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Design of an Optical Thomson Scattering Diagnostic at the National Ignition Facility

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Design of an Optical Thomson Scattering Diagnostic at the National Ignition Facility

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ABSTRACT

The National Ignition Facility (NIF) is a 192 laser beam facility designed to support the Inertial Confinement Fusion program based on laser-target interactions[1]. The Optical Thomson Scattering (OTS) diagnostic 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[2].

A deep-UV probe beam is needed to overcome the large background of self-Thomson scattering produced by the 351nm (3ω) NIF drive beams. A two-phase approach to OTS on NIF will mitigate the risk presented by background levels. In Phase I, the diagnostic will assess background levels around a potential deep-UV probe wavelength considered for 5ω Thomson scattering measurements to be conducted in Phase II.

The Phase I design of the diagnostic includes an unobscured collection telescope, dual crossed Czerny-Turner spectrometers, and the shared use of one streak camera located inside of an airbox. The Phase II design will include a 5ω probe laser.

We will describe the engineering design and concept of operations of the Phase I NIF OTS diagnostic, with a focus on optomechanical disciplines.

Keywords: Optical Thomson Scattering, OTS, National Ignition Facility, NIF

1. INTRODUCTION

The National Ignition Facility (NIF) is a 192 laser beam facility designed to support the Inertial Confinement Fusion program based on laser-target interactions[1]. The Optical Thomson Scattering (OTS) diagnostic 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[2].

A deep-UV probe beam is needed to overcome the large background of self-Thomson scattering produced by the 351nm (3ω) NIF drive beams. A two-phase approach to OTS on NIF will mitigate the risk presented by background levels. In Phase I, the diagnostic will assess background levels around a potential deep-UV probe laser wavelength considered for 5ω Thomson scattering measurements to be conducted in Phase II.

The Phase I DLP (Diagnostic Load Package) design is shown in figure 1. This design includes an unobscured collection telescope, dual crossed Czerny-Turner spectrometers, and the shared use of one streak camera located inside of an airbox. These modules are mounted to a cart which can be inserted and positioned by a DIM (Diagnostic Instrument Manipulator) into the NIF target chamber from both equatorial and polar positions (figure 2). The Phase II design will include an independent 5ω probe laser to be focused on the target and used to generate the 5ω Thomson scattered signal then collected by the DLP.

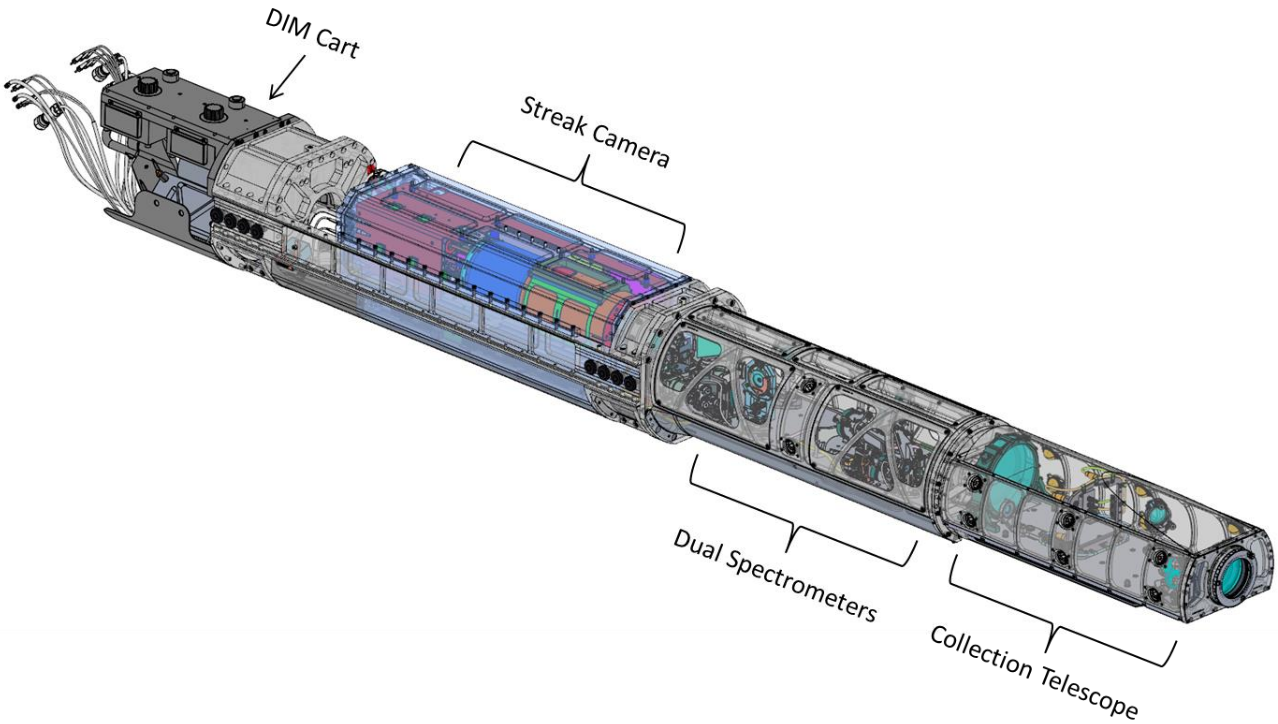


Figure 1. The OTS DLP design includes telescope, spectrometer, and streak camera modules mounted to a DIM cart.

