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L. Cupido[1], A. Cardinali[2], R. Igreja[1], F. Serra[1], M. E. Manso[1], A. Murari[3]
and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Av Rovisco Pais, 1049-001 Lisbon, Portugal
[2]Associazione EURATOM-ENEA sulla Fusione, C.R. Frascati, Roma, Italy
[3]Associazione EURATOM-ENEA sulla Fusione, Consorzio RFX Padova, Italy,
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ABSTRACT.

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. A 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. Moreover, a good measurement of relative concentration of atoms with different charge to mass ratio would allow a better control of the heating power deposition profile and the transport of particles of different masses is an important issue to understand particle transport coefficients.

Fast Wave Reflectometry, with the potential capability to provide fuel isotope mix ratio with good spatial and temporal resolutions, is expected to be a valuable diagnostic for ITER. Experiments performed at DIIID tokamak have shown that this technique is quite promising to provide fuel isotope mix ratio within a few percent resolution [1].

Here we present a system design with improved performance that uses a novel signal generation and coherent signal detection capable of operating in ITER-like scenarios.

1. 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 cut-off 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 propagating in the plasma, reaches the cut-off 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 DIIID 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 cm, depending on the signal to noise ratio, and a temporal resolution in the range of 1 millisecond. Lower temporal resolutions, hence higher integration times, will allow higher spatial resolution and vice versa.

2. DESIGN OF A FAST WAVE REFLECTOMETER

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

3. INSTRUMENT DESIGN

An RF measurement instrument for the Fast Wave Reflectometer consists essentially of a programmable RF generator and a 2 channels 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 figure 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 no 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 trough the vessel structure and cabling crosstalk. To 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 figure 3 where all other sources of signal coupling are represented as a single crosstalk.

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 minute, and should be capable of measuring in a difficult electrical environment such as in the JET nuclear fusion experiment. 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 and RX, antenna operation of the transmitter under severe mismatch is also required.

The range of frequencies predicted by the theory will extend from 10 to 60MHz in the worst case, corresponding to tritium in a 2T magnetic field to Hydrogen at 4T magnetic field. The generator should have frequency agility with switching times of about 1μs or less. The very low efficiency of the antennas due to its reduced size and more important (while comparing with DIIID [2]) 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 used at DIIID, that is about 0.2W. Since technology for this power levels at this range of frequencies is not a problem, and taking into consideration the high SWR operating conditions, we would propose a power output of 5W to 10W.

4. OVERVIEW OF THE SYSTEM

A 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 Ohm coaxial cable that will connect to the instrument, about 60 m away from the reactor, located in 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 50Ohm cable. Independent ICE (ion cyclotron emission) radiation RX measurements (with a spectrum analyzer) should be also possible in the band of 10 to 500MHz, therefore the balun and DC break boxes should also let in signals in the 10 to 500MHz. 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 insure the operation of the system in the presence of strong interference from ICRH operating in the 38 to 54MHz range. Each filter will attenuate whenever necessary any of the 4 signals that ICRH can launch simultaneously.

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

The power amplifier should deliver 10W of non saturated power with controllable gain from 20 to 40dB for a drive power of 0dBm. This corresponds to a controllable power output from 100mW to 10W. The full band of 10 to 60MHz 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 ADC/DSP 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.

5. INTERFERENCE PROBLEMS AT JET (OR ITER)

Operation of an FWR system in large tokamak will encounter severe interference of different nature namely ICRH heating operating about 50MHz with massive amount of power, and broadband radiation across our range of frequencies from ICE.

Large coupling of ICRH signal into the FWR antennas may put at risk the diagnostic integrity 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 feasable 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 are considerably small about –90dBm[1MHz] at TFTR [3] and expected to be about -80dBm[1MHz] worst case at JET (that is the same as –110dBm [1KHz] which is likely the bandwidth to be used in a FWR experiment that corresponds to a 1ms time resolution). Some ICE features may be present but can be easily disregarded by the statistical nature of their occurrence

[3, 4]. 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.

6. 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 has shown values of about 30% plasma coupling; this result in 1.5% overall efficiency (or −18dB). The additional damping and impedance matching may also produce an extra 6dB loss we arrive to about -24dB. Considering a transmitted power of 37dBm (5W) and a received ICE signal of -80dBm (this considering is the signal at the receiver port that include receive antenna coupling and electrical efficiencies).

To achieve a 1 degree (in 1μs) resolution (that corresponds to about 2cm at the plasma) 45dB 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.

