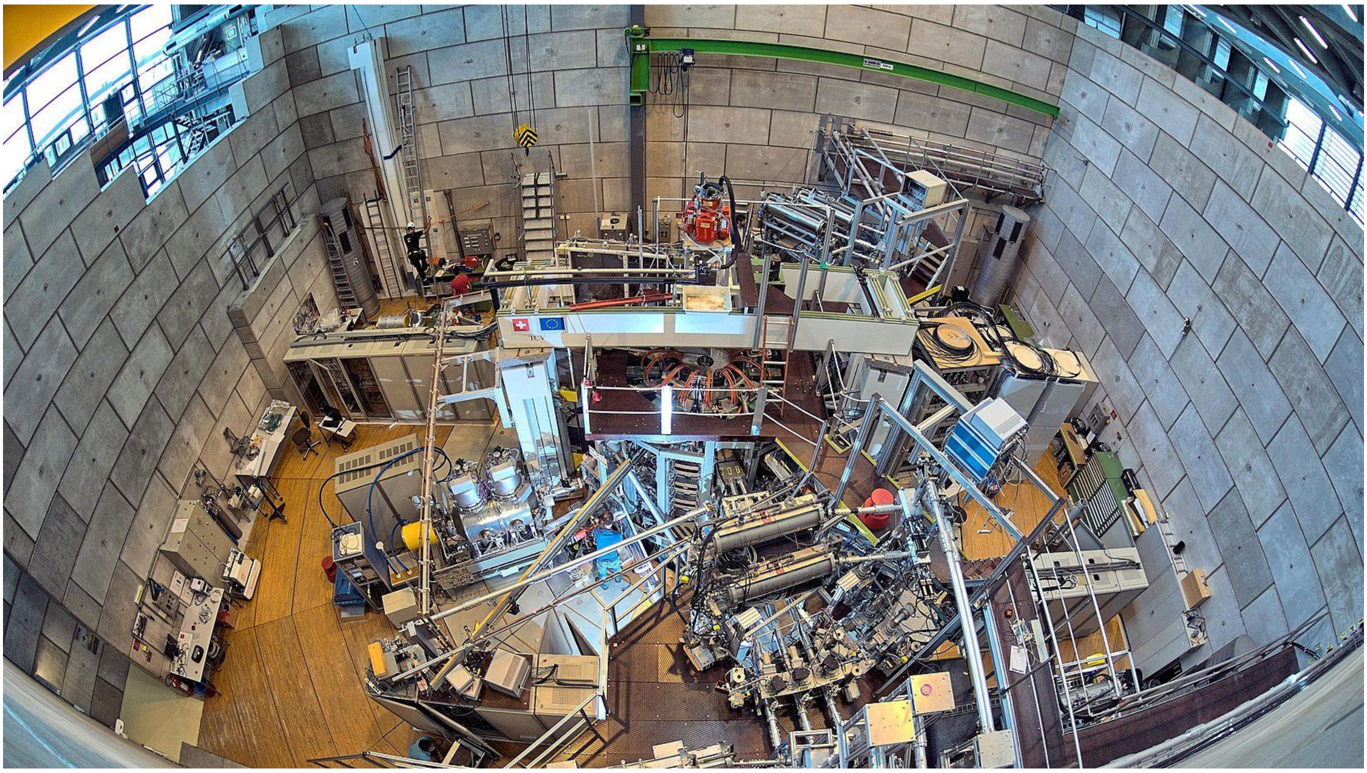

14th International Reflectometry Workshop

Swiss Plasma Center

Ecole Polytechnique Fédérale de Lausanne

22 – 24 May 2019

14th International Reflectometry Workshop: 22 – 24 May 2019

The 14th IRW will take place in Lausanne, within the Ecole Polytechnique Fédérale de Lausanne (EPFL) and the Swiss Plasma Center (SPC) that houses an officially medium sized tokamak; Tokamak à Configuration Variable (TCV).

The mission of the TCV is to apply its highly flexible plasma shaping and heating capabilities to the exploration of the physics of magnetically confined plasmas, partly in support of the ITER project, but also charting, in parallel, some of the alternative paths that may be required beyond ITER on the road to a prototype fusion reactor.

Strongly electron and/or ion heated plasmas with highly variable shapes are the primary focus of research on TCV, employing its unique tools, namely a highly adaptable ECRH/ECCD installation and a neutral beam heating system. 16 independently driven poloidal shaping coils and two internal coils, for fast vertical control, allow TCV to access a wide range of plasma shapes.

The research mission of TCV is also sustained by a continuous development and modernization of its diagnostic systems complemented by a strong plasma control interest in both hardware and software.

Some of the most recent diagnostic development has been in the domain of profile reflectometry and Doppler backscattering and both of these innovative measurements systems will be described during the course of this 14th IRW.

We welcome 45 participants to this 14th IRW and have the pleasure of presenting a very full 3-day program with 42 presentations covering theoretical, experimental and engineering aspects of reflectometry and closely related subjects.

We thank you for your participation at this workshop and we wish you a rich and rewarding workshop.

Laurie Porte + LOC

WORKSHOP AGENDA

	Wednesday 22 May 2019		Thursday 23 May 2019		Friday 24 May 2019
08:30 - 09:00	Introduction & Dsitribution of Abstracts and Agenda etc	08:30 - 09:00	**J. Vicente** : Full-wave simulations of conventional O-mode fixed frequency probing aof plasma turbulence with REFMUL/GEMR codes	08:30 - 09:00	**L. Vermare** : Perpendicular flows in Tore Supra plasmas
09:00 - 09:30	**Molina-Cabrera** : AWG-driven short pulse reflectometer diagnostic in the TCV tokamak	09:00 - 09:30	**Molina-Cabrera** : Doppler back-scattering diagnostic in the TCV tokamak	09:00 - 09:30	**M. Peret** : Perpendicular velocity evolution in the first plasmas of the WEST tokamak
09:30 - 10:00	**Y.M. Wang** : Recent Status of the electron density profile and fluctuation reflectometer on EAST tokamak	09:30 - 10:00	**T. Tokuzawa** : Dual-Comb Microwave Doppler Reflectometer System in LHD and Feasibility Study for a JT-60SA Doppler Reflectometer	09:30 - 10:00	**T. Estrada** : Turbulence $k_\perp$ spectrum and perpendicular plasma flow asymmetries measured using Doppler reflectometry at TJ-II plasmas
10:00 - 10:20	coffee break	10:00 - 10:30	coffee break	10:00 - 10:30	coffee break
10:20 - 10:50	**F. Clairet** : 1μsec broadband frequency sweeping reflectometry for plasma density and fluctuation profile measurements	10:30 - 11:00	**Z.B. Shi** : Development of multi-channel Doppler reflectometer for MAST-U and HL-2A	10:30 - 11:00	**K. Höfler** : Study of poloidal asymmetries in the flow perpendicular to the magnetic field of the ASDEX Upgrade tokamak
10:50 - 11:20	**A. Medvedeva** : Development of the synthetic diagnostic for the ultra-fast swept reflectometer	11:00 - 11:30	**R. Vann** : SAMI-2 ; 2-D microwave Doppler backscattering at MAST-U	11:00 - 11:30	**S.J. Freethy** : Measurements of the density-temperature cross-phase angle of turbulent flctuations at ASDEX-Upgrade and comparison to theory
11:20 - 11:50	**R.B. Morales** : The reconstruction of hollow areas in the density profiles from frequency-swept reflectometry	11:30 - 12:00	**J.O. Allen** : Dual-polarisation broadband sinuous antenna and RF downconverter design for the Synthetic Aperture Microwave Imager-2 diagnostic	11:30 - 12:00	**R. Sabot** : Trends emerging from a systematic analysis of a decade of fluctuation reflectometry measurements on Tore Supra
11:50 - 13:20	lunch	12:00 - 13:30	lunch	12:00 - 13:30	lunch
13:20 - 13:50	**T. Happel** : Design of a Variable Frequency Comb Reflectometer System for the ASDEX Upgrade Tokamak	13:30 - 14:00	**P. Hennequin** : Correlation Doppler Back-Scattering on ASDEX Upgrade : optimisation for extended spatial structure studies	13:30 - 14:00	**W. Lee** : Effect of the quasi-coherent mode on the intrinsic rotation of ohmic plasmas in KSTAR
13:50 - 14:20	**S-H. Seo** : Precise density profile reconstruction of FMCW reflectometer	14:00 - 14:30	**T. Windisch** : Doppler Reflectometry at Wendelstein 7-X	14:00 - 14:30	**E. Trier** : Comparison of poloidal correlation reflectometry measurements in W7-X and ASDEX Upgrade plasmas
14:20 - 14:50	**X. Han** : Development of a dual band X-mode reflectometer for the density profile measurement at the ICRF antenna in W7-X	14:30 - 15:00	**D. Carralero** : First V-band Doppler reflectometer results from the OP1.2b campaign in Wendelstein 7-X	14:30 - 15:00	**V.A. Vershkov** : Spatial Structure of Density Fluctuations in T-10 Tokamak
14:50 - 15: 20	**J.W. Oosterbeek** : Edge Electron Density Profile Reflectometer Study W7-X	15:00 - 15: 30	**D. Woodward** : Fuil wave numerical simulations of cross polarization Doppler backscattering	15:00 - 15: 30	**A. Krämer-Flecken** : Effects of the magnetic topology on turbulence in the SOL and plasma edge of W7-X
15:20 - 15:40	coffee break	15:30 - 16:00	coffee break	15:30 - 16:00	**G.V. Zadvitskiy** : Modelling of simultaneous measurements of turbulence correlation lengths and turbulence amplitudes using multi-channel radial reflectometry
15:40 - 16:00	**A. Sirinelli** : Update on ITER construction and integration of reflectometry systems				
16:00 - 16:30	**J. Martinez** : In-port-plug transmission line design of the ITER plasma position reflectometer	16:00 - 16:30	**V.H. Hall-Chen** : Modelling the effects of misaligning the probe beam and magnetic field in Dopplker backscattering measurements	16:00 - 16:30	Coffe Break & END
16:30 - 17:00	**D.A. Shelukhin** : Findings on the way : towards ITER HFS reflectometry	16:30 - 17:00	**E.Z. Gusakov** : Validation of full-f global gyrokinteic modelling results against the FT-2 tokamak Doppler relectometry data using different synthetic diagnsotics	16:30 - 17:00	
17:00 - 17:30	**C.M. Muscatello** : Preliminary design overview and performance assessment of the low-field-side reflectometer for ITER	17:00 - 17:30	**V.V. Bulanin** : Full wave modelling of Doppler backscattering from filaments	17:00 - 17:30	
17:30 - 18:00	**G.J. Kramer** : Simulation of the antenna-plasma coupling for the ITER low-field-side reflectometer system	17:30 - 18:00	**G.D. Conway** : Recent progress in modelling the resolution and localization of Doppler reflectometry measurements	17:30 - 18:00	
18:00 - 18:30	**D.J. Lee** : Collective Scattering system developed for high-k turbulence study in KSTAR	18:00 - 18:30	**C. Lechte** : Fullwave Doppler Reflectometry Simulations for Turbulence Spectra Using GENE and IPF-FD3D	18:00 - 18:30	
18:30 - 19:00	**S. Heuraux** : Full-Wave simulations of the enhanced Upper-Hybrid Resonance Scattering (UHRS)	18:30 - 19:00	Tour of TCV & SPC	18:30 - 19:00	
		> 20:00	Workshop Dinner		

