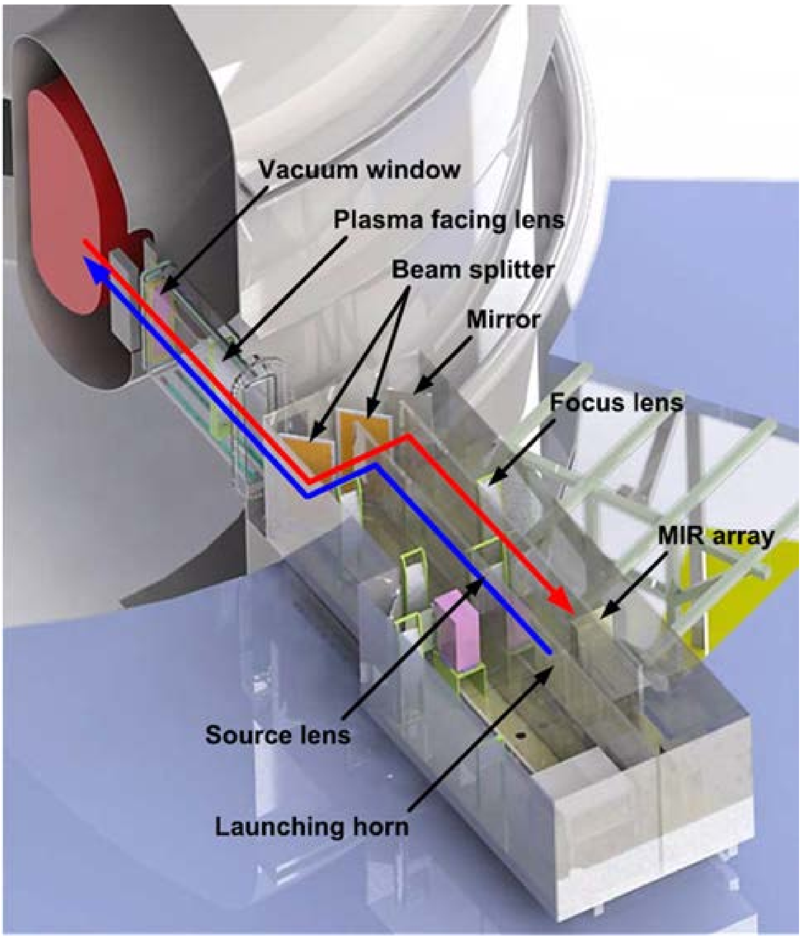
International Reflectometry Workshop
(IRW13)

May 10th - 12th, 2017

NFRI HQ, Daejeon, Korea



http://irw13.nfri.re.kr

IAEA International Atomic Energy Agency

NFRI 국가핵융합연구소 National Fusion Research Institute

Technical Program Overview

- (B1F) Room.B120, NFRI HQ

May 10th, 2017 (Wednesday)	
9:00~9:10	**Opening & Welcome Address**
9:10~10:40	**Session 1** **- ITER**
	Coffee Break
11:00~12:00	**Session 2** **- Numerical Simulation for Design and Data Analysis**
	Lunch Break (SELF HOSTED)
14:00~15:30	**Session 3-1** **- Theory and Experiments for Doppler reflectometer**
	Coffee Break
15:50~16:50	**Session 3-2** **- Theory and Experiments for Doppler reflectometer**
16:50~17:40	**Discussion and Adjourn**
May 11th, 2017 (Thursday)	
9:00~10:30	**Session 4-1** **- Fluctuation Measurement**
	Coffee Break
10:50~11:50	**Session 4-2** **- Fluctuation Measurement**
	Lunch Break (SELF HOSTED)
14:00~15:30	**Session 5-1** **- Density Profile Measurement**
	Coffee Break
15:50~16:20	**Session 5-2** **- Density Profile Measurement**
16:20~17:10	**Discussion and Adjourn**
17:40~	***Welcome Dinner***
May 12th, 2017 (Friday)	
8:30~9:00	**KSTAR tour**
10:00	*More presentation*

※Guidance for Oral/Plenary Speakers.

- Official language: English
- File format: photoshop (.pdf), powerpoint (.ppt, pptx)
- If you want to change your presentation file, Please bring latest version in USB before the session
- Recommended presentation time:
    - 30min.= 25min.(presentation) + 5min.(discussion)

May 10th, 2017 (Wednesday)

ITER

(Chair: Seong-Heon Seo)

1. A. Sirinelli – Reflectometry infrastructure components developed at ITER Central Team
2. P. Varela – Recent design activities for the in-vessel components of the ITER Plasma Position Reflectometry diagnostic
3. Mark Smith - General overview of the ITER low field side reflectometer diagnostic system

Numerical Simulation for Design and Data Analysis

(Chair: Andreas Krämer-Flecken)

1. Filipe da Silva – Assessment of the measurement performance of the in-vessel systems of gaps 4 and 6 of the ITER Plasma Position Reflectometer using a FDTD Maxwell full wave code
2. J. Vicente – Application of 2D full-wave simulations to study plasma turbulence with conventional reflectometry
3. Filipe da Silva – Introducing REFMULF, a 2D full polarization code and REFMUL3, a 3D parallel full wave Maxwell code

Theory and Experiments for Doppler reflectometer

(Chair: P. Varela)

1. E. Gusakov – Benchmarking the global FT-2 tokamak gyrokinetic modeling results against the radial correlation Doppler reflectometry data
2. T. Tokuzawa – Progress of Frequency Comb Doppler Reflectometer System in LHD and Feasibility Study of Doppler Reflectometer for JT-60SA
3. T. Happel – Comparison of detailed experimental wavenumber spectra with gyrokinetic simulation aided by two-dimensional full-wave simulations

