Theory on Dynamic Matching with Adjustable Capacitors for the ICRF System of ASDEX Upgrade

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Abstract

The coupling of electromagnetic waves in the Ion Cyclotron Range of Frequencies (ICRF) is an important method to heat magnetically confined plasmas. Changing plasma conditions, which originate from processes like L-mode to H-mode transition or gas puffing, vary the load impedance of the ICRF antennas. To optimize the power transfer from the radio frequency (RF) generators to the antennas and consequently to the plasma, as well as to protect the RF sources against too high reflected power, a system that matches (i.e. transforms) the antenna input impedance to the impedance required by the generator is necessary. At ASDEX Upgrade this matching system consists of two stub tuners for each antenna, which match the antenna impedance for a value preset before the discharge. The length of the stubs cannot be changed fast enough to compensate plasma variations even on the moderate timescale of the confinement time in ASDEX Upgrade. The use of 3dB-couplers allows operation even with varying load, at the cost of a reduced power to the plasma.

When adjustable capacitors are applied in parallel to the stubs, dynamic matching becomes possible on the tens of ms timescale. The paper describes first the calculation of the required capacitance using transmission line theory. In a second model a minimum search algorithm finds, for a given antenna impedance, the length of the stubs needed for matching, now including the initial values of the capacitors. For the chosen pre-match point in the Smith chart, the range of impedances around this point is calculated for which the voltage standing wave ratio (VSWR) can be lowered below a minimum value by readjusting the capacitors within their maximum and minimum values. The matching range is thereby significantly larger than without the application of adjustable capacitors, at least with a frequency of 30 MHz and 36.5 MHz.

Key words: Plasma heating, ion cyclotron domain, impedance matching, stub tuning, adjustable capacitors
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1. Introduction

ASDEX Upgrade is a medium-size Tokamak experiment for studying reactor relevant issues and providing physical and technological results for ITER. To heat the magnetically confined plasma or to investigate non-ohmic current drive RF power can be transferred to either the ions or the electrons by launching electromagnetic waves. The ICRF system consists of two antenna pairs and each antenna of two toroidally spaced straps; electrical and mechanical details are given in [1]. The corresponding circuit for impedance matching is described below.

The applied frequency, f, of the wave depends – among others – on the choice of the absorption mechanism in the plasma, e.g. fundamental ion cyclotron (IC) resonance for minority heating. For hydrogen-ions the angular frequency of the particles' gyro motion, ω_H, is proportional to the modulus of the magnetic flux density, B, according to

$$\frac{\omega_H}{B} = 2\pi \cdot 15 \cdot 10^6 \ \frac{\mathrm{s}^{-1}}{\mathrm{T}} \,. \tag{1}$$

In the IC domain 30 MHz is a typical resonance frequency for a magnetic field with $B = 2$ T at the nominal Tokamak radius, $R = 1.65$ m in ASDEX Upgrade. Frequently, experiments with 36.5 MHz are carried out, too.

In Tokamak operation there are a number of processes leading to a variation of the antenna loading. The rise of the load caused by ELMs occurs in a timescale of 100 µs followed by a decay in a few milliseconds [2]. On the contrary, the sudden transition from L-mode to H-mode decreases the load within typically a few milliseconds. The

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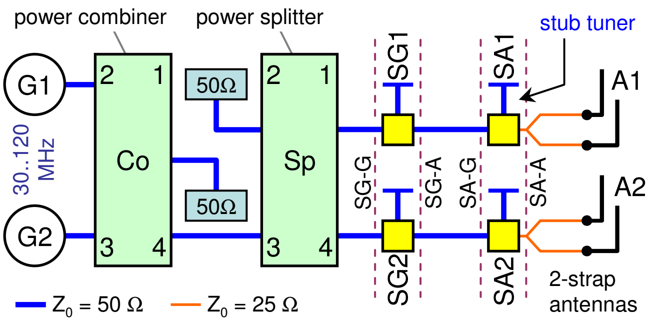

Fig. 1. Simplified circuit, e.g. without phasing network, of one antenna pair of the ICRF system at ASDEX Upgrade

effect of gas puffing to increase the coupling is even slower. Since the RF generator must see a 50 Ω input impedance of the system at the transmitter, to have an optimum power transfer, one must deal with dynamic changes of the antenna loading. In order to protect a RF source from high power reflection the VSWR needs to be kept lower than 1.25 during a discharge.

