Summary for Nuclear Fusion special issue on reflectometry

# Microwave Reflectometry for Fusion Plasma Diagnosis

**G.D.Conway**
Max-Planck-Institut für Plasmaphysik, EURATOM-Association IPP, Garching, D-85748, Germany

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## 1. Introduction

Microwave and millimetre-wave reflectometry is a type of radar for diagnosing fusion plasmas. Introduced in the early 1980's reflectometry is now common-place and forms part of the diagnostic suite on all major fusion research devices. Reflectometry has undergone tremendous advances in the last few years, both in hardware development, signal processing and data interpretation. In addition to traditional electron density profile and density fluctuation measurements reflectometry is finding new applications in core MHD localization, plasma position control, plasma rotation measurements via Doppler frequency shifts, and sophisticated systems for turbulence imaging. This article is both a report of the last Reflectometry Workshop, the seventh, and an editorial of the Nuclear Fusion special issue of papers which grew out of the workshop. The special issue includes 21 papers which touch upon practically all aspects of microwave reflectometry, not just the diagnostic developments but also some of the unique applications and physics results obtained. Together, the workshop summary and editorial should give an overview of the current activities and a guide to future trends within the field.

## 2. Reflectometer Workshop summary

The seventh International Reflectometry Workshop for Fusion Plasma Diagnostics (IRW7) - organized in cooperation with the International Atomic Energy Agency - was held at the Max-Plank-Institut für Plasmaphysik in Garching, Germany between May 9th and 12th, 2005. The workshop was attended by 43 reflectometry specialists from around the world with a total of 40 oral papers presented in 8 consecutive sessions (density profile measurements, theory and simulations, Doppler reflectometry, microwave imaging reflectometry, three sessions on fluctuation and turbulence measurements, and finally one session on hardware developments) spread over three and a half days, making this the largest and longest workshop in the series to date. On the last day, the workshop was followed by a meeting of the ITPA specialist working group on reflectometry to discuss progress in the design of the ITER reflectometer diagnostics. The workshop proceedings, consisting of 37 formal papers plus editorial, were published as an IPP report, both in hardcopy form and electronically [1].

Reflecting the current trends within the field the workshop saw a substantial increase in the number of papers presented on fluctuation measurements (over twice as many) compared to density profile measurements. Profile measurements are now perceived as almost routine employing a relatively mature technique. Most development work has concentrated on just two measurement techniques: Fast swept FM systems [ASDEX Upgrade (AUG), Tore Supra, Doublet III-D and the Mega-Amp Spherical tokamak] and Ultrashort pulse reflectometers [Large Helical Device, GAMMA-10 and others]. AM profile reflectometers are also in operation on the Alcator C-Mod tokamak and the TJ-II stellarator, although they were not reported on at this workshop. The current emphasis is on improving profile reliability, radial coverage - particularly in the core, and the processing of an ever increasing amount of data.

The rise in fluctuation measurements is driven largely by interest in MHD and fast particle modes. An example of particular relevance to ITER is the localized core measurement of Alfvén Eigenmodes and cascades [Joint European Torus (JET), DIII-D and TCABR tokamaks]. Although fixed probing frequency measurements remain the bedrock technique for plasma density turbulence and correlation studies [T-10, Tore Supra, TEXTOR, DIII-D, AUG] there is also a growing trend of cross-over measurements, for example extracting information on MHD and turbulence from the FM-swept group-delay data of profile systems [Tore Supra, AUG]. Significant progress has been made in the simulation and modelling of the fixed frequency reflectometer response function, but the final step of extracting an absolute density fluctuation level $\delta n/n$ and an associated transverse correlation length from the reflectometer phase and amplitude fluctuation signals remains problematic and application dependent.

