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High-density carbon (HDC) capsule designs for a- heating and for ignition

D. Ho

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High-density carbon (HDC) capsule designs for α-heating and for ignition

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Darwin Ho

In collaboration with:
S. Haan, L. Berzak Hopkins, J. Milovich, J. Salmonson, G. Zimmerman, L. Benedict, J. Biener, C. Cerjan, D. Clark, E. Dewald, T. Doeppner, J. Edwards, S. Le Pape, T. Ma, A. Mackinnon, M. Marinak, J. McNaney, N. Meezan, S. Ross, R. Tommasini, K. Widmann, D. Young

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LLNL

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Outline of this presentation

- Advantages and disadvantages of high-density carbon (HDC) ablator
- HDC designs with 2, 3, and 4 shocks: performance comparison
- Shot summary and data analysis for HDC 4-shock DT Symcap N130628 shows no shell breakup with a 6.5 Mbar 1st shock
- 2-shock designs:
  - obtain an accurate fds source by matching simulation to 2-shock DD Symcap using near-vacuum hohlraum (shot N130813).
  - capsule optimization for obtaining:

neutron yield ~ 1.e16
By optimizing pulse to prevent burn through

→

neutron yield ~1.e17
By lowering the foot and stretching the pulse to lower the fuel entropy. Thicker ablator to improve Atwood number

→

neutron yield 1.e18
By stretching the pulse further to minimize coasting

- NLTE modeling of W and Si radiation in hot spot: simulations using NLTE modeling show W radiates considerably less than LTE and implosion can tolerate similar amounts of Si-doped or W-doped HDC ablator material

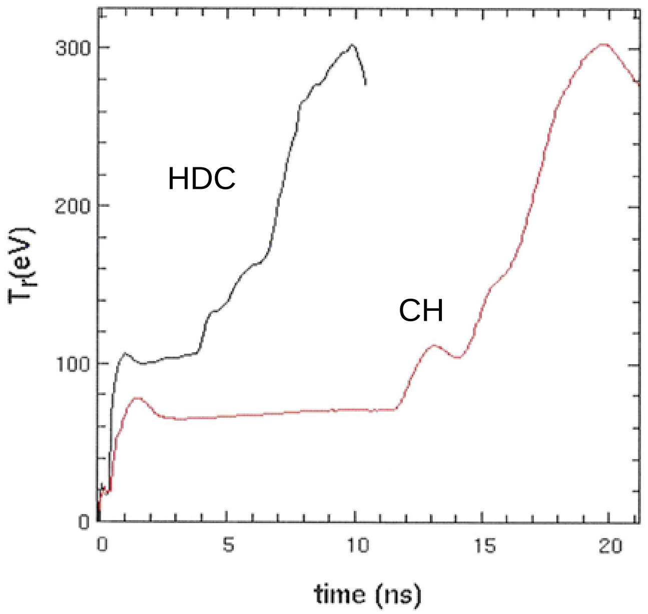
HDC has several advantages and challenges as an ablator for ignition capsules

NIF

Advantages:

- **HDC Symcap shots N130628 and N130813 have high neutron yield of 1.7×10^{15} and record Trad coupling efficiency of 98%, respectively. (Ross et al. this conference).**
- **HDC ablators fabricated using CVD deposition have surfaces that are smoother than Be or CH.**
- **HDC capsules have higher velocity than Be and CH capsules. This is because for the same outer radius, HDC's thinner and denser shell (3.32 g/cc) absorbs more energy.**

Tr vs time



- **High HDC density provides large hydrodynamic impedance mismatch which allows strong 1st shock (> 10 MB) in HDC while fuel entropy can still remain relatively low. Strong 1st shock also shortens the laser pulse.**
- **Laser pulse for HDC is short compared to that for Be and CH capsules. This allows the use of near-vacuum hohlraum and can reduce the risk of LPI.**

Challenges:

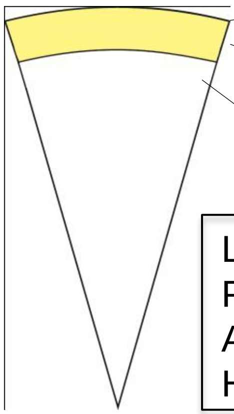
- **First shock needs to be stronger than 7 Mbar for uniformity of 1st shock velocity.**
- **Shorter pulse creates an elevated level of "M-band" radiation --- non-thermal (> 1.8 keV) hard X-ray --- which requires more dopant.**

1-D neutron yield of 1.7×10^{15} from DT-filled Symcap using HDC ablator (shot N130628) shows that HDC can tolerate strong 1st shock of 6.5 Mbar without shell breakup

Main result:

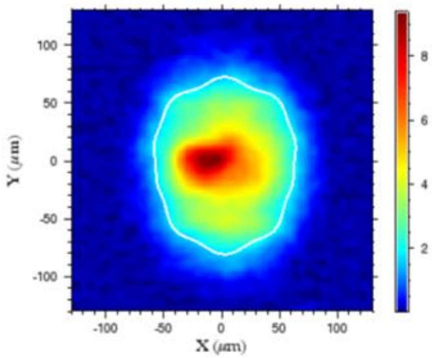
- DT yield ~ 1.7×10^{15}
- Tion ~ 2.8 keV
- P2/P0 ~ 14%

capsule configuration for shot N130628



Laser energy 1.24 MJ
Peak power 350 TW
Au hohlraum dia. 5.75 mm
Hohlraum fill 1.2 mg/cc

x-ray image time integrated P2/P0 = 14%



Parameters from 1-D capsule-only simulation are in good agreement with measurements

	measured	Calculated
Neutron yield (e15)	1.67	1.74
Burn wt. Ti (keV)	2.85	2.56
Burn wt. P (Gbar)	32.5*	30.1
Burn wt. density (g/cc)	14.6*	15.7
DSR (%)	0.96	1.06 (from C)
ρr (hot spot) (g/cm^2)	0.09*	0.13
ρr (HDC shell to ablator front)		0.52
Burn width (fwhm) (ps)	370	361
Max. shell velocity (10^7 cm/s)	2.5	2.35
KE at max shell velocity (kJ)		20.1
Hot spot neutron 13 -15 (MeV) radius (μm) to 17%	57	64
Convergence ratio at peak eprodr		14
Mass remaining at vpeak (%)	12.5	19.3
Initial gas density (mg/cc)	7.85	7.85
Bangtime (ns)	12.56	12.58

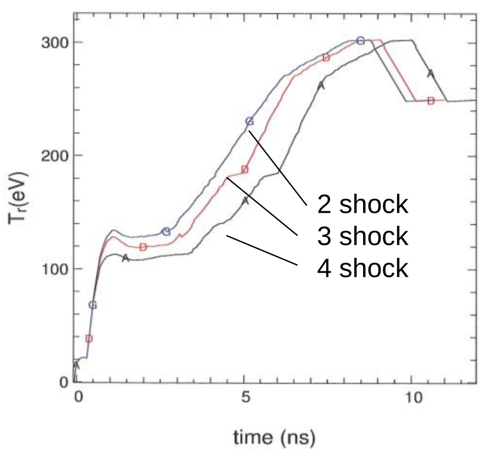
HDC designs with 2, 3, and 4 shocks: performance comparison --- low adiabat design gives higher yield but more RTI

- 4-shock design has lowest fuel adiabat and the highest 1-D margin
- 2-shock has the lowest growth factor and the shortest pulse length which allows the use of near-vacuum hohlraum. 2-shock is currently the design of choice for obtaining α heating in the near term.

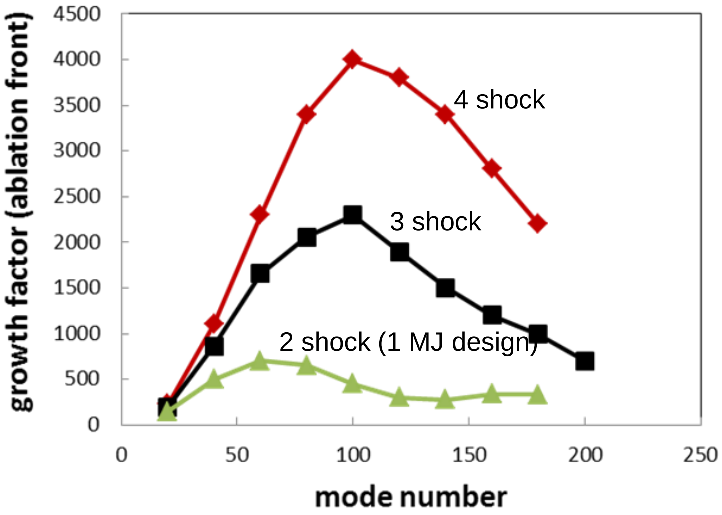
HDC ignition designs (0.25 at.% W doped)

No. of steps in Tr profile	4	3	2
1st shock strength (MBar) (outer ablator/inner ablator)	7	12.5/10	14/12
Yield (MJ)	19.7	17.2	13.5
Bangtime (ns)	11.06	10.1	9.6
Energy abs. (kJ)	206	207	208
Peak vel (km/sec)	380	383	380
Stagnation pressure (Gbar)	763	635	515
Fuel ρR (g/cm^2)	1.42	1.25	1.0
Adiabat	1.53	2.01	2.24
Conv. ratio to hot spot @ ignition	33.0	31.8	25

