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Microwave Reflectometry Diagnostics: Present Day Systems and Challenges for Future Devices[*]

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Microwave reflectometry technique has experienced significant advances in the last two decades becoming a very attractive diagnostic presently used in almost all fusion devices. This technique allows measuring electron density profiles, plasma instabilities, turbulence and radial electric fields with excellent spatial and temporal resolution. Although it is not straightforward, the extension of reflectometry to future devices is possible partially due to the limited access needed to accommodate the antennas inside the vacuum vessel keeping the sensitive elements as microwave sources and detectors outside the radiation area. However, in order to achieve a good diagnostic performance, limitations related to relativistic effects, intense neutron- and γ-radiation and long pulse operation have to be considered in the reflectometer design phase.

Keywords: radio-frequency and microwave measurements, tokamak, stellarator, steady-state operation

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1. Introduction

Microwave Reflectometry, a radar technique used initially in ionospheric studies and since the early 1980's for diagnosing fusion plasmas, has experienced significant advances in the last two decades. By probing the plasma perpendicularly to the density cut-off surfaces, microwave reflectometry diagnostics allow measuring the electron density profile, plasma instabilities and density turbulence. For a review see Ref. [1]. During the 1990's different approaches were developed to overcome the deleterious effect of the turbulence on the density profile measurement, becoming nowadays an almost routine diagnostic for profile measurements in many devices. Similarly, turbulence measurements have been extended from the initial single frequency systems to multiple frequency correlation systems and ultra-fast sweep frequency systems. Furthermore, in the last decade a new technique, Doppler reflectometry, has been developed able to measure simultaneously plasma turbulence and flows with excellent spatio-temporal resolution. All these advances, briefly outlined in section 2, make reflectometry a very attractive diagnostic presently used in almost all fusion devices. The International Reflectometry Workshop series proceedings [2] and the special issue of Nuclear Fusion journal dedicated to Reflectometry, published in Sept. 2006 [3], represent an excellent summary of the developments and present applications of this technique. Although it is not straightforward, the extension to future devices like ITER is still possible partially due to the limited access needed to accommodate the antennas inside the vacuum vessel and the possibility to use stainless steel or carbon-based materials for the antennas keeping the sensitive elements as microwave sources and detectors outside the radiation area. However, limitations related to relativistic effects, intense neutron- and γ-radiation and long pulse operation may hinder the good performance of reflectometry diagnostics in future devices if these effects are not properly considered in the diagnostics design and construction phases. Present-day reflectometry applications using both, conventional and Doppler systems and some of the latest advances are outlined in section 2. The main difficulties found when extrapolating present-day reflectometry systems to future fusion devices are discussed in section 3: the limitations due to relativistic effects in section 3.1, the influence of radiation heating on the diagnostic front-end design in section 3.2 and the need for real time plasma monitoring and control in section 3.3. Finally some conclusions are drawn in section 4.

2. Present-Day Reflectometry Systems

Microwave reflectometry systems can be grouped in two categories, conventional and Doppler reflectometry, depending on which of the physical processes undergone in the plasma by the probing microwave beam is dominating the recorded signals. Whereas conventional reflectometry measures the signal reflected at the plasma cut-off layer, Doppler reflectometry measures the Bragg back-scattered

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2.1 Conventional reflectometry systems

Conventional reflectometry is used to measured electron density profile, plasma instabilities and density turbulence by probing the plasma perpendicularly to the density cut-off surfaces and detecting the signal after reflection at the cut-off layer. To measure the density profile the probing frequency must be swept in time or multiple frequencies must be used to cover the whole density range. Present systems use different approaches to minimize the effect of the plasma turbulence on the profile measurements, i.e., Amplitude Modulation, Pulse or Fast Frequency Modulation reflectometry. A detailed description of these techniques can be found in [4]. Although the first two techniques have been used in a number of devices with satisfactory results (e.g. [5–13]), the extrapolation to next generation devices involving long and complex transmission lines may present some limitations due to their different response to parasitic reflections in waveguides. The third technique, Fast Frequency Modulation reflectometry, is presently used in many devices and its use is envisaged in ITER reflectometry systems. However, the selected technique to be finally used in ITER reflectometers may change depending on future advances and progress of the different approaches. The frequency sweeping time in the Frequency Modulation systems dropped from few milliseconds in the early 1990's to tens of microseconds a decade later, with the subsequent improvement in the quality of the profile measurements and in the diagnostic capabilities (e.g. [14–17]). Furthermore, during the last years ultra-fast frequency sweeping systems are being developed [18, 19] reducing the frequency sweeping time to two microseconds.

