

Improved measurements of ICRF antenna coupling at ASDEX Upgrade and comparison with the ICRF coupling code TOPICA

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Three methods of measuring antenna impedance on the transmission lines of the ASDEX Upgrade ICRF system have been compared on a 50 Ω test line – by using directional couplers, voltage probe arrays and voltage/current probe pairs. Under the best available conditions (straight 50 Ω line), the voltage/current probe pair consistently shows the highest accuracy, up to 1.2%, independent of VSWR. The current and voltage probes have been calibrated by measuring their coupling values on the 50 Ω line; the values for a 25 Ω line were obtained from the 50 Ω measured values by computing the difference in coupling in the two lines for both probes using simple circuit models. The new measurement system is implemented on ASDEX Upgrade antennas and will complement the already available measurements from directional couplers. In addition to improving the accuracy, it will also have the advantage of yielding two complex reflection coefficients per antenna (one for each strap) instead of one. The measurement is located significantly closer to the antenna input (~ 3 m from the strap input), thereby reducing errors due to the geometrical complexity of the transmission lines.

Keywords: ICRF, coupling, antenna impedance.

1. Introduction

The ICRF system on ASDEX Upgrade consists of 4 two-strap antennae, each strap fed by its own line as depicted in Fig. 1. The ICRF power coupled to the plasma is currently measured by directional couplers installed on the transmission lines on the generator side of the matching network (see Fig. 1) [1,2]. There are two disadvantages in this configuration. On one hand, there is a lengthy (~20 m) and geometrically complex transmission network between the couplers and the antenna input; on the other hand, no information is obtained on the individual behavior of the two antenna straps, e.g., the power distribution between them. Obtaining accurate and detailed information on the coupled power – or equivalently, the antenna input impedance or reflection coefficient – is important not only for the routine operation of the ICRF system, but also for the comparison of experimental data with ICRF coupling codes such as TOPICA [3]. Such a comparison serves to strengthen our confidence in TOPICA to predict the coupling for ITER.

2. Preliminary comparison

A preliminary comparison between TOPICA and experimental results on ASDEX Upgrade has been attempted, using two kinds of experimental data: 1) the measurements from the directional couplers as described above and 2) measurements from voltage probe arrays installed on the individual strap feeding lines on each antenna (see procedure below); these voltage probes had been functioning but not used for ICRF measurements (the detectors used with these probes were recalibrated prior to these measurements). The main quantity of

interest was the complex reflection coefficient Γ , defined by

$$\Gamma = \frac{Z_T - Z_0}{Z_T + Z_0}, \quad (1)$$

where Z_T is the input impedance measured at the T-connection, where the two feeding lines are merged into a single line at the matching network (see Fig. 1), and Z_0 is the characteristic impedance of the common line (50 Ω).

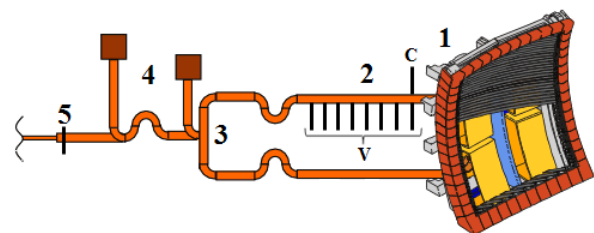


Fig. 1. One of four ASDEX Upgrade antennas with transmission lines and matching network. 1 – antenna; 2 – location of voltage (V) and current (C) probes; 3 – T-connection; 4 – matching network; 5 – location of directional couplers [1 and references therein].

The following procedure was followed:

1. The antenna model and an experimental plasma density profile, measured at the equatorial plane (reconstructed from Li beam, laser interferometer and Thomson scattering and averaged over a time of the order of 10 ms) were used as input for a TOPICA simulation. The result was a 2×2 scattering matrix (or S-

matrix) computed at a plane intersecting the two strap feeding lines at a distance of 156 mm from the antenna input. The computed S-matrix is translated backwards from the antenna through the two feeding lines up to the T-connection, where the joint reflection coefficient Γ is calculated.

2. For the same time period, two directional couplers located behind the tuning stubs (on the generator side) are used to measure the Γ , which is then translated forward through the matching network up to the T-connection, and then compared with the Γ obtained from the TOPICA computation.
3. For the same time period, the Γ at the T-connection is reconstructed from the measurements of the voltage probe arrays. This Γ is then compared with the one directly obtained from TOPICA and the one translated from the directional couplers' measurements.

