How the concepts of coast time and radius of peak velocity were a key part to achieving capsule gain > 5 in ICF

APS DPP

Talk BI01

O. A. Hurricane

November 8, 2021

LLNL-PRES-828331

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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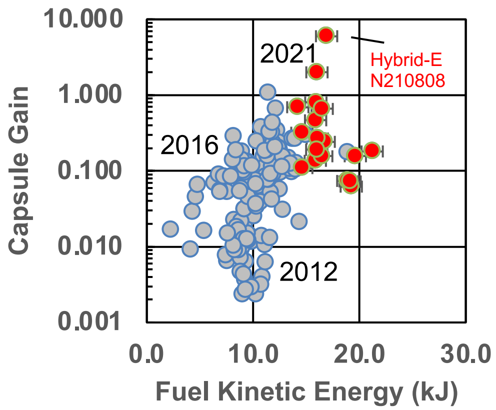
Thanks to my collaborators and colleagues

D. Callahan, D.T. Casey, S. Haan, A. Kritcher, O. Landen, R. Nora, P.K. Patel, J. Ralph, P.T. Springer, and A. Zylstra

We will focus upon the subtle concept of coast time, how our understanding of it changed over time, and how we've leveraged it for recent advances

- Record fusion gain levels have been achieved
- We presently believe that reduced coast time was a key contributor to the recent performance advance
- Coast time is an important duration of time between the end of the drive on the capsule and the time of peak neutron production ("bang time" aka "BT")
- The effectiveness of reducing coast time has been demonstrated several times over the past 8 years of work on the NIF
- Our present understanding is that reducing coast time reduces the radius at which peak implosion velocity is achieved
- Reducing the radius of peak velocity increases the rate of mechanical energy transfer from implosion kinetic energy into hot-spot internal energy

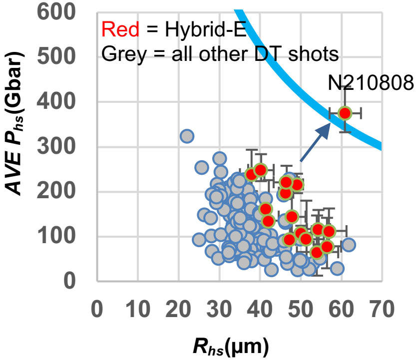


Gain	N210207	N210307	N210808
G_{fuel}	7.8 ± 1.0	6.2 ± 0.9	70 ± 7
$G_{capsule}$	0.75 ± 0.05	0.57 ± 0.04	6.0 ± 0.2
G_{target}	0.09	0.07	0.7

(NAS 1997 report definition of ignition is $G_{target} = 1$)

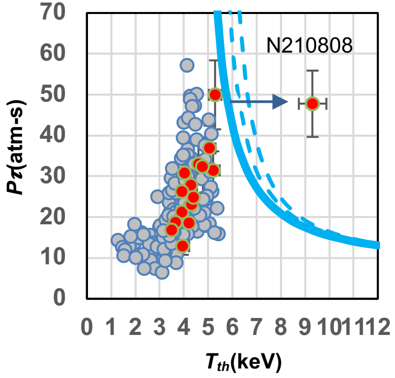
N210808 ignited (i.e. passed the tipping-point of thermodynamic instability) by many published metrics as the hot spot pressure and temperature increased

Metric: J.D. Lindl et al., Phys. Plasmas 25, 122704 (2018)



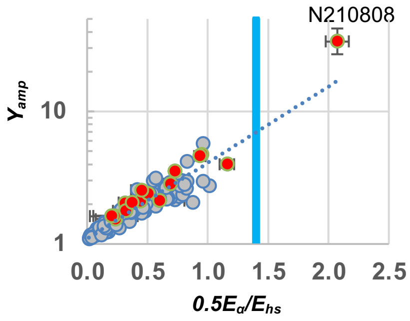
Pressure doubled

Metric: O.A. Hurricane et al., Phys. Plasmas 28, 022704 (2021)

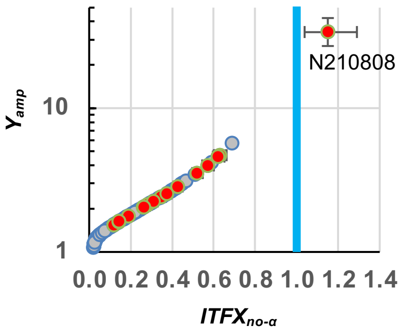


Temperature doubled

Metric: A.R. Christopherson et al., Phys. Plasmas 27, 052708 (2020)



Metric: Patel et al., PoP (2020)

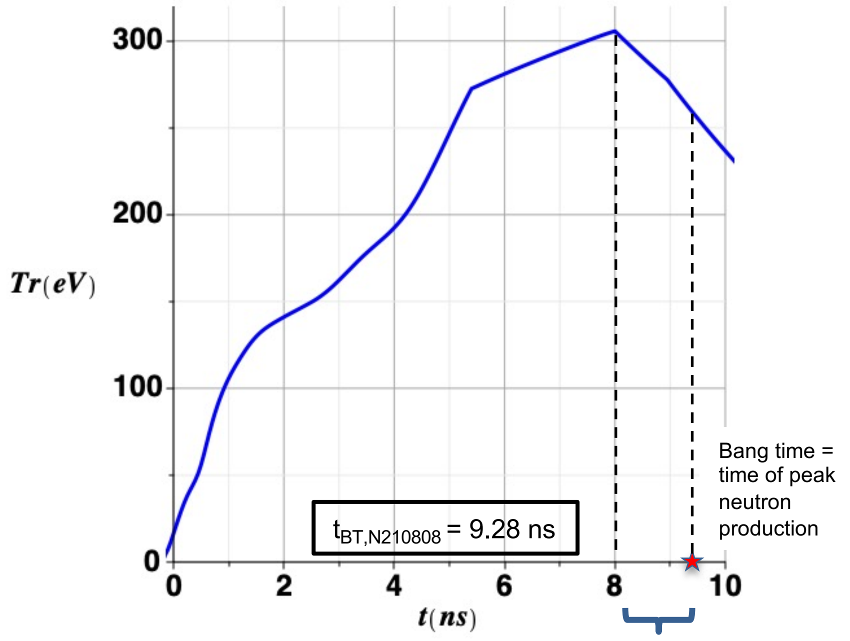


How did reducing coast time contribute?

see talks by A. Zylstra ZI02.00003; A. Kritcher GO04.00002; A. Christopherson CO04.00005; P. Patel CO04.00001

There have been many definitions of coast time, in this talk we will focus upon the definition linked to peak hohlraum T_{rad}

T_{rad} inferred from N210808 pulse-shape[1]



$t_{coast\text{-}time} = t_{BT} - t_{Tr,max}$

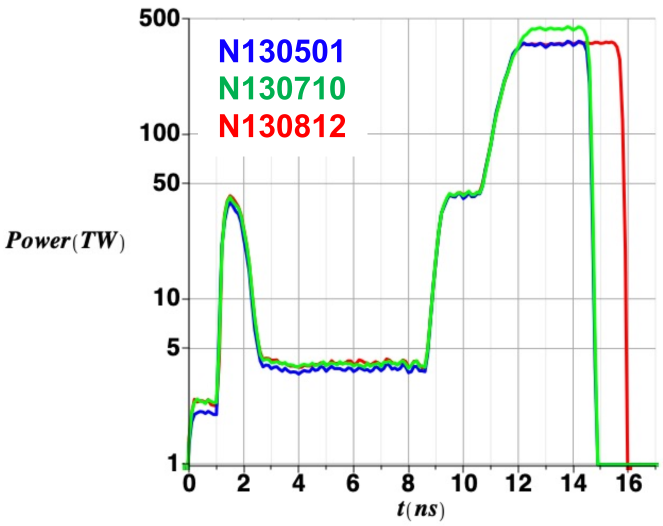
- Historically, coast time was defined using the laser off time, but this made less sense as the physics was better understood
- Time of maximum radiation temperature ($T_{rad,max}$) is the time of maximum ablation pressure (p_{abl})
- The theory of this talk will define the coast time (t_{coast}) as

$$t_{coast} = t_{bang\text{-}time} - t_{Trad,max}$$

Data plots use the **50% max laser power falling edge** definition (time differences can be 0 – 0.36 ns)