4. J. R. Pinzon – Power response in Doppler reflectometry

May 11th, 2017 (Thursday)

Fluctuation Measurement

(Chair: T. Tokuzawa)

1. Y. Sun – SYSTEMATIC STUDY OF CORE TURBULENCE BY REFLECTOMETRY FLUCTUATION FREQUENCY SPECTRA
2. A. Krämer -Flecken – Rotation and properties of plasma turbulence in W7-X measured by a PCR-system
3. W. Lee – Measurement of broadband fluctuations and comparative study with gyro-kinetic simulations
4. J. A. Lee – Measurements of quasi-coherent modes in KSTAR ohmic and ECH L-mode plasmas
5. P. Dhyani – Oscillatory EGAM Excitation by the Energetic Electrons Generated During the Sawtooth Crash in KSTAR

Density Profile Measurement

(Chair: E. Gusakov)

1. P. Molina-Cabrera – Millimeter-Wave Reflectometry on the Tokamak a Configuration Variable
2. R. B. Morales – New density profile reconstruction methods for X-mode reflectometry
3. S. H. Seo – Perfect Linear Frequency Modulation of Voltage Controlled Oscillator
4. R. B. Morales – Density profile reconstruction over blind regions for X-mode reflectometry 15:50

◎ Transportation

1. by Airport Limousine Bus (KRW 23,100, 2h 50min, Recommended)

○ Incheon Air port → **Daejeon**

- You can buy ticket from any ticketing kiosk at the 1st floor outside the Incheon airport building. The bus stop to Daejeon is "No. 9D" after crossing the street.

- Bus stops after exiting from the highway: Lotte Hotel - **Daejeon Government Complex-** Dongboo Cross Country Bus Terminal Center,

You should take off at the stop of **Daejeon Government Complex**

○ Government Complex Terminal → Toyoko inn Hotel : 10 min by walk

○ Government Complex Station → Yuseong Spa Station: 8 min by subway +

Yuseong spa Station ->Interciti Hotel : 12 min by walk

※ Government Complex Terminal → Interciti Hotel : Taxi (KRW 10,000 , 10min)

2. by Train

○ Incheon Air port → **Daejeon**

- KTX direct: (Airport → Daejeon Station, KRW36,100, 2h, not many trains)

- Airport→Seoul Station by subway (KRW 4,150, 1h) +

Seoul Station → Daejeon Station by KTX (KRW 23,700, 1h)

○ Daejeon Station → Government Complex station: 15 min by subway

Government Complex Station ->Toyoko inn Hotel : 10 min by walk

○ Daejeon Station → Yuseong Spa Station: 23 min by subway

Yuseong Spa Station ->Interciti Hotel : 12 min by walk

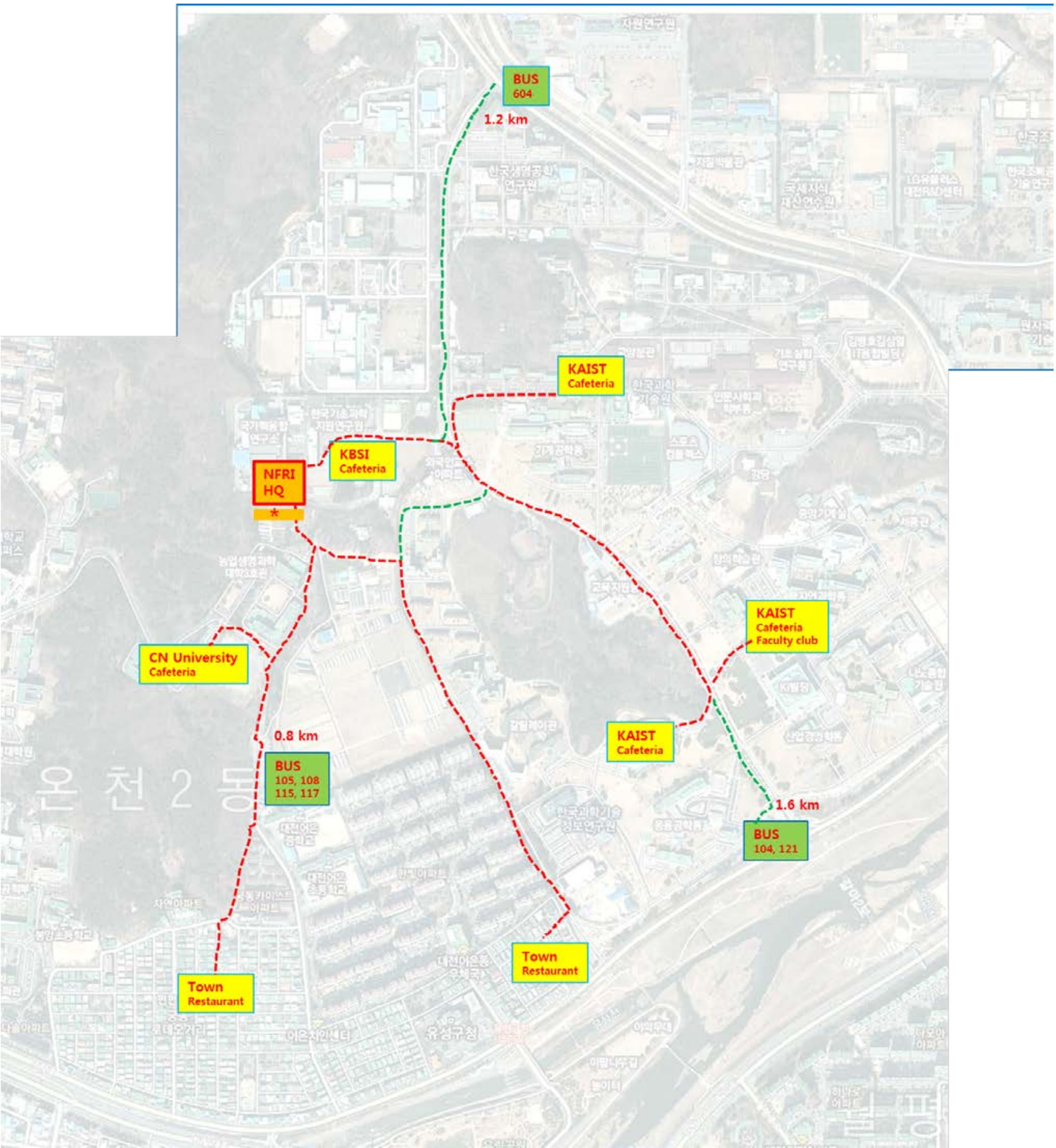
※ Daejeon Station → Hotels : Taxi (about KRW15,000 , 20 min)

