EFDA–JET–CP(08)04/18

F. Durodié, M. Nightingale, A. Argouarch, G. Berger-By, T. Blackman, J. Caughman,
V. Cocilovo, P. Dumortier, P. Edwards, J. Fanthome, D. Frigione, R. Goulding,
M. Graham, J. Hobrik, S. Huygen, S. Jachmich, P. Jacquet, A. Kaye, P.U. Lamalle,
E. Lerche, T. Loarer, M.-L. Mayoral, A. Messiaen, I. Monakhov, M.F.F. Nave,
K. Nicholls, J. Ongena, F. Rimini, D. Van Eester, M. Vervier, M. Vrancken, C. Sozzi,
D. Stork, M. Tsalas, A. Walden, A.Whitehurst, K.-D. Zastrow
and JET EFDA contributors

Commissioning of the ITER-Like ICRF Antenna for JET

Commissioning of the ITER-Like ICRF Antenna for JET

F. Durodié[1], M. Nightingale[2], A. Argouarch[3], G. Berger-By[4], T. Blackman[2], J. Caughman[4],
V. Cocilovo[5], P. Dumortier[1], P. Edwards[2], J. Fanthome[2], D. Frigione[5], R. Goulding[4],
M. Graham[2], J. Hobrik[6], S. Huygen[1], S. Jachmich[1], P. Jacquet[2], A. Kaye[2], P.U. Lamalle[7],
E. Lerche[1], T. Loarer[3], M.-L. Mayoral[2], A. Messiaen[1], I. Monakhov[2], M.F.F. Nave[8],
K. Nicholls[2], J. Ongena[1], F. Rimini[3], D. Van Eester[1], M. Vervier[1], M. Vrancken[1],
C. Sozzi[5], D. Stork[2], M. Tsalas[9], A. Walden[2], A.Whitehurst[2], K.-D. Zastrow[2]
and JET EFDA contributors*

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

[1]*ERM-KMS, Association EURATOM-Belgian State, Brussels, Belgium*
[2]*UKAEA/Euratom Fusion Association,Culham Science Centre, Abingdon, Oxon, OX14 3DB, United Kingdom*
[3]*Association,Euratom-CEA Association, DSM/IRFM, CEA-Cadarache, 13108 St Paul lez Durance, France*
[4]*Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, United States*
[5]*Associazione EURATOM-ENEA sulla Fusione, C.R. Frascati, Roma, Italy*
[6]*Max-Planck-Institut für Plasmaphysik, EURATOM-Assoziation, D-85748 Garching, Germany*
[7]*ITER Cadarache Joint Work Site, F-13108, St. Paul lez Durance, France*
[8]*Associação EURATOM/IST, Centro de Fuso Nuclear, Instituto Superior Técnico,*
Av Rovisco Pais, 1049-001 Lisbon, Portugal
[9]*Association EURATOM-Hellas, NCSR "Demokritos", Agia Paraskevi Attica, Greece*
** See annex of M.L. 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
25th Symposium on Fusion Technology, Rostock, Germany
(15th September 2008 - 19th September 2008)

ABSTRACT

The new JET Ion Cyclotron Resonance Frequency (ICRF) ITER-like antenna (ILA), which was assembled during 2006, was commissioned on the JET RF testbed prior to installation on the JET torus. The 4 Resonant Double Loops (RDL) of the ILA were tested at high power at 42 MHz up to 42kV for 5 seconds in 10 minute intervals. Low power matching studies using a saltwater load placed in front of the ILA have allowed testing and optimizing proposed matching algorithms on single RDLs, paired RDLs and finally on the full array. The upper limit of the frequency range of the ILA appears to be limited to 47–49MHz due to the effect on the electrical lengths of the connection between the capacitors and the conjugate T point. Capacitor position scans have allowed obtaining the necessary data to confirm the RF model of the RDL which is necessary for the Scattering Matrix Arc Detection. The latter is deemed necessary in order to detect arcs at the low impedance conjugate T of the circuit.

