Experiments on Minimizing ELM-induced Fast Wave Antenna Breakdown in DIII-D

R.I. Pinsker[1], T.E. Evans[1], F.W. Baity[2], P.M. Ryan[2], and J.C. Hosea[3]

[1]*General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA*
[2]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[3]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA*

All present-day fast wave (FW) antennas operating into H-mode plasmas encounter a limit in coupled power set by antenna breakdown. This limit is due to the low antenna/plasma coupling characteristic of H-mode plasmas with a large antenna/plasma distance ("outer gap"), which leads to high antenna rf electric fields that exceed the dielectric strength of the antenna parts immersed in the far scrape-off layer (SOL) plasma. As previously observed by the AUG [1] and DIII-D [2] groups, this problem is aggravated by large edge localized modes (ELMs): the arrival of an ELM at the antenna can substantially reduce the voltage at which breakdown occurs. This issue has been addressed experimentally in three ways at DIII-D. An approach to this problem, suggested by previous work on AUG and DIII-D, is to reconsider the use of a nearly optically-opaque Faraday screen (FS) to reduce the ELM-induced plasma density and ultraviolet light around the antenna elements. A second approach is to stabilize the ELMs with resonant magnetic perturbations (RMP) [3], since it may be that large ELMs are intolerable in ITER and future devices for other reasons in any case. Thirdly, the physics of the antenna breakdown mechanism has been studied at extremely high time resolution (data sampling rates up to 1 GHz). This work may lead to new antenna arc prevention and mitigation measures.

1. Nearly Optically-opaque Faraday Screen

The oldest of the three antenna arrays on DIII-D, known as the "285/300" antenna, has been used since 1990. Several different FS configurations have been used [4]: initially, a double-layer horizontal screen was used, with two offset rows of round bars. This screen was replaced with a slanted (12 deg from the toroidal direction) single-layer screen which was used with several different coatings [4]. Recently (since 2006) the original double-layer FS was reinstalled. The purpose of this revival of the double-layer FS was specifically to test the following hypothesis: the observed depression of the maximum achieved rf voltage standoff with increasing density in the far SOL is due to plasma and/or light entering the antenna structure and reducing the dielectric strength below the nominal 15 kV/cm parallel to the static magnetic field. The greater opacity of the double-layer FS should therefore permit higher rf voltage to be reliably sustained in the presence of the substantial density pulses at the antenna from large ELMs. Since the distance between the antenna elements and the rear surface of the screen is kept at 1 cm in all of the FS geometries tested on DIII-D and the plasma-facing surface of the FS is maintained at a constant major radius in all cases, the thicker the screen, the greater the antenna/plasma distance for a fixed "outer gap". Therefore we expect for a given plasma geometry and conditions a lower maximum coupled power level will be obtained with the thicker double-layer FS for a given maximum voltage. The most important quantity is the peak antenna voltage that can be sustained experimentally; if the peak electric field that can be sustained increases with shield opacity, a future FS may be developed that is both opaque and nearly as thin as the single-layer open screens that have been used so far.

Operation of the 285/300 array in 2006 and most of 2007 was compromised by some technical faults (imperfect alignment, damaged surfaces) in the vacuum transmission lines connecting the four vacuum feedthroughs to the four antenna elements, which were corrected in autumn 2007. Upon resumption of antenna vacuum conditioning in December 2007, the design level of 30 kV peak in the antenna in vacuum was recovered. The first attempt to operate the antenna into an ELMing H-mode in January 2008 (P_{nbi} = 9 MW, I_p= 1 MA, gap from the FS surface to the separatrix = 12.5 cm) resulted in successful arc-free rf pulses 1.8 s long at antenna voltage between ELMs of V_{max}= 28 kV (Fig. 1). The ELM frequency varied between 80-100 Hz depending on the up/down magnetic balance, which was varied during these discharges. Due to the very low coupling resistance between ELMs, the net power to the antenna was 0.45 MW, and the coupled power was only half of the net power. The net power at the peak of an ELM was 0.9 MW, of which ~90% was coupled. The time-averaged net power was 0.6-0.75 MW, depending on the ELM frequency and character. The peak voltage between ELMs is a record high value for an arc-free pulse for this particular antenna array in the presence of tokamak plasma. At slightly higher antenna voltages (close to 30 kV), frequent arcing occurred either at or just after the onset of an ELM, indicating that even with the nearly closed FS, ELMs can still trigger arcs in the antenna, albeit at higher voltages.

A possible effect of boronization of the vacuum vessel (including the plasma-facing surfaces of the FS) was observed, in that the above results were obtained just after a boronization; a degradation of the voltage standoff was observed in the subsequent months. Particularly noticeable was a decline in the standoff after 0.1-0.2 s into the rf pulse. Another boronization in May 2008 appeared to restore the good standoff. Sensitivity to the history of the plasma-facing surface implies that the recycling properties of the parts of the antennas near the plasma may be important.

