EFDA–JET–CP(07)01–04

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** 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

The observation of parasitic low-VSWR activity during operations of JET RF plant and the damage caused by arcing at the voltage-node in the vacuum transmission line (VTL) in 2004 highlight the importance of the problem of low-voltage breakdown in the ICRH systems. Simulations demonstrate little response of the RF circuit to the voltage-node arcing which explains why it remains largely unnoticed and complicates the design of protection systems. Analysis of the damage pattern produced by the voltage-node arcing suggests that multipactor-related phenomena occurring at elevated voltage thresholds in conditions of unfavorable VTL geometry are most plausible arc-provoking factors.

INTRODUCTION

Arcing in vacuum components has always been a troublesome issue of high-power RF technology [1]; advances in load-tolerant matching schemes [2] turn it into one of the most critical problems of the ICRH system design. Until recently, the main concern has been over the high voltage breakdown [3] triggered by electron emission in presence of strong electric fields. While common enough, the high voltage arcing is relatively easy to detect - a short circuit created by an arc at high impedance point causes significant voltage redistribution accompanied by noticeable transients and mismatch. Breakdown at low voltage points is different in nature and it could leave the RF system almost unperturbed, which makes the arc detection much more difficult and increases the risk of severe damage. Some problems related to the ICRH system electrical strength at low voltage points have been reported lately [4, 5]. Evidence of these phenomena at JET and their understanding are summarized below.

SIMULATIONS OF RF SYSTEM RESPONSE TO ARCING

The main features of RF system responce to arcing at low voltage points can be illustrated by simulations of simplified matching scheme (Fig. 1) with an inductive short circuit representing the arc. Arcing close to a voltage node causes little change in the typical monitored RF parameters, such as the VSWR (Fig. 2(b)), the reflection coefficient's phase (Fig. 2(c)) or the delivered power (Fig. 2(d)), while it increases the apparent coupling resistance to high values (Fig. 2(e)). These factors could make the observation of such arcs, in particular in presence of ELMs, quite difficult. Because the voltage-node arcing doesn't strongly mismatch the system, the arc current (Fig. 2(f)) is higher and potentially more damaging as compared with the high-voltage arcing. Finally, arcing at the voltage node could cause over-voltages 'upstream' the arc (Fig. 2(g)) and so trigger a high-voltage breakdown in the line nearer the generator.

VULNERABILITY OF VACUUM TRANSMISSION LINE

Unlike ICRH antennae used on smaller tokamaks, JET A2 antennae [6] have long (>2m) vacuum transmission lines (VTL) exceeding the quarter-wavelength at the operational frequencies' midband which allows the voltage node location in vacuum. At the frequencies of 35-43MHz (depending on particular array strap and plasma loading) the voltage node position coincides with the VTL section where the inner conductor incorporates a pressurized (4 Bar abs.) bellow and the outer conductor has a Ø10cm side port. This part of the system proved to be particularly vulnerable to the low-voltage breakdown: in 2004 (Pulse No: 62608, f=37.2MHz) undetected voltage-node arcing caused a perforation in the VTL bellow leading to a major vacuum leak at JET. The analysis of the damage has shown that prior to the fatal failure, the area was exposed over a long period of time to a persistent but relatively low-destructive breakdown activity. The distribution of superficial discoloration and erosion in front and inside the side port suggests that multipactor-related phenomena played an important role in the localized degradation of the VTL electrical strength.

OBSERVATIONS OF PARASITIC LOW-VSWR ACTIVITY

According to simulations, the low-level VSWR perturbations in the matched section of line could be one of the few 'telltale' indications of voltage-node arcing. Examination of the RF data collected at high sampling rate during operations at troublesome frequencies of 37MHz and 42MHz revealed several instances of such events. Figure 3 gives an example of 'spiky' low-VSWR activity triggering a high- voltage (high-VSWR) breakdown followed by a protection trip during plasma operations with the line voltages over 30kV. The behavior of sub-harmonic voltage signal (Fig. 3(d)) is noteworthy - unlike the onset of the high-VSWR arc, the precursor generates very little noise which could be attributed to the absence of strong transients during low-voltage breakdowns. Extended parasitic activity accompanied by some VTL pressure increase was observed during commissioning of hybrid couplers [7] in ELMy plasma (Fig. 4). (Note that lines A2 and B2 are individually matched by stub tuners and fed by an amplifier through the 3dB coupler). The elevated coupling resistance values (Fig. 4(d)) recorded during the event deserve special attention.

MECHANISM OF LOW-VOLTAGE BREAKDOWN

A combination of interrelated factors (Fig.5) which enable and enhance multipactoring [8] at the vacuum voltage node during JET ICRH operations seem capable of creating the arc-provoking environment. Crucially, both the unfavorable VTL geometry near the side port and the electron stimulated gas desorption from the unbakable VTL bellow, accompanied by a multipactor plasma discharge [9] contribute to a noticeable increase of the upper voltage limit for sustained multipactor and bring it within typical voltage-node values (≥1kV). A further voltage surge (e.g. induced by an ELM) occurring at the voltage node on the adverse background can trigger an arc.