The antenna was installed onto JET during August 2007 and commissioning on plasma started May 2008. At present the commissioning of the ILA on JET is ongoing in a series of dedicated experimental campaigns.

1. INTRODUCTION

The ILA [1,2] project set out in 2001 with the aim of demonstrating coupling of ICRF power to plasmas in conditions relevant to ITER: a power density in the range of 8-10MW/m^2 as well as robustness against load perturbations caused by Edge Localized Modes (ELM). The design 6 is based on a close-packed array of short low inductance straps mounted as four Resonant Double Loops (RDL's) arranged in a 2 toroidal by 2 poloidal array. Each RDL consists of two poloidally adjacent straps which are fed through matching capacitors located in-vessel from a T-junction 11 which in turn is fed from a 1.76m long Vacuum Transmission Line (VTL) with a low characteristic impedance (~ 9Ω). Tolerance to plasma load variations is achieved by adjusting the matching capacitors' values such that the twobranches of an RDL have approximately complex conjugate impedances. The impedance, Z_{CT} , at their connection 17 point, referred to as Conjugate-T (CT), is then typically between 3 and 6Ω with optionally a small imaginary part which is used to equalize the voltages between straps of an RDL. The paper will summarize the main results on obtained on testbed as well as report on the present status of the commissioning of the ILA on plasma.

2. COMMISSIONING ON TESTBED

Upon reception of the components, the ILA was initially assembled on the JET RF testbed facility. The antenna array scattering matrix was measured using a salted water tank to simulate a plasma load [3] (figure 1) and subsequently the four RDLs were matched separately in turn at low power on vacuum and tested at high power. The various conditioning phases, multipactoring, increasing pulse lengths at moderated power, short pulse voltage hardening and finally going to long pulse high voltage, were carried out without major issues aside from one capacitor, C_4, failing due to an uncontrolled RF power surge. About 250kW per RDL was required to reach the target of 42−45kV, corresponding to a dissipation of 1MJ per RDL [4].

An important aspect of the commissioning on testbed was the testing of algorithms for simultaneously matching all 4 RDLs making up the ILA and is described next.

2.1. MATCHING CONTROL OVERVIEW

Figure 2 shows the control system for the ILA in-vessel capacitors. Two types of matching algorithms have been considered so far: the Z_{CT} algorithm controls the impedance at the conjugate T-junction of the two branches of the RDL, while the V_C algorithm controls the complex voltage ratio of the two straps of the RDL [5,6]. The RF signals necessary for these algorithms are the forward and reflected voltages, respectively V_+ and V_-, measured by directional couplers on the Antenna Pressurized Transmission Line (APTL) sections and the capacitor voltages, V_a and V_b, measured with voltage probes located in-vessel at the level of the capacitors' fixed electrodes (i.e. on the strap side). These signals are transmitted by ~110m long 50Ω heliax RF cables from the torus hall to the generator building and converted down to the 1.3 MHz RF plant phase referenced signal frequency [7] RF Conversion Modules (RFCM). Because the ILA was powered using a 10W RF source on the testbed, the measured RF signals were amplified by about 60dB. Amplitude and phase demodulator modules (APDM) finally allow the amplitudes and phases of the RF signals to be captured by the matching control computer based on a National Instruments PXI system running Labview. The computation of the capacitor position error signals is carried out every 5ms. Only the Z_{CT} matching algorithm was extensively tested : Z_{CT} is estimated using the APTL forward and reflected voltages in conjunction with an RF model of the APTL and low impedance vacuum transmission line circuit. The difference with this estimation and target Z_{CT} drives the capacitors.

