

High resolution fast wave reflectometry: JET design and implications for ITER^{a)}

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The measurement of the fuel mixture remains a very difficult task in thermonuclear plasmas, where the hydrogen isotopes are fully stripped and do not emit line radiation. On the other hand, direct determination of the ion species mix will be essential in the reactor to keep the mixture close to 50/50 and maximize the fusion output. In this paper, the design of fast wave reflectometry for JET is reviewed to show the potential of such a method in the perspective of ITER. The main design elements of the antenna and the detection system, based on vectorial measurements, are reported. The main challenges to such a diagnostic, mainly the intrinsic ion cyclotron emission from the plasma and the extensive use of ion cyclotron radiofrequencies as additional heating, are addressed in detail. The overall design indicates that the proposed system would be able to provide a measurement of the fuel ratio with spatial resolution in the range of few centimeters and temporal resolution in the range of 1 ms in the vast majority of JET scenarios. © 2008 American Institute of Physics. [DOI: 10.1063/1.2953576]

INTRODUCTION

The idea that sustains this kind of diagnostic is simple and it is based on the fact that the fast wave branch of the dispersion relation is characterized by a cutoff in the perpendicular wave number, which depends on the concentration of the various species composing the plasma. When the wave, launched from external antennas and propagates in the plasma, reaches the cutoff, it is reflected back. At the edge, the reflected component of the wave can be collected by a receiving antenna and it can be examined to deduce the concentration of the species under consideration.

Previous feasibility experiments performed at DIII-D tokamak have shown that this technique is quite promising to provide fuel isotope mix ratio within a few percent resolution.¹ The implementation of a fast wave on JET is of interest to study the potential of such a method in the perspective of ITER. It is foreseen to obtain a spatial resolution in the range of few centimeters, depending on the signal to noise ratio, and a temporal resolution in the range of 1 ms. Lower temporal resolutions, hence higher integration times, will allow higher spatial resolution and vice versa.

DESIGN OF A FAST WAVE REFLECTOMETER

The design of a fast wave reflectometer (FWR) encounters two main areas where performance critical components have to be carefully analyzed and designed: in-vessel and the signal generation and detection (see Fig. 1). All the in-vessel components suffer from a series of limitations both in space/size and materials; these impacts directly on the antenna shape, size, and location which set tough requirements on the signal generation and detection.

INSTRUMENT DESIGN

A rf measurement instrument for the FWR consists essentially of a programmable rf generator and a two channel vectorial (amplitude and phase) receiver. The basic measurement principle relies on a full vectorial transmittance measurement, the commonly called S21 parameter of network analysis. This, however, cannot be achieved without a proper measurement and characterization of the cable network connecting to the antennas in a process called amplitude and reference plane normalization. The basic principle and relations of the scattering parameters S11 and S21 can be seen on Fig. 2.

The normalization calibration process will bring the reference plane to the antenna position, resulting in S21 parameter being only the path from the transmitting antenna to the receiving antenna. This, however, does not represent the signal path through the plasma but a combination of the signal through plasma with other signal paths not through the plasma such as the direct coupling between antennas, propagation through the vessel structure, and cabling cross-talk. To

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^{c)} See the Appendix of M.L. Watkins *et al.*, Fusion Energy 2006 (Proceedings of the 21st International Conference, Chengdu, 2006) IAEA, (2006).

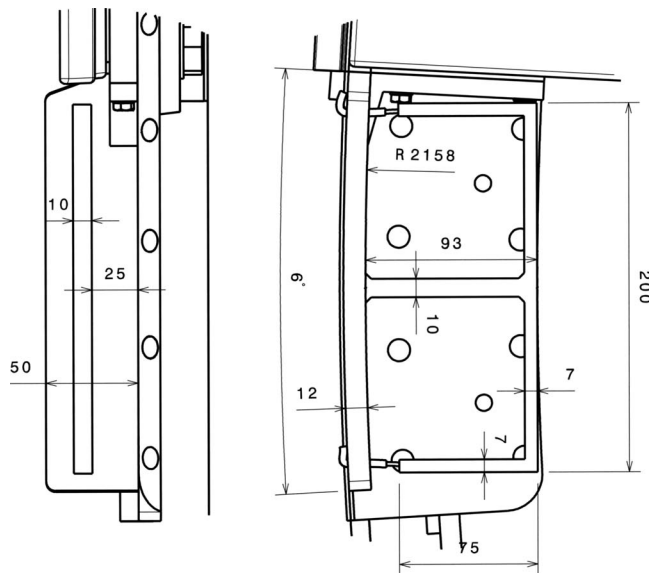


FIG. 1. The lower FWR antenna design proposed for JET, shaped along the poloidal limiter, front and side views, linear dimensions and radius (R) in millimeters.

address this issue, an additional calibration is required to de-embed the plasma path from the complex signal measurement. A simplified representation of the process can be seen on Fig. 3 where all other sources of signal coupling are represented as a single cross-talk.

