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Title: Material for Point Design (final summary of DIME material)

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LA-UR-14-

Material for Point Design
(final summary of DIME material)

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(with contributions from many others)

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Contributors to this project

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  - R. Wallace, S. Bhandarkar, NIF operations crew
- Omega
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- General Atomics
  - P. Fitzsimmons, M. Hoppe, A. Nikroo
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- MIT
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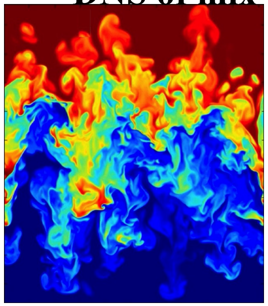
ABSTRACT

These slides summarize the motivation of the Defect Induced Mix Experiment (DIME) project, the "point design" of the Polar Direct Drive (PDD) version of the NIF separated reactant capsule, the experimental requirements, technical achievements, and some useful backup material. These slides are intended to provide much basic material in one convenient location and will hopefully be of some use for subsequent experimental projects.

Our goal is to constrain mix/burn models with DIME

DNS of mix



Livescu, JoP, Conf. Ser. 318, 082007, 2011

- Computer codes do not have validated subgrid mix and burn models
- Present models of mix/burn interaction are overly simplistic
- Important to know if mix is "atomic" or "chunky"
  - Chunky implies mean free path of particles (D and T) are shorter than size of "blob" and they do not necessarily "see" each other
  - Atomic implies D's and T's homogeneous in a cell
- This affects ignition campaign at NIF and other areas
- The challenge is how to get enough data to determine "chunkiness"?

- To do this, we need to constrain N_D, N_T, and T_{ion} as a function of position and time
- This leads us to a separated reactant capsule design with dopant within D_2 fuel and T_2 gas
- Number of DT reactions depends on mix
- Spatially resolved spectra gives us T_{elec} that we can related to T_{ion} and we have burn average T_{ion} constraint

We use the RAGE code for this work

- RAGE (Radiative Adaptive Grid Eulerian) is a radiation hydrodynamic fluid code being adapted for laser HED applications (M. Gittings et al. Computational Science and Discovery, **1**, 015005 (2008))
- Do not have lasers, but being put in
- We use multigroup diffusion in an energy source in the outer layer of the capsule
- We tune source width and energy to match bang time and about 65% of incident laser energy (E.S. Dodd et al. Phys. Plasmas, **19**, 042703 (2012))
- We have BHR mix model for subgrid turbulent mix (A. Banerjee, R.A. Gore, and M.J. Andrews, Phys. Rev. E, **82**, 046309, (2010))
- Plan is to match 1) hydro, 2) spectra, 3) yield and bang time

BHR is a RANS subgrid turbulence model

- We have BHR (Besnard, Harlow, Rauenzahn) mix model for subgrid turbulent mix (Schwarzkopf et al. Jour. Turbulence, 12, 1, 2013; A. Banerjee, R.A. Gore, and M.J. Andrews, Phys. Rev. E, **82**, 046309, (2010); Stalsberg-Zarling and Gore, memo LA-11-04773, unpub)
- It is a single-fluid (multi-species) Reynolds Averaged Navier-Stokes (RANS) model that has two initial conditions to set
- The scale (can be thought of as amplitude of most unstable mode),
  - we set to 50 nm (look at 25 and 100 nm)
  - based on metrology of Omega capsules
- The initial turbulent specific kinetic energy (cm^2/s^2)
  - Use less than 1% of total specific kinetic energy to avoid perturbing flow
  - For BHR-2, we use 10^{11} cm^2/s^2 (0.1% of total specific KE)
  - For BHR-3, we use 5×10^5 cm^2/s^2 (<<0.1% of total specific KE)

The burn requirements are driven by PDF burn model

- The Probability Density Function (PDF) burn model has both temperature and mix sensitivity

$$\overline{\frac{dN_{DT}}{dt}} = c_D\, c_T \left(\frac{A_v^2}{A_D A_T}\right)\left(\int_0^1 \left(cP(c)\rho(c) - c^2 P(c)\rho(c)\right) dc\right)\langle\sigma v\rangle$$

- The $<\sigma\upsilon>$ term is sensitive to temperature, the rest is sensitive to mix
- The burn rate is sensitive to temperature (see NRL Plasma Formulary P.45)

$$\langle\sigma v\rangle_{DT} = 3.68x10^{-12}T^{-2/3}exp^{[-19.94T^{-1/3}]}$$

- We co-locate dopant material in CD layer to know the D concentration
- Use DT and TT yield, along with neutron images to infer T concentration
- We can infer burn volume from neutron images
- We need T_{ion}, which we infer from the T_e distribution obtained from MMI images
- With T_{ion} known, we can determine $<\sigma\upsilon>$ (this term dominates sensitivity)
- The burn rate term has the most effect on the yield

We use the following "data" in our example to constrain the chunk/atomic fraction

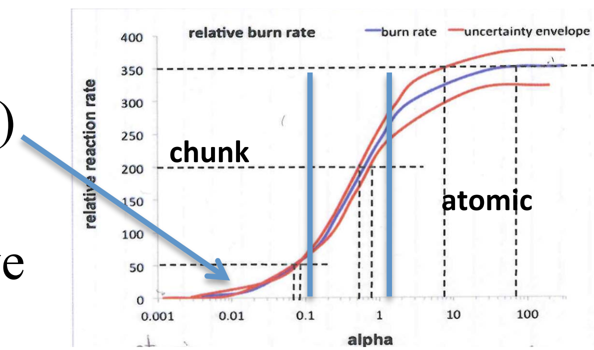
- Assume we know DT, TT, and DD yields to within 10% (yields are DT=2.1±0.2x10^{13}; TT=3.0±0.3x10^{13}; DD=1.5±0.2x10^{10})
- Assume x-ray burn width known to 20 ps (use 700±20 ps) (note: bang time of 4.2±0.1 ns is not used)
- Assume we know DT burn averaged T_{ion} to within 0.3 keV (3.3±0.3 keV)
- Assume a DT neutron image that is a 110±2 μm radius spot and a a TT neutron image that is a 95±2 μm radius spot (assume DT burning ring 15±2 μm wide outside the "hot spot"; need MMI to confirm)
- Assume an MMI map that is a 60 μm wide ring with an inner radius of 100 μm (for now, assume 2 keV mean T_e with a variation of 100 or 200 eV; not used here)

The uncertainties on N_D, N_T, and burn region are small enough to provide a meaningful chunk/atomic fraction constraint

- Time-integrated version of burn rate equation is:

$$\overline{N_{DT}} = N_D\, N_T \left(\frac{1}{Vol}\right)\left(\int_0^1 (c\,P(c)\rho(c) - c^2\,P(c)\rho(c)dc)\right)\langle\sigma v\rangle(burn)$$

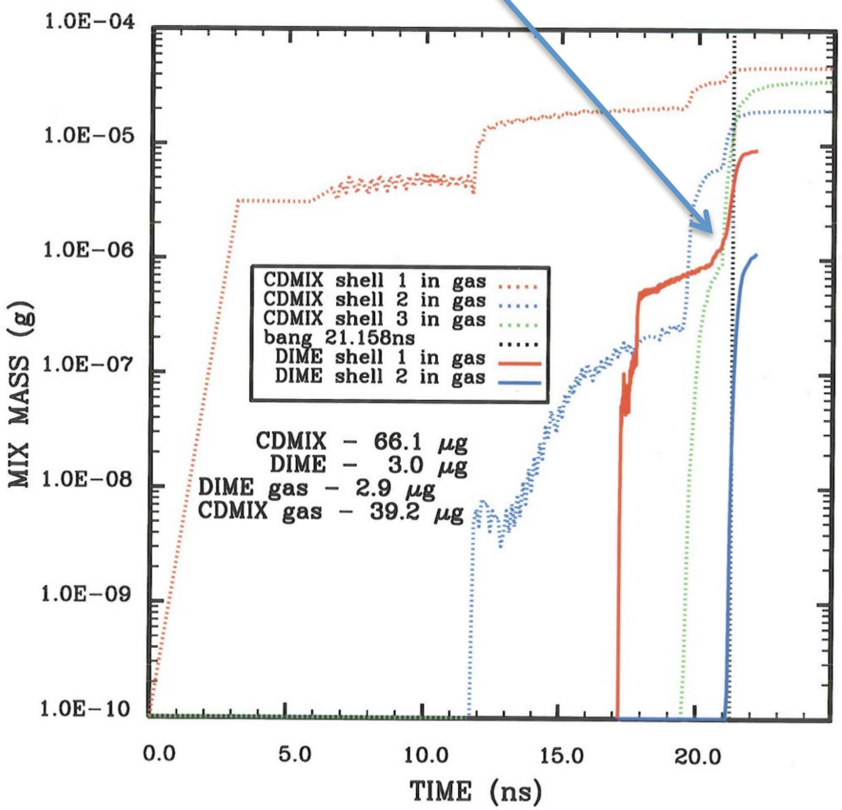
- We need to solve for the integral term ("mixedness" parameter)
- A plot of this term shows a variation from chunk (left) to atomic (right)
- To distinguish between chunk/intermediate/atomic, we need to know the integral term within ~33%
- We use the experimental values from the previous slide to determine N_D, N_T, and the burn region
- Solving for the "mixedness", we find a mix fraction of 0.035(+0.012/-0.0083) for a +34%/-23% uncertainty
- This falls within the ~33% uncertainty requirement



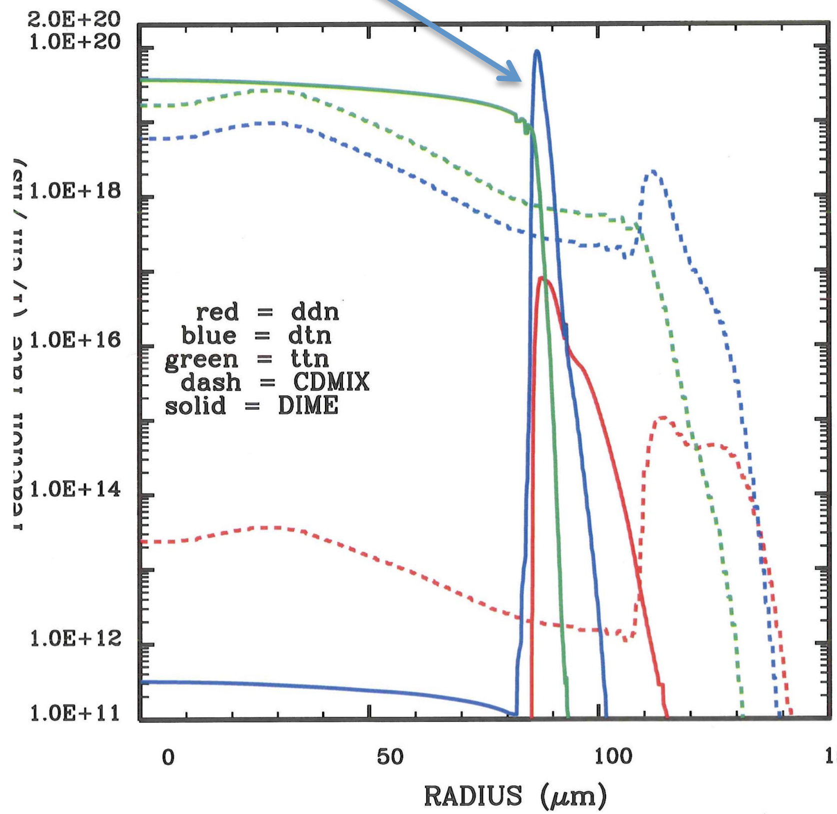
This example comes from an "atomic" simulation

The simple pulse shape of the DIME capsule leads to less mix and narrower burn region than CDMIX

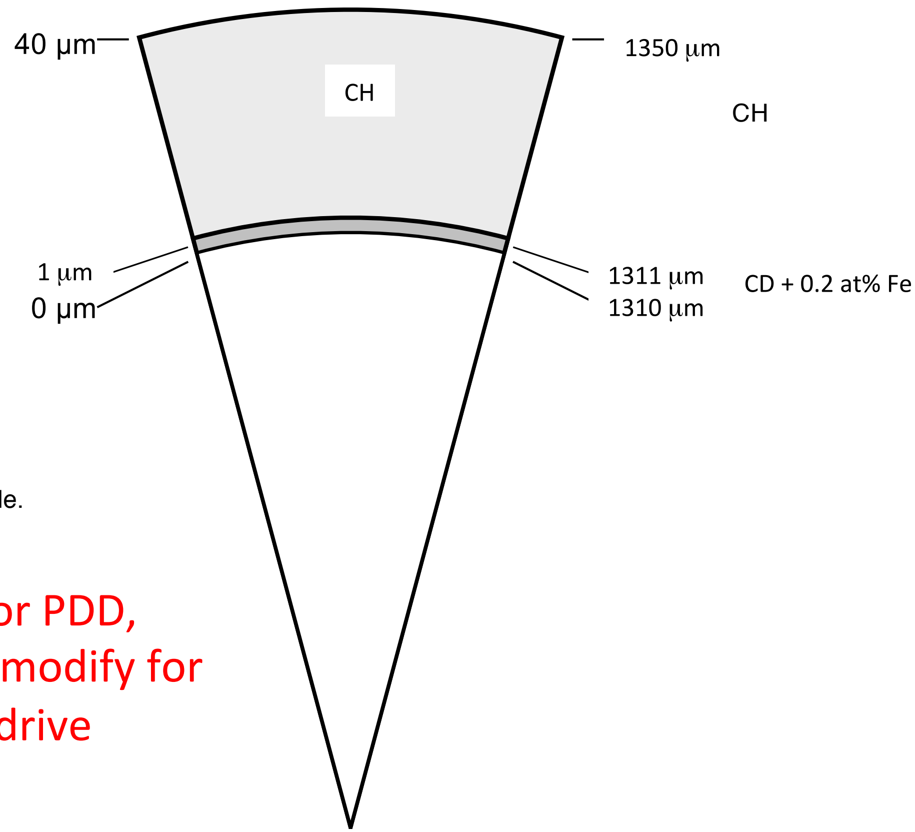
About 20% of shell mixes into gas of DIME capsule



A lack of feedthrough mix leads to narrow burn region



The DIME separated reactant capsule has a simple design



Not to scale.

Design for PDD,
Need to modify for
Indirect drive

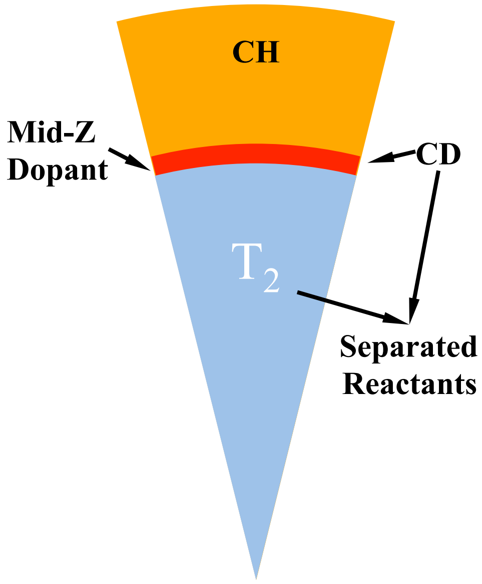
Outer Radius:	1350 ± 50 µm
Total Thickness:	40 ± 2 µm
CD layer thickness:	1.0 ± 0.3 µm
CD layer dopant:	Iron
Dopant concentration:	0.2 ± 0.1% at
Flash coating material:	Al
Flash coating thickness:	0.10 ± 0.05 µm

Drive Energy	510 kJ
Drive pulse	2.15 ns "square"

Fill gas:	Tritium
Gas purity:	<1% D by atom
Fill pressure:	4 atm
Temperature at shot time:	20 ± 5° C

The DIME capsule is physically relevant

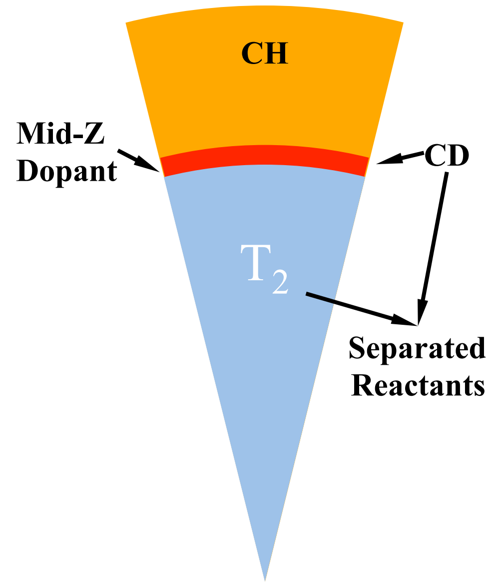
- The Reynolds number of the mix region is 1 to 2×10^5 during the implosion
- The turbulence time scale is about 0.8 ns, compared to bang time of 3.5 to 4 ns (turbulence is fully developed)
- Most of the yield comes from recompression, so we are not an “exploding pusher”
- The Knudsen number is ~0.01, so ion loss effects are <30%
- The triton mean free path is a few microns near the mix region
  - Our implosion is not “kinetic”
  - Fluid model for turbulence is relevant

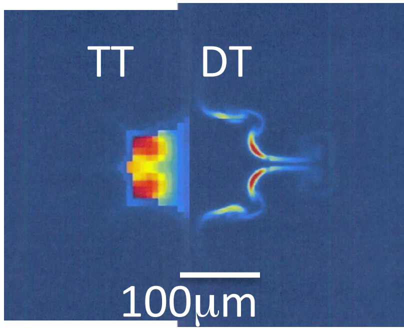


The predicted performance of the DIME capsule will meet our goals

- The predicted DT yield is 2.1×10^{13}; TT yield is 3×10^{13}; the DD yield is 1.5×10^{10} (uncertainty is ±50%)
- The DD T_{ion} value is 2.5±0.5 keV and the DT T_{ion} is 3.3±0.5 keV
- The bang time is 4.2±0.2 ns (CR~11)
- The time and space averaged T_e is 2.3±0.2 keV

- These yields and T_{ion} values are comparable to that of MIXCAP, which has neutron images
- Our ability to predict spectral response of Ge and Cu for several shots gives us confidence in predicting Fe emission spectra





We computed an error budget based on known uncertainties

- BHR parameters – reasonable changes are 30% change in yield
- Laser drive – 10% change is 22% change in yield
- Capsule thickness – 2 μm change is 20% change in yield
- Symmetry -- ±10% change in P_2/P_0 is ~10% change in yield
- Dopant concentration – 10% change in dopant is 4% change in yield
- Capsule size – 25 μm change is 1% change in yield
- Quadrature sum of above is ±44% change in yield (round to 50%)

- Yield changes less than 10% between 2 and 5 atm – we choose 4 atm
- Yield changes little for CD layers between 1 and 5 μm – choose thinner layer to minimize dopant perturbation

We have not yet demonstrated sensitivity to chunk fraction on burn

- Our previous experimental results show there is little “feedthrough” mix
- Therefore we can induce arbitrary amounts of “chunky” mix, either by roughening the inner or outer surface or by using an equatorial trench
- Simulations with equatorial grooves show only about 1% yield change when AMP changes from 0.2 to 0.8
- We need more sensitivity than this for a viable experiment
- We will continue to probe this as the code advances

We made extensive use of Omega for "proof of principle" before going to NIF

- We used MMI in three positions on Omega in symmetric drive to assess its utility (we also had streak spectra and neutron yields)
- We used polar direct drive shots with MMI to demonstrate that mix does not change significantly
- We involved U Nevada/Reno in fielding/analysis of MMI
- We conducted symmetry tuning shots on Omega to control P_2/P_0 and P_4/P_0 with pointing and pole/equator beam balance
- We conducted shots with multiple dopants to assess their utility
- The extra shots on Omega allow us to obtain some shot-to-shot statistics

- We used a combination of Hydra and RAGE to model these shots and have/are publishing papers on these results

We are using CD MIXCAP results to calibrate our DIME simulations

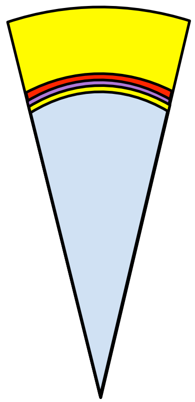
- Successful simulations of other NIF experiments provides confidence; set diagnostics correctly
- From other NIF experiments, know diagnostic requirements (diagnostics returned useful data)
- From NIC and MIXCAP, know neutron imaging requirements; designing capsule for this

- Quantifying mix mass for a different platform will help us understand origin of mix
- This will help guide experiment design to control mix

