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Title:	PhD Dissertation Proposal - Introduction to Dark Mix Concept: Gamma Measurements of Capsule Mixture
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PhD Dissertation Proposal
Introduction to Dark Mix Concept: Gamma Measurements of Capsule Mixture

Kevin Meaney

September 2017

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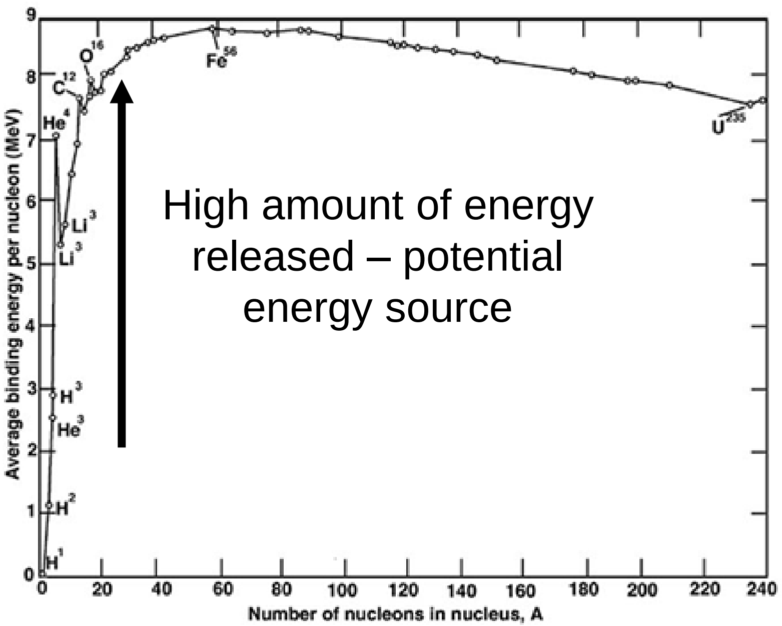
Outline

1. **Intro to Inertial Confinement Fusion**
2. Types of Mixture in ICF capsules
3. Previous mixture experiments
4. Dark Mix Concept
5. Measuring Dark Mix with Gamma Cherenkov Detector
6. Dissertation Outline

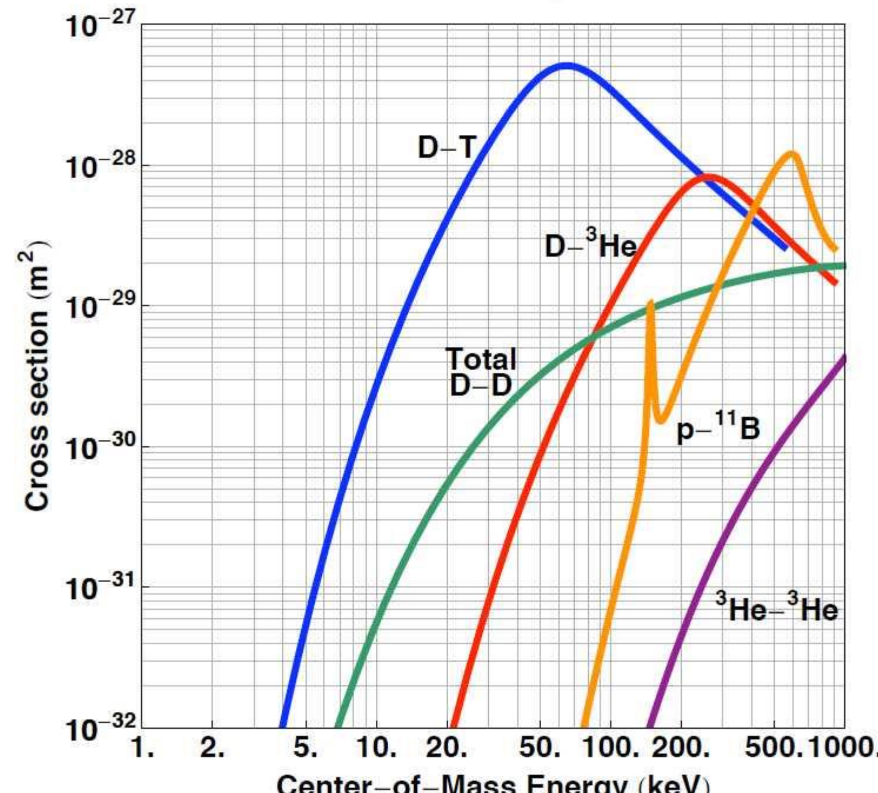
Need high temperatures or densities for man-made fusion

- Fusion could be used for energy production
- Temperatures (many keV) are too hot for any material to contain the reaction
  - Lawson Criteria: $nT\tau_E$
  - Magnetic confinement, high τ_E
  - Inertial confinement, high n



Biding Energy of Elements, Carl Jason Hepburn, Splung.com

But need extremely high temperatures ($7 * 10^7$ K) or densities for cross sections high enough for self-sustaining



Fusion cross sections, University of Wisconsin-Madison

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GOT ICF?

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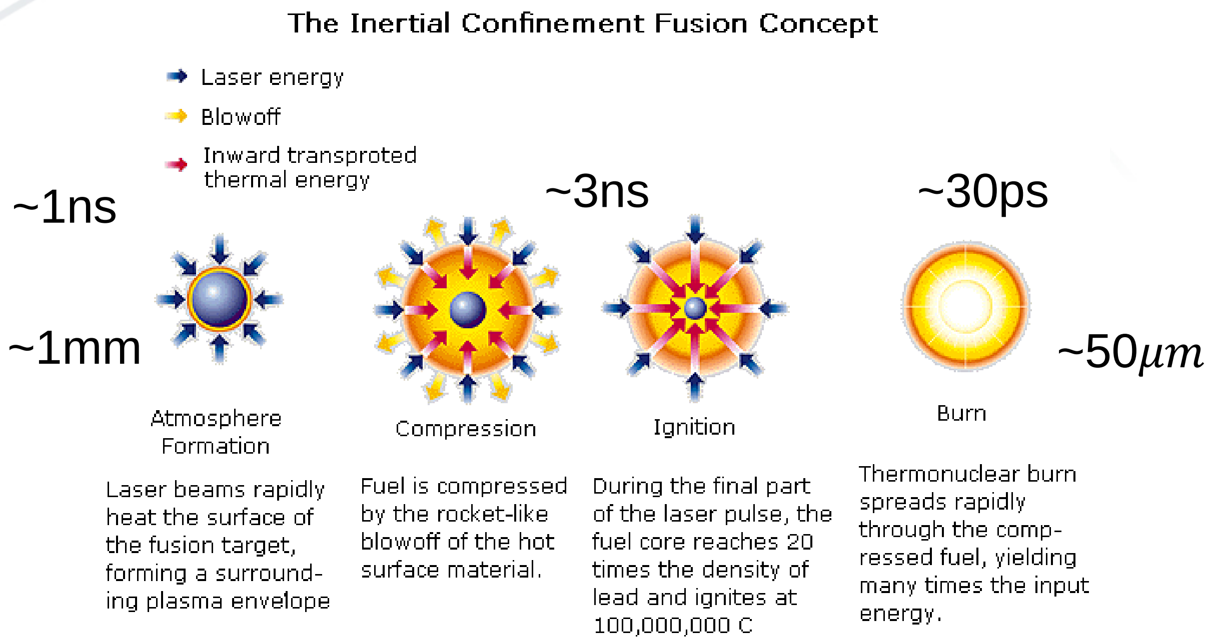
Nuclear processes are fast – can do fusion before object blows apart: Inertial Confinement Fusion

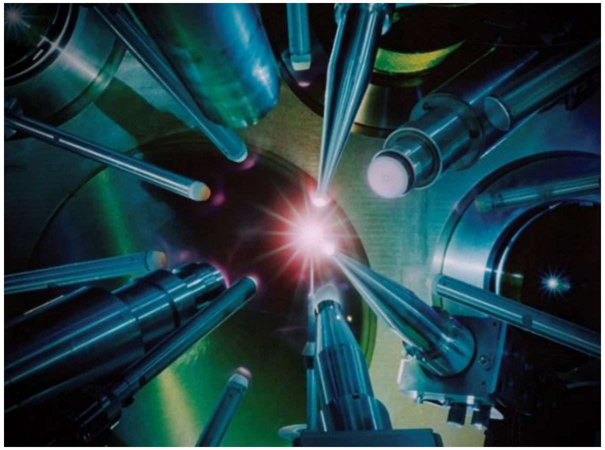


Schematic of Inertial Confinement Fusion, Lawrence Livermore National Lab

- Direct Drive - hit capsule directly with UV laser – more energy coupled
  - At OMEGA laser facility
- Indirect Drive – heat hohlraum, makes x-ray heat bath which hits capsule – more symmetric
  - At National Ignition facility

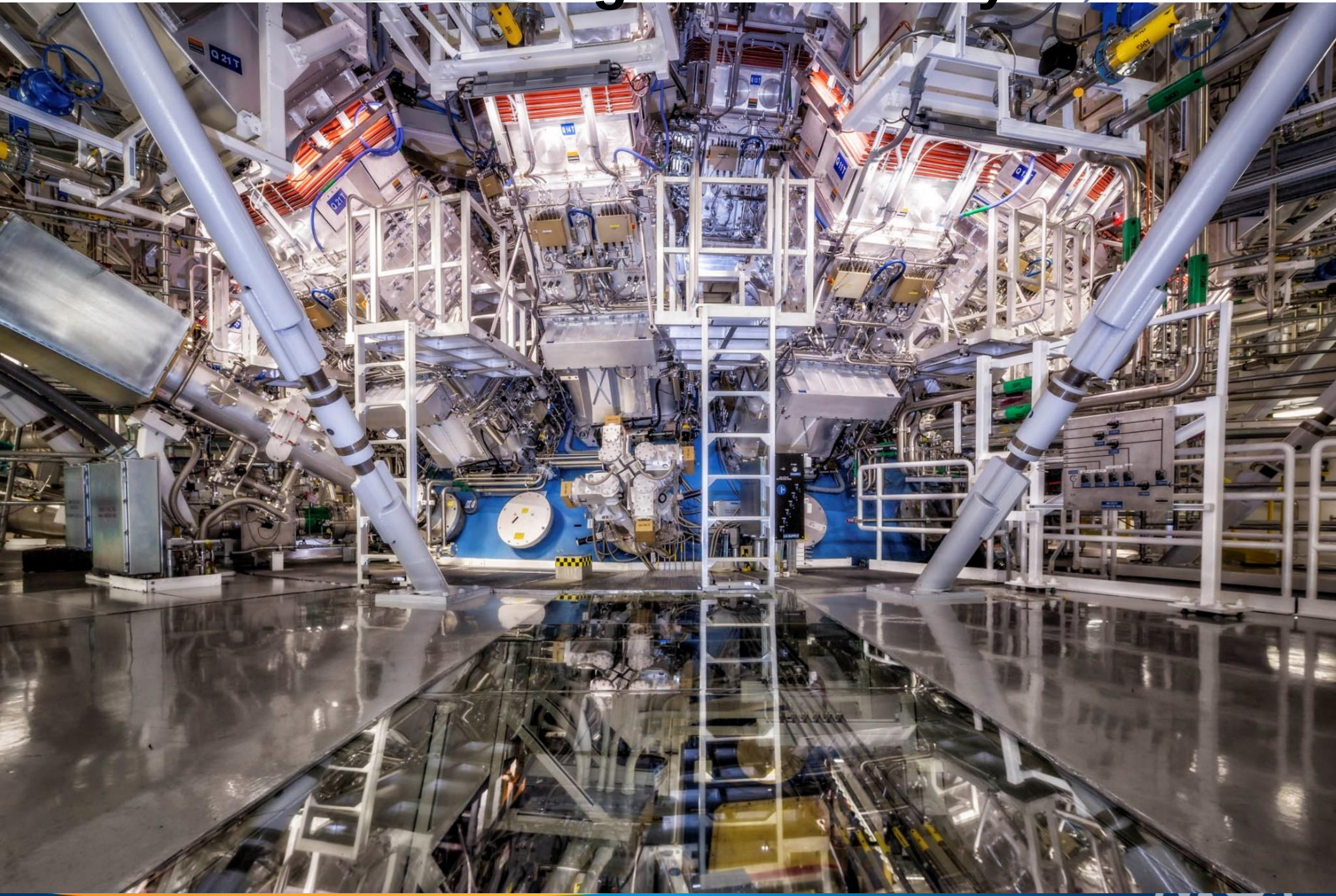
Inertial Confinement Fusion can achieve high gains through alpha heating

