J-M. Noterdaeme, Vl.V. Bobkov, S. Brémond, A. Parisot, I. Monakhov,
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J-M. Noterdaeme[1,2], Vl.V. Bobkov[1], S. Brémond[3], A. Parisot[6], I. Monakhov[5], B. Beaumont[3], Ph. Lamalle[4], F. Durodié[4], M. Nightingale[5], the ASDEX Upgrade Team[1], the Tore Supra Team[3] and the JET-EFDA contributors

[1]Max-Planck IPP-EURATOM Assoziation, Garching, Germany
[2]Gent University, EESA Department, Belgium
[3]Association EURATOM-CEA, CEA-Cadarache, France.
[4]Association EURATOM - Belgian State, LPP-ERM/KMS, TEC 5EURATOM/UKAEA Fusion Association, Abingdon, U. K.
[6]Plasma Science Fusion Center, MIT, Cambridge, USA

ABSTRACT.

The coupling of ICRF antennas to the plasma represent a load impedance different from the generator requirements for optimal power transfer. The matching must be able to cope with changes in coupling impedance due to varying plasma conditions. The changes occur on a timescale varying between particle confinement time and MHD events. In ELMy plasmas, the latter can be as fast as 50 ms. Several methods are in use, but only a few can cope with this most challenging condition: hybrid couplers and conjugate-T. Hybrid couplers have been implemented on ASDEX Upgrade, Double-III-D and will be on JETore Supra have been outfitted with conjugate-T.

1. INTRODUCTION

The ICRF generators (typically operating in the 20-180MHz region, with single-unit power in the 2MW range, see table 1) are designed to operate into a constant, matched load. The antennas, which couple the power to the plasma, present a loading impedance different from that needed by the generator for optimal power transfer (30 or 50Ohm). The mismatch is overcome by a matching system that transforms the antenna impedance to that required by the generator. Since the antenna impedance depends on varying boundary conditions in front of the antenna, dynamic matching methods, or passive load isolation, are needed to cope with the variations. Different approaches [25] can handle diverse timescales. The choice has a substantial impact on the flexibility of the system, its efficiency and operational reliability.

2. SOURCES AND TYPES OF VARIATIONS

The antennas consist of one or more current carrying conductors, connected to transmission lines with a characteristic impedance Z_0. Z_0 is often, but not necessarily, the same as the loading impedance required by the generators. The antenna load, defined as the equivalent complex impedance terminating a transmission line with the characteristic impedance Z_0, depends on the antenna geometry and on the boundary conditions for the electromagnetic fields excited by it. In contrast to antennas radiating in an infinite medium, changing boundary conditions for the fields lead to a changing load. In many cases the field pattern is dominated by an exponential decay up to the location where the plasma density is high enough for the wave to start propagating. Consequently the loading is sensitive to changes of the plasma density, and the density gradient in front of the antenna. The fields and thus the antenna loading can also be affected by changes in absorption of the wave inside the plasma, or by variations of the fields excited by neighboring straps. Changes occur in the real and imaginary part of the antenna impedance, while the ratio between both is not constant. For JET [41] the value range from 2 to 8Ohm in the real part with changes in electrical length of up to 35cm. Similar values are found for ASDEX Upgrade (1 to 10Ohm, 35cm)[54]. The timescale of the density variation split naturally into two types depending on the cause. Slower timescales are related to particle/thermal confinement time and are, depending on machine (size, confinement properties) in the range ms to sec. An L to H transition, which changes suddenly the

confinement properties of the plasma edge on the ms timescale is the fastest of this type[2]. Faster timescales results from MHD events such as ELMs (rise time of the order of 100 -200ms) [9,41, 54].

