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Radio-frequency hands-on for nuclear fusion Master's sudents

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Abstract

High-power continuous-wave radio-frequency (RF) systems in the megawatt range are commonly used in nuclear fusion experiments. Such kinds of RF systems being rather rare, Master's students do not know how these systems are used in practice – even students engaged in nuclear fusion courses. This is the reason why, as part of the French and European Master's in fusion physics and technologies, dedicated practical work on topics related to plasma RF heating are proposed to students. Over a few days, these students discover how to perform RF measurements and succeed in characterizing real-scale components used in plasma RF heating experiments. This paper details four hands-on approaches which have been conducted over eight years with several tens of students having no prior knowledge in RF engineering.

Keywords: radio-frequency, high power, plasma heating, nuclear fusion, hands-on

(Some figures may appear in colour only in the online journal)

Introduction

The objective of nuclear fusion research is to demonstrate the scientific and technological feasibility of nuclear fusion (as opposed to nuclear fission) to create electricity. However, in order to achieve the necessary conditions allowing light nucleii to fuse, plasmas of temperature greater than 100 million degrees must be generated and sustained. Devices called tokamaks [1] are developed and used all around the world to study the magnetic confinement of such plasmas. WEST [2] (previously known as Tore Supra [3]), is a superconducting tokamak located in Cadarache, France, which has demonstrated the sustainment of long plasma pulses (up to 6 min 30 s) [4].

In order to sustain these long plasma pulses, a part or all of the plasma current which is circulating inside the plasma ring must be generated non-inductively. This additional plasma current is driven at WEST via a lower hybrid (LH) radio-frequency (RF) system [5, 6]. High-power RF sources (klystrons) generate up to 7 MW at 3.7 GHz, which are carried through 25 meter-long transmissions lines (rectangular waveguides) up to the LH antennas facing the edge plasma. These antennas (two at WEST) are made of rectangular waveguide phased arrays, which excite a plasma wave mode that ultimately accelerates electrons and create an electric current inside the magnetically confined plasma [7].

Ion cyclotron resonance heating (ICRH) is another RF system used to increase the plasma temperature by launching RF waves with frequencies that are equal to the gyro-frequency of one ion species of the plasma [8]. In WEST, the ICRH system can generate up to 9 MW in the frequency range of 48–60 MHz, where rigid coaxial lines feed three antennas made of an array of four short 'straps' [9]. Future IC systems are also under design for the next generation of fusion tokamaks [10].

In order to train future fusion scientists and engineers, French and European Master's programs exist to provide teaching on plasma sciences and associated technologies. These Master's programs deal with most scientific and technological fields related to the ionized media via theory, numerical modelling, material sciences, cryotechnology and superconductivity, and instrumentation in extreme environments. However, for a vast majority of them, no dedicated courses are provided on RF sciences and technologies, despite their widespread use at fusion research facilities.

During two weeks at the beginning of the civil year, both French and European Master's students gather in the Cadarache research centre in order to participate in small groups in 'hands-on' activities organized by fusion researchers. The topics of these hands-on cover the large spectrum of fields used in fusion research: cryotechnology and superconductors, infrared measurements, numerical modelling, tokamak data analysis, virtual reality, etc. Among these hands-on, some are devoted to RF component measurements and analysis and are described in this paper. Section 1 details the LH-specific hands-on devoted to two particular components of the LH antennas used at WEST. Section 2 focuses on the ICRH-specific hands-on regarding high-voltage probe calibration and the design of a possible future ICRH antenna. The last section concludes with the students' and authors' feedbacks on these hands-on activities. Because some of the components used are very specific to high-power RF, and especially to fusion applications, in particular for LH topics, it is probably not easy to reproduce them in other teaching places. The last topic described in this paper, however, only uses phase shifters and 3 dB hybrid junctions, which are much more commonly available in laboratories.

Lower hybrid frequency range hands-on

Two hands-on have been proposed to the students on two RF components constituting the real WEST LH launchers: a mode converter (in red in figure 1) and a 'multijunction' (in blue in figure 1). These RF components have multiple functions, but the main one is to split the RF power coming from the klystron to numerous waveguides facing the plasma. These two components and their associated hands-on are described in the sub-sections below.

