Latest Achievements of the JET ICRF Systems in View of ITER

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Abstract. During the 2008-2009 JET campaigns, ICRF power was coupled to ELMy H-mode plasmas using 2 distinctly different antenna systems. The newly added ITER-like ICRF antenna aimed in priority at the validation for ITER of high power density load resilient antenna concepts while the A2 antennas were equipped with 2 different load resilient transmission line circuits in order to increase the power coupled to the JET H-mode plasmas. An external conjugate-T junction layout was implemented between the A2 antennas C and D and 3dB hybrid couplers between the A2 antennas A and B. Both load tolerant approaches have demonstrated robust and reliable performance during operations in a variety of plasma loading conditions including on large Type I ELMs. Depending on the plasma scenario, the trip-free time-average power levels coupled to ELMy H-mode plasma during long pulse operations have reached 3.3MW for the 3dB hybrids and 4MW for the external Conjugate-T system. Up to 7MW total ICRF power was coupled to ELMy plasmas simultaneously by all four conventional JET ICRF antennas. The ITER-like ICRF antenna has demonstrated efficient trip-free ELM tolerant operation on ELMy plasmas with power densities up to $6.2MW/m^2$ on L-mode and $4.1MW/m^2$ on H-mode with voltages up to 42kV without significant impurity production. It also provided validation of the ICRF coupling modelling code TOPICA confirming that the ITER ICRF system could couple the 20MW requested at a system voltage below 45kV.

1. Introduction

The capability of Ion Cyclotron Resonance Frequency (ICRF) systems to reliably inject high power into ELMy plasmas is essential both for the JET research program and for future ITER operations. ITER is presently planned with two ICRF antennas aiming to couple in the long term, 20 MW each in ELMy H-mode plasmas with plasma separatrix - antenna distances around 17 cm [1]. The ability to couple ICRF power to H-mode plasmas, one of the main challenges of JET program of the past years, was addressed by modifying the existing ICRF systems and the addition of a new antenna referred to as the ITER-like ICRF antenna (ILA).

The ICRF system used during JET divertor operations since 1994 comprised sixteen similar circuits (FIG.1) where 2MW amplifiers were individually energising each of four straps belonging to four A2 antennas (antennas A, B, C and D) [2]. Impedance transformers

* See the Appendix of F. Romanelli et al., paper OV/1-3, this conference

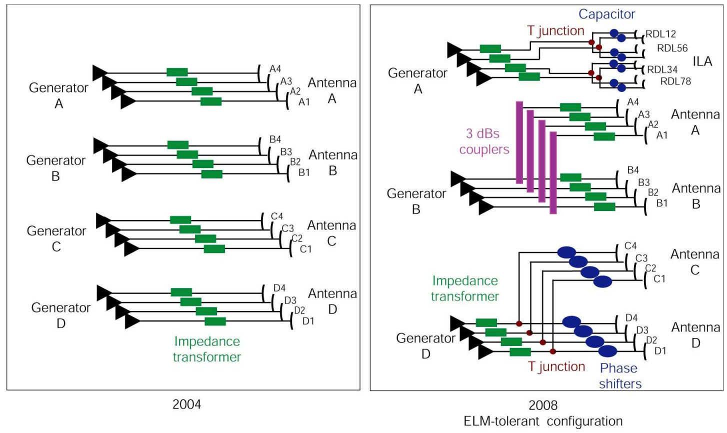

FIG. 1. Overview of the JET system before and after modification.

