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Design calculations for a Xenon Plasma X-ray Shield to Protect the NIF Optical Thomson Scattering Diagnostic [a)]

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An Optical Thomson Scattering (OTS) diagnostic is currently being developed for the National Ignition Facility (NIF) at Lawrence Livermore National Labs (LLNL). This diagnostic is designed to make measurements of hohlraum plasma parameters, such as the electron temperature and density, during inertial confinement fusion (ICF) experiments. NIF ICF experiments present a very challenging environment for optical measurements; by their very nature hohlraums produce intense soft x-ray emission, which can cause "blanking" (radiation induced opacity) of the radiation facing optical components. The soft x-ray fluence at the surface of the OTS blast shield, 60 cm from the hohlraum, is estimated to be ~ 8 J cm^{-2}. This is significantly above the expected threshold for the onset of "blanking" effects. A novel Xenon Plasma X-ray Shield (XPXS) has been proposed to protect the blast shield from x-rays and mitigate "blanking". Estimates suggest that an areal density of 10^{19} cm^{-2} Xe atoms will be sufficient to absorb 99.5% the soft x-ray flux. Two potential designs for this shield are presented.

I. Introduction

Gaining a deeper understanding of hohlraum plasmas is an essential step on the road to being able to properly predict the complex plasma physics processes that can adversely affect drive symmetry in inertial-confinement fusion (ICF) experiments. To this end an optical Thomson scattering (OTS) diagnostic is currently being developed for the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), with the aim of making detailed measurements of hohlraum plasma parameters[1,2]. The fundamental design of this diagnostic is based on the successful OTS diagnostic implementation currently fielded at the Omega laser facility at the Laboratory for Laser Energetics (LLE), Rochester[3]. Light scattered from a probe beam of a known wavelength (λ) is collected by a reflective telescope and coupled into a temporally resolved (streaked) spectrometer. The diagnostic records the spectrum of the scattered light, the form of which is sensitive to many of the important plasma parameters, such at the electron density (n_e), electron temperature (T_e), ion temperature (T_i) and bulk plasma flow velocity (v_f)[4]. The scattering signal is collected only from the volume defined by the overlap of the spectrometer collection cone and the probe beam; this allows measurements of local values of the plasma parameters, an improvement over the line-averaged measurements typically produced using other diagnostic techniques, e.g. spectroscopy. The broad range of quantitative data that will be produced by this diagnostic will potentially revolutionize our understanding of hohlraum plasmas.

NIF ICF experiments present a challenging environment in which to make successful OTS measurements. One example of these challenges is the extreme x-ray flux environment presented by hohlraums. The x-ray flux measured by NIF-Dante[5] peaks at ~ 12 TW sr^{-1} with a duration of ~5 ns, corresponding to ~ 60 kJ sr^{-1} of soft x-ray (< 3 keV) or ~ 16 J cm^{-2} at the OTS blast shield, 60cm from the hohlraum. For comparison, in a typical 1 ns, 500 J per beam gold sphere[6] experiment on Omega, Dante[7] measures a peak flux ~1.2 TW sr^{-1}, and a time-integrated x-ray fluence of ~1.2 kJ sr^{-1}. The Omega OTS blast shield is at 26cm, giving a cumulative flux of 1.7 J cm^{-2}, an order of magnitude lower than that which will be seen on NIF. Experiments carried out on OMEGA to investigate the "blanking" phenomenon in support of the development of the NIF Near Backscatter Imager (NBI) diagnostic[8] have indicated that the threshold for the onset of blanking effects (~ 20% absorption) in fused silica (SiO_2) is as low as ~ 0.3 J cm^{-1}. While modeling suggests the x-ray fluence seen along the polar line of sight, where the NIF OTS diagnostic is intended to be fielded, will be reduced, it is still likely to be ~ 8 J cm^{-2}; it is therefore imperative to develop a method to shield the blast window from soft x-rays in order to mitigate blanking.