TE_{10}-TE_{30} mode converter

A mode converter is an RF device which aims to convert an electromagnetic mode of propagation in a waveguide into another mode [11]. In particular, the TE_{10}-TE_{30} mode

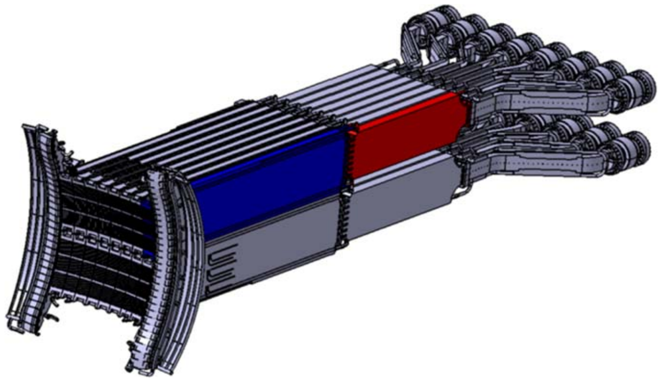

Figure 1. CAD view of a WEST lower hybrid antenna (aka 'LH1'). The red part is the TE_{10}-TE_{30} mode converter. The blue part is the 'multijunction'. Dimensions: $0.7 \times 0.7 \times 5$ m. Weight: a few tons.

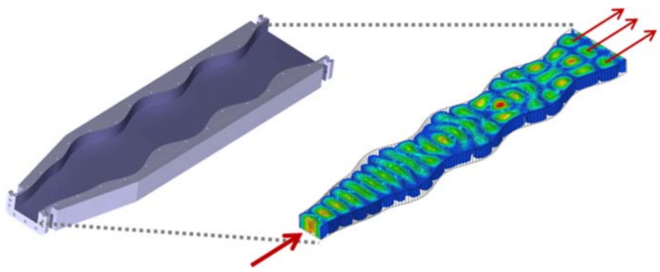

Figure 2. CAD internal view and its associated radio-frequency modelling (electric field).

converter converts a low-order incident transverse electric mode (TE_{10}) into a higher-order TE mode (TE_{30}) [12, 13]. Once this mode conversion has been performed (figure 2), the power is then split into three independent waveguides by placing two thin metallic walls (in the E-plane) at the zero electric field location of the TE_{30} mode section. Thus, three TE_{10} mode waveguides are obtained and the device has thus divided the power in three. This device is used on WEST to split in three the RF power in the vertical direction of the antenna, in order to feed three rows of waveguides in each half part of the lower hybrid and current drive antenna (figure 1).

During this hands-on, students measure the RF performances of a TE_{10}-TE_{30} mode converter prototype (figures 3 and 4) which has been developed for the LH1 antenna [14]. The performances of an RF device being generally expressed via scattering parameters (or S-parameters), a general introduction to the S-parameter is given to the student groups in the first hours of the hands-on.

Like a role-playing game, the advisors ask the students to act as an RF technician who has been asked by his/her boss to characterize this TE_{10}-TE_{30} mode converter prototype and to report its performances as soon as possible. Unfortunately, the prototype had not been built exactly as designed: during the brazing operation, which was performed to assemble all the stainless-steel and copper parts of the structure, the mechanical pressure was not homogeneous, leading to local deformations of less than a millimetre. These are, however, sufficient to perturb

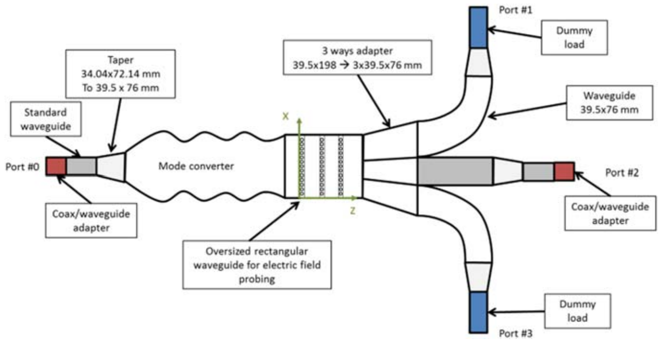

Figure 3. Illustration of the measurement setup.