Reflectometry has been applied to turbulence measurements since the 1980's, although in some cases, the reflecting layer for microwave frequencies shows a complex corrugated structure which can lead to strong interference in the reflected beam that hinders the density fluctuation information and makes difficult to extract quantitative information. Even in those cases, valuable qualitative information on the turbulence characteristics can be obtained as, for example, in turbulence studies during the development of transport barriers (e.g. [20–22]). Quantitative description of the density fluctuations is possible for specific scenarios and in particular for coherent plasma perturbations, e.g. MHD modes [23] or high frequency Alfven eigenmodes [24, 25]. Fast frequency hopping reflectometers [26] and multiple frequency correlation systems (e.g. [27, 28]) have broadened the reflectometry applications as they allow for turbulence correlation -radial, poloidal and/or toroidal correlation- and turbulence propagation velocity measurements. Besides, these multiple systems allow measurements of the poloidal and/or toroidal distribution of density fluctuation [29].

To ensure a correct interpretation of the turbulence and correlation measurements two-dimensional full-wave codes have been developed during the last years to simulate the reflectometry response under different plasma conditions (e.g. [30–32]). A cooperative effort is under way for extending these codes toward a three-dimensional full-wave code able to simulate reflectometry in ITER-like plasmas [33].

Microwave Imaging Reflectometry (MIR) was proposed to overcome the problems found in the single line-of-sight systems by measuring the two dimensional structure of plasma fluctuations near the cut-off layer [34]. To that end this technique uses an optical system making an image of the reflecting layer onto an array of microwave receivers what requires a careful alignment and focusing of transmit and receive components. After several years of unfruitful attempts, recent results have shown promising capabilities of optimized MIR systems [35].

As already pointed out, ultra-fast frequency sweeping systems are being developed [18, 19] reducing the frequency sweeping time to two microseconds. These systems, initially devoted to density profile measurements, offer the possibility to measure both, density profiles with excellent time resolution and the dynamics of the plasma turbulence from the plasma edge to the core, providing the access to new plasma physics phenomena. Outstanding results, reported by Clairet *et al.* in the last International Refletometry Workshop [36], have been recently obtained in the Tore Supra tokamak.

2.2 Doppler reflectometry systems

Doppler reflectometry makes use of a finite tilt angle between the probing beam and the cut-off layer normal to measure the Bragg back-scattered process that takes place at the cut-off layer. This technique allows the measurement of the density turbulence and its perpendicular rotation velocity, at different turbulence scales and with good spatial and temporal resolution [37–40]. The perpendicular rotation velocity of the plasma turbulence has been shown to be dominated by the $E \times B$ velocity, which allows the determination of the radial electric field, E_r. Full-wave simulation studies have shown the good performance of this technique and its capability to measure the perpendicular rotation velocity and the perpendicular wave-number spectrum of the density fluctuations without the limitations found in conventional reflectometry [41, 42]. A critical point in the design of a Doppler reflectometry system is the optimization of the spectral resolution. For that, Gaussian beam antennas and steerable focusing mirrors installed inside the vacuum vessel offer a good solution as it is shown in present-day devices. An optimized spectral resolution is important for the good determination of the perpendicular rotation velocity [43] and to avoid large errors in its determination if a strong velocity shear layer exists in the plasma [44]. Recenty, experimental results have been reported on the plasma collisionality dependence of the turbulence wave-number spectrum [45] and on the scale-resolved turbulence reduction in H-mode plasmas [46]. Furthermore, Doppler reflectometry is presently being applied in several devices to unravel the turbulence and flow interaction processes involved in the L-H transition physics [47–51].