[1]Analytic hohlraum model of Callahan, et al., PoP (2020)

The first systematic study of coast time started with the high-foot* and tests that intercompare high power with high energy

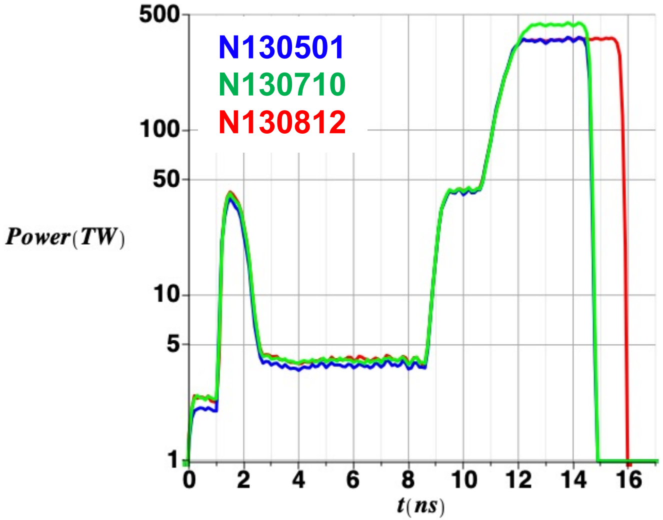


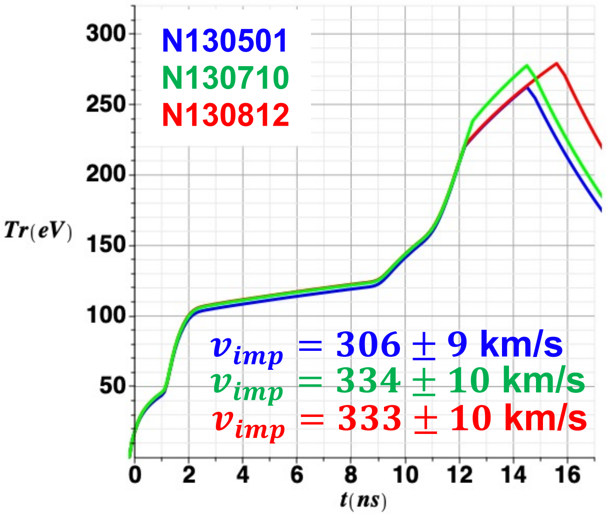
Note: D.Hinkel – lead hohlraum designer

*Dittrich, et al., PRL, 112, 055002 (2014); Park, et al., PRL, 112, 055001 PRL (2014)

With fixed target geometry, these three pulse shapes resulted in three different x-ray drives on the implosion

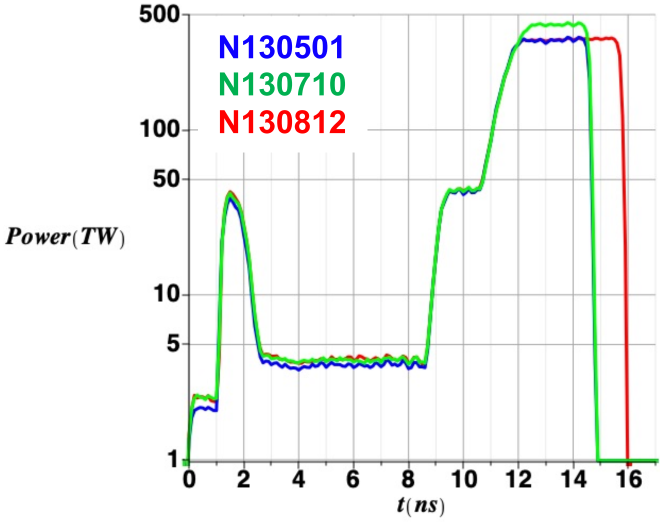
Same target geometry

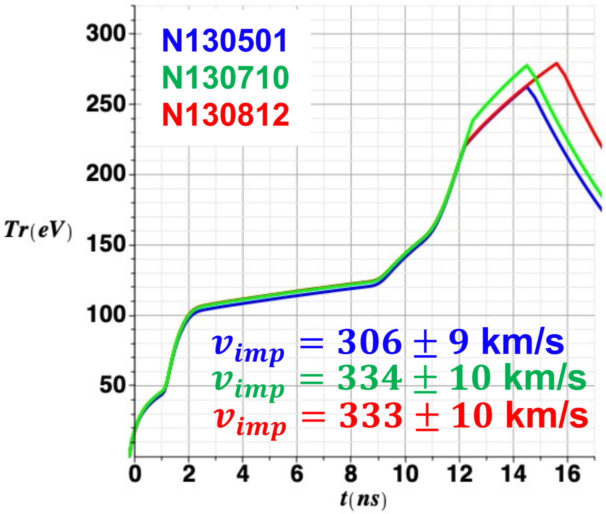


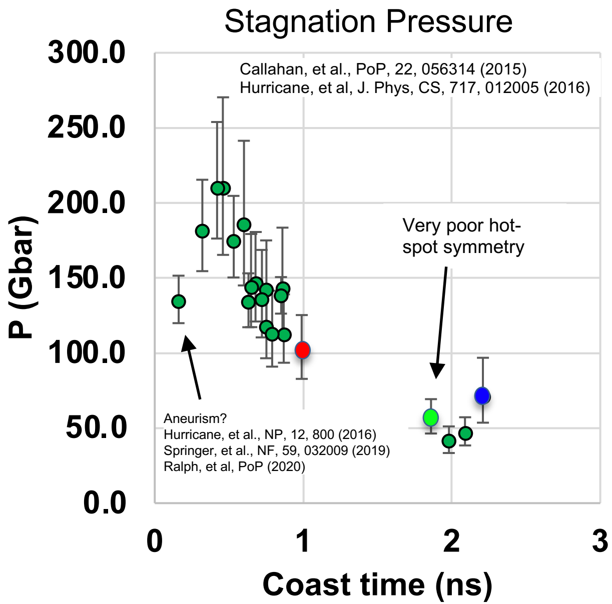


*Dittrich, et al., PRL, 112, 055002 (2014); Park, et al., PRL, 112, 055001 PRL (2014)

This exploration of higher power vs. lower coast time pointed us towards lower coast, which we scanned to obtain 200+ Gbar