(stub and trombone tuners) as well as the RF frequency were controlled in real-time to match the load provided by the plasma, typically 1-3 Ω [3], to one suitable for the RF sources (~30Ω). The system demonstrated successful multi-megawatt performance during slowly evolving, plasmas but occurrence of ELMs producing strong, fast and frequent antenna loading perturbations (up to 10-fold load increase in less than 100 μs), proved to be a serious problem for the RF plant. Insufficient intrinsic load tolerance and the slow response of the impedance transformers due to their inertia caused the power reflected to the generators during ELMs to reach unacceptable levels, triggering protective power trips. Indeed, the standard technique for protecting the RF sources, transmission lines and antennas in case of arcing and based on monitoring the Voltage Standing Wave Ratio (VSWR), a measure for the mismatch between the load and the RF source, cannot distinguish the power reflections due to ELMs and those due arcs. The latter requires much longer power trip time (~30-50ms) than the former (~ 1ms). As a result the 'power-off' time during discharges with frequent ELMs was reaching 50-70% and the total averaged coupled power was typically limited to 2-3MW. The breakthrough in reliable RF power injection into ELMy plasma by the A2 antennas was made after the installation of two matching systems intrinsically tolerant to antenna loading perturbations. The implementation in 2005 of 3dB hybrid couplers feeding antennas A and B [4] was followed in 2008 by the installation of External Conjugate-T (ECT) [5] feeding antennas C and D (see FIG.1). Section 2 provides an overview of the 3dB hybrid and the ECT projects and summarises the experimental results obtained so far.

The new ICRF ITER-like antenna (ILA) [6,7], was installed in 2007 and commissioned during the JET experimental campaign in 2008 and 2009. The ILA consists of a closely packed array of 8 short straps fed in pairs through in-vessel matching capacitors from conjugate-T point thus constituting 4 Resonant double loops (RDLs) (see FIG.1). This antenna was specifically designed to provide crucial information for future antenna design and ITER operation in terms of high voltage operation, high power density operation, ELM tolerance, matching and control algorithms, impurity production and to validate the ICRF coupling modelling codes used to estimate the ICRF system capability for ITER. The main results are summarised in section 3.

Both ILA and ECT rely for ELM tolerance on the conjugate-T concept comprising a T-junction layout for which the impedance Z_T is optimally a few times the plasma load and thus much lower than the characteristic impedance of transmission lines, Z_0 (at JET Z_0=30Ω). A "fixed" impedance transformer (also referred to as 2nd stage matching and made of stub and trombone tuners) matches the low Z_T value to Z_0. The intrinsically load-tolerant characteristic of such a circuit limiting the variations of the Z_T values even for strong load transients due to ELMs allows continuous power injection into ELMy plasmas. The main difference between the conjugate-T layout of the A2 antennas and that of the ILA is that for the ECT the matching elements required to adjust Z_T are located outside the vacuum vessel, and the whole system is made of standard coaxial components, e.g. phase-shifters are used instead of the ILA in-vessel capacitors. Note that the ECT is considered as a backup option for ITER, the preferred option being the hybrid coupler feeding circuit, and JET has provided the first ever experimental assessment of such a system.

2. ELM-tolerant systems for conventional JET ICRF antennas

The 3dB hybrid coupler system installed for feeding JET antennas A and B is based on the principle of diverting the reflected power occurring during ELM loading transients to a dummy load, and it is adopted as the main option for ITER. The approach provides the safest operational conditions for the RF generators at the expense of wasting a small fraction of the generated power during ELMs. Using the full potential of the 3dB hybrids as an ELM-tolerant system requires substantial relaxation of the VSWR protection limits in order to prevent the ELM-triggered power trips. Unfortunately, this contradicts the requirements of arc detection and increases the risk of antenna damage. Such concerns had slowed the initial progress in high power operations of the 3dB hybrids at JET [4] but after additional investigations, an acceptable compromise (VSWR=15) was found for the protection threshold in the lines between the hybrids and the stubs. This allowed trip-free performance during most types of ELMs, and the time-averaged power levels delivered by the 3dB hybrid couplers system into H-mode plasma has now reached 3.3 MW.

