EFDA–JET–CP(07)01–06

M.-L. Mayoral, I. Monakhov, T. Walden, Vl. V. Bobkov,
T. Blackman, M. Graham, J. Mailloux, J.-M. Noterdaeme,
M. Nigthingale, J. Ongena and JET-EFDA contributors

Hybrid Couplers on the JET ICRF System: Commissioning and First Results on ELMs

Hybrid Couplers on the JET ICRF System: Commissioning and First Results on ELMs

M.-L. Mayoral[1], I. Monakhov[1], T. Walden[1], Vl. V. Bobkov[2],
T. Blackman[1], M. Graham[1], J. Mailloux[1], J.-M. Noterdaeme[2],
M. Nigthingale[1], J. Ongena[3] and JET-EFDA contributors*

[1] UKAEA/Euratom Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK.
[2] Max-Planck Institute, EURATOM Associatio , Germany
[3] ERM-KMS, Association EURATOM-Belgian State, Brussels, Belgium
** See annex of M. Watkins et al, "Overview of JET Results ",*
(Proc. 21st IAEA Fusion Energy Conference, Chengdu, China (2006).

Preprint of Paper to be submitted for publication in Proceedings of the
17th Topical Conference on Radio Frequency Power in Plasmas,
(Clearwater, Florida, USA, 7-9th May 2007)

ABSTRACT

During the 2004-2005 shutdown, hybrid 3 dB couplers were installed between the A2 ICRF antennas A and B. The goal was to free one of the generators to power the new ITER-like ICRF antenna, but also to use the coupler properties to increase the ICRF power on ELMs. Furthermore, the fast data acquisition system was upgraded in order to monitor the forward and reflected voltage amplitudes with a time resolution up to 4 μs. As expected, the first tests showed that the reflected powers during ELMs was successfully directed to the coupler dummy load instead of the generators and that a clear improvement in the averaged coupled power in the presence of the ELMs could be obtained. However, the existing levels of the VSWR protection against arcs appeared not satisfactory for ELM-tolerant operation and had to be re-assessed. Moreover, evidence of parasitic low-VSWR activity in the vacuum transmission lines was found, emphasizing the importance of developing VSWR independent arc detection systems.

INTRODUCTION

The hybrid 3 dB couplers installed in the 2004-2005 shutdown, between generator B and the A2 antennas A and B [1] had as initial goal, the release of the generator A to power the oncoming JET ITER-like antenna [2]. In parallel, it was also expected that the coupler properties could be used to increase the ICRF power coupled to plasma with edge localised modes (ELMs) as done on ASDEXUpgrade [3][4]. Indeed, the couplers are installed in such a way that the two output ports are connected via the splitter transmission lines (STLs), to similar A and B antenna arrays and that the fourth port is connected, via the output transmission line (OTL), to the generators (see Fig. 1). During ELMs, the fast change in antenna loading (up to few tens of μs) results in unmatched STLs [3][5]. Because of the 3 dB couplers properties, the resulting reflected power on the STLs is expected to go the coupler dummy load instead of going back to the OTL, avoiding the trip of the generator done for protection if the OTL reflected power become too high.

This paper summarises the results obtained during the 3 dB couplers commissioning phase and different issues related to the protection against arcs.

FIRST RESULTS ON THE ELM-TOLERANCE

The first tests performed, showed that the STL reflected powers occuring during ELMs was indeed successfully directed to the 3 dBs load instead of the OTL [5]. A typical case is represented on Fig. 2. One can see the fast change in A1 and B1 antenna straps coupling resistance during ELMs (Fig. 2e) and the related increase in the A1 and B1 STL reflected powers (Fig. 2b and 2c) as the automatic matching system [7] cannot react fast enough to the change in loading. Nevertheless, due to the presence of the 3 dB couplers, the STLs reflected powers were successfully directed to the 3 dB coupler load (see Fig. 2d) instead of the OTL. Consequently, almost no reflected power was seen on B1 OTL, and the generator was not tripped, as it would have been prior to the installation of the 3 dB couplers.

An example of the improvement in the coupled power is illustrated on Fig. 3, where one can see clearly the difference between the behaviour of antenna A and B (dashed lines) and the one from antenna C and D (dotted lines) that do not have ELM-tolerant system. The much lower number of trips for A and B leads to a significant increase in averaged coupled power.