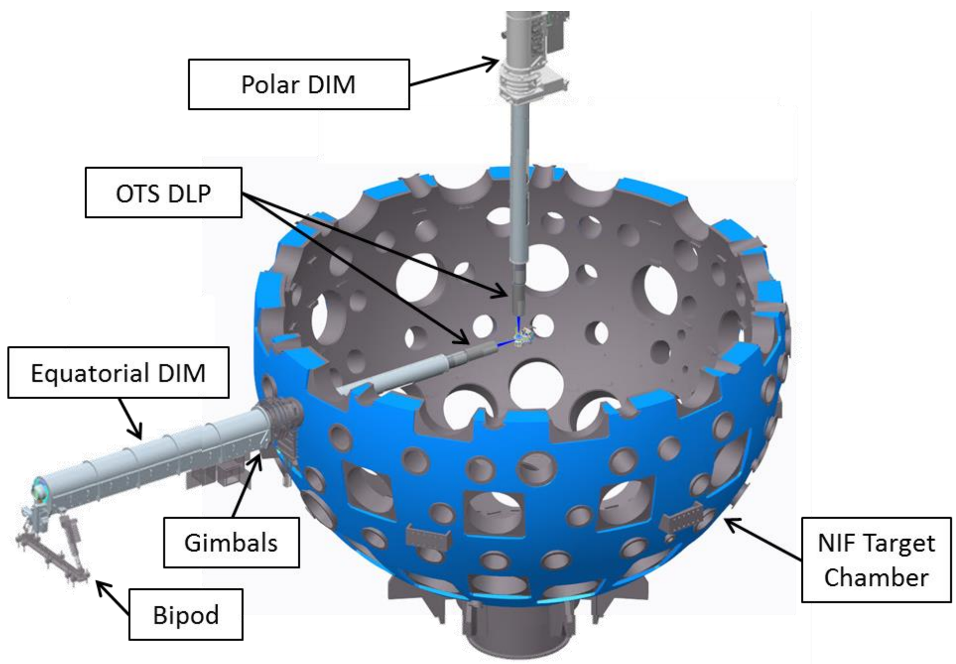


Figure 2. The OTS DLP is inserted and pointed in the NIF target chamber by DIMs and can be fielded in equatorial and polar orientations.

2. DESIGN

2.1 Overview

Figure 3 shows an overview of the OTS instrument. Subsequent sections will discuss various subsystems in detail.

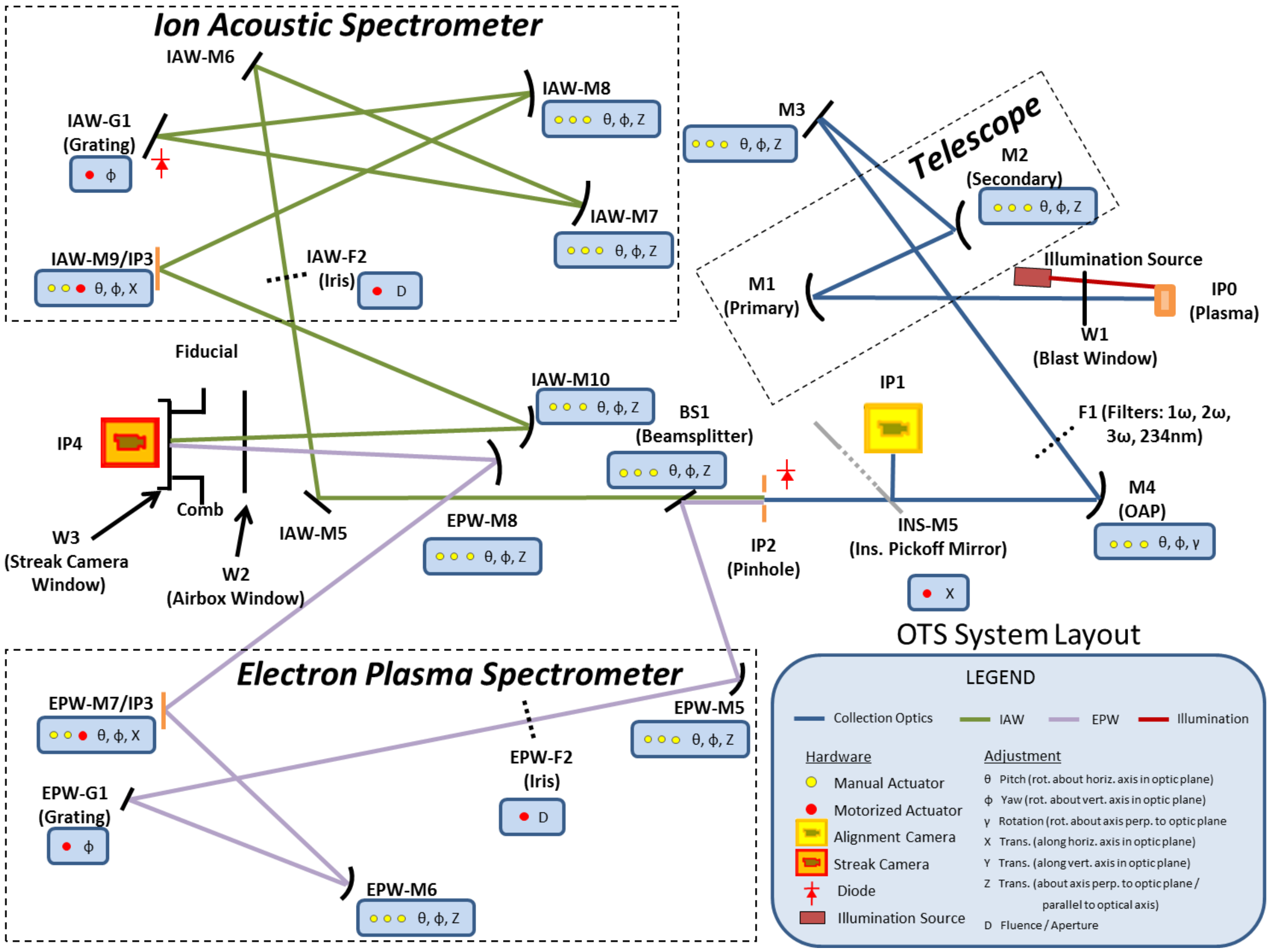


Figure 3. A system layout of the OTS instrument

2.2 General Design

The telescope and spectrometer frames are constructed from 6061-T6 aluminum, as this material features favorable stiffness, weight, and low neutron activation characteristics. Each module is mounted via precision pins and bushings, which allows for precise repeatability during assembly and disassembly. Frame components are fastened together to allow for modular-type replacement of hardware, as well as to avoid the strength reducing properties of heat-affected zones in welded aluminum. Care is taken to vent hardware, preventing virtual leaks that would slow pump down time in the vacuum target chamber environment during deployment.