A new area of development, Microwave Imaging Reflectometry (MIR), has unfortunately been mired by controversy. Nevertheless recent full-wave modelling has hopefully restored a sense of perspective by clarifying the benefits and limits of MIR and single line-of-sight antenna fluctuation measurements. MIR (based on large-lens optical style imaging) attempts to capture two-dimensional time-frame pictures (in the poloidal and toroidal directions) of density turbulence at a specified radial location - just like a photograph. However, like a camera, optical MIR also experiences similar limitations, such as restricted depth of field, spatial/temporal resolution, and optical aberrations etc. Nevertheless, encouraging initial results have been obtained from the single frequency MIR on the TEXTOR tokamak. Simulation studies of both optical and synthetic imaging [Princeton PPL and KASTEC Japan] were also reported, which show not just the limitations of imaging but also demonstrate the possibilities of alternative techniques such as single-antenna synthetic aperture and multi-antenna measurements. Despite the immense challenges it is expected that a wealth of new information on turbulence properties can be provided by imaging techniques.

The second new area of Doppler reflectometry and plasma velocity measurements has seen an explosive growth in interest in the last couple of years. There has been much analytic and numerical simulation work on the Doppler concept [St.Petersburg SPU, Ioffe Institute, CIEMAT Spain, IST Portugal, IPF Stuttgart] which has now placed this technique on a firm footing. Several groups are actively engaged in Doppler measurements and the results give a clear demonstration of the ability of the diagnostic to provide high resolution radial electric field profiles and associated shearing [AUG, Tore Supra], together with $E_{\mathrm{r}}$ fluctuations [AUG]. It is expected that this new technique will have an increasing impact on the wider fusion community in the coming years.

Each workshop also brings forward new hardware and software developments. Hardware includes diagnostic front-end designs, i.e. antennas and transmission lines [JET, AUG, W7-X stellarator] as well as the back-end, which concerns the reflectometer transmitter/receiver electronics and control [JET, AUG]. Continuing diagnostic improvements provide access to new physics discoveries and are important for the next generation of machines, such as ITER, by providing the opportunity for concept testing and performance modelling.

Finally, a new International Advisory Committee has been constituted for the next workshop, which is planned for spring 2007 and is to be hosted by the Ioffe Physico-Technical Institute in St. Petersburg, Russia.

## 3. Special issue overview

Attendees at the IRW7 were invited to submit extended versions of their workshop contributions (or an equivalent) to this special issue of Nuclear Fusion. No attempt was made to pre-select or define the topics, nor were general review papers solicited. Nevertheless, the range and number of papers submitted per topic mimics the distribution of papers presented at the Workshop and is indicative of the relative weight of interest and current activity within the field as a whole. The contributions have been divided into five broad themes according to physics aims. To place the papers in context and show how they either address specific critical issues or reveal new physics each section includes a brief background with selected key references. However, this summary report is not intended to be an exhaustive review of the field and fuller reference to the appropriate literature can be found in the individual special issue papers.

### *3.1. Density Profile Measurements*

A microwave beam will propagate into an inhomogeneous plasma until the refractive index $N$ goes to zero - reaching a cutoff - and is then reflected. As $N$ depends on the microwave frequency and plasma density (and magnetic field for X-mode polarization) by varying the frequency different radial positions in the plasma can be probed. Overviews of the reflectometry basics are given by Mazzucato and Nazikian [2, 3]. To determine the cutoff position (and hence the radial density profile) requires only a measurement of the microwave propagation delay. This necessitates some form of time marker in the launched wave; either envelope modulation as in traditional pulse radar, which is the topic of **Tokuzawa** and colleagues [4] who detail the multi-frequency pulse radar system on the Large Helical Device, or amplitude modulation (AM), or frequency modulation (FM) - see Laviron [5] for a comprehensive review of the various reflectometer profile techniques. FM systems are by far the commonest. The time (group) delay $\tau_g$ is obtained by sweeping the launch frequency $f_o$ and then down-converting the reflected signal (by homodyne or heterodyne mixing [6]) to give a beat frequency $f_b = \tau_g \times df_o/dt$. The group delay as a function of launch frequency can then be (Abel) inverted to give the radial position. **Zeng** and colleagues [7] present examples from the dual band and dual O/X-mode polarization FM system on DIII-D. They describe the current state of technology which allows automatic inter-shot profile evaluation. Core plasma access requires high frequency sources and X-mode polarization. Advances in microwave technology now make it possible to operate fast swept FM systems in D-band (105 - 155GHz), as demonstrated by **Sabot** and colleagues [8] on Tore Supra. The processing of the raw $f_b$ signal is usually performed in software which is optimized to the hardware. **Varela** [9] reviews the evolution of the profile evaluation techniques applied to the ASDEX Upgrade multichannel FM profile reflectometer.

