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Laser plasma density measurements using interferometry

S. S. Harilal and M. S. Tillack

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Fusion Division
Center for Energy Research

University of California, San Diego
La Jolla, CA 92093-0417

Abstract: Fabrication of an interferometer is planned at the UCSD Laser Plasma and Laser-Matter Interactions Laboratory. The primary goal of this project is to measure the density at early times in the evolution of highly transient laser created plasmas. We describe the design concepts and details of different kinds of interferometer for measuring density evolution, especially during early time of plasma expansion. This diagnostic tool is very important for characterizing EUV laser produced plasma light as most of the EUV radiation is emitted only during the laser pulse.

Introduction

Pulsed laser induced plasma has a very short temporal existence and is transient in its nature, with a fast evolution of the characteristic parameters that are heavily dependent on irradiation conditions such as incident laser intensity, irradiation spot size, ambient gas composition and pressure. It is also true that these parameters vary drastically with axial or radial distance from the target surface under the same irradiation conditions. The key parameters of laser-ablated plumes are density and temperature. As the degree of ionization under ordinary ablation conditions is not negligible, one is led to consider the density and the temperature of the several species constituting a plasma, i.e. ions, electrons and neutral atoms. But at early times, the characteristics of the plume are governed primarily by electron contributions to temperature and density. The temperature can be estimated for the entire duration of the expansion of the plume with the aid of x-ray and visible spectroscopy. There are several diagnostic techniques employed for the determination of electron density, which includes, plasma spectroscopy, Langmuir probe, microwave and laser interferometry, and Thomson scattering. Plasma density determination using Stark broadening of visible spectral lines is a well-established and reliable technique in the range of number density from 10^{15} to 10^{18} cm^{-3}. But optical emission spectroscopy is not a good tool at early times in evolution of the plume (<50 ns) as most of the emission is contributed by continuum radiation. Electron density measurements in the early time can be done using the Stark broadened spectral profile of EUV radiation, but the resolution of the EUV spectrograph should be very high, which can be very costly. Thomson scattering is the most direct and least theory dependent method, even though the very low cross section of the underlying process makes the experiments very difficult to undertake. The usage of Langmuir probes is limited at early times of transient plasma diagnostics because of the slowness of the electronic system for the measurement. Laser interferometry, based on the analysis of the fringe structures originated by a probe beam crossing the plasma cloud, is a versatile tool for estimating the plume density at earlier times. It permits a very accurate determination of the electron density and is particularly used in the first instants of plume expansion, when the strong continuum associated with bremsstrahlung and recombination emissions does not allow a clear detection of the emission line-shape.

Since the advent of optical lasers, interferometry has been widely used to study different types of plasmas. This powerful technique provides information in the form of two-dimensional maps of the electron density, often without the need of extensive modeling. In a laser interferometric set-up, a probe beam is split into two and allowed to recombine to form the fringes. The expanding plasma is placed in one of the arms of the interferometer, where the probe beam passes parallel to the target or orthogonal to the plume expansion direction. The interferometric method utilizes the fact that the plasma index of refraction is proportional to the density of free electrons in plasmas. The variation in the index of refraction is similar to a change in the path length of the probe laser beam, resulting in a phase shift, which can be determined by the fringe amplitude of combined probe and reference beams. The time resolution of the interferometer depends on both the duration of the probe pulse as well as the gate timing of the detector system. The Nd:YAG laser in our lab provides 8 ns FWHM pulses at 532 nm and usage of these pulses for probing the laser created plasmas will provide the density mapping with a time resolution equivalent to its pulse width. The relatively long duration of the pulses may make the interferograms susceptible to blurring of the interference fringes that results from the rapid local variations of the electron density during the exposure time within fast moving plasma. But an 8 ns pulse probe laser is adequate for mapping the density far from the target surface in a laser-produced plasma where density variations are not as fast compared to the plume evolution at early time. Currently we are developing a Stimulated Brillouin Scattering cell for compressing the Nd:YAG pulse from 8 ns to below 1 ns. With 1 ns probe pulses, better information of the electron density profiles during or at the end of the pump laser pulse will be obtained.