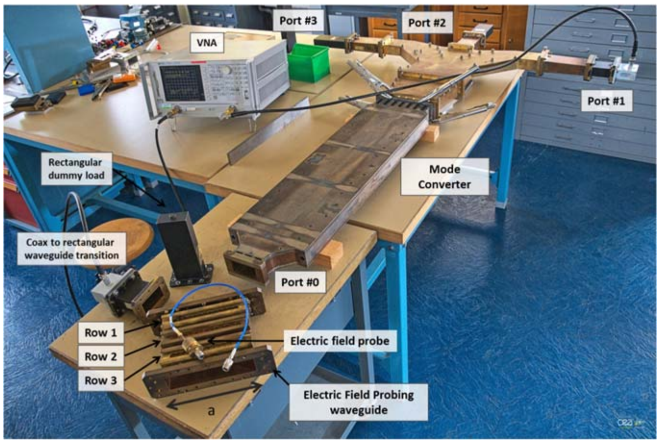

Figure 4. Picture of the mode converter setup.

the RF performance: the mode converter and its splitter are supposed to split the power in three evenly (−4.77 dB) but instead do so unevenly to −5.4, −4.2 and −5.3 dB for the left, central and right branches, respectively, at the frequency of interest (3.7 GHz).

However, the students are not told of this fact (which retrospectively was discovered once the RF measurements had been made during prototype acceptance test). They thus find unexpected results and the supervisors act as if they are surprised, telling the students that the 'RF design' is supposed to be perfect. Generally puzzled by their finding, very few students guess at first that a problem may have occurred during manufacturing. Students are thus asked how sure of their measurements they are, which is a good opportunity to discuss and explain the importance of calibrations, power conservation, statistics and uncertainties in experimental physics.

In order to help them to find the origin of the mode converter problem, students are provided the opportunity to measure the electric field at the end of the mode converter, in the TE_{30} section (output), using a dedicated waveguide pierced by an array of very small holes inserted between the mode converter and the 3-way adapter and an appropriate probe collecting a fraction of the electric field propagating inside the waveguide (figure 4). Once measured in various positions (figure 5), students are asked to deduce from these data the mode content inside the mode converter, i.e. the amplitude of the modes propagating inside the structure, to complete their analysis. This task requires the students to make a numerical

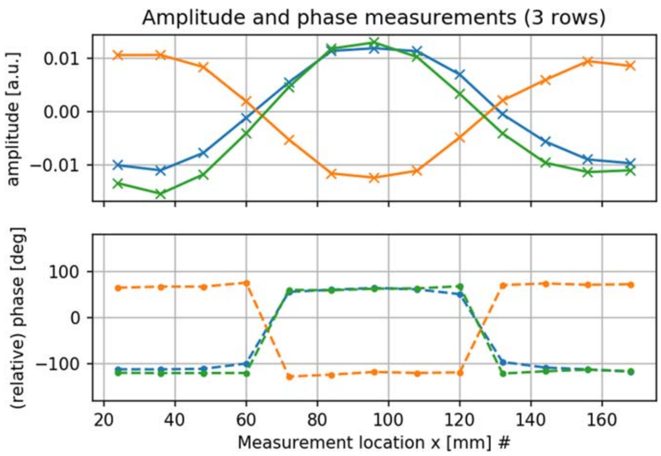

Figure 5. Measurement of amplitude and phase at various positions in the TE_{30} section of the TE_{10}-TE_{30} mode converter for the three rows.

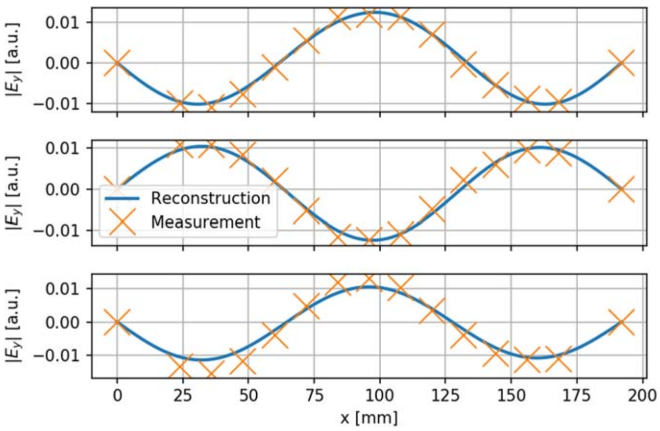

Figure 6. Once the unknown coefficients a_n have been found, one can reconstruct the electric field everywhere in the waveguide section and compare to the measurements. In this example, additional points have been added at the edges of the waveguide, where the electric field is zero, to additionally constrain the model.