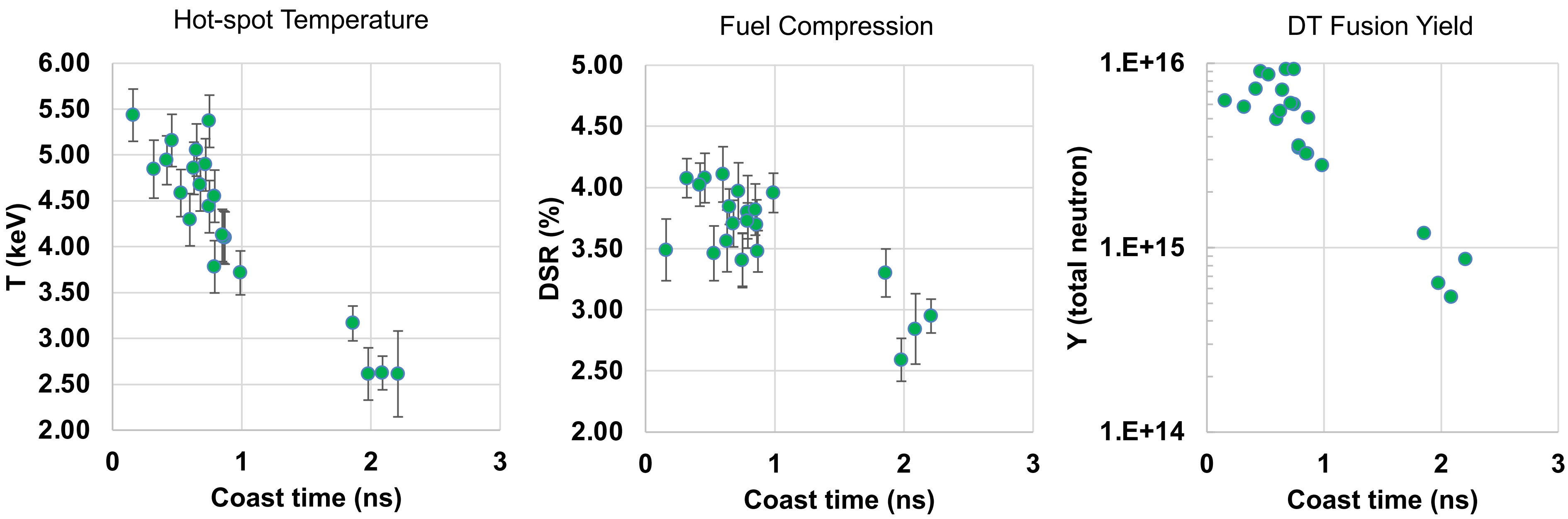




After this initial 3-shot study, systematically reducing coast-time at relatively low laser power became a cornerstone of the high-foot shot plan

*Dittrich, et al., PRL, 112, 055002 (2014); Park, et al., PRL, 112, 055001 PRL (2014)

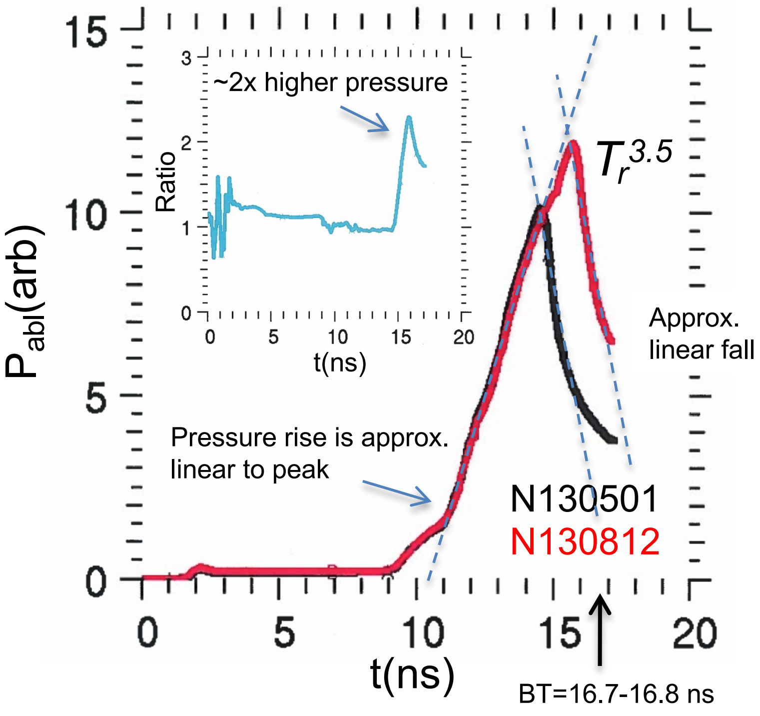
In addition to stagnation pressure, other hot-spot properties were seen to increase with reduced coast time



At the time, we didn't fully understand why coast time reduction was such a strong lever on performance, but we treated it as an observational fact and used it

Reducing coast time results in a larger late time ablation pressure increasing implosion velocity and increasing shell compression

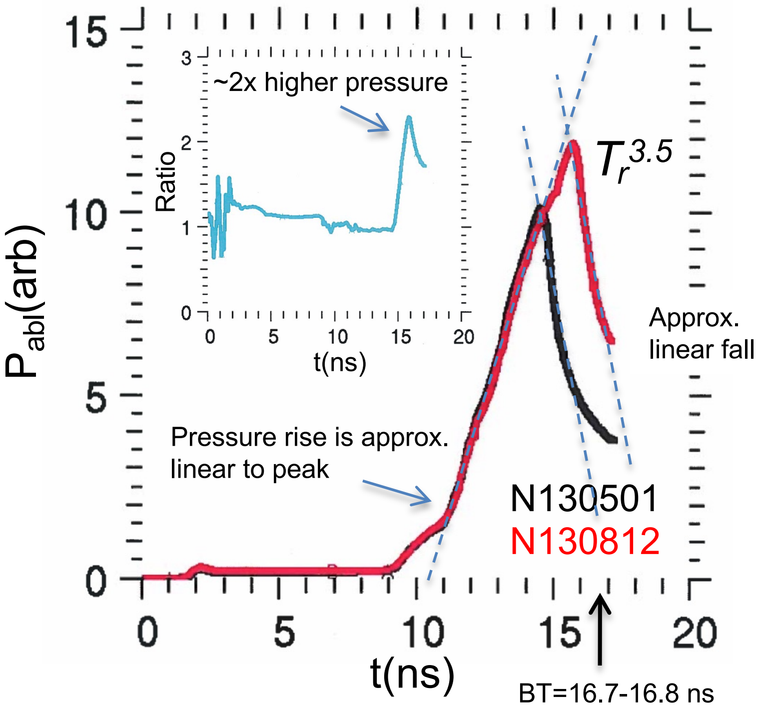
Ablation Pressure



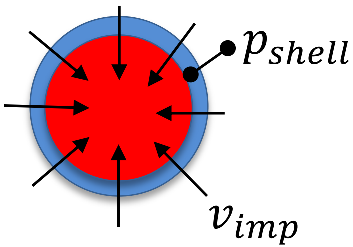
Hurricane, et al., Physics of Plasmas 24, 092706 (2017); doi: 10.1063/1.4994856

The stagnation pressure should be related to the DT shell pressure at peak velocity and the Mach number of the DT shell

Ablation Pressure



In-flight



$$p_{stag} = p_{shell} M^3$$

Kemp, Atzeni, Meyer-ter-Vehn, PRL (2001):

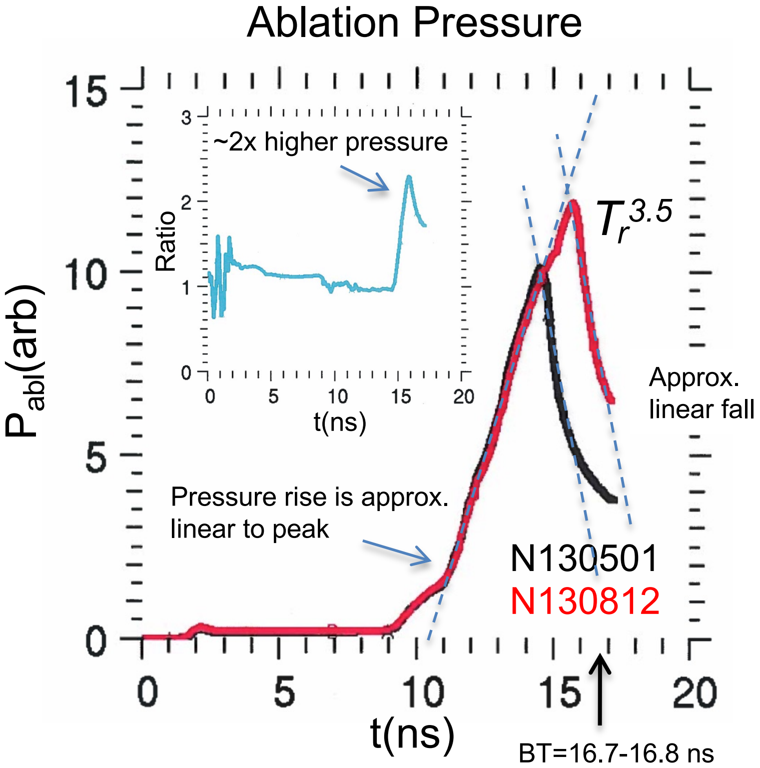
Rocket model +

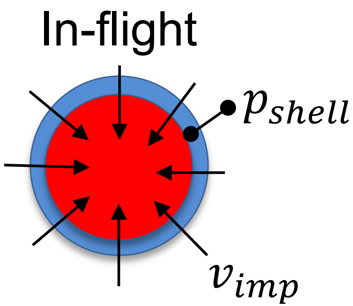
$p_{shell} \approx p_{abl,max}$

$\rightarrow\ p_{stag} \sim T_r^{7/5} v_{imp}^3$

Hurricane, et al., Physics of Plasmas 24, 092706 (2017); doi: 10.1063/1.4994856

One finds that the stagnation pressure of the implosion is linked to both the implosion velocity and the late time hohlraum T_{rad}





