Developing a platform for Fresnel diractive radiography with 1 m spatial resolution at the National Ignition Facility

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An x-ray Fresnel diractive radiography (FDR) platform was designed for use at the National Ignition Facility (NIF). It will enable measurements of micron-scale changes in the density gradients across an interface between isochorically-heated warm dense matter materials, the evolution of which is driven primarily through thermal conductivity and mutual diusion. We use 4.75 keV Ti K-shell x-ray emission to heat a 1000 m diameter plastic cylinder, with a central 30 m diameter channel lled with liquid D_2, up to 8 eV. This leads to a cylindrical implosion of the liquid D_2 column, compressing it to 2.3 g/cm^3. After pressure equilibration, the location of the D_2/plastic interface remains steady for several nanoseconds, which enables us to track density gradient changes across the material interface with high precision. For radiography, we use Cu He- x-rays at 8.3 keV. Using a slit aperture of only 1 m width increases the spatial coherence of the source, giving rise to signicant diraction features in the radiography signal, in addition to the refraction enhancement, which further increases its sensitivity to density scale length changes at the D_2/plastic interface.

I. INTRODUCTION

The warm dense matter (WDM) state is found in several astrophysical environments such as planetary interiors, or white dwarfs[1,2] and holds relevance in understanding controlled inertial connement fusion (ICF)[3]. The structure and dynamics of these systems crucially depend on transport properties such as thermal conductivity, viscosity, and diusion. For example, Rayleigh-Taylor growth rates are dampened by viscosity and mutual diusivity[4{6]. In ICF, hydrodynamic instability growth leading to the mixing of ablator material into the fuel and hot spot is one of the leading degradation mechanisms of implosion performance[4,5].

Theoretical descriptions of plasma transport properties typically have their roots either in the plasma or the condensed matter limits; however, these usually break down in the WDM region. Modeling matter in this parameter regime is particularly challenging as one often encounters systems with strong ion-ion correlations and electrons that exhibit distinct quantum behavior. To date, only a few experiments have attempted to measure transport properties in the WDM regime, with those that have concentrated on either thermal conductivity[7,8] or viscosity[9]. Recently, there have been promising results at the Linac Coherent Light Source (LCLS) in which inelastic x-ray scattering was used to measure the transport properties in WDM. Fitting the ion component of the experimental spectra using hydrodynamic modeling has allowed the properties of the bulk plasma to be extracted. Unfortunately, these measurements remain bandwidth limited[9{11].

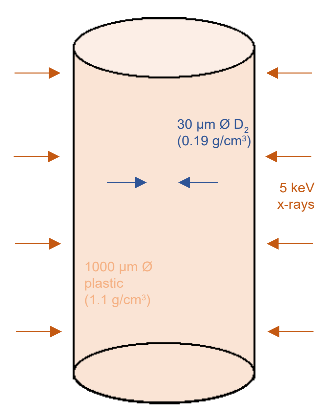

FIG. 1. Conceptual design of the physics package. A 30 m diameter D_2 channel inside a 1000 m diameter plastic cylinder is isochorically heated to warm dense matter conditions by 5 keV x-rays, triggering a cylindrical compression of the liquid D_2 column to 10 its original density.

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We have developed a Fresnel diractive radiogra-phy (FDR) platform for the National Ignition Facility (NIF)[12] designed to probe WDM with an unprecedented spatial and temporal resolution. Combining this radiography platform with a cylindrical implosion geometry, we can measure the equation-of-state of compressed matter and potentially determine transport properties such as thermal conductivity and diusion. Our platform leverages previous work developing 1D refractive enhanced imaging at the Omega, and NIF lasers[13,14], and adapts the Fresnel diractive radiography concept recently demonstrated at the Omega Laser Facility[15,16]. In contrast to previous work on NIF, we have reduced the width of the slit aperture, which denes the x-ray source size, from 5 to 1 m to enhance the spatial coherence of the source and hence signicantly increase diraction features.