3. MATCHING METHODS

The matching methods can be broadly divided into four categories (Table 2). Methods of the first category keep the changes in antenna load small enough. In the second category, additional impedance are added to transform the antenna impedance to the matched load. The third category uses network components which insulate the generator from variations in the load. The fourth category includes ways to connect varying loads such that their variations compensate each other to a large extent. The boundaries between the categories can vary depending on the point of view and on where the boundary of the antenna is set, but the general approach above helps the classification. A distinction can also be made with respect to the location of the components: internal or external matching. With the matching close to (or even in) the antenna, the unmatched region is smaller, resulting in lower losses and lower voltages in the longer matched lines. Components further away are more easily serviceable. At least two methods need to be used simultaneously since both real and imaginary part of the antenna load vary, while a matching method can only adapt one parameter. We will concentrate on discussing the timescales, with emphasis on the fastest ones.

3.1. MAKING THE ANTENNA LOAD VARIATIONS SMALL ENOUGH

This can be achieved either by having the boundary conditions for the fields less dependent on plasma variations or by readjusting the boundary conditions. A travelling wave antenna [15] consists of many strongly coupled straps. The fields from the strap and from the adjacent ones are only marginally affected by changes in boundary conditions due to the plasma. A wide array may be required since each strap radiates only a small fraction of the total power. Power remaining at the end of the array is dumped or re-circulated[21]. With the load remaining mostly constant, plasma variations on all timescales can be handled. The antenna is fixed frequency or tunable. The phasing between the antenna straps is fixed. It has not yet been validated by a high power experiment. Another way to keep the antenna load constant is by readjusting the boundary conditions. A change in plasma density can be compensated by readjusting the plasma position. This method was developed on JET [10] and implemented on other machines (TFTR[8]). Disadvantages are: unwanted plasma motion, strains on the magnetic position coils and still too slow to cope with ELMs.

3.2. TRANSFORM THE LOAD TO A MATCHED LOAD

The real and imaginary part of the antenna load can be transformed to the (real) matched load required by the generator by adding, at one or more appropriate locations, a complex impedance in parallel or series to the antenna load. The impedance can be either lumped elements such as capacitor [43] or inductance. It can also be a piece of transmission line, whose complex impedance value is

2

adjusted by changing its electrical length. This length can be varied mechanically, as in simple tuners and trombones; or electrically by changing the frequency [10, 16], the electrical properties of the medium (as in liquid tuners [26, 28, 29, 32, 46]) or its magnetic properties (as in ferrite tuners [23, 5, 19, 27, 34]). The impedance can be located along the transmission line or integrated in the antenna (capacitors in the case of the resonant loop antenna in Tore Supra[6], or tuners in the ITER reference design [30, 35]). The large variety of options, more or less validated by high power experiments have different advantages and disadvantages. The speed with which variations can be compensated depends on the choice of the network and its components. The frequency variation to change the electrical length of the transmission line is fastest and is regularly used on JET. With a standard transmission line however, this change can only compensate changes in the imaginary part of the load. By inserting in the transmission line appropriate components (length of transmission lines with different characteristic impedance – called Sliding Impedance Transformers –SLIMPs [16, 20], or stubs[13]), the frequency variation can be used to compensate for a specific combination of real and imaginary part. This was shown to work in theory and in tests on JET[31], but the implementation was not practical as the matching required an elaborate self-consistent solution, dependent on parameters which were difficult to measure with the required accuracy. The long stretch of unmatched lines (necessary to change the electrical length with only small frequency changes) leads to high losses. Ferrite systems, utilizing the change in magnetic properties of a ferritic material with an applied magnetic field can in principle operate on the ms timescale, they are however still under development. Changing the value of a capacitor has been done on the tens of ms timescale. Adjusting the level of liquid to change the dielectric properties occurs on a timescale of hundred of ms, while changing mechanical length of a transmission line by moving a short circuit requires seconds. It is possible to built systems using these approaches which can cope with all but the fastest variations of the ELM rise, which remain the most critical area[7]. Only the methods of the third and fourth categories are able to cope with them.