A novel Xenon Plasma X-ray Shield (XPXS) is proposed to protect the blast shield from hohlraum soft x-ray emission and prevent "blanking". Xe gas has previously been explored as a potential radiation shield in ICF reactors as part of the LLNL Laser Inertial Fusion Energy (LIFE) reactor research program[9]; a low density Xe gas fill was proposed to shield the walls of the reactor vessel and final optic assembly blast shields. The XPXS design will use a small volume of Xe gas placed in front of the OTS blast window to shield it from soft x-rays. The Xe will absorb the x-ray flux over depth, forming a sub-critical density photo-ionized plasma that will remain transparent to the desired optical signal for the duration of the experiment.

II. Blast shield design and flux estimates

The NIF OTS diagnostic is designed to operate over a wavelength range from the optical all the way down to vacuum ultra-violet (VUV). For ICF experiments the diagnostic will operate using a 5ω (λ = 210.6 nm) probe beam, with the scattered signals from electron plasma waves (EPW) expected to extend down to λ ~ 150 nm. In this range practical choices for the blast

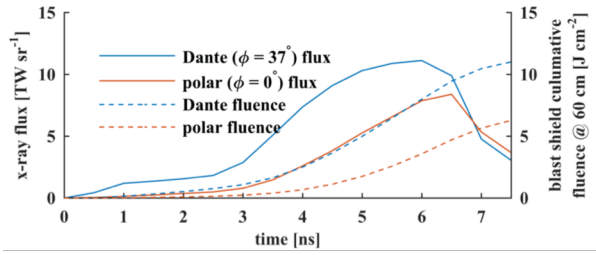

FIG. 1 Hohlraum x-ray emission seen by the south- pole Dante diagnostic (blue), by the Thomson scattering diagnostic in the Polar DIM (red). Flux is plotted with solid lines, fluence at 60 cm is plotted with dashed lines

window are limited to magnesium fluoride (MgF_2) or sapphire (Al_2O_3); the current design uses MgF_2 due to its superior mechanical properties as a blast shield. While no published data is currently available to compare the "blanking" performance of MgF_2 and SiO_2, it seems reasonable to assume that any difference between these materials is unlikely to extend much beyond a factor of two.

The NIF OTS diagnostic load package (DLP) will be inserted into the chamber via the polar diagnostic instrument manipulator (DIM). The collection telescope will therefore have a view directly down the axis of the hohlraum, through the laser entrance hole and onto the capsule surface. Calculations have been carried out to investigate the variation in the x-ray flux emitted towards the pole and towards the NIF Dante diagnostic; FIG. 1 contains plots of the results of these calculations. The upper plot shows the x-ray flux the while the lower plot shows the cumulative time-integrated fluence. The flux towards the south-pole Dante (37° polar angle) is plotted in blue and the flux towards the pole is plotted in red. The polar flux is roughly half of the Dante flux; the anisotropy is due to different views seen from these two directions. The polar view is dominated by the low albedo (~ 0.3) capsule surface, while Dante directly views the high albedo (~ 1) hohlraum gold wall. The calculations indicate that the blast shield will be exposed to a cumulative soft x-ray fluence of ~ 8 J cm^{-2} during a typical ICF experiment; this is much greater than the previously established threshold fluence for the onset of "blanking" in SiO_2 (~ 0.3 J cm^{-2})[8]. The data in FIG. 1 implies that without mitigation, the OTS blast window is likely to "blank" within ~ 3 ns of the start of the experiment, during the trough of the drive pulse.

III. Xe x-ray shield design

The generic term "blanking" refers to the symptom of radiation-induced opacity; two mechanisms are thought to drive this in the blast shield. Firstly, surface absorption of the soft x-ray flux can lead to rapid heating and the formation of an expanding, super-critical surface plasma that will both absorb and reflect light. Secondly, higher energy x-ray photons that penetrate deeper will produce free electrons in the glass bulk. These free electrons facilitate rapid absorption of light via collisional inverse-bremsstrahlung in the solid density glass[8]. In order to prevent "blanking", it is proposed to place a volume of Xe gas in front of the blast shield. With is sufficient areal density of the Xe the majority of the x-ray flux will be absorbed before it reaching the blast window. The absorbed x-rays will photo-ionize the Xe gas, however the Xe plasma can be made to remain sub-critical so long as the Xe is distributed over a sufficient depth.

