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Visualizing deceleration-phase instabilities in inertial confinement fusion implosions using an "enhanced self-emission" technique at the National Ignition Facility

L. A. Pickworth,[1] B. A. Hammel,[1] V. A. Smalyuk,[1] H. F. Robey,[1] L. R. Benedetti,[1] L. Berzak Hopkins,[1] D. K. Bradley,[1] J. E. Field,[1] S. W. Haan,[1] R. Hatarik,[1] E. Hartouni,[1] N. Izumi,[1] S. Johnson,[1] S. Khan,[1] B. Lahmann,[2] O. L. Landen,[1] S. Le Pape,[1] A. G. MacPhee,[1] N. B. Meezan,[1] J. Milovich,[1] S. R. Nagel,[1] A. Nikroo,[3] A. E. Pak,[1] R. Petrasso,[2] B. A. Remington,[1] N. G. Rice,[3] P. T. Springer,[3] M. Stadermann,[1] K. Widmann,[1] and W. Hsing[1]
[1]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[2]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[3]*General Atomics, San Diego, California 92186-5608, USA*

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High-mode perturbations and low-mode asymmetries were measured in the deceleration phase of indirectly driven, deuterium gas filled inertial confinement fusion capsule implosions at convergence ratios of 10 to 15, using a new "enhanced emission" technique at the National Ignition Facility [E. M. Campbell *et al.*, AIP Conf. Proc. **429**, 3 (1998)]. In these experiments, a high spatial resolution Kirkpatrick-Baez microscope was used to image the x-ray emission from the inner surface of a high-density-carbon capsule's shell. The use of a high atomic number dopant in the shell enabled time-resolved observations of shell perturbations penetrating into the hot spot. This allowed the effects of the perturbations and asymmetries on degrading neutron yield to be directly measured. In particular, mix induced radiation losses of ∼400 J from the hot spot resulted in a neutron yield reduction of a factor of ∼2. In a subsequent experiment with a significantly increased level of short-mode initial perturbations, shown through the enhanced imaging technique to be highly organized radially, the neutron yield dropped an additional factor of ∼2. *Published by AIP Publishing.*
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In inertial confinement fusion (ICF)[1–6] cryogenic layered implosions on the National Ignition Facility (NIF),[6] hydrodynamic instabilities[7–10] have been shown to mix higher Z ablator into the DT hot spot, leading to radiative cooling and neutron yield degradation.[11,12] Significant insights into physics of these instabilities in NIF implosions have been provided by experimental development. This was initiated by the Hydrodynamic Growth Radiography (HGR) platform, directly measuring the instability dispersion curves using pre-imposed two-dimensional (2-D) sinusoidal perturbations at capsule convergences up to ∼2, during the acceleration phase of the implosion.[13–19] The perturbations due to 3-D "native-roughness" were measured using a modified HGR platform with convergence ratios up to ∼3, still in the acceleration phase. These first x-ray radiography experiments showed that the 3-D broadband modulations and perturbations due to the capsule support membrane (a "tent")[20] were growing unexpectedly strongly and were close to perforating the plastic CH capsule even at relatively low convergences.[21–23] The perturbations caused by the fill tube (FT) (used to fill the capsule with DT fuel) were also measured to be larger than expected, primarily due to the x-ray shadows cast by the fill tube at the capsule surface during the early time x-ray drive.[23] Other unexpected and significant "coherent structures" discovered in these HGR experiments were oxygen-induced perturbations seeded during the target assembly processes.[24] At higher convergence (∼5–10) near peak capsule velocity, an "argon self-backlighting" x-ray radiography platform was developed resulting in measurements of the highest instability growth factors (GF) ever observed in ICF implosions, GF ∼ 7000[25,26] and their asymmetry, pole vs. equator. The unexpected asymmetries in the instability growth of 2-D pre-imposed modulations and 3-D perturbations were also measured using this technique near peak compression.