CDMIX and DIME capsules have different properties

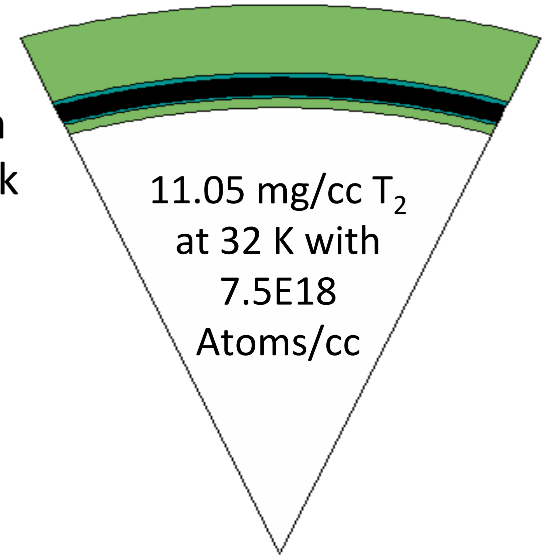
DIME uses 510 kJ 2.15 ns PDD pulse

OR 1350 μm
40 μm thick



CDMIX uses ~20 ns 1.4 MJ NIC ID pulse

OR 1140 μm
210 μm thick



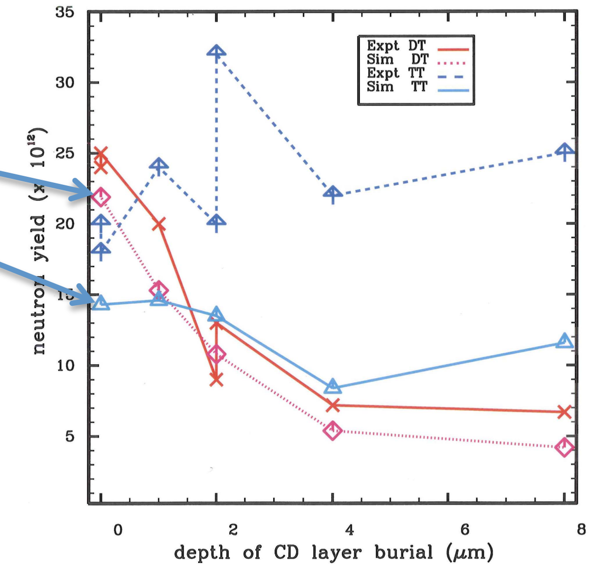
- Single shock drive simple to model and produces less mix
- Simulations show 3 to 6μg of CD layer mixes into the gas
- Mix depth ≤1 μm
- Simulations suggest DT burn will be in a narrow ring
- Predict DT and TT yields around 2×10^{13}

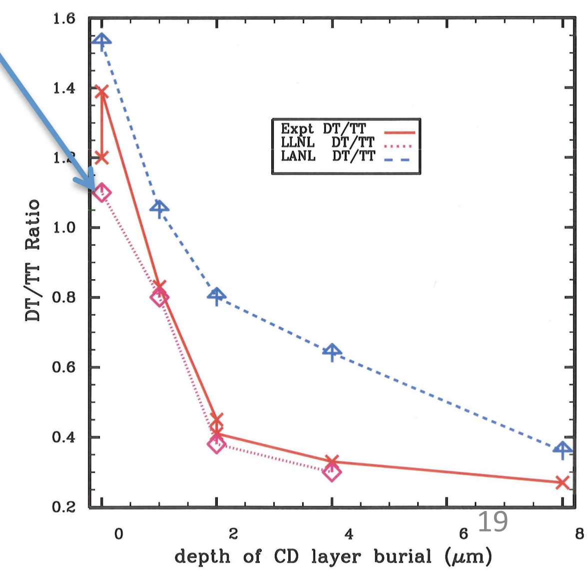
- Multiple shock drive harder to model and has more mix
- Simulations show 44μg of CD layer mixes into the gas
- Mix depth ~2 μm
- Simulations and data show nearly homogeneous DT burn region slightly large than TT burn region
- DT and TT yields ~2×10^{13}

Our ability to model CD MIXCAP adds confidence to our separated reactant capsule predictions

- Our simulations (pink line) match the trend of MIXCAP DT yields nicely and yields within 20% (red line)
- Our simulations noticeably under-predict the TT yield (factor of 1.85)
- LLNL uses the ratio of DT/TT yield is a mix diagnostic, where higher values indicate more mix
- We (blue line) replicate the same trend as LLNL (pink line) and the data
- Our predicted drop in DT/TT is not as steep as LLNL tuned model or data (however, LLNL uses surface imperfections and a mix model)
- We did not tune our model to match MIXCAP data, we use standard mix settings from Omega and NIF DIME capsules (but no surface roughness)
- We and LLNL match the burn Tion to within 0.4 keV (not shown)

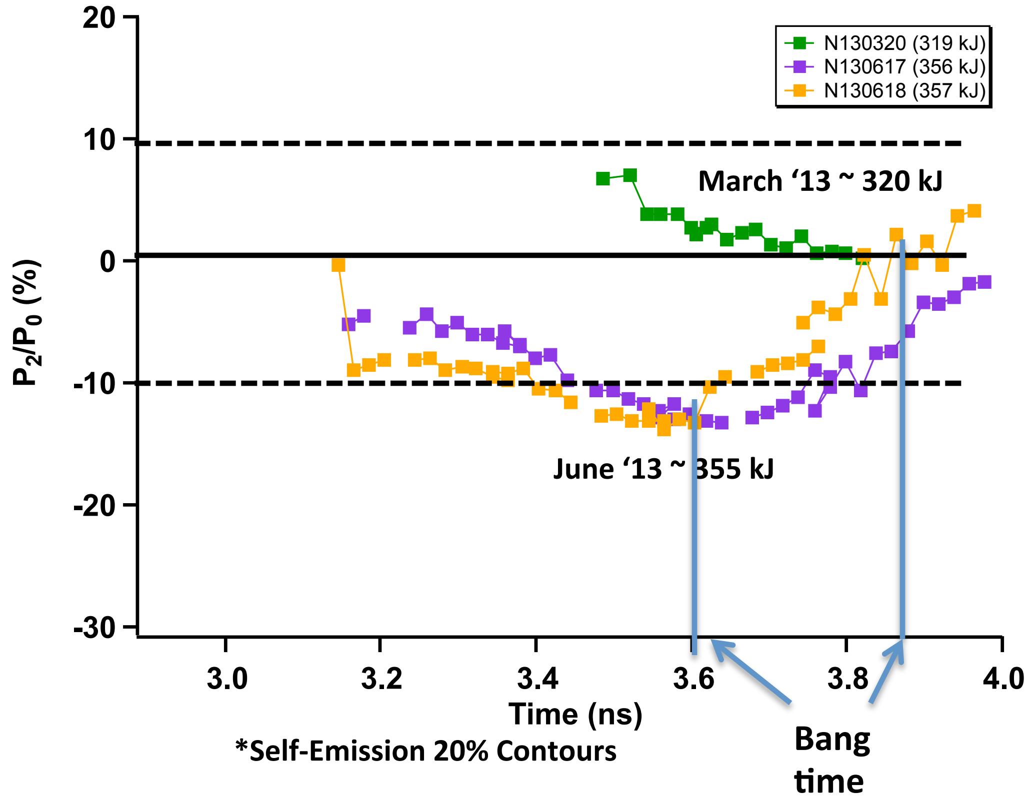
Nominal BHR-2 uses SKE=10^{11}; scale = 50 nm; AMP=0.8





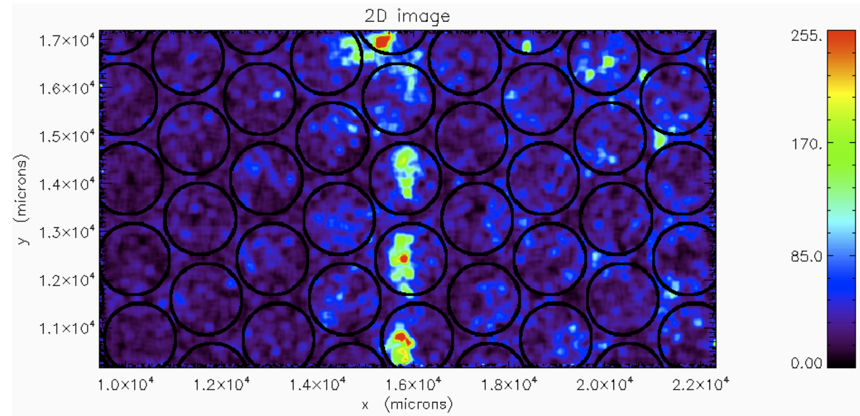
We need to show we can replicate ±10% symmetry control

- Decreased (80%) drive on the poles reduces P_2/P_0 asymmetry
- Symmetry was excellent in March 2013
- Need to confirm that 10% increase in energy was responsible for symmetry change in June
- P_4 symmetry, as predicted, was not affected
- P_4 symmetry will be difficult to control with available beams

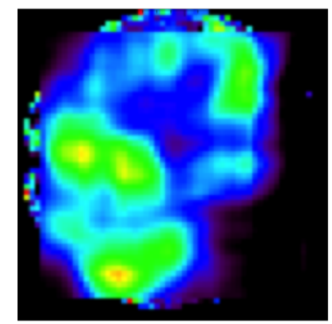


We have qualified the MMI diagnostic for NIF and have specified Fe dopant

- PQ shots in October 2012 showed MMI works as designed
- Shot N121119 shows we need larger pinholes/more emission from capsule
- Subsequent shots and successful modeling implies that Fe is dopant of choice
- We are redesigning mirrors and point design reflects dopant change



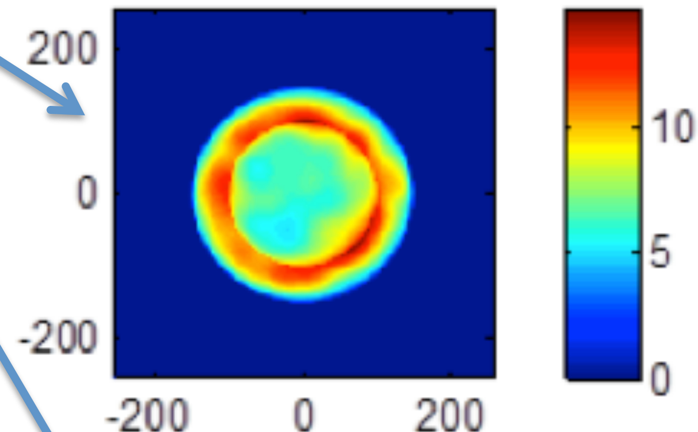
Reconstructed Ge He-α image of NIF MMI data from R. Shah



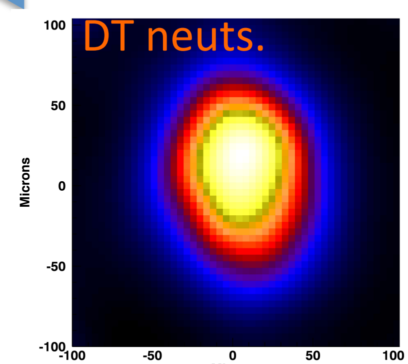
Our point design capsule should produce $2x10^{13}$ DT neutrons, enough for imaging

- We produce a satisfactory image with 10^{13} neutrons
- Neutron imaging diagnostic already produces DT and TT images with $2x10^{13}$ neutrons
- Our predicted yields are $2x10^{13}$ DT and TT neutrons
- Postprocessed simulation images are small; <20 μm across

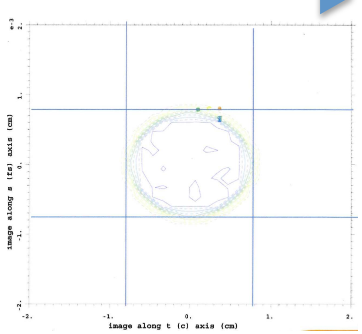
A primary diagnostic for DIME is a neutron image (NI) produced from shell D mixing with core T



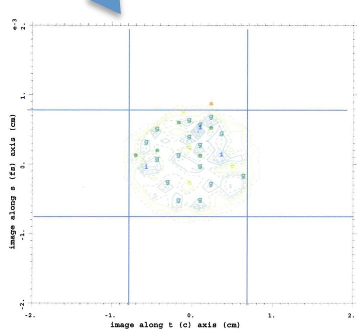
Synthetic DT NI based on inferred DT results from June '13 DD data



N121125
MIXCAP
Image
$2.4x10^{13}$



DT image



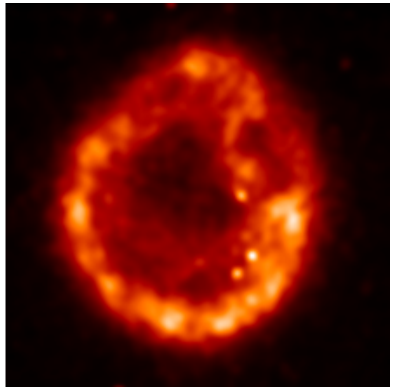
TT image

Lines are 16 x 16 μm across

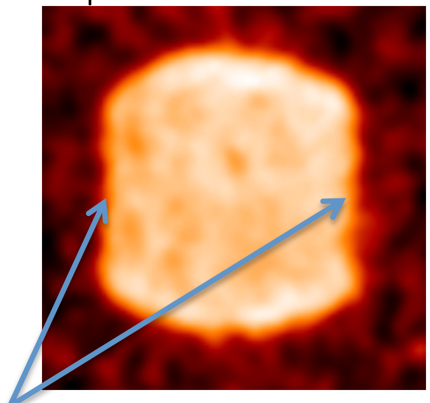
Polar Direct Drive and Indirect Drive are both viable platforms for DIME

Equatorial view

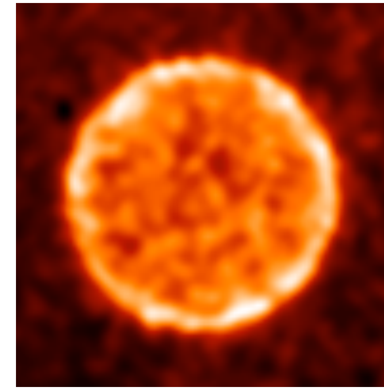
Polar view



Equatorial view



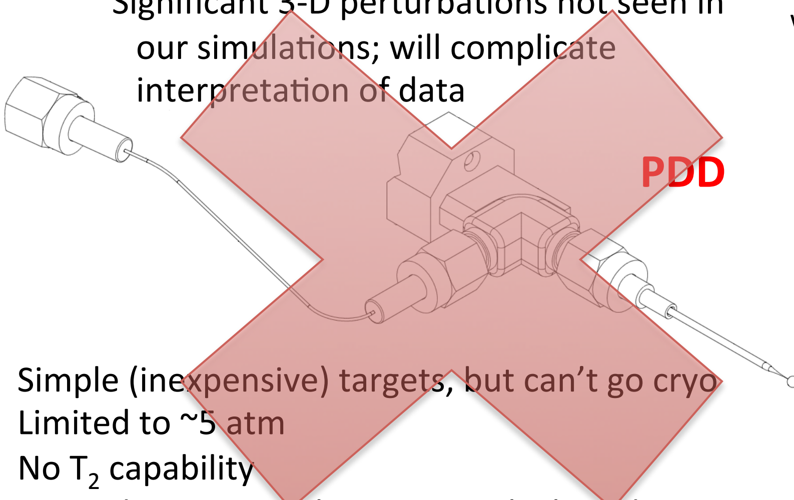
Polar view



Edges of diagnostic window

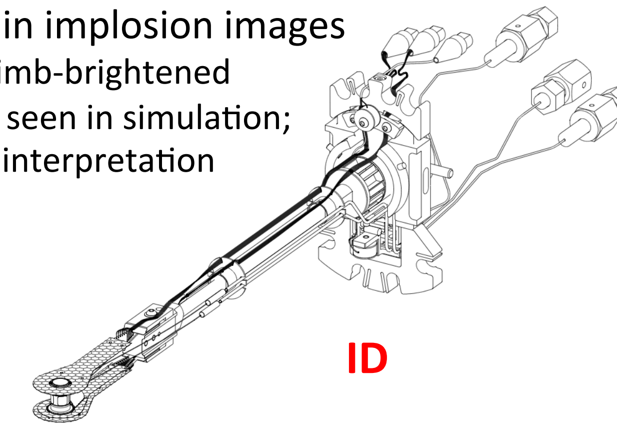
Significant structure in implosions

Significant 3-D perturbations not seen in our simulations; will complicate interpretation of data



Less structure in implosion images

Much closer to limb-brightened 1-D implosions seen in simulation; would simplify interpretation



- Simple (inexpensive) targets, but can't go cryo
- Limited to ~5 atm
- No T_2 capability
- Limited experience base upon which to draw

- Complex (expensive) targets, especially for cryo
- Have gone to 40 atm STP equiv
- T_2-fills demonstrated
- Many LLNL users of Indirect Drive

Challenges remain even if we switch to Indirect Drive

Same shot sequence needed for both:

- 1 – 2 shots with new capsule for symmetry, dopant emission, bang time determination, yield from CD capsule with H_2 fill
- 1 shot with CD buried 1 μm to verify negligible feed-through mix
- 1-3 shots to assess depth of feed-through mix, if necessary
- 1 shot with doped CH shell, T_2 fill to get DT background
- 1 shot with doped CD shell + T_2 fill

- Polar Direct Drive
- Path forward: larger capsule with similar laser intensity
  - Need NIF to engineer and implement T_2 fill capability for PDD capsules or re-engineer targets for Cryo-TARPOS
  - Need to understand how to obtain profiles from non-symmetric data
  - Will require collaboration with U of R/LLE
  - Need new MMI mirrors and MMI snout modifications

- Indirect Drive
- Path forward: same diameter but thicker capsule with hohlraum drive
  - We will need to engineer the MMI snout to be compatible with indirect drive hohlraum debris and x ray flux
  - Need to develop hohlraum modeling capability (or learn how to use LLNL results with our capsules)
  - Will require collaboration with LLNL WCI
  - Probably need new MMI mirrors

The ASC codes are evolving to meet HEDP needs, but much work remains

- Do not (and will not) have LPI effects in codes
- Rage is having lasers put in (will need considerable V&V effort)
- Knudsen package needs testing (and maybe more development)
- There are issues with BHR, CPT, new 3T, TN burn, and other packages working together
  - Some parameter settings will cause code to crash
  - Some packages do not work with others yet
- Need to continue making post-processing tools more automatic

So what do we need?

- Finish adding lasers to RAGE
- Need established capability to include surface roughness
- Need to demonstrate simulation sensitivity to chunk mix in capsule design

- Need to demonstrate minimal feedthrough on indirect drive capsule with simple laser pulse
- Need to get ≥2 keV dopant Te and at least 2×10^{13} DT neutron yield (preferably with CR<10)
- Need to obtain high enough experimental MMI and neutron imaging resolution to constrain mix models

Critical issue is resolving mix requires <5 μm resolution

- Simulation mix widths are typically 10-20 mm (need <5 μm effective resolution, 2 μm is better)
- Neutron imaging data from CD MIXCAP suggests location of edge can be measured to within 2 to 4 μm (probably ok here)

- This may also be true of MMI images if they are solid circles
- If neutron or MMI image is an annulus, resolution will be worse (per pixel 25 to 50 μm)
- MMI image pixel resolution is ~50 μm (could go as low as 40 μm)
- This is good enough to tell if mix is in a ring or centrally peaked

- Will need additional information for higher effective MMI resolution
- Could try to obtain images at different times to observe change in mix layer
- Could combine with a streak spectrometer to know when shock hits center and time history of spectral emission

What will the next burn/mix experiment look like?

