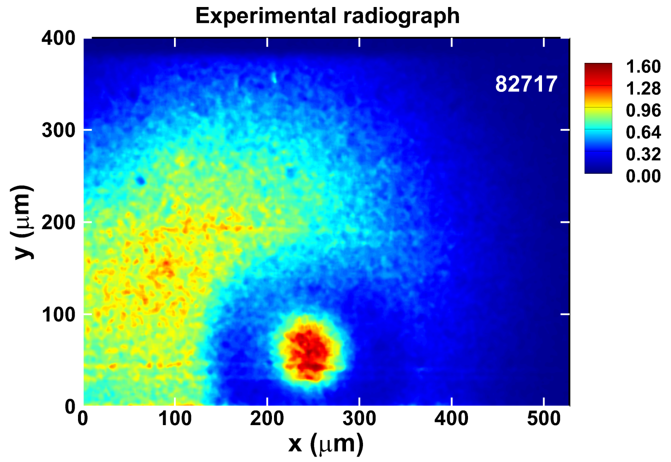
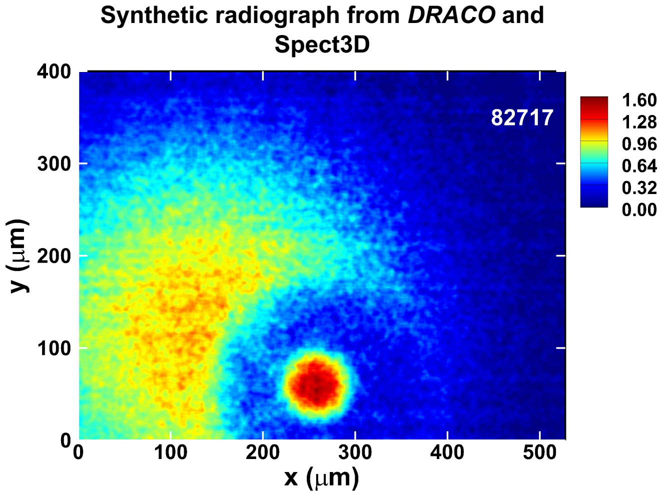
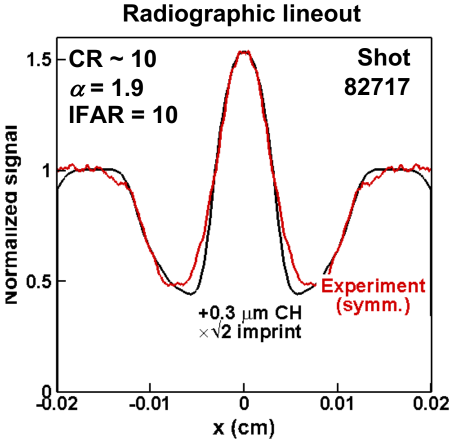
Mixing at the fuel-ablator interface in backlit OMEGA cryogenic implosions







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Summary

Simulated radiographs of backlit OMEGA implosions provide a sensitive measure of both fuel-ablator mixing and the unablated CH

- Moderate- and low-adiabat cryogenic implosions have been backlit with OMEGA EP*
- 2-D *DRACO* simulations, post-processed with Spect3D,† show substantial agreement with experimental radiographs only when modeling includes greater unablated CH, either due to thicker shells or a reduced mass ablation rate
- 2-D simulated radiographs have been generated which complement lineouts by showing signatures of multidimensional effects

* C. Stoeckl *et al.*, Rev. Sci. Instrum. 85, 11E501 (2014)
† *PrismSPECT,* Prism Computational Science Inc., Madison, WI 53711

Collaborators

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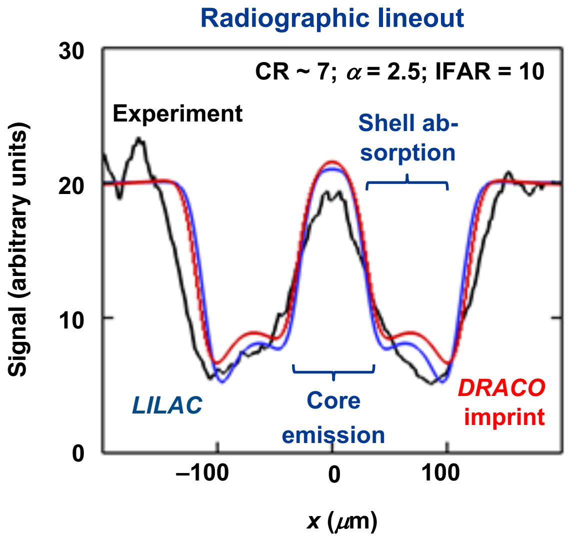
Low- and moderate-adiabat cryogenic implosions which straddle the stability boundary* were backlit with OMEGA EP

- A crystal imager** was used to produce a short-pulse (40-ps), monochromatic Si He$_\alpha$ x-ray backlighting source
- Radiographic lineouts for the moderate adiabat implosion reproduce the shell absorption and limb darkening due to unablated CH
- Due to the moderate adiabat of this implosion, the depth of the shadow cast by the shell is largely unaffected by mixing due to imprint

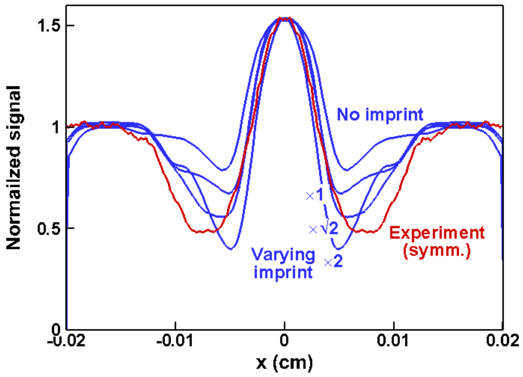


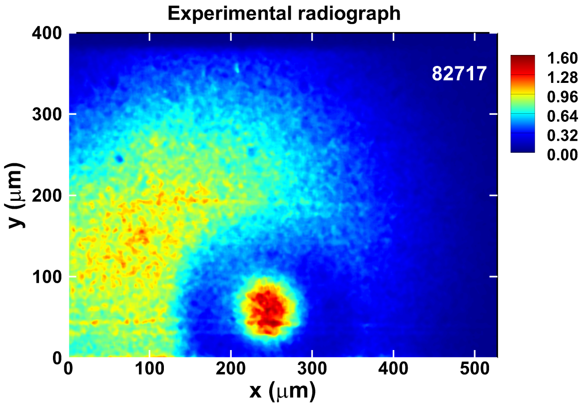
CR: Convergence ratio
IFAR: In-flight aspect ratio

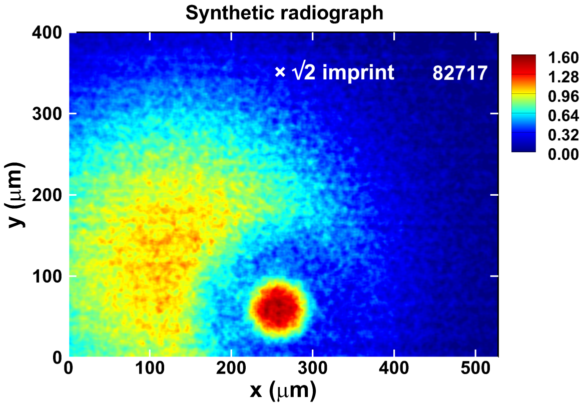
* V. N. Goncharov et al., Phys. Plasmas 21, 056315 (2014)
** C. Stoeckl *et al.*, Rev. Sci. Instrum. 85, 11E501 (2014)

DRACO simulations of the low-adiabat implosion show signatures of imprint-induced mix of CH into the DT fuel layer

- 2-D *DRACO* simulations have been performed incorporating CBET and NL electron heat transport
- *DRACO* and Spect3D* have been used to generate synthetic radiographs incorporating the experimental noise spectrum
- *DRACO* simulations with a ×√2 increase in the nominal imprint level produce a shadow depth comparable to the experimental value but fail to reproduce the radial extent of the shadow







CBET: Cross-beam energy transfer
NL: Non-local
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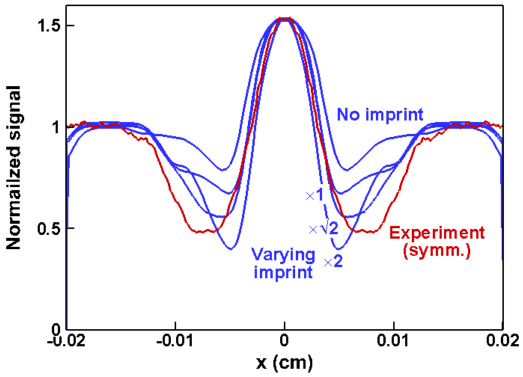

