Proposals for Invited Talks / EC22, Daejeon

January 5, 2024

1 Theory and design studies

Name	Affiliation	Title/Topic
B. Baiocchi	CNR Milan	ECH in DTT: system capabilities and applications in plasma scenarios
B. Biswas	York University	Fully-relativistic electron Bernstein wave current drive predictions for STEP
Y. Oda	Setsunan University	ECCD system design activities for JA-DEMO
M. Preynas	ITER Org.	EC Stray Radiation in ITER: development of a consolidated strategy to avoid any potential system failure during plasma operation

2 Experiments

Name	Affiliation	Title/Topic
E. Gusakov	Ioffe Institute	Anomalous emission and absorption of microwaves in ECRH experiments
M. Huang	SWIP Chengdu	Developement of ECRH system for HL-3 tokamak
Y.-S. Hwang	Seoul University	Various Ohmic startup schemes with electron cyclotron heating via direct XB mode conversion in VEST
J. Stober	IPP Garching	ECCD, flux pumping and T_i peaking by q-profile shaping in ASDEX Upgrade

3 ECE / Diagnostics

Name	Affiliation	Title/Topic
N. Chaudhary	IPP Greifswald	Advanced Bayesian analysis of ECE at W7-X stellarator
J.-H. Lee	Korea Inst. Fus. En.	Broadband Electron Cyclotron Emission Measurement System for Studying Small-scale Fluctuation Structure and Dynamics in KSTAR
C. Yoo	MIT	Overview of recent turbulence studies across multiple confinement modes at the ASDEX Upgrade tokamak using the Correlation Electron Cyclotron Emission diagnostic

4 Technology

Name	Affiliation	Title/Topic
G. Gantenbein	KIT	Development of gyrotrons for fusion in Europe
S. Laxmikant Rao	ITER India	Commissioning of 1 MW gyrotrons at IPR
D. Wagner	IPP Garching	In-situ Low Power Tests of the ASDEX Upgrade ECRH Transmission Line

ECH in DTT: system capabilities and applications in plasma scenarios

B.Baiocchi[1],L.Aucone[1], I.Casiraghi[1], L.Figini[1], G.Granucci[1,2], S.Garavaglia[1], P.Mantica[1], A.Moro[1]

[1]Institute for Plasma Science and Technology – CNR, via Cozzi 53, 20125 Milano, Italy
[2]DTT S.c. a r.l., C. R. Frascati, via E. Fermi 45 00044, Frascati, Italy

The Electron Cyclotron (EC) Heating and Current Drive (CD) is the main heating system foreseen for the Divertor Tokamak Test facility (DTT) [1], new device currently under construction, which is aimed to perform investigations regarding power exhaust and divertor load. Besides contributing to assure high power flow, the EC system has the aim of accomplishing several operational and physics tasks. To this purpose comprehensive studies regarding the propagation, absorption and current drive of the EC beams to optimize launchers performances have been carried out [2]. The capabilities of the EC system must be then evaluated investigating how the EC beam injection influences and is influenced by the plasma parameters which can be critical for proper EC system operation. Focusing on the full power scenario E1 [3], high density, strong radiation by impurity seeding and fuelling by pellet injection are required for the scenario sustainment and for assuring compatibility with the divertor in the detached condition and with first wall power handling capability. In addition significant sawteeth are found to characterize such scenario. Giving indication regarding the potential and the issues of the EC system applied to the plasma scenarios is also relevant in the view of future fusion devices, for which the EC system is foreseen to be fundamental.

This work presents numerical investigations performed with the beam-tracing code GRAY [4], used in stand-alone version and coupled with the 1.5D transport code JETTO and the quasi-linear anomalous transport model QuaLiKiz [5] for the core region. First, the role of EC on the sustainment of the plasma density fuelled by pellets is investigated. The theory-based integrated modelling included the code HPI2 [6] for self-consistent simulations of the pellet ablation and deposition. The core density strongly depends on the EC power deposition width: a very peaked EC power deposition profile does not allow high density plasmas, while enlarging the EC power deposition profile permits to achieve the expected density, without significantly increasing the impurity accumulation in the plasma central region. Varying the width of the EC power deposition profile allows to explore scenarios with higher Greenwald density fraction (up to~0.6), and to verify the compatibility of the EC system with peaked density profiles. Then a preliminary investigation of the use of EC beams to mitigate sawteeth instabilities is performed, including the Porcelli/Kadomtsev models in the integrated modelling. Last, the evaluation of the residual EC radiation due to low EC absorption has been carried out. Critical cases for the flat top phase and for the ramp up phase of the full power scenario have been investigated.

References: [1] R. Martone *et al*, DTT Divertor Tokamak Test facility. Interim Design Report, ENEA (ISBN 978- 88-8286-378-4), April 2019 ("Green Book") [2] Baiocchi B. et al 2023 21st joint workshop on electron cyclotron emission and electron cyclotron resonance heating (EC21) EPJ Web Conf. (Cadarache, FR, 20–25 June 2022) vol 277 p 01006 [3] Casiraghi I. et al 2023 Plasma Phys. Control. Fusion 65 035017 [4] Farina D. 2007 Fusion Sci. Technol. 52 154–60 [5] Bourdelle C. et al 2016 Plasma Phys. Control. Fusion 58 014036 [6] Pegourie B. et al 2007 Nucl. Fusion 47 44–56

Fully-relativistic electron Bernstein wave current drive predictions for STEP

B. BISWAS[1], J. DECKER[2], B. ELIASSON[3], S. J. FREETHY[4], C. HOPKINS[1],
A. KÖHN-SEEMAN[5], M. G. SENSTIUS[6], D. C. SPEIRS[3], R. G. VANN[1], T. WILSON[1]
[1]York Plasma Institute, University of York. York, UK. [2]Ecole Polytechnique Fédérale de Lausanne. Lausanne, Switzerland.
[3]University of Strathclyde. Glasgow, UK. [4]UKAEA, Culham Science Centre. Abingdon, UK.
[5]University of Stuttgart, IGVP. Stuttgart, Germany. [6]Technical University of Denmark. Lyngby, Denmark.

