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EVALUATION OF RAYLEIGH TAYLOR INSTABILITY GROWTH AND MIX IN NIC CAPSULES USING X-RAY RADIOGRAPHY

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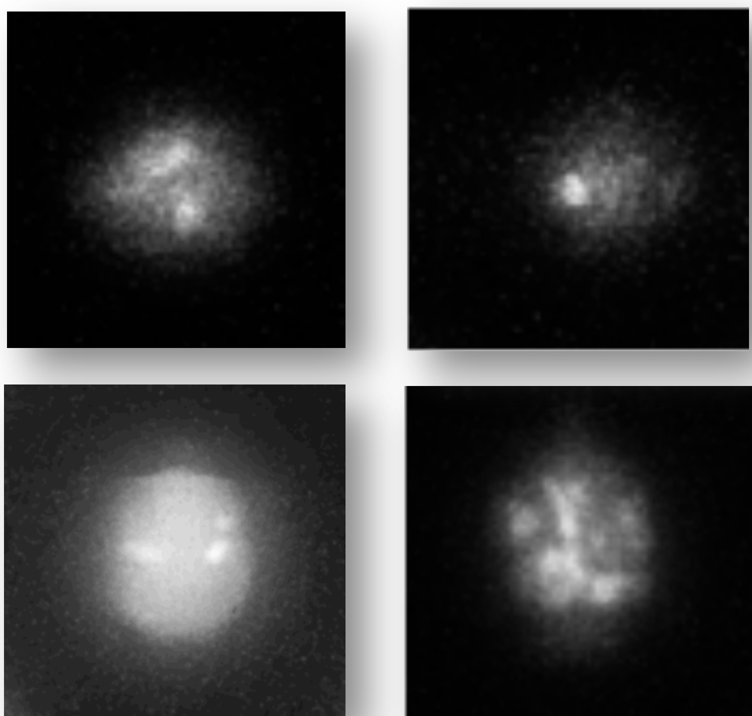
Abstract

- The ultimate goal of the National Ignition Campaign (NIC) is to achieve thermonuclear burn and energy gain in inertial confinement fusion capsules. Small defects and other imperfections in the capsule shell can seed short wavelength instability growth as the capsule is compressed. If the amount of growth is large enough, small amounts of shell ablator can be injected into the central hot spot and detrimentally affect ignition[1]. It is therefore critical to understand and control hydrodynamic instabilities. To this end, experiments are planned on the National Ignition Facility (NIF) that are designed to measure instability growth of well characterized engineered defects placed on the surface of a capsule utilizing x-ray radiography. Although short wavelength instability growth and mix has been inferred in NIC capsules with Ge spectroscopy and hot spot self emission imaging, x-ray radiography is capable of measuring the time dependent instability growth of surface perturbations as the capsule implodes. Measurements of how instabilities develop from initial surface perturbations is important not only for code validation, but also to assess what effect capsule design changes have on instability growth. We will present results from several 2D and 3D HYDRA simulations of isolated defects and surface roughness that have been post processed to produce realistic synthetic radiography images. These results demonstrate how x-ray radiography can be used to diagnose signatures of short wavelength instability growth and mix in NIC capsules and provide a benchmark for code predictions. We will also discuss correlations between x-ray radiography measurements and overall capsule performance.

[1] B. A. Hammel, S. W. Haan, D. S. Clark, *et al., HEDP* 6, 171 (2010).

Understanding the growth of instabilities and mix is critical to achieving ignition of NIF

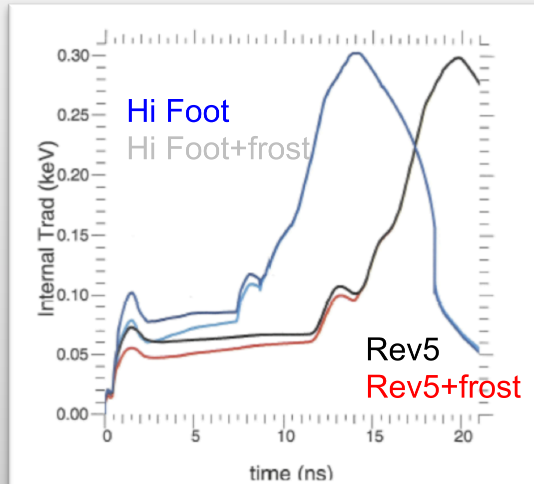
Gated X-ray images
at peak X-ray emission time

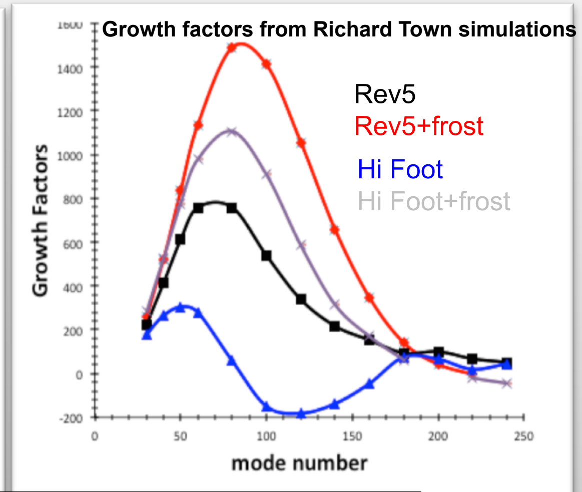


- Previous NIC experiments showed bright spots* of Ge self emission from ablator mass getting injected and mixing into the hot spot
- Numerical simulations of instability growth are relied upon to set capsule fabrication requirements and optimize target design to mitigate detrimental effects of instability growth in NIC capsules
  - 70% of the DT ice must be unmixed at peak velocity which places limits on the amount of perturbation growth from surface roughness
  - Capsules can tolerate a maximum of 75ng of injected ablator mass due to isolated capsule defects

*Hammel, B.A., et al., High Energy Density Physics, 6(2) 2010

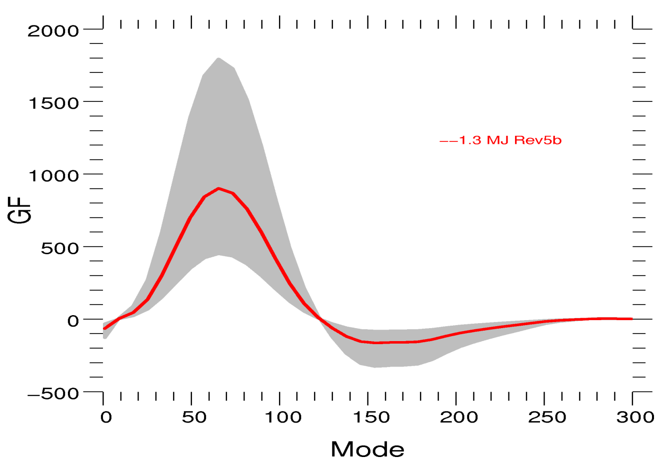
Significant sensitivities and uncertainties exist in instability growth modeling of NIC capsules





Hydro Instability growth factor simulations show a strong dependence on the early time pulse shape

- Uncertainty in X-ray drive and spectrum on capsule
- Uncertainty in material properties
- Uncertainties in initial seeds
- Rezoning in Lagrangian codes
  - Different rezoning schemes do make differences
- Radiation and heat transport
  - On nonorthogonal meshes
  - For very extended features is diffusion adequate?
- 2D versus 3D differences
  - Physics differences in bubbles/spikes evolution in 2D versus 3D
  - Are there special issues with our modeling of the pole in 2D calculations?



- Factor of 2 estimated uncertainty currently exists in our growth factor calculations
- The ultimate goal is to reduce growth factor uncertainty to 25%

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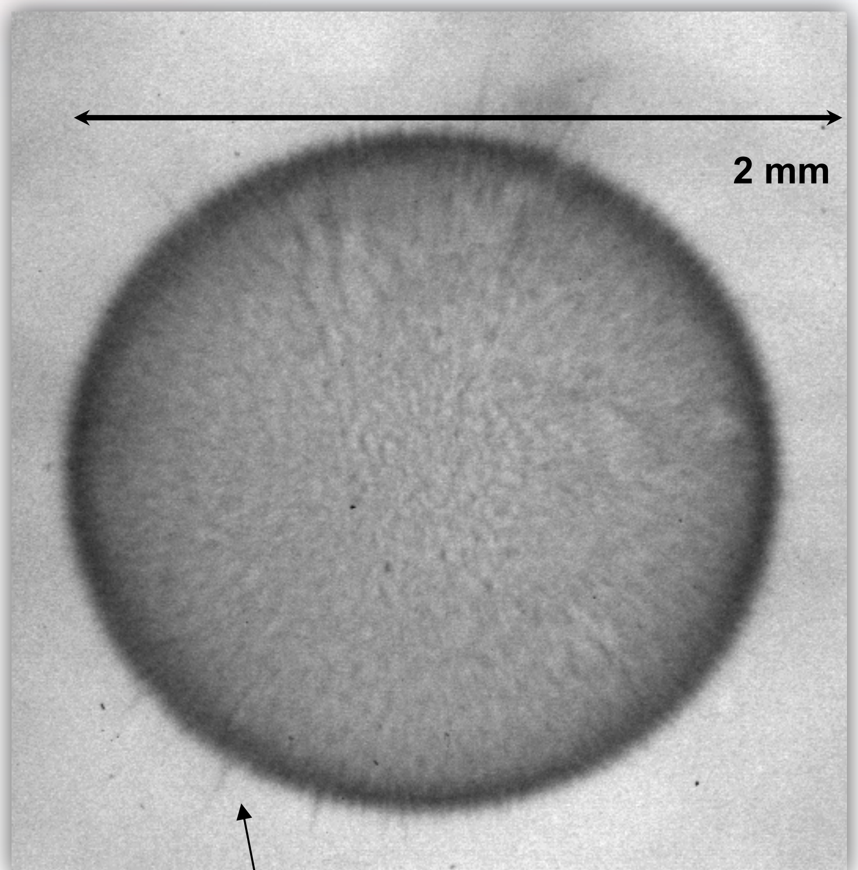
In-flight radiography has already been shown to be a powerful technique in assessing instability growth on ICF capsule shells

