Time-Resolved Femtosecond Laser-Plasma Measurements by a Mach-Zehnder-Like Interferometer

Armando Valter Felicio Zuffi[1,*], Edison Puig Maldonado[2], Nilson Dias Vieira Jr.[1], Ricardo Elgul Samad[1]
[1] *Nuclear and Energy Research Institute – IPEN-CNEN/SP, Av. Prof. Lineu Prestes, 2242, 05508-000, São Paulo, SP, Brazil*
[2] *Aeronautics Institute of Technology – ITA, Pç. Mal. Eduardo Gomes, 50 Vila das Acácias, 12228-900 São José dos Campos, SP, Brazil*
* *armandozuffi@gmail.com*

Abstract: This work reports measurements of the density profile of laser-generated plasmas by a home-built time-resolved Mach-Zehnder-like interferometer. This device will integrate our laboratory infrastructure for laser wakefield acceleration experiments. © 2022 The Author(s)

1. Introduction

Compact particle accelerators based on laser wakefield acceleration (LWFA) can be used in a wide range of applications [1], including radioisotope production for medicine [2]. In this technique, high-intensity laser pulses are focused on a gaseous target in a vacuum chamber, creating a plasma wave whose electric fields are efficient in accelerating electrons [1]. Our research group is working to implement the first laser electron acceleration infrastructure in Latin America, at the Nuclear and Energy Research Institute (IPEN) [3], aiming to promote ^{99}Mo production by photonuclear reactions driven by LWFA accelerated electrons [4]. For this goal, we are developing diagnostic techniques to characterize femtosecond laser-generated plasmas and the LWFA dynamics, and we built a time-resolved Mach-Zehnder-like interferometer [5]. Here we present femtosecond pump-probe measurements of plasma formation in the atmosphere.

2. Mach-Zehnder-like interferometer

A Ti:Sapphire CPA (Femtolasers Femtopower Compact Pro HR/HP) generates 25 fs (FWHM) pulses, centered at 785 nm with 40 nm of bandwidth (FWHM), with energy up to 650 µJ, at 4 kHz repetition rate, which were used for plasma density measurements. Fig. 1 shows a scheme of the home-made Mach-Zehnder-like interferometer coupled to a pump-probe setup. A beam sampler (BSa) extracts a fraction of the beam, which is sent through a delay line and focused in a BBO to generate second harmonic pulses (~20 fs, 395 nm), which are collimated into a ~5 mm diameter beam; this beam enters the interferometer to characterize the plasma formed by the fundamental pulses (pump) focused on the atmosphere by a 50 mm off-axis parabolic mirror (OAP). The temporal delay between the pump and probe beams is controlled by a translation stage (delay 1), allowing pump-probe measurements with femtosecond precision.

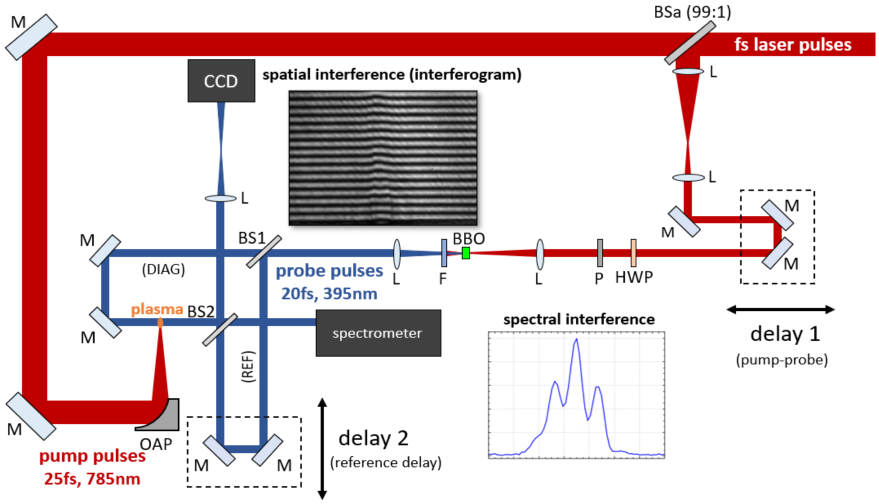

Fig. 1. Pump-probe setup containing the Mach-Zehnder-like interferometer.