List of Participants

Joe	**ALLEN**	University of York, UK
Rennan	**BIANCHETTI MORALES**	CCFE, UK
Viktor	**BULANIN**	Peter the Great St. Petersburg Polytechnic University, Russia
Daniel	**CARRALERO**	CIEMAT, Spain
Frederic	**CLAIRET**	CEA - Cadarache, France
Stefano	**CODA**	EPFL - SPC, Switzerland
Garrard	**CONWAY**	IPP Garching, Germany
Teresa	**ESTRADA**	CIEMAT, Spain
Simon	**FREETHY**	CCFE, UK
Evgeniy	**GUSAKOV**	Ioffe institute, Russia
Valerian	**HALL-CHEN**	University of Oxford / CCFE, UK
Xiang	**HAN**	Forschungszentrum Juelich GmbH, Germany
Tim	**HAPPEL**	IPP, Garching, Germany
Pascale	**HENNEQUIN**	LPP , Ecole Polytechnique, France
Stephane	**HEURAUX**	IJL-CNRS-Univ of Lorraine, France
Klara	**HOEFLER**	IPP, Garching, Germany
Gerrit J.	**KRAMER**	PPPL, Princeton University, USA
Andreas	**KRAMER-FLECKEN**	Forschungszentrum Juelich GmbH, Germany
Carsten	**LECHTE**	IGVP, Stuttgart, Germany
Woochang	**LEE**	National Fusion Research Institute, South Korea
DongJae	**LEE**	National Fusion Research Institute, South Korea
Jose	**MARTINEZ-FERNANDEZ**	CIEMAT, Spain
Anna	**MEDVEDEVA**	CEA Cadarache, France
Pedro	**MOLINA CABRERA**	EPFL - SPC, Switzerland
Christopher	**MUSCATELLO**	General Atomics, USA
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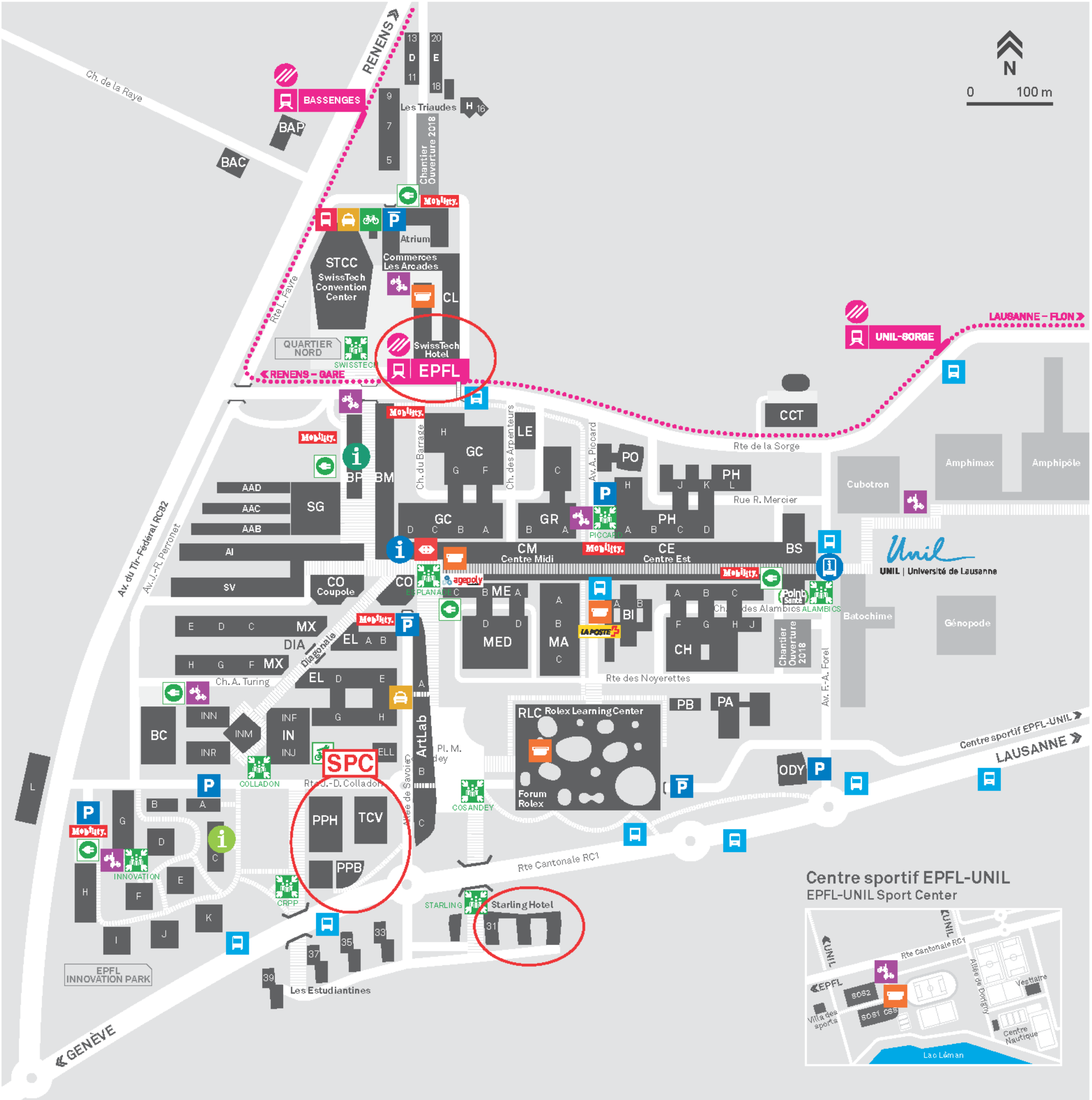
Mathieu	**PERET**	CEA Cadarache, France
Laurie	**PORTE**	EPFL - SPC, Switzerland
Roland	**SABOT**	CEA/IRFM, France
Jorge	**SANTOS**	Instituto Superior Tecnico, Portugal
Seong-Heon	**SEO**	National Fusion Research Institute, South Korea
Dmitry	**SHELUKHIN**	International Fusion Projects - Coordinating Centre, Russia
Zhongbing	**SHI**	Southwestern Institute of Physics, China
Antoine	**SIRINELLI**	ITER Organization, France
Tokihiko	**TOKUZAWA**	NIFS, Japan
Elisee	**TRIER**	IPP Garching, Germany
Roddy	**VANN**	University of York, UK
Laure	**VERMARE**	LPP , Ecole Polytechnique, France
Vladimir	**VERSHKOV**	NRC "Kurchatov institute", Russia
Jose	**VICENTE**	Instituto Superior Tecnico, Portugal
Yumin	**WANG**	Institute of Plasma Physics, Hefei, China
Thomas	**WINDISCH**	IPP Greifswald, Germany
David	**WOODWARD**	University of Strathclyde, UK
Georgiy	**ZADVITSKIY**	Universite de Lorraine, France

Plan d'orientation EPFL

EPFL - DII - 12.06.2017



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CHEMIN DU CRÊT 7, 1025 ST SULPICE

OUVERT TOUS LES JOURS DE 10H À 23H30

Thursday 23rd May from 20 :00 we will have the ‘pay as you go’ workshop dinner.

40CHF per head (drinks not included)

Within walking distance of the laboratory : 1.3km

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09:30 - 10:00	**Y.M. Wang** : Recent Status of the electron density profile and fluctuation reflectometer on EAST tokamak
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AWG-driven short pulse reflectometer diagnostic in the TCV tokamak

P. Molina Cabrera, S. Coda, L. Porte, A. Smolders, P. Lavanchy, N. Offeddu, M. Silva, M. Toussaint, and the TCV team[1]

Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland.

A broadband short pulse reflectometer has been developed in TCV to complement Thomson Scattering measurements of electron density, greatly increasing temporal resolution and also effectively enabling fluctuation measurements. Short pulse reflectometry consists of sending short pulses (<1ns) of varying frequency and measuring the round-trip group-delay with precise chronometers. To improve resolution and flexibility of traditional implementations, a fast arbitrary waveform generator (AWG - 65GSa/s, analog BW 20GHz) is used as a microwave pulse source to commercial frequency multipliers (VDI x6 varactor multipliers) that bring 8-12GHz pulses up to the V-band (50-75GHz). Two different timing techniques have been tested: direct digital sampling and traditional analog detection featuring constant-fraction-discriminators (CFD) and time-to-analog converters (TAC). A group-delay resolution of 17ps in average over the V-band has been achieved with both approaches, corresponding to a vacuum range resolution of 2.5mm.

The direct sampling technique allows pioneering measurements of pulse amplitude and width in addition to the group-delay. It has been confirmed that even in strongly turbulent L-mode plasmas, pulse dispersion is in the same order as the hardware timing precision and not a showstopper for the technique. Raw histograms of group-delay data show interesting qualitative changes from L to H-mode. Frequency spectra of group-delay data allow the identification of macroscopic density fluctuations as well as edge quasi-coherent modes during ELM-free H-modes. Lastly, fast changes to the density profile have been measured with microsecond time resolution.

A contributed article has been recently submitted to the Review of Scientific Instruments journal.

[1] See author list of S. Coda et al 2017 Nucl. Fusion 57 102011

Recent statues of the electron density profile and fluctuation reflectometers on EAST tokamak

Y. M. Wang[1*], T. Zhang[1], F. Wen[1], H. M. Xiang[1,2], K. N. Geng[1,2], G. S. Li[3,4], M. F. Wu[1,2], K. X. Ye[1,2], F. B. Zhong[1,2], J. Huang[1,2], X. Han[1], X. Gao[1,2] and EAST team

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Email: ymwang@ipp.ac.cn

The reflectometry on EAST have been used for two major measurements, i.e., the electron density profiles and fluctuations.

The density profile measurement reflectometers with separate frequency bands were lunched independently in previous experiments and now combined together by applying advanced microwave technology. A quasi-optical (QO) combiner / de-combiner by using frequency selective surfaces (FSSs) has been built to combine the Q-, V- and W-bands microwaves, so that these waves (32-110 GHz) can be transmitted to the antenna by using single pair of oversized waveguides. Two double-ridged horns are used for launcher and receiver. The received waves are decoupled by using a QO de-combiner, similar with the combiner. The polarization of the detecting waves is X-mode and using heterodyne detection. A 5-channel 250MSPS arbiter waveform generator (AWG) is used to control voltage control oscillators for frequency sweeping.

For the density fluctuation measurement, multi-channel correlation reflectometers have been developed including O-mode polarized (20-60 GHz) correlation reflectometer and X-mode polarized (50-110 GHz) correlation reflectometer. Two poloidally separated receiving antennas can realize both the radial correlation and poloidal correction measurements. The angle of the lunching antenna and the equatorial plane is 7 degree optimized by using ray-tracing code.

The PXIe-based data acquisition and control system (DACS) have been developed to satisfy the requirement of all the developed reflectometers. The PXIe-based DACS include two 8-channal 14-bit 20 MSPS digitizers and ten 8-channel 12-bit 60 MSPS digitizers. The total data rate from the digitizers is 2515 MB/s.

1 µs broadband frequency sweeping reflectometry for plasma density and fluctuation profile measurements

F. Clairet[1], C. Bottereau[1], A. Medvedeva[1], D. Molina[1], G.D. Conway[2], U. Stroth[2,3], ASDEX Upgrade team[2,a)], Tore Supra team[1,b)] and EUROfusion MST1 team[c)].

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[2] *Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany*

[3] *Physik-Department E28, Technische Universität München, 85747 Garching, Germany*

a) For a list of team members, see Appendix of H. Zohm et al., Nucl. Fusion 55 (10), 104010 (2015)

b) For a list of team members, see Appendix in Fusion Science and Technology, 56(3), pp. 1453–1454(2009)

c) For a list of team members, see "H. Meyer et al, Overview of progress in European Medium Sized Tokamaks towards an integrated plasma-edge/wall solution, accepted for publication in Nuclear Fusion"

Frequency swept reflectometry has reached the symbolic value of 1 µs sweeping time [1], this performance has been made possible due to an improved control of the ramp voltage driving the frequency source. In parallel, the memory depth of the 1 Gs/s acquisition system has been upgraded and can provide up to 200 000 density profiles during a plasma discharge. Additionally, improvements regarding the trigger delay determination for the acquisition, which needs to be precisely set and the frequency sweep linearity required by this ultra-fast technique along with the stability of the ramp voltage driving the VCOs, have been made. While this diagnostic is traditionally dedicated to the density profile measurement, such a fast sweeping rate can provide the study of fast plasma events and turbulence with unprecedented time and radial resolution from the edge to the core and thus compete with the fixed frequency systems. Experimental results obtained on ASDEX Upgrade plasmas will be presented to demonstrate the performances of the diagnostic.