◎ (Hotel to NFRI) : by Taxi (about KRW10,000 , 10min) or by Bus

no.604 (stop : Korea Aerospace Research Institute) - 10 min. on foot

no.105/108/115/117 (stop : College of Agriculture, Chungnam National University, the end of the line) - 5 min. on foot

no.104/121 (stop : Korea Advanced Institute of Science and Technology) - 15 min. on foot



*** gate is opened with an ID card. But there are many people in the morning.**

◎ Lunch (SELF HOSTED)

○ KBSI Cafeteria (KRW 4,000 / Korean Food)

○ KAIST Cafeteria (KRW 3,000 ~ KWR 5,000 / A Variety of choices available)

○ KAIST Faculty club (KRW 15,000 ~ KWR 30,000 / High quality and Quiet)

○ Town Restaurant (KRW 5,000 ~ 10,000)

ABSTRACT

Reflectometry infrastructure components developed at ITER Central Team

A. Sirinelli,[1,*] M. Dapena,[1] T. Giacomin,[1] J. Guirao,[1] P. Maquet,[2] V.S. Udintsev,[1] and G. Vayakis[1]

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ITER will have 3 independent reflectometry systems designed and built by different Domestic Agencies (DA). Their main measurement requirements are covering all the plasma radius: Low-Field-Side Reflectometry by United States DA is dedicated to plasma edge; Plasma Position Reflectometry by European DA measures the plasma-wall gap; High-Field-Side Reflectometry by Russian DA provides core plasma measurements. They are either localised inside the vacuum vessel or in the Equatorial or Upper Port Plugs.

ITER Central Team (IO-CT) role is to ensure these systems are well integrated into the machine and all the system requirements are fully propagated to the design developer. IO-CT has also the responsibility to develop some common features and interfaces. Two of them will be presented:

- Primary vacuum windows act as primary confinement barriers and ultra-high vacuum boundaries. Two different concepts are developed for microwave diagnostics: in-waveguide windows and more traditional ones allowing quasi-optical coupling. Both concepts and their recent developments will be presented.
- ITER vacuum vessel is a primary confinement barrier. Therefore, any component attached to it must demonstrate the non-aggression. To simplify the diagnostic developments, attachments to the vacuum vessel are being standardized by IO-CT. A generic boss concept has been developed and analysed for different sizes, localisations and external forces. A concept has also been proposed to attached in-vessel waveguides on these attachment.

These components are either Protection Import Components (PIC) or their designs include Protection Import Activities (PIA), therefore design processes and qualification activities have to follow strict requirements and monitoring.

New requirements are also sometimes introduced in the ITER project. Among them is the new operation scenario at 1.8 T. The impact study for ITER reflectometers will be presented.

These different developments and designs will be presented together with an update on ITER construction and expected research plan.

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

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Recent design activities for the in-vessel components of the ITER Plasma Position Reflectometry diagnostic

P. Varela[1] (on behalf of the PPR IST-Team)

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Abstract

This presentation reports on the recent design activities for the in-vessel components of the ITER Plasma Position Reflectometry (PPR) systems of gaps 4 and 6, namely: (i) the electromagnetic tests performed on the prototypes of the in-vessel waveguides and flanges, currently proposed for both the PPR and the High Field Side Reflectometry (HFS-R) diagnostics; (ii) the design optimization of the critical in-vessel waveguide components such as the 90-degree bend of gaps 4 and 6 and the 125-degree bend of gap 4; (iii) the preliminary nuclear, thermal and electromagnetic analysis of the in-vessel components; (iv) the design, optimisation and performance assessment of the in-vessel antennas; (v) the measurement of the total length of the transmission lines during operation; and (vi) the design changes required to accommodate the new concept proposed by the IO for the vacuum vessel attachments. The tests performed to the prototypes have shown that it is possible to manufacture stainless-steel copper-coated waveguides with adequate performance to satisfy the requirements of both the PPR and HFS-R systems. The tests of the waveguide flanges point to the need of new design that mitigates crosstalk while maintaining a straight-forward assembly sequence. The design development of the critical in-vessel waveguide bends has shown that it is possible to improve the performance of the baseline designs by optimising the hyperbolic-secant shape of the 90-degree bends considering only the PPR TE01 mode and by adopting the hyperbolic-secant geometry for the 125-degree bend. Concerning the engineering analysis of the in-vessel components, we've completed the nuclear analysis and both the thermal and electromagnetic analysis are on-going. For the latter, a FEM model of a vacuum vessel sector, including the PPR in-vessel components, is being developed from scratch. Following the decision not to use the high-gain antenna developed for the HFS-R system, we consider a pair of parallel quasi-sectoral asymmetric horns and assessed their performance considering the surrounding blanket modules and first-wall structures. The accurate inversion of the density profile from PPR data requires the precise calibration of the measured phase due to changes of the total length of the transmission lines due to thermal expansion. Here, we describe a robust and passive waveguide device that can be installed in-vessel to provide on-demand measurement during operation of the total length of the TLs. Finally, in the aftermath of the difficulties in validating the non-aggressive behaviour of the many and varied diagnostic attachments to the ITER vacuum vessel, the IO has proposed a standard approach based on the use of pre-designed attachments, the so-called bosses, for the attachment of diagnostic components to the vacuum vessel. The adoption of this new method required the redesign of the waveguide and 90-degree bend supports, which we report here.