Based on the data taken from shots 25634 and 25654, the following conclusions were made:

1. There is good agreement in $|\Gamma|$ ($\leq 10\%$) for all antennas between TOPICA and data from the directional couplers, with TOPICA usually predicting a slightly lower $|\Gamma|$. There is a large discrepancy in $|\Gamma|$ (up to $\sim 20\%$) for antennas 1, 2 and 4¹ between TOPICA and the voltage probe arrays, with the probes yielding a higher $|\Gamma|$ than both TOPICA and the directional couplers.
2. There is a large discrepancy (up to $\sim 90^\circ$, depending on the antenna) in the phase of Γ , between TOPICA and both probe arrays and directional couplers. This is smaller between TOPICA and the probes, most likely due to the fact that the same line lengths are used processing these two results.

A typical result is shown in Table 1 (antenna 1, shot #25634, $t = 1.71 - 1.72$ s, $f = 30$ MHz; values are time-averaged). It can be seen that the difference in $|\Gamma|$ from TOPICA and the directional couplers is 11%, whereas it is 15% between TOPICA and the voltage probes. Note the large phase difference between TOPICA and the directional couplers.

Possible reasons for the discrepancy between TOPICA results and directional coupler measurements include the geometrical complexity of the transmission network and uncertainties in line length measurements. The feeding lines include a large number of elbows and ceramic spacers whose impedance differs from the characteristic impedance of the line; this introduces uncertainties in the measurement and/or computation of the electrical lengths of the lines.

¹ No voltage probe data exists for antenna 3.

Regarding the large difference seen between TOPICA results and voltage probe array data, the problem here (although the method is in principle independent of the VSWR) lies in the low number of voltage sampling points and the finite resolution in the measurement of the probe coupling factors, which is 0.01 dB. The higher the VSWR, the more localized the minimum is, and more sampling points are in principle needed to keep it accurate. As the number of sampling points is always the same (10 to 12 depending on the antenna), the resolution above some value of VSWR is not enough to accurately visualize the minimum, and hence $|\Gamma|$ is incorrectly computed.

Table 1: An example result of the comparison between TOPICA and ASDEX Upgrade experimental data (antenna 1, shot #25634, $t = 1.71 - 1.72$ s).

	$ \Gamma $	$\Phi(\Gamma)$
VP	0.84	87.07°
DC	0.79	17.11°
TOPICA	0.68	82.63°

3. Comparison of impedance measurement methods

From the discrepancies seen in the results above, it is clear that an assessment must be made about the accuracy and applicability of the different methods of measuring an antenna impedance. These methods are a) directional couplers, b) voltage probe arrays and c) a pair of voltage and current probes, which was not used in the comparison, as at the time this system was not yet implemented at ASDEX Upgrade.

In order to compare the three measurement methods (directional couplers, an array of eight voltage probes, voltage and current probe pair) under controlled conditions, all the sensors were mounted on a 50 Ω test line and used to measure artificial loads of 50 Ω , 25 Ω , 12.5 Ω , 6.25 Ω , 4.3 Ω ², open line and short circuit. A signal generator with a 30 dB amplifier was used as input, with two filters³ used to suppress generator harmonics. The measurement procedure was the following:

- 1) Measure the exact impedance Z_L of each load and compute the reflection coefficient.
- 2) Measure the impedance at the location of the sensors.
- 3) Translate the measured impedance towards the load⁴ and compute the measured reflection coefficient.

² These values are not exact; the real values were measured on the network analyzer and vary with frequency.

³ A low-pass filter when using 30 MHz and a band-pass filter when using 36.5 MHz.

⁴ The translation distance between the sensor and the load was taken to be the mechanical one, measured with a meter tape; the accuracy of the electrical length measurement by time-domain reflectometry was far too low.

Results of the measurements at a frequency of 36.5 MHz are shown in Tables 2 and 3 (measurements at 30 MHz gave similar results and are omitted for brevity). Γ_L is the reflection coefficient of a given load, measured by network analyzer per step 1.

Table 2: Measurements of $|\Gamma|$ using a directional coupler (DC), voltage probe array (VP) and voltage and current probe pair (IV).

$ \Gamma_L $	$ \Gamma_{DC} $	$ \Gamma_{VP} $	$ \Gamma_{IV} $
0.00	0.01	-	0.00
1.00 (open)	-	0.91	-
1.00 (short)	1.01	0.75	0.99
0.83	0.84	0.72	0.83
0.77	0.77	0.70	0.77
0.59	0.59	0.58	0.59
0.33	0.33	0.33	0.33

Table 3: Measurements of the phase of Γ using a directional coupler (DC), voltage probe array (VP) and voltage and current probe pair (IV).