- It will use an indirect drive platform
- Will most likely be done in close collaboration with LLNL
- There will be a separated reactant capsule in the experimental plan
- Data will include neutron yields, T_{ion}, MMI data, and neutron images
- The design will have a free parameter for mix variation
  - Change “roughness” of capsule surface
  - Add a known large-scale defect (ex. equatorial grooves used by DIME)
  - Change gas fill pressure
- If one wants to know morphology of mix from shock passing through shell/gas interface, a planar experiment might be useful
- If yields great enough for burn to influence mix is desired, capsule will likely be some variant of ignition design

LANL is at a crossroads with mix/burn experiments

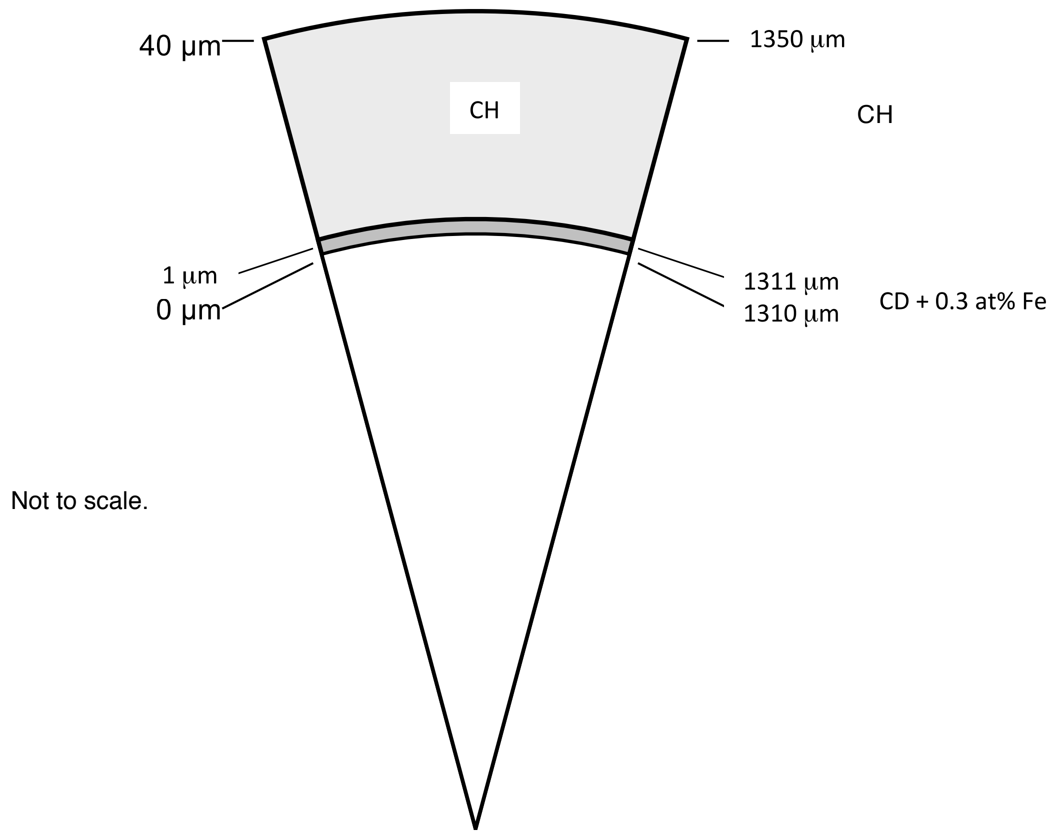
- We have a wealth of data from DIME and other mix experiments to draw on for ideas
- We are presently pursuing “two shock” indirect drive experiments with LLNL
- DIME and CD MIXCAP experiments on NIF laid much groundwork for future
- A committee will issue recommendations on burn/mix experiments shortly

- Needed – good designs (requirements) and path forward for a future experiment

EXPERIMENTAL SETUP SECTION

This is for Polar Direct Drive “point design” material

The DIME separated reactant capsule has a simple design

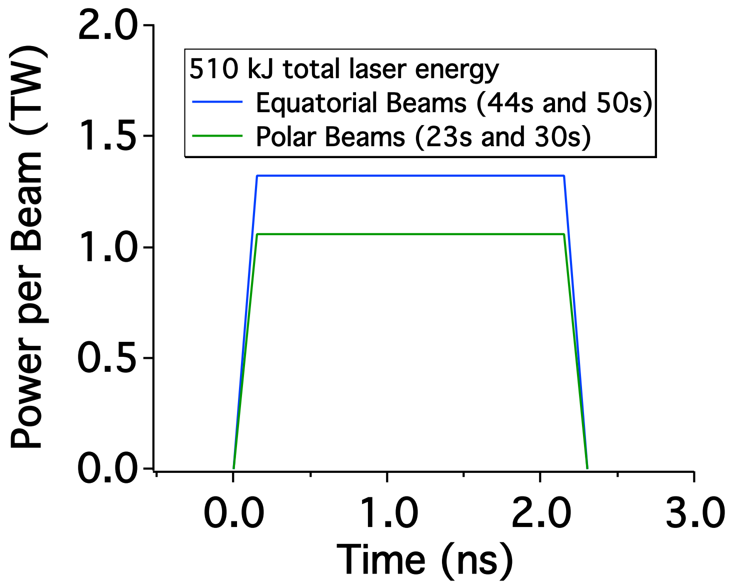


Outer Radius:	1350 ± 100 µm
Total Thickness:	40 ± 2 µm
CD layer thickness:	1.0 ± 0.3 µm
CD layer dopant:	Iron
Dopant concentration:	0.2 ± 0.1% at
Drive Energy:	510 kJ

Fill gas:	Tritium
Gas purity:	<1% D by atom
Fill pressure:	4 atm
Temperature at shot time:	20 ± 5° C

Laser Drive

Pulse Shape
Square pulse
2.15 ns FWHM
150 ps rise and fall time



Laser Energy
510 kJ total
Polar beams (23° and 30°) at 80% of equatorial beams (45° and 50°)

Laser Color

	Wavelength
λ_{23}-λ_{outer}	8.1 Å
λ_{30}-λ_{outer}	6.6 Å
λ_{outer}	10524.3 Å

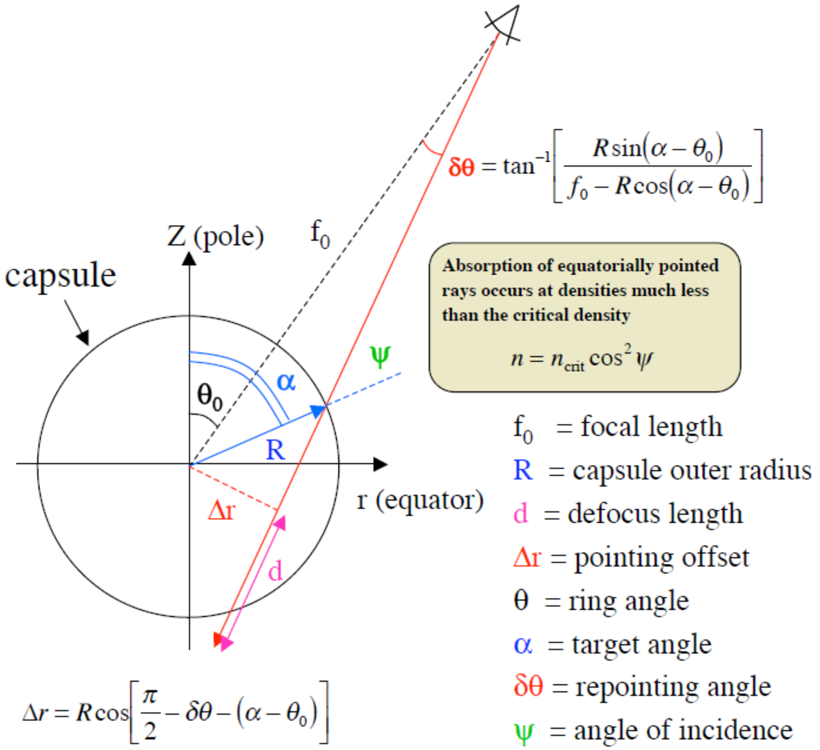
Laser Energy and Power balances

Laser Energy Balance
<10% RMS by beam, relative to average for polar or equatorial beams
Polar beam average energy at 80±5% of equatorial beam average energy

Laser Power Balance
<20% RMS by beam, relative to average power for polar or equatorial beams

Laser Pointing

Ring	α	Defocus (mm)
23.5°	31.3°	18
30°	37.8°	19
44.5° C&D	42.2°	24
44.5° A&B	79.9°	16
50°	83.0°	12
130°	97.0°	12
135.5° C&D	100.1°	16
135.5° A&B	137.8°	24
150°	142.2°	19
156.5°	148.7°	18



Pointing error: 100 µm RMS

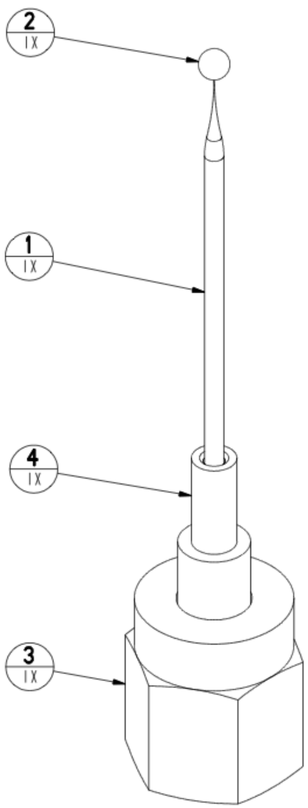
Defocus error: ± 2 mm

Laser beam smoothing

Ring	Phase Plate	Minor Radius (μm)	Major Radius (μm)
23.5°	rev3_inner (scale 1.07)	0.882	0.631
30°	rev1a_inner (scale 1)	0.824	0.590
44.5° C&D	rev3_outer (scale 1.07)	0.635	0.367
44.5° A&B	rev3_outer (scale 1.07)	0.635	0.367
50°	rev1_outer (scale 1)	0.593	0.343
130°	rev1_outer (scale 1)	0.593	0.343
135.5° C&D	rev3_outer (scale 1.07)	0.635	0.367
135.5° A&B	rev3_outer (scale 1.07)	0.635	0.367
150°	rev1a_inner (scale 1)	0.824	0.590
156.5°	rev3_inner (scale 1.07)	0.882	0.631

SSD: On
SSD bandwidth: 45 GHz

Mounting



Capsule is mounted on a glass fill tube that also serves at the mounting stalk
Fill tube diameter at capsule penetration is 30 ± 5 µm
Penetration beyond inner wall is <100 µm

These requirements have been met with previous DIME PDD capsules

Requirements Section

Some are PDD Capsule specific

Requirements

- Relevance (are we turbulent?)
- Implosion (hydro and symmetry)
- Mitigation of CBET and LPI (equatorial feature issue)
- Spectroscopy (need to see Heβ and Ly β lines)
- Provides T_{elec} map that can be related to T_{ion}
- Burn information (N_{DT}, N_{TT}, N_{DD}, T_{ion}, burn history)
- Burn imaging (see if DT burn coincides with dopant mix and provide map of N_{DT})

Physical and Non-dimensional quantities

- Implosion velocity ($v=1$ to 3×10^7 cm/s)
- Mix width growth velocity ($u=$about 10^6 cm/s)
- Mix width (d=typically up to few tens of microns)
- Viscosity (values of 0.005 to 0.01 are reasonable)
- Reynolds # --values are typically 1 to 2 $\times10^5$(need$>10^4$)
- Turbulence time scale t (Zhou PoP, 14, 082701, 2007)
  - $t = (d/u)\ (100/C_{\_D})^2\ (Re)^{-1/2}$
  - $t = (0.001/10^6)\ \ (100/5)^2\ (1.5\times10^5)^{-1/2}$ = **0.8ns**
- Flow is turbulent by bang time

Capsule Fabrication Requirements

- OD 2700±100μm, thickness 39.5±1.5 μm (PDD)
- CD (+dopant) layer thickness is 1.0±0.2 μm
- Shell thickness variation is 0±1 μm

- Fe dopant concentration needs to be 0.2±0.1 atom%
- Buried Fe dopant layer placement accuracy is about 0.4±0.1 μm
- Fill tube diameter at capsule surface ≤30 μm
- Penetration of glass stalk into capsule is ≤70 μm
- Glue spot diameter ≤100 μm

- Surface roughness is similar to previously fired capsules
- This appears to be about 100 nm in amplitude for isolated defects and 100 nm in terms of amplitude of low-mode "waves"

- Note: given prior fabrication experience, these requirements can be met

Implosion (hydro) Requirements

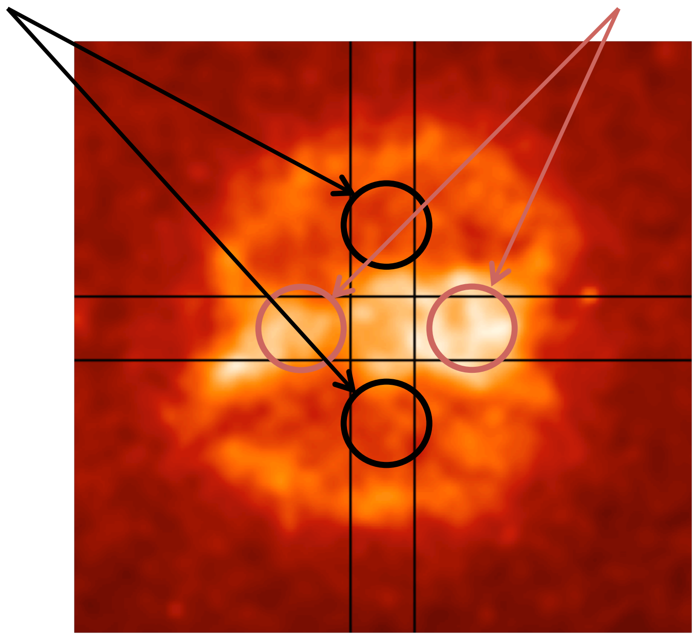
- Measurement of implosion trajectory to within 10 μm for a given time
- For radius versus time, we require a measurement error for each time less than 5 μm
  - Averaging many chords in an image with ±10μm resolution gives 5 μm
  - This precision is better than shell thickness and laser energy uncertainty
- Bang time requirement is <±100 ps
  - Constrains hydro about the same as above $\Delta r/r$ requirement
- Ability to match core self-emission images (size and shape)
- Simulation limits tell us if dopant gets into hot core
- Turbulent mix model suggests 24 μg of shell (0.52 μg Fe) mixes into fuel (but not into center)
- Will need surface roughness requirements similar to NIC symcaps to avoid "meteors" into core

Symmetry (and LPI) requirements

- For indirect drive, need to keep SBS and SRS symmetry effects to level of NIC campaign
- From PDD, requirement for P_2/P_0 near bang time (and over roughly 500 ps before bang time) is <±10%, which results in a ±10% change in yield
- We should have ±5% symmetry induced mix to avoid issues with interpretation of mix from symmetry versus implosion
- Measurement error of P_2/P_0 at a given point is about 1%, effect on yield is also about 1% (thus, a small contributor to mix-induced yield uncertainty)

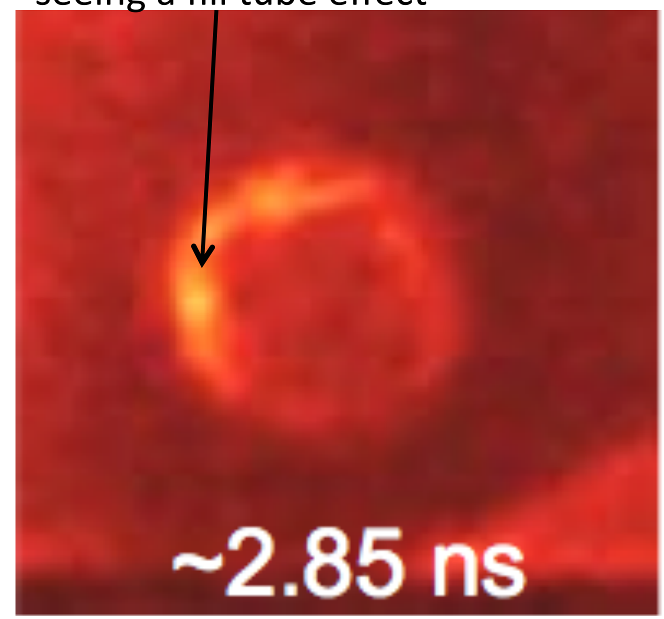
Presence of equatorial feature is based on equatorial and polar images

Compare brightness here… to here…



N121207 equatorial image

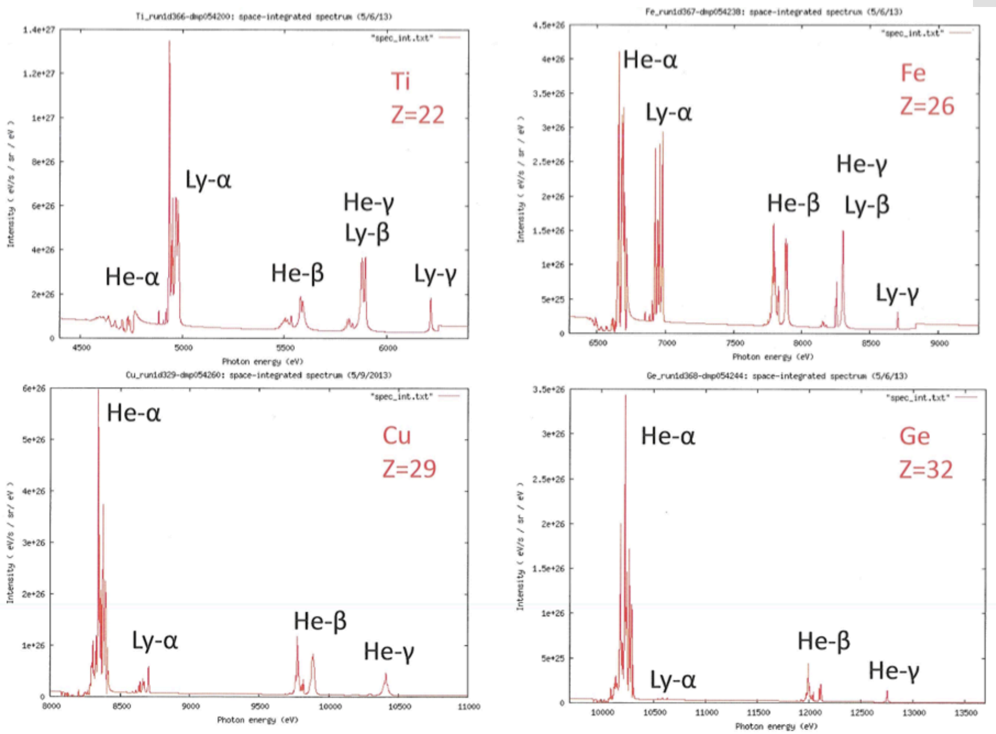
Use polar image to verify we are not seeing a fill tube effect



N120728 polar image

- **Equatorial and polar images will analyzed to determine if the equatorial feature is seen on the first shot.**
- **If brightness between 50 and 100 μm radius along the equator is more than 30% brighter than along the polar axis, then we say the feature still exists <u>unless the polar view shows that enhanced emission is primarily from the fill tube region.</u>**

We now have confidence in predicted spectra, allowing informed choice of dopant for MMI applications



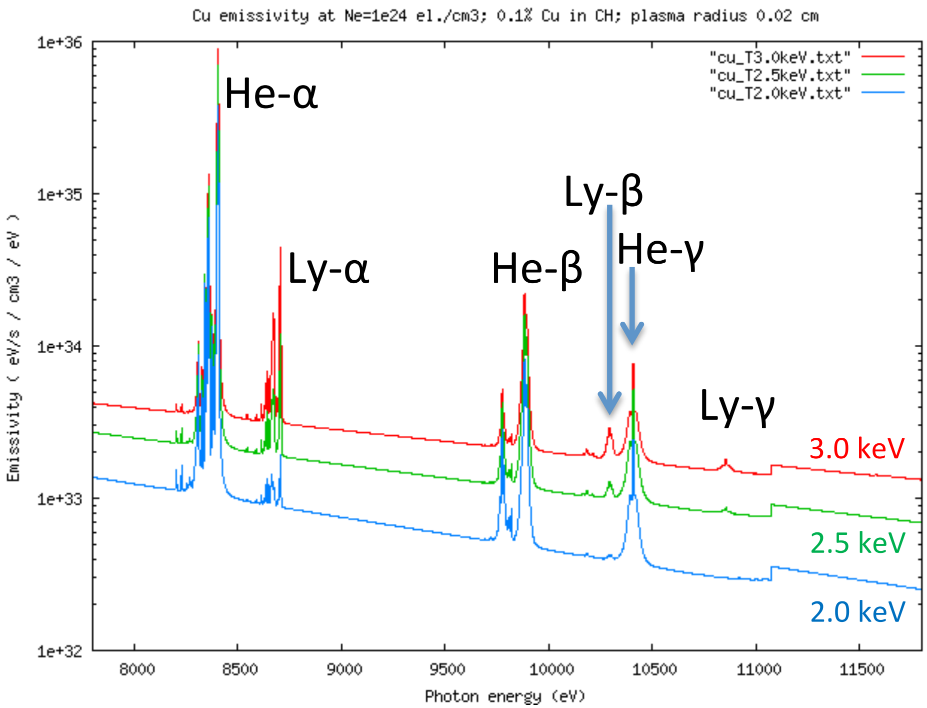
X ray line	Ti (J/sr)	Fe (J/sr)	Cu (J/sr)	Ge (J/sr)
He-α	0.02	2.25	3.93	2.72
He-β	1.62	1.50	1.10	0.28
H-α	5.61	1.63	0.26	0.01
H-β, He-γ	2.61	0.58	0.34	0.04

Spectroscopy (and MMI) requirements

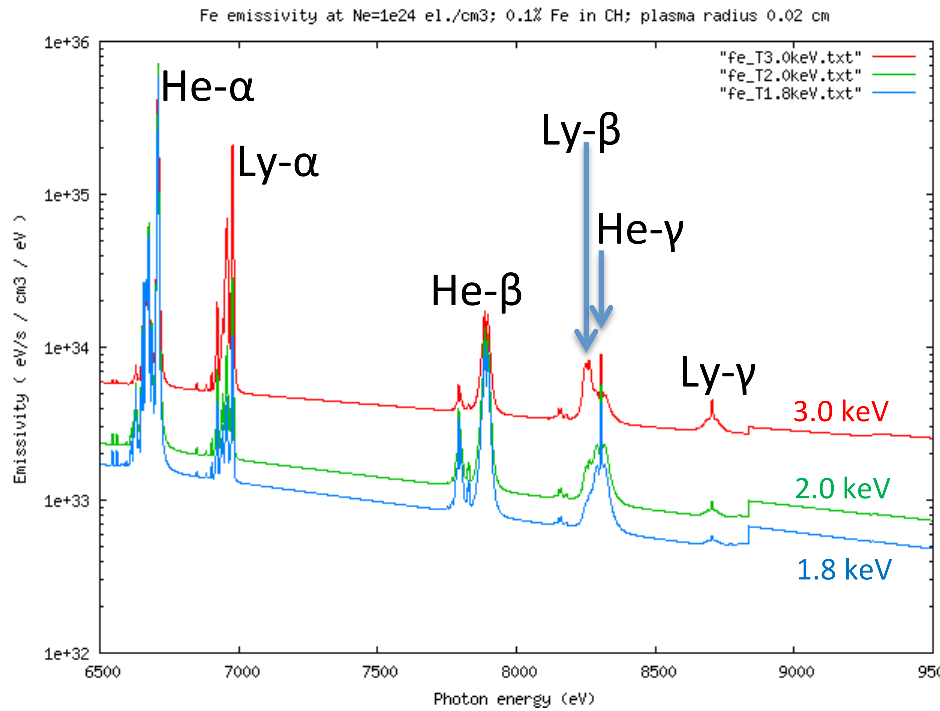
- Must be hot enough for Heβ and Lyβ lines to be visible to obtain Te map from MMI data
- For Cu, need temperature of ≥2.5 keV
- For Fe, need temperature of ≥1.8 keV
- We need at least 0.1 atom% of Fe to see lines satisfactorily
- Line/continuum contrast ratio of at least 1.05 for line visibility
- What is uncertainty from (line ratio → T_e) formula?
- For ΔT=100eV (at 2 keV) need Lyβ/Heβ line ratios to within 3% (implies S/N=25 for T_e to 10% and S/N=50 for T_e to 5%)
- This ΔT is the same for all temperatures of interest
- Based on N121119, we need 1 J/ster for MMI visibility
- Reasonable to expect measurement uncertainty of 2-3x on electron density maps (Stark broadening effects are subtle)

