Experimental Evidence of TIAGO Torch Plasma as a Surface Wave Discharge and Identification of the Radiation Zone: Improving Graphene Synthesis.

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Microwave plasma technology at atmospheric pressure arouses interest thanks to its remarkable performance in many challenging areas, such as green energy generation and graphene production by hydrocarbon decomposition. One of the most outstanding devices in this field is the TIAGO (Torche à Injection Axiale sur Guide d'Ondes) torch. It generates a plasma where two luminous regions can be distinguished: a bright filament (dart) and a fainter shell (plume). This dart has been experimentally demonstrated to be a Surface Wave Discharge (SWD) by the analysis of the axial distribution of electron density [1]. This kind of plasmas are usually enclosed in dielectric tubes. Thus, surrounding air must behave as a virtual dielectric cylinder to allow the propagation of the surface wave along the plasma column. Among other features, SWDs are characterized by the existence of a radiation zone previous to the formation of the surface wave, an increase of its length with the power supplied and a linear decrease of electron density along the discharge whose slope does not depend on applied power.

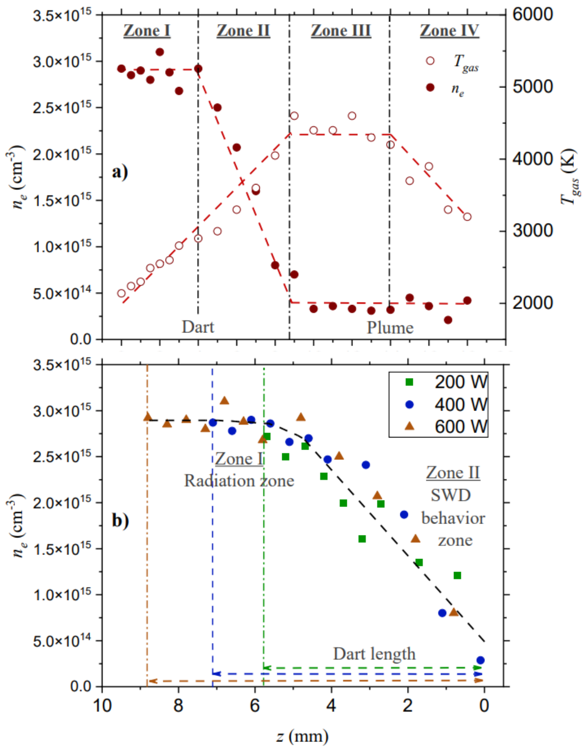

Fig. 1: a) Zones identified along the TIAGO torch (600 W) b) Axial distribution of the electron density with the origin of coordinates at the end of the dart, taking the positive direction towards the injector.

In Fig 1, an axial characterization of the main parameters—electron density and gas temperature—of the plasma generated at 600 W has been carried out [1]. Based on these parameters, four zones can be identified along the plasma (Fig 1a), with the first two corresponding to the dart and the next two corresponding to the plume. If the origin of coordinates is placed at the end of the dart and the data obtained for different microwave power supplied to the plasma are plotted together (Fig 1b), it is observed that the value of the electron density is independent of the applied power. It can be seen that there is a region where the electron density remains constant at its maximum value and then decreases linearly as we move away from the injector. This corresponds to the radiation zone (Zone I), which, as expected, is followed by the zone where the surface wave forms (Zone II), exhibiting SWD-type behavior. Zones III and IV (plume), are characterized by a reduced presence of electrons (Fig 1a), suggesting that the plume behaves as a postdischarge.

This research provides valuable information for the optimization of TIAGO torch applications, concretely the formation of graphene nanosheets, application for which this device has proven to be suitable [2]. In [1], and taking in account the numerical analyses of Nowakowska et *al*. [3], the unshielding of this plasma results in the radiation of electromagnetic energy into space (aproximately 43%), especially along positions closer to the nozzle exit, *i.e*. Zone I, the radiation zone. This energy, in consequence, is not being utilized during the graphene synthesis process. To optimize this process, a crucial step is to minimize energy loss through radiation to maximize the available microwave energy input. To this aim, a metallic shielding has been placed around the TIAGO reactor, essentially creating a Faraday cage (Fig 2). The shielding strategy prevents radiation losses and results in a remarkable increase in graphene formation up to 22.8%. This value, along with the emitted gases proportions and plasma volume increase, shows a correlation with conditions associated with higher input power [4], which demonstrates a greater utilization of the energy supplied to the plasma. The synthesized material undergoes a thorough examination, employing diverse techniques like Raman spectroscopy (Fig 3), X-ray photoelectron spectroscopy (Fig 4), and others. These analyses highlight that the quality of graphene remains consistent, even with the implementation of shielding. Therefore, the electromagnetic shielding of the TIAGO torch discharge significantly boosts solid material formation and energy yield without compromising the intrinsic properties and quality of the synthesized graphene.

Fig. 2: TIAGO torch shielded plasma during graphene synthesis

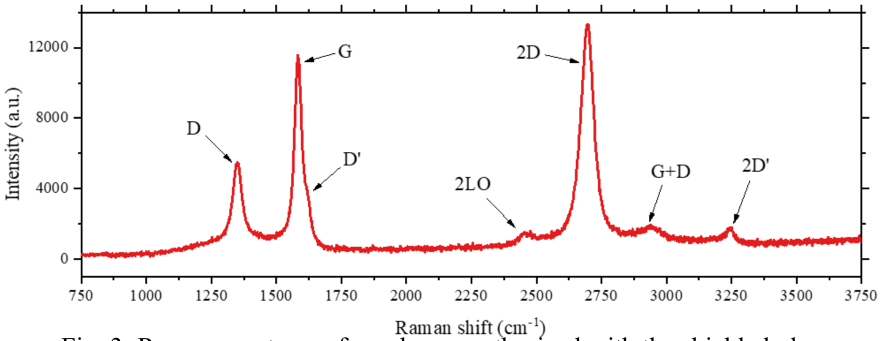

Fig. 3: Raman spectrum of graphene synthesized with the shielded plasma

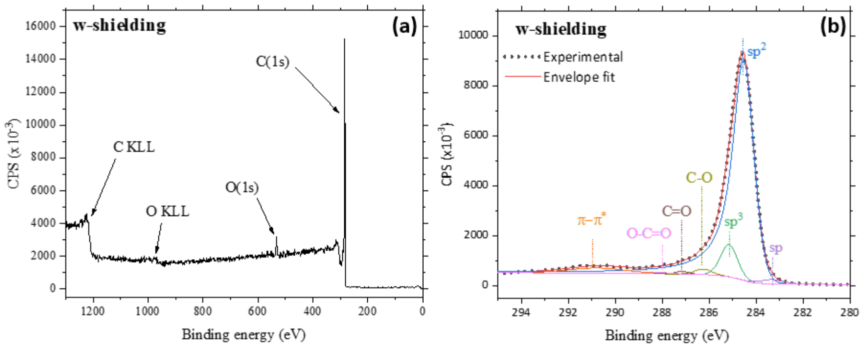

Fig. 4: XPS spectrum (a) and C(1s) peak deconvolution (b) of graphene synthesized with the shielded plasma

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Aknowledgments: This work was partially supported by Grant TED2021129261AI00 funded by MCIN/AEI/ 10.13039/501100011033 and by the European Union NextGenerationEU/PRTR. The predoctoral contract of F.J. Morales-Calero was granted by a MOD-2.2 from Plan Propio de la Universidad de Córdoba (2020). Finally, the authors of the present work are greatly thankful to Prof Michel Moisan of the Groupe de Physique des Plasmas (University of Montreal) for the TIAGO torch donation.