model of the electric field E_y inside the waveguide, as a combination of TE modes (assuming only forward waves for simplicity):

$$E_y(x, z) = \sum_{n=1}^{N} a_n \sin\left(\frac{n\pi}{a}x\right)e^{-j\beta_n z}$$

with $\beta_n = \sqrt{k_0^2 - \left(\frac{n\pi}{a}\right)^2}$ the guided wavenumber, k_0 the wavenumber in vacuum and a the large side of the waveguide. Coefficients a_n are unknown and represent the mode content coefficients. Students must solve the inverse problem to deduce the a_n coefficients (figure 6). The mode converter prototype fails to convert 100% of the input mode TE_{10} into the TE_{30} mode. Solving for the a_n coefficients leads to a number around 76% to TE_{30} mode, 13% to TE_{10} mode and the rest into other modes. Since 2011, this problem had been solved using

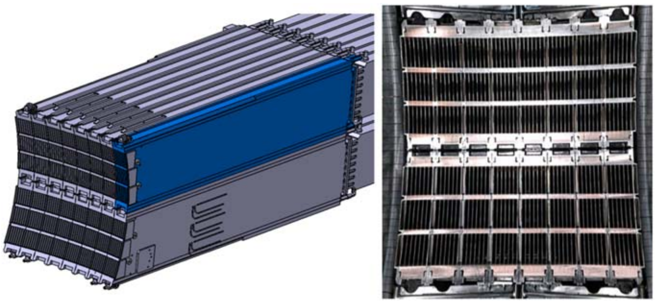

Figure 7. Left: Close-up of one of the sixteen multijunction modules of the C3 launcher. Right: Picture of the launcher front face.

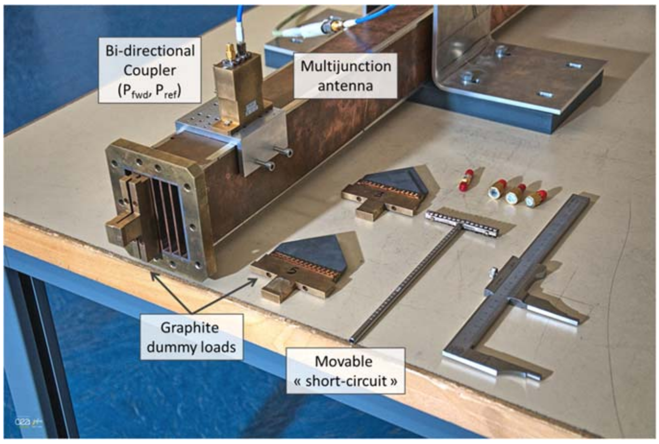

Figure 8. Multijunction hands-on setup and description of its components.

various approaches and computer languages by the students: from least-squares fits to Fourier transforms, with Matlab, Python, Excel or even compiled languages such as Fortran or C.

Lower hybrid multijunction antenna prototype

A lower hybrid (LH) antenna is generally made of numerous waveguides (figure 7), stacked next to each other by their large sides. A phase shift between each waveguide in the toroidal direction (the direction mostly parallel to the confinement magnetic field) is created inside the antenna by reducing the width of the rectangular waveguide, so increasing the phase velocity and making a phased array. Due to this phase shift between adjacent waveguides, the RF power is transmitted mostly parallel to the magnetic field, which excites a quasi-electrostatic plasma wave in the confined plasma, ultimately driving some additional plasma current in the tokamak [15].