[1] F. Clairet *et al.* RSI 88, 113605 (2017)

Development of the synthetic diagnostic for the ultra-fast swept reflectometer

A. Medvedeva[1], C. Bottereau[1], F. Clairet[1], R. Marcille[2], S. Hacquin[1,3], G. Dif-Pradalier[1], G. D. Conway[4], U. Stroth[4,5], S. Heuraux[6], D. Molina[1], A. Silva[7], ASDEX Upgrade team[4], EUROfusion MST1 team[a]

[1]CEA, IRFM, 13108 St-Paul-Lez-Durance, France

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[6]Institut Jean Lamour UMR 7198 CNRS, Université de Lorraine, 54000 Nancy, France

[7]Instituto de Plasmas e Fusão Nuclear, IST, Universidade Lisboa, Lisbon, Portugal

[a]For a list of members, see H.Meyer et al, Nucl. Fusion 57 102014 (2017)

The ongoing research with the ultra-fast swept reflectometer is focused on the experimental study of the flows and their influence on the turbulent transport in L- and H-mode. For an accurate interpretation of reflectometry data from ASDEX Upgrade and WEST tokamaks, a synthetic diagnostic has been developed. The synthetic diagnostic couples turbulence maps with a 2D code used for the simulation of the reflectometer signal. The wave propagation FDTD (Finite Domain Time Difference) 2D full-wave code has been commissioned. Optimisation of the numerical calculation led to a factor of hundred improvement of the simulation speed. The computational grid simulates the propagation of an electromagnetic wave in 2D in X-mode polarisation. Absorbing boundaries were implemented to avoid parasitic reflections. The probing wave emission corresponds to the realistic antenna radiation pattern of a Gaussian beam. At each time step, the source beam is added to the calculated field forming a so-called soft source. The code efficiency has been proved in terms of propagation, boundary absorption and cutoff reflection. The 2D code has been coupled with the turbulence maps resulted from the GYSELA gyrokinetic simulations. First results of the comparison between the experimental and numerical reflectometry data will be presented.

The reconstruction of hollow areas in the density profiles from frequency-swept reflectometry

R. B. Morales[1], S. Heuraux[2], R. Sabot[3], and S. Hacquin[3,4]

[1]*United Kingdom Atomic Energy Authority, Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*

[2]*IJL, University of Lorraine, UMR 7198 CNRS, BP 50840, 54011 Nancy Cedex, France*

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[4]*EUROfusion Programme Management Unit, Culham Science Centre, Culham, OX14 3DB, UK*

All density profile reconstruction techniques for both O-mode and X-mode are based on the assumption that the cut-off frequency profile is monotonic. However, there are many sources of perturbations to the plasma that generate hollow areas in the cut-off frequency profile, breaking the aforementioned assumption. This causes a significant localized reconstruction error that is not rapidly damped. Inside these hollow areas, the probing microwaves exhibit no specular reflections, so they are referred to as *blind areas*. It is demonstrated that even though no reflections occur inside the blind areas, the higher probing frequencies that propagate through these areas carry information that can be used to estimate their characteristics. The relevant information to reconstruct the blind area is the perturbation signature imprinted in the time-of-flight signal. These results have been developed in [1].

In addition to the reconstruction algorithm not handling well non-monotonic cut-off profiles, the reconstruction algorithm is based on the WKB approximation of the reflectometer signal. This approximation ignores all full-wave features associated to non-monotonic index profiles that are present in experimental signals. The corresponding effects were investigated in Ref. [1] with the use of time-dependant full-wave simulations in 1D, with a special attention paid to the perturbed frequency band. The simulated signals of excess time-of-flight, coming from sine shaped perturbations, are used to build a database of perturbation signatures on 5 dimensions of parameters. The database is then used in a synthetic example to invert the perturbation signature and determine its size. The same procedure is also demonstrated in experimental reflectometry data corresponding to a magnetic island during a Tore Supra discharge.

The new adapted reconstruction scheme, when compared to the standard reconstruction algorithm, improved the description of the density profile inside the blind area and along 10 cm after. This technique is pioneering in describing the density profile in blind areas to the reflectometer. Further research will focus on applying the method to additional experimental cases with improved techniques to extract the perturbation signature and shape.

This approach to treating the time-of-flight signal (comparison of perturbed excess time-of-flight against unperturbed signal) is also applicable to positive density perturbations. Future research will also take into account dense perturbations in the plasma edge that strongly perturb the initialization of the profile reconstruction.

[1] R. B. Morales, *Density profile reconstruction methods for extraordinary mode reflectometry.* PhD thesis, Université de Lorraine, 2018. http://docnum.univ-lorraine.fr/public/DDOC_T_2018_0031_BIANCHETTI_MORALES.pdf

Design of a Variable Frequency Comb Reflectometer System for the ASDEX Upgrade Tokamak

T. Happel,[1,*] W. Kasparek,[2] P. Hennequin,[3] C. Honoré,[3]
K. Höfler,[1,4] and the ASDEX Upgrade Team[5]

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[5] *see the author list "A. Kallenbach et al, Nucl. Fusion* **57***, 102015 (2017)"*

Comb reflectometers offer the advantage of measuring at several radial positions in the plasma simultaneously [1–5]. This allows the investigation of fast timescales during L-H transitions, I-phases, I-mode bursts, transients during heat wave propagation, etc. A drawback of present-day systems is that they use a fixed frequency difference between the probing frequencies. This means that usually, although the central probing frequency can be varied, the probing frequency difference is fixed. There is one concept which uses two input frequencies [6], which is the design the ASDEX Upgrade system is based upon.

The comb reflectometer system to be employed on the steerable ASDEX Upgrade Doppler reflectometer frontend [7] will work in the W-band of frequencies (75 – 110 GHz), and the probing frequency difference will be variable, also during the discharge. This results in a multitude of capabilities: radial profiles and radial propagation events can be measured if the system is set to cover a medium to large radial range, or the radial correlation function can be measured on a fast timescale if the difference between frequencies is set to low values. Depending on plasma parameters (density and magnetic field), both core and edge measurements will be possible.

The variable-frequency comb reflectometer uses a conventional frequency hextupler, which is fed by two frequencies. This results in the generation of a comb spectrum of several equidistant frequencies. Their individual frequency differences depends on the multiplier input frequency difference. Therefore, the comb reflectometer can be built on the basis of a conventional single-frequency reflectometer. However, the powers of the input frequencies have to be chosen carefully in order to generate a comb of comparable output power. The design of the IQ detection system is based on variable frequency YIG filters. The state of the development is reported, and first laboratory measurements of the output frequency comb are presented.

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[1] J. C. Hillesheim *et al.*, Rev. Sci. Instrum. **80**, 083507 (2009).
[2] W. A. Peebles *et al.*, Rev. Sci. Instrum. **81**, 10D902 (2010).
[3] T. Tokuzawa *et al.*, Plasma Fus. Res. **9**, 1402149 (2014).
[4] R. Soga *et al.*, Journal of Instrumentation **11**, C02009 (2016).
[5] T. Tokuzawa *et al.*, Rev. Sci. Instrum. **89**, 10H118 (2018).
[6] P. Molina Cabrera *et al.*, Rev. Sci. Instrum. **89**, 083503 (2018).
[7] T. Happel *et al.*, Phys. Plasmas **22**, 032503 (2015).

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Precise density profile reconstruction of FMCW reflectometer

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The accuracy of the density profile measurement with FMCW reflectometer is closely dependent on how precisely the frequency is calibrated. To calibrate the instantaneous frequency, a fixed frequency signal from a synthesizer is fed to the LO port of receiver. The IF signal of receiver is analyzed based on Morlet wavelet transform. The frequency of the microwave arriving in the RF port of receiver can be obtained by adding (or subtracting) the measured IF and the given LO frequency. By repeating this process as increasing the synthesizer frequency in the step of 0.1 GHz, the whole time trace of the frequency sweep can be calibrated. The measurements of IF show peculiar signals other than the expected frequency component. These signals are identified to be generated by the multiple harmonics of frequency multiplier. The full characterization of the sweep frequency gives more information in the analysis of the IF measurements.

In this calibration, the frequency is measured at the position of the RF port. Strictly speaking, the frequency is not identical along the beam path because the frequency is modulated and the microwave propagates at a finite speed. Therefore the group delay obtained by measuring the IF signal is characterized not by the frequency at the RF port but by the average frequency along the whole path. To get a precise density profile, this effect of the frequency variation along the path should be carefully considered. This effect gives a minor correction in the KSTAR reflectometer where the frequency sweep time is 20 μs and the round transit time of microwave is about 40 ns. It gives a profile reconstruction error less than 1 mm. Therefore the frequency variation along the path can be neglected without significant errors for a moderate sweep rate. This condition is implicitly assumed in Bottollier's profile reconstruction algorithm. However as the frequency sweep rate or the path length increases, the frequency variation along the path becomes significant. The profile measurement error will be 10 mm if the frequency of KSTAR reflectometer is swept at a 10 times faster rate. So we modify the profile reconstruction algorithm by considering the frequency variation along the path.

Development of a dual band X-mode reflectometer for the density profile measurement at the ICRF antenna in W7-X

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A frequency modulated continuous wave (FMCW) reflectometer is developed for the edge electron density profile measurement at the ICRF antenna in Wendelstein 7-X (W7-X). This system operates in extraordinary polarization mode (X-mode) covering the E and W frequency bands (67.2 - 110 GHz), which corresponds to a cut-off density range of $\mathrm{n_e} \leq 6 \times 10^{19}\mathrm{m}^{-3}$ at the central magnetic field of $\mathrm{B_0} = 2.5$ T. The front-end of the reflectometer is integrated with the ICRF antenna. The Ka-band waveguides (WR-28) are equipped in the vacuum, which length is 3.5 m per path. And the waveguides in the vacuum are banded with certain angles due to a low space availability. Two sector horns are placed between the rods of the ICRF's Faraday shield and the frame. The horns with an elongated H-plane are manufactured for a sufficient directivity and gain. In the reflectometer electronic, a layout for a fast frequency sweep in the heterodyne measurement is assembled. The electronic circuit is integrated into an individual metal box, which locates on the upper layer of the ICRF antenna sliding carrier.

This reflectometer diagnostic is planned to be operated in the OP 2 campaign of W7-X in 2021. The installation and in-situ calibration are linked to the ICRF schedule. The arrangement of the front-end in the vacuum, the performances of key components, and the calibration of the beat frequency are presented in detail.

Edge Electron Density Profile Reflectometer study W7-X

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A key target in stellarator optimisation is improved confinement [1]. In confinement studies the plasma edge - the region around the last closed flux surface - is important and edge plasma parameters must be diagnosed with good accuracy. One of these is the electron density; in particular perturbations in electron density and the velocity of the perturbations over the flux surfaces. Edge electron density *fluctuations* in Wendelstein 7-X are measured with high temporal resolution by Doppler Reflectometry [2] and Correlation Reflectometry [3]. Presently, electron density *profile* data in the edge is obtained from Thomson Scattering measurements [4] and Alkali Beam measurements [5]. However, the Thomson system observes the plasma from a different toroidal and poloidal location. This makes mapping the radius to the location of the reflectometers difficult due to the 3D-stellarator field, in particular in the presence of islands. The reduced number of data points in the edge and the 100 ms temporal resolution are a drawback for edge confinement studies too. The Alkali Beam shares the port with the reflecometers and has a high temporal resolution. However, a problematic area remains inside the separatrix where attenuation of the probing beam increases. In this region the reflectometer could complement the electron density profile data.

A study is presented on a dedicated Edge Electron Density Profile Reflectometer with a near-identical viewing line as used by the other reflectometers, and with similar temporal resolution. Antennas and infrastructure are readily available, however, a custom designed reflectometer instrument has to date not been available. The physics requirements - and challenges - are discussed. From this, the instrument requirements are obtained. These requirements narrow down to a sub-set of known reflectometer architectures which are presented with the aim to come to a candidate instrument.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Update on ITER construction and integration of reflectometry systems

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with contributions from ITER Domestic Agency Teams and UKAEA, Culham, UK

ITER has 3 reflectometry systems being designed and procured by different Domestic Agencies (DA). The systems cover all plasma radius:

- Plasma edge and core (18 to 155 GHz in O and X-mode): High-Field-Side Reflectometry (HFS-R) by Russian DA;
- From Scrape-Off Layer to pedestal top (50 to 165 GHz in O and X-mode): Low-Field-Side Reflectometry (LFS-R) by American DA;
- Plasma edge for gap measurement (15 to 75 GHz in O-mode): Plasma Position Reflectometry (PPR) by European DA.

While all systems measure density profiles, LFS-R and HFS-R systems also contribute to density fluctuation measurements. Finally, LFS-R system measures poloidal velocity using an antenna designed for Doppler Back Scattering. LFS-R system has performed its Preliminary Design Review (PDR) and the 2 other systems will have PDR in the coming months.