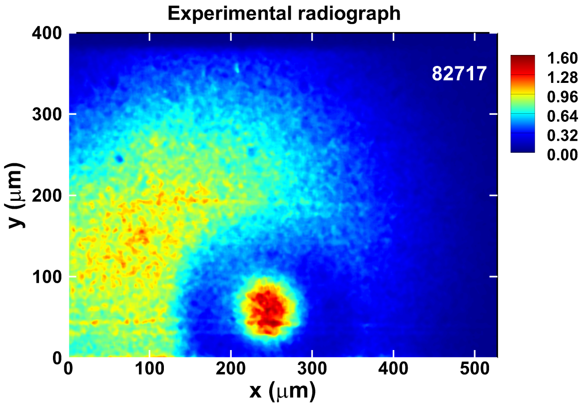

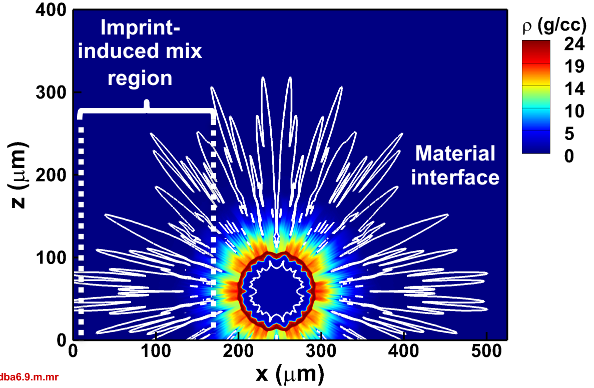

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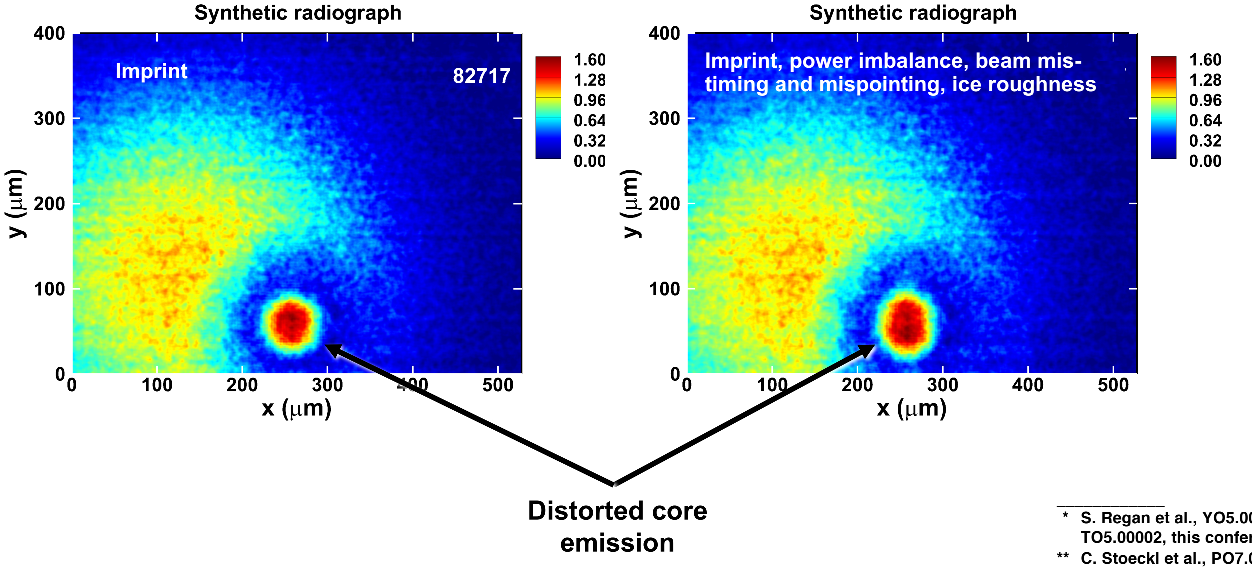
Low-mode target and drive uniformities affect the shape of the core emission but do not affect the shadow cast by the cold shell

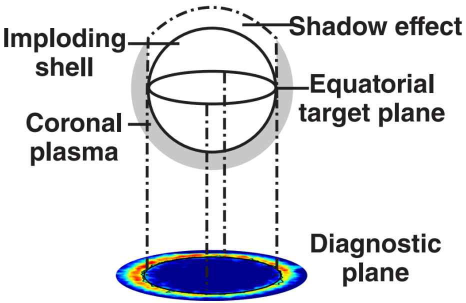
- **Low modes result in hot-spot flows which affect the shape of core emission and target performance* and have been systematically addressed experimentally****
- **Unlike imprint and low-mode perturbations, unablated CH is able to affect the optical depth out to the mix region, potentially affecting the shadow width**

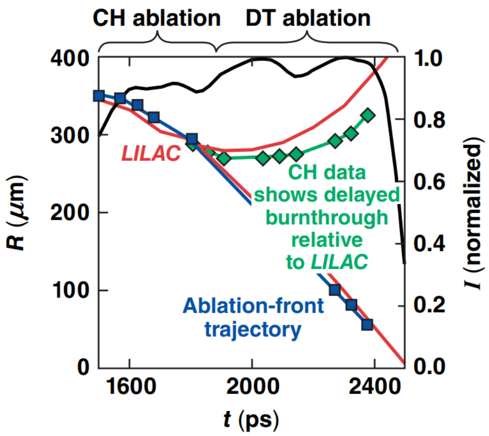


* S. Regan et al., YO5.00002; R. Shah et al., YO5.00001; O. Mannion et al., TO5.00002, this conference
** C. Stoeckl et al., PO7.00010

Unablated CH may be the result of a reduced ablation rate

- Coronal self-emission imaging provides high-resolution tracking of the ablation front and experimental measurement of the ablation rate*
- A measurable delay in the CH burn-through time is observed in typical cryogenic implosions suggesting a lower mass ablation rate than that predicted by laser coupling and thermal transport models
- *DRACO* simulations of backlit implosions are underway with an improved CBET model** to determine its effects on the simulated ablation rate





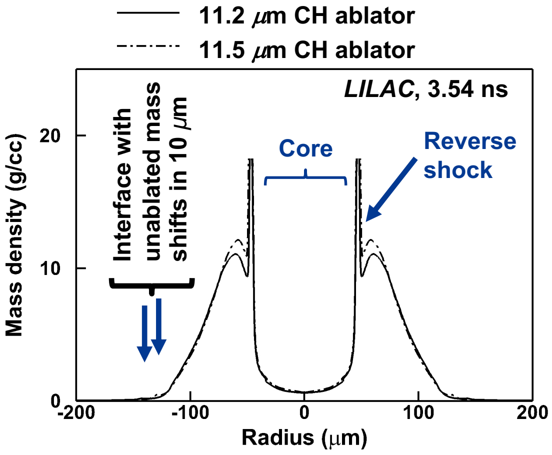
Ablation and material interface trajectories for a typical cryogenic implosion

* D. T. Michel et al., High Power Laser Sci. Eng. 3, e19 (2015).
** J. A. Marozas et al., YO5.00010, this conference.

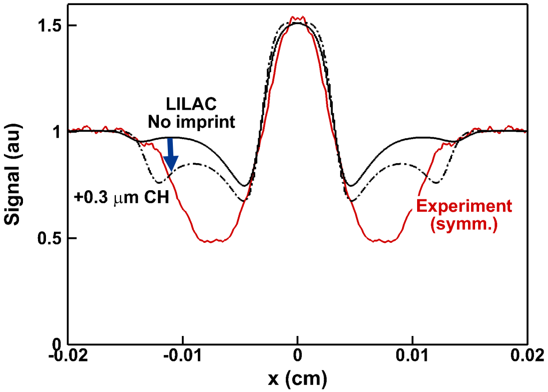
Cf. E22994; E27499

Modeling with unablated CH and elevated imprint reproduces the experimental shadow for the low-adiabat implosion

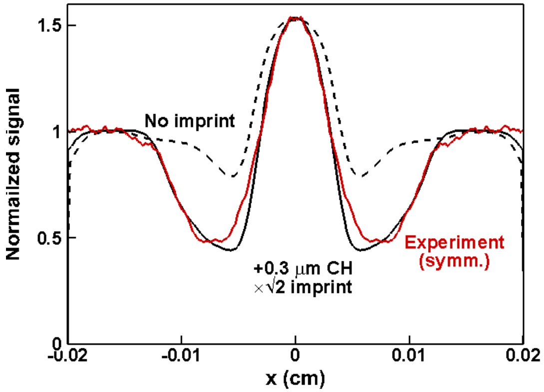
- The measured pre-shot ablator thickness is 11.2 ± 0.5 *μ*m
- An ablator thickness of 11.5 *μ*m, within the measurement uncertainty, causes the mix region to shift in by ~10 *μ*m, resulting in greater absorption and a wider shell shadow
- It is possible with current techniques to measure the ablator thickness with a precision of ~ ±0.1 *μ*m
- The low target performance (Y_{exp}/Y_{sim}~10%) and core temperature (simulated T_{ion} = 2.56 keV > T_{exp}= 2.4 keV) for these shots suggest additional mix* may be transporting carbon to the core