The reflectometry developments outlined in this section can in principle be applied to the reflectometry measurements in future devices. However, the final diagnostic performance will depend to a large extent on the quality of the reflectometer front-end: antennas, waveguides, etc, and, as discussed in the next section, the full optimization of the front-end will not be always possible. Neutron and γ-radiation challenge the front-end design as an accurate design is necessary to keep the radiation, thermal load and stress at acceptable levels. Large aperture front-end systems like those used in MIR or dynamical steerable systems like those used in Doppler reflectometry are hardly feasible in this harsh environment.

3. Challenges for Future Devices

The extension of the reflectometry systems to future devices is possible partially due to the limited access needed to accommodate the antennas inside the vacuum vessel while keeping the sensitive elements as microwave sources and detectors outside the radiation area. Signal transmission to the detectors typically far away from the torus can be conducted using low-loss oversized waveguides. However, this extension is not straightforward. In addition to the problems associated with long pulse operation and with intense neutron- and γ-radiation, the limitations imposed by relativistic effects have to be also considered. For a review on the problems related to the development of diagnostics for steady state plasmas see [52].

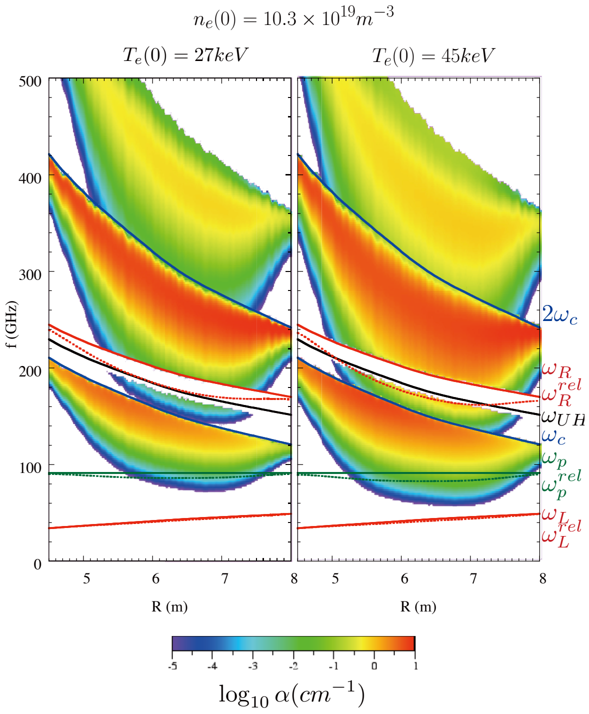

Fig. 1 Cut-off and resonance frequencies for two ITER plasma conditions: H-mode with $n_e = 10^{20}\,m^{-3}$ and $T_e = 27\,keV$ (left) and an extremely high temperature case with $n_e = 10^{20}\,m^{-3}$ and $T_e = 45\,keV$ (right). ω_c, ω_p, ω_L and ω_R are the electron-cyclotron resonance, O-mode cut-off, X-mode lower cut-off and X-mode upper cut-off frequencies. Cold approximation and relativistic calculated frequencies are shown. Color contours represent the local absorption coefficient due to EC downshifted resonances for X-mode propagation. Adapted from [53].