GENERAL OVERVIEW OF THE ITER LOW FIELD SIDE REFLECTOMETER DIAGNOSTIC SYSTEM*

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The Low-Field- Side (LFS) Reflectometer is one of several reflectometer systems planned for ITER. The LFS Reflectometer microwaves reflecting off the O and X-mode cutoffs in the plasma, are used to probe the on and off-axis edge pedestal and scrape-off layer (SOL) electron density (n_e) profiles. The LFS reflectometer will also be used for core MHD and turbulence measurements on ITER. The LFS system includes the antenna and transmission line for a Doppler reflectometer for turbulence rotation measurements. The front-end components of the LFS Reflectometer are housed in an equatorial port plug. The current LFS Reflectometer design contains 6 circular waveguides that function as both launch and receive antennas, with penetrations through the diagnostic first wall providing access to the plasma. The millimeter waves are coupled quasi-optically to the corresponding waveguides outside the vacuum through double quartz windows and quasi-optical Gaussian telescopes. The reference design features 6 broadband multimode corrugated circular waveguide transmission lines. The total length of the waveguide run from launch/receive horn to source/detector is approximately 40 meters. Details of the current mechanical, thermal and instrumentation design of the diagnostics system will be presented.

Key Words: ITER, Microwave Diagnostics, Reflectometry

Assessment of the measurement performance of the in-vessel systems of gaps 4 and 6 of the ITER Plasma Position Reflectometer using a FDTD Maxwell full-wave code

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We conducted a first assessment of the measurement performance of the in-vessel components at gaps 4 and 6 of the ITER Plasma Position Reflectometry (PPR) with the aid of a synthetic Ordinary Mode (O-mode) broadband Frequency-Modulated Continuous-Wave (FMCW) refletometer implemented with REFMUL, 2D Finite-Difference Time-Domain full-wave Maxwell code. These simulations take into account the systems location within the vacuum vessel as well as their access to the plasma. Two plasma cases are considered, a baseline scenario from Fusion for Energy (F4E) and He plasma from ITER Org (IO). These two scenarios were considered more relevant to the PPR system because (i) they correspond to plasma scenarios expected to be used at the start of ITER operation and (ii) have different plasma densities, which allows us to simulate the behaviour of the PPR system on two different operating regions. The official plasma databases used (F4E and IO) lack information outside the separatrix, in the Scrape-Off Layer (SOL) region. We propose to extrapolate the SOL data from the available core plasma data using two different models: one with lower density and a fast decay to null density at the first wall, and a second one with higher density and a slower decay to non-null density at the first wall position. Turbulence may originate two different scattering effects: Bragg backscattering, occurring when the turbulence wavenumber k_f and the local wavenumber of the injected wave $k(r)$ are resonant: $k_f = 2k(r)$, and forward scattering, which becomes dominant for $k_f < 2k_A$ where k_A is the Airy wavenumber. To evaluate scattering effects we adopt two turbulence models: one with a low wavenumber spectra and another with high wavenumber components, allowing to simulate the effects of forward scattering with the first model and to consider the effects of Bragg back-scattering with the second. Concerning the radial distribution of the turbulence amplitude, we use a linear regime and a non-linear regime, which allows, in conjunction with the choice of spectra, to weight the influences of Bragg backscattering and forward scattering.

Abstract for 13th IRW, Daejeon, May 2017

Application of 2D full-wave simulations to study plasma turbulence with conventional reflectometry

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The problem of interpreting reflectometry measurements and inferring turbulence characteristics from a fusion plasma that is probed with a microwave beam remains complex. Numerical simulations are an important tool to improve the capabilities and reliability of those experimental measurements.

A well established 2D full-wave FDTD code, REFMUL [1], is used here to extend the understanding of conventional reflectometry measurements. The status of this research project is reported here where reflectometry simulations are performed using synthetic diagnostics similar to those found in experimental reactors by matching radiation patterns, using fixed frequency probing, and I/Q detection schemes for phase $\varphi(t)$ and amplitude A(t) measurements. To obtain numerical instances of the plasma, analytical models of turbulence or the output of gyro-fluid (e.g. GEMR) or gyro-kinetic codes (e.g. GENE) can be used. While results with analytical Kolgomorov like turbulence models are revisited and shown to provide valuable insights to reflectometry measurements, turbulence codes are nowadays capable of reproducing the experimental particle and power fluxes in selected plasma regimes with very good accuracy (e.g. see [2]). In order to compare experimental measurements with synthetic reflectometry simulations, it is aimed to obtain a complete work chain from measured turbulence properties through a full-wave code simulating reflectometry techniques in realistic gyro-kinetic simulations.

[1] F. da Silva *et al*, Journal of Computational Physics, **203**:467-492 (2005)

[2] A. E. White *et al*, Physics of Plasmas **20**, 056106 (2013)

Introducing REFMULF, a 2D full polarization code and REFMUL3, a 3D parallel full wave Maxwell code

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An important tool for the progress of reflectometry is numerical simulation, able to assess the measuring capabilities of existing systems and to predict the performance of future ones in machines such as ITER and DEMO. A novel 2D full-wave FDTD code, REFMULF, presented here is able to cope with full polarization waves, coupling the Transverse-Electric Mode (TE, X-mode) with the Transverse-Magnetic Mode (TM, O-mode) via a linear vector differential equation for **J** with a generic external magnetic field $\mathbf{B_0}$. This equation, coupling wave propagation, described by Maxwell curl equations to the plasma media, is solved using a modified Xu-Yuan kernel [1], [2] with extended long-run stability. The external magnetic field components of $\mathbf{B_0}$ lying on the propagation plane are responsible for linking the TE and TM modes. For a $\mathbf{B_0}$ purely perpendicular to the propagation plane, the code describes simultaneously O-mode and X-mode propagation. This code enlarges the possibilities of simulation of microwave reflectometry, including depolarization processes in turbulent plasmas, offering capabilities unavailable in present day 2D reflectometry codes.