2.2. MATCHING STUDIES

As it was not possible to implement the 4 feeding transmission line (TL) circuits on the testbed, the experimental set up for studying the simultaneous matching of the 4 RDLs was somewhat different than that of the final installation on JET (figure 3). The main differences were the characteristic impedance of the feeding TLs and second 7 stage matching network (50Ω coax RG232 cable instead of 30Ω 9 inch diameter Spinner TL), the use of low power 50Ω 3dB hybrid splitters with near ideal response as compared to the high power 30Ω 3dB Spinner splitter/combiners as well as the service stubs necessary to route the hydraulic, water and electric services to the capacitors and actuators. Except for the different response of the 3dB splitters, these differences should not alter the characteristics of the matching of the whole ILA array. The matching studies activities were curtailed due to time lost for the repair of capacitor C_4 failing during the high power test phase as well as time taken to test an ex-vessel monitoring system for controlling capacitor C_2 whose in-vessel position sensor signals quality was marginal (the sensors were damaged by an hydraulic fluid leak during the assembly in 2006).

The proposed Z_{CT} matching algorithm was succesfully used to home in on a match of the 4 RDLs simultaneously at different frequencies and for various toroidal antenna phasings (29MHz (dipole), 33MHz (dipole), 42MHz (monopole, dipole)). At the higher frequencies, the matching succeeded for either the lower or upper half of the ILA separately (47MHz (dipole, using the algorithm), 49MHz (dipole, manually adjusted)). Different target $Z_{CT} = R_{CT} +jX_{CT}$ were used : R_{CT} of 3 and 6Ω and XCT ranging from −2 to +2Ω.

It was however observed that the setting of the various 2nd stage and main phase shifters is very sensitive to obtain a correct voltage distribution on the 8 ILA straps or even making the algorithm converge to a matching solution. This is due to the rather large cross-coupling between adjacent toroidal straps as well as the 4 inner straps (2,3) and (6,7): slight phase differences away from 0 or π . Note that it was not possible to successfully match the ILA even on separate RDLs at 51MHz or above. Recent analysis using 3D-EM modelling indicates that the capacitor cannot be considered as a lumped element (including its series inductance) located between the antenna strap feeder ange and the ”bridge” (the region of connection between the two branches of the RDL circuit) as it was assumed during the design of the ILA.

The load tolerance could not be convincingly demonstrated due to the relatively low load and small variation that the salted water load provided. This low load is most likely due to the step in dielectric constant unavoidable in the practical implementation of the water load rather than a smoother transition that a plasma edge provides.

3. COMMISSIONING ON JET PLASMAS

Commissioning of the antenna on JET plasmas started in May 2008 (figure 4). After about half a day of conditioning of the ILA on vacuum and finding the match on plasma, the milestone defined as achieving capacitor voltages of 15kV on lower and upper half of the ILA separately was easily achieved at 42MHz π-phasing and formally proved the JET Operator team. The further commisioning of the ILA to its specificed performance is on-going with most operation at 42MHz on the lower half of the array: until now a maximum of 2.55MW with strap feeder voltages of about 42kV has been coupled int an L-mode plasma at a distance between separatrix and the limiter in the equatorial plane (ROG) of 4cm (about 10cm between separatrix and the strap front face for the lower half of the ILA). This corresponds to a power density of about 5.7MW/m^2.

In order to balance the voltages as much as possible, the imaginary part of Z_{CT}, X_{CT}, was required to be −1 or −3Ω depending on which of the two available matching solutions for a single RDL was chosen [6]. Numerical simulations based on the ILA scattering matrix measured with the salted waterload predicts that the sign of XCT depends on the chosen matching solution and the discrepancy with the experimental observation on plasma is not well understood yet.