3.1 Limitations due to relativistic effects

Relativistic effects modify plasma resonance and cut-off frequencies and can limit reflectometry measurements [54, 55]. As an example Fig. 1 shows the resonance and cut-off frequencies calculated using the relativistic code TRECE [56] for two ITER plasma conditions. H-mode with flat density profile, $n_{e0} = 10^{20}\,m^{-3}$ and $T_{e0} = 27\,keV$, and an extreme hight temperature plasma with $n_{e0} = 10^{20}\,m^{-3}$ and $T_{e0} = 45\,keV$. The relativistic correction to the cut-off frequencies reduces the gradients in the cut-off frequency profiles in a way that depends on density and temperature profiles. This effect can hinder core density measurements using either O-mode or Low Field Side (LFS) X-mode upper cut-offs in plasma scenarios with flat density profiles. Besides, wave absorption due to downshifted electron cyclotron harmonics may preclude plasma core measurements using LFS X-mode upper cut-off independently of the density profile shape. On the other hand, X-mode lower cut-off profile is not very much affected by relativistic effects: it keeps the moderate gradient and is not affected by the electron cyclotron absorption. As a consequence, the access to the plasma core in high temperature plasma scenarios requires the use of the High Field Side (HFS) X-mode lower cut-off. Probing the plasma from the HFS adds further complexity to the reflectometer front-end design due to the lack of near vacuum vessel ports to access the plasma. Long and often complex waveguide runs have to be used inside the vacuum vessel from the closest port to the final antenna location. Two-dimensional calculations of the relativistic effects in ITER plasmas show a deformation of the X-mode upper cut-of layer surfaces in the poloidal plane [57]. Cut-layer surfaces become concave and as a consequence focus the reflected beam which may not longer return to the location of the emitting antenna. Plasma edge and gradient regions are in general less affected by relativistic effects and both O-mode or LFS X-mode upper cut-off can be used. In any case, due to the relativistic modification of plasma cut-off frequencies, the knowledge of the electron temperature profile becomes essential to determine the density profile from the reflectometer data or to radially localized fixed frequency reflectometry measurements.

In ITER several reflectometry systems are being de-

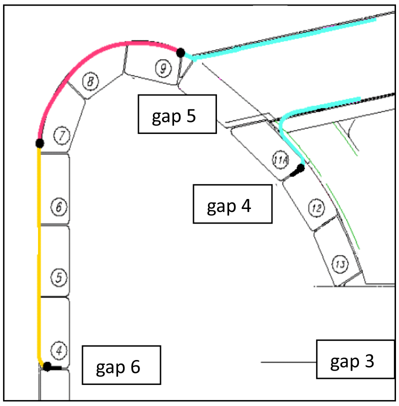

Fig. 2 Poloidal allocation of the ITER plasma position reflectometers. The waveguide path for gaps 4 and 6, running along the upper port-plug and behind the blanket modules, is also indicated.

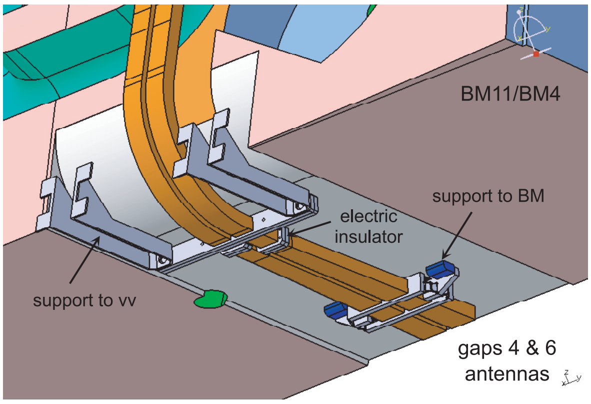

Fig. 3 Design proposed for ITER plasma position reflectometer gap 4 and gap 6 antennas. The antennas are located in the toroidal gap between two adjacent blanket modules: BM11 and BM12 for gap 4 & BM4 and BM3 for gap 6. Electric insulators and support structures to the vacuum vessel and to the upper blanket module are indicated. Adapted from [59].

veloped to measure density profiles, plasma instabilities, turbulence and flows [53]. To meet the ITER measurement requirements, covering from the plasma edge to the core and taking into account the referred limitations both, LFS as well as HFS reflectometers are needed. Probing frequencies from 15 to 180 GHz will be used both in X-mode and in O-mode, to cover a broad range of densities, from 5×10^{18} to $3 \times 10^{20}\,\mathrm{m}^{-3}$. HFS and LFS reflectometry systems are intended to measure the electron density profile from the plasma core to the edge. In addition, they are expected to provide information on MHD modes, disruption precursors, high frequency instabilities, Edge Localized Modes (ELMs) and L-H mode transition. Information on plasma turbulence and radial electric field should be provided by the LFS system. Besides, reflectometry will be used for plasma position control in long pulse operation as an alternative approach to the magnetic systems. The plasma position reflectometer diagnostic is intended to measure the distance between the plasma column and the first wall by measuring the electron density profile in the scrape-off-layer up to the separatrix, at four different poloidal locations shown in Fig. 2. These four reflectometers work in the O-mode polarization in the frequency range from 15 to 60 GHz and are distributed poloidally, from the LFS up to the HFS both in the equatorial plane (gaps 3 and 6), with two other reflectometers at intermediate positions (gaps 4 and 5).