Along with the previous assessment, the cross talk determines the system 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 mid plane at the same toroidal position at a distance to the plasma in the order of 10cm, show simulation cross talk values ranging from -80 to -65dB figure 5. These values are smaller than the simulation for the plasma plus antenna total path, which leave us in a quite favorable position.

A resolution of one degree sets out the need for at least 9 bit 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 10dB maintaining our target 1 degree resolution we would require 12 to 14 bit ADC resolution. Since these ADC's running below 100MHz are common technology nowadays, the system is feasible.

CONCLUSIONS

The direct determination of the ion species mix on thermonuclear plasmas is of great interest for ITER. Fast Wave Reflectometry 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 fast wave reflectometer 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 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 fast wave reflectometer within the desired performance and operation under the typical JET and ITER relevant conditions.

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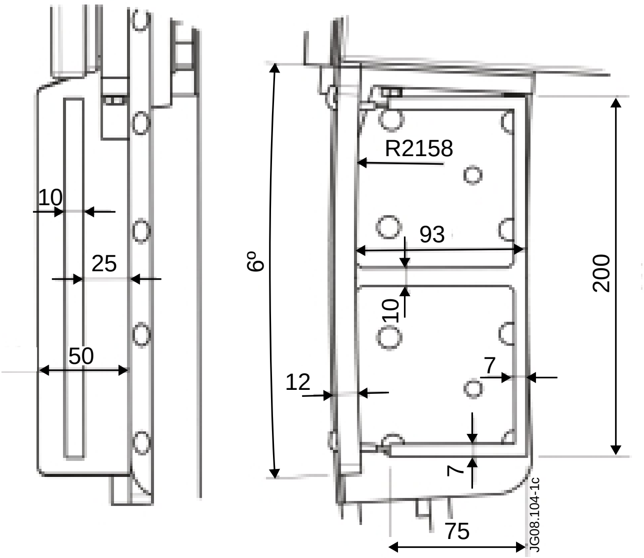

Figure 1: The lower FWR antenna.

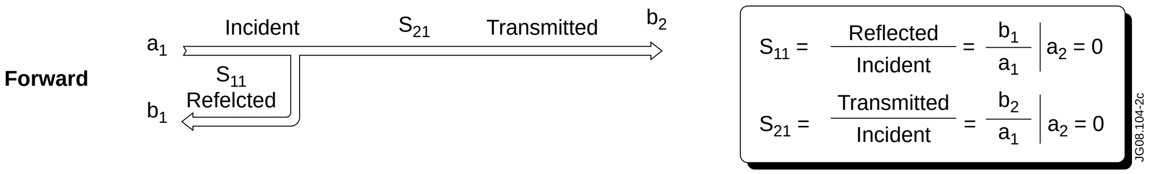

Figure 2: Complex impedance/transmittance measurement. method

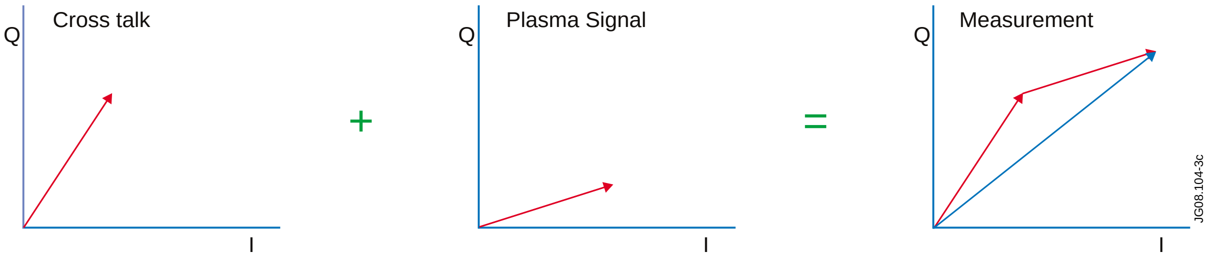

Figure 3: Complex composition of the measured S21.