Unablated CH deepens shell absorption *and* width in 1-D



Imprint combined with a thicker ablator reproduces the experimental lineout in 2-D



* Igumenshchev et al., NO5.00006, this conference

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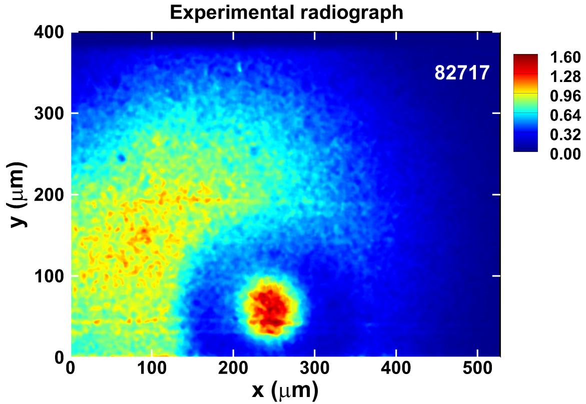
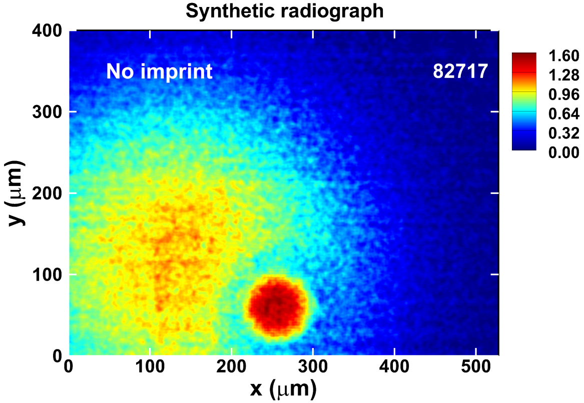
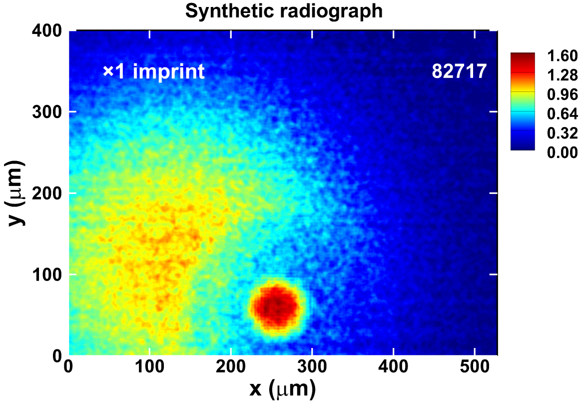
Backup slides

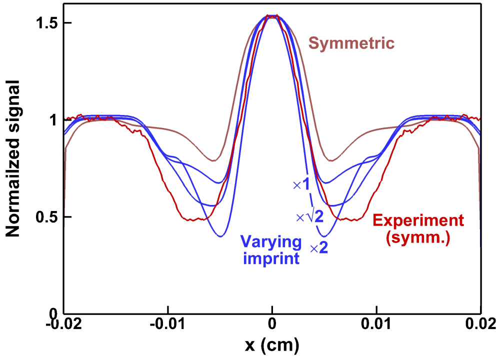
- …

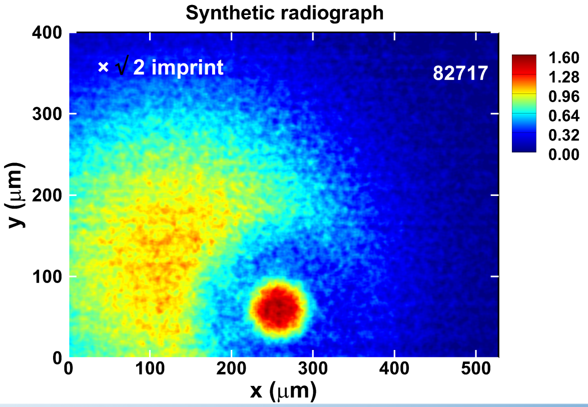
Variations in imprint level can be seen in the shell shadow in synthetic radiographs

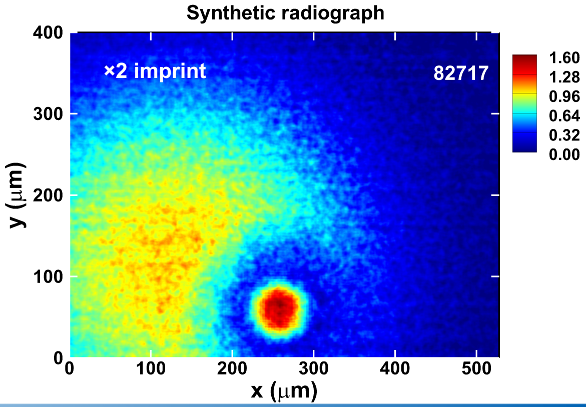




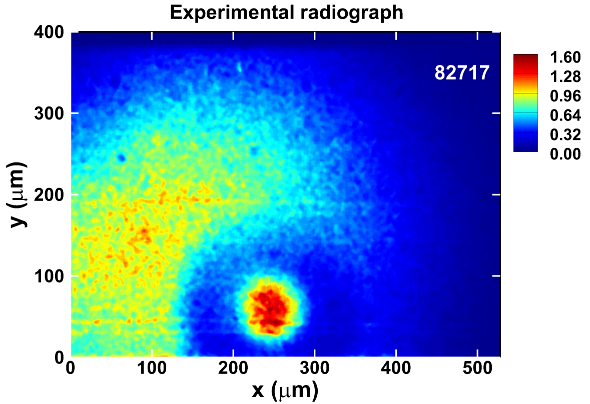


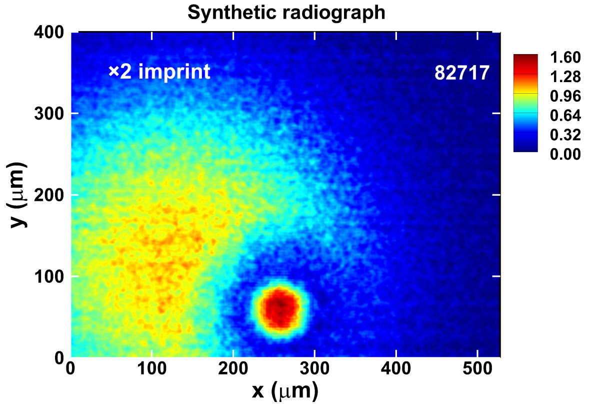


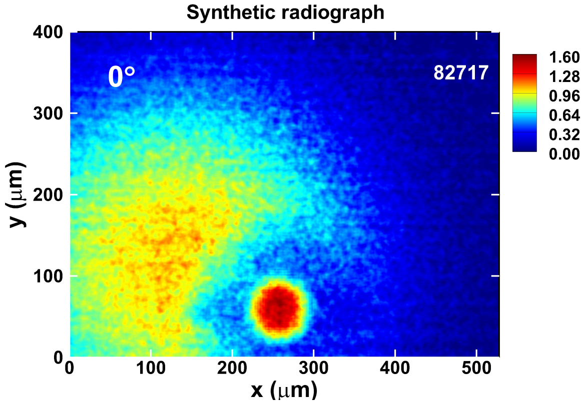




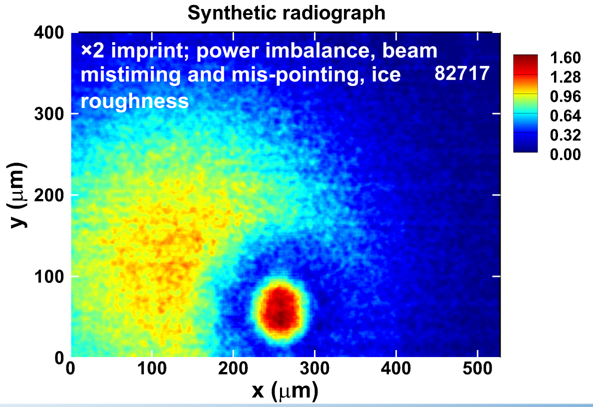
Neither low modes nor viewing angle is capable of reproducing the width of the ice shadow in the experimental radiograph

