HIGH-SENSITIVITY INTERFEROMETRY OF PLASMAS AND GASES IN PULSED POWER EXPERIMENTS†

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Abstract

Accurate measurements of plasmas and gases in pulsed power devices are needed so they can be used (or avoided) as desired. This paper reviews measurements of plasmas and gases using the high-sensitivity, two-color interferometer in use at the Naval Research Laboratory (NRL) since 1993. The instrument uses two cw Nd:YAG lasers at 1.064 and 0.532 μm wavelengths that can be aligned along the same line-of-sight to simultaneously measure electron and neutral densities. This interferometer can measure optical path changes (phase shifts) as small as 10^{-5} waves. The interferometer's capabilities are illustrated by several examples, including the first measurement of electrons co-moving in vacuum with an intense proton beam, detection of gas turbulence, preionization of gas from a supersonic nozzle, and gas desorption from a metal surface exposed to intense UV.

I. INTRODUCTION

A high-sensitivity, two-color interferometer[1] was built by Science Research Laboratory in 1993 for the Hawk generator at NRL, supported by the (now) Defense Threat Reduction Agency. This device has proven to be a unique and powerful diagnostic tool for many pulsed power applications.[2] The interferometer was first used to diagnose plasmas and neutrals in a plasma opening switch (POS) experiment on Hawk.[3] The interferometer was subsequently adapted to many other pulsed power experiments and has yielded important information that cannot be obtained by any other means.

The instrument uses two cw Nd:YAG lasers at 1.064 (IR) and 0.532 (green) μm wavelengths that can be aligned along the same line-of-sight to simultaneously measure electron and neutral densities, as illustrated in Fig. 1. Each laser beam propagates through an independent Mach-Zender interferometer that measures the time-dependent line-integral of the density (line-density) of the medium being probed. The time response is limited only by the few-ns rise time of the photodiode detector circuit. The spatial resolution is determined by the laser beam diameter in the measurement region, typically 0.5 mm or less. The interferometer signals are directly proportional to the sine of the phase shift between the reference and scene beams. For many applications, the phase sensitivity is as small as 10^{-5} waves, limited by shot noise in the detectors. For the IR beam, this corresponds to a change in optical path length of 0.1 Å, less than the diameter of a hydrogen atom! This high-sensitivity is accomplished by a sophisticated vibration isolation system and detection circuit with common mode rejection and control of the initial phase. For more information on the operation of the interferometer, see Refs. [1] and [2].

The phase shift, $\Delta\phi$ (radians), is related to electron and neutral densities by

$$\Delta\phi = \frac{c_1}{\lambda}\int n_{neutral}dx - c_2\lambda\int n_e dx \qquad (1)$$

Here, λ is the laser wavelength, $n_{neutral}$ and n_e and are the neutral and electron densities, respectively, $c_2 = e^2/mc^2 = 2.82 \times 10^{-13}$ cm and $c_1 = 2\pi(\nu-1)/n_0$, where ν is the index of refraction of the neutral specie at density n_0.

The interferometer is limited to a horizontal, free-standing line-of-sight less than 1.1 m long. Also, the apparatus must straddle the experimental chamber. Despite these limitations, a large variety of measurements have been successfully accomplished in three different locations at NRL: Hawk, Gamble II and a test stand. On Hawk, densities in POS and PFD (plasma filled diode) experiments were diagnosed during pulsed power shots.[2,3] On Gamble II, electrons were measured when an intense proton beam propagated through low-density gas.[4] The test stand is used for diagnosing plasma sources, gas distributions from supersonic nozzles used in PRS (plasma radiation source) experiments,[5] gas preionization,[6] gas desorption from a surface exposed to intense UV, and gas evolution from a pulse-heated foil. The four examples below illustrate these capabilities.