In the proposed experiments, we use Ti K-shell x-ray emission to isochorically heat a 1000 m diameter plastic cylinder with a 30 m diameter channel at its center lled with cryogenic (21 K) liquid D_2 (Fig. 1). This sets up a temperature dierential between the two ma-terials, with the deuterium initially remaining cold. The resulting pressure dierence across the interface triggers a cylindrical implosion, compressing the deuterium column by about 10, where the nal deuterium density is larger than the plastic density. The rapid motion of the interface leads to an outgoing shock wave into the plastic and an incoming rarefaction wave, which can be used to determine the equation of state of these materials. Moreover, after an initial equilibration phase, the evolution across the interface is primarily driven by transport properties such as thermal conductivity or diusion. Our experimental platform leverages NIF's outstanding capabilities to produce a macroscopic warm dense matter sample that remains in a steady state for several nanoseconds, enabling the direct measurement of transport coefcients at the material interface.

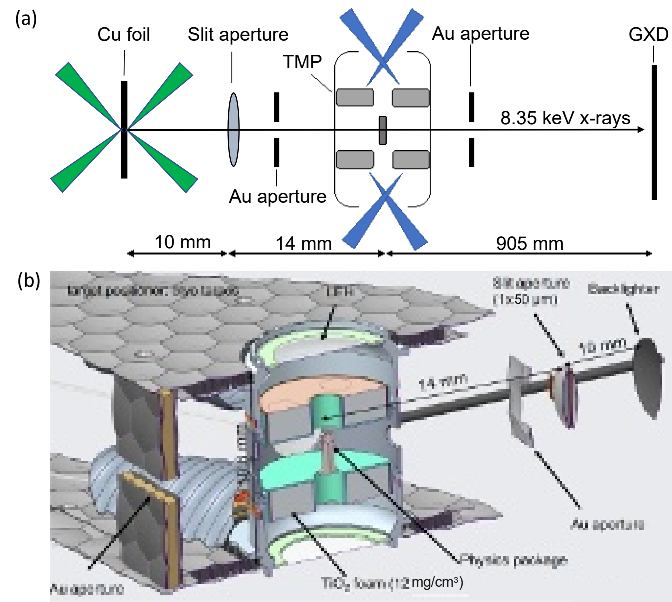

FIG. 2. (a) Schematic of the FDR imaging setup. Blue arrows represent drive beams, and green arrows represent backlighter beams. (b) Cut-away of the NIF target: A standard thermo-mechanical package (TMP) holds two TiO_2 foam disks on either side of the physics package at the center of the target. A Cu backlighter and a slit aperture are placed next to the TMP with additional Au apertures between the backlighter, target, and diagnostic, which shield against hard x-rays from the hohlraum and help collimate the beamprobe x-rays.

II. EXPERIMENTAL PLATFORM AT THE NIF

A. Geometry of the experimental setup

A schematic of the proposed experimental setup at NIF is shown in Figure 2. The target consists of a 10.8 mm tall, standard Al thermo-mechanical package (TMP) with an inner diameter of about 8 mm, as used in ICF implosions[12,17]. However, instead of containing an Au hohlraum, the TMP holds two 100 m thick polyimide containers on each side of the physics package at the center of the target, both encapsulating an annulus of TiO_2 foam (= 12 mg/cm^3). The polyimide containers have an opening (1.5 mm in diameter) along the vertical target axis since the target assembly requires a view along the vertical axis. 176 NIF drive beams (44 quads) pointed through the 4.88 mm laser entrance holes (LEH) of the TMP with a 1 mm diameter focal spot, and a 2 ns square pulse will be used to deliver a total energy of 600 kJ onto the TiO_2 foams, subsequently generating around 5 keV Ti K-shell x-ray emission. TiO_2 foams were chosen for their demonstrated high laser to x-ray conversion eciency, up to 5%[18]. The absorption length of the x-rays emitted from the foams is matched to the sample radius to ensure heating uniformity. The generated x-rays will be absorbed by the physics package, heating it to 8 eV (Fig. 3a).