The telescope and spectrometer frame geometries are optimized to minimize weight and maximize stiffness utilizing finite element analysis. Each frame features removable sheet metal panels that engage floating nuts. These sheet metal panels are designed to be much more compliant than their respective frames. This allows for final access to and alignment of the optical system with the covers removed. Upon installation of the panels, impact to optical alignment is minimized. The telescope and spectrometer frames are shown in figure 4. Also shown are retroreflectors, which are discussed in greater detail in Section 2.8.

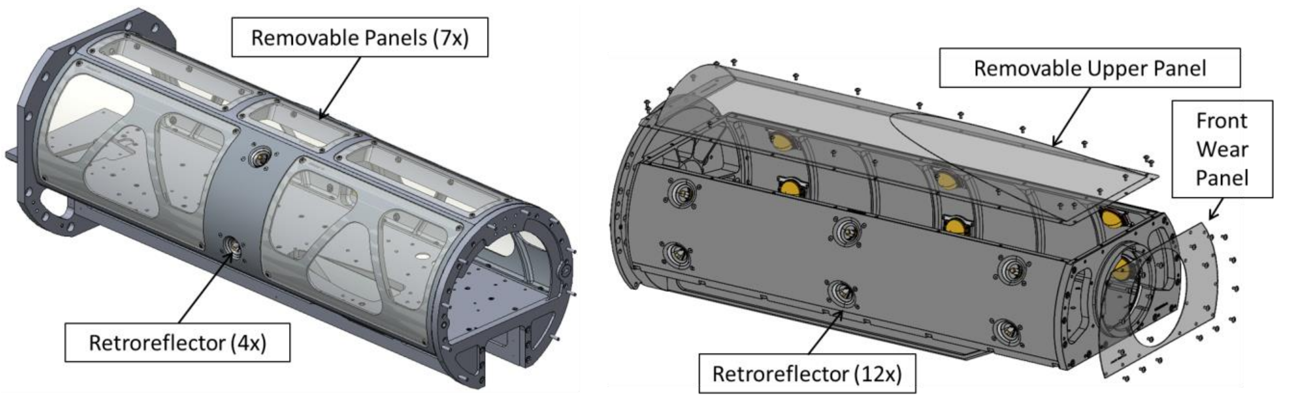


Figure 4. OTS telescope (right) and spectrometer (left) frames feature removable sheet metal panels for hardware access (shown here translucent), as well as retroreflectors for alignment within the target chamber.

2.3 Telescope (Collection Optics)

The telescope subsystem is shown in figure 5. The telescope module features an MgF_2 blast window, which protects internal hardware from target debris but allows for propagation of light down into the deep UV. Light is then collected and collimated by the primary and secondary mirrors (M1 and M2), which together function as a Schwarzschild telescope. This telescope features a 6” primary aperture and a focal ratio of 8.3. Collimated light is then redirected by the M3 fold mirror to the M4 off-axis parabola mirror, which redirects and focuses the light to the pinhole entrance to the spectrometers. Optical modeling and measurement of the as-built system show the collection optics to be nearly diffraction limited. Illumination sources are mounted within the telescope and focus through the periphery of the blast window to the target location. These sources provide lighting for an alignment camera which is discussed in Section 2.8. Various filters can be installed in the collimated beampath between M3 and M4.

