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► **To cite this version:**

G. Chichignoud, Y Delannoy, F Cocco, P Rivat, L Natale. E–H Mode Transition of an Inductively Coupled Plasma Torch at Atmospheric Pressure. 8th International Conference on Electromagnetic Processing of Materials, Oct 2015, Cannes, France. hal-01335950

HAL Id: hal-01335950

<https://hal.science/hal-01335950>

Submitted on 22 Jun 2016

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E–H Mode Transition of an Inductively Coupled Plasma Torch at Atmospheric Pressure

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Abstract

Inductively coupled plasma torches need high ignition voltages for the E–H mode transition and are therefore difficult to operate. In order to reduce the ignition voltage of an RF plasma torch with a metallic confinement tube the E–H mode transition was studied.

A spark generator was used to initiate an arc and the E–H mode transition of the plasma was then filmed using a high-speed camera. The electrical potential of the metallic confinement tube was measured using a high-voltage probe. It was found that an arc between the grounded injector and the metallic confinement tube is maintained by the electric field (E-mode). The transition to H-mode occurred at high magnetic fields when the arc formed a loop. An equivalent circuit for the set-up is proposed in order to assess the relative importance of the forces involved in the curvature of the arc (Lorentz force and drag force). As a result, the ignition voltage could be significantly reduced by connecting the metallic confinement tube with a capacitor to the RF generator. Consequently conditions to ignite an inductive plasma at atmospheric pressure operating a solid state power source can be achieved.

Keywords: inductive plasma ignition, atmospheric pressure, MOSFET generator, low frequency, silicon purification

Introduction

The so-called thermal plasma torches can be divided into two main families, arc torches and inductively coupled torches. Whilst this latter family is generally applied to low power applications such as chemical analysis, due to its better homogeneity, inductively coupled plasma torches shall be relevant in industrial processes thanks to very low chemical contamination. Indeed, as energy is transferred to the plasma by the magnetic field of the coil, no electrode is needed, contrary to arc plasma. In addition the electrode is eroded during the process and represents an additional cost for maintenance. However the use of high power (40kW-1MW) ICP torches impose to implement a water cooled confinement tube [1] instead of the generally used quartz confinement tube. In addition metallic tubes present better resilience both to mechanical shocks and to high heat fluxes - which will prevent major failure that would induce water leakage directly onto the hot target to be processed - so this metallic confinement appears to have an interesting practical potential. For instance inductive thermal plasma can be useful for the purification of silicon for solar cells [2][3] and for earth re-entry simulations [4]. However plasma ignition at atmospheric pressure in a torch confined by a segmented copper tube is a challenging issue as was previously investigated in a preliminary study [5]. The E/H mode transition was observed and characterized in a laboratory scale pilot. Based on this first study propositions were made in order to facilitate plasma ignition even at operating frequency low enough to be compatible with a solid state generator. The present study is a transposition of the previous work at lower frequency, in order to test the validity of our assessments. In collaboration with an industrial manufacturer, a solid state power source operating at 400 kHz (MOSFET technology) is tailored specifically for this purpose of ignition at low frequency.

E/H Mode transition

The plasma torch is described in Figure 1 and is used in industrial conditions. It is composed by a copper confinement tube divided into eight water cooled segments. To increase the velocity of the argon flow inside the torch a silica auxiliary tube can be placed into the confinement tube so that its lower end is tangent with the top of the electromagnetic coil. Its diameter is close to the inner diameter of the confinement tube so that the space between the two tubes is narrow, around two millimetres. The main gas flow is injected across this narrow annulus.

A water cooled injector is placed along the axis of the torch and is dipped inside the coupling zone at about one third of the total height of the coil. Three different argon flows are injected respectively in the outer, auxiliary and inner inlets. For better stability of the plasma the outer flow is injected with swirl. The outer confinement tube and the inner injector are electrically insulated from each other so that a discharge can be triggered at the bottom end of the injector.

