W7X. The measured signal is down-converted in two stages and digitized by a fast Analog-Digital-Converter system at a sampling rate of 6.25 GS/s. In the post processing, a Fourier transform is used to obtain the CTS spectra with typical frequency resolution in MHz range on a sub-millisecond time scale.

The quasi-optical transmission lines allow measurements at two toroidal locations with different topologies of the magnetic field. The transmission line in the bean-shaped cross-section is equipped with steerable mirrors, which allow flexible scattering geometries on the low field side. In the triangular cross-section, remote steering antennas are installed both for the receiver and the probe. This enables the search of optimum overlap and ion temperature profile measurements.

In this contribution, we will show first results of CTS from the newly installed system on W7X. We present CTS signals that are in agreement with our CTS forward model. Finally, we discuss the potential of the diagnostics and the experimentally found limitations due to parasitic interaction between the gyrotron radiation and the plasma.

[1] Stejner, M., Rasmussen, J., Nielsen S. K., et al. (2017). Main-ion temperature and plasma rotation measurements based on scattering of electron cyclotron heating waves in ASDEX Upgrade. *Plasma Physics and Controlled Fusion*, ***59***, 75009.

Developments for collective Thomson scattering equipment with a sub-THz gyrotron in LHD

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Plan of collective Thomson scattering (CTS) experiment with a 303 GHz gyrotron is under way. CTS diagnostics systems with gyrotrons for electron heating have been developed for LHD in NIFS and several tokamaks. Scattering signals have been successfully detected and now those systems provide valuable data about the ion temperature and high-energy ions. Use of a sub-THz gyrotron expands the CTS-applicable region of plasma parameters. In LHD, sub-THz CTS can be applied to the high density operation region, plasmas with impurity hole, etc. Moreover, sub-THz CTS is expected to be free from ECE noise. Its “collective” use with 77 GHz and 154 GHz CTS will compose a powerful diagnostic system.

A high power sub-THz gyrotron with a frequency of 303 GHz has been successfully developed. Its maximum power is 320 kW. It oscillates in pulse mode and the maximum pulse width is around 100 μs, which is sufficient for use in CTS experiments. Parasitic oscillations are a serious problem for application to CTS. A whispering gallery mode TE22,2 was adopted for this gyrotron to avoid mode competition. Careful frequency measurement has proved purely single mode oscillation of the TE22,2 mode including turn-on and turn-off phases of the oscillation pulse. This is consistent with mode competition calculations taking account of a finite voltage rise time.

A low loss transmission line is necessary. We have two possibilities. One is a new line with 1.25 inch corrugated waveguides that are optimized for the 300 GHz band. Transmission test with the 303 GHz gyrotron has been carried out and a sufficiently low loss coefficient has been confirmed. The other is to use an existing line with 3.5 inch corrugated waveguides for lower frequencies such as 77 GHz and 154 GHz. Transmission test has been carried out with the 303 GHz gyrotron and a

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sufficiently low loss coefficient has been confirmed also for 3.5 inch corrugated waveguides. An existing line with 3.5 inch corrugated waveguides will be used in the initial phase of 303 GHz CTS experiment.

References

[1] Y. Yamaguchi, *et al*., Journal of Instrumentation **10**, C10002 (2015)

[2] T. Saito, *et al*., Plasma Fusion Res. **12**, 1206013 (2017)

[3] T. Saito, *et al*., 42nd Int. Conf. IRMMW-THz, RA2.1 (2017)

[4] K. Ohkubo, *et al*., J. Infrared Milli. Terahz Waves **38**, pp.853-873 (2017)

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Adaptation of a Dual-Frequency 104/140 GHz Gyrotron for Operation at 175 GHz

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A dual-frequency gyrotron capable of operation in the $TE_{28,7}$ cavity interaction mode at 140 GHz, or in the $TE_{22,5}$ mode at 104 GHz, has been developed for use in electron cyclotron heating in the W7-X stellarator at IPP Greifswald. The gyrotron incorporates an internal converter design that has been numerically optimized to convert either of the two operating modes into a high-quality Gaussian output beam. During short-pulse factory testing, the gyrotron produced 900 kW at 140 GHz, and 520 kW at 104 GHz. After delivery to IPP, the gyrotron was conditioned to long-pulse operation at 140 GHz, demonstrating 30-minute pulses at several power levels up to 811 kW, and producing ten consecutive ten-minute pulses at 811 kW as well. After long-pulse capabilities were demonstrated at 140 GHz, IPP requested an analysis of the feasibility of operating the gyrotron (without internal modification) in an additional mode with a frequency near 175 GHz. Several potential interaction modes were evaluated to determine the required operating parameters for excitation of these modes, and to assess the expected interaction efficiency, output power, internal diffraction losses, and output beam quality. The most promising modes appear to be the $TE_{33,9}$ (173 GHz) or the $TE_{34,9}$ (176 GHz), which should generate 400-500 kW of RF in a suitable magnet capable of producing the necessary 7.1 T field required for operation at these higher frequencies. Because the existing gyrotron's internal converter was not optimized for these modes, however, internal losses are expected to be higher than usual (up to 7%), and the output beam pattern will require substantial external phase-correction in order to produce a Gaussian beam. A preliminary feasibility analysis for such external phase correction has been performed, demonstrating that a high-quality beam can be recovered using numerically synthesized external phase-correcting mirror surfaces.

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S7: Diagnostics: ECE and Imaging

Viktor Udintsev: Progress in ITER ECE Diagnostic Design and Integration

Liu Yong: Overview of the ECE measurements on EAST

Roddy Vann: Measurements of edge magnetic pitch angle on MAST & NSTX-U using the Synthetic Aperture Microwave Imager

Min Jiang: Development of ECE/ECEI diagnostics and multi-scale transport study on HL-2A tokamak

Progress in ITER ECE Diagnostic Design and Integration

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The design of ITER Electron Cyclotron Emission (ECE) diagnostic is progressing towards its Preliminary Design Review (PDR). In parallel, the diagnostic integration in the Equatorial Port is ongoing. Port Integration has to address the structural integrity to withstand various loads, maintenance and the safety aspects of ECE diagnostic. ITER ECE system includes radial and oblique lines-of-sight. Recently, a successful peer-review of the in-port plug Hot Calibration Source has taken place and its performance and integration feasibility has been demonstrated. Four 45-meter long low-loss transmission lines are designed to transmit mm-wave power in the frequency range of 70- 1000 GHz in both X- and O-mode polarization from the port plug to the ECE instrumentation room in the diagnostic building. Prototype transmission lines are being tested and first results will be presented at this workshop [1]. A prototype polarizing Martin-Puplett type Fourier Transform Spectrometer (FTS) operating in the frequency range 70-1000 GHz. The FTS has a fast scanning mechanism and cryo-cooled dual-channel THz detector system and its performance has been tested as per ITER requirements. Assessment of the instrumentation and control requirements, functional and non-functional requirements, operation procedures, plant automation are ongoing for the PDR. The current status of the diagnostic, progress in design achieved since the EC-19 Workshop, as well as the integration activities, will be presented.

References

[1] R. Kumar *et al.*, "Comparative studies of various types of transmission lines in the frequency range 70 GHz -1 THz for ITER ECE diagnostic", this Workshop.

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Overview of the ECE measurements on EAST

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Complementary systems for ECE measurements have been commissioned at EAST. A few radiometer systems have been developed in the past few years. The radiometer systems cover a frequency range of 97-167 GHz. The frequency interval is 1 GHz for the frequency range of 97-121 GHz, while it is 2 GHz for the range of 121-167 GHz. The RF bandwidth is roughly 500 MHz, and the video bandwidth is up to around 400 kHz. Besides the radiometer systems, a Michelson interferometer, on loan from EFDA-JET (Culham, United Kingdom) has been commissioned on EAST since the 2014 experimental campaign. The frequency coverage is roughly 80-350 GHz, and the spectral resolution is around 2.8 GHz. The temporal resolution is about 33 ms for the plasma operation.

All the systems share the optics and the transmission line. The quasi-optics is comprised of an ellipsoidal mirror and two flat mirrors, and forms a beam pattern of roughly 5 cm FWHM. The transmission line is comprised of ~45 meters corrugated waveguides, 8 miter bends, and two power dividers.

In order to provide independent absolute electron temperature information, in-situ calibration was carried out by using the hot/cold load method. Two kinds of hot sources have been developed. One of them (#1) is a copy of the JET hot source, and the other one (#2) is the ITER prototype developed by the Institute for Fusion Studies. The source #1 operates at atmosphere, while the source #2 needs to be operated in vacuum. Normally, an in-situ calibration was carried out before an experimental campaign by using the hot source #1, and the calibration was carried out again by using the hot source #2 at the end of a campaign. The radiometer systems and the Michelson interferometer are calibrated independently, and the results show a good agreement between the electron temperature profiles.

In addition to the conventional ECE diagnostic, a 4-channel correlation ECE (CECE) diagnostic has been developed recently to diagnose the small-amplitude electron temperature fluctuation measurement. This system has been commissioned in 2017, and broadband T_e fluctuation has been measured.

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Measurements of edge magnetic pitch on MAST & NSTX-U using the Synthetic Aperture Microwave Imager (SAMI)

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Measuring the tokamak edge current density is crucial for developing and constraining models of stability including the behaviour of edge localised modes.

The Synthetic Aperture Microwave Imager (SAMI) is an independently-phased array of 8 antennas switching between 16 frequency channels in the range 10-34.5GHz with a signal bandwidth of 100MHz. An additional antenna illuminates the whole of the plasma surface (at a density specified by the frequency); the phased array enables reconstruction of a 2-D Doppler intensity map of the back-scattered radiation.

The Bragg back-scattering condition is most strongly satisfied perpendicular to the magnetic field since turbulent density fluctuations are elongated along magnetic field lines. Since the plasma is rotating, this back-scattering is Doppler-shifted away from the directly-reflected signal. Localising the Doppler-shifted power maxima therefore enable us to measure the magnetic field pitch angle. This technique has been employed successfully at MAST and NSTX-U [1,2].

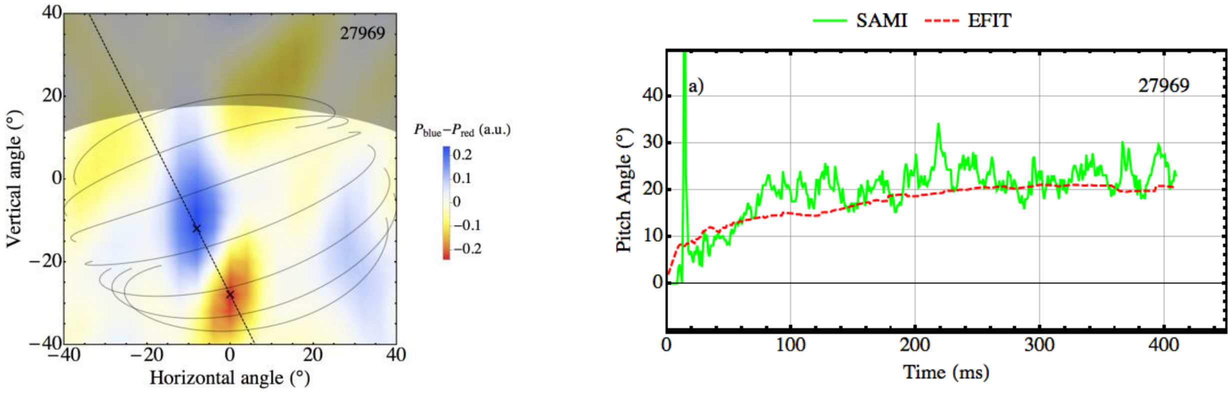

Figure: Data from MAST shot 27969: (left) SAMI image showing blue-red Doppler power imbalance superimposed over EFIT magnetic field reconstruction (grey lines); (right) time-dependendence of edge pitch angle measured by SAMI (green) compared with EFIT at f = 10GHz

In principle, we can then make pitch angle measurements at different radial locations (by imaging at different frequencies) in order to measure the edge current density – this is the objective of SAMI-U, currently being designed and built for MAST-U [3].

References

[1] R.G.L. Vann *et al.*, Rev. Sci. Inst. **87**, 11D902 (2016)

[2] D. A. Thomas *et al.*, Nucl. Fusion **56** 026013 (2016)

[3] J. O. Allen *et al.*¸ *elsewhere at this conference*

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Development of ECE/ECEI diagnostics and multi-scale transport study on HL-2A tokamak

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A novel 64-channel electron cyclotron emission (ECE) radiometer has been designed and tested for the measurement of electron temperature profiles on the HL-2A tokamak [1]. This system is based on the intermediate frequency filter detection technique, and has the features of wide working frequency range and high spatial resolution, which can cover the whole plasma region. Two relative calibration methods have been investigated: sweeping the toroidal magnetic field and hopping the output frequency of the local oscillator. Also, the electron cyclotron emission imaging (ECEI) system has been developed for studying the two dimensional temperature fluctuations [2]. It is comprised of several front-end quasi-optical lenses, a 24 channel heterodyne imaging array with a tunable RF frequency range spanning 60-135 GHz, and a set of back-end electronics that together generate two 24×8 array images of the 2nd harmonic X-mode electron cyclotron emission from the HL-2A plasma. The measurement region can be flexibly shifted due to the independence of the two local oscillator sources, and the field of view can be adjusted easily by changing the position of the zoom lenses as well. The temporal resolution is about 2.5 μs and the achievable spatial resolution is 1 cm. The ECE/ECEI diagnostics have been demonstrated to be a powerful tool on HL-2A tokamak to study the multi-scale transport physics associated with the interaction between macro-scale MHD, meso-scale plasma flows and micro-scale turbulence [3, 4].

References

[1] Z. B. Shi *et al.*, Rev. Sci. Instrum. **85**, 023510 (2014)

[2] M. Jiang *et al.*, Rev. Sci. Instrum. **84**, 113501 (2013)

[3] M. Jiang *et al.*, Nucl. Fusion 58 026002 (2018)

[4] M. Jiang *et al.*, Phys. Rev. Lett. submitted (2017)

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S8: Diagnostics: Scattering and Emission

Timothy P. Goodman: Experimental study of high power mm-waves scattering by plasma turbulence in TCV and TORPEX

Stefan Kragh Nielsen: Overview of experimental observations of parametric decay of mm-waves in fusion plasmas

Alessandro Bruschi: Side Emissions during EC Injection for PDI Studies in FTU Tokamak

Alf Köhn: The deteriorating effect of plasma density fluctuations on microwave beam quality

Experimental study of high power mm-waves scattering by plasma turbulence in TCV and TORPEX

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High power mm-waves used to heat and drive current locally in magnetically confined plasmas of fusion devices must pass through the turbulent Scrape-Off Layer (SOL) and the plasma edge. The SOL is characterised by large electron density fluctuations from field-aligned elongated filaments that detach from the confined plasma and propagate towards the walls. Numerical simulations suggest that the long path lengths from the SOL to the resonance in ITER may lead to broadening of the driven current profile and concomitant loss of efficiency in NTM stabilization.

On the Tokamak à Configuration Variable (TCV), high-power 118GHz radiation is launched from a moveable mirror on the top of the machine. An X3 Transmission Diagnostic (X3TD) is situated directly below the X3 launcher on the floor of the machine to measure transmitted power at a distance that approaches the launcher-to-resonance distance in ITER. The poloidal beam transmission profile is found by sweeping the beam across the X3TD using the launcher mirror. Several plasma shapes are explored; in particular, a Simple Magnetized Torus (SMT) configuration similar to that explored on Toroidal Plasma Experiment (TORPEX).

Direct experimental measurements of mm-beam scattering by plasma turbulence in TORPEX and TCV are described and compared. In TORPEX, a 2D array of *in situ* Langmuir probe measurements allows the beam-plasma interaction to be calculated along the entire beam path from transmitter to receiver [1]. In TCV, wall/floor-mounted Langmuir probes measure density fluctuations at the graphite tiles. Strong fluctuations of the transmitted power (up to 70% of the peak power) are caused by fluctuations of the electron density and show a 10% correlation with the electron density fluctuations measured by the floor-mounted Langmuir probes. The spatial scale of the turbulent edge structures is of a few centimeters.

Modeling efforts using a variety of 2D and 3D codes are underway to compare transmitted profiles with experiments. Following free-space and simple refractive benchmarking, scattering calculations based on the Global Braginskii Solver (GBS) code [2] statistics are carried out. An overview of progress and prospects will be given.

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References

[1] O. Chellai et al., *Millimeter-Wave Beam Scattering by Field-Aligned Blobs in Simple Magnetized Toroidal Plasmas*, accepted for publication in Phys. Rev. Lett.

[2] P. Ricci et al., *Plasma Phys. Control. Fusion* 54, 124047 (2012)

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Overview of experimental observations of parametric decay of mm-waves in fusion plasmas

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In a parametric decay instability (PDI), an incident wave decays into two daughter waves once the power in the incident wave inceeds a threshold. If microwave heating waves decay before reaching the electron cyclotron resonances, not all power will reach the desired heating position and additional plasma waves will be excited in the plasma. The excited waves may modify the heating and current drive profiles. Furthermore, the waves may escape the plasma and pose a risk to diagnostics systems operating near the frequencies of the daugther waves.

Until recently, PDI of mm-waves at frequencies well above the upper hybrid frequency, where heating and diagnostic systems often operate, was not expected at the power levels of gyrotrons in tokamaks and stellerators. However, observation of high power microwave scattering near the gyrotron frequency during Electron Cyclotron Resonance Heating (ECRH) from TEXTOR, ASDEX Upgrade and Wendelstein 7X (W7X) has initiated new theoretical considerations within the field which has resulted in a reduced power threshold PDI theory [1].

In this contribution we will provide an overview of experimental observations of PDI processes of mm-waves in tokamaks and stellerators. We will focus on results involving gyrotron based second harmonic ECRH and gyrotron based collective Thomson scattering (CTS). In the ECRH scenario, PDI processes are mainly observed to take place when the probe beam passes through the point in the plasma where the gyrotron frequency is twice the upper hybrid frequency. The process seems furthermore to be triggered by a density perturbation at the interaction position. Examples of such density perturbations which triggers the PDI process are 1) tearing modes located near the plasma centre and the plasma edge, and 2) Edge Localized Modes (ELMs) located in the plasma edge. In both cases the observations have been explained theoretically [1] and the calculated power thresholds are well below the values used in the experiments. In the CTS senario the PDI processes are associated with X-mode radiation hear the Upper hybrid resonance. The X-mode radiation comes from the high-field-side wall when incident O-mode radiation reflected used in CTS is reflected partly in X-mode. In some cases the X-mode radiation will reach the upper hybrid resonance were the wave will decay into an upper hybrid wave and a lower hybrid wave [2]. This scenario is very similar to the Electron Bernstein Wave (EBW) heating scenario where PDI has also been seen take place.