- If enough fuel is heated enough to undergo fusion and emit α particles, a chain reaction can occur
  - Range of 3.5 MeV alpha is about $\rho r_{\alpha\, range} = 0.3 \frac{g}{cm^2}$ (10% of fuel)
  - Heat up 10% of fuel → α heat surrounding layer → all of fuel can burn
- Energy yield from burning ~1 mg of DT fuel ~ 500 MJ:
- Internal energy of a compressed polytropic fluid ~ 0.2 MJ
  - Gain around 2500!
    - Many steps of inefficiency to power plant:
    - Shell to internal energy (~30%)
    - Laser to shell (~50%)
    - Wall plug to laser (~10%)
    - Neutrons to useful energy (~10%)
- Gains of this size would be valuable



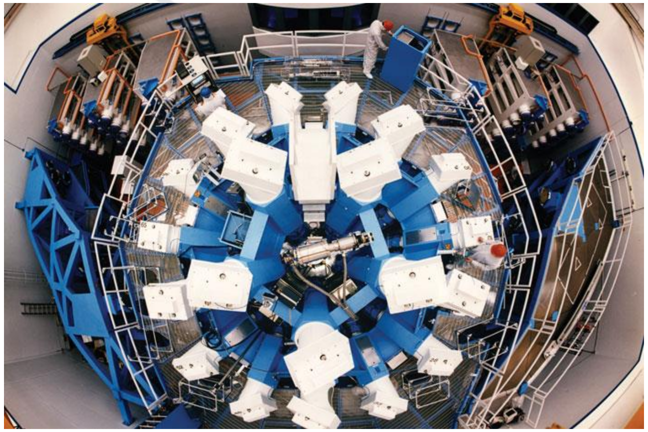
OMEGA Laser, University of Rochester, Laboratory of Laser Energetics

National Ignition Facility

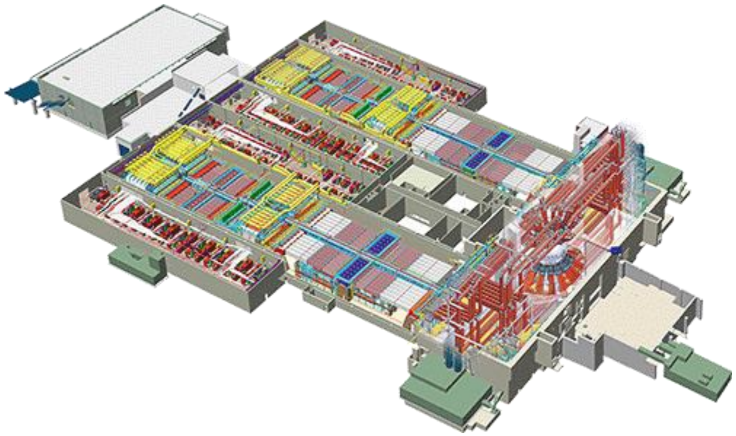


Laser facilities NIF and OMEGA can create ICF conditions

- OMEGA Laser at Rochester University
  - 60 beams ultraviolet
  - Can deliver 30kJ
    - Up to 60 Terawatts
  - Depending on capsule type and set up, can shoot 12~14 capsules each shot day
  - Direct drive
- National Ignition Facility Laser located at Livermore National Lab
  - 192 beamlines
  - Can deliver 1.8 MJ
    - Up to 500 Terawatts
  - 1 shot per shot day
  - Indirect drive
    - Gold and uranium hohlraums
- OMEGA often used for dry running designs before moving to NIF



OMEGA 60 Laser, University of Rochester



National Ignition Facility Schematic, Lawrence Livermore National Lab

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National Ignition Facility constructed to achieve ignition, but failed – ablator/fuel mix one source of degradation

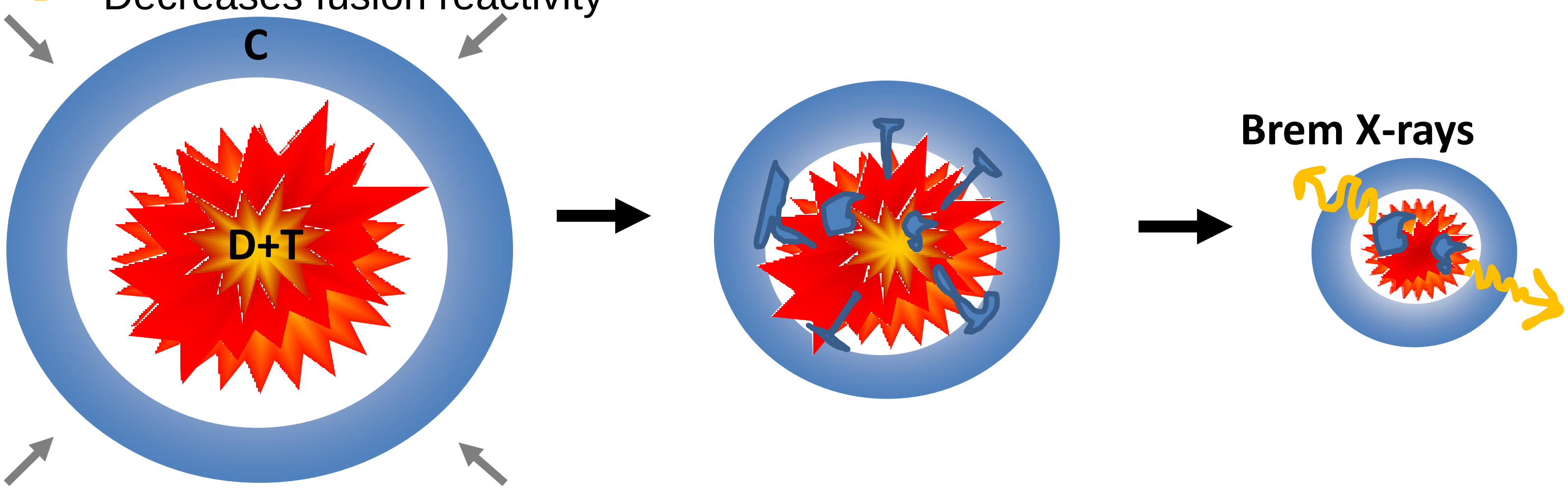
National Ignition Facility Inner Chamber, Lawrence Livermore National Lab

- NIF constructed in 2009 predicted to create ignition conditions
  - Campaign ended in 2012 with no ignition
- DOE 2012 report suggests sources of lost efficiency:[1]
  - **ablator/fuel mix**
  - low implosion velocity
  - low mode asymmetries
- Complex interaction between degradation sources – fixing one may hurt another
  - Very hard to predict scaling to higher energies

[1] *"External Review of the National Ignition Campaign" Princeton Plasma Physics 2012*

Mix is one major source of yield degradation

- Mix throughout this presentation means any movement of ablator material into the fuel
- Higher Z material goes into hot spot
- When heated, ablator material gives much larger bremsstrahlung radiation losses
  - $P_{Brem} \propto Z^2$
- Less energy makes it into the fuel
  - DT needs to be higher than 4.4 keV to overcome bremsstrahlung
- Decreases fusion reactivity



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Hydrodynamic mixing in ICF moves bulk matter of ablator into fuel

- ‘Hydrodynamic’ is blanket term for many different mechanisms that move bulk material through fluid processes
- Capsule and laser have small initial perturbations which can be amplified
- ICF has many unstable processes
  - Laser sends multiple shocks
  - High density ablation front accelerated into low density fuel
  - Inner shell surface decelerated
  - Instabilities exaggerate perturbations
    - Less energy into fuel
- The main simulation software (Hydra, RAGE) packages include mix models that mainly incorporate hydrodynamic mixing

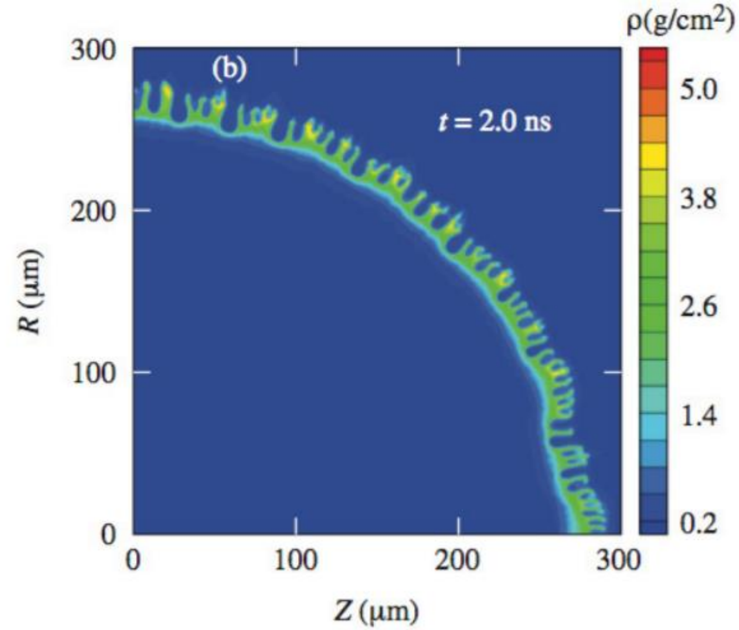

Figure 7. (a) Central 200-μm-square parts of the images were used to analyze the growth of the 3D broadband modulations. (b) An example of a 2D *DRACO* simulation showing a shell mass-density contour in an experiment with a 24-μm-thick CH shell at 2.0 ns driven with a low-intensity, 3-ns square laser pulse at an intensity of $\sim 2 \times 10^{14}$ W cm^{-2}.

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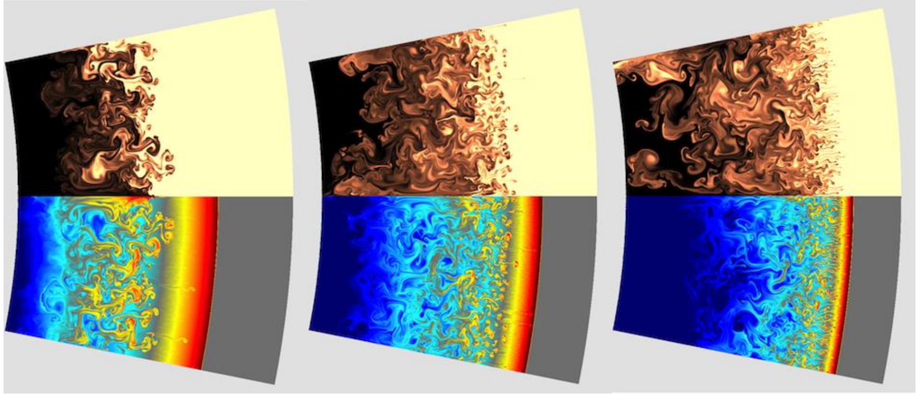
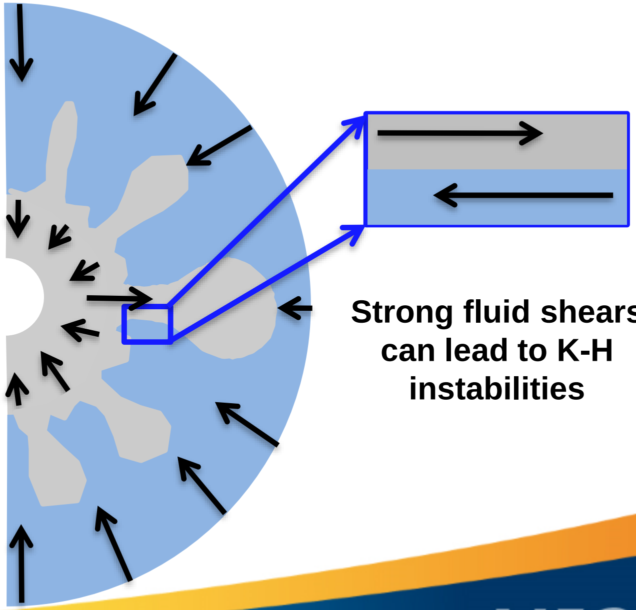
Rayleigh-Taylor, Richtmyer-Meshkov and Kelvin-Helmholtz instabilities are major sources of hydrodynamic mixing

