EFDA–JET–CP(06)04–16

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** See annex of J. Pamela et al, "Overview of JET Results",*
(Proc. 20th IAEA Fusion Energy Conference, Vilamoura, Portugal (2004).

Preprint of Paper to be submitted for publication in Proceedings of the
SOFT Conference,
(Warsaw, Poland 11th – 15th September 2006)

ABSTRACT

A plasma torch aiming to assist the detritiation process of Tokamak tiles in gaps and zones with difficult access, like in the divertor regions was designed and built up. The torch operation is based on the expansion of a radiofrequency discharge constrained to burn in a limited space. The plasma torch is small size, flexible and compatible with mounting on a robotic arm, and can be operated stable both in argon and nitrogen at low and atmospheric pressure. The capability of source in cleaning surfaces was proved by experiments on material removal from graphite and CFC tiles.

1. INTRODUCTION

Tritium accumulation in walls is a limiting factor in efficient long term operation of fusion machines. The studies on the tritium trapping in Plasma Facing Components (PFC) have shown that a large amount of tritium is retained in the co-deposited layers [1]. A number of detritiation techniques are under assessment, like laser, discharge, flash lamp based cleaning which acts by removal of these layers and tritium desorption [2]. One of the encountered difficulties is the limited access of the detritiation tool in narrow spaces as inter-tiles or inside gaps, where an enhanced co-deposition and tritium trapping were observed [3]. This problem is expected to be enhanced for ITER because castellated armour consisting of cells separated by submillimetric gaps is proposed for divertor [4], in order to ensure thermo-mechanical stability.

This contribution addresses the problem of elaboration of a plasma torch as a tool appropriate for removal of co-deposited layers and stimulating detritiation in such spaces with difficult access and inside gaps. Accordingly, the requirements imposed to the plasma source were related to reduced size, reasonable power, compatibility with inside torus operation, large range of working pressures from vacuum to atmosphere, closed loop cooling, flexibility in order to allow scanning and mounting on a robotic arm. The approached design is based on a radiofrequency discharge constrained to burn in a limited space between an active radiofrequency electrode and a grounded nozzle, from where plasma expands outside as a directional beam. The found solutions have led to a flexible hand held plasma torch working stable in the 100 - 600W range of injected power and consisting of a cylindrical body of 20 mm diameter including the external water jacket embracing the discharge and an inside cooling circuit.

In the following the principle of source operation will be discussed first. Afterwards a description of the plasma torch will be given and the discharge characteristics will be presented. Further the obtained plasma jet is described by gas temperature measurements and optical emission spectroscopy. Finally, the experiments performed to asses the torch as tool for wall cleaning are presented and discussed.

2. PRINCIPLE OF PLASMA TORCH OPERATION

The discharge configuration used for the plasma jet generation is presented in figure 1. It consists of two electrodes facing each other, separated by a small gap (D) of 2-8mm. One of the electrodes is shaped as cylinder and is RF powered; the other is a plate shaped like a disk with a hole (d, 1-3mm) machined in its centre. An insulator ceramic tube holding its end on the plate surrounds the electrodes and defines inside an axisymmetric discharge chamber. The gas is admitted in the chamber through the other end of the tube, via a channel performed in the RF electrode holder. Without gas flow, at low pressure, the discharge is mainly sustained in the narrow gap delimited by the powered RF electrode and the plate [5]. Under gas flow operation the perforated plate plays a role of nozzle and plasma expands outside the interelectrodic space as a sub-atmospheric directional beam (Figure 2).

3. DESCRIPTION OF THE ATMOSPHERIC PRESSURE PLASMA TORCH

Some characteristics of this plasma source, operated at low pressure (10^{-2}-1 mbar) were presented and discussed before [6]. The low pressure RF plasma jet proved to be a useful tool for silicon-carbon interface construction [7] and for carbon nitride [8] or nanostructured carbon [9] thin film depositions. Later, the source was developed as a tool for assisting Pulsed Laser Deposition (PLD) of functional oxides [10].

The phenomena associated with the extension of source operation at atmospheric pressure are related to constriction of discharge with the pressure increase due to the thermal instabilities [11]. Such as, the volumetric plasma filling the interelectrodic gap transforms into a thin fast movable column (filament) of around 1mm diameter, which at intermediate pressures (~400 mbar for nitrogen) is stabilized by flow with one end on the inside of the nozzle hole. The column remains anchored in this position up to atmospheric pressure and even higher, constituting the ionizing source for the incoming gas flowing through the nozzle.