References

[1] E. Gusakov, *et al.*, Physics of Plasmas 23, 082503 (2016)

[2] S. Hansen, *et at.*, et al PPCF 105006 (2017)

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Side Emissions during EC Injection for PDI Studies in FTU Tokamak

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The evidence of parametric decay instabilities (PDI) excited by the ECH power injected at the 1st Harmonic in O-Mode has been explored in FTU Tokamak, using the Collective Thomson Scattering (CTS) diagnostic. The aim was to add experimental evidences to confirm the hypotheses of low-threshold excitation of waves generated by PDI mechanisms, formulated in several papers ([1], [2] and reference therein), based on the observation of back-scattered power in the case of 2nd harmonic X-mode injection in TEXTOR and ASDEX-U. Theoretical analysis predicts [3] analogous low-threshold parametric decay for O-mode pump-wave injection, which can be explored at frequencies close to the first Harmonic resonance in FTU. Experiments were made at different magnetic fields, injecting the 140 GHz probe and observing the emission from the second antenna of the EC launcher in symmetric and asymmetric configurations, in presence of MHD islands stimulated by Ne injection. The signal is split in two orthogonal polarizations and detected with two channels of the CTS radiometer, with a fast digitizer connected to the IF of the two front-ends, allowing the spectral reconstruction at very fine time and frequency scales by FFT. Different types of emissions have been reported [4], some of which are studied in further detail, to exclude gyrotron spurious emission and to verify the synchronism with the magnetic island rotation. The plasma conditions in which the various types of emissions are found have been extensively studied. In order to locate the plasma volume originating the emissions, a new antenna and receiving line has been installed.

References

[1] E. Z. Gusakov and A Y Popov, Plasma Phys. Control. Fusion 60, 025001 (2018)
[2] S. K. Hansen, *et al.*, Plasma Phys. Control. Fusion 59, 105006 (2017)
[3] E. Z. Gusakov, *et al.*, Plasma Phys. Control. Fusion 59, 075002 (2017)
[4] A. Bruschi, *et al.*, Nucl. Fusion **57**, 076004 (2017)

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The deteriorating effect of plasma density fluctuations on microwave beam quality

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Microwaves play an indispensable role in present plasma experiments for heating and diagnostic purposes. When injected into the plasma or emitted by it, they have to traverse the plasma boundary where substantial plasma density fluctuations are known to occur. The fluctuation levels can be as large as 100 %, deteriorating the microwave beam. This can lead to a reduction in heating efficiency or ambiguous diagnostics results. In particular for tokamaks this can be a problem as the control of MHD instabilities requires highly localized current drive. Here we present numerical simulations of the interaction of microwaves with a fluctuating plasma density layer. Two full-wave codes are used, IPF-FDMC [1] and EMIT-3D [2], and the wave kinetic code WKBeam [3]. The latter is based on a statistical description of the turbulence which allows for much faster simulations as compared to the full-wave codes which, in order to properly take into account the effect of fluctuations, require an ensemble-average. WKBeam is based on the Born approximation and its range of validity is explored by benchmarking it against full-wave simulations. Extrapolations towards ITER are drawn with WKBeam [3] to assess the feasibility of the foreseen microwave heating system to control neoclassical tearing modes, one of the aforementioned MHD instabilities.

At sufficiently low plasma densities, the wave modes are not well separated and cross polarization coupling can occur. The amplifying effect of fluctuations at such low densities on the polarization scattering is estimated from simulations.

In a series of experiments at the DIII-D tokamak, the broadening of an injected microwave beam could be linked to plasma edge density fluctuations [4]. This was confirmed by 3D full-wave simulations in a reduced geometry.

References

[1] A. Köhn *et al.*, Plasma Phys. Control. Fusion **50**, 085018 (2008)

[2] T.R.N. Williams *et al.*, Plasma Phys. Control. Fusion **56**, 075010 (2014)

[3] A. Snicker *et al.*, Nucl. Fusion **58**, 016002 (2018)

[4] M.W. Brookman *et al.*, EPJ Web of Conf. **147**, 03001 (2017)

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S9: Diagnostics: Physics and Modelling

Simon Freethy: Advances in turbulence measurements using new Correlation ECE and nT-phase diagnostics at ASDEX Upgrade

Alexander Creely: Measurement of Perturbative Thermal Diffusivity with Partial Sawtooth Heat Pulses on Alcator C-Mod and ASDEX Upgrade

Udo Höfel: Bayesian modelling of ECE calibration and measurements at Wendelstein 7-X

Nikolai Marushchenko: Mixed Scenarios with X3 heating in W7-X

Advances in turbulence measurements using new Correlation ECE and nT-phase diagnostics at ASDEX Upgrade

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An experimental understanding of turbulent fluctuations in tokamak plasmas is necessary for providing confidence in the extrapolation of heat transport models to future experimental devices and reactors. Guided by predictions from nonlinear gyrokinetic simulations, two new turbulence diagnostics were designed and installed at ASDEX Upgrade (AUG) to probe the fundamentals of ion-scale turbulent electron heat transport.

The first, a 30-channel correlation ECE (CECE) radiometer (105-128 GHz, 2nd harmonic X-mode), introduces a novel channel comb arrangement [1]. This allows measurements of high radial resolution profiles ($0.5 < r/a < 0.8$) of low-k ($k_\theta \rho_s < 0.3$) temperature fluctuation amplitudes, δT_e, frequency spectra and radial correlation length, $L_r(T_e)$, profiles in unprecedented detail. The second diagnostic is formed by the addition of a W-band X-mode reflectometer on the same line of sight to enable measurements of the phase angle between turbulent density and temperature fluctuations (α_{nT}). Previously the radial alignment between reflectometer and radiometer has been a challenge due to the requirement that alignment is achieved within a radial correlation length (< 5-10 mm). This challenge is significantly alleviated by using the CECE channel comb arrangement and the maximal coherence between reflectometer and radiometer can be unambiguously captured.

Measurements of these quantities have been made in an AUG L-mode plasma, at the same radial location and have provided simultaneous *quantitative* constraints on realistic gyrokinetic simulations using the gyrokinetic code GENE [2]. A gyrokinetic sensitivity scan is performed by varying the input gradients (∇T_i, ∇T_e) within their experimental uncertainties. A combined metric [3] is used for the first time to quantify the level of agreement between simulation and experiment. Simultaneous quantitative agreement is found for electron and ion heat flux, α_{nT} and $L_r(T_e)$, whereas δT_e is found to be higher in simulations compared to the experiment.

References

[1] A.J. Creely *et al*, *Rev. Sci. Instrum.*, submitted.

[2] S.J. Freethy *et al*, *Phys. Plasmas*, accepted.

[3] P. Ricci *et al*, *Phys. Plasmas* **18**, 032109 (2011)

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Measurement of Perturbative Thermal Diffusivity with Partial Sawtooth Heat Pulses on Alcator C-Mod and ASDEX Upgrade

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A key parameter for validation of turbulent transport simulations, the perturbative thermal diffusivity, has been calculated on Alcator C-Mod and ASDEX Upgrade using partial sawtooth heat pulses measured with ECE diagnostics. Recent advances in validation of gyrokinetic simulations have revealed that comparing more than just experimental heat fluxes may be vital to differentiating between models [1, 2]. One such parameter is the perturbative thermal diffusivity of the plasma, which is related to the incremental change in electron heat flux given an incremental change in electron temperature gradient [4]. The perturbative thermal diffusivity can be measured based on the propagation of heat pulses generated by partial sawtooth crashes [5].

Partial sawtooth heat pulses are tracked on Alcator C-Mod using a grating polychrometer [5] and on ASDEX Upgrade using an ECE radiometer [6]. The high spatial and temporal resolutions of these diagnostics, as well as their relatively low noise levels, when compared to Thomson Scattering for example, make them vital to this measurement. This method of measuring perturbative thermal diffusivity has been compared to heat pulses generated from modulated electron cyclotron heating, a well-established method, finding good agreement for the discharges analyzed. In addition, the two machines show a common trend of perturbative thermal diffusivity with plasma collisionality. Finally, experimental measurements have been compared to the results of the reduced transport code TGLF [7]. Results to date suggest good agreement with multi-scale simulations in all cases, but often disagreement with ion-scale only simulations.

[1] C. Holland, Phys. Plasmas 23, 060901 (2016).
[2] N.T. Howard et al., Plasma Phys. Control. Fusion 60, 014034 (2018).
[3] N. J. Lopes Cardozo, Plasma Phys. Control. Fusion 37, 799 (1995).
[4] A.J. Creely et al., Nucl. Fusion 56, 036003 (2016).
[5] J. O’Shea et al., 9th Joint Workshop on ECE and ECRH Borrego Springs, page 7 (1995).
[6] M. Willensdorfer et al., Plasma Phys. Control. Fusion 58, 114004 (2016).
[7] G.M. Staebler et al., Phys. Plasmas 23, 062518 (2016).

Bayesian modelling of ECE calibration and measurements at Wendelstein 7-X

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The electron cyclotron emission (ECE) diagnostic at Wendelstein 7-X (W7-X) uses a 32 channel heterodyne radiometer covering a frequency range of 120 GHz to 160 GHz. The absolute calibration of the ECE diagnostic is done using a hot/cold load rotating mirror technique, for which multiple forward models have been developed with Minerva, the framework in which the bayesian diagnostic modeling at W7-X is done. Inference on these models via maximum a posteriori and Markov chain Monte Carlo methods allows for a systematic uncertainty treatment.

As the ECE measures radiation temperature and not the electron temperature directly, the most accurate way to extract electron temperature profile information is given by inferring it from the measured radiation temperature spectra. TRAcing Visualized (TRAVIS) [2] is a ray tracing code that has been fully integrated in Minerva. TRAVIS includes a radiation transport model that is used to predict the ECE spectrum allowing for a comparison to the measured value provided by a data source using the calibration factors determined as described above. The magnetic equilibrium of W7-X that is used for ECE modelling in both the Minerva framework and the TRAVIS code is calculated with the Variational Moments Equilibrium Code (VMEC) [3]. Forward models for the ECE diagnostic have been developed in Minerva, which also allows for straightforward combination with other previously developed diagnostic models like Thomson scattering or X-ray imaging crystal spectrometry models. The inference is done by assuming an electron temperature and density profile, calculating the predicted spectrum and comparing it with the observed spectrum, thus allowing for iterative improvements on the initial guesses. The standard ECE Minerva model uses Gaussian processes to describe the electron temperature and density profiles with five hyperparameters, although they are normally kept at the values of the initial guess to keep computational time reasonable. Due to its generality and modular nature, the Minerva forward model can be extended very easily to add further ECE observations and other diagnostics such as the Michelson interferometer.

References

[1] J. Svensson, A. Werner and JET EFDA contributors, IEEE International Symposium on Intelligent Signal Processing (2007)

[2] N. B. Marushchenko, Y. Turkin, H. Maassberg, Computer Physics Communications **185**.1 165-176 (2014)

[3] S. P. Hirshman and J. C. Whitson, Physics of Fluids **26** 3553 (1983)

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Mixed Scenarios with X3 heating in W7-X

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During the initial experimental campaigns at the W7-X Stellarator, the principal ECRH scenarios have been well tested. The frequency of the RF beams at 140 GHz corresponds to the 2nd cyclotron harmonics at the magnetic field 2.5 T. Both the extraordinary and ordinary wave-modes (X2 and O2, respectively) were applied. The RF beams were launched from the main ports near the maximum of B (bean-shaped plane) as well as from the remote steering launcher (RSL) near the minimum of B (triangular plane). Several magnetic configurations with different mirror-ratios and ι-profiles were used. However, due to technical limitations, magnetic configurations with very high mirrors ($B_{01}/B_{00} \simeq 15\%$ and 24%) have not yet been cleared for operation at the nominal magnetic field strength of $B_0 \simeq 2.5$ T. Such configurations may become accessible at reduced magnetic field, 1.75 T, however, to allow studying plasmas with high β. This magnetic field approximately corresponds to both the 3rd cyclotron harmonic at 140 GHz and the 2nd one at 105 GHz (the last frequency can also be generated by the gyrotrons). Since operation of the gyrotrons at 105 GHz is limited to pulses of several seconds, the X2 heating can be applied only for plasma breakdown and establishment of sufficiently high electron temperature. Then, similar to the O2 heating (tested already well experimentally), the X3 heating is expected to be quite efficient for long operation. It has to be noted also that the scenario with reduced magnetic field and X3 heating becomes to be attractive if the target plasmas with the required parameters can be created by ICRH and NBI. In the present work, we analyze the reliability of this kind of scenario numerically.

Apart from this, the magnetic configuration with $B_{01}/B_{00} = 15\%$ and the field reduced to$B_0 \simeq 2.3 - 2.35$ T can also be applied. The main advantage of this scenario is a possibility to allow ECRH with both X2 and X3 modes at the same frequency, 140 GHZ, but launched from different ports. Due to a very different geometry of the magnetic field in the different cross-sections, the physics related to the deposition of different modes can also differ significantly. While the X-mode launched near the maximum of B (2.35 T on axis) has the 2nd harmonics resonance at $B \simeq 2.5$ T (actually, this is off-axis heating, $\rho < 0.5$, located on the high-field-side), the X-mode launched with high obliqueness near the minimum of B has the resonance interaction at the 3rd cyclotron harmonics with a very broad deposition profile, $\rho < 0.8$. And the main factor here is that the power absorbed due to X2 cyclotron interaction is deposited only into passing electrons, while the X3 deposits the power only in trapped electrons.

Since the density range for this scenario is limited, $(1 - 5) \times 10^{19}$ m^{-3}, high electron temperature (of about 10 keV) can be established due to the X2 heating. For these conditions, selective heating of trapped electrons can, in principle, induce non-local convection. The standard neoclassical transport theory does not describe these effects, but the experiments can help to indicate this discrepancy from the theoretical predictions.

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S10: Theory and Modelling

Daniela Farina: Nonlinear collisionless Electron Cyclotron interaction in the pre-ionisation stage

Alexei Popov: Anomalous absorption and backscattering in ECRH experiments due to parametric low-threshold excitation of localized UH waves

Pavel Aleynikov: 3D Full-Wave modelling and EC mode conversion in Wendelstein 7-X

Atsushi Fukuyama: Kinetic full wave analysis of O-X-B mode conversion in tokamak plasmas

Nonlinear collisionless Electron Cyclotron interaction in the pre-ionisation stage

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Investigation of plasma startup assisted by Electron Cyclotron (EC) waves has recently received a renewed interest in view of ITER, where EC power is foreseen to be injected to initiate the plasma discharge both at full and half field of operation. The present ITER scenario requires that volt-second consumption of the main transformer be drastically reduced in the breakdown, and alternative and efficient ionisation mechanisms have to be used.

The physics of the overall startup process is quite complex and involves various mechanisms, like wave-particle interaction, particle collisions with both neutrals and ionised plasma, particle confinement and plasma build-up. A proper theoretical and modelling description would require sophisticated codes to describe the different stages of the process. The focus of the present analysis is on the very first phase of the process before collisions start to play a role, i.e., on the EC wave interaction with the seed electrons in the vacuum chamber, with the goal to investigate theoretically the electron dynamics under the action of a localised electromagnetic (e.m.) field, and determine under which conditions and parameters the electrons can gain enough energy to initiate the ionisation process.

In the very first phase of a plasma discharge with EC-assisted breakdown, the motion of an electron at room temperature in a static magnetic field under the action of a localised microwave beam is nonlinear (as pointed out long ago [1]), and transition to states of larger energy can occur via wave trapping [2, 3, 4, 5]. Within a Hamiltonian adiabatic formalism, a rigorous analysis can be performed that allows to derive the conditions at which the particles gain energy in single beam crossing and to characterise the energy variation quantitatively as a function of the wave frequency, harmonic number, polarisation and EC power and beam width. Estimates of interest for applications to tokamak start-up are derived for the first, second and third cyclotron harmonic. The investigation confirms that electrons can easily gain energies well above the ionisation energy in most conditions at the first two harmonics, while not at the third harmonic, as observed in experiments.

References

[1] E. V. Suvorov, M. D. Tokman, *Sov. J. Plasma Phys.* **14** 557 (1988)

[2] W. M. Nevins, T. D. Rognlien and B I Cohen *Phys. Rev. Lett.* **59** 60 (1987)

[3] I. A. Kotelnikov and G. V. Stupakov *Phys. Fluids B* **2** 881 (1990); I. A. Kotelnikov and G. V. Stupakov *J. Plasma Phys.* **45** 19 (1991)

[4] D. Farina and R. Pozzoli *Phys. Fluids B* 1991 **3** 1570; D. Farina, R. Pozzoli and M. Romé *Phys. Fluids B* **3** 3065 (1991)

[5] D. Farina, *EPJ Web Conf.*, **157** 03012 (2017)

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Anomalous absorption and backscattering in ECRH experiments due to parametric low-threshold excitation of localized UH waves

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Electron cyclotron resonance heating (ECRH) and current drive is widely used in toroidal plasmas and is considered for application in ITER for heating and neoclassical tearing mode control. The parametric decay instabilities (PDIs), which can accompany the ECRH experiments, are believed to be deeply suppressed by huge energy loss of daughter waves from the decay region, according to the predictions of theory developed in 80^{th} [1]. However, during the last decade many experiments have demonstrated excitation of the anomalous phenomena in the ECRH experiments at TEXTOR, TCV, TJ-II, ASDEX-UG, LHD and FTU. The clearest evidence of the nonlinear effect was obtained at TEXTOR [2, 3] where the strong backscattering signals down–shifted in frequency and amplitude modulated by the magnetic island were observed. A convincing demonstration of the anomalous ion heating during the ECRH pulse under conditions when the energy exchange between the ion and electron components is negligible was obtained at TCV [4].

In the present paper we describe a theoretical model taking into account, as distinct from the standard theory [1], the presence of a non-monotonous density profile, which always exists on the discharge axis or may be present due to the magnetic island or the density pump-out effect. We interpret the generation of backscattering signal and the anomalous ion heating, as a result of secondary nonlinear processes that accompany a primary low – threshold two–upper-hybrid (UH) – plasmon PDI of the pump X wave. The threshold of the primary PDI is shown [5] to be smaller than the one predicted in [1] due to the trapping of at least one UH wave in the presence of the non-monotonous density profile. The primary PDI is absolute due to the finite-size of the pump beam. Its growth enhancing the UH wave fluctuations from the thermal noise level is saturated in our theory due to both the secondary decays of the daughter UH wave that leads to excitation of the secondary UH and ion Bernstein (IB) waves [6] and the pump wave depletion. The threshold of this spontaneous parametric frequency down-conversion can be easily overcome for the secondary radially trapped UH waves. The coupling of different daughter UH waves is responsible in the theory for generation of the backscattering signal [7]. This mechanism appears capable of reproducing the fine details of the frequency spectrum of the anomalously reflected X wave and the

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absolute value of the observed backscattering signal in TEXTOR experiment. It also predicts substantial (up to 25%) anomalous absorption in the electron channel and explains the anomalous ion heating at TCV by the generation of the secondary IB waves which directly transfer the pump power to the ion component. The results of a model experiment demonstrating strong anomalous absorption of the X-mode pump in a plasma filament due to the two-plasmon decay [8] and thus confirming the theory are presented. The possibility of anomalous absorption of the O-mode pump in the ECRH experiment due to parametric excitation of the trapped UH wave [9] is discussed as well.