During this hands-on, students have to measure the RF characteristics of a real multijunction mock-up, which was used to validate the LH1 antenna design [14]. First, they have to understand how a multijunction structure achieves both splitting and phase shifting the RF power (figure 9). They have to determine analytically and numerically the spectral power density spectrum excited by the antenna (figure 10). This quantity is an important parameter

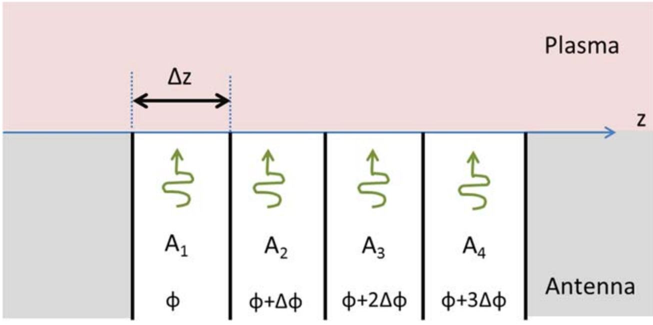

Figure 9. Simplified LH antenna: An ideal 4-waveguide phased array radiating power to a plasma medium.

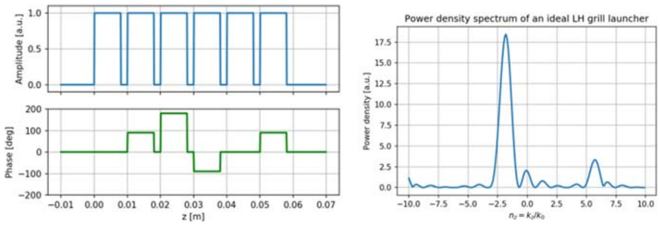

Figure 10. Left: Ideal amplitude and phase excitation of the multijunction waveguides. Right: Associated power density spectrum.

for the antenna operation and it corresponds to the spatial Fourier transform of the power density at the antenna mouth.

This first part is thus the opportunity to discuss and clarify how waves can be described either in spatial and spectral domains. The differences between Fourier transform and discrete Fourier transforms are also always discussed, since the latter is used in a fast Fourier transform algorithm but not always to the awareness of the students. The direction in which the RF waves should be preferentially launched inside the tokamak plasma, which is related to the usual phased array angle, is also discussed.

Then students can perform RF measurements of the prototype multijunction module. However, since this structure uses thin rectangular waveguides (70×8 mm), no standard RF components exist for this task. Specific home-made RF loads and couplers have been built to measure a fraction of the power in each waveguide. Students are then guided in the calibration methods required for these probes, again using specific home-made tools such as tapers, reduced-size waveguides and matching loads made in graphite (figure 8).

Once the prototype measurements have been made, the students can compare their results to their antenna model and discuss the importance of measurement uncertainties and the origin of these uncertainties. Finally, the supervisors give the student a movable short-circuit (figure 8) which can be inserted inside a reduced waveguide. This short-circuit is a rough way to model an arc happening inside the waveguide. Students are then asked if it is possible to (i) detect arcs in the multijunction from the analysis of the reflected power, and (ii) if it is possible to locate the arcs in the multijunction. They are then left free to do any measurements they wish to gain first insights to these questions. During this part the importance of

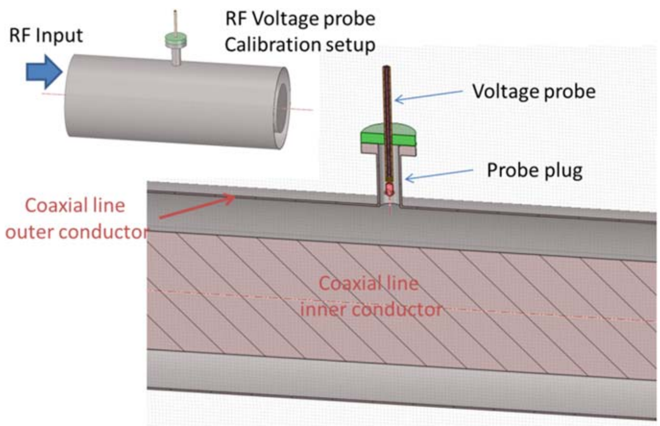

Figure 11. Radio-frequency probe calibration setup.

establishing a proper test protocol is discussed (what to do? How to do it?) and the expected measured values (too much or not enough data?) to analyse an experimental problem.

Ion cyclotron resonance heating hands-on

Two different hands-on related to the ICRH range of frequency (around 50 MHz) have been proposed in recent years to the students. The first one focuses on the voltage measurement apparatus used inside the IC antennas of the Tore Supra/WEST [16]. The second one brings the students to build step-by-step a low-power mock-up of a representative high-power feeding circuit for the next generation of antenna currently under design for future fusion reactors. These two hands-on are described in the sub-sections below.