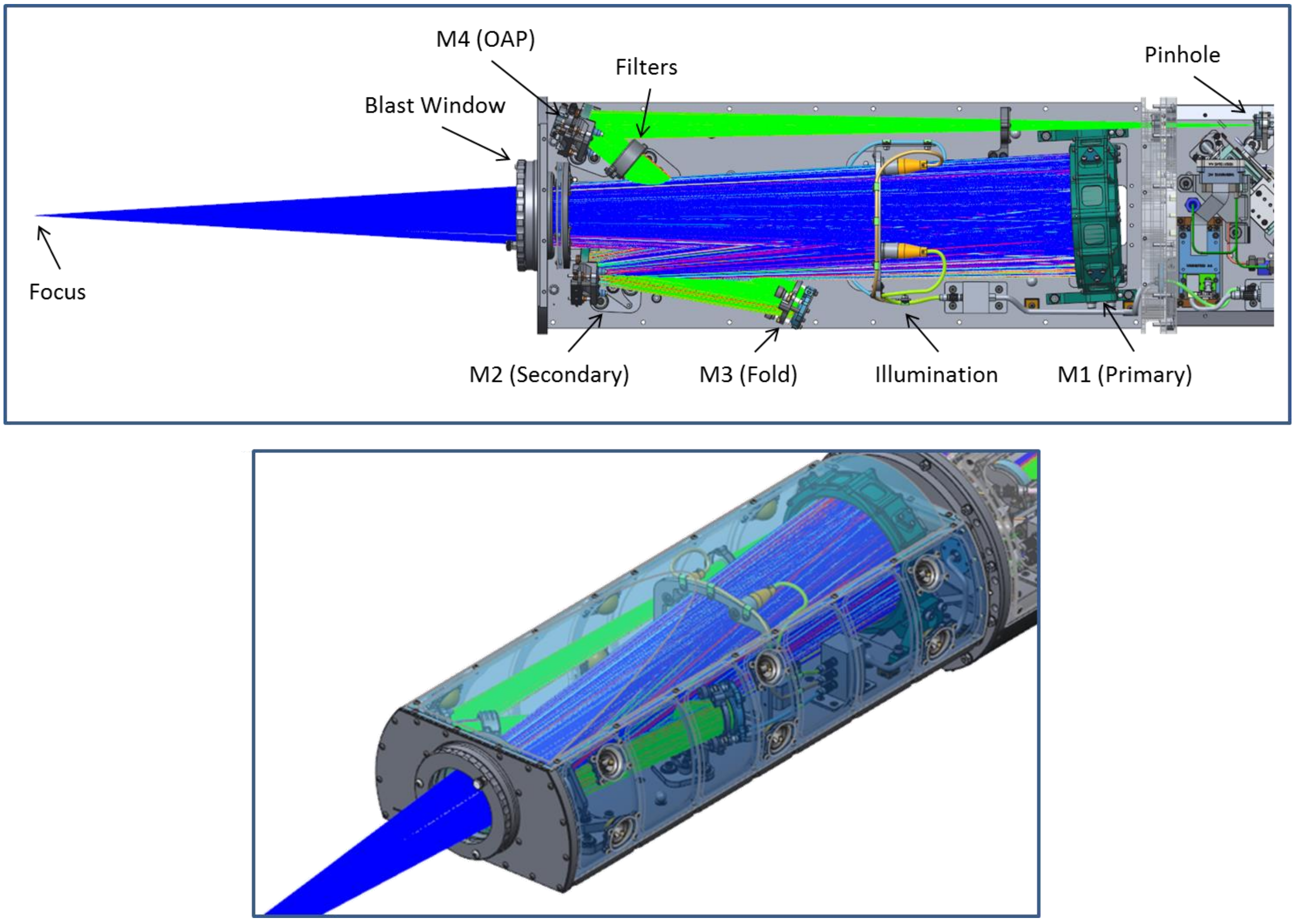


Figure 5. The OTS telescope (collection optics) module with critical components and optical ray trace shown.

2.4 Spectrometers

The OTS spectrometer subsystem is shown in figure 6. The IAW (Ion Acoustic Wave, 0.6 m, 206-214 nm) and EPW (Electron Plasma Wave, 0.15 m, 150-200 nm) spectrometers both share a common module. Light enters the spectrometers through a single pinhole, circular with a 135 µm diameter, and is redirected to either the IAW or the EPW spectrometer leg by means of a beamsplitter.

The EPW signal is reflected off of the beamsplitter BS1 and onto a powered mirror EPW-M5, where it is collimated and passes through a motorized iris, which acts as an ND filter. The signal is then spectrally dispersed by a diffraction grating EPW-G1, reflected and focused by mirror EPW-M6, and imaged on to the flat fold mirror EPW-M7, where a motorized mask plate can be inserted to block unwanted spectral portions of the signal. The signal is then relayed to the streak tube photocathode by a final powered mirror, EPW-M8.

The IAW signal is transmitted through the beamsplitter BS1 and redirected by a series of flat fold mirrors IAW-M5 and IAW-M6, where, like the EPW signal, it passes through a motorized iris. The signal is then collimated by mirror IAW-M7 and directed to grating IAW-G1, where it is spectrally dispersed. The signal is then focused by mirror IAW-M8 and imaged onto mirror IAW-M9, where an additional motorized mask plate can be inserted to block portions of the signal. Lastly, the signal is refocused by mirror IAW-M10 onto the streak tube photocathode.