- Rayleigh Taylor instability
  - Occurs whenever a heavier density material is accelerated into a lighter density material
    - Creates fingers and bubbles that grow exponentially
- Richtmyer-Meshkov instability
  - Occurs when a strong shock is refracted through small perturbation
- Kelvin Helmholz instability
  - Occurs on strong shear flows
- Transforms directed energy into dispersive energy
- Moves ablator material into fuel
- All three instabilities are coupled and interact with each other



Duffell, "Rayleigh-Taylor Instability in a Relativistic Fireball on a Moving Computational Grid" *Astrophysics 2013*



Perturbations on capsule surface can jet bulk material into fuel

- At NIF, capsules are held with a tent and use fill tube. At OMEGA capsule is held by stalk
  - Perturbations on the surface of the shell are amplified
- Can cause outer parts of shell to be jetted into the fuel
  - 3D simulations show that the tent, fill tube and stalk can cause jets
  - Seen as major cause of yield degradation and mixing
- Major campaign to shrink fill tube and holding tent[2], however, some support structure is required

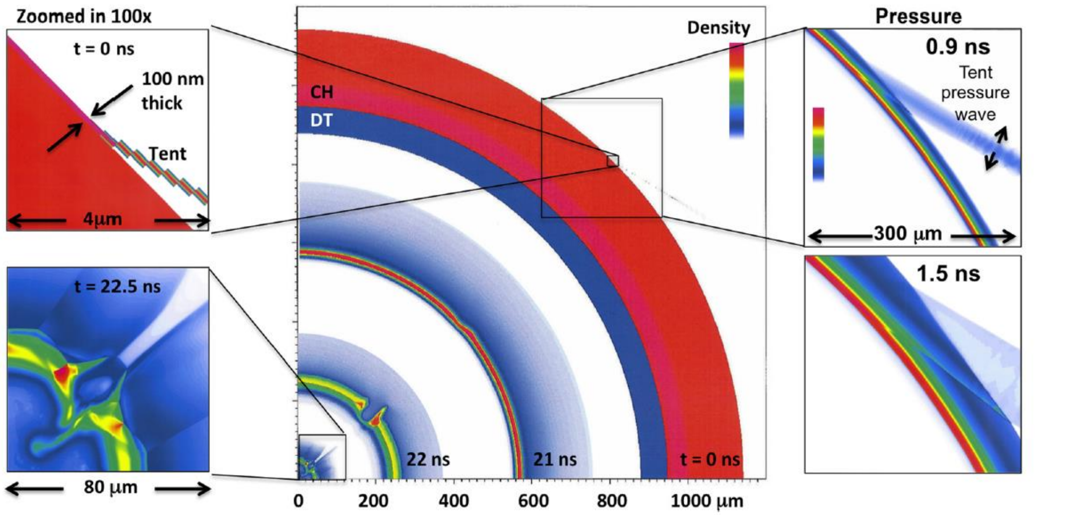


FIG. 2. Sequence of images showing the development of the tent perturbation from a high resolution simulation. Simulation is of low-foot experiment N120321 which used a 100 nm thick tent and lifted off at $\theta = 45°$ with a lift-off angle 14° larger than the tangential. The left insets show zoomed-in images of the initial tent contact location (top) and the implosion at bang time (bottom). The right shows the early-time blow-up of the tent, which interacts with the ablation front leading to the perturbation.

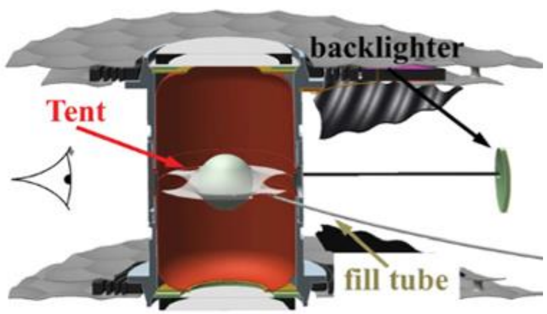


Diagram of tents on ICF capsules, Lawrence Livermore National Lab

[2] Weber, Casey,,et al, "Improving ICF implosion performance with alternative capsule supports" *Physics of Plasmas 2017*

Meteors are another source of bulk ablator mixing into fuel

- Large, discrete spherical chunks observed in fuel
- Casey's symcap experiments show "large brightly radiating objects traversing through the hotspot around bang-time, which are likely chunks of CH/CD plastic" [3]
- Not well understood, root cause unknown, observations seem to be erratic
  - High Foot campaign (High adiabat, warmer pre-compressed fuel) does not observe them as often
- Orth model describes shocks fragmenting shell, then blowing fragments into hot spot [4]

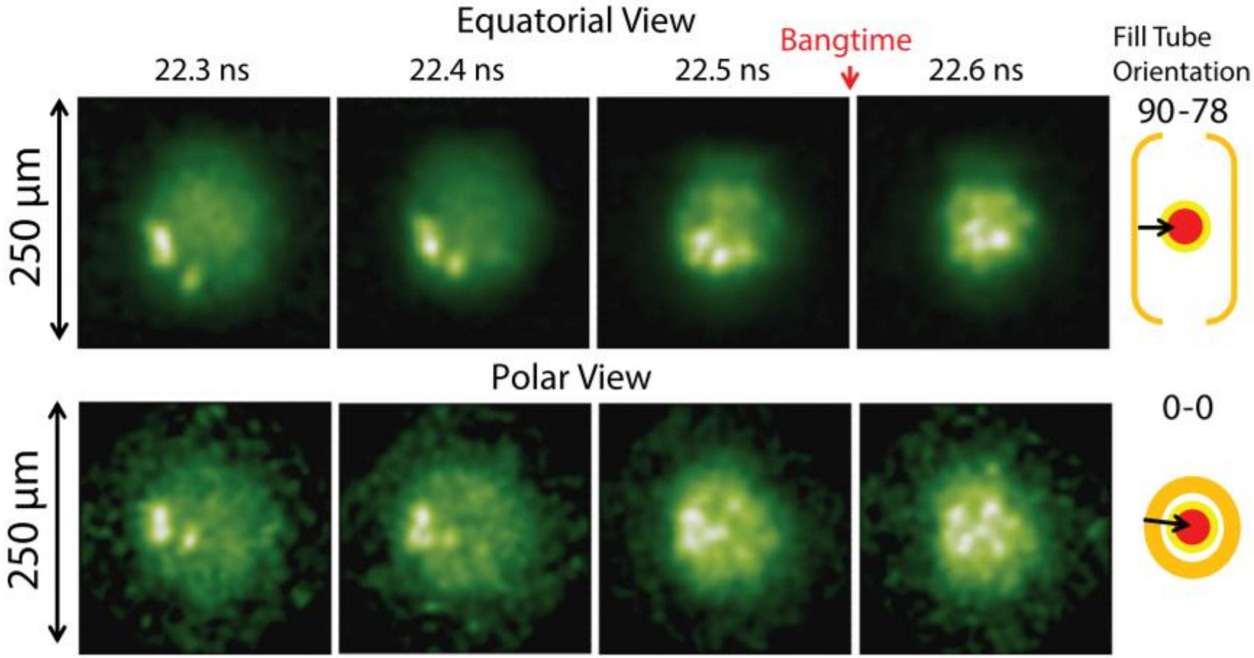


FIG. 14. Time gated self-emission x-ray images of shot N130315 from an equatorial view obtained with the hGXD instrument, and the polar view (viewing into laser entrance hole) obtained from the GXD instrument. Several bright spots of radiating plastic chunks are observed traversing the core near bang-time.

[3] Casey, Smalyuk ,et al, "Development of the CD Symcap platform to study gas-shell mix in implosions at the National Ignition Facility" *Physics of Plasmas 2014*
[4] Orth, *"Spallation as a dominant source of pusher-fuel and hot-spot mix in inertial confinement fusion capsules" Physics of Plasma 2016*

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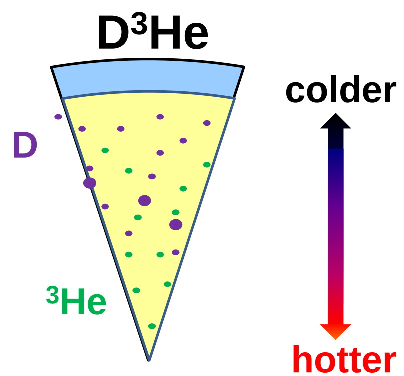
Diffusion can separate different mass materials and cause atomization of nearby fuel and ablator

- Diffusion is major process for converting bulk material flow into atomic mixing
- Inner most layer of ablator can diffuse into the fuel and the hot spot
  - Hasn't been, until recently, studied in detail
- For warm OMEGA shots, heavier fuel species pulled towards center, lighter species pushed outwards [5]
  - Higher Z materials diffuse to center faster
  - Could possibly separate high mass X-ray dopants from the layer they're placed in
  - $F = -\rho D \left(\nabla c + k_P \nabla \log P + \frac{e\, k_E}{T} \nabla \Phi + k_T \nabla \log T_I + k_T \nabla \log T_e \right)$ [6]



[5] Casey,et al, "Evidence for Stratification of Dueterium-Trituium Fuel in Inertial Confinement Fusion Implosions" Physical Review 2012
[6] Kagan, Tang "Electro-diffusion in a plasma with two ion species' Physics of Plasmas 2012

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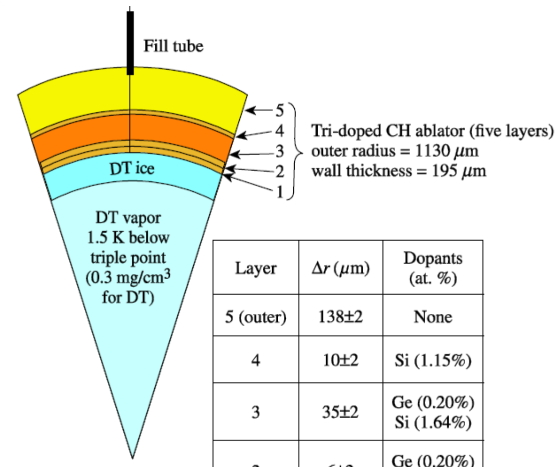
X-Ray emission from high Z dopant layers can be used to infer mixing

- Plastic ablator doped with high Z (i.e Cu and Ge) dopants at different radial locations
- Dopants that are heated to fusion temperatures give off K shell emission
  - Can also do mid-Z (Si) and measure continuum emission
- Emission compared to atomic spectrum models used to find amount of mixed material



Layer	Δr (μm)	Dopants (at. %)
5 (outer)	138±2	None
4	10±2	Si (1.15%)
3	35±2	Ge (0.20%) Si (1.64%)
2	6±2	Ge (0.20%) Si (0.87%)
1	6±2	Cu (0.14%)
DT ice	69	None
DT vapor (inner)	935	None

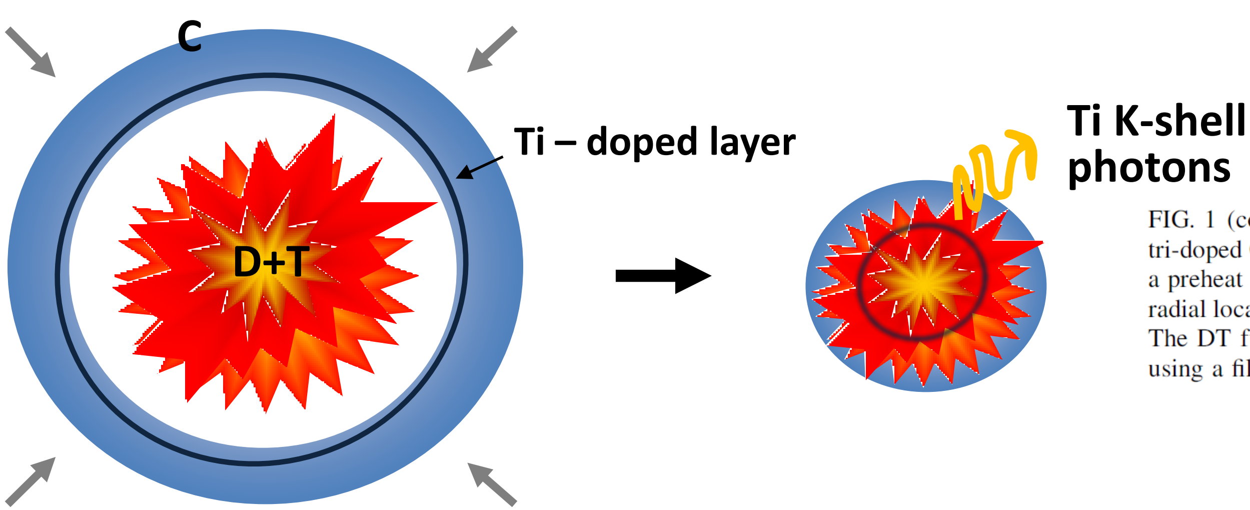


FIG. 1 (color online). Schematic of an ignition target with a tri-doped CH ablator and a cryogenic DT layer. The Si dopant is a preheat shield. The Cu and Ge dopants are placed at different radial locations to determine the origin of the hot-spot mix mass. The DT fuel is transported to the interior of the plastic ablator using a fill tube.