The UK's Spherical Tokamak for Energy Production (STEP) will rely on electron cyclotron (EC) and electron Bernstein waves (EBW) for fully non-inductive steady-state operation. While EC is lower-risk, EBW enables a higher efficiency, and therefore higher Q_{eng} , device. To assess EBW current drive (CD) performance, an extensive modelling program is underway to predict wave coupling, propagation, damping, and the electron response. Analytic and numeric full-wave modelling is conducted to optimise O-X-B mode-conversion at the plasma edge. Reduced models of parasitic losses, including collisions and parametric decay, are also being investigated. This talk discusses these efforts, with a particular emphasis on the core microwave physics where ray-tracing and Fokker-Planck models are being used to optimise wave propagation and current-drive performance.

At reactor-relevant temperatures ($T_e > 5$ keV), relativistic effects can significantly modify EBW propagation and polarisation. In particular, rays that deeply penetrate the hot plasma cannot be simulated in the non-relativistic limit (due to breakdown of the weak-damping approximation). These rays could be of interest for near-axis current drive. Kramers-Kronig relations are exploited to efficiently evaluate the fully-relativistic dispersion relation for arbitrary wave-vectors[1], leading to a > 50x speed-up compared to previous efforts[2] at relativistic ray-tracing. A recently verified linear adjoint model[3] is used to estimate CD efficiency. Thus, for the first time, large parametric scans of fully-relativistic EBW CD simulations are performed. In STEP, relativistic physics are found to severely alter CD performance if rays are able to propagate sufficiently far into the core ($\rho < 0.7$). In contrast, rays that damp strongly far off-axis are sufficiently short and "cold" such that relativistic effects are unimportant. These discoveries are factored into the design of STEP's microwave launchers.

STEP will utilise multiple launchers - totalling ~150MW of microwave power - for steady-state operation. In this regime, strong quasilinear effects are expected to impact wave absorption and CD efficiency. A quasilinear Fokker-Planck solver is coupled to the fully-relativistic ray-tracer, enabling high-fidelity predictions in reactor-relevant conditions. Modelling shows that quasi-linear effects can be expected on MAST Upgrade, and plans for experimental validation of this physics will be discussed.

References

[1] S. PAVLOV and F. CASTEJON, Nuclear Fusion. **58**, 126030 (2018)

[2] E. NELSON-MELBY, *et al.*, Plasma Physics and Controlled Fusion. **49**, 1913–1929 (2007)

[3] B. BISWAS, *et al.*, Nuclear Fusion. **63**, 126011 (2023)

Corresponding author: B. BISWAS *bodhi.biswas@york.ac.uk*

ECCD system design activities for JA-DEMO

Yasuhisa Oda[1], Kazunobu Nagasaki[2], Atsushi Fukuyama[2], Takashi Maekawa[2], Hiroshi Idei[3],
Tomohiro Seino[4], Kota Yanagihara[5], Nobuyuki Aiba[5], Satoru Yajima[5], Takahiro Shinya[5],
Ryosuke Ikeda[45], Ken Kajiwara[45], Shin Kubo[6], Kenji Tobita[4], Shota Sugiyama[7], Hiroyasu Uto[7],
Yoshiteru Sakamoto[7]

[1] *Setsunan University, Neyagawa, Osaka, Japan*
yasuhisa.oda@mec.setsunan.ac.jp

[2]*Insitute of Advanced Energy, Kyoto University, Uji, Kyoto, Japan*
[3]*Kyushu University, Kasuga, Fukuoka, Japan,* [4]*Tohoku University, Sendai, Miyagi, Japan*
[5]*National Institute for Quantum Science and Technology, Naka, Ibaraki, Japan*
[6]*Chubu University, Kasugai, Aichi, Japan,*
[7]*National Institute for Quantum Science and Technology, Rokkasho, Aomori, Japan*

Electron cyclotron current drive (ECCD) system is one of the major components of JA DEMO tokamak[1], and it is expected to play an important role in its plasma operation scenario, especially in ECCD operation. Since the EC system has an advantage in radiation conditions among various heating systems, ECCD is expected to be a primary current drive method for DEMO tokamaks. However low current drive efficiency of ECCD has disadvantage in power consumption for tokamak operation, which declines output electric power from the plant.

As activities of physical analysis of ECCD operation in JA DEMO aims to improve the current drive efficiency. A Survey of the frequency, injection port, and some new approaches, multi-frequency heating, tokamak start scenario, and etc., has been performed to find how to improve the efficiency using various analysis codes, namely TRAVIS, TASK, and PARADE. As result, upper port injection was found to have more preferable performance than equatorial port injection case since it can avoid unwanted absorption at higher order resonance area.[2]

From point of engineering design activity, a launcher port location in JA DEMO tokamak vacuum vessel is evaluated. The location of the launcher port is determined by avoiding interference with the toroidal field coil support structure. To produce proper injection angle from launcher, research works on a remote steering mechanism is in progress.

As another activity of engineering design, a conceptual design of the ECH/CD system RF power plant for JA DEMO is represented. As a preliminary RF power plant specification, the power level is assumed to be 100 MW class with a frequency range > 200 GHz. This conceptual design aims to clarify the engineering development target of gyrotrons, transmission line and other components in the next step of JA DEMO development, planned to start in 2027.

1. K. Tobita, et al., Fusion Science and Technology, 75, 5, 372-383 (2019).
2. T. Seino, et al., Fusion Engineering and Design, submitted.

EC Stray Radiation in ITER: development of a consolidated strategy to avoid potential system failures during plasma operation.