The commissioning of the ECT has quickly revealed its robust and reliable performance [5]. Simultaneous matching of all four ECT circuits has been successfully achieved under a variety of antenna loading conditions including vacuum, L-mode plasmas with 'sawtooth' activity and ELMy H-mode plasmas with mid-plane limiter-separatrix distances in the range of 4-14 cm. The implemented real-time control algorithms [8] have proven stable and effective during changing experimental conditions. The ECT has been fully commissioned at four frequencies of 32.5 MHz, 42.5 MHz, 46.0 MHz and 51.0 MHz covering the majority of JET operational scenarios. Most of the experiments were performed at standard $(0,\pi,0,\pi)$ phasing of the antenna straps; transition to alternative phasings, such as $\pm(0,\pi/2,\pi,3/2\pi)$ and $(0,\pi,\pi,0)$ has been found to be straightforward and since 2009 the ECT system has been routinely used during ICRF operations at JET. Experiments in ELMy plasma conditions have confirmed the expected high load-tolerance of the ECT system. In good agreement with simulations, the dependence measured during ELMs (FIG. 2) has demonstrated low sensitivity of the VSWR at the amplifier Output Transmission Line (OTL), to the antenna loading variation. During all types of ELMs, the OTL VSWR value has remained well below the VSWR protection trip threshold of 3 traditionally used at JET. This allowed trip-free amplifier operations and continuous power injection even during big ($\Delta W_{DIA}\leq0.7$ MJ) Type-I ELMs accompanied by strong changes of antenna resistive and inductive loading (FIG. 3). The observed momentary increase in the power levels coupled to plasma during ELMs (FIG. 3e) is explained by a reduction of power losses in the long transmission lines

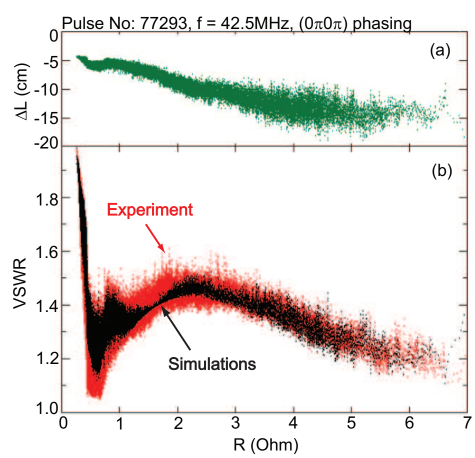

FIG. 2. ECT tolerance to antenna loading perturbations during ELMs: (a) Measured antenna strap equivalent length deviation from the vacuum value (measured)vs. loading variation (b) Measured (red) and simulated (black) VSWR at the amplifier output vs. loading variation; data for one pair of conjugated straps with 5μs sampling over 200 consecutive ELMs.

during high loading conditions. Depending on the JET discharge scenario, the trip-free time-average power levels delivered to ELMy H-mode plasma by the ECT system have reached 4 MW.

Simultaneous operations of the ECT and 3dB systems allowed to increase the total ICRF power coupled to ELMy plasma by all four A2 antennas to 7 MW. The ECT has been found slightly outperforming the 3dB hybrids in identical experimental conditions (e.g. see FIG. 4); this is explained by the peculiarities of the systems reactions to ELMs leading to opposite momentary changes of the power coupled to plasma and by higher flexibility of the ECT circuit in equalizing the voltages on the paired straps in presence of coupling asymmetries. Further progress in increasing the power levels injected into plasma by both systems requires more effort for antenna conditioning at voltages exceeding 30 kV.

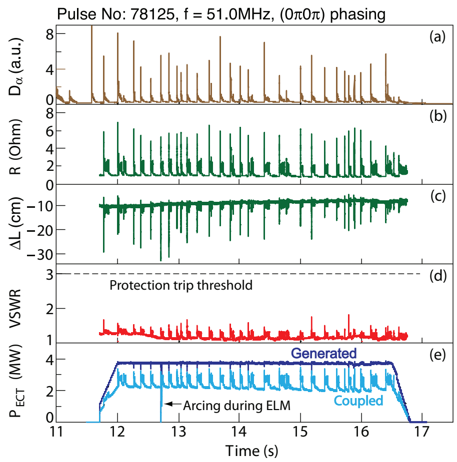

FIG. 3. ECT behavior during big ELMs: (a) mid-plane D_α line emission intensity, (b) antenna strap coupling resistance, (c) antenna strap equivalent length deviation from the vacuum value, (d) VSWR at amplifier output, (e) ICRF power generated and coupled. Plots (b), (c) and (d) are averaged values over the 4 ECT circuits; 5μs RF data sampling.