Operation on H-mode has been successfully obtained at a ROG of 5cm after offsetting the match point for a substantially higher loading than that appearing between ELMs (Pulse No: 73987 shown in figure 5). This has been achieved by freezing the capacitors’ positions on a high loading L-mode match prior to the transition into H-mode. Testing of a modified algorithm to achieve an offset match during H-mode without requiring a initial L-mode phase and freezing of the tracking of the match is still outstanding. The maximum power coupled during an H-mode has been 1.75MW with voltages as high as 40kV, corresponding to a power density of about 3.9MW/m^2 . The load, TotalR$_{feeder}$ in figure 5 incl. 130mΩ losses, is estimated by multiplying a suitable ILA impedance matrix measured on testbed with the measured complex strap voltages to obtain the strap currents. The Root Mean Square (RMS) amplitudes of these currents are squared and summed per RDL and divided by the measued APTL net power for that RDL. The result obained is the real part of the strap impedance measured at the location of the voltage probes (note that it is not possible to differentiate between the two straps of an RDL: this would be possible in theory by evaluating the real part of the complex RMS current multiplied with the conjugate complex RMS voltage, however the relative large uncertainties of the angles between currents and voltages makes this approach not usable). The load variations thus estimated during the ELMs are about a factor 3 and the ILA efficiency is estimated at 1.75MW$_{coupled}$/2.05MW$_{generator}$ ~ 85%. The transition into the H-mode exhibits an initial increase in loading due to the slight shift in plasma position at the application of the neutral beam power required to get to the H-mode. As the position is recovered and the H-mode is entered the loading further decreases to about half of the initial L-mode one. The shift in plasma position from ROG 4cm in L-mode to 5cm in H-mode is required in order to avoid excessive thermal loading of plasma facing components elsewhere on JET during the phase with additional beam power.

Fast data acquisition sampling the ILA RF signals at 200kHz has allowed resolution of the evolution of the Main Transmission Line (MTL) Voltage Standing Wave Ration (VSWR) during ELMs, as shown in figure 6. The expected load response is clearly present. Prior to the ELM the RDLs which are matched for a high L-mode loading, produce a relatively large VSWR inde range of 1.5 to 2 on the low H-mode base loading. During the rising flank of the ELM the VSWR exhibits a fast transition through a minimum and coming up again and later as the increased loading caused by the ELM relaxes, the VSWR path is reversed going back trough the minimum and up the high initial VSWR of before the ELM. Further adjustments of the base load VSWRs on the feeding TLs and their upswing during ELMs are still required to keep both below 1.5 for which the JET RF amplifiers are specified to be able to deliver full power. This might require, depending on the operating frequency, to further lower the impedance of the CT which however increases the risk of failing to detect arcs occurring at the CT bridge. These arcs are a key concern as shown on the Tore Supra (TS) prototype antenna [8] because they cannot easily be detected by the classical VSWR based arc detection schemes. Two additional arc detection schemes are currently being tested: the SubHarmonic Arc Detection (SHAD) such as used on ASDEX-U and Tore Supra [9] and the Scattering Matrix Arc Detection (SMAD), a novel technique proposed by LPP-ERM/KMS, based on the redundancy of measured RF signals measured on the circuit [10]. At the time of writing, work on both additional arc detection systems is still in progress.

It also is observed that the abrupt change in VSWR already occurs before the D$_\alpha$ signal indicates the occurence of the ELM. The reasons for the delay of the D_α signal and the VSWR, varying between 0.3 and 0.7ms, are not well understood and may have implications for other ELM mitigation techniques such as trip management if confirmed. The simultaneous operation of the 4 RDLs on L-mode plasmas has been postponed due to the further deterioration of the signal quality of the position sensors of C_2 since testbed operation until the installation and commissioning of an ex-vessel actuator position monitoring system. However, for the short period that it has still been possible to operate the upper and lower halves simultaneously drifting matching solutions as well as very unbalanced voltages have been observed (see figure 7).

The feeding transmission line circuit is therefore being modified so that the phases of the voltages of the 4 inner straps can be feedback controlled by 4 independent amplifiers feeding the 4 RDLs separately. It is then expected that the drifting of the matching which is a result of an initial phasing error enhanced by the capacitor tracking the matching solution, can be neutralised i.e. the phasing of the voltages (currents) on the these straps will be constant and not affected by the matching solution.

Operation at 33 MHz has been successfully achieved on L-mode plasmas while operation at 47MHz is starting at the time of writing.

