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Journal of Nuclear Materials 313–316 (2003) 956–961

journal of nuclear materials

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Influence of the plasma on ICRF antenna voltage limits

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Abstract

An ion cyclotron range of frequencies (ICRF) probe [F.W. Baity, G.C. Barber, V. Bobkov, R.H. Goulding, J.-M. Noterdaeme, D.W. Swain, in: 14th Topical Conference on Radiofrequency Power in Plasmas, Oxnard 2001, AIP Conference Proceedings 595, AIP, Melville, NY, 2001, p. 510] has been implemented to study voltage stand-off of the ICRF antennas on ASDEX Upgrade (AUG). The probe was operated at first in a test stand where features of high RF voltage operation in vacuum and plasma created by an ion source of the Hall type [Plasma Sources Sci. Technol. 8 (1999) R1] were studied. Vacuum arcs as well as ignition of high voltage glow discharge are candidate processes to explain voltage limits of the ICRF antennas. The setup on AUG was used to expose high RF voltages in real conditions of the tokamak scrape-off layer which are faced by the ICRF antennas. It is found that high voltage breakdown on the ICRF antenna is often correlated with ELM activity. The maximal RF voltage increased from shot to shot, i.e. the conditioning effect is observed. For the good-conditioned ICRF probe it was shown experimentally that the voltage limit can be increased while the rectified current is suppressed at the same time.

Keywords: ICRF antenna; ASDEX Upgrade; RF high voltage breakdown; Voltage stand-off; Scrape-off layer

1. Introduction

Power launched by the ion cyclotron range of frequencies (ICRF) heating system is proportional to the square of the voltage on the ICRF antenna. The voltage is often limited by the plasma presence when all other factors are eliminated. The voltage limits are studied to increase the power launched by the ICRF antennas. For experimental studies of the voltage limits a well-diagnosed ICRF probe (high voltage breakdown tester) is used [1].

2. Experimental concept

The concept of the setup is presented in Fig. 1. The ICRF probe is the open end of a resonant coaxial line to model the antenna high voltage region. The probe has only one voltage value simultaneously exposed to the scrape-off layer (SOL) plasma while the ASDEX Upgrade (AUG) ICRF antenna has a range of voltages from zero to the maximal one facing the plasma.

The outer conductor of the ICRF probe is a 3 mm thick tube with outer diameter of 89 mm. The inner conductor has a diameter of 55 mm. The RF conductors consist of stainless steel components. The corresponding characteristic impedance of the coaxial line is 25 Ω. Matching of the probe is realized by a frequency change and adjusting the movable short. For the $5\lambda/4$ resonator a frequency of 51.52 MHz is used. The high-Q circuit ($Q = 230$ in vacuum) is used to achieve high voltage near plasma boundary for moderate input RF power. However Q value is about 20 times higher than that for the ICRF antenna during operation with the plasma.

An inner DC-break (capacitor for the inner conductor) allows for a control of the DC boundary condition for the inner conductor. The cables from the inner conductor are connected through the movable short. RF

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PII: S0022-3115(02)01396-X

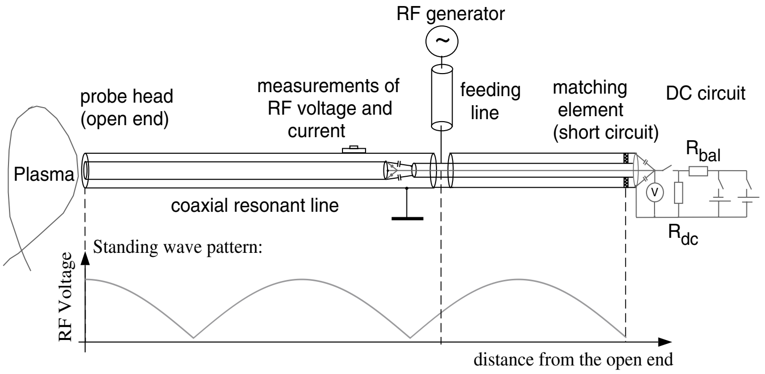

Fig. 1. Concept of the ICRF probe experiment.