3.2 Radiation heating influence on the diagnostic front end design

Reflectometry systems working in future devices will face some difficulties linked to the intense neutron- and γ-radiation. This imposes a careful design of the reflectometer front-end to keep radiation and thermal and mechanical stresses at acceptable levels, and also to allow maintenance by remote handling.

In W7-X, the first plasma facing element of the reflectometer will be a metallic mirror [58]. The mirror must cope with a high radiation heat-load which requires active cooling, adding complexity to the front-end design and construction.

In ITER, plasma position reflectometer gaps 4 and 6 and HFS reflectometer antennas should be allocated between two blanket modules, slightly retracted from the first wall panel [53]. This imposes severe restrictions in the antenna design due to space limitations and to radiation heating from the plasma: high thermal loads can cause high temperatures and excessive stress. In the design proposed in [59] for the plasma position reflectometer gaps 4 and 6, the antennas are attached to the upper blanket module for a good structural support (see Fig. 3). This configuration allows some heat to be transfered to the blanket module, however, it requires the use of an electric insulator between the antennas and the waveguides attached to the vacuum vessel to prevent both, currents flowing from the plasma to the waveguides, and unsuitable currents flowing from the blanket module to the vacuum vessel. This electric insulator prevents the heat to be dissipated through the waveguides and support structure to the vacuum vessel, therefore the support structure to the upper blanket module should be able to provide good heat transfer together with good structural support and also some flexibility to allow radial displacements due to thermal loads. Simulations performed taking into account the expected thermal and nuclear loads in ITER indicate that for the proposed tungsten antenna design, the maximum temperature distribution, shown in Fig. 4, is kept at acceptable levels. The associated maximum radial displacement and thermal stress as well as the total stress calculated including thermal and electromagnetic loads are all kept at tolerable levels [59]. These antennas, suitable to work under the hard ITER conditions and appropriated to measure the electron density profile in

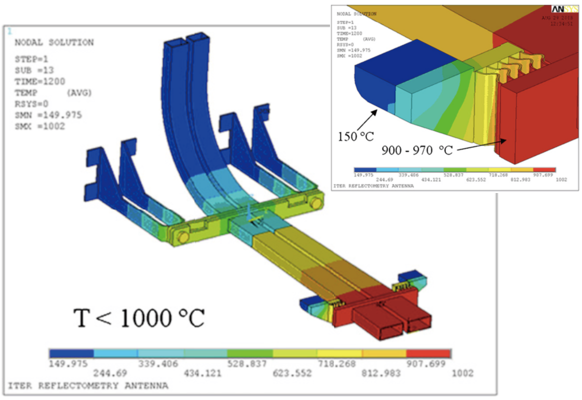

Fig. 4 Maximum temperature distribution calculated taking into account the thermal and nuclear loads at the ITER plasma position reflectometer gap 6 antennas for a pulse length of 1200 s. The higher values, kept below 1000° C, are acceptable due to the high temperature melting point of tungsten. Adapted from [59].

the scrape-off-layer up to the separatrix, are not suitable for the HFS reflectometer as higher gain antennas have to be used to access the core plasma region. To cope with the restrictions of limited space between blanket modules and low level of received signal, a high toroidal gain antenna system has been proposed which combine emitting horn and receiving mirror. An antenna system prototype was made and successfully tested at the HFS reflectometry mock-up at RRC Kurchatov Institute [60]. Heat load simulations are under way as well as an optimization of the antenna design to cover a wider range of antenna-plasma cut-off distances. In both cases, plasma position gaps 4 and 6 and HFS reflectometers, the limited space between the blanket modules does not allow tilting the antennas to be aligned to the magnetic filed. As a consequence, a fraction of undesired polarization mode will be launched to the plasma. O-mode fraction can come back after reflection in the plasma when working in X-mode (HFS reflectometer) appearing in the measured signal as a parasitic component, and although X-mode fraction when working in O-mode will not be reflected by the plasma the related losses can be significant. A further difficulty on these systems relates to the waveguides and antennas maintenance. Long and bended waveguides have to be installed attached to the vacuum vessel during the machine assemblage with no possibility for maintenance or replacement during the whole ITER operation period. As for the antennas, replacement will be possible but due to the possible high activation it has to be done by remote handling and from the inner side of the vacuum vessel.