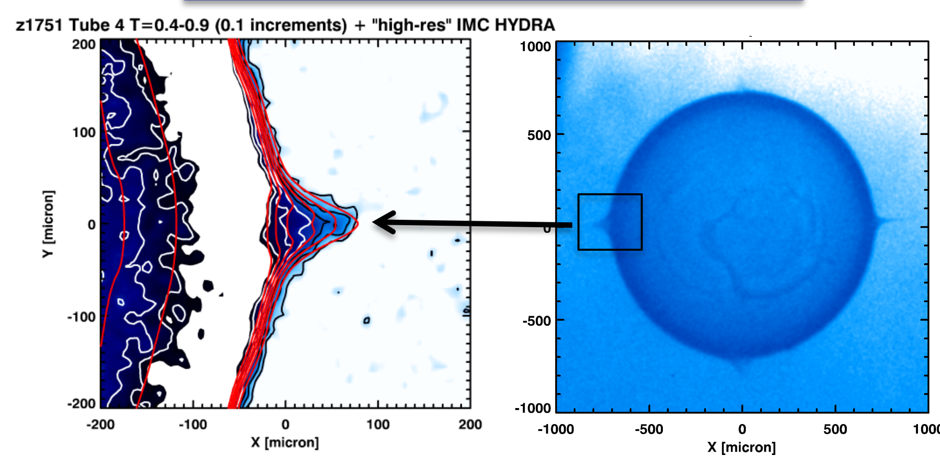


20 μm diameter jet/5 pixels

Cuneo, Bennett, Sinars, Vesey et al

- **Experiments on Sandia's Z machine at 6151 eV**
- **3.2 mm capsule with embedded glass layer**
- **Hundreds of large (~ 1 μm amp, 10 μm FWHM) isolated defects**

Verified prediction of instability growth from fill tube at CR ~2



Herrmann, et al. APS DPP 2006
Bennett, et al. PRL 2007

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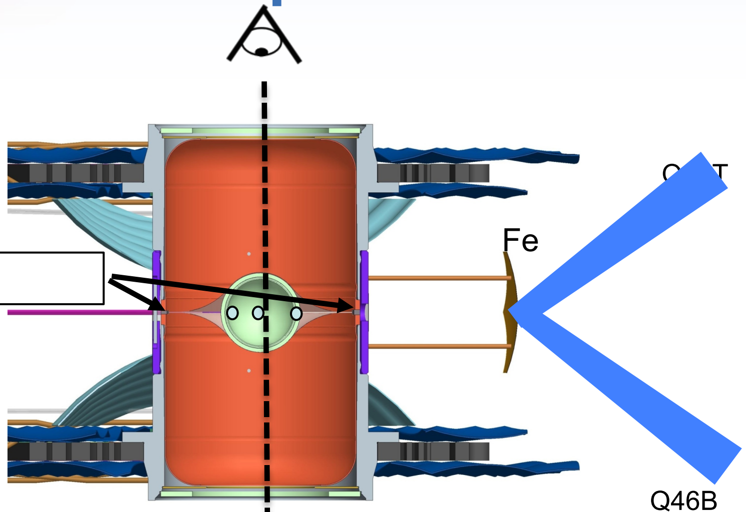
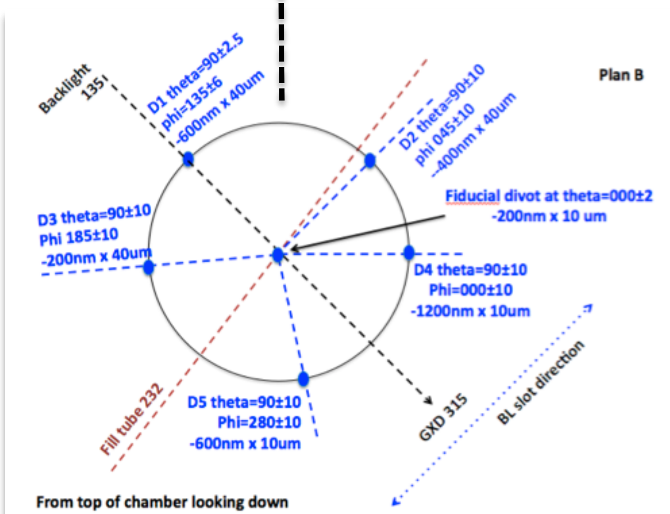
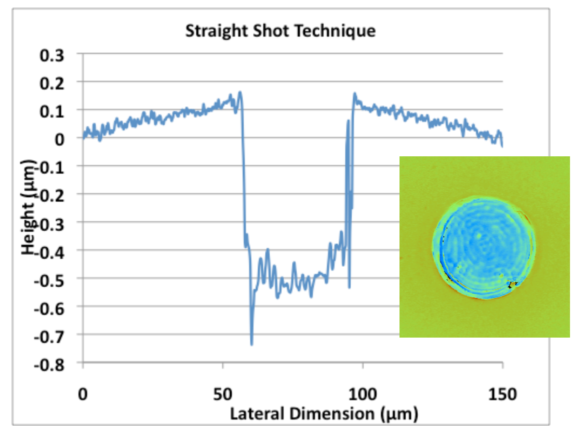
Face-on radiography experiments of well characterized capsule defects are planned for NIC







See P.Tu_39, D.R. Farley, "Face-on radiography experiments of isolated defects on NIF capsules" for more details

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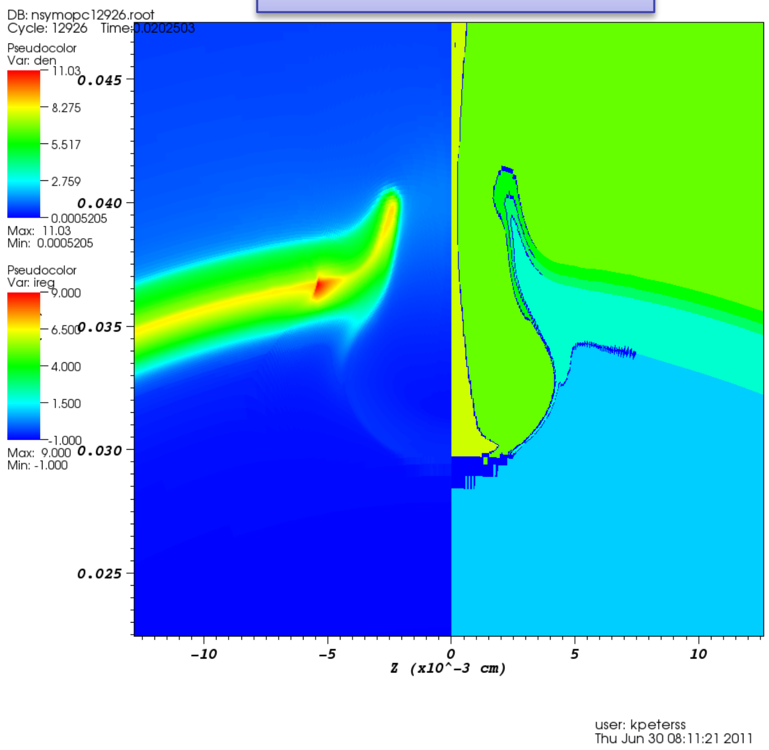
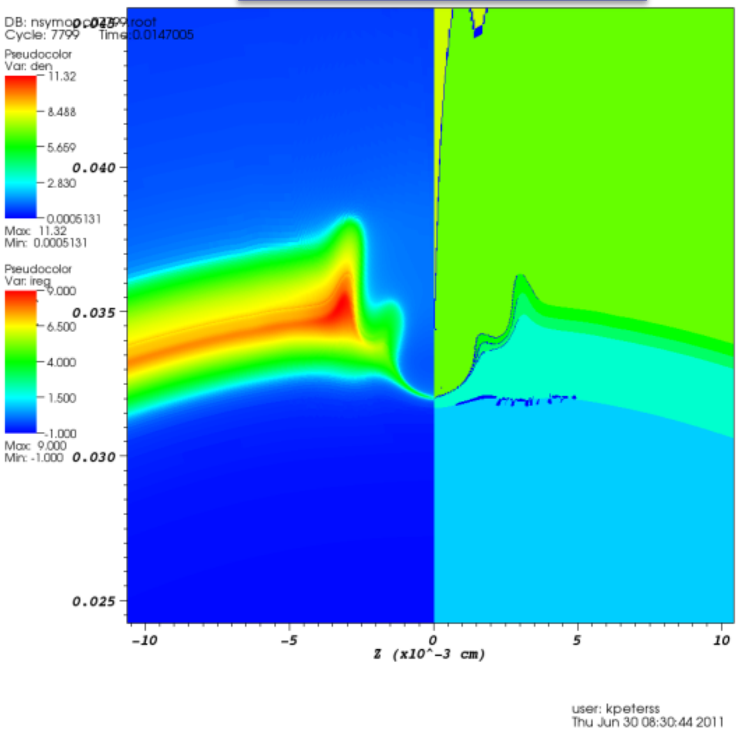
The simulated evolution of a divot (-600nm x 40μm) is significantly different for a high and low foot drive

1.3 MJ Low Foot



1.0 MJ High Foot



Convergence Ratio (CR) 3.1

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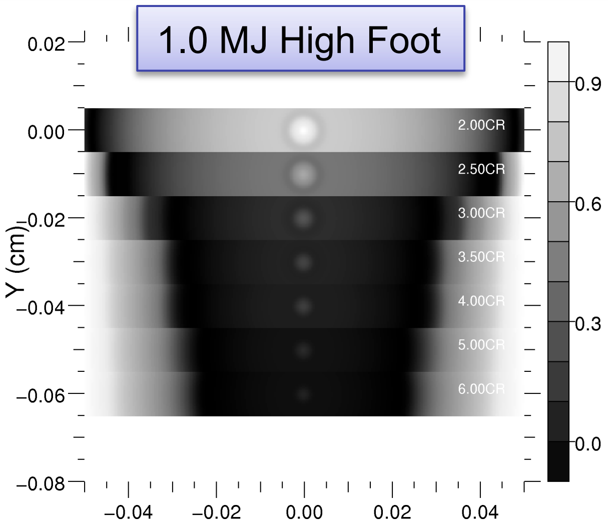
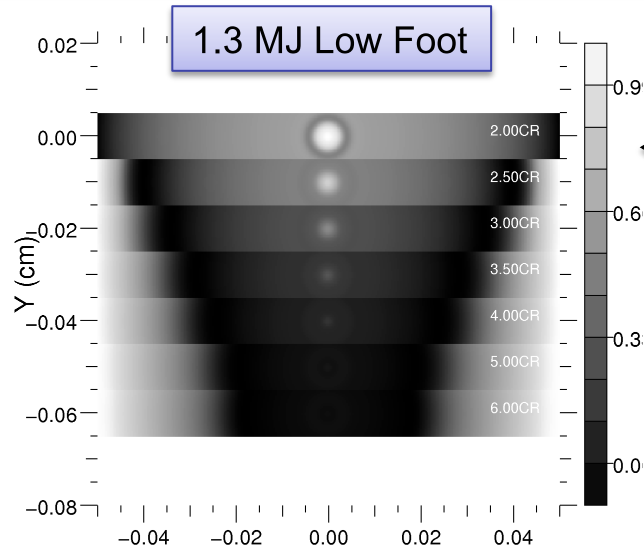
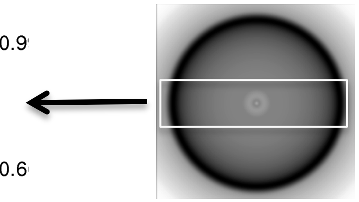
We will test predictions of instability growth by comparing simulated radiography against experimental radiographs

