Development of an Optical Probe for a Laser Wakefield Accelerator in Gemini Target Area 2

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1 Abstract

A high repetition rate laser-wakefield accelerator will be established in TA2. This will allow for testing of optimisation, automation and stabilisation techniques that will be implemented at the Extreme Photonics Applications Centre (EPAC). This report details the commissioning of the optical probe that will allow us to monitor the plasma formed during accelerator operation.

2 Introduction

Laser wakefield acceleration (LWFA) is a novel method for electron acceleration, capable of generating high quality electron beams with energies in the GeV range in centimeter scale acceleration lengths [1]. This laser-plasma acceleration technique is at the core of the EPAC facility's operations. Target area 2 in Gemini will provide a testing ground for the EPAC facility, with developments currently ongoing towards an optimised LWFA. As part of these advancements in TA2, an optical probe diagnostic has been developed to characterise the laser-plasma interaction and investigate the plasma properties.

Probe beams within LWFA experiments are crucial for analysing ultra-fast interactions, creating a freeze frame of the plasma expansion processes evolving on a nanosecond time scale. The captured images provide a wealth of information about the laser guiding taking place and properties of the density profile. In TA2, the probe diagnostics consist of a shadowgraphy arrangement capable of high resolution imaging in parallel with a Michelson interferometer, giving an evaluation of the plasma density.

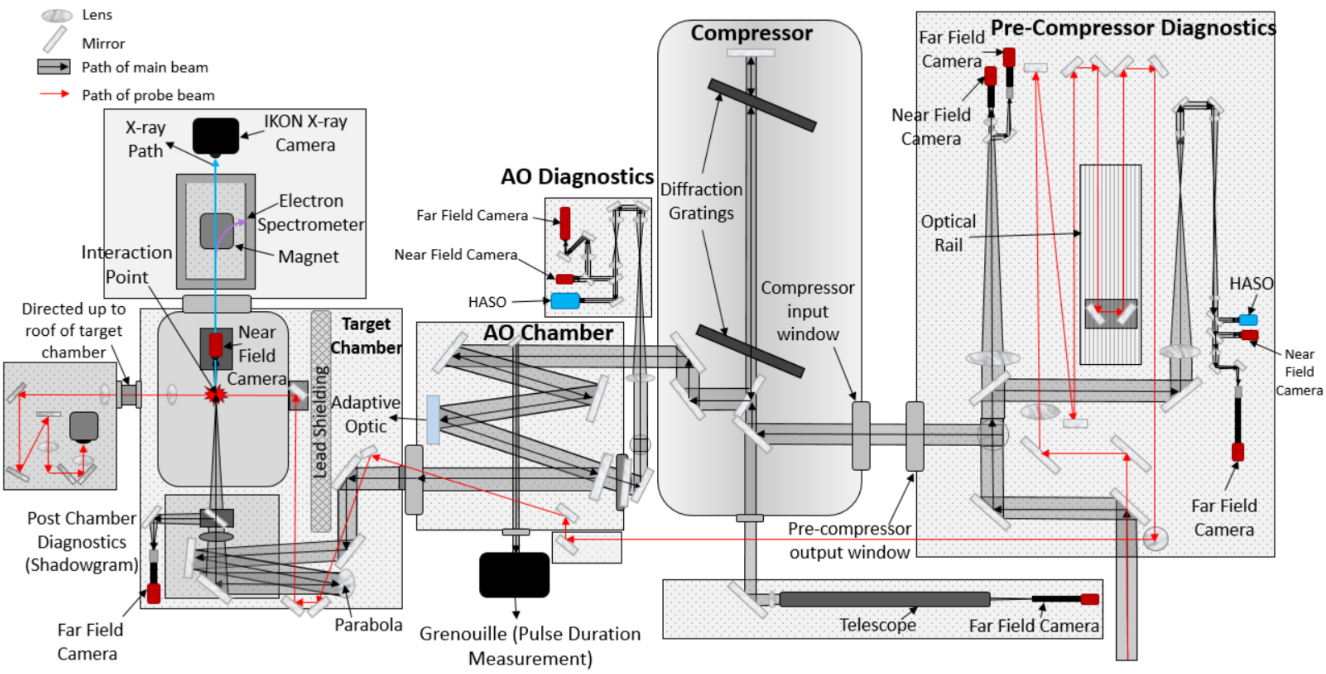

Figure 1: The layout of target area 2, with both the main and probe beam line shown. Up to date probe diagnostics layout shown in Figure 4.