Antennae are located either in-between blanket modules or inside diagnostic Equatorial or Upper port plugs. Transmission lines (20 to 70 m long) route microwaves between the antenna and back-end equipment located in either the Diagnostic or the Assembly building. Three confinement barriers are crossed by each transmission line including double vacuum windows designed by IO-CT. The design activities of these windows has included dimension and material optimisation for microwave performances. Prototypes are being manufactured and transmission tests will be performed.

As the buildings are close to completion and installation of transmission lines and supports is planned for a near future, emphasis has been put on solving integration issues in-vessel, in port cells, in the galleries and in Diagnostics and Assembly Buildings. Fire insulation and protection of Safety Important Components (SIC) have been implemented.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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In-port-plug transmission line design of the ITER plasma position reflectometer.

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This work describes the microwave design of the transmission line and antennas contained in the in-port-plug region of the ITER plasma position reflectometer (PPR). The main goal of the PPR system is to provide a supplementary contribution to the magnetic measurements of the distance (gap) between the first-wall and the last closed flux surface. The PPR consists of five reflectometers located in four different poloidal/toroidal positions, named gaps 3 to 6, operating in the 15-75 GHz frequency range in O-mode. The front-ends are located both in-vessel (gaps 4 and 6) and in-port-plug (gaps 3 and 5). The design of the in-port-plug components of gap 3, located in equatorial port-plug 10 (EPP10), and gap 5, located in upper-port-plug 01 (UPP01) is presented in this work.

Starting from two selected ITER baseline scenarios (15 MA / 5.3 T/ D-T) and 7.5 /2.65 T/4He)) optimum power coupling positions, orientations and dimensions of the launching and receiving antennas were computed using analytical far field approximation and 3D ray tracing simulations.

From this point, 2D full wave simulations using a finite difference time domain (FDTD) code were performed to obtain the complex wave amplitudes and phases at the detection antenna end. Performing the spectrogram of these data allows then to obtain the time delay of the signal which is then used to reconstruct the plasma density profile. This sort of synthetic diagnostic is used to get an estimation of the error in the determination of the position of the last closed flux surface in both static and turbulent plasmas [1].

Apart from the launching/receiving antennas, the waveguides carrying the signal have been also designed. Oversized tall waveguides were chosen in order to reduce ohmic losses. Besides, due to space constraints in the ITER crowded environment, bends in oversized waveguides were unavoidable and thus mode conversion is produced. In order to keep mode conversion losses at bay, hyperbolic secant curvature bends had to be used whenever possible. However, E-plane bends in tall waveguides proved to be especially critical, making it necessary to employ other approaches when higher bending angles were needed.

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FINDINGS ON THE WAY: TOWARDS ITER HFS REFLECTOMETRY

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Electron density profile measurement in ITER will be the main task for high field side (HFS) reflectometry. This report focuses on the review of the development status of ITER HFS reflectometry diagnostic as well as proposed solutions that could be used in existing and new machines. The most activity for diagnostic development focuses now on the passive elements of transmission line. The main challenge is to guarantee structure integrity, integration, nuclear safety and good microwave performance.

The recent loads assessment forced to switch from stainless steel to Allow 718 waveguides as primary option for in-vessel part of transmission line. The sample batch of waveguide was successfully made and will be copper-plated this spring.

The original in-waveguide window design was failed on manufacture stage. The new proposed design utilizes traditional attachment of fused silica windows to ferrules. The simulation demonstrates that it is still possible to install small-aperture window in waveguide gaps without dramatic degradation of microwave performance.

The additional windows in atmosphere part of transmission line are required by nuclear safety to perform sectioning of different areas. Rohacell - based windows are proposed for these additional windows with intensive test support for such a solution. It was shown that dielectric permittivity and loss tangent for Rohacell are constant in frequency range 12-170 GHz whereas the gas penetration measurements demonstrate low deuterium diffusion through the material.

The early-reported coupler design was extended to 5 frequency band and to 140 GHz maximum frequency. The measurements demonstrate good performance of the mock-up.

The new look-though channel was included into diagnostic to extend its capabilities in measurements of the line-averaged density. The recent design is based on optimized rectangular horn and conventional waveguide. Two algorithms of data processing were proposed to reconstruct line-averaged density: the multidimensional simplex minimization and using of neural networks. Both approaches demonstrate good performance in terms of reconstruction time and accuracy on the baseline ITER profiles and will be developed further.

Intensive simulation of diagnostic performance was performed to assess various concerns. It was demonstrated that about 0.1% density perturbations lead to impossibility of profile reconstruction due to the loss of phase track at certain frequencies in single sweep. However, the 10-sweep averaged spectra demonstrate good tracking of beating frequency with only 2 dB decrease of main peak amplitude. Reconstruction algorithm was updated to improve performance and accuracy.

Synthetic diagnostic approach was used to analyze reflectometry response on TAE modes in ITER. The relative amplitude of signal perturbation was found to be about 0.4 and should be resolved by reflectometry. It was also found that response for TAE modes will be seen in narrow range of probing frequencies so strategy for mode measurement in ITER need to be revised.

Preliminary design overview and performance assessment of the low-field side reflectometer for ITER

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The low-field side reflectometer (LFSR) for ITER has matured to a complete end-to-end preliminary design. The LFSR is responsible for supplying three important plasma measurements: 1) edge electron density profile, 2) electron density fluctuations, and 3) poloidal rotation. Simultaneous measurements of the three quantities are enabled by an array of six monostatic antennas which inject from equatorial port EP11 on the outboard side of the ITER vessel. Transmission lines consisting of corrugated, overmoded waveguide and miter bends transmit the microwaves to and from the ITER plasma. Integrated transmission-line components serve a range of purposes, such as protection from high-power stray radiofrequency radiation, accommodation of transmission-line displacement due to thermal motion of the vacuum vessel, and in-situ measurement of the reference phase. Microwave transceivers, located in the diagnostic hall about 50 m from the ITER vessel, generate broadband 30 – 165 GHz signals and process the various reflectometer signals. A field-programmable gate array (FPGA) processor demodulates the profile reflectometer signals, enabling real-time density profile measurements for plasma control. A full-scale microwave transmission line test facility is used to test critical LFSR components. Theoretical modeling together with insertion loss measurements provide the basis for a comprehensive power budget, which accounts for source output power, transmission line losses, antenna coupling, and plasma effects. Results indicate that high spatial resolution (~ 5 mm) is achievable with the current design. A synthetic reflectometer model, using real design parameters and baseline ITER profiles, has been developed to estimate the return signal. Pedestal and scrape-off-layer profile measurements with high time resolution are possible using ultrafast-swept microwave sources and data acquisition hardware with bandwidth in the GHz range.

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Simulation of the antenna-plasma coupling for the Low-field side ITER reflectometer system

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The primary measurement requirements for the ITER Low-Field Side Reflectometer (LFSR) are electron density profiles in the plasma edge and fluctuations measurements while secondary measurement requirements are for core profile measurements and edge rotation measurements using Doppler reflectometer techniques.

Because of the high magnetic fields (5.4 T) and densities ($n_e \approx 10^{20}$ m^{-3}) the system is designed to operate over a frequency range from 30 to 165 GHz in both O- and X-mode polarization whereby all the antennas have to handle this frequency range. This leads to antennas with a moderate antenna gain at the low frequencies and a high antenna gain at the high frequencies. We will show that these antennas give an excellent antenna-plasma coupling when the plasma mid-plane is aligned well with the antennas.

The plasma mid-plane in ITER, however, is expected to vary vertically over a range of 0.5 m. Such a wide range cannot be covered by a single antenna and therefore, a vertical array of five antennas will be used. During operations the antenna that is closest to the plasma mid-plane can be selected for optimum coupling.

In order to optimize the antenna array lay-out of the LFSR, its performance was studied extensively with a 3D full-wave reflectometer code that include field-line aligned density fluctuations and relativistic effects. From Parameter scans in which density gradients, L- and H-mode profiles, and fluctuation characteristics were varied at various microwave frequencies it was found that an antenna-plasma coupling of better than -15 dB can be obtained which is sufficient to satisfy the edge density profile requirements while denstity fluctuations can be measured down a level of about 0.1%.

A separate antenna for Doppler reflectometry measurements will also be installed as part of the LFSR. We will show that the proposed arrangement for this Doppler antenna is also adequate for measuring the plasma rotation in the plasma edge in the velocity range (1 to 50 km/s) as specified in the LFSR measurement requirements.

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Collective scattering system developed for high-k turbulence study in KSTAR

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A collective scattering system (CSS) [1] was commissioned for the 2018 KSTAR campaign. This system has been developed to measure the micro-scale electron density fluctuations with four simultaneous channels (k_θ = ~14 - 26 cm^{-1}) using a 300 GHz millimeter-wave probe beam. The probing position is designed with remote control capability ranging from the plasma center to outer edge at high sampling rate (10 MS/s typically). The spatial resolution~~,~~ is ~6-10 cm in the radial direction and ~1-2 cm in the poloidal direction, depending on the poloidal wavenumber and scattering position. Initial data were obtained in various discharges such as ohmic and H-mode discharges. A preliminary analysis on the H-mode discharges showed significant reduction of high-k density turbulence after the L-H transition throughout the whole plasma (both the core and pedestal). Details of system configuration and preliminary analysis of the data will be presented. *This work is supported by the NRF of Korea under contract numbers, NRF-2015M1A7A02002627 and NRF-2014M1A7A1A03029865, and the Ministry of Science and ICT under the KSTAR project.

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Full-Wave simulations of the enhanced Upper-Hybrid Resonance Scattering (UHRS)

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A simple interpretative model was usually applied to extract turbulence characteristics of tokamak plasmas using data of Upper-Hybrid Resonant Scattering experiments [1]. To evaluate the limits of such model, full-wave simulations were performed. These computations are complex due to the fact that the spatial scales change a lot when both components of the wave electric field are taken into account. Looking specifically at the electromagnetic component E_y, its amplitude remains finite overall the propagative zone in the cold plasma approximation. However the group velocity decreases drastically and can reach in principle a velocity close to zero as shown numerically. As this case is unphysical, the thermal effects have to be included as we did. This permits to describe the wave conversion from X-mode to a warm plasma mode as mentioned in [1]. However the possible mode conversion described by the warm plasma model used corresponds to a warm wave propagating in an opposite direction to the one expected in tokamaks for the probing frequency close to the fundamental electron cyclotron harmonic. Assuming that the probing wave propagates along the resonance layer as supposed, 1D-studies on the Doppler shift induced by moving structures near the resonance were performed to evaluate if the effective Doppler shift obtained is directly connected to the velocity of the scattering structure. The scattering efficiency above the limitations of the [1] model is also provided for different cases. By playing with the terms inducing scattering in the wave propagation equations we answer the question about the contributions of the electrostatic and electromagnetic electric field components to the scattering signal in the cold plasma approximation when we are close to the upper-hybrid layer. To conclude the presentation, we provide an estimation of the parameters required to simulate realistic cases corresponding to the existing devices as FT2, WEST, and what could be expected from the full-wave simulation to interpret more accurately the UHRS diagnostic measurements.

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Thursday 23 May 2019	
08:30 - 09:00	**J. Vicente** : Full-wave simulations of conventional O-mode fixed frequency probing aof plasma turbulence with REFMUL/GEMR codes
09:00 - 09:30	**Molina-Cabrera** : Doppler back-scattering diagnostic in the TCV tokamak
09:30 - 10:00	**T. Tokuzawa** : Dual-Comb Microwave Doppler Reflectometer System in LHD and Feasibility Study for a JT-60SA Doppler Reflectometer
10:00 - 10:30	coffee break
10:30 - 11:00	**Z.B. Shi** : Development of multi-channel Doppler reflectometer for MAST-U and HL-2A
11:00 - 11:30	**R. Vann** : SAMI-2 ; 2-D microwave Doppler backscattering at MAST-U
11:30 - 12:00	**J.O. Allen** : Dual-polarisation broadband sinuous antenna and RF downconverter design for the Synthetic Aperture Microwave Imager-2 diagnostic
12:00 - 13:30	lunch
13:30 - 14:00	**P. Hennequin** : Correlation Doppler Back-Scattering on ASDEX Upgrade : optimisation for extended spatial structure studies
14:00 - 14:30	**T. Windisch** : Doppler Reflectometry at Wendelstein 7-X
14:30 - 15:00	**D. Carralero** : First V-band Doppler reflectometer results from the OP1.2b campaign in Wendelstein 7-X
15:00 - 15: 30	**D. Woodward** : Fuil wave numerical simulations of cross polarization Doppler backscattering
15:30 - 16:00	coffee break
16:00 - 16:30	**V.H. Hall-Chen** : Modelling the effects of misaligning the probe beam and magnetic field in Dopplker backscattering measurements
16:30 - 17:00	**E.Z. Gusakov** : Validation of full-f global gyrokinteic modelling results against the FT-2 tokamak Doppler relectometry data using different synthetic diagnsotics
17:00 - 17:30	**V.V. Bulanin** : Full wave modelling of Doppler backscattering from filaments
17:30 - 18:00	**G.D. Conway** : Recent progress in modelling the resolution and localization of Doppler reflectometry measurements
18:00 - 18:30	**C. Lechte** : Fullwave Doppler Reflectometry Simulations for Turbulence Spectra Using GENE and IPF-FD3D
18:30 - 19:00	Tour of TCV & SPC
> 20:00	Workshop Dinner

Full-wave simulations of conventional O-mode fixed frequency probing of plasma turbulence with REFMUL/GEMR codes

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Abstract
Complete chains from realistic gyro-fluid simulations through full-wave codes simulating reflectometry have been implemented recently, as in [1,2]. In this work, simulations with the two-dimensional full-wave code REFMUL [3] and the outputs from the three-dimensional GEMR code based on gyro-fluid theory [4,5] are continued to be explored aiming to characterize plasma turbulence with conventional O-mode reflectometry. In particular, synthetic measurements of fixed frequency probing with In-phase/Quadrature detection and focused antennae are employed to model fluctuation measurements. Capabilities to infer turbulence properties are discussed in light of the knowledge gained by the simulations.