[1]M. Preynas, [1]N. Casal, [1]M. Choe, [1]F. Gandini, [1]F. Carlaco, [1]S. Carpentier-Chouchana, [1]L. Chen,
[1]Q. Deliege, [1]D. Iglesias, [1]W. Helou, [1]R. Hunt, [3]C. Lechte, [1]S. Nicolici, [3]B. Plaum, [1]M. Schneider,
[2]J. Stober, [1]H. Wang, [1]T. Wauters

[1]*ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St Paul Lez Durance Cedex, France*
[2]*Max-Planck-Institute for plasma physics, Boltzmannstrasse 2 85748 Garching, Germany*
[3]*Institute of Interfacial Process Engineering and Plasma Technology,*
University of Stuttgart, Pfaffenwaldring 31, D-70569 Stuttgart, Germany

Melanie.preynas@iter.org

Since 2023 the ITER Organization put the focus on a significant re-baseline exercise [1] that has a strong implication for the heating mix of ITER. The power available to heat the plasma is increased in the New Baseline, with a change of proportion between Electron Cyclotron Heating (ECH) and Ion Cyclotron Heating (ICH) from what is considered in the 2016 ITER baseline. The new heating mix comes with a tungsten first wall armour that will replace the beryllium one. A modified ITER Research Plan is under development with an Augmented First Plasma (AFP) campaign and two Deuterium-Tritium operation phases (DT-1 and DT-2). AFP requires 40 MW of ECH and 10 MW of ICH power in the plasma. This will allow access to H-mode (DD) together with the demonstration of ICH effectiveness and RF wall conditioning in an all-tungsten ITER. A further upgrade to 67 MW of ECH, up to 20 MW of ICH and 33 MW of NBI is foreseen for DT-1 to enable sufficient total heating power to achieve Q = 10 within the neutron fluence limit.

Considering the new operation conditions that derive from the new baseline, the development of a consolidated strategy to mitigate any potential system failure is required. Depending on the phase of the plasma pulse and the use of the ECH system, the intensity and distribution of stray radiation in the vacuum vessel can vary strongly. Transient and static stray radiation during plasma ramp-up has to be differentiated from the stationary and localized stray radiation related to the fraction of the beam in the wrong polarization (X1 instead of O1 at 5.3T) and reflected at the cut-off layer back to the outboard first walls and ports. ECH Stray radiation loads in the vacuum vessel were calculated for the 20 MW ECH system [2,3]. In the new baseline, only the background stray radiation will increase due to a larger number of EC beams used simultaneously, as each beam generates local stray load individually.

New functionalities of TORBEAM are developed [4] to provide the mapping of ECH loads in the Tokamak General Coordinate System for the first and subsequent reflections of the ECH beams on the wall. For that purpose, a set of scenarios that are considered for the new ITER research plan is used. One focus is to define those loads on the inertially cooled W temporary first wall that are proposed for AFP. Another key aspect is the propagation of the stray radiation further in the sub-systems like the glow discharge cleaning system, divertor, diagnostic ports, IC antennas, and in the EC launchers themselves. The FRED software is selected to estimate the stray level loads in the different sub-systems as being used for Upper Launcher (UL) [5]. To improve the load estimates on the different components of the sub-systems, the wave interaction with material samples (W, Cu, SS, Al_2O_3, etc and varying surface roughness) is characterized using the 3-mirror resonator technique. The data complements the existing database of reflection loss at 170 GHz [6]. Complementary tests under high power microwave stray radiation conditions in the MISTRAL facility [7] are foreseen as well. Dielectric characterization of ceramic material (measurements of relative permittivity and loss tangent) is foreseen at microwave frequencies to evaluate the volumetric loss in the ceramics due to EC stray radiation.

Investigations for potential mitigations are part of the activities for machine protection against stray radiation. Design modifications of parts with integration of additional sensors and protections when possible, to detect and to be more resilient against stray radiation are investigated and presented in this paper. Critical level of stray radiation that can be handled during AFP and DT operations are discussed, for localized and diffused radiation, in transient and stationary conditions. These provide the necessary input for refining the ECH operation plan including Electron Cyclotron Wall Conditioning (ECWC) and present a preliminary guideline for developing the new ITER Research Plan.

[1] P. Barabaschi, IAEA FEC 2023
[2] F. Gandini, EPJ Web of Conferences **277**, 01007 (2023) https://doi.org/10.1051/epjconf/202327701007
[3] J. Stober et al, 49th EPS conference, Bordeaux, France (2023)
[4] M. Schneider, this workshop
[5] C. Gómez, ISFNT-15 2023
[6] W. Kasparek, International Journal of Infrared and Millimeter Waves, Vol. 22, No. 11, November 2001
[7] J. W. Oosterbeek, EPJ Web of Conferences **277**, 04009 (2023) https://doi.org/10.1051/epjconf/202327704009

Anomalous emission and absorption of microwaves in ECRH experiments

E.Z. Gusakov and A.Yu. Popov

Ioffe Institute, St. Petersburg, Politekhnicheskaya 26, Russia

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. Nowadays an abrupt increase of the ECRH power from 20 MW up to 60 MW is under discussion by the ITER team. According to the predictions of the theory developed in 80th nonlinear effects and first of all parametric decay instabilities (PDIs), which can accompany the ECRH experiments, were believed to be deeply suppressed by huge energy loss of daughter waves from the decay region. However, during the last 15 years many experiments have demonstrated excitation of the anomalous nonlinear phenomena at the 1 MW level ECRH experiments. The clearest evidence of the nonlinear effects onset was obtained first at TEXTOR and then at ASDEX-UG and W-7X, where the strong microwave emission down–shifted in frequency was observed. At ASDEX-UG recently emission of the half harmonic of the pump wave was observed in addition. 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 and TJ-II. Besides this a substantial broadening of the power deposition profile was reported at L2-M, T-10 and D-IIID in the second harmonic ECRH experiments. In this talk we present a review of experimental observations and of theory progress taking into account, as distinct from the standard approach, trapping of the decay waves due to non-monotonous features of the density profile, which always exist on the discharge axis or may be present due to the magnetic island, the density pump-out effect or ELM filaments. We interpret the anomalous microwave emission and the ion heating, as a result of secondary nonlinear processes that accompany a primary low–threshold PDI leading to excitation of trapped waves. The primary PDI growth is saturated in our model due to both the secondary decays of the daughter waves and the pump wave depletion. The coupling of different daughter waves and the pump is responsible in the model for the strong microwave emission, which is a spurious signal for a tokamak microwave absorption reported by L-2M and T-10 where broadening of the power deposition profile was observed will be presented.

Corresponding author: Evgeniy Gusakov *e-mail address: evgeniy.gusakov@mail.ioffe.ru*

The analytical treatment of emission signal is supported under the RSF 22-12-00010 grant, the numerical modelling – by the Ioffe Institute contract 0040-2019-0023 whereas the code for the PDI saturation modeling was developed under the Ioffe Institute contract 0034-2021-0003.