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References

[1] M. Porkolab, B.I. Cohen, Nucl. Fusion **28**, 239 (1988)

[2] E. Westerhof, S. Nielsen, J. W. Oosterbeek, *et al.*, Phys. Rev. Lett. **103**, 125001 (2009)

[3] S.K. Nielsen, M. Salewski, E. Westerhof, *et al.*, Plasma Phys. Control.Fusion **55**, 115003 (2013)

[4] A.N. Karpushov, *et al.*, Proc.of 33rd EPS Conference on Plasma Physics **30I**, P–1.152 (2006)

[5] A.Yu. Popov and E.Z. Gusakov, European Phys. Lett., **116**, 45002 (2016)

[6] E.Z. Gusakov and A.Yu. Popov, Plasma Phys. Control. Fusion **59**, 025005 (2017)

[7] E.Z. Gusakov and A.Yu. Popov, Physics of Plasmas 23, 082503 (2016)

[8] L.V. Simonchik, A.B. Altukhov, *et al.*, EPJ Web of Conferences **149**, 03013 (2017)

[9] E Z Gusakov, A.Yu. Popov, *et al.*, Plasma Phys. and Control. Fusion **59**, 075002 (2017)

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3D Full-Wave modelling and EC mode conversion in Wendelstein 7-X

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Electron Cyclotron Resonance Heating (ECRH) is the main plasma heating mechanism in Wendelstein 7-X (W7-X) Stellarator. It is provided by 10 gyrotrons at 140 GHz (corresponding to the second harmonic cyclotron resonance at 2.5 T) with the power of 1 MW each. The X- and the O-modes were successfully used in a wide range of operation scenarios: X-mode for low and moderate densities (up to the cutoff at $1.2 \cdot 10^{20} m^{-3}$), and O2-mode for higher densities (up to $\approx 2 \cdot 10^{20} m^{-3}$).

Possible operation at yet higher densities would involve double mode-conversion from O- to slow X- and to Bernstein-mode, i.e. an OXB-scenario. The physics of O-X conversion is outside of applicability of the routinely used geometrical optics approximation (WKB-theory) and should be considered within a full-wave approach [1, 2].

In this work, the wave physics of O-X conversion in overdense W7-X plasma is investigated. The results are also applicable to the inverse problem of electron Bernstein emission (EBE) diagnostics. The work discusses: (a) Possibilities for the realization of this mode conversion scenario within the capabilities of the existing ECRH system in W7-X; (b) Development of the “optimal” O- to X- conversion scenario within the constraints set by the 3D plasma equilibrium. A feasible heating scenario with $> 85\%$ efficiency is identified. (c) The effect of turbulence on the conversion efficiency is assessed.

For this study, a new 3D, cold plasma full-wave code has been developed. The code utilizes the Finite Difference Time Domain (FDTD) technique [3]. The computational domain is “minimized” around the WKB-trajectory of the reference ray, and is matched to the surrounding plasma by using the so-called “convolutional perfectly matched layers (CPML) boundary condition” [4]. The background magnetic field is recovered from the pre-computed 3D equilibrium data. The code takes advantage of massive parallel computations with Graphics Processing Units (GPUs), which allows for up to 100 times faster calculations than on a single-CPU. This feature allows for efficient parametric optimization studies over a broad range of possible experimental conditions.

References

[1] E. Gospodchikov T. Khusainov, A. Shalashov , Plasma Phys. Control. Fusion. **54** (2012)

[2] A. Popov, Plasma Phys. Control. Fusion. **53** (2011)

[3] U. Inan. R. Marshall, Numerical Electromagnetics: the FDTD method, Cambridge, (2011)

[4] J. Roden, S.D. Gedney, MICROWAVE AND OPTICAL TECH. LETT **27** (2000)

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Kinetic full wave analysis of O-X-B mode conversion in tokamak plasmas

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For electron cyclotron (EC) heating and current drive in overdense plasmas, quantitative description of mode-conversion to the electron Bernstein waves in realistic configurations has been desired. The O-X-B mode conversion process is a promising scheme for central absorption by low-field-side launching in tokamak configuration. The existence of an evanescent layer between the O-X cutoff surfaces for slightly off-optimum injection angle prevents from reliable description of wave behaviour after the tunneling by means of conventional ray tracing analyses. In order to describe the tunneling of the evanescent layer and the successive mode-conversions from backward X to forward X and from forward X to Bernstein wave, full wave analysis including kinetic effects is required. We have developed one-dimensional and two-dimensional full wave codes (TASK/WF series) using the finite element method (FEM) and implemented the kinetic dielectric tensor in an integral form. Since the dielectric tensor in an integral form does not require the use of wave number, it is applicable to the FEM analysis with efficient use of computational resources. The one-dimensional code was applied to the O-X-B mode conversion in tokamak configuration adn the EC resonance absorption in overdense plasma was confiremed. The mode-conversion efficiency is consistent with analytical estimates. Preliminary results of two-dimensional analyses on an equatorial plane and a poloidal cross section in tokamak plasmas indicated the wave structure after the mode conversions. More systematic analyses are under way. Computational performance of integro-differential equation solver using FEM will be also discussed.

Poster 1 (Tuesday)

(Tue 1) Avramides: Studies towards an upgraded 1.5 MW gyrotron for W7-X

(Tue 2) Brunner: O2 ECRH as a reliable high-performance scenario for W7-X

(Tue 3) Caughman: Electron Heating and Particle Trapping in the Proto-MPEX Linear Device

(Tue 4) Cengher: Protection of the DIII-D Vessel, Diagnostics and Windows from Microwaves Injected by the ECH/ECCD System

(Tue 5) Ell: Conceptual design and simulation of a gyrotron multistage depressed collector based on E×B drift

(Tue 6) Huang: Recent upgrade and results of ECRH system at HL-2A

(Tue 7) Illy: Recent Status and Future Prospects of Coaxial-Cavity Gyrotron Development at KIT

(Tue 8) Jin: Improved Simulation of Quasi-Optical Launchers with Smoothing Algorithm for High Power Gyrotrons

(Tue 9) Kobayashi: Development of ECH/CD system and preparation toward first plasma of JT-60SA

(Tue 10) Kumar: Comparative studies of various types of transmission lines in the frequency range 70GHz -1THz for ITER ECE diagnostic

(Tue 11) Lechte: Simulation of Polarising and Reflecting Gratings for High Power mm Waves

(Tue 12) Lohr: Performance, Plans, and Experiments for the ECH System on DIII-D

(Tue 13) Marsen: Stray radiation in Wendelstein 7-X - Experience from the first experimental campaigns

(Tue 14) Oosterbeek: Impact of non-absorbed ECH power on the Michelson Interferometer spectrum at W7-X

(Tue 15) Pagonakis: Overview on recent progress in magnetron injection gun theory and design for high power gyrotrons

(Tue 16) Rathod: Developments towards 1MW Gyrotron Test Facility at ITER-India

(Tue 17) Ruess: Theoretical Study on the Operation of the EU/KIT TE34,19-Mode Coaxial Cavity Gyrotron at 170/204/238 GHz

(Tue 18) Tang: Conceptual design of CFETR ECRH equatorial launcher and upper launcher

(Tue 19) Wang: Research activities and progress on the long pulse ECRH launcher for EAST

(Tue 20) Xia: Plans for the electron cyclotron heating system on J-TEXT

(Tue 21) Zanini: ECCD operations in the second experimental campaign at W7-X

(Tue 22) Zhang: Study on the Soft-start process of PSM high voltage power supply for ECRH

Studies towards an upgraded 1.5 MW gyrotron for W7-X

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The stellarator Wendelstein 7-X (W7-X) is equipped with a steady-state (1800 s) ECRH system consisting of ten 1-MW gyrotrons, which operate at 140 GHz. The available EC heating and current drive power in the plasma ranges from 7 to 9 MW [1]-[2]. Hence, W7-X is using the world's largest ECRH system today. The ECRH is used for plasma start-up, heating and current drive, and plasma vessel conditioning. The possibility of even higher ECRH power in the future is under consideration. Motivated by this, studies towards an upgraded 1.5-MW gyrotron design have been initiated at Karlsruhe Institute of Technology. Several possibilities have been investigated, using successful existing European gyrotron designs as a starting point [3]. It has been identified that the most promising development path, with respect to risk and cost, would be the upgrade of the existing $TE_{28,8}$-mode gyrotron at W7-X, in order to operate in the $TE_{28,10}$ mode. A detailed gyrotron cavity design has been obtained, which fulfils the specifications and requires the smallest changes with respect to the existing gyrotron layout. A first assessment of the necessary modifications of the rest of the gyrotron components has also been made. The possibility of MW-class operation at the additional frequency of 175 GHz for Collective Thomson Scattering diagnostics is currently under study. In support to the investigations above, the components of a $TE_{28,10}$ mode generator for low power tests of the quasi-optical mode converter system of the gyrotron have been designed and manufactured. The mode generator has been assembled and improvements on the experimental set-up are underway. Experimental results with the mode generator are expected soon.

References

[1] R. C. WOLF, *et al.*, Nucl. Fusion **57**, 102020 (2017)

[2] T. STANGE, *et al.*, EPJ Web of Conf. **157**, 02008 (2017)

[3] F. MENTGEN, Master Thesis, Karlsruhe Institute of Technology, IHM, (2016)

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O2 ECRH as a reliable high-performance scenario for W7-X

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ECRH is the primary heating method used at the Wendelstein 7-X (W7-X) stellarator. Ten gyrotrons with a total peak power of 7.5 MW can be launched at a semi-arbitrary launch angle and an arbitrary polarization. Normally second harmonic X-mode (X2) heating will be employed due to the high absorption efficiency even at low densities of $1 \times 10^{19}\,\mathrm{m}^{-2}$ and temperatures around 1 keV. However, during high density operation this heating scheme becomes hazardous due to the cut-off density of $1.2 \times 10^{20}\,\mathrm{m}^{-3}$ being approached. For this reason O2 heating is envisaged as the primary candidate for high performance operation at W7-X.

During the OP1.2a operation campaign, which finished Dec 2017, several high performance scenarios have been developed relying solely on O2-heating. A reliable transition to fully O2 heated plasmas above the X2 cut-off was demonstrated achieving record plasma densities of $1.4 \times 10^{20}\,\mathrm{m}^{-3}$ line-averaged electron density. An absorption efficiency of over 90 % could be achieved during these discharges by using tungsten coated reflector tiles designed to guide each gyrotron beam through the plasma axis on the second and third pass, thus maximizing absorption (see fig. 1).

In this paper we will present the results of the O2 heating optimization efforts conducted during the OP1.2a campaign. The results will be used to plan and expand the high performance operation during OP1.2b scheduled for the second half of 2018.

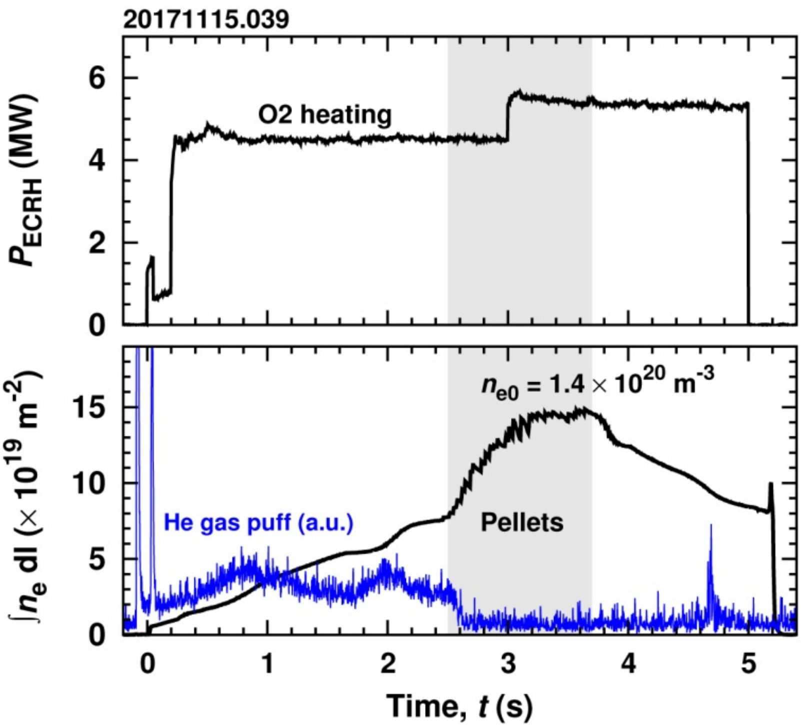

Figure 1: During the OP1.2a campaign of W7-X plasma densities in excess of $1.4 \times 10^{20}\,\mathrm{m}^{-3}$ line-averaged electron density, and the X2 cut-off, were reached. The plasma was fully sustained using O2 heating and pellets used to raise the density.

Electron Heating and Particle Trapping in the Proto-MPEX Linear Device

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The Prototype Material Plasma Exposure Experiment (Proto-MPEX) is a linear plasma device that is designed to deliver a high plasma heat flux to a material target. It consists of a helicon-based plasma source (~100 kW) with auxiliary ion and electron heating sections. Ion cyclotron heating at 7-9 MHz (~25 kW) is via the magnetic beach approach, and electron heating of over-dense plasmas is accomplished at 28 GHz (~20 kW) via electron Bernstein wave heating using the OXB mode conversion approach. Changes in the electron temperature from ~5 eV to ~20 eV have been observed using Thomson Scattering in high-density deuterium plasmas [1], but the variation of the magnetic field along the axis of the device results in several magnetic wells that seem to affect the transport of the heated electrons from the electron heating location to the target. Reduction of the magnetic field between the heating location and the target increases the core electron temperature near the target and the total heat flux delivered to the target, indicating that some of the heated electrons are trapped. The field reduction also increases the delivered heat flux in the under-dense plasma region at larger radii, which may be due to electron cyclotron heating and/or supra-thermal electrons in the edge. Experiments to understand these heating mechanisms and modelling of the trapping is currently being explored. Experimental details and heating results will be presented.

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References

[1] T.M. Biewer, *et al.*, Physics of Plasmas **25**, 024501 (2018)

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Protection of the DIII-D Vessel, Diagnostics and Windows from Microwaves Injected by the ECH/ECCD System

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The gyrotron complex on DIII-D has six gyrotrons connected through 31.75 mm evacuated, corrugated transmission lines to real-time steerable mirrors, which inject the rf power from the tokamak low field side. The transmission lines have been upgraded by installation of new rf power monitors at the last miter bends before the connection to the tokamak. These monitors can measure wave polarization, mode content, and rf power reflected from the plasma. Recent years have seen an increase in the large variety of experiments involving injection of 110 GHz EC power into the tokamak plasma, with operational regimes approaching or exceeding the density limits for absorption at the second harmonic resonance. Protective measures are in place to reduce the likelihood of refracted rf power potentially reaching sensitive areas of the vacuum vessel or diagnostics. A combination of density interlock and fault recovery systems ensure that rf generation and injection into the plasma are stopped for the duration of overdense plasma causing refraction of the rf beams. Generation and injection are resumed when absorption conditions are optimal. In addition to operational limits for the line averaged plasma density, visible light cameras which monitor the light in the launchers, single-channel light detectors, and reflected power sniffers complete the array of diagnostics used for EC protection. A new design depressed collector gyrotron in the 1.5 MW class, operating at 117.5 GHz, was installed at DIII-D in 2017 and is being conditioned to high power. The new frequency allows for higher operation density, while providing a higher efficiency for current drive, and better operation at higher magnetic field than the 110 GHz frequency generated by the other five gyrotrons.

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Conceptual design and simulation of a gyrotron multistage depressed collector based on E×B drift

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Single-stage depressed collectors with efficiency of about 60 % have been successfully used in gyrotrons, increasing the overall electrical efficiency to above 50 %. In order to further increase the tube overall efficiency it is necessary to consider a multistage depressed collector (MDC) system. Although MDCs have been successfully used in the past in TWTs and klystrons, the design of MDC for gyrotron is not trivial due to the presence of a high magnetic field at the collector region. Several theoretical design approaches based on the E×B drift have been recently published [1-5]. The E×B drift concept was proposed in Ref. 1 for the efficient sorting of the magnetic confined gyrotron electron beam on the electrodes. In that primary investigation, a theoretical design was also proposed for the demonstration of the E×B drift concept. A collector efficiency in the order of 91 % was demonstrated for a spent electron beam of a high power gyrotron. However, in that study an ideal situation with an infinite number of electrodes was considered due to limitations of the simulation tool used that time. In this work, a conceptual design of this type of MDC is numerically investigated with a full three dimensional simulation tool. MDCs with two, three and four stages were optimized for a high power gyrotron spent beam. A high efficiency is demonstrated for a variety of realistic spent beam energy distributions with a negligible reflected current. The results of this work will be presented.

References

[1] I. PAGONAKIS, *et al.*, IEEE Trans. Plasma Science, 36(2), 469-480 (2008)

[2] I. PAGONAKIS, *et al.*, Physics of Plasmas 23(4), 043114 (2016)

[3] C. WU, *et al.*, Physics of Plasmas 24, 043102 (2017)

[4] C. WU, *et al.*, Physics of Plasmas, submitted (2018)

[5] O. LOUKSHA, *et al.*, Tech. Phys. Lett. 41(9), 884–886 (2015)

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Recent upgrade and results of ECRH system on HL-2A

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As the main heating method, 5MW ECRH system has been developed on HL-2A during the last decade-year, which includes 3MW/68GHz/1s first-harmonic ECRH system, 1MW/105GHz/3s and 1MW/140GHz/3s second-harmonic ECRH system. Up to now, the 3MW/68GHz sub-system has been applied on HL-2A experiments successfully and the 1MW/140GHz and 1MW/105GHz sub-systems had been finished commissioning.

The power sources of HL-2A ECRH system were selected as six 68GHz/0.5MW/1s, one 105GHz/1.0MW/3s and one 140GHz/1.0MW/3s CPD gyrotrons. Two different types of TLs have been developed and fabricated, one is Φ80mm un-evacuated line for 68GHz sub-system, the other is Φ63.5mm evacuated line for 140GHz/105GHz sub-system. For the first type, the high power test results demonstrated that the 90% high transmission efficiency could be obtained run of 10m in length. For the second type, the performance has been tested on test-stand and the characteristic can totally satisfy the 1MW/3s requirement. Two upgraded fast steerable antennas were used to inject eight wave beams into plasma from low field side through two Φ350mm equatorial tokamak ports, which have the capability of two-dimensional beam scanning for narrow localized power deposition profile. The scan range in poloidal direction is around $-25^0 \sim 25^0$ and toroidal direction $-17^0 \sim 17^0$. The response time of full scan range in poloidal direction is about 250ms and the resolution is about 0.3^0 corresponding to 4mm in plasma section, which could meet the experimental requirement of suppressing the NTM totally in real time. Meanwhile, a couple of fast rotable polarizers have been manufactured, so that the polarization and ellipticity of the beams could be controlled to launch the wave with the desired mode, pure O- or X-mode, into the plasma along with the beam injection angle changed.