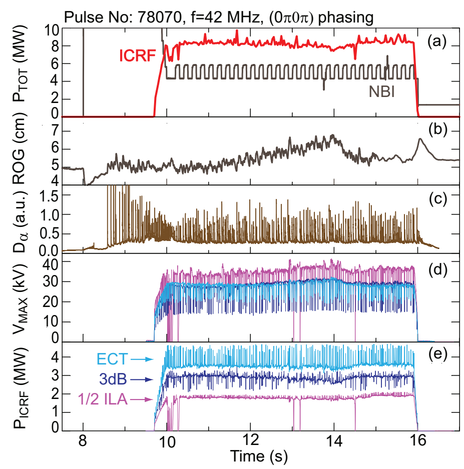

FIG. 4. Example of high power performance of the JET ICRF system during ELMy plasmas: (a) total ICRF and NBI power, (b) mid-plane distance between the separatrix and antenna limiters, (c) mid-plane D_α line emission intensity, (d) maximum voltages on the antenna straps of ILA, ECT and 3dB systems, (e) ICRF coupled power by the ILA, ECT and 3dB system

Finally successful implementation of ELM-tolerant matching revealed a new challenge to high-power ICRF operations in H-mode plasmas. Together with previously observed antenna breakdown at high voltages, occurrences of ELM-triggered arcs are suspected on both the ECT and 3dB systems despite substantial reduction of the voltages in conditions of high antenna loading during ELMs. Both simulations [8] and measurements [5] have shown that the traditional arc detection method based on observation of the VSWR in the matched transmission line is inadequate for the ECT antenna protection. A new Advanced Wave Amplitude Comparison System (AWACS) has been proposed [8] to cope with the problem. Unlike the VSWR protection, which monitors reflected and forward voltage amplitudes in the same line, the AWACS compares the voltages measured in different parts of the system, specifically, the reflected voltages at the amplifier OTL and the forward voltages in the mismatched lines on the antenna side of the T-junction. Such an approach appears to be highly sensitive to the loading asymmetry introduced by an arc in one of the conjugated antenna straps while it remains relatively immune to symmetric loading perturbations due to ELMs. The routine use of the AWACS at JET has so far proven highly efficient for arc protection of the ECT system [5]. As for the 3dB system, the existing dubious compromise between the VSWR requirements for the ELM-tolerance and arc protection still requires resolution by the introduction of new arc detection techniques.

3. The ITER-like ICRF Antenna

The ILA was installed on JET in 2007, commissioned on plasma from May 2008 to March 2009 and is presently not operational due to a capacitor failure that occurred early 2009. It has been partially removed (vacuum transmission lines) during the 2010 shutdown to avoid compromising JET's torus vacuum and a decision for a future repair is still outstanding. During this period, successful operation of the ILA on L- and H-mode plasmas was achieved at frequencies of 33 and 42 MHz (with a few pulses at 47 MHz) [6,7]. Up to 4.76M of ICRF power was coupled to L-mode plasmas (pulse 75329) and power density up to 6.2MW/m^2 (pulse 75370) were reached (2.80 MW from the antenna lower half for a total ILA Faraday Screen surface ~0.91m^2). This value is in the range of the one for the ITER ICRF system: 6 to 8 MW/m^2. An important question about operation at high power density was whether or not it would increase the impurity influx into the plasma due to RF sheath effects. FIG. 5 shows that the impurity influx from the ILA is in fact slightly lower than for the A2 antennas for comparable total power coupled [9] knowing that the ILA data pertains to 5-10 times higher power densities than that of the A2 antennas. Although there are objective differences between the A2's and the ILA's front face designs as well as electrical grounding to adjacent protective limiter structures that explain this result, it proves that high power density antenna's can be designed that do not imply a high impurity influx [10].