In this Communication, a new "self-emission imaging" technique is presented, complementing the "argon self-backlighting" radiography technique[25,26] to study instabilities of implosions on NIF around peak compression. It is based on enhanced x-ray emission of the capsule inner shell using a high atomic number dopant, enabling visualization of the high-mode perturbations and low-mode asymmetries at high convergences (>10). With this new technique, we were able to clearly visualize and study the effect of tents, fill tubes, and low-mode asymmetries on the final implosion performance. Previously, high-Z dopants were instrumental as diagnostic tools of the gas fuel and ablator shell conditions in implosions on the Nova, Omega, and NIF lasers. On Nova, an Ar dopant was used to study conditions in the gas using spectroscopy, and a Cl dopant was used to study the shell integrity and shell-gas mix.[27–31] Self-emission from the shell was enhanced with a Ti dopant to study symmetry,[32–41] 1s-2p Ti absorption and K-shell imaging investigated shell perturbations and mix, while Ar doping investigated mix on OMEGA laser.[42–49] On NIF, numerous dopants (including

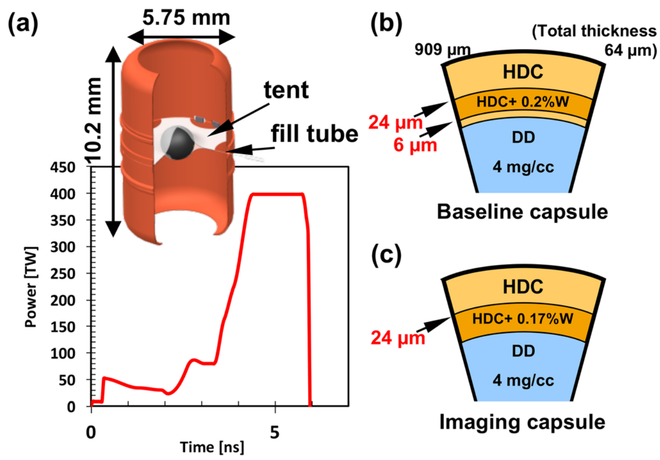

FIG. 1. The schematic of the target shows (a) the U hohlraum and the 3-shock laser pulse shape with a peak power of ∼360 TW and a total energy of ∼1.1 MJ.[67–70] The high-density-carbon (HDC) capsule, support "tents," and a fill tube are also illustrated. The schematics of capsules show (b) nominal W-doped layers in the baseline configuration and (c) W-doped layer extended to the inner shell surface in the "self-emission imaging" configuration.

Ge, Cu, Kr) have been used to deduce hot spot conditions from their x-ray signatures and more recently, nuclear reactant dopants in the shell have been used to examine shell mix into the hotspot.[12,14,17,50–57] In all cases, the dopant provides a unique signature that can be used to tag the material or region of interest. When using this technique, care is required to density match the doped layer to the shell, and to not further perturb the region undesirably.

In the experiments described in this Communication, the enhanced x-ray emission due to the high-Z dopant in the inner shell of the high-density-carbon (HDC) capsule[58,59] resulted in high-resolution observations of perturbations around peak compression using a Kirkpatrick-Baez microscope (KBM)[60–66] on NIF. This allowed systematic studies of neutron yield degradation due to high-mode perturbations, low-mode asymmetries, and x-ray radiation losses, using the "self-emission" imaging technique in low-convergence (>10×) implosions with gas fuel. Figure 1(a) shows a schematic of the target, which includes a uranium cylindrical hohlraum used to implode a HDC capsule supported by 45-nm thick membranes ("tents"). The hohlraum length was 10.2 mm, with a diameter of 5.75 mm, and a laser entrance hole (LEH) diameter of 3.37 mm. The hohlraum was driven with the 6-ns long laser pulse based on using a 3-shock design with a nominal peak power of 400 TW and an energy of 990 kJ.[67–70] The capsules were filled with 4 mg/cc deuterium (DD) gas through a 10-μm diameter glass fill tube at a temperature of 40 K. The HDC capsules were nominally 64-μm thick with an outer radius of 909 μm, as shown in Fig. 1(b). The baseline capsule had 18 μm thick, 0.2% atomic W-doped layers offset by 6 μm thick undoped HDC layers from the inner capsule surface, while the "imaging" capsules had 24-μm thick, 0.17% atomic W-doped layers that extend all the way to the inner surface of the capsule. These implosions do not have a DT ice layer, leaving the inner surface of the capsule to freely expand into the deuterium fuel. The purpose of the W-doped inner layer in the "imaging" capsules was to enhance x-ray emission of the inner shell surface near peak compression, and to study the effects of the enhanced x-ray radiation on the implosion performance.