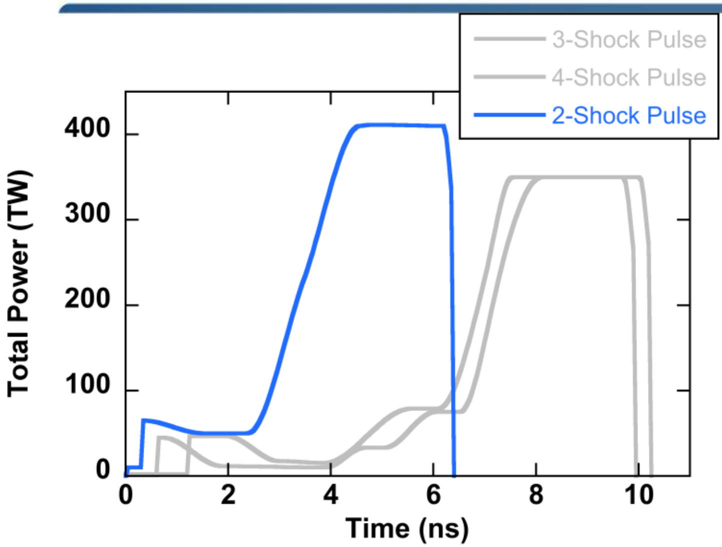
Tr profiles for 2, 3, 4 shock HDC capsules

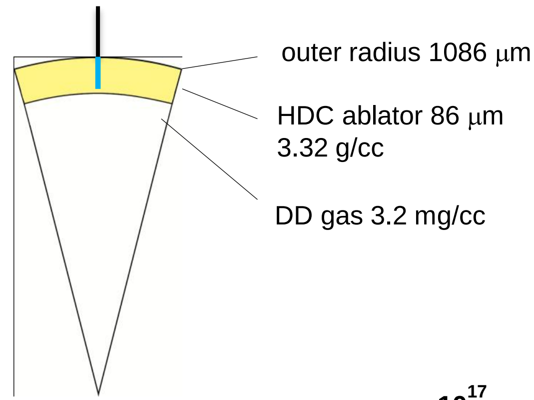


Ablation front growth factors for ignition capsules



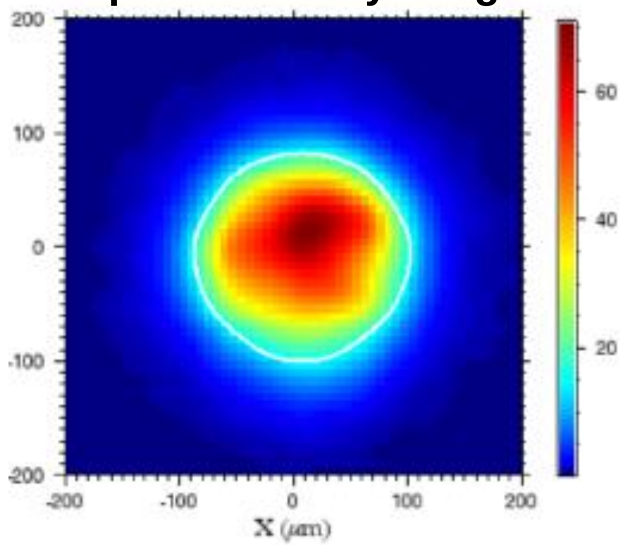
The 2-Shock design was fielded on a near-vacuum-hohlraum symcap (shot N130813) and gave record radiation coupling efficiency of 98%



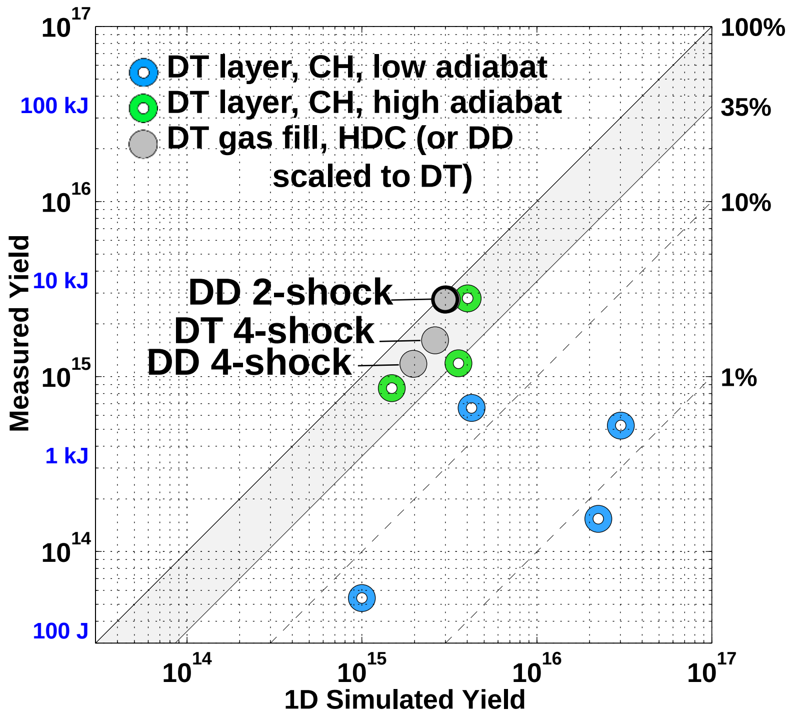


Capsule Thickness: 86 μm
Hohlraum length: 10.1 mm
Capsule fills: 3.2 mg/cc (DD)
Hohlraum fill: 0.032 mg/cc (He)

Equatorial x-ray image



P0 = 91.4 μm
P2/P0 = -3.0%
P4/P0 = 2.5%

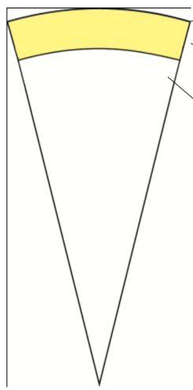


Excellent symmetry achieved without delta lambda tuning for the cone fraction. Total coupling ~98%. And record DD yield of 2.2×10^{13}

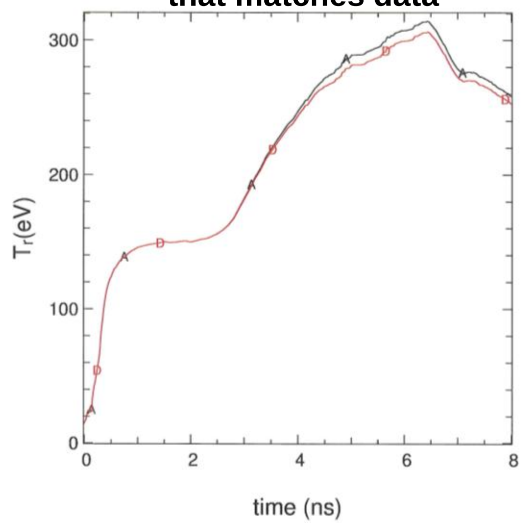
The success of 2-shock shot N130813 suggests pursuing 2-shock designs that can provide higher neutron yield

- To obtain an accurate radiation source for 2-shock HDC capsule designs, we attempt to match 1-D simulation with the date from shot N130813
- To match the data, we modified the fds source from integrated hohlraum simulation by Berzak Hopkins by reducing the peak radiation flux to account for laser deviations from requested pulse and adjusting the M-band fraction to the observed value of 21.8%

capsule configuration for shot N130813



pulse shape specified for N130813 vs. pulse that matches data



original drive from hohlraum simulation by Berzak Hopkins

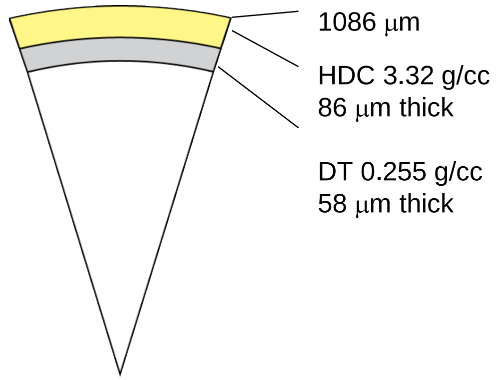
"reference drive"
-- modify the original drive to match data

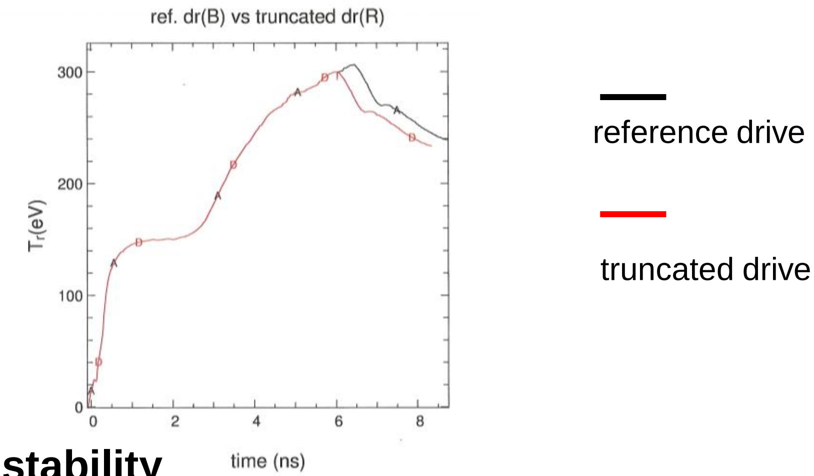
1-D capsule only simulation shows good agreement with data from shot N130813

	DD neutron yield	Bang time (ns)	Burn ave. Tion (keV)	DSR_DD	Peak shell vel. (km/s)
data from N130813	2.2×10^{13}	7.82	3.6	0.0153	not available
1-D simulation using "reference drive"	2.4×10^{13}	7.75	3.3	0.0156	440