Several interferometric configurations can be used for density mapping in a laser-produced plasma. The most common configurations for density measurements are Michelson, Mach-Zehnder and Normarski. In the following sections a brief description is given for these interferometers along with optics layout, diagnostics, and test procedures. A brief section is also added for Moiré deflectometry, which is a complimentary technique for measuring plasma density with the help of couple of Ronchi gratings.

Background on Laser Interferometry

Measurement of the variation of refractive index allows the determination of several properties of a transparent medium. There are two different ways to obtain that variation: by beam-deflection angle measurement (shadowgraphy) or by phase measurement (interferometry). The shadowgraph technique consists of passing a pencil of light through the test section and letting it fall directly, or via an imaging lens, onto a recording device such as a photographic plate or a charged coupled device (CCD) matrix. In interferometry, the beam of light traversing the medium undergoes phase variations that can be revealed by interferometric methods.

In an interferometer, two beams travel along separate paths before they are recombined. This requirement has led to the development of a number of interferometers for specific purposes. Firstly, the phenomena observed can be classified according to the method used to obtain these two beams. One way to obtain two beams from a single source is to use two portions of the original wavefront, which are then superimposed to produce interference. This method is known as wavefront division. Usually Fresnel mirrors are used to produce interference by wavefront division. Other arrangements incorporating wavefront division include Young's double slit, Lloyd's mirror *etc*. [1]. The other method by which two beams can be obtained from a single source is by division of the amplitude over the same section of the wavefront and this method is known as amplitude division. Typical interferometers using amplitude division are the Michelson interferometer, Mach Zehnder Interferometer, Sagnac Interferometer, *etc*. Amplitude-division interferometers do not have a limitation on the spatial coherence of the laser source and can probe larger objects [1].

For measuring electron densities of a laser created plume using an interferometric method, the plasma formed should be placed in one of the arms of the interferometer. The plasma may consist of ions, atoms and molecules in addition to free electrons; the probe laser wavelength selected should be well away from any absorption resonances in the plume so that contributions to the refractive index from bound electrons is negligible compared to that of free electrons in the plasma. Then the refractive index (μ) can be expressed as

$$\mu = (1 - n_e/n_c)^{1/2} \qquad (1)$$

where n_e is the electron number density and n_c is the critical electron density corresponding to the probe laser wavelength λ ($n_c = 10^{21}\lambda^{-2}$ cm^{-3}, where λ is in microns). The probe laser radiation penetrates the plasma only to the point where the electron density reaches the critical density, at which point the reflection occurs. The ratio of the fringe shift to the fringe spacing (Δ) can be related to the line integral of electron density along the probe beam path by

$$\Delta = (2\lambda n_c)^{-1} \int n_e(l)dl \qquad (2)$$

where λ is the probe laser wavelength and l is the optical path length through the plume. A 2-dimensional mapping of the density can be obtained with the help of Abel inversion technique.

The most common interferometric methods for measuring the density of laser-produced plumes are Michelson, Mach-Zender and Nomarski, the details of which are given in the following sections. We can also employ Moiré deflectometry for measuring density of the plasma without many modifications of the experimental set up. A brief section is also given for Moiré deflectometry after the interferometry sections.

The Michelson Interferometer

In a Michelson Interferometer, the light from the probe laser source is split into two beams using a beam sampler (BS) with nearly equal amplitudes as shown in figure 1. These beams are reflected back at two mirrors (M) and return to beam sampler. For measuring refractive properties of laser created plasma, the target is placed very close to the one of the arms of interferometer such a way that the beam grazes the sample surface [2]. The output of the interferometer depends on the phase difference between light rays traversing the two arms. The shift in the fringe pattern is measured as a voltage change using a fast photo diode or a photo-multiplier tube. Measurements using interferometers are expressed in fringes per unit length. Walkup *et. al* [3] successfully used Michelson interferometer for free electron density measurement in a laser created plasma. One of the limitations of the Michelson interferometer is that the probe beam must pass through the test area (plasma) twice, thereby complicating alignment and data reduction.