X-ray dopants have been a vital tool to improving capsule yield

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- X-ray dopants has been main source of mixture measurements
- Low foot campaign (low adiabat, cooler pre-compressed fuel) saw a large amount of mix[7]
- Current high foot campaign (higher adiabat, higher pre-compressed) sees less mix
  - High foot pulses have less shocks (less RM instability) and lower convergence
  - Unstable growth rates ~5x less in high foot
- Ablation front instability dominates over RT at the ablator-ice interface on NIF targets[8]
- Low mode asymmetry due to direct laser on OMEGA has been observed to be main cause of mix[9]

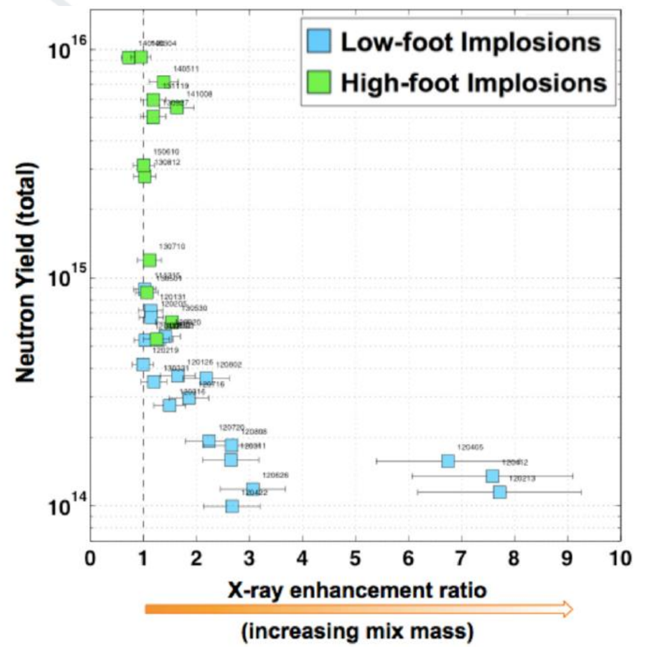


FIG. 5. DT neutron yield versus measured x-ray enhancement ratio for the layered low-foot (blue) and high-foot (green) implosions.

[7] Ma, Patel, et al, "The role of hot spot mix in the low-foot and high-foot implosions on the NIF" Physics of Plasmas 2017
[8] Regan, Epstein,et al, "Hot-Spot Mix in Ignition-Scale Inertial Confinement Fusion Targets" *Physical Review 2013*
[9] *Shah, Haines, et al, Systematic Fuel Cavity Asymmetries in Directly Driven Inertial Confinement Fusion Implosions" Physical Review 2017*

Mix can also be measured by separated reactant experiments - placing one fusion reactant into shell layer and measuring yield

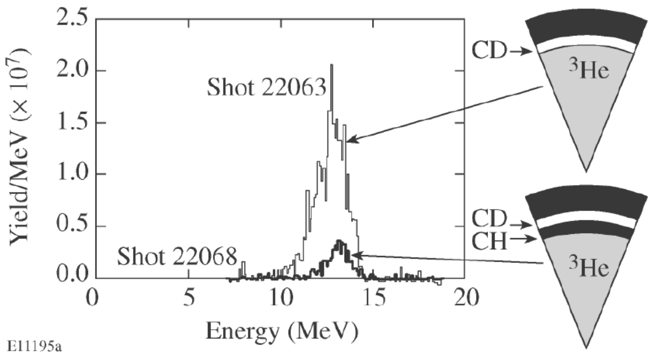
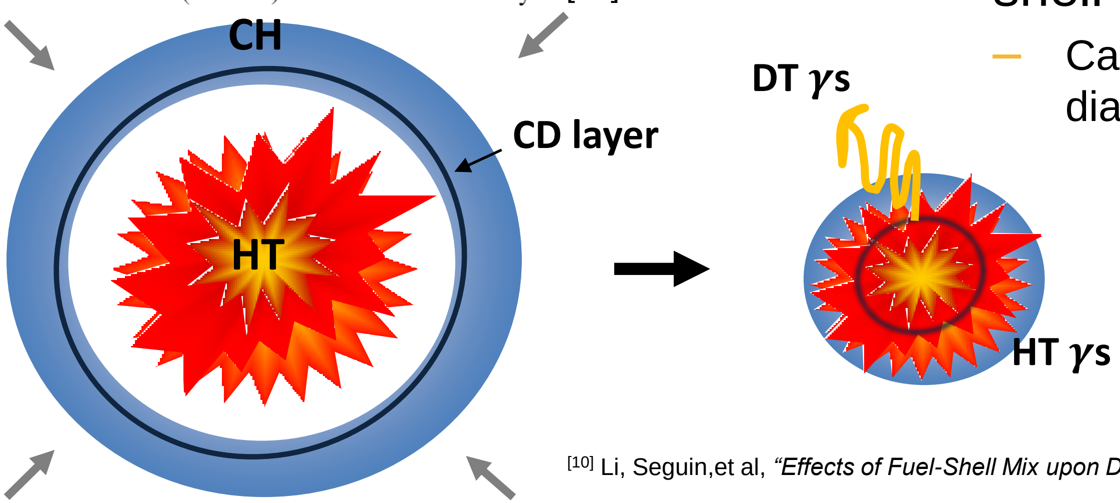


FIG. 1. The structures of two different capsules filled with 4 atm of pure ^{3}He gas, and measured spectra of primary D^{3}He protons from implosions at OMEGA. The ratio of number densities (D to C) is 1.56 in the CD layer. [10]



- Place fusion reactant into shell layer
  - Deuterium in layer, HT, TT or ^{3}He in fuel
- Fusion fuel needs to be atomized and heated to fusion temperatures
- Amount of fusion signal observed is indicator of how much mixture of shell into fuel occurred
  - Can be observed with neutron or gamma diagnostics

[10] Li, Seguin,et al, *"Effects of Fuel-Shell Mix upon Direct Drive ,Spherical Implosions on OMEGA" Physical Review 2002*

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Separated reactant measurements have given insight into mixture mechanisms

- Previous separated reactant experiments on OMEGA have suggested Rayleigh Taylor fingers main cause of mixing and atomizing of shell[11]
  - Comparing OMEGA experiments to 3D simulation suggests[12]
    - Short wavelength asymmetries seed localized mixing zone
    - Long wavelength asymmetries (mount, shape distortion) seed jets and transport shell towards hot spot
- Recent, higher resolved, OMEGA experiments suggest diffusion dominated region and possibly jet[13]
- Platform (CD Symcap) developed for use on NIF[3]

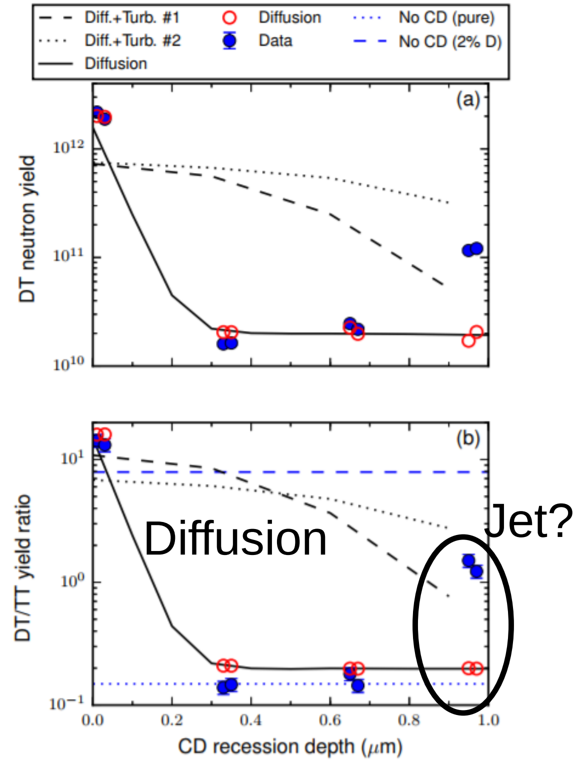


FIG. 3: Nuclear data versus CD recession: DT neutron yield (a), and DT/TT yield ratio (b). Model curves are shown by the black curves. In (b), the blue horizontal dashed and dotted lines represent values from 2% D in the gas or contamination D. Red circles are individual shots simulated with the diffusion-only model.

[11] Haines, Grim ,et al, "Detailed high-resolution 3D simulations of OMEGA separated reactants inertial confinement fusion experiments" *Physics of Plasmas 2006*
[12] Rygg, Frenje,et al, "Time Dependent Nuclear Measurements of Mix in Inertial Confinement Fusion" *Physical Review 2007*
[13] Zylstra, Hoffman, Herrmann, Schmitt, Kim, Meaney, et al "Diffusion-dominated mixing in moderate convergence implosions" *Submitted to Physics of Plasmas*

The two mixture methods have pros and cons – however both require shell to be heated to keV

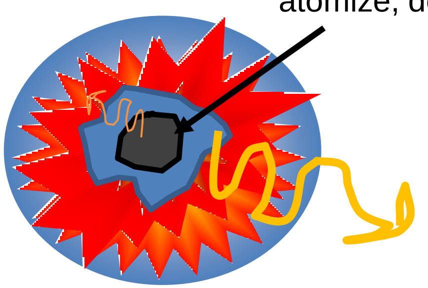
Measurement Type	Pros	Cons
X-ray dopants	• Easy to add to experiments • Similar capsule experiments give relative mixture comparison	• **Dopants need to be heated to keV temperatures** • Need temperature, density and spectroscopic model to get absolute values • Assumption that dopant moves with ablator
Separated reactants	• Measuring yield gives integrated value of mixture	• **Reactants need to be heated to keV temperatures** • Reactants need to be atomized • Gives low yield, can't simply add to any experiment

Colder ablator may also be mixed into fuel, but not hot enough to be measurable

- Previous methods of mix measurements require material to be heated to keV temperatures
  - Separated reactants also needs to be well atomized
- Large amounts of mix may not become hot enough to be observed
  - Center of meteors not atomized or hot enough
  - Similarly with jetting shell, possibly not atomized or hot enough
  - Diffusion that is on edge of fuel
- Shell mixed into colder fuel is still damaging to implosion performance

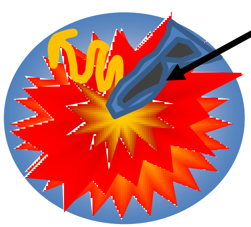
Meteors

Edges heat up to keV and atomize, does center?



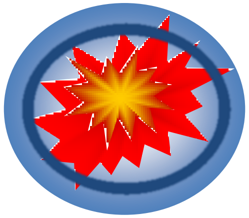
Jets

How much of jet atomizes? How much of it is heated?



Diffusion

Shell cooling edges of fuel, not observed?