Voltage probe calibration

On the WEST ion cyclotron ICRH antennas [9], RF probes are used to measure RF voltages and deduce RF currents [17]. These signals are mandatory in order to monitor the antenna behaviour as well as for its automatic safety interlocks. While providing accurate measurement, these probes have to operate under a severe environment (vacuum and steady-state RF power, which can lead to severe probes heating/arcing if not properly taken into account). Low-gain (−80 dB) probes have been manufactured in order to cope with steady-state operations (reduced RF power collected by the probe, thus reduced heat loads). On the other hand, such low-gain probes are delicate to calibrate, since their accuracy is hard to predict due to the probe plug cavity ('edge effect'), but also by mechanical discrepancies.

During this hands-on, students have to calibrate such an RF voltage probe. The aim of the calibration of such a probe is to determine the relationship between the voltage in the coaxial line and the voltage got for the probe. In order to perform such a calibration, a home-made calibration setup is provided (figure 11). This setup mimics a section of a high-power coaxial line and the depth of the probe inside its plug can be varied (figure 12).

The calibration setup uses a 30 Ω, 9″ coaxial line (internal conductor: $\phi_{ext} = 140$ mm; external conductor: $\phi_{int} = 230$ mm) which is equipped with a probe plug (a DN25 vacuum flange). This choice of 30 Ω lines comes from the fact that this characteristic impedance

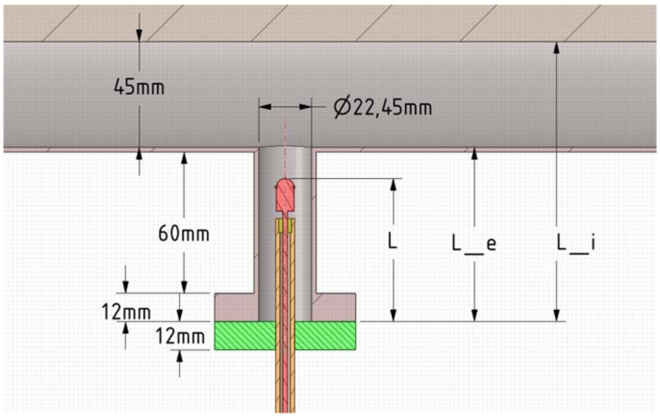

Figure 12. Calibration setup dimensions.

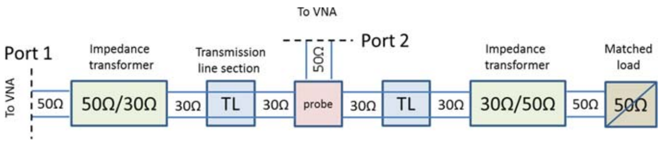

Figure 13. Electrical circuit of the setup.

allows one to maximize the peak power handling on our high-RF power system. Two impedance transformers, 30 Ω−50 Ω, are used to match the vector network analyzer (VNA) ports. The entire probe was manufactured at CEA and the detailed drawings are given to the students. The probe copper head is located in or close to the coaxial E-field between the inner and outer conductors. The gain of the probe depends on its depth inside its plug as well as the plug geometry. Geometrical discrepancies are present with non-perfect circularity and coaxiality of the inner and outer conductors (1 mm discrepancy has been measured during dimension control), radial distance between inner and outer conductor (due to the whole assembly) and with the probe manufacturing. This hands-on is thus a mean to introduce students to the necessity for them to take into account discrepancies and discuss their origins.

The voltage in the high-power coaxial line is expected to be between 5 kV and 55 kV. The students are then asked to tune the probe depth in order to obtain an output signal from 0 to 10 V, as required for the acquisition system and to deduce the target attenuation of the probe at 60 MHz +/− 5 MHz. For that, the voltage in a coaxial line is explained, as well as the matching requirements for usual low-power coaxial cables, in order for them to deduce the optimum dimensions and RF parameters with respect to power handling. The challenge is then to properly calibrate the probe; that is, to determine all the gains and losses to deduce the voltage inside the rigid coaxial line.