Dopant Ly-β visibility requirements

Cu dopant: Te ≥ 2.5 keV



Fe dopant: Te ≥ 1.8 keV



He-γ:Ly-β separation in Cu: +102 eV

He-γ:Ly-β separation in Fe: +43 eV
the lines can blend somewhat, since resolution is 60 eV

For comparison:

He-γ:Ly-β separation in V: -5 eV

He-γ:Ly-β separation in Ti: -19 eV

MMI requirements

- MMI specification requires 8×10^{-4} J/KeV/ster/μm^2 for useful signal
- Spatial resolution of each MMI pixel needs to be <20μm (need 10-15 pixels to constrain shape)
- MMI resolution is smaller in y direction than x direction (energy and spatial blurring)
- For 10 μm pinhole, R_x=44 μm and R_y=34 μm
- For 35 μm pinhole, R_x=63 μm and R_y=56 μm
- For 50 μm pinhole, R_x=84 μm and R_y=80 μm
- If image is filled circle, then may be able to obtain 10 to 20 μm error
- Will not be able to directly image dopant in a ring, since predicted to be about 15 μm wide
- If we assume ring radius of 120 μm, circumference is 750 μm, and would have 12 to 18 resolution elements around circle

Burn requirements

- Want DT yield from D_2 impurity in T_2 gas to be less than 5% (measurement error)
- Need to know number of DD and DT neutrons to within 10%, this implies needing TT neutrons to within 14% (NIF can meet this)
- Need Doppler broadening of both DD and DT peaks to obtain +/- 0.5 keV accuracy in Tion values (note: DD T_{ion} ~2.5 keV, DT T_{ion} ~4.0 keV)
- Need 5 orders of magnitude range in neutron ToF detector to see DD peak versus DT peak
- If available, resolve burn history to ~25-50 ps (need GRH?)
- Mix model sensitivity can be ±40% in DT yield and ±0.5 keV
- Preheat uncertainty could result in factor of 4 uncertainty in yield

Neutron Imaging requirements

- Typical burn material widths are ~20 μm and DT burn region is about 10 μm larger than TT burn region
  - CD MIXCAP burn material width is ~30 μm wide and DT burn region is also about 10 μm larger than TT burn region
- Thus, like MMI, need ≤5 μm resolution of contour to get several pixels
- Per pixel resolution of NI is about 50 μm at 10^{13} neutrons and gets better with more neutrons
- From CD MIXCAP, filled circles have measurement errors of ± 4 μm
- If burn/mix expt images are also filled circles, then we can meet requirement
- If image is an annulus, we are likely to be only about 1 pixel wide
- This could present problems in meeting requirements

Technical Achievements

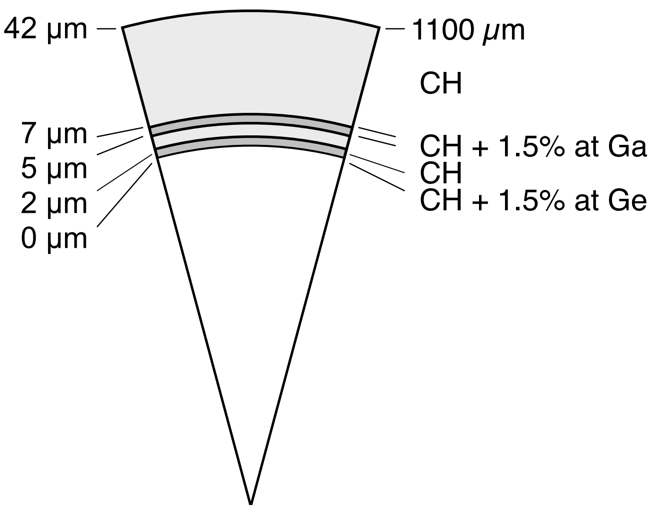
DIME fielded three basic capsule types on NIF

CH shell, 1 or 2 dopants

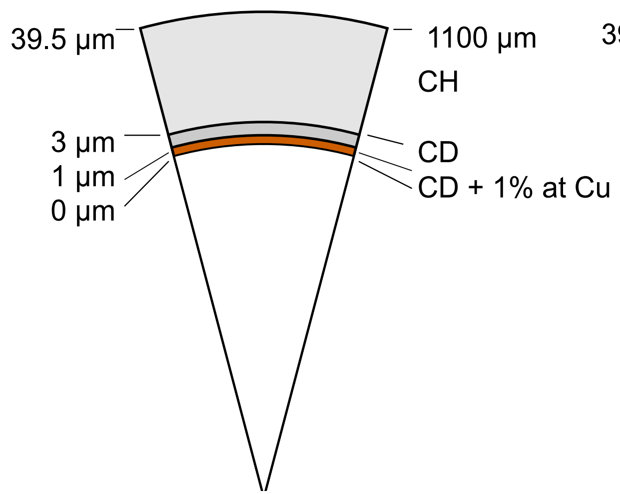
Check symmetry, yield, Tion, burn-through, and dopant

CH+CD shell, Cu dopant

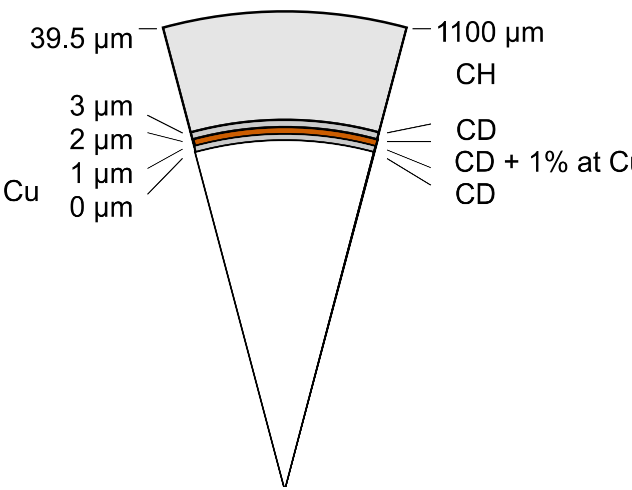
Check mix depth, DD yield, and dopant



Never saw Ga lines



Dopant next to gas

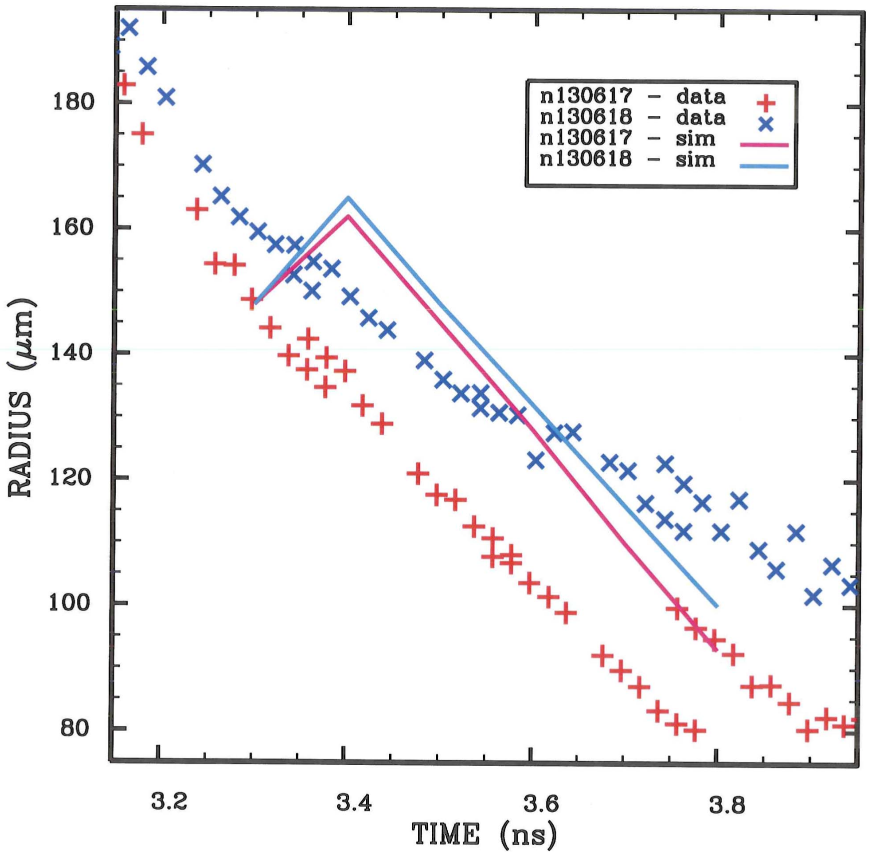


Dopant buried 1 μm

We match experimental r vs t data to within 20 μm rms

- Most experimental radius data come from self-emission images
- Present comparison does not compare contour levels explicitly, only about 20 μm rms accurate
- We predict smaller diameter when dopant is next to gas
- Dopant in the gas cools plasma, reducing self-emission region

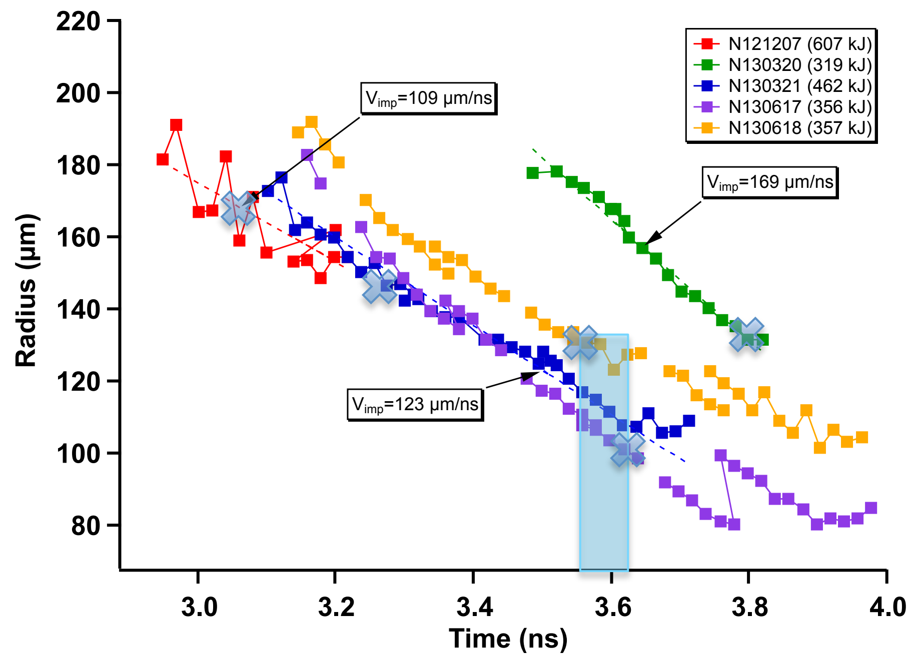
- Post-processing has issues in producing self-emission images that we are working to resolve



We correctly capture larger diameter of the buried dopant capsule

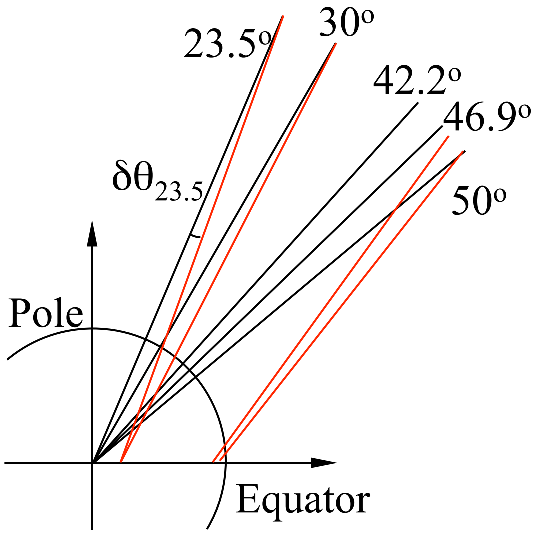
Capsule size continues to decrease after bang time

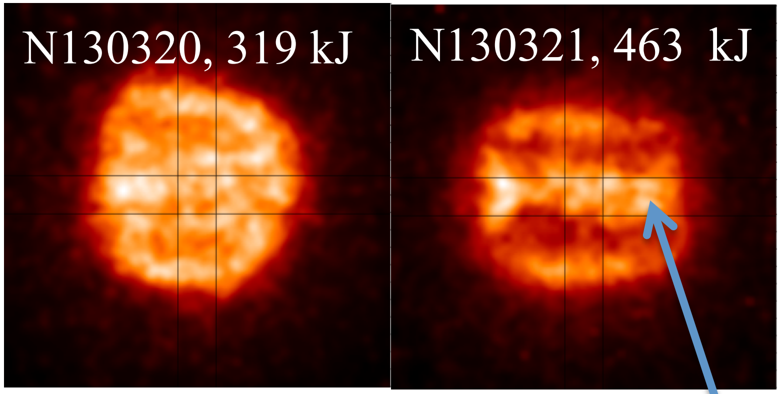
- In all cases, the radius continues to decrease after neutron bang time
- Radii at bang time (marked with an “x”) vary from 100 to 170 μm
- N130617 has smallest radii, but could be due to presence of dopant in gas and burn only in CD shell
- Three shots with D_2 gas have bang time radii of 130 to 170 μm

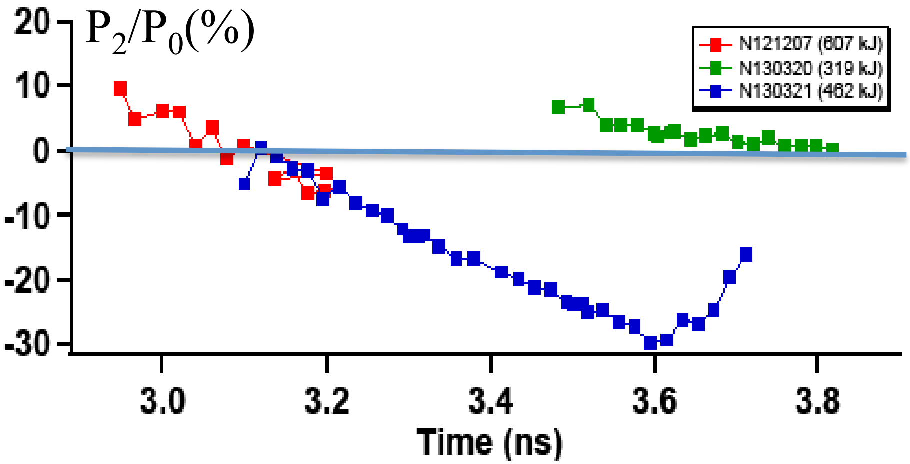


March 2013 350 kJ shots showed good P_2/P_0 and P_4/P_0 symmetry

- Spherical implosion symmetry in PDD configuration requires laser offsets, which lead to oblate implosions (P_2/P_0~ -30% at peak compression)
- Adjusting laser pointing and cone energy allows for asymmetry compensation (P_2<5% around bang time)
- Implosion symmetry is sensitive to overall energy in the implosion
- Good symmetry can improve yield (50%) and ion temperature (15%) without changing the dynamics of the implosion



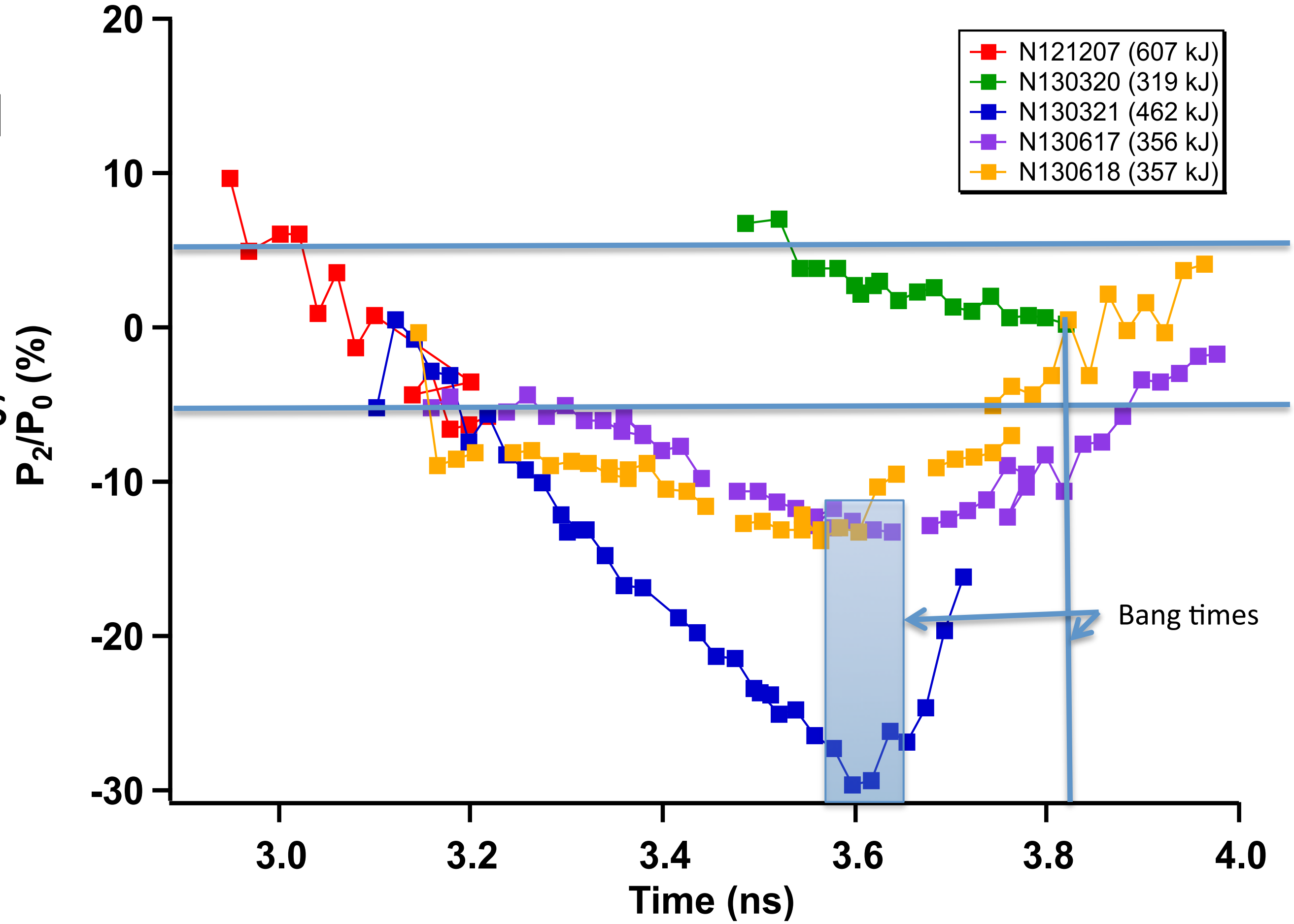




LPI Equatorial "feature"