Corresponding author: Evgeniy Gusakov   e-mail address: evgeniy.gusakov@mail.ioffe.ru

Development of Electron Cyclotron Resonance Heating and Current Drive System on HL-3 Tokamak

Mei Huang[1,*], *Feng* Zhang[1], *He* Wang[1], *Gangyu* Chen[1], *Guoyao* Fan[1], *Cheng* Chen[1], *Jieqiong* Wang[1], *Wanxing* Zhen[1], *Jiang* Li[1], *Qing* Li[1], *Jiruo* Ye[1], *Kun* Feng[1], *Bo* Lu[1], *Jun* Liang[1], *Chao* Wang[1], *Jun* Rao[1], *Xiaohui* Mao[1], *Yinqiao* Wang[1], *Min* Xu[1], *Xuru* Duan[1]

[1]Southwestern Institute of Physics, P.O. Box 432, Chengdu, China

The major radius of HL-3 is 1.78m and minor radius 0.65m. The maximum toroidal magnetic is expected to be 2.2T and plasma current is about 2.5MA.[1] 1MA plasma current has been realized at the end of 2021 after one year device upgraded to divertor configuration since the first plasma at the end of 2020.[2] For the HL-3 tokamak, Electron Cyclotron Resonance Heating and Current Drive (ECRH/ECCD) system will be acted as one of the key plasma heating methods for central electron heating, current profile control and NTM suppression. A preliminary design of 8MW ECRH/ECCD system for HL-3 tokamak has been conducted and finished in 2016.[3] Key components of this system have been designed, manufactured and tested since then. At the end of 2022, a 7MW ECRH system has been developed on HL-3 tokamak for half a year installation, which consists five 105GHz/1MW/3s subsystems and two 140/GHz/1MW/3s subsystems. The 7MW high-power microwaves are produced by seven GYCOM 1MW gyrotrons, transported by seven Φ63.5mm evacuated over-mode corrugated transmission lines (TLs) and injected into plasma by three fast steerable launchers. Fig. 1 shows the sketch of the layout of ECRH system on HL-3. All gyrotrons are settled in the RF heating hall which is in the south of HL-3 tokamak hall. The consideration of TLs routing and TLs installation was mainly focused on getting the best solutions of attenuation issues. The mode purity could be reached about 94% which was analyzed by phase retrieval method through testing the power distribution by thermal imager and the transmission efficiency is about 92% for ~40m TLs. Since the two 140GHz gyrotrons could be operated at 140GHz and 105GHz frequencies, wideband polarizers and power monitors were designed.[4] For the three launchers, the 4MW mid-plane and 2MW 1# upper launchers have been integrated on HL-3 and the 1MW 2# upper launcher is under manufactured and will be installed on HL-3 in 2024. In the poloidal direction, more complicated push rod framework for three launchers was employed for NTM suppression in real time. The total response time of control activities is less than 100μs and the dynamic response time of mechanism for the full scan range is less than 200ms in the poloidal direction for full scan range. Commissioning half a year, in July 2023 maximum 1.4MW output power of four 105GHz subsystems was injected into plasma. The power was deposited at the high field side and plasma heating effect was significant at the range of 1.5-1.7T toroidal field. With 800kW ECRH, the storage energy was increased about 50% when the plasma current is 500kA and toroidal field is 1.69T. With 1.2MW NBI, 0.3MW LHCD and 1MW ECRH, high confinement mode discharge was achieved when the plasma current is 1MA and toroidal field is 1.59T, illustrated in Fig.2, the signals represent NBI power, EC power, LH power, plasma current, toroidal field, storage energy and divertor Da separately. [2]

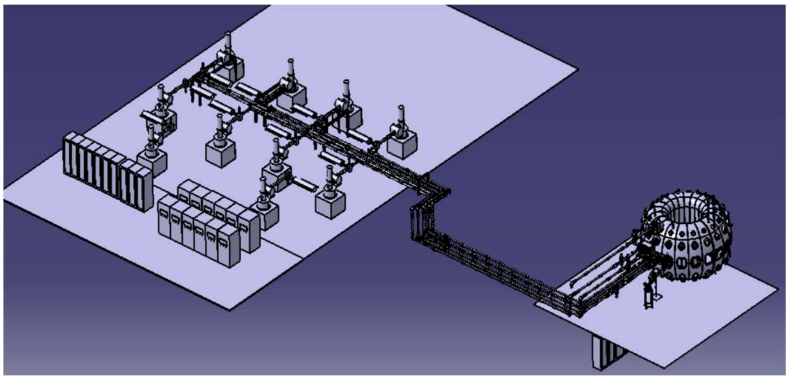


Fig. 1. Sketch of the layout of ECRH system on HL-3 tokamak

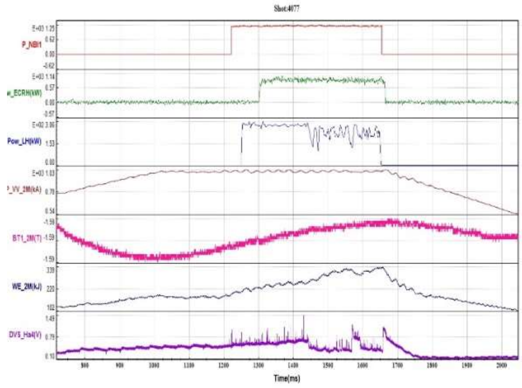


Fig. 2. Time re1MA plasma current H-mode discharge of HL-3 tokamak

References

1. Dequan Liu, et al., Fusion engineering and design, **96-97**, 298-302(2015)
2. Xuru Duan, et al., Recent Progress of HL-3 Experiment, 29th IAEA Fusion Energy Conference (FEC 2023), 16-21 October 2023, London, United Kingdom, OV2362
3. Mei Huang, et al., Design and Research of Electron Cyclotron Resonance Heating and Current Dive System on HL-2M Tokamak，EPJ Web of Conferences 2017, 147, 04006
4. Feng Zhang, et al., Study of dual-frequency polarizer for electron cyclotron resonance heating system of 105 GHz and 140 GHz，IEEE Transactions on Plasma Science (online), May 2020, 48(5), 1298-1302

Various Ohmic startup schemes with electron cyclotron heating via direct XB mode conversion in VEST