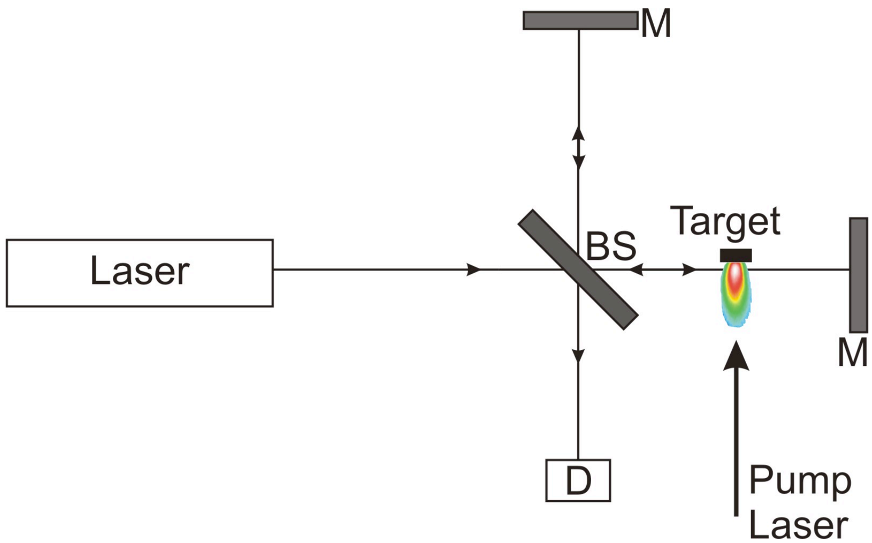

Fig. 1. Typical set-up for plasma density measurement using Michelson Interferometer

Mach Zehnder Interferometer

In the Mach-Zehnder interferometer the probe beams follow different pathways before interfering. This simplifies the interpretation of the observed fringes by passing light through the test area only once. A typical set-up for the Mach-Zehnder interferometer for plasma density measurement is given in figure 2. Mach-Zender interferometers have been used extensively for measuring free electron densities of laser produced plasma by different groups. Doyle *et. al* [4] used this method for investigating spatio-temporal evolution of the electron number density in the initial stages of plume expansion. They used a YAG pumped dye laser (FWHM 5 ns) as the probe laser and a 2 ns gated ICCD for the detection. Villagran-Muniz *et. al* [5] and Mao *et. al* [6] used the above experimental set-up for doing interferometry and shadowgraphy in laser created plasmas. A shadowgram can be recorded instead of an interferogram, when the reference path of the interferometer is blocked.