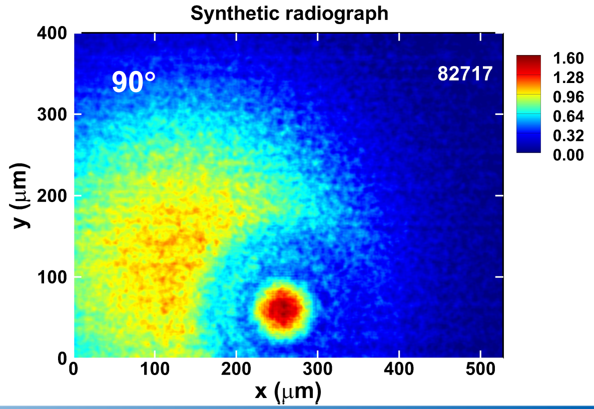




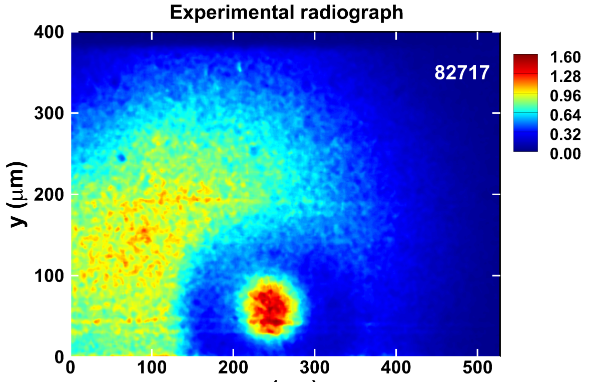


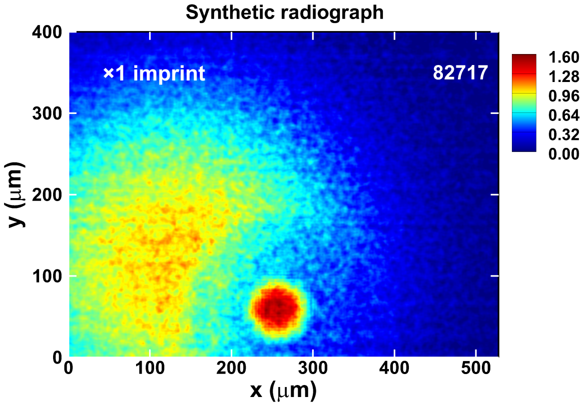
- Low modes distort the core without changing other features such as width and depth
- Viewing angle can introduce artifacts in the shell region but does not alter its basic properties

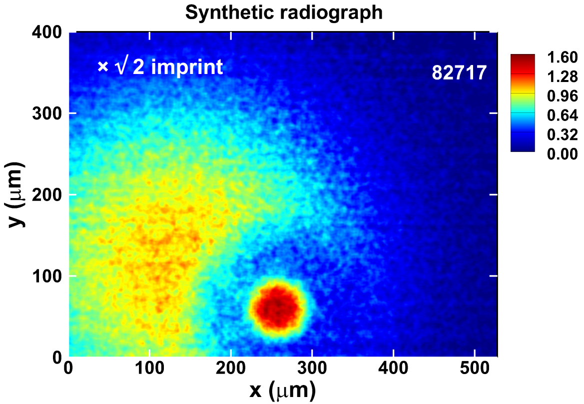


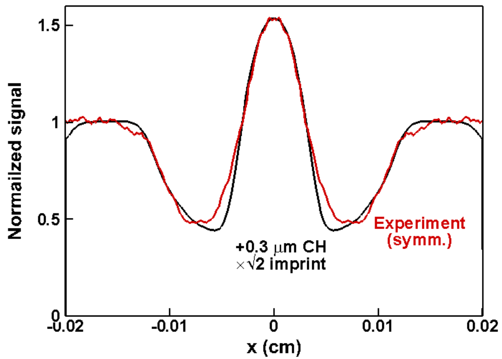


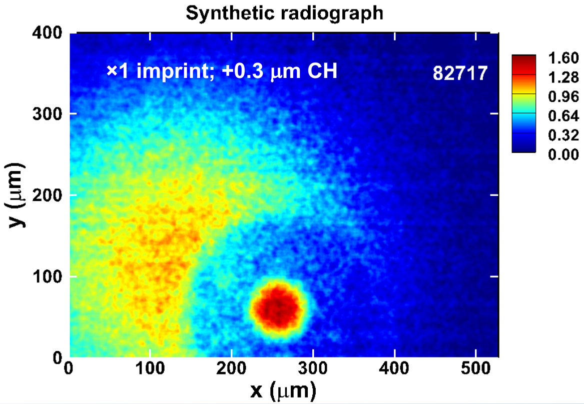
Simulations with a 0.3 μm thicker ablator more closely reproduce the depth and width of the shadow cast by the ice

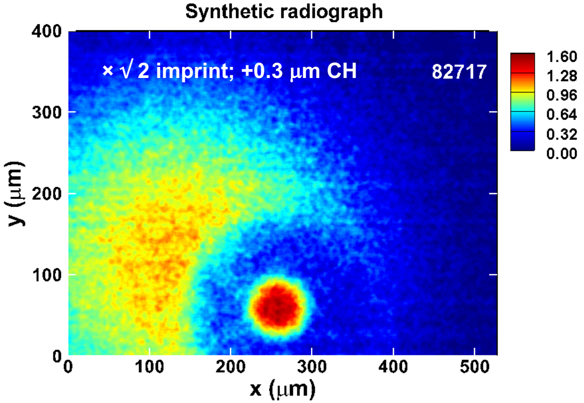












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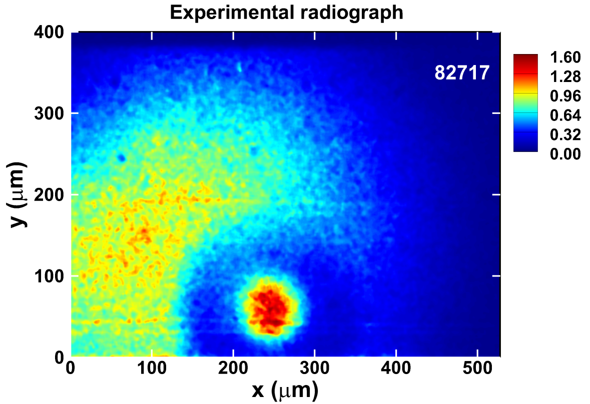
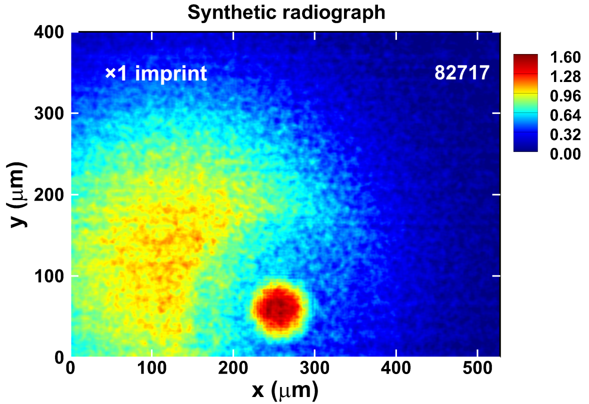
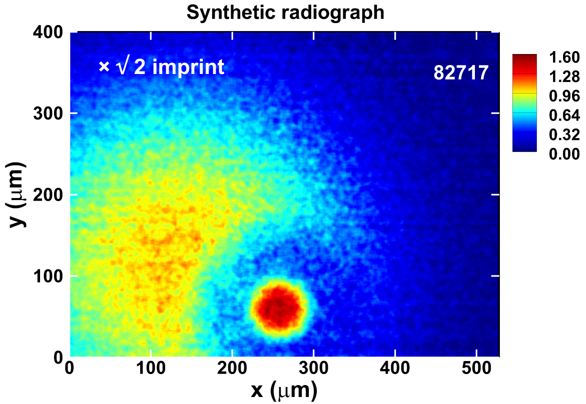
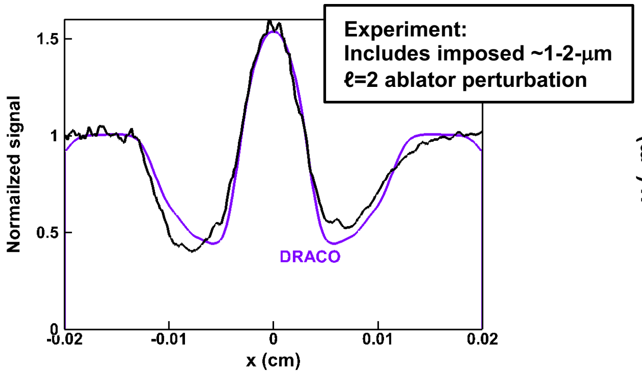
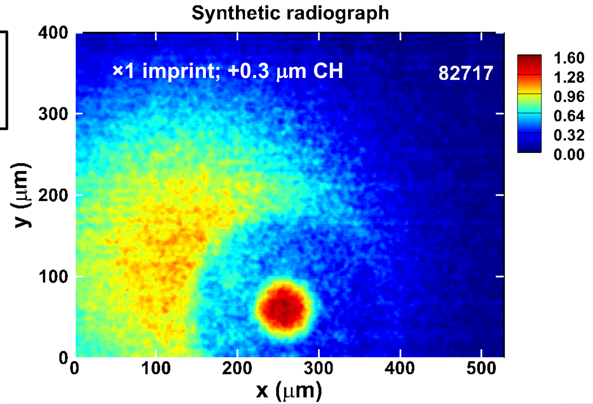
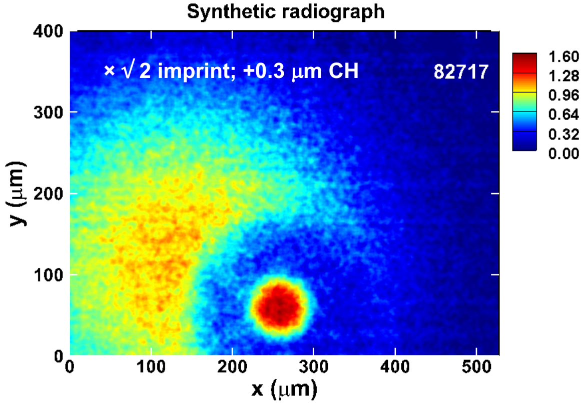