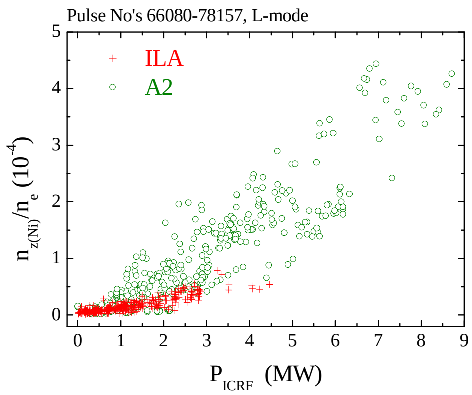

FIG 5. Correlation between Ni concentration (r/a ≈ 0.5–0.6) obtained with the horizontal VUV spectrometer (KT2) [8] for the ILA (+) and the four A2 (o) antennas as function of the total ICRF power applied.

On H-mode, the maximum coupled power was less than expected due a lower antenna coupling than was assumed during the design of the ILA. Also, RF power plant issues slowed down progress to achieving higher power or power densities before the aforementioned capacitor failure. A maximum coupled power of 1.88 MW was achieved (pulse 78070 from the ILA upper half, FIG. 4) with a power density of 4.1 MW/m^2. It is important to mention that coupling simulations performed recently using TOPICA code [11], which was not available at the time the ILA was designed, have been able to reproduce ILA coupling values obtained. Dedicated pulses were performed where the distance of plasma separatrix to the ILA straps was varied while measuring all relevant plasma density and temperature profiles. The good agreement between the modelled and measured values is illustrated on FIG.7 where the estimated error bars are also shown. The horizontal bars pertain to the uncertainties on the exact position of the separatrix while the vertical error bars pertain to the uncertainties on the RF voltage and power measurements. These JET results associated with results obtained on Tore Supra [12], DIII-D [13] and Alcator-C [14] allowed the validation of TOPICA in order to predict the performance of the ITER ICRF antenna. Finally, an analysis of the plasma profile data on JET compared to those predicted for ITER showed that the rather modest coupling obtained on JET is not inconsistent with the favourable coupling predictions for ITER using TOPICA [15].

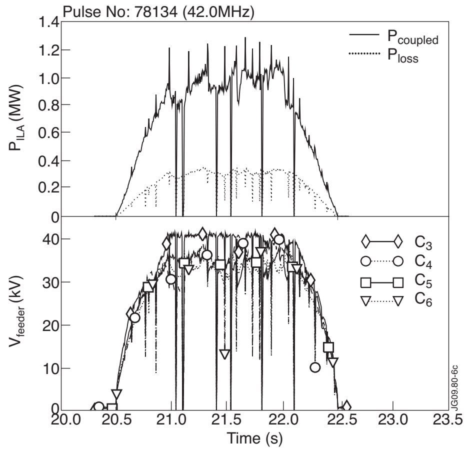

FIG. 6. Pulse JPN 78134. The feeder voltage on strap 1 (C_1) is limited at ~42kV limiting the power output of the amplifiers on this pulse with strong ELMs. During the ELMs, when the strap voltage is lower, the power output is raised to the requested value.

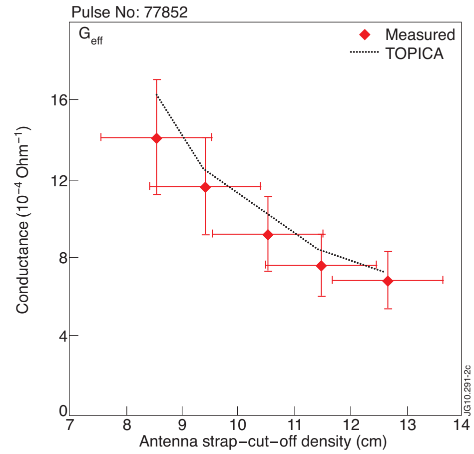

FIG. 7. Comparison of the measured and predicted coupling as represented by G_{eff} (a proportionality constant between the power coupled and the square of the system voltage)

