The preliminary design of the optical Thomson scattering diagnostic for the National Ignition Facility

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Abstract. The National Ignition Facility (NIF) is a 192 laser beam facility designed to support the Stockpile Stewardship, High Energy Density and Inertial Confinement Fusion programs. We report on the preliminary design of an Optical Thomson Scattering (OTS) diagnostic that has the potential to transform the community’s understanding of NIF hohlraum physics by providing first principle, local, time-resolved measurements of under-dense plasma conditions. The system design allows operation with different probe laser wavelengths by manual selection of the appropriate beamsplitter and gratings before the shot. A deep-UV probe beam ($\lambda_0$ between 185-215 nm) will optimally collect Thomson scattered light from plasma densities of $5 \times 10^{20}$ electrons/cm$^3$ while a 3$\omega$ probe will optimally collect Thomson scattered light from plasma densities of $1 \times 10^{19}$ electrons/cm$^3$. We report the phase I design of a two phase design strategy. Phase I includes the OTS recording system to measure background levels at NIF and phase II will include the integration of a probe laser.

1. Introduction

A Diagnostic Instrument Manipulator (DIM) based optical Thomson scattering diagnostic (OTS) is being designed for operation at the National Ignition Facility (NIF) to characterize under-dense plasmas [1]. The diagnostic is being built to characterize plasma conditions in ICF hohlraums[2,3]. This information is critical to understand crossed-beam energy transfer, hohlraum wall motion and wall-hohlraum/gas-fill mix, all of which can greatly impact symmetry control and implosion performance. Typical gas-filled hohlraums have densities of $1 \times 10^{20}$ electrons/cm$^3$ to $1 \times 10^{21}$ electrons/cm$^3$ and temperatures of 2.5 to 5 keV. With a planned scattering angle of ~11 degrees for these conditions we are expecting a collective scattering signal on the order of a hundred nano-joules for a 10J probe at 5$\omega$. In this regime, scattering from the blue shifted electron plasma wave (EPW) feature will allow us to characterize both the electron temperature and density. The ion acoustic feature (IAW) feature will be used to measure the plasma flow velocity and the ion temperature. We expect modest gradients for our scattering volumes which are ~50 microns in length. The system is designed to measure density to within 20% and the temperature to 25%. This accuracy is primarily limited by the expected hohlraum background, which is driving the choice of the probe beam wavelength to 5$\omega$. The system is focused on the blue shifted EPW resonance due to the lower expected background at these wavelengths. One peak should be sufficient for an accrualment fit and measurement [4]. The OTS diagnostic will be inserted into the target chamber by a DIM which requires it to have a compact design, see figure 1. The baseline concept of the system includes a blast window, an unobscured collection telescope, transport and focusing optics, two crossed Czerny-Turner spectrometers and a shared optical streak camera photocathode.
located inside of an airbox. The collection telescope is an off-axis Schwarzschild design that relays a 50 µm spot (Thomson volume) to the entrance of the spectrometers. One high resolution (~0.6 meter) spectrometer will measure the ion acoustic wave feature (e.g. 206-214 nm for a 5ω probe laser) and one low resolution (~0.15 meter) spectrometer will measure a tunable 50 nm band to measure the electron plasma wave feature. The EPW spectrometer range will be tunable from 150-400 nm. The outputs of the spectrometers are relayed to a gated optical streak camera with selectable sweep windows between 3 and 40 ns. The inherent optical path delay between the two spectrometer systems allow the output signals to be superimposed on the same photocathode separated by approximately 5 ns and having a spatial extent of 20mm. We report on the current design status and operational performance at NIF.

Figure 1. The Diagnostic Instrument Manipulator (DIM) for optical Thomson scattering, which includes the telescope, spectrometer group and the airbox optical streak camera assembly.

2. Optical Design

2.1 Telescope Collection System

The optical design is separated into two major sections, the telescope and the spectrometers. Following the spectrometers is the airbox assembly containing the optical streak camera.

The telescope consists of an off-axis Schwarzschild design of 9.8° allowing an unobstructed view of the targets. The f/8.3 collection optics is the fastest system possible while still maintaining the temporal resolution requirement of 200 ps set by the relationship between the grating illumination of the IAW spectrometer and the telescope focal length. An off-axis parabolic mirror focuses the collimated light onto a pinhole that defines the entrance aperture for the two spectrometers. The system magnification from target chamber center to the streak camera photocathode is 2.0 for the IAW and 2.7 for the EPW. Preceding the telescope is a nominal (100 mm diameter x 8 mm thick) MgF₂ blast window which blocks particulate debris emanating from the laser target interaction during the shot.

2.2 Spectrometer System

The spectrometer group contains two Czerny-Turner type spectrometers that disperse the Thomson scattered light into two distinct bands, the IAW band and the EPW band. The spectrometers share the same 135 µm diameter input aperture pin hole (50 µm in the target image plane) and disperses the bands following a beam splitter that separates the light into two wavelength groups. The deep UV band 150-200 nm is reflected off the front surface and the near UV band 206-214 nm is passed through the splitter. Table 1 is a list of the associated design values for the optical system.