3.3. ISOLATING THE GENERATOR FROM THE LOAD CHANGES

At higher frequencies (lower hybrid frequency – GHz range), it is common to use circulators (three port network) to protect the generators from the reflected power. A similar approach is only practical in the ICRF domain in the hundred of MHz frequency range because of acceptable dimensions[4]. It has been implemented at 200MHz in the JFT-2M tokamak [3] and at 433MHz for FTU[14]. The reflected power is directed to a dummy load. With each strap fitted with a circulator, full flexibility of phasing and power is maintained. A hybrid (3dB) couplers [11] is a 4 port network that also isolates the generators from reflected power. If two of the ports are terminated in identical arbitrary impedance, and the third port is terminated in a matched load, then the fourth port is matched. The phasing between the current in the two output ports is 90°. The requirement for the two arbitrary impedance (and their changes) to be identical, requires special provisions, such as canceling or minimizing the mutual inductance (e.g. by choosing straps that are sufficiently far from each other,

or inserting a septum). The straps however cannot be too far from each other since an ELM does not appear simultaneously around the machine: differences of 50ms have been observed in AUG [52, 54]. The advantage is that they are completely passive, very reliable, and maintain good phasing. Disadvantages can be that the phasing is fixed at 90° and that there is a transient power loss during the ELM. In order to reduce the losses, the lossy methods can be combined with any of the preceding ones to provide a prematching so that the lossy systems need only to cope with the very fast transients[17]. With a pre-matching between the transients, the overall losses are minimized, and the power reduction during the transient is maximal. Prematching set to some intermediate value will result in larger overall losses but smaller power transients. Since the power launched into a plasma during an ELM transient may not reach the central plasma [36] [45]but be lost in the edge, a power reduction during a transient may even be beneficial. ASDEX Upgrade has implemented load isolation using 3dB couplers [12, 18, 22, 24]. The system has strongly improved the performance of the ASDEX Upgrade system[49], with up to 90% of the installed generator power transmitted to the antenna even under strong type I ELMing conditions. With the matching fixed set so that the reflection coefficient is lowest between ELMs, the energy lost during the transients is typically 3 to 4%. Even with large and frequent ELMs (high triangularity and high density[54]), the loss increases to no more than 7%. An intermediate matching decreases the amplitude of the transients by up to a factor of 4. D-III-D has used 3dB couplers for a long time, at first to take advantage of the 90° phasing for current drive. Following[11], the benefit of ELM resilience was recognized[25].

3.4. COMPENSATING THE CHANGES

The variations of an impedance can be minimized by combining two conjugate complex impedance with proper choice of the matching point and of R0, the characteristic impedance to match[44]. The load sensitivity is smallest when R0 is near the real part of the antenna load around which the changes occur. Changes in the reactive part are difficult to compensate. Mutual coupling has to be minimized since it influences the matching equations through a ratio term k*X/R0 where k is the coupling factor and X the reactive part of the strap input impedance[48]. With this "conjugate-T" matching approach, there is no power reduction during an ELM. The phasing and current distribution are load dependent. In an array where the straps are coupled, the load will depend on the current in neighboring straps, which in turn depend on the matching. A sophisticated, selfconsistent matching algorithm must thus be found that takes this non-linearity into account. The matching may further demand very precise (sub-millimeter) settings [39] of the components, as even small setting errors influence negatively the overall matching[1]. Alcator C-mod [53] and JET [42] [51]have recently tested conjugate-T matching on plasma with external junctions. On JET neighboring antenna straps were conjugated, a more stringent condition than using similar straps of different arrays, but less than using more strongly coupled straps within an array. Clear evidence of ELM tolerance and reliable operation of the RF generators was observed. The main negative factors were the loading asymmetry and the change in electrical length of the straps. In C-mod, which conjugated two poloidal

