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Fusion Engineering and Design 123 (2017) 285–288

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Commissioning and first results of the reinstated JET ICRF ILA

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HIGHLIGHTS

- The JET ICRF ITER-like Antenna (ILA) has been reinstated.
- A comprehensive calibration and verification of all RF measurements has been performed.
- New algorithms were implemented for the second stage matching and the – toroidal and poloidal – phase control of the array.
- The operating space has been extended towards lower and upper frequencies (29–51 MHz) and to toroidal dipole and current drive phasings.

ARTICLE INFO

Article history:
Received 30 September 2016
Received in revised form 8 May 2017
Accepted 9 May 2017
Available online 22 May 2017

Keywords:
JET
ICRF
ICRH
ILA
Antenna

ABSTRACT

The JET ICRF ITER-like Antenna (ILA) has been operated at 33, 42 and 47 MHz in 2008–2009 but stopped operation in 2009 due to the failure of one of the tuning capacitors inside the antenna. Tests on a spare capacitor showed that a micro-leak was caused by the cycle wear of a capacitor's internal bellows. The ILA was reinstated with a new operating scheme minimizing the full stroke requests of the capacitor.

This contribution gives an overview of the works undertaken to reinstate the JET ILA up to the first results on plasma.

The capacitors were replaced and high voltage tests of the capacitors were performed. An extensive calibration of all the measurements in the RF circuit was carried out. New simulation tools were created and control algorithms were implemented for the – toroidal and poloidal – phase control of the array as well as for the matching of the second stage. New protections are being implemented for the thermal and voltage protection of the capacitors. Low voltage matching tests were performed before the high power commissioning. Finally the first results on plasma are presented, showing that the new controls allow extending the range of the operation to lower (29 MHz) and higher (51 MHz) frequencies than previously achieved.

1. Introduction

The JET ICRF ITER-like Antenna (ILA) is a close packed ICRF antenna array composed of four resonant double loops (RDLs) arranged in a 2 toroidal by 2 poloidal array. Each RDL consists of two poloidally adjacent straps fed through in-vessel matching capacitors from a common Vacuum Transmission Line [1]. Two toroidally adjacent RDLs are fed through a 3 dB combiner-splitter.

The JET ILA antenna has been operating essentially at 33 MHz and 42 MHz on L and H-mode plasmas in 2008–2009 and has stopped operation in March 2009 due to a failure of one of the tuning capacitors inside the antenna [1].

Although the baseline design of the ITER antenna [2] has changed since the JET ILA design and is not using any inside matching components anymore the JET ILA has nevertheless demonstrated the following features of interest for ITER [1,3]: operation of high power density close-packed array antennas (up to 6.2 MW/M^2 in L-mode and 4.1 MW/m^2 in H-mode), ELM-resilient operation, reliable operation at voltages up to 42 kV (correspond-

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[1] See the Appendix of F. Romanelli et al., Proceedings of the 25th IAEA Fusion Energy Conference 2014, Saint Petersburg, Russia.

http://dx.doi.org/10.1016/j.fusengdes.2017.05.050
0920-3796/

ing to electric fields of 2.5 kV/mm in all directions w.r.t. the toroidal magnetic field), development of the S-Matrix Arc Detection (SMAD) [4] and validation of the RF modeling and coupling predictions. It was also demonstrated that the ILA had comparable heating efficiency and impurity production for a given power level to the conventional A2 antennas although they have a higher power density. Incidentally the capacitor failure also demonstrated the vulnerability of moving components inside the vacuum vessel and hence validated the choice of ITER to move towards an externally matched system.

The decision was taken to reinstate the JET ILA as the most schedule and cost effective solution to provide additional RF power for the JET scientific campaigns. The reinstated ILA is operational since October 2015.

2. Main new features of the reinstated ILA

Tests on a spare capacitor showed that a micro-leak was caused by the cycle wear of a capacitor's internal bellows after about 4500 cycles. The ILA was therefore reinstated with a new operating scheme minimizing the full stroke requests of the capacitor in order to extend its lifetime on the machine.

The 3 dB combiner-splitter had to be removed during the 2008–2009 operation in order to have a stable phase control. However stability issues then arose related to the simultaneous start of the 4 generators. It was decided to put the 3 dB combiner-splitter back again as they provide an isolation of the generators from the system and hence provide a more stable operation of the generators [1]. The new toroidal phase control algorithms [5,6] allow operating the system without any phase stability issues.

