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F. Durodié, M. Nightingale, M.-L. Mayoral, A. Argouarch, T. Blackman,
M. Gauthier, R. Goulding, M. Graham, S. Huygen, P. Jacquet, E. Lerche,
J. Ongena, D. Van Eester, M. Vrancken, A. Whitehurst, E. Wooldridge
and JET EFDA contributors

Present Status of the ITER-Like ICRF Antenna on JET

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F. Durodié[1], M. Nightingale[2], M.-L. Mayoral[2], A. Argouarch[3], T. Blackman[2], M. Gauthier[4], R. Goulding[5], M. Graham[2], S. Huygen[1], P. Jacquet[2], E. Lerche[1], J. Ongena[1], D. Van Eester[1], M. Vrancken[1], A. Whitehurst[2], E. Wooldridge[2] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Association EURATOM-Belgian State, Koninklijke Militaire School - Ecole Royale Militaire, Avenue de la Renaissance 30, B-1000 Brussels Belgium
[2]EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[3]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[4]JET-EFDA Close Support Unit, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[5]Oak Ridge National Laboratory, Oak Ridge, United State
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ABSTRACT.

The commissioning of the ITER-Like ICRF Antenna (ILA) [1] on JET plasmas from May 2008 to April 2009 in various conditions (33, 42 and 47MHz, L- and H-mode, antenna strap-plasma separatrix distances of ~9 to 17cm) has provided relevant information for future antenna design and operation. The maximum power density achieved was 6.2 MW/m2 in L-mode with strap to plasma separatrix distance of ~ 9-10cm at 42MHz on the lower half of the ILA extrapolating to 8MW/m^2 if the full generator power had been available. Efficient (trip-free operation) ELM tolerance was obtained both at 33 and 42MHz on a large range of ELMs with strap voltages up to 42kV and a maximum power density of 4.1MW/m^2. The paper reviews these achievements as well as remaining issues.

1. INTRODUCTION

The commissioning of the ILA during 2008 and early 2009 demonstrated operation of the ILA on L- as well as H-mode at various frequencies (mostly 33 and 42MHz and occasionally 47MHz). The maximum voltage of 42kV (limited by protective electronics) was achieved rather swiftly and repeatedly on L- as well as H-mode. The maximum achieved coupled power of 4.76MW on L-mode (Pulse No: 75329) was limited by RF power plant issues while on H-mode 1.88 MW was achieved (see figure 2 Pulse No: 78069) on the ILA upper pair of Resonant Double Loops (RDLs). The highest power densities achieved have been 6.2MW/m^2 on L-mode for the lower pair of RDLs (higher RF plant power availability, see figure 2 Pulse No: 73941) and 4.1MW/m^2 on Hmode for the upper pair of RDLs of the ILA (e.g. figure 3 Pulse No: 78070, easier matching conditions and slightly higher coupling).

A number of technical issues encountered were not directly related to the new launcher concept and substantially reduced the overall availability of the whole ILA array of 4 RDLs in the desired configuration : reliable operation of the amplifiers and their power supplies at high power, the installation of an ex-vessel monitoring system to recover the damaged position sensors of C2 and the commissioning of the additional arc detection systems [2, 3] to allow low Conjugate-T point (CT) resistance (Re[Z_{CT}]) operation with increased load resilience. The remaining difficulties are mostly related to matching: feeding of the whole array of 4 cross-coupled RDLs and optimizing the load resilience at low coupling during H-mode. Overall, the outcome of the ILA commissioning is deemed successful, meaningful to qualify certain aspects of the design of the ICRF antenna for ITER while highlighting other aspects for closer investigation [4, 5]. Unfortunately, at the time of writing the ILA is not operational any longer due to a faulty capacitor : the analysis of the fault points to a leaking internal bellows.