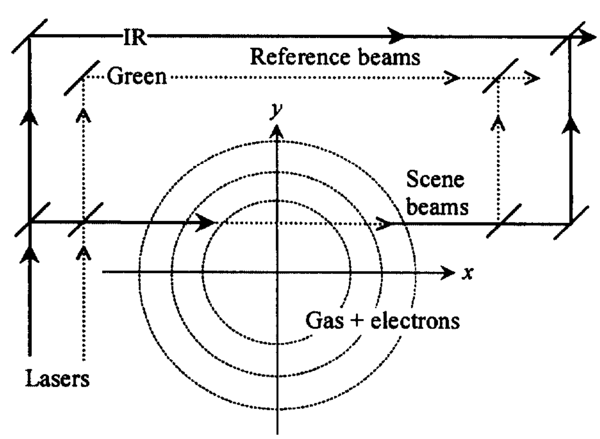

Figure 1. Two-color interferometry configuration.

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14. ABSTRACT

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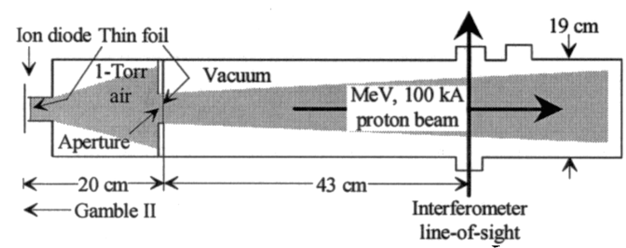
II. SINGLE-COLOR INTERFEROMETRY

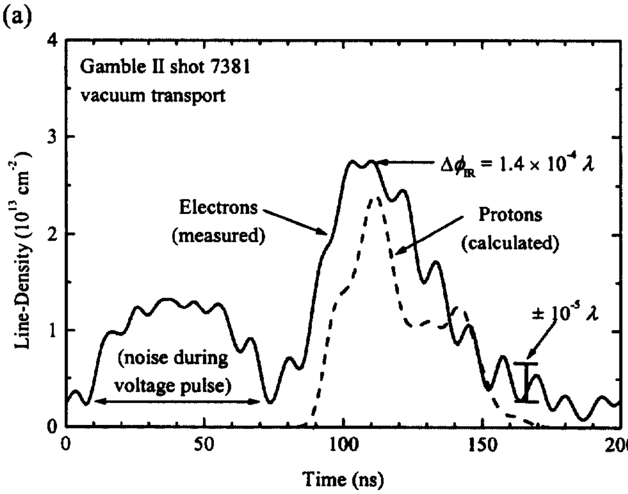
If the medium being probed consists of plasma or neutrals, but not both, single-color interferometry may be sufficient to determine the line-density. The exception is when the medium has atoms or ions in excited states with strong resonance transitions close in energy to the laser line. Two-color interferometry can be used to expose this problem because the line-densities will disagree. The two examples below do not suffer from this anomaly, and illustrate high-sensitivity, single-color measurements of electrons (using the IR beam) and gas turbulence (using the green beam in a differential interferometer configuration).

A. Measurement of Electrons Co-Moving in Vacuum with an Intense Proton Beam

The interferometer was installed on the Gamble II ion transport experiment to diagnose electrons generated when an intense (MeV, 100 kA, 50 ns) proton beam propagates through gas and vacuum.[4] The experimental setup is depicted in Fig. 2a. The interferometer measures the electron density, integrated along a diameter of the transport chamber, 43 cm from the entrance aperture. For transport in vacuum, charge neutrality is required (electrons are emitted from the entrance foil and the chamber walls). In this case, the beam propagation is ballistic and the beam fills the transport chamber uniformly at the location of the interferometer line-of-sight. The proton line-density for a 100 kA, MeV, uniform beam inside a 9.5-cm radius is about 3×10^{13} cm^{-2}. The corresponding electron line-density will shift the phase of the IR beam by only 10^{-4} waves, a challenging test of the interferometer sensitivity.



(a)



(b)

Figure 2. IR Interferometry of electrons co-moving with an intense proton beam a) setup b) measurement compared with the estimated proton line-density.