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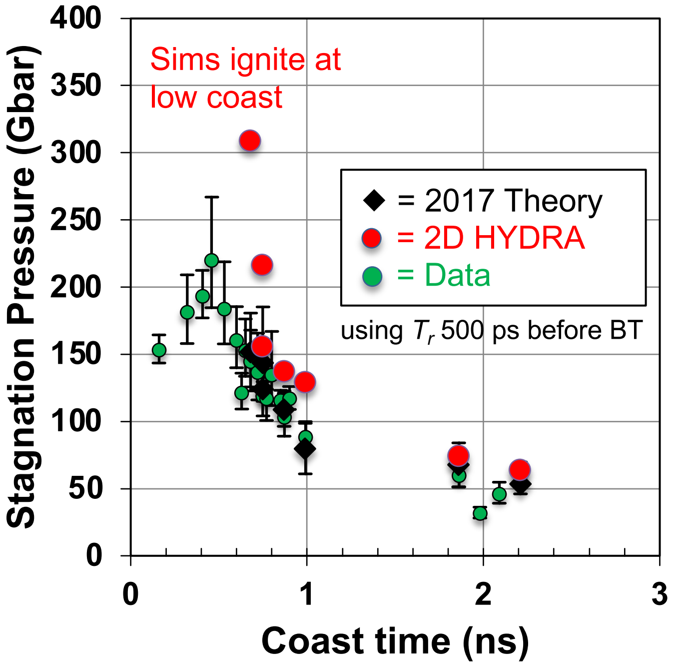
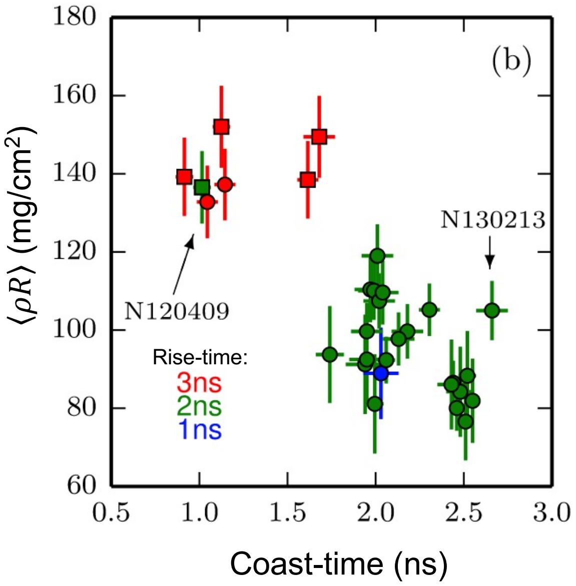


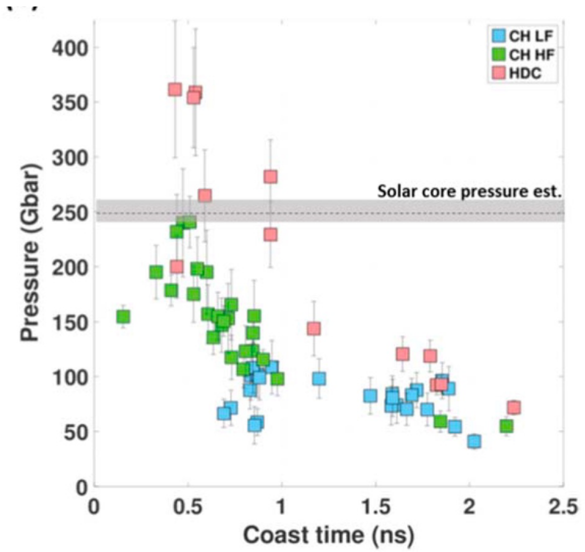
Hurricane, et al., Physics of Plasmas 24, 092706 (2017); doi: 10.1063/1.4994856

A variety of different indirect-drive implosions have responded favorably to reduced coast time

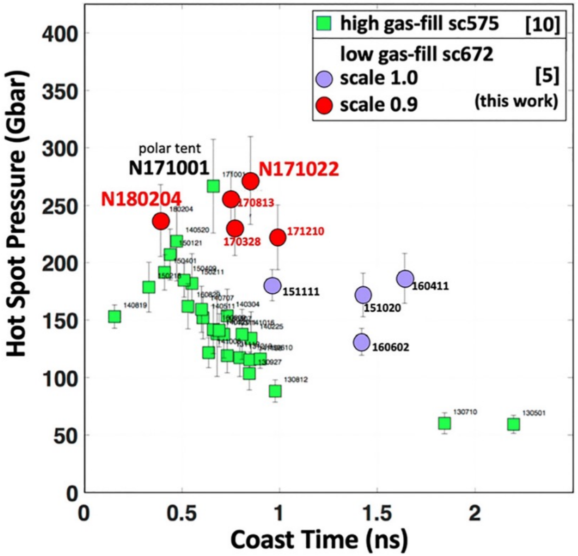
High gas-fill hohlraum D³He gas capsules
Zylstra, et al., PoP, 21, 112701 (2014)



Low gas-fill hohlraum HDC DT implosions
L. Berzak Hopkins, et al., PPCF, 61, 014023 (2019)

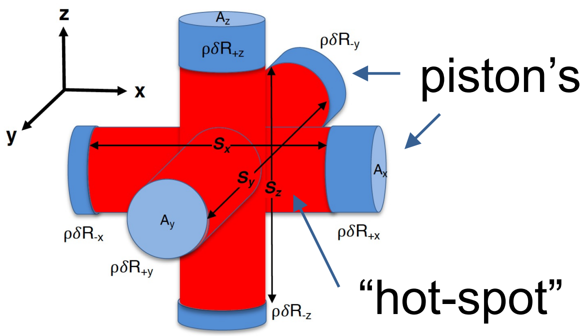


Low gas-fill hohlraum CH DT implosions
T. Döppner, et al., PoP, 27, 4 (2020)



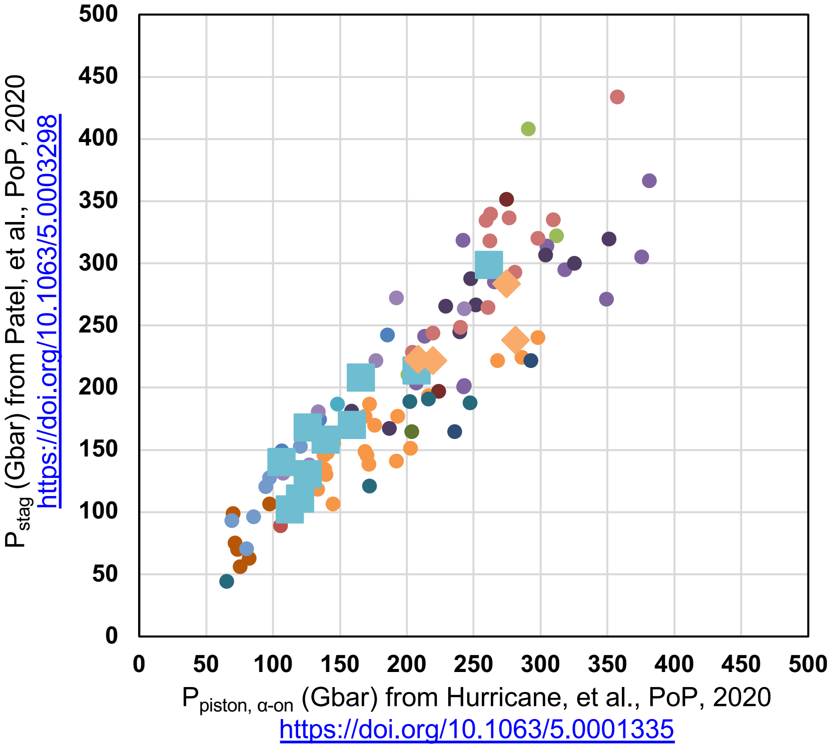
Coast time reduction is only effective if implosion degradations (e.g. mix, asymmetry, etc.) are controlled

Piston models, developed for studying implosion asymmetry, also appeared to match data well, but how related to our 2017 picture?