The operation in 2008–2009 suffered from the lack of feedback on the second matching stage. This resulted in a tedious manual second stage matching procedure for optimization of load-resilience done on a shot-by-shot basis, which was time-consuming and eventually resulted in loss of valuable experimental time. A new second stage matching fully described in [5,6] has dramatically improved the situation and allows having a proper offset match to optimize the response to load variations.

Finally a poloidal phase control acting on the generator phases to control the phase of the voltage probes of the inner straps was implemented [5,6]. Whereas the toroidal phase control allows operating half the array (upper or lower RDLs) the combination of the toroidal and poloidal phase controls allow operating the full array.

First tests were performed with all the new feedbacks in place and are promising. However the JET operating requests and several technical issues (see Section 5) hampered the progress of the full array operation commissioning.

Several improvements were performed ranging from new modeling (used for simulations, SMAD and voltage probe calibration) to full integration of the control in Level 1 (RF pilot interface). A new simulation tool was developed [5] to test the feedback algorithms as well as new data analysis tools allowing a.o. easier trip identification.

Additional protection is also provided by the implementation of an improved capacitor thermal protection through RFLM (RF Local Manager) as well as a new protection limiting the voltage on the capacitors, called ALM2, which is automatically adjusted for the frequency of operation. SMAD is also being re-commissioned (see Section 6).

3. Operational verifications and calibrations

In order to maximize the lifetime of the antenna all capacitors were replaced. This involved the removal of the antenna and second stage matching from JET, the opening of the IVTLs (Inner Vacuum Transmission Line), the opening of the pressure boxes, the replacement of all capacitors, the closing back of the IVTLs and the re-installation of all the components. This work is not trivial and involves several difficult welds.

All capacitors were tested for voltage stand-off (2 min at 48 kV DC). One capacitor proved not to withstand the voltage and needed reconditioning.

The capacitors were also calibrated in order to determine the linear relationship between capacitor position potentiometer readings and the capacitance. This was performed on a test-bench with the capacitors installed in the IVTLs prior to the installation of the IVTLs on JET and relying on the use of the hydraulics for the capacitor actuation. All potentiometers proved to be operational before installation and all capacitors were covering the required 80–300 pF range [7].

The re-installation of the 3 dB combiner-splitters prompted for the verification of the achievable toroidal phase range over the operating frequency range. It appeared that toroidal dipole phasing was not achievable over the whole frequency range. The necessary changes to the Main Transmission Line (MTL) layout were identified and implemented allowing to achieve toroidal phases ranging from dipole ($0\ \pi$) to Current Drive ($0\ \pi/2$) over the whole operation frequency range [7].

The 2008/2009 experience demonstrated the importance of accurate RF measurements to control the full ILA close-packed array and to operate SMAD. An extensive RF calibration campaign has been conducted prior to the operation and global complex calibration coefficients combining all elements in the measurement chain have been produced for all RF measurements [7].

All directional couplers in the transmission line (TL) system were calibrated in frequency using network analyzer (NWA) measurements. This includes the APTL (Air Pressurized TL), MTL (Main TL), CSTL (Combiner-Splitter TL) and OTL (Output TL). The directional couplers were calibrated in-line requiring measurement adaptors to connect the 9"–30 Ω and 6"–30 Ω transmission lines to the 50 Ω coaxial cables connected to the NWA. These measurement adaptors were themselves characterized in function of frequency using a novel Open + Line calibration technique [7]. The measurement adaptors were de-embedded from the NWA measurements and the measurements themselves shifted to the directional couplers plane in order to provide the requested calibration coefficients vs frequency (coupling and directivity).

The capacitor voltage probes were calibrated in-situ (inside the antenna housing on JET) prior to the antenna re-installation. All 16 probes were calibrated in phase and amplitude using a dummy capacitor. The attenuation of the signal is roughly in f^{-1} with oscillations due to the Thermocoax cable characteristics [8].

All RF cables running from the torus hall to the generator hall also have been calibrated using a reflection measurement to determine the attenuation and electrical length of these long (~120 m) RF cables.

Finally the electronics treating the signals were also calibrated. In particular the APDMs (Amplitude and Phase Detection Modules) were checked, tuned for IQ and the signal levels adjusted. All attenuators and couplers in the system were also calibrated vs frequency using NWA measurements.