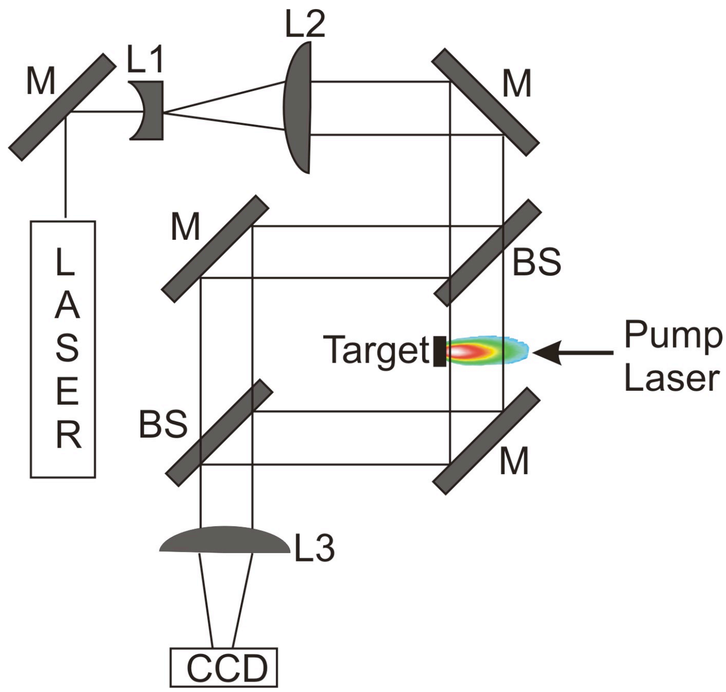

Fig. 2. Mach-Zender interferometer set up for plasma density measurement.

Nomarski Interferometer

The Nomarski interferometer employs a Wollaston prism for dividing the beam, and is used widely for interference microscopy. Using a Wollaston prism as a beam splitter, its main advantages are its relative simplicity, the absence of alignment and stability problems. Nomarski has been used often in measuring plasma density; in this procedure the polarized probing laser beam passes through the plasma and is separated by a Wollaston prism into ordinary and extraordinary light that travels through the analyzer.

The working principle of the interferometer is as follows. Let us assume the probe laser is polarized at 45 degrees to the vertical. A single lens is used in the interferometer after the target plasma so that the interferometer depends upon the spherical wavefronts. After passing through the lens, the beam converges to a focus and diverges in a spherical wavefront. As the diverging beam passes through the Wollaston prism it is split into two beams (one with vertical and other with horizontal polarization) with an angular separation. The diverging beams in the two polarizations can be projected backwards to two apparent foci, which are the centers of the two spherical wavefronts for the interferometer. A polarizer, oriented parallel or perpendicular to the 45 degree incident polarization, is placed in between the Wollaston prism and detector so that the transmission is the same for both polarizations and the two beams will interfere at the detector plane.

A typical set up for the Nomarski interferometer for plasma density measurement is given in figure 3. The interferometer ensures equal optical path length between ordinary and extraordinary rays and the central fringe located at the axis of the interferometer. It is therefore ideally suited for illumination with very short pulses (picoseconds) with their inherently low temporal coherence. The spatial resolution of the system is determined only by the quality of the imaging lens and can therefore reach very high values. The fringe separation can be easily adjusted by the spacing between imaging lens and Wollaston prism. The Nomarski interferometer produces two partially overlapped images of the region of interest, two images of the targets are visible in the detector plane.

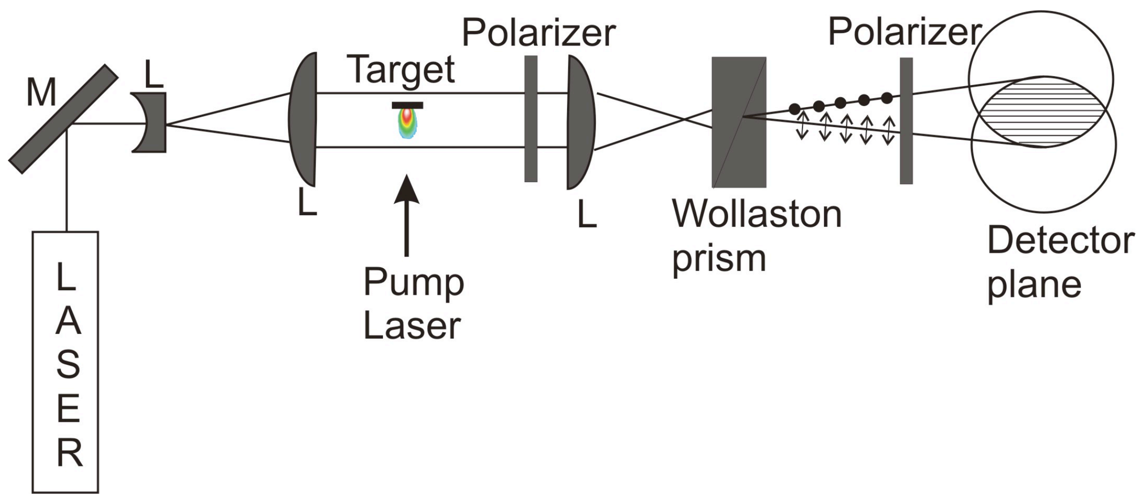

Fig. 3. Schematic of the Nomarski interferometer for measuring plasma densities. For better illustration the detector plane is shown tilted by 90 degrees.

