Plasma by THz (PbT)

Report activity 2024

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Plasma by Terahertz (PbT) project proposes an R&D activity through a collaboration of TERA-Lab at the Department of Physics, INFN Section Roma1 (**ROMA1 unit**), and SPARC_LAB LNF-INFN (**LNF unit**), for the development of an innovative diagnostic approach for the plasma density detection based on the exploitation of plasma optical criticality as measured by Terahertz radiation. This innovative technique will be used for measuring the properties of plasmas generated in the plasma laboratory (*Plasma_lab*) of the SPARC_LAB facility. It is particular important in view of the EUPRAXIA facility that will be developed at LNF-INFN.
The time schedule of the 3-years long project is presented in the following table.

Unit	Description	Deadline
ROMA1	THz-TDS multishot technique	31/12/2022
LNF	Design/Building of a dedicated multidiagnostic plasma chamber	31/12/2022
ROMA1	THz-TDS single shot technique	31/07/2023
LNF	Adapting single and multishot THz technique to the multidiagnostic plasma chamber and tests	31/12/2024

3rd YEAR (2024) Milestones for LNF Unit

In the third year, the characterization of materials to be used for the THz diagnostics has continued, comparing plastic materials with more resistant materials, such as sapphires and glass, which were found to be more suitable for use in plasma sources for accelerators. Indeed, the requirement for operating at kHz repetition rates with plasmas for particle accelerators in future applications demands the mitigation of the erosion of the capillary walls material due to thermal energy produced during the electrical discharges. The channel deformation indeed produces a change of the matching between plasma and electron bunches, caused by modifications of transverse and longitudinal distribution of the plasma.
The gas-filled discharge capillaries that are tested are presented in Fig. 2, where plasmas are generated through a high-voltage electrical discharge. A specialized experimental setup was constructed in the *Plasma_Lab* to test these plasma sources (Fig. 1). Plasma ionization occurs within a cylindrical hydrogen-discharge plasma capillary, where neutral gas is ionized by a high-voltage discharge applied via two copper electrodes. These discharge capillaries are typically 30 mm in length and a 1 mm in radius. Hydrogen gas is introduced into the capillary through two gas inlets. The plasma density is controlled based on the neutral gas density before ionization, as governed by Paschen's law.

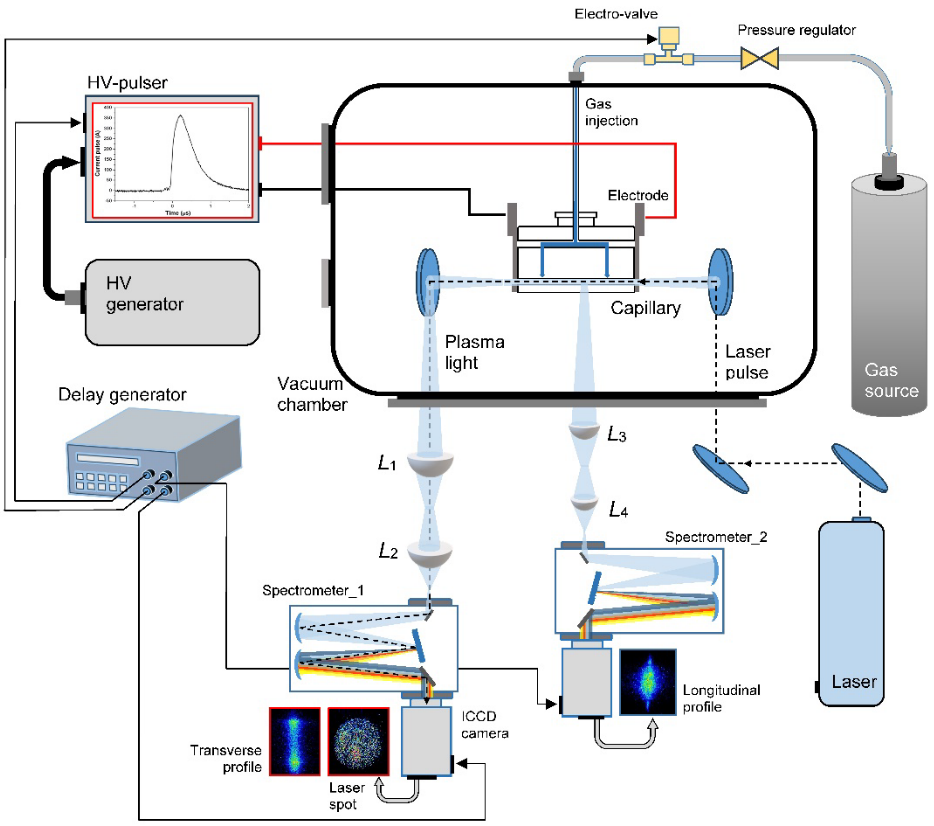

Figure 1. Plasma module used at the *Plasma_Lab* to test plasma sources by using the Stark effect. The plasma diagnostics is based on the Stark broadening technique, for which the emitted plasma light is collected into an imaging spectrometer allowing to measure the enlargement of wavelengths of the Balmer series.