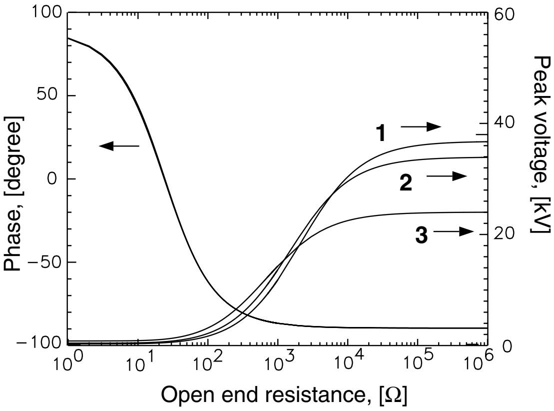

Fig. 2. Sensitivity at the point of measurements for 300 kW net power. Voltage curves: 1 – system matched for 1 MΩ, 2 – system matched for 5 kΩ, 3 – system matched for 1 kΩ.

voltage and current probes mounted on the resonant line allow for the voltage and phase measurements. A fast data acquisition (500 Msamples/s, BW 150 MHz) can sample RF signals directly and makes time-resolved phase measurements possible. For a model with constant stray capacitances, voltage and phase depend on the open end resistance according to Fig. 2. Values of RF voltage depend strongly on the matching position. The phase has a low sensitivity to a change of the load resistance. However we are interested in the effects connected to the change of the load resistance by orders of magnitude (transition to RF glow discharge, RF sustained arcing).

3. Measurements in test stand

The probe was initially mounted in a test stand without magnetic field. A 6-inch tube was used as a vacuum vessel and a Hall-type ion source was used as a plasma source. Ions are accelerated by the anode layer of the axisymmetric discharge in crossed electric and magnetic fields [2]. The discharge exists in the circular electrode gap with a 10 cm diameter and a 4 mm thickness. The tubular ion beam was injected perpendicular to the open end of coaxial line. The mode of operation allowed to have ion energy distribution function close to Maxwellian with the maximum number of ions at about 30% of accelerating voltage. The measurements of ion saturation current by a Langmuir probe near the ICRF probe head were made. The Langmuir probe was collecting the beam ions. For the plasma density estimation the value of electron temperature was substituted by the energy corresponding to the maximum of the initially known ion energy distribution function.

The probe was conditioned in vacuum ($p < 10^{-4}$ Pa) by high power pulses to reliable operation with 60 kV, 200 ms or 80 kV, 20 ms pulses. During conditioning vacuum arcs appeared at lower voltages.

At the voltage higher than 40 kV field emission dark currents in vacuum could be observed by a positive DC self-bias on the inner conductor. The reason for the biasing lies in the asymmetry of the coaxial system. With the Fowler–Nordheim formula [3] one can easily prove that the electron current emitted by the inner conductor in RF half-period is larger than the one by the outer conductor. The asymmetry was further increased by mounting the cone-like tips on the inner conductor with the local field amplification factor ≈ 7.5.

Ignition of a self-sustained glow discharge followed the Paschen curve. The conditioning was made by glow discharge in He. This increased significantly the threshold He pressure for the ignition from the initial (unconditioned) value. The pressure required to ignite the discharge in He before the conditioning at 80 kV was $p_{\mathrm{He}} = 0.5$ Pa. After the conditioning the threshold pressures were $p_{\mathrm{He}} = 2$ Pa for He and $p_{\mathrm{air}} = 0.18$ Pa for air.

Operation of the ion source did not affect the voltage stand-off until the pressure was increased. At pressures

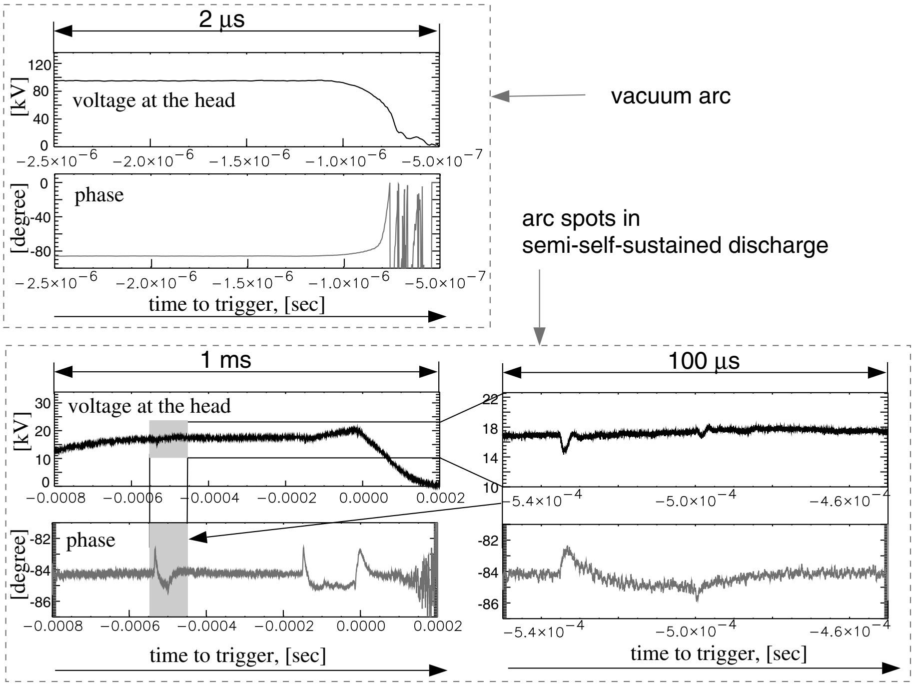

Fig. 3. Arcing phenomena in vacuum and in semi-self-sustained RF discharge.