THE VSWR TRIP LEVEL ISSUE

On JET, the protection against arcs is based on the Voltage Standing Wave Ratio defined as $VSWR = (1 + \rho)/(1 - \rho)$ with $\rho = |V^{reflected} / V^{forward}|$ the reflection coefficient and $V^{reflected}$ ($V^{forward}$) the reflected (forward) voltage amplitude. For the antennas A and B transmission lines in the 3 dB configuration, VSWR protections were set up from STLs and OTLs measurements. The "3:1" VSWR levels initially used (plain black lines on Fig. 4) were the existing ones. During ELMs, in order for the power reflected on the STLs to reach the couplers, it was necessary to increase the STL VSWR levels. This is referred as the ELM-tolerant mode. The first test in this mode of operation used a trip level of "9:1" already available on the existing VSWR cards (dashed black line on Fig. 4b). Nevertheless, looking at the fast data acquisition signals (0.02 to 0.1 ms in these tests), it was possible to identified two issues.

The first issue was related to the arc detection as it was observed that the time to trip following an arc on the STL could be more than twice the time on the other antennas. Indeed, because of the strong dependence on the forward power of the "9:1" STL VSWR level, a very high reflection could be tolerated. Furthermore, because of intrinsic 3 dBs couplers' properties and if the other STL is matched, the resulting OTL reflected power would stay very low (VSWR < 3). It was then decided to decrease the OTL VSWR to safer levels and to smooth the dependence with the forward power (grey lines on Fig. 4). Two new STL VSWR levels for the ELM tolerance mode were created (Fig. 4a): "6:1" level (dotted grey line) and "13:1" level (dashed grey line).

The second issue was the observation of parasitic low VSWR activity in the vacuum transmission lines (VTL) that could indicate voltage-node arcing [8]. Arcing at low voltage points are particularly problematic at JET when occurring near fragile points in the VTL and it is suspected that such an arc caused a puncture in one of the VTL bellow in the past. The main problem being the detection of such arc, as they do not lead to high VSWR increases (see Fig. 5). The use of the antenna A and B in the ELM-tolerant mode with high tolerated STL VSWR led to an increase in risk towards such arcing. Simulations were performed for a typical antenna inner and outer straps in order to restrict the used of the ELM-tolerant mode to frequencies for which the voltage nodes were not near the VTL bellow (see Fig. 5). The dependence of the antenna equivalent length leq, on the frequency was taken into account and the position of the voltage minimum identified for two extreme cases i.e. in vacuum and during ELMs (assuming that ELMs lead to a change in l_{eq} ~ -45 cm [5]). It was thus decided to operate only in the ELM-tolerant mode for frequencies below 35 MHz and above 43 MHz.

CONCLUSION

The 3 dB couplers installed between antenna A and B have been successfully used in order to increase the averaged coupled power on ELMs. Redesign of the VSWR protection was performed. Nevertheless, the observation of parasitic low-VSWR activity in the VTL and the lack of adequate detection system, led us to impose restriction on the ICRF frequency that could be used in the ELM tolerant-mode. Unfortunately, the allowed "safe" frequencies (< 35 MHz and > 43 MHz) are not the one commonly used for H minority heating of ELMy H-mode with type I ELMs. This constraint prevented us to use the 3 dBs couplers ELM-tolerance routinely, emphasizing the fact that development of new arc protection schemes are critical for ELM tolerant systems.

ACKNOWLEDGMENTS

This work was performed under EFDA and partly funded by the United Kingdom Engineering and Physical Sciences Research Council and by Euratom. It is a pleasure to thank our colleagues from the ASDEX ICRF team for their advices.

REFERENCES

[1]. A. Kaye, et al., " Present and future JET ICRF antennae", Fusion Eng. Des. **24** (1994) 1-21.

[2]. F. Durodié, et al. , "Main Design Features and challenges of the ITER-like ICRF antenna for JET", Fusion Eng. Des. 47 (2005) 223-228.