The fringe separation δ in a Nomarski interferometer is given by

$$\delta = \lambda b/\varepsilon a \qquad (3)$$

where ε is the angle that the orthogonal polarized beam are created by the Wollaston prism, a is the separation distance between prism and focusing lens and b is the separation between the prism and the detector plane. So the fringe separation can be easily varied by changing the distance between the focus of the lens and the Wollaston prism. The fringe orientation can also be varied by a rotation of the polarizing elements.

In the previous sections, the details of the different kinds of interferometric set up were given for plasma electron density measurements. The use of a Michelson interferometer is limited as the probe beam passing through the plasma medium twice, thereby complicating alignment and data reduction. The probe passes through the test medium only once in both Nomarski and Mach-Zender interferometers. Based on Wollaston prism as beam splitter, the main advantages of Nomarski interferometers are its relative simplicity, the absence of alignment and stability problems. The basic experimental arrangement for Nomarski is similar to high-speed photography (light source – object- lens – film). The interferometer ensures equal optical path-length between the split beams and hence it is ideally suited for illumination with very short pulses with their inherently low temporal coherence. The Nomarski interferometer may be used at different wavelengths without modifications.

Typical problems with interferometers:

The two primary performance parameters which characterize interferograms are fringe visibility and resolution. The resolution of an interferometer depends on the minimum fringe shift that the analysis program can resolve. The minimum density increment Δn_e that can be measured depends on the minimum detectable fringe shift. The measurements in plasmas with no density gradients allow direct correspondence of the fringe shift and plasma density along the laser line of sight. The maximum electron density measurable with interferometry is limited to the critical density of the plasma that relates to the probe laser wavelength. However, when the plasma density approaches a fraction of a percent of the critical density, refraction and opacity effects can significantly limit these kinds of diagnostics. The change of the interferometer contrast due to scene beam deflection in plasmas with density gradients reduces the fidelity of interferometer measurements due to the change in the contrast of the fringe. The decrease of the fringe contrast reduces the accuracy of fringe amplitude measurements and sometimes it makes an accurate measurement impossible, especially in high plasma density experiments. Knowledge of the extent and effect of refraction is therefore an important consideration for accurate analysis of the data. Lisitsyn *et al* [7] documented the effect of laser beam deflection on the accuracy of interferometer measurements. They derived analytical expression for the maximum acceptable deflection angle and compared to the experiment.

Another important factor affecting the observability of the temporal fringes is the contrast ratio, which depends not only on the time resolution but also on the attenuation of the probe beam in the plasma. At high plasma densities, free-free absorption can attenuate the probe beam, obscuring part of the interferogram. Nevertheless, both of these adverse effects can be greatly reduced by significant shortening of the wavelength of the probe beam. For plasma-probing experiments, good intensity is also needed for the probe laser to overcome absorption and intense plasma self-emission. Hence typical laser energies ~ 20 mJ are necessary for probing transient laser created plasmas.