A number of concepts are available to meet this goal. An overview on the different methods can be found in both ref. [2,3]. The present impedance matching circuit of the ICRF antenna system at ASDEX Upgrade is a combination of a power splitter and a double-stub tuner (Fig. 1). With the latter a certain value of the antenna impedance is matched to the characteristic impedance of the transmission lines which are connected to the outputs of the power splitter. The stubs cannot be readjusted fast enough when the antenna load changes but the splitter configuration provides a good load resilience, i.e. the reflected power at port Sp3 is rather low. Even in the case of ELMs the reflected power is transferred to the 50 Ω dummy load. The scattering matrix of an ideal 4-port hybrid can be written as

$$\mathbf{S} = \begin{bmatrix} 0 & i\delta & \alpha & 0 \\ i\delta & 0 & 0 & \alpha \\ \alpha & 0 & 0 & i\delta \\ 0 & \alpha & i\delta & 0 \end{bmatrix} \qquad \text{with} \qquad \alpha = \sqrt{1-\delta^2}\,. \tag{2}$$

Using κ as the squared ratio of the transmission coefficients, α and δ, the required condition for load resilience is derived as follows:

$$\kappa\Gamma_1 = \Gamma_4 \qquad \text{with} \qquad \kappa = \left(\frac{\alpha}{\delta}\right)^2 . \tag{3}$$

The reflection coefficents Γ_1 and Γ_4 are those at port 1 and 4 of the splitter, Sp. At ASDEX Upgrade the used splitter device is a 3dB-type, i.e. $\delta = 1/\sqrt{2}$, so that the input power, P_3, is halved. For achieving load resilience the reflections must be symmetric in amplitude and phase. However, condition (3) is not always fulfilled sufficiently and, in any circumstance, the reflected power is lost.

To improve the efficiency of the system dynamic matching is necessary. That means that, driven by the change of the antenna load, the matching circuit is readjusted automatically. Since the active control of the antenna loading leads to experimental restrictions recent developments for a compensation of load variation are more promising [2]. When a non-travelling wave antenna is applied the possible concepts are the use of
– ferrite loaded transmission lines [4],
– liquide stub tuners [5],
– real-time frequency feedback control [6] or
– adjustable capacitors [7].

Each solution for dynamic matching has its advantages and disadvantages. For example, the frequency feedback control suffers from technical constraints in the high-power regime, e.g. the small band width of a RF generator. Adjustable capacitors are sucessfully utilized at TEXTOR. The adjustment of the capacitors can compensate load variation within a limited range around the initial pre-match point on the timescale of a few tens of ms. This system is very interesting for ASDEX Upgrade because the technical realization does not require elaborate modifications.

The TEXTOR's capacitor system is located between the generator and a standard double-stub matching unit for coarse pre-matching. It consists of two variable capacitors with distance of 1 m (electrical length, frequency band: 25-38 MHz) [7]. Each of them is compensated in the initial state by an inductive stub. The configuration enables low voltages at the capacitors and a low power dissipation.

In ASDEX Upgrade the integration of adjustable capacitors in parallel to the pre-matching stubs (mechanical position: cf. yellow squares in Fig. 1) should be sufficient. The results below refer to ideal RF components; a TL-connection of the capacitors is not yet considered.

2. Analytical approach

First of all we have to keep in mind that the mutual coupling between the antenna straps is not negligible. Moreover, components like the Faraday screen in front of the straps or the phasing network influence the matching relevant impedance. In practice the input impedance at the positions SA1-A and SA2-A is measured with discrete time intervals during a discharge. The corresponding values, normalized to 50 Ω, are monitored in the Smith chart. One center point of the scatter-plot of a previous similar shot needs to be choosen for pre-matching.