Advanced physical experimental research could be put into effect based on the upgraded ECRH system on HL-2A. Continues or modulation ECW has been injected into HL-2A in O1 mode or X2 mode to explore plasma heating or current driving experiments. Some perfect experimental results had been obtained on MHD suppression, plasma confinement improvement, transport, plasma disruption and plasma start-up. The phenomena of real time control of TM mode has been observed by ECRH system based on the technology of TM mode excited actively by SMBI, plasma temperature profile resolution by ECE, real time EFIT and reflective memory.

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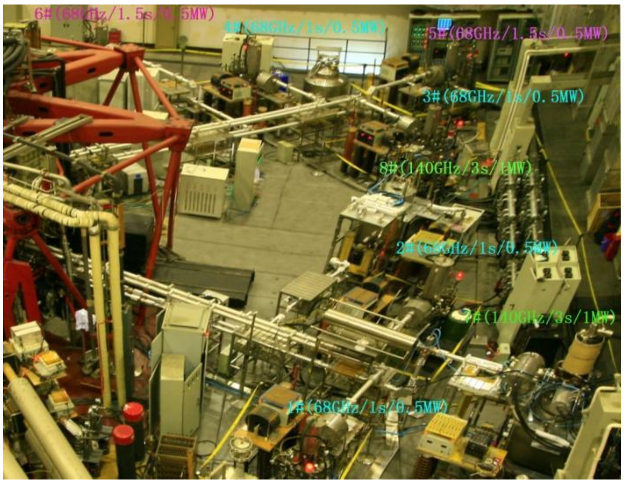

Figure 1 5MW ECRH system on HL-2A tokamak

References

[1] M. Huang et al., 37th EPS Conference on Plasma Physics, P5.166(2011)

[2] M. Huang et al., 17th Joint workshop ECE and ECRH, **32**, 04012(2012)

[3] J. Zhou et al., Nuclear Fusion and Plasma Physics, **27 (4)**, 277-279(2007)

[4] F.Zhang et al., Review of Scientific Instruments, Journal of Infrared, Millimeter, and Terahertz Waves, **37(6)**, 572-581(2016)

[5] H. Wang et al., Fusion Engineering and Desing, **101**, 61-66(2015)

[6] M. Huang et al., Plasma Science & Technology, **15(12)**, 1247-1253(2013)

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Recent Status and Future Prospects of Coaxial-Cavity Gyrotron Development at KIT

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Coaxial-cavity gyrotrons are microwave sources that can extend the possible power levels of hollow cavity gyrotrons significantly. This makes them attractive for future fusion experiments and power plants, since an increase of the power per unit will reduce the size, cost and complexity of the required ECH installations. The performance increase of coaxial-cavity gyrotrons is achieved by enhanced mode selectivity and reduced voltage depression effects due to the presence of the carefully designed longitudinally corrugated coaxial insert.

KIT already successfully demonstrated operation of a modular short-pulse 170 GHz coaxial-cavity gyrotron with an output power of 2.2 MW, operating in the $TE_{34,19}$ mode [1]. Nonetheless, until today, the coaxial-cavity gyrotron technology has not been verified at longer pulses above a few milliseconds. Therefore, a focus of KIT is the verification of this technology at pulse lengths up to one second which will prove the long-pulse capabilities for longer pulses also. At the moment, the current KIT prototype has been extended with cooling capabilities for all critical, highly loaded components of the tube [2]; a new triode electron gun equipped with non-emissive coating at the emitter edges [3] has been procured and a new inverse triode gun has been manufactured in-house [4]; both electron guns should increase the electron beam quality and therefore the overall performance and operation stability of the tube.

Intense theoretical design activities to support the manufacturing have been performed and are still on-going to assist during the experimental activities. This includes the simulation of the gyrotron interaction and quasi-optical output launcher (focusing also on a future dual frequency operation at 170 GHz / 204 GHz), simulation of advanced cooling concepts for the outer cavity wall of the resonator (including the manufacturing of mock-ups), fluid-dynamics simulations of the cooling structure of the coaxial insert and investigations of enhanced longitudinal sweeping concepts for the collector.

References

[1] T. Rzesnicki, *et al.*, IEEE Trans. on Plasma Science, Vol. 38, No. 6 (2010)

[2] S. Ruess, *et al.*, 47th European. Microwave Conf., 8 – 12 October 2017, Nuremberg, Germany

[3] I. Gr. Pagonakis, *et al.*, Physics of Plasmas **23**, 083103 (2016)

[4] S. Ruess, *et al.*, IEEE Trans. on Electron Devices, Vol. 63, No. 5 (2016)

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Improved Simulation of Quasi-Optical Launchers with Smoothing Algorithm for High Power Gyrotrons

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As the highest-power millimetre wave sources, gyrotrons are used for Electron Cyclotron Resonance Heating (ECRH) of fusion plasmas. That megawatt-level gyrotrons are usually operated in very high order cavity modes. Quasi-optical mode converters are employed to transform the short-wavelength and rotating asymmetric high-order cavity mode into a Gaussian-like distribution, which is directly usable for low-loss transmission in free space. The quasi-optical mode converter consists of a specific mode-converting waveguide/launcher and a mirror system. In 2006, by use of the Huygens' principle, a numerical method was developed for the synthesis of oversized mirror-line launchers for high power gyrotrons [1]. Later in 2009, a completely different numerical method was developed for the design of such mirror-line launchers at KIT [2]. Later, a novel numerical method was developed at KIT for the synthesis of hybrid-type launchers [3]. The profiles of the numerically optimized launchers are relatively complicated. In order to smoothen the wall surface to satisfy fabrication requirements and to improve the tolerance of the launcher to fabrication errors and frequency shifts, it is very important to develop a method for smoothing of the surface of the launcher wall in the numerical synthesis procedure. A numerical method for the smoothing of wall surfaces has been developed based on the spectrum reconstruction method [4]. As an example, the mirror-line launcher developed for the KIT 170 GHz 2 MW $TE_{34,19}$-mode coaxial-cavity gyrotron has been investigated with and without the wall smoothing in terms of the spectrum reconstruction method. In the case of the smoothened launcher wall, the minimum wall contour curvature radius increases from 1.5 mm (without smoothing) to 29 mm. The simulation results show that the Gaussian mode content of the RF beam at the launcher aperture only decreases from 96.26 % (without smoothing) to 96.0 %. The high power experimental results reveal that the Gaussian mode content of the RF beam is 96 % at the output window, and the stray radiation is decreased from 5.5% (without smoothing) to 3.5 %. From the experimental results we can see that although the Gaussian mode content of the RF beam is slightly decreased when the wall surface is smoothed based on the spectrum reconstruction method, the stray radiation can be obviously reduced.

Acknowledgements

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References

[1] A.V.Chirkov, *et al.*, Radiophysics & Quantum Electronics, Vol. 49, No. 5, pp. 344-353 (2006).
[2] J. Jin, *et al.*, IEEE Trans. Microw. Theory Techn., Vol. 57, No. 7, pp. 1661-1668 (2009).
[3] J. Jin, *et al.*, IEEE Trans. Microw. Theory Techn., Vol. 65, No. 3, pp. 699-706 (2017).
[4] J. Jin, et al., “Improvement of tolerance of quasi-optical launchers for high power gyrotrons,” to be published.

Development of ECH/CD system and preparation toward first plasma of JT-60SA

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An Electron Cyclotron Heating and Current Drive (ECH/CD) system will be used for many experimental purposes in JT-60SA (Super advanced) [1] such as localized electron heating and current drive, instability control, start-up assist and wall cleaning. The ECH/CD system is featured by the use of multi-frequency gyrotron, which was successfully developed in QST. The high-power, long-pulse gyrotron operation of 1 MW/100 s was successful at both 110 and 138 GHz, and these frequencies will be used as second harmonic electron cyclotron waves. An oscillation of 1 MW/1 s at 82 GHz was also successful and it will be used as a fundamental electron cyclotron wave, which is more effective for the start-up assist and wall cleaning. In preparation for the first plasma experiment in 2020, the development/preparation of the ECH/CD system components are on-going.

Based on the successful result on high-power (1 MW), long-pulse (100 s) transmission during the gyrotron development, the design of the waveguide components was finalized. Then the fabrication of the first set of the waveguide transmission line including torus window, gate valve, dc-break, miterbends, polarizer and vacuum pump out has been started. These components will be delivered by the end of March 2018 and will be tested at high-power in 2018. In addition, it was quantitatively confirmed that the maximum temperature rise of the waveguides near miterbends was 1.2 °C/MJ while the minimum temperature rise was 0.2 °C/MJ at the middle part of 12 m-long straight section of the 40m-long waveguide transmission line with 7 miterbends. Note that the waveguides are non-cooled. Considering the above results, a waveguide cooling jacket was designed and tested at high-power. The final design of the cooling system is on-going by taking into account the above results. In addition to the above progress in the transmission line, R&Ds and design/fabrication/test status of the two dimensional steering launcher, control and power supply will be reported.

References

[1] H. Shirai et al., Nucl. Fusion, 57 (2017) 102002.

[2] T. Kobayashi et al., Nucl. Fusion, **55** (2015) 063008.

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Comparative studies of various types of transmission lines in the frequency range 70GHz -1THz for ITER ECE diagnostic

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In ITER [1], the electron cyclotron emission (ECE) diagnostic will be used to determine the plasma electron temperature by measuring the intensity of electron cyclotron emission in the frequency range 70 GHz - 1 THz. The typical ECE system consists of front end optics including in-situ calibration sources, a set of transmission lines (TLs), and ECE instruments like radiometers and Michelson interferometers. However, achieving low attenuation in the long transmission line (~43m length) for a broad frequency is one of the challenging requirements for ITER ECE Diagnostic. Particularly challenging because of the low power (~ few nW) thermal radiation emitted from the in-situ calibration sources located in the port plug which needs to be measured by the ECE instruments that are located nearly ~ 43 m away in the diagnostic building. The challenging part is to transmit the signal over such a long distance with low attenuation in the frequency range 70 GHz - 1 THz. This plays a vital role in determining the accuracy of measurements performed. Various investigations are underway to find a suitable TL system meeting this crucial requirement. Three types of TLs are being considered, namely circular smooth walled, circular corrugated and circular dielectric coated waveguides are being studied to find the most suitable TL for this application. Therefore, various components of these TL systems, like 90^{o} miter bends, waveguide joints, pump out units and straight waveguide pieces have been characterized. The attenuation in the TLs has been measured using the cutback method in the frequency range 70 GHz - 1 THz using a black body source and Fourier-transform-based Michelson interferometer. It is known that water vapour attenuates the millimetre waves at its absorption bands. To remove absorption of the millimeter wave radiation due to water vapour, the TLs are evacuated for these measurement. It has been observed that there is a significant reduction in transmission attenuation in the evacuated TL and also continuum water vapour or atmosphere gas absorption of millimeter wave radiation above 550GHz [2]. The details of waveguide components, experimental set up and the results of the comparative studies of attenuation in three types of TLs will be presented.

References:

[1] www.iter.org

[2] Pandya et al., Review of Scientific Instruments 84, 103505 (2013)

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Simulation of Polarising and Reflecting Gratings for High Power mm Waves

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In ECRH systems, polariser gratings are used to provide the optimal elliptical polarisation of the beam. The shape of the grooves strongly affects the ohmic losses. Furthermore, the high plasma densities achievable in experiments like Wendelstein 7-X and ASDEX Upgrade necessitate the development of advanced heating scenarios at higher EC harmonics. Because of the lower absorption in O2 and X3 mode, the beam shines through the plasma and should be reflected back for a second pass. Reflecting gratings that conform to the inner vessel wall have been designed for this purpose (see B. Plaum's talk in this conference).

The fullwave finite difference code IPF-FD3D was used to calculate the efficiency of these 2 kinds of gratings in 3D. For the polarisers, the ohmic efficiency is the main interest, while for the reflecting gratings, the most important aspect is the reflection of the beam into the correct diffraction order with the correct polarisation. Measurements were made in both cases.

3D simulations are necessary because of the arbitrary angle of the grooves with respect to the plane of incidence, especially with the non-planar reflecting gratings. An optimised groove shape for the polarisers has been shown to reduce the ohmic losses compared to a standard sine shape.

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Performance, Plans and Experiments for the ECH System on DIII-D

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The ECH complex on the DIII-D tokamak presently comprises six gyrotrons, five of which operate at 110 GHz and a sixth, which operates at the new frequency of 117.5 GHz. Positions and power supplies for 8 gyrotrons are available. The system is planned for expansion to a total of 10 gyrotrons, the frequency mix depending on the performance of the 117.5 GHz tube. This gyrotron, operating in the new $TE_{20,9}$ mode, has demonstrated 1.7 MW generated power at short pulses and 550 kW for 10 sec pulses, with performance limited by the capabilities of the test set at the manufacturer, Communications and Power Industries. After a development program, this gyrotron is presently installed and operating both for experiments and continuing conditioning. A new FPGA based gyrotron control system has increased the reliability by accommodating greatly improved fault handling and more flexible modulation envelopes with microsecond time resolution. Overall, the system reliability exceeds 90%, where the actual individual gyrotron performance is being compared with the requests. There have been two recent gyrotron failures on the system, one from an internal water leak and the second from a mechanical failure in the gun region. Parts from these two tubes are being combined, along with upgrades, particularly to the collector, into a new tube, which should be available at the end of 2018. The system is in daily use in support of a variety of experiments. Among these have been attempts to modify the kinetic profiles at extreme rho values near 0.9; periodic suppression of a 2/1 locked mode using modulated operation; prediction and demonstration of access to high beta regimes using stairstepped ECH injection; and high beta operation in L-mode with reverse triangularity. The system is routinely controlled by the DIII-D plasma control system, which is used both for control of the gyrotron outputs and the steering of the rf beams.

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DISCLAIMER

Stray radiation in Wendelstein 7-X - Experience from the first experimental campaigns

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W7-X is equipped with a steady state capable ECRH system providing up to 7.5MW heating power from 10 gyrotrons. Non absorbed microwave power distributes in the torus as more or less isotropic stray radiation after multiple reflections. Depending on their absorption coefficient in vessel components can suffer from heating up due to stray radiation. The microwave beams are injected within a torus sector of 72°, typically with perpendicular incidence to the magnetic field lines. The resultant distribution of stray radiation within the torus was simulated with a model of coupled resonators. Assuming 1MW of total non absorbed power the expected levels of stray radiation in W7-X are $P_{stray} \approx 90\mathrm{kWm}^{-2}$ close to the launching antennas and up to one order of magnitude less on the opposite side of the torus. Stray radiation diagnostics were installed in order to measure the real distribution during pulsed operation. Diode based stray radiation monitors, so called sniffer probes, are installed in each of the five modules of W7-X. Apart from measuring the stray radiation distribution around the torus they act as input for a fast plasma interlock system switching off the ECRH if the absorption is lost. This proved to work reliable during the first experimental campaigns. The sub-divertor region where cryo-pumps will be installed for steady state operation and the bellows connecting the cryostat vessel to the plasma vessel in the ports are especially sensitive to stray radiation. Small microwave bolometers consisting of a thermocouple in a copper cylinder coated with microwave absorbing ceramics were installed here. In the ECRH launcher ports P_{stray} was found to be higher than allowed for steady state operation which could lead to an overheating of the bellows. The levels here depend on the launching angles of the ECRH beams.

The worst case in terms of stray radiation in the plasma vessel is O-mode heating at densities above the X-mode cut off. Here, P_{stray} is highest because there is no absorption of the X-mode content in the stray radiation by the plasma. The levels found here were below those expected from simulations.

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Impact of non-absorbed ECH power on the Michelson Interferometer spectrum at W7-X

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Electron Cyclotron Heating and Electron Cyclotron Current Drive are key components for heating and control in magnetically confined fusion plasmas. The high power microwaves are not always completely absorbed leading to stray radiation [1]. At W7-X, the total injected microwave power can be up to 10 MW @140 GHz while the Electron Cyclotron Emission picked-up by an observer at the edge of the plasma is only of the order of 1 mW per mode of emission (taking central T_e = 10 keV and a 500 GHz bandwidth). The stray radiation problem is well known and to protect microwave receivers that are tuned to discrete frequencies, notch filters and pin-switches are mostly adequate [2]. In the situation of a Michelson Interferometer [3], the principle measurement is the entire ECE spectrum. Thus, any stray radiation is bound to enter the spectrum. A notch filter can no longer be based on a single mode cavity as the instrument is multi-mode. Moreover, the gyrotrons will produce power at other frequencies under certain conditions [4] such as satellite modes that can be excited in the cavity or parasitic modes as a result of undesired beam-wave interactions outside the cavity. While the power in such spurious modes is low compared to the gyrotron fundamental mode it may be large compared to the ECE spectrum. Given that any sizeable ECH installation will use multiple gyrotrons, e.g. 10 at W7-X and 40 at ITER, and with possibly multiple spurious modes per gyrotron, there is the potential that some attributes in the ECE spectrum originate from stray ECH power. This paper explores expected stray radiation power in the Michelson Interferometer spectrum at W7-X. The assessment is supported with W7-X data from broad band detector diodes connected to antennae and waveguides from different sections of the torus. Data is taken at different ECH launcher angels and at different receiver polarisations. During a number of these experiments a direct ratio of ECH to ECE power could be inferred. Given that it may not be possible to avoid all stray power in the instrument, laboratory experiments are prepared to assess compression of the detector by controlled injection of 140 GHz power during a hot-cold calibration.

References

[1] S. Marsen *et al.*, Stray radiation in W7-X - Experience from the first experimental campaigns, this workshop.

[2] D. Moseev *et al.*, A Collective Thomson Scattering Diagnostic for W7-X, RSI Manuscript, in prep.

[3] N. Chaudhary *et al.*, Investigation of optically grey electron cyclotron harmonics in Wendelstein 7-X, this workshop.

[4] F. Wilde *et al.*, Measurements of Satellite Mode Activity and Automated Mode Recovery in 140 GHz Wendelstein 7-X Gyrotrons, this workshop.

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Overview on recent progress in magnetron injection gun theory and design for high power gyrotrons

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The magnetron injection gun (MIG) is one of the most critical subcomponents in gyrotrons. The electron beam, which has the primary role on the gyrotron operation, is generated and configured at this part of the gyrotron. The electron beam properties determine the excitation mode in the cavity, the power of the generated microwaves and the gyrotron efficiency.