Truncate the reference pulse by 400 ps to prevent burn through for a 2-shock HDC capsules with THD or DT layer

undoped HDC capsule



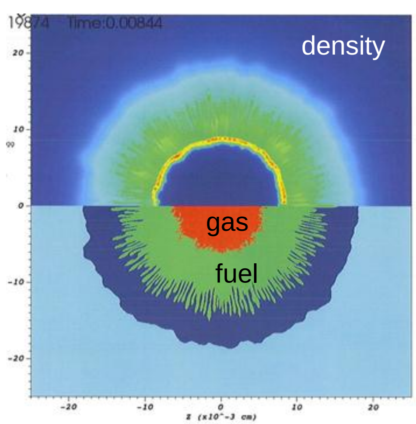


1-D performance: truncating pulse improves stability

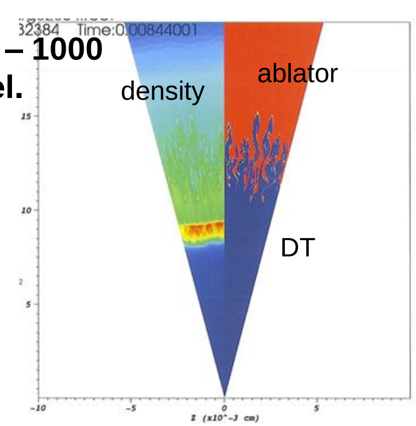
peak Tr (eV)	neutron yield 1-D	peak velocity (km/s)	fuel ρr (g/cm²)	adiabat	Atwood no	M band (%)
300 (truncated)	1.8×10^{16}	390	0.84	3.75	0.25	19
307 (ref. drive)	6×10^{16}	450	0.77	5.5	0.53	21.8

- **Preliminary multi-mode simulations with 2x nominal surface roughness on all surfaces show 50% YoC and shell does not breakup**

modes 1- 250 @ peak vel.

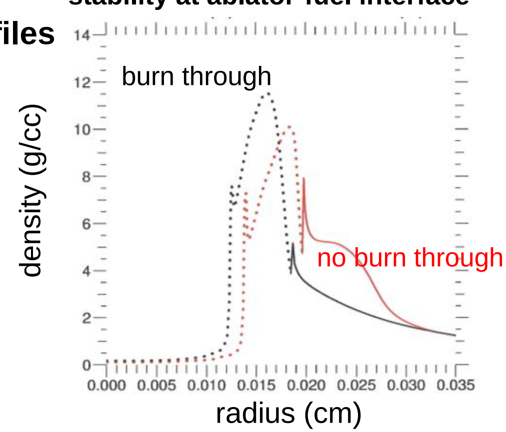


modes 12 – 1000 @ peak vel.



density profiles @ peak vel.

truncating the pulse improves stability at ablator-fuel interface



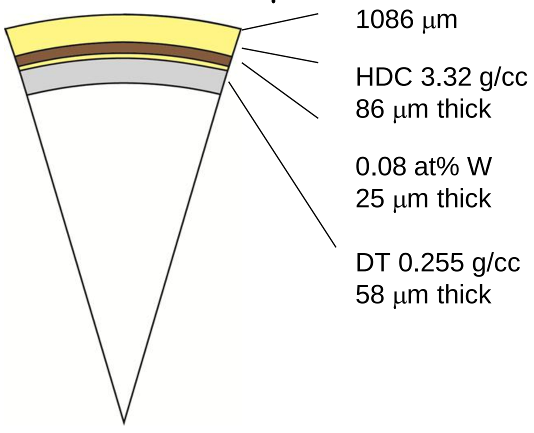
To improve the 1-D yield beyond 10^{16} with reasonable stability behavior, it is necessary to take a number of steps

- **Each of these improvement steps comes at a cost. Therefore it is important to evaluate the overall capsule performance by performing both 1- and 2-D simulations.**

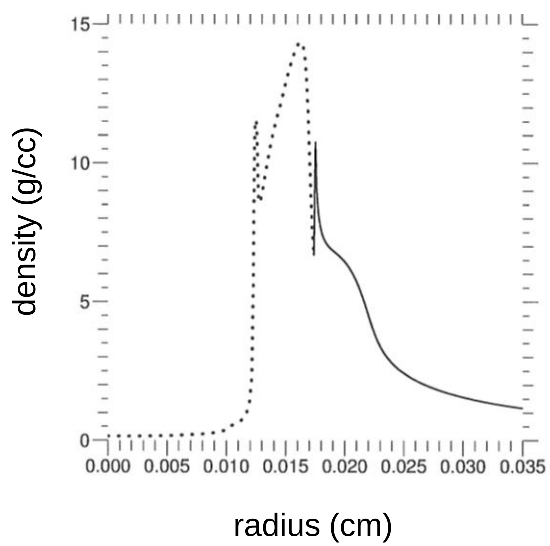
steps to improve yield	positive impact	negative effect
W dopant	better Atwood number	worse RTI at ablation front
lower foot	lowers fuel entropy	more hohlraum filling because delayed bang time and more RTI
stretch the rise to peak Tr	lowers fuel entropy and reduces coasting	more hohlraum filling because delayed bang time
thicker ablator	allows higher Tr and better Atwood number	same as above

Adding W dopant raises neutron yield to ~ 10^{17} in 1-D using the full reference drive and the same capsule dimensions

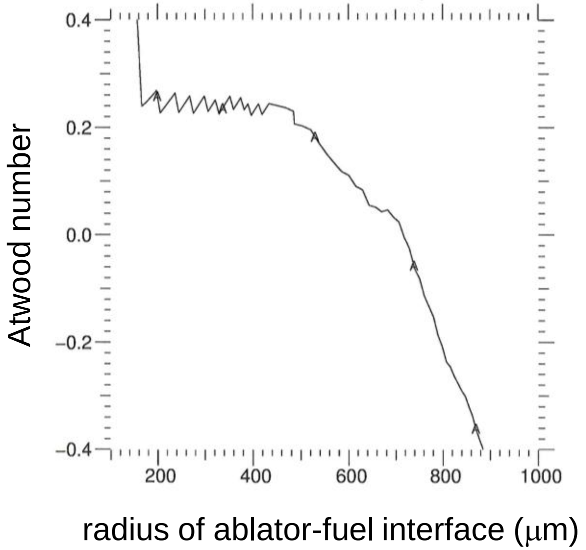
W doped HDC capsule shell thickness = 86 μm



density profile at peak velocity



2 shock 86 μm 0.08 at.% W doped

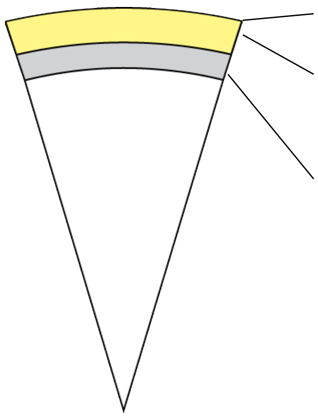


- **We have capsules in fabrication that are doped with 0.08 at.% of W**
- **Dopant improves ablator-fuel interface Atwood number but shortens ablation scale length, 2-D simulations are in progress**
- **Atwood number can be improved by lowering the peak Tr but with a corresponding reduction in yield.**

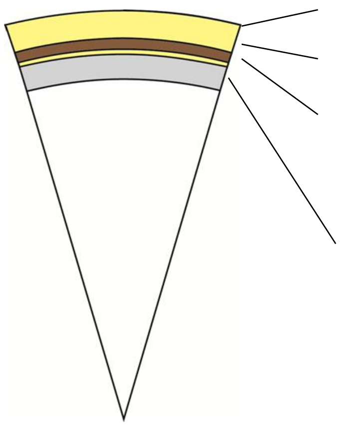
Ablator thickness	**neutron yield 1-D**	**peak velocity (km/s)**	**fuel ρr (g/cm^2)**	**adiabat**	**Atwood no**	**conv. ratio**	**M-band fraction (%)**
86 μm doped	1.3×10^{17}	421	0.73	3.63	0.245	18.7	21.8

Reducing the 1st shock from 20 to 15 Mbar (lower foot), stretching the rise to peak Tr, and using a thicker ablator can give 1-D neutron yield > 10^{17} using the full reference drive

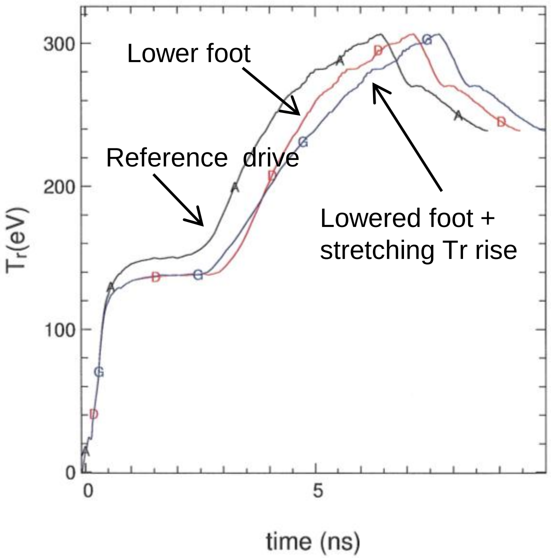
undoped HDC capsule
shell thickness = 92 μm