of $p_{\mathrm{He}} = 0.15$ Pa and $p_{\mathrm{air}} = 0.03$ Pa, and corresponding plasma densities $n_e^{\mathrm{He}} = 9 \times 10^{14}$ m^{-3} and $n_e^{\mathrm{air}} = 2 \times 10^{15}$ m^{-3} the so-called semi-self-sustained RF glow discharge was ignited. No resolvable dependence of the threshold pressure on the voltage applied was observed. Both with and without ignition of the discharge the inner conductor collects negative charge, as expected from the RF sheath theory in the asymmetrical electrode gap [4].

In the semi-self-sustained cathode spots appeared at RF voltage higher 5 kV. Furthermore for the voltage lower 20 kV the cathode spots are self-suppressed and do not evolve into a quasi-stationary arc discharge. In Fig. 3 voltage and phase measurements for this effect are shown together with the measurements for vacuum arc. Vacuum arc develops in 100–300 ns while the spots in the RF semi-self-sustained discharge have a characteristic time of formation from 1 to 3 µs. The damage of the electrodes was observed to be single points for vacuum arc and arc tracks (spread erosion) for cathode spots in the RF discharge.

4. Results from ASDEX Upgrade

The ICRF probe was designed to be mounted on AUG midplane manipulator. The manipulator, situated at the low-field side (as well as AUG ICRF antennas), was used to reach the same radial positions as the ICRF antenna strap (~3 cm behind the antenna limiter).

The breakdown voltage was measured by making a linear power ramp. Two types of ramps were used: from 0 to 750 kW in 50 ms and from 0 to 750 kW in 300 ms. Since the system dissipates the energy mostly as intrinsic RF losses the matching position changes during the pulse due to surface heating (skin effect). The matching is adjusted to have minimum reflected power in the middle of the power ramp (RF voltage of about 50 kV peak).

Voltage limitation by the plasma presence is observed. The breakdown correlates with ELM activity, in particular with type I ELMs, for the most of the pulses. Typically achievable voltage of 55 kV with plasma presence is higher than that for the AUG ICRF antennas (25–30 kV). The high Q of the ICRF probe (it is close to the vacuum value in ELM-free phases) leads to the relatively high sensitivity of the probe mismatch to the load changes during ELMs. In other words the RF voltage at the probe head may decrease significantly during ELMs and change the dynamics of the breakdown compared to the ICRF antenna. However the relative change of the voltage during type I ELMs was typically only about 2 times higher for the probe than for the antenna. For the most of the cases during ELMs, the voltage on the probe exceeded the voltage on the antenna which operates at the critical voltage values in the similar conditions.

In Fig. 4 voltage stand-off in AUG discharges and in vacuum is shown. On the x-axis of the figure the voltage

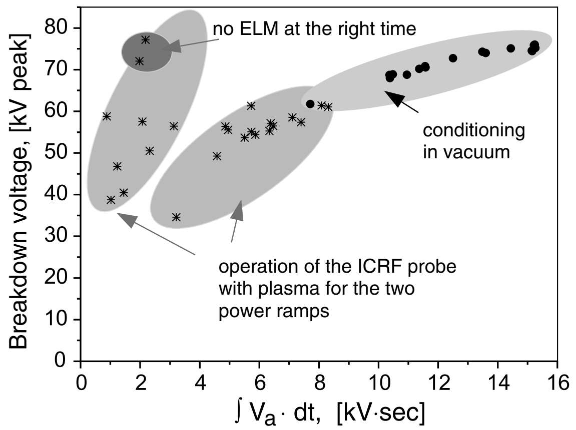

Fig. 4. Operation of the ICRF probe in vacuum and plasma. Stars – maximum voltage limited by plasma, circles – the voltage during conditioning in vacuum. Earlier measurements correspond to the lower voltages for the majority of the points.

exposure parameter $\int_0^{t_b} V_a \,dt$ is used where V_a – amplitude value of the voltage, t_b – time of the breakdown counting from the ramp start. The fast power ramp duration is of the order of only a few typical ELM periods. Thus the voltage limit associated with the ELM appearance can be overestimated, because it is probable that there is no ELM at the time when the voltage on the probe corresponds to the limit. The second, slower power ramp is better suited for the measurements of ELM-correlated RF breakdown, though additional measures are applied to control gas desorption in the vacuum lines.