The operation of MIGs could be influenced by several factors such as trapped electrons, manufacturing tolerances, roughness of the emitter ring, emitter temperature inhomogeneity, electron beam neutralization effect, etc. The influence of many of these factors on the electron beam quality has been systematically investigated during the last years. Several novelties have been proposed in order to limit the influence of these factors on the gyrotron operation. In particular, a new type of the emitter ring has been proposed to minimize the influence of the manufacturing tolerances and edge effects on the beam quality [1], new design criteria have been proposed for the suppression of electron trapping mechanisms [2], alternative MIG design approaches have been proposed [3], etc. An overview of all these works will be presented.

References

[1] I. PAGONAKIS, *et al.*, Physics of Plasmas 23, 83103 (2016)

[2] I. PAGONAKIS, *et al.*, Physics of Plasmas 23, 23105 (2016)

[3] S. RUESS, *et al.*, IEEE Trans. Electron Devices, 63, 2104 (2016)

Acknowledgments

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Developments towards 1MW Gyrotron Test Facility at ITER-India

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ITER-India, the Indian domestic agency for the ITER project, has the responsibility to supply a set of two high power Gyrotron sources (1 MW, 170 GHz, 3600 s) along with the auxiliary systems for Electron Cyclotron Heating & Current Drive applications [1] [2]. For such high power Gyrotron systems, one of the challenging areas is the system integration and establishment of reliable integrated system performance. ITER-India plans to establish the integrated Gyrotron system performance that essentially meets the ITER requirements in a Gyrotron Test Facility (called as IIGTF) which is specifically being developed at ITER-India. This paper discusses about the recent updates towards the IIGTF development which includes, development of cost effective & modular Body Power Supply (BPS), Industrial grade prototype interlock & protection modules, a Gyrotron field simulator and cooling water distribution system.

As an alternate solution to PSM, a cost effective and modular solution using high voltage solid-state switches (push-pull type MOSFET) is adopted for prototype development to meet the high frequency modulation requirement for the Gyrotron Body Power Supply (35kV/5 kHz). Initial test results at lower parameters on equivalent RC load were promising. And further testing at enhanced parameters is ongoing. Towards development of ITER Local Control Unit (LCU), prototype design and development activities have been carried out [3]. Under this, a prototype industrial grade Centralized Interlock Module (CIM) has been designed, developed and tested successfully against EMC compliance. The main features of CIM includes fail-safe logic, fault sequence & spurious fault detection logic using FPGA with a total response time ~ 1.5μs. Further a LabVIEW™ based Gyrotron field simulator is being developed to test the LCU's hardware & its software applications. In order to remove the significant thermal heat loads (~ 2.5 MW) across various components of Gyrotron system, the active cooling water distribution system (2700 LPM, 6 bar) has been designed and developed. Currently the installation and testing of the same is ongoing.

References

[1] C. DARBOS et al., Journal of infrared, millimeter and terahertz waves, 37, issue-1, 4-20 (2016)
[2] S.L. RAO et al., Fusion Science & Technology, 65, 129-144 (2014)
[3] V. RATHOD et al., Fusion Eng. Design, 112, 897-905 (2016)

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Theoretical Study on the Operation of the EU/KIT $TE_{34,19}$-Mode Coaxial-Cavity Gyrotron at 170/204/238 GHz

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Fusion gyrotrons for DEMO and future Fusion Power Plants (FPP) will require multi-megawatt continuous-wave (CW) operation at multiple possible frequencies starting from 170 GHz up to significantly above 200 GHz. The 170 GHz 2 MW $TE_{34,19}$-mode coaxial-cavity modular short-pulse (SP) pre-prototype gyrotron, currently under development at KIT, was recently modified in order to verify the multi-megawatt coaxial-cavity technology at longer-pulses, up to 100 ms [1]. As a further step, in order to confirm the CW capability of the coaxial-cavity technology, the pulse lengths are planned to be increased up to 1 s after installation of a CVD-diamond output window and new long-pulse collector. In parallel to this, theoretical investigations on a possibility to operate the 170 GHz $TE_{34,19}$-mode coaxial-cavity prototype at multiple frequencies up to 238 GHz have started, with a goal to find a configuration at which the tube could operate in the KIT FULGOR gyrotron test facility [2] using the new 10.5 T SC magnet. As a background for that approach three frequencies already proposed for DEMO and FPP, namely 170/204/238 GHz, have been considered as the operating ones, to be compatible with the resonant thickness of the existing CVD-diamond window. First theoretical investigations showed that the gyrotron cavity is able to operate at 170, 204, and 238 GHz with $TE_{34,19}$, $TE_{40,23}$, and $TE_{48,26}$-mode, respectively, without any additional modification of the cavity and Magnetron Injection Gun. The expected generated output power would be in range of 2.3, 1.8, and 1.0 MW, at mentioned frequencies, respectively. Here it shall be noted, that the gyrotron design was optimized for single frequency operation at 170 GHz. As it has already been proven by simulation, a slightly modified cavity design allows RF output powers above 2 MW at dual-frequency 170/204 GHz operation. The verification of the compatibility of other internal key gyrotron components, such as beam tunnel and quasi-optical converter, has been studied as well. Achieved results will be presented and discussed.

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the European Commission. Parts of the simulations presented in this work have been carried out on the Marconi-Fusion super-computer facility.

References

[1] S. Ruess, et al., “KIT coaxial gyrotron development: From ITER towards DEMO”, *47th European Microwave Conference*, 8 - 12 October 2017, Nuremberg, Germany.
[2] M. Schmid et al., “The 10 MW EPSM modulator and other key components for the KIT gyrotron test facility FULGOR”, Fus. Eng. Des. **123**, 485, 2017.

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Conceptual design of CFETR ECRH equatorial launcher and upper launcher

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Abstract

The Electron Cyclotron Resonance Heating (ECRH) system of China Fusion Engineering Test Reactor (CFETR) is designed to inject 20 MW RF power into the plasma for heating and current drive (H&CD) applications. The ECRH system consists of 20 gyrotrons, the associated power supplies, the transmission lines and one launcher. In order to compare the launcher performance from equatorial and upper ports, two types of launcher are designed in this paper. In equatorial launcher (EL), twenty in-vessel transmission lines are divided into four groups. Every five gaussian beams from in-vessel transmission lines face one fixed focusing mirror and one steering mirror. All gaussian beams are injected into the plasma with optimal toroidal and poloidal angles calculated by C3PO/LUKE code. In upper launcher (UL), twenty-one transmission lines are supposed and divides into three groups. Every seven gaussian beams are injected into one fixed focusing mirrors and all twenty-one beams reflected to one common steering mirror finally. The optical transmission characteristics and the convergence information of gaussian beams are checked and optimized by ZEMAX. The EL or UL is installed on the equatorial or upper port with a port-plug modular structure.

Figure1: The structure of equatorial launcher and the transferring route of gaussian beams

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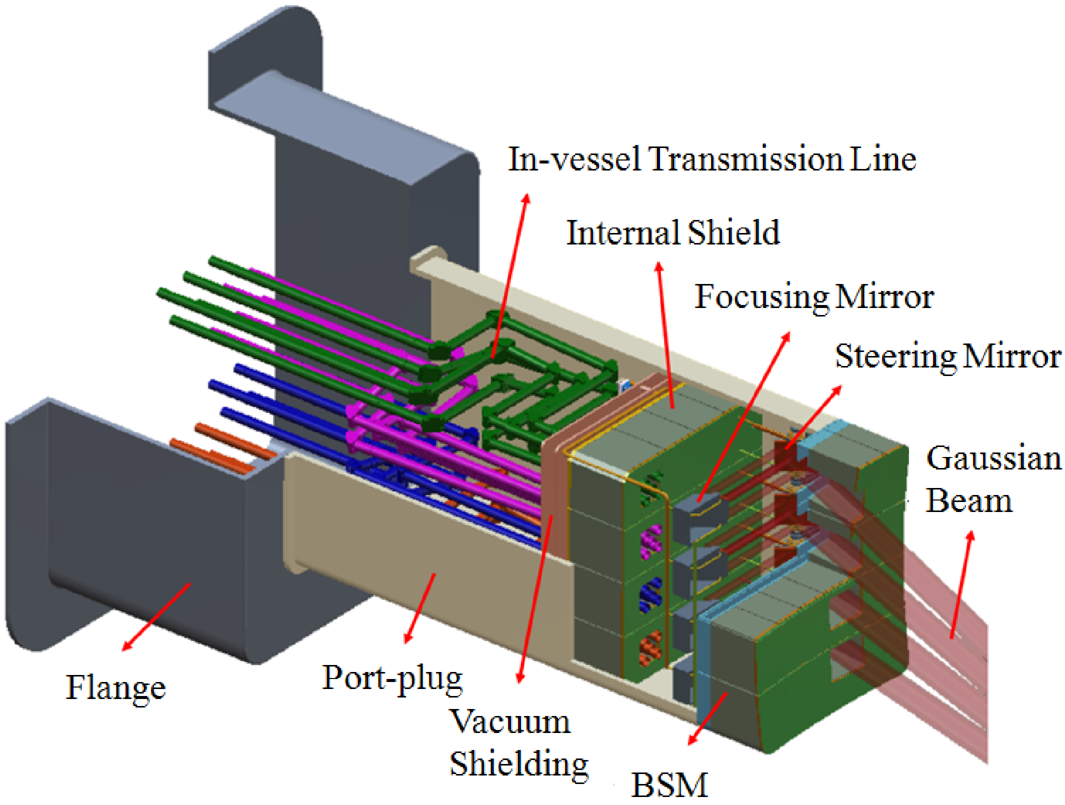
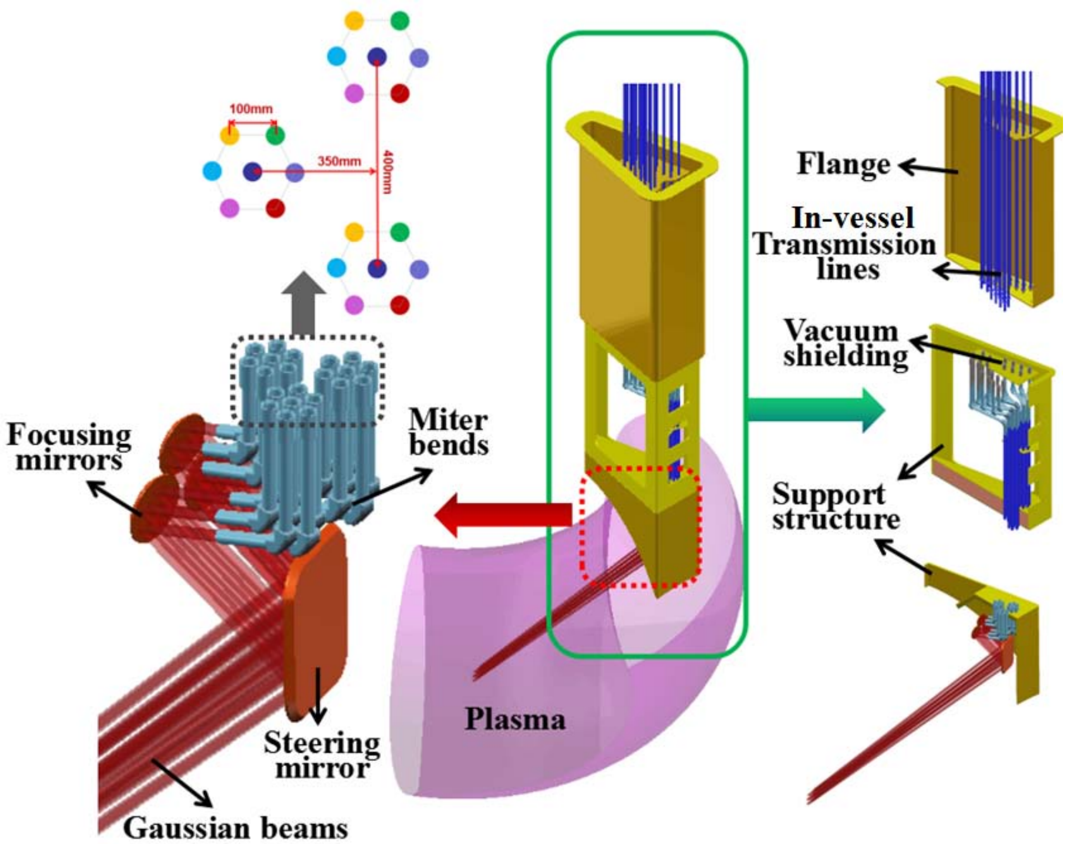


Figure2: The structure of upper launcher



References

[1] Jiangang Li, et al., EPJ Web Conf. **149**, 01011 (2017)

[2] Yun Tao Song, et al., IEEE Trans. Plasma Sci. **42**, 503-509 (2014)

[3] Baonian Wan, et al., IEEE Trans. Plasma Sci. **42**, 495-502 (2014)

Corresponding author: Yunying Tang *yytang@ipp.ac.cn*

[4] Wang X J, et al., Fusion Eng. Des. **96**, 181-186 (2015)

[5] Xu H D, et al., Plasma Sci. Technol. **18**, 442-448 (2016)

[6] Yunying Tang, et al., Fusion Eng. Des. **94**, 48-53 (2015)

[7] T. Omori, et al., Fusion Eng. Des. **86**, 951-954 (2011)

[8] K. Takahashi, et al., AIP Conference Proceedings **1580**, 546-549 (2014)

[9] K. Kajiwara, et al., Fusion Eng. Des. **89**, 6-10 (2014)

[10] D. Strauss, et al., Fusion Eng. Des. **89**, 1669-1673 (2014)

[11] F Gandini, et al., Fusion Sci. Technol. **59**, 709-717 (2011)

[12] P. Spaeh, et al., EU-CN ECRH meeting on ECRH, Culham (2015)

[13] D. J. Wu, et al., Journal of Fusion Energy **33**, 634-639 (2014)

[14] Wei Wei, et al., Chin. Phys. B **25**, 015201 (2016)

[15] Peter Spaeh, et al., Fusion Eng. Des. **89**, 960-964 (2014)

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Research activities and progress on the long pulse ECRH launcher for EAST

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A long pulse Electron Cyclotron Resonance Heating (ECRH) system is developed on EAST tokamak for plasma heating and current profile tailoring. The ECRH system is designed to operate at 140GHz and to inject 4MW CW power. With respect to the physical objectives of the newly built ECRH system, a quasi-optical launcher is designed to inject 4MW continuous wave into plasma through an equatorial port. Gaussian beams delivered from evacuated corrugation waveguides will be focused and reflected by high thermal conductive metal mirrors, and then steered by using push-rod steering mechanism with entire scanning range of ±25° toroidally and over 30° poloidally in plasma cross section. The mirrors are carefully designed with mega watts power handling capability and optimum optical characteristics. The performance of the steering mechanism has been tested before installation, an open-loop control system for ECRH launcher has been implemented for required mirror movement and proper polarization between plasma discharges.

This paper will present the overall design and progress of the launcher, along with the performance in EAST campaigns. Considerations and possible upgrade of the design features relevant to long pulse operation are discussed.

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Plans for the electron cyclotron heating system on J-TEXT

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A 105 GHz/500 kW/1s electron cyclotron heating system is being developed on J-TEXT. With this system, experiments related to plasma heating, start up, MHD control, etc. can be carried out. The system consists of a wave source, a transmission line, a launcher and other auxiliary units. Based on corrugated waveguides, the wave from the gyrotron can be efficiently transmitted with HE_{11} mode to the steerable quasi-optical launcher for injection. The transmission efficiency is about 85%, and the injection angle of the wave can be adjusted by the flat mirror of the launcher. Commissioning of this electron cyclotron heating system is scheduled to be done at the beginning of 2019.

References

[1] R. Prater, Phys. Plasma **11**, 2349-2376 (2004).

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ECCD operations in the second experimental campaign at W7-X

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In the Wendelstein 7-X stellarator, up to 7MW of power are delivered to the plasma by an electron cyclotron resonance heating system consisting of ten 140 GHz gyrotrons [1].
Due to the flexible front steering mirror of each beam line, the power deposition can be varied over the whole plasma radius and is optionally combinable with additional current drive. This flexibility, together with small toroidal currents in the stellarator, makes W7-X a perfect testbed for electron cyclotron current drive (ECCD) experiments, which have been successfully accomplished during the first two experimental campaigns OP1.1 and OP1.2a.
Long discharges (lasting up to 30s) have been performed in OP1.2a, thus allowing the study of the current drive time evolution and the possibility to compensate the bootstrap current.
ECCD efficiency has been studied using different power deposition profiles combined with a variation of the injection angles in relation to the magnetic field.
During ECCD experiments, sawtooth-like oscillations have been observed. Depending on the driven current density, ECCD can significantly modify the rotational transform (iota) profile, which can locally reach low order rationals, thus triggering plasma instabilities.
Different current density profiles have been tested, in order to try to understand the main trigger parameter for the instabilities. In particular, effects caused by current density gradient have been investigated producing both co- and counter-current drive at different radial positions: the total current drive is negligible, but a strong current gradient arises by driving currents in opposite directions.
In this work an overview of ECCD operations in OP1.2a is given and first results, comparing different diagnostics, are presented. An initial 1-D model, coupled with the ray tracer TRAVIS, is developed, in order to have an estimation of current diffusion times and the radial position where a low order rational crosses the disturbed iota profile.

References

[1] T Stange, *et al.*, EPJ Web of Conferences **157**, 02008 (2017)

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Study on the Soft-start process of PSM high voltage power supply for ECRH

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Abstract: A -60kVDC/80A high voltage power supply based on pulse step modulation（PSM）has been developed for ECRH on EAST, the soft-start process is the first procedure of HVPS system operation. For charging without overshoot of the capacitor and safety of the power devices, the soft-start process is necessary to be researched. The response process is analyzed detailedly by proposing DC equivalent circuit model, and process analysis and performance comparison is given under the conditions of different soft-start resistance parameters, then the theoretical analysis is proved by Simplorer simulations. Finally the scope of soft-start resistance is calculated for the HVPS of 140GHz ECRH system. The final experimental results show that it is in agreement with the theoretical analysis and has s good performance.