B. Backlighter and slit aperture setup

Sixteen NIF beams will be pointed onto a 10 m thick Cu foil, which serves as the backlighter for this experiment (Fig. 2). Irradiation of the Cu foil with the laser beams will generate Cu He- x-rays (8.35 keV) that will pass through a 1 50 m^2 slit aperture placed 10 mm downstream towards the main target. The slit is milled into a 50 m thick Ta plate that tapers on the side facing the target to 10 50 m (for a detailed description, see[15]). The slit is fabricated by a focused ion beam (FIB) at the University of Nevada, Reno. The slit will be lled with CH to absorb the soft x-ray load at the wide end of the slit and hence delay slit closure. The spatial-coherence requirement for diraction-based imaging constrains the slit size, which must be on the order of a few microns

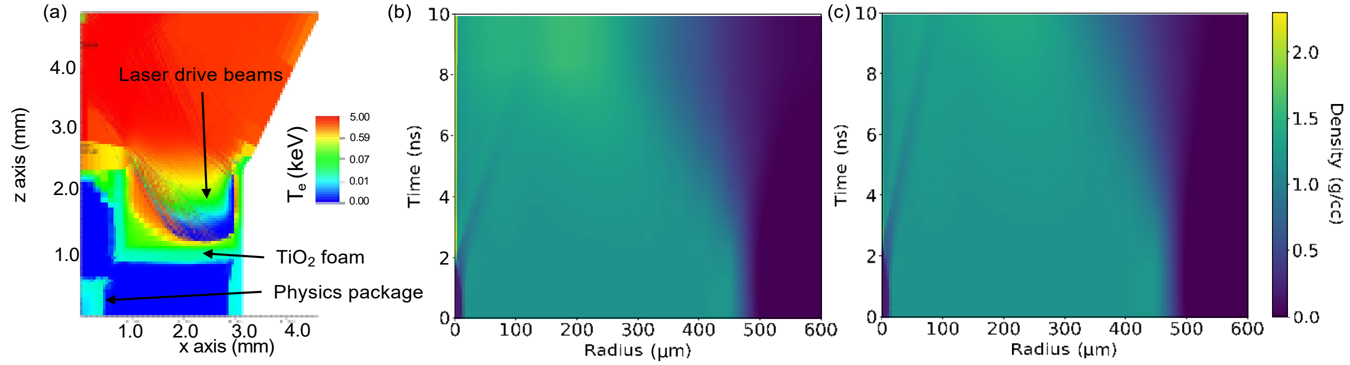

FIG. 3. Results of fully integrated hydrodynamic simulations using the Hydra code[19]. (a) Simulation of one quadrant of the hohlraum near the end of the 2-ns-long drive. The laser energy is almost completely absorbed inside the TiO_2 foam, heating it to temperatures of up to 5 keV. In this simulation, the physics package at the center of the thermo-mechanical package reaches a temperature of 8 eV. (b) Density evolution of the channel and surrounding plastic as a function of time and radius calculated for 8 eV heating of the plastic coating and (c) 4 eV (half drive) heating of the plastic coating. The simulations depict a shock wave launched outwards into the plastic and a rarefaction wave propagating into the cylinder.

or less[20]. Because of this, the slit will also diract the transmitted x-rays. We calculated the diraction parameter of the slit to be $\sqrt{10\ \mathrm{mm}\ \ 1{:}485\ \mathrm{A}}=1.2$ m. This is comparable to the slit width of 1 m; thus, we will be in the Fresnel regime with diraction angles of the order of 1.48 A/1 m 0.1 mrad. However, the slit (even account-ing for its 50 m thickness) will transmit a broad range (0.2 rad) of photon angles from a typical 1.2 mm diam-eter backlighter source size, which will result in complete blurring of the slit diraction pattern. Thus, the slit will produce a partially coherent point-like source with a source spread function of 1 m.

C. Diagnostics

A gated x-ray detector (GXD) with 240 ps integration time will record the radiography signal across four microchannel plate (MCP) strips that can be independently timed. The GXD is located 905 mm away from the target, yielding a large magnication of M = (905 mm+14 mm)/14 mm = 65.6 and ensuring that diraction features are visible given the 50 m point spread function of the MCP. A 50 m thick W wire will be placed at the exit window (225 m oset from the di-rect line of sight). This wire will help to determine the eective source function and spatial scale of the recorded image. Further, the DANTE diagnostics at NIF will record the temporal evolution of the Ti K-shell emission, thermal emission, and hard-ray emission from the target drive.