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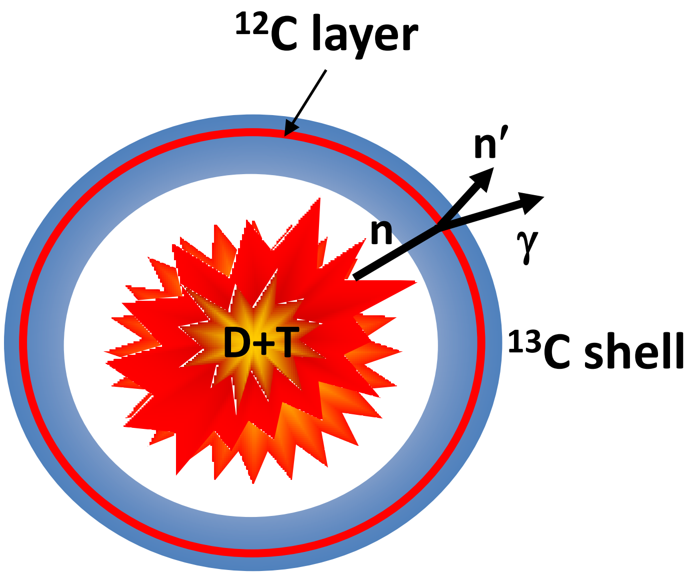
Neutron induced gamma signal is independent of material temperature - can give correlation to amount of mix

- Want to measure mixed material everywhere – not just when it's hot
- Neutron induced gamma signals are independent of temperature
- Gamma detector can measure the areal density, ρR, of a specific layer of a shell
  - Areal density is a combination of spatial location, density and compression
- Previous investigation: place ^{12}C tracer layer in ^{13}C shell [14]



- ^{13}C was not expected to give neutron-induced gamma signal ^{12}C
  - Turned out to be incorrect, strong ^{13}C(n,2n)^{12}C* line does exist (~80% of 12C)

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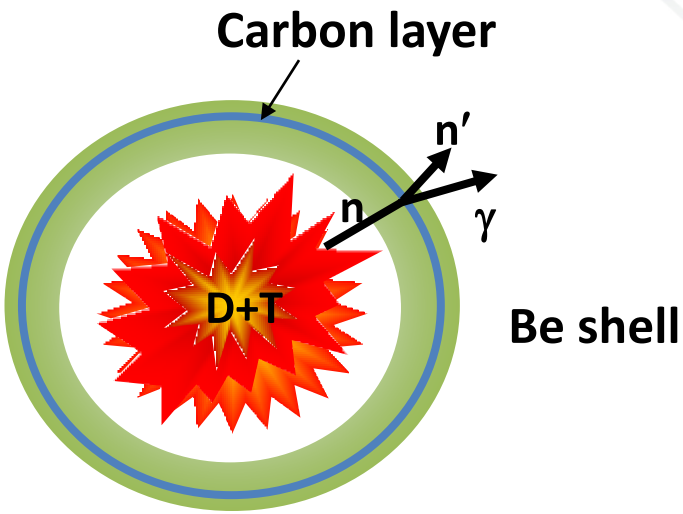
[14] McEvoy paper about this investigation to be submitted soon

Beryllium capsules allow for tracer layer that gives distinct gamma signal

- Current beryllium campaign is investigating new ablator
  - Beryllium has low neutron-induced gamma cross section
- Can put observable tracer layer in beryllium shell



- Gamma detector measures ρR_C for a given layer
- Simple 1D model or simulation gives expected ρR of a given recessed layer with no mixing
  - Observed deviation from simple model suggests mixture
- Use simulations and other mixture measurements to estimate and isolate what type of mix causes observed deviation from 1D scaling

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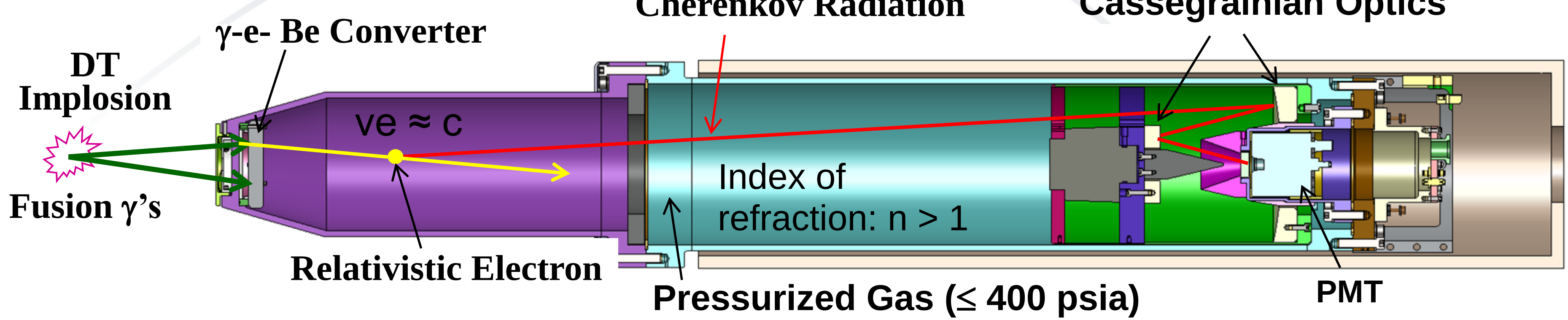
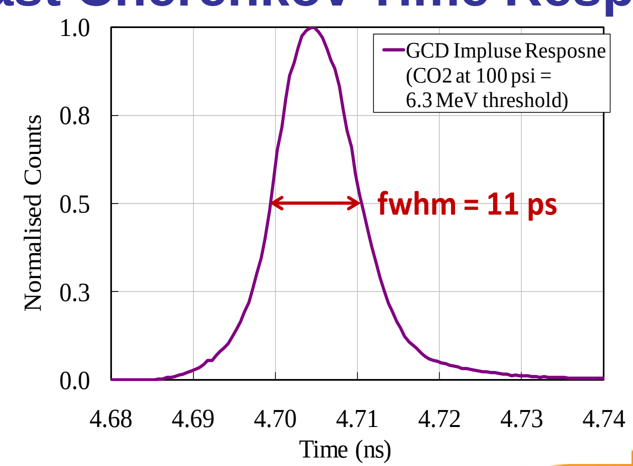
Gas Cherenkov Detector (GCD) measures the gammas given off in ICF shots and can be used to measure carbon ρR

Converts MeV γ-rays to UV/Visible photons for easy detection



Fast Cherenkov Time Response



- Detector converts gammas to light for fast PMT
- Can change what energy of gammas are seen by changing gas pressure, which changes Cherenkov threshold
- High temporal response (~20 ps resolution)

Graphics courtesy of Hans Hermmann and Yongho Kim

GCD can isolate the carbon gamma signal by changing gas pressure to change Cherenkov threshold

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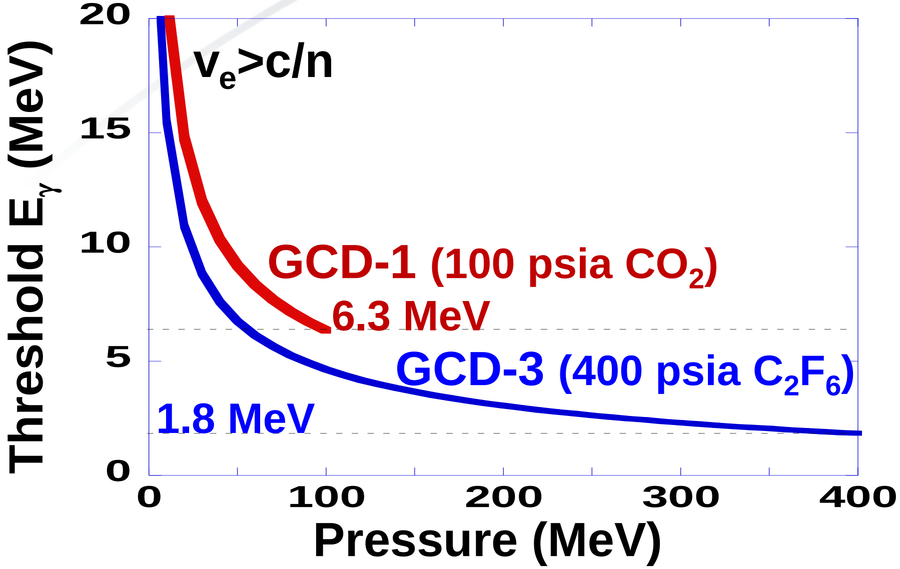
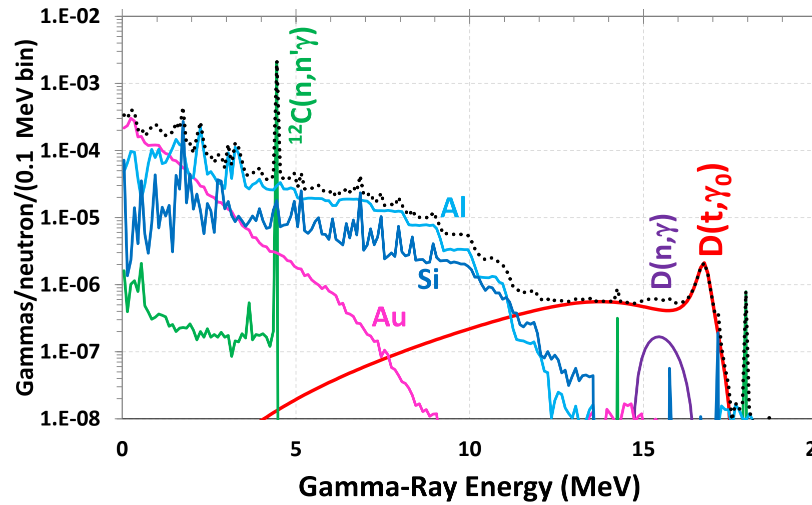
Variable Energy Thresholding



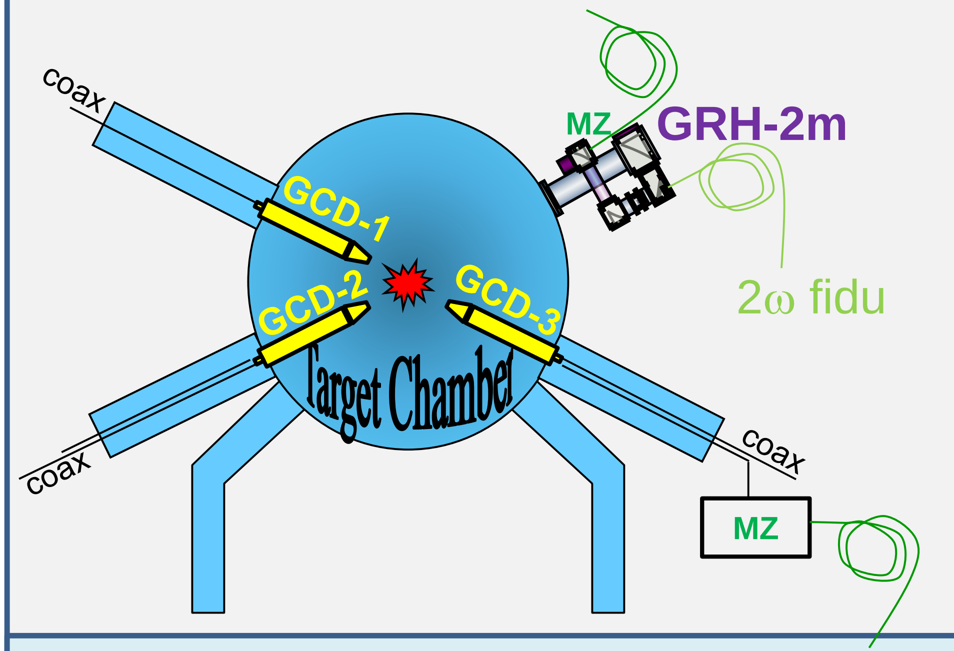


- Changing gas pressure allows one to select a lower cutoff of gamma spectrum
- Can select for fusion gammas (DT, TT, HT, possibly DD)
- Can observe neutron inelastic scattered gammas (**Carbon**, Oxygen and high Z)
- **Used measure carbon signal to measure shell ρR**

Graphics courtesy of Hans Hermmann and Yongho Kim

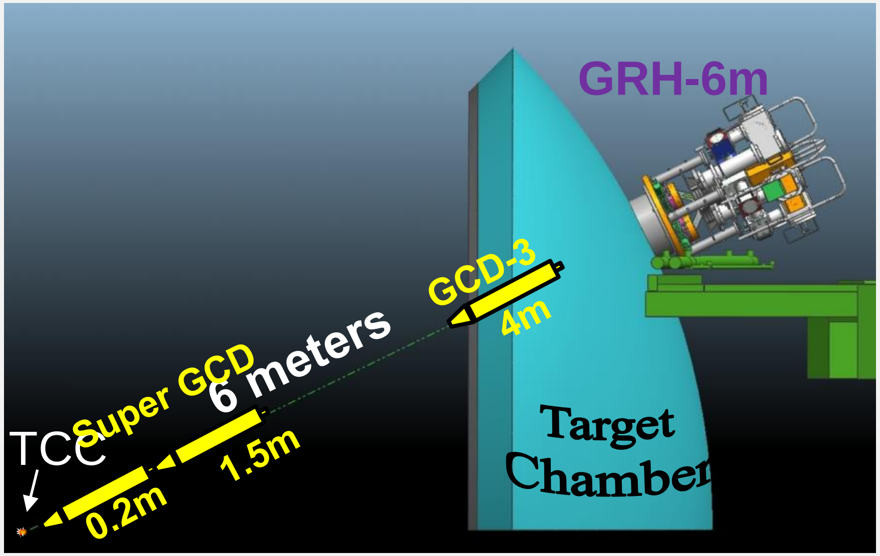
Gas Cherenkov Detectors have been in operations at OMEGA & NIF for many years