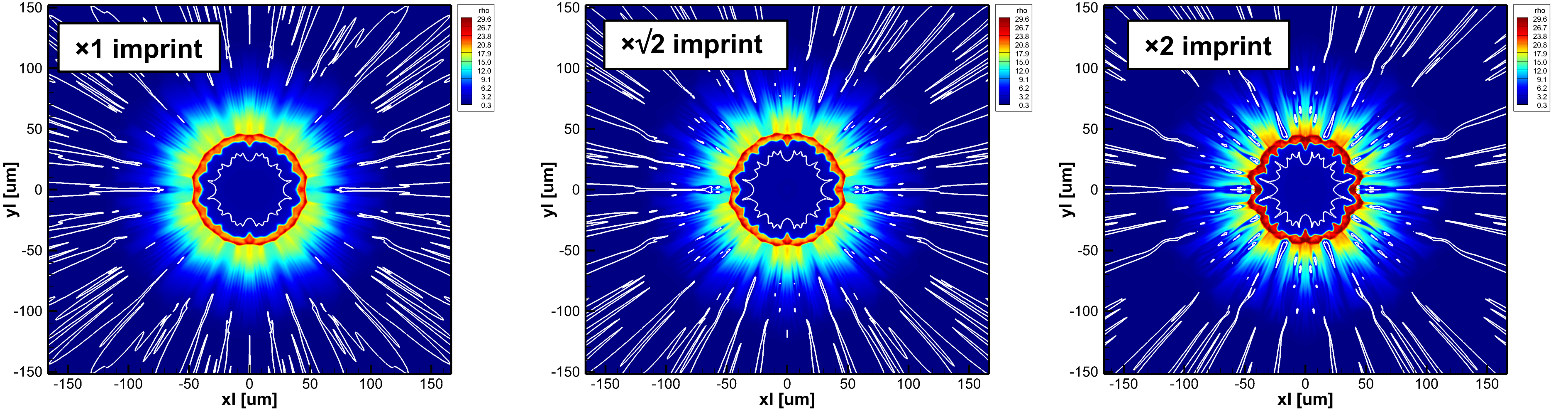




DRACO simulations of the low-adiabat shot show imprint efficiently transports carbon deep into the shell, but not the core

- **2-D DRACO simulations of shot 82717 were performed with varying levels of imprint**
- **The depth of the shadow cast by the shell requires transport of carbon deep into the shell**

Mass density, shot 82717; α = 1.9



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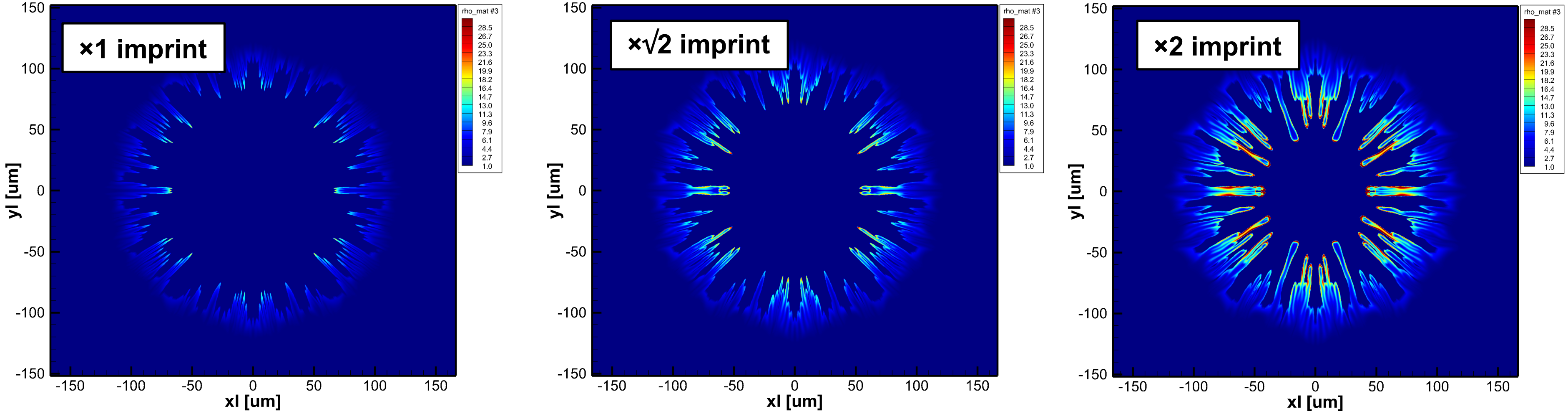

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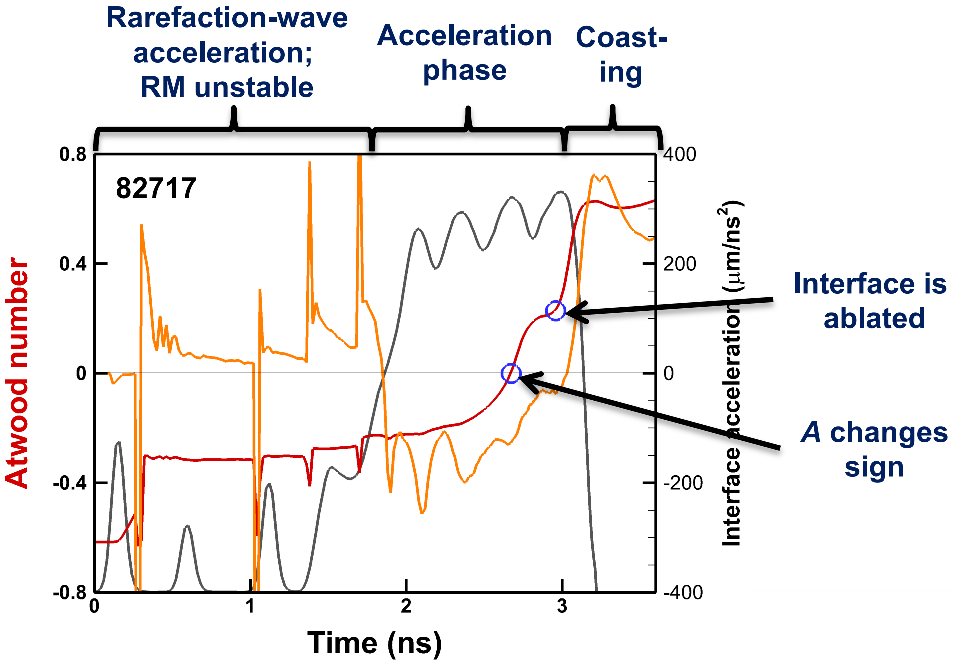
Isolated perturbations at the fuel-ablator interface have also been proposed as a possible seed for fuel-ablator mix