CONCLUSIONS

Except for the damage on the capacitor position sensors of capacitor C2, the ILA was successfully assembled and tested on testbed. The matching studies phase allowed testing of the matching algorithm in conditions easier than would have been the case on JET plasmas. The most severe deficiency observed was the shortfall of the frequency bandwidth which limited the operation of the ILA to about 49MHz at best instead of originally specified 55MHz.

The commissioning of the ILA on plasma is ongoing and the results are encouraging. The plasma loading is slightly lower than expected hence the best power density achieved on H-mode plasmas has been just below $4MW/m^2$ at 42MHz for a plasma separatrix to antenna strap front face 260 of about 11cm. The optimisation of the load variation response during ELMs awaits the successful deployment of at least an additional arc detection system.

Matching of the whole ILA simultaneously with well balanced stationary strap voltages has not been achieved yet: an ex-vessel capacitor position monitoring system to recover the control of C2 is currently being installed while changes to the feeding TL circuit will allow the electronic feedback control of phase of the voltages for the straps with the highest cross-coupling.

Finally, operation at other operating frequencies has started without major difficulties.

ACKNOWLEDGMENTS

This work was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. The work carried out by UKAEA personnel was jointly funded by the UK Engineering and Physical Sciences Research Council and EURATOM.

REFERENCES

[1]. Durodié F., et al., in Radio Frequency Power in Plasmas, AIP 282 Conference Proceedings 595, New York: Melville, 2001, p. 122.

[2]. Durodié F., et al., in Fusion Engineering and Design Vol. **74**, 284 Issues 1-4, November 2005, p. 223

[3]. Vranken, M., et al., in Radio Frequency Power in Plasmas, AIP 286 Conference Proceedings 933, New York: Melville, 2007, p. 135.

[4]. Durodié, F., et al., in Radio Frequency Power in Plasmas, AIP Conference Proceedings 933, New York: Melville, 2007, p. 131.

[5]. Evrard, M., et al., in Radio Frequency Power in Plasmas, AIP Conference Proceedings 787, New York: Melville, 2005, p. 168.

[6]. Lamalle, P.U., et al., LPP-ERM/KMS Laboratory Report 127, December 2005.

[7]. Wade, T., et al., Fusion Engineering and Design, vol.**24** nos.1&2 February 1994 pp.23-46

[8]. K. Vulliez, G. Bosia, S. Brémond, et al., First results of the Tore Supra ITER like ICRF antenna prototype, Fusion Engineering and Design, vol. **74**, 267 (2005).

[9]. Berger-By G. et al., in Radio Frequency Power in Plasmas, AIP Conference Proceedings 933, New York: Melville, 2007, p. 211.

[10]. Vrancken, M. et al., these proceedings, SOFT 2008.

Figure1: View of ILA antenna housing and the salted waterload during the measurements of the ILA impedance matrix