D. 2PP printed physics package

At the center of the TMP is the physics package, a 1000 m diameter, 1.5 mm tall plastic cylinder with a 30 m diameter channel running through the center (Fig. 4a). Creating such a small feature is extremely challenging with conventional milling techniques; however, it can be accomplished with 2 Photon-Polymerization (2PP) techniques. The 2PP additive manufacturing process utilized a femtosecond laser and optical system to

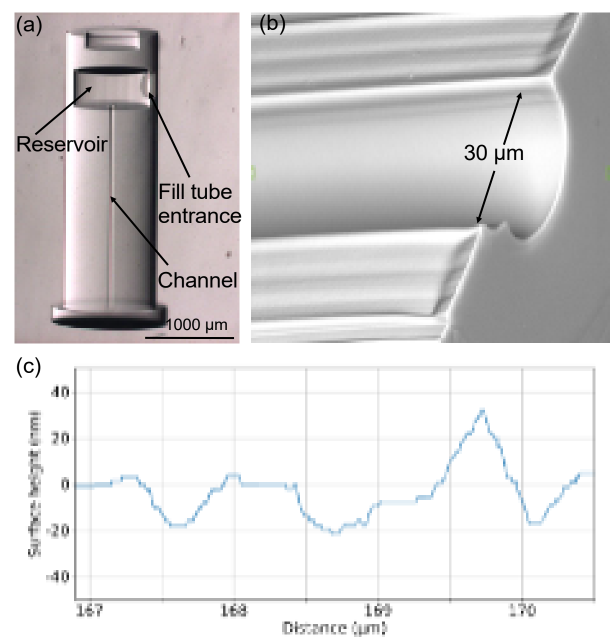

FIG. 4. (a) X-ray image of the 2PP printed cylinder along channel axis including the 1.5 mm long and 30 m in diameter channel holding the liquid D_2. The reservoir above the channel is 500 m in diameter, 170 m in height, and the ll tube entrance is 150 m in diameter. The total diameter of the cylinder is 1000 m. (b) Scanning electron microscopy image of the channel that was printed only one-sided. (c) Lineout of the measured surface roughness of the channel.

achieve ellipsoid-shaped polymerized voxels on a micron scale which are overlapped along the length of the inner channel in 50 nm steps by translating the part with a precision direct drive linear motor stage.

As the goal of the experiment is to measure transport properties at the material interface between deuterium and plastic, it is vital that the interface is not rough to begin with. A surrogate sample to measure the roughness of the inner channel was fabricated by printing a semi-cylinder with the same printing parameters as the full cylinder. The semi-cylinder was imaged with scanning electron microscopy (Fig. 4b), and a surface roughness of sub 50 nm was measured in the exposed channel with a white light interferometer at multiple points (Fig. 4c). The 2PP cylinder encapsulates a 30 m diameter channel which is connected to a reservoir on top of the cylinder (Fig. 4a). The reservoir is attached to a ll tube that is used to ll the channel with cryogenic cooled D_2 (= 0.19 g/cm^3). The plastic cylinder will be slowly cooled down, and the D_2 gas will condense within the channel and reservoir. The TMP itself will be low-level gas lled with He (<0.03 mg/cc) as a requirement for the tempera-ture equilibration (the target is elded at 21 K). The CH cylinder (= 1.15 g/cm^3) is made out of 60 % Bisphenol A ethoxylate diacrylate ($C_{20}H_{26}O_6$) and 40% Dipenta erythritol penta-/hexa-acrylate ($C_{25}H_{32}O_{12}$).

III. SIMULATIONS

Radiation-hydrodynamic simulations showing the evolution of the target have been performed with Hydra[19]. First, the 2PP printed cylinder will be heated by the Ti He K-shell x-rays, which ultimately lead to propagating shocks and rarefaction waves in the plastic cylinder and D_2 channel (Fig. 3). After the rst two nanoseconds, the temperature of the plastic will rise to approximately 8 eV, leading to the compression of the central channel and an increase of the D_2 density to 2.3 g/cm^3 (Fig. 3b). At this point, the interface between D_2 and plas-tic will stagnate, after which the evolution of the density prole is driven by transport properties, namely thermal condition and particle diusion. As heat ows from the plastic into the D_2 we observe an increase in the density of the plastic next to the interface and a corresponding decrease in the D_2 density[13,21]. At the same time, parti-cle diusion acts to smooth out the density jump at the interface itself. Lineouts showing the evolution of the density prole across the channel are depicted in Figure 5a. The expected diraction patterns are shown in Fig-ure 5b, which combine the complex transmission function of the target with the optical transfer function for Fresnel diraction. A sharp fringe contrast at the D_2/plastic interface is expected, which will ultimately move to smaller radii at later probe times. At 4 ns, the conductivity-sensitive diraction peaks are located at approximately 3 m radius. Parameterization of the diraction signal will be used to obtain information on the density prole and will help to determine the scale-length of thermal conduction in the D_2 and plastic. All calculations assumed a 1 m source size and were performed with the predicted density evolution shown in Figure 5a. Further details of the diraction calculation can be found in Pogany et al.[22].