CONCLUSIONS

The experimental evidence of VTL voltage-node arcing at JET broadens the problem of electrical strength of ICRH vacuum components highlighting the role of low-voltage breakdown. Relatively little response of RF plant to the voltage node arcing explains why it remains largely unnoticed and complicates the design of protection systems. Multipactor-related phenomena occurring at the elevated voltage thresholds in conditions of unfavorable VTL geometry and electron-stimulated gas desorption seem to be plausible factors in provoking arcing at low RF voltages.

ACKNOWLEDGMENTS
The work was performed under the European Fusion Development Agreement and funded by the UK Engineering and Physical Sciences Council and by EURATOM.

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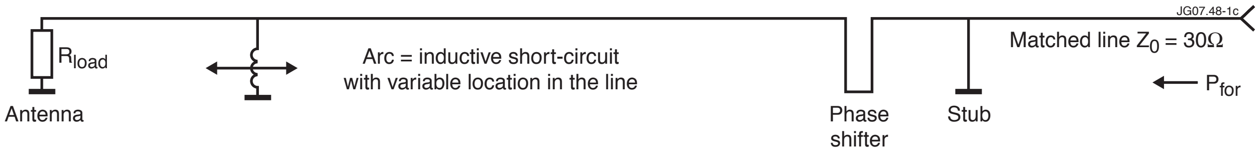

Figure 1: Equivalent circuit used during simulations of RF system response to arcing.

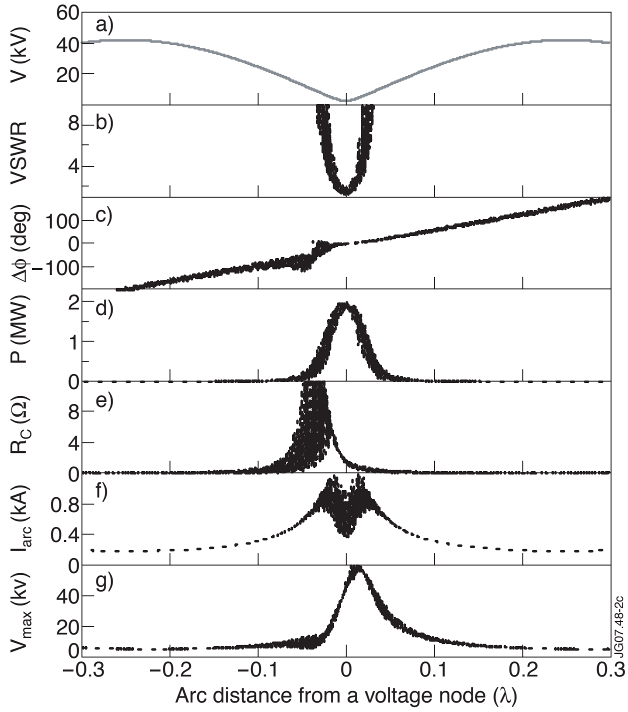

Figure 2: Simulations of RF system response to arcing at different locations in the line; P_{for} = 2MW, R_{load} = 2Ω, f = 42MHz. The arc inductance is randomized in the 10-30nH range. The horizontal axis represents the distance from a line voltage node expressed in terms of the line wavelength. The vertical axes correspond to (a) line voltage amplitude before the arc, (b) VSWR in the line on the generator side of the stub tuner, (c) reflection coefficient phase change in the line on the antenna side of the stub tuner, (d) RF power delivered to the antenna load, (e) coupling resistance 'seen' by the stub tuner, (f) arc current amplitude and (g) maximum voltage amplitude in the line 'upstream' the arc.

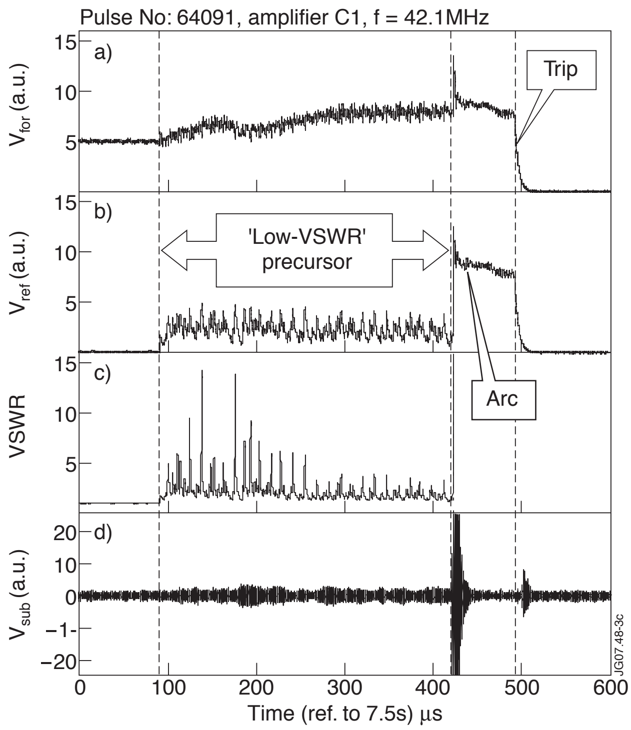

Figure 3: High-voltage arc with low-VSWR precursor; 40MS/sec sampling rate: (a) and (b) respectively forward and reflected voltage wave amplitudes in matched line, (c) VSWR in matched line, (d) sub-harmonic (<15MHz) voltage noise in unmatched line.