The time resolution of the interferometer set up basically depends on both the probe laser pulse width and detector gating. In principle, with the use of fast-gated (2 ns gated) intensified CCD, we can easily achieve 2 ns resolution in the interferometry set-up. But a lot of effort is needed to protect the intensified CCD from over exposure. With 8 ns probe laser pulse, and with a free running CCD detector the maximum time resolution achievable is the probe laser pulse width itself. But during the probe laser duration the density variations will create blurred fringe structures. Borghesi *et al* [8] used a 100-ps laser as the probe, but failed to gather density information at the peak of the pump laser pulse, even at times at which the peak density was well below critical. The loss in the fringe visibility was caused by density variations taking place throughout the duration of the laser pulse. They achieved density information at the peak of the pump laser pulse by using a 1-ps probe laser pulse [8]. So a probe laser with shorter pulses and lower wavelengths is needed for getting good interference fringes.

Moiré deflectometry

Moiré deflectometry is a refinement of the Schlieren imaging technique that provides a quantitative means to measure transverse gradients in the object's refractive index [9]. The technique involves passing a highly collimated light beam through a phase object and analyzing the transmitted light with a pair of ''Ronchi'' rulings. The Ronchi ruling essentially consists of opaque and transparent stripes of equal width separated by a distance, p. The rulings are placed transverse to the light path, parallel, and separated from one another by a distance, $D = Nd$. The rulings are rotationally offset by a small angle θ. N assumes an integer value and d is called the

‘‘Talbot spacing.’’ The Talbot spacing is the distance at which the geometric shadows produced by the first Ronchi ruling are co-located with the nontransparent stripes of the second ruling. The result is a Moiré fringe pattern (Moiré deflectogram) that can be recorded using a detector placed behind the second Ronchi rulings. Note that a high contrast fringe pattern is feasible only for small offset angles θ and at limited distances between the rulings (usually few Talbot spacings), since the diffraction patterns lie along an arc, and at larger spacing the fringe image is no longer formed.

Moiré deflectometry has been used extensively to measure a variety of physical phenomena. It is a relatively recent technique that yields optical phase information similar to that obtained in interferometry. Deflectometry has been used to perform routine characterization of optical components and dynamical studies of fluid flow. It has also been used to measure plasma density of a laser created plume. A typical Moiré pattern and the configuration of Moiré deflectometry showing the probe beam passing through two rotationally offset ruling separated by a distance D is given in figure 4. Ress and co-workers [10] constructed soft X-ray Moiré deflectometer for the measurement of high-density laser produced plasma and a peak density ~ $3.2\text{x } 10^{21}$ cm^{-3} was measured.

With the help of two Ronchi ruling we can fabricate a moiré deflectometer set up and this should be complimentary to interferometric methods for measuring density.

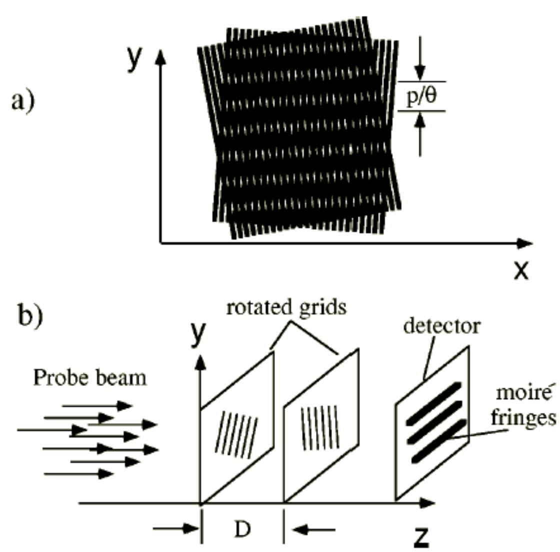

Fig. 4. Typical Moiré pattern (a) and the configuration of Moiré deflectometry showing the probe beam passing through two rotationally offset ruling separated by a distance D (b)

Design Options and Rationale

There are several key issues that must be addressed in order to ensure the success of laser plasma density measurements using interferometry. Most important of them are refractive and opacity effects. Moiré deflectometry is a complementary method to interferometry can be also used to verify the results obtained with interferometry. The basis of all interferometric methods is the interference pattern formed by superposition of two or more light waves originating from the same coherent source, but propagating in different paths. The fringe pattern indicates the local phase shifts arising from the difference in the optical path traversed by the interfering beams. Comparing various configurations of interferometry, the Nomarski interferometer is considered to be very stable. Moreover, with slight modifications, the interferometer can be converted into deflectometer.