J.H. Byun[1], J.I. Wang[1], H.Y. Lee[2], and Y.S. Hwang[1]

[1]Seoul National Univ., Seoul 08826, Korea

[2]Korea Fusion Energy Institute, Daejeon 34133, Korea

In Spherical Torus (ST) with relatively low toroidal field, electron Bernstein wave (EBW) is known to be an efficient heating mechanism for high density plasmas without accessibility problem even at low frequency. Over-dense plasmas beyond L cut-off density was obtained via direct XB mode conversion from perpendicular low-field-side injection in Versatile Experiment Spherical Torus (VEST),[1] and they are utilized as an efficient pre-ionization in Trapped Particle Configuration for the development of a reliable and robust Ohmic start-up method in VEST and later in KSTAR.[2,3]

Relatively large wavelength of 2.45GHz at low toroidal field of the VEST was helpful for the microwave to transmit directly through the evanescent layer between R cut-off and upper hybrid resonance, allowing direct XB mode conversion instead of OXB mode conversion. Efficient XB mode conversion scheme was achieved in both short density scale length (L_n) and magnetic scale length (L_B) regions positioned at outboard and inboard sides, respectively.

Pre-ionization scheme utilizing short L_B region at the high field side of ST is more favorable to low loop voltage start-up by taking advantage of relatively strong electric field as well. With the enhanced pre-ionization a new merging start-up scheme can be developed by utilizing partial solenoids in VEST, where large stray field from the solenoid is unavoidable because of its geometry. Solenoid-free start-up scenario is another scheme to be developed with the enhanced pre-ionization by utilizing low loop voltage from the evolution of equilibrium field of outer PF coils. Efficient XB mode conversion scheme utilizing short L_n region at the low field side of ST make this scenario feasible. Flux from external inductance change can be utilized when the plasma is started from outboard and moved inward. Various start-up schemes utilizing the improved EBW-assisted pre-ionization in VEST will be presented.

References

[1] J.G. Jo, et al., Phys. Plasmas **24**, 012103 (2017)

[2] Y. An, *et al.*, Nucl. Fusion **57**, 016001 (2017)

[3] J.W. Lee, *et al.*, Nucl. Fusion **57**, 126033 (2017)

Corresponding author: Y.S. Hwang *yhwang@snu.ac.kr*

ECCD, Flux pumping and T_i peaking by q-profile shaping in ASDEX Upgrade

J. Stober, A. Bock, A. Burckhart, R. Fischer, I. Krebs, M. Reisner, A. di Siena, E. Poli, H. Zohm, (to be extended?), ASDEX Upgrade team

One target for the extension of the ECRH system on ASDEX Upgrade (AUG) during the last decade to 6 MW, 10 s (in the plasma), is the use of ECCD (together with the existing NBCD systems) to modify the plasma current profile to improve normalized plasma pressure β (typically limited by macroscopic MHD instabilities), energy confinement and peaking of ion temperature and density profiles. These experiments were prioritized for the last two experimental campaigns. Here we report on two clear effects related to the strong localization of ECCD.
In these so-called advanced Tokamak studies, two main lines are followed:
1) A q-profile clamped centrally to q=1 for a significant part of the minor radius. This q-profile results from a self-organizing current redistribution due to the presence of continuous or fishbone like (1,1) or (3,2)-modes at sufficient β. The phenomenon is known as flux pumping. The automatically generated q-profile corresponds to the most peaked current-profile possible without sawteeth, thus combining enhanced profile peaking with maximum stability. An open question is how much current the system can redistribute before it starts to collapse, crucial for its scalability and model verification. On AUG, flux pumping in the presence of a continuous (1,1) mode is studied. The interplay between overdriving the system with increasing central co-ECCD and reestablishing it increasing β is documented and successfully compared to modelling. The amount of redistributed current is estimated. Note that ECCD is more efficient when being applied in the center, another advantage of flux-pumping. Details can be found in (NF, Dec 2023, https://iopscience.iop.org/article/10.1088/1741-4326/ad067b)
2) A q-profile larger than unity over the whole radius. This requires driving significant off-axis current and subtle q-profile tailoring/control (and measurement). This may be a fallback if flux-pumping does not scale favorably to larger devices or if other beneficial effects can be expected from inverted/more elevated q-profiles. On ASDEX Upgrade we have observed for such scenarios a strong effect of moderate changes of the co-ECCD profile on ∇T_i. Driving current between [0.15, 0.5] in ρ, increases T_i in the center form 5 keV to 7 keV comared to ECCD in [0.05, 0.4]. While the latter results follow expectations from quasi-linear modelling, the first can only be reproduced with non-linear GENE simulations and crucially depend on q (and the derived magnetic shear) as well as on the fast particle pressure driven by neutral beam heating.
Finally, future plans for both development lines will be discussed.

Advanced Bayesian analysis of ECE at W7-X stellarator

N. CHAUDHARY, J. F. GUERRERO ARNAIZ, M. HIRSCH, U. HOEFEL, N. MARUSHCHENKO, J.W. OOSTERBEEK, R.C. WOLF and the W7-X TEAM

Max-Planck-Institut für Plasmaphysik, Greifswald, Germany

W7-X is a low-shear optimized stellarator with an operational goal of 30 minutes of steady-state detached plasma heated by 10 MW of ECRH. W7-X is currently equipped with two ECE diagnostics: a 32-channel heterodyne radiometer [1] measuring X2-mode from 120-160 GHz corresponding to a central magnetic field of 2.5 T with a spatial resolution of 1-2 cm behind cold resonance position and a temporal resolution in the order of µs, and a Michelson interferometer [2] measuring the higher ECE harmonics in the spectral range of 50-500 GHz with a temporal resolution of 22 ms and a spectral resolution of 5.66 GHz. The X2-mode radiometer is calibrated using a time-integrated hot-cold calibration technique using a black-body ceramic hot source with a maximum radiation temperature of 600°C [3]. Due to W7-X's 3D geometry, a sightline with a sufficiently lower magnetic field gradient is available, and the spectral ranges of the X2 and X3 modes do not overlap. Stellarators inherently do not have Greenwald density limit and aim at achieving high confinement using higher densities, n_e; hence, the X3 emission was explored for the high n_e application of ECE [3]. An X3 radiometer covering 190-220 GHz will be commissioned in the following operational campaign to track electron temperature, T_e, for high n_e O2 ECR and NBI heated plasma beyond X2-mode cutoff of 1.2×10^{20} m^{-3} and for high beta operation at a reduced magnetic field of 1.7 T.