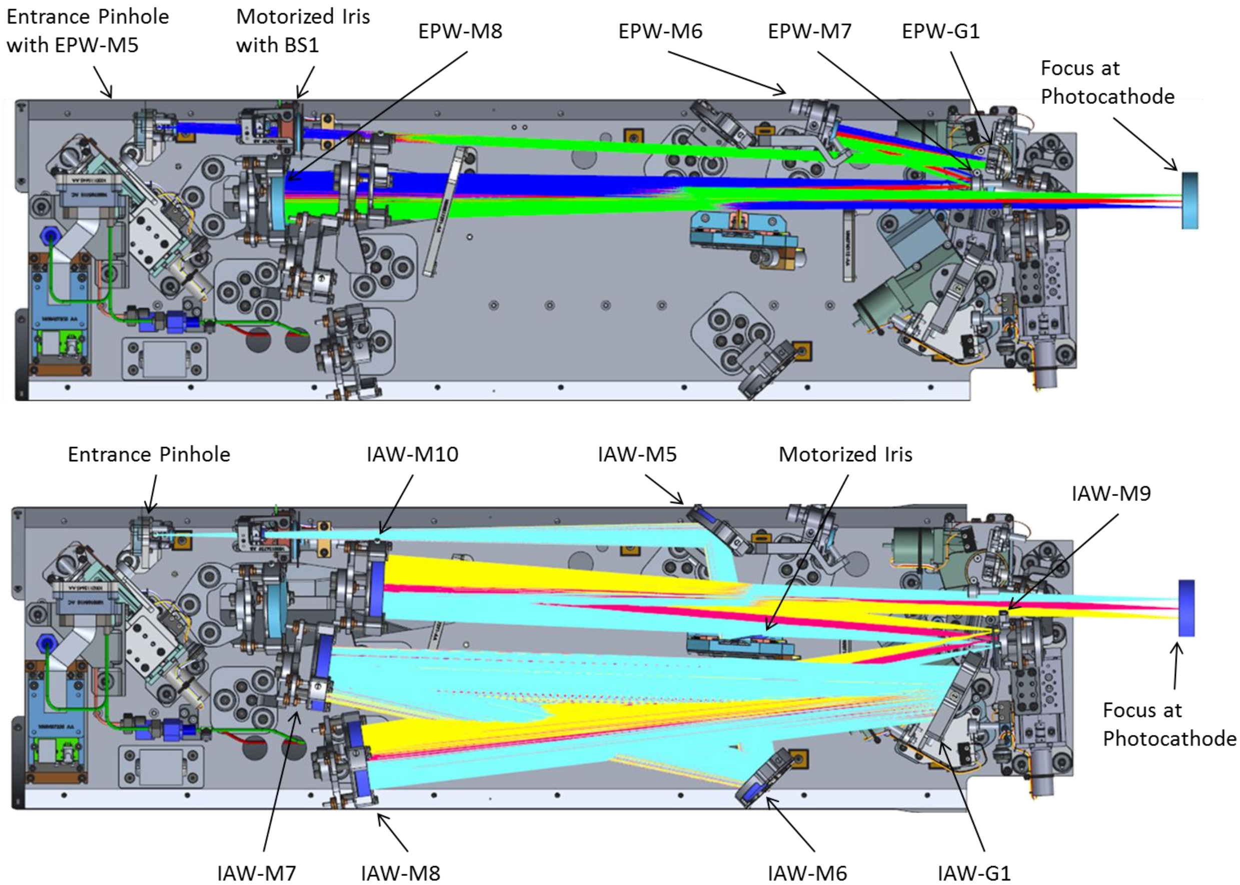


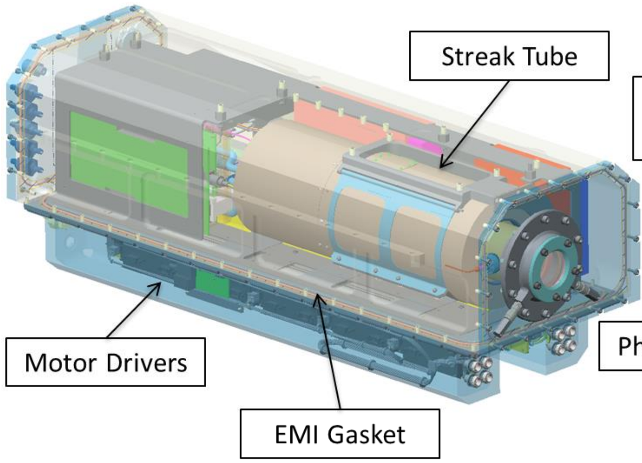
Figure 6. OTS EPW (upper) and IAW (lower) spectrometers with critical components and optical ray trace shown.

2.5 Streak Camera

The streak camera airbox subsystem is shown in figure 7. A path length difference ensures the IAW and EPW signals arrive at the streak tube photocathode without temporal overlap – this is referred to as time multiplexing and allows both IAW and EPW signals to occupy the entire slit width without interference. This streak tube is housed inside a hermetically sealed airbox which separates associated electronics from the target chamber vacuum environment. The spectrometer signals are launched into the airbox through a CaF_2 vacuum window. This vacuum window is coupled directly to the input flange of the streak tube by means of a compliant Viton bellows. This bellows mounts to the front panel of the airbox and a PEEK spool that is flange mounted to the front end of the streak tube. This creates an additional hermetically sealed environment through which the spectrometer signals are launched onto the photocathode. This spool environment is filled with dry nitrogen. This environment, distinct from the remainder of the airbox, protects the streak tube input optics from outgassing from electrical components within the airbox and also provides a low moisture environment for the input signal, which is critical for propagation of vacuum UV wavelengths.

Hardware within the airbox is actively cooled by means of cooling water run through a chill plate as well as two small panel fans which help to circulate air throughout.

Various motor drivers for other OTS systems are also packaged within this airbox. The volume in which the motor drivers are mounted is electrically separated from the streak tube volume by means of an EMI gasket. This gasket features mesh panels which allows air to circulate throughout both volumes, which helps to cool hardware and keep the airbox at a more uniform temperature.



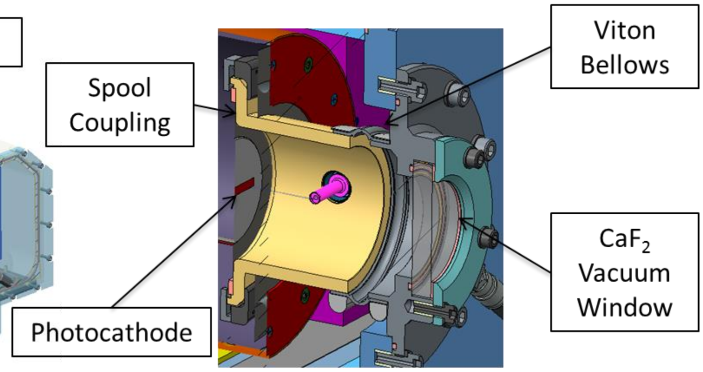


Figure 7. The OTS airbox houses a streak camera system in its upper volume and various motor controllers in its lower volume (left). The CaF_2 vacuum window, PEEK spool coupling, Viton bellows, and Photocathode are shown in cross-section (right).

2.6 Optical Mount Design

Due to the challenging packaging requirements of the OTS optical system within the DIM as well as anticipated transport and handling loading between NIF shots, many of the OTS optical mounts were custom designed.

The primary mirror mount (M1) is a fixed mount, with the corresponding strategy that M1 serves as an optical datum to which all other elements are aligned. This mount features qty. 5 spring loaded cartridges which provide sufficient stability and axial and radial restraint of the optic, while minimizing over-constraint that could contribute to wave front distortion. The M1 mount engages the optic with Vespel contact pads, to provide a compliant bearing surface and minimize point contact loading (figure 8).