The remark should be made for the most of the points in Fig. 4: the early measurements correspond to the lower voltages. The conditioning effect in vacuum, as is presented in the figure, can be observed in the beginning of each day of operation. For the operation of the ICRF probe in AUG plasma, the voltage stand-off in vacuum was sustained at the level higher than 75 kV. This was realized by intense high voltage conditioning between AUG discharges. One observes the conditioning effect for the maximal voltage in the presence of the AUG SOL plasma. The conditioning effect with the plasma is more emphasised after the AUG torus opening, despite very intense conditioning in vacuum. Therefore the surface state is important for the breakdown caused by ELM activity, and even intense conditioning of the probe in vacuum has a little influence on the maximal voltage in the presence of plasma.

Variations of the distance between the ICRF probe head and the limiter (from 2.5 to 4 cm) do not affect the voltage stand-off noticeably if the breakdowns on the probe are triggered by type I ELMs. For the specific experiments (see below) the AUG discharges with edge optimized configuration (EOC) characterized by relatively small distance (≈2 cm) between the separatrix and the antenna limiter were used.

In Fig. 5 the influence of SOL plasma in EOC discharge on the probe measurements and breakdown is presented. The rectified current registered with DC load resistance of 10 Ω is positive and follows the changes of the edge plasma. The current can rise to few amperes during type I ELMs. The sign of the current is opposite to the expected current based on the RF sheath theory and the real electrode asymmetry in the AUG discharge (where magnetic field is essential) found from DC voltage–current characteristic measurements. The hypothesis is proposed to explain the phenomena: the front surface of the inner conductor head of the ICRF probe serves as an ion collecting area. The estimation of the electron to ion flux ratio to the front surface can be made via a ratio of the electron to ion displacements across the magnetic field:

$$\frac{d_{e,\perp}}{d_{i,\perp}} = \frac{m_e}{m_i}\frac{\omega_0^2}{\omega_{ci}^2} \ll 1, \tag{1}$$

where $d_{e,\perp}$ – electron displacement associated with the polarization drift, $d_{i,\perp}$ – ion displacement in vacuum without magnetic field as an estimation for the case of the high voltages ($d_{i,\perp} \ll \rho_i$, ρ_i – ion gyroradius). The frequency of the ICRF probe operation $\omega_0 \approx 4\omega_{ci}$.

The phase transient of an arc in Fig. 5 after the ELM is similar to the cathode spot formation in the semi-self-sustained RF glow discharge and develops in a characteristic time of 2 μs. In the experiments with the ICRF probe the conventional ICRF antenna on AUG (normally used for heating) could be used as a RF pick-up probe and measure the power transmitted from the ICRF probe to the antenna. One of the directional couplers installed in the antenna resonant line was used for the measurements. In Fig. 5 the measurements of the power transmission are shown. The strong decrease in the transmitted power is observed during the ELMs. The decrease cannot be explained by a mismatch during ELMs (see net power signal which is on the same relative scale) or by mismatch of the antenna directional coupler.

A specific experiment was conducted to find out the influence of the DC biasing of the inner conductor on the voltage limited by the plasma presence. The probe was preliminary conditioned in vacuum and with plasma in 6 AUG discharges. A series of very similar consequent EOC discharges was made. For each discharge the same power ramp (from 0 to 750 kW in 300 ms) and a unique DC voltage were applied. The ballast resistance of 50 Ω was used. To minimize the influence of the probe conditioning (the maximal voltage increases from shot to shot) the DC bias was changed using a non-monotonic order of voltages for the series of AUG discharges. The measurements are presented in Fig. 6 showing that application of DC voltage affects the maximum voltage which correlates with the time-averaged rectified current. The