OMEGA-60



3 GCDs (20cm), 1 GRH (187cm)

NIF



4 GRHs (607 cm), 1 GRH (400 cm)

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Ran preliminary Helios simulations, calibrated to other experiments, to see if there is viable signal

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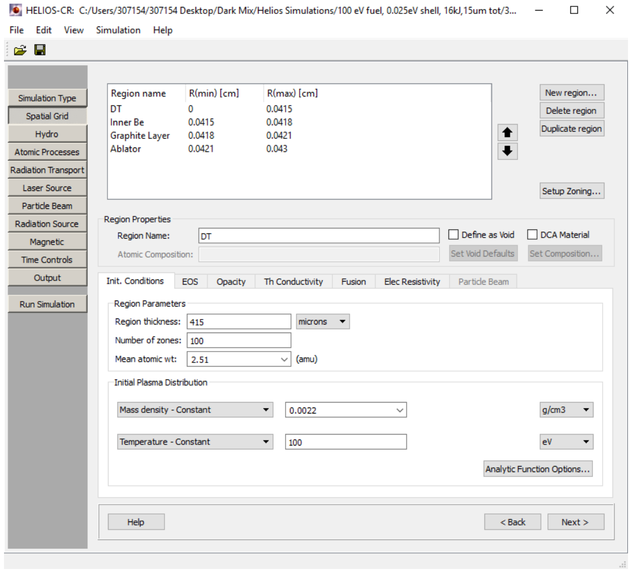
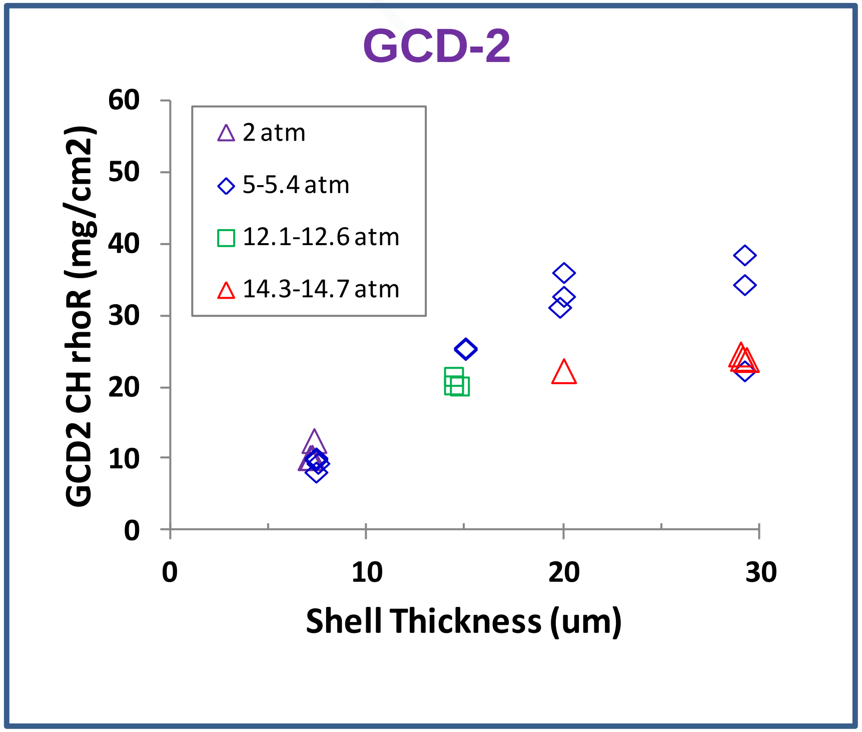
- Estimated trend of ρR vs recession depth of carbon through Helios simulations
- Helios is a lagrangian 1D hydrodynamic code
  - Often used as a first estimate before doing more intensive simulations (RAGE, Hydra)
- **Helios is not predictive, but calibrated to other experiments can help predict trends**
  - Ran Helios for beryllium capsules with carbon layers, output carbon $\rho\Delta R$
- Want to check whether the $\rho\Delta R$ is high enough for enough to be measured and have a 1D comparison

PRISM
Computational Sciences, Inc.



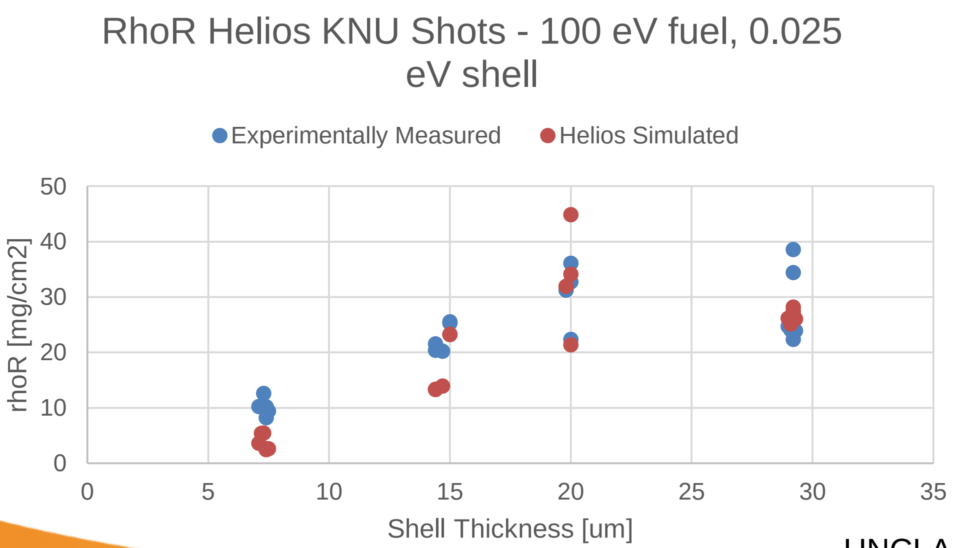
KNU shots in 2013 measured carbon ρR for various capsule conditions – used to set shell and fuel preheat in Helios

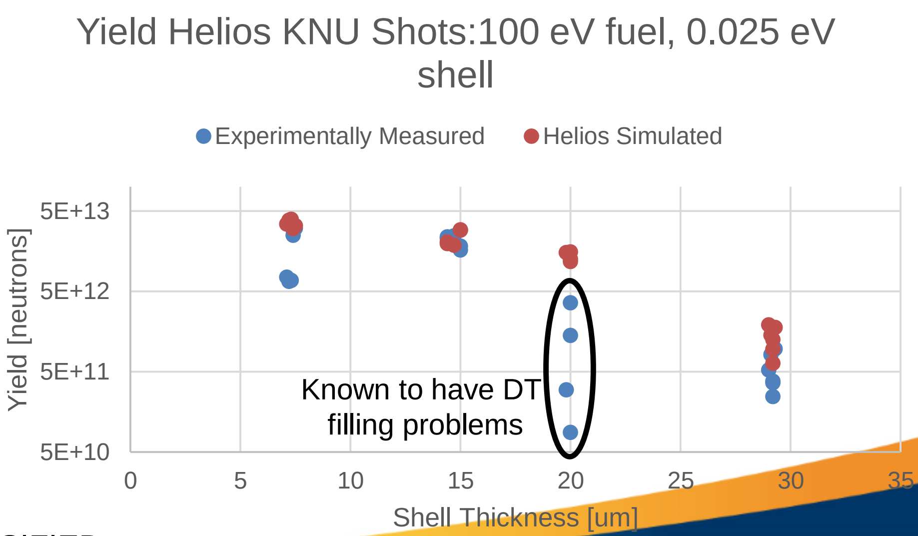
- Preheat is often set artificially higher in Helios to decrease amount of convergence to be more inline with experiments
- KNU shots were experiments that measured the diffusion scale length (Knudesen number)
  - **Provides carbon $\rho\Delta R$ database**
- Used shot database and measured $\rho\Delta R$ to tune preheat on simulation
  - With agreement, those preheat conditions then used to simulated Dark Mix capsules



Preheat settings found to approximately match $\rho\Delta R_C$ of previous KNU experiments

- Reasonable preheat settings found to be 100 eV in fuel (decreasing compression) and 0.025 eV in shell (increasing ρR)
  - Unrealistic preheat, just used as scaling factor to ballpark $\rho\Delta R_C$
- Approximately matches KNU shots





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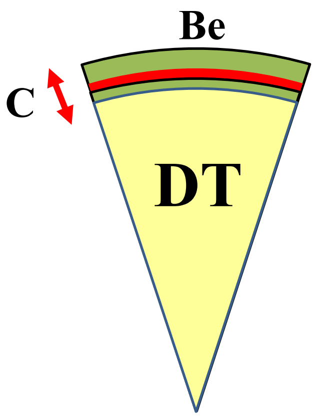
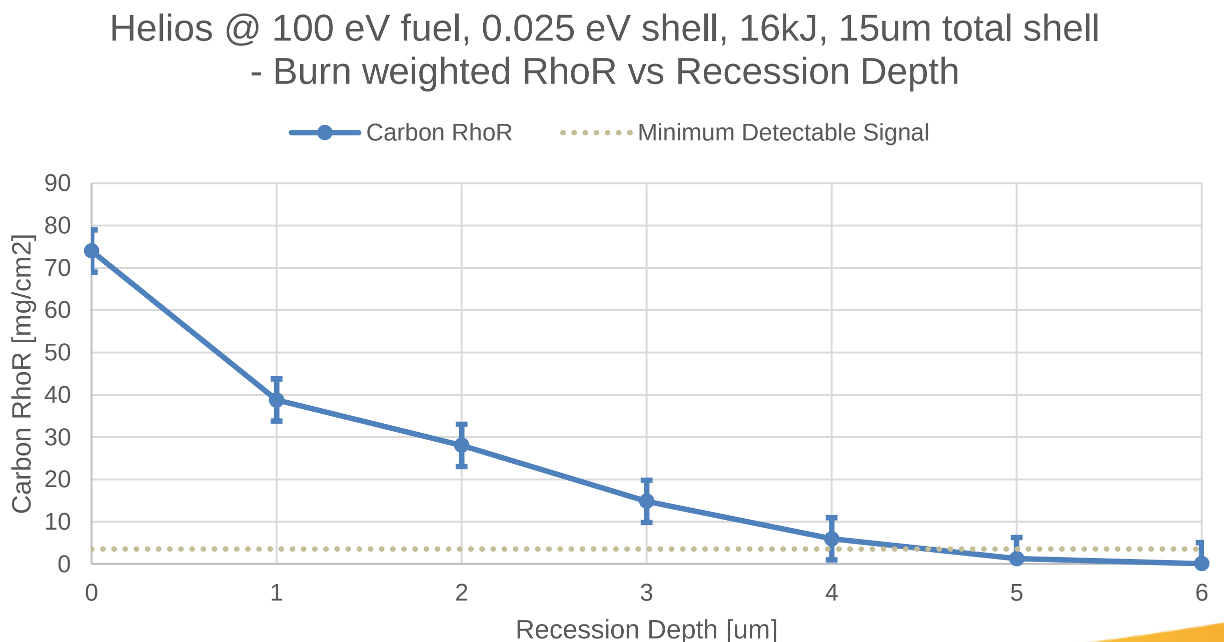
Preliminary Helios simulations suggest viable signal for various carbon recession depths

- Helios simulation using calibrated preheat condition
- 415μm, 10 atm DT fuel with 15μm total shell, 3μm carbon layer recessed, 16kJ total absorbed laser energy in 1ns pulse
- Provides baseline 1D expected $\rho\Delta R$
  - Deviation from 1D would be potential mix measurement





