A fibre based triature interferometer for measuring rapidly evolving, ablatively driven plasma densities

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We report on the first use of a fibre interferometer incorporating triature analysis for measuring rapidly evolving plasma densities of $n_e \sim 10^{13} / \text{cm}^3$ and above, such as those produced by simple coaxial plasma guns. The resultant system is extremely portable, easy to field in experiments, relatively cheap to produce and – with the exception of a small open area in which the plasma is sampled - safe in operation as all laser light is enclosed.

Introduction

Many different types of interferometry are used in plasma physics research; broadly speaking these interferometers can be grouped into 2 classes – spatially resolved or ‘imaging’ interferometers, and temporally resolved interferometers that sample fringe shifts at a single point over time. Temporally resolved interferometers have been used to, for instance, provide the measurements of electron densities during the ablation stage of a wire array z-pinch [1], sample the jet of plasma produced by a coaxial plasma gun [2], understand plasma densities inside tokamaks [3], and study atmospheric pressure plasmas [4]. Several separate points can be sampled by

multiple individual interferometers, and these measurements are often supplemented by one or more 2D, spatially resolved interferograms provided by a short pulsed laser, e.g. [1]. The resultant data enables reconstruction of the plasma density in space and time, enabling comparison of theory and simulation.

Temporally resolved interferometers are often built as ‘open beam’ systems with simple arrangements of mirrors, beamsplitters and sensors to sample a target. However, producing an accurate record of plasma density evolution can prove difficult in many situations. In particular, the fringe shift produced by an increase in plasma density is sometimes very small, meaning the

interferometer itself must be remarkably stable on timescales appreciably longer than the event under study, lest any background noise, such as external mechanical vibrations or air currents, obscures the measurements. Ideally the interferometer should also incorporate polarising optics to provide quadrature data analysis [3] - enabling the observer to know whether the plasma density is increasing or decreasing at any particular time, as well as providing increased accuracy. These needs can result in such interferometers being extremely large and expensive, though they offer incredible accuracy. A good example of such a system is the two colour heterodyne interferometer used extensively at the Naval Research Labs [5]. Here, the addition of a second colour allows the contributions to the phase shift from neutral density gas and electron density in the plasma to be extracted. In the last 10-20 years, fibre optic systems used in the telecommunications industry have developed immensely. This has enabled the development of fibre based interferometry systems such as [6]. These have offered the potential for portability, whilst reducing costs associated with needing extremely stable optical tables for mounting multiple mirrors. Operating typically at 1550 nm, the sensitivity of the interferometers to changes in plasma

density is increased compared with many open beam systems operating at 532 or 652 nm. However, most fibre-based interferometers operate using single mode fibres and have no simple 'quadrature' like system for discriminating increasing or decreasing densities. This can lead to confusion during analysis.

In this paper we describe a new type of fibre based interferometer that has been developed to study the evolution of plasma from a 'cable gun' (also referred to as a "plasma gun") – a simple coaxial arrangement of radial electrodes separated by a Teflon insulator, which, on the application of high voltage pulse ablates to form a wide jet of plasma [7]. Rather than using single mode fibre-optics, the interferometer relies on polarising optics and employs an 'in fibre' triature (aka three-phase) system to provide an unambiguous signal for data analysis.

Triature systems are similar to quadrature systems in principle, but triature analysis can be accomplished with a single fibre-optic component, whilst quadrature analysis (for technical reasons) usually requires far more components, usually external to the fibre. As with quadrature systems, triature can determine whether the phase shift is increasing or decreasing and, as at least one channel is

always passing through an area of the phase shift where the amplitude varies significantly with time, sensitivity is increased.

Apparatus

Figure 1 shows the layout of the triature fibre-optic interferometer (FOI) system, both in schematic and photographic form.

Fig 1: Top: Simple Schematic of the FOI, showing key components (PD – photodetector, OPM – Optical Power Meter). Bottom: A photograph of the equipment used. The plasma under study is created in the vacuum chamber in the High Voltage cage at the rear of the optical table.

The interferometer operates at 1550 nm. The main component in the triature system is the 3x3 coupler. The 3x3 coupler combines the

three input channels onto the three output channels with a (nominally) 120° phase shift between them. By combining a balanced reference signal with the reflected signal, it is possible to obtain an interferometry signal.

The interferometry chord is the only open beam section of the system, and passes through a vacuum chamber containing the plasma gun.

The collimating lens and mirror are approximately 50 cm apart. The beam diameter is about 1 mm in the open beam section. Our current configuration is a Michelson formation, which leads to the beam passing through the plasma twice, which provides double the fringe shift, increasing the sensitivity of the system.

The collimating lens was implemented to remove the divergence of the beam when it exits the fibre, enabling the beam to maintain a ~1 mm diameter throughout its transit through the open-beam region. A small diameter is key to ensuring good spatial resolution. The spatial resolution could be further improved by using focussing, rather than collimating lenses. This would remove potential refraction issues when dealing with large plasma density gradients causing the light to be refracted out of the system, lowering the signals. However, if a small amount of light is lost by being refracted out of the system, the analysis is not unduly

affected, as the triature analysis is dependent on the relative intensities of the three signals, not their absolute values.