In the following, the resulting SA-A input impedance (no distinction between antenna 1 and 2) is denoted as "remote" antenna input impedance, $\tilde{Z}_A$, and used as variable for calculation. Since both antenna circuits are similar it is sufficient to calculate only one of them. The normalized remote antenna input admittance, with respect to $Y_0 = 1/Z_0$, can be written as usual as

$$\tilde{y}_A = \tilde{g}_A + i\tilde{b}_A\,, \tag{4}$$

taking into account the normalized remote conductance, $\tilde{g}_A$, and susceptance, $\tilde{b}_A$. When we consider the input impedance of the SA stub, Z_{SA}, and that of the capacitor, Z_{CA}, which is mounted in parallel to the stub, the total normalized admittance at the generator side is

$$y_{SA-G} = \tilde{y}_A + y_{SA} + y_{CA}\,. \tag{5}$$

The input conductance of both the stub and the capacitor is almost negligible so that we simply derive

$$y_{SA-G} = \tilde{g}_A + i\left(\tilde{b}_A + b_{SA} + b_{CA}\right)\,. \tag{6}$$

Assuming l_S for the distance between the two stubs the normalized input admittance, y_{SG-A}, at the antenna side of the SG stub is calculated. Here we can use the non-lossy impedance transformation equation

$$Z_{SG-A} = Z_0 \frac{Z_{SA-G} + iZ_0 \tan(\beta l_S)}{Z_0 + iZ_{SA-G}\tan(\beta l_S)} \quad \text{with} \quad \beta = \frac{2\pi}{\lambda}\,. \tag{7}$$

The propagation constant, denoted with β, is therefore just correlated with the vacuum-wavelength, λ. Finally, after using the substitution

$$L_S = \tan(\beta l_S)\;, \tag{8}$$

we get explicitely

$$y_{SG-A} = \frac{\tilde{g}_A + i\left(\tilde{b}_A + b_{SA} + b_{CA} + L_S\right)}{1 - \left(\tilde{b}_A + b_{SA} + b_{CA}\right)L_S + i\tilde{g}_A L_S}\,. \tag{9}$$

There are two tasks possible, pre-matching by stub tuning (note: the initial values of the capacitors must be considered) and dynamic matching, i.e. readjustment of the capacitors, where the input impedances of the stubs are taken into account. Hence, we introduce the known normalized susceptance, b_x, and the one which has to be calculated, b_y. The corresponding equations are defined as followed.

Case (a): Stub tuning

$$b_y = b_{SA} \qquad \text{and} \qquad b_x = \tilde{b}_A + b_{CA} \tag{10}$$

In this case $\tilde{b}_A$ denotes the normalized susceptance at SA-A with respect to the chosen remote antenna input impedance for pre-matching. The normalized suceptance of the CA-capacitor, b_{CA}, must be set to the corresponding initial value. That means both $\tilde{b}_A$ and b_{CA} are fixed.

Case (b): Dynamic matching

$$b_y = b_{CA} \qquad \text{and} \qquad b_x = \tilde{b}_A + b_{SA}\,. \tag{11}$$

Contrary to case (a) the value of $\tilde{b}_A$ is here variable. This simulates the variation of the antenna input impedance during a discharge. The normalized input susceptance of the stub, b_{SA}, is equal to the calculated value from case (a).

The characteristic impedance, Z_m, of the transmission line between the power splitter and the stubs SG can be different compared to the characteristic impedance, Z_0, of the transmission lines that connect the stubs together. The remote antenna input impedance must be transformed by the matching circuit towards that value. Hence, for perfect matching ($\Gamma_{SG-G} = 0$) the condition

$$y_{SG-A} + y_{SG} + y_{CG} = \eta\,, \qquad \text{with} \qquad \eta = \frac{Z_0}{Z_m}\,, \tag{12}$$

needs to be fulfilled. Here the input impedances Z_{SG} and Z_{CG} of the SG stub or the corresponding capacitor respectively have to be considered. Equation (12) can be rewritten as

$$g_{SG-A} + i\left(b_{SG-A} + b_{SG} + b_{CG}\right) = \eta \tag{13}$$

and, since η is just a real number, we derive as the first matching equation

$$g_{SG-A} = \eta\,. \tag{14}$$

Using the real part of expression (9), (14) gives a quadratic equation in b_y. The two roots are

$$b_y = \frac{1}{L_S}\left[1 - L_S b_x \pm \sqrt{\frac{\tilde{g}_A}{\eta}\left(1 + L_S^2\right) - \tilde{g}_A L_S^2}\,\right]\,. \tag{15}$$