Figure 2 shows a time sequence of x-ray images measured with the four-channel KBM, ranging from 290 ps before to 60 ps after peak compression for the inner W-doped "imaging" capsule. The KBM mirrors used multilayer coatings to image narrow-band x-rays from ∼8.8 keV to ∼11.8 keV with ∼6-μm spatial and ∼100 ps temporal resolution (including the resolution of the framing camera[71–73]) at a magnification of ∼11. One of the prominent features in the images is a fill-tube perturbation on the left side of the x-ray image moving toward the center, as time progresses. While dominant in the early-time images, its emission becomes comparable to the emission from the rest of the shell near peak compression (time = 0ps). The perturbations from the capsule membranes ("tents") are also visible in the early-time image (at 190 ps before peak compression) along with top-to-bottom asymmetry. While emission from the tents persists in the late-time images, the shell emission (enhanced by the W dopant) becomes dominant around peak compression. In addition to the instrument spatial resolution, the images are affected by motion blur. Before deceleration, the shell travels with a peak velocity of ∼0.3 μm/ps, while it slows down to zero at peak compression. This contributes a maximum motion blurring of ∼30 μm at peak velocity to the radial extent of the capsule image. However, the object emission history, instrument gate gain profile, and deceleration of the shell act to reduce this contribution.

Figure 3 compares the measured x-ray image at 190 ps before peak compression [Fig. 3(a)] with 2D HYDRA simulations[74] including the tents, the measured 3% top-bottom laser energy asymmetry in the drive [Fig. 3(b)], and the fill-tube perturbation without drive asymmetry [Fig. 3(c)] calculated at

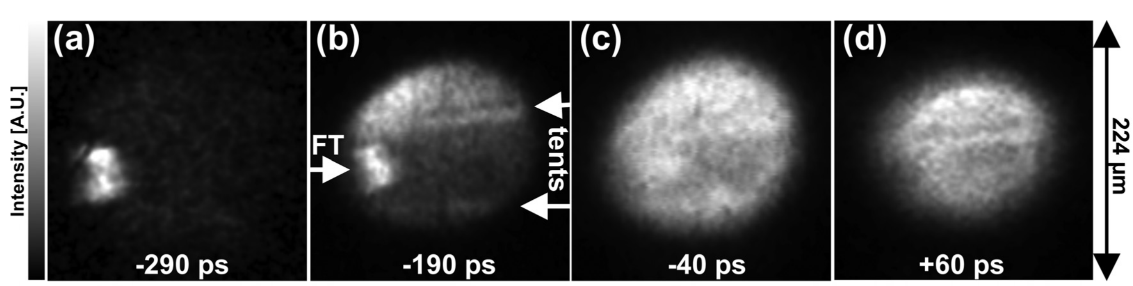

FIG. 2. Time sequence of equatorial x-ray images measured with the Kirkpatrick-Baez microscope at 10.3 ± 1.5 keV. The locations of the perturbations from the fill tube (FT), and the tents are indicated in the image (b). The direction of the bulk neutron velocity is towards the top left-hand corner of these images. The time of the images is given at the bottom of each image, relative to the time of peak x-ray emission.

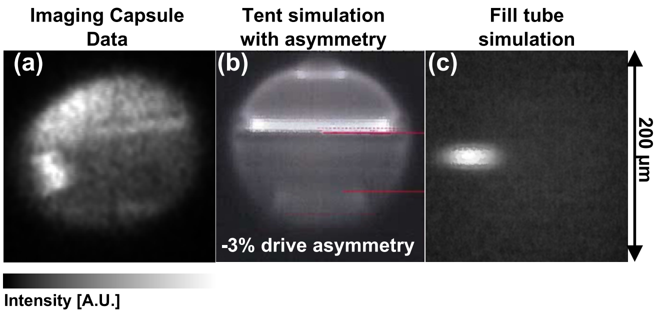

FIG. 3. (a) The measured equatorial x-ray image at 190 ps before peak convergence, as shown in Fig. 2(b). (b) The HYDRA simulated x-ray image shows low-mode x-ray asymmetry due to laser drive asymmetry and tent perturbations. (c) The simulated x-ray image shows that the width of the fill-tube perturbation is smaller in HYDRA compared to the experiment [as shown in (a)].