Keywords: EAST, ECRH, pulse step modulation (PSM), soft-start

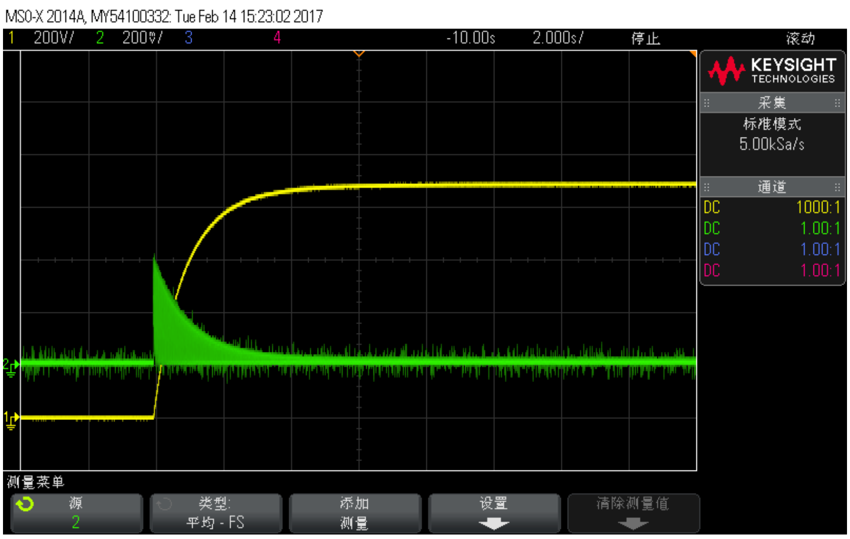

Figure1: The experimental result of charging process with soft-start resistance

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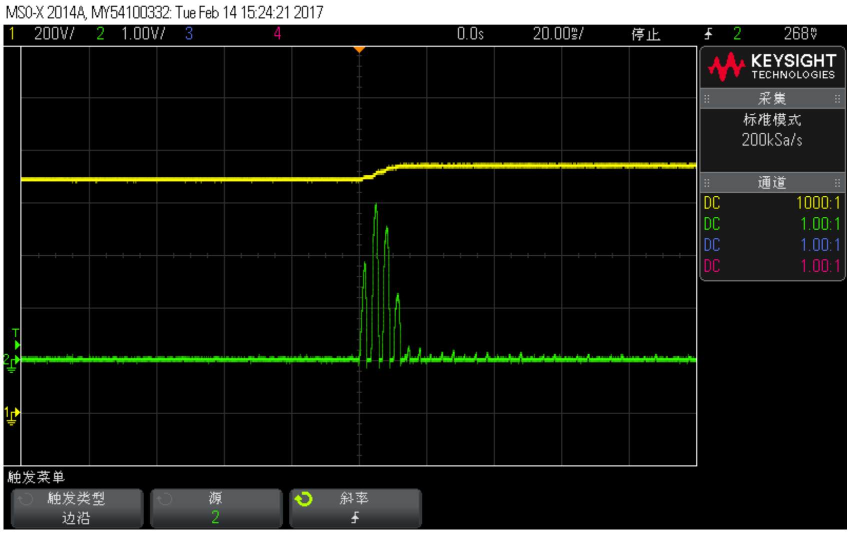

Figure2: The experimental result of charging process of removing soft-start resistance

References

[1]X. Hao, et al., Design and application of a new control system for tokamak ECRH power supply [J]. Radiation Effects & Defects in Solids, (3-4):1-10. (2016)

[2]N. Chiesa, et al., Transformer Model for Inrush Current Calculations: Simulations, Measurements and Sensitivity Analysis [J]. IEEE Transactions on Power Delivery, 25(4):2599-2608. (2010)

[3]J. Zhang, et al., The Design of PSM-Based ECRH Power Supply Control System [J]. Journal of Power & Energy Engineering, 04(4):91-102. (2016)

[4]L. Xia, et al., Analysis of the Soft-Start Circuit of the High Voltage Power Supply Based on PSM Technology [J]. IEEE Transactions on Plasma Science, 42(4):1026-1031. (2014)

[5]S. Ma, et al., Analysis and Design of the Module for PSM High-Voltage Power Supply [J]. Journal of Fusion Energy, 34(2):261-266. (2015)

[6]M. Jamali, et al., Calculation and Analysis of Transformer Inrush Current Based on Parameters of Transformer and Operating Conditions [J]. Chemosphere, 109(3):1392-1215. (2011)

[7]S. Ma, et al., High-voltage power supply for ECRH system on J-TEXT Tokamak[C]// Fusion Engineering. IEEE, 1-5. (2013)

[8]X. Hao. The Transient Analysis of PSM High Voltage DC Power Supply and the Research of Its Control Strategy [D]. University of Chinese Academy of Sciences. (2012)

[9]L.Xia. The Study on Several Key Techniques of High Voltage Power Supply for Auxiliary Heating System in Tokamaks [D]. Huazhong University of Science and Technology (2015)

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Poster 2 (Thursday)

(Thur 1) Abramovic: Collective Thomson Scattering in Non-Axisymmetric Plasmas with Absorption

(Thur 2) Allen: Design of the Synthetic Aperture Microwave Imager Upgrade for measurement of the edge current density on MAST-U

(Thur 3) Austin: Emissivity measurements of SiC and Carbon with the DIII-D Michelson interferometer

(Thur 4) Bae: Study of off-axis current drive using EC top-launch in KSTAR

(Thur 5) Chaudhary: Investigation of optically grey electron cyclotron harmonics in Wendelstein 7-X

(Thur 6) Chen: Top Launch for Higher Off-axis Electron Cyclotron Current Drive

(Thur 7) Farník: Runaway electron diagnostics for the COMPASS tokamak using EC emission

(Thur 8) Goto: Research of the Electron Cyclotron Emission with Vortex Property from Multi Electrons

(Thur 9) Hansen: Observation and Modelling of the Onset of Parametric Decay Instabilities during Gyrotron Operation at ASDEX Upgrade

(Thur 10) Hirsch: ECE Diagnostic and Measurements during initial Operation of Wendelstein 7-X

(Thur 11) Kubo: Study of sub-Tera-Hz gyrotron scattering for a direct detection of EBW in QUEST

(Thur 12) Liu: Intense intermittent radiation at the plasma frequency on EAST

(Thur 13) Micheletti: EC absorption efficiency in ITER at one-third nominal magnetic field strength

(Thur 14) Minashin: Effect of multipass absorption of external electron cyclotron radiation at the initial stage of ITER discharges

(Thur 15) Minashin: Modelling of electron cyclotron resonance heating and current drive in the T-15-MD tokamak

(Thur 16) Nagasaki: Development of a Correlation ECE Radiometer for Electron Temperature Fluctuation Measurements in Heliotron J

(Thur 17) Poli: Fast evaluation of the ECCD efficiency for reactor studies

(Thur 18) Ram: Current drive by high intensity, pulsed, electron cyclotron wave packets

(Thur 19) Sabot: Development of an Electron Cyclotron Emission Imaging diagnostic on the WEST tokamak

(Thur 20) Senstius: Particle-in-cell simulations of parametric decay instabilities near the upper hybrid layer

(Thur 21) Vanovac: Characterization of MHD modes with ECE(-I) and the influence of large density fluctuations

(Thur 22) Weir: Development of a Poloidal Correlation ECE Diagnostic for Electron Temperature Fluctuation Measurements on W7-X

(Thur 23) Yanagihara: Extension of a ray tracing for polarized diffracting wave beams description in inhomogeneous magnetized plasmas

Collective Thomson Scattering in Non-Axisymmetric Plasmas with Absorption

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The collective Thomson scattering (CTS) diagnostic has been partially commissioned in the last operational campaign on Wendelstein 7-X. Spectra have been measured from which the bulk ion temperatures were successfully inferred [1] using the forward model eCTS [2,3] developed in the Bayesian framework Minerva [4]. In preparation for the next campaign we are investigating the possibility of measuring the radial electric field by the means of CTS and the effects of spatial dispersion on the measured spectra.

In practice the radial electric field measurement by CTS is indirect. The measured quantity is the drift velocity component perpendicular to the magnetic field which can be used to calculate the radial electric field from the force balance equation. To this end a favorable choice of scattering geometry, and the development of a forward model which is sensitive to the perpendicular drift velocity, are crucial. Here we present the novel derivation of the CTS model suitable for this application. The model is derived for an arbitrarily drifting Maxwellian for a non-axisymmetric plasma. We first present a scattering calculation for a Maxwellian drifting parallel to the magnetic field which has rotational symmetry. We generalize this in order to make the model applicable to stellarator plasmas by allowing a perpendicular drift which breaks this rotation symmetry in the laboratory frame. In this case, we show the calculation for a parallel drifting Maxwellian distribution described in a reference frame moving away from the plasma in a direction perpendicular to the magnetic field. Calculating the CTS spectra for this model requires an additional step (with respect to the rotation symmetric case) namely, the transformation of the incident and scattered waves into the drifting frame and back into the laboratory frame. Example synthetic spectra will be shown.

The source of probing radiation for the CTS system on Wendelstein 7-X is a gyrotron operating at the electron cyclotron resonant heating frequency of 140 GHz. This constrains the system to measurement locations away from the central part of the plasma where the probing radiation would be efficiently absorbed. However, even when the measurement location is shifted towards the plasma edge, we might need to consider the absorption of probing radiation on thermal Doppler-shifted electrons. The effects of absorption on the synthetic spectra will be discussed.

References

[1] M. Stejner, *et al.*, First collective Thomson scattering results from Wendelstein 7-X, contributed talk EC20, (2018)

[2] I. Abramovic, *et al.*, Forward Modelling of Collective Thomson Scattering for Wendelstein 7-X Plasmas, submitted to CPC (2017)

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[3] I. Abramovic, *et al.*, Collective Thomson scattering data analysis for Wendelstein 7 – X, JINST, (2017)
[4] J. Svensson, *et al.*, Modelling of JET Diagnostics Using Bayesian Graphical Models, Contributions to Plasma Physics 51 (2-3) (2011)
[5] H. Bindslev, On the Theory of Thomson Scattering and Reflectometry in Relativistic Magnetized Plasmas, Riso National Laboratory, (1992)

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Design of the Synthetic Aperture Microwave Imager Upgrade for measurement of the edge current density on MAST-U

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The Synthetic Aperture Microwave Imager (SAMI) has demonstrated the feasibility of 2D Doppler backscattering for measurement of the edge magnetic pitch angle on MAST and NSTX-U [1, 2]. The aim of SAMI-Upgrade (SAMI-U) is to build on the methodology behind edge pitch angle results from SAMI to produce higher quality pitch angle data in multiple spatial locations, enabling calculation of the edge current density.
This movement from proof of principle to production quality necessitates several alterations to the design. There will be a fourfold increase in the number of antennas, as minimising the sidelobe level [3] is key to ensuring maximum resolution in the reconstructed Doppler backscattered power map. SAMI-U will actively probe the plasma with at least two simultaneous frequencies. These correspond to two different backscattering locations in the edge plasma which allows the edge current density to be calculated from the measured magnetic field vector. Dual-polarised sinuous antennas will be used in the array as they are planar and broadband. Polarisation separation is necessary for differentiation between the O- and X-mode cut off surfaces, as their locations can be separated by up to a few centimetres. A representation of the RF circuitry for a single antenna polarisation is shown in figure 1, with repeating sections omitted. Due to spatial constraints many of the components will be placed on a PCB behind each antenna. FPGAs will be used to stream the high data rates of over 16 GB s^{-1} into memory, after the down-conversion stage, throughout a plasma shot [4]. This way SAMI-U can accommodate planned increases in pulse length on MAST-U and is only limited by the amount of RAM available.

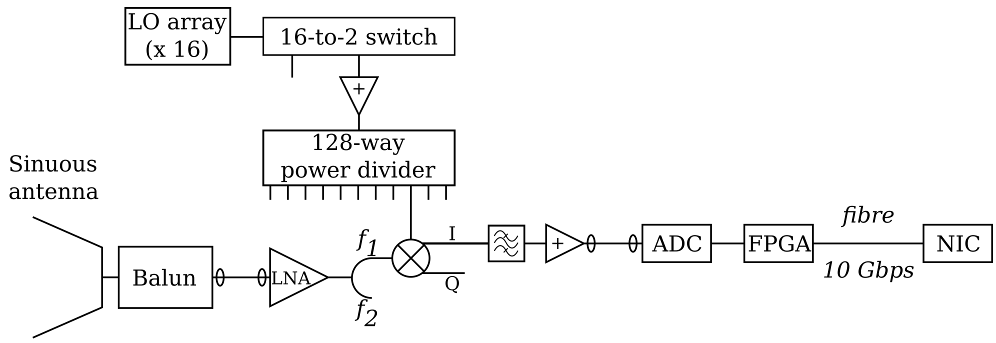

Figure 1: A block circuit diagram of the circuitry for one antenna in the SAMI-U array.

References

[1] R. G. L. Vann *et al.*, 20th Joint Workshop on ECE and ECRH (2018)

[2] Shevchenko, V. F. *et al.*, J. Inst. **7** (2012) P10016

[3] Freethy, S. J. *et al.*, IEEE Transactions on Antennas and Propagation **60** (2012) 5442

[4] Huang, B. K. *et al.* Fusion Engineering and Design **87** (2012) pp. 2106-2111

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Emissivity measurements of SiC and Carbon with the DIII-D Michelson interferometer*

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The emissivity of refractory materials at millimeter wave frequencies is important for calibration sources used for electron cyclotron emission (ECE) measurements from tokamaks as well as for modeling the effect of wall reflections on ECE for non-blackbody conditions. The DIII-D Michelson interferometer has been employed to measure the emissivity of a SiC blackbody source intended to be used as a calibration source for the ITER ECE system. A technique relying on the comparison of the temperature from the Michelson system to a calibrated IR camera finds an emissivity very close to 1 for the moth-eye SiC surface. In addition, the intensity of mm-wave emission from the DIII-D tokamak with carbon walls during a high-temperature bake (T = 350 ˚C) has been analyzed to determine an effective emissivity of the hot vessel. The motivation is to explore the use of the hot vessel as a calibration source for the ECE diagnostics in ITER if, for example, the planned hot source in the front end were to fail. Preliminary analysis indicates an effective emissivity of 0.8 that is relatively flat across the frequency range 70-1000 GHz. The limitations of this method and how the emissivity might change for the tungsten and beryllium walls of ITER are discussed.

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Study of off-axis current drive using EC top-launch in KSTAR

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The off-axis current drive using electron cyclotron (EC) wave is typically very low due to the low density and temperature and electron trapping effect when it is launched from outboard midplane. However, the heating and current drive by EC wave is being regarded as a essential element as an off-axis current drive source together with lower hybrid current drive (LHCD) for advanced tokamak operation research in KSTAR in future. Therefore, the reliable and high efficient ECCD using top launch has been studied. The ray tracing (GENRAY) and Fokker-Planck (CQL3D) simulation studies show that a broad ECCD profile peaked off axis is obtained with a high dimensional current drive efficiency for the second harmonic X-wave of 140 GHz which is the main EC frequency of currently operating 105/140 GHz dual-frequency gyrotron in KSTAR.

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Investigation of optically grey electron cyclotron harmonics in Wendelstein 7-X

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In W7-X for a magnetic field of 2.5T, electron cyclotron emission from second harmonic X-mode (140-160GHz) is scanned using a heterodyne radiometer consisting of 32 channels. Since for many plasma conditions this X2 mode emission is optically thick, it can be taken as a blackbody emission representing an electron temperature.

For confinement reasons the W7-X stellarator is intended to work at high densities requiring O2 ECRH. Because of the absence of strong toroidal plasma currents, the current dependent Greenwald density limit, usually observed in tokamaks, does not exist. In the case of overdense plasmas, which already have been demonstrated in the previous experimental campaign [1], the X2-mode emission goes into cutoff and the higher harmonics of the ECE spectrum provide the only access to the ECE emission and hence the physics of core electrons.

The objective of this work is to extract these higher harmonics by performing a broadband scan (70-500GHz) of ECE spectrum using a Michelson Interferometer and compare it to the already existing radiation transport calculations (TRAVIS). The technicalities of Michelson Interferometer will be discussed.

Stray radiation (140 GHz) from non absorbed ECRH is in the middle of the X2 emission spectrum. Hence it will be difficult to scan the second harmonic of ECE emission from Michelson Interferometer. Therefore a stray radiation notch filter is required. The design for such a notch filter consisting of multiple dielectric layers has been tested and will be presented.

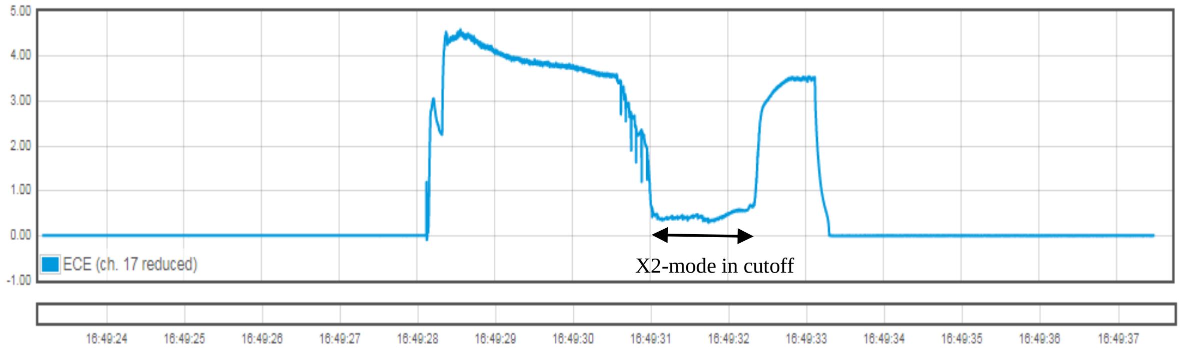

Figure1: Ch17 of Radiometer showing X2 mode of ECE in cut-off for a plasma discharge of 5 sec (start at 16:49:28-end at 16:49:33)

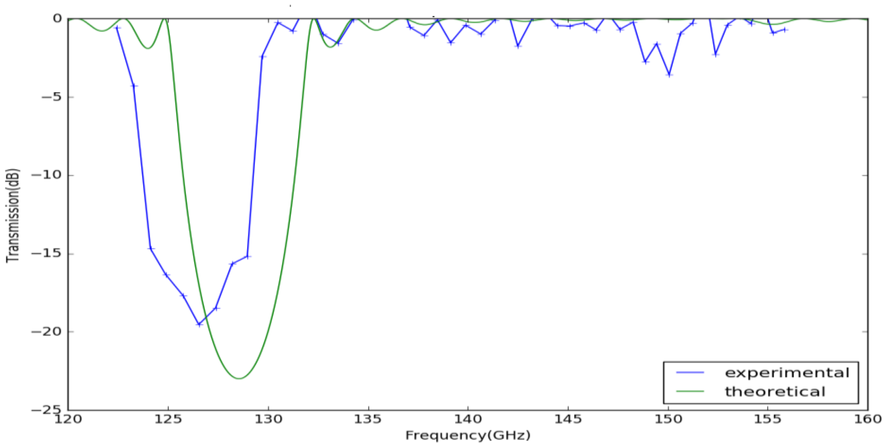

Figure2: Experimental and theoretical characteristics of the notch filter

References

[1] K.J.Brunner, *et al.*, O2 ECRH as a reliable high-performance scenario for W7-X, this workshop

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Top Launch for Higher Off-axis Electron Cyclotron Current Drive

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Efficient off-axis current drive is crucial for economic, steady-state tokamak fusion power plants. "Top Launch" electron cyclotron current drive (ECCD) is one of the few promising methods for driving strong off-axis current to achieve the desired broad current profile. By launching the electron cyclotron (EC) waves downwards (or upwards) nearly parallel to the resonance plane with a large toroidal steering, high current drive efficiency can be obtained at large radii owing to the large Doppler shift, wave-particle interactions on HFS of the plasma, and the long absorption path.