Absorption calculations were carried out to gauge areal density of Xe gas required; the results are plotted in FIG. 2. The x-ray source was approximated as a 280 eV Plankian and the absorption was modeled using the Henke cold opacity tables[10]. To meet the "blanking-threshold" of 0.3 J cm^{-2}, the Xe needs to attenuate the incoming x-ray flux by at least a factor of ~ 30. The blue line in FIG. 2 shows the unfiltered soft x-ray spectrum, while the red, yellow, and purple lines show the spectrum transmitted through 10^{17}, 10^{18} and 10^{19} cm^{-2} of Xe atoms. An areal density of 10^{19} cm^{-2} transmits only 0.5% of the x-ray spectrum; this would reduce the 8 J cm^{-2} reaching the blast window down to 0.04 J cm^{-2}, providing a 7.5× safety factor with respect to the 0.3 J cm^{-2} "blanking" threshold. This safety factor should cover the uncertainty in the blanking threshold for MgF_2, as well calculation errors arising from deviations from the assumed cold opacity. The extra Xe will also help to further attenuate the harder, more penetrative gold m-band x-rays, which are not modeled by the assumed Plankian spectrum.

The density of the photo-ionized Xe plasma should be kept as low as possible; this can be achieved by distributing the gas over as deep a shielding path length as possible. On the NIF, the practical depth scale of the gas shield range between 10 and 50 cm; this range corresponds to initial Xe number densities (n_{Xe}) between 10^{18} and 2×10^{17} cm^{-3} and pressures between 0.040 and 0.008 Bar at normal temperature (20°C/68°F).

An estimate of the inverse bremsstrahlung absorption[11] (IB) for $\lambda = 210.6$ nm light was carried out for a 10 cm deep $n_{Xe} = 10^{18}$ cm^{-2} XPXS design. A simple "cartoon" ionization model was used to estimate the $\bar{Z}$ (and therefore n_e) profile of the photo-ionized Xe plasma; the energy density of the x-ray flux deposited into each layer of the Xe gas was calculated using the Henke cold opacity[10], and the local mean ionization state of the plasma was increased until the local T_e was equal to 1/5th of the next available ionization energy. The resulting n_e profile peaks at 3×10^{18} at the front surface of the shield and falls approximately exponentially, with an e-folding length of ~ 1 cm. A uniform T_e of 0.5 eV was used for the inverse bremsstrahlung estimate in order to take account of the potential for radiative cooling of the

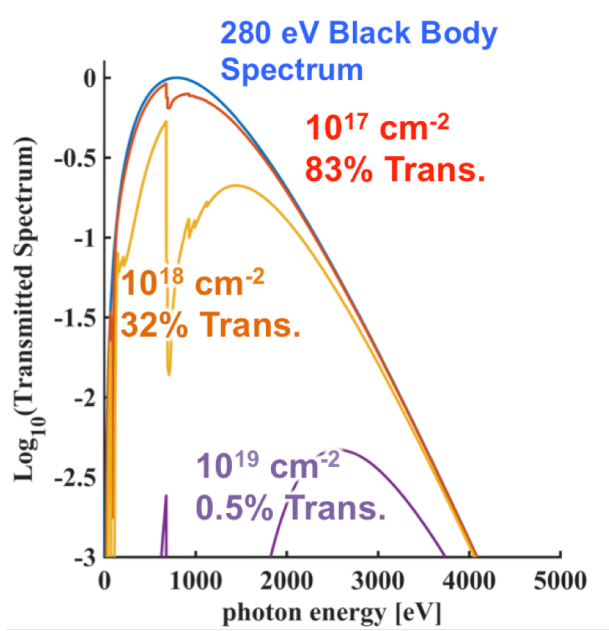

FIG. 2 Transmission of a normalized 280 eV Plankian x-ray spectrum through increasing areal densities of Xe gas.