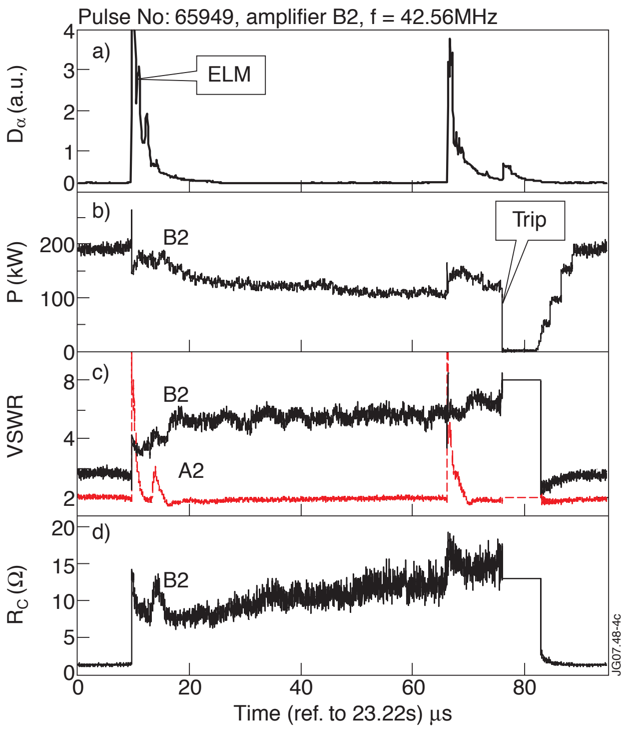

Figure 4: Parasitic low-VSWR activity triggered by an ELM; 10kS/sec sampling rate: (a) intensity of Dα line emission from plasma, (b) RF power delivered to line B2, (c) VSWR in matched sections of lines A2 and B2, (d) coupling resistance 'seen' by B2 stub tuner.

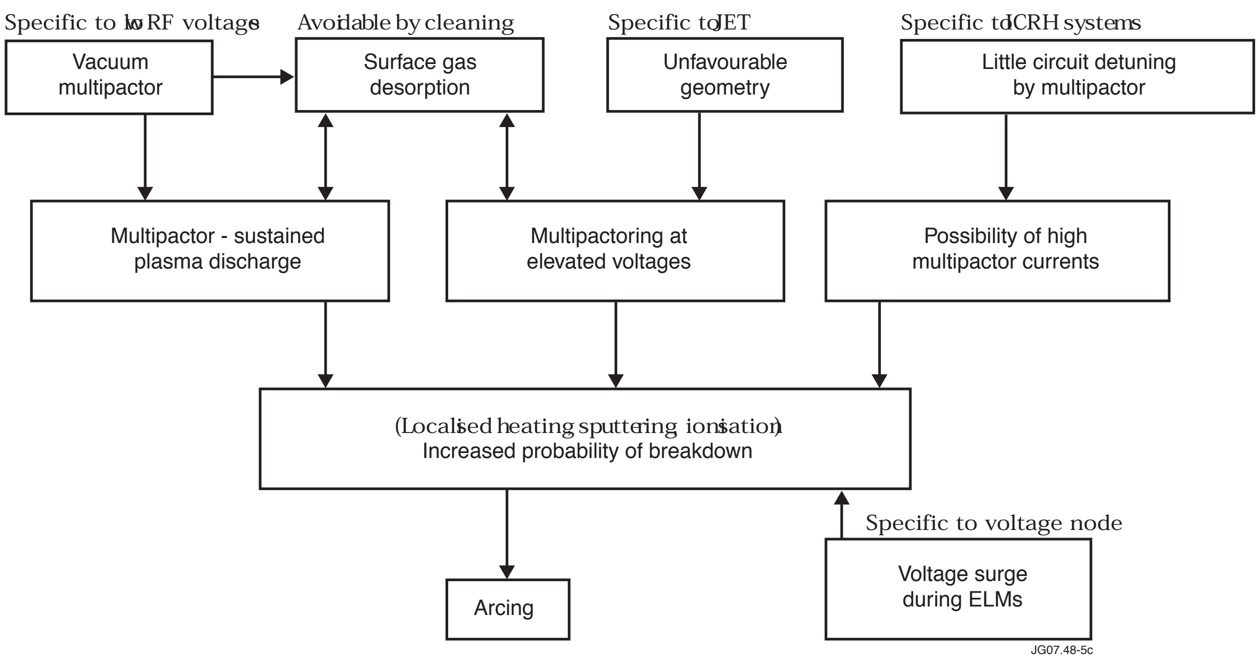

Figure 5: The interplay of various phenomena contributing to development of voltage-node arcing.