### *3.2. Turbulence and MHD Measurements*

By holding the microwave frequency fixed localized information on density turbulence and MHD activity can be obtained from the time variations in the reflected signal amplitude and phase - cf. [10, 11]. Several papers address a topic of particular relevance to burning plasma experiments: the detection and study of fast particle driven modes such as Alfvén Eigenmodes - which are expected to be ubiquitous and potentially deleterious to confinement [12]. Using stepped frequency reflectometers **Wang** and colleagues [13] investigate the localization of Alfvén and other mode behaviour in DIII-D. In principle stepped frequency reflectometers can give the radial structure, i.e. the radial eigenfunction of the mode. The rather flat core density profiles in JET pose a problem for localizing O-mode cutoff layers. So **Hacquin** and colleagues [14] have adopted a different approach. By launching at a frequency just above cutoff and reflecting from the vessel inner wall - a technique called refractometry - they obtain enhanced phase signal sensitivity to core density fluctuations but at the expense of localization. They report on Alfvén cascades which can give information on the minimum $q$. In a similar vein **Elfimov** and colleagues [15] investigate local Alfvén wave resonances in the TCABR tokamak using fixed frequency reflectometers. When combined with modelling predictions they demonstrate the potential of both passive and actively driven resonances to be used as a diagnostic tool (MHD spectroscopy) for determining the effective mass and $q$-profile.

Deducing the turbulence amplitude from the reflectometer fluctuations is, unfortunately, not straightforward because of complex interference effects resulting from the general two-dimensional (2D) structure of the cutoff layer perturbations. This is an area of intense study and debate, and progress in fluctuation signal interpretation has been closely coupled to advances in simulation codes - see below. Generally, 1D models appear sufficient for small amplitude modes with fluctuation wavelengths larger than the microwave beam dimension [16], but 2D models (which include the diagnostic and plasma geometry) are necessary for broad-band shorter wavelength turbulence [17].

However, using correlation reflectometry with poloidally displaced antennas (multiple lines-of-sight) **Krämer-Flecken** and colleagues [18] deduce turbulence decay lengths during dynamic ergodic divertor operation in TEXTOR. From the decay lengths and the reflectometer RMS phase width they estimate the $\delta n/n$ level and diffusion rates using a 1D model. **Wang** and colleagues [13] have also employed a 1D phase-screen model for long wavelength modes and 2D full-wave simulations for broad-band turbulence to estimate the density fluctuation amplitude in DIII-D. They find reasonable agreement between the reflectometer results and beam-emission spectroscopy measurements. All interpretation models require knowledge of the local density gradient scale length, i.e. $\delta\phi \propto L_n \, \delta n/n$. **Sabot** and colleagues [8] obtain estimates of $\delta n/n$ in Tore Supra using a combined reflectometer with a synthesiser source for fluctuation measurements and a swept source for density profiles.

Fixed frequency reflectometers are not the only method of obtaining localized fluctuation measurements. **Vermare** and colleagues [19] describe a cross-over technique based on fast swept FM profile reflectometry measurements on Tore Supra. Using multiple frequency sweeps they build up a picture of the variation in the group delay from which the RMS fluctuation level can be estimated as a function of radius. This profile can then be Fourier transformed to give the local radial wavenumber spectrum $S(k_\mathrm{r})$ of the turbulence.

### *3.3. Turbulence Imaging Measurements*

The effect of the 2D interference on the reflectometer fluctuation signal becomes progressively more pronounced the higher the fluctuation level and the further the cutoff layer is from the receiver antenna. That is, the turbulence scatters the microwave beam into higher Bragg orders and information is effectively lost. The concept behind imaging reflectometry is to extend the antenna size to capture as much as possible of the scattered signal [20]. The result is a raising of the maximum $\delta n/n$ for which the reflectometer phase signal replicates the density perturbation. There are two approaches to imaging: classical large aperture optical type imaging, or synthetic aperture imaging using either an array of poloidally and/or toroidally displaced antennas, or a single antenna with a rotating plasma (assuming the turbulence mutation rate is smaller than the rotation velocity) and inverting the signal time evolution to give the turbulence spatial (poloidal) structure [21]. The turbulence propagation (plasma rotation) has of course been employed with traditional single line-of-sight antenna reflectometers for many years to give turbulence statistical parameters: RMS amplitude and wavenumber spectral width - cf. [22].