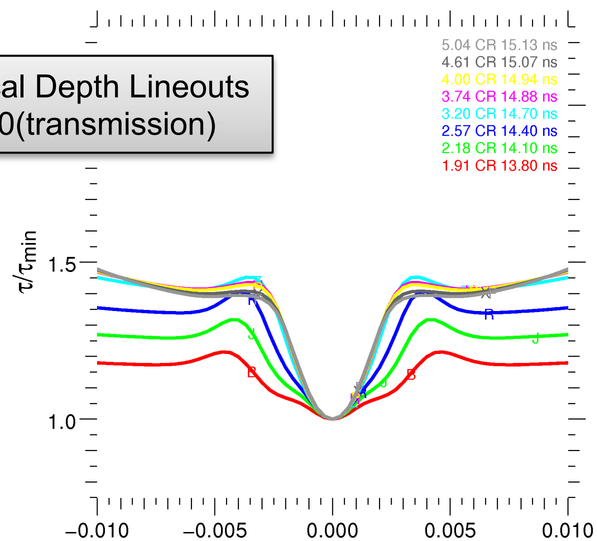


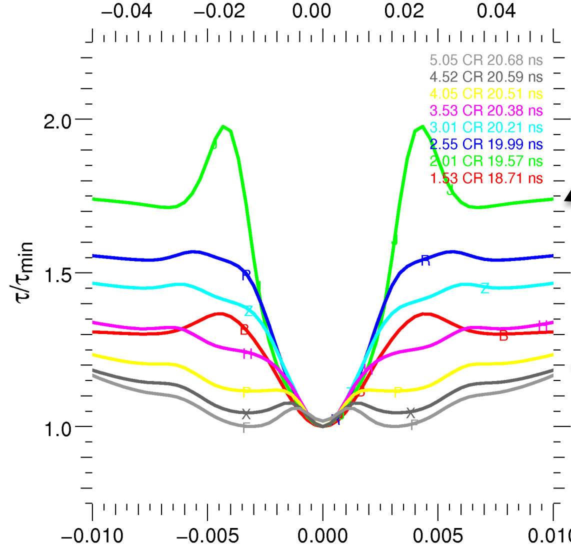


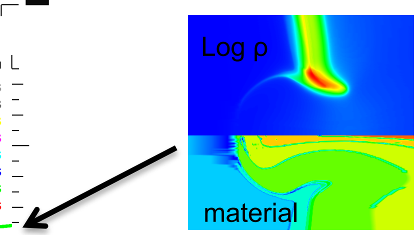


Fe Backlighter ~6.7 keV
GXD gate time= 270ps
Spatial Resolution = 15 µm

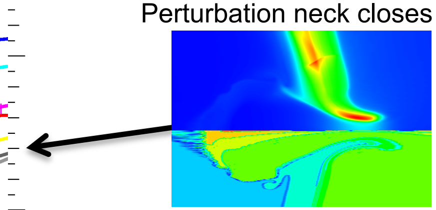
Optical Depth Lineouts
-log10(transmission)







Perturbation neck closes off



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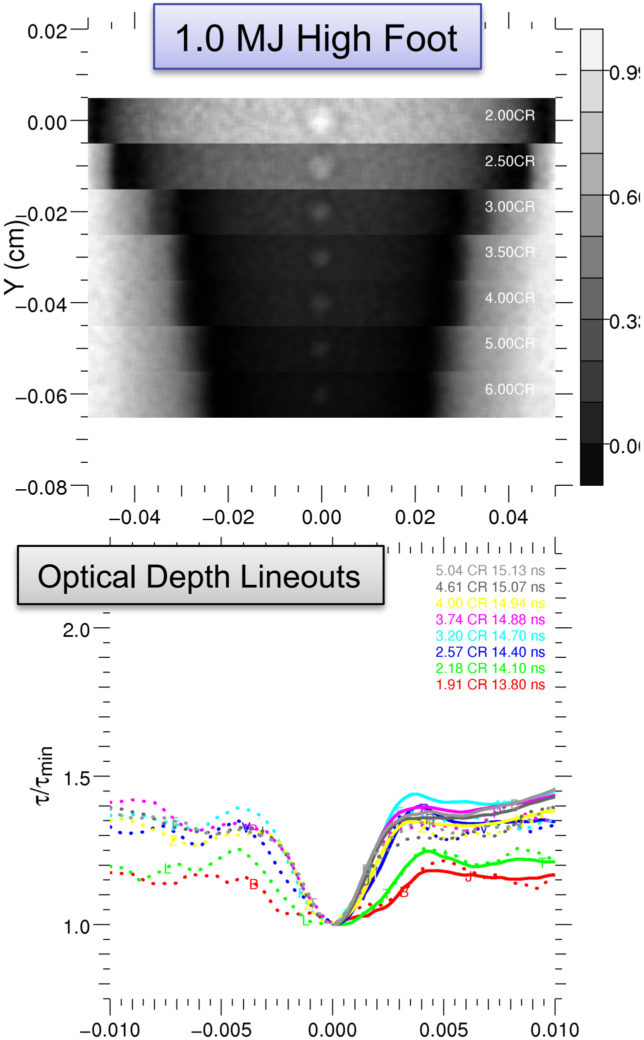
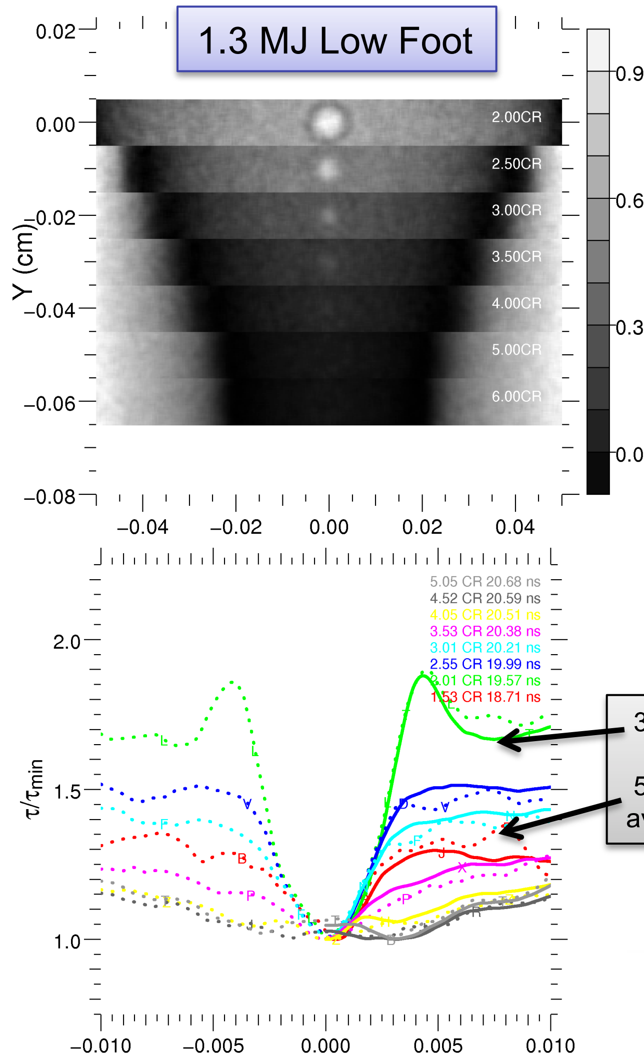
Proposed experimental experimental configuration on NIF is predicted to provide adequate photon statistics





Fe Backlighter ~6.7 keV
GXD gate time= 270ps
Backlighter Power: 16 TW
Backlighter Intensity: 3.0e15 W/cm^2
Magnification: 15X, 10 μm pinhole
Filters: 5 μm Fe + 275 μm Kapton
Photons/ res element / frame = 26

S2N = 25.66 (7 frame summation) at 100% transmission

$$S2N = \frac{S * frames^{0.5}}{\sqrt{S + (S * FPN)^2 + S * DRN^2}}$$

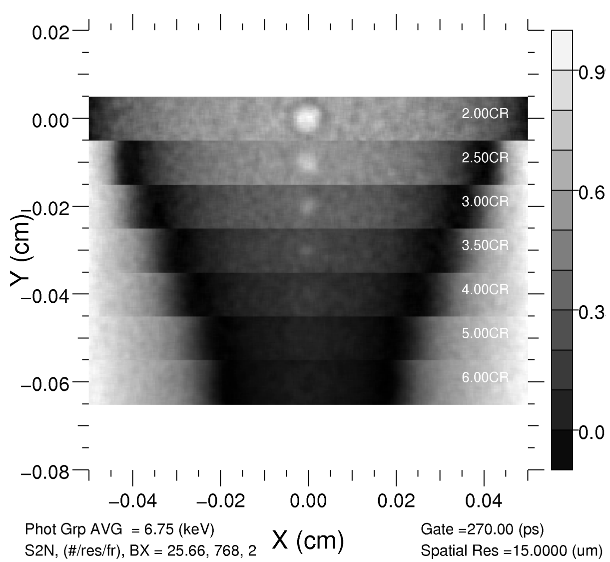
FPN= Fixed pattern noise = 0.022
DRN= Detector noise = 1.0

360 radial lineout average (solid)

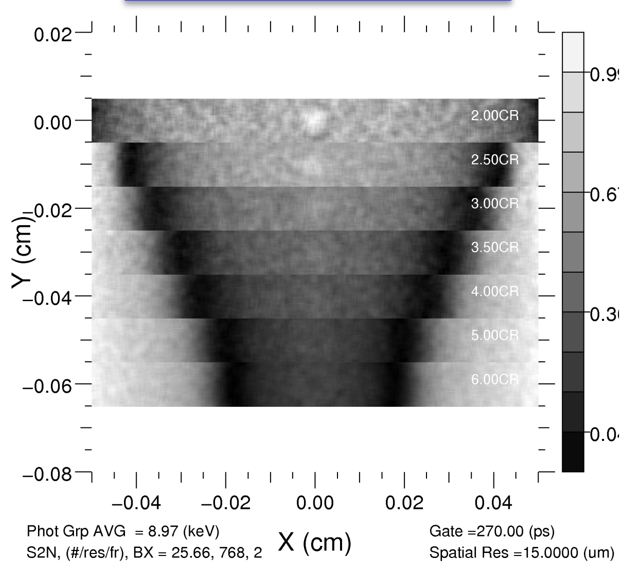
50 micron width horizontal lineout average (dotted)

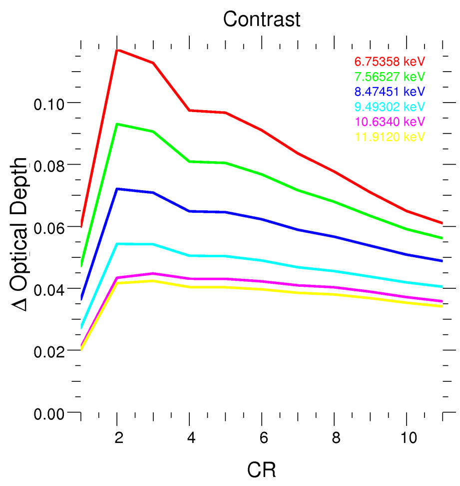
Lower photon energies provide greater contrast. However, higher photon energies are required to penetrate shell at high CR