Our existing laser produced plasma chamber can be used for performing interferometry without any modifications. The schematic of the present experimental set-up including EUV transmission grating spectrograph, energy monitor, optical spectroscopy, and Nomarski interferometry are given in figure 5.

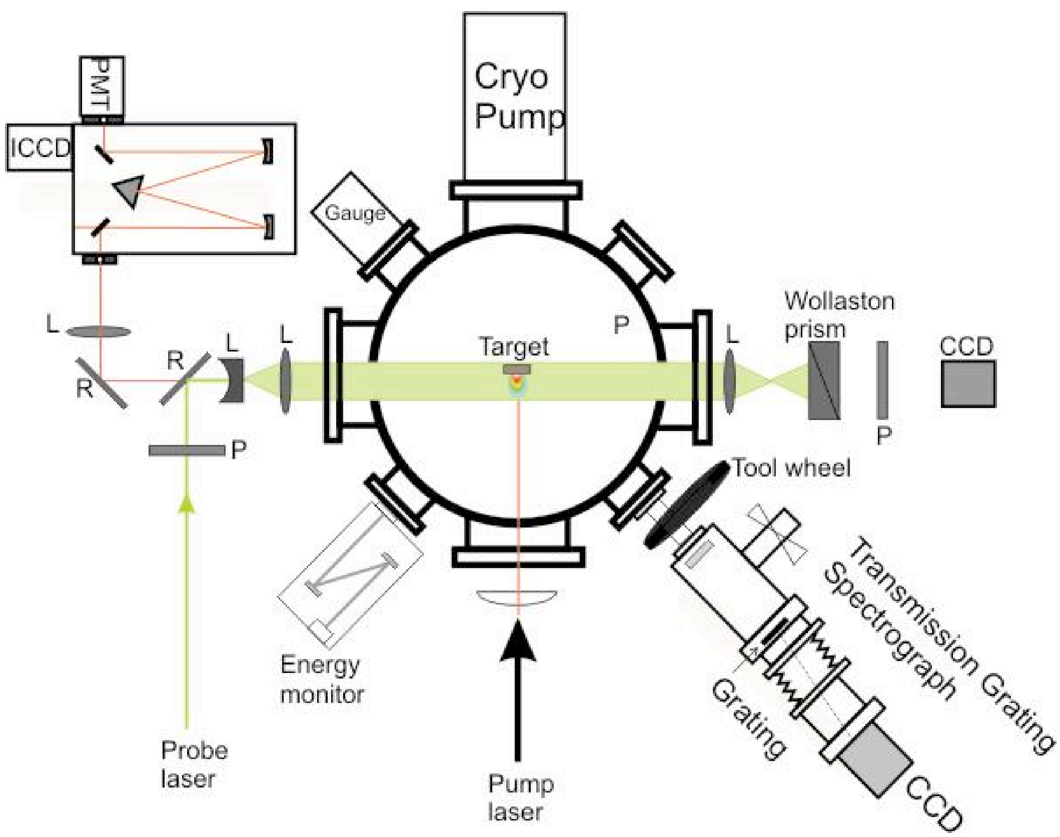

Figure 5. Schematic of the experimental arrangement for Nomarski interferometer.

Several design variations can be explored for the Nomarski interferometer set-up. This includes the source of the probe beam (either SBS compressed beam or DCR 2) and the detector selection. In principle it is better to use shorter pulse-length lasers for probing that will provide better time resolution. We can also achieve better time resolution by using fast-gated cameras (for example ICCD). The replacement of the Wollaston prism and polarizers with Ronchi rulings will convert the experimental system from interferometry to deflectometer. A schematic of the Moiré deflectometer is given in figure 6.