In addition, we have simulated a low laser drive (Fig. 3c), which assumes that only half of the drive energy is delivered into the TiO_2 foams. In this case, the plastic is only heated to 4 eV, leading to a density increase of the D_2 to 1.7 g/cm^3. As the outgoing shock wave scales quite strongly with the drive (17.5 km/s for the high drive and 10.5 km/s for the low drive), we will be able to use this information to infer sample temperature. Furthermore, our simulations show that the target survives at least 10 ns in both laser drive cases before the incoming rarefaction wave reaches the D_2 channel.

IV. CONCLUSION

In summary, we have developed an experimental platform at the National Ignition Facility to probe the interface between warm dense deuterium and plastic using Fresnel diractive radiography with a 1 m spatial resolution. We expect to be able to determine the equation of state of D_2 and plastic and further investigate diffusion and thermal conductivity before the destruction of the interface due to inward propagating rarefaction waves. Liquid D_2 and plastic are ideal materials for the proposed experiment due to their dierences in density and opacity as well as their relevance to inertial fusion experiments.

V. ACKNOWLEDGEMENTS

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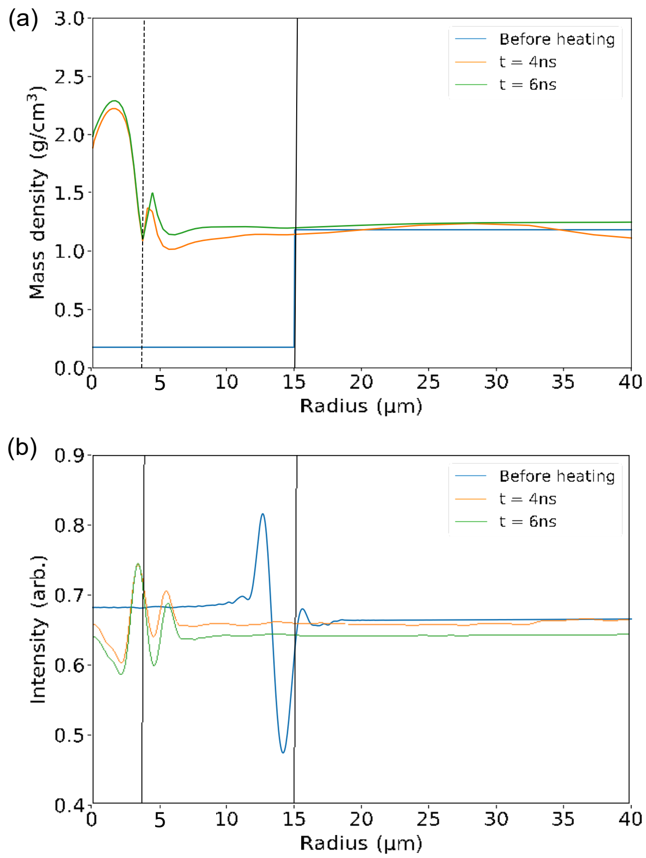

FIG. 5. (a) Density lineouts at three dierent probe times. The lineouts show the evolution of the density prole across the D_2 channel due to compression by the heated 2PP printed cylinder. The liquid D_2 column is compressed by 10 to 2.3 g/cm^3. After a few reverberations, a quasi-steady state is reached at 4 ns due to pressure equilibration between the D_2 and the surrounding plastic. (b) Simulated diraction patterns derived from the predicted density lineouts. The solid black line represents the interface between D_2 and plastic at ambient state, the dashed line the interface at driven state.