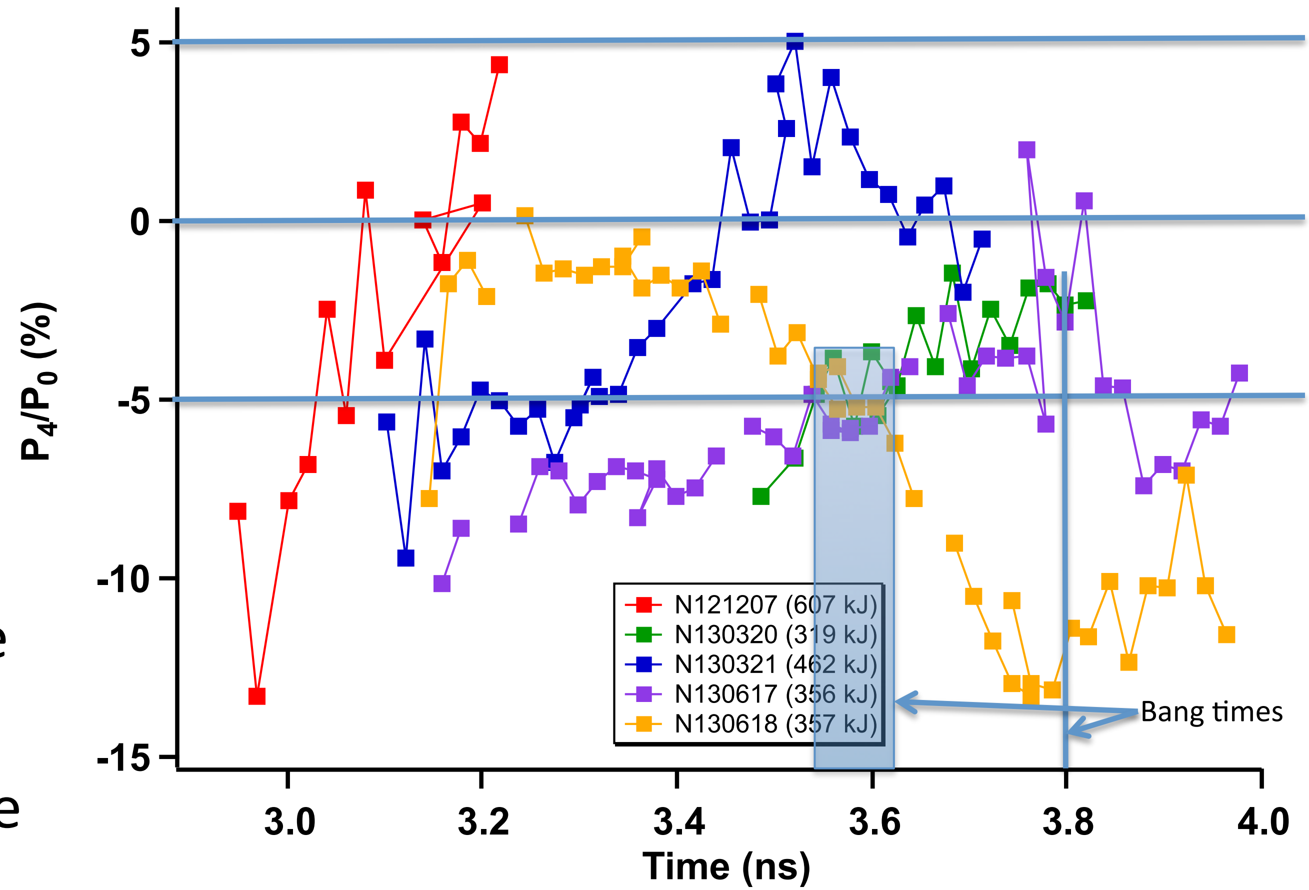
We have some variation in P_2/P_0 symmetry

- We have fielded three 350 kJ shots on the NIF
- Shot N130320 had $P_2/P_0 < 5\%$ for ~250 ps before bang
- Cu doped capsules had P_2/P_0 ~10%
- Need to improve this to <5%
- Need more shots to demonstrate symmetry control



The P_4/P_0 symmetry is quite variable

- We have fielded three 350 kJ shots on the NIF
- All three have P_4/P_0 near -5% at bang time
- Shots N130320 and N130617 had $P_4/P_0 > -5\%$ before bang
- We have not made a concerted effort to control P_4/P_0 yet

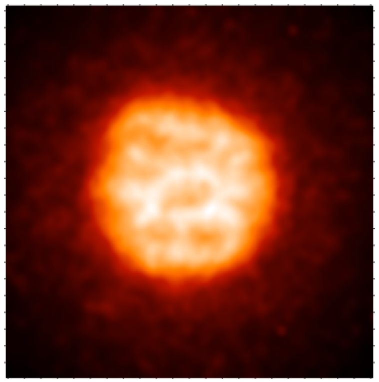
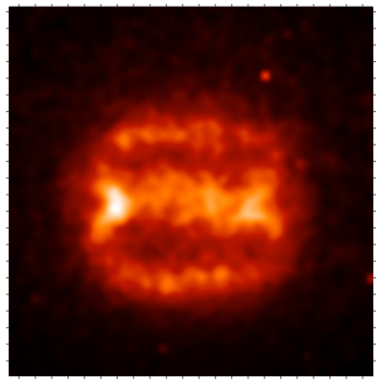
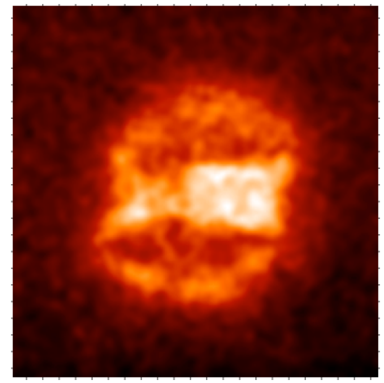


LPI limits our intensity to 10^{15} W/cm^2 in square pulse

- Our first four shots used ~650 kJ (I~2x10^{15} W/cm^2)
- We saw a significant equatorial "feature" in self-emission from hot dopant being injected into the gas
- Subsequent shots consistent with our hypothesis that two-plasmon decay (or similar LPI effect) was responsible (onset at ~10^{15} W/cm^2)
- Shots at ~320 kJ energy do not show the equatorial feature and have similar neutron yields (CBET is not affecting symmetry)
- As a bonus, our best pointings at ~320 kJ produced good symmetry
- The dopant temperatures of ~2.0 keV are too low to obtain Heβ and Lyβ lines for Cu, but are predicted to work nicely for Fe.

NOTE: 320 kJ applies to ~1100 μm OR capsules

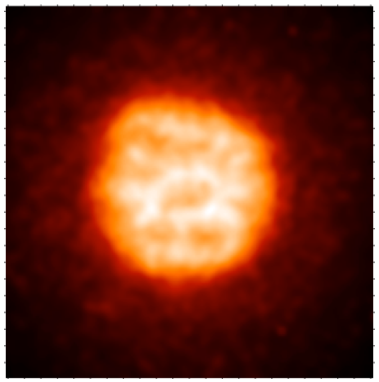
350 kJ shots do not show equatorial “feature” but show different P_2/P_0

1.0×10^{15} W/cm^2	1.4×10^{15} W/cm^2	1.9×10^{15} W/cm^2
		
N130320-001	N130321-001	N121207-001
E_L = 319 kJ	E_L = 462 kJ	E_L = 607 kJ
E_p/E_e = 0.833	E_p/E_e = 0.842	E_p/E_e = 0.771
t = 3.80 ns	t = 3.24 ns	t = 3.04 ns

500 µm x 500 µm images
20% contour used

350 kJ shots do not show equatorial “feature” but show different P_2/P_0

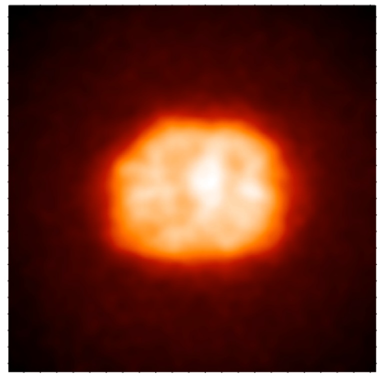
1.0×10^{15} W/cm^2



N130320-001
E_L = 319 kJ
E_p/E_e = 0.833

t = 3.80 ns

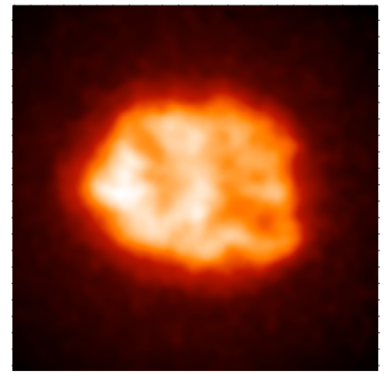
1.1×10^{15} W/cm^2



N130617-001
E_L = 356 kJ
E_p/E_e = 0.822

t = 3.60 ns

1.1×10^{15} W/cm^2



N130618-001
E_L = 357 kJ
E_p/E_e = 0.808

t = 3.60 ns

500 µm x 500 µm images
20% contour used

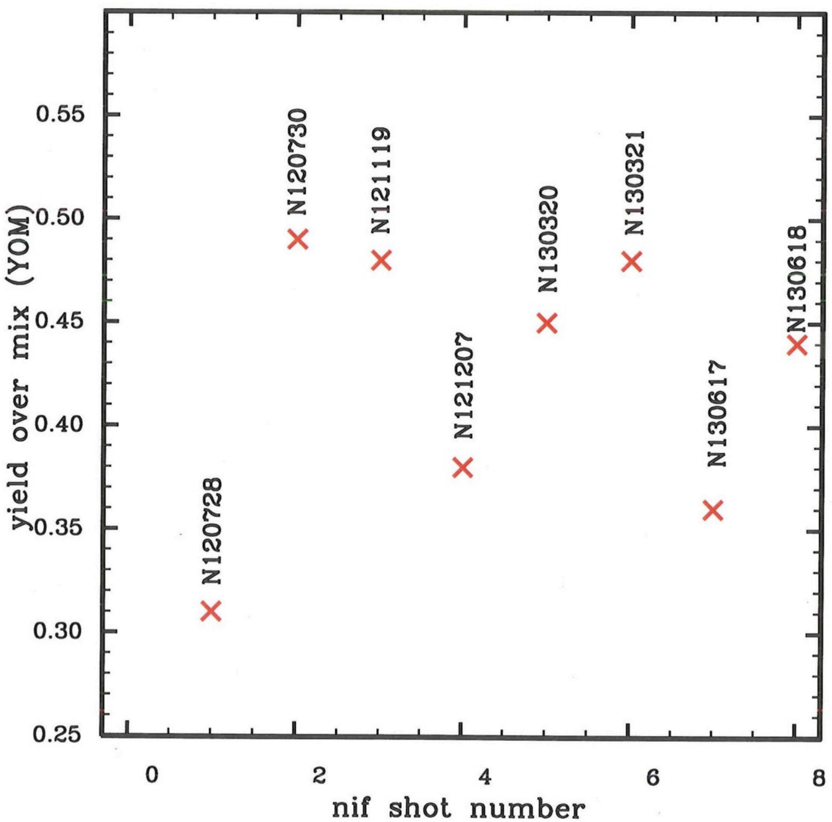
RAGE does a decent job of fitting a variety of shots with one set of mix parameters

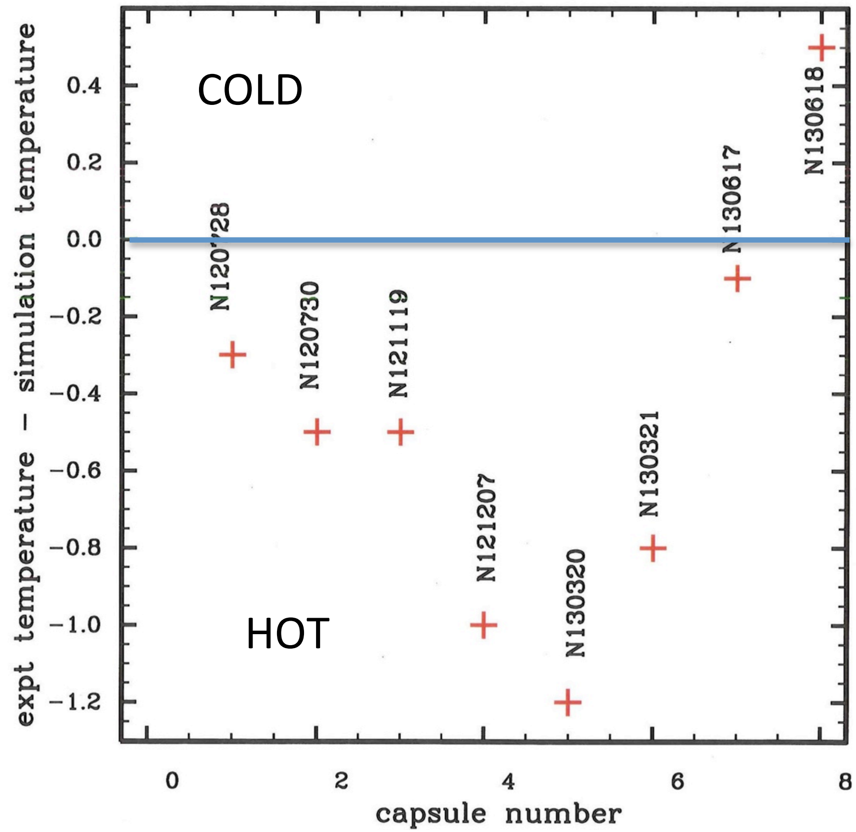
Shot	Drive energy (kJ)	N yield (x10^{11})	Tion (keV)	Bang time (ns)
N120728 data	666 (23.8 kJ)	5.8+/-0.5	4.4+/-0.3	2.72+/-0.1
simulation	700 (200 eV)	17.8 (YOM=0.31)	4.7 (-0.3)	2.7
N120730 data	665 (22.1 kJ)	6.5+/-0.4	4.2+/-0.4	2.91+/-0.1
simulation	700 (200 eV)	13.4 (YOM=0.49)	4.8 (-0.6)	3.2
N121119 data	659 (14.1 kJ)	8.6+/-0.6	4.3+/-0.3	3.0+/-0.2
simulation	700 (200 eV)	17.8 (YOM=0.48)	4.7 (-0.4)	2.7
N121207 data	630 (15.8 kJ)	3.7+/-0.2	3.4+/-0.2	3.04+/-0.1
simulation	630 (150 eV)	9.6 (YOM=0.38)	4.4 (-1.0)	3.10
N130320 data	319 (4.2 kJ)	7.2+/-0.2	3.7+/-0.2	3.80+/-0.1
simulation	350 (50 eV)	16.0 (YOM=0.45)	4.9 (-1.2)	3.86
N130321 data	463 (11.1 kJ)	5.8+/-0.2	3.7+/-0.2	3.24+/-0.1
simulation	500 (150 eV)	12.1 (YOM=0.48)	4.6 (-0.9)	3.33
N130617 data	356 (3.0 kJ)	1.3x10^{9}	2.0	3.62+/-0.1
simulation	350 (50 eV)	3.6x10^{9} (YOM=0.36)	1.9 (-0.1)	3.76
N130618 data	358 (2.8 kJ)	7.4+/-0.4x10^{9}	3.0	3.55+/-0.1
simulation	350 (50 eV)	1.7x10^{10} (YOM=0.44)	2.2 (+0.8)	3.7

50nm scale and 10^{11} ske (same as used on Omega shots)

A single set of BHR parameters describes Omega and NIF yield and T_{ion} data to date

We use the same BHR-2 settings (50 nm; 10^{11}; AMP=0.8)for Omega and DIME shots



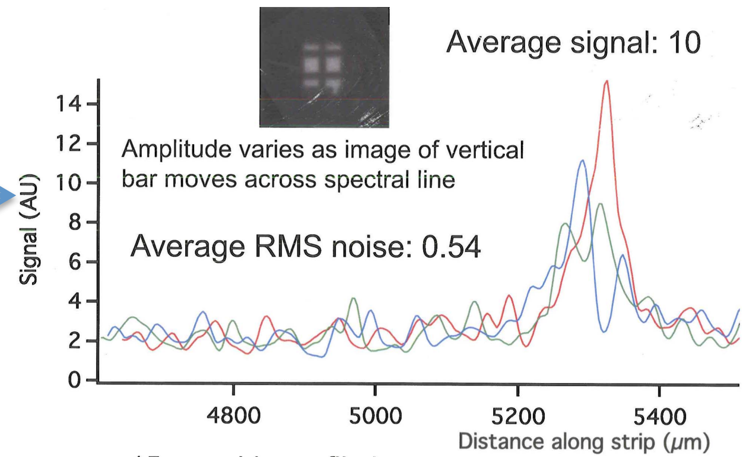


Average YOM value of 0.42 is consistent with previous Omega results

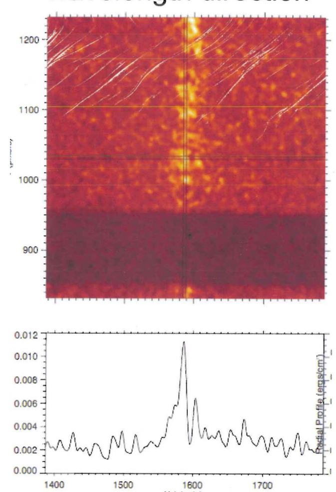
N121207, N130320, N130321 had experimental temperature drop

We developed an MMI diagnostic for NIF that performs as designed

- We successfully fielded the new MMI diagnostic in October 2012
- X-ray throughput better than predicted (18 vs 10 S/N)
- Obtained a test image with <15 μm resolution
- Capsule implosions need hotter dopant temperatures for adequate S/N

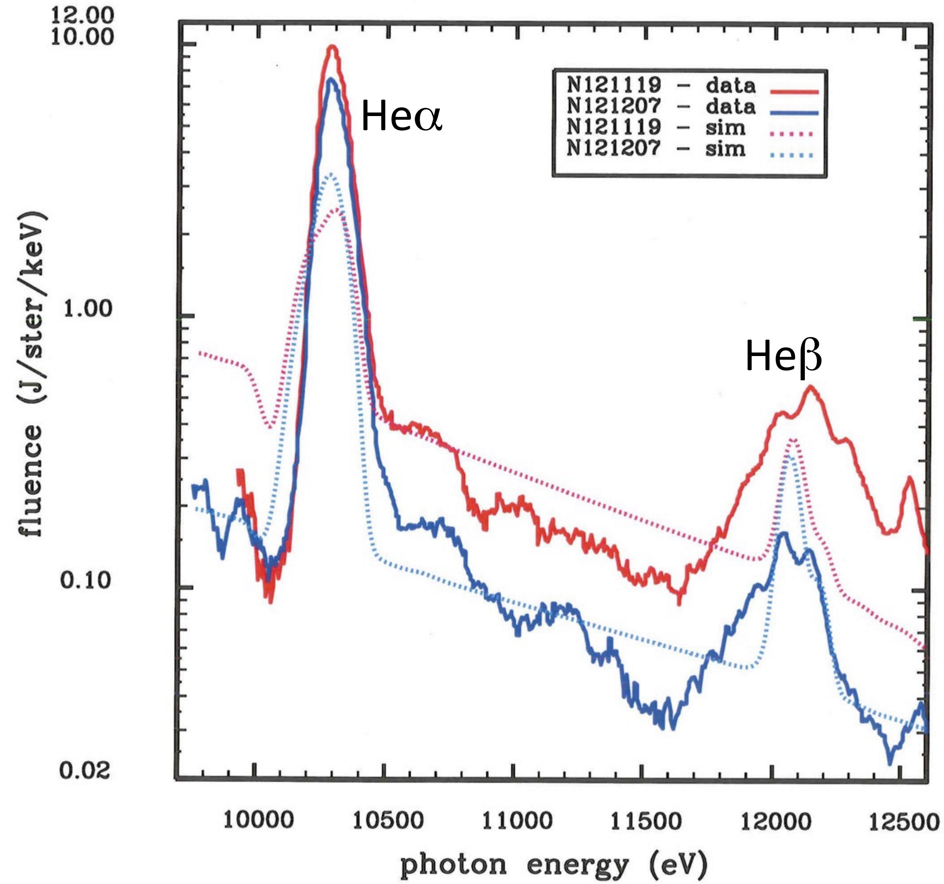


15 μm wide profile in wavelength direction



We used Supersnout spectra to assess Ge dopant conditions

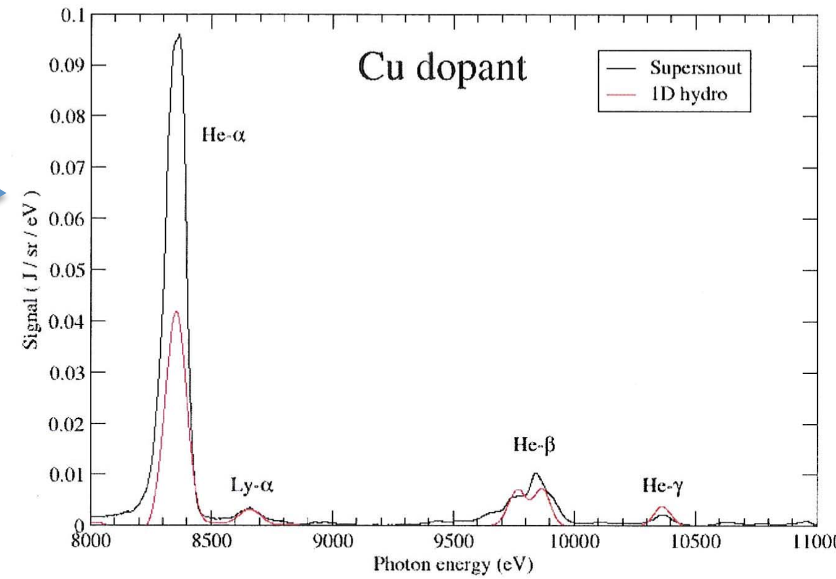
- Starting in November 2012, we used supersnout for absolutely calibrated dopant spectra
- Simulations and data show that Ge does not get hot enough (no Ly lines) to create MMI Te maps
- Simulations and data show Ge He-α and He-β lines
- We scaled simulated spectra near bang time to match continuum near 11200 eV
- Qualitative features are consistent with data, but He-α/He-β line ratios are off