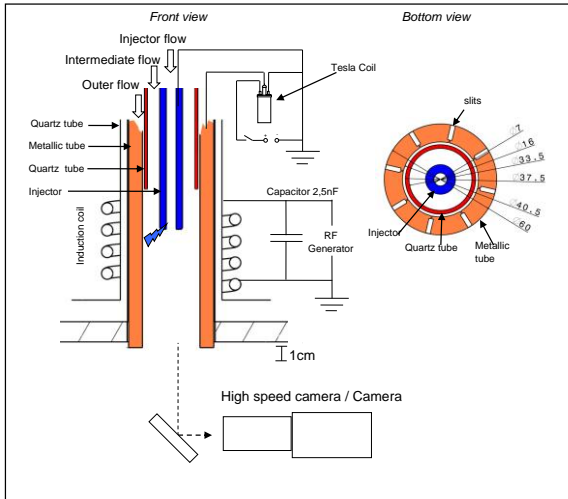


Fig.1: Experimental set-up

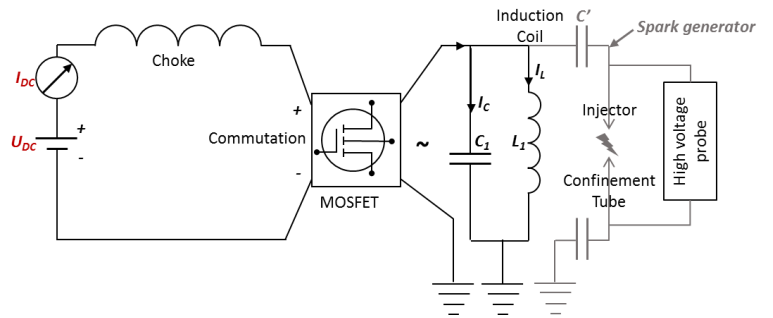


Fig 2:Electrical configuration

The coil is connected in parallel with a tank capacitors bank to the MOSFET type power source (SAET 140kW) (Figure 2). As suggested by Altenberend [5] additive capacitors are connected to the injector and the confinement tube to ease the ignition step. The voltage between the injector and the confinement tube can be measured at each step by a specific probe. The generator operates at 400 kHz, which correspond to the resonance frequency of the tank circuit constituted by the inductor and the tank capacitors. To start the E-mode a high voltage provided by a 50Hz transformer was sent to the injector so that argon breaks down in the torch, between the injector and the confinement tube.

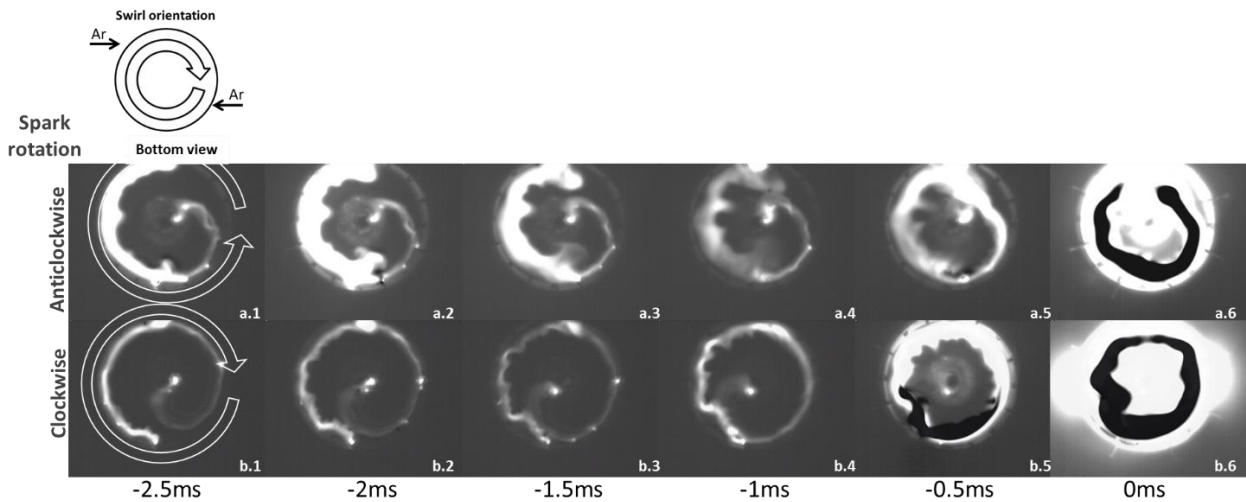


Fig. 3 The transition from E-mode to H-mode (Frame rate 2 kHz). The arrows indicate the arc movement.

The ignition phase is observed thanks to a high speed camera (AOS X-motion, Objective: Sigma 150mm, 1:2.8, aperture: 32, shutter time: 200 μ s, frame rate: 2000 Hz) from the bottom of the torch. At first a discharge is applied by the high voltage transformer to the torch between the outer and the inner copper tube. The gas breaks down in straight arc but the transition to the H-mode cannot occur (no closed loop for inductive currents). Then the electromagnetic field provided by the coil should be high enough to promote a current in the arc in phase with the magnetic field (E-mode). The E-mode will eventually turn into the H-mode when a closed loop is formed (Figure 3 a.5&b.5). Indeed to transfer power by induction to the plasma and yet stabilise the H-mode, one needs to apply the electromagnetic field to a continuous electrically conductive loop – partially ionised argon - that plays the role of the secondary stage of a transformer.

The first arc triggered by the high voltage discharge begins to rotate, and is transformed from straight shape to a spiral thanks to the Lorentz force (Figure 3.1-6). The rotation is assumed to be driven by a balance between the Lorentz force and the drag force of the arc with the gas flowing inside the torch. The spiral shape is assumed to be produced by a uniform velocity rather than a uniform angular velocity. In order to strengthen this mechanism the magnitude of both forces was assessed in a previous study [5], thanks to simplifying assumptions.