The system is very quick and simple to construct, being completed easily in just a few hours. Aligning the open beam section is the most time-consuming part of the process, the rest of the system is fibre-based, so requires no alignment apart from standard fibre hygiene habits during construction.

Once made, the fibre components are rugged, and multiple channels could readily be mounted in the same standard instrumentation rack unit. Each channel requires approximately 100 mm of vertical space, though this will depend on the choice of detector, as the other components do not require very much space.

Initial Testing

The initial deployment and configuration of the system was very straightforward. A Class 1 laser (3S photonics – LMI 1905 butterfly InGaAsP 10 mW 3CN00386##) was used, and it was found to be powerful enough to provide a signal, but significant noise was experienced on the signals, rendering the analysis difficult (the analysis compares the relative amplitude of the different signals over time, and so any large fluctuations caused by noise would

require smoothing, potentially obscuring high speed events). A second laser was tried, the Class 3R version of the first laser (3S photonics – LMI 1905 butterfly InGaAsP 30 mW 3CN00302##). The idea behind switching to a Class 3R was to increase the signal strength. It was found, however, that the noise strength also increased by the same factor. The noise is understood to be largely due to the linewidth and stability of the laser used. The two lasers diodes mentioned above have relatively large linewidths of ~5 MHz. Another laser (an NP Photonics RFLS-50 (Class 3R), set to an output power of 35 mW) with a much narrower linewidth specified as <3 kHz was used, and this led to a dramatic improvement in the quality of the signal.

Figure 2 shows screen captures of these changes (note the scale changes between images). The first two images show the signals from the butterfly mounted lasers, the poor signal to noise ratio is obvious. The third image was obtained using the NP Photonics laser, and shows a significant improvement. The scale is the same for the two 3R captures, middle and bottom in the figure. The interference patterns shown in Figure 2 were caused by introducing a small vibration into the system. Even without these vibrations, over long time periods the signals from the three

detectors do vary. Background noises, thermal currents and so on all contribute. These, though, occur over timescales (ms) far longer than the timescale of interest to our study (ns - μ s), and so do not cause significant hindrances.

Figure 2: showing typical traces obtained by the Class 1 (top) and the Class 3R laser units (middle and bottom).

The photodiodes initially used in our experiments were shielded, unamplified Thor Labs DET01 units. The background electrical noise level during experiments was estimated to be around 5-10 mV, and the relatively low amplitude signals (<100mV at best) from these detectors limited the plasma density that could

be accurately measured. A further, significant improvement was obtained by using Miteq DR-125G amplified detectors. The signal acquired then increased to ~ 2 V, whilst the noise level remained similar to before. This enables the interferometer to probe plasma densities in the order of $n_e \sim 10^{13} / \text{cm}^3$.

Analysis of data

The interferometer measures the change in optical path length caused by the change in refractive index of the material under study. An increase in neutral density leads to an increase in the refractive index, whereas an increase in electron density leads to a decrease. In highly ionised plasmas, the increase due to the neutrals and ions is small compared to the decrease due to the free electrons, and so can be ignored. The decrease in refractive index arises as the exposed electric fields of the free electrons interact with the electric field of the laser beam.

R. Priest gives a good analysis of the 3x3 coupler in [8], and D. Dolan describes a method for analysing the three phase signals in [9]. Both authors state that the three signals can be reduced to two quadrature signals, thereby simplifying the analysis.

If perfect coupling, and perfect 120° lead and lag angles are present, the phase angle reduces

to Eq (2) (from [8]) which is the ratio of the two quadrature signals:

$$\tan(\phi) = \sqrt{3} \frac{D_3 - D_2}{2D_1 - D_2 - D_3} \quad (2)$$

$D_{1,3}$ are the amplitudes of the signals from the three photodetectors, with the baselines removed. D_2 leads D_1 by 120° , D_3 lags D_1 by 120° .

If the system is not perfect, there are many extra terms that need to be ascertained by characterising the system in situ immediately prior to the production of any plasma. The lead and lag angles are approximately 120° , but vary over long timescales, and between different 3x3 couplers. Similarly the coupling coefficients of the 3x3 coupler (the amount of signal shared between neighbouring channels) may not have be the perfect 1:1:1 relationship, and so this also needs characterisation.

The THRIVE method described by Dolan ascertains the parameters of the 3x3 coupler through ellipse characterisation, which then provides the lead and lag angles, and other parameters enabling a unique determination of fringe shift and hence plasma density vs time.

A reliable characterisation requires the interferometer signal to pass through a large part of a fringe shift. Prior to each shot, external sources such as ground vibrations provide a source of oscillation that is sufficient

to allow for characterisation of the 3x3 coupler, but do not cause problems in the short timescale of the experiment. Failure to perform such an in-situ characterisation leads to a poor fit to the 3x3 couplers characteristics, and limits the accuracy of the analysis.