All this complex signals and impedances vary with frequency; therefore, all the calibration procedures mentioned above are to be carried at each particular operating frequency. A FWR system should operate continuously without dead times for more than 1 min, and should be capable of measuring in a difficult electrical environment such as in the JET nuclear fusion experiment (see Fig. 4). This means that the system should have both tolerance to interference and capacity to handle high signal levels. As the test media and interface will present essentially reactive impedance to both TX (transmission) and RX (reception), antenna operation of the transmitter under severe mismatch is also required.

The range of frequencies predicted by the theory will extend from 10 to 60 MHz in the worst case, corresponding to tritium in a 2 T magnetic field to hydrogen at 4 T magnetic field. The generator should have frequency agility with switching times of about 1 μ s or less. The very low efficiency of the antennas due to its reduced size and more important [while comparing with DIII-D (Ref. 1)], and more importantly, the higher distance to the plasma will lower the coupling efficiency. Therefore, we clearly aim at a power level at least an order of magnitude higher than that used at DIII-D, that is, about 0.2 W. Since the technology for this power levels at this range of frequencies is not a problem,

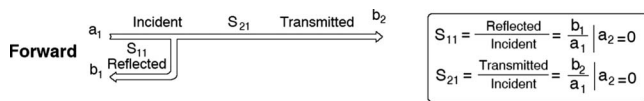


FIG. 2. Complex impedance/transmittance measurement method.

and taking into consideration the high standing-wave ratio (SWR) operating conditions, we would propose a power output of 5–10 W.

OVERVIEW OF THE SYSTEM

A balanced-unbalanced network (BALUN) and dc break located near the vessel serve the purpose of common mode electrical isolation between the fusion reactor and the rf equipment and also makes the transition from the balanced twisted pair transmission line (that goes inside the vessel) to the 50 Ω coaxial cable that will connect to the instrument, about 60 m away from the reactor, located at the diagnostic hall. These components should be broad enough to cover the frequency range and should promote some degree of impedance matching and also some damping to artificially lower the SWR on the long 50 Ω cable. Independent ion cyclotron emission (ICE) radiation RX measurements (with a spectrum analyzer) should be also possible in the band of 10–500 MHz; therefore, the BALUN and dc break boxes should also let in signals in the 10–500 MHz range. The TX unit will have also a sampling of voltage and a sampling of current for the purpose of establishing the phase reference by defining the impedance at the antenna. Notch filter boxes will ensure the operation of the system in the presence of strong interference from ion cyclotron resonance heating (ICRH) operating in the 38–54 MHz range. Each filter will attenuate whenever necessary any of the four signals that ICRH can launch simultaneously.

The generator section will deliver signals in the 10–60 MHz range using direct digital synthesizers (DDS) to have the minimum switching time possible. The DDS chips will communicate to a rf microcontroller board. Each DDS is implemented in a field programmable gate array (FPGA) so that switching times can be set by design to the minimum technologically feasible (as all frequency configurations could be programmed to random access memory tables inside the FPGA and therefore be switched in a single clock cycle by an external trigger).

The power amplifier should deliver 10 W of nonsaturated power with controllable gain from 10 to 40 dB for a drive power of 0 dB m. This corresponds to a controllable power output from 100 to 10 W. The full band of 10–60 MHz should be covered with better than 1 dB flatness.

The receiver is mainly done in the digital domain and their characteristics are fully software defined. The code for the DSP (digital signal processor) boards will implement a full digital phase/amplitude measurement receiver in DSP software. The control software runs preferably on a separated microcontroller board that configures the rf hardware, namely, the DDS generators, the notch filters, and the power amplifiers.

INTERFERENCE PROBLEMS AT JET (OR ITER)

Operation of a FWR system in large tokamak will encounter severe interference of different nature, namely, ICRH heating operating about 50 MHz with massive amount of power, and broadband radiation across our range of frequen-

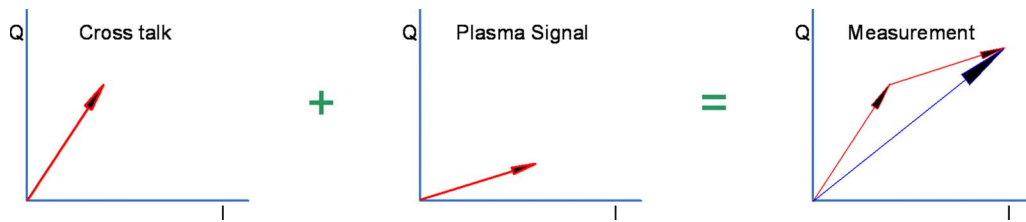


FIG. 3. (Color online) Vectorial composition of a measured S_{21} , showing that it is possible to de-embed the plasma signal from a measurement by knowing the parasitic cross-talk.