As with the ECT, the T-junctions layout demonstrated tolerance to the load variation occurring during ELM (see FIG.4 and FIG. 8). By setting appropriate values of the impedance at the T-junction, Z_T, ($Re(Z_T)$~3Ω maximizes the load resilience properties while $Im(Z_T)$~-2 balances the voltages on the straps fed from the T-junction), and the impedance transformer, it was possible to keep the VSWR on the amplifier output transmission line below the level (2.7) at which the power is tripped for safety. The real-time tracking of the chosen Z_T values was done with a feedback control system on the 8 capacitors of the system [16] while the stub and trombone tuners constituting the impedance transformer were adjusted to optimal values using software tools in between pulses [17]. Except for cases with very low coupling (e.g. at 33 MHz and a high strap to plasma separatrix distance imposed by experimental necessities) the VSWR could be kept below the 2.5 for operation on either the upper or lower pair of RDLs. Nevertheless, the simultaneous operation of the whole antenna, particularly in H-mode, posed difficulties in its own right due to the power cross-coupled across the antenna front face. While full array operation is relatively easy to achieve on L-mode plasmas due to higher and quiescent loading, such operation in H-mode required a tight control of the phasing of

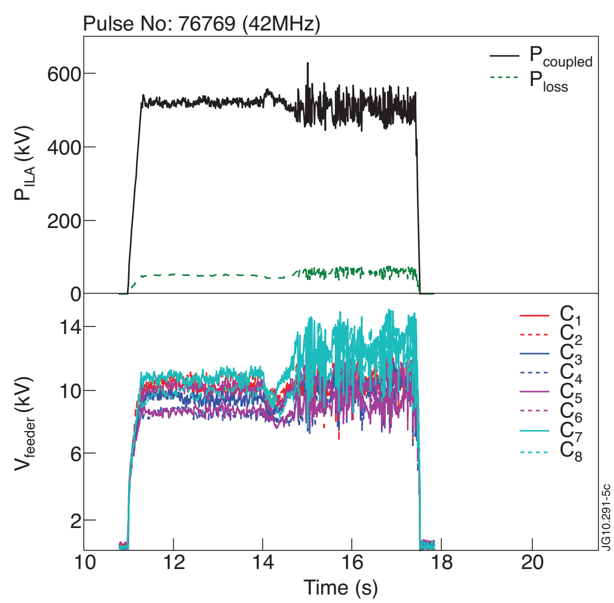

FIG. 8. ILA full array operation during and L-H mode transition (14.5s) and subsequent ELMy H-mode plasma.

the various straps with respect to each other (to minimise the cross-coupled power) as well as a careful setting of the impedances of the 4 T-junctions (to optimise the load resilience) and post pulse analysis software had to be used to converge on a shot by shot basis to the optimal settings for the impedance transformers. A successful example is represented on FIG. 8 at modest power levels. Unfortunately, the capacitor failure prevented further development and optimization for higher power on different plasma conditions featuring stronger ELMs.

As mentioned in section 2, an important aspect of the operation in H-mode, is the arc detection. Indeed, arcs occurring at low impedance points, in particular the T-junction set for ELM tolerant operation ($Re(Z_T) \sim 3\Omega$) do not significantly change the VSWR and hence traditional VSWR measurements in the feeding transmission lines are likely to fail detecting these arcs. Therefore, until a novel arc detection technique, referred to as Scattering Matrix Arc Detection (SMAD) [18], was fully commissioned only late in the program $Re(Z_T)$ had to be kept to 6Ω leaving load resilience characteristics less than optimal. In parallel another arc detection approach referred to SubHarmonic Arc Detection (SHAD) [19] was also tested.