REFMUL3, presently in an advanced stage of development, is a 3D full-wave code. Its numerical kernel shares a similar structure to the other 2D codes in the REFMULx family, but involves more equations to be solved, Furthermore, its 3D nature translates into increasing the grid-count by two or three orders of magnitude when compared with 2D codes., making the computational burden more stringent and the memory demands discouraging. This implied the usage of a parallel approach from the beginning, since only with a highly scalable parallel code can useful simulations be made. This goal could be achieved by employing a hybrid MPI/OpenMP parallelization with a 3D domain decomposition.
REFMUL3 is of great interest for the reflectometry community as an essential tool to capture the full description of reflectometry in a synthetic diagnostic. It is particularly suitable for the studies on the amplitude of reflected signal because the true geometry of the probing beam is taken into account, and can account for possible resonance contributions due to the surrounding geometry, as it is the case of ITER plasma position reflectometers inserted in the blanket.

[1] Lijun Xu, Naichang Yuan, IEEE Antennas And Wireless Propagation Letters 5, 335-338 (2006).

[2] F. da Silva, M. Campos Pinto, Bruno Després and Stéphane Heuraux, Journal of Computational Physics 295, 24-45 (2015).

Fullwave Doppler Reflectometry Simulations for Turbulence Spectra

C. Lechte[1], G. D. Conway[2], T. Görler[2], T. Happel[2], C. Tröster-Schmid[2], and the ASDEX Upgrade Team[2]

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Doppler reflectometry is a microwave scattering diagnostic used to measure the wavenumber spectrum of the turbulent density fluctuations and the perpendicular velocity in fusion plasmas. Experimental Doppler spectra and density spectra from turbulence simulations show marked differences in the position and shape of the inertial range of the turbulence. In a typical tokamak plasma, the density fluctuation strength can be several percent at the edge. While this does not impact the velocity measurement very much, it does complicate the determination of the fluctuation spectrum, because the density fluctuations themselves can non-linearly influence the instrument function of the reflectometer. In order to investigate this effect, we use turbulent density fields as inputs and simulate the Doppler reflectometer response to it with the fullwave code IPF-FD3D. From the known wavenumber spectrum of the input turbulence, and the resultant spectrum from IPF-FD3D, the instrument function can be estimated, and its reverse subsequently applied to the experimental results. This paper concentrates on the fullwave simulations of the reflectometer with a given turbulence field. The source of the turbulence field is either the gyrokinetic code GENE (run at equivalent conditions to the experiment), or a mixture of random modes that follows a typical turbulence power spectrum. This allows the isolation of some of the different mechanisms that produce the wavenumer spectrum observed with Doppler reflectometry.

For each kind of turbulence, the effect of the turbulence strength and the beam polarisation on the scattering process is investigated. It was found that the 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. This is much more pronounced in X mode polarisation. Finally, experimental wavenumber spectra in X mode are compared to the simulation.

Benchmarking the global FT-2 tokamak gyrokinetic modeling results against the radial correlation Doppler reflectometry data

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[4] *Institute of Interfacial Process Eng. and Plasma Technology, 70569 Stuttgart, Germany*

Gyrokinetic (GK) modeling, in particular the global one, is widely used nowadays to analyze the physics of multi-scale anomalous transport phenomena in toroidal fusion experiments. The Doppler reflectometry (DR) or Doppler backscattering diagnostics provide possibility of comprehensive benchmarking of the GK computations, against the experimental data on plasma rotation (velocity mean value profile and its oscillations) [1], turbulence poloidal wavenumber spectrum [2], turbulence radial correlation length [3, 4] and, potentially, turbulence radial wavenumber spectrum [5]. Unfortunately, interpretation of the DR data is complicated by the contribution of poor localized small-angle scattering along the wave trajectory, which can lead to overestimation of the turbulence radial correlation length in the linear scattering regime and to its underestimation in the nonlinear regime. In the latter case the turbulence wavenumber spectrum measurements are questionable as well and only the plasma turbulence velocity could be determined, however with poor spatial resolution. Development of the synthetic DR diagnostics allowing the direct experimental signal computation based on the results of gyrokinetic (GK) modeling is helpful in this case.

In the present paper the results of ELMFIRE global GK modeling of the FT-2 tokamak ohmic discharge [6] are benchmarked against the set of experimental data obtained with O and X-mode Doppler reflectometers situated at different poloidal angles. Both linear and nonlinear synthetic diagnostics are utilized in the comparison. The former one is using the reciprocity theorem utilizing the probing wave field provided by the full-wave computation accounting for the 2D plasma inhomogeneity effects, whereas the latter is based on the full-wave IPF-FD3D code [7]. The DR signal frequency spectra, its dependence on the probing diagram tilting angle and the RCDR CCF are computed and compared to those measured at the FT-2 tokamak. It is shown that the linear synthetic diagnostic, which is less time consuming, adequately reproduces the experimental DR spectra and there dependence on the probing angle, however fails to describe the RCDR CCF. The latter is perfectly fitted by the nonlinear synthetic diagnostics which correctly describes the probing wave multiple small-angle scattering or the phase modulation playing significant role in FT-2 for O and X- mode DR, as it is shown both by direct measurement of the phase fluctuations standard deviation and by its estimation from the GK modeling results.