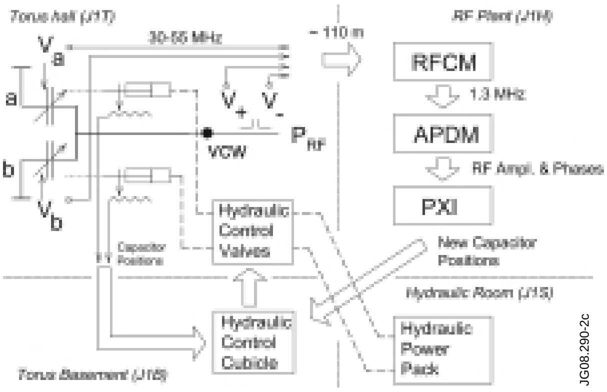

Figure 2: ILA Matching Control Schematic

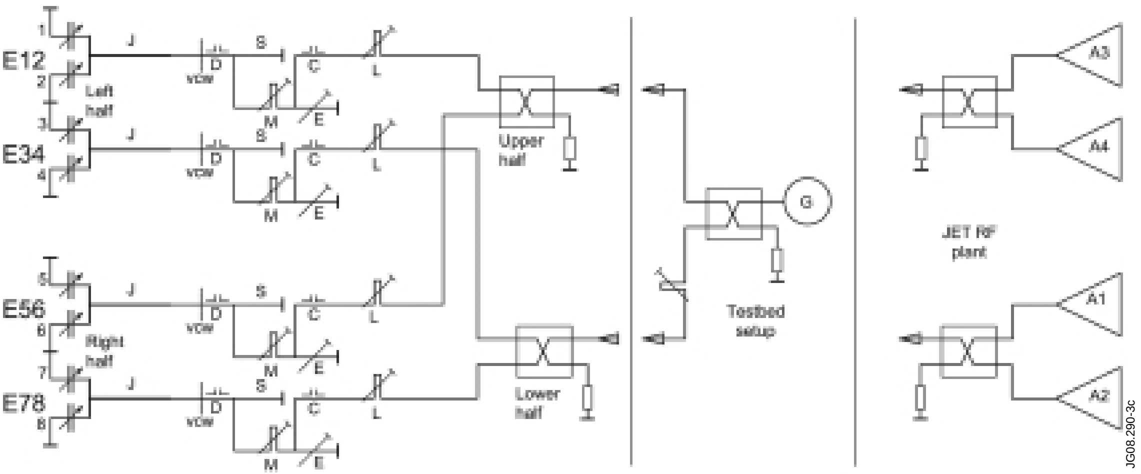

Figure 3: RF feeding circuit for the ILA matching studies on testbed and on JET. (J) low Z VTL, (VCW) vacuum window, (D) APTL directional couplers, (M) 2 nd stage matching trombone, (E) 2 nd stage stub, (C) MTL directional couplers, (L) main phase shifters, (G) 10W signal generator, (An) high power amplifiers

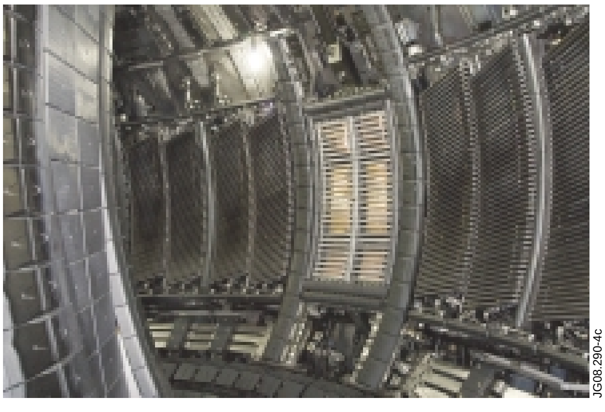

Figure 4: The ILA installed on JET between A2 antenna arrays A and B. The surface of the ILA aiming at coupling 7.2MW with a power density of ~ 8MW/m^2 is less than half of that of one A2 array.