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Doppler back-scattering diagnostic in the TCV Tokamak

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A newly-installed V-band heterodyne DBS diagnostic [2] in the TCV tokamak will be presented. The diagnostic can be uniquely configured for both sweepable single and multi-channel operation and is coupled to a flexible steerable quasi-optical launcher with in-shot adjustable polarization stages. It may reach densities between 0.8-7 x 10^{19} m^{-3} . The accessible $k_\perp$ range has been determined as 3-16± 2-4 cm^{-1} using 2D 3-point ray-tracing. The first results show DBS electron turbulence perpendicular rotation velocities in agreement with ExB poloidal rotation estimates from the CXRS diagnostic.

Innovative experiments demonstrate a new approach to generating and detecting multiple simultaneous frequencies using a digital AWG and direct sampling. Conventional multi-channel DBS systems use a comb frequency generator, a frequency multiplier, and a fixed set of filters in a heterodyne receiver. The newly proposed method consists of creating a double frequency spectrum with the AWG and feeding this signal into the varactor multipliers inside VDI modules. The non-linear response of frequency multipliers implies the generation of frequency products of the form nf1 + mf2 . Therefore, if a two-tone input composed of f1 and f2 is fed into the x6 VDI varactor multiplers, their output consist of 6f1, 6f2, and also (at least) 5 other inter-modulation products in between. The distance between the first two tones can be changed and is only limited by the maximum IF bandwidth of the receiver at 10GHz. A fast oscilloscope with 13GHz analog bandwidth is used to directly sample the IF output of the receiver mixer. Three different frequency spacings were tested in similar discharges and good agreement is found with regular monotonic swept DBS and CXRS.

A pair of motorized HE11 polarizer miter bends have been used to change the inclination angle of the polarization ellipse α while keeping a constant elliptical polarization angle β in search of an independent measurement of the magnetic field-line pitch. The best coupling (ideal α and β) to either X or O mode can be calculated by matching the launching beam wavevector and polarization to the relevant mode in the plasma's LCFS based on the magnetic field reconstruction. If the plasma conditions are stable, the coupling of the launched wave to either X or O mode at the plasma LCFS can be made to change by varying α while keeping β constant. If both the effective α and the power of the DBS signal during the shot are examined, a measurement of the magnetic field pitch angle at the edge of the plasma is possible. A proof-of-concept shot 59679 showed that sweeping α between +20 and -40 degrees while keeping β between -5 and -6 degrees, led to a peak DBS signal power measured at α=84.5 +/- 3 in agreement within uncertainty with the LIUQE magnetic reconstruction suggestion of 81.7 +/- 0.4.

[1] See author list of S. Coda et al 2017 Nucl. Fusion 57 102011
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Abstract of IRW14

Dual-Comb Microwave Doppler Reflectometer System in LHD and Feasibility Study for a JT-60SA Doppler Reflectometer

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New Ka-band frequency comb Doppler reflectometer system has been installed in LHD. Previous frequency comb system needs a very high sampling rate (40 GS/s) digital storage system to obtain all frequency comb components in the probing beam, and the observable time is limited by the memory size. This time, dual frequency comb sources with a 20 MHz difference are used to reduce the IF frequency components to less than 2 GHz, leading to lower sampling rate digitizers. In addition, the new receiver circuit requires the lower radio frequency range components and a circuit board thanks to the IF reduction. Cost saving and better performances are achieved. Details of new system and some topical results observed in LHD plasma, such as the isotope effect of turbulence, the processing technique to improve the accuracy of Doppler shift measurement, etc. are presented.

Study of the feasibility study of Doppler reflectometer to JT-60SA has been carried. The preliminary results of a full-wave 3D numerical simulation using launching / receiving antenna are presented.

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Development of multi-channel Doppler reflectometers for MAST-U and HL-2A

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Abstract: Doppler backward scattering (DBS) reflectometer has become a powerful technique to study the transition physics, plasma transport, turbulence and zonal flows through measurement of density fluctuation and plasma rotation in magnetically confined fusion experiments. Previously, the DBS systems typically utilized frequency hopping sources with a maximum of two simultaneous channels. In this work, a novel multiple fixed-frequency array source with a filter type phase locked loop technique is developed and applied in the multi-channel DBS system. Two 8-channel (Q/V bands) DBS systems with the channel frequencies of (34, 36, 38, 40, 42, 44, 46, and 48) GHz and (52.5, 55, 57.5, 60, 62.5, 65, 67.5, and 70) GHz are designed to measure the fluctuations in high confinement plasmas on MAST-U and HL-2A. The details of the system design and laboratory tests are presented. Preliminary plasma results of Doppler shift frequency spectra and characteristics of plasma rotation and turbulence in pedestal on HL-2A illustrate the system capabilities. The new developed Q/V bands multi-channel DBS systems will be delivered to MAST-Upgrade under the SWIP-CCFE collaboration in 2019.

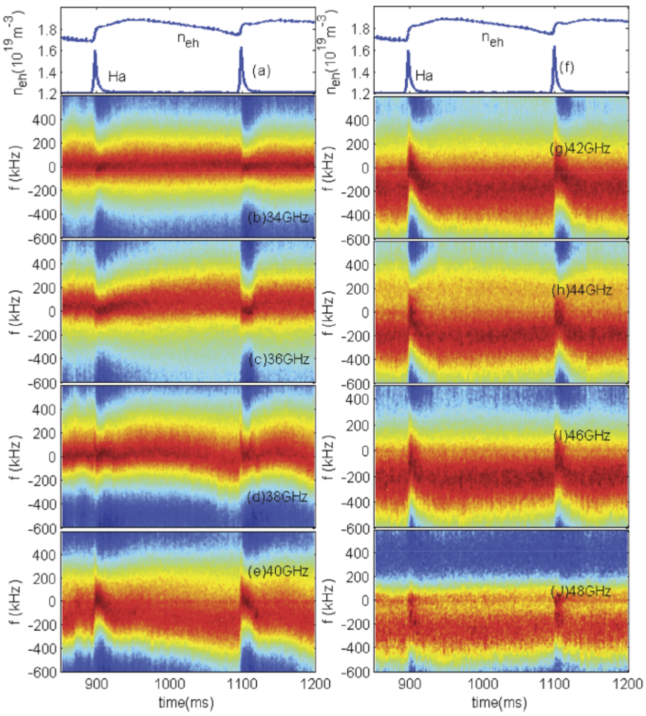

Figure 1: Spectrograms of 34, 36, 38, 40, 42, 44, 46, and 48 GHz X-mode DBS channels in shot 28498 on HL-2A.

SAMI-2: 2-D microwave Doppler backscattering at MAST-U

Roddy Vann[1], Joe Allen[1], Simon Bale[2], Finn Hambly[1], Charlie Vincent[3] and the MAST-U team[4]

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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. A first step is to measure the magnetic pitch angle at a variety of radial locations – in principle the current density can then be calculated from Ampère's Law. The 2-D Doppler backscattering technique measures the magnetic pitch angle by illuminating the plasma edge with a broad microwave beam (typically in the range 10-40 GHz). The Bragg back-scattering condition is most strongly satisfied perpendicular to the magnetic field since turbulent density fluctuations are elongated along magnetic field lines. Because the plasma is rotating, this back-scattering is Doppler-shifted away from the directly-reflected signal. Localising the Doppler-shifted power maxima therefore enables us to measure the magnetic field pitch angle. Different frequencies are mapped to radial locations using Thomson scattering.

The prototype 8-antenna Synthetic Aperture Microwave Imager (SAMI) successfully employed 2-D Doppler backscattering for the first time at MAST [1] and NSTX-U [2]. Results from MAST were presented at IRW12; at this meeting we will begin by providing a brief account of the campaign at NSTX-U.

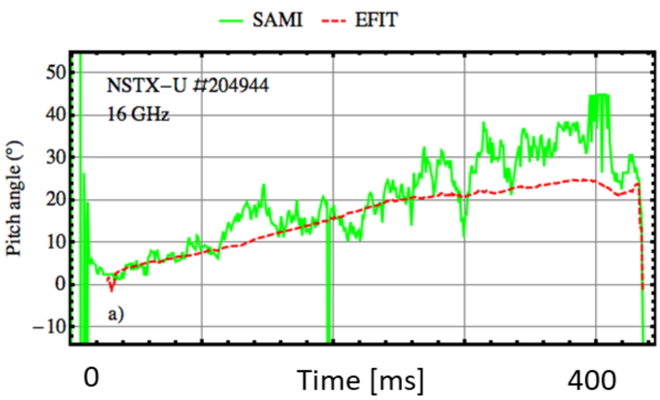

Figure: Comparison of edge pitch angle measured using SAMI and calculated by EFIT for NSTX-U shot 204944

The Synthetic Aperture Microwave Imager mark 2 (SAMI-2) is now being designed and built for deployment at the MAST-U spherical tokamak when it starts operations later in 2019. Building on SAMI's proof-of-principle measurements of the pitch angle, the objective of SAMI-2 is to make routine measurements of the edge current density. SAMI-2 has 32 dual polarisation sinuous antennas [3] and can simultaneously acquire at two RF frequences in the range 24-40 GHz (thereby enabling correlations between signals at two radial locations). The system is being designed and built at component level (employing surface mount rather than connectorised technology). The data acquisition system is demanding: we will be acquiring 256 analogue channels at a cumulative data rate of 160Gb/s. We will present the detailed design of SAMI-2 including our plans for exploitation at MAST-U.

The authors acknowledge funding from UK Engineering & Physical Science Research Council grants EP/S018867/1 and EP/L01663X/1.

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Dual-polarisation broadband sinuous antenna and RF downconverter design for the Synthetic Aperture Microwave Imager-2 diagnostic

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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]. The aim of SAMI-2 is to build on this methodology to produce higher quality pitch angle data simultaneously in multiple spatial locations, enabling calculation of the edge current density. This movement from proof of principle to production quality necessitates a major overhaul of the design [2].

There will be 32 antennas in the SAMI-2 array, a fourfold increase on SAMI, as minimising the sidelobe level is key to ensuring maximum resolution in the reconstructed Doppler backscattered power map. SAMI-2 will actively probe the plasma with two frequencies simultaneously. Sinuous antennas are the ideal choice for SAMI-2. They have a wide field of view and are broadband whilst remaining relatively small in diameter. Their planar shape allows them to be etched onto a printed circuit board (PCB), ensuring correct alignment of the polarisations and good repeatability. Two orthogonal sinuous antennas can be interleaved on either side of a PCB to create a dual-polarised version. Polarisation separation is necessary in 2D DBS for differentiation of the O- and X-mode cut off surfaces, as without it the uncertainty in backscattering location is significant.

When designing a sinuous antenna for use up to high frequencies the central area becomes small making the connection with its feed network the most challenging part. A dual-polarisation sinuous antenna with frequency up to 40 GHz, shown in figure 1, has been designed and tested in conjunction with a microstrip balun for use in the SAMI-2 array. An RF downconverter module to mix the two polarisations' signals with two local oscillator frequencies has been designed. It uses four Analog Devices' ADMV1014 surface mount IQ downconverters and four RF microstrip power dividers to produce the IF outputs to send to analogue to digital converters.