Finally, the neutral gas pressure inside the capillary is regulated by an electromechanical controller, maintained in the 10-50 mbar range throughout measurements. Additionally, a high-speed electromechanical valve, positioned 5 cm from the capillary, regulates the gas injection frequency, ranging from 1 to 10 Hz. For future applications, the repetition frequency will have to be increased to 100 Hz, which is why materials capable of withstanding up to operating conditions must be investigated. Also, in such configuration, the electromechanical valve will be removed to work in continuous flow.

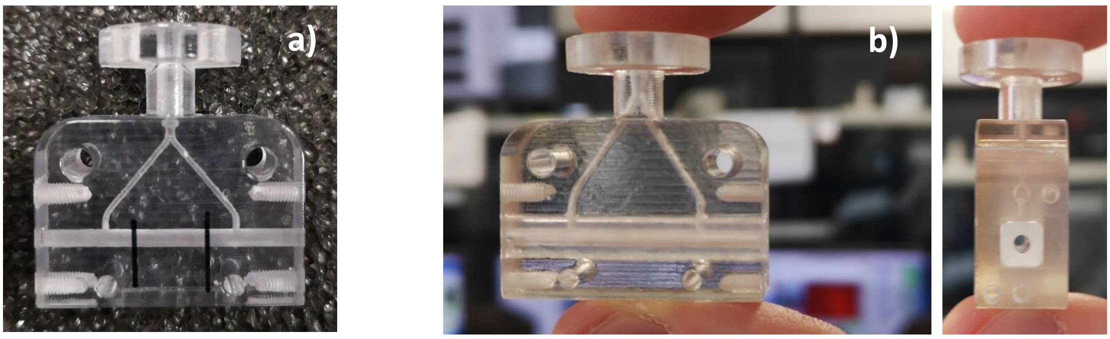

Figure 2. Gas-filled discharge capillaries tested for experiment by using Terahertz radiation. a) 3-cm long capillary composed of plastic material and realized by using 3D printer. b) 3-cm long capillary composed consisting of two different parts, a holder made of 3D-printed plastic and an inner part made of sapphire.

In the third year, in parallel to the work at ROMA1 unit, a dedicated innovative plasma chamber has been designed for installing the THz source/receiver system (studied by the ROMA1 unit) and testing of the gas-filled discharge capillaries, which has been characterized by the conventional Stark broadening technique. This plasma has been implemented in the *Plasma lab* at LNF-INFN. The design of the chamber includes supports for different capillary dimensions and materials (to be studied at ROMA1 being compatible with THz radiation), and viewports for passing through of THz radiation to allow the interaction with plasma in the plasma source.
The design of the plasma vacuum chamber for installing the THz diagnostic system and measuring the properties of plasmas for acceleration is shown in figure 3. It is suitable for hosting two plasma sources and includes five viewports to be used for passing through the THz radiation and the plasma light needed to characterize plasmas produced inside the gas-filled discharge capillary.