Fe Radiographs (6.7keV)



Cu Radiographs (9 keV)





600nm x 40μm, Rev 5b drive

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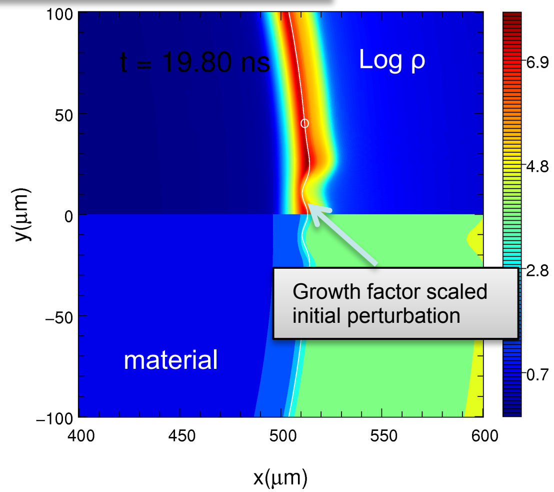
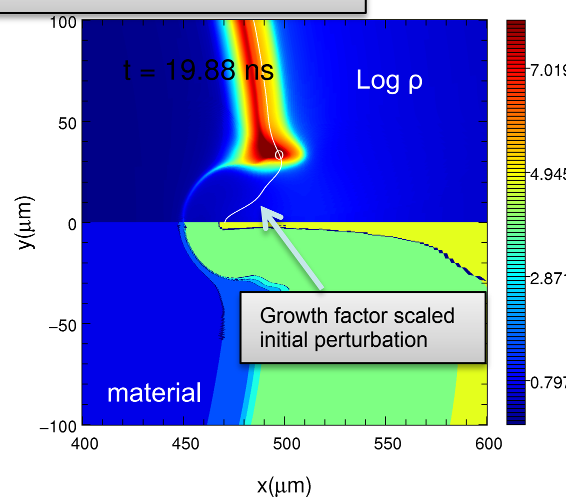
Areal density modulations directly correspond to growth factor curves as long as perturbation growth is linear

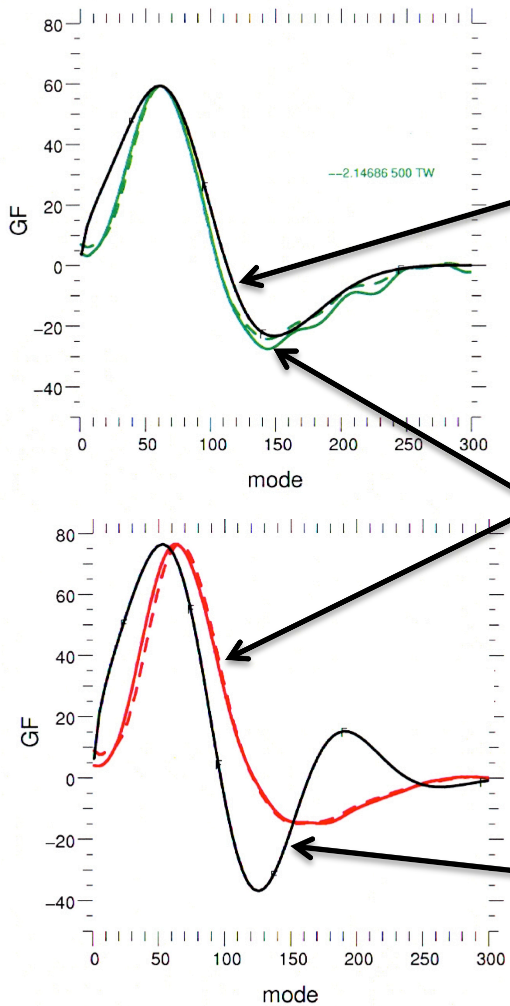
200 nm divot – CR ~ 2



400 nm divot – CR ~ 2.2



Legendre Mode Spectrum



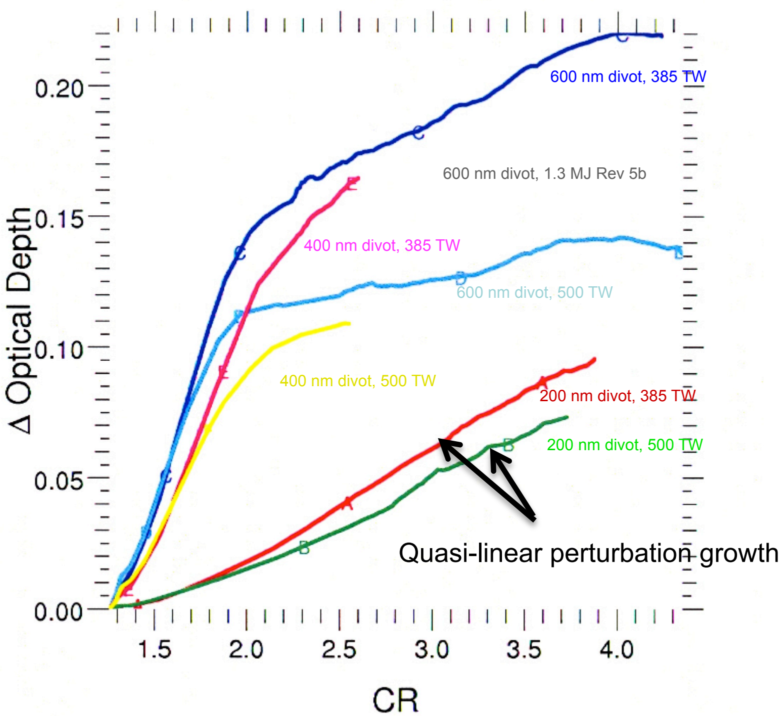
Radiograph optical depth mode Spectrum (normalized to peak of GF spectrum at same CR)

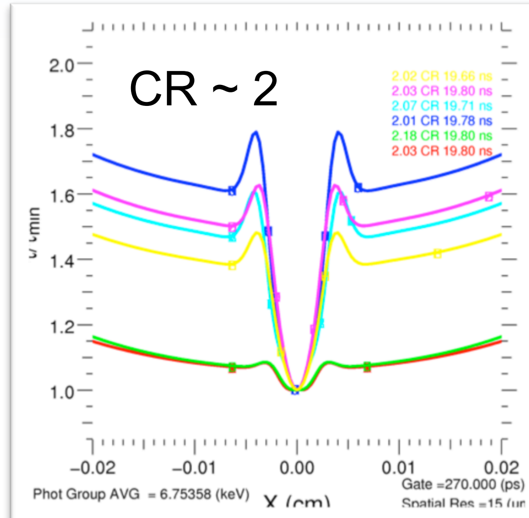
Growth factor mode spectrum at CR 2.2 (solid)

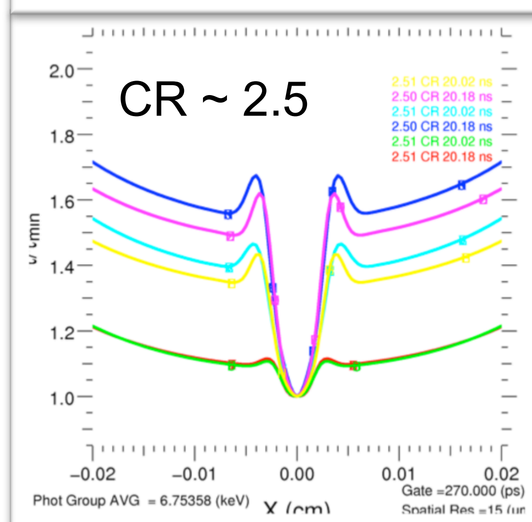
- - - Areal density growth factor mode spectrum at CR 2.2 normalized to peak of GF curve (dashed)

Radiograph optical depth mode spectrum (normalized to peak of GF spectrum at same CR)

Face-on radiography can also provide qualitative and quantitative time dependent measurements of instability growth







At low CR, magnitude of optical depth modulations is weakly dependent and inversely correlated with drive power

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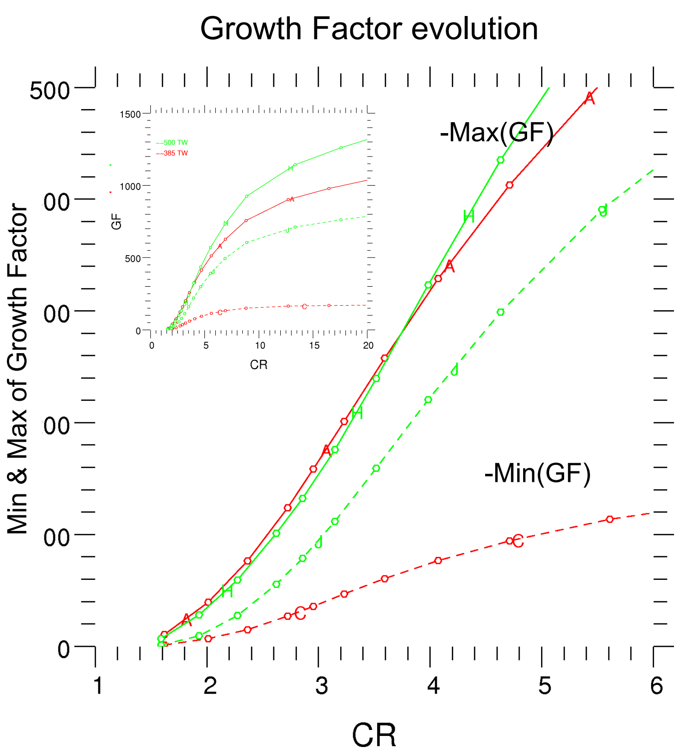
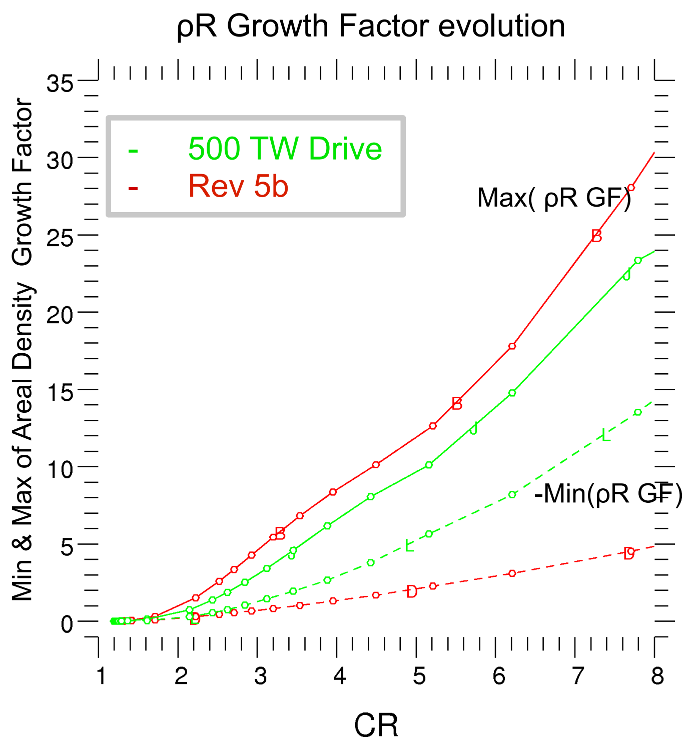
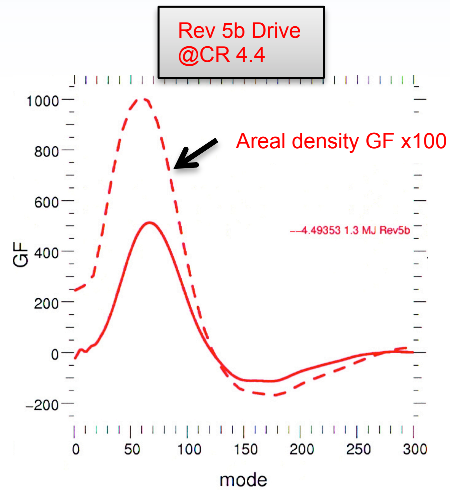
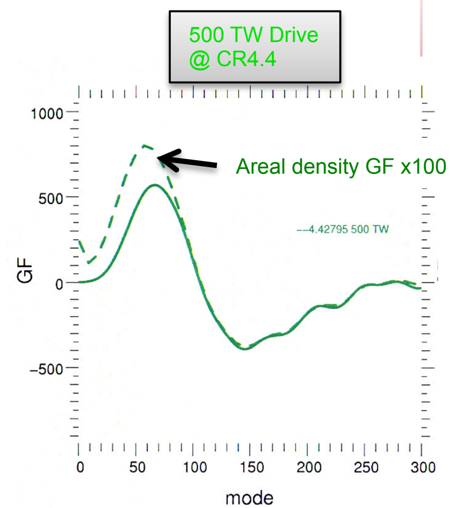
Counter intuitively, areal density perturbations decrease with increased drive in contrast to the perturbation growth factor