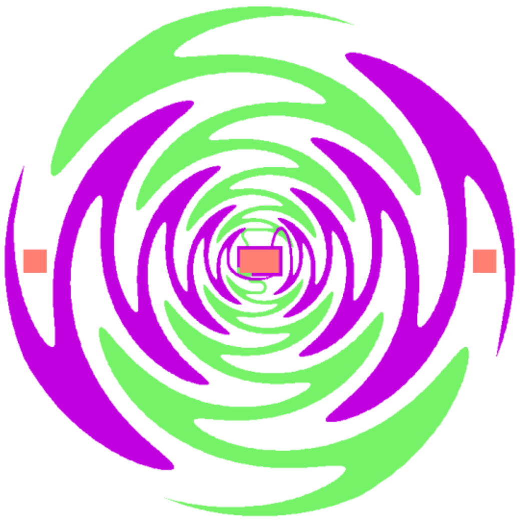

Figure 1: Artwork of the dual linearly polarised sinuous antenna. Slots in the substrate are shown in orange, the central slot is plated through so as to ensure connection with the microstrip balun inserted into the slots orthogonally to the antenna.

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[2] R.G.L.Vann *et al*. at IRW14

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Correlation Doppler Back-Scattering on ASDEX Upgrade: optimisation for extended turbulence spatial structure studies

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The spatial structure of turbulence is a key element for setting the turbulent transport rate in tokamaks. Measuring its different characteristics can bring constraining information for the validation of first principle turbulence codes, as they result from non-linear development of instabilities and interaction between disparate scales and flows as well. To this end, correlation or multi-point Doppler back-scattering, in addition to wavenumber spectra, can provide typical eddy size (e.g. correlation length), eddy anisotropy and eddy tilting, fluctuation velocity shearing and decorrelation rates. On ASDEX Upgrade, several Doppler back-scattering channels have been installed since 2014, sharing the steerable antenna of the IPP W band channel. They form now an ensemble of 4 coupled channels in W and V bands optimised for correlation or multi-point studies, thanks to several hardware/scheme improvements which limit spurious contributions. The capabilities of the systems will be illustrated by correlation lengths measurements in L-mode and H-mode, and by the measurement of eddy characteristics in different regimes and along the plasma radius.

Doppler reflectometry at Wendelstein 7-X

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The approximately quasi-isodynamic stellarator Wendelstein 7-X (W7-X) is equipped with multiple Doppler reflectometry systems. These are mainly located at the outboard mid plane of an elongated bean shaped plane, which represents a corner of the five-fold symmetric device. Here, the magnetic field scales approximately as $1/R$ (R being the major radius) and the flux surface curvature is large to ensure good wavenumber resolution. The local co-existence of a helical magnetic well and negative magnetic field curvature at the measurement position favors the investigation of trapped particle instabilities. In W7-X, power exhaust is achieved by means of an island divertor, which utilizes the $5/m$ resonance with poloidal modenumbers m ranging from four to six for the available magnetic configurations with varying edge rotational transform. Hybrids of these magnetic configurations allow to study the influence of internal islands. This contribution introduces the systems and presents results from the latest experimental campaign. It focuses mainly on measurements obtained from a monostatic Doppler reflectometer system (W-band) with extraordinary wave polarization. A large shot-to-shot variation of the peak densities ($n = 2 - 12 \cdot 10^{19}\,\mathrm{m}^{-3}$) allows resolution of the SOL (island) region up to the plasma core. The key issue in the analysis is the validation of the radial electric field E_r in the confined region, which is for stellarators an important quantity to understand neoclassical transport. The process of enhanced scattering in the complex SOL island geometry is illuminated by means of full-wave simulations. The current fixed tilt angle of the system limits the investigations across a broader fluctuation wavenumber spectrum but large-scale MHD modes and filaments are frequently observed and the influence of varying pressure gradient lengths on the observed fluctuations is discussed. A novel phased array antenna that steers the microwave beam by $\pm 20^\circ$ [1] extends the system's abilities towards the investigation of broader wavenumber spectra.

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First V-band Doppler reflectometer results from the OP1.2b campaign in Wendelstein 7-X

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Wendelstein 7-X is a novel kind of optimized stellarator in which the concept of quasi-isodinamicity is used to reduce drift orbit losses caused by collisions and the three-dimensional magnetic field inhomogeneity, thus addressing the traditional low confinement of stellarators at low collisionalities. This device, which began operation in 2016 [1], has conducted its third experimental campaign (OP1.2b) between the months of August and October of 2018. The diagnostic layout of Wendelstein 7-X includes a several reflectometer systems [2]. For this work, we will consider one of the monostatic frequency hopping Doppler reflectometers installed at the elliptical toroidal section. This system uses frequencies in the V-band with O-mode polarization and probes the plasma from an equatorial antenna with a fixed injection angle. The routinary use of boronization to condition the wall during the OP1.2b campaign allowed substantially higher densities to be achieved in H plasmas than in preceding campaigns [3]. Thanks to this, density profiles compatible with operation for the V-band DR were typically achieved, thus allowing for the evaluation of rotation and fluctuation amplitude under a wide number of magnetic configurations and operational scenarios. In this work we will report the main experimental results obtained by the V-band reflectometer during OP1.2b, and discuss the first analysis carried out from them: in the first place, a systematic characterization of the measurements of turbulence rotation profiles is carried out to describe the influence of density and heating power under four most frequent magnetic configurations. For a number of relevant cases, these profiles are compared to those measured with other diagnostics and to neoclassical predictions. Based on this, a first discussion is carried out on the influence on the profiles of several parameters of the configuration such as neoclassical optimization, rotational transform, edge island width and position, etc. Another aspect of particular interest is the suppression of turbulence associated to the presence of strong velocity shear layers which has been related in the literature to the formation of transport barriers [4]. This can be studied in W7-X thanks to the steep rotation sign reversal that typically appears around the LCFS when the ion root E_r in the confined region transits to the electron transport-dominated positive electric field in the SOL. To this end, several parameters such as the E_r variation, E_r value at the SOL or the turbulence amplitude around the shear layer are calculated and included in the aforementioned discussion. Finally, the probing frequency at which the mentioned sign reversal is observed can be used to determine the density at the separatrix. This measurement is compared to density profiles from other diagnostics, such as the Alkali-beam or the Thomson scattering, and discussed under a number of different configurations and scenarios, including divertor detachment.

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Full wave numerical simulations of cross polarization Doppler backscattering

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Control over the instability prone pedestal region of an H-mode tokamak plasma is vital to the viability of achieving a sustained burning plasma. Cross polarization Doppler backscattering (CP-DBS) is a novel diagnostic technique which enables local measurements of instability driven magnetic perturbations. Use of CPDBS in conjunction with conventional Doppler backscattering (DBS) enables the local measurement of both density and magnetic fluctuations. MAST CP-DBS experimental shots 30150 and 30422/3 have measured intermediate fluctuation wave numbers $3 \lesssim k_\perp \rho_i \lesssim 4$ at the top of the pedestal. However, the experimental pedestal background density length scales can be as low as $Ln \approx 1.72cm$ for CP-DBS and $Ln \approx 1.13cm$ for DBS which is comparable to the vacuum wavelengths of the probing beams $0.40 < \lambda_i(cm) < 1.0$. Scattering in this strongly in-homogeneous environment may require consideration of non-WKB interactions between the ordinary (O) and extraordinary (X) modes. The influence of polarization interaction on scattering efficiency is particularly concerning when the radial separation between the O-mode and X-mode cutoff surfaces is small, causing $|k_o - k_x| << \frac{2\pi}{Ln}$ where k_o and k_x are the O-mode and X-mode wave numbers, respectively.

3D modeling has been performed using the full wave code EMIT3D with the fluid Hermes model, under the BOUT++ framework, as an input for electromagnetic turbulence. A 55GHz wave is launched perpendicular to a homogeneous background magnetic field with zero curvature, at a angle of $\theta = 7.0$ degrees to the normal of the beam's cutoff surface. The beam propagates into the pedestal until it interacts with it's cutoff surface with $L_n \approx 2.0cm$. Electromagnetic turbulence around the cutoff contains several dominant poloidal wave numbers of $0.1 < k_\perp \rho_i < 3.0$. However, the beam launch angle is chosen to match the Bragg condition for backscattering at $k_\perp \rho_i \approx 2.8$ which is comparable to experimental wave numbers. Backscattering along the beam path passes through the antenna and is then detected.

Remaining consistent with experimentally inferred values, the ratio of the fluctuations levels was kept constant at $(\delta B/B)/(\delta n/n) = 1/20$. The scaling of the backscattered response was measured for a range of $10^{-5} < \delta n/n < 10^0$ where the magnetic fluctuation level is also varied to maintain the $(\delta B/B)/(\delta n/n) = 1/20$ ratio. The fluctuation amplitude is defined as the RMS value taken at the probing beam's corresponding cutoff. Both modes were found to have DBS electric fields scale linearly with $\delta n/n$, and had a non-linear saturated backscattered response at very high $\delta n/n \approx 10^0$. Both modes were also found to have enhanced non-linear CP-DBS signals at larger $\delta n/n$. The O-mode CP-DBS signal became enhanced at $\delta n/n \approx 10^{-1}$ while the X-mode CP-DBS signal became enhanced at $\delta n/n \approx 10^{-2}$. Both the O-mode and the X-mode CP-DBS signals featured a non-linear saturation near to $\delta n/n \approx 10^0$.

Previous electrostatic 2D full wave simulations have studied DBS to determine the $\delta n/n$ fluctuation level required to cause the enhanced non-linear response for both the O-mode and the X-mode. This was found to be a function of the poloidal launch angle θ. Larger θ caused the enhanced non-linear response to occur at weaker $\delta n/n$. Comparing these 2D results to our 3D results, both the O-mode and the X-mode DBS response is consistent with essentially no enhanced scattering. Magnetic scattering was not studied in the 2D simulations so it is not possible to compare the CP-DBS response. However, the 3D EMIT3D simulations suggest that the CP-DBS response is more susceptible to enhanced scattering at weaker $\delta n/n$.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053, the RCUK Energy Programme [grant number EP/N509760/1] and the DTP 2016-2017 University of Strathclyde.

Modelling the effects of misaligning the probe beam and magnetic field in Doppler backscattering measurements

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The use of Doppler Backscattering (DBS) in spherical tokamaks is challenging since the magnetic pitch angle can be large (up to 35°, compared to 15° in standard tokamaks like JET). Moreover the pitch angle varies both spatially and temporally. Hence, the probe beam is generally not perpendicular to the magnetic field. This misalignment, which affects the backscattered signal, can be empirically optimised with 2D beam steering [1]. However, empirical optimisation is inefficient, requiring repeated pulses with different diagnostic settings, and may not always be possible. Hence, it is important to develop a model to quantitatively account for the effect of the misalignment on the backscattered signal, avoiding the need to optimise empirically.

We used beam tracing (Torbeam [2] as well as a newly written code) and the reciprocity theorem to derive a model for the backscattered power and its dependence on the mismatch angle. Unlike previous work on reciprocity [3], our model works for both the O-mode and X-mode in tokamak geometry. We present the analytical results of our model, providing an understanding of the effect of the mismatch angle. In addition, it also gives interesting insight into how the DBS signal is localised. We implemented this model numerically and evaluated the validity of the various approximations used in the analytical derivation. More importantly, the numerical implementation enables our model to be accurately applied to experimental measurements, allowing one to correct for the effect of the mismatch angle.

Acknowledgements

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Validation of full-f global gyrokinetic modeling results against the FT-2 tokamak Doppler reflectometry data using different synthetic diagnostics

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Two versions of the X-mode Doppler reflectometry (DR) synthetic diagnostics are developed in the framework of the ELMFIRE global GK modeling of the FT-2 tokamak ohmic discharge. In the "fast" version [1] DR signal is computed in the linear theory approximation using the reciprocity theorem utilizing the probing wave field pattern provided by computation taking into account the 2D plasma inhomogeneity effects, whereas the alternative "slow" version DR synthetic diagnostic is based on the full-wave code IPF-FD3D [2] describing the probing and scattered wave propagation in turbulent plasma. The DR signal frequency spectra and the dependence of their frequency shift, width and shape on the probing antenna position are computed and shown to be similar to those measured in the high field side probing DR experiment at the FT-2 tokamak. The GAM characteristics provided by the measurements and by the synthetic DR are close within a 12% accuracy. However a substantial difference was found in the decay of the DR signal cross-correlation functions with growing frequency shift in the probing wave channels. The quick decrease of the radial correlation DR coherence observed in the experiment and full-wave synthetic diagnostic compared to the fast synthetic DR is attributed to the nonlinear effect of the probing wave phase modulation by the turbulence in the former two cases. The variation of the DR signal at growing incidence angle in experiment is also shown to be slower than predicted by both of the synthetic diagnostics presumably due to underestimation of probing wave phase modulation and consequent nonlinear saturation of the DR signal at lower incidence angles in modelling.