$\Phi(\Gamma_L)$ (°)	$\Phi(\Gamma_{DC})$ (°)	$\Phi(\Gamma_{VP})$ (°)	$\Phi(\Gamma_{IV})$ (°)
0.00	-73.34	-	0.00
0.00 (open)	-	0.00	-
180.00 (short)	174.26	175.64	172.01
175.61	168.16	170.57	167.07
163.78	155.06	157.75	155.28
172.90	164.86	167.25	164.06
175.40	168.16	171.05	166.00

The best accuracy among the three methods is obtained when using the voltage/current probe pair, independent of the VSWR. The directivity of the directional coupler is ~ 35 dB, errors are in the range 0.04% - 4.3% (also taking into account the results obtained at 30 MHz). These errors depend on VSWR as expected, due to the finite directivity of the coupler. The error of the voltage probe array method also seems to depend on the VSWR (the higher the VSWR, the more difference between measured and expected $|\Gamma|$) and is in the range 0.2% - 25%. The error on the voltage/current probe pair is in the range of 0.02% - 1.2%. Clearly, the voltage/current probe pair method shows the highest accuracy in these experiments. In all cases, the translated values are a few degrees off the expected values, and the error is systematic; this is attributed to an uncertainty in the measured length of the test line, probably due to the presence of a ceramic spacer and several low impedance transition sections. No measurements were done with DC and IV probes with the open line, as the vector analyzer used gave unreliable readings in these conditions. Likewise, no measurements on a 50 Ω load were made with the voltage probe array, as the routine used to reconstruct the standing wave produced unreliable results.

Regarding the voltage probe array method, numerical experiments showed that, to consistently keep errors in $|\Gamma|$ under $\sim 5\%$ in the high reflection cases, the coupling factors of each probe have to be known with a resolution

of about 0.005 dB, which is not achievable with the given setup. Hence, even under the best conditions this method will be unable to correctly measure high reflection coefficients and therefore cannot be employed for the purposes of this work, at least in the present configuration.

4. Probe calibration

Since the voltage probe array is not accurate enough, and the directional couplers could be strongly affected by the reflected power, the optimal measurement method is the one involving the voltage/current probe pair. However, the probes had to be calibrated first; they had been built by the manufacturer for the original 50 Ω feeding lines, which had later been changed to 25 Ω ; therefore their coupling factors were not known. Since a 25 Ω calibration kit was not available and would have required considerable time to build, it was decided that the coupling factors of the probes would be measured on the existing 50 Ω setup, and then recomputed for 25 Ω . In order to do this, calculations using simple equivalent models were made for both types of probes (Fig. 2).

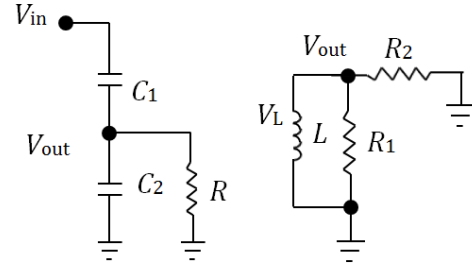


Fig. 2. Voltage probe (left) and current probe (right) equivalent models.

The voltage probe is essentially a capacitive divider installed into the outer conductor of the transmission line. It has an internal capacitance C_2 and an external capacitance C_1 formed by the probe cover and the inner conductor of the line. The output voltage given by

$$V_{out} = \frac{V_{in} j\omega C_1}{j\omega(C_1 + C_2) - \frac{1}{R}} \quad (2)$$

where $R = 50 \Omega$, $C_2 \cong 2$ nF (internal capacitance of the probe, measured) and $C_1 \cong 0.22$ pF for a 50 Ω line and $\cong 0.45$ pF for a 25 Ω line (given by a geometrical factor times the characteristic capacitance of the line). Hence the ratio V_{out}/V_{in} increases by a factor of $\cong 2.01$ or 6.07 dB when transitioning to a 25 Ω line. The coupling (absolute value and phase) of each probe was measured (4 probes per antenna, 16 total). This was done by installing each probe on the 50 Ω line, which was terminated by a 50 Ω load. The input of the line was fed from port 1 of a network analyzer, and the output of the probe was connected to port 2. The transmission coefficient S_{21} , measured by the network analyzer, was then taken to be the coupling factor of the probe on the 50 Ω line. The absolute value of S_{12} is the ‘‘measured’’ curve in Fig. 3; the phase is not shown. To determine the coupling of each probe at each frequency point, on the

25 Ω line, only the constant obtained above needs to be added.