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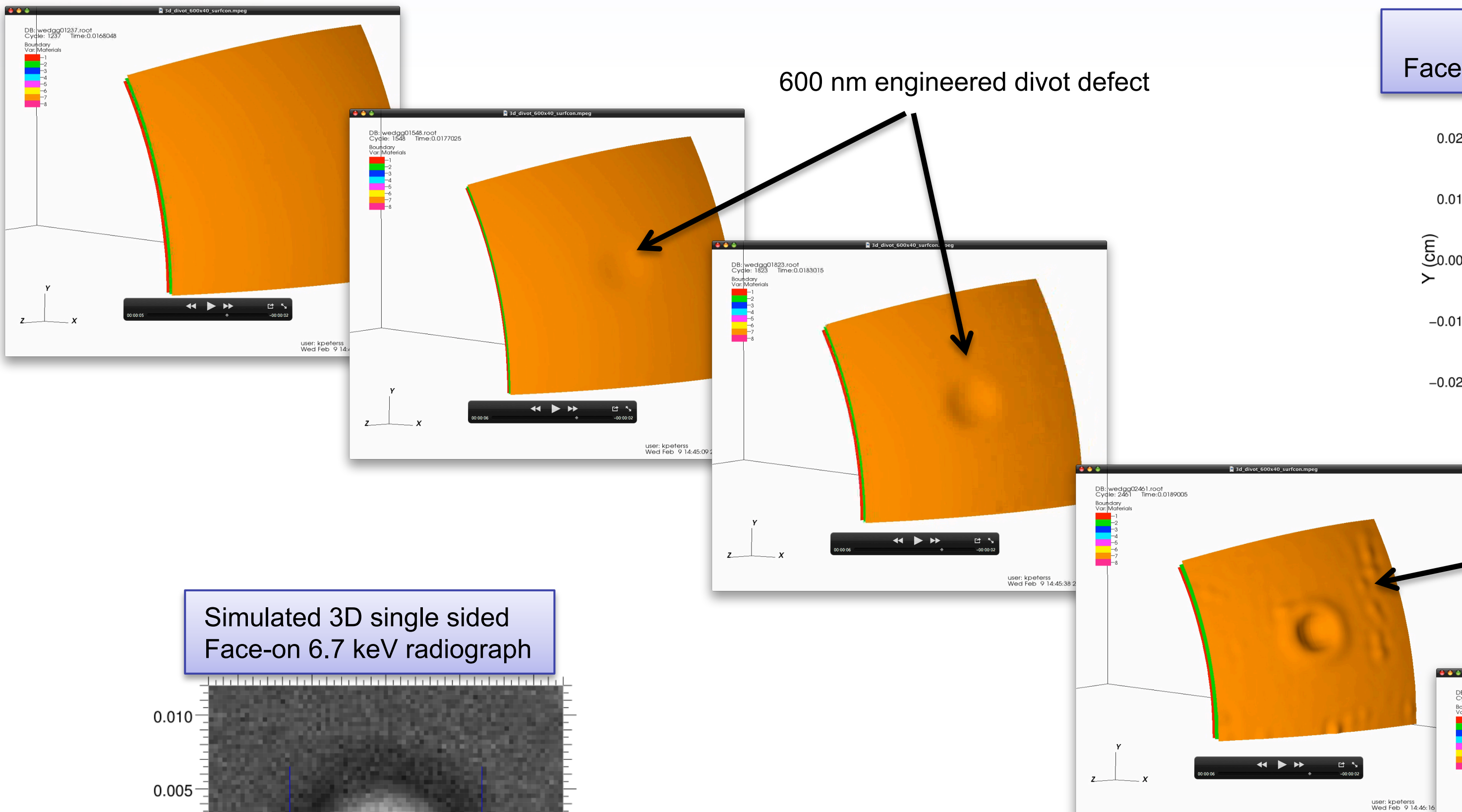
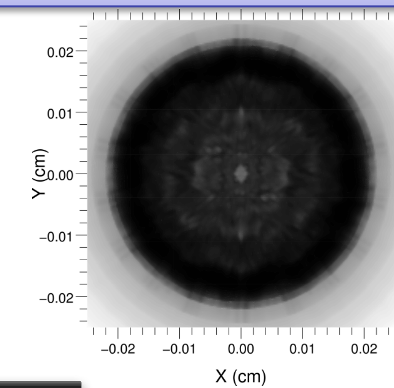
We are also assessing isolated defect instability growth with 3D simulations

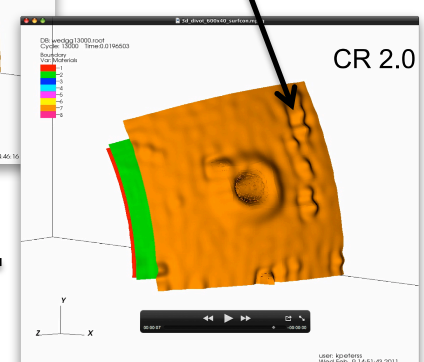
600 nm engineered divot defect



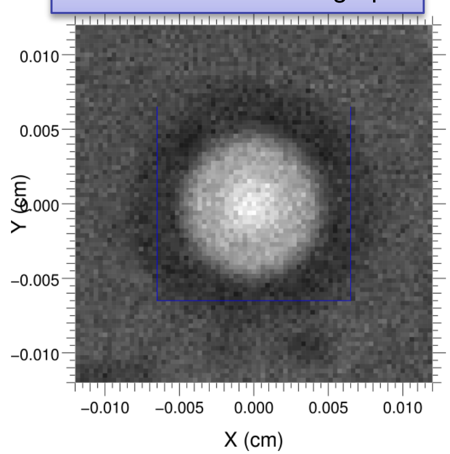
Simulated 4π (replicated)
Face-on 6.7 keV radiograph @CR5.5



Growth from characterized ablator surface roughness



Simulated 3D single sided
Face-on 6.7 keV radiograph



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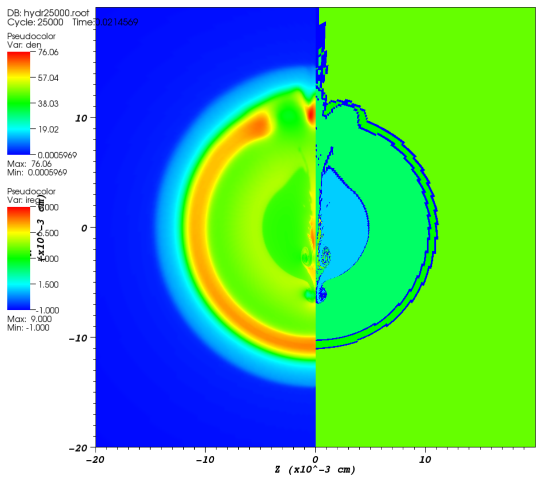
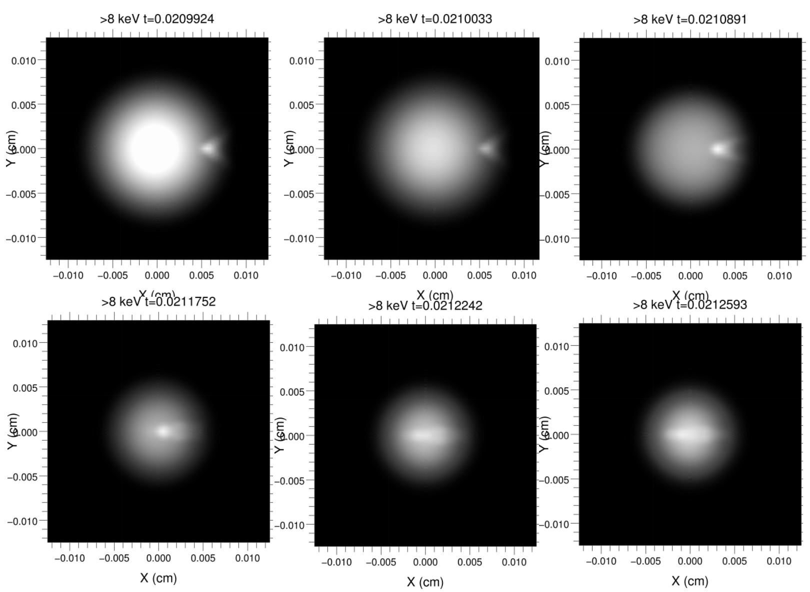
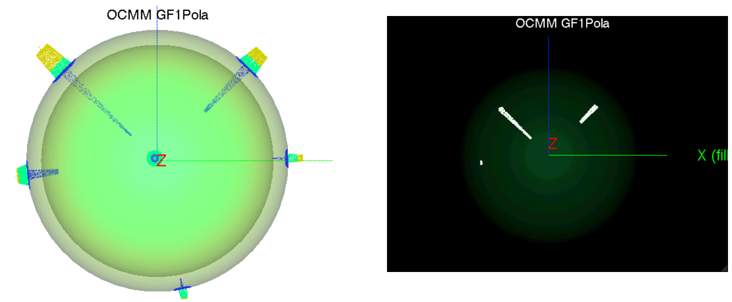
Simulations also predict engineered features produce clearly observable jets penetrating the capsule's core