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Full wave modeling of Doppler backscattering from filaments

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It is recognized that the filaments have a significant effect on the anomalous energy and particle transport in the tokamak periphery. They are actively investigated using various diagnostics in this regard. Recently three studies of filaments using the Doppler backscattering (DBS) method have been performed in Globus-2 [1] and ASDEX-Upgrade [2, 3]. Backscattering from filaments manifests itself in approximately the same way as a burst of quasi-coherent oscillations of the signals of IQ detectors. Such signals are easy to describe in the Born approximation using the diagnostic weighting function [1]. However, the filaments in tokamaks differ noticeably in their size and intensity. With an increase in the amplitude of the filaments, it is necessary to consider the transition from linear scattering to nonlinear scattering up to the transition from backscattering to reflection from a moving filament. This problem can be solved only using a full wave code. Our simulation was carried out using finite-difference time-domain code IPF-FD3D in slab geometry [4]. We did not resort to using well-known non-linear MHD codes to determine filament parameters. In the simulation artificial filament-like perturbations were used, the parameters of which varied over a wide range. Modeling DOR signal was focused on the identification of the influence of the amplitude of the filament and its size on the shape and size of the DOR output signal. The results obtained largely explain the similarity of the IQ detector data registered in different tokamaks.

The work is supported by RSCF grant 18-72-10028 and Ioffe Institute.

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Recent progress in modelling the resolution and localization of Doppler reflectometry measurements

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Microwave Doppler reflectometry (backscatter) can offer perpendicular plasma velocity $u_\perp$ and turbulence wavenumber $k_\perp$ measurements with sub-millisecond temporal and mm spatial (radial) resolution. The minimal (e.g. ideal) diagnostic spatial localization and $k_\perp$ resolution are defined fundamentally by wave-physics and the probing beam / plasma geometry.
A previous study investigated the diagnostic measurement accuracy using 2D full-wave and weighting-function simulations (IPF-FD3D code) of a set of experimental V-band, upper X-mode Doppler reflectometer measurements from the edge region of ASDEX Upgrade L-mode discharges. The simulation results were contrasted with practical estimates obtained with beam tracing (Torbeam code) and analytic formulas [1].
In this contribution we present an update of this study using improved analysis techniques and an extended simulation database, with new discharge conditions (density and magnetic field) and a wider parameter range of probing frequencies, tilt angles etc. as well as O-mode polarization. In addition, a first assessment of lower X-mode probing capability is presented.

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Fullwave Doppler Reflectometry Simulations for Turbulence Spectra Using GENE and IPF-FD3D

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Doppler reflectometry is a microwave scattering diagnostic that uses the enhanced field strength at the cutoff layer to increase spatial localisation compared to regular scattering techniques. This complicates the calculation of the scattering efficieny, i.e. what amplitude of density fluctuation will result in what amount of backscattered power fraction. The fullwave code IPF-FD3D simulates the scattering process for each probed wavenumber, using as input the density fluctuation fields from the plasma turbulence code GENE. The scenarios that were modeled are ASDEX Upgrade discharges where experimental Doppler reflectometer data in both polarisations is available.

Experimental Doppler spectra and density fluctuation spectra from turbulence simulations show marked differences in the position and shape of the inertial range of the turbulence. It was found [1] that strong turbulent fluctuations can significantly change the overall shape of the spectrum, especially shifting the apparent position of the turbulent drive. The main effect is non-linear saturation of the signal at low and intermediate probed wavenumbers, and a non-linear enhancement at large wavenumbers. These effects are much more pronounced in X mode polarisation.

Recently, the fullwave code was optimised to efficiently simulate many more probing wavenumbers than before, significantly enhancing the confidence in the spectral comparisons. Furthermore, inital investigations of the sensitivity to the radial wavenumbers are presented.

[1] T. Happel, T. Görler, C. Lechte, M. Bernert, G. Conway, S. J. Freethy, P. Hennequin, C. Honoré, J. Pinzón, U. Stroth, and the ASDEX Upgrade Team. *Plasma Phys. Contr. Fusion*, **59** (5) 054009, 2017. doi:10.1088/1361-6587/aa645b.

Friday 24 May 2019	
08:30 - 09:00	**<u>L. Vermare</u>** : Perpendicular flows in Tore Supra plasmas
09:00 - 09:30	**<u>M. Peret</u>** : Perpendicular velocity evolution in the first plasmas of the WEST tokamak
09:30 - 10:00	**<u>T. Estrada</u>** : Turbulence $k_{\perp}$ spectrum and perpendicular plasma flow asymmetries measured using Doppler reflectometry at TJ-II plasmas
10:00 - 10:30	coffee break
10:30 - 11:00	**<u>K. Höfler</u>** : Study of poloidal asymmetries in the flow perpendicular to the magnetic field of the ASDEX Upgrade tokamak
11:00 - 11:30	**<u>S.J. Freethy</u>** : Measurements of the density-temperature cross-phase angle of turbulent flctuations at ASDEX-Upgrade and comparison to theory
11:30 - 12:00	**<u>R. Sabot</u>** : Trends emerging from a systematic analysis of a decade of fluctuation reflectometry measurements on Tore Supra
12:00 - 13:30	lunch
13:30 - 14:00	**<u>W. Lee</u>** : Effect of the quasi-coherent mode on the intrinsic rotation of ohmic plasmas in KSTAR
14:00 - 14:30	**<u>E. Trier</u>** : Comparison of poloidal correlation reflectometry measurements in W7-X and ASDEX Upgrade plasmas
14:30 - 15:00	**<u>V.A. Vershkov</u>** : Spatial Structure of Density Fluctuations in T-10 Tokamak
15:00 - 15: 30	**<u>A. Krämer-Flecken</u>** : Effects of the magnetic topology on turbulence in the SOL and plasma edge of W7-X
15:30 - 16:00	**<u>G.V. Zadvitskiy</u>** : Modelling of simultaneous measurements of turbulence correlation lengths and turbulence amplitudes using multi-channel radial reflectometry
16:00 - 16:30	Coffe Break & END
16:30 - 17:00	
17:00 - 17:30	
17:30 - 18:00	
18:00 - 18:30	
18:30 - 19:00	

Perpendicular flows in Tore Supra plasmas

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Flows play a key role in the performance of tokamak plasmas, primarily because they are known to stabilize MHD modes and to affect both neoclassical and turbulent transport. In particular, it is widely admitted that the radial shear of the perpendicular velocity reduces the turbulent transport by shearing the turbulent structures and that the radial profile of this velocity is crucial to access the H-mode regime.

What sets up and sustains large scale flows and their gradient is however not fully elucidated. One view is that nonambipolar neoclassical (i.e., collisional including 3D effects) fluxes generate a radial electric field in order that the resulting charge transport remains ambipolar. However, this would imply that the resulting poloidal and toroidal velocity should also be neoclassical. Since toroidal rotation is rarely neoclassical, one has to consider the alternative view, which is that the turbulence can generate toroidal and poloidal rotation, which together with the pressure gradient determine the radial electric field via the radial force balance.

In this contribution, we investigate the shape of the radial profile of the perpendicular velocity approaching the edge through several comparisons between gyrokinetic simulations using the GYSELA code [1] and experimental measurements obtained using Doppler Back-scattering system [2] in Tore Supra plasmas.

In particular, we will show how, in the simulations, the edge conditions (with or without limiter) affect the shear of the radial electric field at the edge. In addition, we will present simulations with a toroidal magnetic ripple and discuss its influence on the perpendicular flows in both neoclassical and turbulent simulations (with and without turbulence) and its possible role in the poloidal asymmetry observed in Tore Supra [3].

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[3] L. Vermare et al., Physics of Plasma (2018)

Perpendicular velocity evolution in the first plasmas of the WEST tokamak

Mathieu Peret[1], Laure Vermare[2], Nicolas Fedorczak[1], Cyrille Honoré[2], Pascale Hennequin[2], Frederic Clairet[1] and the WEST team

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Edge plasma flows present a huge interest in the quest for controlled fusion. Indeed, the radial profile of the perpendicular velocity and more particularly the well, which establishes close to the last closed flux surface, is commonly assumed to be linked to the transition to a high confinement regime (H-mode) through the effect of the velocity shear on turbulence [1]. Doppler reflectometry is particularly appropriate to measure the radial profile of the velocity of structures following the background flows [2].

This contribution aims at summarizing the first observations of the Doppler backscattering instrument during the last experimental campaign on the WEST tokamak. Effects of heating systems, geometry configurations and Magneto Hydrodynamics instabilities on the radial profiles of transverse velocities are investigated here. As expected, the measurements show that the increase of the heating power results in an increase of the edge velocity shear but the deepening of the profile is limited by the development of MHD instabilities. The geometry of the plasma is also known to affect the velocity profile. An ion diamagnetic drift towards the X-point is favorable to increase the shear and to reach the H-mode [3]. The experimental observations on WEST point out this behavior on WEST.

Keywords : *Fusion plasmas, WEST tokamak, shear flows*

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Turbulence $k_\perp$ spectrum and perpendicular plasma flow asymmetries measured using Doppler reflectometry at TJ-II plasmas

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Dedicated experiments have been carried out in the stellarator TJ-II for a systematic comparison of turbulence wavenumber spectra and perpendicular rotation velocity measured by Doppler Reflectometry (DR) at poloidally separated positions on the same flux-surface [1]. The rationale behind this study is twofold, namely, validation of the spatial localization of instabilities predicted by gyrokinetic simulations in stellarators and validation of the electrostatic potential variation on the flux surface as calculated by neoclassical codes and its possible impact on the radial electric field.

In stellarators, the geometric properties of the field lines, which affect instabilities, vary over the magnetic surfaces much more than in tokamaks. As a consequence, the unstable modes appear in simulations more localized in stellarators than in the tokamak counterpart. In TJ-II, gyrokinetic simulations show that the electrostatic instabilities are localized in narrow stripes along certain magnetic field lines, having the maximum amplitude in locations of bad magnetic field line curvature and small local magnetic shear [2]. These simulation results indicate that the amplitude of unstable modes can be significantly different in regions poloidally separated and accessible by the DR system installed in TJ-II [3]. Thus, the predicted localization of instabilities has motivated a number of experiments in TJ-II for a systematic comparison of the perpendicular wavenumber spectra measured at two poloidally separated positions using DR.

On the other hand, in stellarators, it is the neoclassical transport that determines the electric field. In most cases, neoclassical calculations only consider the lowest order electrostatic potential that only depends on the flux surface label, and gives the radial electric field. However, variations of the neoclassical electrostatic potential over the flux surface, so called φ_1, can be relatively large under certain plasma conditions, in particular at low collisionalities, giving electric fields tangential to the flux surface. In addition, φ_1 may impact the local radial electric field through its radial variation [4]. This possible impact has been studied in this work by the comparison between the perpendicular rotation velocity of the plasma turbulence at two poloidally separated positions using DR.

Different plasma scenarios have been investigated for a systematic comparison of DR measurements at poloidally separated positions in the same flux-surface; namely, different plasma profile shapes, ECH vs. NBI heated plasmas and standard vs. high rotational transform magnetic configurations. This work focuses on the description of these experimental results and how they compare with numerical simulations.

