Design of First Magnetized Hohlraum-Driven Implosions on NIF

D. J. Strozzi, J. D. Moody, H. Sio, B. B. Pollock, D. D. Ho, C. A. Walsh,
G. B. Zimmerman, J. D. Salmonson, J. M. Koning, S. O. Kucheyev

APS DPP Meeting

Talk CO5.8

9 November 2020

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Lawrence Livermore National Laboratory

Goal: demonstrate B field compression in hohlraum-driven implosions *measured by* improved nuclear performance

Design starting point: subscale BigFoot symcap

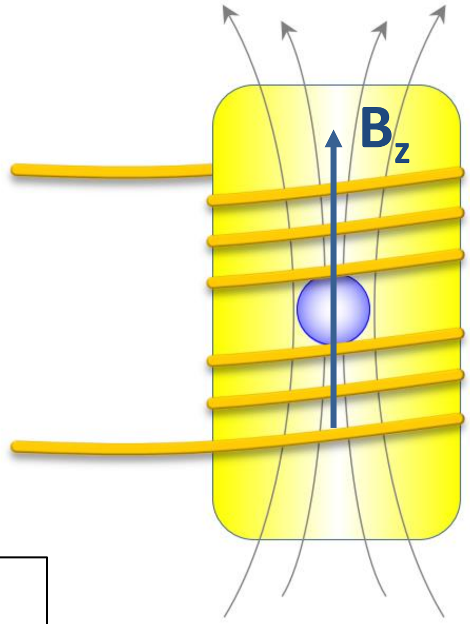
- High-adiabat, high-performing, reliable platform
- More aggressive, lower-adiabat designs can be tried next
- Modified due to NIF constraints

MHD hohlraum modeling with imposed field

- Small effect on x-ray drive and plasma conditions
- Even though heat flow magnetized in hohlraum fill

Capsule performance with imposed axial field of 30 T:

- DDn yield 30-50% higher, T_{ion} 0.5 – 0.7 keV higher
- Hotspot P2 5-10 um more prolate

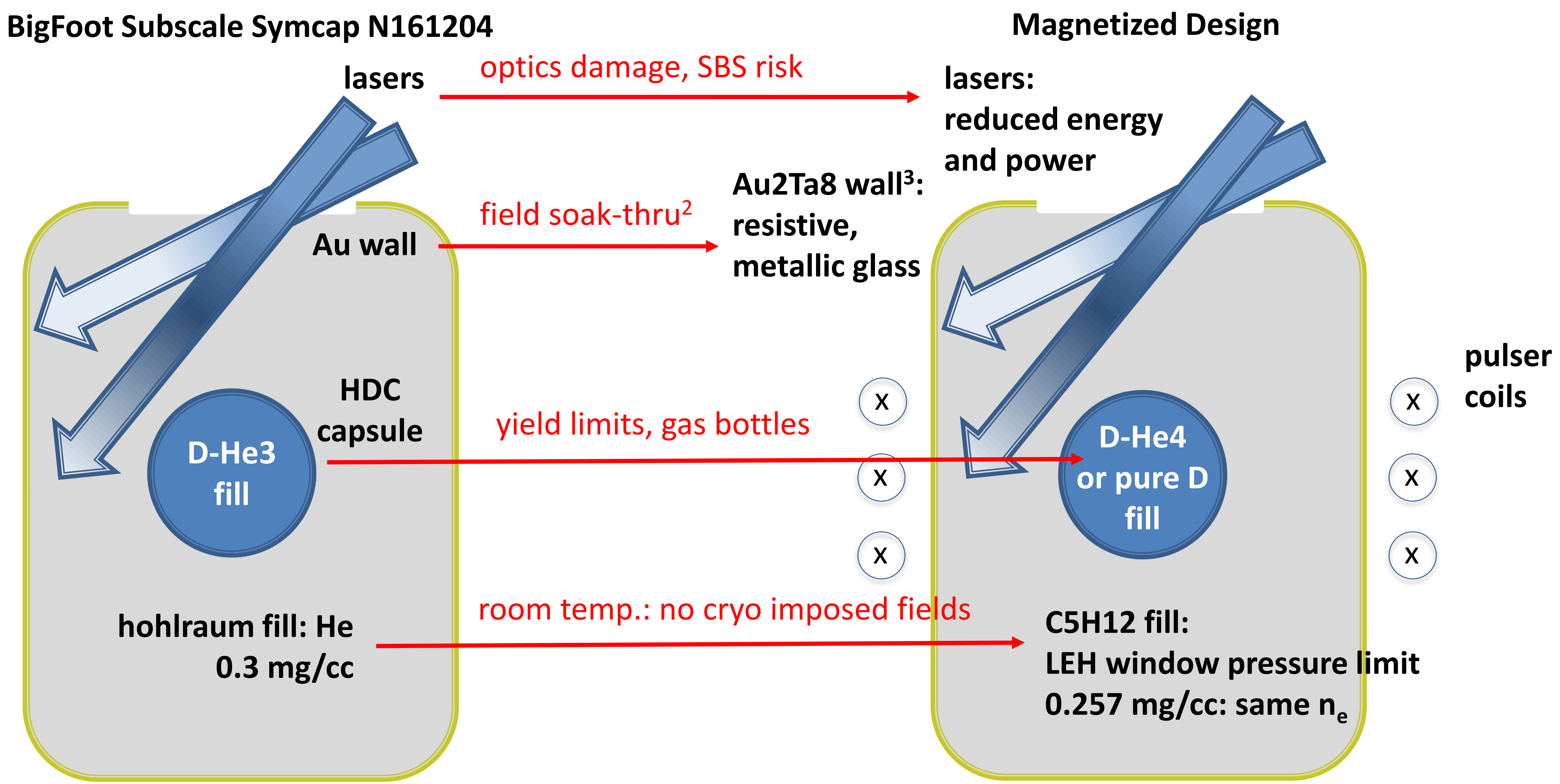


Other APS talks this session

- John Moody – next talk
- Darwin Ho – 4pm

Goldilocks principle: enough convergence to compress B and improve nuclear performance, not so much that hohlraum or implosion become challenging, unstable, or hard to model

Magnetized Design: Bigfoot[1] Symcap plus Constraints



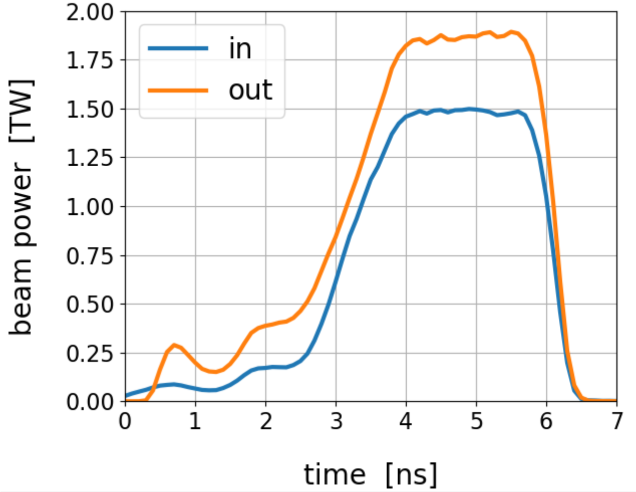
[1] C. A. Thomas+, PoP 2020

[2] J. D. Moody+, PoP 2020

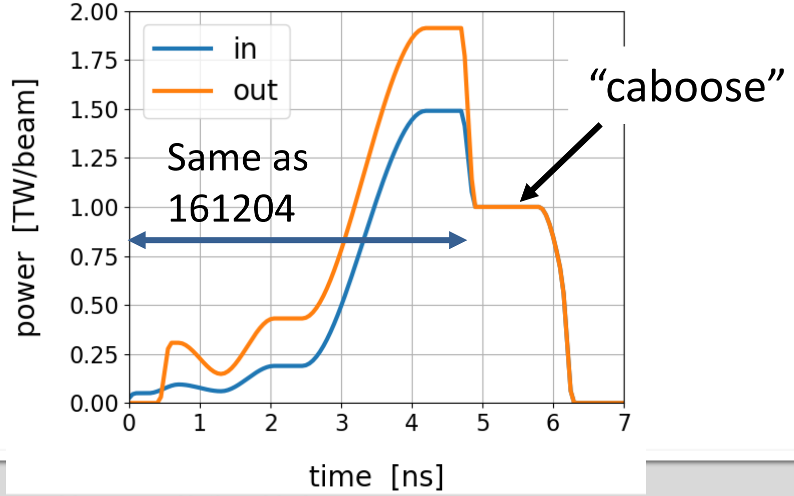
[3] S. O. Kucheyev et al: provisional patent

Laser pulses: Bigfoot shot N161204 and magnetized design

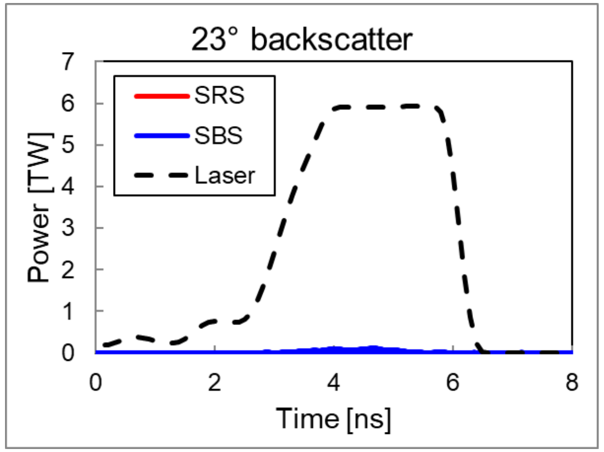
N161204: 1106 kJ, 340 TW
peak CF (cone frac) = 0.28

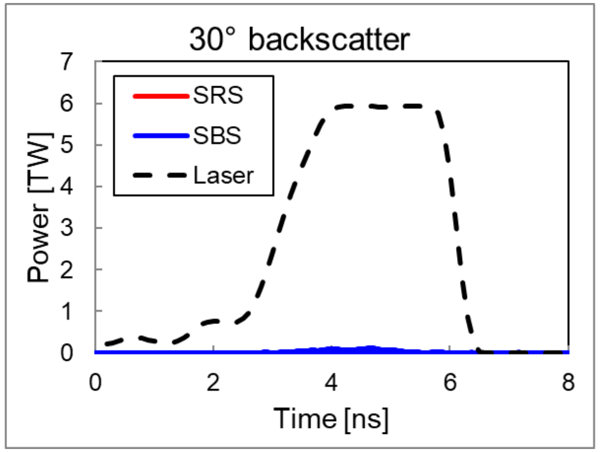


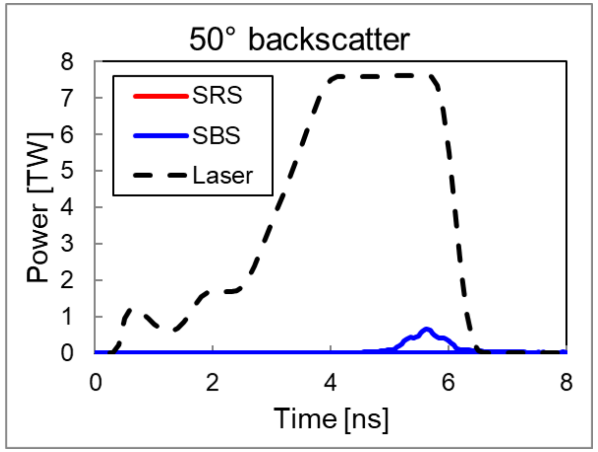
Warm design: 908 kJ
low-power "caboose" for SBS risk