Table 1. Spectrometer design specifications for the optical Thomson scattering system.

| Specification                   | IAW   | EPW   |
|---------------------------------|-------|-------|
| Spectrometer size (meter)       | 0.58  | 0.14  |
| Spatial extent of recording window (mm) | 20    | 20    |
| Desired bandwidth (nm)          | 4°    | 50    |
| Wavelength band (nm)            | 206-214 | 150-200 |
| Spectrometer resolution (dλ/λ)  | 0.0001 | 0.01  |
| Nominal grating spacing (gr/mm) | 2400  | 1200  |
| Grating order                   | 2     | 1     |
| Dispersion at photocathode (nm/mm) | 0.2293 | 4.437 |
| Time resolution (ps)            | 200   | 200   |
The 4 nm band is smaller than the full band. The grating will be adjusted to record any 4 nm band in the overall specified wavelength band.

An unfolded optical model describing the key parameters of the optical Thomson scattering collection system is shown in figure 2.

Figure 2. The unfolded optical layout of the NIF DIM based optical Thomson scattering system is described using optical component callouts following the direction of light propagation from right to left. M describes mirrors, F describes filters, BS describes beam splitters, G describes gratings, and W describes windows. The labeled f/#s are based on the beam diameter at the primary mirror (M1) \( D_1 = 154.3 \text{ mm} \). The IAW magnification is optimized for the resolution element of the streak camera recording system measurement to be a nominal \( \sim 100 \mu \text{m} \).

The (0.14 meter) EPW spectrometer is a low resolution design with expected resolution \( \delta \lambda / \lambda = 0.00331 \) and operated in first order. The output of the spectrometer is passed to an intermediate image plane that allows for wavelength masking as required. The image plane is then relayed to the input window of the streak tube for recording.

The (0.58 meter) IAW is the high resolution spectrometer design with expected resolution \( \delta \lambda / \lambda = 0.00011 \) and is operated in second order. The image size on the grating also sets the temporal resolution limit of 200 ps [5]. The input light is processed from the upstream beam splitter in transmission, dispersed and then directed to an intermediate image plane where the probe wavelength line can be masked. This intermediate image plane is re-imaged onto the photocathode of the streak tube. There is an inherent delay between the two spectrometers of approximately 5 ns where the EPW is recorded first and the IAW is recording second on the same recording window. The IAW second order grating configuration was selected based on the availability of gratings with the desired groove density and blaze angle that matched the requirements for this system.

Figure 3 above describes the complete collection system. There are several undesirable sources of light that are managed in the telescope and spectrometer sections of the instrument. In the telescope section, the debris window, telescope optics and relay optics are coated to reject \( 1\omega \), and \( 2\omega \) laser light. The strongest attenuation occurs at the blast shield to prevent high \( 1\omega \) fluence at the secondary mirror where the light is converging before collimation. Also in the telescope are filters operating in transmission that adds additional attenuation to the \( 1\omega, 2\omega, 3\omega \) and \( 3/2\omega \) before the light enters into the pin-hole aperture of the spectrometer. The light that enters into the spectrometer is separated into two bands at the beam splitter. Light outside the two bands is...
Further attenuated by the splitter before the light hits the grating. The light that hits the grating is dispersed and light out of band is not seen by the photocathode. Undesirable light that is inside the measurement band, is blocked by an adjustable masked the tacks independently from the grating orientation. The mask is located at the intermediate image plane (IP3) and is adjustable in the wavelength plane. This mask is designed to block the probe laser wavelength and other in band undesirable scattering features.

3. Recording System

The recording system for the Thomson scattering is an optical streak camera utilizing a Photonis, Inc. P510 sealed streak tube with an S20 photocathode deposited on a CaF$_2$ window. The data from each spectrometer is recorded in the same sweep window with the IAW spectral content arriving approximately 5 ns later than the EPW spectral content. Simulated response from a NIF hohlraum target has been generated using the expected system throughput, quantum efficiency and estimated back ground levels. The synthetic data described in figure 4 shows the temporal separation between the EPW and IAW spectrometers and their nominal wavelength band.

![Figure 4](image)

**Figure 4.** Simulated recorded optical Thomson scattering data as expected on the 30 ns recording window. The data includes quantum efficiency, background levels, the expected noise levels and expected system throughput.

5. Summary

An optical Thomson scattering system is being designed to measure the IAW and EPW features of various plasma environments generated at the NIF. The recording system resides inside a NIF DIM and can be operated in the equator or the polar locations. The system will operate in the deep-UV and provide temporal information during the plasma evolution. The system will be implemented in two phases, where phase I will be used to measure the NIF background environment in the deep UV and make Thomson scattering measurements using a 3ω probe. Phase II implementation shall include a UV laser operating at the 5th laser harmonic.

6. References

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