Data courtesy S. Regan and M. Barrios

We match Cu spectra of the June 2013 shots

- We had two goals for June
  - Obtain "baseline" CD yield
  - Assess suitability of Cu as dopant material
- We matched supersnout spectra (sim=1.8 keV)
- We also predicted lack of Cu lines when dopant was buried 1 μm
- Subsequent spectral modeling (Schmitt talk) shows Fe is best dopant for MMI



Data courtesy S. Regan and M. Barrios

BACKUP

RAGE settings and resolution results

- In 1-D, mesh resolution is 0.25 μm; 2-D it is 1 μm
- Resolution studies in 2-D shows 10% change for factor of two increase in mesh resolution
- 1-D resolution study shows <10% change in yield for ±4x change in mesh size
- We have not used CPT yet

Other physical quantities

- Sound speed (*c*) (about 3×10^7 cm/s)
- Pressure (P=about 3×10^{13} dyne/cm^2)
- Density ~0.1g/cc in front of shock; 1.5 g/cc post shock
- Electron density ($n_e = 10^{23}$)
- Thermal Diff Coeff. About 40; Peclet # about 1000
- Euler # = (10^7 / {sqrt(3×10^{13} / 1.5) }) ~ 2.1
- Mix region Mach # ($10^6/3 \times 10^7$)~ 0.03 (not compressible)
- Turbulent Mach # ($10^7/3 \times 10^7$)~ 0.33 (borderline compressible)
- Atwood # (1.5-0.1)/(1.5+0.1)~ 0.88

Spectroscopy (and MMI) requirements

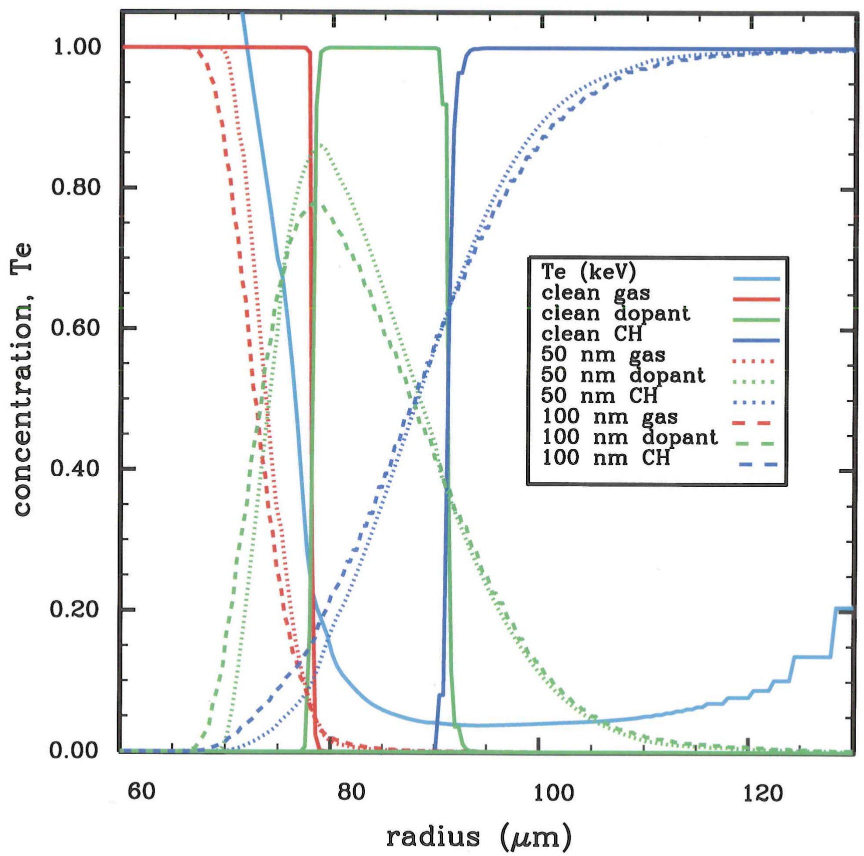
- Based on N121119, we need 1 J/ster for MMI visibility
- Spatial resolution of each MMI pixel needs to be <20μm (need 10-15 pixels to constrain shape)
- Average resolution ≤10μm (need for <20% radius widths azimuthally averaged)
- If we have 50 μm per pixel resolution, what does that tell us?
- If image is filled circle, then may be able to obtain 10 to 20 μm error

- If we have time-dependent/space-integrated spectra with MMI, then mix width resolution is YYμm
- Need sensitivity study on line strength and MMI images vs BHR

The amount of mix depends on the "scale" parameter

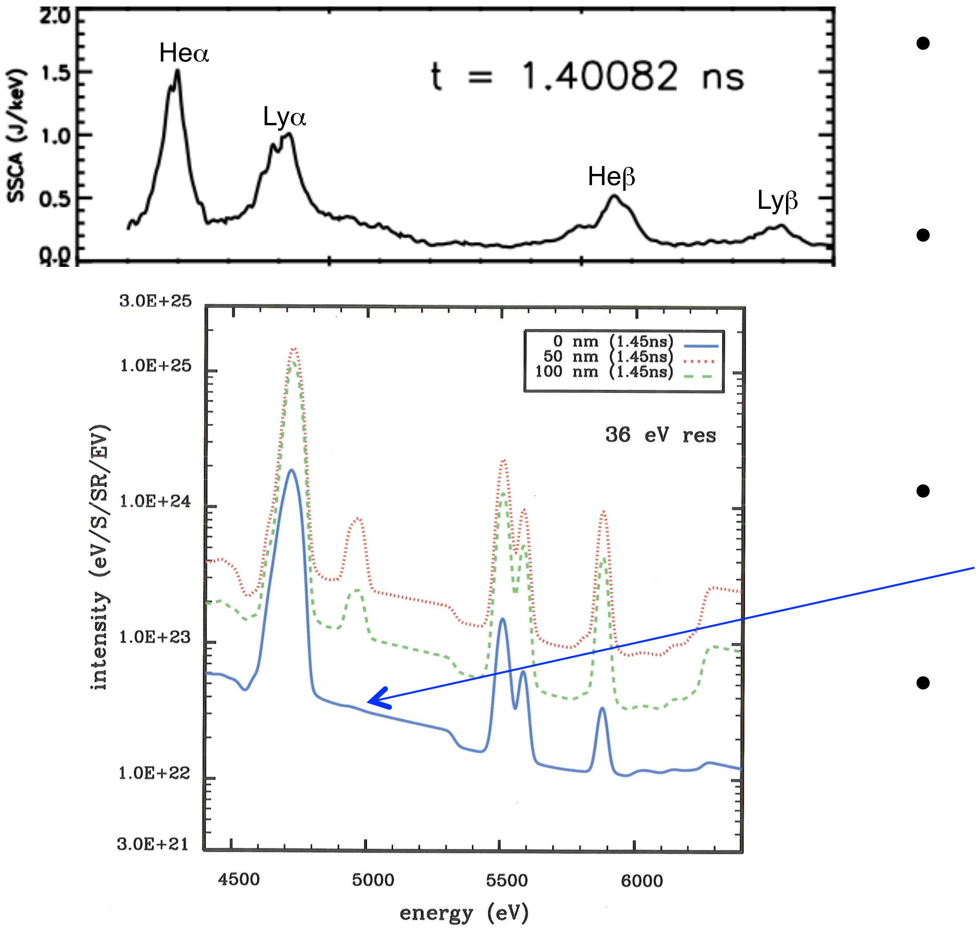
- **Our simulations are no mix (Eulerian advection), some mix (25 and 50 nm scale), and more mix (100 nm)**

run	Width (0.01-500eV)	Mix mass (ng)
clean	0.2 μm	10
10 nm	2.3 μm	158
25 nm	3.1 μm	212
50 nm	6.7 μm	244
100 nm	8.5 μm	275



Above 25 μm, material is spread out over wider region

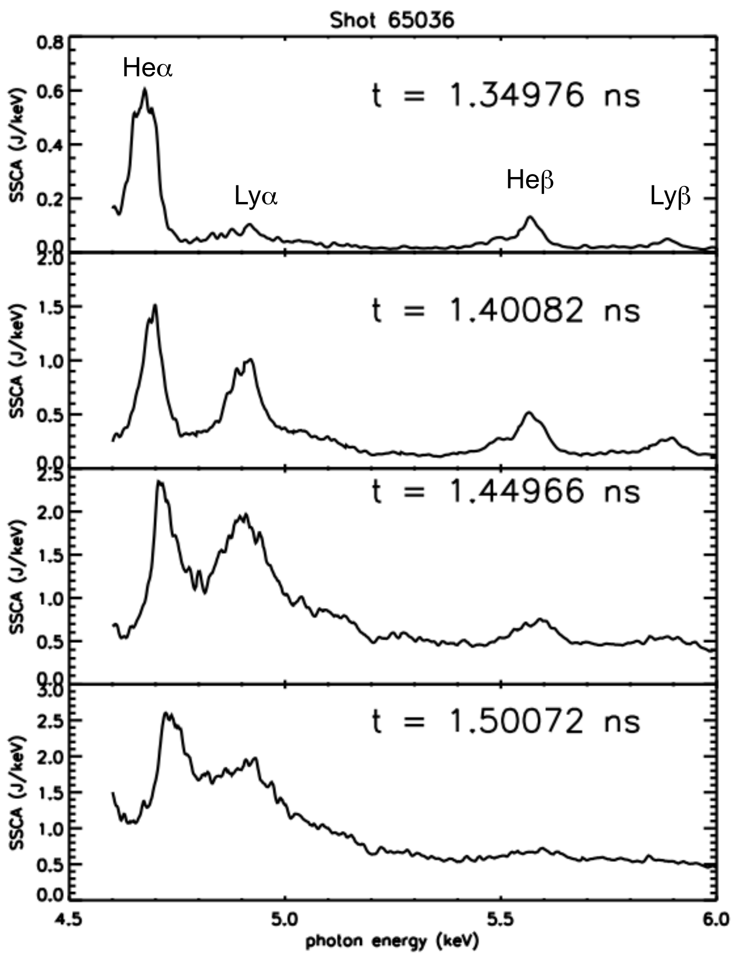
We can eliminate the no-mix simulation with streak spectra data

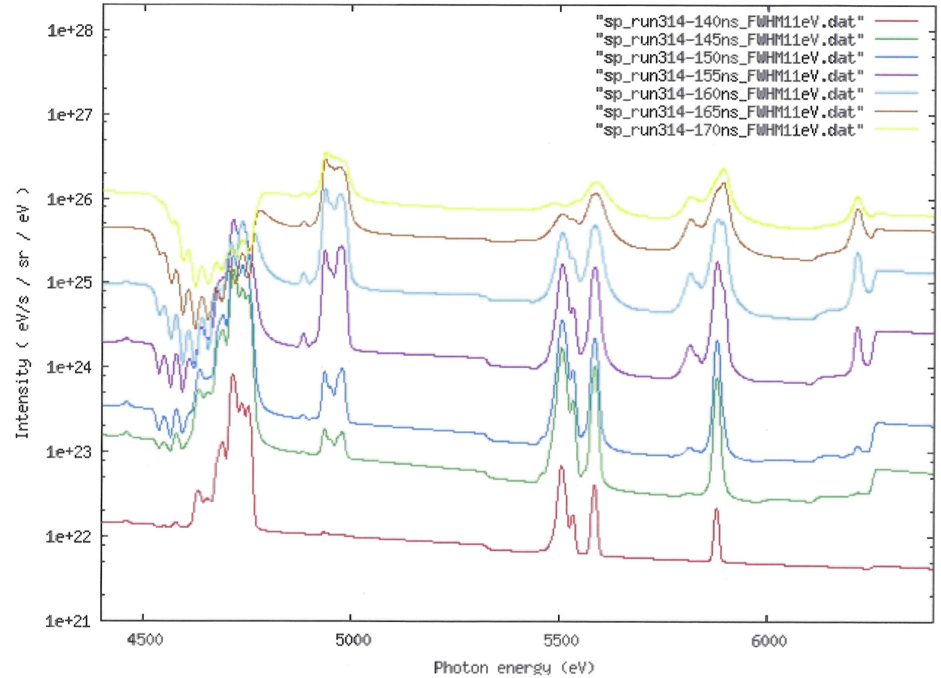


Notes: 1) The best match of simulation to data requires a 50 ps shift

- Here we compare streak spectra data from shot 65036 to three different mix width runs
- Simulation spectra from three different runs (no mix, some mix, and more mix) are in the bottom panel
- We can clearly rule out the no mix case, since no Ly-α line is present in the simulation
- There is too little difference between the two mix runs to differentiate

Simulations show similar time dependent behavior as data



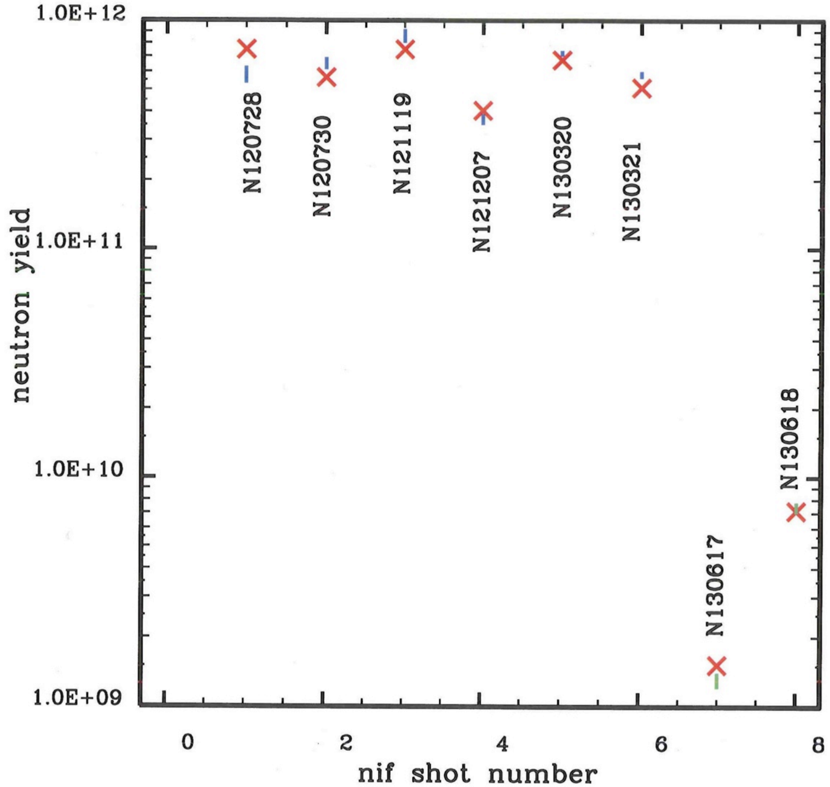


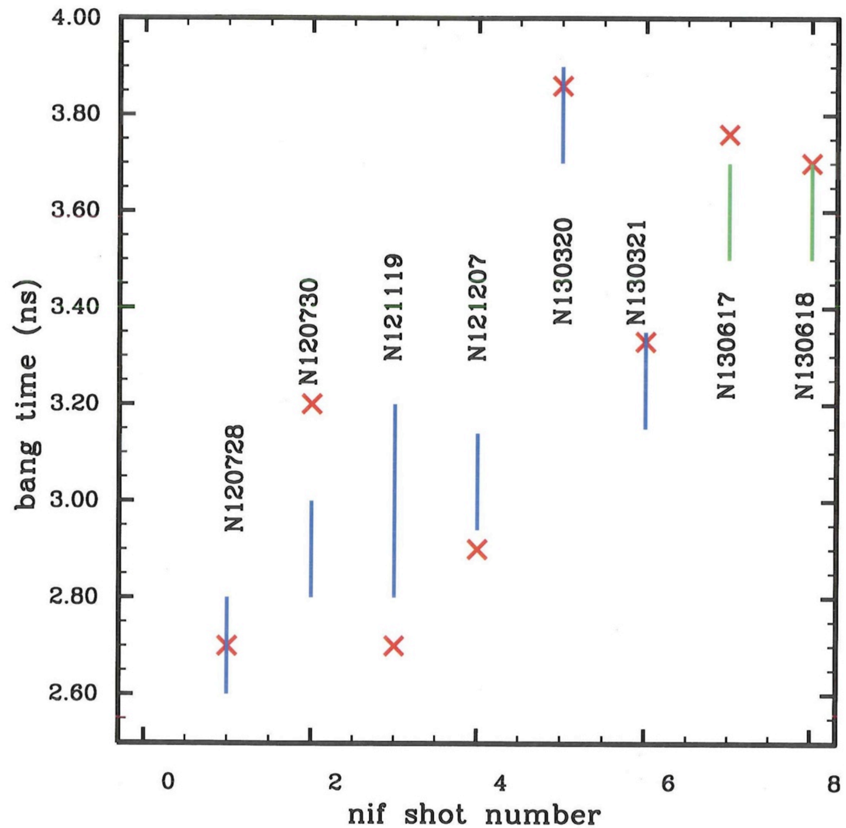
- The simulations appear to be 50ps later than data
- The simulations show the same rise of the Lyα line as the data
- The Lyman lines stay visible longer in simulations than in data

Note: 1.6x10-25 J/ns/keV = 1 eV/s/sr/eV

Post-shot comparisons of yield and t_{bang} match NIF data with a single set of BHR parameters

We use the same BHR-2 settings (50 nm; 10^{11}; AMP=0.8)for Omega and DIME shots





The yields are in or near experimental errors for a multiplier of 0.42

We match bang times to within 200 ps

Capsule specifications show we never shot the same thing twice

Shot (capsule#)	Dopant (conc)	Dopant (location)	thickness	diameter
N120728 (E-01)	Ge (1.9 atom%)	0 to 2.4 μm	40.5 μm	2261 μm
N120730 (F-01)	Ge (1.8 atom%)	0 to 2.6 μm	42.2 μm	2246 μm
N120730 groove	82 microns w	9.6 microns deep		
N121119 (E-02)	Ge (1.8 atom%)	0 to 2.4 μm	40.1 μm	2260 μm
N121207 (E-01)	Ge (1.4 atom%)	0 to 2.2 μm	44.4 μm	2262 μm
Ga layer	Ga (1.3 atom%)	5.2 to 7.4 μm		
N130320 (A-02)	Ge (2.1 atom%)	0 to 2.1 μm	41.0 μm	2260 μm
Ga layer	Ga (1.3 atom%)	5.1 to 6.7 μm		
N130321 (A-04)	Ge (2.4 atom%)	0 to 2.3 μm	41.5 μm	2271 μm
Ga layer	Ga (1.3 atom%)	5.3 to 6.9 μm		
N130617 (B-01?)	Cu (0.9 atom%)	0 to 1.08 μm	40.1 μm	2244 μm
CD layer	3.08 μm thick			
N130618 (C-01?)	Cu (1.16 atom%)	0.97 to 1.93 μm	38.1 μm	2328 μm
CD layer	2.77 μm thick			

Separated Reactant Data

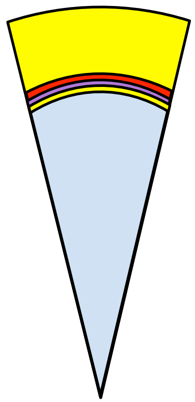
- CD+T_2 capsules (we have modeled these)
  - Wilson et al. (PoP, 18, 112707(2011)) – CD and CH +T_2 capsules on Omega with three thicknesses (modeled with RAGE)
  - LLNL MIXCAP results in many presentations (modeled with RAGE)

- CD+^{3}He capsules
  - Marshall et al. (PoP, 7, 2108 (2000))
  - Li et al. (PRL, 89, 165002 (2002)) – D^{3}He yield versus fill pressure
  - Radha et al. (PoP, 9, 2008 (2002)) – D^{3}He fill data used with DT and D_2 fill data to determine mix
  - Rygg et al. (PRL, 98, 215002 (2007); PoP 14, 056306 (2007)) – CH(D^{3}He) compared to CD(^{3}He) capsules (modeled with RAGE)
  - Rinderknecht et al. PRL (2014) submitted (modeled with RAGE)

DIME capsules have less intrinsic mix but similar yields to CDMIX

DIME uses 510 kJ 2.15 ns PDD pulse

OR 1350 μm
40 μm thick



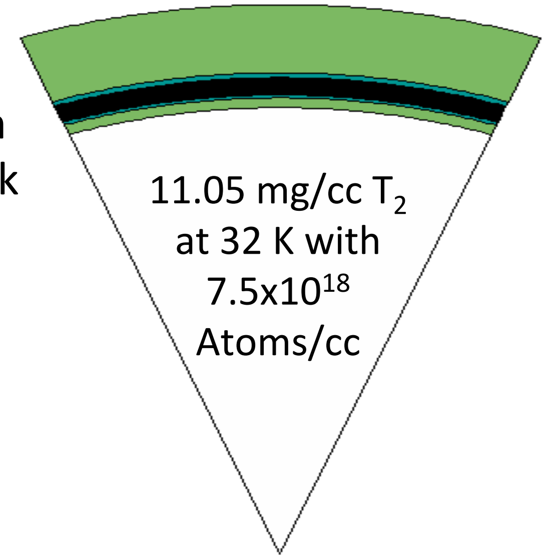
3 atm T_2 gas
at 298K
(ρ=0.625 mg/cc)

Cryo makes
no difference!