The electrical equivalent circuit of the calibration setup is illustrated in figure 13. While usual RF calibration techniques such as the through-reflect-line could be used to remove the effect of impedance transformers and geometrical adapters [18], they are out of the learning scope of these Master's students. Instead, we reduce the frequency to 0.3–2.4 MHz in order to reduce transmission line length effects, so that the voltage could be considered comparable at two different points of the line (figure 14). Thus, assuming that the voltage is uniform in this

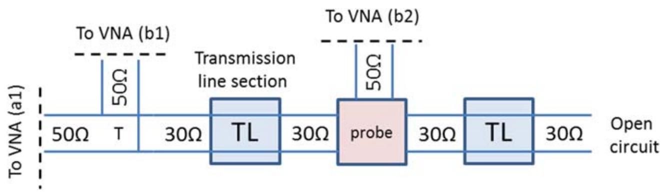

Figure 14. Electrical circuit of the setup at low frequency.

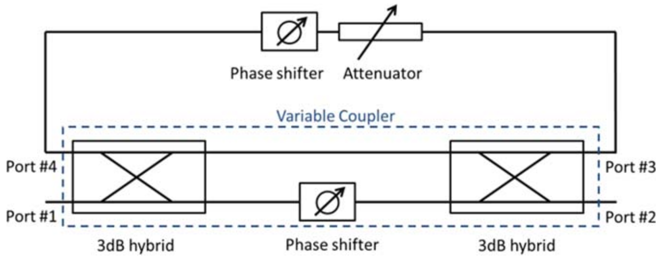

Figure 15. Equivalent circuit of a resonant ring assembly.

frequency range, i.e. the probe voltage probe is equal to the open voltage, the student can extrapolate the b_2/b_1 signal from the VNA to deduce the transmission coefficient at 60 MHz.

This hand-on illustrates to the student the difficulty of realizing high-power RF measurements, especially in continuous-wave power operation in which the probe heating and cooling can be a problem. When a very low coupling coefficient is obtained, its value greatly varies with its geometry, in particular the probe depth. Hence, a precise measurement requires a precise calibration procedure, highlighting the requirements of a precise measurement chain to the students.

Resonant ring RF circuit

The second hands-on related with the ICRH range of frequency concerns the realization of a resonant ring feeder circuit. This circuit is illustrated in figure 15. The advantage of such a circuit is that when the phase shifters are properly tuned, the power injected in the system (on port 1) gets recirculated and almost no power is reflected or transmitted to port 2. In principle, this feeding scheme could be used to feed an ICRH antenna such as a travelling wave antenna for a future fusion reactor [19], in order to improve the power budget of the system. Such a circuit is also load-resilient: changing the attenuator value slightly perturbs the system. In real situations in a high-power case, the attenuator corresponds to the travelling wave antenna radiating its power to the plasma. In case of a fast change of the plasma and thus of the loading of the antenna, a water-cooled dummy load would be placed at port 2 to dump the power eventually transmitted to this port.

Before showing the students how to assemble and characterize this circuit, they are introduced to RF phase shifters and directional couplers, for which they are guided to first deduce from analytical expressions then measure their main figures of merit (phase shift, directivity, isolation and losses). Then they build a variable coupler using two hybrid couplers and a phase shifter (blue dashed in figure 15). Once done, the students are brought

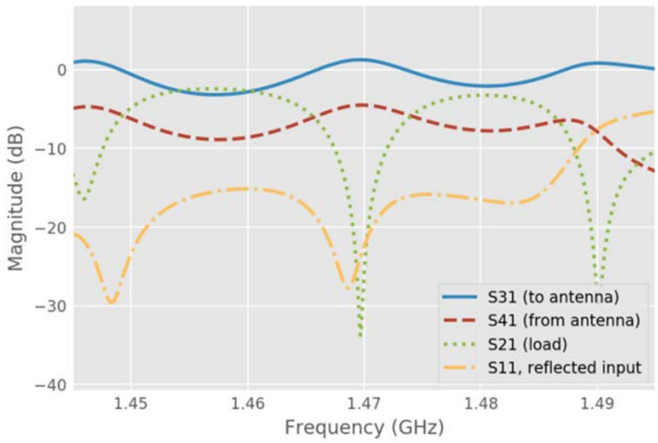

Figure 16. Scattering parameters of the (tuned) resonant ring.