One of the many formulas:

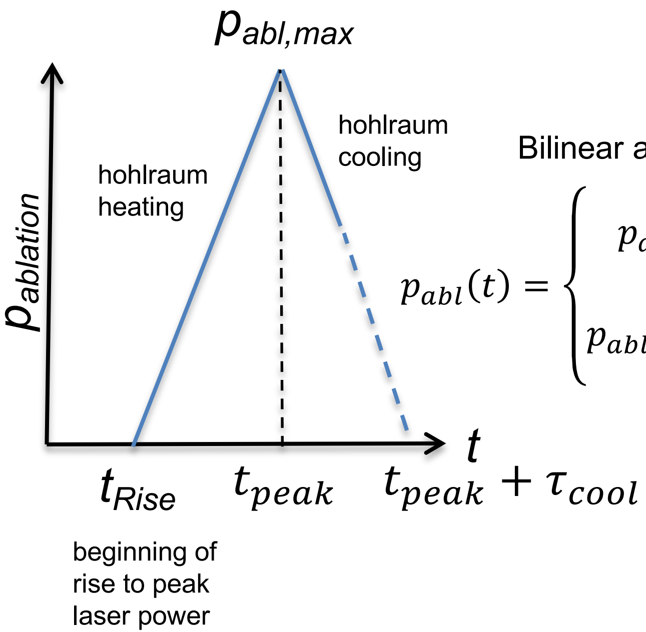
$$P_{piston,no-\alpha} = \frac{v_{imp}^5}{P_{pv}^{3/2}}\left[\frac{\rho\delta R_{WHM}}{R_{pv}}\right]^{5/2}$$



Also see D. Casey, et al., PRL, 126, 025002 (2021) and 2nd PoP paper in preparation;

The radius of peak velocity, R_{pv}, must be related to the coast-time

As the hohlraum is cooling, the ablation pressure outside of the implosion is dropping, while the hot-spot pressure is increasing

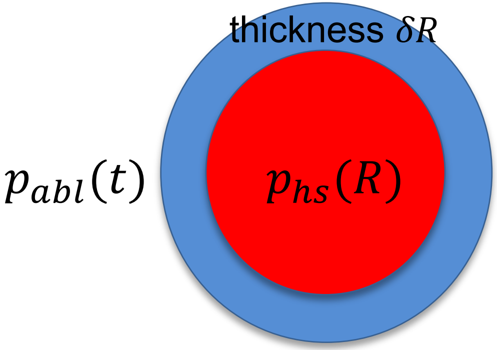


Bilinear ablation pressure*:

$$p_{abl}(t) = \begin{cases} p_{abl,max}\dfrac{t}{t_{peak}}, t_{rise} \le t \le t_{peak} \\ p_{abl,max}\dfrac{t_{peak} + \tau_{cool} - t}{\tau_{cool}}, t > t_{peak} \end{cases}$$

Newton's Law for shell motion:

$$\frac{d\dot{R}}{dt} \approx \frac{p_{hs}(R) - p_{abl}(t)}{\rho \delta R(R)}$$



we will assume shell mass conserved after peak velocity

*Exponential cooling is more accurate, e.g. Moody et al., Phys. Plasmas, 24, 042709 (2017), but the physics argument is unchanged

We don't need the full Newton's law solution to make the connection between the radius of peak velocity and coast-time

The shell acceleration is zero at peak velocity -- *the moment of free-fall*

So, we get a relation connecting the pressure at peak velocity to the time of peak velocity,

$$p_{pv} = p_{abl}(t_{pv}) \approx p_{abl,max} \frac{t_{peak} + \tau_{cool} - t_{pv}}{\tau_{cool}}$$

Deceleration time from piston model differential equation solution:

$$t_{decel} = \frac{R_{pv}}{v_{imp}} = t_{BT} - t_{pv} \rightarrow t_{pv} = -\frac{R_{pv}}{v_{imp}} + t_{BT}$$

We find that the coast-time, hohlraum cooling time, and radius of implosion peak velocity are all related

Stagnation pressure from piston model (one of a couple forms in $Y_{amp} < 2$ limit):

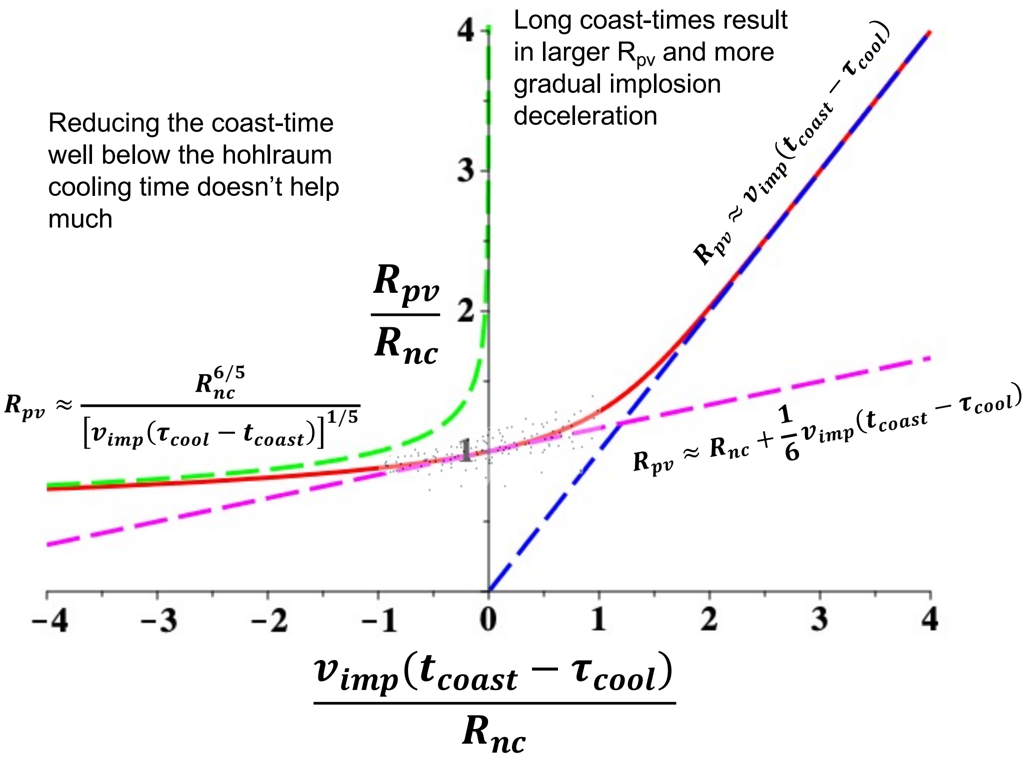
$$p_{piston} = \frac{\rho \delta R_{WHM} v_{imp}^2}{R_{hs}} = p_{pv} \left(\frac{R_{pv}}{R_{hs}} \right)^5$$