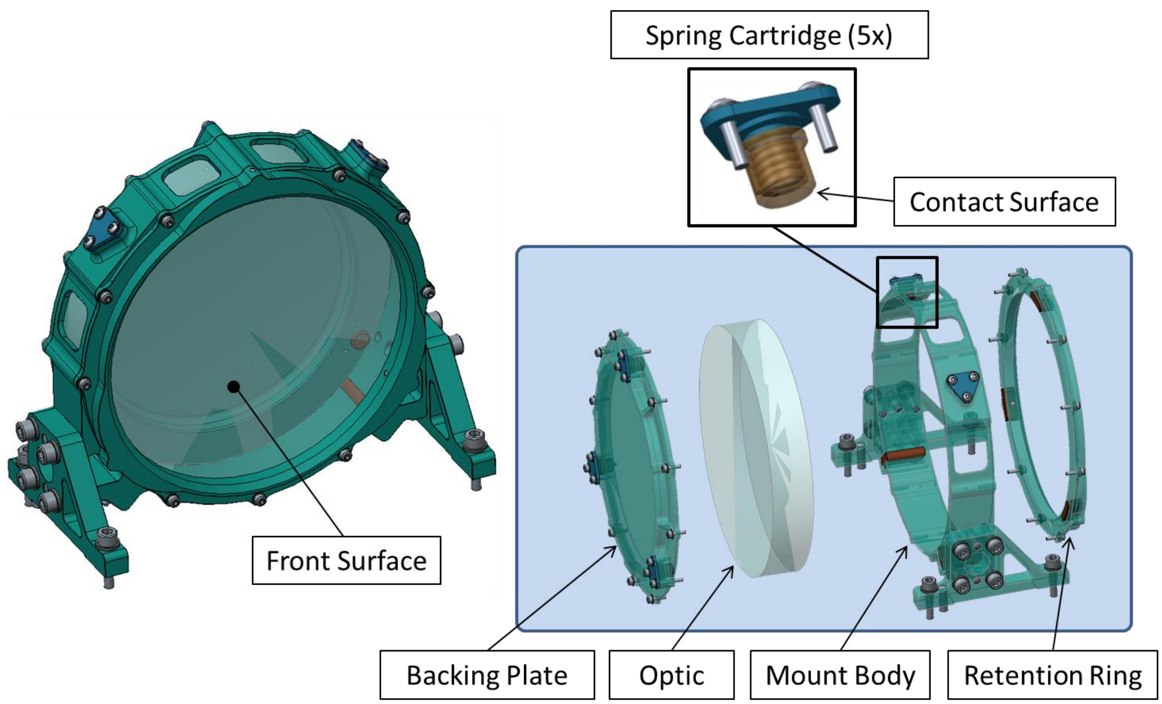


Figure 8. The M1 (primary) mirror mount features spring cartridges to provide a compliant yet stable platform while minimizing over-constraint.

Custom small mirror mounts utilize flexures and spring-loaded, Delrin-tip plungers for optical restraint, again with the intent to reduce the risk of over-constraint and wave front distortion while providing adequate stability and restraint of the optics. These small mounts feature commercial off-the-shelf Newport precision adjusters engaging kinematic v-groove seats for pitch, yaw, and focus adjustment. These mounts are also compatible with a kinematic base assembly, for quick replacement between NIF shots (figure 9).

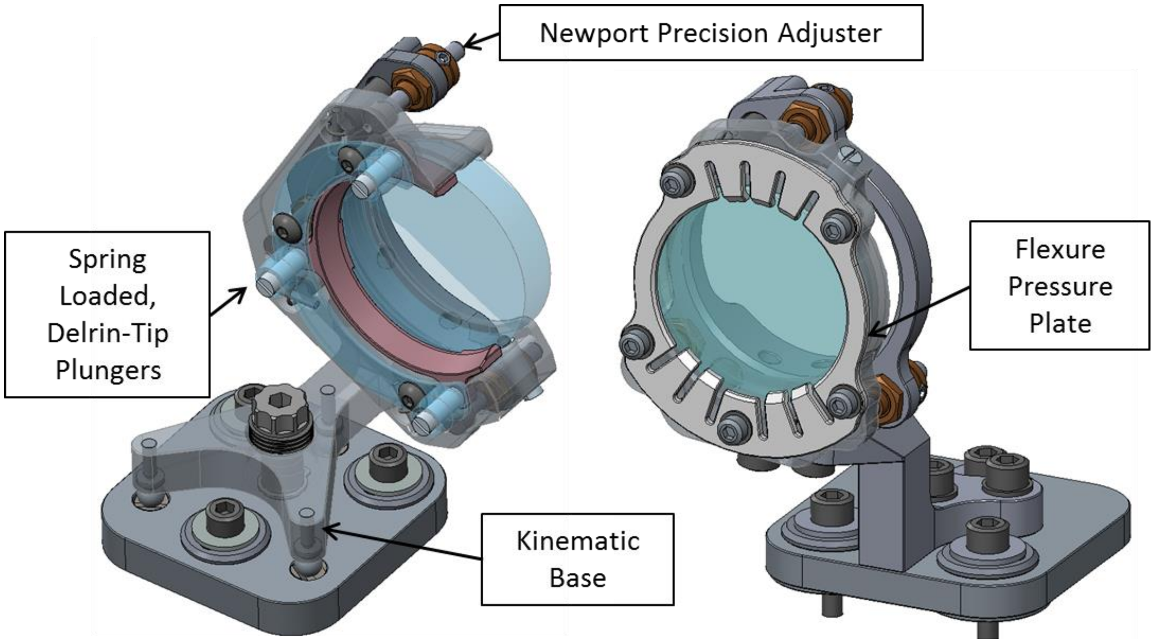


Figure 9. The OTS small mirror mounts feature flexures and spring loaded plungers to provide a compliant yet stable platform while minimizing over-constraint and are compatible with kinematic bases for quick and repeatable replacement.

2.7 DIM Interface

The telescope, spectrometer, and airbox modules are mounted to a DIM cart, which serves as the mechanical structure that couples the diagnostic to its DIM positioner. The DIM cart features a dual pinion gearbox and drive unit which engages a rack in the DIM boom and provides focus adjustment of the instrument. The DIM boom can also be inserted and retracted from the target chamber to adjust focus. Moreover, the DIM is mounted to the target chamber on one end with a pair of gimbals, and to the target bay floor on the other end by means of a motorized and adjustable bipod which can be driven to adjust the diagnostic in pointing (figure 2). The DIM cart features a lifting fixture that can be used to rig the assembly into the polar DIM, which is located at the top of the target chamber and oriented vertically (figure 10).