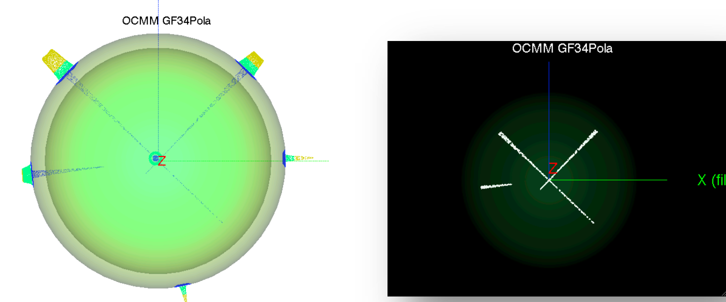


Spect3D NLTE post processing

"Meteor" evolution and mixed mass estimates based on growth factors (polar view)



Bruce Hammel's 1.3 MJ, Rev5 GFs (111 ng mix)



Richard Town's 1.3 MJ, Rev5 GFs (77 ng mix)

Correlating time dependent radiography and Ge self emission from resulting jet will test mix mass estimates based solely on growth factors

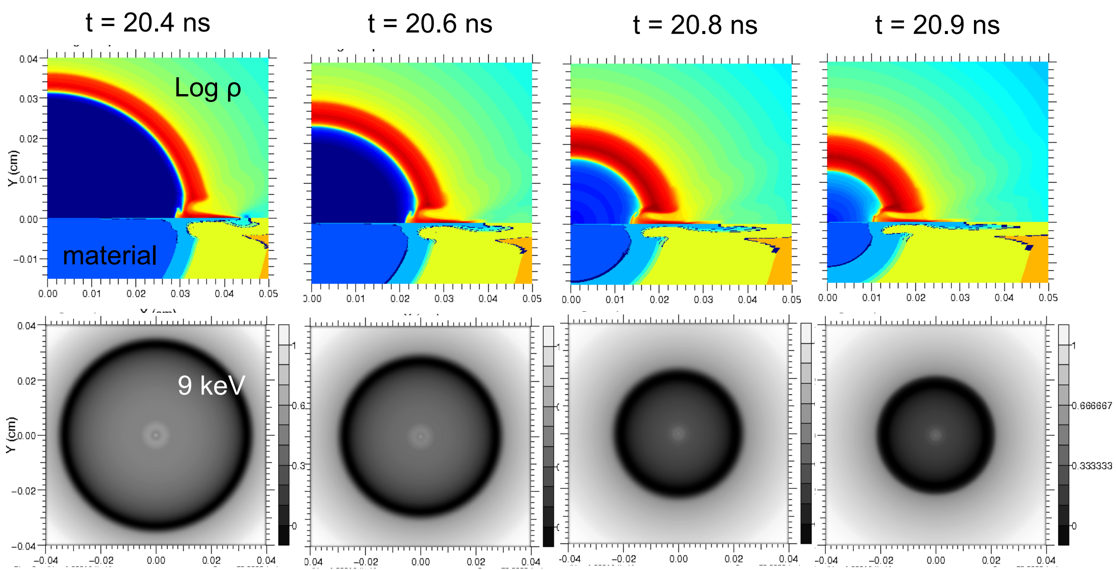
Conclusions

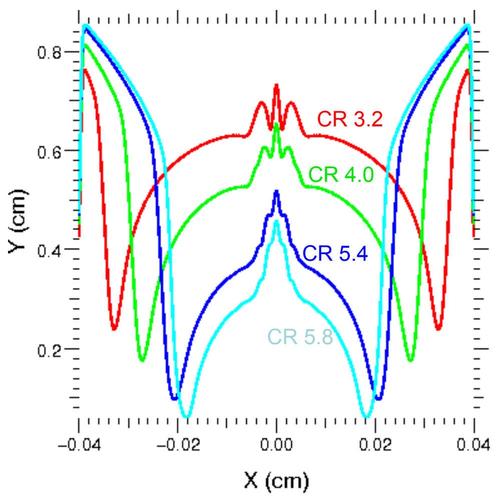
- Face-on radiography of engineered defects will provide valuable measurements of instability growth and provide key validation metrics for simulations codes
- Technique is sensitive to measuring difference in hydrodynamic instability growth as a result of changes to the foot of the drive. Changes to peak drive are less sensitive and are marginally quantifiable with expected noise levels
- Face-on radiography at low convergence ratios can probe instability mode structure and infer the state of instability growth at peak velocity
- Correlation of face-on radiography with predicted Ge core emission and capsule performance will provide a powerful test of our simulation codes and understanding of instability growth in NIC capsules

Backups

Face-on radiography can assess growth rates of isolated defects

HYDRA 2D simulation of 500 nm high 20 μm gaussian bump on pole

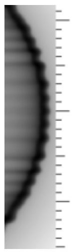




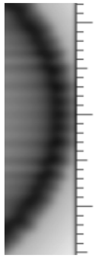
Quantitative analysis of limb radiography is difficult because fast implosion speeds and finite time gating lead to significant temporal blurring

- 30 cm/μs velocity produces ~21 microns of blurring on GXD with 70 ps gate time
- Face-on radiography has significantly less temporal blurring since the velocity vector is primarily orthogonal to detector

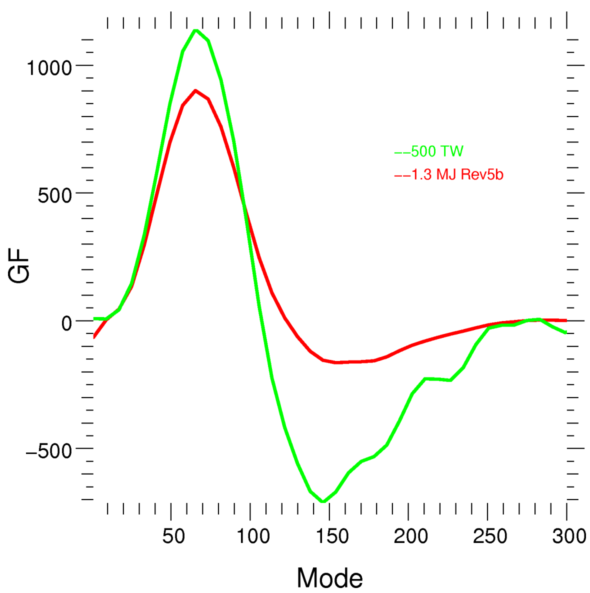
2D Ideal Image

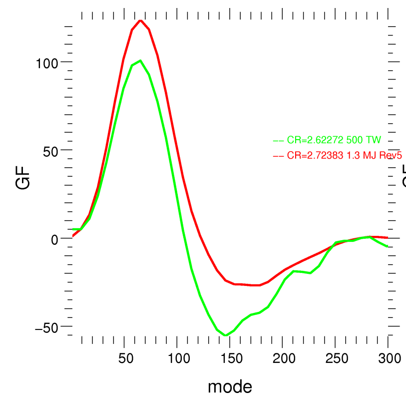


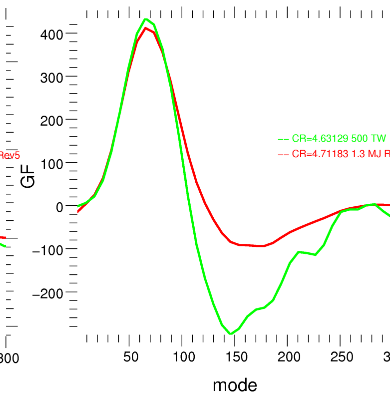
Simulated motion blurring due to 70 ps time gate

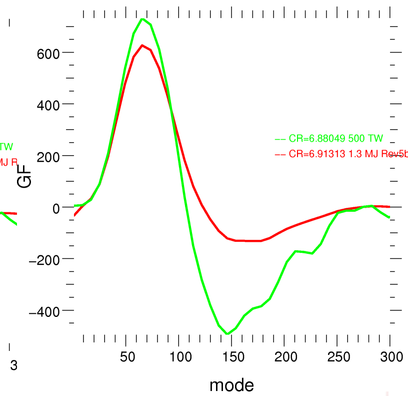


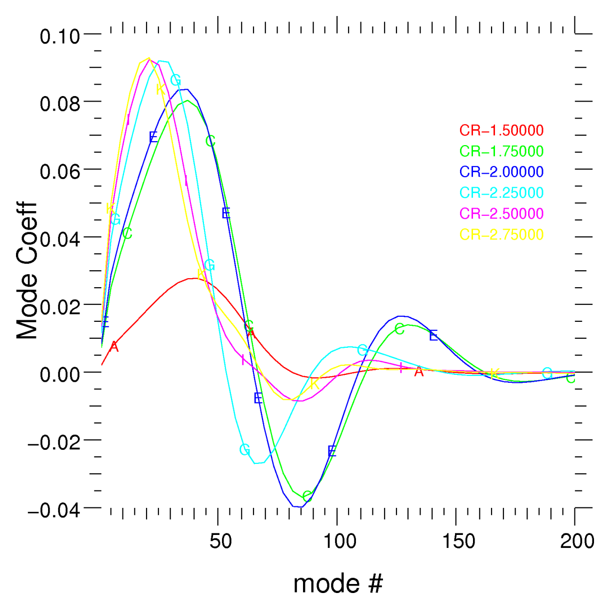
Growth factor curves maintain similar spectral shape as the capsule implodes