Now eliminate p_{pv} and t_{pv} noting that $t_{coast} = t_{BT} - t_{peak}$ and we get the following:

$$R_{pv}^6 - v_{imp}(t_{coast} - \tau_{cool}) R_{pv}^5 - \frac{\rho \delta R_{WHM} v_{imp}^3 \tau_{cool} R_{hs}^4}{p_{abl,max}} = 0$$

(see Hurricane et al., LLNL-JRNL-823920 submitted to Phys. Plasmas)

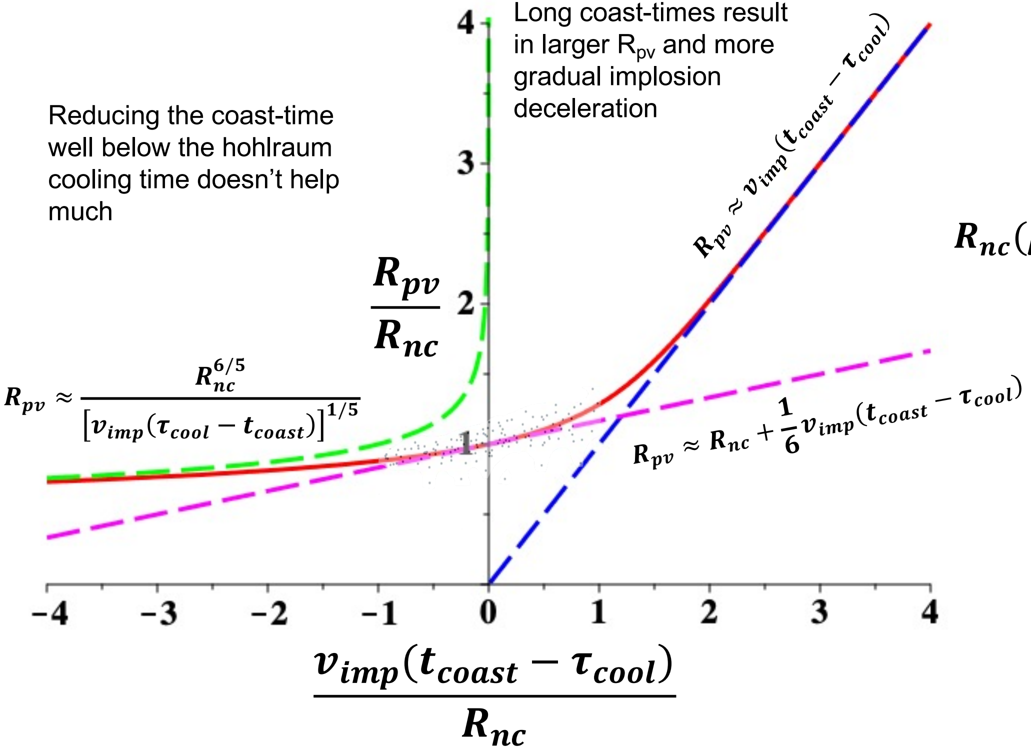
So, what reducing coast-time does is it reduces the radius at which peak kinetic energy is obtained, forcing the implosion to decelerate more aggressively



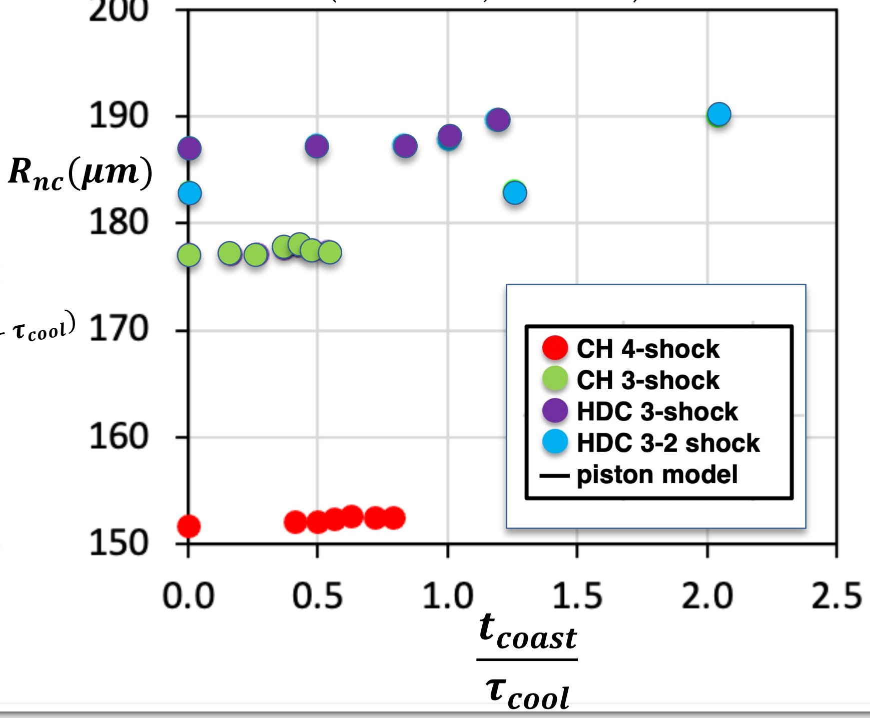
The no-coast radius (R_{nc}) is the minimum R_{pv} possible for a given design

Long coast-times result in larger R_{pv} and more gradual implosion deceleration

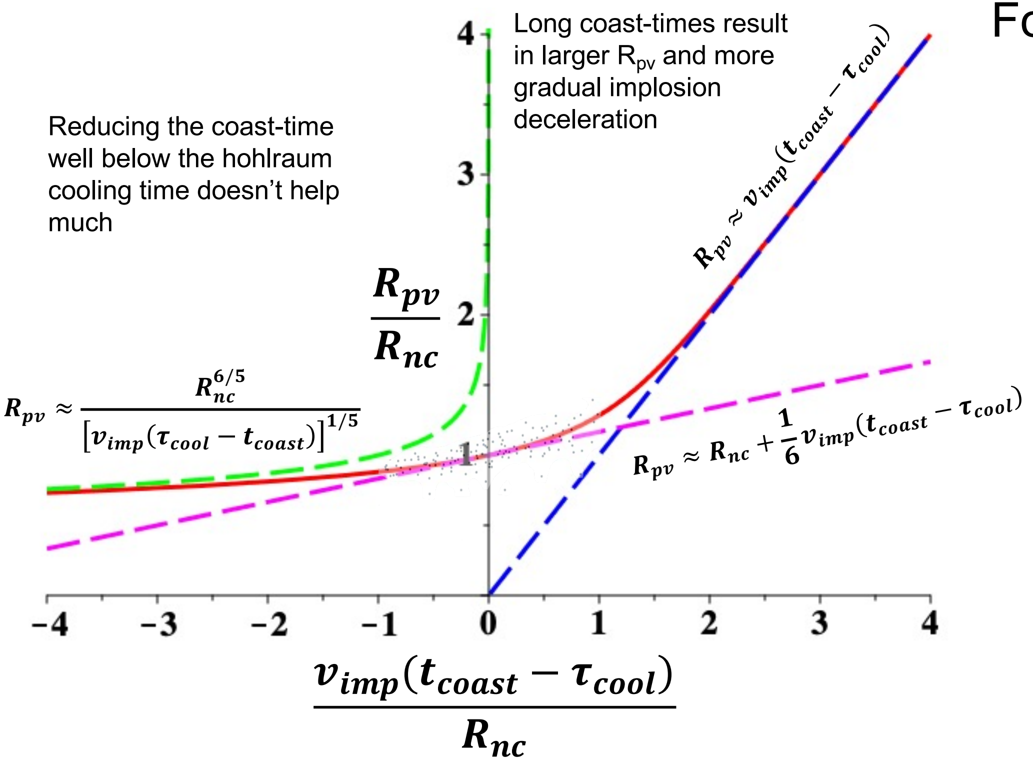
Reducing the coast-time well below the hohlraum cooling time doesn't help much



$$R_{nc} = \left(\frac{\rho \delta R_{WHM} v_{imp}^3 \tau_{cool} R_{hs}^4}{p_{abl,max}}\right)^{1/6} \approx const.$$