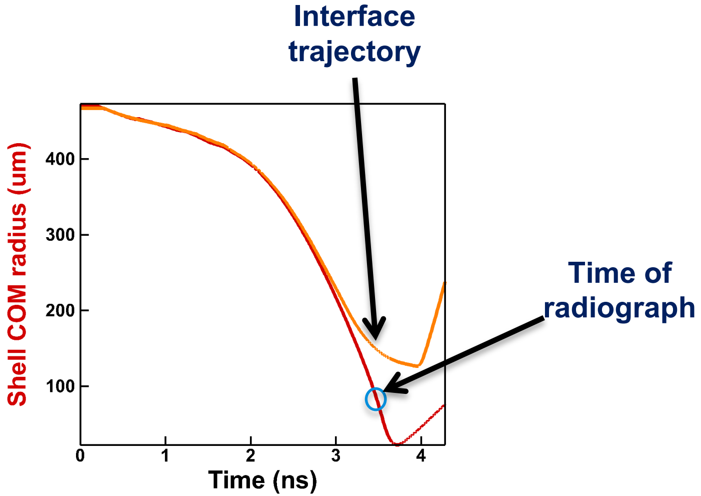
- The calculated hot-spot T_{ion} (with imprint) is 2.56 keV, greater than the experimental value of 2.4 keV (T_{min}=1.8 keV, $\Delta T \sim 0.6$ keV), suggesting additional mix may be responsible for reduction in core temperature and target performance
- Radiation from tritium decay in permeation-filled targets can cause localized perturbations at the inner shell surface
- OMEGA cryogenic targets are estimated to have $\sim 10^2$ micron-sized features with < 0.1 μm amplitude
- Many features would be needed to cause mix without being visible as individual features in backlighter radiographs
- Similar isolated features at the ablation surface and in the shell have been shown to be capable of transporting ablator material into the core*
- Voids in the ice and defects at the material interface may also contribute to mixing

* I. V. Igumenshchev et al., Phys. Plasmas 20, 082703 (2013)

The fuel-ablator interface is a classical interface, stable to Rayleigh-Taylor (RT) growth during acceleration but susceptible to Richtmyer-Meshkov growth

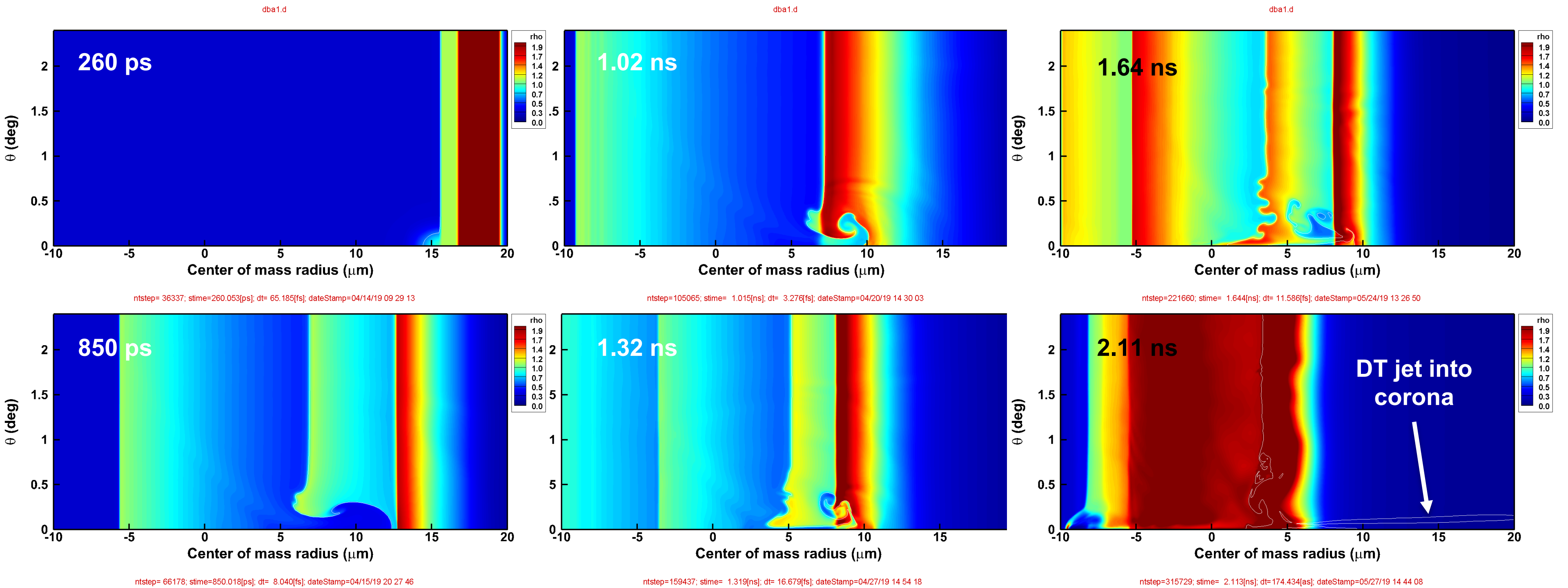
- The interface has a negative Atwood number until halfway through the drive, and is ablated soon after
- Interface perturbations are expected to experience some small RT growth due to post-picket rarefaction waves and Richtmyer-Meshkov (RM), but little RT growth during the acceleration phase





A simulation of an isolated fuel-ablator perturbation shows signs of localized mixing and transport of DT into the corona

- **The interaction of the planar shock with the feature perturbation generates vorticity which is magnified by subsequent shocks, and the post-shock rarefactions generate further RTI perturbation growth**



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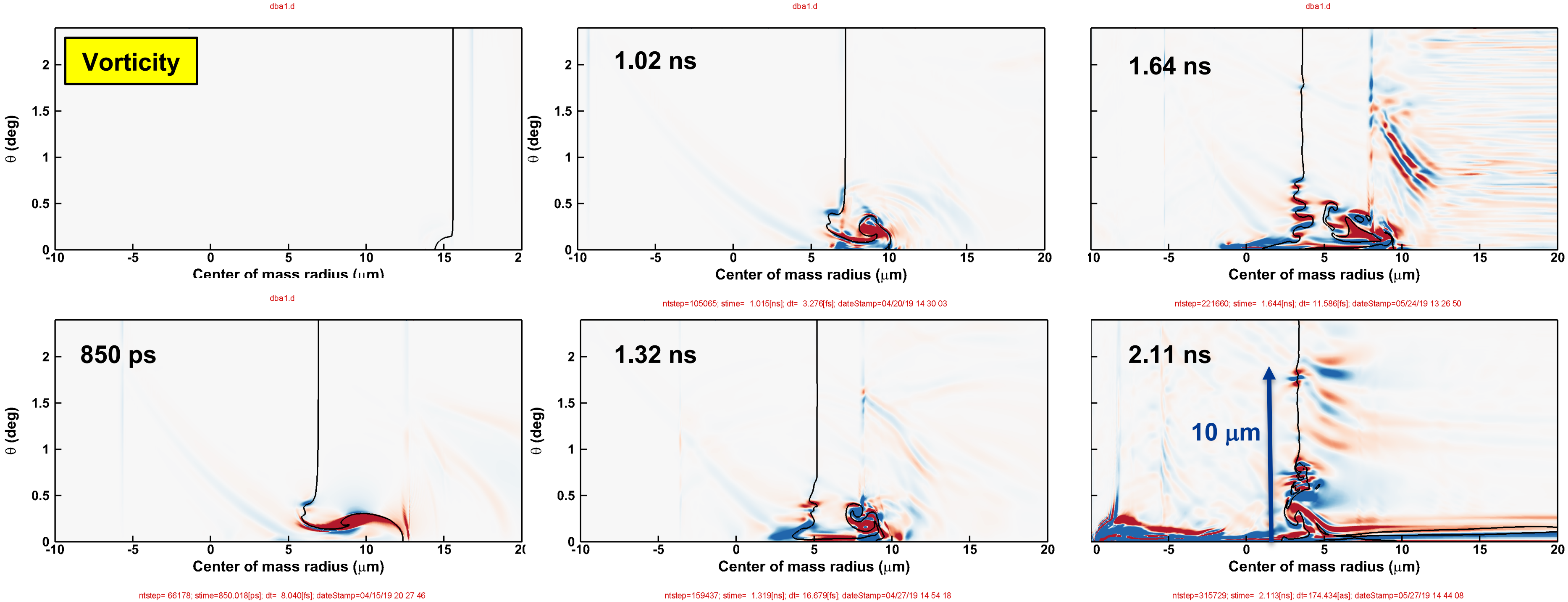
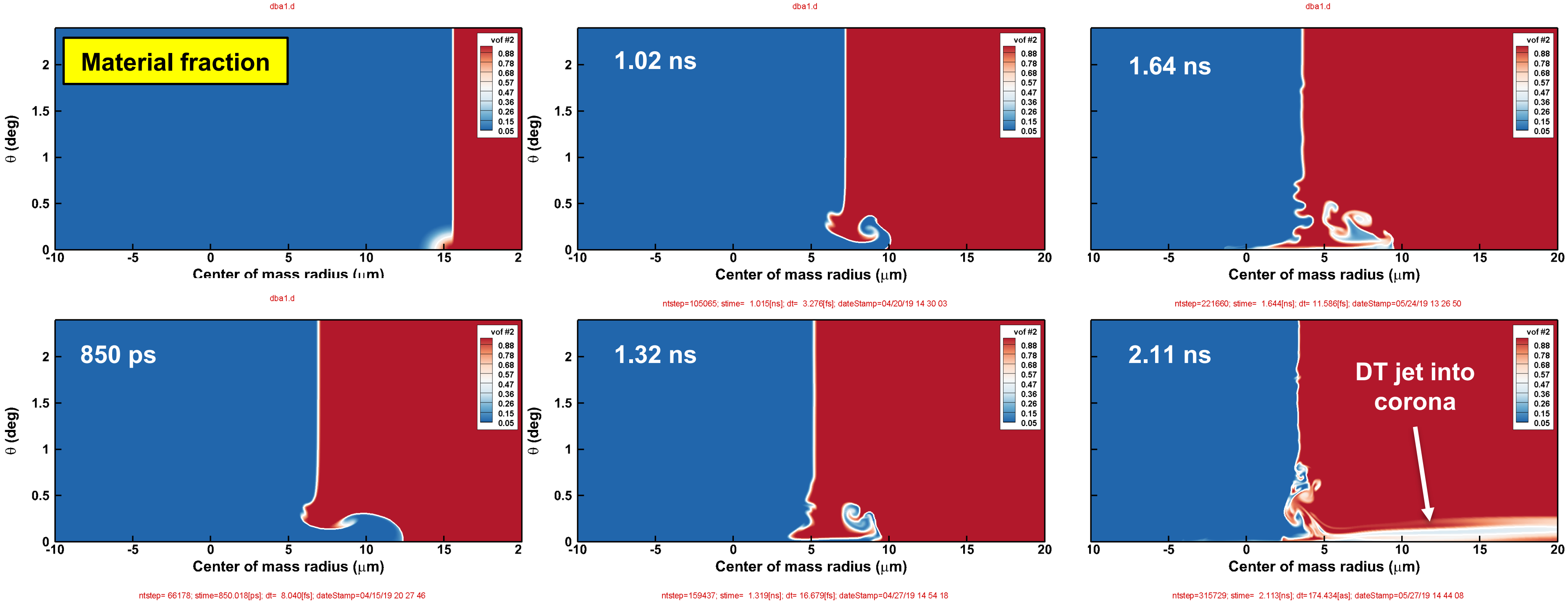
- Shocks launched by the second and third pickets and the drive pulse interact with reflected waves to broaden the range of influence of the localized features