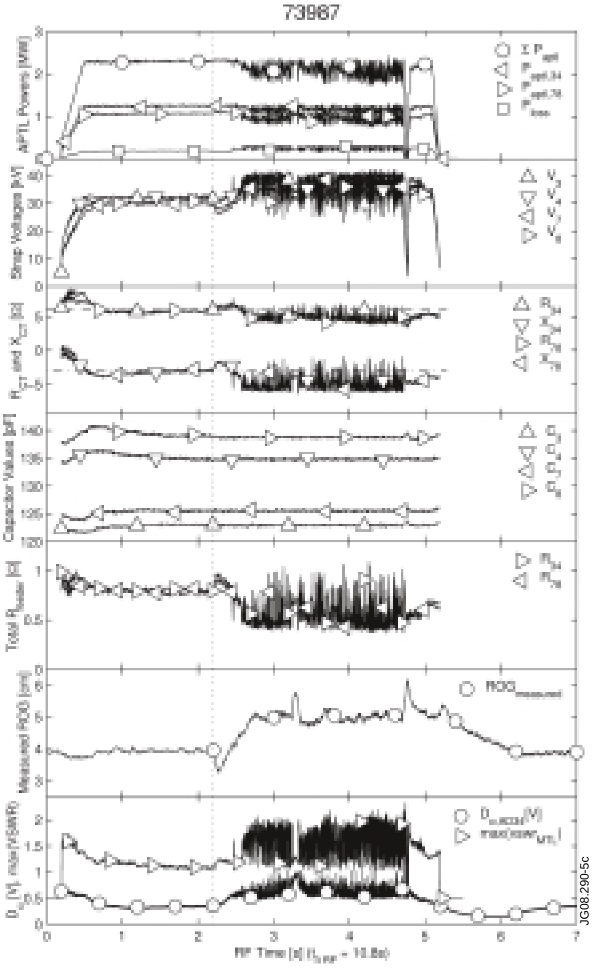

Figure 5: JET Pulse No: 73987 at 42MHz: the capacitors are allowed to track the high loading L-mode match until their positions are froozen just prior to the transition into H-mode at 2.185s into the RF pulse.

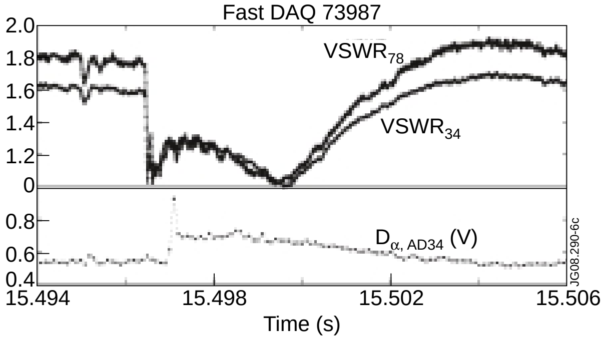

Figure 6: VSWR on the two MTLs during and ELM.

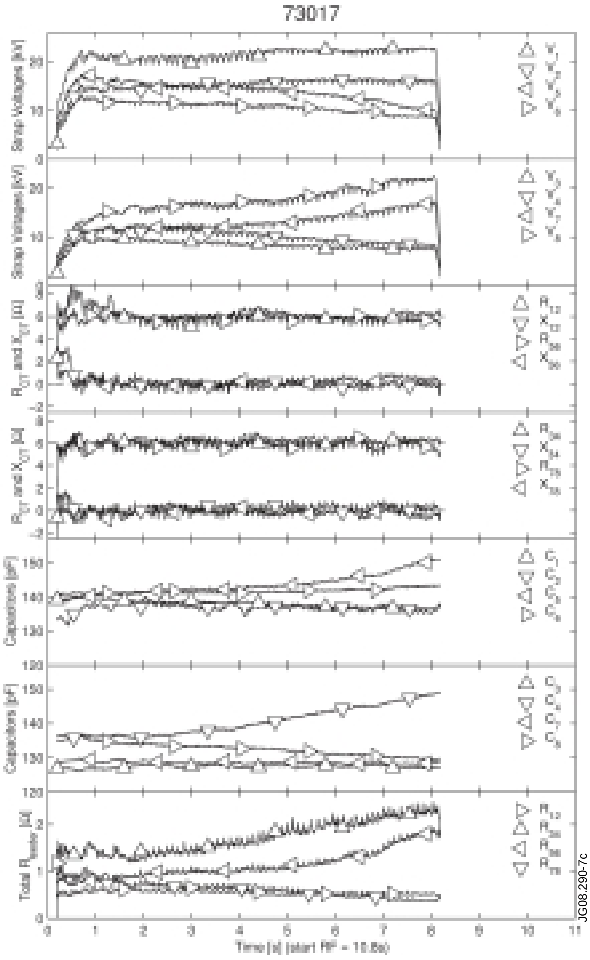

Figure 7: JET Pulse No: 73017 at 42MHz.