An advanced integrated data-analysis scheme utilizing the Bayesian forward modeling [4] of both radiometer and interferometer using ray tracing and radiation transport calculations from TRAVIS code is adopted to deal with the measured radiation temperature spectrum to infer the T_e profile, as shown in *Figure 1*. The integrated forward model of ECE and line integrated n_e measurement from laser interferometer enables to infer T_e and n_e profiles simultaneously as the optically thin emission contains the information on the n_e profile, which can be disentangled using Bayesian analysis. Additionally, this data-analysis approach can infer the non-negligible mode-scrambling factor, which is approximately 15%, and hampers the classical approach of using radiation temperature as T_e. As a next step, the ECE also contains information on the magnetic field in addition to the T_e and n_e profiles, and this fact can be exploited for integrated forward modeling to extract the plasma pressure profile information at W7-X.

Corresponding author: N. CHAUDHARY *neha.chaudhary@ipp.mpg.de*

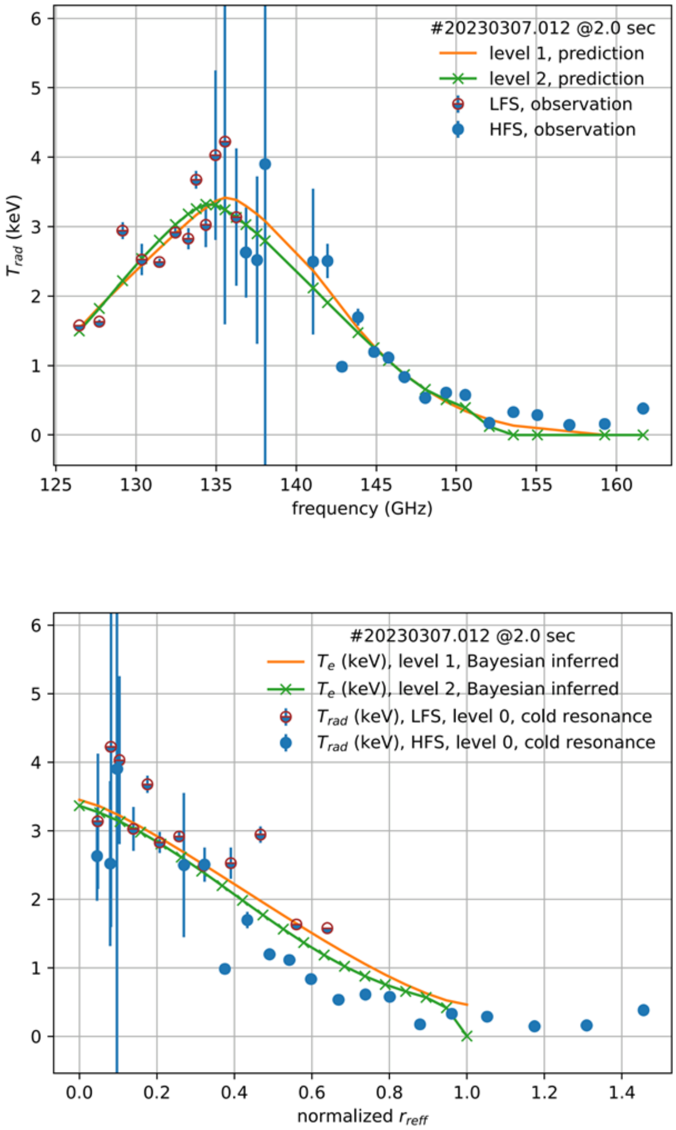


Figure1: ECE spectrum measurement with radiometer (top plot, blue spectrum) is shown alongside prediction from the forward model including TRAVIS using two different profile priors: parametric (orange spectrum) and Gaussian processes (green spectrum), and the corresponding Bayesian inferred T_e profiles are shown in bottom plot alongside the cold resonance mapped profile.

References

[1] M. HIRSCH *et al.*, EPJ Web of Conferences 2019 (Vol. 203, p. 03007)

[2] N. CHAUDHARY et al., 2020 JINST 15 P09024

[3] U. HOEFEL *et al.*, Review of Scientific Instruments 90.4 (2019)

[4] N. CHAUDHARY *et al.*, 2022 Plasma Phys. Control. Fusion 64 055016

Corresponding author: N. CHAUDHARY *neha.chaudhary@ipp.mpg.de*

Broadband Electron Cyclotron Emission Measurement System for Studying Small-scale Fluctuation Structure and Dynamics in KSTAR

Jaehyun Lee[1], Minho Kim[1], Gunsu S. Yun[2], Minwoo Kim[1]
[1] *Korea Institute of Fusion Energy, Daejeon, 34133, Republic of Korea*

[2] *Pohang University of Science and Technology, Pohang, 37673, Republic of Korea*

A new diagnostic method using broadband electron cyclotron emission (ECE) measurements was introduced to explore small-scale turbulent fluctuation structure and dynamics in KSTAR plasmas [1]. Broadband ECE is measured using a recently built high-speed digitizer and ECE imaging (ECEI) detection system. The ECEI detection system observes a 2nd harmonic extraordinary mode (X-mode) ECE emitted in the range of 75-110 GHz (W-band) in a typical KSTAR discharge [2]. Since signal processing is difficult at such high frequencies, the signal must be converted to lower frequencies before further processing. The ECEI heterodyne mixer receives an input RF signal from the plasma together with a coherent local oscillator (LO) signal to produce a beat signal at an intermediate frequency (IF). The mixing process is linear, which means that the output IF power is proportional to that of the RF signal and that the phase of the RF is also recovered. The heterodyne mixer is broadband (DC-20 GHz) and has a 3 dB loss bandwidth.

The high-speed broadband digitizer has an analog bandwidth of 6.5 GHz on a 4-channel basis and provides a sampling rate of 16 Gsa/s. The broadband analog bandwidth and high sampling capability of the digitizer can improve the radial resolution and extend measurement limits. In addition, 52 Gpts can be stored with up to 256 GB of acquisition memory, allowing data to be saved for approximately 1.5 s. It can easily be used to measure irregular or long-term observations.