W doped HDC capsule
shell thickness = 90 μm



radiation temperature

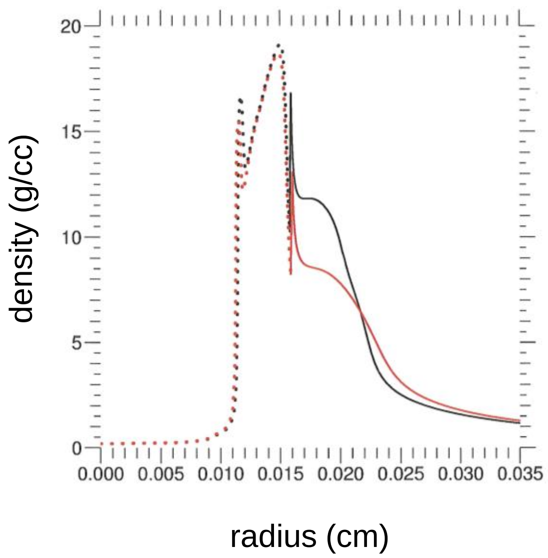


- **Lowering the 1st shock and a slower rise to peak Tr (stretched by 0.8 ns) reduces fuel entropy and consequently increases yield.**

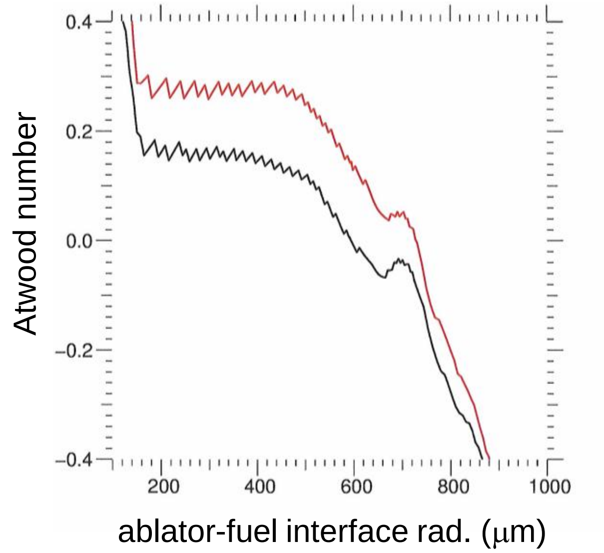
Ablator thickness	drive	neutron yield	peak vel. (km/s)	fuel ρr (g/cm^2)	adiabat	Atwood no	conv. ratio	M-band fraction (%)
90 μm doped	lower foot	6.6×10^{16}	398	0.78	3.23	0.215	24.2	21.8
90 μm doped	lower foot + stretching Tr rise	3.7×10^{17}	387	0.82	2.76	0.19	22.4	21.8
92 μm undoped	same as above	3.8×10^{17}	396	0.87	2.93	0.29	23.8	21.8
94 μm undoped	same as above	1.7×10^{17}	389	0.81	2.9	0.28	20.3	21.8

Stability behavior of the capsules for > 10^{17} neutron yield

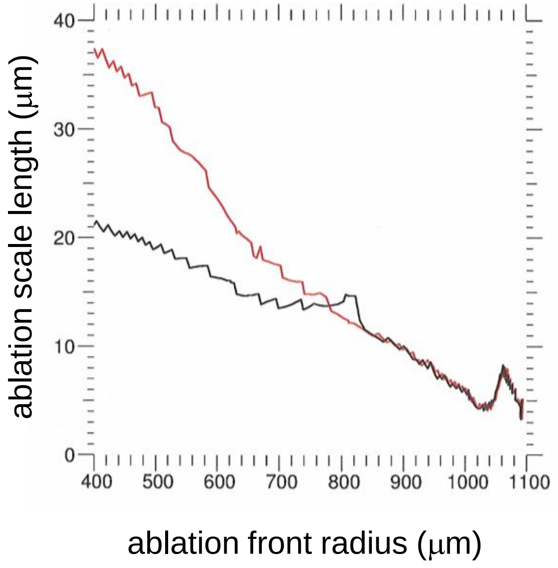
density profile at peak vel.



Atwood no. vs interface radius



Atwood no. vs ablation radius



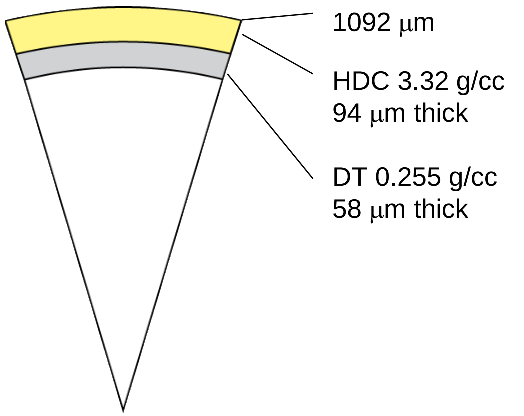
0.08 at.% W doped
with ablator thickness of 90 μm

undoped
with ablator thickness of 92 μm

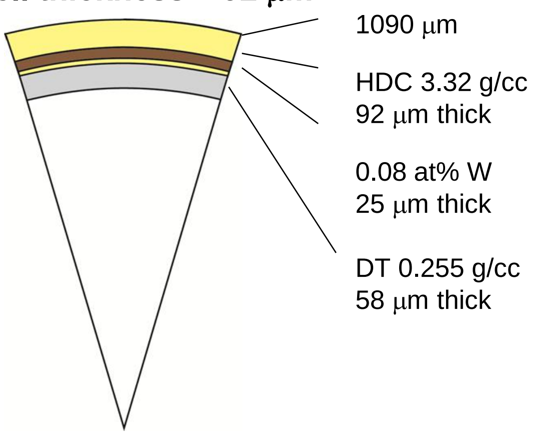
- **Dopant improves Atwood number but increases ablation scale length.**
- **For the undoped capsule with ablator thickness of 92 μm, increases fuel thickness from 58 to 65 μm reduces the Atwood number by 10% and yield drops from 3.8 to 2.3 $\times 10^{17}$ neutrons**
- **2-D simulations are in progress.**

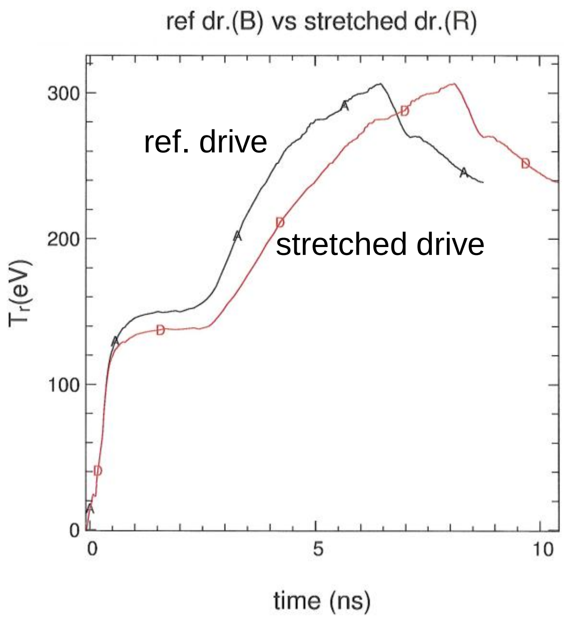
1-D neutron yield > 10^{18} is obtained by stretching the rise to peak Tr further by another 0.4 ns

undoped HDC capsule
shell thickness = 94 μm

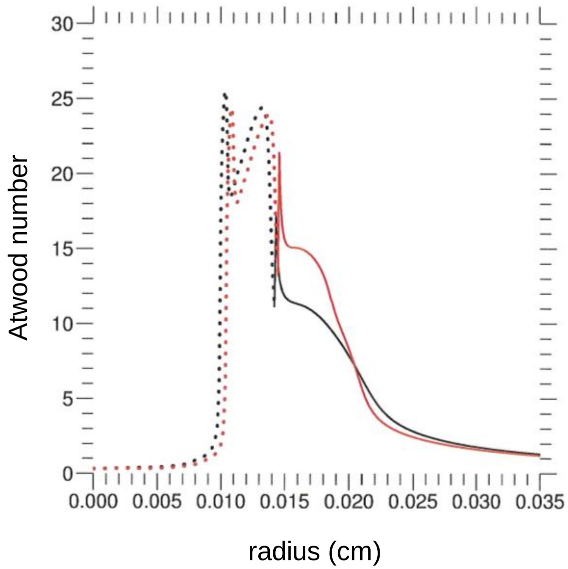


W doped HDC capsule
shell thickness = 92 μm





density profile at peak velocity

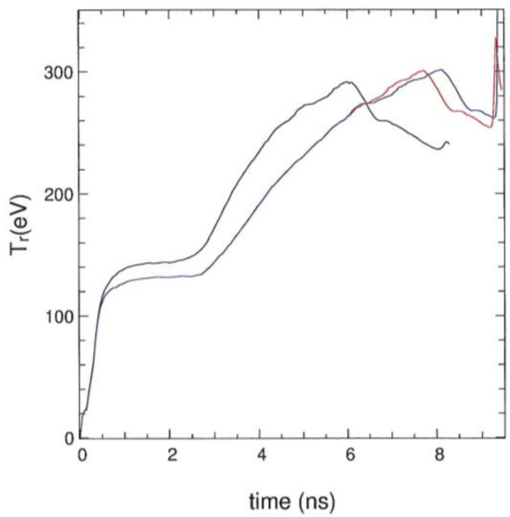


- stretching the main Tr rise by another 0.4 ns further reduces the strength of the 2nd shock and consequently rises fuel ρr
- may need a slightly larger hohlraum because larger capsule radius and longer pulse.
- lowering the 1st shock further from 15 to 12 Mbar can further increase yield.