to assemble the full resonant ring and to tune it. Although proposed for the ICRH frequency band (30–70 MHz), the circuit can also be built at higher frequencies. The hands-on is performed at 1–2 GHz in order to use reduced-size components[3]. When properly tuned using the two phase shifters, both the reflected power to port #1 (toward RF source) and the forward power to port #2 tends to zero. Students can verify (from analytical calculations or by direct measurements) that the electrical length of the resonant ring has to be an integer number of 2π [20]. Moreover, adding additional 10 dB directional couplers before and after the 'antenna' (simulated by the attenuator in series with the phase shifter) allows monitoring the injected and recirculated power in the resonant ring (figure 16). If properly tuned, the ratio of the forward power of the antenna to the input power is greater than 0 dB, due to the recirculated power in the circuit. Thus, from simple tabletop components (figure 17), students understand how such a circuit can ensure the integrity of the high-power RF generators while minimizing the losses and providing a reliable power feeding network.

Conclusion

Over the 8 years since we have started the RF hands-on, as part of the IRFM Master's fusion event, we have been pleased to help students discover the tools and subjects related to plasma RF heating and current drive. As none of the students had followed any RF courses during their course of study, RF theory and measurements are not immediately comprehendible to them. The challenges were thus to create hands-on activities in which they could perform RF measurements and data analysis without having to possess typical knowledge of RF engineering. If the RF hand-on topics are not always their first choices, students are still happy to learn new things, in particular that from design to application, many steps pave the road of researchers and that none of them must be neglected.

[3] Narda 3752 coaxial phase shifters and NARDA 3032 coaxial N-connector 3 dB hybrid coupler.

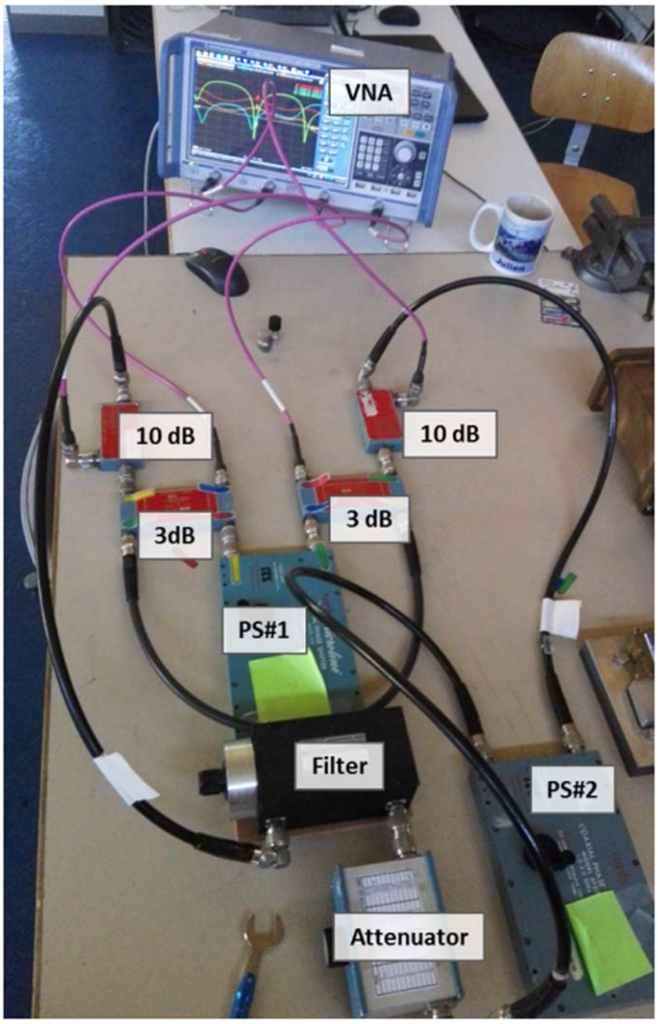

Figure 17. Example of student resonant ring setup. '3 dB' stands for 3 dB hybrid couplers, '10 dB' for 10 dB directional couplers (used as signal probes to properly tune the resonant circuit). 'PS' stands for phase shifter. A band-pass filter is added to the setup to better 'simulate' a travelling wave antenna section, which is equivalent to a radio-frequency band-pass filter [20].

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