A Knock-On Deuteron Imager for Measurements of Fuel and Hot-Spot Asymmetry in Direct-Drive Inertial Confinement Fusion Implosions

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A knock-on deuteron imager (KoDI) has been implemented to measure the hot spot and fuel asymmetry of cryogenic inertial confinement fusion implosions on OMEGA. Energetic neutrons produced by D–T fusion elastically scatter ("knock-on") deuterons from the fuel layer with a probability that depends on ρR. Deuterons above 10 MeV are produced by near-forward scattering, and imaging them is equivalent to time-integrated neutron imaging of the hot spot. Deuterons below 6 MeV are produced by a combination of sidescattering and ranging in the fuel, and encode information about the spatial distribution of the dense fuel.

The KoDI instrument consists of a multi-penumbral aperture positioned 10 to 20 cm from the implosion using a ten-inch manipulator (TIM) and a detector pack at 350 cm from the implosion to record penumbral images with magnification of up to 35×. Range filters and the intrinsic properties of CR-39 (Ref. 1) are used to distinguish different charged-particle images by energy along the same line of sight. Image plates fielded behind the CR-39 record a 10-keV x-ray image using the same aperture.

Differential filtering is used to distinguish between high- and low-energy deuteron populations. The left half of the CR-39 is filtered by 135 μm tantalum, transmitting only deuterons initially above 10 MeV. The right half is filtered by 10 μm tantalum, transmitting deuterons initially above 2 MeV. The diameter of tracks is used to further discriminate the data into rough energy bins to interpret the images. While the exact diameter–energy relationship varies from sample to sample, the energy order and approximate energy range can be inferred. The analysis of the x-ray data is described in Ref. 2.

Penumbral imaging maximizes the statistics of the recorded signal. Each penumbral aperture is made by laser drilling a 200-μm-thick tantalum or 175-μm-thick tungsten substrate, producing a conical hole with an opening angle of 10°. Two effects cause the point-spread function (PSF) of the penumbral apertures to differ from the ideal knife edge: charged-particle scattering in the substrate and electrical charging of the array. Because of the high magnification of the camera, even a small amount of straggle is sufficient to produce a uniform background and the effect of scattering on the PSF blur is negligible. Electrical charging of the aperture array is more significant. A semi-analytic form of the charged-aperture PSF was derived using a numerically integrated electric field inside the array, $E(r)$:

$$\mathrm{PSF} = \left[\frac{\mathrm{d}r_\mathrm{i}'}{\mathrm{d}r_\mathrm{a}'}\right]^{-1}, r_\mathrm{i}' = r_\mathrm{a}' + \frac{e\Delta z}{4\pi\varepsilon_0}\left[\frac{Q}{K}\frac{D}{R_\mathrm{a}}\frac{M-1}{M^2}\right]E'\left(r_\mathrm{a}'\right), \tag{1}$$

where r_a and r_i are radial position in the aperture and image plane, R_a is the aperture radius, D the detector distance to target chamber center (TCC), Δz is the aperture thickness, M is the camera magnification, Q is the aperture charge density, K is the deuteron kinetic energy, and primes indicate normalized quantities $\left\{r_\mathrm{a}' = r_\mathrm{a}/R_\mathrm{a}, r_\mathrm{i}' = r_\mathrm{i}/R_\mathrm{a}M, E' = E'/\left[Q/2\pi\varepsilon_0\right]\right\}$. The charged-aperture PSF is a family of curves that depends only on the value of the coefficient in square brackets, which we call V. [We select

$\Delta z = 200$ μm and V has units of (coulomb/cm^2)/MeV.] Charging effects are negligible for values $V \lesssim 10^{-7}$, but become dominant for $V \gtrsim 3 \times 10^{-5}$. For accurate reconstructions using a charged aperture, the amount of charging must be known and the blurring caused by charging effects must not dominate the structure caused by the object. The PSF radius at 50% of maximum increases monotonically with the charging coefficient. The amount of charging from the data is inferred by comparing the projected radius of the deuteron aperture images with x-ray measurements of the camera magnification. Since V depends on particle energy, low-energy deuterons are more susceptible to the effects of charging than high-energy deuterons.

The images of the source are encoded in the recorded penumbral images and are recovered using the iterative reconstruction algorithm described by Gelfgat *et al.* in the limit of Poisson statistics.[3] We include a uniform background and begin with a uniform prior. Numerical testing shows that for N total tracks, the required number of iterations to converge grows as roughly $N^{0.33}$ for a fixed image size. The asymptotic reconstructions are overfit, concentrating numerical noise into high variations between neighboring pixels. To avoid overfitting, a condition for when to terminate the reconstruction is desirable and is under investigation.