In Gemini TA2, the practical constraints of the target area have required compact, efficient optical designs and innovative mounting solutions. In this report, we present the development of the new probe beam line in TA2, and the unique difficulties involved with the installation of an interferometer.

3 Probe Specifications

3.1 TA2 Layout

Gemini delivers a 700 mJ, 500 ps, chirped laser pulse into TA2, the current layout of which is shown in Fig. 1. The probe beam is then initialised as a 5% leakage taken from the uncompressed main beam as it enters the pre-compressor diagnostics table. The beam's path includes an extensive delay line, fitted with an optical rail to allow for precise adjustments to the path length. This provides a method for accurate timing with the main beam on target. The probe was measured to arrive on target $\approx$ 0.5 nanosecond after the main beam. Also within the delay line, the beam passes through a long focal length lens before re-collimation, reducing its size from 60mm to 18mm.

Before entering the target chamber, the beam size is further reduced to 6mm using a serrated aperture to minimise any introduced diffraction as far as possible. The beam arrives perpendicularly to the main beam on target, traversing the gas cell. No frequency doubling was required for the imaging as the 5% leakage is brighter than any plasma scatter from the main beam interaction.

3.2 Pulse Length

A short pulse probe beam is required in LWFAs, however the practicalities of the target area do not allow for the probe to be synthesised after the compressor. Therefore, to reduce the pulse duration, a 5 nm bandwidth band pass filter was tested in the beam at a range of orientations, the resulting spectra shown in Fig. 2a. From the obtained spectra, a fast Fourier transform was performed to give the corresponding pulse duration at each angle, shown in Fig.2b.

The filter will be installed in the linearly chirped pulse at the angle corresponding to the highest transmission ratio to reduce the duration of the probe pulse with minimal energy loss. This installation reduces the pulse length from 500 ps to $\approx$ 100 ps. In the case that a probe on the femtosecond scale is required, there is a proposed method of rerouting the beam from target area 1 to provide this, however this requires further production and testing.

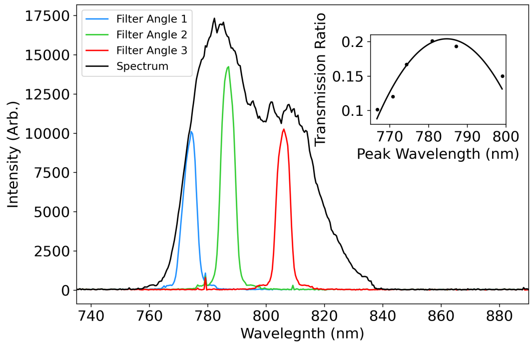

Figure 2a: The spectra collected using a spectrometer in the beam path for 3 angles of band pass filter, coloured, as well as with no filter, black.

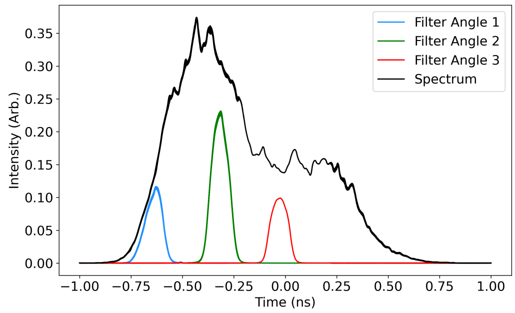

Figure 2b: The pulse duration of each spectra obtained, calculated using a Fourier transform of the spectra in Fig. 2a.

4 Interferometry System

The next stage of development for the probe diagnostics was building an interferometer. This would allow us to observe the phase shift caused by the beam travelling through the gas, and through analysis of the interferogram, reconstruct the gas density profile. The density profile is directly related to the acceleration capabilities of the plasma, therefore it is imperative to the optimisation of a LWFA to assess and understand its shape and features. It is also useful for initial characterisation of an untested gas jet, assessing the structure of its profile and the effects on a generated electron beam.

During 5Hz accelerator operation, the target chamber requires a significant lead shielding construction around the interaction chamber. The probe beam line must therefore be directed up to the roof of the target chamber, as shown in Fig. 3. The first lens with focal length 500mm is situated before the bottom periscope mirror. The diagnostics breadboard is then mounted to the aluminium framework above the chamber, not the chamber itself, to minimise the affect of vibrations produced from the vacuum pumping system.