**Ignatenko** and colleagues [23] investigate the operational range of the optical approach using 2D full-wave and optical simulations for both stationary spatial and time evolution techniques. For the geometry of the GAMMA10 tandem mirror device they find, for turbulence amplitudes below a few percent, comparable performance between imaging and conventional antenna systems with similar spectral resolution ranges.

One major issue with optical MIR is that because of the large antenna aperture the antenna/plasma alignment must be exceptionally good (within a fraction of a degree) or the reflected signals will experience a Doppler shift (phase ramping) which severely complicates the signal interpretation.

### *3.4. Plasma Rotation and $E_{\rm r}$ Measurements*

The problem of continuous phase ramping or run-away which plagued early fluctuation measurements has now been turned to advantage to create a new diagnostic technique: Doppler reflectometry. By deliberately tilting the reflectometer antenna the Bragg scattered component can be made to dominate over the normal specular reflection giving a Doppler frequency shift in the detected signal $\omega_D = u_\perp k_\perp$ where $u_\perp$ is the perpendicular (mostly poloidal) rotation velocity and $k_\perp \approx 2k_o \sin\theta_o$ the Bragg wavenumber [24, 25]. **Hennequin** and colleagues [26] show how the technique has been implemented on Tore Supra to give not only rotation profiles but also turbulence $k$-spectra by using a variable tilting antenna to scan $\theta_o$ and hence $k_\perp$. The measured velocity $u_\perp = v_{E\times B} + v_{\rm phase}$ is the turbulence velocity moving in the plasma $E_r \times B$ frame. Generally $v_{E\times B} \gg v_{\rm phase}$ for tokamak plasmas which allows a simple extraction of the radial electric field $E_{\rm r}$. Radial profiles of $E_{\rm r}$ from ASDEX Upgrade are presented by **Schirmer** and colleagues [27] and show that the negative $E_{\rm r}$ well associated with the edge pedestal scales with the confinement through various scenarios. Schirmer has also extended the technique with the addition of a second channel to measure the instantaneous $E_{\rm r}$ shear profile. A strong velocity shear is also observed by **Estrada** and colleagues [28] in the TJ-II stellarator. Comparing Doppler results with 2D full-wave simulations they show that the maximum velocity shear resolvable is limited by the radial width of the cutoff zone which leads to smearing in the measured profile. In the absence of external momentum driven plasma rotation (e.g. NBI) the $E_r \times B$ velocity drops to a few $\rm km\,s^{-1}$ and becomes comparable to the intrinsic turbulence phase velocity. **Conway** and colleagues [29] use this feature to investigate ITG to TEM core turbulence transitions in ASDEX Upgrade. Combining experimental results with turbulence simulations shows the core $E_{\rm r}$ reversing direction with the dominant turbulence. For plane or nearly flat cutoff layers the probed Bragg wavenumber is given by $k_\perp = 2Nk_o = 2k_o \sin\theta_o$, however, with strong cutoff curvature $N^2 > \sin^2\theta_o$. **Honoré** and colleagues [30] investigate this problem for the circular plasmas of Tore Supra using beam-tracing techniques. They show that ray/beam tracing is essential in high curvature conditions, e.g. plasma core, to give the correct cutoff position and $N^2$. Doppler reflectometry is most accurate for large rotation velocities, i.e. large Doppler shifts, but an alternate approach appropriate for small velocities is to measure the turbulence movement using time delay techniques. **Krämer-Flecken** and colleagues [18] demonstrate the use of cross-correlation analysis with poloidally displaced antennas in TEXTOR to give the turbulence propagation velocity from the correlation time lag. This technique works well for quasi-coherent fluctuations where the decorrelation time is longer than the convection time. In this respect Doppler reflectometry and poloidal correlation reflectometry can be seen as complementary techniques.