The observation that at high pressure the plasma volume does not make use of the whole interelectrodic space opens the way to realize small diameter sources, by designing configurations centered on the constricted plasma column axis. Nevertheless, there are other constraints which have to be considered in realizing a small size plasma source. The most important is related to heat dissipation, as a part of the injected power is dissipated via the plasma resistance and by recombination and processes at electrodes. Beside of choice of refractory electrode materials, ceramic or quartz tubing for insulator wall, a design considering active cooling of the discharge space is mandatory. Experiments were performed with a small size, 22mm diameter source manufactured in copper and with an external water jacket surrounding the insulating tube and the expansion nozzle. In this arrangement the source could operate stable in argon at atmospheric pressure, without electrode damage up to forwarded power values of 100W. For stable operation at higher power active cooling of the internal electrode was included. The image of plasma torch of 20 mm diameter, made in stainless steel and with internal and external cooling circuits, working in nitrogen at atmospheric pressure, is presented in figure 3. The torch has the RF electrode made from tungsten, the nozzle from stainless steel and an alumina insulating tubing.

4. BREAKDOWN ASPECTS AND ELECTRICAL CHARACTERISTICS OF THE PLASMA TORCH DISCHARGE

One of the problems associated with the atmospheric pressure discharges is the difficult breakdown. The Paschen curves representing the breakdown voltage V_b upon pd (pressure multiplied by the interelectrodic gap) have, depending on gas, their minima around 3-8 mbar_cm., and show that high voltages are necessary to produce breakdown directly at high pressure. This condition is partially relaxed at frequencies in the range 1-50 MHz, for such frequencies the breakdown decreasing with up to 20% as compared with the DC voltages [12]. In addition, by choosing a small interelectrodic gap, one may move the minima towards high pressure; nevertheless a gap smaller than 1 mm do not let enough room for discharge development. Another solution, the breakdown at low pressure followed by gradual pressure increase is not practical, because requires an additional system for producing an initial vacuum. In spite of these unfavorable circumstances the breakdown of the presented plasma torch can be performed directly at atmospheric pressure. In Figure 4 the current-voltage (curve ABCD) and power-voltage (curve A'B'C'D') characteristics are presented, for the plasma torch of 20 mm diameter working in argon at a mass flow rate of 1500 sccm. The electrical measurements were performed by using an Tektronix digital oscilloscope (type 2432A), with current and voltage probes (type P 6021 and P 6137) via a GPIB interface connected to a computer. The curves were obtained by gradually increasing the RF power and recording the corresponding current and voltage values. The pairs of points (A, A'), (B, B'), (C, C') and (D, D') are homologues corresponding to the same state of discharge. Particularly, the points B and B' are important, they marking the breakdown. They separate the regions AB (respectively A'B') describing the flowing of current through the capacitance of the interelectrodic gap (displacement current, no discharge), from the regions CD (C'D') corresponding to discharge impedance (presence of plasma with both resistive and capacitive components). A significant aspect revealed by the curves is the low voltage and the corresponding low power (less than 200W) necessary for breakdown. In order to explain this result a study of the breakdown dependence upon pressure and mass flow was performed on a discharge configuration as in Figure 1, in which the RF electrode and the plate were separated by 4mm distance. The curves in Figure 5 show the pressure dependence of the breakdown power, at different flow values. They reveal that comparing with the static regime (no flow) the flowing of gas decreases considerably the breakdown threshold providing the present plasma torch with the capability to be switched on directly at atmospheric pressure.

5. CHARACTERIZATION OF THE PLASMA JET

As it is expected that detritiation and material removal from surfaces is driven by both temperature and chemical effects the gas temperature of plasma jet and the content of reactive species are parameters of large importance. The temperature field in the jet was measured by means of a small chromel-alumel thermocouple inserted in the jet. The results are shown in Figure 6, where the temperatures at different distances from nozzle are shown for argon and nitrogen plasmas. The used mass flow and power values correspond to stable operation of the torch with 2 mm interelectrodic distance for operation in argon and respectively, 3 mm distance for nitrogen. The curves in Figure 6 show that plasma torch in argon works stable at lower power, and give 250-350 oC at 8-10 mm distance from nozzle. The nitrogen plasma torch can be operated at larger powers and provides at the same distances temperatures about 800-1000 oC, appropriate for stimulating detritiation by gas desorption.