N161204: Backscatter: low, coupling 98.8%, some late 50º SBS



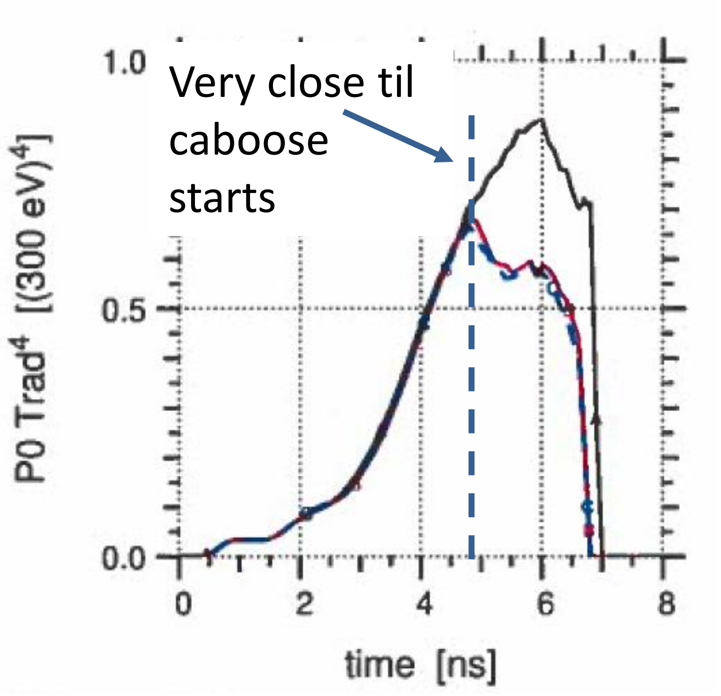




Magnetized hohlraum rad-hydro + MHD modeling

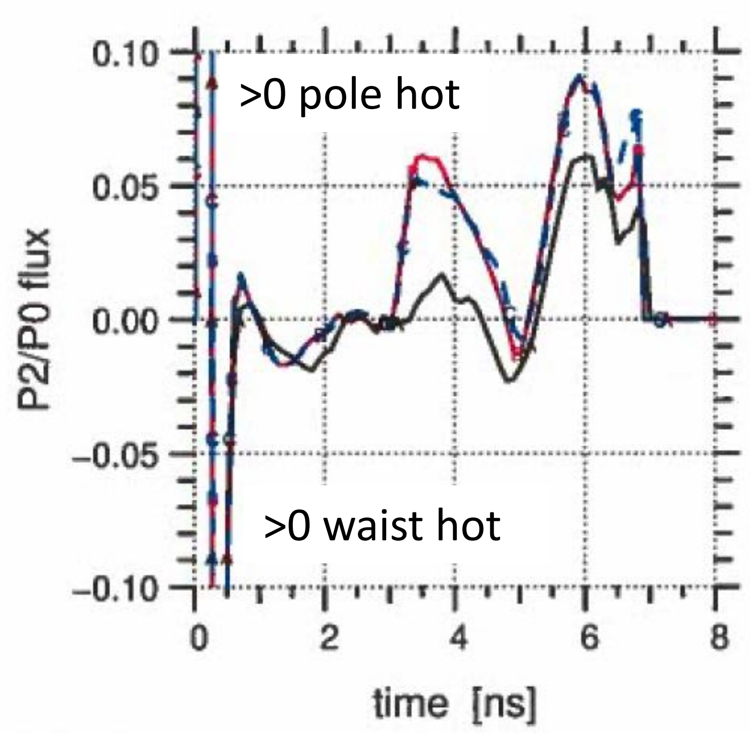
- **Lasnex LHT deck** – best-effort model from Oggie Jones's hohlraum modeling group
  - Electron flux limit f=0.03 in wall after 2.0 ns – reduces drive deficit
  - MHD: turn off Hall and Leduc-Righi terms: numerical issues
  - Multi-species hydro, one T_{ion} : similar to "classic" single-species
- **Hydra HyPyd deck** – Pythonic framework (J. Salmonson, J. Koning)

Total x-ray flux on capsule ~ T_{rad}^4



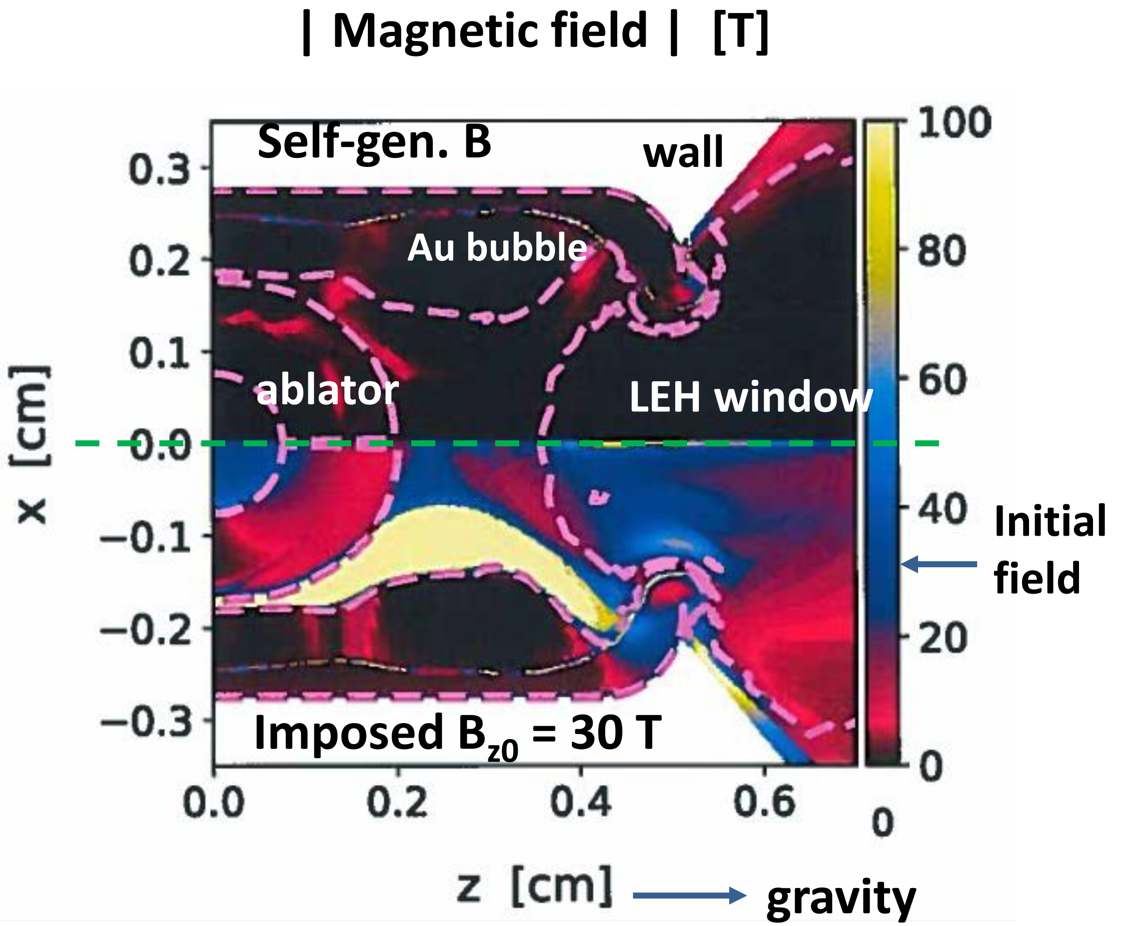
Lasnex runs
N161204 post-shot
Magnetized design, $B_{z0} = 0$
Mag. design, $B_{z0} = 30$ T

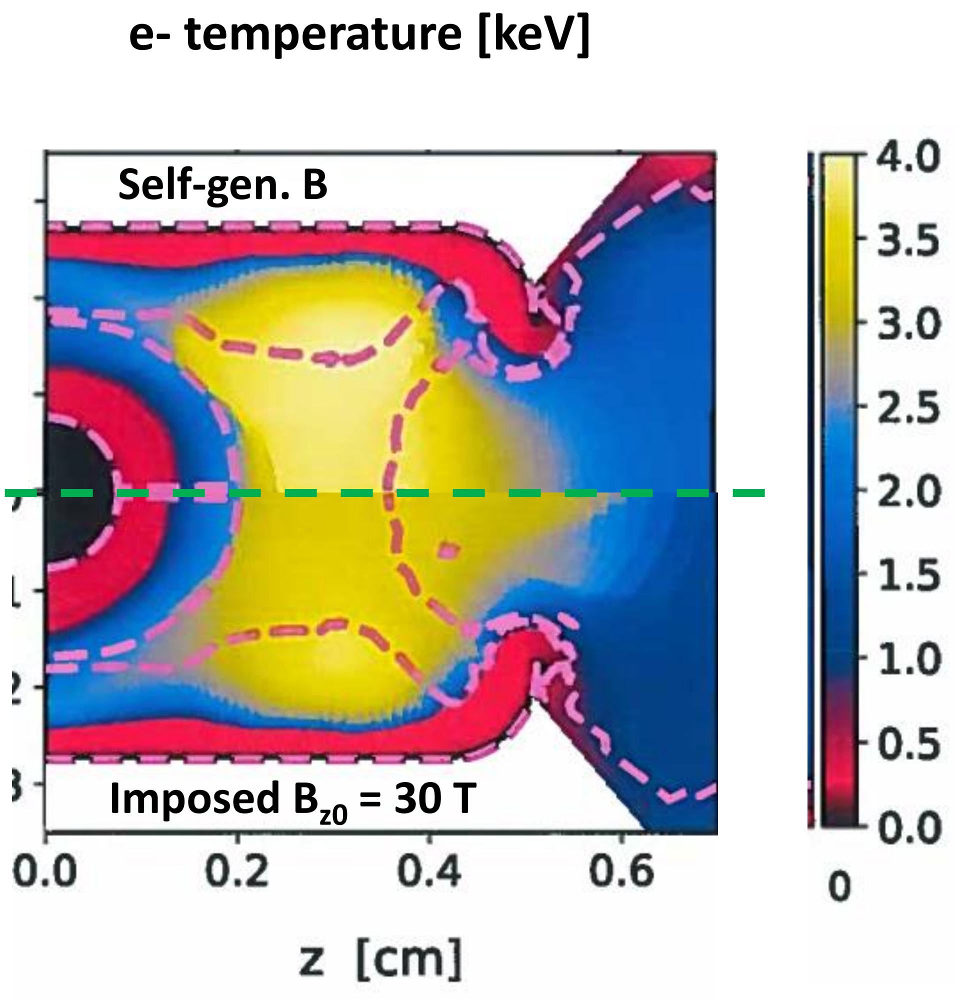
P2/P0 x-ray flux
Magnetized drive pole-hot:
Au2Ta8 vs. Au wall main reason