- Predicted DT yields ~2.1×10^{13}
- Predicted TT yields ~2×10^{13}
- Predicted T_{ion} values are 3.3(±0.5) keV
- Mix depth ≤1 μm
- DIME has little mix from imprint or CBET
- Single shock drive easier to model

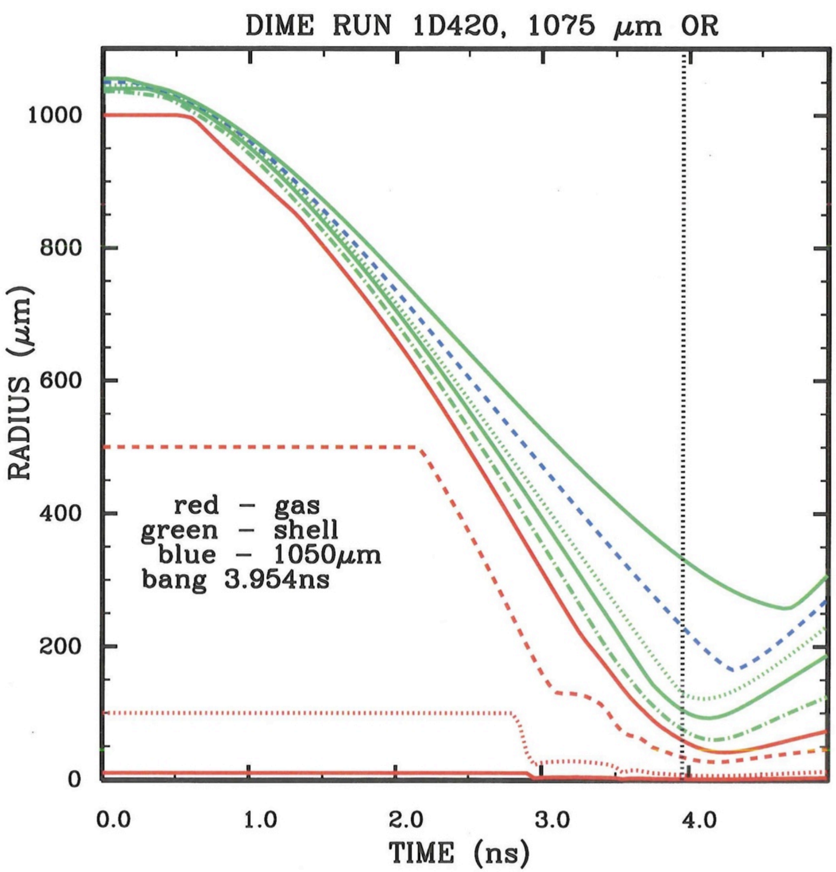
CDMIX uses ~20 ns 1.4 MJ NIC ID pulse

OR 1140 μm
210 μm thick

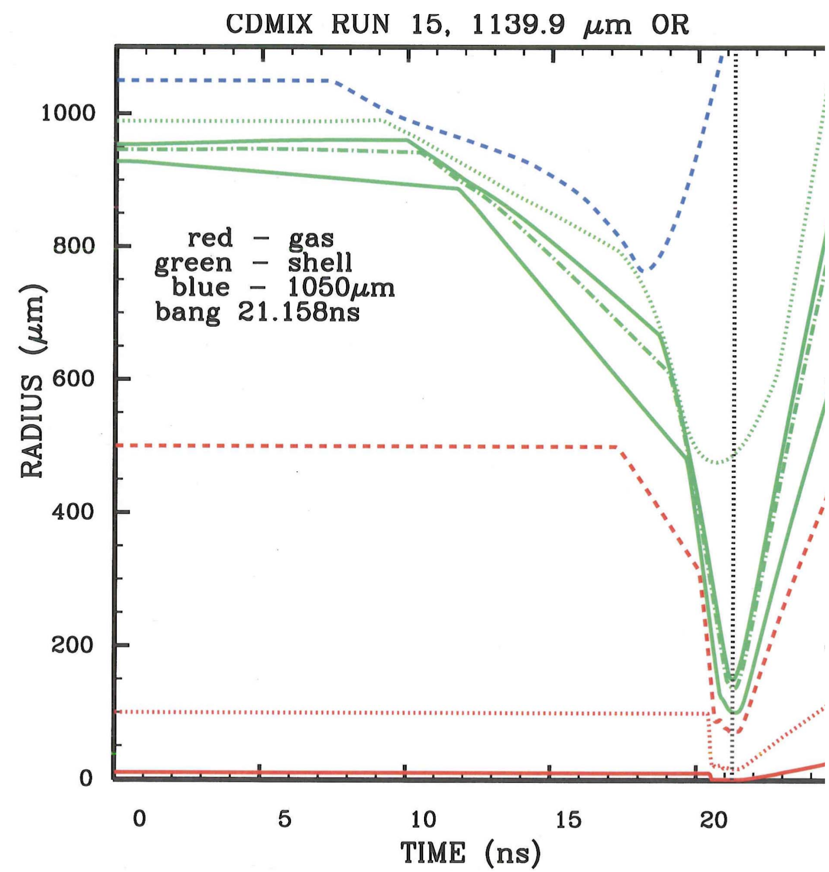


- Expt DT yields up to 2.4×10^{13}
- TT yields up to 2.3×10^{13}
- T_{ion} values up to 2.2 (±0.4) keV
- Mix depth ~2 μm
- CDMIX has "baseline" DT yield of 7×10^{12} from imprint/feedthrough
- Must model multiple shock drive

The DIME capsule has a less complicated shock structure than CDMIX



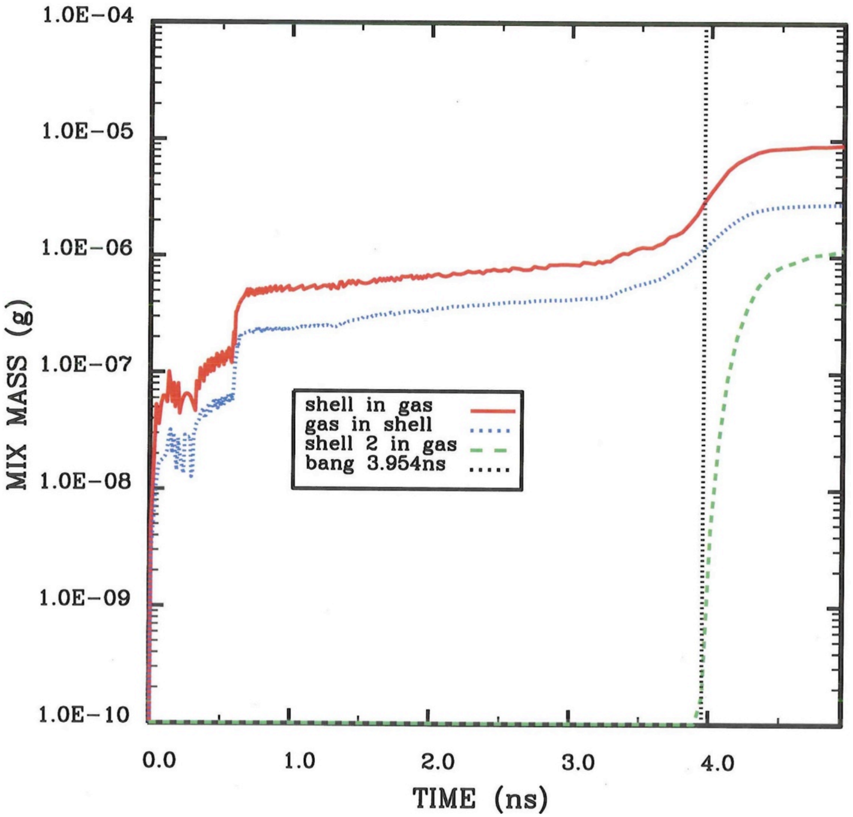
OR 1075 μm, rad at bang time is 76 μm, min radius 60 μm at 4.18 ns



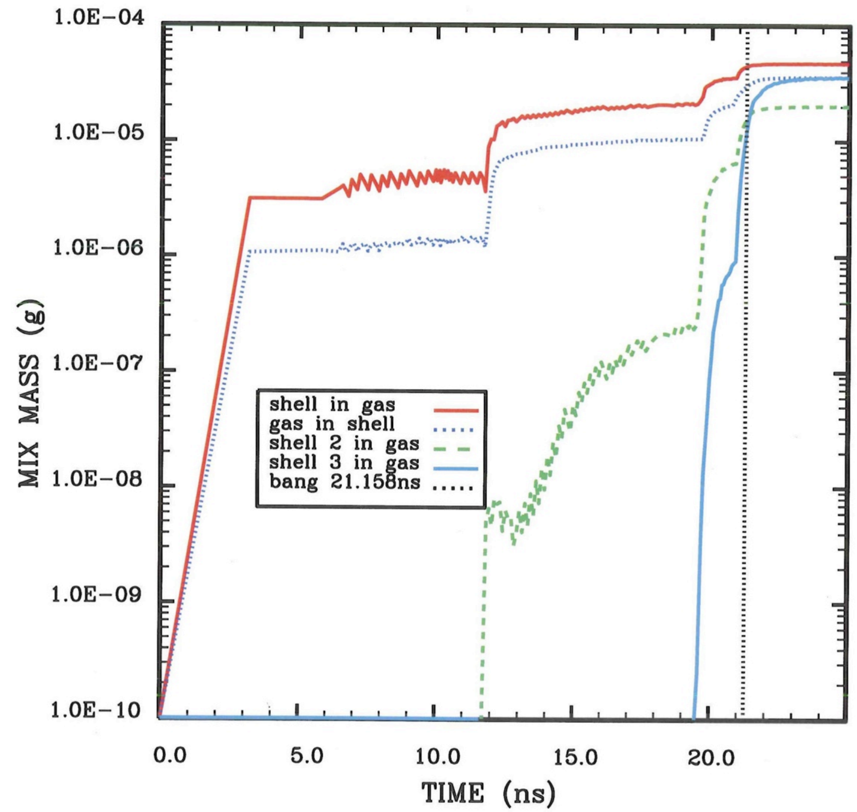
OR 1140 μm, rad at bang time is 105 μm, min radius 102 μm at 21.34 ns

The DIME capsule has much less mix than CDMIX

The reduced amount of mix in DIME is borne out by mix depth; DIME is <1μm, CDMIX is ~2μm



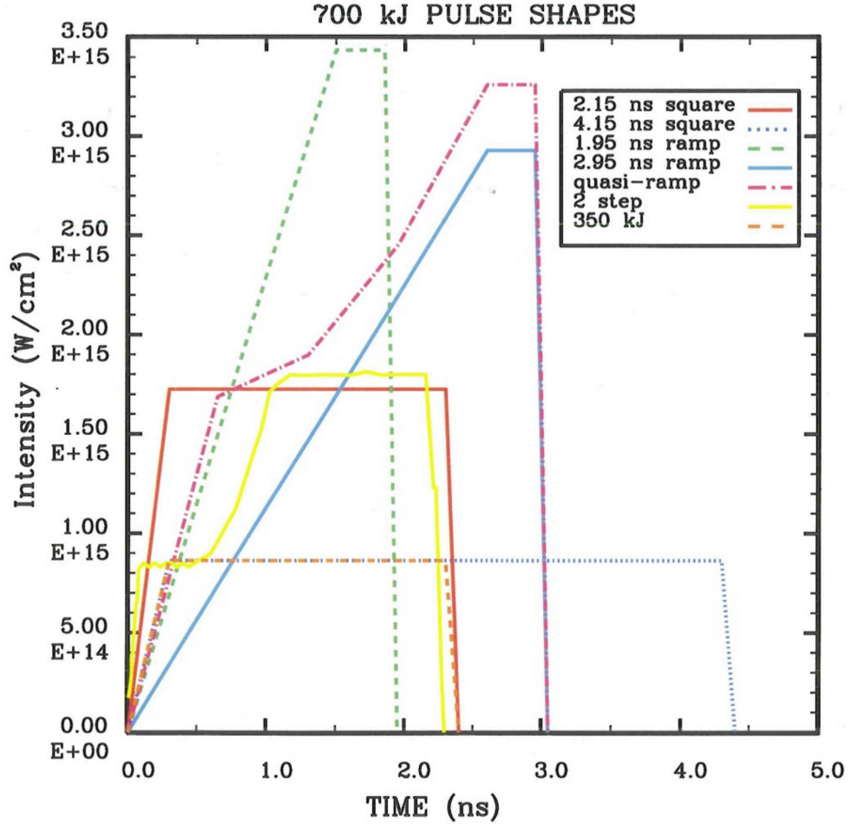
Gas mass $1.2x10^{-6}$; shell $3.0x10^{-6}$
20% of 1st shell mixes into gas, <1% of 2nd shell mixes



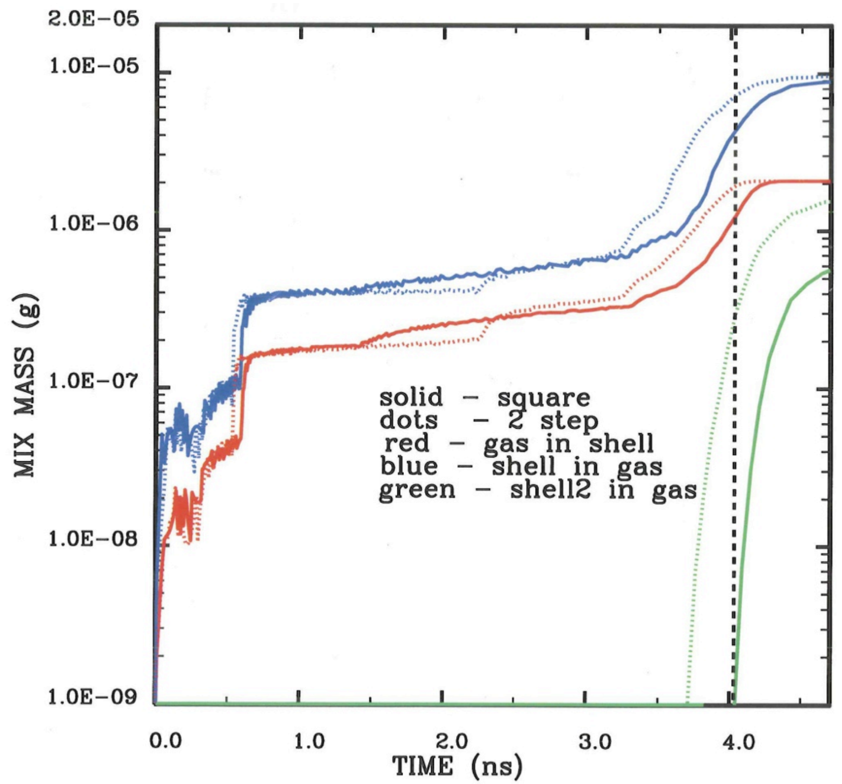
Gas mass $3.9x10^{-5}$; shell $5.0x10^{-5}$
87% of 1st shell mixes into gas, 60% of 2nd shell mixes

We predict similar performance with a square or 2-step pulse

We examined several pulse shapes

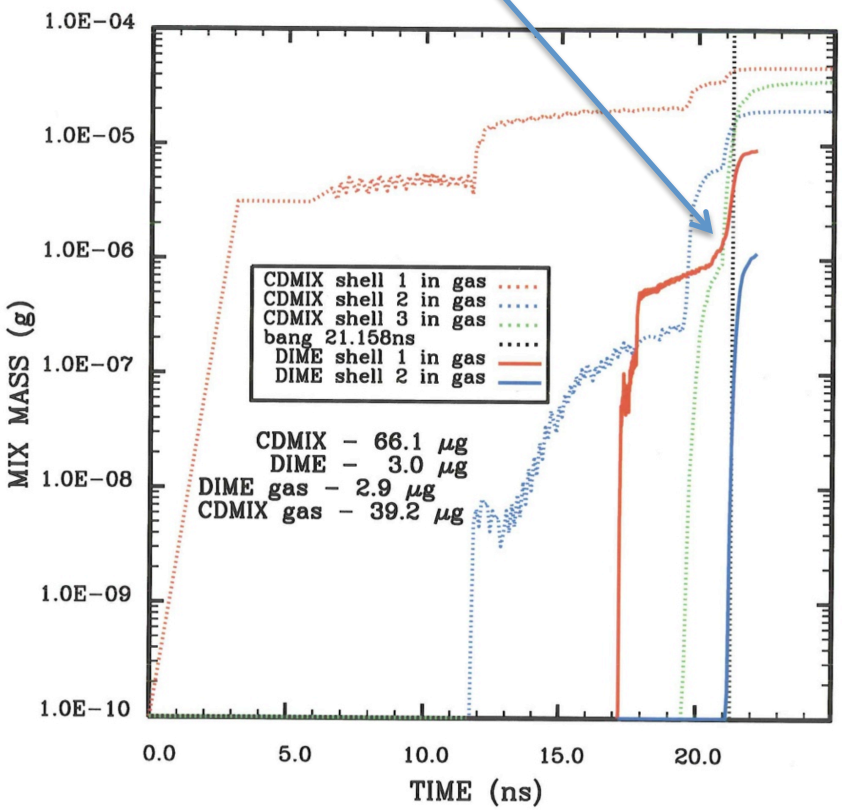


The amount of mix is similar for a square or 2-step pulse

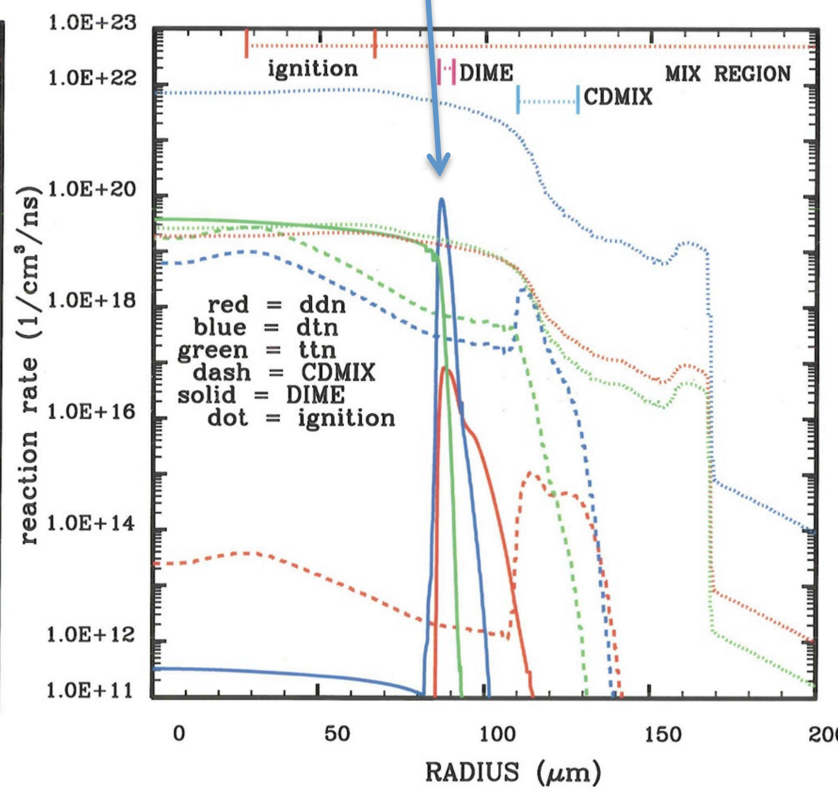


The simple pulse shape of the DIME capsule leads to less mix and narrow burn region

About 20% of shell mixes into gas of DIME capsule



A lack of feedthrough mix leads to narrow burn region



Key performance – CDMIX Campaign summary

	N130614 8um offset CD layer	N130612 4um offset CD layer	N130512 2um offset CD layer	N130315 2um offset CD layer	N130317 1um offset CD layer	N130510 Inner CD layer	N121125 Inner CD layer
Capsule fill	1.0 TT w 0.08-0.13%D	1.0 TT w 0.08-0.13%D	1.0 TT w 0.08-0.13%D	1.0 TT w 0.08-0.13%D	1.0 TT w 0.08-0.13%D	1.0 TT w 0.08-0.13%D	1.0 TT w 0.08-0.13%D
Hohlraum and Capsule	3.375 mm LEH 1.5 MJ Au, 1xSi, T0	3.375 mm LEH 1.5 MJ Au, 1xSi, T0	3.375 mm LEH 1.5 MJ Au, 1xSi, T0	3.375 mm LEH 1.5 MJ Au, 1xSi, T0	3.375 mm LEH 1.5 MJ Au, 1xSi, T0	3.375 mm LEH 1.5 MJ Au, 1xSi, T0	3.375 mm LEH 1.5 MJ Au, 1xSi, T0
T_i (keV) [ntof]	3.4 ± 0.1	2.85 ± 0.13	2.6 ± 0.1	2.2 ± 0.2	2.1 ± 0.3	2.2 ± 0.1	2.0 ± 0.1
DT Yield	0.67 ± 0.04 e13	0.72 ± 0.03 e13	1.3 ± 0.04 e13	0.90 ± 0.03 e13	2.0 ± 0.06 e13	2.5 ± 0.08 e13	2.4 ± 0.07 e13
TT Yield	2.5 ± 0.2 e13	2.2 ± 0.2 e13	3.2 ± 0.2 e13	2.0 ± 0.2 e13	2.4 ± 0.2 e13	1.8 ± 0.2 e13	2.0 ± 0.2 e13
DSR (%)	0.88 ± 0.17	0.95 ± 0.13	1.0 ± 0.1	1.2 ± 0.4	1.2 ± 0.2	1.0 ± 0.1	1.2 ± 0.4
X Bangtime (ns)	22.6 ± 0.0	22.39 ± 0.0	22.53 ± 0.02	22.53 ± 0.03	22.55 ± 0.04	22.53 ± 0.02	22.50 ± 0.05
X-ray burn (ps)	323 ± 16	319 ± 15	320 ± 30	316 ± 9	309 ± 11	312 ± 30	307 ± 12
X-ray P_0 (µm)	64 ± 5†	63 ± 5	59 ± 2†	53 ± 4†	59 ± 3†	55 ± 2†	60.2 ± 4†
X-ray P_2/P_0 (%)	23 ± 6†	24± 4	15 ± 2.4†	8.4 ± 2.6†	1.3 ± 1.9†	16 ± 1.1†	13 ± 0.7†
X-ray M_0 (µm)			58± 1.4†	65 ± 6†	65 ± 5†	57± 8†	NA
X-ray M_4/M_0 (%)			2.8 ± 0.3†	4 ± 4†	4.7 ± 3.6†	1.9 ± 0.9†	NA