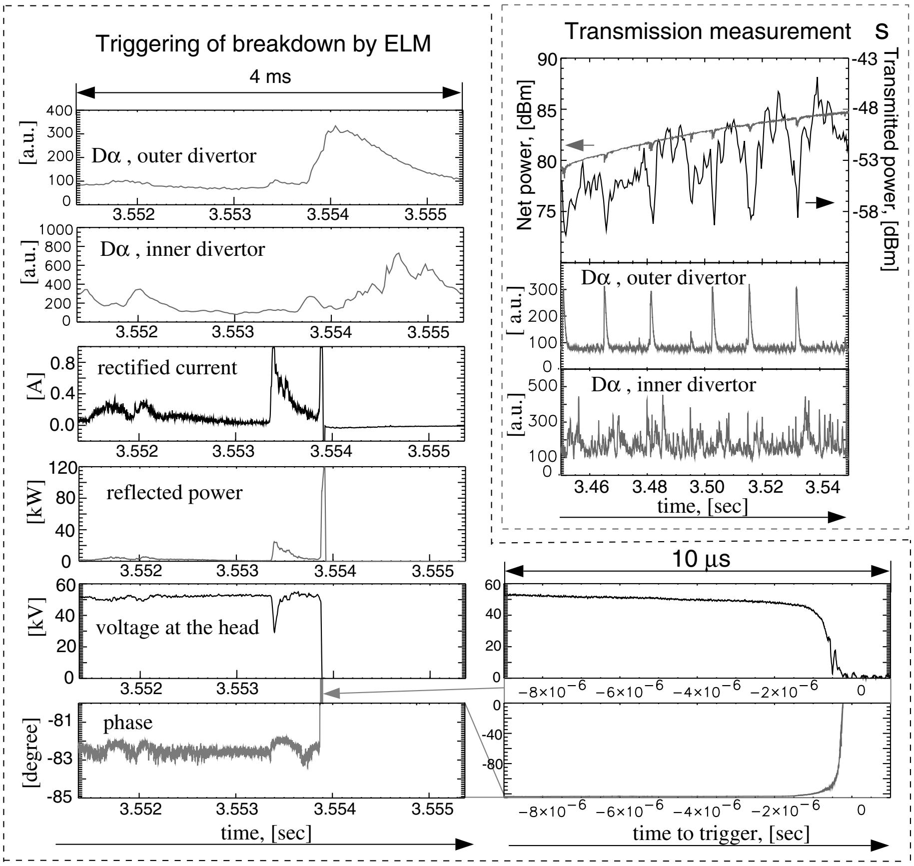

Fig. 5. Influence of the plasma in the SOL.

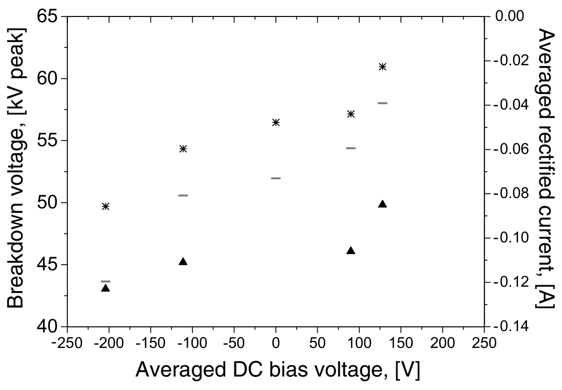

Fig. 6. Affecting the voltage stand-off by controlling the rectified current. Stars – voltage of the breakdown correlated with an ELM, lines – voltage corresponding to the previous ELM, triangles – rectified current averaged between the last two ELMs.

voltage limit of 55 kV without DC bias could be increased to 63 kV suppressing the rectified current and reduced to 49 kV increasing the current. Because of the finite ELM period, the real voltage limitation should lie between the voltages corresponding to the two last ELMs.

5. Conclusions

Measurements from the ICRF probe on a test stand and on AUG show that various breakdown mechanisms are the reason for the reduced voltage stand-off on the ICRF antennas in the presence of plasma. One of the most frequently observed phenomena is the breakdown following the transient change of the SOL plasma parameters in the tokamak, e.g. ELMs. A high loss of the power transmitted from the ICRF probe to the ICRF antenna functioning as a RF pick-up probe was observed during the ELM phase. The maximal voltage with the plasma presence increases by the probe conditioning with plasma.

It was shown experimentally that voltage stand-off of the good-conditioned probe with the plasma presence can be affected and correlates with the suppression of the rectified current. One can formulate few points for a concept of the ICRF antenna with an increased voltage stand-off:

- implementation of a new conditioning technique using a glow discharge inside the antenna;
- improvement of the geometrical shape of the antenna to increase the voltage stand-off in vacuum and to reduce the rectified current increasing the voltage strength in the presence of plasma;
- improvement of the vacuum conditions (pumping) for the ICRF antennas;
- design the antennas with varying DC boundary condition.

Acknowledgements

We would like to thank RF group of Oak Ridge National Laboratory (ORNL, USA), especially to Dr F.W. Baity, Dr D.W. Swain, Dr R.H. Goulding for cooperative work on the probe design and the problem in general.

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