Hohlraum dynamics: frozen-in B field, small temperature change

Hydra runs: N161204 post-shots   4.5 ns: early peak power

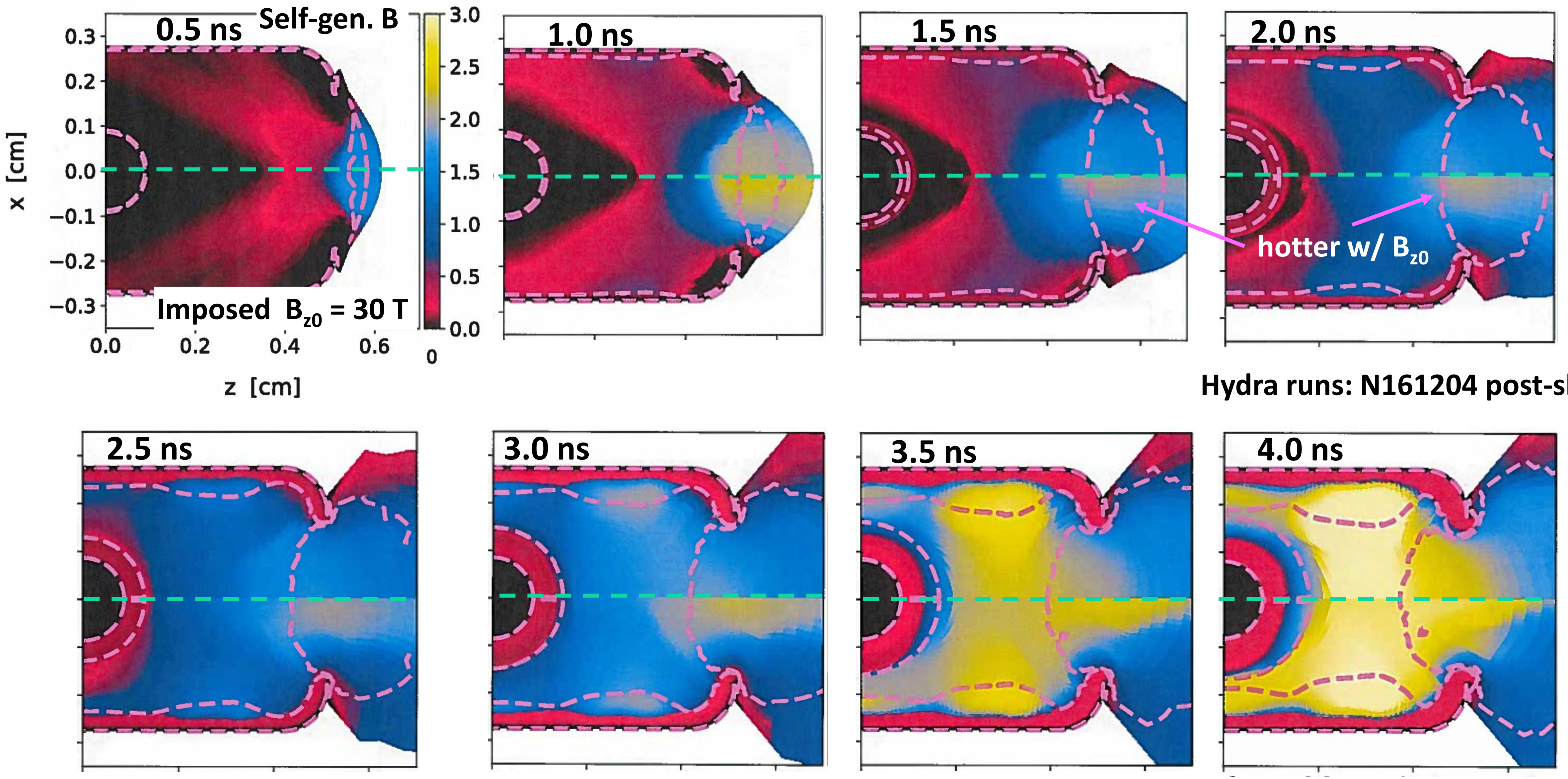




Unlike Montgomery et al. PoP 2015: gas-filled Omega hohlraums.

- Very different system: smaller, shorter pulses, less laser energy

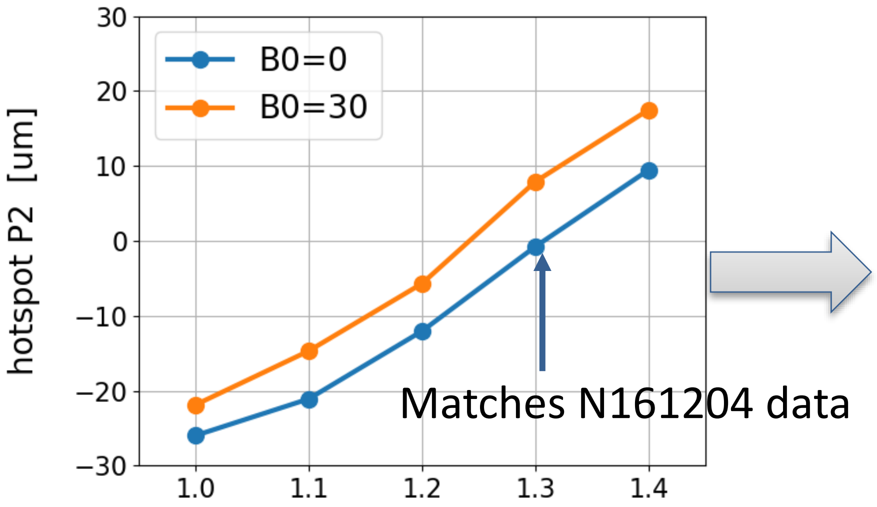
T_e [keV] Movie: hotter in LEH w/ imposed B, not in rest of fill



Hydra runs: N161204 post-shots

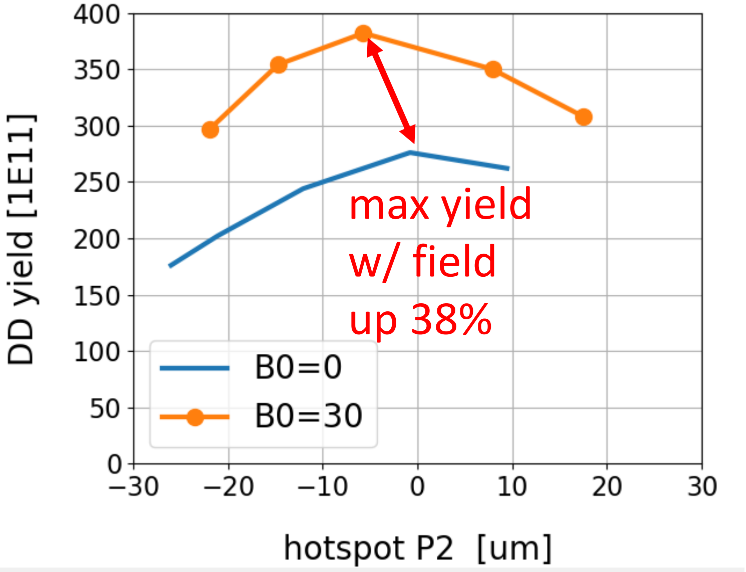
Magnetized design: Simulated yield 30-50% higher with 30 T field