Updated by Peggy Kervin

† from hGXI2 or HGXI1

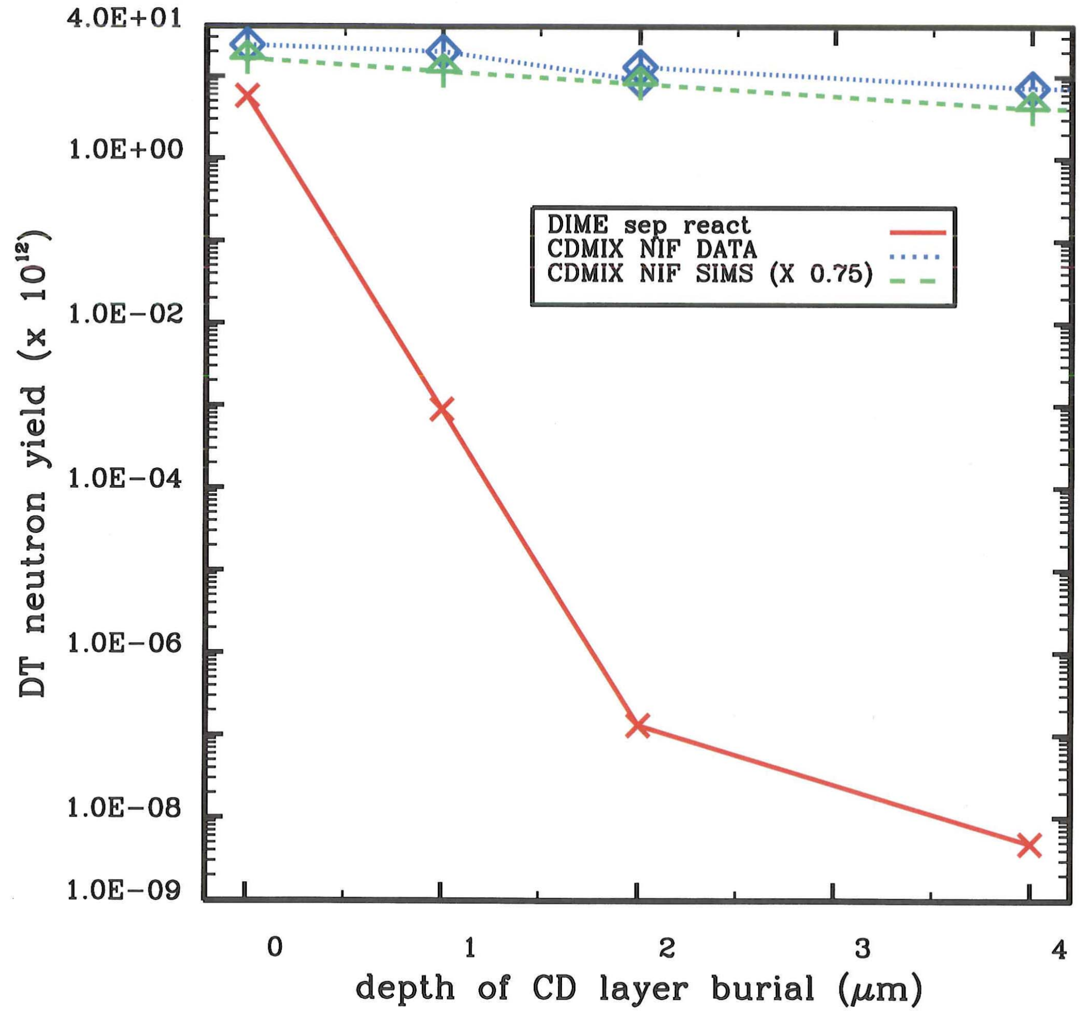
Key performance – CDMIX Campaign summary

	N130317 6.6 Å, 8.1 Å 3.375 mm LEH 1.5 MJ Au, 436 TW, 2 ns 1xSi, T0, 1um offset CD	N130315 6.6 Å, 8.1 Å 3.375 mm LEH 1.5 MJ Au, 436 TW, 2 ns 1xSi, T0, 2um offset CD	N121125 6.6 Å, 8.1 Å 3.375 mm LEH 1.5 MJ Au, 436 TW, 2 ns 1xSi, T0, Inner CD layer	N121119 6.6 Å, 8.1 Å 3.375 mm LEH 1.5 MJ Au, 436 TW, 2 ns 1xSi, T0 No CD layer	N120904 6.6 Å, 8.1 Å 3.375 mm LEH 1.5 MJ Au, 436 TW, 2 ns 1xSi, T0 No CD layer
Capsule fill	1.0 TT w 0.08-0.13%D	1.0 TT w 0.08-0.13%D	1.0 TT w 0.08-0.13%D	1.0 TT w 0.08-0.13%D	1.0 TT w 0.08-0.13%D
T_i (keV) [ntof]	2.1 ± 0.3	2.2 ± 0.2	2.0 ± 0.1	3.4± 0.1	3.4 ± 0.4
DT Yield	2.0 ± 0.07 e 13	9.0 ± 0.3 e12	2.4 ± 0.07 e13	4.0 ± 0.1 e12	4.2 ± 0.13 e12
TT Yield	2.2 ± 0.4 e13	2.1 ± 0.4 e13	2.3 ± 0.3 e13	1.9 ± 0.3 e13	1.9± 0.2 e13
DSR (%)	1.2 ± 0.2	1.2 ± 0.4	1.2 ± 0.4	1.2 ± 0.5	
X Bangtime (ns)	22.55 ± 0.04ns	22.53 ± 0.03ns	22.50 ± 0.05	22.55 ± 0.07	22.58 ± 0.07
X-ray burn (ps)	309 ± 11	316 ± 9	307 ± 12	267 ± 36	291 ± 60
X-ray P_0 (μm)	59 ± 3†	53 ± 4†	60.2 ± 4†	59.8 ± 3.6†	56.3 ± 10.0†
X-ray P_2/P_0 (%)	1.3 ± 1.9†	8.4 ± 2.6†	13 ± 0.7†	12.3 ± 0.7†	10.0 ± 1.4†
X-ray M_0 (μm)		65 ± 6†		59 ± 3.4†	69 ± 2.5
X-ray M_4/M_0 (%)		8 ± 2†		1.5 ± 5.2†	2.1 ± 3.2

† from hGXI2 or HGXI1

Nominal BHR-2 model predicts a very different DT yield behavior between CDMIX and DIME shots

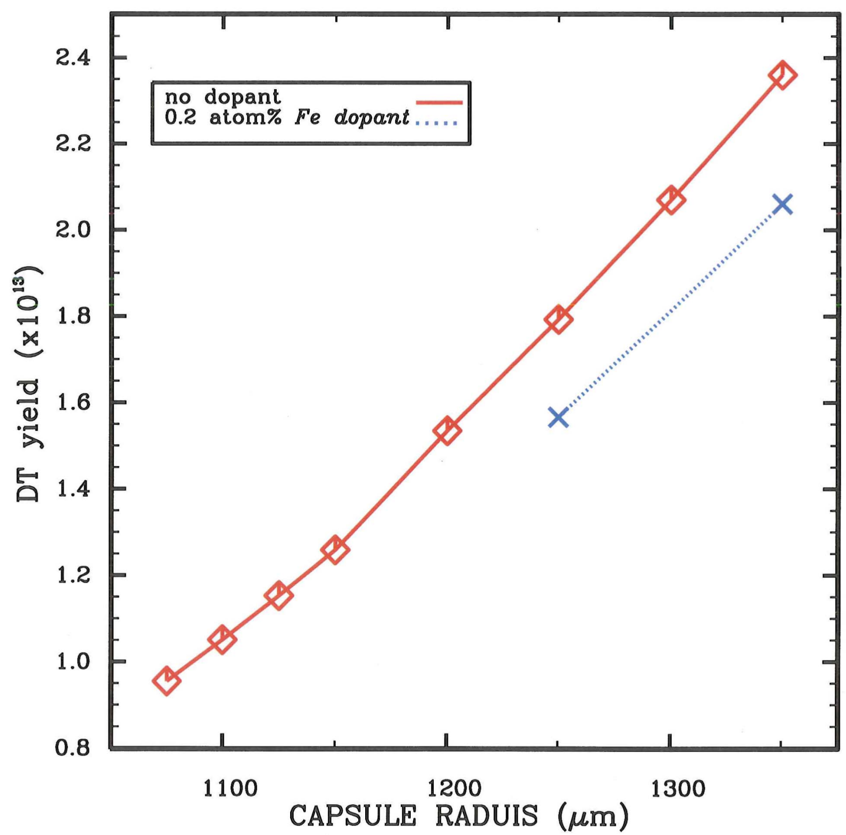
- The CDMIX capsules have TT yields near 2×10^{13} neutrons
- The DIME capsules have TT yields near 10^{13} neutrons
- The plot shows that the DT yields have very different trends
- The predicted DIME point design yield falls off rapidly with burial depth for two reasons
  1. There is less CD being mixed into the T_2 gas
  2. With increasing DOB, the CD that is being mixed is too cool to burn
- Our best models to date predict yields of ~2×10^{13} DT neutrons for a 510 kJ square pulse
- Need a 1350 μm radius capsule with 510 kJ drive



Nominal BHR-2 uses SKE=10^{11} and scale = 50 nm

We predict yields up to $2x10^{13}$ neutrons with dopant

- "Baseline" 1350 μm OR capsule design and gas fill (3 atm T_2) predict $2.1x10^{13}$ neutrons
- 0.1 to 0.2 atom% Cu or Fe incurs 8 to 15% yield penalty
- The 1350 μm capsule uses 510 kJ of energy; same laser intensity on capsule as 350 kJ shot at 1125 μm OR



Separated Reactant Comparison (5 atm T_2)

run	dopant	Yield (10^{12})	Bang (ns)	Dop Te	DD Ti	DT Ti
411	No Cu	9.40	4.02	1.05	1.23	3.04
427	Cu, 0.1 atom%	8.64	4.02	1.15	1.51	3.10
428	Cu, 0.2 atom%	8.04	4.02	1.14	1.46	3.08
429	Cu, 0.5 atom%	6.82	4.02	1.10	1.35	3.06
430	Cu, 0.9 atom%	5.93	4.02	1.06	1.25	3.05
402	Cu, 1.0 atom%	5.74	4.02	1.05	1.23	3.04
431	Cu, 1.1 atom%	5.62	4.02	1.05	1.22	3.01

The Cu layer is 1 μm thick and next to the gas
The drive is 350 kJ
"Te" is electron temperature and "Ti" is ion temperature; all values are in keV

Yield drops significantly when concentration >0.5 atom%, so want less than this

We could have had a platform ready in 5 to 7 shots with the PDD configuration

1. CD+dopant next to H_2 gas – calibrate DD yield for new size capsule and dopant concentration
2. CD+dopant 1μm from H_2 gas – confirm negligible feedthrough of dopant into gas
3. CH+dopant 1μm from T_2 gas – obtain “baseline” T_2 yield
4. CD next to T_2 gas – baseline mix yield + calibrate neutron imager and MMI
5. CD+dopant next to T_2 gas – assess affect of dopant + calibrate neutron imager and MMI

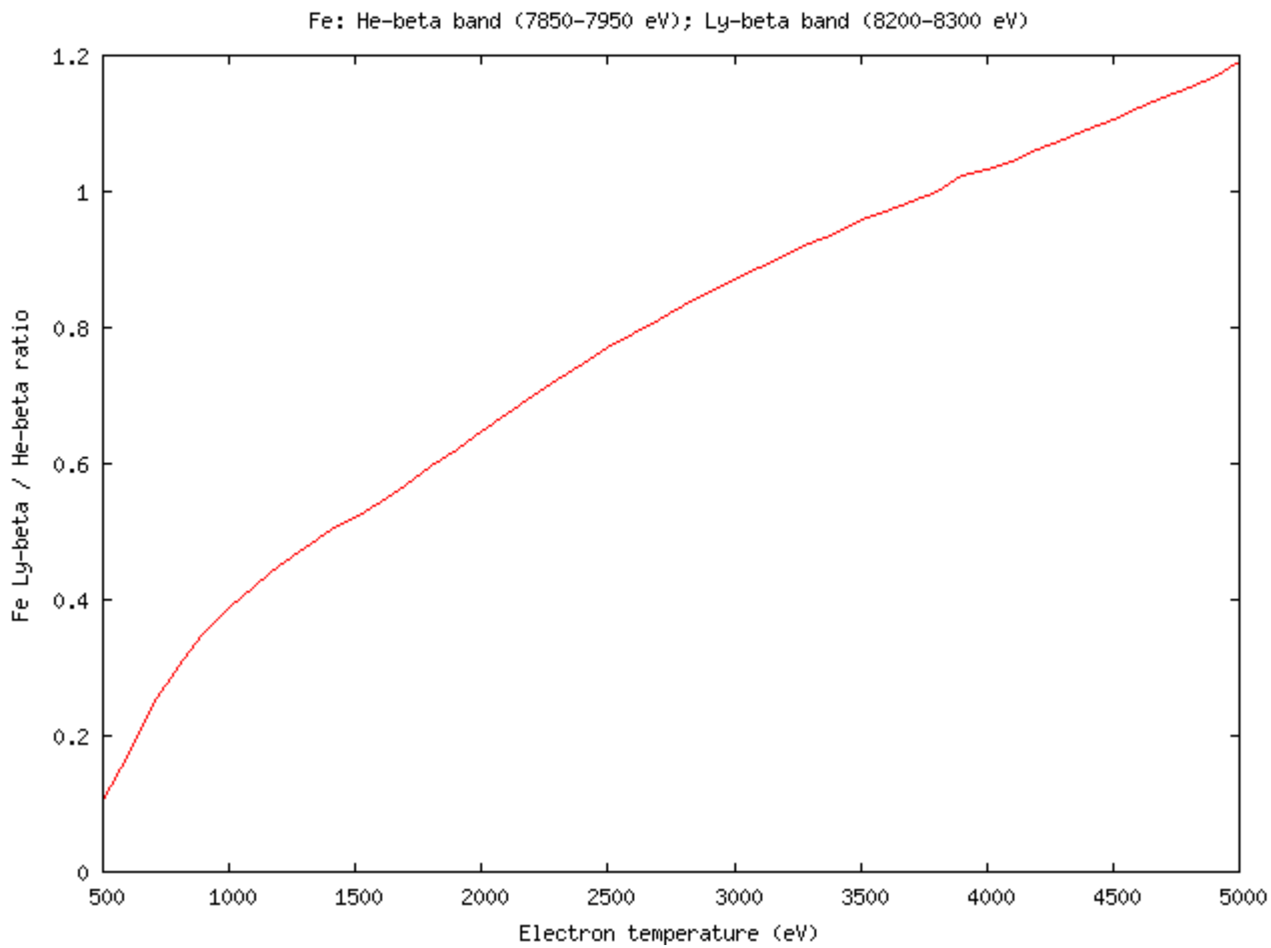
- Preliminary design work done; need detailed design and max cred yield work (HYDRA for symmetry and RAGE for rest)
- We should repeat some of these shots to obtain shot to shot variation

- The above shots are needed to establish the platform; subsequent shots would explore parameter variations to constrain PDF burn model

Indirect drive would require at least 4 to 8 shots and much new modeling

- We would need to spend considerable time on hohlraum design with HYDRA
- Indirect drive shots would need to address (may have been done by LLNL):
  - Drive shape and hohlraum emission spectrum (2 shots)
  - 1 backlit shot for implosion r vs t needed?
  - Add diagnostic "windows" to hohlraum for extra data (2 shots CH shell with dopant to assess symmetry and emission)
  - If there are symmetry or diagnostic perturbation issues, we would need extra shots to address/mitigate these issues
- Then
  - 1 shot with CD next to H_2 gas for background D_2 yield
  - 1 shot with CD(dopant) next to H_2 gas to assess dopant effect
  - 1-2 shots with CH shell and T_2 for "baseline" T_2 yield
  - 1-5 shots with buried CD layer and T_2 to determine mix depth, calibrate NI and MMI
- Total is at least 4 to 8 shots for ID and a DIME capsule

Line ratios vs. Te link uncertainties

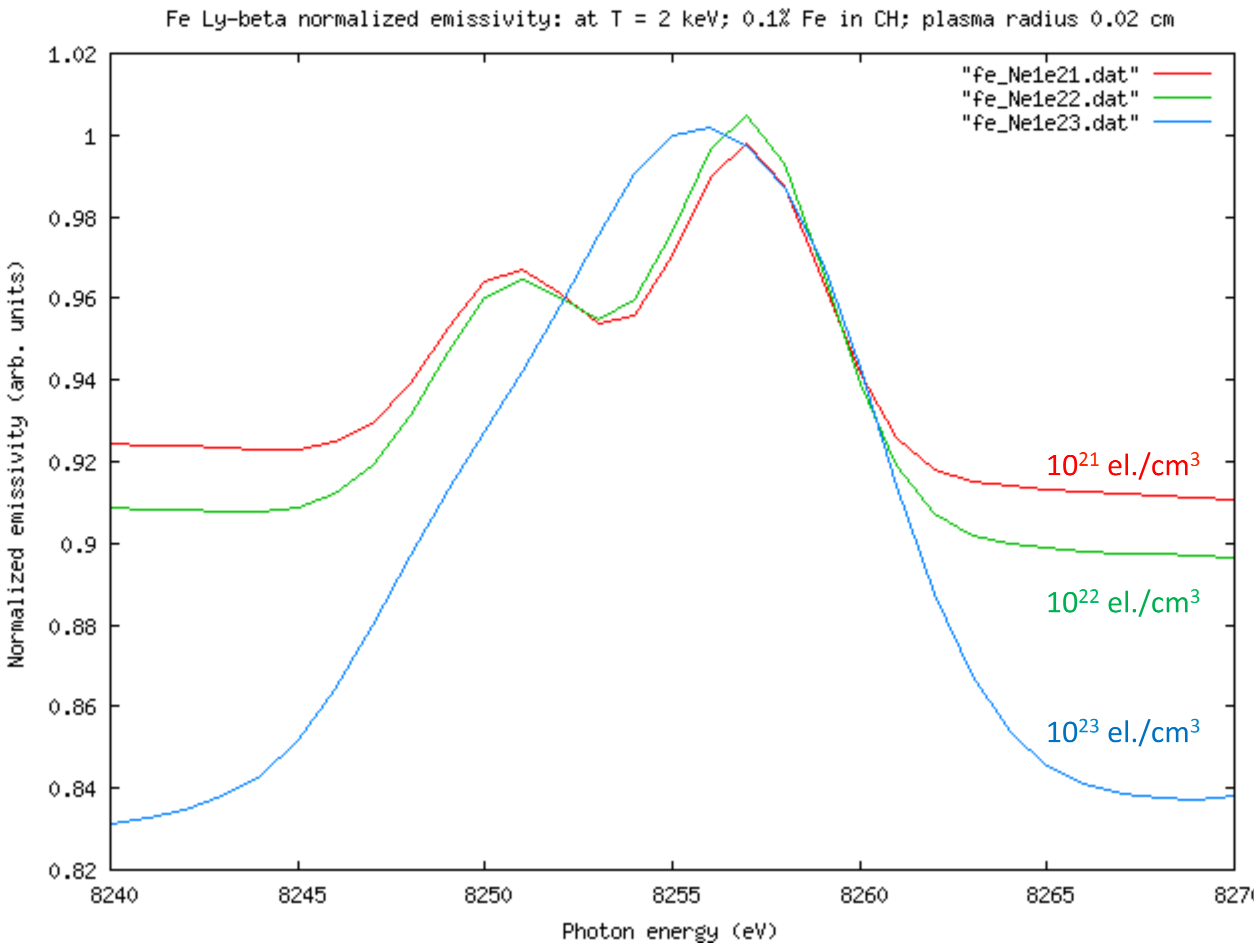


Te(eV)	ratio
2000	0.647067
2100	0.673479

At 2 keV, ΔTe ~ 100 eV ⟷ Δratio ~ 0.03

Near constant slope above 1 keV says same requirement at all temps

Stark broadening of the Fe Ly-β line illustrates Ne diagnostics



Will the NIF MMI have sufficient photon-energy resolution to detect this broadening?