Previous modeling work for FNSF predicts Top Launch ECCD can provide significantly higher (~50%) ECCD efficiency with broader profile peaked off-axis than standard LFS launch for the same injected power [1]. In this work, a systematic study of Top Launch ECCD for CFETR (Bt~5T, R~5.7m baseline scenario), using the applied EC frequency and launch location as free parameters, finds that a 35-40% improvement in off-axis ECCD can be obtained over the conventional outboard off-midplane launch base case, with a dimensionless current drive efficiency (CD_eff) of $\zeta \sim 0.375$ at $\rho \sim 0.5$. In addition, the physics potential of Top Launch ECCD in various DIII-D scenarios (i.e., high performance, high q_{min} steady-state scenario) is investigated along with the sensitivity to launch location, magnetic field, and plasma and EC beam parameters such as equilibrium, density profile, beam aiming and divergence, etc. Improvement in ECCD efficiency of up to a factor-of-2 seem possible (Fig. 1). These studies are mainly conducted using the TORAY ray tracing code, but comparisons with the quasi-linear Fokker-Plank code CQL3D have confirmed the TORAY calculations. A prototype fix-injection Top launch ECCD system is being designed and planned to be installed on D3D to characterize and evaluate effects of this injection scheme.

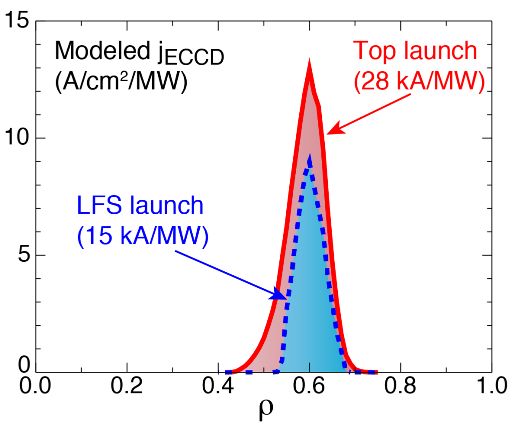

Figure 1: Driven current density profile for Top launch and LFS launch for a DIII-D discharge modeled using CQL3D

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References

[1] R. Prater, et al., "Improvement of current drive efficiency in projected FNSF discharges", 54th APS-DPP, Providence, Rhode Island, 2012.

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Runaway electron diagnostics for the COMPASS tokamak using EC emission

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COMPASS is a compact-sized tokamak operated at IPP Prague. An electron cyclotron emission (ECE) diagnostic of suprathermal electrons in the runaway region of the velocity phase space was utilised for runaway electron (RE) experiments purposes. Electron cyclotron emission measured vertically along the line of a constant magnetic field can yield information about the electron velocity distribution function and its evolution during a discharge [1].

Our vertical ECE (V-ECE) system consists of a 16-channel heterodyne radiometer and an E-band horn antenna with a 76.5-88 GHz frequency range front-end. The SPECE ray-tracing code [2] was employed for designing of the device and for analysing experimental data. SPECE simulations show a possibility of detecting 3rd harmonic ECE emmited by low energy (50-140 keV) runaway electrons. However, the optical depth in the low electron density RE experiments ($n_e < 3 \cdot 10^{19}$ m^{-3}) is rather low, which complicates the measured data interpretation. We realized measurements with both extraordinary (X-) and ordinary (O-) mode linear polarizations. The amplitudes of the X- and O-mode signals are similar, which can be explained by depolarised reflected radiation.

V-ECE measurements in low-density flattop discharges and in discharges with massive gas injections (MGI) of high-Z elements show correlations with other RE diagnostics, such as hard X-rays (HXR), photoneutron detectors and high-speed RIS cameras for visible light. Our results seem to be in an agreement with principles of the primary runaway generation mechanisms. From comparison with the HXR diagnostic we can obtain RE confinement time in the flattop phase of the discharge. Data interpretation in terms of runaway physics will be realised. The low optical depth indicates a necessity of taking reflections from walls into account.

References

[1] K. Kato, I. H. Hutchinson, Phys. Rev. Lett. **56**(4) 340-343 (1986)

[2] D. Farina, *et al.*, AIP Conf. Proceedings **988** 128-131 (2010)

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Research of the Electron Cyclotron Emission with Vortex Property from Multi Electrons

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The wave with Orbital Angular Momentum(OAM) is known as the Laguerre-Gauss (LG) beam, especially the LG beams with frequency band of the visible light is called an optical vortex. Optical vortex created so far utilized passive optical components such as helical phase plate, holography and q-plate from normal Gaussian beam having plane or spherical surface. It was shown by Kato[1] in 2017 that the vortex property exists universally in nature. This is an amazing result that the radiation field created by charged particles moving a spiral orbit has a vortex property. There are many charged particles which has spiral orbit in the natural. For example, the charged particles rotating in the Earth's magnetic field and the solar magnetic field are popular in nature. In addition, it is possible to artificially create the charged particles which has spiral orbit easily. For example, it has been experimentally observed that the radiation from the helical undulator has vortex property, which is first result in the world to experimentally show that the charged particles which has spiral orbit have vortex property. In addition, it is theoretically shown that the inverse Compton scattering using a high intensity circularly polarized laser also has vortex property[2]. Any methods can be seen as having a pure spiral motion of electron by Lorentz transformation. This radiation process can generate vortex radiation of any wavelength band by controlling the rotation frequency of electron. Actually, the vortex radiation in pure cyclotron motion has never been observed in spite of existing in nature universally because the vortex property is cancelled due to the random phase in the electrons cyclotron motion. In this research, we are developing a method to generate the vortex radiation directly from multi electrons in cyclotron motion with controlled gyro-phase by right-hand circular polarized (RHCP) wave. It is also possible to increase the power of the radiation by matching the rotation phases of the electrons.

References

[1] M. Katoh, *et al.*, Phys. Rev. Lett. **118** 094801 (2017)

[2] Y. Taira, *et al.*, Sci. Rep. **7**, 11D831 (2017)

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Observation and Modelling of the Onset of Parametric Decay Instabilities during Gyrotron Operation at ASDEX Upgrade

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When high power gyrotron beams are injected into magnetically confined fusion plasmas, the wave amplitude may in some cases become so large that the linear approximation breaks down and a parametric decay instability (PDI), which couples the incoming electromagnetic wave to two (electrostatic) plasma waves, is excited. The plasma waves excited by PDIs are shifted in frequency relative to the gyrotron radiation, often by a sufficient amount to fall outside the notch filters employed by millimeter-wave diagnostics such as ECE or collective Thomson scattering (CTS), hampering or potentially even damaging such diagnostics; if properly understood, PDIs may, however, provide diagnostic tools themselves.

This contribution concerns PDIs occurring for X-mode radiation near the upper hybrid resonance (UHR) at the ASDEX Upgrade tokamak, and is motivated by observations of strong anomalous (PDI generated) scattering made by means of the CTS diagnostic. In the experiments, gyrotron radiation for CTS is injected in O-mode from the low-field side of the torus. Since the plasma is optically thin to the radiation, a non-negligible fraction of the gyrotron power may be reflected off the high-field side vessel wall, re-enter the plasma in X-mode and reach the UHR, where PDIs may occur due to field enhancement effects [1]. To characterise the PDIs, we measure anomalous scattering frequency power spectra, using the high resolution, fast receiver CTS system installed at ASDEX Upgrade, and determine their dependence on the injected gyrotron power by means of fast analog modulation of said power. The gyrotron power threshold, which must be exceeded to excite PDIs, can be modelled using previously published theoretical results [1]; the power dependence of the anomalous scattering signal expected from such modelling is found to agree well with the experimental observations. Apart from characterising anomalous scattering during CTS experiments, the present findings may also have relevance for O-X-B heating experiments, planned for W7-X, and O1 ECRH, planned for ITER.

References

[1] S. K. Hansen, *et al.*, Plasma Phys. Control. Fusion **59** 105006 (2017)

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ECE Diagnostic and Measurements during initial Operation of Wendelstein 7-X

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During the first operational phases of the optimized stellarator Wendelstein 7-X an integrated high-performance plasma scenario is being developed as a basis for steady-state operation heated by the flexible ECRH system with total power > 7 MW provided by the cw-gyrotrons.

The Electron Cyclotron Emission Diagnostic (ECE) was operated throughout the experiments acting as a major tool to monitor plasma heating and to study electron heat confinement as well. In standard operation the diagnostic measures in X2 mode polarization (X2) with a 32 channel radiometer in the frequency band around 140 GHz supplemented with a 16 channel zoom device with 4 GHz span for higher frequency resolution at a suitable radial range. The overall system is absolutely calibrated by means of a hot-cold source placed outside the torus in front of a Gaussian telescope optics with identical geometry and transmission line as it is installed for the measurements in the plasma vessel.

Besides blackbody emission the ECE radiation temperature spectra T_{rad} (f) show features that display EC emission from hot electrons under conditions where the plasma is optically grey. T_e profiles are derived using ray tracing of the radiation transport along the line of sight with the TRAVIS code, equilibrium calculations from VMEC and the Bayesian framework Minerva. The latter allows for a rigorous error analysis and the integration with the information obtained from other diagnostics as well. The T_e-profiles measured during the first campaigns of W7-X are highly reproducible with peaked shape for central heating and broaden if heating is more off-axis; maximum core temperatures reach 10 keV. Dynamic phenomena have been studied as well such as heatwaves induced by ECRH power modulation or resulting from spontaneous temperature perturbations, MHD mode activities and T_e fluctuations, or individual events such as pellet injection and current induced crash events. The system is being supplemented with a broadband Michelson interferometer capable to measure in both X- and O-mode to explore the diagnostic capability of higher harmonics in overdense plasmas.

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Study of sub-Tera-Hz gyrotron scattering for a direct detection of EBW in QUEST

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QUEST is a spherical tokamak device which has been working on the topic of steady-state operation. One of the main issues is the non-inductive current drive, including the steady state current drive. Among several non-inductive current drive methods, electron Bernstein wave (EBW) heating/current drive is the most attractive method, because EBW can propagate over the cut-off density and give a chance to drive current steadily at over the cut-off density. Since the EBW can be excited through mode conversion process, it is important to clarify and optimize the injection condition by checking the excited EBW near the core region. Expected wavenumber in the perpendicular to the magnetic field ranges 10^4-10^5 m^{-1}. The direct and detailed measurement of the density fluctuation associated with the EBW gives clear evidence of the excited EBW inside the core, since it is an electro-static wave. Such measurement can be performed by measuring the sub-Tera-Hz wave scattering.

Recently, the collective Thomson scattering (CTS) experiments using high power gyrotrons are performed successfully to obtain the density fluctuation spectrum associated with the ion thermal fluctuation[1]. In order to apply the CTS in high density region, 300-400 GHz gyrotrons at the power level of more than 100 kW have been developed[2]. Developed method utilizing sub-Tera-Hz gyrotron is directly applicable to the detection of EBW in QUEST.

The detection of the EBW in QUEST by the scattering measurements requires a wide range and flexible scattering configuration under limited port access and boundary condition due to the presence of hot first wall covering the surface of the plasma. Here, a Littrow mount grating plates to attach to the wall is proposed to realize flexible measurement configuration. The heterodyne amplitude and phase detection technique to verify the EBW propagation will also be proposed along with the EBW propagation analysis.

References

[1] M. Nishiura, *et al.*, Nuclear Fusion **54**, 023006 (2014).

[2] T. Saito *et al.*, Physics of Plasmas **19**, 063106 (2012).

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Intense intermittent radiation at the plasma frequency on EAST

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Intense intermittent radiation has been observed regularly in EAST by using a Michelson interferometer and a Q-band radiometer system. The radiation bursts are related to a fast process with characterization time of a few microseconds. The radiation is very intense with an equivalent radiation temperature of the order of 10^5 keV. An electron density window exists for the occurrence of the bursts, and the upper electron density threshold is dependent of the toroidal magnetic field. The frequency of the emission f is at the plasma frequency, and the frequency bandwidth Δf is very narrow (~1.5 MHz FWHM, $\Delta f/f$~$3\text{x}10^{-5}$). Fine structure of the spectrum with multi-peaks have been observed, and the frequency interval is around 3 MHz.

The phenomenology observed on EAST is not the ones correlated with ELMs [1,2] and sawteeth. However, what observed on EAST is very similar to that on Alcator C [3]. A Maser mechanism [3] and a triple-wave resonance model [4] have been proposed independently to interpret this phenomenon qualitatively. Both models rely on a beam-driven excitation mechanism, while the latter uses the wave-particle or wave-wave resonance and chooses a different geometry. Numerical simulation results of cavity modes indicate that the frequencies of these modes are close to the central plasma frequency, and the departure from the central plasma frequency becomes larger for higher order modes.

[1] Ch. Fuchs and M. E. Austin, Physics of Plasmas **8** (2001) 1594

[2] S. J. Freethy *et al.*, Phys. Rev. Lett. **114** (2015) 125004

[3] R. F. Gandy *et al.*, Phys. Rev. Lett. **54** (1985) 800

[4] R. O. Dendy *et al.*, Nucl. Fusion. **25** (1985) 721

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EC absorption efficiency in ITER at one-third nominal magnetic field strength

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During the initial phases of ITER operations, First Plasma and the first phase of the Pre-Fusion Operation (PFPO-1), the Electron Cyclotron Radio Frequency (ECRF) system will be the main source of heating and current drive [1]. Evaluations of the L-H power threshold [2] have shown that H-mode is unlikely to be achieved in PFPO-1 scenarios at half-field (B_0=2.65T). For this reason, the use of one-third field strength (B_0=1.8T, I_p=5MA) in an early phase might be desirable to lower the power threshold and demonstrate access to H-mode.

The ITER ECRF gyrotrons, designed for the nominal field B_0=5.3T, will operate at 170 GHz [1]. This means that at B_0=1.8T the heating system would use 3rd harmonic resonance, whose absorption efficiency is lower than for 2nd harmonic. In fact, 3rd harmonic EC-assisted breakdown has not been achieved up to now. Using EC gyrotrons at a lower frequency, namely 104 GHz, could allow 2nd harmonic EC-assisted breakdown and heating.

The present work aims at presenting a preliminary evaluation of the performances of an EC system using the 104 and 170 GHz frequencies in a 1.8T magnetic field scenario, obtained by adequately rescaling a reference H-mode half-field scenario (He plasma, B_0=2.65T, I_p=7.5MA) [3]. The absorption efficiency and access to the inner plasma regions of O and X-mode polarized waves injected from the equatorial launcher are calculated via a parametric scan of the main plasma parameters, such to cover the range of possible values that are expected to occur during the discharge process. The purpose of this study is to provide an estimation of the parameter space (T_e, n_e) region where the use of both frequencies allows a good absorption efficiency. A complete assessment of the performances would need a more in-depth analysis, accounting for self-consistency between plasma profiles evolution and EC power absorption.

References

[1] M. Henderson et al, Phys. Plasmas 22, 021808 (2015)

[2] Y. R. Martin et al, Journal of Physics: Conference Series 123 (2008) 012033

[3] V. Parail et al, Nucl. Fusion 53, 113002 (2013)

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Effect of multipass absorption of external electron cyclotron radiation at the initial stage of ITER discharges

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Due to technical issues, the ohmic breakdown and plasma start-up in the ITER tokamak reactor is only possible over a narrow range of plasma pressure and magnetic field configuration parameters. For a reliable plasma start-up in ITER, electron cyclotron (EC) resonance heating is planned [1-4].

In this paper, we simulate the evolution of the spatial distributions of the main plasma parameters at the initial stage of the discharge in ITER, taking into account the multipass absorption of the injected EC radiation. In the full-scale simulation of the non-inductive current ramp-up phase of the discharge, the transport code DINA [5] uses an updated version of the numerical code ECH_Multipass for calculating the multipass absorption of the EC radiation [6]. Calculation of the absorption of the EC power is performed in the semi-analytical manner of the CYNEQ code [7, 8], taking into account the following processes: (a) multiple reflection of the radiation of the injected ordinary EC wave from the walls of the vacuum chamber; (b) conversion of the ordinary EC wave into the extraordinary EC wave due to reflection from the wall; (c) full absorption (i.e. on the first pass) of the extraordinary EC wave. This model is verified using ray-tracing calculations with the GENRAY code [9], adapted for reflections of injected EC wave from the walls of the vacuum chamber.

The simulation of the initial stage of the discharge using the DINA code allowed us to find the threshold for the power of EC heating required to overcome the radiation barrier in ITER. In the case of beryllium concentration at 2% of the electron density, the required level of injected EC power at the initial stage of the discharge should be not less than 3 MW.

References

[1] ITER Physics Expert Group on Energetic Particles, Heating and Current Drive, ITER Physics Basis Editors, Nucl. Fusion **39**, 2495 (1999)
[2] T. Omori, et al., Fusion Engineering and Design **86**, 951-954 (2011)
[3] J. Stober, G. L. Jackson, E. Ascasibar, Y. S. Bae, et al., Nucl. Fusion **51**, 083031 (2011)
[4] G. Granucci, S. Garavaglia, D. Ricci, G. Artaserse, et al., Nucl. Fusion **55**, 093025 (2015)
[5] R. R. Khayrutdinov , V. E. Lukash, Journal of Computational Physics **109**, 193-201 (1993)
[6] P. V. Minashin, A. B. Kukushkin, R. R. Khayrutdinov, V. E. Lukash, EPJ Web of Conferences **87**, 03005 (2015)
[7] A. B. Kukushkin, P. V. Minashin , A. R. Polevoi, Plasma Phys. Rep. **38**, 211-220 (2012)
[8] A. B. Kukushkin, JETP Letters **56**, 487 (1992)
[9] A. P. Smirnov, R. W. Harvey, K. Kupfer, Bull. Am. Phys. Soc. **39**, 1626 (1994)

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Modelling of electron cyclotron resonance heating and current drive in the T-15-MD tokamak

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The T-15-MD tokamak (labeled MD for "modified divertor") is planned as a normal magnetic-coil tokamak with a flexible ITER-like configuration of the poloidal magnetic field. The main goal of the tokamak T-15-MD is the achievement of long pulse, non-inductive current drive regimes for a high-aspect-ratio divertor plasma configurations [1], [2].