Hotspot P2 5-10 um more sausaged w/ field

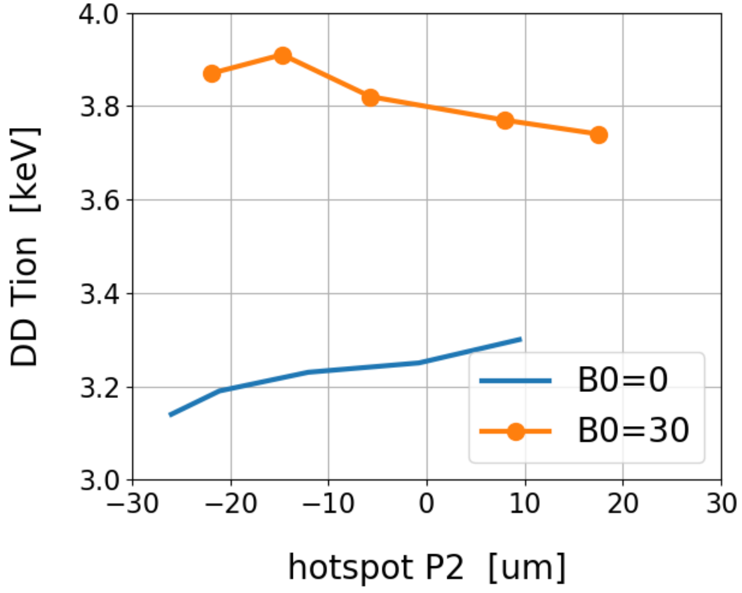


Cone fraction multiplier
CF = inner / total power

Yield: 30-50% higher w/ field



T_{ion} 0.5 – 0.7 keV higher w/ field

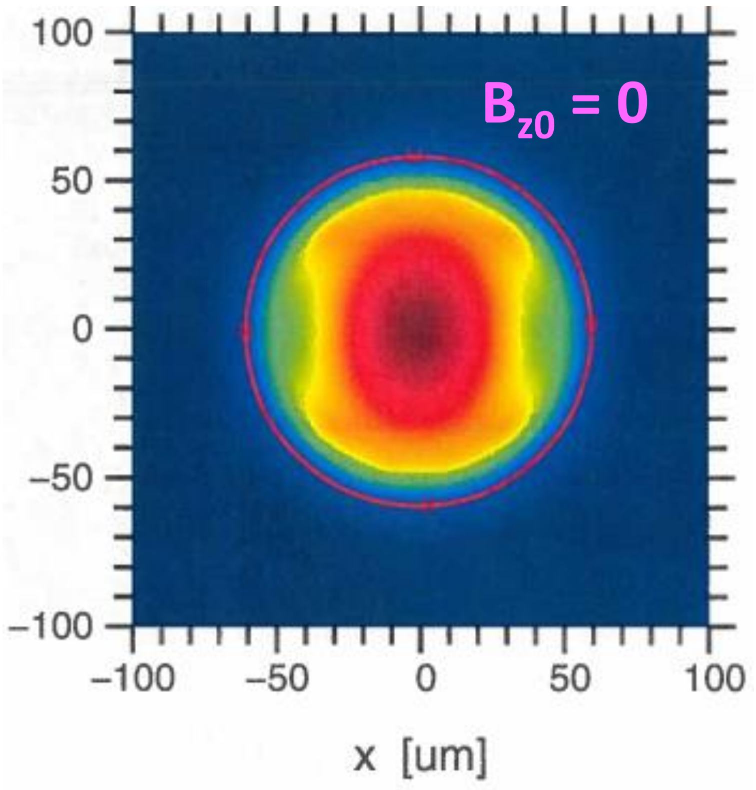


Lasnex MHD simulations

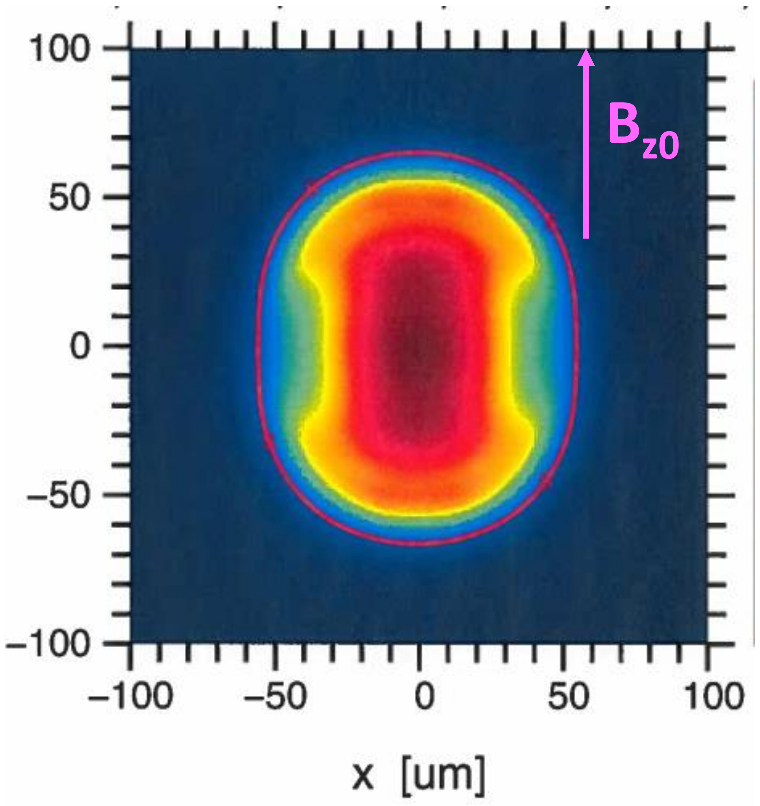
Changes in yield and T_{ion} out of errors bars for gas-filled NIF capsules

Lasnex modeling: magnetized design: hotspot x-ray images

Peak cone fraction * 1.3:
P2/P0 = -1.3%
Convergence = initial IR / P0 = 14



Peak cone fraction * 1.3:
P2/P0 = 13.1%
Convergence = 14



Increased P2 with field likely due to effect on e- thermal conduction in capsule, not change in x-ray flux

Magnetized hohlraum shot plan: 4 NIF shots to demonstrate magnetization via improved nuclear performance

1 29 Dec. 2020

E_{laser} ~ 900 kJ @ B_{z0} = 30 T

2 28 Feb. 2021

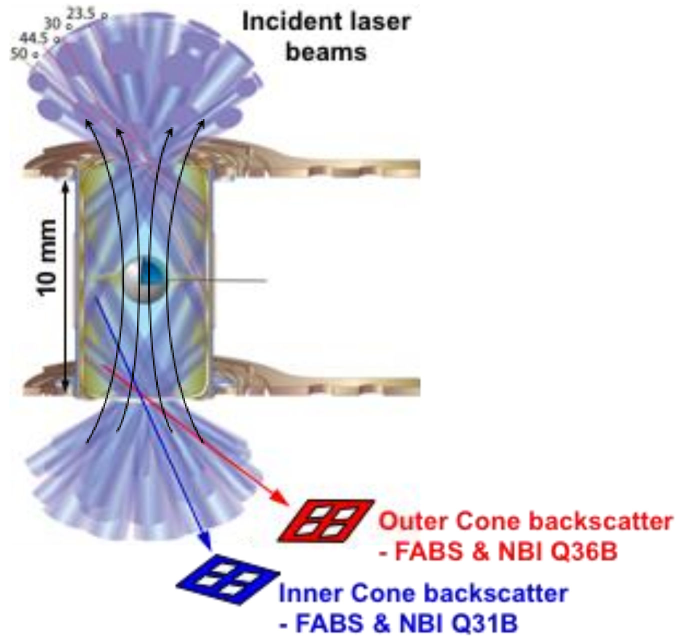
Shape tune via laser cone fraction @ B_{z0} = 30 T

3 June – Sep. 2021

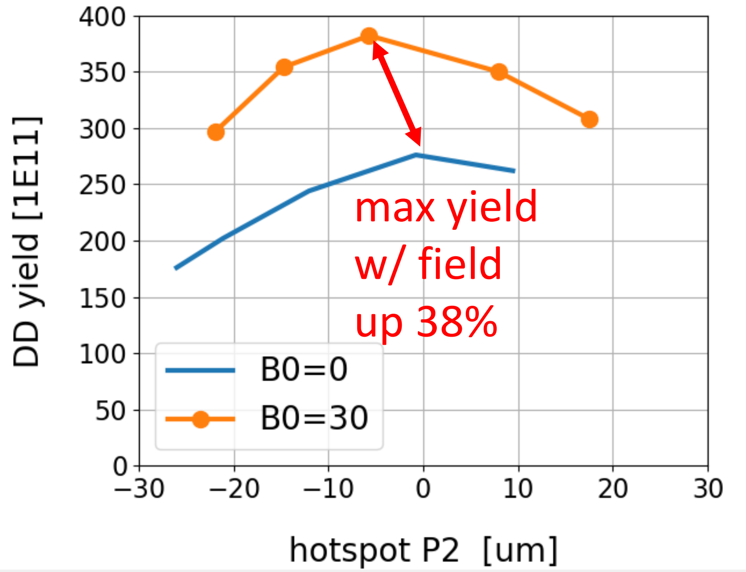
B ~ 0 control shot repeat of 1 or 2

4 June – Sep. 2021

B-field scan repeat of 1 or 2



Yield: 30-50% higher w/ 30 T field



BACKUP BELOW

BigFoot platform chosen for *first* magnetized implosions

- **Start with existing platform,** stick with it through DT layered implosions in several years
  - We don't have the shots to make a new design, or switch horses after a year

- **Be bold**: start with a high-yield platform: Yield meaningfully > 1E16 → BigFoot, HDC, Hybrid E

- **Subscale:** limited to < 1 MJ laser energy
  - High-yield platform with subscale version → BigFoot, HDC

- **Start easy:** first demonstrate B field benefit in "lower risk" platform → BigFoot
  - Low shot rate: minimize surprises: mix, meteors, …
  - Bigfoot lower risk due to higher adiabat, better stability
  - Bigfoot used for 2019 hydro scaling (Baker et al., yield > 1E16), basis of SQ* designs (Clark et al.)
  - Higher risk (e.g. lower adiabat) targets can be magnetized subsequently

- **AuTa resistive hohlraum wall:** closer to pure Au than DU: almost all BigFoot shots have been Au

Goldilocks principle: enough convergence to compress B and improve nuclear performance, not so much that hohlraum or implosion become challenging, unstable, or hard to model

Lasnex hohlraum modeling: magnetized design capsule performance

N161204 post-shots: bangtime within 90 ps, yield within 6%

Case	neutron bangtime – 7.12ns [ps]	DDn yield [1E11]	DD Tion [keV]	hotspot x-ray P2 [um]	Comment
N161204 data	0	9.07 := 1x	3.09 := 0	+11.2	Sausage
N161204, nominal	-90	9.41 (1.04x)	2.96 (-0.13)	-9.0	BT+yield close, pancake
N161204, peak CF*1.3	-50	9.63 (1.06x)	2.99 (-0.1)	+9.9	Sausage like data

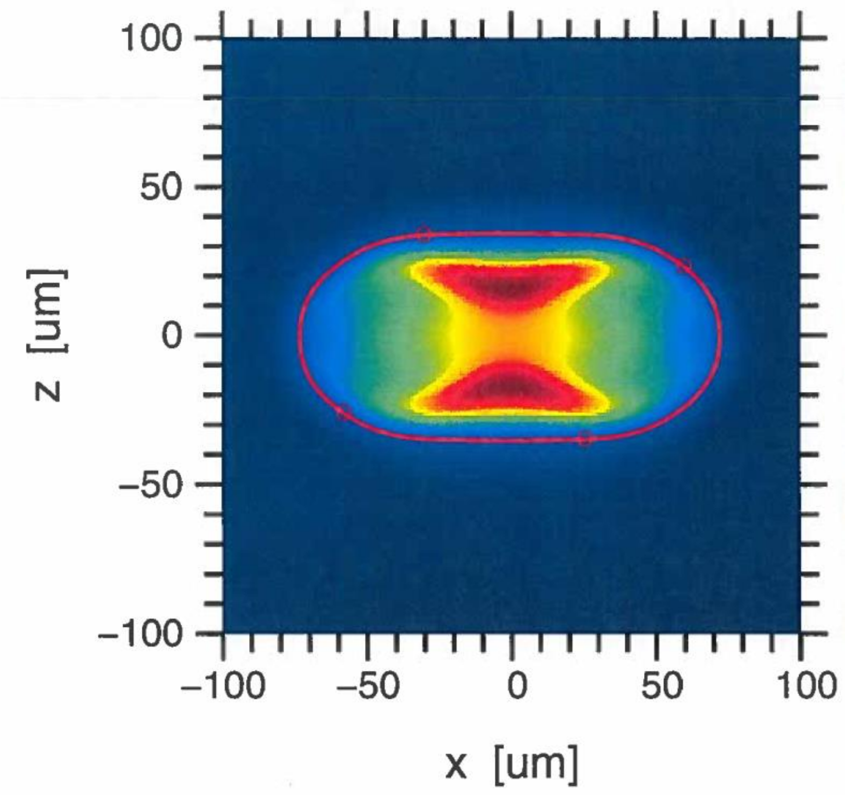
Magnetized design, peak CF *1.3

no B_{z0}	+240 less E_{laser}	276 pure D fill	3.25 no He, less rad.	-0.8	Close to round Au2Ta8 pole-hot drive vs. Au
B_{z0}=30 T	+240	350 = 1.27x B_{z0}=0	3.77 B_{z0}=0 + 0.52 kV	+7.9	Sausage w/ B_{z0}