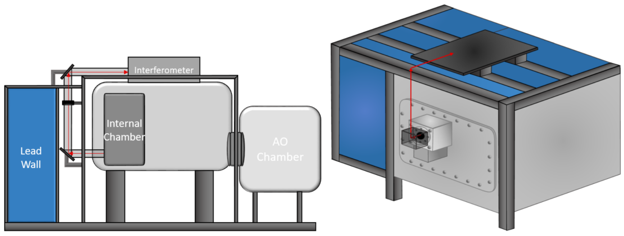

Figure 3: Diagrams showing the trajectory of the probe beam after the interaction point onto the roof of the chamber.

When choosing an interferometer design, the main consideration was giving control over both the spatial and angular separation, whilst keeping in mind the compactness required. A Mach Zehnder configuration was implemented, fitted with a delay line in one arm to allow for precise matching of path lengths. The layout of the interferometer is depicted in Fig. 4, shown with the shadowgraphy system on the same breadboard. Testing of the interferometer with a 25 μm micron wire positioned at the interaction point using the continuous wave beam produced clear, vertical fringes shown in Fig. 5. This indicated that the two arms were suitably spatially overlapped, and that the system was aligned. The temporal overlap of the two paths was assessed using the low power pulsed laser. Using the adjustable stage in one of the arms of the interferometer, the path length was varied until high contrast fringes were seen on the camera, demonstrating good temporal overlap.

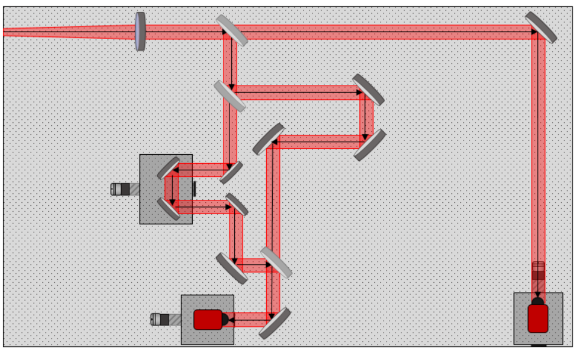

Figure 4: The layout of the probe diagnostics breadboard. The achromatic lens has a focal length 750mm. The beam is split 50:50 to a shadowgraphy system and a Mach Zehnder interferometer with delay stage.

The imaging system produced an overall magnification of x1.25, which fitted the theoretically predicted plasma channel size comfortably on the camera chip. The probe was spatially calibrated by placing an object of known diameter at the interaction point, taking an in focus image, and measuring the distance in pixels of the object.

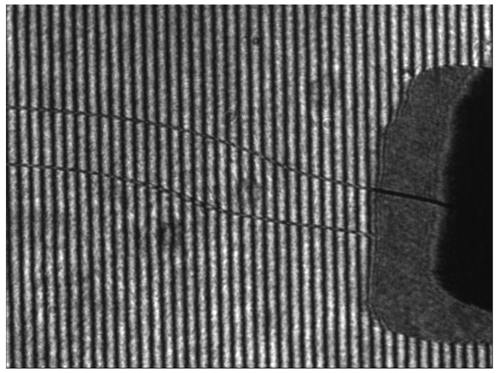

Figure 5: Interferometry image of a 25 micron horizontal wire at focus to simulate a plasma channel.

5 Results

During the first full power shots in TA2, data was captured from both the shadowgraphy and interferometry systems. Fig. 6. shows a raw interferogram taken during laser wakefield operation. The reduced width of the image is as a result of the probe passing through the $\sim$ 2 mm long aperture in the gas cell. Clearly, a significant phase shift is present.

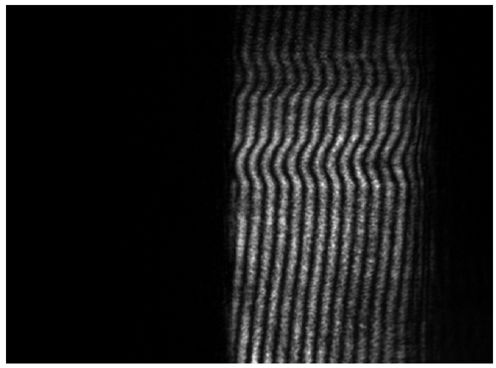

Figure 6: An interferometry image captured by the probe diagnostics showing a phase shift caused by the plasma during laser wakefield operation.

Two areas of disturbance can be seen due to the folded Mach Zehnder interferometer setup [2], and are reflected duplicates of one another, and so only the more central shift was chosen for further analysis.