Fig. 2b compares the electron line-density measurement with a proton line-density estimated using electrical measurements in the diode, ion diagnostics and orbit modeling. The measurement shows two peaks. The first peak is noise associated with the voltage pulse in the diode, probably related to x-rays. The second, larger peak is the line-density of electrons co-moving with the protons. This second peak is separated in time from the diode voltage and is free of noise caused by x-rays. The ripple on the measurement corresponds to $\pm 10^{-5}$ waves measurement uncertainty. The agreement between the estimated proton line-density and measured electron line-density is remarkable, given the uncertainties in the proton calculation. By inference, the physical requirement of charge neutrality makes the electron measurement an independent, quantitative diagnostic of the proton line-density, a difficult quantity to measure by other techniques. This measurement is also useful to benchmark codes that model the beam transport physics.

B. Detection of Gas Turbulence

The standard Mach-Zender interferometer configuration illustrated in Fig. 1 has been used extensively to map the gas distributions produced by supersonic gas nozzles used in PRS experiments.[5] The line-densities, N, measured along many chords are abel-inverted to yield the local gas density $n(r, z, t)$. This process requires computing the derivative dN/dy which tends to amplify measurement errors. The interferometer was reconfigured as a differential interferometer,[7] shown in Fig. 3a, to measure dN/dy directly, basically moving the reference beam close to the scene beam so the phase shift corresponds to the difference in line-densities, ΔN. The line-density gradient is then $\Delta N/\Delta y$, where Δy is the spacing between the beams. This is essentially a common-mode rejection technique that should reduce the uncertainty of the abel-inverted densities. This approach reduces the phase shift ($\Delta\phi \rightarrow 0$ as $\Delta y \rightarrow 0$), requiring high sensitivity interferometry to take advantage of this technique.

A surprising result from these differential measurements was the detection of turbulence in the gas flow. Simultaneous measurements of the line-density (using the IR beam) and the line-density gradient (using the green beam with $\Delta y = 1.6$ mm) are shown in Fig. 3b. These measurements were made along a diameter of a PRS nozzle with a 7-cm diameter exit aperture and a 1-cm diameter center electrode, as indicated in Fig. 3b. The argon line-density measurements (N) show reasonable shot-to-shot reproducibility. The differential measurements (ΔN) would be zero if the gas distribution were perfectly symmetric about $y = 0$. Instead, the ΔN values oscillate with amplitudes that increase with time, and show random shot-to-shot variations, both indicative of turbulence in the gas flow. When the same

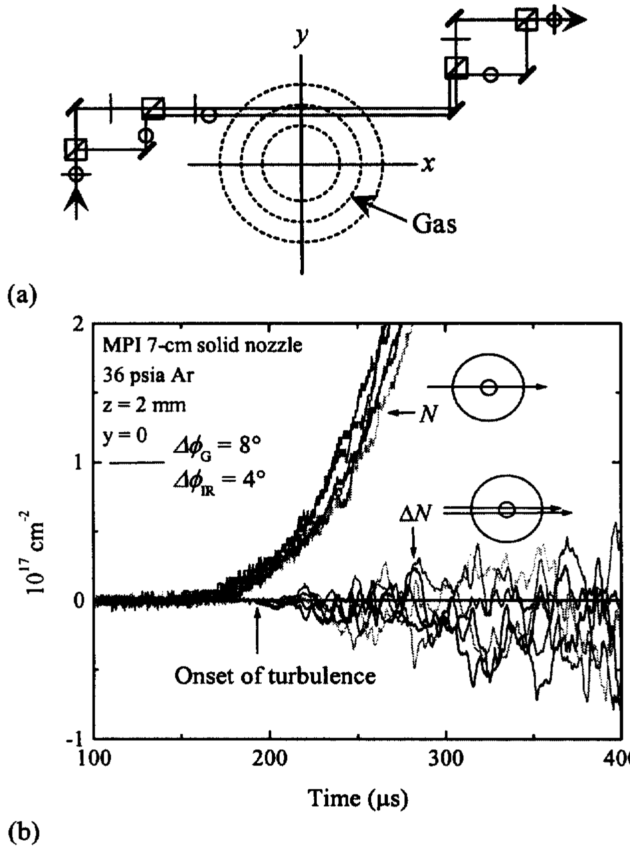


Figure 3. a) Differential interferometry setup, b) simultaneous standard (N, IR) and differential (ΔN, green) measurements for six gas pulses.

measurements are made in low-density regions outside the nozzle, there is no evidence of turbulence, suggesting the turbulence is associated with the gas interactions with the nozzle walls. These measurements may help quantify the conditions that lead to the onset of turbulence in these gas flows and enable evaluation of their effects on PRS implosion dynamics.