Finally, the ability to operate an ICRF antenna reliably at voltage in the 40 kV range, was another critical aspect for the future ITER ICRF antenna, and that was successfully demonstrated on the ILA. Operation at maximum voltage of 42 kV was achieved easily and reproducibly on L- and H-mode. Note that it was decided to limit deliberately the maximum system voltage to 42kV using electronic feedback circuitry (FIG. 6) and not to exceed the voltages achieved on testbed. The maximum electric field in torus vacuum appears on the matching capacitor's corona ring connected to the strap's feeder and is 2.5 kV/mm at 42 kV in all directions with respect to the total magnetic field. Inspection of the extracted vacuum transmission lines carrying the matching capacitors did not reveal obvious traces of arcing or other damage in this area. A statistical analysis of all the ILA data assessed the reliability of high voltage operation. About 18% of the 1603 ILA pulses recorded on the ILA control computer (excluding pulses predating this recording and concerning the first low level ILA commissioning) fail due to causes not related to the antenna itself (test pulses for commissioning the arc detection, pulses disrupting before the RF pulse, RF plant issues, hydraulic plant and capacitor control issues, …). One can see on FIG. 9 that the quality factor, Q, calculated for the remaining 1309 pulses, and defined as the ratio of the delivered to the requested energy when the former has reached 97% of its total, does not degrade with increasing voltage and power.

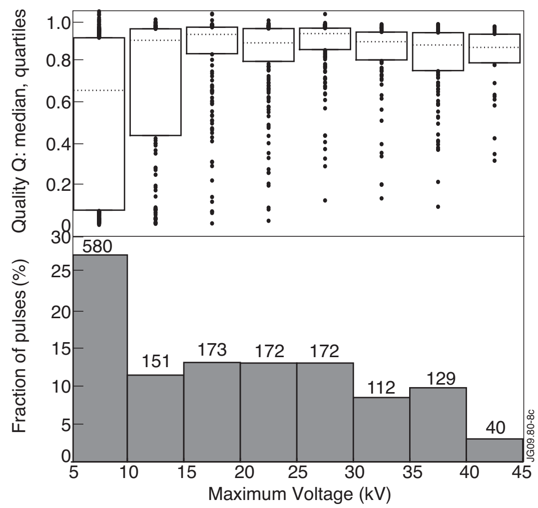

FIG 9. a) quality factor Q and (b) distribution of the number of pulses vs. antenna voltage. 50% of the pulses lie in the inter quartile's box while 50% of the pulses lie above the dotted median line shown in the box Q allows discarding the trailing part of pulses that fail due to either power supply issues, amplifiers not restarting correctly after a trip or a lost match and/or insufficient load resilience

4. Conclusions

The installation, commissioning and operation of the ILA and load resilient transmission line circuits feeding the JET's A2 antennae successfully culminated in a series of JET pulses with a record high level of ICRF power (~ 8.3MW) coupled to an ELMy plasma (see Fig. 4). The two alternative ITER-relevant external matching schemes that have been successfully implemented on the A2s antennas solved the problem of ELM-tolerant operations of conventional JET ICRF antennas. The demonstration of 7MW trip-free power injection by these antennas into ELMy H-mode plasmas considerably expands JET's research capabilities in this field. The performance of the ECT system has been found to compare favourably with the 3dB hybrids proving the viability of such a system. Antenna arcing during ELMs has been identified as an emerging challenge for load-tolerant ICRF systems; the AWACS approach developed for the ECT scheme has demonstrated adequate protection against this threat. The main objectives of the ILA with regard to ITER have been achieved: The ILA demonstrated operation at 42 kV and electric fields of 2.5 kV/mm regardless of their orientation with respect to the magnetic field 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 6.2 MW/m^2 in L-mode and exceeding 4 MW/m^2 in H-mode. It does not appear that these power densities which are substantially higher (~6.3 times in pulse 78070) than hitherto available on JET, cause any detrimental effects on impurity generation or loss heating efficiency. The matching on ELMs sometimes suffered from the low coupling in H-mode, but it was in general possible for operation on pairs of RDLs 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. An important aspect of the ILA endeavour has been the successful validation of the TOPICA coupling code allowing to favourably extrapolate the feasibility of the 20MW ICRF system planned for ITER.

Acknowledgements

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