Decelerating harder, forces a more rapid transfer of kinetic energy into internal energy and this also reduces the time over which the hot-spot can cool



Forces implosion to slam on the brakes! ("late apex" in racing)

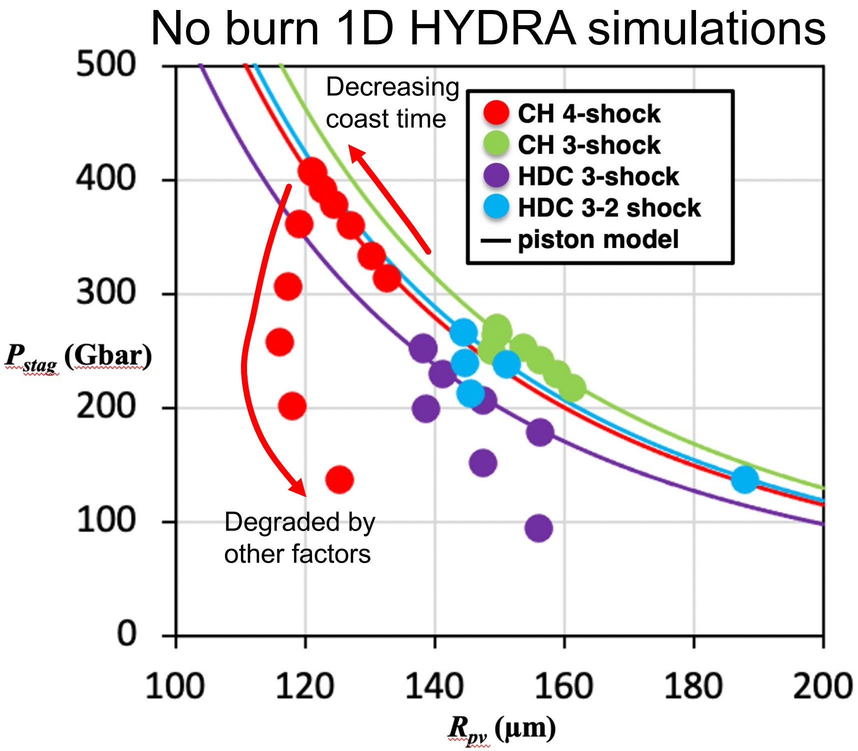
Less time for the heat to escape

$$R_{hs} T_{hs}^{7/2} \sim \frac{m_{shell} v_{imp}^2}{\tau_{decel}}$$

Compression in accelerated frame

$$g_{eff} = \frac{v_{imp}^2}{R_{pv}}$$

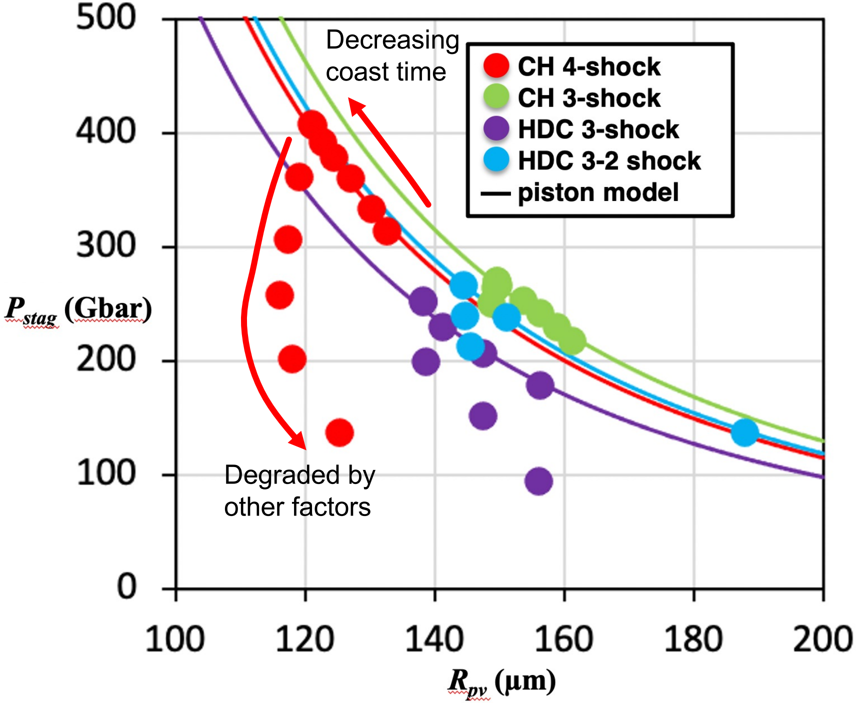
Stagnation pressure increases with reduced coast-time because the radius of peak velocity is decreasing



A high adiabat design can be made to act more like a low adiabat design by reducing R_{pv} and visa-versa

Stagnation pressure increases with reduced coast-time because the radius of peak velocity is decreasing

No burn 1D HYDRA simulations



Many hot-spot properties are linked to R_{pv}:

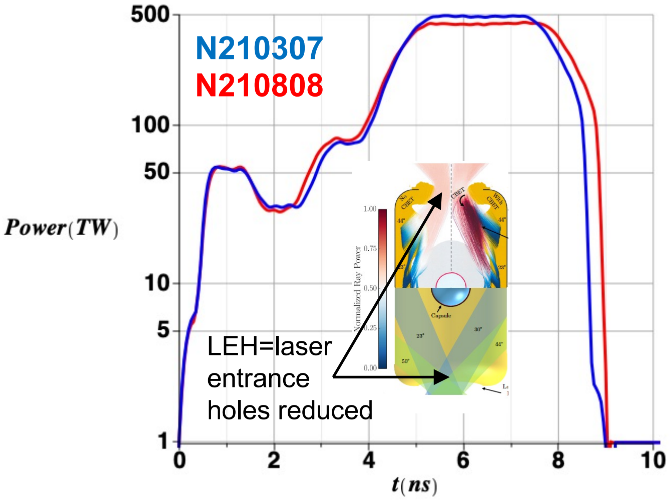
$$P_{stag} \sim \frac{1}{R_{pv}^{5/2}}$$

$$R_{hs} \sim \sqrt{R_{pv}}$$

$$P_{stag}^2 E_{hs} \sim \frac{1}{R_{pv}^6}$$

A high adiabat design can be made to act more like a low adiabat design by reducing R_{pv} and visa-versa

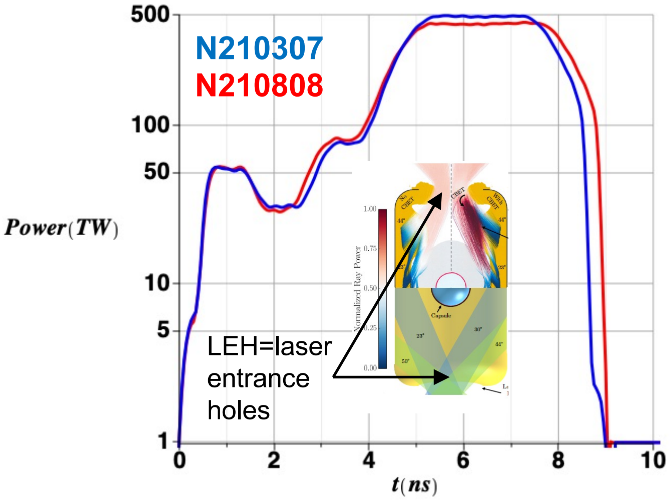
Part of the Hybrid-E strategy+ and design* was to again leverage the tactic of reducing coast-time