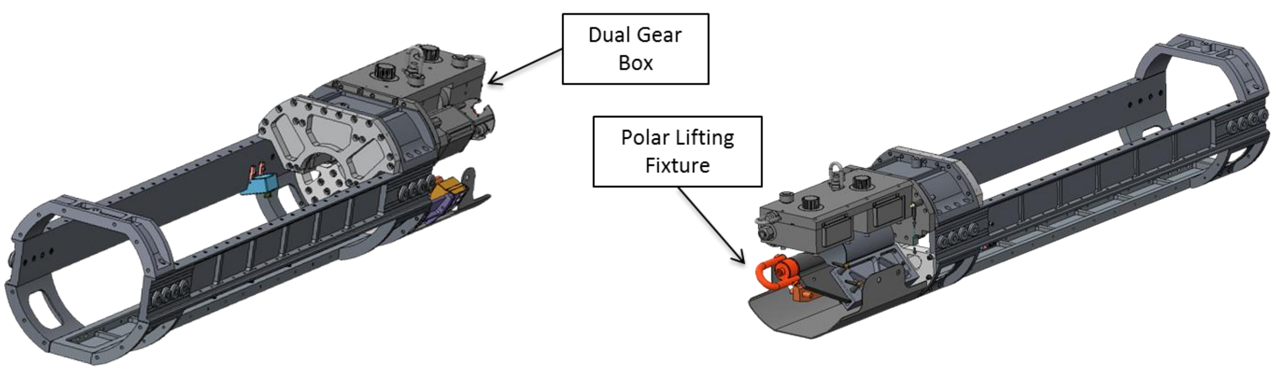


Figure 10. OTS DIM cart features a dual gear box that engages a rack within the DIM allowing for focus adjustment. A polar lifting fixture allows the cart to be installed in the polar DIM.

2.8 Alignment System

The OTS diagnostic can be aligned to its target by means of two systems: a set of externally mounted retroreflectors that engage a target chamber mounted laser tracker and an internal alignment camera.

The diagnostic features qty. 16 retroreflectors mounted to the telescope and spectrometer module frames (figure 4). These retroreflectors are adjustable and oriented such that they point toward a permanent laser tracker system mounted in the target chamber called ATLAS (Advanced Tracking Laser Alignment System). ATLAS is capable of achieving alignment repeatable to ~200 µm.

An alignment camera is mounted in the spectrometer module. An insertable pickoff mirror INS-M5 is driven in front of the pinhole and redirects light from the pinhole to the alignment camera CCD (figures 3, 11). A set illumination sources are mounted in the telescope module and pointed toward the target, providing illumination for the alignment camera (figure 5).

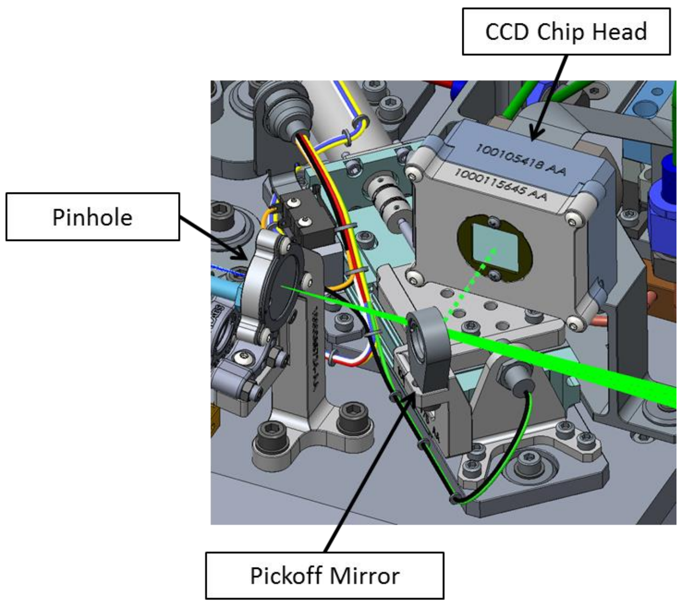


Figure 11. A motorized pickoff mirror redirects light from the pinhole to an alignment camera.

2.9 Future Design – X-Ray Blanking Mitigation

A significant next step in the OTS DLP design will be the addition of an x-ray blanking mitigation system. The following discusses an early baseline concept for the design (figure 12).

X-rays generated during the target / laser interaction interact with the OTS optics and can cause optical blanking, where the x-rays bombard the outer surface of optics and generate plasma which causes normally transmissive optics to become optically opaque[3]. A baseline conceptual design features a "snout" addition to the telescope module that will be filled with low pressure xenon gas which absorbs x-rays and can prevent blanking. The front end of the snout features a ~200 nm thick silicon nitride membrane. The back end of the snout features an MgF_2 blast window. Both the membrane and the blast window are hermetically sealed with o-rings. The thin membrane is designed to hold the xenon gas inside the snout until the shot, when the x-rays from the target then penetrate or "blow down" the membrane, allowing the signal of interest to pass through the diagnostic collection system. A pressure relief device allows the inner volume of the snout to be filled with xenon gas to a pressure ~0.2 psi gauge in an offline lab prior to the shot, then relieves pressure within the snout as the DIM is pumped down to vacuum prior to the NIF shot, maintaining a constant positive pressure differential between the snout and its surrounding environment throughout vacuum pump down. At the time of the NIF shot, the pressure of xenon gas is ~0.2 psi absolute. A pressure transducer is coupled to the system and allows for active pressure monitoring until shot time. Pressure regulation across the membrane is critical because the thin membranes are fragile and cannot withstand significant pressure loading. However, the membranes must remain thin otherwise they risk not blowing down and blocking all signal from input into the instrument.