According to equation (15) the matching can be achieved with two different parameter settings. However, one must take into account some technical aspects. For instance, the possible range of capacitance as well as the minimum and maximum of the stub's length are always limited.

Furthermore, it can easily be seen from the "general" matching condition (12) that the imaginary part of the input admittance at SG-A must be compensated. This leads to the second matching equation.

$$b_{SG-A} + b_{SG} + b_{CG} = 0 \tag{16}$$

Depending on the task, the normalized susceptance of the stub, b_{SG}, or the capacitor, b_{CG}, at the generator side can be calculated. We should again point to the defined initial value of the capacitor or the stub's input impedance of the pre-matching respectively, that must be considered. The normalized input susceptance at position SG-A, with respect to the determined b_y, is given by

$$b_{SG-A} = \frac{\left[1 - (b_x + b_y)L_S\right](b_x + b_y + L_S) - \tilde{g}_A^2 L_S}{\left[1 - (b_x + b_y)L_S\right]^2 + \tilde{g}_A^2 L_S^2}\,. \tag{17}$$

Finally, a correlation between the calculated normalized input susceptance, b_C (capacitor) or b_S (stub tuner), and the corresponding capacitance, C, or stub's lenght, l_{stub}, is needed. The formulae are valid in general, i.e. no distiction between generator and antenna side is necessary. Since the normalization was done with respect to the characteristic impedance Z_0 the capacitance is derived as

$$C = \frac{b_C}{\omega Z_0}\,. \tag{18}$$

The characteristic impedance of each stub tuner is Z_0. The stubs are short-circuited at the end, i.e. $Z_{load} = 0$, so that the stub's length is consequently given by

$$l_{stub} = -\frac{1}{\beta}\arctan\left(\frac{1}{b_S}\right)\,. \tag{19}$$

At ASDEX Upgrade the stubs are mounted at the T-junctions on a piece of transmission line. Hence, the stub's lengths consist of a fixed part, the corresponding lengths are $l_{A,off} = 0.8$ m and $l_{G,off} = 2.5$ m, and a moveable part.

3. Numerical $|\Gamma|_{min}$-approach

From the practical point of view, i.e. the easy operation of the ICRF system, not the required capacitances are of importance but the question on the achievable matching range arises. As already mentioned in section 2, during a discharge the remote antenna input impedance is calculated [1] and monitored in a Smith chart with respect to 50 Ω. The corresponding cloud of points shows the variation of the antenna impedance. Hence, the best solution would be if the system is matched for the whole measured $\tilde{z}_A$-region. We define the "non-perfect" but technically adequate matching range by comparing the voltage standing wave ratio (VSWR), S_{SG-G}, at position SG-G, which is a function of $\tilde{z}_A$, with a certain threshold.

$$\mathbb{M} := \{\tilde{z}_A : S_{SG-G}(\tilde{z}_A) \leq S_{thres}\} \tag{20}$$

In general, the VSWR is derived from the calculation of the modulus of the reflection coefficient, Γ. When Z is considered to be the relevant impedance the equation is

$$S = \frac{1+|\Gamma|}{1-|\Gamma|} \qquad \text{with} \qquad \Gamma = \frac{Z - Z_0}{Z + Z_0}\,. \tag{21}$$

A program, developed with *Mathematica*, calculates the complex Γ_{SG-G} and the corresponding VSWR, depending on the $\tilde{z}_A$ value. The input impedance at position SA-G is transformed with eq. (7) to that at SG-A. Because of ceramic parts in the transmission lines the electrical length, l_{el}, has to be used instead of the mechanical length, l_{mech}. The electrical length of the distance between two stubs of an antenna pair at ADSEX Upgrade is about 3.1 m, measured by time-domain reflectometry.