Recent predictive modelling [3] of the operating steady-state scenarios of the T-15-MD tokamak (major torus radius 1.48 m, minor torus radius 0.67 m, aspect ratio 2.2-3.0, elongation 1.7-1.9, on-axis toroidal magnetic field 2.0 T) with a semi-empirical model of ECRH/ECCD show the possibility of two basic scenarios: (1) the inductive scenario with the ~4 s plasma discharge (and ~1 s duration of current plateau) and (2) the hybrid scenario with 12 MW auxiliary heating (6 MW NBI + 6 MW ECRH) with the increased to ~10 s duration of the current plateau for the same value of the nominal plasma current 2 MA. A steady-state scenario with 18 MW auxiliary heating (6 MW NBI + 5 MW ECRH + 7 MW RF power), higher value of plasma discharge duration ~20 s, increased density, and with fully non-inductive plasma current 1 MA and on-axis toroidal magnetic field 1.5 T, has also been examined.

The planned ECRH and ECCD system for T-15-MD (gyrotrons with frequency ν=56/112 GHz (extraordinary fundamental harmonic X1- and second harmonic X2-wave, resonance magnetic field on axis B=2 T) and ν=82 GHz (X2-wave, resonance magnetic field on axis B_0=1.5 T)) will provide the following expanded range of functionalities: microwave breakdown, neoclassical tearing mode stabilization, ELM stabilization, and non-inductive current drive. Therefore, it is necessary to perform extensive optimization studies of the EM-wave launcher operation for the specified regimes of the T-15-MD tokamak.

Here we perform simulations of the ECRH and ECCD in the above two scenarios for two different EM-wave injection geometries, from an equatorial port on the low-magnetic-field side and from an upper port on the high-magnetic-field side. The simulations of the ECRH and ECCD are carried out with the ray-tracing code GENRAY [4] and the kinetic Fokker–Planck code CQL3D [5]. ECRH power density and ECCD efficiency results for the flat-top stage of discharge are presented for various injections angles and EC wave modes. It is shown that, for the ECCD in the hybrid scenario, the injection of the X2-wave from the low magnetic field side is more effective than injection of the X1-wave from the high magnetic field side.

References

[1] E. Azizov, et al., *23rd IAEA Fusion Energy Conference*, FTP/P6-01 (2010)
[2] P. P. Khvostenko, et al., Fusion Engineering and Design **98-99**, 1090-1093 (2015)
[3] V. M. Leonov, Probl. of Atom. Sci. and Tech., ser. Thermonuclear Fusion **30**, 73 (2016)
[4] A. P. Smirnov, R. W. Harvey, K. Kupfer, Bull. Am. Phys. Soc. **39**, 1626 (1994)
[5] R. W. Harvey, M. G. McCoy, *IAEA Technical Committee Meeting on Advances in Simulation and Modeling of Thermonuclear Plasmas*, 489-526 (1992)

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Development of a Correlation ECE Radiometer for Electron Temperature Fluctuation Measurements in Heliotron J

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Turbulence in density and temperature is believed to govern global energy/particle confinement in toroidal fusion plasmas. A single-sightline radial Correlation Electron Cyclotron Emission (CECE) radiometer has been developed and implemented on the Heliotron J helical device for studying bulk electron temperature fluctuations. The new radiometer consists of two detection systems. One system covers the 2nd harmonic of the electron cyclotron frequency from 60 to 72 GHz by using a high frequency resolution variable local oscillator and an 8GHz intermediate frequency bandpass filter of 0.200 GHz bandwidth. The other system has a fixed frequency 56 GHz local oscillator, and the down-converted intermediate frequency signal is split into four 0.200 GHz bandpass filters with center frequencies at 4, 8, 12, and 16 GHz. The measured frequency range spans from the plasma core to the half radius of Heliotron J. The CECE radiometer simultaneously measures the background electron temperature and the electron temperature fluctuations with high resolution by splitting the ECE signals into AC and DC coupled channels. Preliminary results in optically thick ECH plasmas show that the radial correlation length of the electron temperature fluctuations is on the order of a few mm, which is comparable to that of electron density fluctuations measured with a two-frequency reflectometer. The details of the radiometer system and the first experimental results will be presented.

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Fast evaluation of the ECCD efficiency for reactor studies

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A current produced by the injection of electromagnetic waves in the electron cyclotron frequency range will likely be essential in fusion reactors as an actuator for the control of magnetohydrodynamical instabilities and is a strong candidate for the support of steady state operation [1]. The impact of current driven by auxiliary heating systems on the overall performance of a reactor can be evaluated employing systems codes like PROCESS [2, 3]. Since such codes perform an optimization over a large number of parameters and aim to combine physics, engineering and economical aspects, each element of the modelling has to be kept as light as possible from the computational point of view, still retaining a sufficient degree of accuracy.

The calculation of the ECCD efficiency in the frame of this kind of applications has the peculiarity that some of the parameters (most notably the wave frequency and the injection geometry) are not known, but rather have to be determined on the basis of the global machine and plasma parameters being considered at a given optimization step. A determination of the highest reachable ECCD efficiency based on a ray/beam tracing scan of the relevant parameters [4] is not possible, both because of the associated computational effort and because the magnetic equilibrium is not available. The approach adopted here is based on the basic observation that optimum current drive results from a compromise between sufficient absorption (which excludes the very tails of the distribution functions) and low collisionality (which would require high-energy electrons). Combining constraints obtained from an analytic estimate of the absorption coefficient and from the resonance condition allows the determination of the parameters to be supplied for a single evaluation of the ECCD efficiency based on the adjoint method [5], including momentum conservation [6]. This procedure is shown to agree with full ECCD optimization loops performed with the beam tracing code TORBEAM [7, 8] for a set of reactor-relevant plasma scenarios within an accuracy of ca. $\mp 15\%$.

References

[1] H. Zohm *et al.*, Nucl. Fusion **53**, 073019 (2013).

[2] M. Kovari *et al.*, Fus. Eng. Des. **89**, 3054 (2014).

[3] M. Kovari *et al.*, Fus. Eng. Des. **104**, 9 (2016).

[4] E. Poli *et al.*, Nucl. Fusion **53**, 012011 (2013).

[5] Y. R. Lin-Liu *et al.*, Phys. Plasmas **10**, 4064 (2003).

[6] N. B. Marushchenko *et al.*, Nucl. Fusion **48**, 054002 (2008).

[7] E. Poli *et al.*, Comp. Phys. Comm. **136**, 90 (2001).

[8] E. Poli *et al.*, Comp. Phys. Comm. (2018), in press.

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Current drive by high intensity, pulsed, electron cyclotron wave packets

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In the early 1990s, high power, pulsed, microwaves, in the electron cyclotron (EC) frequency range, were used in the Microwave Tokamak Experiment (MTX) [1] for heating and for current generation in high density plasmas. Bursts of pulses were generated by a free-electron laser at a frequency of 140 GHz with powers up to 2 GW, and pulse durations of 20-30 ns. It was noted in [1] that "extrapolation to reactor heating and current drive predicts high efficiency." In the intervening years, significant advances have occurred in the technology of high power millimeter wave sources. Gyrotrons now routinely achieve megawatt power levels in continuous wave operations – 140 GHz for W7-X and 170 GHz for ITER. Relativistic gyrotrons can operate in a pulsed mode, in the millimeter wavelength range, at power levels ranging from 10 to 100 MW [2]. These developments have led to our studies on the interaction of electrons with high peak power EC fields, while, simultaneously, aiming to optimize current drive in fusion plasmas.

The nonlinear interaction of electrons with high intensity wave packets in the EC frequency range is described by the relativistic Lorentz equation. The wave packet is spatially localized perpendicular to its direction of propagation. We find that the extraordinary and the ordinary EC waves interact strongly with the electrons when the wave frequency f_0 is either slightly larger or slightly smaller than the local electron cyclotron frequency f_{ce}. The interaction is stronger for the ordinary wave, as compared to the extraordinary wave, when $f_0 \lesssim f_{ce}$, and vice-versa for $f_0 \gtrsim f_{ce}$. The components of the electron momentum, along and across the magnetic field, are a function of the wave power and the direction of wave propagation. There is no saturation of the momenta as the wave power is increased, so that the plasma current increases with wave power. The nonlinear effects manifest themselves when the beam power is around 5 MW for a Gaussian wave packet of width 12 cm. The interaction of electrons with a wave packet is significantly different from that with a large amplitude plane wave, and leads to a wider variety of nonlinear phenomena including spatial modifications to the temperature profile as well as affecting MHD activity. Our calculations lend credence to the claims made in [1], that high powered EC waves will lead to efficient heating and current drive in fusion plasmas. These theoretical studies of wave-particle interactions, along with the advances in the technology of high peak power sources, may offer a breakthrough in achieving steady-state operations in reactor scale plasmas.

References

[1] E. B. Hooper, *et al.*, "MTX Final Report," [https://www.osti.gov/scitech/servlets/purl/10194124] (1994).

[2] M. Thumm, "State-of-the-Art of High Power Gyro-Devices and Free Electron Lasers," KIT Scientific Report 7735 (2016).

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Development of an Electron Cyclotron Emission Imaging diagnostic on the WEST tokamak

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Electron Cyclotron Emission imaging (ECEI) diagnostic system has been proven to be a unique tool for visualizing the magnetohydrodynamic (MHD) or turbulent instabilities [1]. For WEST tokamak, teams from UNIST, Korea and IRFM have collaboratively developed an ECEI diagnostic system that can overcome the accessibility and thermal constraints of the long pulse tokamak dedicated for testing the ITER divertor elements. The man-access is the only possible port to install the large vacuum window and the optics required for ECEI system. To withstand the plasma radiation heating during long discharges, two large metallic reflective mirrors (0.56 m height x 0.18 m width) are employed as the plasma facing front-end optics. They will focus and redirect the beam to the vacuum window. Water-cooling is not required but the first mirror could reach 400°C during long pulses.

A compact optical housing is constructed to fit in the limited space between the port flange and access lobby. The optical components are vertically aligned to take advantage of the height of Tore Supra equatorial plane (~2.5 m above the ground floor). Extra effort was invested in the design to make the imaging optical components including local oscillator as compact as possible. The diagnostic system initially designed for one view image with 24x8 pixels of electron temperature fluctuations for the outer part of the plasma (R= 2.4 ~ 3m) with high spatial (≤1.7 cm) and temporal (≤ 2μs) resolution. A second view image will be added latter to probe the high field side.

Properties of the optical system were evaluated at UNIST laboratory last November. The beam divergence and beam width are in good agreement with the design. Installation is scheduled during the coming summer shutdown. The first imaging results are expected for the WEST C4 campaign starting in November 2018.

References

[1] H. Park, et al, Rev. Sci. Instrum., **74**, 4239 (2003)

[2] Y. B. Nam, et al, Rev. Sci. Instrum. **87**, 11E135 (2016)

[3] R. Sabot et al, COMPTES RENDUS PHYSIQUE, 17, 1018-1026 (2016)

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Particle-in-cell simulations of parametric decay instabilities near the upper hybrid layer

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Observations of strong anomalous scattering in several recent collective Thomson scattering (CTS) experiments has led to investigations to quantify the scattering and uncover the mechanisms that cause it. If not anticipated, the anomalous scattering can be strong enough to damage microwave equipment in current reactors such as ASDEX Upgrade. CTS diagnostics are expected to be installed in ITER and a better understanding of the anomalous scattering is therefore necessary.

The observed anomalous scattering occurs when the CTS gyrotron beam reaches the upper hybrid (UH) layer and it has characteristics associated with parametric decay instabilities (PDIs). An investigation of the daughter waves of such a PDI process may lead to efficient heating schemes and there is experimental evidence to suggest that it is possible to suppress the PDI by angling the CTS microwave beam in certain ways. Better knowledge of this PDI is expected to also benefit investigations of other PDIs such as two plasmon decay during 2nd harmonic ECRH, which may have a significant impact on its heating efficiency.

Using the particle-in-cell (PIC) code EPOCH, a 105 GHz gyrotron beam incident on the UH layer in a fusion plasma is simulated. In a 1D spatial domain with a homogeneous background magnetic field, an X-mode pump wave is propagated towards a region of changing particle density in the direction of propagation. As the wave traverses this region, it reaches the UH layer where it is greatly enhanced due to a change in group velocity. A sufficiently strong pump wave is expected to decay into a warm UH and a warm lower hybrid (LH) wave through a PDI [1]. The scattered waves will differ from the pump wave in frequency, wave length and group velocity, and these characteristics can be determined when the scattered waves reach a homogeneous region of the domain.

In accordance with experiments and theory, the simulations show the expected field enhancement of the pump wave near the UH layer and that waves are scattered off it. Fourier and continuous wavelet transforms in time and space show that the scattered waves differ from the pump wave on a number of parameters which are compared with the predictions. A parameter scan of pump wave power investigates the non-linearity of the PDI.

References

[1] S. K. Hansen, *et al.*, Plasma Phys. Control. Fusion **59** 105006 (2017)

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Characterization of MHD modes with ECE(-I) and the influence of large density fluctuations

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The electron cyclotron emission (ECE) diagnostic is a widely used diagnostic for the electron temperature (T_e) and its fluctuations (δT_e). It measures microwave intensity, which can be converted into a radiation temperature (T_rad). The electron Cyclotron Emission Imaging (ECEI) diagnostic is based on the same principle, with the difference that it has multiple lines of sight (LOS), which allow the poloidal characterization of δT_e.

For many scenarios, it is possible to identify the measured T_rad with T_e and δT_rad with δT_e at the cold resonance position. However, certain effects like relativistic mass shift- and Doppler shift-broadening, low optical depth and the refraction of the line of sight limit the applicability of this approximation. For interpretation of ECE measurements, which accounts for the effects listed above, the geometrical optics equations and the radiation transport equation are solved in an Electron Cyclotron Forward Model (ECFM).

At ASDEX Upgrade the ECFM is routinely used to infer T_e from T_rad within the framework of Integrated Data Analysis[1]. Good agreement between measurements and synthetic T_rad is found for the cases where the ECE spectra is affected by harmonic overlap or relativistic mass shift-broadening in the plasma core. Another application of the model is the determination of the birthplace distribution of observed intensity[2], which can be a requirement for the characterization of MHD modes with ECE(-I) measurements. The modes analysed in this work, are associated with an ELM cycle and are measured in both density and the temperature diagnostics. Furthermore, as will be shown, density perturbations can modulate the optical depth and shift the LOS, both of which can have a large effect on the measured T_rad. This can severely hamper the localization of the modes[3], especially if no additional information on the density fluctuations amplitude is available.

References

[1] R. Fischer et al. *Fusion Science and Technology*, 58(2):675–684, OCT 2010.

[2] S. S. Denk et al. *EPJ Web Conf.*, 147:02002, 2017.

[3] B. Vanovac et al. *Plasma Physics and Controlled Fusion*, 2018.

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Development of a Poloidal Correlation ECE Diagnostic for Electron Temperature Fluctuation Measurements in W7-X

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Correlation radiometers measure the electron temperature fluctuations that are contained within the Electron Cyclotron Emission (ECE) spectrum. The fluctuations in the ECE radiation intensity are dominated by uncorrelated thermal noise, and plasma electron temperature fluctuations are recovered by isolating the correlated signal between two or more ECE measurements [1]. This system operates as a poloidal correlation diagnostic through spatial decorrelation of the electron cyclotron emission. The poloidal correlation ECE (CECE) system on Wendelstein 7-X [2] observes 2nd harmonic extraordinary wave emission and is comprised of two radiometers that view separate sightlines. Each radiometer uses a 133 GHz local oscillator and has eight frequency channels spread over an 8 GHz (~10cm radial) range between 142-150 GHz on the high-field side of the magnetic axis. The center frequency of each 300 MHz bandwidth channel is separated by 1 GHz, corresponding to a radial distance of approximately 1 cm along the view. The post-detection bandwidth of each channel is 900 KHz and the signal is sampled at 2 MHz. The radiometers share an oversized 28mm transmission line and an in-vacuum antenna with two Doppler reflectometer diagnostics. One of the Doppler reflectometers is designed to launch and receive W-band microwaves in the extraordinary wave polarization, while the other is designed for V-band microwaves in the ordinary wave polarization. To separate these signals from the D-band extraordinary wave emission that is measured by the CECE diagnostic, a dielectric beam splitter and a wire grid polarizer are used in each transmission line respectively. Finally, a 141 GHz high pass filter protects each radiometer from electron cyclotron resonant heating at 140 GHz. This poloidal CECE diagnostic was successfully operated during the 2017 experimental campaign of Wendelstein 7-X and the first measurement results will be presented and discussed.

References

[1] Ch. Fuchs and H.J. Hartfuss, *Rev. Sci. Instrum.* **72** 383 (2001)

[2] T. Klinger *et al. Plasma Phys. Control. Fusion* **59** 014018 (2017).

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Extension of a ray tracing for polarized diffracting wave beams description in inhomogeneous magnetized plasmas

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Geometrical optics (GO) ray tracing is typically considered to be an adequate method for describing the propagation of electron cyclotron resonance waves in weakly inhomogeneous magnetized plasma. However, this reduced approach cannot be used to calculate the complicated diffracting focused-wave structure, and is inapplicable in helical fusion plasmas with a strongly sheared magnetic field, where mode coupling between two electromagnetic cold-plasma modes can occur in the low-density region close to last closed flux surface (LCFS). Some extensions of GO that account for diffraction, such as beam tracing [1] and quasi-optical ray tracing [2], can solve the focused/defocused and one mode fixed wave field. Mode coupling near the LCFS can be imitated by applying 1D full wave analysis into GO frame [3], but this method neglect the diffraction. This problem is also treated as an application of the 1st order theory of the extended geometrical optics (XGO) [4]. Here, we propose a more general approach based on the 2nd order theory of XGO, which captures both diffraction and mode coupling simultaneously.

In our approach, reference ray is calculated with ray equation to satisfy the 0th order part of XGO theory. The form of our ray equation is conventional but we use zero-eigenvalue of dispersion matrix as a ray Hamiltonian. Then, an evolution of amplitude profile along the reference ray is calculated with paraxial vector amplitude equation, which is derived from remaining 1st and 2nd order terms of XGO theory. In high-density magnetized plasma where dispersions of two electromagnetic cold-plasma modes are separated well enough, paraxial equation can be reduced into scalar amplitude form. This approximation is adequate for far field of fusion plasma. However, since amplitudes of two electromagnetic cold-plasma modes can interact each other in unmagnetized or low-density magnetized plasma, we should trace amplitude profile with vector form equation near the LCFS. The progress of our extension will be presented.

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References

[1] E. Poli, *et al.*, Computer Physics Communications **136** 90-104 (2001)

[2] A. A. Balakin, *et al.*, J. Phys. D **40** 4285-4296 (2007)

[3] T. I. Tsujimura, *et al.*, Nuclear Fusion **55** 123019-123030 (2015)

[4] I. Y. Dodin, *et al.*, Physics of Plasmas **24** 122116 (2017)

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