2. VOLTAGE AND POWER HANDLING

The analysis is based on the 1603 ILA pulses recorded that are presently stored in the ILA control computer's data base; about 300 pulses predate this storage and concern the first low level ILA commissioning phase. Of the stored pulses 18% failed with less than 2kJ delivered to the ILA due to causes not related to the antenna RF concept itself (test pulses for commissioning the arc detection, pulses disrupting before the RF pulse, RF plant issues, hydraulic plant and capacitor control issues.

In order to assess the voltage and power handling performance of the ILA in the remaining 1309 pulses a quality factor, Q, has been defined (fig.1). For pulses truncated by either a failing power supply, the amplifiers not restarting correctly after a trip or simply a lost match and/or insufficient load resilience this process will tend to base Q on the leading part of the pulse that went through successfully. It can be observed that Q thus defined does not degrade with increasing voltage and/ or power up to the highest achieved values. There is considerable spread of Q in the lower voltage and power brackets due to the fact that most problem finding and setting up happened there.

It is worth noting the possible adverse effect on Q of the electronic limitation of the voltage at 42kV, the value that (after reassessment of the voltage probe calibrations) was reached on testbed. As a result of this limitation the power requested on these pulses is not achieved and Q is degraded although from the point of view of voltage stand off the pulse is of high quality. Figure 2 shows such a pulse with a Q of 83.7% where only the last 2 trips out of 6 occurring can be attributed to a voltage breakdown (in this case on the feeder of strap 2). The other trips happen right after the onset of the ELM and are attributed to insufficient load resilience due to the low coupling.

Highest power densities were achieved in L-mode on the lower half due to RF plant limitations on the upper half. On H-mode, the highest power and power density was achieved on the upper half which, due to the plasma profile, had a slightly higher coupling that eased the match and load tolerance requirements. The restricted time window where the commissioned arc detection was available before the loss of one of the capacitors (C_7) on the lower half was insufficient to do substantial work on matching the whole ILA in H-mode.

3, MATCHING ON ELMS

Once the SMAD arc detection was commissioned, Re(Z_{CT}) could be lowered safely to 3Ω and the matching and load resilience on ELMs optimized. Due to the lower coupling in H-mode the matching point had to be offset from perfect match at Z_{CT} on H-mode base load. After choosing the appropriate Im(Z_{CT}) to balance the strap feeder voltages within the RDLs, the optimized load resilience was achieved by setting the second stage matching circuit using various software tools [7,8] so as to keep the excursions of the Voltage Standing Wave Ratio (VSWR) on the Main Transmission Lines (MTLs) due to ELMs below the trip level of 2.7. Except for cases with very low coupling (e.g. at 33MHz and a high strap to plasma separatrix distance imposed by the experimental necessities) these VSWR excursions could be kept between 2 and 2.5. However, it was found that the unavoidable asymmetry of the match point across the powered RDLs (due to calibrations errors of various sorts and possibly the nonreprocity of the antenna impedance matrix with plasma) becomes an extra source of degradation of load resilience as shown in Figure 3.

CONCLUSIONS

The ILA has been able to operate at 42kV on JET in L- as well as H-mode without observable degradation of the pulse quality inherent to voltage handling capabilities. It has also coupled power to the plasma in conditions relevant to ITER at power densities up to 6.2MW/m^2 in L-mode (limited by RF power plant) and exceeding 4MW/m^2 in H-mode. It does not appear that these power densities which are substantially higher (~6.3 times in Pulse No: 78070) than hitherto available on JET [9], cause any detrimental effects on impurity generation or loss heating efficiency. The matching on

ELM sometimes suffered from the low coupling in H-mode, but it was in general possible to keep the VSWR excursions between 2 and 2.5 by properly offsetting the 2nd stage match. The simultaneous operation of the whole ILA array was less trivial due to the cross-coupling between the various RDLs affecting the reliable operation of the 4 independent amplifiers.