4. Matching and power conditioning

To gain precious machine time an extensive low power matching campaign has been conducted. The aim was to determine the matching conditions for the different operating frequencies and T impedances (Z_T) to provide adequate initial capacitor positions for the operation on JET. This low power matching exercise was per-

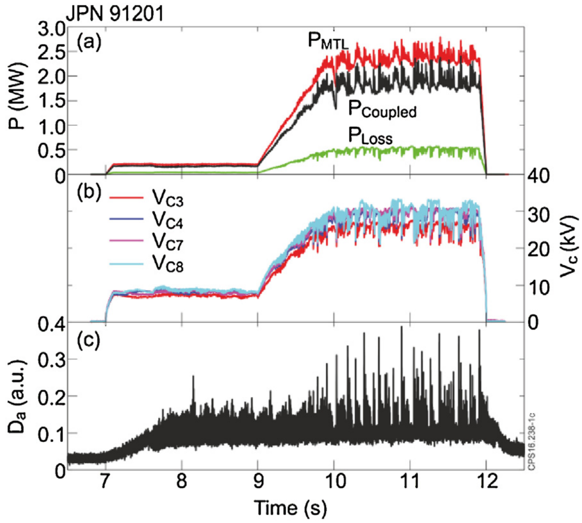

Fig. 1. Example of operation in dipole phasing at 29.2 MHz (lower half) on ELMy plasma. (a) MTL power, coupled power and losses (b) voltage at capacitors (c) D-alpha.

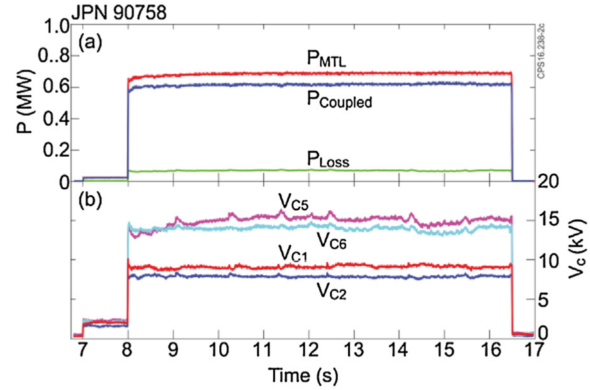

Fig. 2. Example of operation in CD phasing at 33 MHz (upper half) on L-mode plasma. (a) MTL power, coupled power and losses (b) voltage at capacitors. The high mutual coupling between RDLs in CD operation leads to voltage imbalance between the straps of the two RDLs ($V_{C5} \sim V_{C6} > V_{C1} \sim V_{C2}$).

formed using a NWA to feed the antenna and read the measured signals (the electronics chain not being used here). A dedicated Labview programme has been developed to control the capacitors and tests were carried out to find the right matching algorithm parameters. Each RDL has been matched separately and matches were found for several frequencies ranging from 29 to 49 MHz, for one or the two matching solutions and for different T impedances: $Re(Z_T) = 3, 6, 10\,\Omega$ and $Im(Z_T) = 0, -2, -5\,\Omega$.

The high power conditioning procedure remains unchanged. A first multipactoring phase allows removing gas from the RF surfaces. The RDLs are unmatched at 42 MHz, the second stage matching stubs are set neutral at $\lambda/4$ and the power is in the range of 0–50 kW. Gas release is monitored from the vacuum pressure gauges. The power is then scanned upwards in 2–10 ms pulses every 2–5 s to slowly bring the voltage up to the nominal operating value of 40–45 kV.

5. Extension of the operating space

The new algorithms together with comprehensive RF calibration allowed the extension of the ILA operation space towards lower (down to 29 MHz, see Fig. 1) and higher (up to 49 MHz for both halves and up to 51 MHz for the upper half) frequencies. It also allowed Current Drive (CD) operation (0 π/2 toroidal phase) besides the usual dipole operation (0 π toroidal phase). The high mutual coupling between toroidal RDLs in CD operation leads to voltage imbalance between the voltages and currents of the straps of the two RDLs (see Fig. 2). Table 1 summarizes the maximum achieved coupled power for the different frequencies and phasings tested so far within the boundaries set by the JET experimental programme.

The power delivered by the antenna was mostly limited by the available power from the RF plant rather than from the voltage on the antenna. Coupling efficiency is generally about 85–90%.

The additional RF power available was extensively used during the JET experimental campaigns and proved especially useful in the lower frequency range where the A2s can only provide limited power as the voltage limits are reached due to the poor coupling. At 33 MHz one half of the ILA provides as much power as two A2 antennas, which corresponds to about a 10 times higher power density.

Several issues however have affected the ILA operation after the restart in July 2016: low voltage arcing ($V_T \sim 3$ kV) appeared on RDL 56 and capacitor C6 is suffering from deficient position sensors. Both hampered the progress in the commissioning of the poloidal phase control for the full array operation. Inspection of the pressure box of RDL 56 revealed these were caused by a hydraulic fluid leak preventing operation of the upper half until repair.