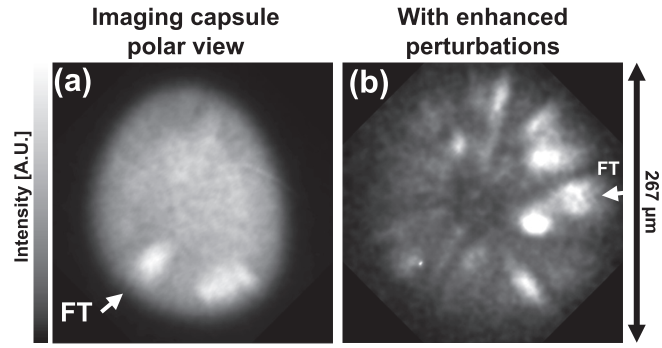

FIG. 4. Recorded polar x-ray images from (a) the nominal self-emission "imaging" experiment compared to (b) the experiment with an increased number of visible high-mode perturbations. The increased level of perturbations resulted in $\sim 2\times$ degradation in the neutron yield.

the time of the measurement. The simulated fill-tube perturbation is a factor of $\sim$1.5 longer and a factor of $\sim$2 narrower than the experimentally measured image. The larger lateral extent of the measured fill-tube perturbations up to peak compression may be the result of x-ray shadowing of discrete laser spots (not included in current simulations), as observed in lower convergence HGR experiments with laser drive similar to our experiments.[23] Recently published simulations[75,76] that attempt to include a surrogate fill-tube "shadow" perturbation on the capsule show some qualitative similarity to the fill tube jet observed in this experiment. In those cases, the shorter extent of the jet into the hot spot is due to hydrodynamic turbulence or "roll-up" at the tip of the jet. We note that the tent perturbations were measured in these HDC implosions, as indicated in Fig. 2. While the tent perturbations were very pronounced in CH implosions at both low and high convergences,[20,77–79] they were not detectable at peak compression in similar HDC experiments until these new results with imaging capsules. A mode 1 asymmetry in the hot spot x-ray emission was also measured for the first time, due to the increased sensitivity of the inner-shell emission with this new platform. As shown in Fig. 3(a), the top left part of the x-ray image is brighter than the bottom part, and the tent emission also shows asymmetry with respect to the equator. These asymmetries are the result of a 3% up-down asymmetry in delivered laser energy, due to four missing drive beams. The simulation results shown in Fig. 3(b) exhibit very similar features and time progression, when similar drive asymmetries are applied. The higher drive on the bottom of the capsule shifts the hot-spot upward, causing the upper tent perturbation to appear closer to the center of the image. The lower tent perturbation is less apparent because it is stretched by the upward flow and it is penetrating a colder region of the hot spot. Based on the neutron measurements,[80] the fuel had a bulk velocity of $\sim$125 μm/ns toward the top pole, consistent with the observed brighter top region in the x-ray images. We might expect the velocity to result in a small, only a few percent, reduction in the yield due to the residual bulk motion of the fuel. This conclusion is consistent with results from a companion experiment [Fig. 4(a)] which shows a similar neutron yield without a large up-down velocity asymmetry. The contribution to the yield degradation from the fill tube and tent perturbations at peak convergence was estimated based on their geometrical extent and the radiation levels deduced from the measured x-ray images. The estimated contribution of the fill tube to the total yield degradation was about $\sim$1%, while that from the tent perturbations was $\sim$20%. The primary factor in the yield degradation from these perturbations was estimated to be their geometrical extent, in both the enhanced emission and the baseline experiments. The fill tube radiation is most significant early in time, accounting for $\sim$20% of the total radiative losses $\sim$300 ps before peak convergence. Measured low-mode asymmetries due to drive perturbation were also estimated to have a small effect on the yield degradation. Earlier experiments reported changes in the shape and shell areal density due to large polar velocities,[80] though the effect on the neutron yield in the case of gas filled implosions was small ($\sim$6% yield reduction[81]).