In the interferometer, the probe pulses are divided by a beamsplitter (BS1) into reference (REF) and diagnostic (DIAG) beams. The DIAG pulses propagate through the target (plasma) and the phase it accumulates can be retrieved by interference with the REF pulses, after recombination in the BS2 beamsplitter. The temporal overlap between REF and DIAG pulses is obtained by adjusting the REF delay (delay 2). After the BS2, the recombined pulses propagate through a 150 mm convergent lens that produces a 3× magnified interferogram of the target at the CCD (spatial interference). BS2 also directs other recombined pulses to a spectrometer, creating a spectral fringe pattern (spectral interference). The spectral interference pattern is easier to find than the spatial one when adjusting the delay 2, and it is used to set the two arms with the same optical length; once this “zero-delay” position is found, the interferogram is seen on the CCD. Furthermore, this interferometer design allows small adjustments in the reference arm mirrors to define the fringes direction and spatial frequency. From an interferogram, the phase accumulated in the plasma is extracted, and its density profile is evaluated [5].

3. Laser-generated plasma formation characterization

The plasma was formed in the atmosphere by focused pump pulses (25 fs, 785 nm, 200 µJ, and $M^2 \approx 1.5$) reaching intensities above 1×10^{15} W/cm^2, and interferograms were measured for 6 different delays after the plasma formation (100, 300, 500, 700, 900 and 1100 fs). The retrieved density maps are shown in Fig. 2a, and Fig. 2b presents the temporal evolutions of the plasma peak density and its longitudinal length.

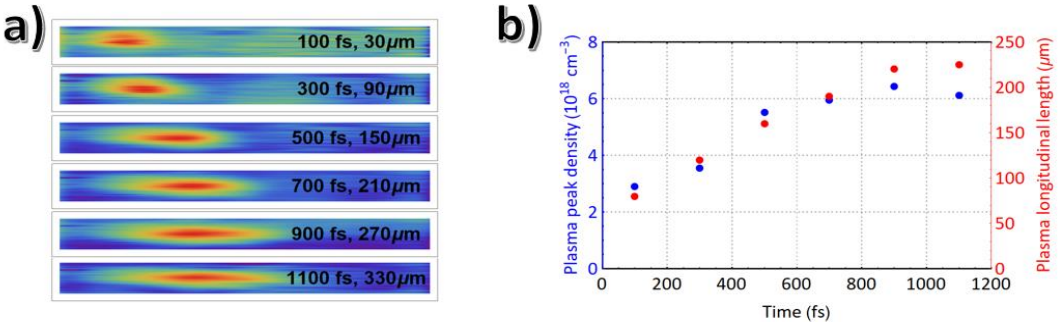

Fig. 2. a) Plasma density maps for 6 different delays after plasma formation. Inset: delay and pump pulses propagation distance. b) Temporal evolution of plasma peak density and longitudinal length.

The plasma temporal behavior during its formation can be analyzed from Fig. 2a, which clearly shows that the plasma density and longitudinal length increase with time, demonstrating that the interferometer spatial and temporal resolution are suitable for this characterization. Fig. 2b shows that the plasma peak density increases up to a saturation around 6.2×10^{18} electrons/cm^3, and its longitudinal length similarly saturates at ~220 µm, close to the OAP-defined confocal parameter. Nevertheless, improvements are needed in our experimental setup and methodology since the densities measured are 1 order of magnitude below the theoretical prediction [5]. This plasma density determination has also been reported as a challenge by other authors [6].

4. Conclusion

We developed and built a time-resolved Mach-Zehnder-like interferometer that can be used to characterize laser-generated plasmas spatially and temporally, allowing the characterization of the plasma evolution on femtosecond scale. These outcomes contribute to our goals to establish a future laser-plasma accelerator infrastructure in Brazil.

5. Acknowledgments

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6. References

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