thickness of ablator (μm)	drive	neutron yield 1-D	peak vel. (km/s)	fuel ρr (g/cm^2)	adiabat	Atwood no	conv. ratio	bang Time (ns)	M-band fraction (%)
94 undoped	red drive	1.5×10^{18}	393	1.07	2.9	0.28	28.8	9.32	21.8
92 doped	red drive	2.2×10^{18}	385	0.96	2.76	0.18	22.4	9.34	24.8

Stretched pulse reduces 1st and 2nd shock pressure in fuel and reduces time of coasting

Tr profiles

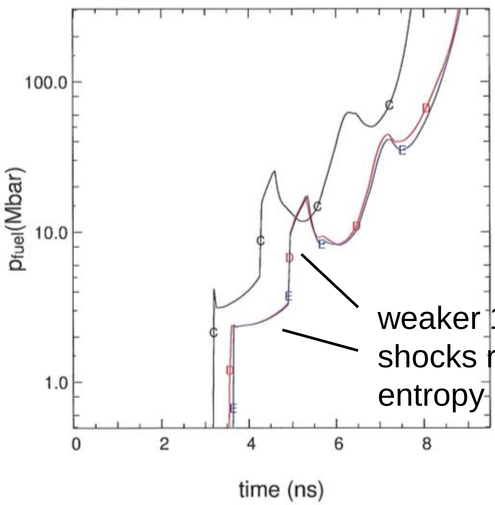


pulse gives
1.3e17 neutron yield

pulse gives
3.7e17 neutron yield

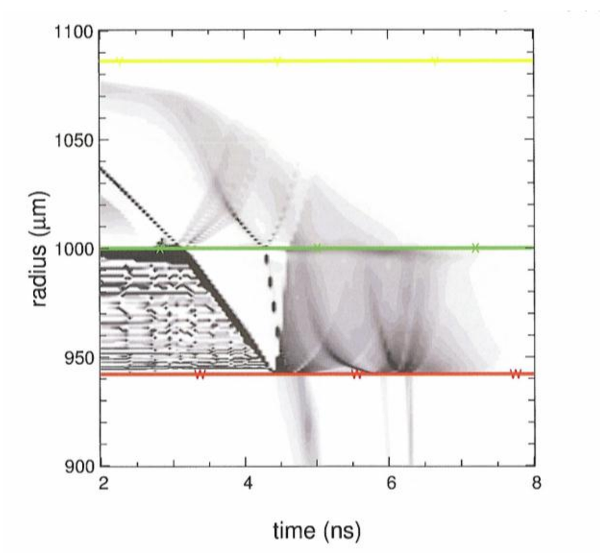
pulse gives
2.2e18 neutron yield

fuel pressure vs. time

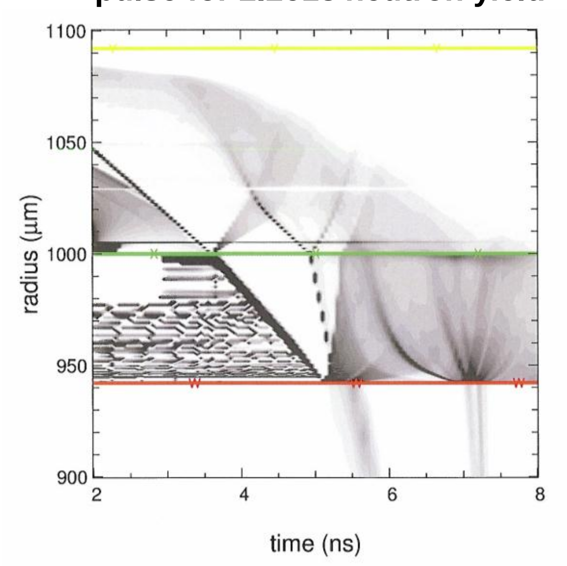


weaker 1st and 2nd shocks reduces fuel entropy

Shock trajectories using pulse for 1.e17 neutron yield



Shock trajectories using pulse for 2.2e18 neutron yield

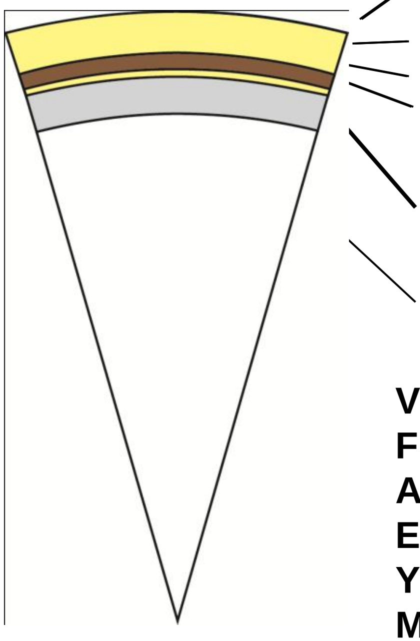


Longer pulse pushes the capsule longer. This increases fuel ρr and consequently yield

To study the W and Si in hot spot, we use W and Si doped HDC capsules with 4 shocks

- W and Si doped HDC capsules shown here have comparable 1-D performance. But uniformly doped HDC with Si is less robust to RTI.

HDC - W doped @ 0.3 at. %



Outer radius 1108 μm

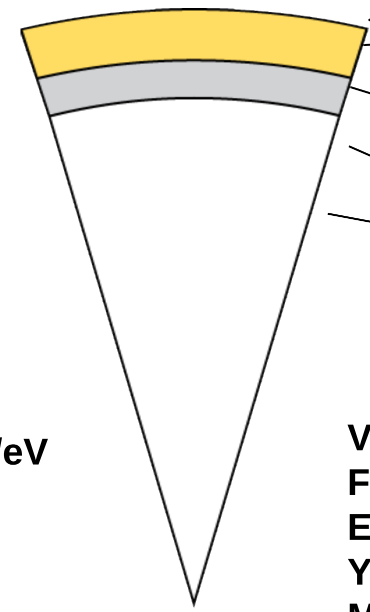
HDC 45.6 μm, 3.476 g/cc
W @ 0.3 at.%, 25.5 μm, 3.6 g/cc
HDC 5 μm, 3.476g/cc
Ablator mass = 3.85 mg

DT fuel 0.255 g/cc
Fuel mass = 0.18 mg

DT gas 0.3 mg/cc with
Gas mass = 1.2 μg

Vpeak = 3.8 x 10^7 cm/s
Fuel entropy = 0.464 MJ/g/eV
Adiabat = 1.525
Eabs = 206 kJ
Yield = 19.7 MJ
Mass remaining = 7.5% (0.29 mg)
Stag. pressure = 763 Gbar

HDC - Si uniformly doped @ 3 at. %



Outer radius 1108 μm

HDC 76.1 μm, with Si @ 3 at.%, 3.448g/cc
Ablator mass = 3.78 mg

DT fuel 0.255 g/cc
Fuel mass = 0.18 mg

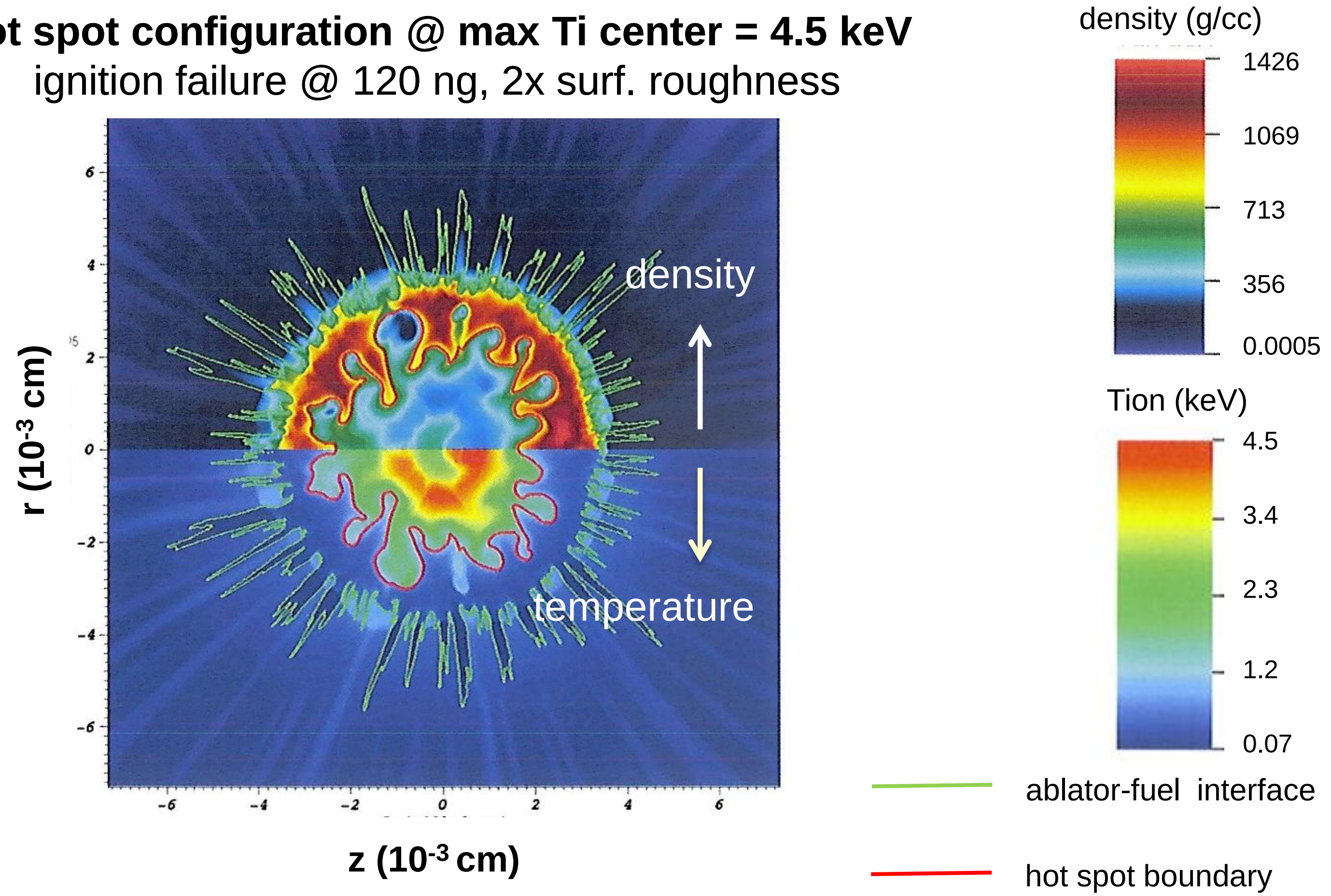
DT gas 0.3 mg/cc
Gas mass = 1.2 μg

Vpeak = 3.9 x 10^7 cm/s
Fuel entropy = 0.46 MJ/g/eV
Eabs = 195 kJ
Yield = 19 MJ
Mass remaining = 6.8% (0.26 mg)
Stag. pressure = 780 Gbar