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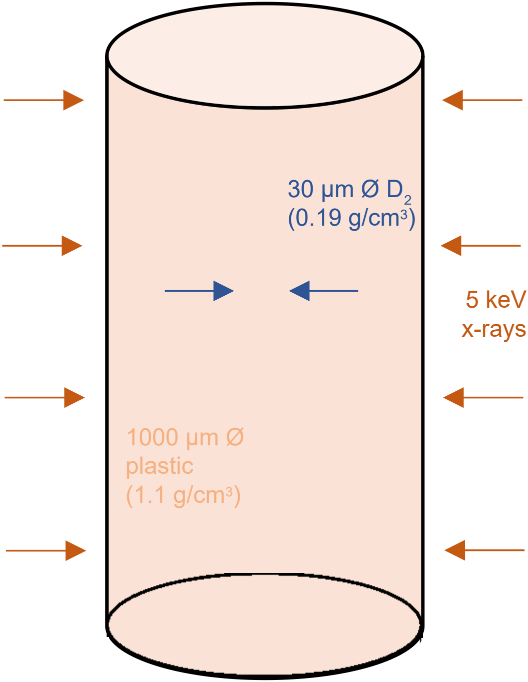
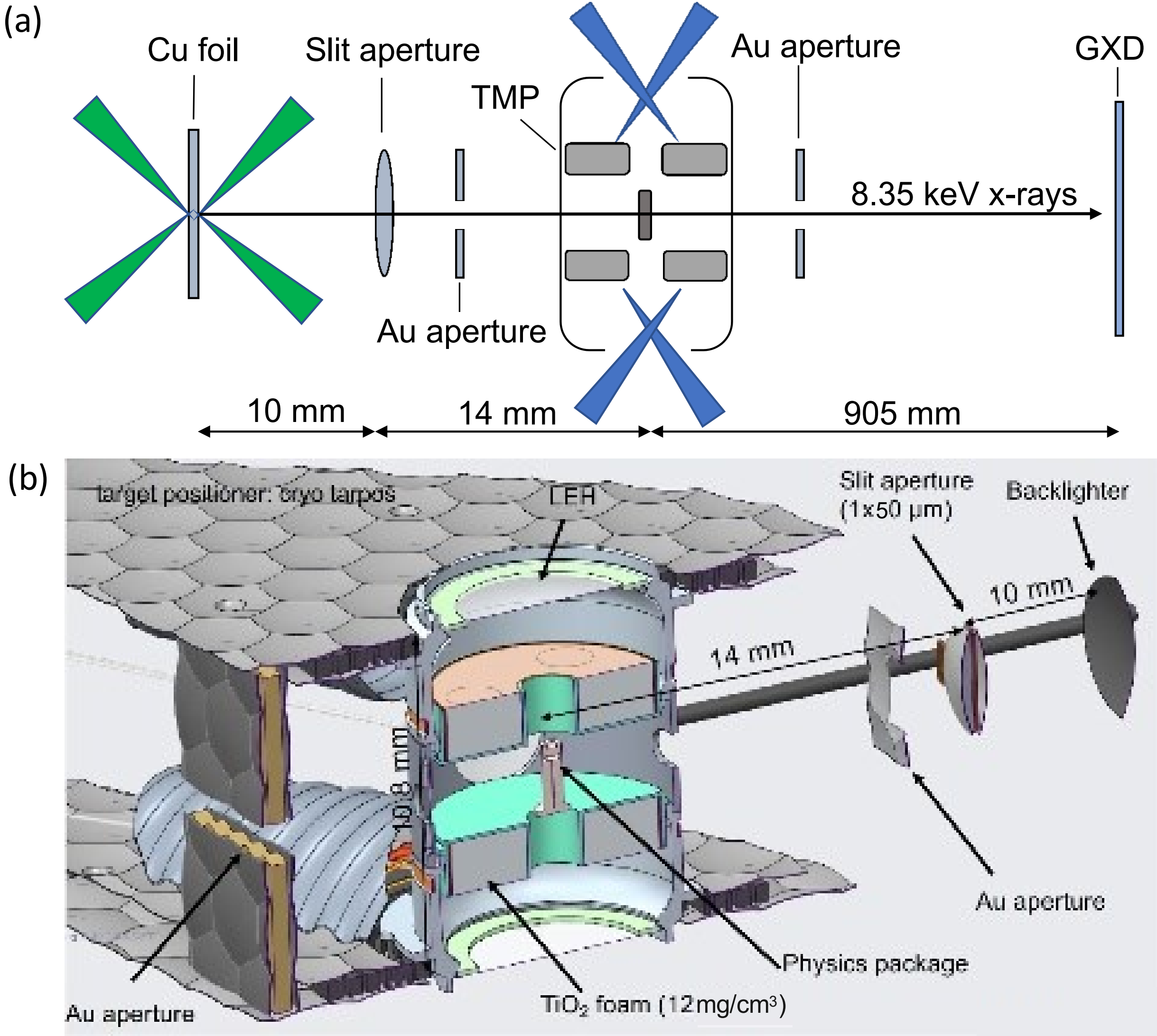
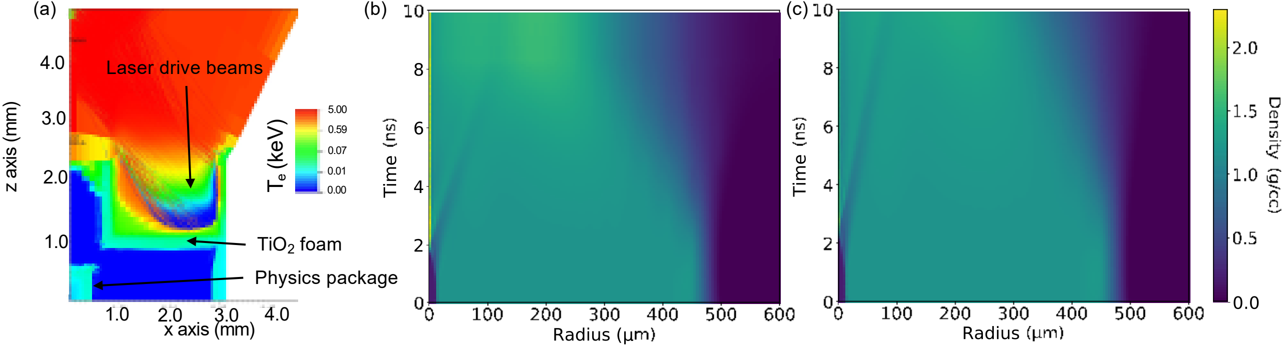
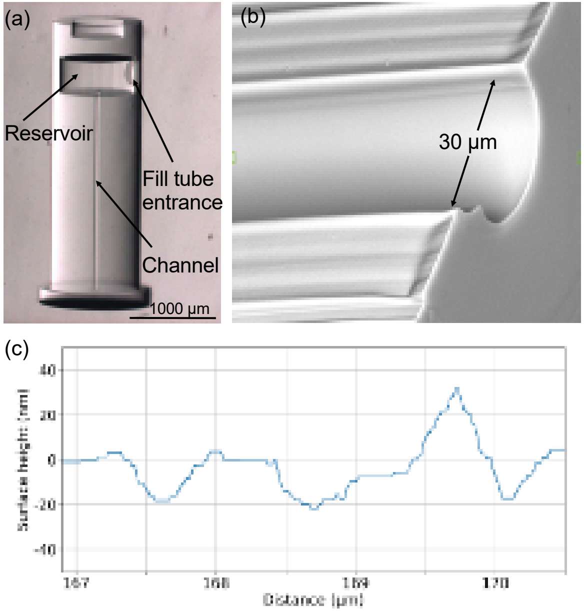