A simulation of an isolated fuel-ablator perturbation shows signs of localized mixing and transport of DT into the corona

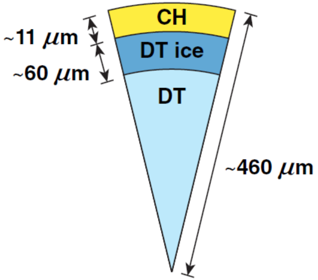
- A modest amount of interfacial mixing is sufficient to provide a channel for the DT to ablate
- The simulation below is underway



Comparison of moderate- and low-adiabat backlit cryogenic implosions* shows a drop in performance for the lower-adiabat implosion

						LILAC	Experiment		
Shot	α	IFAR	V_{imp} (μm/ns)	ρR (mg cm^{-2})	$T_{i,LILAC}$ (keV)	Y_{LILAC} (10^{13})	ρR/clean	$T_{i,Exp}$ (keV)	YOC
81590	2.5	10	240	250	2.2	1.4	78%	2.7	19%
82717	1.9	14	280	246	2.4	2.6	41%	2.4	8%

- The pulse and dimensions of the backlit implosions were chosen to straddle the stability boundary**
- Offsets are small (~10 μm)
- $I_{1/4}$~3x10^{14} W cm^{-2}
- CR~24



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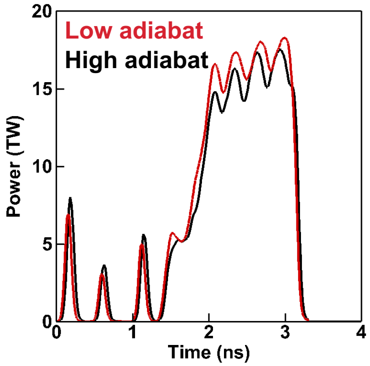


* C. Stoeckl *et al.*, Phys. Plasmas 24, 056304 (2017);
R. Epstein *et al.*, HEDP 23, 167 (2017)
** V. N. Goncharov et al., Phys. Plasmas 21, 056315 (2014).

IFAR: In-flight aspect ratio
V_{imp}: Peak shell implosion speed
ρR: Shell areal density
$\alpha = P/P_{fermi}$
Y: Neutron yield
YOC, Yield over clean: Ratio of experimental to 1-D yield
CR: Convergence ratio

Ion mass diffusion has been investigated as a possible carbon transport mechanism

- The ablator–fuel interface introduces a boundary in ion concentration, driving flow across the interface
- Mass diffusion has been demonstrated in the context of OMEGA exploding pushers* and is tied to similar effects such as baro- and thermodiffusion and nonequilibrium shock-species separation

$$\mathrm{i} = \boxed{-\rho D\Big(\underbrace{\nabla c}_{\text{concentration}}} + \underbrace{k_p \nabla \log p_i}_{\text{baro}} + \underbrace{\frac{e k_E}{T_i}\nabla\Phi}_{\text{electro}} + k_T^{(i)} \underbrace{\nabla \log T_i}_{\text{ion-thermal}} + k_T^{(e)} \underbrace{\nabla \log T_e}_{\text{electron-thermal}}\Big)$$

- 2-D ion mass diffusion has been implemented in *DRACO*, with flux J_k calculated by Fick's First Law,** $J_k = -D_k \nabla n_k$, where D_k is the diffusion coefficient, and n_k is the ion number density, using a momentum-conserving collision frequency based on Simakov and Molvig (2016) ‡
- The classical diffusion coefficient is given by† $D_k \sim v_{\text{th}}^2 \tau = \dfrac{\left(\langle Z\rangle + 1\right) kT}{\langle A\rangle \nu_{k,l\neq k}} \sim \dfrac{T^{5/2}}{n}$
- Ion mass diffusion will be important when temperature is high and density is low, when

  $\mathrm{Kn} = \lambda_{\mathrm{i}} / L_{\mathrm{hydro}} > 1$

- For these implosions the diffusion coefficient does rise to ~10^2 μm^2/ns but only late in time

* H. G. Rinderknecht *et al.*, Phys. Rev. Lett. 112, 135001 (2014); P. Amendt, C. Bellei, S. Wilks, Phys. Rev. Lett. 109, 075002 (2012); C. Bellei and P. Amendt, Phys. Plasmas 24, 040703 (2017); P. Amendt, *et al.*, Phys. Rev. Lett. 105, 115005 (2010); etc.

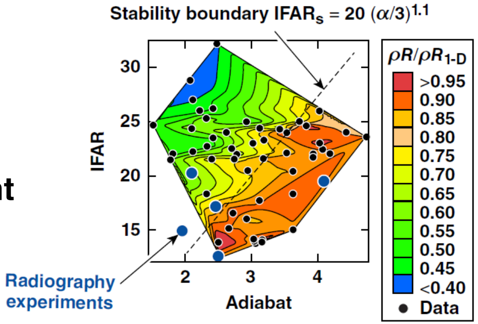
** R. Bird, *et al.*, *Transport Phenomena 2nd Ed.*, (2007) 525; R. Present and L. Schiff, *Kinetic Theory of Gases* (1958) 145; H. G. Rinderknecht , Phys. Rev. Lett. 112, 135001 (2014)

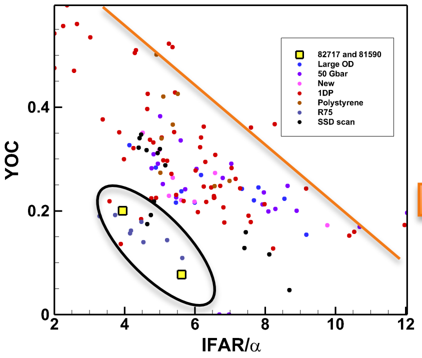
† P. Amendt, C. Bellei, S. Wilks, Phys. Rev. Lett. 109, 075002 (2012)

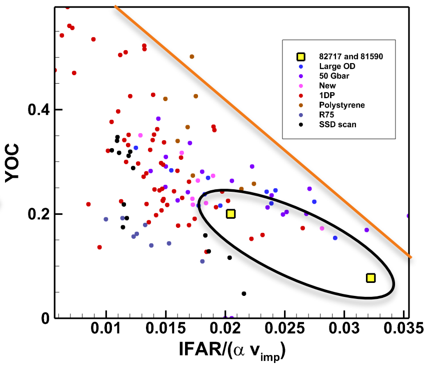
‡ A. N. Simakov, K. Molvig, Phys. Plasmas 23, 032115 (2016)

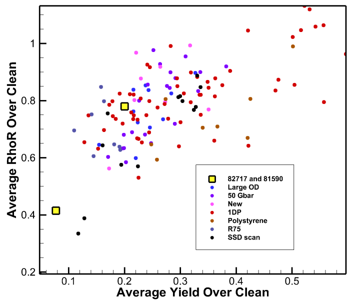
The pulse and dimensions of the backlit implosions were chosen to straddle the stability boundary*