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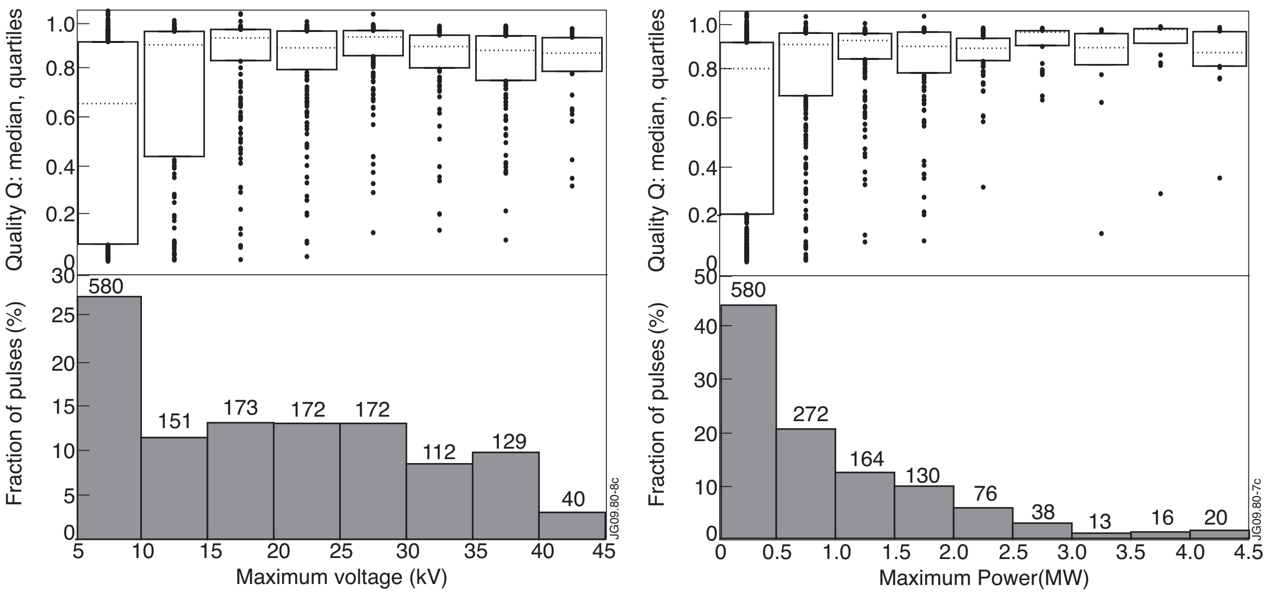

Figure 1: Statistics on achieved voltages (a) and powers (b). The bottom graphs show the distribution of the number of pulses versus voltage/power also showing the number of pulses in each voltage/ power bracket. The top graphs show the quality factor Q, defined as the ratio of the delivered to the requested energy when the former has reached 97% of its total, for the pulses in each bracket : 50% of the pulses lie in the inter quartile's box while 50% of the pulses lie above the dotted median line shown in the box. The pulses lying outside of the inter quartile's box are also shown.