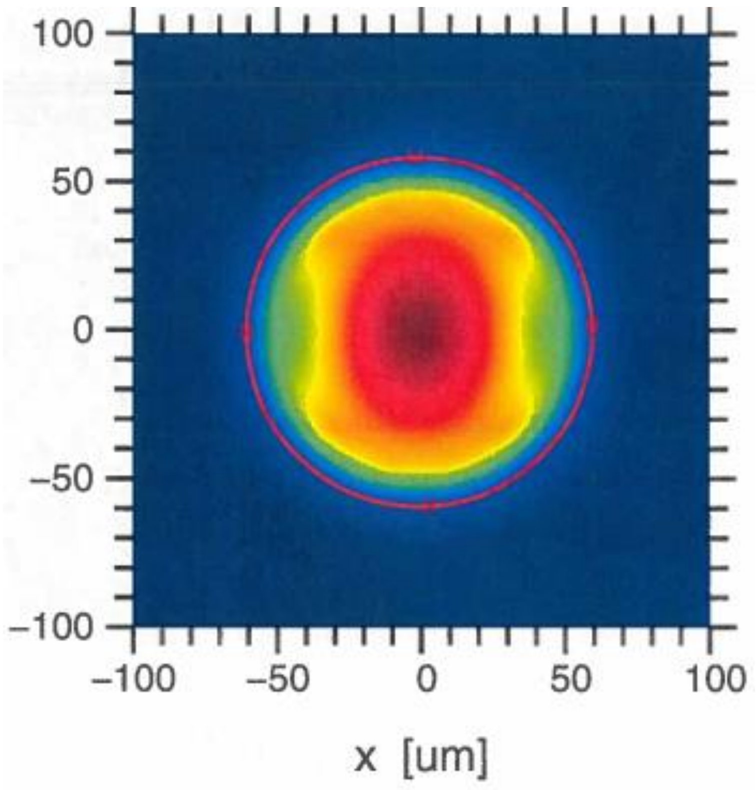
x-ray P2 at time of peak emission

Lasnex modeling: magnetized design: hotspot x-ray images

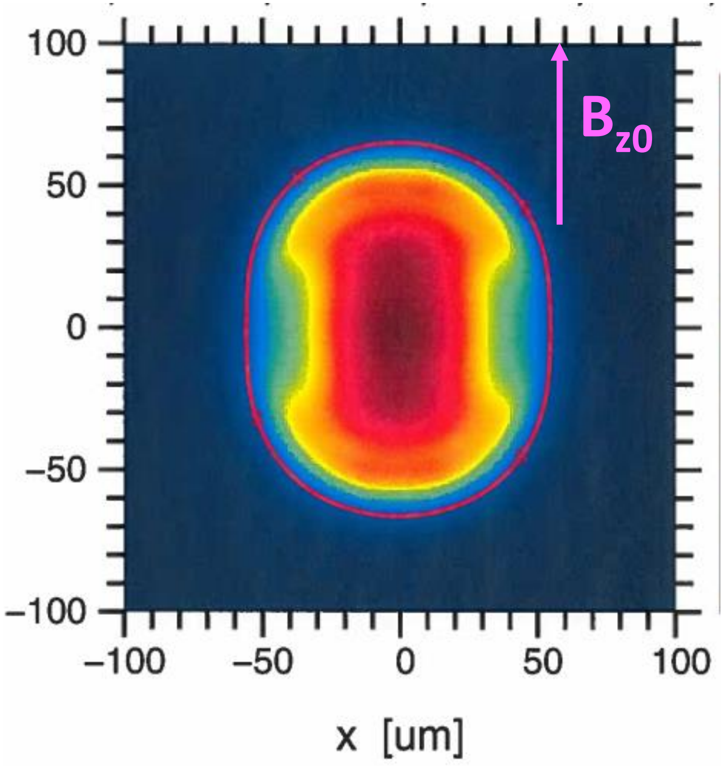
No imposed field, Nominal pulse:
P2/P0 = -48.3%



Peak cone fraction * 1.3:
P2/P0 = -1.3%
Convergence = initial IR / P0 = 14



Peak cone fraction * 1.3:
P2/P0 = 13.1%
Convergence = 14

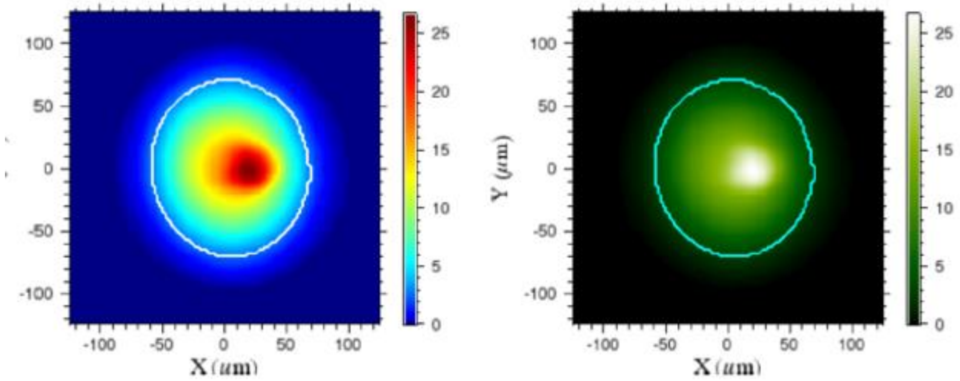


Increased P2 with field likely due to effect on e- thermal conduction in capsule, not change in x-ray flux

BigFoot Shot N161204: sausaged hotspot @ CF=0.28

**Equatorial x-ray image:
Time integrated**

N. Izumi



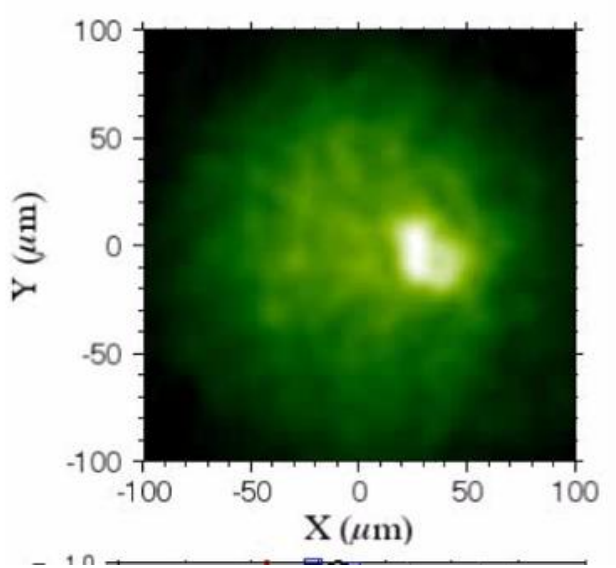
Brightness (PSL)	26797 $^{+1953}/_{-2052}$
P0 (μm)	63.63 $^{+0.81}/_{-2.17}$
P2/P0 (%)	6.68 $^{+1.20}/_{-1.76}$
P3/P0 (%)	-0.22 $^{+1.53}/_{-0.35}$
P4/P0 (%)	0.94 $^{+0.66}/_{-0.83}$
RMS_P0 (%)	4.13 $^{+0.61}/_{-0.86}$
RMS_P0_P2_P4 (%)	1.14 $^{+0.66}/_{-0.20}$

Strong fill tube feature:
10% contour used for P_N's

- DDn yield 9.07E11
- T_{ion} 3.09 keV

**Eqautorial x-ray image:
Time resolved**

S. Khan



Bangtime:	7.216 ± 0.070 ns
Emission FWHM:	0.221 ± 0.060 ps
P0:	60.0 ± 4.689 μm
P2/P0:	(18.7 ± 5.6)%
P3/P0:	(-3.1 ± 2.4)%
P4/P0:	(-0.8 ± 1.6)%

N161205: DT symcap: sausaged like 161204, less filltube feature

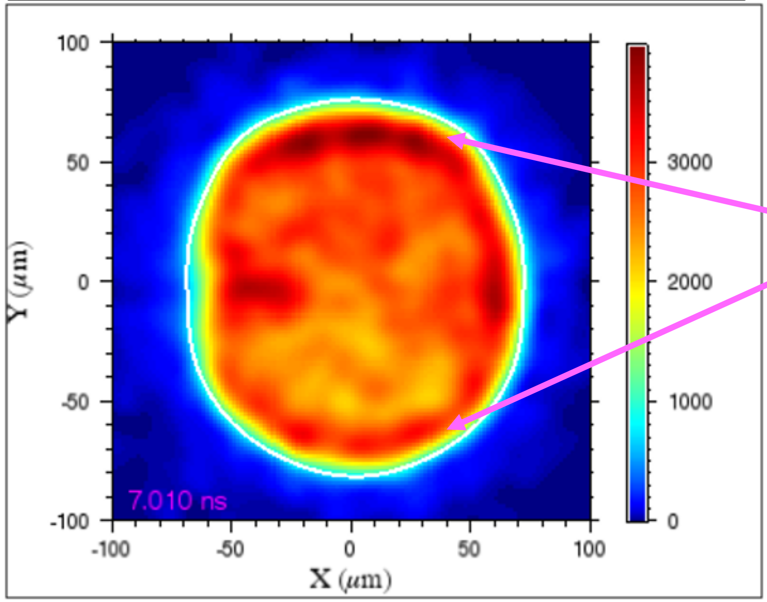
Shot Name: Shot Number:

N161205-003-999, TR Equatorial Shape Summary

The National Ignition Fac

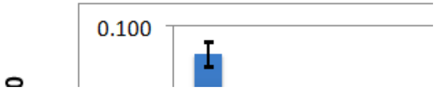
Bangtime:	7.01± 0.08 ns
Emission FWHM:	192 ± 60 ps
P0:	74.2 ± 4.5 μm
P2/P0:	(8.1 ± 0.8)%
P3/P0:	(0.5 ± 0.8)%
P4/P0:	(-2.9 ± 0.8)%
P5/P0:	(-0.5 ± 0.6)%
P6/P0:	(0.1 ± 0.5)%
ΔP0/Δt :	-98.6 ± 2.91 μm/ns
ΔP2/Δt :	13.7 ± 0.67 μm/ns
ΔP4/Δt :	-14 ± 1 μm/ns

Bangtime: Strip 3, image 3



"Ridges" from ablator visible since no He?