The KoDI system was fielded on a series of direct-drive cryogenic implosions on OMEGA during 2021 and 2022. In the majority of the experiments, the diagnostic was fielded in TIM-1 with a magnification of 25 or 35. In one shot series (102560–102571), multiple KoDI instruments were fielded at different magnifications on each shot. Figure 1 shows the (a) deuteron and (b) x-ray data recorded on shot 102568. Analysis of the raw x-ray data indicated a magnification of 35.70±0.10. The deuteron data were analyzed to infer a charge-induced magnification increase of 5.4±0.3%. These values were used to calculate the point-spread function for reconstructing the data. A reconstruction of a high-energy deuteron image is shown in Fig. 1(c), and the corresponding reconstructed x-ray image in Fig. 1(d). The inferred shape and size of the hot spot is comparable between the x rays and deuterons. The 50% radius (P0) of the deuteron image was fit as 30 μm, with a significant mode-2 (P_2/P_0) of 30%. The axis of the mode-2 matches that seen in the reconstructed x-ray image. The camera was fielded in TIM-5, observing the implosion nearly perpendicularly to the stalk axis, and the observed mode-2 is elongated in the stalk direction.

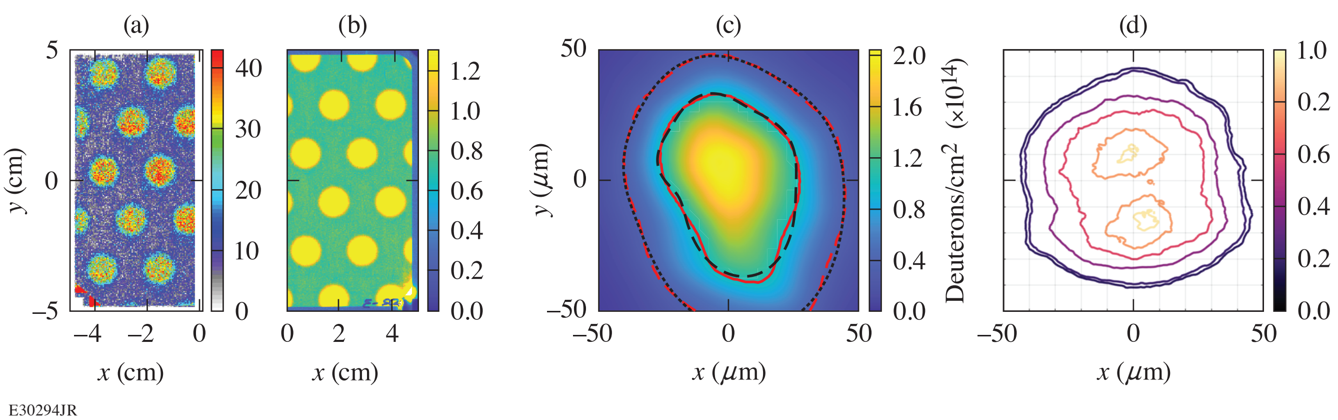

Figure 1
KoDI data recorded on OMEGA cryogenic implosion 102568. (a) High-energy deuteron image (>10 MeV, tracks per 400-μm square pixel); (b) 10-keV x-ray image (PSL per 100-μm square pixel); (c) reconstructed deuteron source with 50% and 17% intensity contours (red curves) and Legendre polynomial fits to $n = 4$ (black curves); and (d) reconstructed x-ray source.

Aperture charging was observed on the majority of the experiments and appears to show increased charging with aperture distance from TCC. The observed trend is not consistent with a prompt charging source that originates at TCC, which should fall off as R^2. The data are roughly consistent with a model in which the electromagnetic pulse (EMP) radiation produced by the laser–target interaction drives currents in the TIM body, for which farther distance from TCC allows a greater amount of time for the aperture to charge before being sampled by the deuterons.

While the charged-aperture PSF is, in principle, sufficient to interpret the diagnostic data, in practice, the reduction or elimination of aperture charging will significantly benefit the experiments by reducing analysis error and maximizing camera resolution, and is necessary for low-energy deuteron images that are more severely distorted. Several approaches to controlling the aperture charging are being investigated, including replacing the front 30 cm of the diagnostic with a nonconductive material; fabricating the aperture from a nonconductive material such as silicon dioxide; and reducing the EMP source by changing the target mounting stalk.[4] These solutions will be tested in upcoming campaigns to assess their effects on the recorded data.

The data recorded by the KoDI diagnostic will enable detailed studies of the hot spot and assembled cold fuel on OMEGA. Comparisons of the high-energy deuteron and x-ray images will be used to infer the profiles of temperature and density to localize mix in the hot spot. Up to six lines of sight will be used to reconstruct the 3-D profiles of neutron emission and cold dense fuel. These data will provide unprecedented constraints on fuel assembly in direct-drive implosions, which will assist in the goals of reaching improved symmetry and hydro-equivalent ignition conditions on OMEGA.

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