30 μm Ø D_2
(0.19 g/cm³)
5 keV
x-rays
1000 μm Ø
plastic
(1.1 g/cm³)

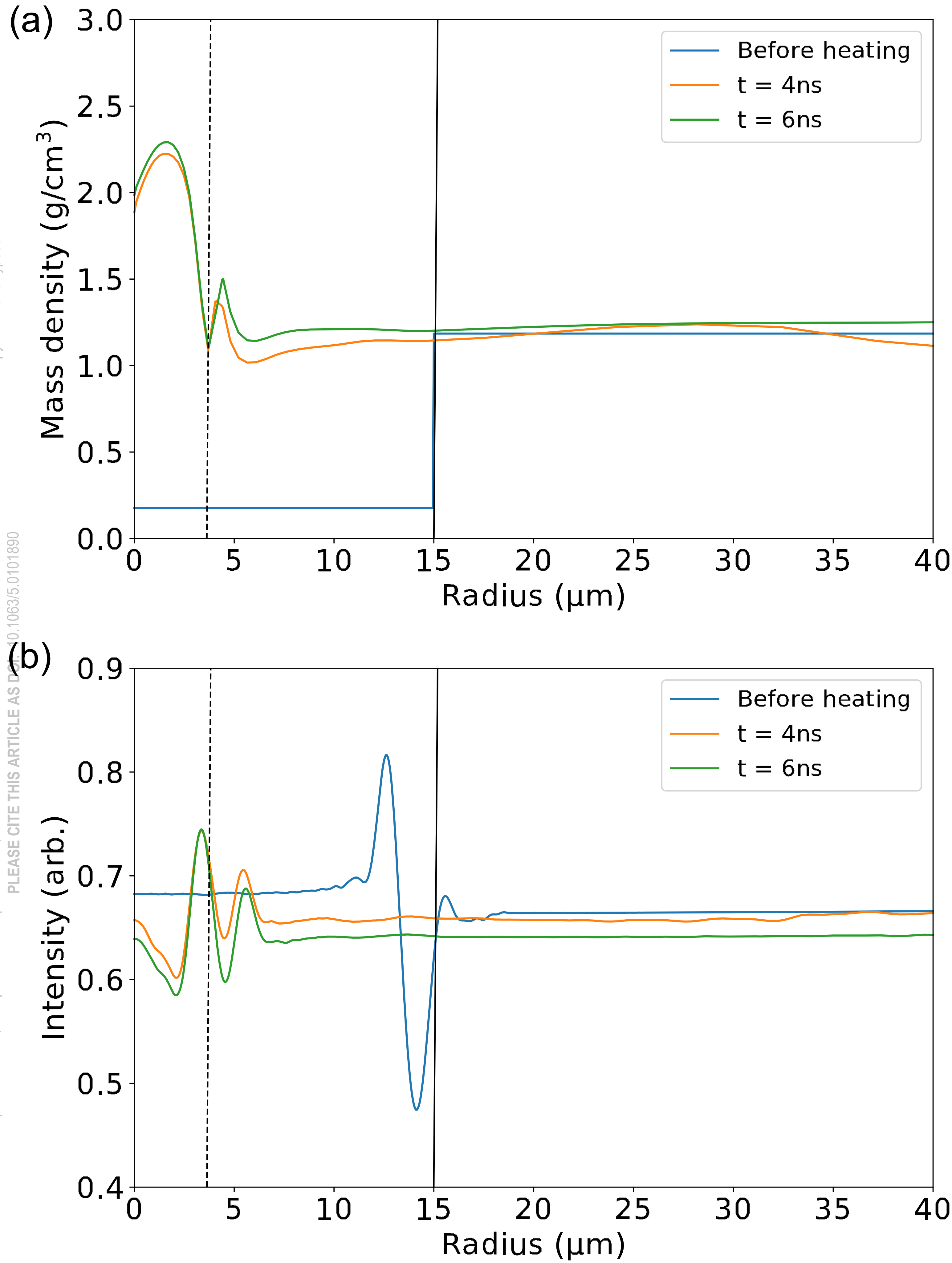

(a)
Cu foil
Slit aperture
TMP
Au aperture
GXD
8.35 keV x-rays
Au aperture
10 mm
14 mm
905 mm
(b)
target positioner: cryo tarpos
LEH
Slit aperture
(1x50 µm)
Backlighter
10 mm
14 mm
10.8 mm
Au aperture
Physics package
TiO2 foam (12mg/cm3)
Au aperture



(a)
(b)
(c)
Laser drive beams
TiO2 foam
Physics package
z axis (mm)
x axis (mm)
Te (keV)
5.00
0.59
0.07
0.01
0.00
Time (ns)
Radius (μm)
Density (g/cc)



(a)
Reservoir
Fill tube
entrance
Channel
1000 µm
(b)
30 µm
(c)
Surface height (nm)
40
20
0
-20
-40
167
168
169
170
Distance (µm)


(a)
Mass density (g/cm^3)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Radius (µm)
0
5
10
15
20
25
30
35
40
Before heating
t = 4ns
t = 6ns
(b)
Intensity (arb.)
0.9
0.8
0.7
0.6
0.5
0.4
Radius (µm)
0
5
10
15
20
25
30
35
40
Before heating
t = 4ns
t = 6ns