Another example of the data from the "imaging" platform is presented in Fig. 4. It shows a comparison of the x-ray images recorded in the polar direction with nominal (left) and enhanced (right) level of high-mode perturbations near peak compression. The features seen in the highly perturbed enhanced case were unexpected (see below).

The experiments with regular HDC capsules, with inner W-doped layers, and with a significant level of high-mode perturbations allow quantitative studies of the effects of x-ray cooling, low-mode asymmetries, high-mode perturbations, fill tubes, and tents on nuclear performance.

To determine if enhanced loss of energy through x-ray radiation may account for the losses observed in neutron yield between the baseline ($\sim 2.3 \times 10^{13}$) and imaging capsule ($\sim 1.2 \times 10^{13}$), we form an experimentally based x-ray enhancement factor similar to that reported by Ma *et al.*[11] The total x-ray emission is given in the following equation:

$$E_x = E_n e^{\tau_E^{shell}} \frac{C_X}{C_N} \frac{e^{-\frac{E_{keV}}{T_e}}}{T_i^{-2/3} e^{-18.76 T_i^{-1/3} (E_{keV})^{0.39} (T_e)^{0.15}}}, \qquad (1)$$

where E_n is the energy in DD neutron yield in J, τE is the attenuation of the shell, $(C_X/C_N) = 1.895 \times 10^{-4}$, E is photon energy in keV, and T_i and T_e is ion and electron temperature, respectively, in keV. We assume local thermodynamic equilibrium (LTE), $T_i = T_e$ and use the lowest reported $T_i \sim 3.7$ keV for all the implosions. The emissivity from the compressed deuterium can be modeled as a free-free continuum, which is estimated from Detailed Configuration Accounting (DCA)[82] non-LTE at 1-GBar and DD reactivity cross section (p. 45)[83] and attenuated by the remaining shell. So that the total emission is modeled with the experimental observables of DD neutron yield, DD temperature, and shell ρR.

We compare this emission to the signal recorded on the image plate pinhole camera,[84] for each experiment. To do this, we convolve the emissivity [Eq. (1)] with the filters used and the image plate sensitivity.[85,86] The pinhole images are filtered with either 1 mm of polyimide or 55 μm of Vanadium. For debris protection, there is an additional 1.5 mm polycarbonate or 275 μm polyimide on both depending on the experiment. The ratio of the measured and predicted signals allows us to determine how much brighter the imaging experiments were than the baseline experiments. The DD neutron yield is plotted as a function of this radiation emission enhancement factor in Fig. 5(a) for x-rays at a mean energy of $\sim$11 (14) keV for the polyimide (vanadium) channels with a relative spectral response shown in Fig. 5(b). The imaging capsule implosions observed a factor of $\sim$2 lower measured neutron yield, and the x-ray enhancement factor is increased by an order of magnitude over the baseline implosions. The enhancement factor is a factor of $\sim$3 higher in the $\sim$11 keV channel compared to the $\sim$14 keV channel.

The estimated internal energy of the hotspot, $3/2(Z+1)NkT$, was $\sim$4 kJ for the baseline and $\sim$3.2 kJ for the imaging experiments. The $\sim$800 J difference represents the internal energy loss responsible for the reduced yield. The observed $\sim 2\times$ reduction in the yield is correlated with the increased measured x-ray signal for energies >8 keV, equating to about 600 J between 8 and 11 keV after shell attenuation. The alternate mechanisms for energy loss, discussed above, do not account for the observed $\sim$50% yield reduction. In addition to free-free emission off the W-doped C ions, free-bound and L-shell line emission of W will contribute to the observed transmitted radiation. Though it is only a small fraction of the shell composition, the 0.17% W dopant emissivity can be important. For an ion charge state Z, the free-free emission scales as Z^2, while free bound recombination radiation to the ground-state M-shell of ionization potential (IP) scales as $Z^2(2IP/3T_e)\exp(IP/T_e)$. Assuming a W ionization, Z, of $\sim$60 with M-shell IP $\approx$ 4 keV vs $T_e \approx 3$ keV, we expect similar emissivity to the fully ionized C even ignoring inner-shell W L-shell line radiation below 10 keV. While the measured radiation was limited to x-rays >8 keV due to absorption in the diagnostic filters and cold shell, it is expected that lower energy x-rays <8 keV including W M-shell lines and recombination radiation will also contribute to the radiation cooling of the hot spot resulting in the yield degradation. Because the ratio of resonance line energy to ionization potential drops as $(2n+1)/(n+1)^2$ with increasing ground-state quantum number n, line radiation from high Z ions at higher ground-state n will always be stronger at lower x-ray energies ($\sim$4 keV) than from mid Z ions (Si, Ge, Cu) from doped layers that were the subject of prior experiments.[11,12]