- A threshold factor ~IFAR/$\alpha^{1.1}$ has been found to correlate with areal density degradation and performance (and YOC has a weaker correlation indicating a stability threshold)
- A peak power of ~18 TW and a thicker shell were optimized for backlighter exposure times
- The YOC for these shots is low, even for the more stable shot (81590), consistent with an extended coasting time and slower implosion speed





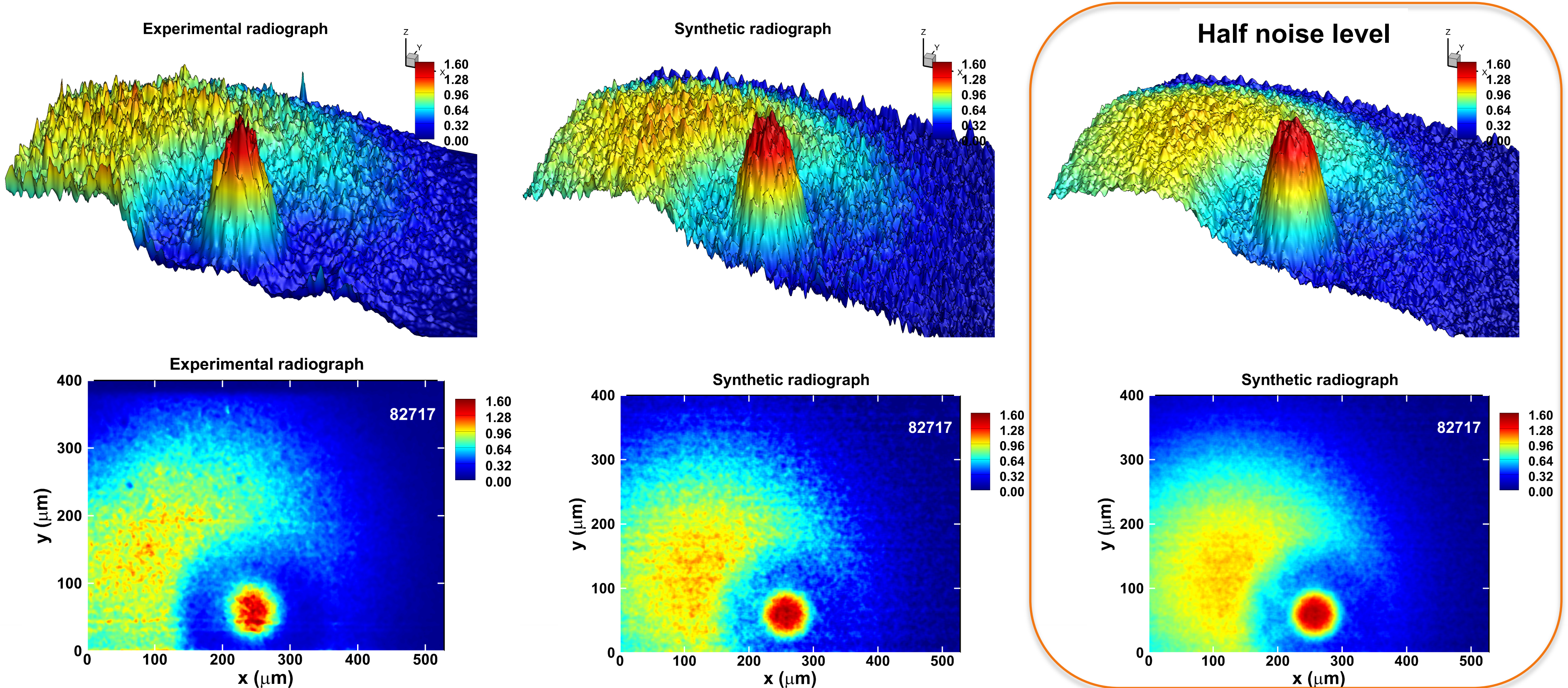




* V. N. Goncharov et al., Phys. Plasmas 21, 056315 (2014).

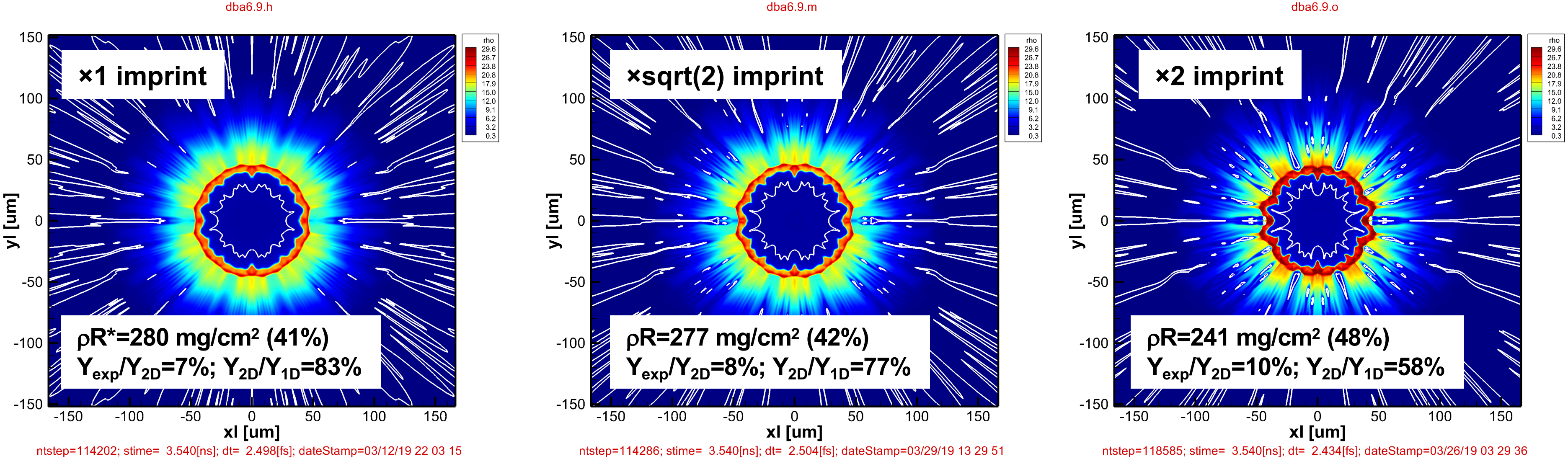
There is significant variation in the signal in the backlighter region

- **Improvements in this diagnostic have led to a ×5 increase in backlighter brightness (Stoeckl APS 2018)**



The ρR/clean is still less than 1, suggesting the need for an expanded modal range and possibly other forms of mix

- A simulation modeling up to mode 200 shows negligible differences in the radiographic lineout
- For sqrt(2) imprint, IRIS calculates T_{ion}=2.56 keV, greater than the experimental value of 2.4 keV (T_{min}=1.8 keV, range~0.6 keV), suggesting addition mix may be responsible for reduction in core temperature

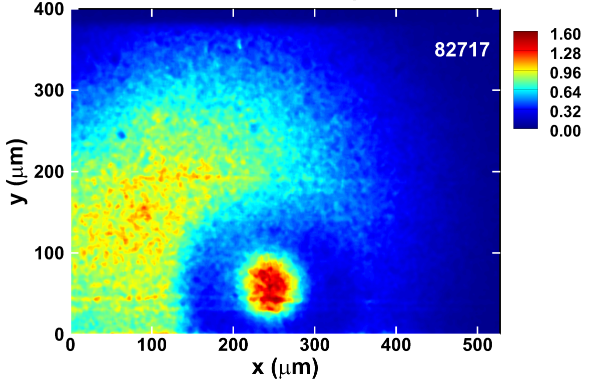


* Straight-line areal density from Target Diagnostic Suite; IRIS3D calculations underway, which will likely be lower

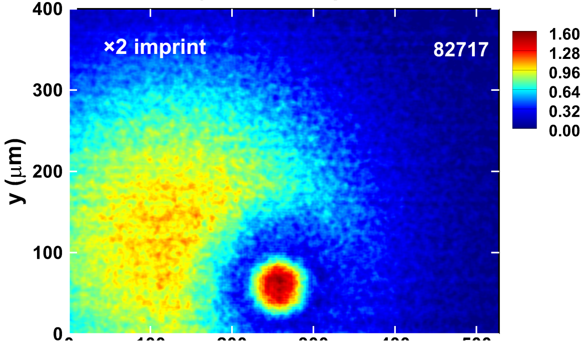
Low modes have a minimal impact on radiographic signatures

- **An imprint run was conducted including beam mispointing, beam mistiming, power imbalance and ice roughness**
- **These modes cause a noticeable distortion of the core emission but not the observed shell attenuation**

Experimental radiograph



Synthetic radiograph



Synthetic radiograph