cies from ICE. Large coupling of ICRH signal into the FWR antennas may put the diagnostic integrity at risk if a power of several watts is actually coupled into the system. Appropriate protection devices should exist in the system front-end. From the measurement point of view, the instrument makes a coherent phase measurement and, therefore, only a signal coherent with the launched one is measured. Needless to say that operation of the FWR at the exact same frequencies of the ICRH is not possible, however, a few percent above or below that frequency becomes feasible and will yield the same plasma physics reality. Unlike ICRH interference, ICE will exist in all the bandwidth of the measurement. The ICE signal levels measured at TFTR,² although with a different type of antenna, are considerably small about -90 dB m (1 MHz). We can do a rough estimate of -80 dB m (1 MHz) worst case at JET considering the different antennas and machine characteristics (that is the same as -110 dB m (1 kHz) which is likely the bandwidth to be used in a FWR experiment that corresponds to a 1 ms time resolution). Some ICE features may be present but can be easily disregarded by the statistical nature of their occurrence.³ A frequency hopping operation scheme would diminish the statistical probability of measurement near these ICE features. The noise level from ICE set the lowest signal level receivable from the FWR transmitter therefore determining the dynamic range useable for fast wave reflectometry.

THE OVERALL SYSTEM PERFORMANCE

The cross-talk and ICE noise floor set the system overall resolution requirements for the receiver performance which is also limited by fundamental time (bandwidth) versus resolution relation if not limited before by the available technology. The maximum antenna efficiency possible will not exceed 5%. The plasma coupling modeling, done with a full-wave code which takes into account the thermal effects on the wave propagation and considering the actual geometry, has shown values of about 30% plasma coupling; this result in 1.5% overall efficiency (or -18 dB) that is the coupling from the TX antenna to the plasma back to the RX antenna. The additional damping and impedance matching may also produce an extra 6 dB loss. We arrive at about -24 dB, considering a transmitted power of 37 dB m (5 W) and a received ICE signal of -80 dB m (this considers the signal at the receiver port that includes receiving antenna coupling and electrical efficiencies).

To achieve a 1° (in $1 \mu\text{s}$) resolution (that corresponds to about 2 cm at the plasma), 45 dB of signal to noise ratio are required and with that (from the 63 dB of maximum plasma attenuation that we calculate from the above numbers) 18 dB of margin still exist. Operation with moderate integration times will sacrifice temporal resolution but enhances sensitivity proportionally.