In addition, Optical Emission Spectroscopy studies were performed to identify species in the plasma jet. The emission of plasma expansion was studied in the spectral range 200-600nm with a set-up consisting of quartz optics, a medium resolution monochromator (SPM-2, Carl Zeiss, and grating 1200 mm-1) photomultiplier (QB 9958) and data acquisition system. Typical spectra obtained from the jet are presented in Figures 7, with the light collected along the flowing axis and perpendicular on the axis. The spectra reveal the presence of emission bands in visible (mostly due to molecular nitrogen Second Positive Spectral System, N2 (SPS)), but also in the ultraviolet region (Figure 7). The UV emission (see inset in Figure 7) is dominated by the gNO and bNO spectral systems, the NO radical being formed presumably by mixing of the excited nitrogen with atmospheric air. The occurrence of UV emission is of interest, because UV photons may stimulate the detritiation process .

6. SURFACE EXPERIMENTS

The ability of the plasma torch for surface cleaning was tested on graphite and CFC materials. A scanning facility was used based on computer controlled stepper motors, allowing scanning of desired shapes on flat surfaces. An image of the plasma torch during scanning operation is presented in Figure 8. The scanned samples were investigated by profilometry and mass gravimetry. The experiments showed that argon plasma alone produces only small effects on the surfaces, and that the treatments at higher power are affected by arcing. Comparatively, the nitrogen plasma torch was more stable in operation. In one set of experiments defined areas of polished graphite samples were scanned with the nitrogen torch for various increased times. The visual inspection indicates a clear modification of surface and the profilometric measurements show an increasing of roughness with the treatment time. IN other set of experiments volume cut small pieces of CFC from Tore Supra tokamak tiles were scanned on the fresh cut surfaces for various increasing times. The scanned area was 170mm^2 ($17\text{mm} \times 10\text{mm}$), with paths separated by 1 mm distance and a scanning speed of 5mm/sec. The mass changes were obtained by weighting the samples at different stages of treatment. Material removal is proved by mass decrease, as exemplified in Figure 9, indicating a removal rate of $2.5\ 10^{-4}$ g/min. This corresponds to an erosion rate of the mentioned scanned surface with 0.5mm/min.

The gradual roughness evolution, as given by profilometry, shows that the mechanism of material removal is not based on particle extraction, but on a continuous process, as physical or chemical erosion. The sputtering threshold of graphite is high and at atmospheric pressure the ions cannot reach high energies required for sputtering because plasma is in collision regime. The only remaining chemical mechanism, should be based on chemical reactions in which plasma generated radicals react with carbon surfaces leading to volatile molecules, easy to be removed with the effluent gas. As an example,

the carbon surface could be chemically etched by the atomic nitrogen via the reaction [13]:
C(solid) + N(S,P,D atomic states) → CN*(excited)

Even this reaction is only slightly exothermic (0.17eV) [14] , the reaction rate will be increased by the substrate temperature and the radical kinetic energy associated to the plasma flow.

CONCLUSIONS

A possible approach for removal of co-deposited layers and detritiation in narrow places and gaps in Tokamaks is the wall cleaning with a plasma torch. The requirements for such a torch are small size allowing access in hidden spaces, stability and easy handling, capabilities to affect the surface by physical and chemical processes, flexibility for mounting on robotic arms. We show that such plasma sources can be obtained by using expanding radiofrequency discharges. The plasma torch presented in this paper is manufactured in stainless steel, has only 20mm diameter and uses refractory materials inside. Operation with powers up to 600W was possible by means of adequate cooling. The breakdown of the discharge sustaining the torch can be realized directly at atmospheric pressure. The plasma torch works stable both in argon and nitrogen. Temperatures of 1000-1200^{o}C were obtained in nitrogen in the nozzle vicinity, and in the range 800-900^{o}C at 8-10mm from the tip nozzle, almost twice the values in argon. Optical Emission Spectroscopy investigations showed the presence of UV emission, which is useful for stimulating surface desorption. Surface experiments realized with the nitrogen plasma torch on graphite and CFC tiles from Tore Supra indicate material removal with a rate of 2.5 10^{-4}g/min. The material removal is done by a chemical process and does not lead to dust formation.

ACKNOWLEDGMENTS

This work was performed under JET Fusion Technology Task Force programme and was partially funded by EURATOM Programme.