[1] Conway A.D., Scott B., Schirmer J. et al. 2005 Plasma Phys. Control. Fusion **47,** 1165.
[2] Hennequin P, Sabot R, Honore C et al. 2004 Plasma Phys.Control. Fusion **46** B121
[3] Schirmer J *et al* 2007 *Plasma Phys. Control. Fusion* **49** 1019
[4] E Gusakov, M Irzak and A Popov 2014 Plasma Phys. Control. Fusion **56** 025009
[5] E Gusakov, M Irzak, A Popov et al. 2017 Physics of Plasmas 24, 022119
[6] S Leerink et al., 2012 Phys. Rev. Lett., **109** 165001.
[7] Lechte C, 2009 IEEE Transaction on Plasma Science **37**, 6

Abstract of IRW13

Progress of Frequency Comb Doppler Reflectometer System in LHD and Feasibility Study of Doppler Reflectometer for JT-60SA

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The frequency comb Doppler reflectometer system is routinely operating in LHD. Recently, LHD starts the deuterium experiment and we upgraded the system with some development (a remote control system, long distance transmission by a corrugated waveguide, etc.). Also, the high sampling rate data acquisition system with 40 GS/s is utilized for the fine structure measurements by the digital signal processing. The detail of the system and some topical results will be presented and the processing technique will be discussed.

We start to study for the installation of Doppler reflectometer to JT-60SA. 3D numerical simulation is carried out for the feasibility study. The preliminary result will be presented.

This work was partially supported in part by KAKENHI (Nos. 26630474, 25289342, 15H02335, and 15H02336), by a budgetary Grant-in-Aid of NIFS LHD project under the auspices of the NIFS Collaboration Research program, by the collaboration programs of the RIAM of Kyushu University, by the Asada Science foundation, and by the collaboration programs of the QST. Additional support was provided by Japan / U.S. Cooperation in Fusion Research and Development.

Comparison of detailed experimental wavenumber spectra with gyrokinetic simulation aided by two-dimensional full-wave simulations

T. Happel,[1] T. Görler,[1] P. Hennequin,[2] C. Lechte,[3] M. Bernert,[1] G. D. Conway,[1] S. Freethy,[1,4] C. Honoré,[2] J. Pinzón,[1,5] U. Stroth,[1,5] and the ASDEX Upgrade Team

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In magnetic confinement fusion research, typically two-dimensional (2D) turbulence is observed due to the strong anisotropy in directions perpendicular and parallel to the magnetic field, $k_\perp \gg k_\parallel$. The density fluctuation wavenumber spectrum has many degrees of freedom, since a variety of effects can influence turbulence drive, damping and dissipation mechanisms. Apart from the fact that wavenumber spectra are of academic interest for the interpretation of the above mechanisms, they are a valuable quantity to be used for the validation of gyrokinetic simulations [1]. Heat fluxes, which are normally used to consider whether a gyrokinetic simulation describes an experimental situation sufficiently well, are 1D quantities and as such much less stringent than the wealth of information obtained when measuring a wavenumber spectrum.

The standard technique to measure local wavenumber spectra in the plasma nowadays is Doppler reflectometry. However, the diagnostic response is non-trivial due to a variety of effects including enhanced scattering [2] and saturation [3], multiple forward scattering [4], wave trapping, etc. In this contribution, wavenumber spectra have been measured on the ASDEX Upgrade tokamak using O-mode and X-mode Doppler reflectometry at the same toroidal, poloidal and radial location. Perpendicular wavenumbers covered are $k_\perp = 4 - 15$ cm^{-1}. Pronounced differences are observed depending on the probing beam polarization. While spectral indices measured with the O-mode system are larger than those measured with the X-mode system, the wavenumber which separates different inertial ranges is larger in X-mode than in O-mode [5]. These effects are reproduced by full-wave analysis of local non-linear gyrokinetic simulations using the Gene code. The discrepancy between different probing beam polarizations can be understood in terms of probing in the nonlinear or saturation regimes [2, 3], which affect the diagnostic power response. These results underline the importance of using synthetic diagnostics when non-trivial diagnostics such as the power response of Doppler reflectometers are used, especially when probing nonlinear or saturation regimes.

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Power response in Doppler reflectometry

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Turbulence plays an important role in determining the quality of the fusion plasma confinement. Hence a deep physical understanding of the turbulence accompanied by accurate experimental measurements are required for performance predictions of next fusion devices. Doppler reflectometry is a standard diagnostic technique widely used for measurements of density turbulence. It uses the backscattering of microwaves in order to provide a measurement of the perpendicular wavenumber ($k_\perp$) spectrum of the density turbulence and the perpendicular plasma flow. However, the physics behind the wave scattering makes the diagnostic response complex, in particular the backscattered power is not always proportional to the turbulence level. Therefore a detailed study of the power response of the diagnostic is required for a correct interpretation of experimental data.

The power response of Doppler reflectometry is investigated in detail for slab geometry and Gaussian synthetic turbulence. The Doppler reflectometer is modelled by using two dimensional full wave (2DFW) simulations and the physical optics model. Apart from the linear and saturation regimes, a new enhanced power response regime is found and characterized by analytical calculations [1]. The linear sensitivity of the diagnostics to different $k_\perp$ is also studied, and its effect on the $k_\perp$-spectra measurement is discussed. The results from the above studies are applied to $k_\perp$-spectra measured on the realistic case of the ASDEX Upgrade Tokamak. There non-linear scattering regimes can be identified experimentally, which is supported by results of 2DFW simulations coupled with gyrokinetic simulations [2].