[3]. J.M. Noterdaeme, et al., 'Matching to ELMy plasmas in the ICRF domain' , Fusion Eng. Des. 74 (2005)191-198

[4]. M F. Hofmeister, et al., "Matching considerations in an ICRH-system with hybrid couplers", in: B. Beaumont, et al. (Eds.), 20th Symposium on Fusion Technology, Marseille, Assoc. Euratom-CEA, 1998, pp. 437–440

[5]. I. Monakhov, et al.,"Studies of JET ICRH antenna coupling during ELMs " Proc. 15th Top. Conf. on RF Power in Plasmas, Moran, USA, 2003, AIP 694, 146-149.

[6]. M. Vranken, et al., "Recent ICRF development at JET", SOFT 2006, to be published in Fusion Eng. Des.

[7]. T.J. Wade, et al., "Development of the JET ICRH plant" Fusion Eng. Des. 24 (1994) 23-46

[8]. I. Monakhov, et al. , "Arcing at the voltage-node of the ICRH antenna vacuum transmission line at JET", this conference (poster A16)

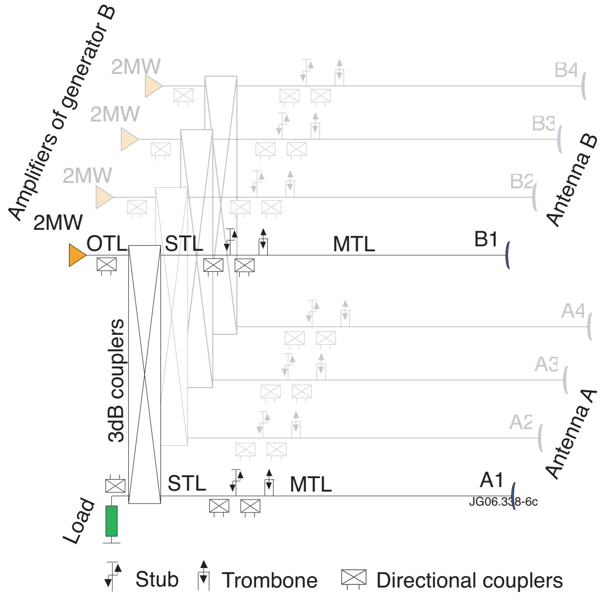

FIGURE 1. Antenna A and B layout after 3 dB coupler installation. OTL, STL, MTL refer to output, splitter and main transmission line, respectively

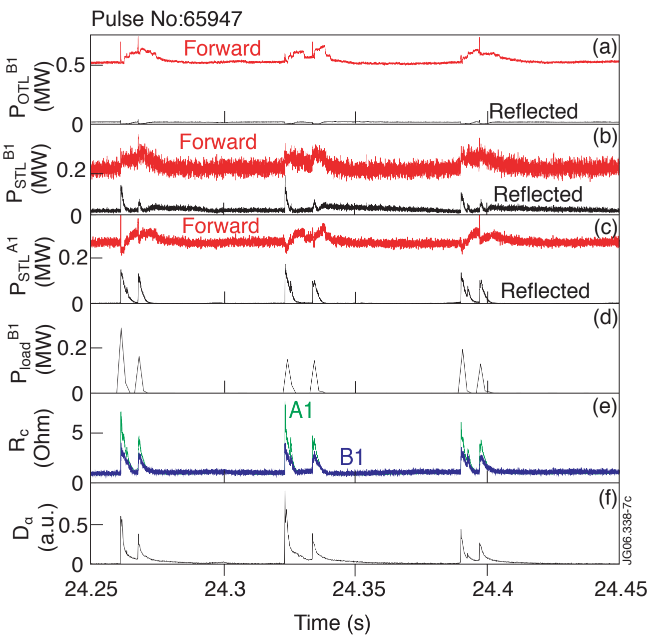

FIGURE 2. (a),(b),(c) forward and reflected power and reflected power on B1 OTL, B1 STL, A1 STL, respectively, (d) power going to load, (e) A1 and B1 coupling resistance and (e) ELMs trace from D_α line emission intensity