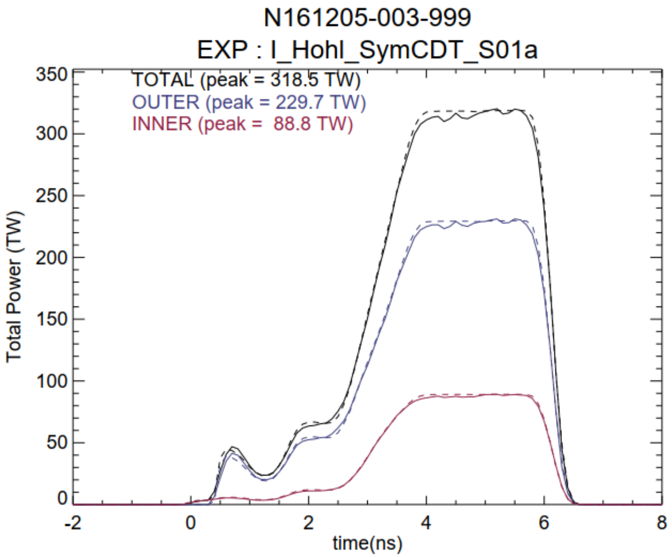
Strip 3, autoscaled ← time Strip 1, autoscaled

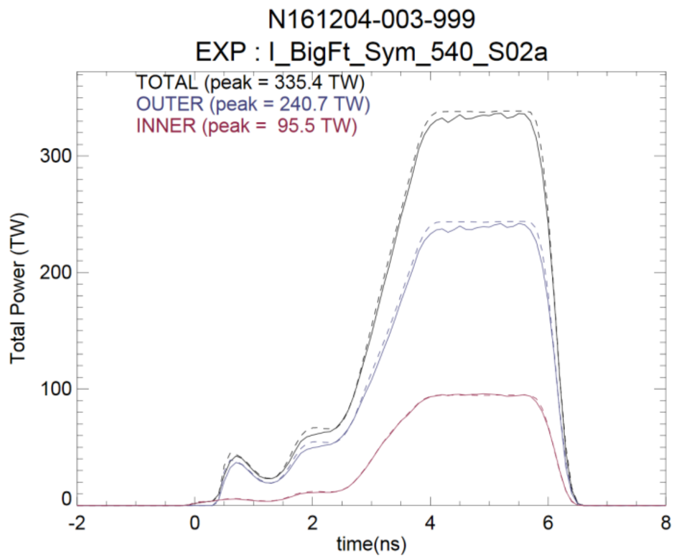


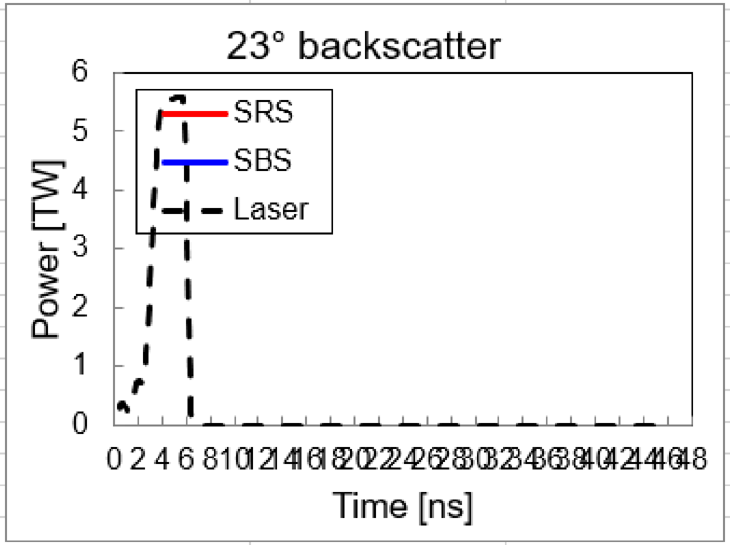
N161205-003: DT symcap: BS low, 98.8% coupling

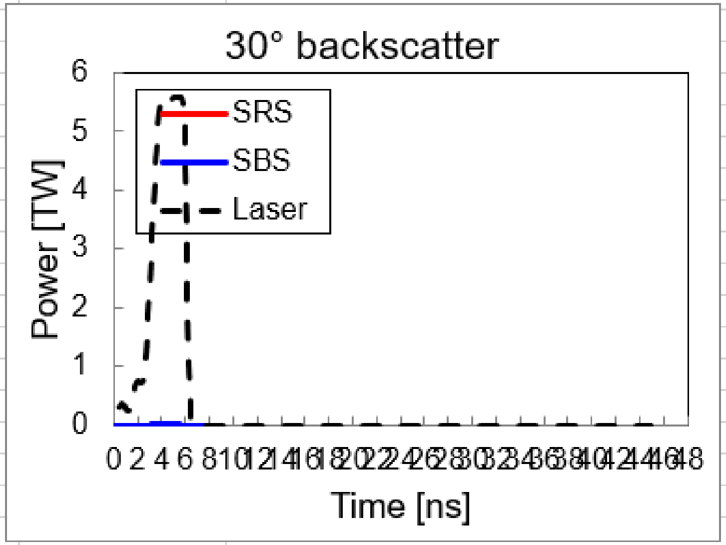
Pulse essentially same as 161204

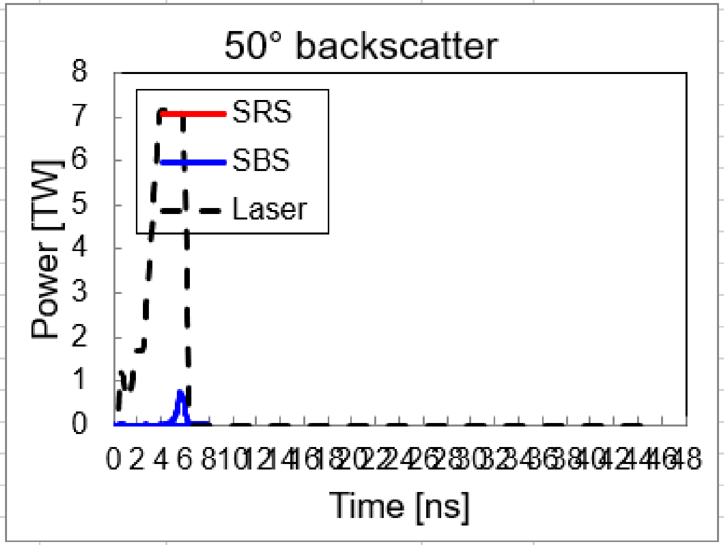
NIF Counts		
Quads	48	
Beamlines	192	
NIF Energy		
OSP	1742.2	kJ
DrD	1074.1	kJ
LEH	1.064	MJ
DrD Peak Power		
Total	321.4	TW
Inner	89.5	TW
Outer	232.0	TW
LEH Peak Power		
Total	318.5	TW
Inner	88.8	TW
Outer	229.7	TW



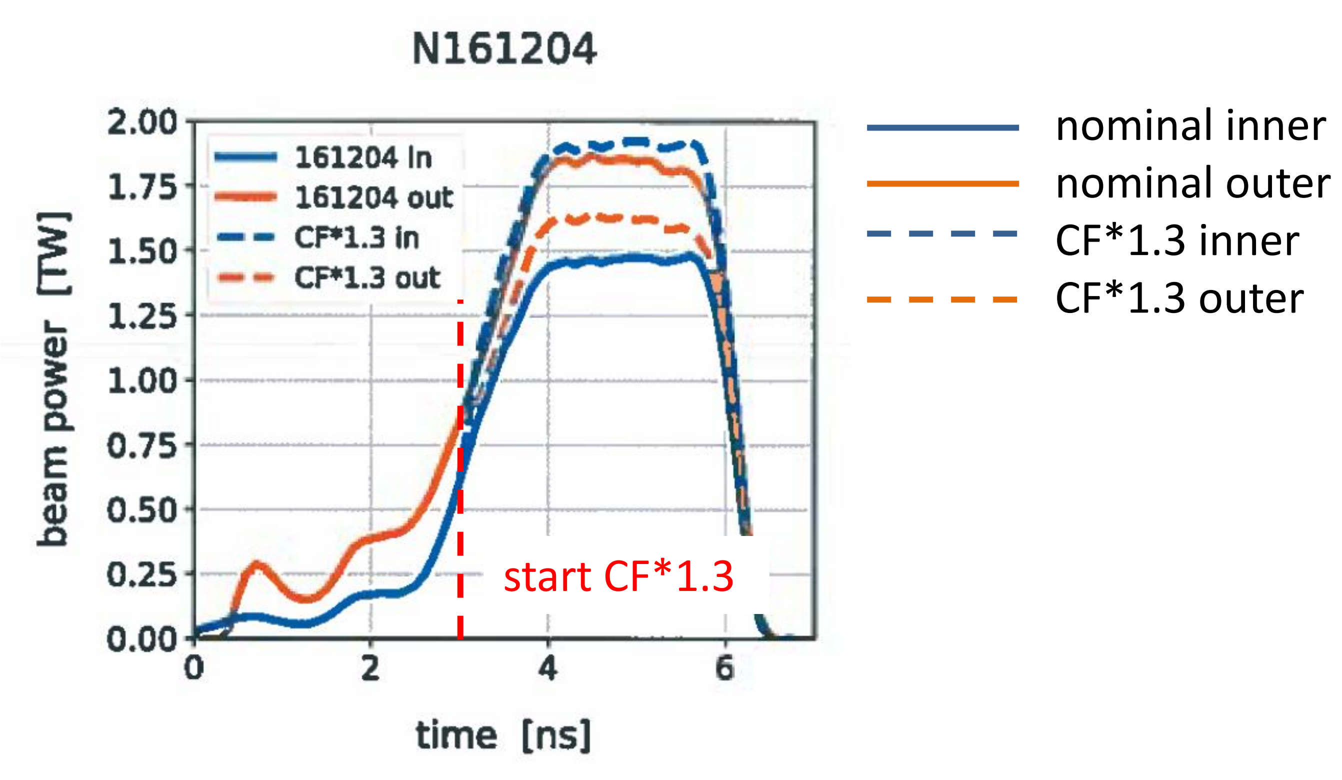


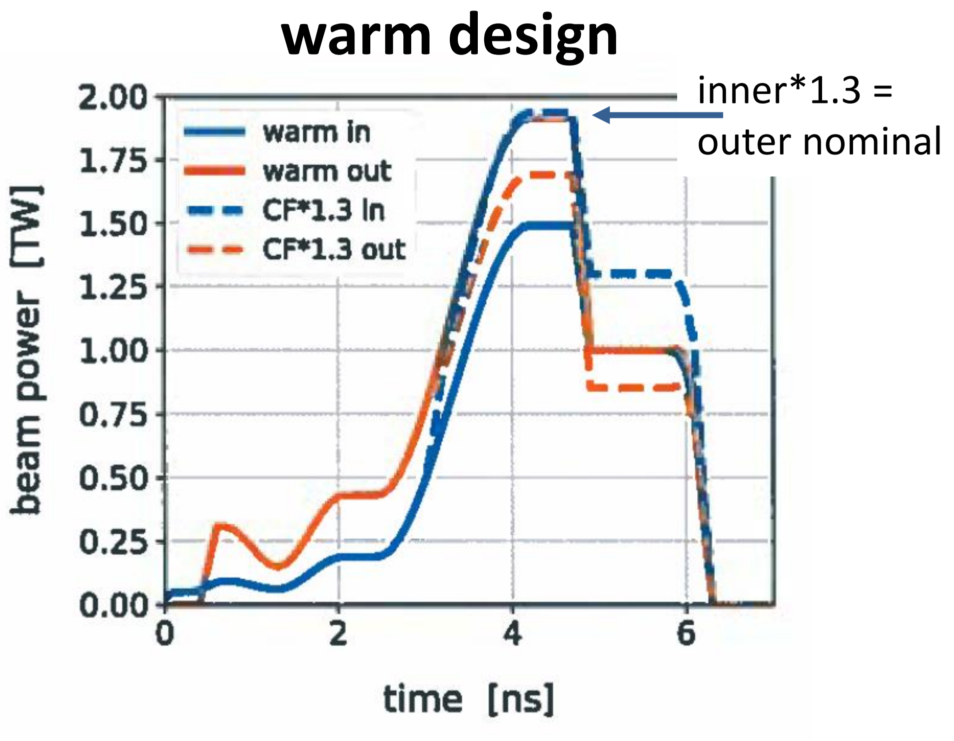






Laser pulses with increased peak cone fraction to match N161204 measured shape





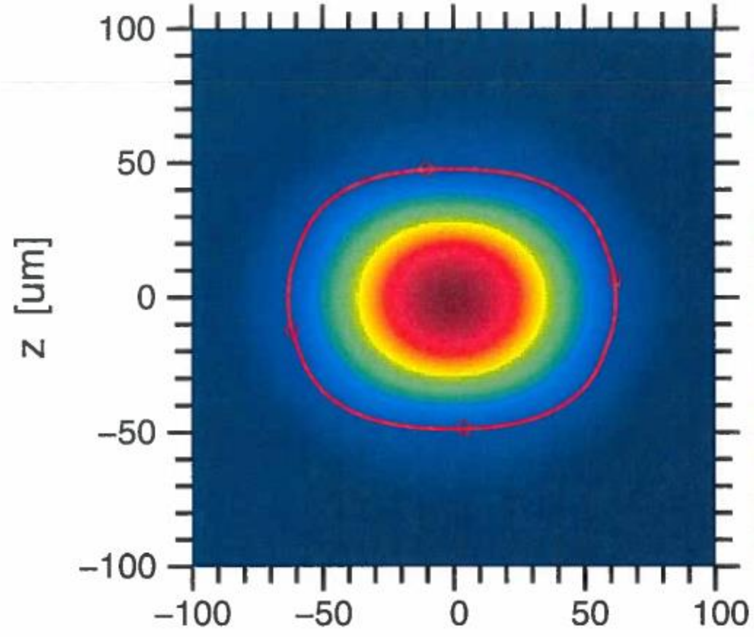
CBET likely culprit, but:

- Inline Lasnex CBET model gives transfer to outers
- Vampire CBET post-processor gives transfer to inners
    - Bailey and Strozzi working on, can't sort out til Lasnex team back on site

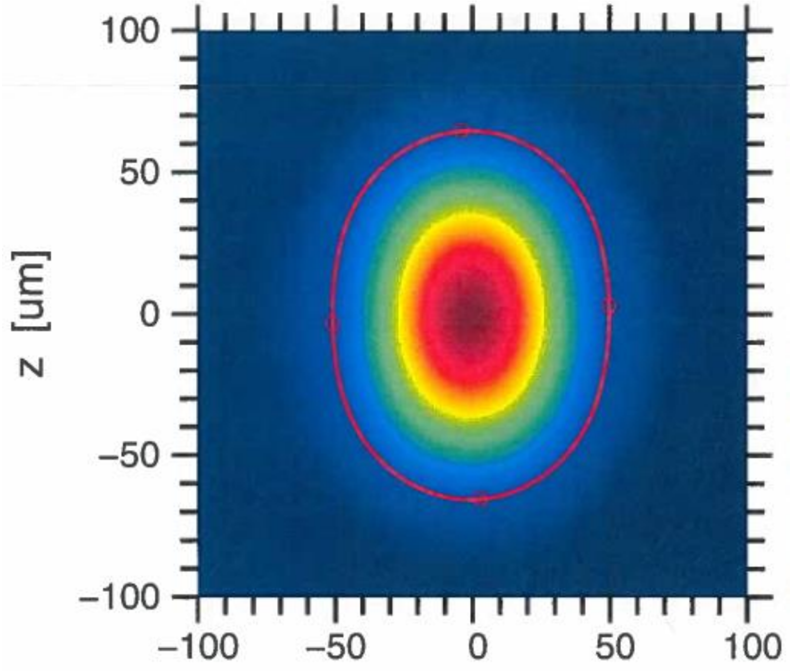
Case	neutron bangtime – 7.12ns [ps]	DDn yield [1E11]	DD Tion [keV]	hotspot x-ray P2 [um]	Comment
N161204 data	0	9.07 := 1x	3.09 := 0	+11.2	Sausage
N161204, nominal	-90	9.41 (1.04x)	2.96 (-0.13)	-9.0	BT+yield close, pancake
N161204, peak CF*1.3	-50	9.63 (1.06x)	2.99 (-0.1)	+9.9	sausage like data
Magnetized design					
No B_{z0}	+180 less E_{laser}	176: pure D fill	3.14	-26.0	Very pancaked: Au2Ta8 vs. Au wall
same + B_{z0} = 30T	+200	297 = 1.69x B_{z0}=0	3.87 = 0.73+B_{z0}=0	-21.9	less pancaked w/ B_{z0}
warm, peak CF*1.3, no B_{z0}	+240	276	3.25	-0.8	Close to round
same + B_{z0}=30 T	+240	350 = 1.27x B_{z0}=0	3.77 = 0.52+B_{z0}=0	+7.9	sausage w/ B_{z0}

Lasnex modeling: N161204: peak cone fraction * 1.3 to match data

01: nominal pulse: pancake, unlike data
P2 = -9.0 um



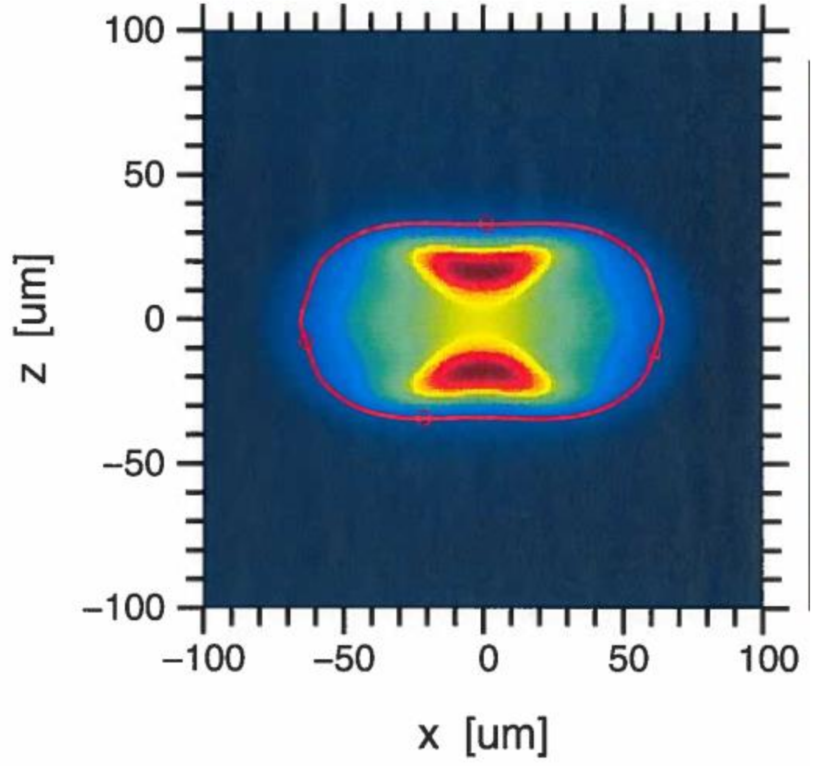
02: peak cone fraction *1.3: sausage, close to data
P2 = 9.9 um
Data: P2 = 11.2 um
Convergence ratio = capsule IR / P0 = 844 / 55 = 15



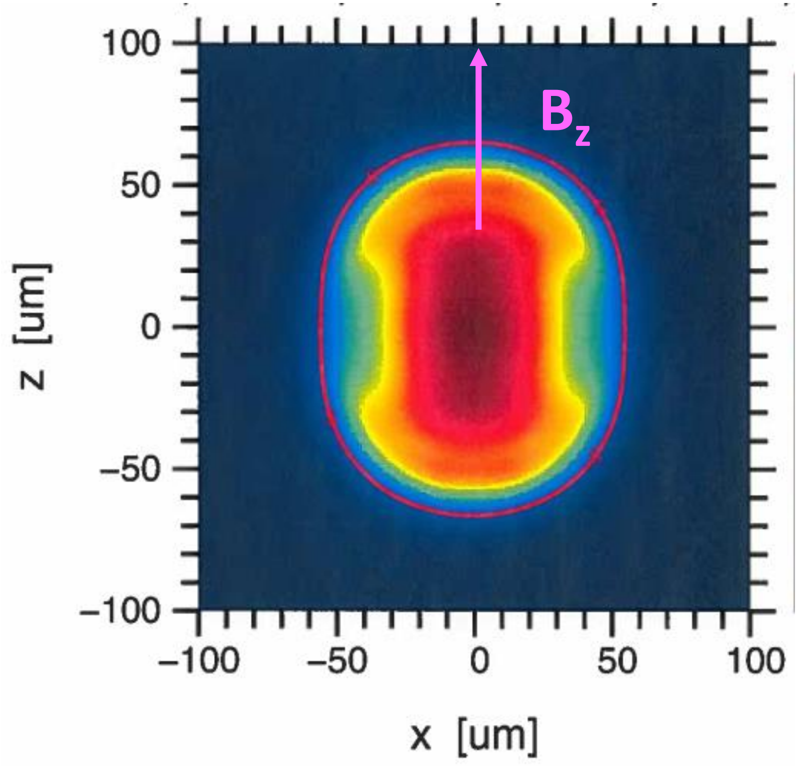
x-ray images at time of peak emission, including instrumental blurring

Lasnex modeling: warm design: Imposed B_{z0} = 30 T: increased P2

Nominal pulse:
P2/P0 = -41.3%



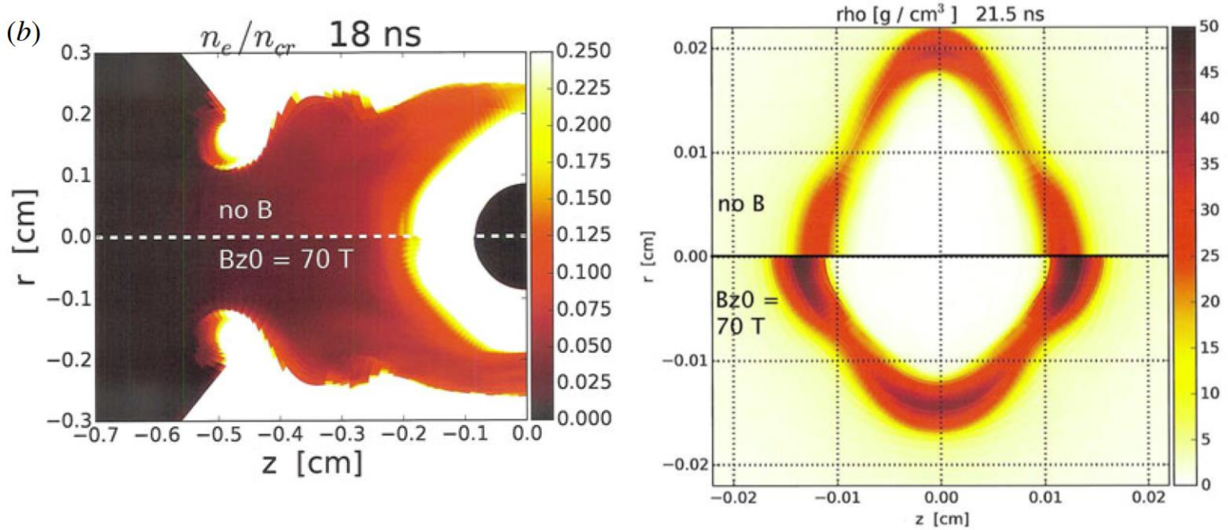
Peak cone fraction * 1.3:
P2/P0 = 13.1%
Convergence ratio = initial IR / P0 = 844 / 60.2 = 14