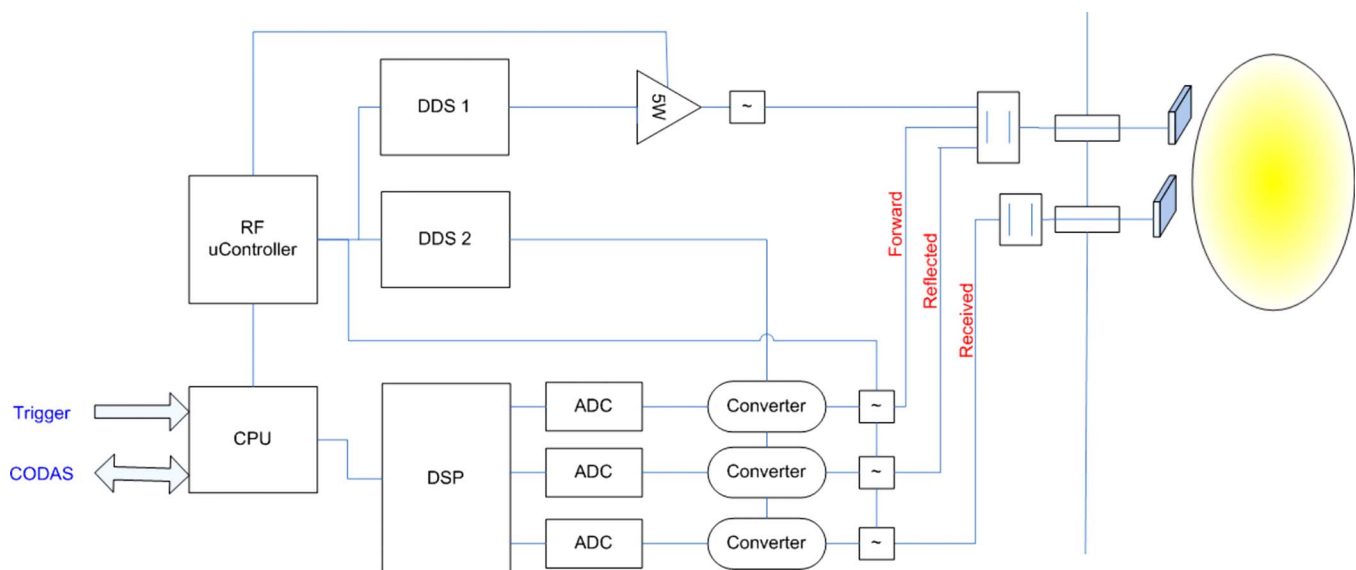


FIG. 4. (Color online) Simplified block diagram of the FWR system.

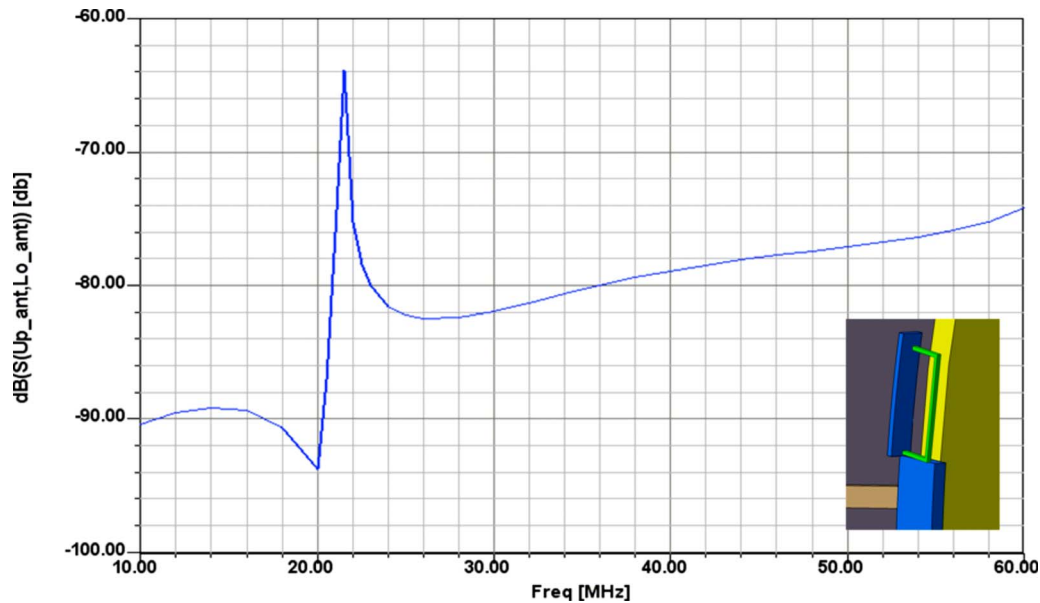


FIG. 5. (Color online) Cross-talk simulation, path from one antenna to another within vessel structure and vacuum. Simulation by a full three dimensional model under high frequency simulator software™ (HFSS).

Along with the previous assessment, the cross-talk determines the system analog-to-digital converter (ADC) requirements that allow us to finally prove the technical feasibility. The antennas at JET placed along the limiter beam, one above and the other below the midplane at the same toroidal position at a distance to the plasma on the order of 10 cm, show simulation cross-talk values ranging from -80 to -65 dB (Fig. 5). These values are smaller than the simulation for the plasma plus antenna's total path, which leave us in a quite favorable position.

A resolution of 1° sets out the need for at least 9 bits of ADC resolution and the worst case where cross-talk and plasma signal are of similar magnitude will add the need of an extra bit. To accommodate the operation with signal amplitude variations of more than 10 dB maintaining our target of 1° resolution, we would require 12–14 bit ADC resolution. Since these ADCs running below 100 MHz are common technology nowadays, the system is feasible.

SUMMARY

The direct determination of the ion species mix on thermonuclear plasmas is of great interest for ITER. FWR has the potential to provide fuel isotope mix ratio with good spatial and temporal resolutions. Such diagnostic is feasible and could be attempted on JET in the perspective of addressing the in-vessel installation issues, the instrumental difficulties, and validating the diagnostic performance.

For such purpose a complete design of a FWR was undertaken and the relevant instrument specifications were derived based on a new design using digital technology as

much as possible. A careful design of all in-vessel parts was also undertaken in order to address all the manufacturing and installation issues. The limitations due to the specific installation on the JET tokamak environment, namely, the feasible antenna arrangement, the ICE, and the ICRH, dictated the main design parameters and was proven not to be an obstacle.

For JET it is possible to implement a FWR within the desired performance and operation under the typical JET and ITER relevant conditions.

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