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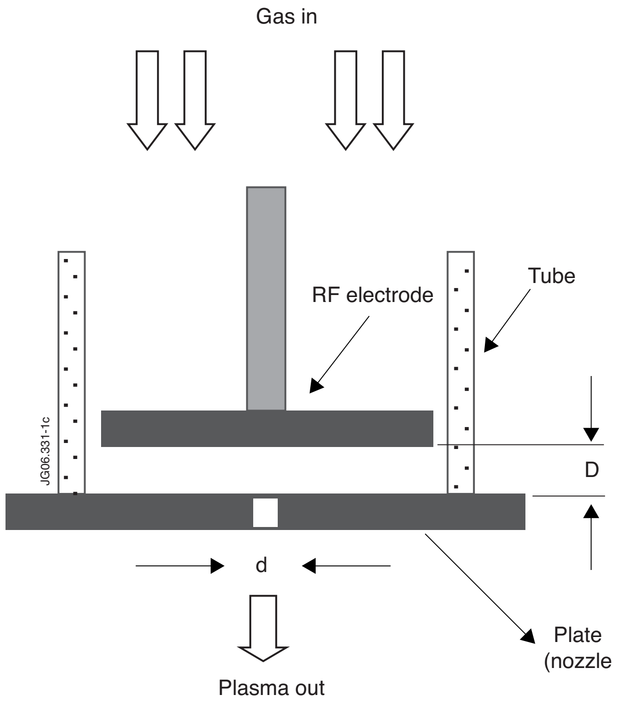

Figure 1: The configuration of discharge which generates the plasma torch.

Figure 2: The aspect of the plasma beam in argon at 133mbar, power 150W.

Figure 3: Image of the small size plasma torch working in nitrogen (300 W, 8000 sccm).

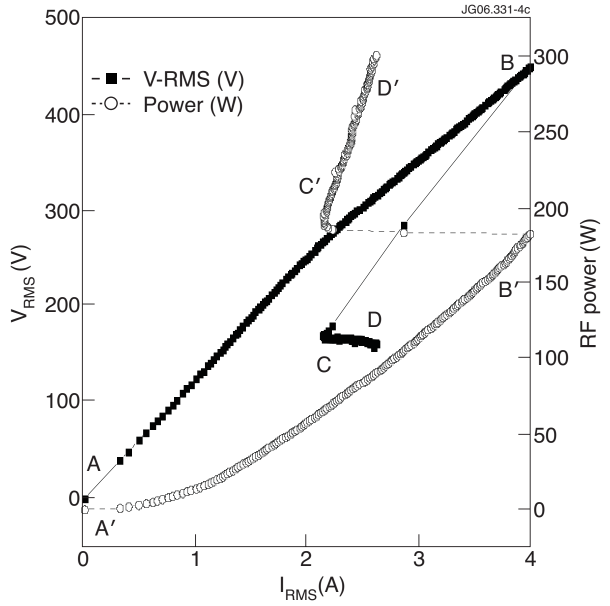

Figure 4:Current voltage and current Power characteristics (argon, plasma torch 20mm diameter, 1500 sccm).

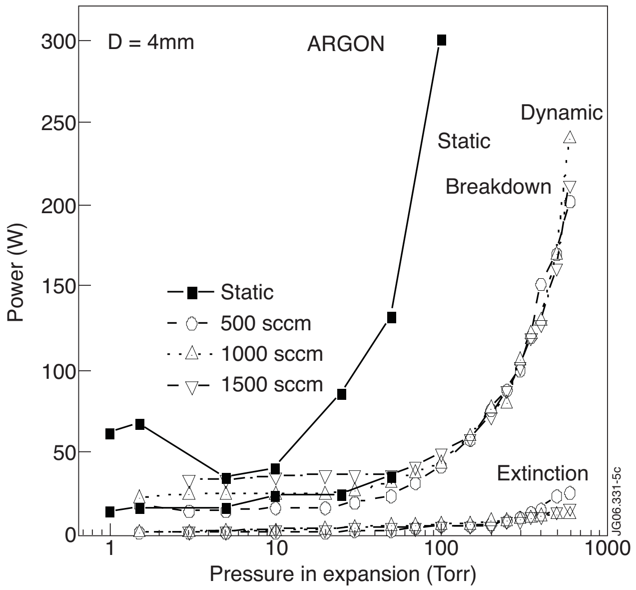

Figure 5: *Dependence of breakdown power on the pressure for various mass flow values.*