A typical ECE radiometer or ECE imaging diagnostics has a fixed spatial and temporal resolution due to analog electronics with a fixed IF and video bandwidth. Meanwhile, using a high-speed digitizer, the KSTAR broadband ECE measurement system can independently generate local electron temperature fluctuation data through digitized signals and digital filters. The data generated in this manner can be arbitrarily adjusted for IF and video bandwidth, thereby optimizing the spatial and temporal resolution of the structure and dynamics of the turbulence to be measured. Such a technique allows us to adjust the spatial and temporal resolution for the desired physical target to minimize the external noise impact and focus solely on the physical phenomena.

Corresponding author: Jaehyun Lee *(jaehyun@kfe.re.kr)*

References

[1] J. Lee et al., “Nonlinear Interaction of Edge-Localized Modes and Turbulent Eddies in Toroidal Plasma under n=1 Magnetic Perturbation” *Phys. Rev. Lett.* **117**, 075001 (2016).
[2] G.S. Yun et al., “Development of KSTAR ECE imaging system for measurement of temperature fluctuations and edge density fluctuations” *Rev. Sci. Intrum.*, **81**, 10D930 (2010).

Corresponding author: Jaehyun Lee *(jaehyun@kfe.re.kr)*

Gyrotron development projects at KIT and first experimental results with FULGOR teststand

G. Gantenbein[1], et. al.

Karlsruhe Institute of Technology, Kaiserstr. 12, 76131 Karlsruhe, Germany

Within Europe and worldwide KIT is strongly involved in the development of high power gyrotrons for application in ECRH and ECCD in magnetic confinment of fusion plasmas. KIT is one of the leading labs in Europe for gyrotron development includung design of gyrotron components as well as experimental verification of the integral systems in short pulse and long pulse/CW operation. KIT is providing major contribution for gyrotron projects on W7-X, ITER, DTT, CEA-WEST and GA-DIII-D. Within the EUROfusion consortium KIT is also working on the definition of gyrotron specifications and verification of new gyrotron technologies for a DEMO reactor. As an example design simulations of the CEA-WEST 105 GHz gyrotron will be given. Gyrotron testing up to full performance with respect to output power and pulse length is performed with the new FULGOR teststand (**FU**sion **L**ong Pulse **G**yrotron Lab**OR**atory). This teststand allows up to 10 MW CW operation at 90 kV and 120 A, an additional body power supply (BPS) for operation of conventional single-stage depressed collector gyrotrons has been installed.

FULGOR has been used to test the CEA-WEST 105 GHz, 1 MW gyrotron, we will report on the results of these investigations.

The power supply of FULGOR supports the operation of so-called multi-staged depressed collectors which are supposed to enhance the overall efficiency of gyrotrons beyond 60 %. An outlook on upcoming experiments with a prototypic two staged depressed collector will be given.

Acknowledgement

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Corresponding author: A. BBBB *e-mail address*

Commissioning of MW class Gyrotron Test Facility at ITER-India & Demonstration of ITER relevant RF performance (1MW for 1000 s at 170 GHz)

S. L. Rao, Vipal Rathod, Anjali Sharma, Ronak Shah, Deepak Mandge, Sharan Dilip, Amit Yadav, Sandip Gajjar, Rasesh Dave, Dishang Upadhyay, Rajvi Parmar, SHK Madeenavalli, Kush Mehta, Vikas Gaur, Azad Kumar Singh, Kumar Rajnish, N.P. Singh

ITER-India, Institute for Plasma Research, Ahmedabad-382424, INDIA

As a part of its in-kind commitments to ITER project, ITER-India has a mandate to deliver two "Gyrotron" based RF source sets with state-of-the-art specifications (170 GHz, 1MW, 3600 s), for Electron Cyclotron Resonance Heating (ECRH) applications [1]. The deliverables include the associated auxiliary systems and a demonstration of complete system performance at ITER site on a dummy load. One of the challenges of these complex high-power RF systems is to establish an integrated system whose performance is reliable, easily repeatable and inherently safe, despite working under the harsh electromagnetic environment.

In order to benchmark and demonstrate the required integrated system performance, a MW class Gyrotron test facility was envisaged [2] and is now developed at ITER-India under the Phase-1 of the execution plan. The facility has been developed with all necessary auxiliary systems and services such as the High Voltage and Low Voltage Power Supplies; Control, Monitoring and Protection Systems; RF diagnostic systems; Cooling and Vacuum Services etc. The developed systems will also serve as the functional templates for the actual ITER deliveries. Further, a test Gyrotron with ITER required specifications (1MW, 170 GHz, 1000s) along with a set of waveguide components including dummy loads have been procured from M/s Gycom, Russia and fully integrated with the test facility.

The test facility consists of a Main High Voltage Power Supply of ratings 55 kV and 110 A that is developed as a predecessor for the ITER deliveries based on PSM topology with very fast time dynamics. A cost-effective anode power supply with ratings of 40 kV, 100 mA is developed using a COTS (commercial-off the shelf) high voltage power supply with a solid-state series switch to obtain the fast time dynamics. A full-fledged control system with a mix of custom designed and COTS products has been developed with an operator friendly user interface for efficient control and live monitoring of various field signals. The system is built around two different controllers: one is PXI-e based fast controller and the other is PLC based slow controller to take care of the various field signals that require fast or slow monitoring. Custom designed hardwired interlock protection system that can act well within 10 micro seconds has been developed and used for the safe operation. An ignitron-based crowbar protection system is implemented to divert the excessive cable energy in case of an arc fault. Various auxiliary power supplies have been organized to drive the magnetic coils and other subsystems of the gyrotron. A heater power supply is used with a beam current feedback loop to stabilize the Gyrotron beam current during the long pulse. A large cooling water distribution system with appropriate instrumentation for various flow parameters has been organized to effectively remove the heat dissipation across various components

Detailed Site Acceptance Tests of the Test Gyrotron have been conducted at the newly developed ITER-India Gyrotron Test Facility (IIGTF). An output RF power of 1MW at 170 GHz for 1000 s with RF efficiency of about 50% has been successfully demonstrated during these tests. Various detailed tests such as the reliability tests with 10 successive pulses of 500s pulse length each, power modulation