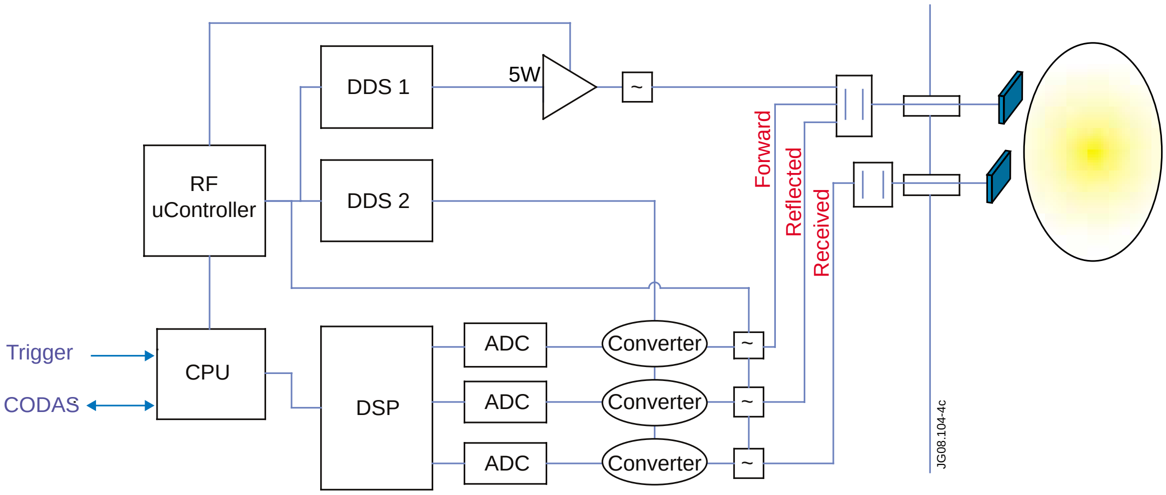

Figure 4: Simplified block diagram of the FWR system.

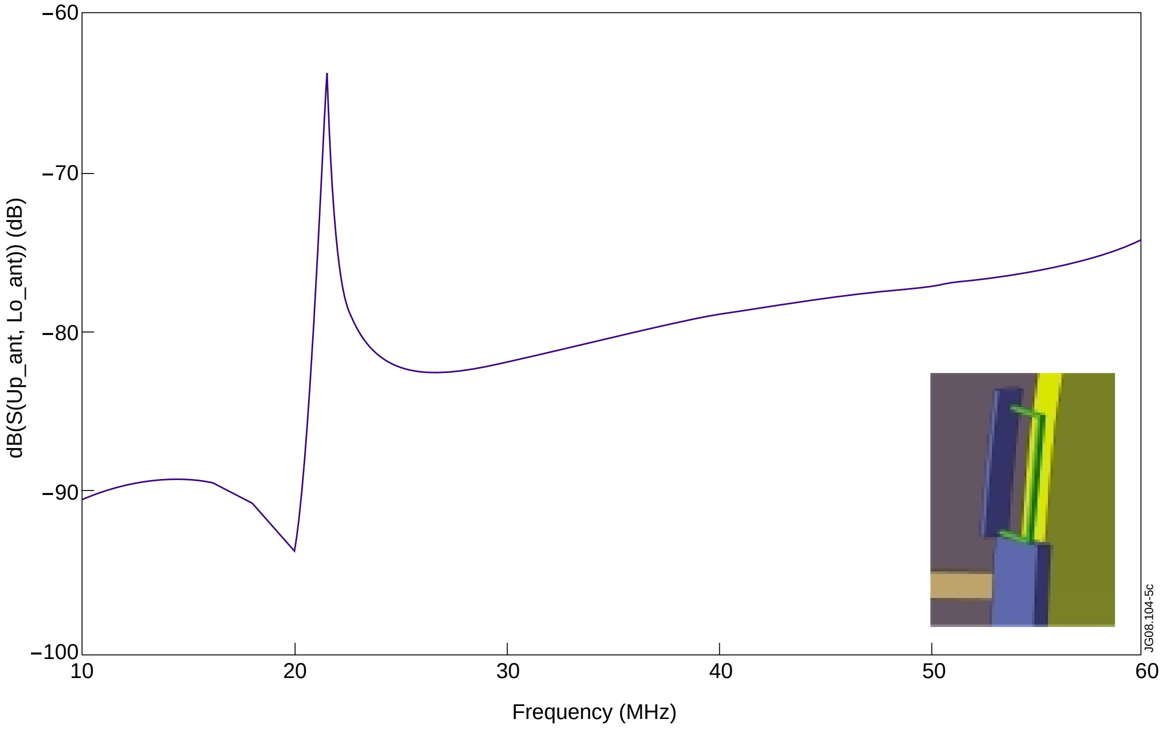

Figure 5: Cross talk simulation, path from one antenna to another within vessel structure and vacuum.