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SYSTEMATIC STUDY OF CORE TURBULENCE BY REFLECTOMETRY FLUCTUATION FREQUENCY SPECTRA

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Abstract

A systematic investigation of Tore Supra core turbulence properties is being carried out using fixed frequency reflectometry data. The heterodyne X-mode reflectometer, operating between 105-155 GHz, probes the plasma turbulence near the cut-off layer from the low field side (LFS), through the center, to the high field side (HFS) [1]. A database was built using primary global parameters and selected local parameters. This database contains more than 6,000 discharges, and includes more than 300,000 reflectometry frequency spectra.

Parameterization of the frequency spectra enables systematic analysis of turbulence characteristics. The spectra are decomposed in several components: the noise level, the broadband (BB) fluctuations, the low frequency (LF) fluctuations and the central spike (CS) near zero frequency. Additional components can be added to account for the quasi-coherent (QC) modes [2]. We use a Gaussian distribution to fit the defined shape components such as the CS, while the generalized Gaussian distribution is employed for components such as the BB.

The first study is based only on Ohmic discharges, focusing on the BB component of the frequency spectrum. The radial variation of the width and energy of the BB suggests different turbulence regimes within and outside the q=1 surface [1]: the BB energy is much lower within the q=1 surface than outside. The BB width exhibits a bump near the q=1 surface. Both bumps, one on the HFS and one on the LFS, move symmetrically further out with decreasing edge safety factor. This is to be expected under the assumption that these peaks are associated to the q=1 surface. Differences between the linear Ohmic confinement (LOC) regime and the saturated Ohmic confinement (SOC) regime are also investigated in connection with the predominant instabilities: trapped electron mode (TEM) in the LOC regime and ion temperature gradient (ITG) in the SOC regime.

Similar data analysis has been applied to discharges with ion cyclotron resonance heating (ICRH) at different powers, and the observed tendencies will be presented as well.

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Rotation and properties of plasma turbulence in W7-X measured by a PCR-system

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Within the first operation phase at W7-X [1], an optimized stellarator in the HELIAS conceptional line, a Poloidal Correlation Reflectometry (PCR) system [2, 3] is installed slightly below the outer midplane at a toroidal position of 71.1° where the plasma cross section is nearly bean shaped. The heterodyne system is operating in O-mode polarization and in the frequency range 22 GHz to 40 GHz. The frequency steps and duration are freely programmable with switching times of $\leq 60\,\mu s$. The antenna array consisting of one launcher and four receiver antenna poloidally and toroidally separated, is focused at $R = 6.0\,\mathrm{m}, z = -0.104\,\mathrm{m}$. After a commissioning phase the system has been operated routinely during the first campaign [4].
The presentation will cover the technical details of the PCR-system and first measurements of rotation and plasma turbulence in the limiter plasmas at W7-X. Due to relatively low mean electron density a significant part of the plasma radius is investigated and velocity profiles could be measured. Also the radial electric field is estimated neglecting the phase velocity and compared with DKES simulations within the radial range given by the measurements. Turbulence properties as decorrelation time and poloidal correlation length are investigated, too. Furthermore an overview of the spectral features of the turbulence will be presented.
An outlook on the ongoing upgrade of the system towards the measurement of radial correlations for the coming campaign 1.2 will be presented as well.

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Measurement of broadband fluctuations and comparative study with gyro-kinetic simulations

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Broadband density fluctuations were measured in the core region of KSTAR L-mode plasmas heated by a tangential neutral beam injection (NBI) using the microwave imaging reflectometer (MIR) [1, 2]. Cross-coherence analysis shows that peak frequencies of the fluctuations range from ~150 kHz to ~400 kHz and frequency widths are ~200 kHz. It seems that the peak frequencies are affected by plasma flow velocities and the frequency widths (and shapes) indicate the nature of the fluctuations. Dominant poloidal wavenumbers of the fluctuations estimated from the peak frequencies and their poloidal rotation velocities are 2−3 cm^{-1} corresponding to the normalized wavenumbers (to ion gyro-radii) of 0.3−0.5. The poloidal wavenumbers are comparable with results from linear gyro-kinetic simulations where the plasma flows are not considered. Note that the frequencies and poloidal rotation velocities of the fluctuations in the laboratory frame are primarily affected by the E x B flow velocities in fast rotating plasmas by NBI. *Work supported by Korean Ministry of Science, ICT, and Future Planning under the KSTAR project contract and National Research Foundation of Korea under contract no. NRF-2014M1A7A1A03029865.

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Measurements of quasi-coherent modes in KSTAR ohmic and ECH L-mode plasmas

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Quasi-coherent (QC) modes, known to be similar to trapped electron modes (TEM) [1-4], have been observed in KSTAR ohmic and ECH L-mode discharges by the microwave imaging reflectometer [5-6]. They are destabilized only in low collisionality regimes and rotate in the electron diamagnetic drift direction in the plasma frame. Linear gyro-kinetic simulations also show that the unstable modes are electron modes in the low collisionality where QC modes were observed. Since the QC modes can be regarded as signatures of TEM, we investigate a theoretical model explaining the reversal of the intrinsic toroidal rotation direction by the change of dominant turbulence between TEM and ion temperature gradient (ITG) mode [7]. However, our measurements show weak dependence of the intrinsic rotation reversal on the turbulence change. *Work supported by National Research Foundation of Korea under contract no. NRF-2014M1A7A1A03029865.

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Oscillatory EGAM Excitation by the Energetic Electrons Generated During the Sawtooth Crash in KSTAR

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In neutral beam (NB) heated L- mode KSTAR plasmas, several magneto-hydrodynamic (MHD) coherent and bursting fluctuations were detected at the frequency up to f~150kHz using microwave imaging reflectometry (MIR) [1, 2], ECE radiometers and magnetic coils. These coherent and bursting fluctuations appear in the core plasma and interact nonlinearly. Toroidally symmetric (n = 0) electromagnetic oscillations are identified as EGAM from magnetic coil signals. Analysis suggests that the observed EGAM oscillations are possibly driven by the energetic electrons generated during the magnetic reconnection phase of the sawtooth crash.