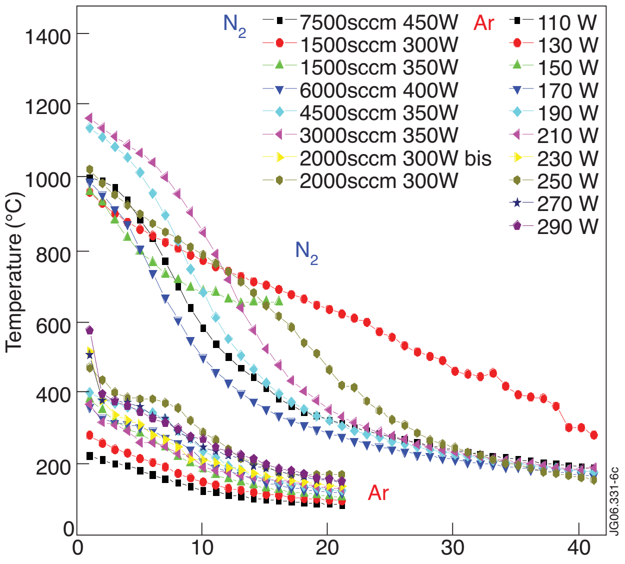

Figure 6: *The dependence of temperatures in the plasma jet on position.*

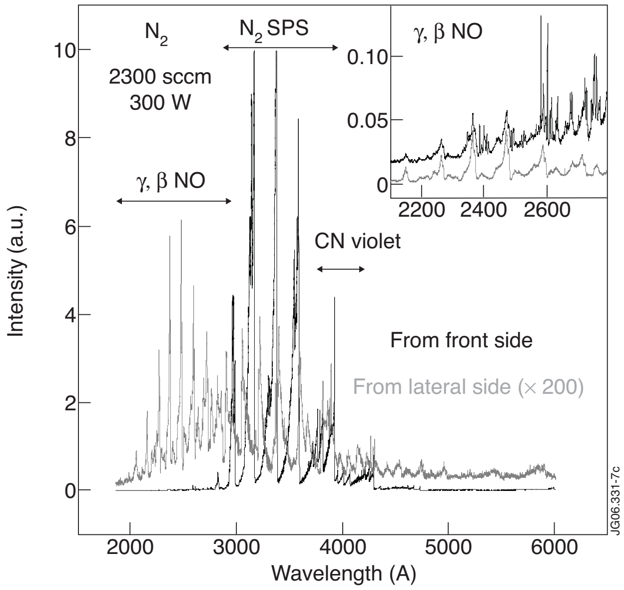

Figure 7: *Spectra emitted by the plasma torch in nitrogen*

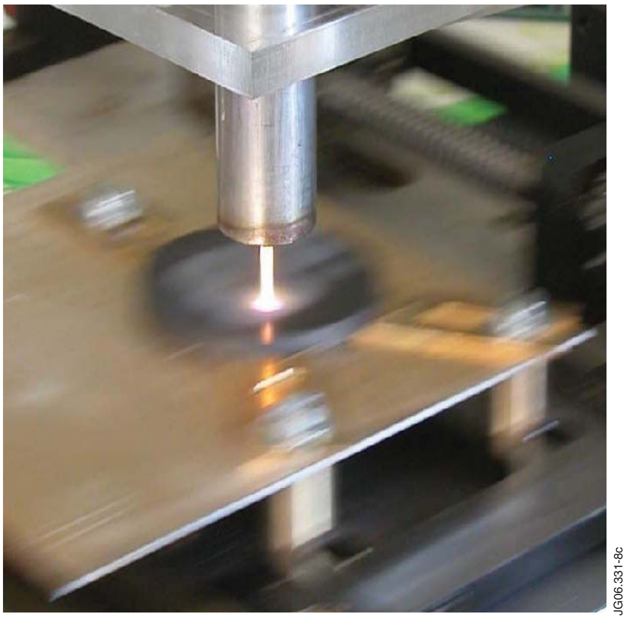

Figure 8: *Image of the plasma torch during scanning procedure*

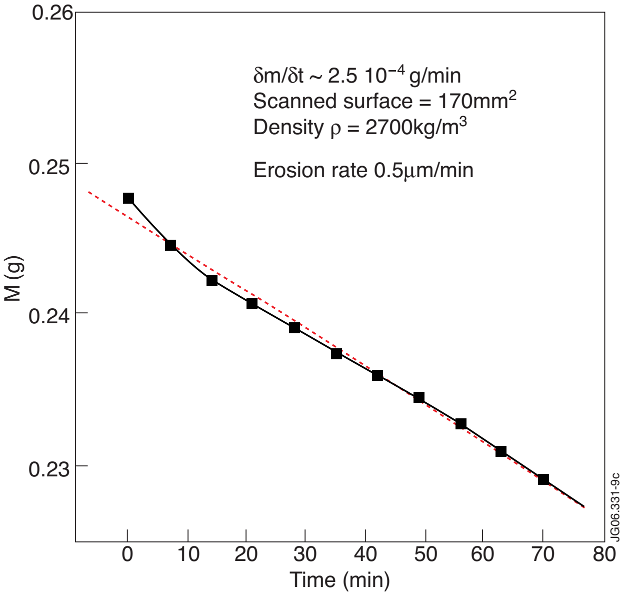

Figure 9: Mass variation of a CFC sample with the treatment time