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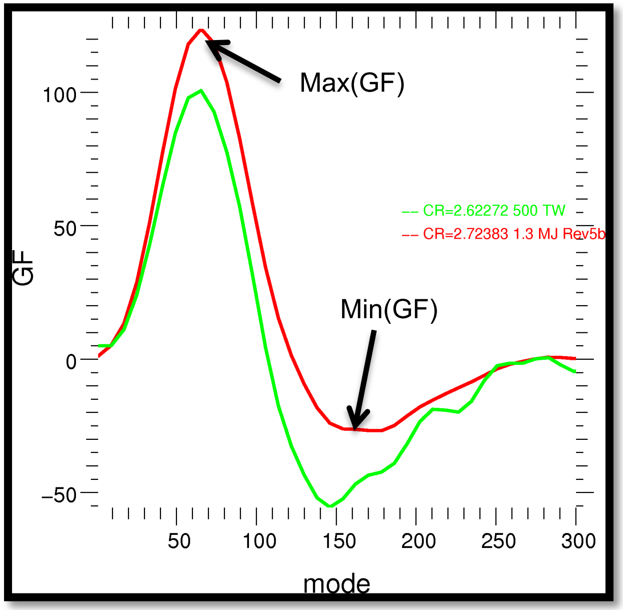
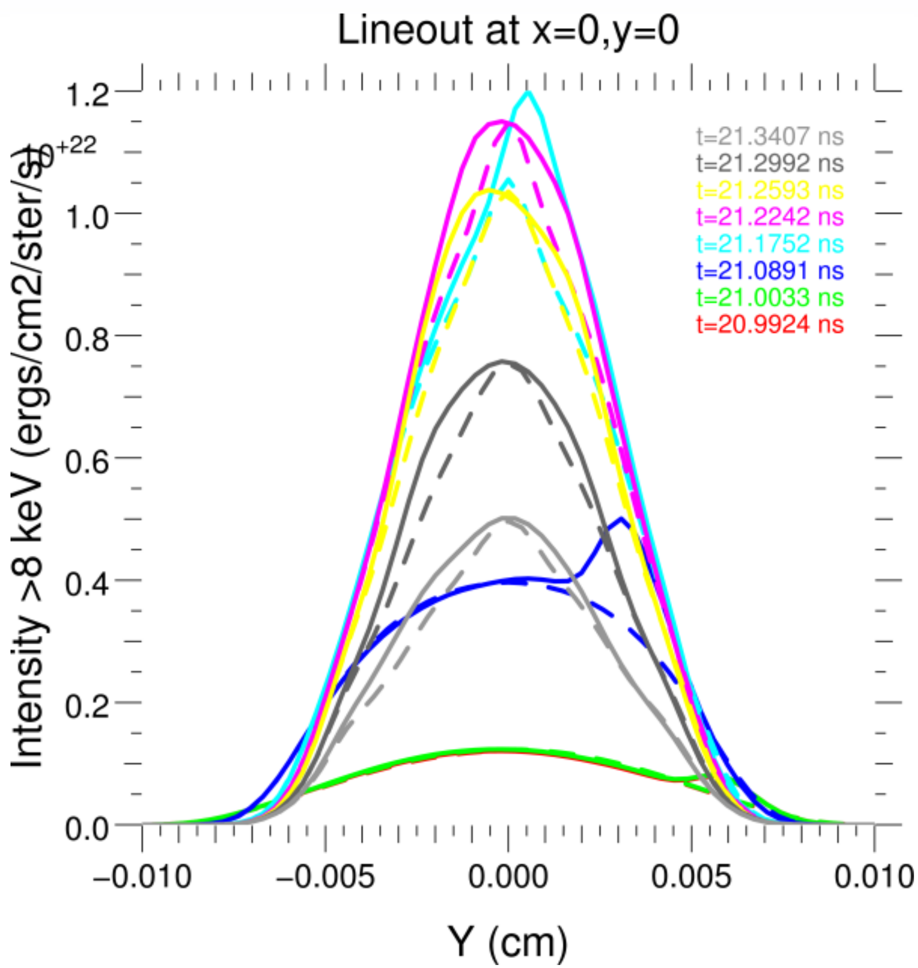
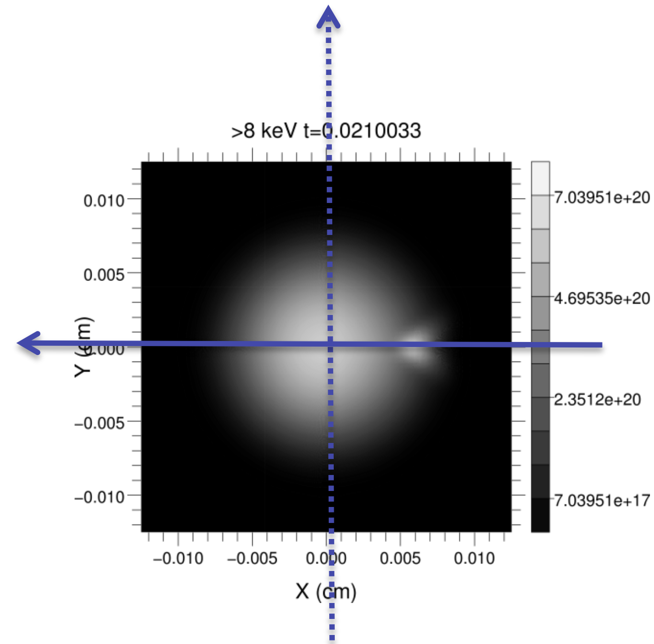
CR ~2.6



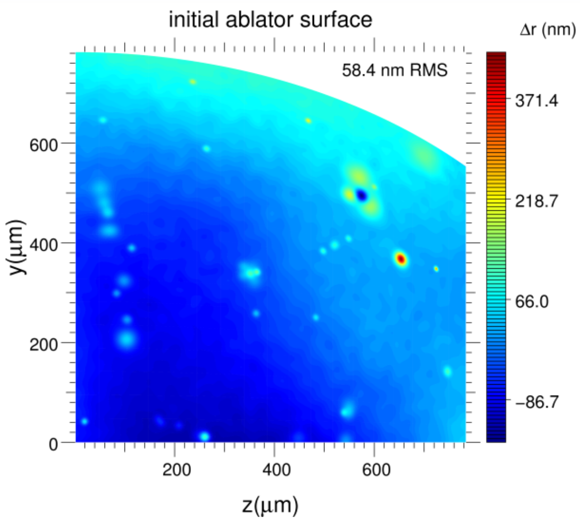
Max(GF)
Min(GF)
-- CR=2.62272 500 TW
-- CR=2.72383 1.3 MJ Rev5b
GF
100
50
0
–50
50
100
150
200
250
300
mode

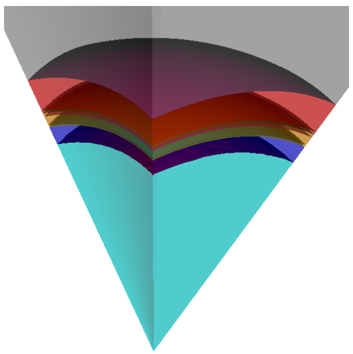
Ge emission from jet is most clearly distinguishable after peak velocity and before peak compression





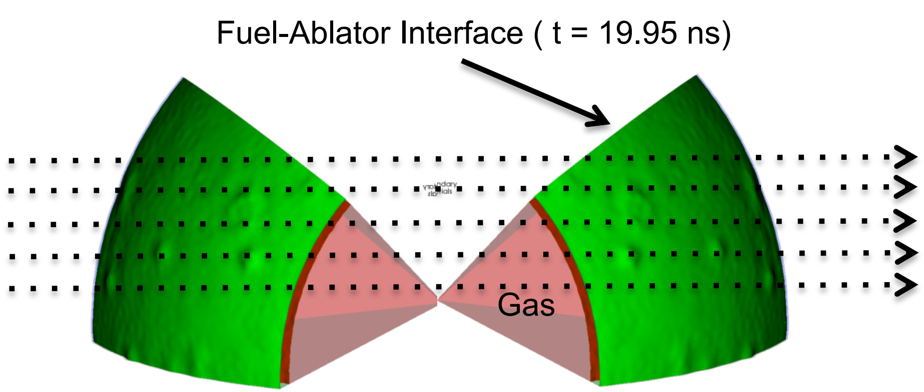
High resolution 3D simulations have been processed with Spect3D to produce synthetic radiographs