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Millimeter-Wave Reflectometry on the Tokamak a Configuration Variable

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Both profile reflectometer and Doppler backscattering (DBS) diagnostics are being developed for the Tokamak à Configuration Variable (TCV). In TCV, density measurements from the plasma core to the last closed flux surface are routinely available from the Thomson Scattering diagnostic with spatial resolution on the cm scale and temporal sampling no better than 30msec. Microwave reflectometry has been identified as a strong candidate to enable high spatial (sub cm) and temporal (µsec.) resolution of edge electron density profiles.

In reflectometry, the electron plasma density is inferred from the round-trip group delay of electromagnetic waves reflected from a plasma cut-off. Pulsed reflectometry consists of sending short pulses of varying frequency and measuring the roundtrip group-delay of each pulse using precise timing systems. To improve resolution and flexibility we plan to use frequency multipliers to bring 8-12GHz pulses programmed on an arbitrary waveform generator (65GSa/s, BW up to 20GHz) up to the V-band (50-65GHz). AWG-driven pulse reflectometry has the potential to remain competitive when compared to other pulse reflectometry techniques and may provide a new perspective in the study of turbulence. The design and progress in construction will be presented.

A DBS diagnostic is currently operational in TCV. DBS has the potential to access density fluctuation, wave-number spectra, and turbulence propagation velocities. Transceiver modules, originally used for metrology measurements, are being used in TCV for DBS. A steerable quasi-optical launcher, adapted from robust ECRH launchers, is used to accurately control the beam angle. First results will be presented.

New density profile reconstruction methods for X-mode reflectometry

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This contribution presents new data analysis techniques to improve the density profile reconstruction for frequency swept X-mode reflectometry. This effort undergoes in three fronts: the initialization of the reconstruction; the inversion method that reconstructs the density profile; and the description of blind areas to the reflectometer. The description of blind areas is the subject of an additional contribution in this same workshop. The initialization technique is assumed well implemented by the established techniques described in Refs. [1, 2] and will be further accessed in the future. The focus of this contribution is on the inversion technique.

The method published by Bottollier-Curtet et al [3] has been the standard density profile reconstruction method in X-mode reflectometry ever since. To improve this method, shapes more complex than linear for the last integration step of the refractive index [4] are investigated. The shapes tested included parabolas, square root and x^{α}, with α between zero and 1/2. A review is done on the reconstruction algorithm and all stability features are explained. They represent well the accuracy and stability observed in the reconstructed profile examples. The most accurate and stable solution is to have a shape x^{α} with α varying radially. The exponent α is demonstrated to be directly translated to an integration weight factor named W. This method achieved an accuracy in the order of 10^{-4} mm everywhere. For a special well known case, the ideal α profile can be determined beforehand or iteratively. The advantages and limitations of this methodology is shown for a typical Tore Supra density profile. Another solution developed shows how to find the α profile from the local plasma properties, more specifically the probing frequency and the local cut-off gradient. This solution is applicable for any profile shape that obeys the boundary conditions assumed when solving for α. An additional application of this solution is to use less probing frequencies for real-time monitoring of fast profile evolution.

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Perfect Linear Frequency Modulation of Voltage Controlled Oscillator

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Reflectometer is a frequency modulated continuous wave (FMCW) radar specialized for the fast and broad frequency modulation (FM). A solid state voltage controlled oscillator (VCO) is widely used to linearly modulate the frequency. As the frequency sweep range and rate are increased, the perfect linearization of FM becomes difficult due to the finite response time of electronic components. The first step for linearization is to measure the instantaneous frequency as the frequency is fast swept. The second step is to remove any nonlinearity from the measured frequency trace. The tuning voltage waveform for the linear FM is calculated by modeling the VCO input circuit as a low pass filter and numerically simulating the circuit behaviour. The calculated voltage waveform is drived by using an arbitrary waveform generator and the output frequency of VCO is experimentally measured to demonstrate the perfect linear FM. The techniques for frequency measurement and frequency linearization are described in detail and the results are presented.

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Density profile reconstruction over blind regions for X-mode reflectometry

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This contribution provides new data analysis techniques to improve the density profile reconstruction for frequency swept X-mode reflectometry. This effort undergoes in three fronts: the initialization of the reconstruction; the inversion method that reconstructs the density profile; and the description of blind areas to the reflectometer. The initialization technique is assumed well implemented by the established techniques in Refs. [1, 2] and will be further accessed in the future. The inversion method is treated in another contribution in this same workshop. The focus of this contribution in on the reconstruction of blind areas.

During a discharge in fusion experiments, many phenomena can introduce perturbations in the density profile. If a valley is present in the cut-off profile, it will contain no reflections of the probing microwaves and is denoted blind to the reflectometer. Even though it is not possible to probe directly inside this area, the higher frequencies that travel through it will carry information about the size of this blind area. As a proof of concept, a mapping of the time-of-flight jump versus the perturbation size is illustrated in the WKB framework. Next, the reflectometer IQ signal [3] is simulated using a full-wave 1D wave equation solver code.

In the full-wave framework, the signature of the blind area in the time-of-flight signal contain time-dependent effects due to the frequency sweep. These effects include the wave tunnelling, frequency mixing, wave trapping, resonant cavities and Bragg backscattering. The magnitude of each effect and their implications on the signal interpretation will be discussed.

Next, it is illustrated the impact of the perturbation skewness and kurtosis on the time-of-flight jump. The skewness is a second order effect, but the kurtosis has a substantial influence. Lastly, the height of the time-of-flight jump is no longer a good scaling parameter due to these time-dependent effects. The decay of the additional time-of-flight contribution is used instead.

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