HYDRA LTE simulations shows that HDC (0.3 at. % W doped) capsules are very robust to RTI but sensitive to tungsten contamination in hot spot

- HYDRA LTE simulations to mode 250 with 3.0x of nominal surface roughness (with 30 ng ablator material mixed into the hot spot) still gives 90% 1-D YoC.
- LTE simulations of 90 ng of ablator material in hotspot with 2x surface roughness gives full YoC but ignition failure occurs at 120 ng. **But LTE is inaccurate to model tungsten radiation in hot spot.**

Hot spot configuration @ max Ti center = 4.5 keV
ignition failure @ 120 ng, 2x surf. roughness



HYDRA 2-D to mode 250, with NLTE–XSN in hot spot and 2x surface roughness, shows the hot spot can tolerate close to 300 ng of W doped ablator material

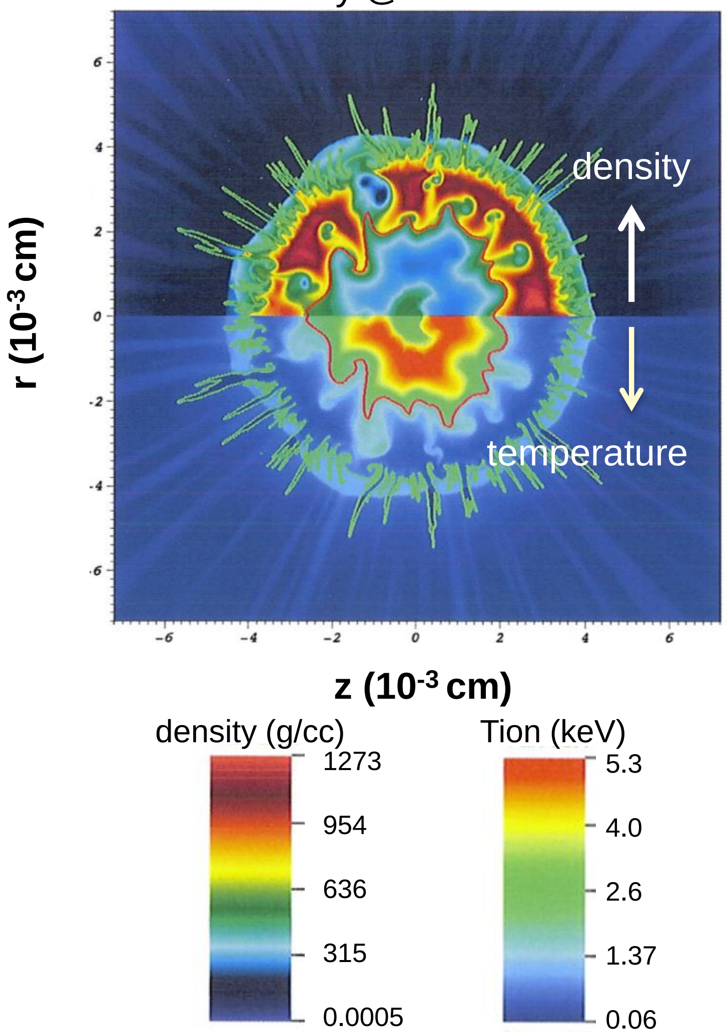
- 20 MJ full YoC with 250 ng of ablator in hot spot
- 4 MJ yield with 300 ng of ablator in hot spot

ablator-fuel interface

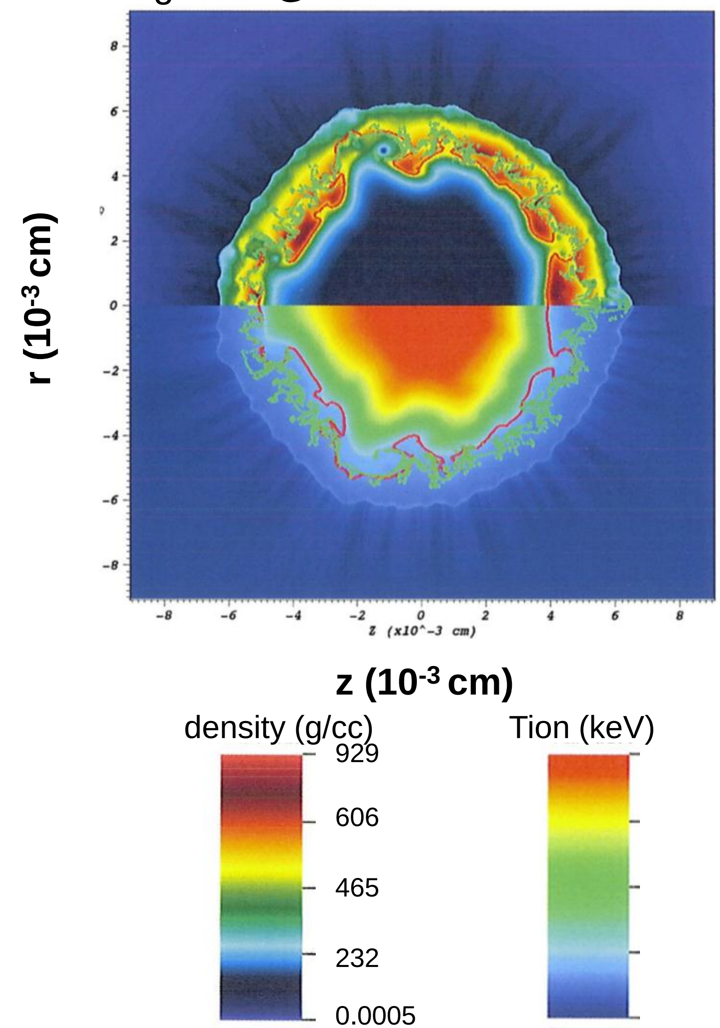
hot spot boundary

300 ng of ablator in hot spot

Peak velocity @ 11.07 ns



Ignition @ 11.14 ns

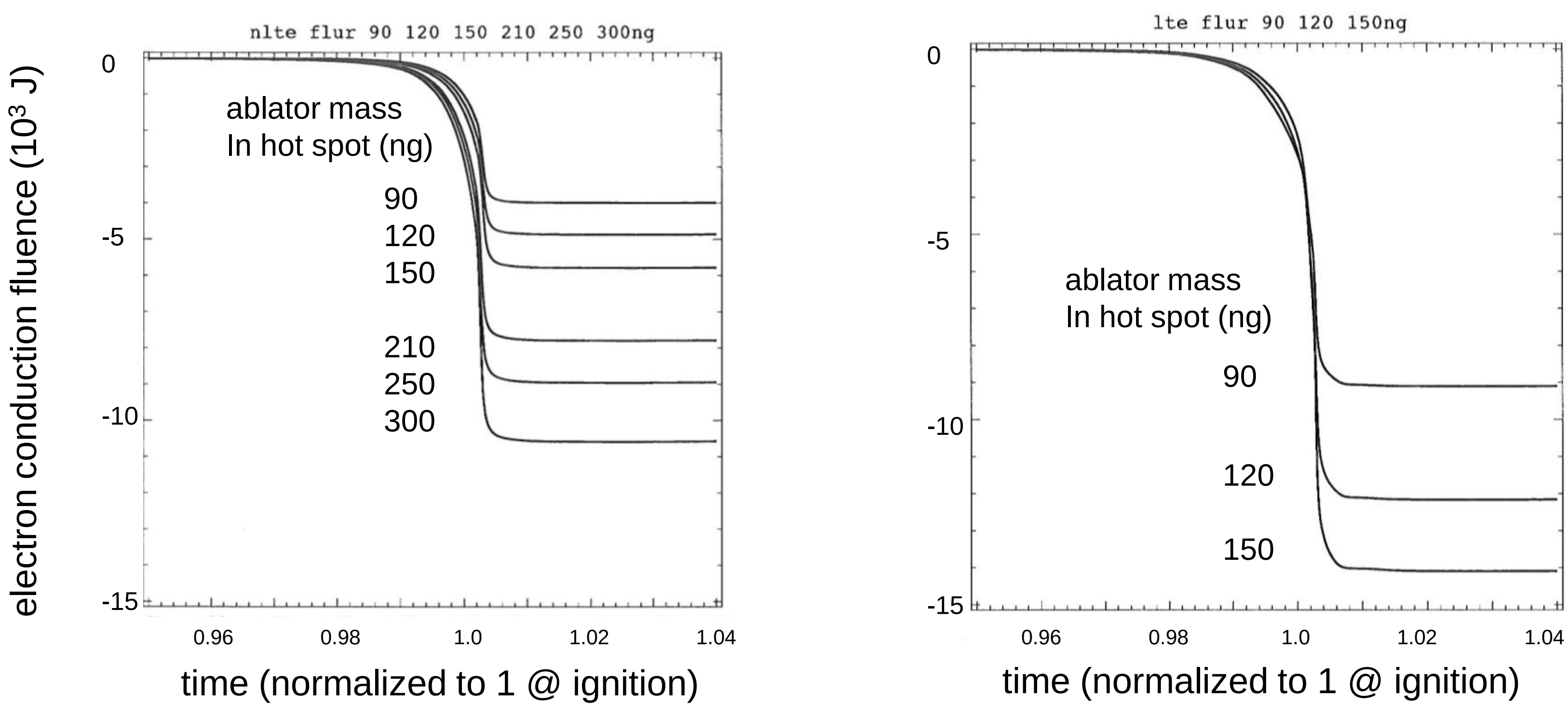


More tungsten can be tolerated in hotspot because radiation fluence across the gas-fuel boundary for NLTE is substantially lower than LTE