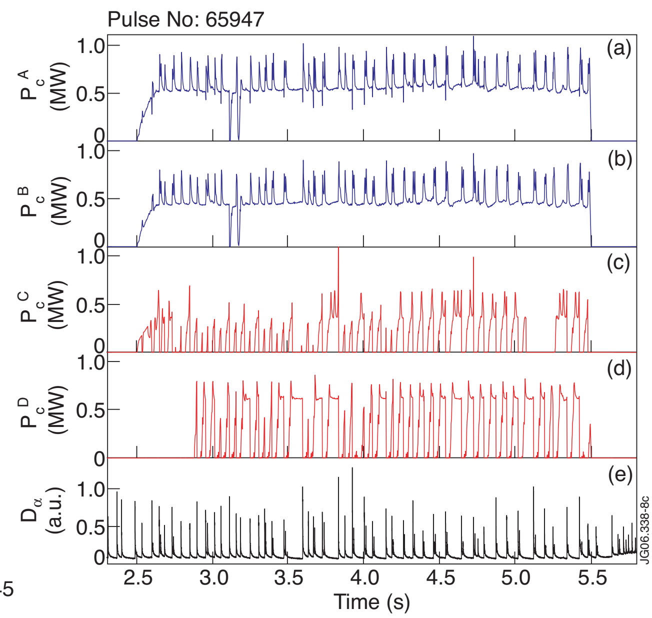

FIGURE 3. (a),(b),(c),(d) coupled powers from antenna A, B, C and D respectively; (e) ELMs trace from D_α line emission intensity

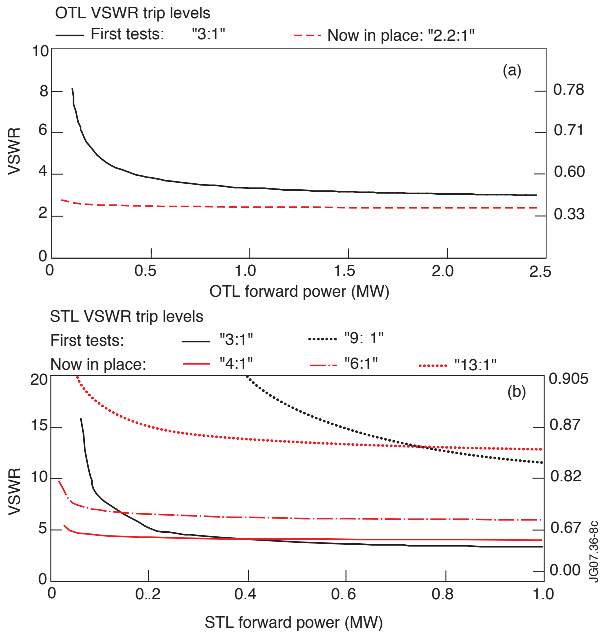

FIGURE 4. (a) OTL and (b) STL VSWR trip level function of the forward power on the OTL or STL, respectively.

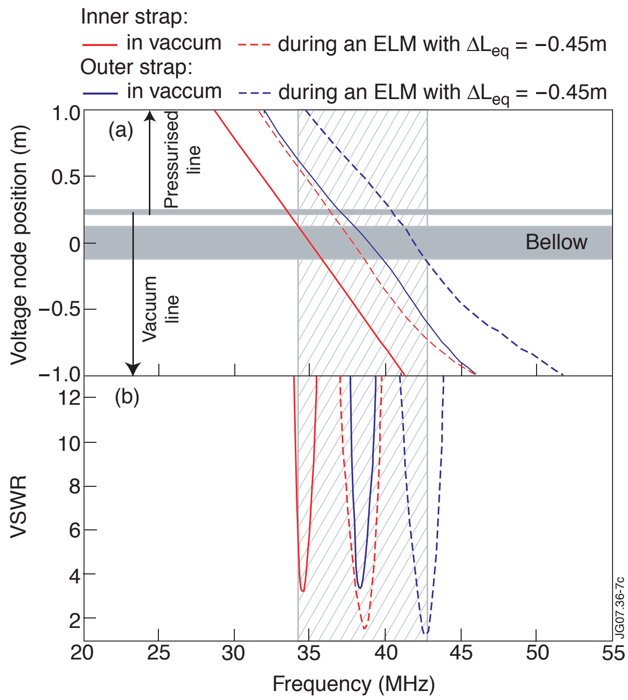

FIGURE 5. Frequency dependence of (a) voltage node displacement from VTL bellow, (b) VSWR in a matched transmission line during arcing at bellow. The dashed area represents the "unsafe" frequencies.