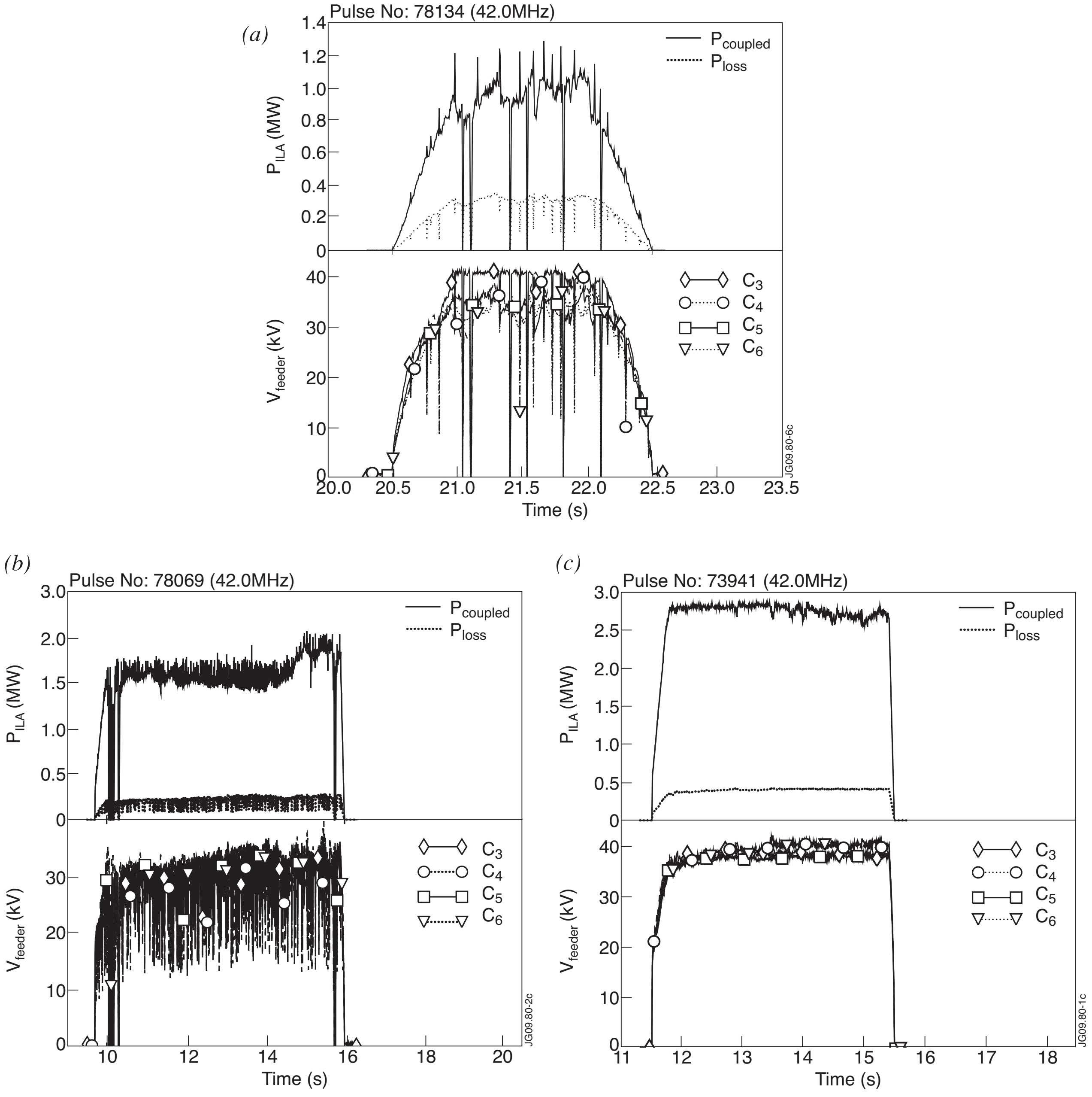

Figure 2: (a) Pulse No: 78134. The feeder voltage on strap 1 (C1) is limited at ~41−42kV limiting the power output of the amplifiers on this pulse with strong ELMs. During the ELMs, when the strap voltage is lower, the power output is raised to the requested value. (b) Pulse No: 78069: Highest Power density in H-mode. (c) Pulse No: 73941 Highest power density in L-mode. Coupled power is measured at the Antenna Pressurized Transmission Line (APTL) directional couplers with power losses subtracted. The power losses are estimated using the reactive parts of the ILA impedance matrix measured on testbed to estimated the amplitude of the strap currents and assuming 65mΩ series resistor per strap representing the losses (as measured on vacuum on the testbed [6]).