- **Electron populations in tungsten in hotspot are more depleted in LTE than in NLTE. More inner-shell electron vacancies in LTE facilities stronger bound-bound (bb) and bound-free (bf) radiation in LTE than in NLTE. Consequently, LTE overestimates the gross radiation.**
- **bb and bf radiation are readily to escape since their mfp is > hotspot size.**

Radiation fluence vs time burn-on

NLTE **LTE**

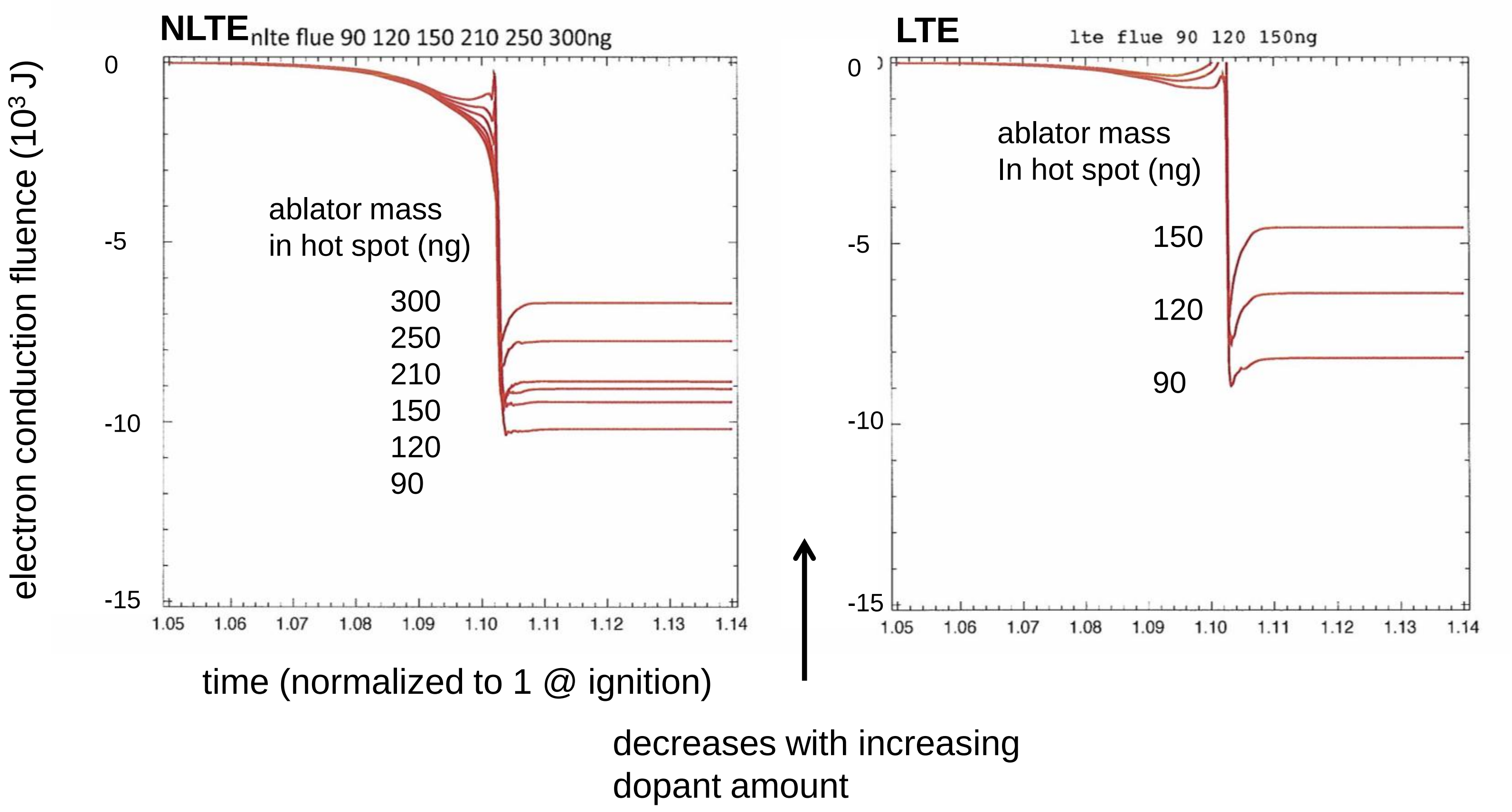


increases with increasing
dopant amount

Electron conduction fluence is however higher for NLTE than for LTE

- Increasing dopant concentration in hot spot reduces electron conduction. This is because increasing dopant concentration in hot spot reduces Te. Lower Te decreases energy lost by electron conduction across the hot spot boundary since electron conduction $\propto T_e^{5/2}$
- For the same amount of dopant concentration in hot spot, electron energy across the hot spot boundary is less in LTE than in NLTE

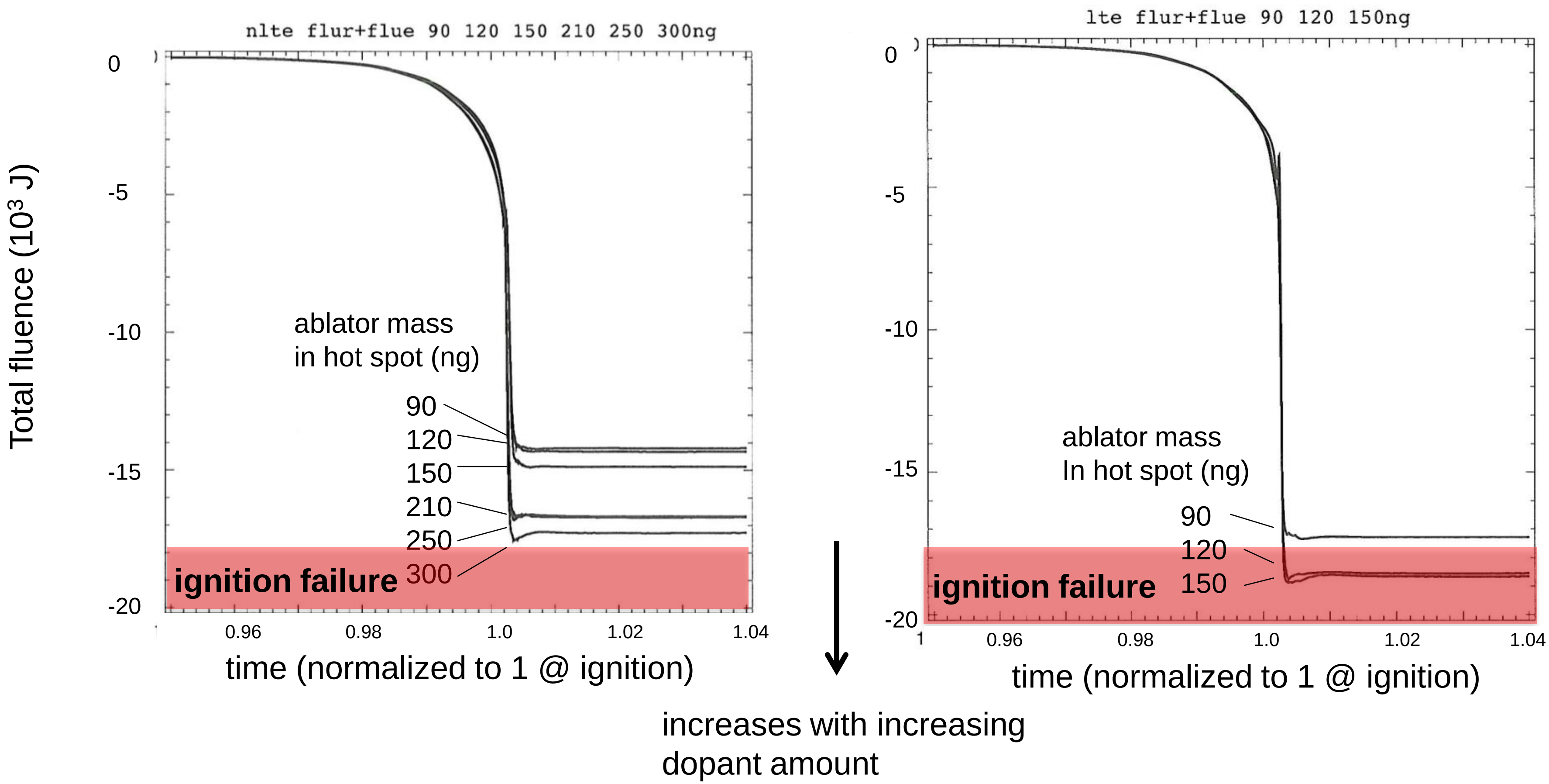
Electron fluence vs time burn-on



Total outflow fluence (radiation + electron conduction) for NLTE is less than LTE and increases with dopant concentration in hot spot