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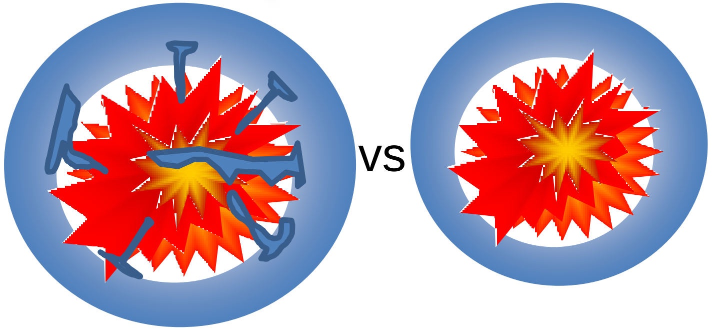
Next step is more sophisticated simulations with RAGE to compare with and without mix parameters

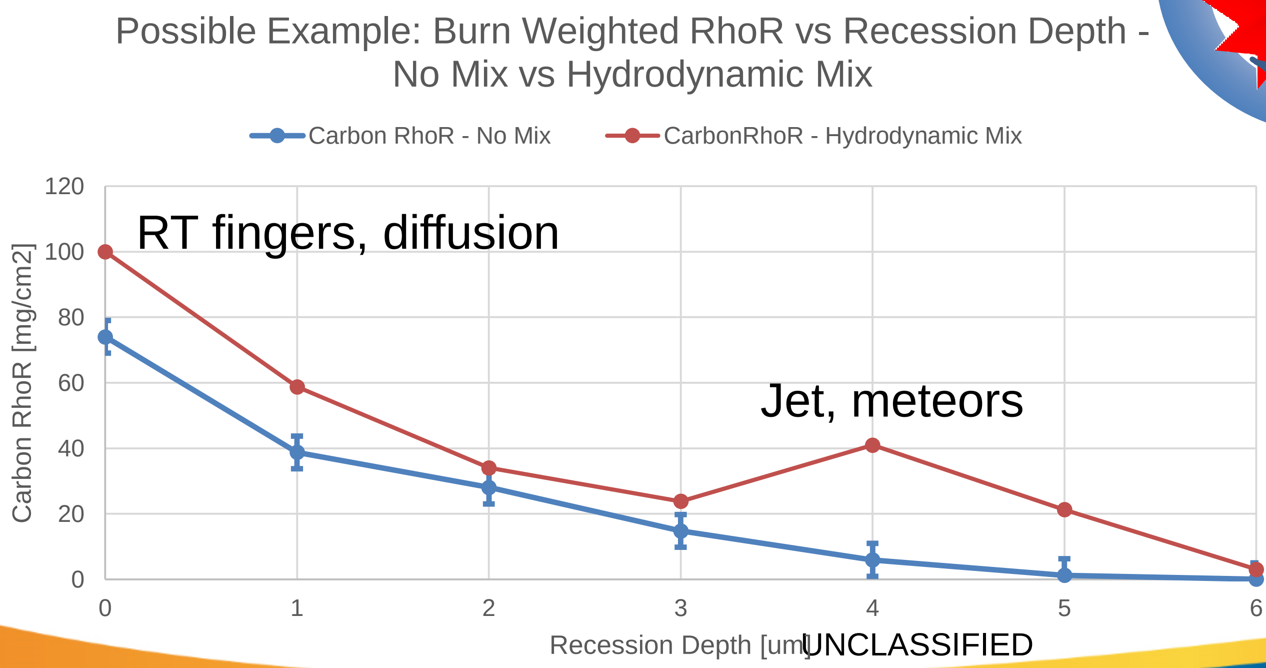
- Post-processing mix models can be applied to Helios to approximate change in $\rho\Delta R$ with and without mixture
- RAGE is a Los Alamos Eulerian, 2D and 3D hydrodynamic code used for capsule design
  - RAGE has Besnard–Harlow–Rauenzahn (BHR) hydrodynamic mix model
  - Capability to input fill tubes, stalks and tents and see their results
- In process of getting simulation support to have better $\rho\Delta R$ estimates and see deviation caused from different sources of mix
  - With and without initial perturbations, stalks, fill tubes, etc

Different types of mixes would have different effects on observed ρR

- Bulk material mixes:
  - Closer to center → higher $\rho \Delta R$
  - More compressed → higher $\rho \Delta R$
- Mixture could make the $\rho \Delta R$ arrive sooner

What observed or simulated data may possibly look like:





Goal would be to investigate different types of mixes and what their effect on observed carbon signal and timing compared to other mixture measuring types

Type of Mixture	Possible observed difference compared to no mix case	Differences in other mix measurements
Hydrodynamic Bulk Mix (RT, RM, KH) near fuel	• Higher ρR in close layers • Broader signal width • Later time arrival to bangtime	• Higher separated reactants signal and x-ray signature in close layers • Separated reactants arrive later than bangtime
Highly diffusion dominated capsule	• Higher ρR in closest layer only • Broader signal width • Earlier time arrival to bangtime	• Higher separated reactants signal and x-ray signature in closest layers only • Separated reactants arrive earlier than bangtime
Meteors and jets from stalks, fill tubes, tents	• Higher ρR in far layers • Broader signal width	• Lower separated reactants signal and x-ray signature

Simulations needed to quantify and separate observed effects

Challenges: Dark Mix measurements may not be distinct enough from each other – results have a large dependence on simulation for interpretation

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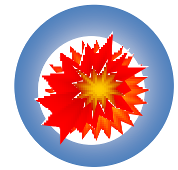
- Question on whether the mixed condition can be differentiated from the non-mixed condition
  - Is $\rho\Delta R_C$ of  different enough from 
  - Could possibly seed higher perturbations to get more mix
  - Could possibly thicken/shrink carbon layer
- Interpretation of results has heavy reliance on simulation support
  - Can do estimates through analytical scaling arguments
  - Could act as simulation benchmark
  - Have both timing information as well as $\rho\Delta R$
  - Can also compare with x-ray hot mix and radiography
- **Lots of physics goes into the detangling of the measurement – reasons for possible null result is still interesting**

Outline

1. Intro to Inertial Confinement Fusion
2. Types of Mixture in ICF capsules
3. Previous mixture experiments
4. Dark Mix Concept
5. Measuring Dark Mix with Gamma Cherenkov Detector
6. **Dissertation Outline**

If Dark Mix is viable, could be valuable tool to learn more about mix

Measurement Type	Pros	Cons
X-ray dopants	• Easy to add to experiments • Similar capsule experiments give relative mixture comparison	• **Dopants need to be heated to keV temperatures** • Need temperature, density and spectroscopic model to get absolute values • Assumption that dopant moves with ablator
Separated reactants	• Measuring yield gives integrated value of mixture	• **Reactants need to be heated to keV temperatures** • Reactants need to be atomized • Gives low yield, can't simply add to any experiment
Dark Mix	• **Measures layer of ablator, independent of temperature or atomization**	• Dependent on mixture model for interpretation • Needs beryllium capsule • *Unsure if measurements distinct enough*

Proposed work will determine feasibility of measuring dark mix

Steps and Goals of Dissertation

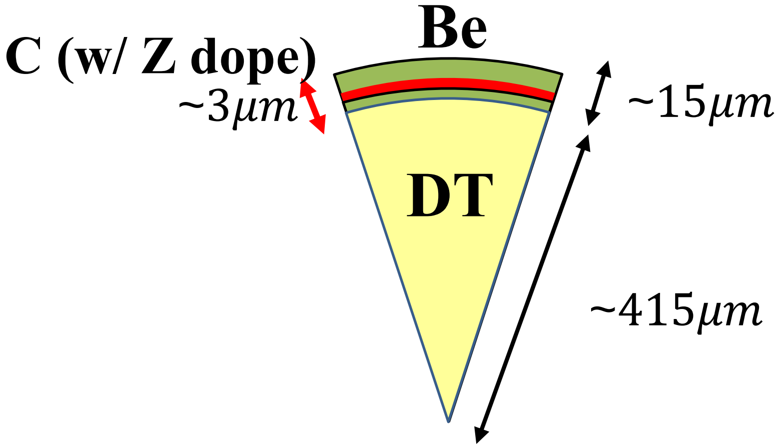
1. Theory and Background: Use existing NIF and OMEGA data to investigate gamma signals and their effect on mix
   – Use Gamma bangtime vs X-ray bangtime to develop a model and understand differences due to mixture
2. Designing: Developing a target design that will maximize the ability to measure dark mix on OMEGA
   1. Run simulations to optimize prospect of measuring dark mix on OMEGA
   2. Work with General Atomics to develop the new test capsules
   3. Plan and set up diagnostic configuration
3. Executate Exeriment: Prepare setup and excute experiment(s) at OMEGA
   1. Set up VISRAD design
   2. Laser set up and parameters
   3. Diagnoitic set up
4. Analysis: Develop tools to untangle detains to back out dark mix

Problems with gamma bangtime solved, now accurate values can be used to investigate physics in comparison to x-ray timing

- Gamma bangtime on NIF shots hadn't been reported since 2015 because of cross timing error
  - Developed deconvolution routine in order to isolate timing errors in older deconvolution
  - Found and corrected timing errors, gamma bangtimes are now regularly reported
- Data sets now exist for a comparison between X-ray bangtime and gamma bangtime
  - Gammas come from fusion, X-ray can come from other atoms
  - Earlier or later X-ray bangtime suggest some type of mixing of other atoms
- Will investigate and develop model

OMEGA shot day next August – have plan in place for experiment

- OMEGA shot day scheduled for August 16th, 2018
- Working to fabricate capsules – analogous to beryllium NIF capsules with carbon layers
  - Plan to dope carbon with high Z
- Plan to set up X-ray cameras to observe X-ray radiography hot mix to compare to observed gamma $\rho\Delta R_C$ dark mix
- Scheduled to move GCD3 from NIF to OMEGA for shot



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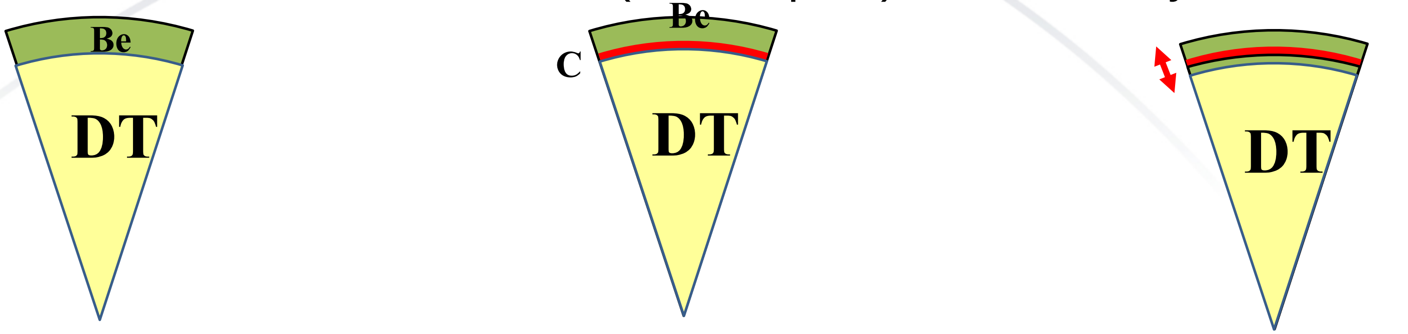
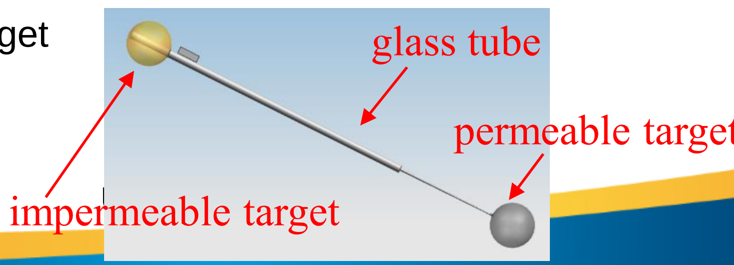
Taking steps to fabricate Dark Mix capsules for shot day