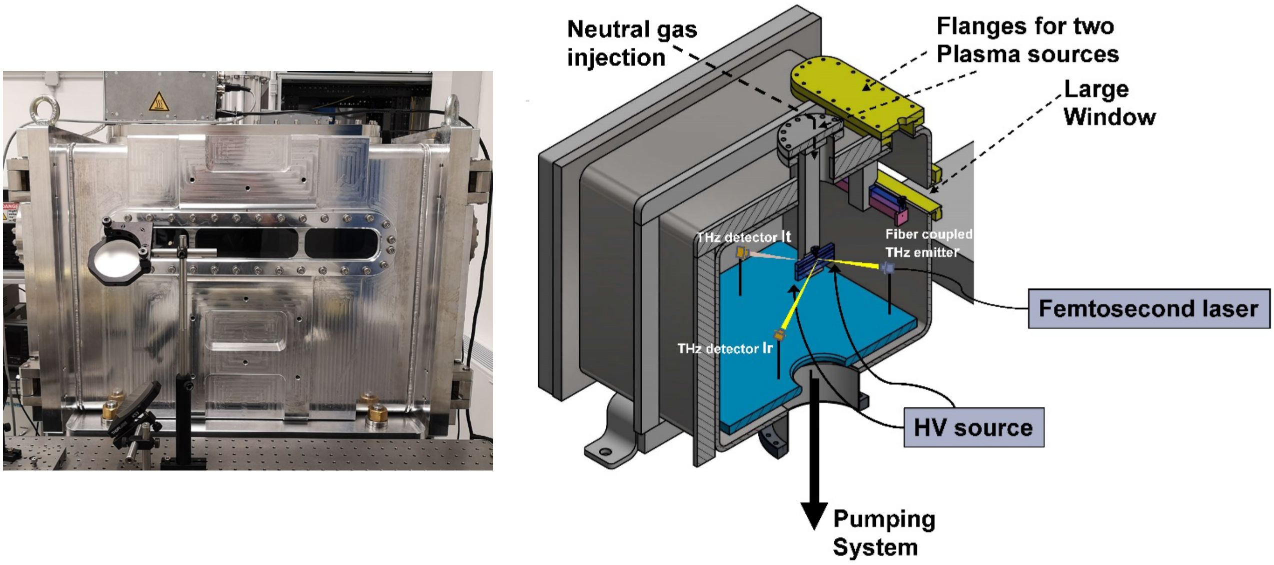

Figure 3. Plasma diagnostic chamber. The image on the left shows the long window used to collect plasma light or THz radiation to characterize discharge capillaries. On the right there is a scheme of the chamber and the THz diagnostic layout.

The characterization of two capillaries made from two different materials is shown in figure 4, where the two longitudinal plasma profiles obtained using the Stark broadening technique are shown. As can be seen, the measurements provide two similar trends even though they were made with materials that present a slightly different transparency at the wavelengths of 480 and 650 nm (Balmer lines) used for the spectrographic analysis. A slight loss of density is observed in the central area of the sapphire capillary, although the average value remains quite similar. These results make it possible to state that both plastic materials, which are easy to make but not very resistant to the stresses of high plasma generation frequencies, and resistant but not very mechanically workable materials such as sapphires are characterized for use with THz radiation. Further results will be presented on the interaction between plasma and THz radiation by the ROMA1 unit.

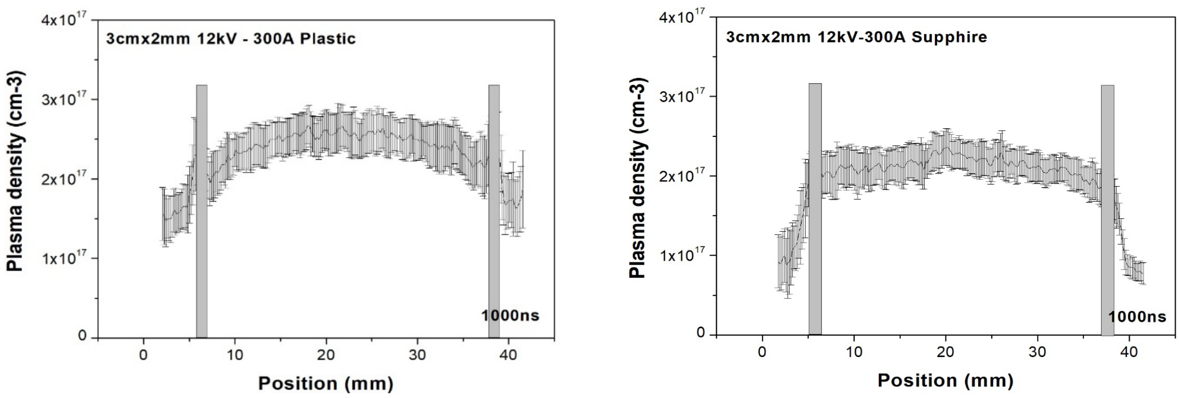

Figure 4. Plasma longitudinal profile obtained by measuring the Balmer *Hbeta* line width along the longitudinal coordinate. a) Longitudinal plasma profile of the 3 cm long plastic capillary measured with a delay of 1000 ns from the starting point of the discharge. b) Longitudinal plasma profile of the 3 cm long sapphire capillary measured with a delay of 1000 ns from the starting point of the discharge. The same discharge voltage and current was used for both gas-filled discharge capillaries.