Corresponding Author: S.L. Rao; Email: slrao@iterindia.in

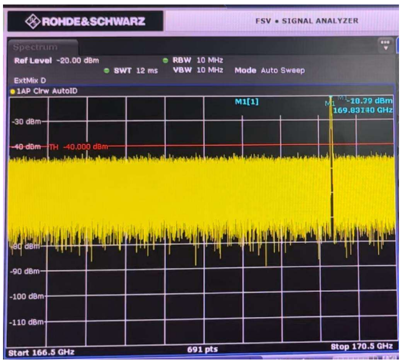
tests up to 1kHz have also been performed. This significant achievement also confirms the successful commissioning of a MW class Gyrotron test facility at ITER-India and also validates the various auxiliary systems and their integrated performance. After successful commissioning several identified improvements have been implemented to enhance the operational reliability and further routine operations are being carried out in a phased manner to generate the operational expertise.

The major challenges and technical issues faced during the test campaign include a misalignment of the wave beam that led to water leakage in the CW Dummy Load. A new CW Load had to be installed with alignment corrections. Operating at high efficiency point (lower magnetic field) required optimal parameters with minimal perturbations to avoid RF disruptions. Active beam current control with an optimal initial value is required to compensate for the cathode cooling during long pulses. False alarms and interruptions due to harsh EMI environment had to be troubleshooted and addressed. To enhance the output RF power, the magnetic field at the cathode region had to be additionally tweaked by removing the magnetic screen.

The paper presents the technical details of the newly commissioned MW class 170 GHz Gyrotron test facility at ITER-India highlighting the achieved ITER relevant results, technical challenges, observations and issues.

Acknowledgements: The authors would like to acknowledge M/s Gycom, Russia and their technical team for their contribution and support in successfully conducting the Site Acceptance Tests of the Test Gyrotron and waveguide set under a Procurement Contract with ITER-India.

Figure 1: Gyrotron Test Stand at ITER-India



Ref Level -20.00 dBm
SWT 12 ms
RBW 10 MHz
VBW 10 MHz
Mode Auto Sweep
ExtMix D
1AP Clrw AutoID
M1[1] -10.79 dBm 169.83140 GHz
Start 166.5 GHz
691 pts
Stop 170.5 GHz

Figure 2: Measured frequency during a long pulse

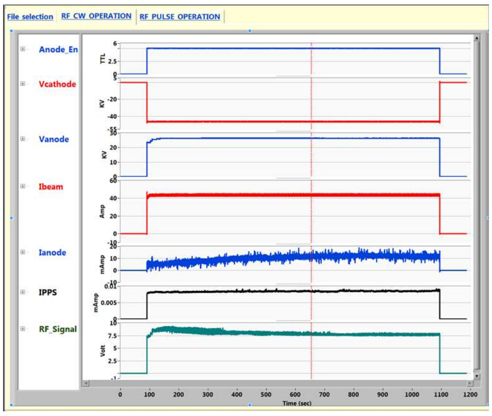


Figure 3: Gyrotron key operating parameters for 1MW,1000s Pulse

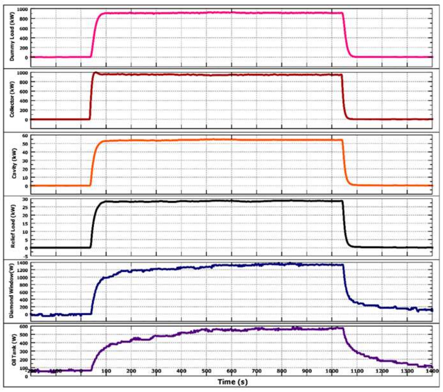


Figure 4: Calorimetric Power Measured in the Dummy Load and other key components of the Gyrotron during 1MW, 1000 s pulse

References:
[1] S.L. Rao et al, Fusion Science & Technology, 65, 129-144 (2014)
[2] Vipal Rathod et al, EPJ Web of Conferences 203, 04013 (2019) EC20

Corresponding Author: S.L. Rao; Email: slrao@iterindia.in

In-situ Low Power Tests of the ASDEX Upgrade ECRH Transmission Line

D. Wagner, F. Leuterer, F. Monaco, H. Schütz, J. Stober

Max Planck Institute for Plasma Physics, Boltzmannstr.2, 85748 Garching, Germany

The 8 MW, 105/140 GHz ECRH system at ASDEX Upgrade employs 8 non-evacuated transmission lines, mainly consisting of corrugated HE11 waveguides with an inner diameter of D=87 mm. The total lengths of the transmission lines are between 65 and 102 meters and the number of miter bends per line is between 6 and 8. The corrugated waveguides have a large inner diameter of 87 mm in order to avoid atmospheric breakdown at power levels up to 1 MW. This is the largest waveguide diameter compared to the wavelength (40.6 λ_0 at 140 GHz) of any existing high-power ECRH transmission line [1]. While mode conversion in miter bends due to diffraction strongly decreases with increasing D/λ_0, a main concern that led to limitation of waveguide diameters in other systems was coupling to lower order asymmetrical modes due to bending of the waveguides caused by sagging or movements of the waveguide supports. We performed low-power measurements at the AUG transmission lines to search for critical sections w.r.t. mode conversion. A lens horn connected to the input waveguide flange of the transmission line provided perfectly alignment of the input beam. We measured the wave beam along the transmission line at several locations using a millimeter wave scanner. A cavity stabilized IMPATT oscillator as source and as receiver a mixer with narrow IF bandwidth allowed for measurements with a sensitivity of -60 dBm with no connection between source and receiver. We found a compact symmetrical beam all along the transmission line with a very high Gaussian content, even after several miter bends. Near-field measurements of the beam radiated from the open-ended waveguide showed a good agreement with numerical calculations.

Figure1: Lens horn connected to a transmission line input (left) and measured beam pattern after 94 m transmission line and 7 miter bends (right).

References

[1] H. Yamazaki *et al*., Fuson Engineering and Design 196, 114015, (2023)

Corresponding author: D. Wagner *dietmar.wagner@ipp.mpg.de*