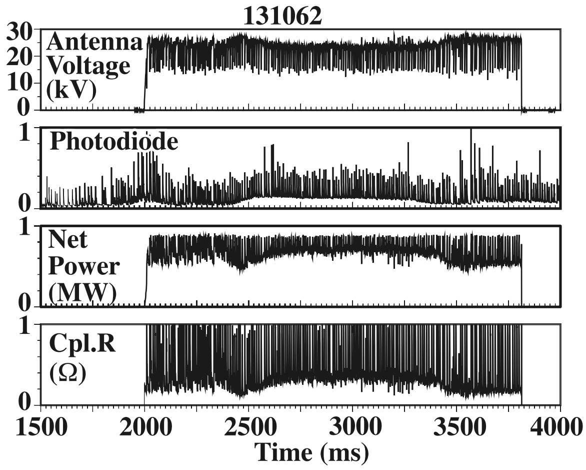

Fig. 1. Arc-free operation of the 285/300 antenna array at up to 28 kV peak in a vigorously ELMing H-mode. From top to bottom, time histories of peak antenna voltage, the D_α light from the edge of the plasma, the net 60 MHz power level applied to the array and the coupling resistance per antenna element are shown.

2. Operation in Different Regimes With Fixed FS Geometry

The 285/300 antenna array was designed (in 1989) to operate at up to about 30 kV peak, and to couple up to 2 MW to plasmas that provided coupling resistance of about at least 1 Ω per array element. Sufficiently large coupling resistance is readily obtained in L-mode plasmas with a small outer gap. However, experience shows that the achievable voltage limit tends to drop with smaller outer gap in L-mode, so that the maximum coupled power levels of ~1.6 MW have been achieved at peak voltages of 18-22 kV and loading resistances of 1.25–1.5 Ω per array element. Advanced Tokamak (AT) plasmas of practical interest generally provide much lower coupling resistance, due to the H-mode edge (very low SOL density between ELMs) and the large outer gap (6-10 cm) that is typically used with high neutral beam heating power levels. Recent data in the AT regime shows that the 285/300 antenna array would need standoff of over 60 kV in the presence of plasma to couple 1 MW between ELMs with an outer gap of 7.4 cm (FS surface-to-separatrix clearance of 11 cm). Data obtained by reducing the outer gap during the rf pulse shows that even at an outer gap of 3.4 cm, standoff of 38 kV between ELMs would be necessary to reach a coupled power of over 1 MW. Due to the decrease in standoff voltage with increasing plasma density in the far SOL, it is not clear that even this relatively modest extrapolation from the 28 kV standoff between ELMs obtained with the 9 cm outer gap is plausible.

Since some ELM control will likely be required in ITER and future tokamaks in any event, it is necessary to study antenna loading and obtainable voltage standoff in plasmas with acceptable ELMs, such as QH mode or with RMPs. We have successfully applied a net FW power of up to 1.7 MW at 90 MHz and 60 MHz to discharges in which ELMs have been suppressed with RMPs, as shown in Fig. 2. In this case, most of the FW power is coupled with the other two 4-element arrays on DIII-D, which have open single-layer Faraday screens. Even with the open FS, antenna breakdown is not observed as long as the ELMs are suppressed. Central electron heating is observed, with a clear break-in-slope of the central ECE channels upon the turn-on of the FW power, until the onset of n=1 MHD activity which then leads to a sawtooth crash. Detailed studies of the relationship between central FW heating and the onset of sawteeth will be carried out in future experiments.

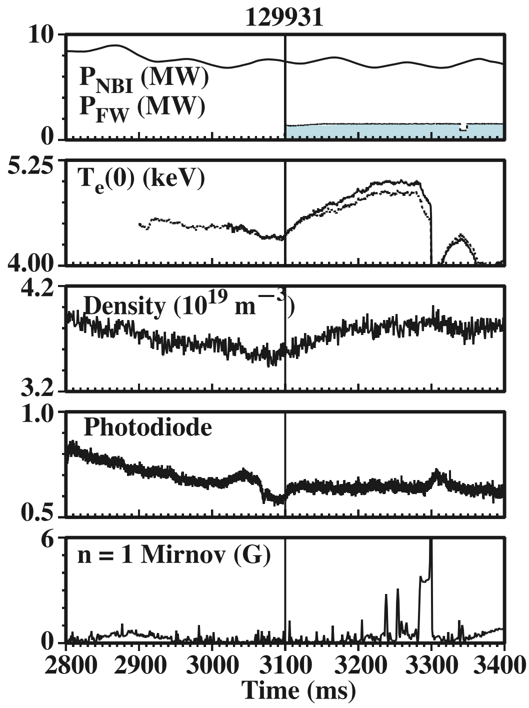

Fig. 2. The first 0.3 s of the FW pulse into an H-mode in which ELMs have been suppressed with RMP. The top trace shows the neutral beam and the total FW power, the second trace shows the central electron temperature from ECE (2 channels), the third trace, the line-averaged density, the fourth trace, an edge D_α signal, and the bottom trace, n=1 Mirnov signal.