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Study of poloidal asymmetries in the flow velocity perpendicular to the magnetic field of the ASDEX Upgrade tokamak

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Shear flows are the main players to decorrelate turbulence. The propagation velocity of turbulent density fluctuations perpendicular to the magnetic field is measured by Doppler reflectometry. It comprises the E×B velocity and the phase velocity characteristic for the probed structure size. The latter can often be neglected in the ASDEX Upgrade plasmas under consideration. Therefore the poloidal dependence of the measured velocity is expected to mainly follow the poloidal change of the electric field, which is inversely proportional to the distance between flux surfaces, and the magnetic field, which decreases with the major radius.
Several Doppler reflectometer channels at various poloidal positions are used to perform poloidally resolved flow velocity measurements at ASDEX Upgrade. Comparing the perpendicular velocity at similar magnetic flux surfaces and similar structure sizes reveals an asymmetry which cannot be explained by the poloidal variation of the E×B drift alone. This behaviour has also been observed on the Tore Supra tokamak [1] and the TJ-II stellarator [2]. This contribution presents asymmetry studies at ASDEX Upgrade including a comparison to charge exchange recombination spectroscopy, specially focusing on poloidal angles between 0° to +45° with respect to the mid-plane on the low field side.

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Measurements of the density-temperature cross-phase angle of turbulent fluctuations at ASDEX-Upgrade and comparison to theory

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The cross-phase angle between turbulent temperature and density fluctuations, α_{nT}, is measured using the cross-correlation of co-located reflectometry and Electron Cyclotron Emission (ECE) measurements. With the constraint that the two diagnostics must measure within a radial correlation length of each other, the uncertainty in the relative measurement positions is mitigated by utilising a channel comb in the ECE diagnostic. It is observed that low frequency fluctuations are suppressed in the cross-correlation with ECE and significant coherence is only observed using the reflectometer amplitude fluctuations. These observations are investigated with a series of full wave simulations of the reflectometer using synthetic turbulence generated by GENE gyrokinetic simulations which also establishes the correct phase relationship between fluctuations in amplitude and phase and the underlying density fluctuations. It is found using the Born approximation that this relationship depends on the effective curvature. The α_{nT} measurement is then used to put a unique constraint on linear, quasi-linear and fully non-linear gyrokinetic models of the plasma turbulence. The experimental plasma is shown not to have a dominating ion-scale driving mode and it is shown using non-linear gyrokinetic simulations that α_{nT} lies in between the linear values for the Ion Temperature Gradient and Trapped Electron modes, in quantitative agreement with the experiment. The measured α_{nT} is then used to constrain a quasi-linear Trapped Electron Gyro Fluid model, where an multi-parameter optimisation framework VITALS is used to explore agreement between theory and experiment.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053, from the RCUK [grant number EP/P012450/1] and is supported by the US DOE under grants DE-SC0006419 and DE-SC0017381. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Trends emerging from a systematic analysis of a decade of fluctuation reflectometry measurements on Tore Supra

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Turbulence is ubiquitous in fusion plasmas, increasing energy, particle and impurity transport. On Tore Supra, the core reflectometer (105-155 GHz, D-band, X-mode) probed the plasma from the low-field side (LFS) to the high-field side (HFS). It operated from 2002 until Tore Supra's last plasma in 2011. It could perform profile (fast sweeps) or fluctuation measurements (hopping mode).

A systematic investigation of the measurements performed with this reflectometer is being carried out. This analysis covers 6000 Tore Supra plasma discharges and more than 350 000 frequency step measurements. A data reduction based on the decomposition of the frequency spectrum in a set of components was first applied. It reduces the thousands of values of a frequency spectrum to a handful set of parameters [1].

The contribution of the broadband component (EBB) to the total spectrum power is observed to be systematically lower in the linear Ohmic confinement (LOC) regime than in the saturated Ohmic confinement (SOC) regime. Investigations point out the effective collisionality as a key parameter to interpret the difference between LOC and SOC regimes. A transition of the dominating instability from Trapped Electron modes (TEM) to Ion Temperature Gradient modes (ITG) could explain the observed spectral changes. This interpretation is supported by analysis of the dependence of density peaking on collisionality and previous GENE simulations of LOC and SOC discharges [2].

The spectrum characteristics were also investigated in L-mode plasmas with ICRH or LH heating. Similar trends of the BB components with collisionality were observed in L-mode plasmas, compared with the Ohmic case, suggesting a similar explanation by linking the effect of collisions on frequency on the underlying instabilities and hence the frequency spectra [2].

This database analysis motivates additional studies by full-wave and gyrokinetic simulations, in order to confirm the suspected link between the reflectometry spectrum and the turbulence instabilities. The D-band reflectometer is now reinstalled on WEST (Tungsten (W) Environment in Steady-state Tokamak). The database will be expanded to WEST discharges to include measurements in different plasma conditions (X-point divertor, high aspect ratio, metallic environment etc.).

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Effect of the quasi-coherent mode on the intrinsic rotation of ohmic plasmas in KSTAR

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The studies of quasi-coherent modes (QCMs) on various tokamaks such as TEXTOR, HL-2A, and KSTAR have shown a common phenomenon that both the QCMs and plasmas poloidally rotate toward the electron diamagnetic direction [1-3]. The poloidal rotation of the QCMs or plasmas in the electron diamagnetic direction could indicate their toroidal rotation in the counter-current direction. Since the QCM is known to have characteristics similar with those of the collisionless trapped electron mode (CTEM), the phenomenon can imply that the CTEM (or QCM) or its driving parameter is responsible for the intrinsic toroidal rotation in the counter-current direction. To verify this hypothesis, more than 80 KSTAR ohmic discharges, in which QCMs were observed by the MIR system [3], have been analyzed, and the initial result will be presented. *This work is supported by the Ministry of Science and ICT of Korea under the KSTAR project and the NRF of Korea under the contract numbers NRF-2015M1A7A02002627 and NRF-2014M1A7A1A03029865.

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Comparison of poloidal correlation reflectometry measurements in W7-X and ASDEX Upgrade plasmas

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Poloidal correlation reflectometry (PCR) is a technique based on the comparison of the reflected signals received by a series of antennas at different toroidal and poloidal locations, which allows the evaluation of the velocity of the density structures. The PCR system previously used at TEXTOR was later installed at ASDEX Upgrade [1]. It uses an O-mode polarized incident wave in the Ka (24-40 GHz) or U-band (40-60 GHz), with an in-vessel array of one transmitting and four receiving antennas. Recently, a similar diagnostic working in the Ka-band has been installed in W7-X [2, 3].

In this contribution, the mean flow and turbulence properties are compared in ASDEX Upgrade and W7-X plasmas with similar local properties, from the mid-radius to edge region. In particular, we will focus on the turbulence autocorrelation time and the mean flow velocity. A possible upgrade of the diagnostic for the next ASDEX Upgrade campaign will also be presented.

References

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Spatial Structure of Density Fluctuations in T-10 Tokamak.

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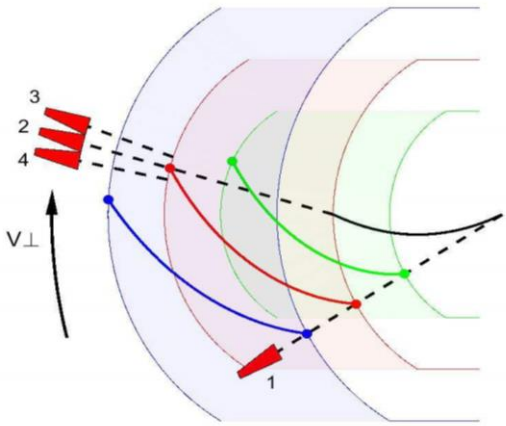
The report continues and expands investigations of the spatial variation of small-scale density fluctuation characteristics. The 3D structure of the density fluctuations was measured by means of correlation reflectometry using the new T-10 antenna set. The four antenna arrays were set at poloidal angles 0, 60, 120 and 180° to investigate poloidal asymmetry of fluctuation amplitudes and radial correlation lengths. Experiments confirm previously found strong poloidal amplitude asymmetry of Broad Band (BB) and Quasi-Coherent (QC, typically 110 - 170 kHz) and uniform poloidal distribution of Stochastic Low Frequency (SLF, 0 - 50 kHz) of density fluctuations. New results of correlation reflectometry support previously found significant difference of the properties of these fluctuation types.

For the first time reflectometer data are compared with the measurements of five channel Heavy Ion Beam Probe (HIBP) diagnostic. Simultaneous registration HIBP signals from 5 poloidally separated points enabled poloidal correlation measurements. The spatial position of HIBP also provided the unique opportunity of Long Range Correlation (LRC) measurements along the field lines between reflectometry and HIBP.

Radial correlation at four poloidal angles were measured to reveal poloidal variation of correlation function for different fluctuation types. The significant decrease of the radial correlation lengths towards high magnetic field side (HFS) observed for all turbulence types. Correlation of SLF and QC fluctuations at low field side (LFS) remains high at radial separation up to 5 cm.



Antenna arrays were installed at ports separated by ¼ of torus toroidally at LFS and HFS and gave a unique possibility to measure LRC correlations along the magnetic field line at both torus circumference. No correlation was observed for BB that means that longitudinal correlation length is much shorter than 2.5 meter. High correlations up to 30% were observed for SLF and QC fluctuations. The schematics of LRC is shown in Figure. Reflection radii are chosen by frequency variation of the launched wave from shot to shot in a series of reproducible discharges. Reflectometers in different ports use ordinary mode probing and have the same frequency provide reflection from the same magnetic surface. In order to investigate possible influence of the effect of the finite propagation velocity along the field line two experimental series were carried out with simultaneous change of B_T and I_P direction. In this case magnetic field line remains the same but direction of poloidal rotation is reversed.

The technique of the LRC correlations with reflectometry may be considered as the new approach for estimations of current profile in present and future reactor grade tokamaks. Modes with constant phase along the magnetic field line (such as Alfven Eigen Modes) should be used for such measurements. The work was supported by Rosatom contract and partially by Russian Science Foundation project 14-22-00193.

Effects of the magnetic topology on turbulence in the SOL and plasma edge of W7-X

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For the OP1.2 campaigns W7-X is equipped with a inertial cooled Graphite divertor. To monitor the effects of different magnetic configurations on the scrape off layer (SOL) and the plasma edge an O-mode Poloidal Correlation Reflectometer is used which allows to monitor low *k*-turbulence. Operating in the density range $0.6 \times 10^{19}\,\mathrm{m}^{-3}$ to $2 \times 10^{19}\,\mathrm{m}^{-3}$ it covers a large part of the SOL and the plasma edge. It allows in low to medium density discharges to monitor the last closed flux surface (LCFS) and the associated shear layer.

In this presentation the effects caused by (i) control coils and (ii) the plasma current on the SOL is presented for the magnetic configuration with a $5/5$-island in the SOL. Both, the plasma current and the control coils change the edge iota and have an effect on the size of the $5/5$-island. The observed movement of the LCFS and its shear is compared with simulations and discussed. Furthermore different magnetic configurations as high and low iota are investigated, too.

The coherence spectra of antenna pairs for different poloidal separations is investigated. Using a decomposition method for the measured coherence spectra allows to characterize the turbulence spectra with respect to e.g. broad band turbulence and quasi coherent modes. A strong reduction of the broad band turbulence is observed in the vicinity of the LCFS. This is evidence for the suppression of low *k* turbulence at the shear layer at the LCFS. Such an effect is expected and will be discussed, too.

Modeling of simultaneous measurements of turbulence correlation lengths and turbulence amplitudes using multi-channel radial reflectometry.

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In Magnetic Fusion plasmas, due to drift-wave turbulence, particle and energy anomalous transport increases leading to a degradation of Fusion machine performance. Therefore turbulence research is one of key objects of interest. In experiments there are various diagnostics able to obtain information about the turbulence [1]. But usually the diagnostic signal interpretation is quite tricky.

The talk will focus on radial correlation reflectometry. Using multichannel correlation reflectometry it is possible to measure turbulence correlation function and turbulence amplitude. For a long-scale weak turbulence density variation amplitude can be expressed through the reflectometry signal phase [2, 3]. However, in order to use this formulation, turbulent wave-number spectra or, at least, the correlation length have to be measured first. Using correlation reflectometry it is possible to get access to turbulence correlation function in the linear regime [4, 5], or to the correlation length in the non-linear regime [2].

The IPF-FD3D full wave code [6] with the ELMFIRE [7] gyrokinetic code turbulence data as input was used to simulate FT-2 high field side radial reflectometry synthetic diagnostic. Synthetic signals were analyzed using proposed techniques. The same ELMFIRE input was also used in Helmholtz equation solver to provide one-dimensional synthetic diagnostic results. Computations were done using various turbulence amplitudes to study weak turbulence regime and reach a transition to nonlinear regimes in one and two dimensional cases. Differences between signals of one-dimensional and two-dimensional computations and signals interpretations will be discussed.

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