Baseline | Be/C(w/ Z dopant) | Vary recession

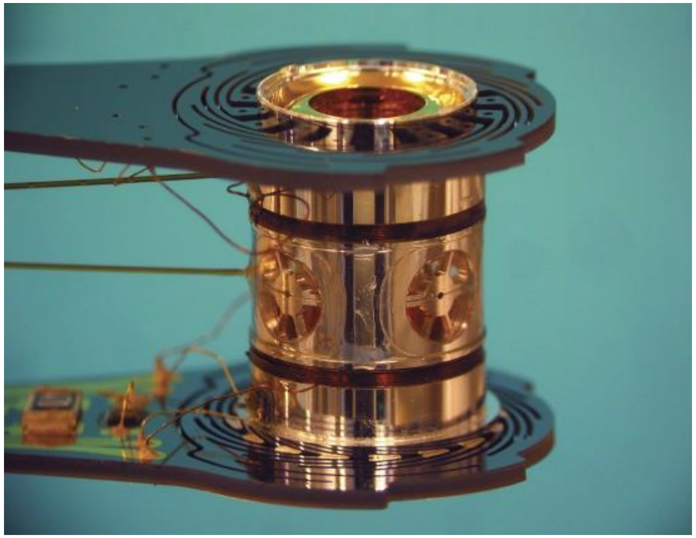


- In discussion with General Atomics to fabricate capsules
- Plan for ~415μm inner radius, 10 atm DT fuel with ~15μm total shell, ~3μm carbon layer graphite, density matched to Be, layer
- Difficultly in creating such a thin layer of carbon along with Beryillium
  - Don’t yet know how much control over graphite density matching
- Complexity in DT filling, beryllium is non permeable to diffusion fill
  - GA currently testing drilling a hole, plugging with carbon, filling with DT
    - Could also do a dumbbell target



Dark Mix, if viable, could be valuable tool on NIF

- Beryllium campaign on NIF is very interested in having a measure of ablator mix that isn't heated to high temperature
- Dedicated shots could be done to investigate amount of hot mix vs dark mix to better understand implosions
- Not planning to be part of thesis – too far out



Closeup of Gold hohlraum, Lawrence Livermore National Lab

Currently working on other projects that could be used as a project back-up if Dark Mix doesn't move forward

- Problems could occur (shot day lost, capsules unable to be fabricated before shot day) that would cause major setback
  - If measurements, even null measurements are made, a lot is still to be gained and learned
    - Depending on reason for null shot, taking to NIF may still be valuable
- Currently doing shot analysis of GRH data for NIF shots, is being used to investigate physics
- Part of aerogel Cherenkov detectors for Enhanced Capability Subcritical Experiments (ECSE) campaign, could possibly be turned into a more substantive project
- Other projects and investigations come and go and focus could be shifted if needed
  - Time-resolved ion temperature

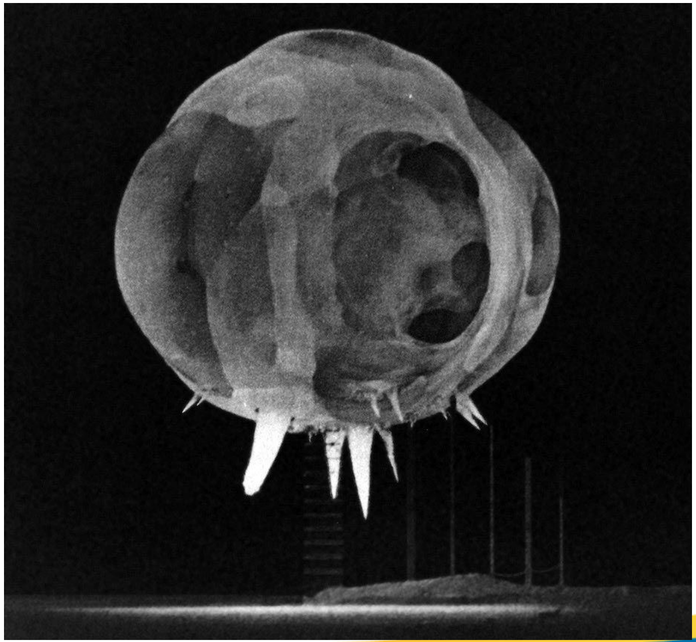
Steps and Goals of Dissertation

1. Use NIF and OMEGA gamma data to investigate gamma signals and their effect on mix
   – Gamma bangtime vs X-ray bangtime
2. Use simulation tools to understand ICF capsule dynamics to design optimal dark mix capsules
   – Be able to approximate the expected difference in signal from different types and magnitudes of sources of mix
3. Set up and execute experiment(s) at OMEGA
4. Handle data analysis converting GCD voltages to $\rho\Delta R$ and absolute timings as well as analyzing x-ray information to infer mix
5. Use results to make quantitative statements about the total shell material in and near the fuel vs the observed shell in the hot spots

Backup Slides

Engineering Fusion

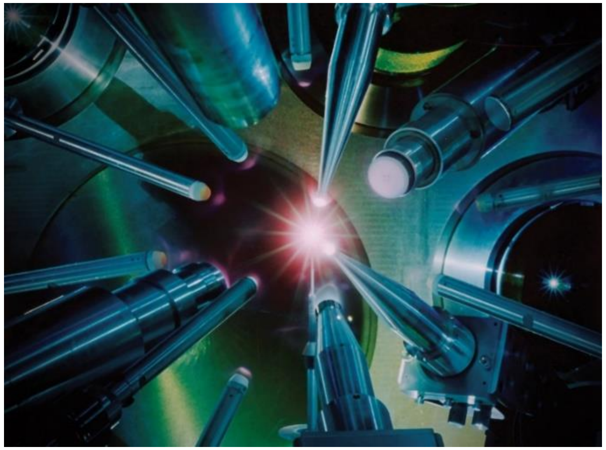
- Fusion burn of fuel happens on time scales of picoseconds
  - $$\frac{Length\ of\ Nuclear\ Fuel}{Speed\ of\ 14\ MeV\ neutron} \approx \frac{1.4mm}{0.17c} \approx 30ps$$
- Object exploding occurs on time scales of nanoseconds
  - $$\frac{Length\ of\ Capsule}{Sound\ speed\ of\ Capsule} \approx \frac{1.5mm}{\sqrt{\frac{10\ keV}{m_{DT}}}} = \frac{1.5mm}{0.002c} \approx 3\ ns$$
- Can do fusion before object is blown apart



Nuclear detonation microseconds after explosion, Lawrence Livermore National Lab

Inertial Confinement Fusion can achieve high gains through alpha heating

- If enough fuel is heated enough to undergo fusion and emit α particles, a chain reaction can occur
  - Range of 3.5 MeV alpha is about $\rho r_{\alpha\, range} = 0.3 \frac{g}{cm^2}$ (10% of fuel)
  - Heat up 10% of fuel → all of fuel can burn
- Energy yield from DT burn:
  - $\mathrm{Y} = \phi_{Burn\ Fraction} \frac{14.1\ MeV * m_{fuel}}{m_{DT}} \approx 535\ MJ$
    - for $\phi = 0.3$ and $m_{fuel} = 3\ mg$
- Internal energy of a compressed polytropic gas
  - $U = \frac{P}{(\gamma-1)\rho}(0.1 * m_{fuel}) = \frac{2k_B T}{m_{DT}(\gamma-1)}(0.1 * m_{fuel}) \approx 0.2\ MJ$
    - for $\gamma = \frac{5}{3}$, $m_{fuel} = 3\ mg$ and $k_B T = 5\ keV$
  - Gain around 2500!
    - Have to fight with hell to internal energy (~10%)
    - Laser to shell (~50%)
    - Wall plug to laser (~10%)
    - Neutrons to useful energy (~10%)



OMEGA Laser, University of Rochester, Laboratory of Laser Energetics

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Three instabilities are major Rayleigh Taylor

- Type of hydrodynamic mixture
- Instability that transforms directed force into dispersive energy
- Occurs when a heavier density is accelerated into a lighter density
  - Creates fingers and bubbles
- Linear analysis gives growth rate of fingers/bubbles
  - $h_{linear}(t) = Ce^{\sqrt{\frac{\rho_H-\rho_l}{\rho_H+\rho_l}*a*k*t}}$
- Once the instability saturates, the atomized region grows quadratically in time
  - $h_{nonlinear}(t) \sim k\frac{\rho_H-\rho_l}{\rho_H+\rho_l}a*t^2$

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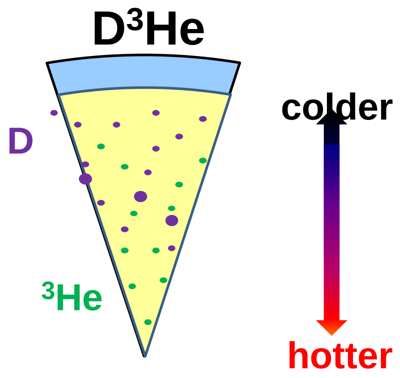
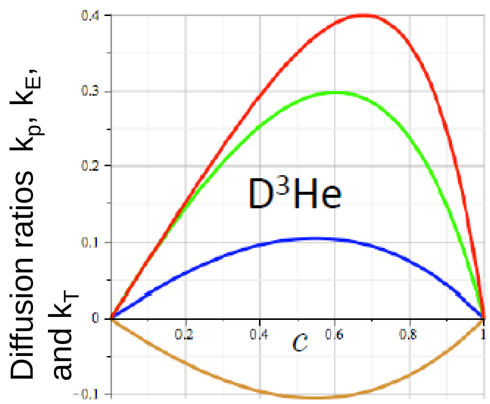
Duffell, "Rayleigh-Taylor Instability in a Relativistic Fireball on a Moving Computational Grid" *Astrophysics 2013*

Turbulence and diffusion atomically mix nearby fuel and shell

- Included under kinetic effects
- Inner most layer of shell can diffuse into the fuel and the hot spot
  - Hasn't been, until recently, studied in detail
    - Thought to be minor compared to hydrodynamic mix
- For warm OMEGA shots, heavier fuel species can move to center, lighter will be pushed outwards [3]
  - Cause Yield Anomalies
  - $F = -\rho D\left(\nabla c + k_P \nabla \log P + \frac{e\,k_E}{T}\nabla\Phi + k_T \nabla \log T_I + k_T \nabla \log T_e\right)$[4]





[3] Casey,et al, "Evidence for Stratification of Dueterium-Trituium Fuel in Inertial Confinement Fusion Implosions" Physical Review 2012
[4] Kagan, Tang "Electro-diffusion in a plasma with two ion species' Physics of Plasmas 2012

Causes of mix: Diffusive

- Suggestion that under certain conditions, the inner most layer of shell can quickly diffuse into the fuel
- Observed in recent OMEGA experiments[5]
  - Hydrodynamic mix models from simulations fail to match experiment
  - Diffusion model does match
- Future experiments to investigate diffusion layer

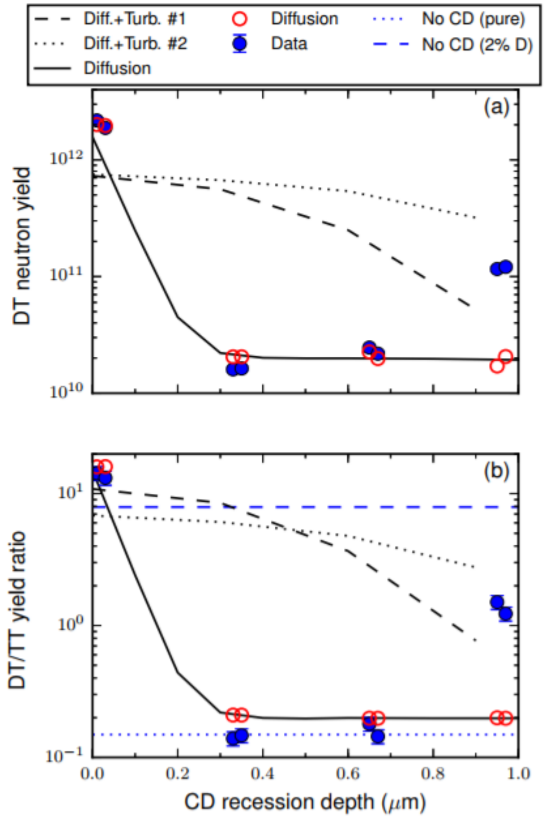


FIG. 3: Nuclear data versus CD recession: DT neutron yield (a), and DT/TT yield ratio (b). Model curves are shown by the black curves. In (b), the blue horizontal dashed and dotted lines represent values from 2% D in the gas or contamination D. Red circles are individual shots simulated with the diffusion-only model.

[5] Zylstra,et al, *"*Diffusion-dominated mixing in moderate convergence implosions*" Still in draft, to be submitted*