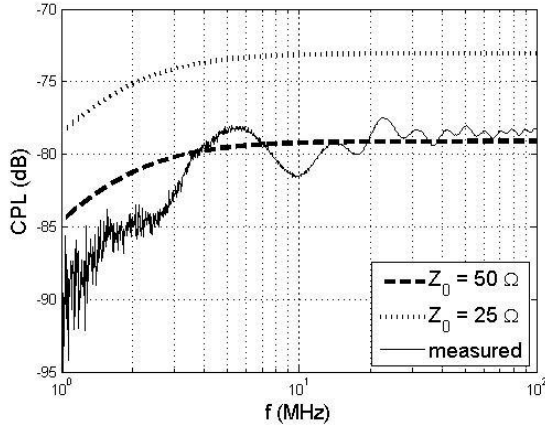


Fig. 3. Coupling of a voltage probe (absolute value), measured and modeled for 50 and 25 Ω . The oscillations in the measured coupling are due to additional equipment parts (cables, connectors, etc.) connected to the probe.

The current probe, on the other hand, is inductively coupled to the line; it consists of a coil wrapped around a ferrite core, positioned in a slot in the outer conductor, that samples the magnetic field inside the line. The output voltage is given by

$$V_{out} = \frac{-j\omega M I_{in} R_1 R_2}{R_1 R_2 + j\omega L (R_1 + R_2)}, \quad (3)$$

where I_{in} is the current flowing on the line, $R_1 = 33 \Omega$, $R_2 = 50 \Omega$, L is the self-inductance of the coil and M is a measurable constant characterizing the magnetic flux through the coil. To compute the coupling we express Eq. (3) as

$$V_{out} = \frac{-j\omega M V_{in} R_1 R_2}{Z_0 (R_1 R_2 + j\omega L (R_1 + R_2))}, \quad (4)$$

where V_{in} is the voltage on the line and Z_0 its characteristic impedance. This increases by a factor of 2 or by 6.02 dB when transitioning to a 25 Ω line. To determine the coupling of each probe on the 25 Ω line, again only this constant needs to be added to the coupling measured at 50 Ω . The same procedure was followed as with the voltage probes. The measured absolute value of coupling of a current probe, as well as the modeled behavior for 50 and 25 Ω , is shown in Fig. 4.

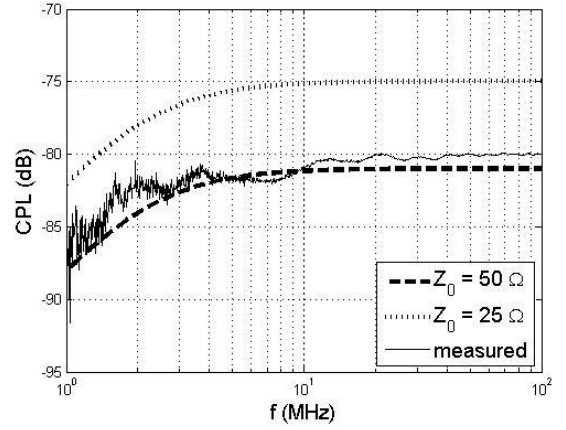


Fig. 4. Coupling of a current probe (absolute value), measured and modeled for 50 and 25 Ω .

As mentioned above, logarithmic RF detectors were installed to read the signals, due to the large amplitude of voltage and current variation expected on the unmatched lines. The dynamic range of the detectors is 65 dB with a maximum input level of 23 dBm, which allows to measure voltages up to 19 kV and currents up to 420 A on the 25 Ω lines. Two selectable low-pass filters, with cutoffs at 50 and 90 MHz, are used to suppress generator harmonics, which can cause errors in the measurement. Phase is measured using two detector circuits, where one of the signals is shifted by 90° , which makes it possible to detect phase shifts of $\pm 180^\circ$.

5. Outlook

After the characterization of the RF detectors, the new measurement system was implemented on both feeding lines of antenna 3 at ASDEX Upgrade and is currently undergoing testing and minor corrections. As mentioned in the introduction, this method has definite advantages over the other two. First, the voltage/current probes are located physically close to the antenna input. Second, they yield two reflection coefficients per antenna. The time resolution of the system varies between 1 μ s and 24 μ s, depending on the ICRF power pulse length. Each signal contains 524288 points. This enables one to resolve the effects of ELMs on the antenna coupling properties.

References

- [1] Bobkov, V. I. *et al.*, Nucl. Fus. **46** (2006), S469-S475.
- [2] Jaquet, P. *et al.*, Nucl. Fus. **62** (2012), 042002.
- [3] Lancellotti, V. *et al.*, Nucl. Fus. **46** (2006), S476-S499.