The Gemini facility designed an interface capable of performing phase and density profile retrieval analysis on interferograms, via both 1D Fourier filtering and continuous wavelet transforms. A snapshot of the density tab from this software is shown in Fig. 7., using the data in Fig. 6. as the input image, as well as a reference image captured during data collection.

The plots produced by the software show a well defined plasma channel with some intensity variation along the laser propagation axis. From this, a density profile was reproduced by assuming a cylindrical phase shape,

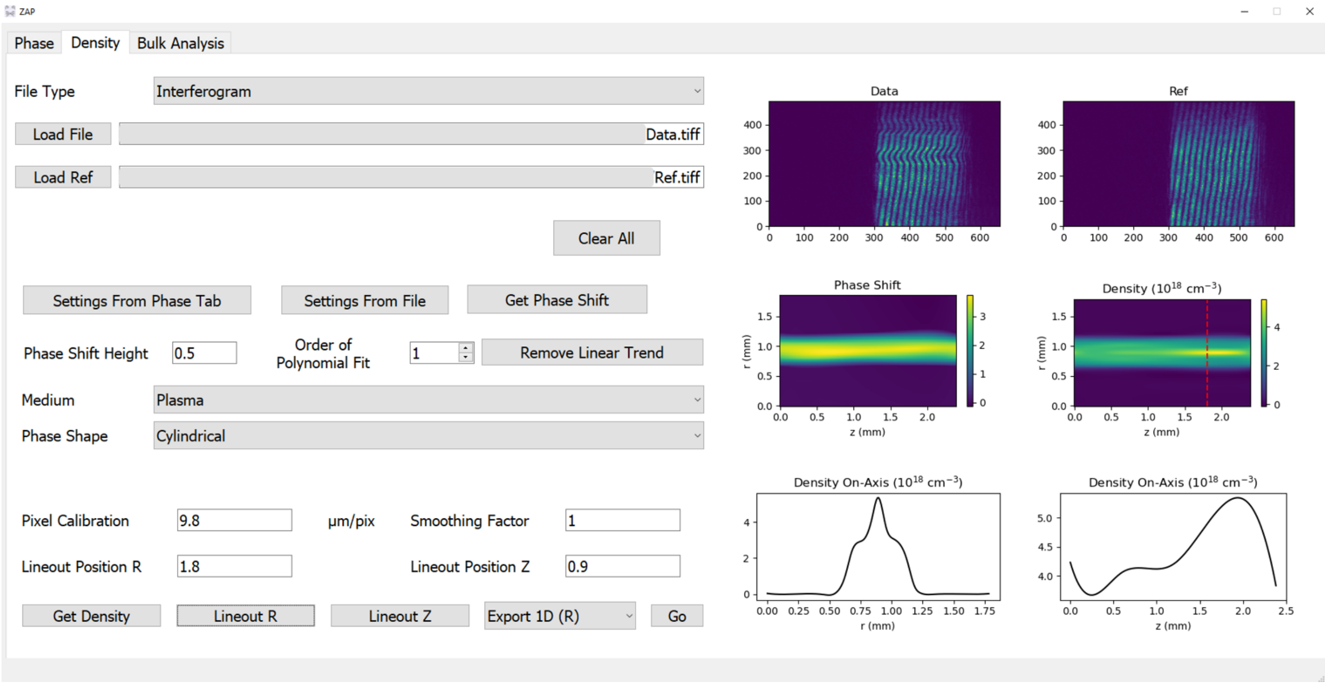

Figure 7: A screenshot of the phase and density retrieval software performing analysis on the data shown in Fig. 6.

as expected from the plasma channel. Line outs of the profile across both axis indicated density peaks of approximately 5x10^{18} cm^{-3}. From these results, a density resolution value can be inferred; one pixel of phase shift in the interferogram is equivalent to a density of 1x10^{17} cm^{-3}.

6 Conclusion

A probe beam has been established within target area 2, with suitable properties and resolution capabilities for imaging the plasma channel in a laser wakefield accelerator. The interferometry system obtained the phase shift introduced by the plasma channel. From analysis of the fringes, a clear phase profile was extracted, from which the density profile within the gas cell was calculated. The ability to access and retrieve this information will be crucial to the optimisation of the plasma accelerator.

References

[1] T. Tajima and J. M. Dawson, *Laser Electron Accelerator*, Phys. Rev. Lett, 43, 036407 (1979)

[2] F. Brandi, L. A. Gizzi, *Optical diagnostics for density measurement in high-quality laser-plasma electron accelerators* High Power Laser Science and Engineering, Vol. 7, 26 (2019)