### *3.5. Modelling and Simulations*

Much of the recent advances in reflectometry have been achieved through the parallel work of diagnostic simulation and modelling. Simulations have aided the interpretation of experimental results, provided diagnostic validation and given insight into the complex diagnostic response function. Two approaches are currently favoured: numerical simulation and analytic formulation. For the numerical approach the accepted baseline is now two dimensional explicit or implicit time-dependent full-wave solutions of Maxwell's wave equation using realistic plasma and antenna/diagnostic geometry, cf. [31, 17, 32]. However, numerical simulations are computationally intensive, therefore simpler models or analytic approaches are also important [22, 33]. As noted previously **Wang** [13] has used extensive 2D full-wave simulation scans to map the level of coherent reflection vs turbulence amplitude and wavenumber which is then employed to interprete experimental signals.

Doppler reflectometry is currently a hot-topic for simulation. **Estrada** and colleagues [28] have used a 2D full-wave code to investigate the ability of Doppler measurements to resolve a sharp velocity shear. This is the same topic of **Silva** [34] who present initial studies on conventional and Doppler reflectometry. Since most experimental Doppler results concentrate on the high velocity shear region of the edge pedestal the question of resolution is of some importance. **Holzhauer** [35] investigates an overlooked additional asymmetry that arises in X-mode due to density gradients in magnetized plasmas. The complement to Doppler reflectometry, poloidal correlation reflectometry, is the subject of analytic modelling by **Gusakov** [36]. Using 3D geometry and WKB approximations they find that poloidal velocities deduced from lateral correlations can deviate significantly depending on density profile shape and radial location. However, they provide analytic expressions to aid experimental interpretation.

### *3.6. New Systems and Future Trends*

The development of new systems shows a healthy and evolving field. And one of the main motivators for development is ITER. **Vayakis** and colleagues [37] present a status report on the current plans for the ITER reflectometer systems. As ITER begins to enter the construction phase nearly all effort to-date has concentrated on optimizing the diagnostic front-end: the antenna and transmission line routing and performance.

This is particularly crucial since there will be little or no opportunity to modify these components once ITER begins operation. Since microwave technology is still developing the back-end system hardware is best left until needed - this means the antennas should be made as flexible as possible to allow for future developments and unexpected new techniques.

One particular challenge for the main profile reflectometers on ITER are the effects of refraction and absorption. **Kramer** [38] has modelled the low field side antennas using a 2D full-wave code for X-mode propagation. They find microwave absorption maybe less disastrous than initially predicted, which may make core access possible from the low-field side of the tokamak. However, the effects of refraction are severe. To overcome the potential loss of signal they propose a poloidal array of receiver antennas - which might be useful also for turbulence imaging.

Another of the new devices under construction is the W7-X stellarator. **Hirsch** and colleagues [39] describe a proposal for a novel flexible system with dynamic steerable high directivity antennas. A pair of poloidally separated sight-lines will give the system full flexibility to operate either as a conventional reflectometer for both density profile and fluctuation measurements, or for rotation measurements via either poloidal correlation or tilted antenna Doppler reflectometry measurements.

## 4. Concluding remarks

The positive aspects of reflectometry have often been stated: It has a simple methodology - you shine a microwave beam at a plasma and see what comes back. What you measure has a direct relation to the parameter of interest, i.e. electron density position, fluctuation and movement. The measurement interpretation is, on the whole, relatively straightforward (for profile and Doppler applications at least) - and it's spatially localized. The diagnostic is self contained, independent, requiring no supporting systems. It uses inexpensive hardware, simple all-metal transmission lines and has minimal access requirements. These last points make the diagnostic particularly tolerant of the harsh environment (e.g. neutron streaming) expected in burning plasma experiments. Nevertheless, the diagnostic is not without problems (ECE noise, cyclotron absorption, refraction and scattering effects amongst others) but the problems are known and in some cases can be avoided or at least mitigated. As with most plasma diagnostics, development is often driven by the physics needs, but occasionally an unexpected spin-off creates a new application and facilitates new physics. Doppler reflectometry is an example where an initial signal problem led to a simple measurement of $E_\mathrm{r}$, while the (just above cutoff) refractometry technique is providing new access to core fast particle modes. Reflectometry continues to surprise.

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