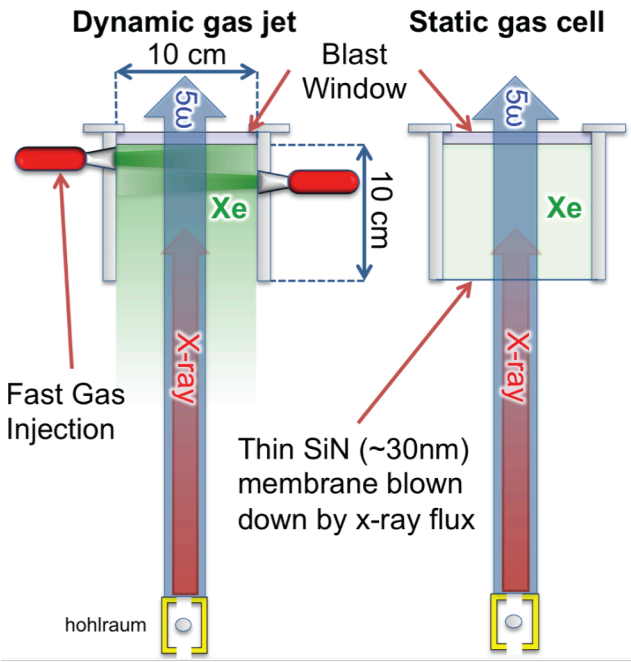

FIG. 3 Two design concepts for the Xenon plasma x-ray shield. The dynamic shield injects gas just before the shot, the static design contains a static gas fill using a thin membrane.

Xe plasma; the true value of T_e is likely to be higher, so this calculation will represent a worst case estimate of the IB. The stimulated emission correction term was also included in the IB calculation, as $h\nu > k_B T_e$. Total absorption of $\lambda = 210$ nm light was ~2%; the first centimeter of Xe is responsible for the majority of this. The effects of IB due to collisions with neutral Xe atoms[12] was assessed and found to be at least an order of magnitude less significant than electron-ion IB. In general, for a fixed areal density, increasing the depth of the gas shield tends to reduce absorption, as the absorption coefficient $\int k_{IB} dz$ scales with the square of density but only linearly with depth. Absorption scales as $\lambda^{\sim 2\text{-}3}$, so absorption will be significantly greater for longer wavelengths, the intensity of the scattered, unconverted 1ω, $\lambda = 1053$ nm light already presents a significant risk to the diagnostic; a simple λ^2 scaling suggests the Xe plasma could absorb up to ~50% of this light before it reaches the blast shield, providing a second layer of protection for the diagnostic.

IV. NIF Design concepts

Two designs concepts are proposed for the NIF OTS blast shield x-ray shield implementation; schematics are presented in FIG. 3. The first design uses gas jets to rapidly inject a plume of Xe gas in front of the OTS blast window just before the start of the experiment. The second design employs a static volume of gas held in front of the blast shield by a thin membrane; the membrane is heated by the incoming x-ray flux, forming a plasma that must "blow-down" to sub-critical density before measurements can be made. The static design is potentially simpler to implement, and has the advantage that the properties of the gas shield should be highly reproducible, providing good shot to shot repeatability. The main difficulty is that extremely thin membranes are required in order to guarantee rapid blow-down. Simple estimates suggest the thickness of the membrane should not exceed 100 nm, and should ideally be uniform over the collection aperture to avoid unwanted optical distortion effects. These requirements are particularly demanding given the large diameter of the OTS blast shield (~10 cm). The gas jet design will be very challenging to implement on the NIF. The jets will require high pressure Xe reservoirs and pulsed power driven valves in order to establish the required shielding density before the gas cloud expands to out to far. The gas jets would likely have to be mounted to the OTS DLP itself, introducing the potential for recoil to interfere with the already challenging optical alignment of the diagnostic.

V. Conclusions

Estimates indicate that x-ray induced optical "blanking" is likely to interfere with optical Thomson scattering measurements on the NIF. The proposed xenon plasma x-ray shield has the potential to prevent blanking, allowing OTS measurements all the way through an ICF drive pulse. This will allow measurements of the hohlraum plasma parameters late into the drive pulse, providing previously unavailable data that may be used to benchmark the computational models used both the design and analyze the performance of ICF experiments.

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