III. TWO-COLOR INTERFEROMETRY

Two-color interferometry can be essential when neutrals and plasmas coexist. For typical gases in PRS experiments (neon, argon) the phase shift from neutrals given by Eq. 1 is much smaller (10-50 times) than that for an equal density of electrons. When the neutral density is much greater than the electron density, the phase shifts can be the same magnitude, and since they have opposite signs, they subtract from each other. The phase shifts for two different wavelengths determine the neutral and electron line-densities unambiguously (assuming the neutral specie is known). Two examples pertinent to pulsed power that demonstrate this technique are measurements of gas preionization, and gas desorption from a surface exposured to intense UV.

A. Gas Preionization

A system to preionize the gas flow from a PRS nozzle is depicted in Fig. 4a. Ionization prior to the power pulse may improve the implosion dynamics by providing a highly conductive region along the periphery of the gas column. The nozzle and preionizer depicted in Fig. 4a were diagnosed specifically for the parameters of the DM2 PRS experiment.[6] The UV source is a flashboard that consists of two half-circles independently powered by 1.8 μF, 22 kV capacitors providing 38 kA in 1 μs. Two-color measurement results at y = 3.5 cm from the nozzle axis and z = 4 cm from the nozzle exit plane are shown in Fig. 4b. The time origin corresponds to the onset of current in the flashboard; the argon first emerges from the nozzle approximately 150 μs earlier. The electron line-density increases rapidly after the current flows in the flashboard, reaching 10% of the gas line-density at t = 3.5 μs. The flashboard is also a copious source of plasma. The line-density for shots with the flashboard, but no gas, indicate this plasma arrives at this location starting at about t = 3.5 μs. This time is therefore the best for avoiding plasma in the PRS region and maximizing ionization. This preionization system has been successfully fielded on PRS experiments at Maxwell Physics International, San Leandro, CA.[8]

B. Gas Desorption from Metal Surface Exposed to Intense UV

Intense UV sources, such as the flashboard described above, can liberate loosely bound gases from surfaces. In pulsed power applications, these gases can be used to

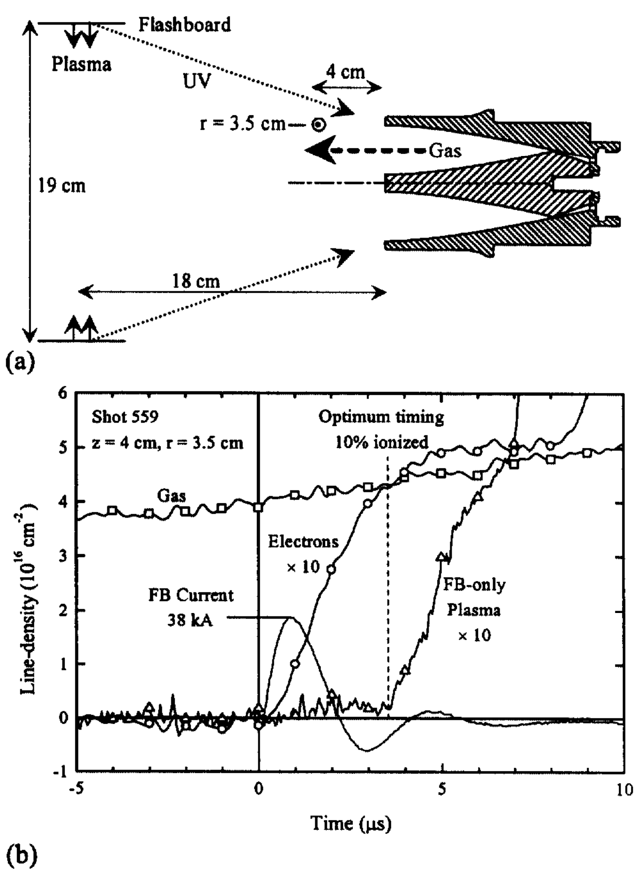


Figure 4. Gas preionization measurements: a) flashboard setup for DM2 nozzle, b) results.