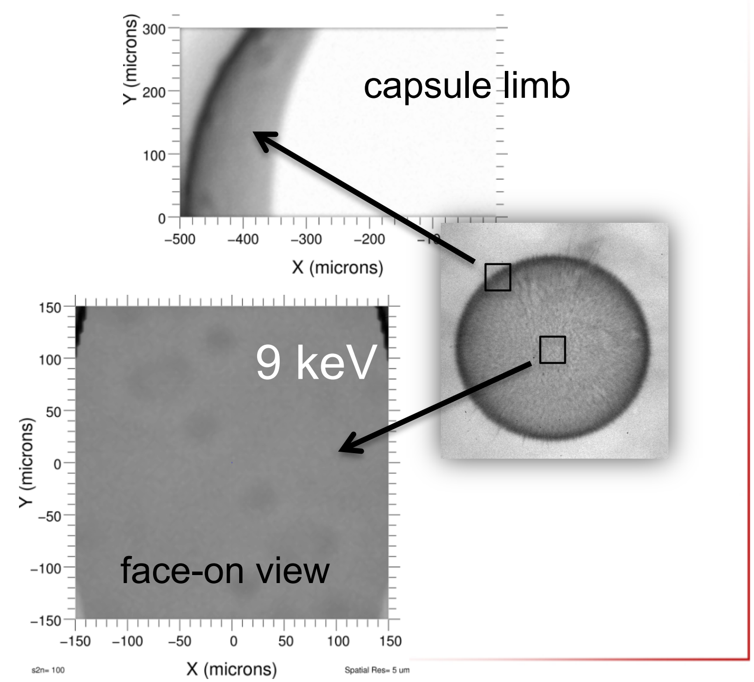




Dan Clark T05.00001

- ℓ = 4-200 & m < 200
- 3D 45° x 45° patch
- 1005 x 512 x 512 zones





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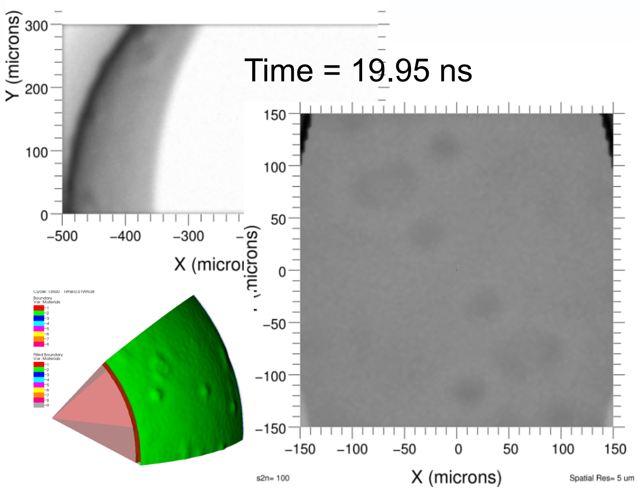
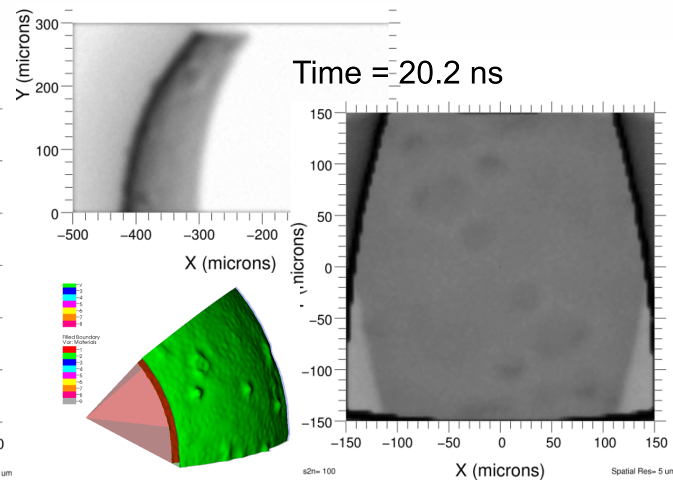
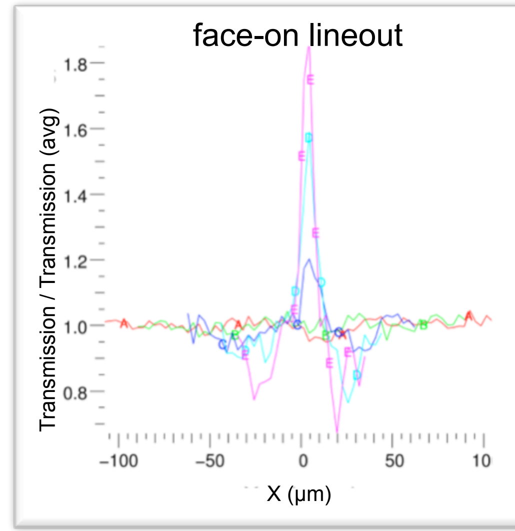
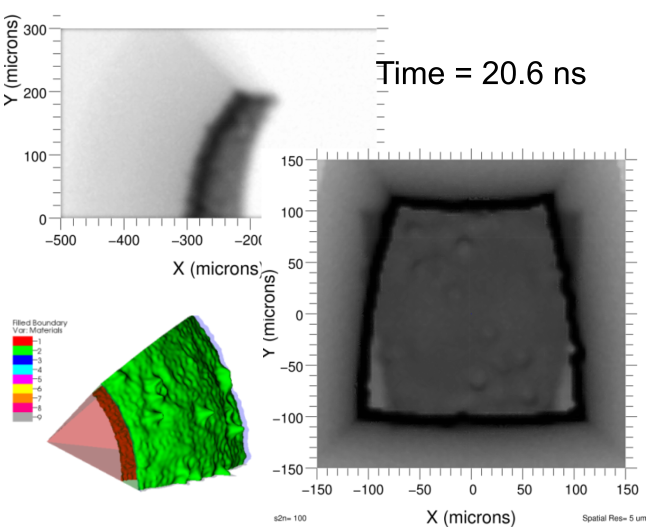
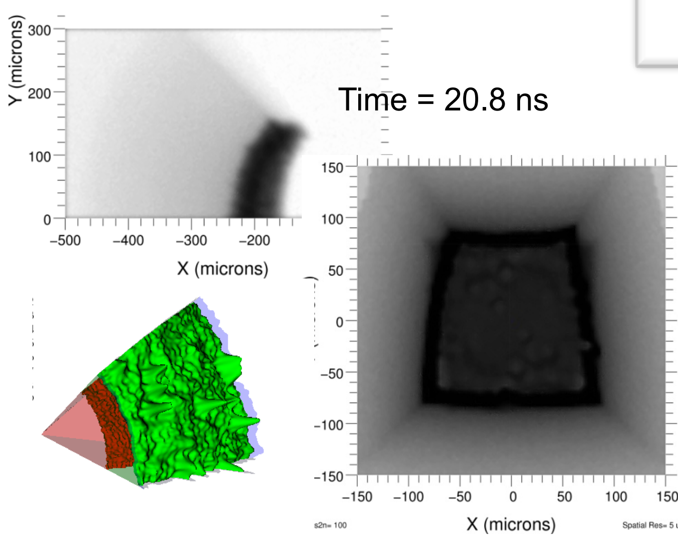
The evolution of small isolated defects on capsules with nominal perturbation amplitudes can be tracked and measured

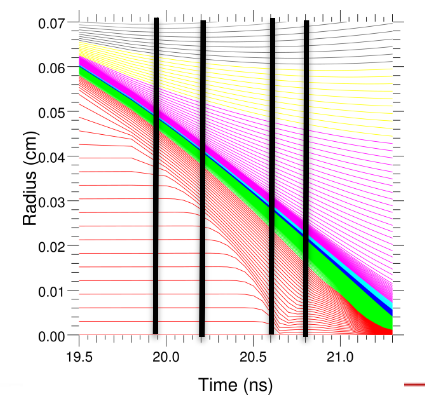












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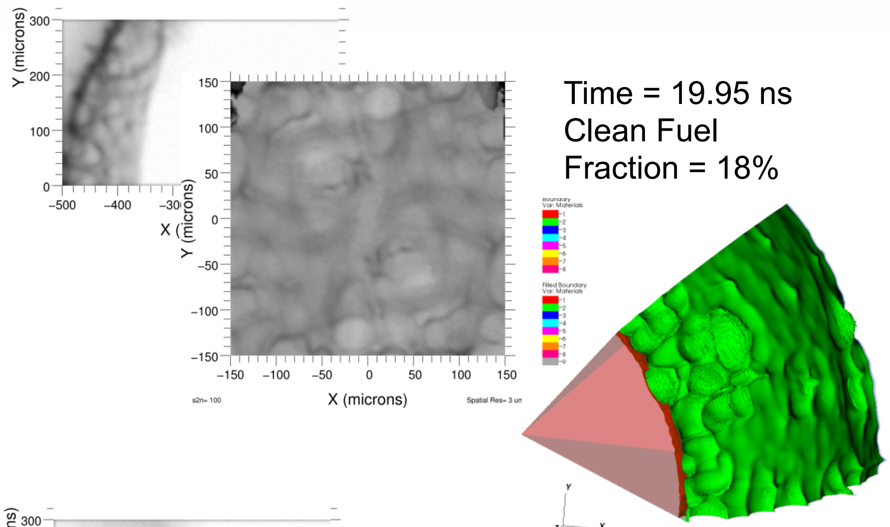
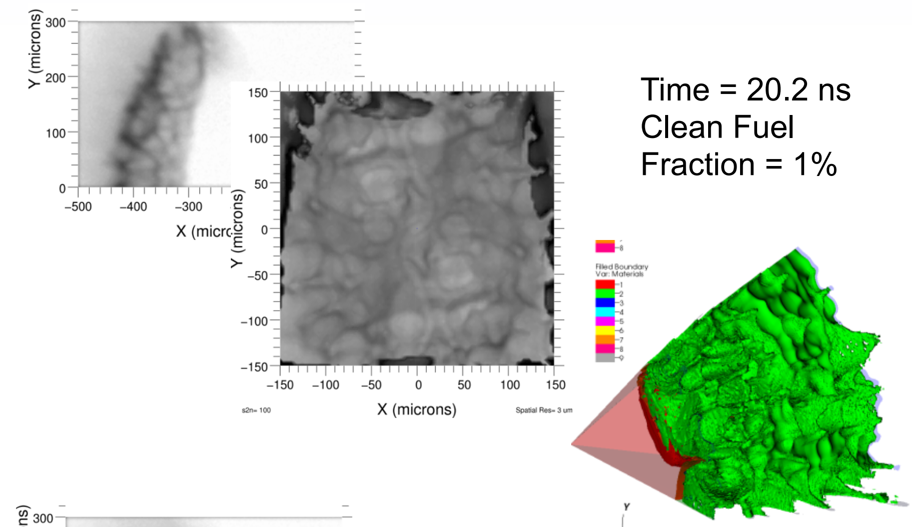
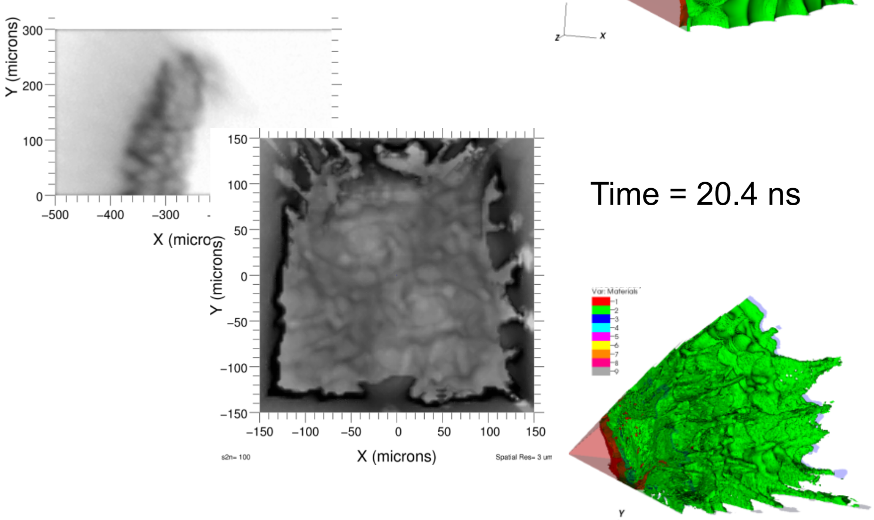
Time gated images also provide a qualitative assessment of the implosion



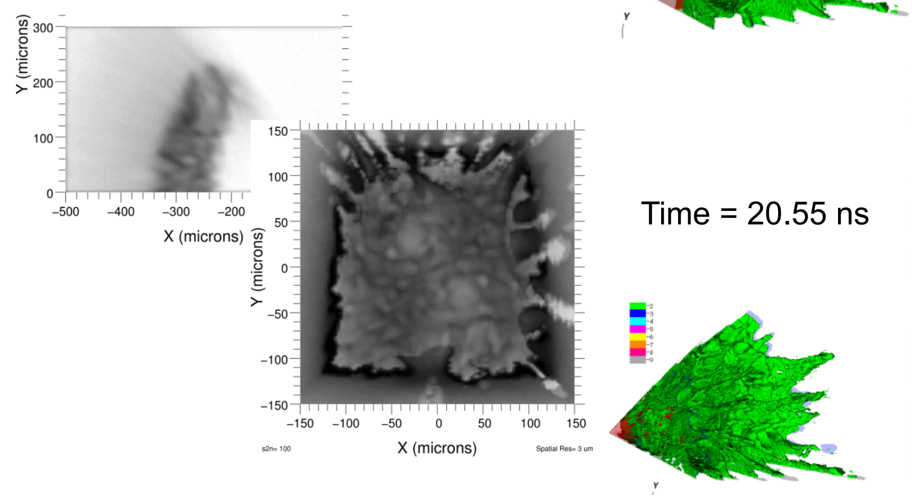
Time = 19.95 ns
Clean Fuel
Fraction = 18%



Time = 20.2 ns
Clean Fuel
Fraction = 1%



Time = 20.4 ns



Time = 20.55 ns

Note: This simulation was done at ¼ of resolution