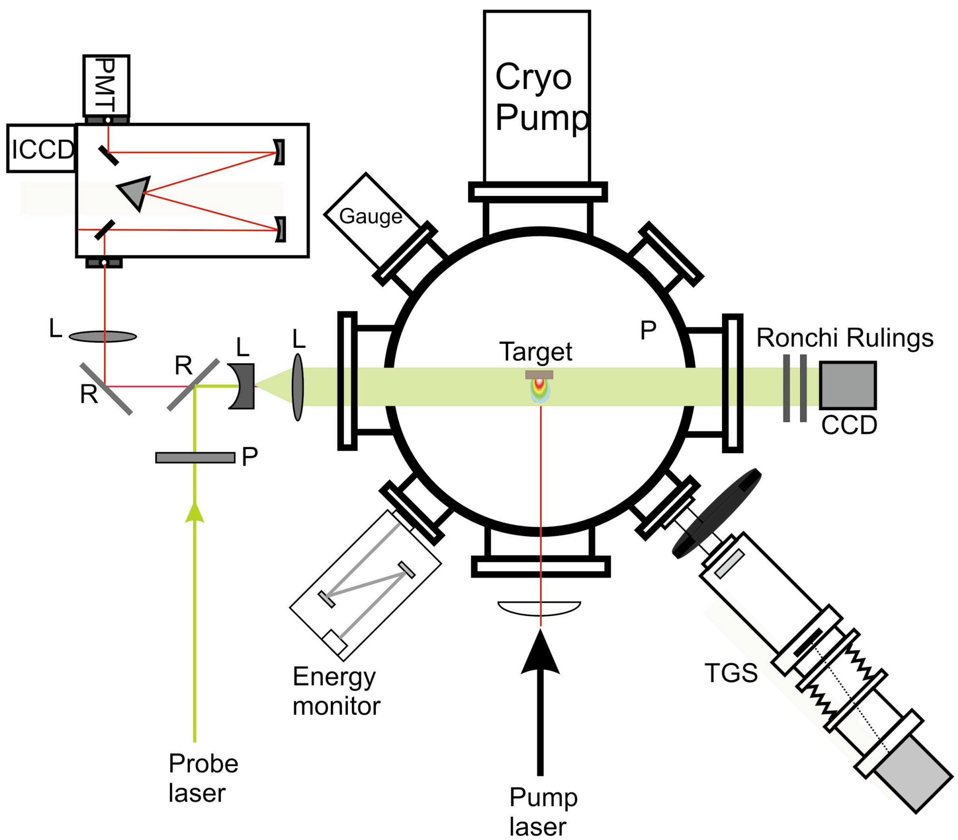

Fig. 6 Schematic of the moiré deflectometer set up.

Facility Description and Table Layout

The energy sources for producing laser plasma (pump source) and probe laser (for interferometry) are Spectra Physics QuantaRay Pro-290 laser with harmonic generators and injection seeding and DCR 2 with SHG. The QuantaRay Pro-290 emits approximately 1 J in 8 ns FWHM at the fundamental wavelength of 1064 nm. At 532 nm, the output energy is approximately 500 mJ. Currently SBS work is progressing to compress the 532 nm beam of the QuantaRay Pro-290 to 1ns or less FWHM. The DCR 2 gives maximum energy 550 mJ at 1064 nm and 250 mJ at 532 nm. The QuantaRay Pro-290 laser and SBS pulse compressor will be located in an optical table along with beam conditioning and diagnostics at both 1064 and 532 nm.

The synchronization of pump and probe beam is an important part in time resolved interferometric set-up. The timing of the probe and pump pulses should be monitored using a photodiode. For proper timing, a pulse generator with timing gate will be used for triggering pump laser, probe laser and detector. Important optics needed for performing interferometry include Wollaston prism, polarizers, Ronchi gratings *etc*. An imaging camera is also needed for capturing the interference fringes.

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