3. Studies of Antenna Behavior at Ultra-High Time Resolution

Study of the behavior of antenna loading at the microsecond time scale has been previously reported from JET [5], using a data acquisition system at a maximum sampling rate of 0.25 MHz to study the effect of ELMs on antenna loading in detail. We have recently commissioned a data acquisition system capable of simultaneously digitizing four channels at a sampling rate of up to 1 GHz, with the primary motivation being to observe arc precursors on the rf timescale (rf period ~ 17 ns) Data with this system was obtained by directly recording the rf signals from directional couplers using a pair of synchronized National Instruments (NI) PXI-5152 digitizers with 128 MB of onboard memory. To study arc precursors, the same signal that is sent to the transmitter to initiate an rf blanking period upon detection of an arc (from the change in standing wave ratio in the transmission line) is used as a stop trigger for the fast digitizers, with mostly pre-trigger samples.

An illustration of the first application of this ultra-fast digitizer is shown in Fig. 3, in which data from the last 5 ms of an rf pulse that terminated in an arc is shown. The data in the uppermost four traces is obtained with a conventional set of amplitude detectors and digitizers at a 5 kHz sampling rate. In this case, 30 kV peak antenna voltage is sustained for 8 ms in an ELM-free H-mode with an outer gap of 5.3 cm. The turn-off of the rf at the time of the arc, at 4.268 s into the discharge, is faster than the detectors can reproduce, due to anti-aliasing filters on their outputs with a low-pass filter with a cut-off frequency of 5 kHz. The fast system captured the 200 microseconds around the time of the arc, and the amplitude of the directly recorded version of the rf signals shows a very fast decrease in reflected power on side "A" as the first event prior to the detection of an arc a few microseconds later (time zero on the plot). An enlargement of the raw signals in the 200 nanoseconds at the beginning of the arc shows that the drop in reflected signal on side "A" occurs within a few cycles of the 60 MHz rf; the apparent speed of this decline is limited by 100 MHz cutoff low-pass filters in the rf signal path. These filters will be removed in the next set of measurements, allowing meaningful analysis in software of these signals at up to 500 MHz (up to 9th harmonic of the applied 60 MHz).

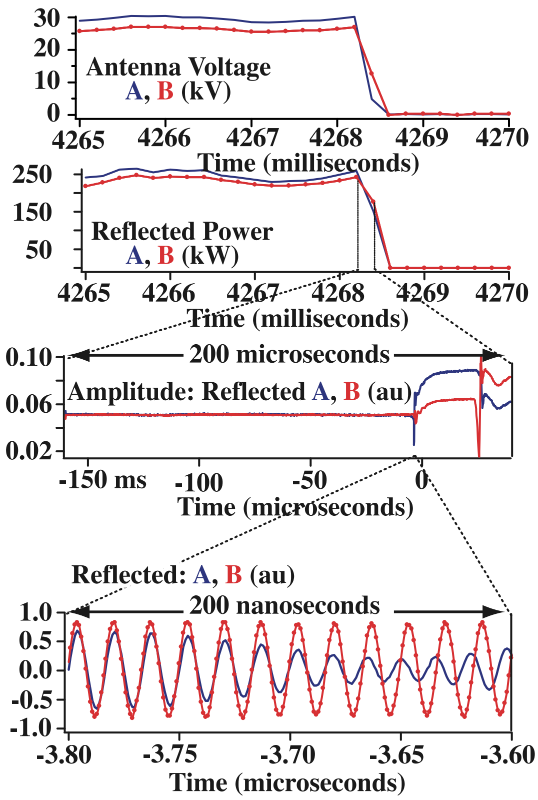

Fig. 3. Illustrating the first application of the ultra-high-speed data acquisition system to study an antenna arc into an H-mode plasma at 30 kV peak antenna voltage at the millisecond, microsecond, and nanosecond timescales. The arc begins on side "A" of the system a few microseconds before it is detected and the generator commanded to shut down.

Similar data has been obtained on antenna arcs in the absence of plasma loading (in vacuum). Future detailed analysis will compare the characteristics of antenna arcs in the absence of plasma loading to those seen with plasma loading of various levels (high loading from L-mode plasmas with small outer gaps, lower loading in H-modes with various outer gaps, arcs induced by ELMs, etc.) The ultra-high speed system will also permit further study of antenna loading during ELMs at unprecedented levels of time resolution.

This work was supported by the US Department of Energy under DE-FC02-04ER54698, DE-AC05-00OR22725, and DE-AC02-76CH03073.

References

[1] J.-M. Noterdaeme, *et al.*, in Radio Frequency Power in Plasmas (Proc. 15th Top. Conf., Moran, Wyoming, 2003) (AIP, New York, 2003) p. 154.

[2] R.I. Pinsker, *et al.*, Proc. 31st Euro. Conf. on Controlled Fusion and Plasma Phys., London, 2004, Vol. 28G (European Physics Society) p-2.175.

[3] T.E. Evans, R.A. Moyer, K.H. Burrell, *et al.*, Nature Physics **2**, 419 (2006).

[4] R.I. Pinsker, Fusion Sci. Tech. **48**, 1238 (2005).

[5] I. Monakhov, et al., in Radio Frequency Power in Plasma (Proc. 15th Top. Conf., Moran, Wyoming, 2003) (AIP, New York, 2003) p. 146.