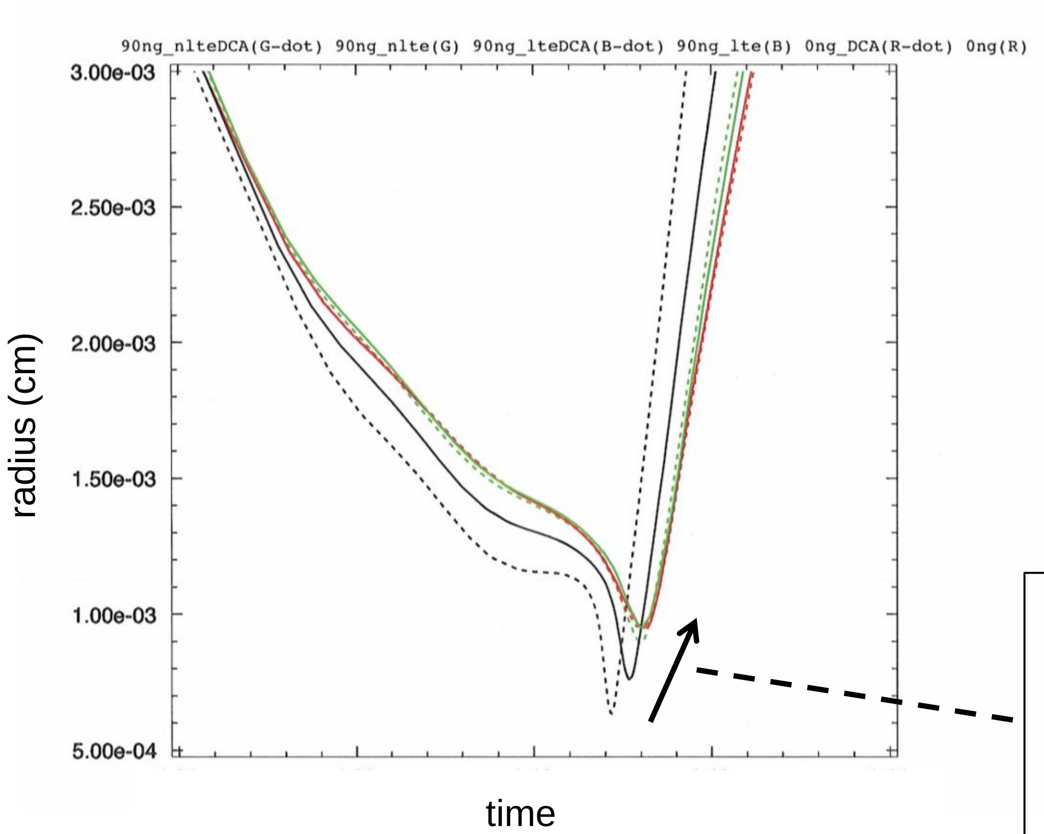
Total outflow fluence vs time -- burn-on

NLTE | **LTE**



Reduced total outflow fluence results in reduction in convergence ratio in NLTE calculations

Gas-fuel interface radius vs time



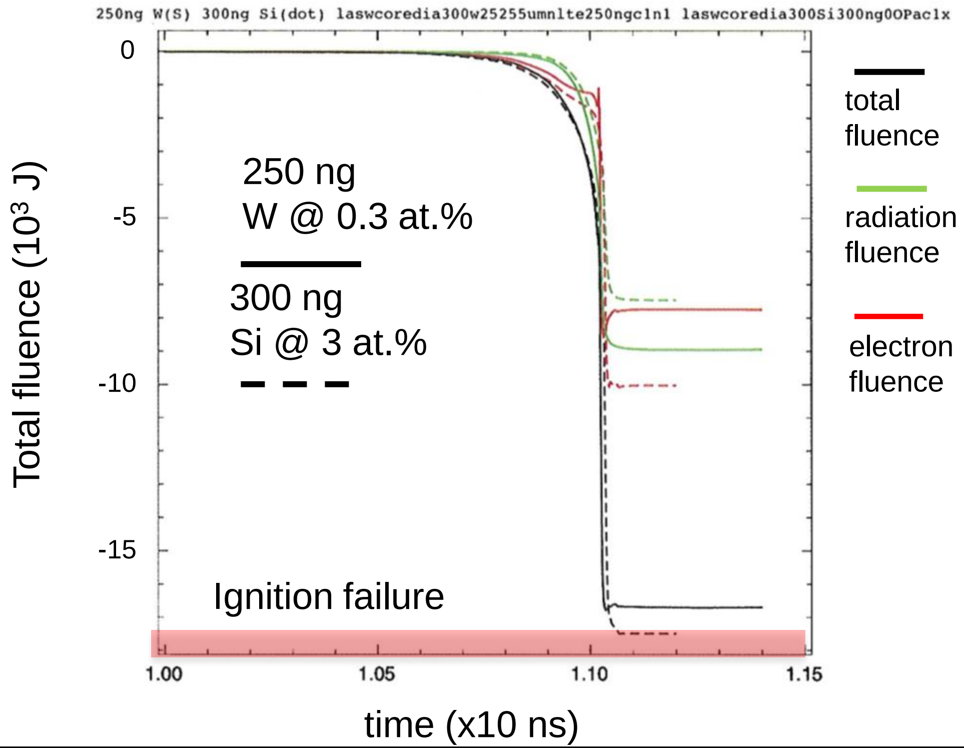
90ng: nlte, xsn
90ng: nlte, dca
0ng: lte, server
0ng: lte, dca
90ng: lte, server
90ng: lte, dca

reduction in outflow fluence based on NLTE calculations
→ increase in hot spot temp.
→ reduction in convergence ration at ignition

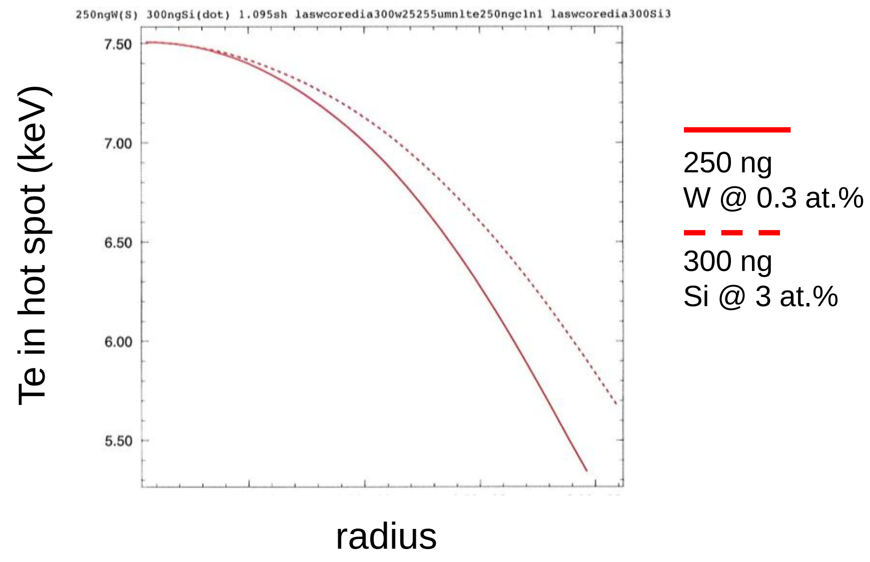
- **Reduction in total outlfow fluence in NLTE increases the hot spot temperature. This reduces the convergence ratio required for ignition. Reduced convergence ratio reduces mix. Consequently, 2-D NLTE simulations allow the capsule to tolerate more than 90 ng of ablator material in the hot spot.**

Ignition failure likely to occur if 300 ng of ablator material with 3 at.% of Si is mixed into hot spot

Total outflow fluence vs time



Te vs radius in hot spot



The max. tolerable amount of Si or W-doped ablator material in the hot spot are remarkably similar although each Si ion radiates less than W ion.

This is because:

(1) Si dopant reduces radiation fluence, electron conduction increases as a result of increased electron temperature because reduced radiation.

(2) There are 10 times more Si ions than W ions.

(3) NLTE physics reduces W radiation while there is no reduction in Si radiation because bb radiation for Si is substantially less than that for W in hot spot and Si atoms are almost completely stripped after shock arrival. Therefore LTE and NLTE give almost identical results.

Conclusions

- **HDC Symcap shots N130628 and N130813 have achieved high DT neutron yield of 1.7×10^{15} and record Trad coupling efficiency of 98%, respectively.**
- HDC ablators with good surface finish and uniformly doped with the required amount of W are now available.
- Optimizing the pulse for the undoped HDC capsule with 86 μm thickness may allow neutron yield > 10^{16} to be obtained.
- By optimizing the ablator thickness, dopant concentration, and the radiation drive, it may be feasible to obtain neutron yield close to 10^{18} for 2-shock designs.
- Must use NLTE to model tungsten radiation in hot spot. NLTE modeling shows that hot spot can tolerate close to 300 ng of W-doped ablator material vs 90 ng using LTE modeling.
- Surprisingly, the hot spot can tolerate about similar amounts of 3 at.% Si-doped ablator material as 0.3 at.% W-doped.


NIF

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