LFS reflectometer front-end will be allocated within an ITER equatorial port-plug. Similarly, gap 3 and gap 5 front-ends will be installed in an equatorial and upper port-plug, respectively. Although much less restrictive, the space available within the port-plugs limits the number of antennas and their placement. The design and configuration of these antennas is presently under discussion to ensure that the measurements requirements are met. Being allocated within a port-plug, the maintenance or replacement of waveguides and antennas is possible although requires remote handling manipulation. The first LFS reflectometer aim is to measure the electron density profile across the plasma edge region, but is also intended to measure ELMs, plasma instabilities -MHD and high-frequency Alfven modes-, plasma turbulence and radial electric field. A careful design of the front-end, using different antenna gains and line-of-sights is important for a successful operation of the reflectometers in all plasma scenarios. The antenna configuration options for the ITER LFS reflectometer are discussed in [61]. Currently, twelve waveguide-antenna systems are considered, two of them devoted to Doppler measurements. Steerable antennas or mirrors are not foreseen precluding turbulence wave-number spectrum measurements. Nevertheless, fixed tilt angle Doppler systems allow the measurement of turbulence and radial electric field simultaneously and with good spatio-temporal resolution, enabling the study of the turbulence-flow interaction proccess.

Problems associated with non-absorbed microwave stray radiation should be also considered as they could damage delicate microwave components. This issue is not exclusive of future steady-state fusion devices, past and present reflectometers already use protection techniques against gyrotron radiation power. Current protection techniques for microwave diagnostics have been recently surveyed and possible options for ITER microwave diagnostic protection discussed by Conway *et al.* [62]. Waveguide microwave filters are used in most reflectometers as the main protection technique. Notch-filters with an attenuation of several orders of magnitude are available which can be integrated into the waveguide path to reduce the radiation level to acceptable values. New designs and prototypes have shown the good performance of notch-filters being free of spurious resonances over the full frequency band [63, 64]. These protection techniques are adequate for the relatively low microwave power used in present-day machines but may be insufficient in next generation devices where a much higher microwave heating power will be used, e.g.: 10 MW at 140 GHz in W7-X or 24 MW at 170 GHz in ITER. A feasible solution consists of a sequence of diverse active and passive protection methods like waveguides shutters, waveguide filters, isolators, etc. [62]. The high background radiation level not only affects sensitive microwave diagnostic components but is high enough to thermally load most in-vessel components. The shielding of diagnostics against microwave stray radiation will be necessary for ITER and for the quasi-stationary operation phase of W7-X. In order to investigate the effect of microwave stray radiation on the W7-X in-vessel components, a test facility, called MISTRAL, has been built. All in-vessel parts are to be tested under conditions with $P(ECRH) = 30$ kW/m^2 for 30 min in the test-chamber [58, 65, 66].