6. SMAD re-commissioning

The S-Matrix Arc Detection system has been implemented for the first ILA operation in 2008/2009 [4]. The SMAD is a consistency check between the forward and reflected voltages measured by the APTL directional couplers and the voltages measured by the voltage probes for each RDL and relies on a model of the antenna structure between these measurements (including the variable capacitors). It is essential in the detection of low voltage arcs (e.g. T-point arcs) when $Re(Z_T) < 6\,\Omega/10\,\Omega$ while respectively operating half/full antenna array. In these conditions low voltage arcs are not detectable by the traditional Voltage Standing Wave Ratio (VSWR) detection system. SMAD operation in 2008/2009 required frequency-dependent fine tuning of the SMAD coefficients. Improvements for the SMAD operation include new numerical modeling and improved accuracy of the measurements through the comprehensive (re)-calibration of all signals.

Fig. 3 displays an example of the detection by SMAD of an arc due to the hydraulic fluid leak in RDL 56.

7. Conclusions

The JET ICRF ILA was successfully repaired and re-installed. All capacitors were replaced and their movements minimized to increase their lifetime. The 3 dB hybrid combiner-splitter system was re-installed for improved stability of operation.

New control algorithms were implemented for the second stage matching (optimization of load tolerance by offset match), toroidal and poloidal phase control. This allowed extending the operational space towards lower and upper frequencies (29–51 MHz) and to toroidal current drive phasing on half arrays. First tests for full array control were performed and are promising.

The additional RF power provided by the reinstated ILA has been extensively used during the JET experimental campaigns. It is particularly useful in the lower frequency range where the A2 s can only provide limited power due to poor coupling and voltage limits. ILA half array provides as much power as two A2 antennas at 33 MHz (i.e. ten times higher power density).

Improvements were performed on several aspects, a.o. extensive calibration improved the measurement accuracy to the level

Table 1
Summary of the explored operating space.

Frequency (MHz)	JPN	Z_T (Ω)	Coupled Power (MW)	Capacitor Voltage (kV)
Half Array – Dipole Toroidal Phasing				
29	91161	6 + 0j	1.9	26
33	91509	6 + 0j	2.6	27
37	89973	10 – 5j	1.6	35
42	91618	6 + 0j	2.2	32
44	90007	6 – 2j	1.5	35
47	89991	6 + 0j	1.6	38
49	91381	6 + 0j	2.2	32
51	90696	6 – 2j	0.6	14
Half Array – Current Drive Toroidal Phasing				
33	90758	6 + 0j	0.6	14
42	90509	6 + 0j	0.5	22
Full Array				
42	89533	10 – 5j	2.1	25

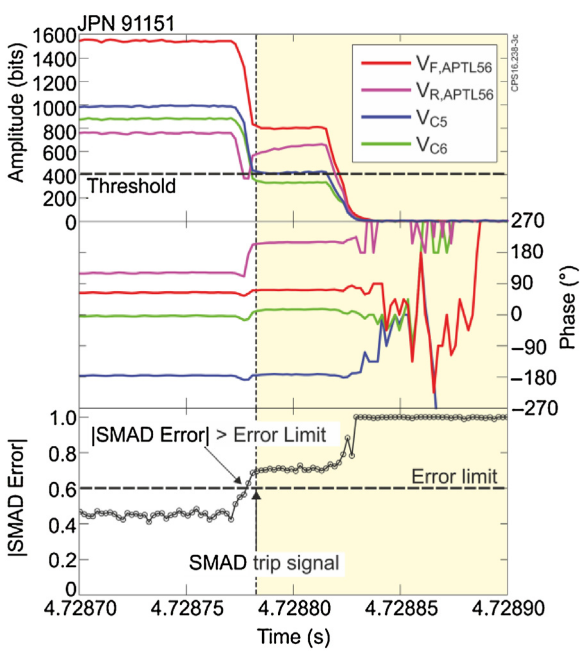

Fig. 3. Low voltage arc detected by SMAD on RDL 56 (JPN 91151–29 MHz). SMAD is set to trip when the SMAD error exceeds the error limit during 3 consecutive points. The SMAD error is calculated every 2 μs.

required by the control algorithms and the SMAD, the SMAD was re-commissioned and improved, capacitor thermal and voltage limits protection are being implemented.

Further tests are needed to finalize the commissioning of the full array phase control. A hydraulic fluid leak unfortunately appeared on RDL 56 in July 2016 currently preventing operation of the upper half (and hence full array operation). The lower half of the ILA is fully operational. Remedial actions are currently being implemented for the upper half. If successful this would allow operating not only the ILA bottom half but also the full ILA array in the next JET campaigns.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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