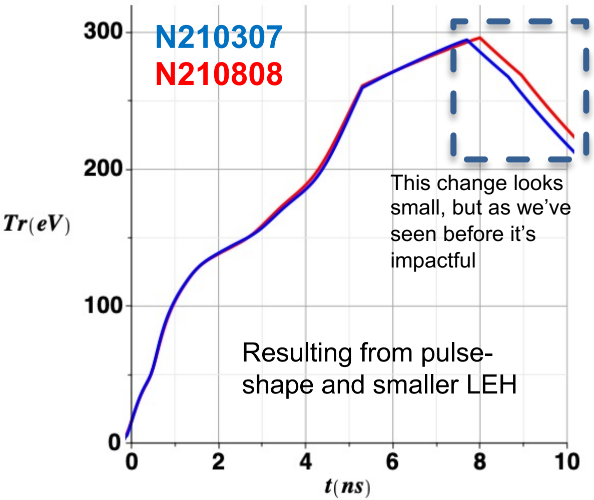


+O. Hurricane et al, APS-DPP, PO7.00001 (2017); PPCF 61, 014033 (2019); PoP 26, 052704 (2019);
*A.B. Zylstra et al., PRL 126, 025001 (2021);
*A.L. Kritcher et al., PoP 28, 072706 (2021)

*see talks by A. Zylstra ZI02.00003; A. Kritcher GO04.00002

In the case of N210808 both a pulse-shape change and a laser entrance hole change resulted in an increased late time T_{rad}





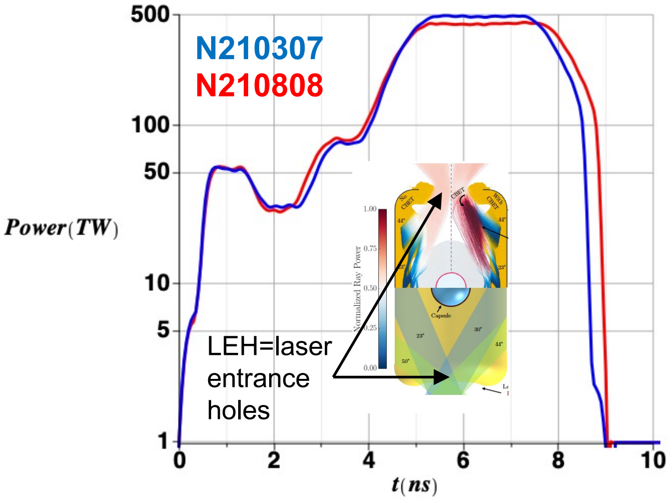
N210808 R_{pv} reduced **30 μm** from N210307 which was 235 μm

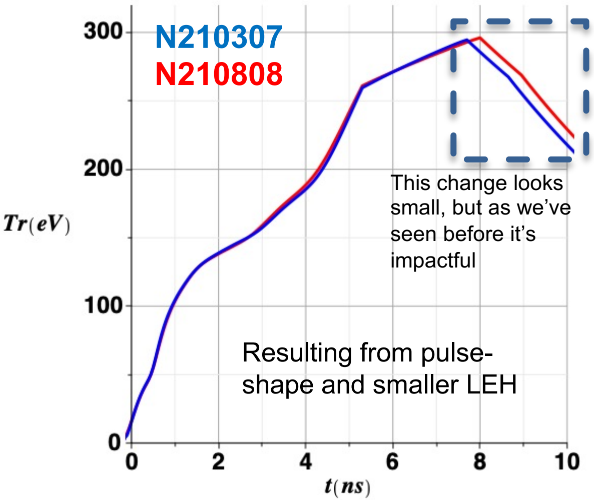
+O. Hurricane et al, APS-DPP, PO7.00001 (2017); PPCF 61, 014033 (2019); PoP 26, 052704 (2019);
*A.B. Zylstra et al., PRL 126, 025001 (2021);
*A.L. Kritcher et al., PoP 28, 072706 (2021)

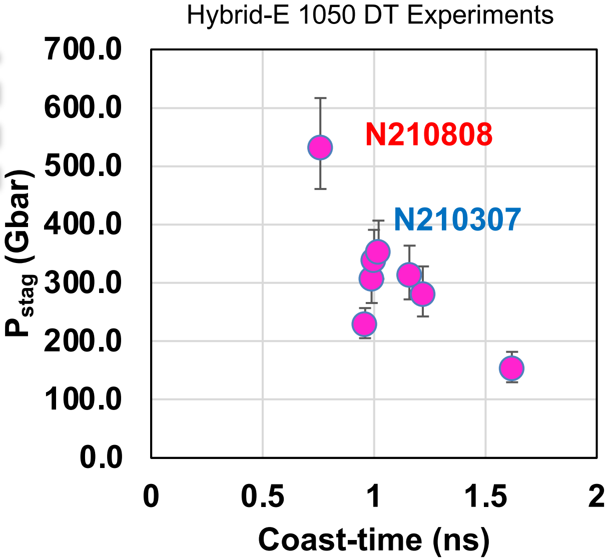
See J. Ralph talk GO04.00003 on reduced hohlraum cooling with reduced LEH

*see talks by A. Zylstra ZI02.00003; A. Kritcher GO04.00002

As seen before, hot spot pressure improved, but this time we finally got to the ignition tipping-point







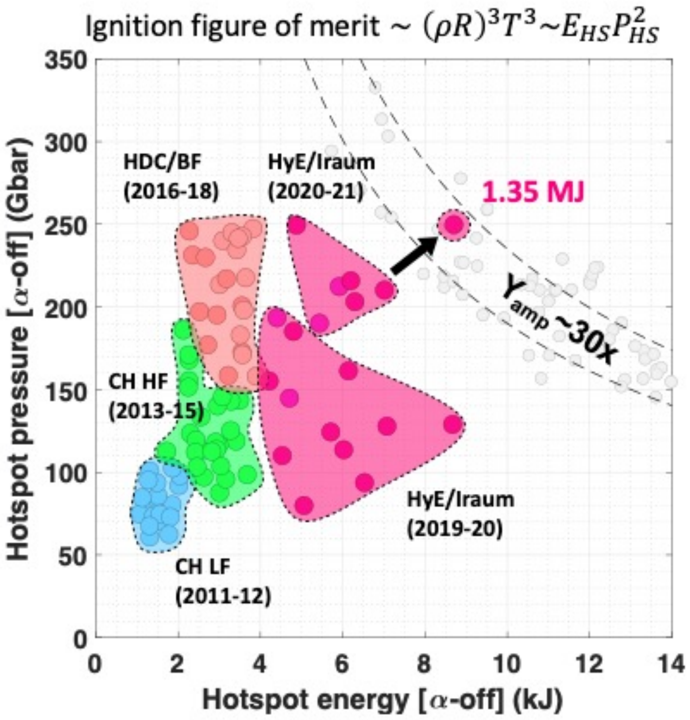
Reduced R_{pv} of 15% resulted in a 1.4x increase in pressure (no-α) and a 2x increase P^2E (no-α)

[+]O. Hurricane et al, APS-DPP, PO7.00001 (2017); PPCF 61, 014033 (2019); PoP 26, 052704 (2019);
[*]A.B. Zylstra et al., PRL 126, 025001 (2021);
[*]A.L. Kritcher et al., PoP 28, 072706 (2021)

[*]see talks by A. Zylstra ZI02.00003; A. Kritcher GO04.00002

Reducing coast-time is an obscure but valuable tactic for increasing indirect-drive implosion performance

- All yield record setting DT experiments on NIF have been those with low-coast time, except for the NIC implosions which mixed
- Coast-time, hohlraum cooling-rate, and the radius at which the implosion achieves its peak velocity (R_{pv}) are related
- The fundamental parameter behind coast-time is R_{pv} and many hot-spot properties have a strong dependence upon it
- Improvements in target quality allowed us to leverage the advantage of low coast for the ignition level shot N210808 by reducing R_{pv} by 15% as compared to N210307 (see talks by Annie Kritcher, et al. GO04.00002 & Alex Zylstra, et al. ZI02.00003)
- More tests isolating coast-time vs. capsule quality are planned
- Understanding of coast-time physics implies that a hotter hohlraum would be very beneficial in general (see talk CO04.00006 by Dan Casey, et al.)



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