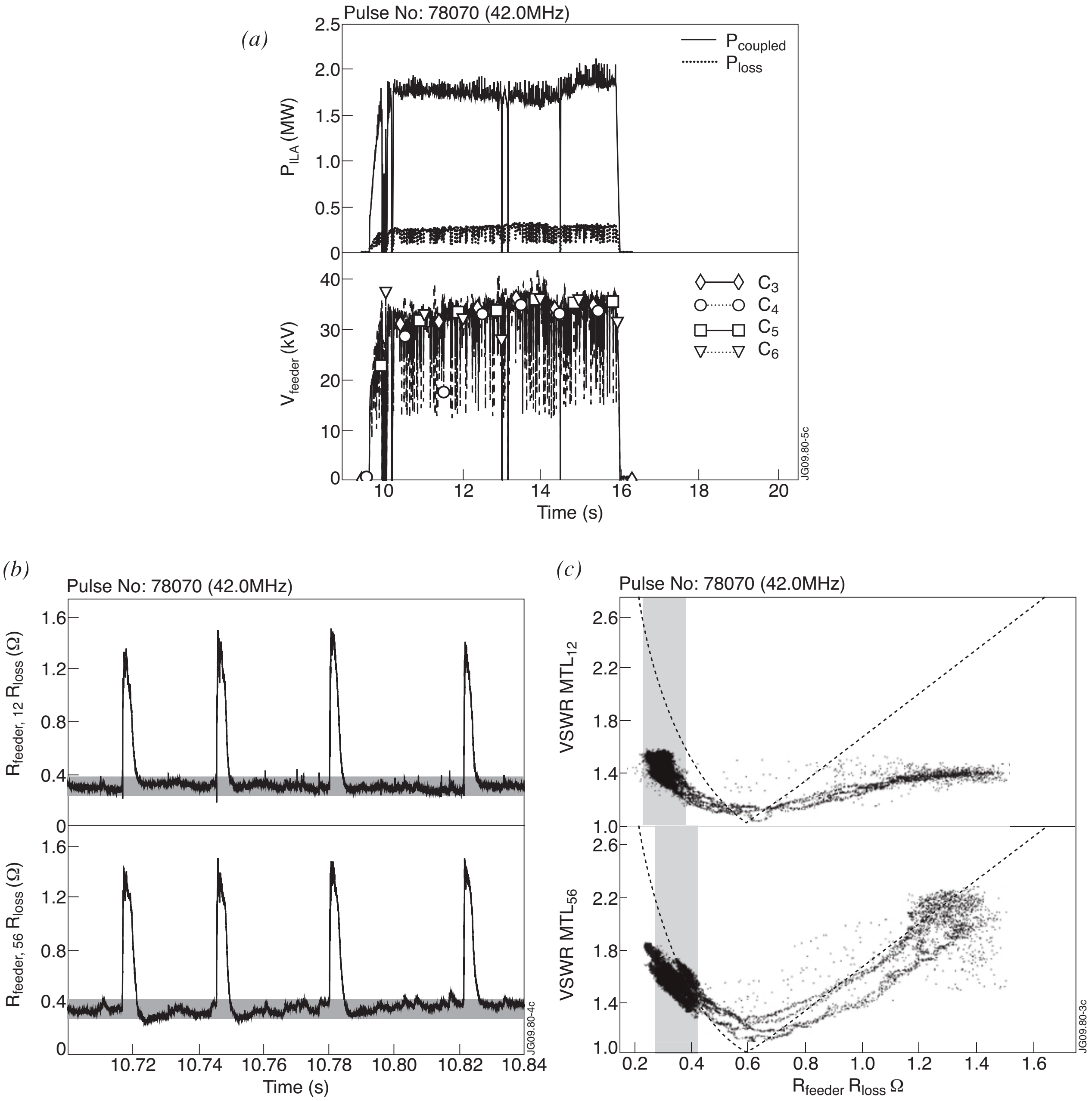

Figure 3: (a) Pulse No: 78070 on the ILA upper half. (b) Coupling data for a small time slice. (c) Load resilience expressed as the VSWR on the MTL versus the estimated coupling for the shown time slice : the dashed line represents what a classic 2-port matching circuit would achieve; the shaded areas correspond to the base load also highlighted in the middle graph.