The calculations include a multiplication factor, the fringe constant, which is defined as $\lambda n_c / \pi$, where n_c is the “critical density” of the plasma, $\lambda n_c / \pi = m_e c^2 / e^2 \lambda$. The fringe constant is the change in plasma (electron) line density that would lead to the interferometer undergoing a complete fringe shift. This was calculated to be approximately $2.3 \times 10^{16} \text{ cm}^{-2}$, which leads to calculated plasma gun densities that are close to those published elsewhere, obtained using different interferometers systems [5, 10].

Figure 3 shows oscilloscope traces of the three output channels from the 3x3 coupler during a typical discharge from a coaxial plasma gun. The gun had an opening angle of ~ 60 degrees with an outer electrode ~ 6.35 mm and in use a $0.15 \text{ } \mu\text{F}$ capacitor, charged to 21 kV, was discharged across it. The interferometer was set to sample across a chord ~ 5 cm from the nozzle of the plasma gun (This distance was used throughout all of the experiments discussed here). The photodetector outputs track the amplitude variations closely as the

response time of the detectors is very short compared to the timescale of the plasma pulse. (1 ns cf. 4 μ s).

Typical line-integrated electron density traces calculated from the outputs are shown in Figure 4, and demonstrate the sensitivity of the interferometer ($n_e \sim 10^{14}$ /cm³), the relatively low noise level and the repeatability of the plasma gun. These data were obtained using the Thor Labs detectors, and so do not show the improvements attained by fielding the Miteq detectors, which exhibit a higher SNR.

Figure 3: Raw triature data showing output of all 3 detectors.

Figure 4: Calculated densities achieved on three shots (single pulse, 21 kV, ~3 kA, 1 mBar). The red trace represents a shot where the switch triggered a little later than the other two shots, leading to a slightly delayed plasma pulse.

Testing on an undamped repetitive plasma source

Use of the plasma gun with an undamped capacitor discharge (creating a rapidly oscillating current source ~16 kA, ~10 μ s period, 0.7 μ F capacitor used here) provided an interesting test for the capabilities of the interferometer.

During the discharge, the raw triature data shows large amplitude, short duration artefacts on all 3 channels, as can be seen in Figure 5.

Figure 5: Raw triature data showing output of all 3 detectors on an experiment where the plasma gun was energised by an undamped capacitor discharge

Calculation of the electron line density from the triature signals demonstrated these artefacts

were short duration spikes in electron density, as shown in Figure 6.

Figure 6: Electron density traces for three separate experiments with an undamped capacitor discharging through the plasma gun. (Note: Line density values are lower in this system due to the discharge occurring in a much lower pressure. $\sim 1 \times 10^{-4}$ mBar was used, rather than previous 1 mBar.)

The frequency of the spikes corresponds to the half-period of the current source, as shown in Figure 7, and the spikes only occur after the first maximum in electron line density. Figure 8 shows a current trace from the rapidly damped system used in the initial testing.

Figure 7: Current trace for the system driving the plasma gun in Figure 6. The trace shows significant

noise at early times, due to the air gap switch in the system breaking as a large discharge.

Figure 8: For comparison with Figure 7., showing rapid damping. As in Figure 7, the early time trace shows significant noise due to the switch firing.

Such variations have not been seen on our other experiments (even when the measured density was significantly greater than those shown in Figure 6) nor have they been reported in any other plasma gun studies.

There are several possible explanations for the spikes in electron density. They could be due to multiple breakdown events across the surface of the plasma gun during the experiment. After the initial peak in the current pulse, the current across the surface of the gun decreases, plasma recombines and conductivity decreases. Voltage across the gun reverses and increases until the surface breaks down again. Alternately they could result from the plasma/neutrals present being (further) ionised by UV emission from surface of the gun during the oscillating current pulse.

They may also result from some of the copper electrode material being ejected from the gun during multiple discharge events.

Figure 6 shows another feature of the triature analysis that users need to be aware of, namely, the density trace may sometimes show as having non-zero values for $t < 0$. This is due to the fact that the comparison essentially compares the relative amplitudes of the three signals in order to obtain the phase shift. If the $t < 0$ signal is noisy, or the characterisation of the 3x3 coupler is not performed, the small deflections in the oscilloscope traces can lead to erroneous analysis, giving non-zero densities. In the case of Figure 6, the $t < 0$ density is due to the noise in the three signals, and could be filtered out if desired. The noise can be seen in Figure 5. Improvements in signal quality ameliorate the zero signal accuracy.

Future work

Now that the interferometer is well understood, work has started on characterising and optimising the output from different plasma gun designs. It is felt that the interferometer is suitable for use as the main diagnostic in the study, and further channels are planned to be deployed, allowing the measurement of plasma density along multiple

chords in a plane. A spatially resolved interferometry system will also be fielded in parallel with the fibre interferometer to enable a more complete picture of the density distribution to be obtained in each experiment. The plasmas obtained in these and many other experiments may only be partially ionised, and so we plan to modify the system to include a second wavelength to allow two colour interferometry [2]. Work will also continue to further understand the nature of the “density spikes” shown in Figure 6. We intend to perform spectroscopic analysis of the optical emission of the plasma, to investigate the species present at different times during the discharge.

Finally we are looking at ways to further ruggedize the system, such as built-in heating and splicing the components to overcome losses at the connectors.

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