The *Mathematica* program includes the lengths of the stubs and the capacitances as parameters. Setting the latter equal to the chosen inital values one can determine the pre-matching by searching the stubs' positions in order to get a minimum for $|\Gamma_{SG-G}|$, which should be almost zero. The matching range, according to definition (20), is calculated practically in the same way. When the possible min-max-intervall of the real and the imaginary part of $\tilde{z}_A$ is discretized the $|\Gamma_{SG-G}|_{min}$ search algorithm finds for all $\tilde{z}_A$-values the required capacitance. Thereby the lower and upper limits of C_A and C_G are taken into account. The stubs' lengths are fixed corresponding to the pre-matching. Finally, the program evaluates, with respect to relation (20), the VSWR around the user-defined pre-match point.

Mathematica provides various algorithms for the search of a function's (global) minimum. The `NMinimize` routine,

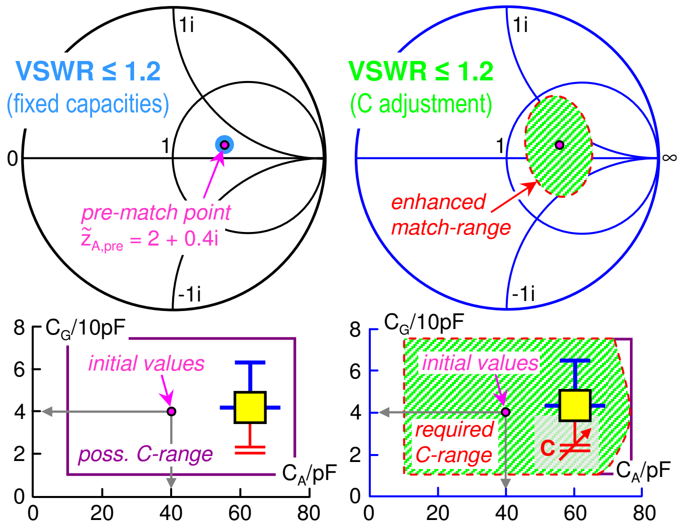

Fig. 2. Example for the enlargement of matching range ($\tilde{Z}_A$-region in Smith chart, normalization by 50 Ω, f = 30 MHz), total stub lengths for pre-matching: $l_{A,pre} \approx 2.3$ m and $l_{G,pre} \approx 3.1$ m

for example, applies the "simulated annealing" method which is a generic probabilistic meta-heuristic. This procedure shows a better convergence, especially at the boundaries, than the `FindMinimum` routine which requires first order derivatives of the corresponding function due to the utilization of the Newton's method.

In Fig. 2 the effect of dynamic matching with adjustable capacitors is shown. Without considering the timescale of the antenna impedance variations the matching range is significantly enlarged by readjusting the capacitors. The matching range depends on numerous parameters, e.g. the inital values of the capacitors, the pre-matching point as well as the minimal and maximal capacitance. The C-intervall does not need to be equal for both the capacitor at the generator and the antenna side. Furthermore, the distance between the two stubs should also influence the matching. Summing up, to maximize the matching range one has to deal with a multi-dimensional optimization problem.

The example of Fig. 2 is based on the application of the COMET's capacitor type CVNA-75AC/60-AAA, for both the capacitor at the antenna and the generator side. This one was chosen because of its relatively high electrical strength. Within the range of 10 − 75 pF a maximum voltage of 60 kV (peak test) or 36 kV (peak working) respectively can be applied [8]. The device provides a 3.6 pF capacitance shift with one turn; the capacitance tolerance is 10%. For the cooling just convection is used. At 25 °C ambient temperature the maximum acceptable current is about 45-65 A_{rms}, at a frequency of 30 MHz and a continous peak voltage of 36 kV, depending on the capacitance.