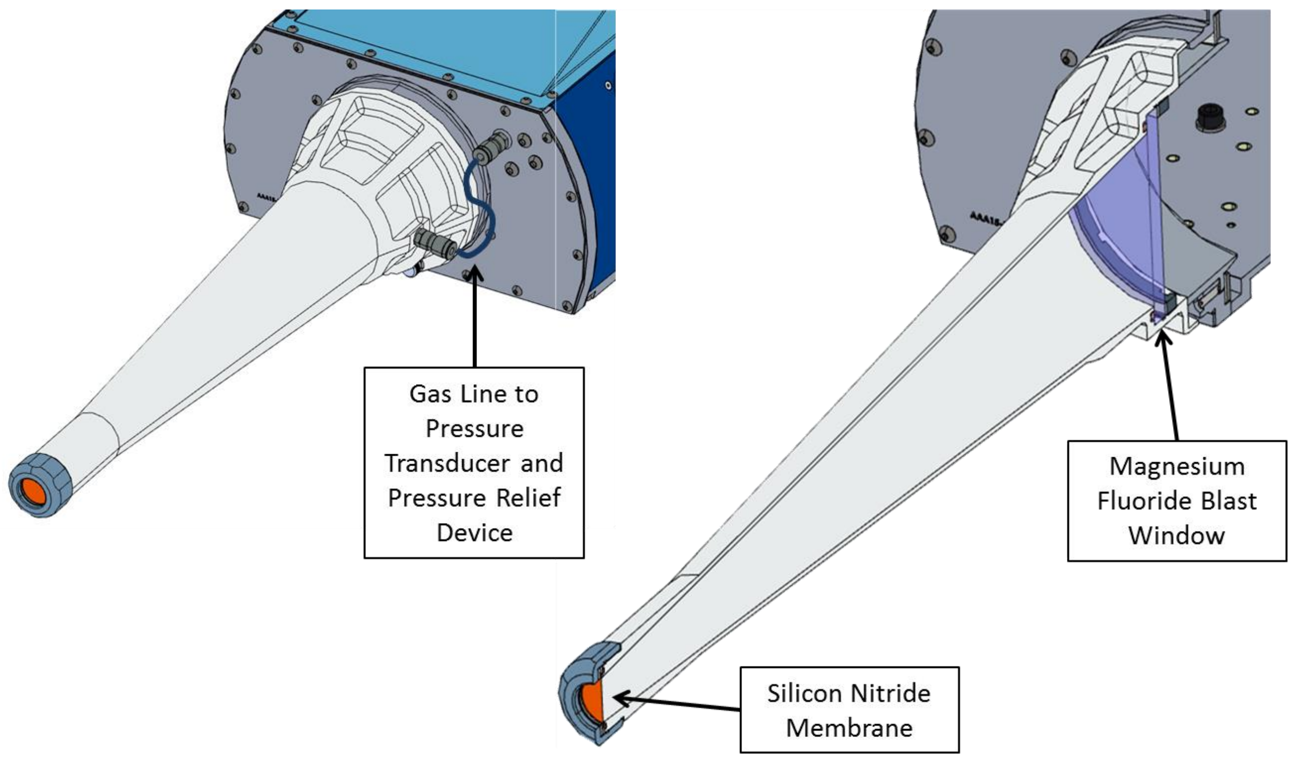


Figure 12. A conceptual x-ray blanking mitigation snout design features a 200 nm thick silicon nitride membrane.

3. CONCLUSION / NEXT STEPS

The Optical Thomson Scattering (OTS) diagnostic 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[2]. Fabrication and assembly of the Phase I DLP is nearly complete (Figure 13). The first Phase I OTS NIF shot is scheduled for late calendar year 2016, at which point background levels around critical 5ω Thomson scattering wavelengths will be assessed. Design of the Phase II laser needed to perform 5ω Thomson scattering is currently underway and is scheduled for completion in late 2017 / 2018.

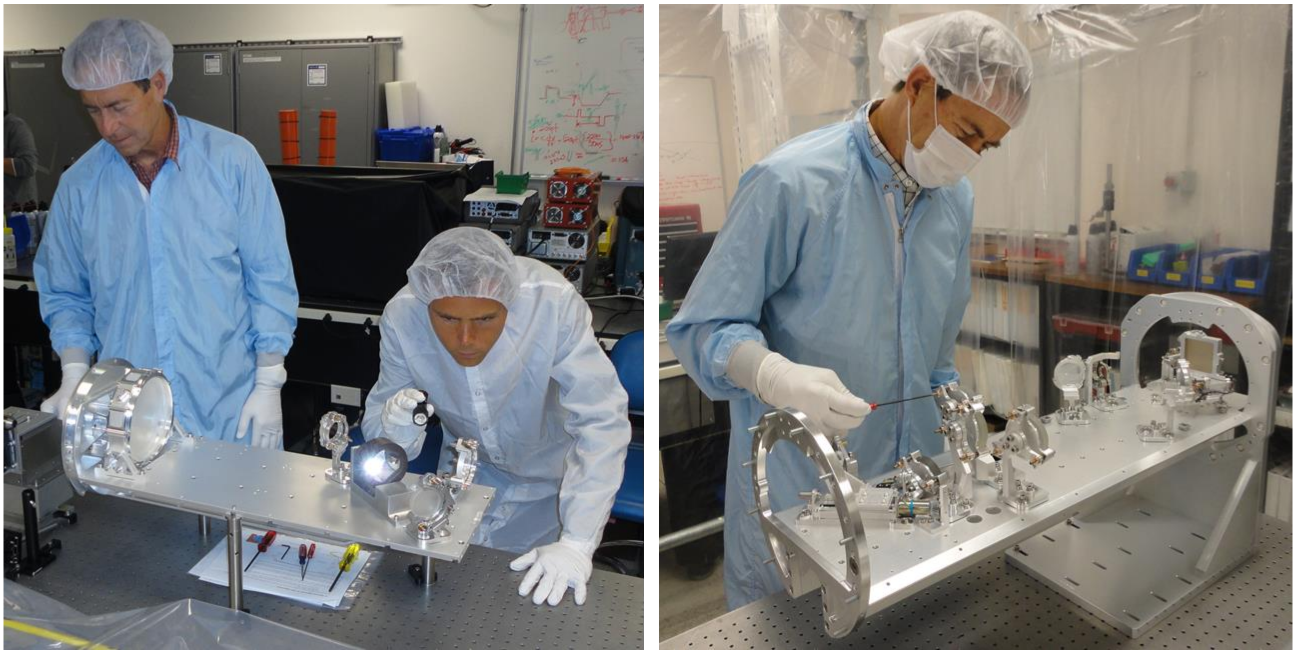


Figure 13. Telescope (left) and spectrometer (right) systems are shown subject to initial assembly and alignment.

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