The obtained values of the Lorentz force and the drag force are of the same order of magnitude. However, the drag force drives the arc in the direction of rotation of the swirling flow, whereas the direction of the Lorentz force can be inverted if the current in the arc is reversed. Figure 3 provides an estimate of the drag force compared to the Lorentz force. As previously described argon is injected along the external diameter of the confinement tube with a swirl. As seen from the bottom of the torch across a mirror, this flow remains clockwise whatever the electrical configuration. Both the injector and the confinement tube are connected to the power circuit *via* capacitors. These two connections can be swapped so that the direction of the Lorentz force can be exchanged from clockwise to anticlockwise. Accordingly two configurations can be obtained:

- a) The first when the argon flows clockwise and the glow moves anticlockwise due to the Lorentz force, opposed to the drag force (Figure 3.a)
- b) The second when the argon and the glow move clockwise so that the Lorentz force accelerates the arc compared to the swirling flow (Figure 3b).

Plasma can be ignited in both configurations. However the effect of the drag force is highlighted in configuration (a). The discharge seems disturbed by the gas flow and even repulsed (Figure 3.a2-3). On the contrary ignition in configuration (b) is much smoother and can be obtained at lower power. This result enlightens the balance between the drag force and the Lorentz force during the ignition. Yet their magnitude can be comparable, the Lorentz force is prominent. Therefore E/H mode transition can be facilitated by adjusting the electrical connections so that both the discharge and the argon flow are rotating in the same direction.

Ignition of a plasma at atmospheric pressure with a solid state power generator

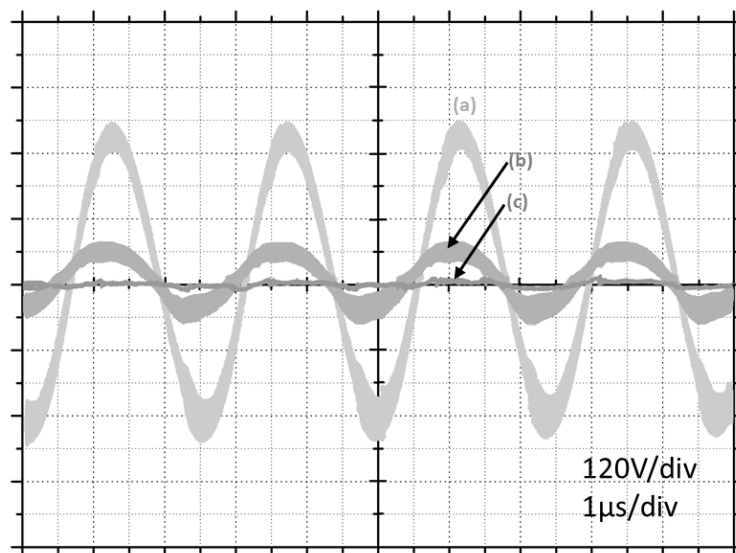


Fig.4: Qualitative evolution of the waveform of the voltage between the injector and the confinement tube (a) with the electric field from the generator but without any discharge (b) with a rotating discharge and (c) after plasma ignition

A special solid state generator (SAET 140kW) operating at 400 kHz [6][7] was adapted to manage the dramatic change in impedance occurring during the plasma ignition. Looking at fig.3, it is possible to estimate that the E/H transition lasts about 2 ms, in this interval the current absorbed from the generator grows up from 40% to 110% of its nominal value. The AC/DC power regulator must be able to manage this fast load transition without tripping any over current fault. A larger plasma torch compared to the lab scale one (70 mm instead of 48 mm in diameter) was connected to this power source. An additive capacitance was linked to the copper based confinement tube in order to maintain a high arc current density whereas the voltage is strongly reduced at the low operating frequency. Ignition is observed by using the previous high speed camera ($f=2$ kHz). Evolution of the voltage between the injector and the confinement tube is recorded thanks to a high voltage probe (Figure 4). Actual plasma ignition corresponds to strong decrease in the measured voltage (figure 4.c). According to the authors knowledge it is the first time that the ignition of a high power inductive plasma at atmospheric pressure using a solid state generator is reported.

The 140kW pilot generator was the starting point for the development of an industrial MOSFET generator devoted to ICP applications with 600kW power rate, operating at 430kHz. With this new generator a 90 mm ID plasma torch was

successfully ignited at atmospheric pressure and is currently used for silicon purification.

Conclusion

The E-H mode transition during the ignition of an inductive plasma at atmospheric pressure occurs thanks to the formation of a closed conductive loop. This loop comes from the deformation of an initial straight arc to a spiral shape discharge driven by a balance between the Lorentz force and the drag force. Increasing the arc current leads to an augmentation of the Lorentz force that is favourable for plasma ignition. This approach was first validated on a lab scale high frequency power source and then transposed to a modified solid state generator. Successful ignition of an inductive plasma at low frequency (400 kHz) using a solid state generator is reported for the first time.

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