4

straps within an array, the predicted strong imbalance in the current was observed, and load tolerant behavior could not be readily obtained. Textor plans [43] to test the concept. Tore Supra has used a new antenna with internal capacitors[48]. Because of the strong coupling and low R_0 it was quite difficult to find the matching and the matching was sensitive to the power balance between the straps. First indications of load tolerant properties were observed. It is expected that a better decoupling of the straps will lead to an improved behavior. The internal matching uses one matching element per strap and could have the advantage that a better control of the current distribution between straps may be possible. On JET-EP[38], both conjugate matching with internal matching elements and 3dB hybrid couplers will be implemented. The reference design of the ITER antenna uses conjugate-T matching. The internal matching elements are all metal tuners similar to[35]. Recent efforts to analyze if ceramics could be used at some distance from the plasmas found that the location at which the capacitors can be used, from the electrical point of view, are rather restricted[47]. Alternative designs, which use conjugate-T matching with external components, are under investigation [40] [37, 50]. Because of the restricted space for the transmission lines, passive junctions then combine internally some traps, which could restrict the control over the current distribution between the straps. The ICRF antenna for ITER presents particular challenges. Since there is only one antenna, there is no possibility to use straps of separate arrays to reduce the mutual coupling. The compact design will lead to strong coupling between the straps with consequently the requirement of a sophisticated matching algorithm. The phasing and amplitude of the currents in the straps will be load and matching dependent. As seen on Alcator C-mod, the rearrangement of the current as the coupling changes, may result in such asymmetric changes to the impedance that the load tolerant operation is no longer achieved. The conjugate-T aspect of the JET-EP antenna will be a critical test on whether it is possible to master this complicated situation.

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Table 1:Major ICRF Systems worldwide

	Frequency range	Installed Generator Power	Marching ststem	System response
ASDEX Upgrade	30 – 120 MHz (30 – 60 MHz used)	4 x 2 MW	Double sub Hybrid coupler	Between shots Fixed
C – Mod	80 MHz 40 – 80 MHz	2 x 2 MW 4 MW	Trombone Stub	Between shots Between shots
D – III – D	60 MHz 60 – 120 MHz	2 MW 1 MW at 120MHz	Hybrid couple	Fixed
JET (10)	23 – 57 MHz	16 x 2 MW	Trombone Stub Frequency	16.5 cm/s 5 cm/s ±200kHz in 1ms
JT –60 U	102 – 131 MHz 112 MHz	8 x 1.5 (?) MW	Trombone Stub Frequency	0.5 cm/s 2 cm/s 400 kHz 10 – 80 ms
NSTX (33)	30 MHz	6 x 2 MW	Trombone Stub	Between shots Between shots
TEXTOR	25 – 38 MHz	2 x 2 MW	Trombone Stub Capacitors	Between shots Between shots 20 – 30 ms
Tore Supra	35 – 80 MHz	3 x 2 x 2 MW	Resonant double loop 9capacitors)	200ms

JG04.513-1c

9

Type		Time scale	Advantages	Limitations
Minimizing changes in antenna load				
	travelling wave antenna - all internal	all	Few feedthrough needed	only one frequency Losses
	- with external connections	all	Multiple frequencies	More feedthroughs
	Plasma position	ms	Fast Simple	Plasma position not fixed
Additional impedance				
	Coaxial			
	- frequency	10 ms	Fast	High VSWR and losses in large part of network,
	- ferrite	ms	Fast, no moving parts	Under development
	- dielectic	10 ms	Compatible with steady state	
	- mechanical	s	Simple	Sliding high current contact may be problematic
	Lumped			
	- capacitor	10 ms	Fast	Location can be critical
	- inductance			Not yet used
Isolation				
	Circulator	all	Phase arbitrary Power distribution fixed	Only practical for high frequency
	3 dB hybrid	all	Phase and magnitude of current fixed	Power loss Phase must be 90°
Compensation				
	Conjugate T	all	Fast Simple	Phase and amplitude of current variable

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10