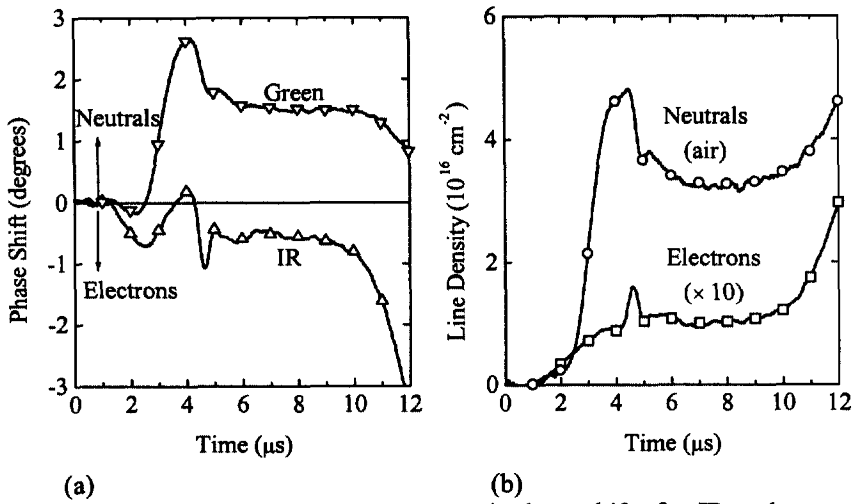


Figure 5. Gas desorption measurements: a) phase shifts for IR and green beams, b) two-color analysis of neutral and electron line-densities.

advantage (flashover switch[9] or active anode plasma[10]), or they may need to be avoided (to prevent shorting). Gas desorption was diagnosed using the two-color technique with the same configuration as in Fig. 4a, except with a flat, 10 cm diameter metal plate at the location of the nozzle exit. The laser beams were located 2 mm from the metal surface. The phase shifts for the two wavelengths are plotted in Fig. 5a. The origin of time corresponds to the onset of current in the flash-boards. The green phase shift is mostly in the positive direction that would result from neutrals, while the IR phase shift is mostly negative, indicative of electrons. The two-color analysis (assuming the neutrals have the index of refraction of air) results in the line-densities plotted in Fig. 5b. Evidently, the UV desorbs gas from the surface which appears in the laser lines-of-sight starting at about 1 μs. This gas is partially (3-10%) ionized by the UV. The flashboard plasma arrives starting at t = 4 μs, causing a transient increase in the electron density and an apparent decrease in neutral density. More likely, the flashboard plasma recombines in the desorbed gas and the species mix changes, making absolute density calculations impossible based only on this data. It is interesting to note that single-color interferometry is misleading in this case, since both neutrals and electrons are present in proportions that indicate neutral-dominated phase for one color and electron-dominated phase for the other color.

IV. SUMMARY

High-sensitivity, two-color interferometry has many applications in pulsed power research. The four examples in this paper illustrate a variety of situations where this technique has been used to determine electron and gas densities relevant to actual experiments, where alternative techniques are difficult or impossible. Many other applications have been demonstrated, including measurements of plasmas in POS and PFD experiments, diagnosing plasma sources, measuring gas evolution from pulse-heated foils, and extensive determination of gas distributions from PRS nozzles. Future applications include diagnosing the initial stages of PRS implosions and extending this technique to a multi-beam system for simultaneous high-sensitivity measurements along many parallel lines-of-sight.

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