The major contribution to the measured $\sim 2\times$ yield reduction in the implosions with the imaging capsule is due to the radiation loss from the doped shell, not due to perturbations from the fill tube, tents, and low-mode drive asymmetries. However, by significantly increasing the levels of high-mode perturbations, as observed in the shot shown in Fig. 4(b), the yield was further reduced by a factor of $\sim$2. The increased number of visible perturbations over the nominal imaging capsule experiment is striking [the polar view from the nominal case is shown in Fig. 4(a)], and the cause is unknown. On this experiment, the beginning of the inner beam pulse shape was extended, introducing a weaker first shock. Although this was expected to have a small effect on the amplification of perturbations, it may have affected the initial seed and material state of the ablator.[87] As the visible emission features are highly organized radially in the polar view, [Fig. 4(b)] the seed which produces these perturbations must also have been radially organized. This may result from a cracking process in the mixed state HDC shell[88–90] or amplify the effect of pre-existing creases or folds in the tent, which may be present on all experiments or exacerbated in this particular experiment.

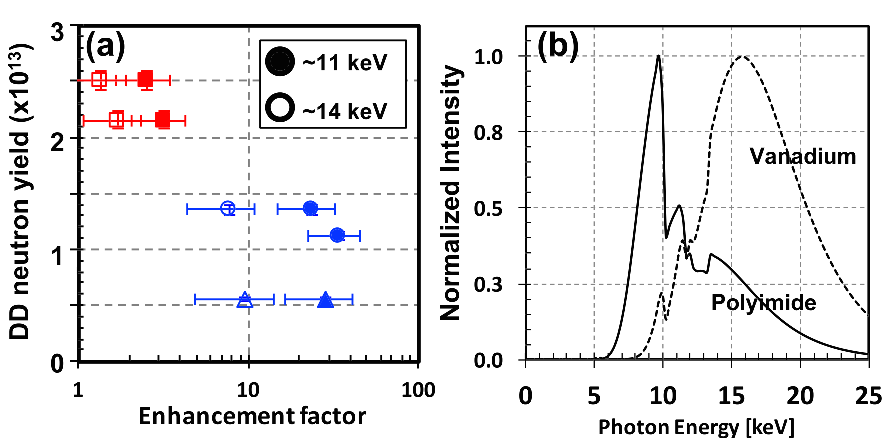

FIG. 5. (a) Measured DD neutron yield vs emission enhancement factor for the measured x-rays with a mean x-ray energy of $\sim$11 keV (solid symbol, polyimide channel) and $\sim$14 keV (open symbol, vanadium channel). Notice that the x-ray emission factor is larger in the lower x-ray energy polyimide channel. The data include baseline experiments without inner-shell dopants (red, square), with an inner-shell dopant (blue, circles), and with the inner-shell dopant and enhanced levels of high-mode perturbations (triangle). (b) Normalized emission spectra for an example imaging experiment used to calculate the enhancement factor. The solid line is polyimide and the dashed one is vanadium filters. Emission includes all diagnostic filters and image plate sensitivity.

Whatever the cause, this experiment illustrates the power of the method to visualize hydrodynamic mix by enhancing self-emission from the mixed region. It is interesting that the measured x-ray enhancement factor was not increased in this experiment, compared to other inner W-dopant experiments. Therefore, the additional yield degradation can be related to the reduced neutron-producing volume caused by the increased levels of high-mode perturbations. A ∼20% reduction in the neutron producing radius would be consistent with the measured reduction in the yield.

In summary, high-mode perturbations and low-mode asymmetries were measured in the deceleration phase of indirectly driven ICF implosions using a new "self-emission" technique at NIF. This high-resolution imaging experiment allows the detailed study of the fuel-shell interface to isolate the relative impacts of different perturbations on neutron yield.

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