One can easily see in Fig. 2 that the available (C_A, C_G)-region, which is linked to the chosen capacitors, is not exploited. However, the upper C_A-boundery represents no limitation due to technical constraints. Even with a higher capacitance at the antenna side the VSWR cannot

[1] The forward and reflected power as well as the corresponding phase difference is measured by using a directional coupler. We derive the input impedance from the complex reflection coefficient.

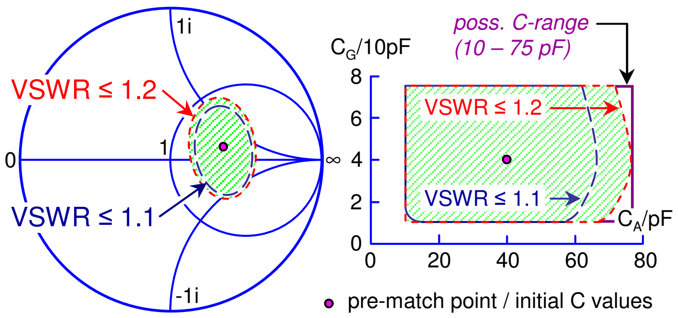

Fig. 3. Correlation between the VSWR threshold, S_{thres}, and the resulting enhanced matching range (left), parameters equal to example of Fig. 2, as well as corresponding capacitance (right)

be lowered below the threshold for a remote antenna input impedance that is located outside the shown matching range. Fig. 3 provides a more detailed insight in the importance of the C_A value. At least with the RF boundary conditions at ASDEX Upgrade the increase of C_A does not lead to a very big progress in terms of the matching range. To extend the latter, a larger interval of the capacitor's value at the generator side is necessary. In this context, the electrical strength of a variable capacitor must be considered though, cf. section 4.

When we apply a higher frequency, e.g. 36.5 MHz, the results are similar. However, the solvability depends strongly on the pre-matching choice and the initial C-values. For instance, there is no matching solution for the parameters of Fig. 2 at 36.5 MHz. The higher frequency requires a modification of the boundary conditions or the initial state of the system, e.g. the choice of another pre-match point.

4. General limitations

First of all, the initial values of the capacitors have to be considered for pre-matching, i.e. one has to adapt the stub's positions. Otherwise there is no gain of matching, or at most a hardly remarkable effect. The result can even be worse compared to an operation without capacitors.

The electrical strength of the capacitors is an important constraint. A large matching range can require a big available C-interval which normally tends to result in a low electrical strength of the capacitor. The voltage anti-node, V_{an}, can occur at the stubs' T-junction. It is a function of the generator's real output power, P_{gen}, where the VSWR at the relevant position must be taken into account.

$$V_{an} = \sqrt{2 Z_0 P_{gen} S} \tag{22}$$

The length of the transmission line, with a characteristic impedance of Z_0, between the capacitor and the stub's T-junction is considered to be almost zero. Hence, the maximum voltage applied to the capacitor unit is equal to V_{an}. Vacuum-capacitors have to be used to ensure a sufficient electrical strength because the value of V_{an} can be rather high. A compromise for the C-range is needed.

Arcing at the antennas, or even in the vacuum section of the feeding transmission lines, leads to a change of the remote antenna impedance. The matching system must compensate changes due to plasma, but care must be taken that it does not match to any arcing.

Inaccuracies of the capacitors could reduce the matching gain dramatically. Their importance, however, depends strongly on the VSWR threshold value. The application of a feedback control system should eliminate this effect.

5. Summary and outlook

The calculations, done for typical frequencies (30 MHz and 36.5 MHz) and ideal capacitors, show the theoretical possibility of dynamic matching. When adjustable capacitors are applied in parallel to the stubs the matching range, around the pre-match point, is significantly larger.

The model will be extended to include the capacitor's junction. This could demand an extra T-junction at the antenna side because there is already a "super-T" installed. In the subsequent step, proper capacitors have to be specified which enable a satisfying matching range. Finally, fast long-life actuators are necessary to complete the concept.

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