3.3 Real time monitoring and control

Present experiments usually evaluate the data recorded by the different diagnostics after the discharge; data collection typically takes a few minutes until data are available for the analysis. However, in long pulse experiments, data analysis must be possible during the discharge for monitoring purposes or even for active plasma control. Automated data monitoring and analysis is essential as manual analysis of the huge data sets is not feasible. A further challenge is the data acquisition at high sample rates needed for profile, turbulence and rotation measurements FPGA-based online processing system allowing the process of several signal in parallel may offer a good solution [67]. Real time monitoring requires reliable and steady state capable diagnostics. In W7-X [52], it is foreseen to get a suitable equilibrium reconstruction by function parametrization routines every 100 ms. Consequently the magnetic diagnostic and the temperature and density profile diagnostics should permanently run at a sufficiently high repetition rate. The ITER time resolution requirement for density profile measurements is 10 ms [53]. Although present-day reflectometers achieve much better time resolution, some of the abovementioned limitations of the ITER reflectometers may hinder that good performance. For example, operation using HFS X-mode lower cut-off to measure the core density profile is yet to be demonstrated. Also the performance of the long waveguide runs inside the vacuum vessel could be an issue for both HFS and plasma position reflectometers. Moreover, the automatic evaluation of the density profile in all relevant plasma scenarios is not an easy task due to the harmful effect of plasma instabilities and turbulence on the reflectometry signals, and due to the presence of parasitic reflections and/or multi-reflection processes in the plasma. Secondary reflections in the plasma may limit the performance of the ITER plasma position and HFS reflectometers due to the small distance between the plasma and the blanket modules. Also, the O-mode parasitic reflection has to be separated from the main X-mode reflected signal of the HFS reflectometry system. As for the hardware developments, a continuos effort on signal processing has been done during the last twenty years. For a review of signal processing techniques for density profile reconstruction using FM-CW reflectometry see [68]. Recently, new signal processing techniques are proposed that allow an automated evaluation of the density profile: by removing automatically measurements performed during density profile gradient collapse and recovery phases of the ELMs [69] and by identifying the relevant plasma reflection and isolating it from the parasitic and multiple reflections [70]. These advances are essential for real time plasma monitoring and control.

As already pointed out, reflectometry will be used in ITER for plasma position control in long pulse operation as an alternative approach to the magnetic systems. Reflectometry has not been applied to plasma position control so far as this is done in present-day devices by magnetic diagnostics. The plasma position measurement and control by reflectometry is presently being demonstrated in the AUG tokamak [71]. Recent results have shown that reflectometry density profiles and an estimate for the density at the separatrix can be jointly used to track the separatrix position within the precision required for the plasma position control on ITER. Besides, the method developed to reject information polluted by the ELMs has shown to be an important development for plasma position feedback control operation [69]. Very recently, it has been successfully demonstrated the capability to switch from magnetic to reflectometry plasma position control during the plasma discharge, both during L- and H-modes and also during the L-H transition. Reflectometry measurements provided the position of the plasma separatrix in real time at a rate of 1 ms and with an accuracy of better than 1 cm. In all cases, even with large ELMs and also during programed plasma radial movement, a good plasma position control was kept [72].

4. Summary and Conclusions

Microwave reflectometry is presently used in almost all fusion devices and its use is also foreseen for future devices like W7-X and ITER. Due to the outstanding advances achieved during the last years, this technique allows measuring electron density profiles, plasma instabilities, plasma turbulence and radial electric field with excellent spatial and temporal resolution. The extrapolation of present day systems to future devices is possible but, in order to achieve a good diagnostic performance, special care must be taken in the diagnostic front-end design and construction. The main limitations are related to relativistic effects, intense neutron- and γ-radiation and long pulse or steady-state operation.

Relativistic effects modify plasma resonances and cut-off frequencies to an extent that limit the plasma core accessibility from the LFS probing the X-mode upper cut-off; HFS systems probing the X-mode lower cut-off have to be used what adds further complexity to the reflectometer front-end design. Moreover, due to the relativistic modification of plasma cut-off frequencies, the knowledge of electron temperature profile becomes essential to determine the density profile from the reflectometer data or to radially localized fixed frequency reflectometry measurements.

Intense neutron- and γ-radiation imposes a careful design of the reflectometer front-end to keep thermal and mechanical stresses at acceptable levels and to allow maintenance by remote handling. Large aperture front-end systems or dynamical steerable antennas like those used in Doppler reflectometry are hardly feasible in this harsh environment. Several designs are under study for the different ITER reflectometry systems.

In ITER, reflectometry will be used for plasma position control as an alternative approach to the magnetic systems in long pulse operation. Very recently, this new application of reflectometry has been successfully demonstrated in AUG for the first time. High sample rate data acquisition systems and automate data analysis algorithms are being developed for real time plasma monitoring and plasma control in future steady-state devices.

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