Magnetized hohlraum science questions

B field direct effects on LPI roughly with increasing field (Yuan Shi):
- Faraday rotation: change polarization, could affect CBET
- Landau damping of SBS
- SBS light spectrum / SRS Landau damping
- SRS light spectrum
- Hot electron generation / transport – see below

Improved inner-beam propagation with imposed B: high-fill designs
- Equator channel hotter and less dense
- Bulk fill *not* hotter in NIF hohlraum sims – unlike Omega shots (Montgomery+ 2015 PoP)



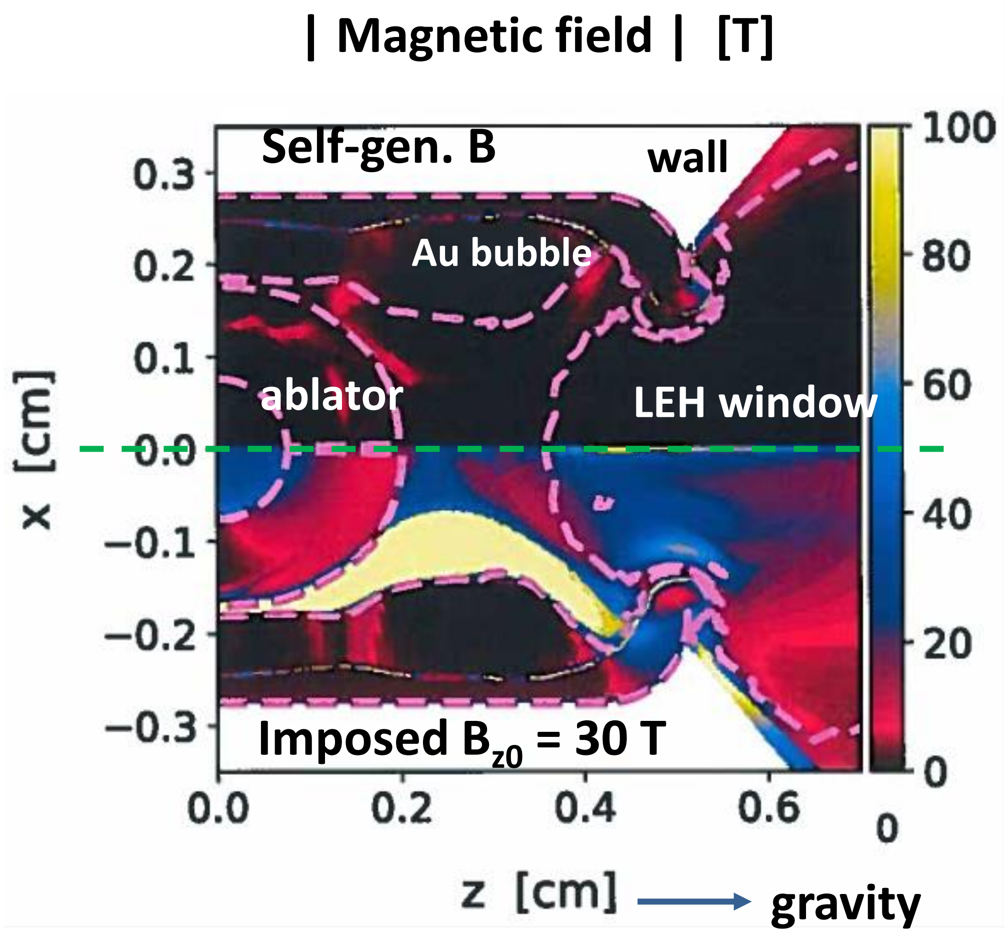
D J Strozzi +, Journ. Plasma Phys. 2015: low-foot design

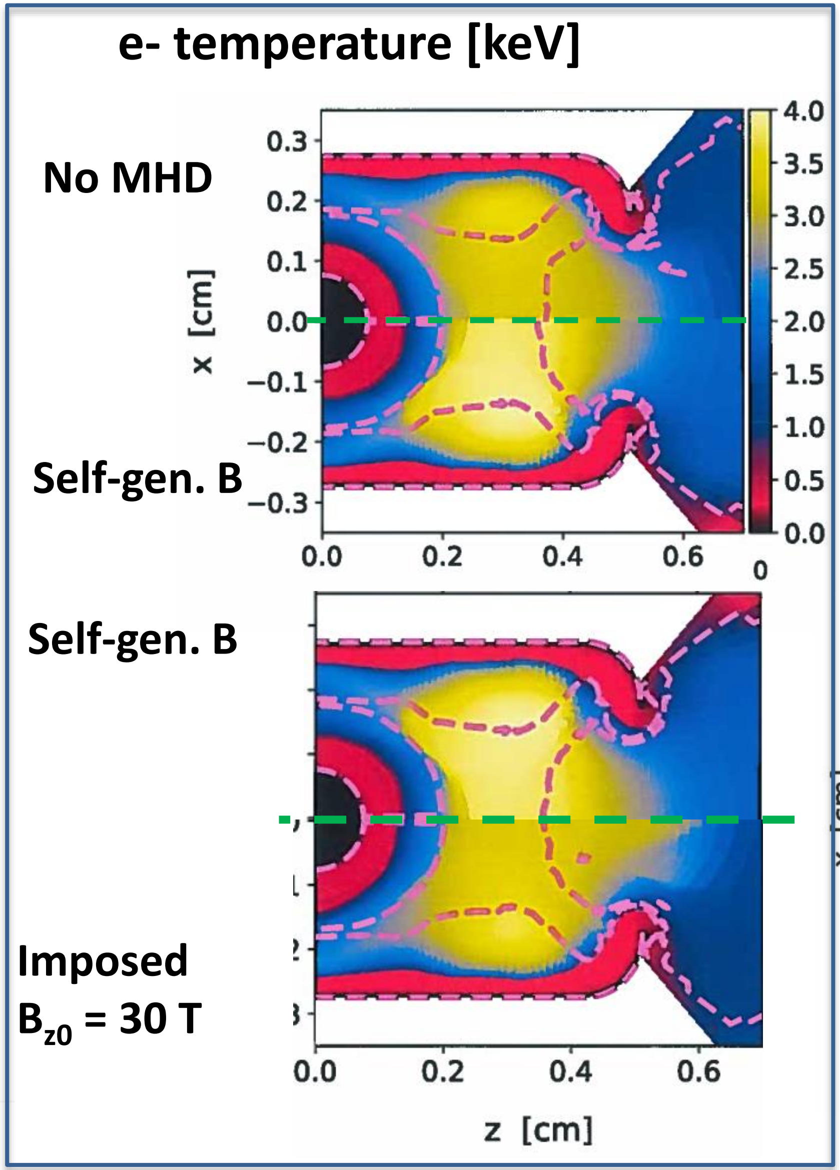
Connection to magnetized ignition SI
- SI pursuing magnetized ignition with bigfoot-like, high-adiabat design, 3-4 shots/year
- Do not have resources to look at things not on this path, like "basic science" or low-adiabat designs
- Complementary work in ICF program could study LPI, improving high-fill designs

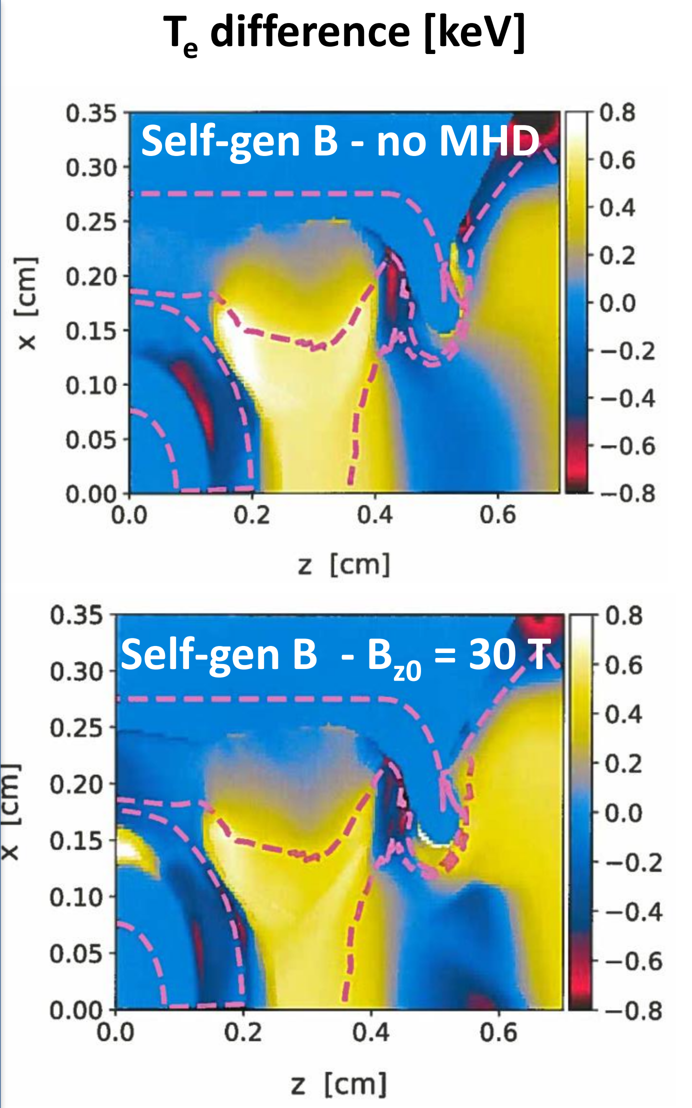
Hohlraum dynamics: frozen-in B field, small temperature change

Hydra runs: N161204 post-shots

4.5 ns: early peak power

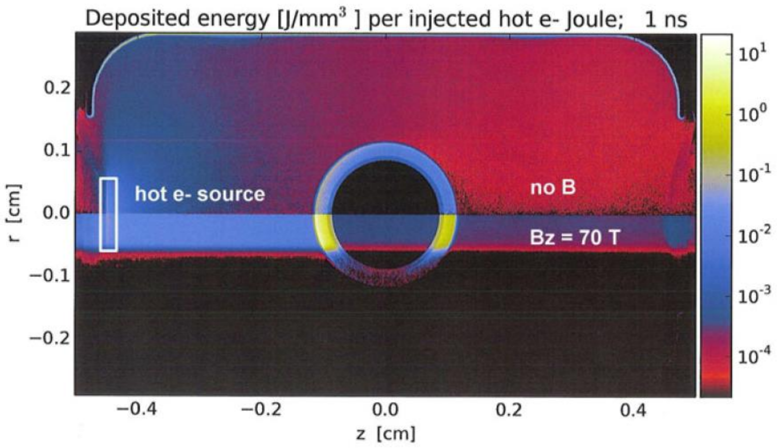




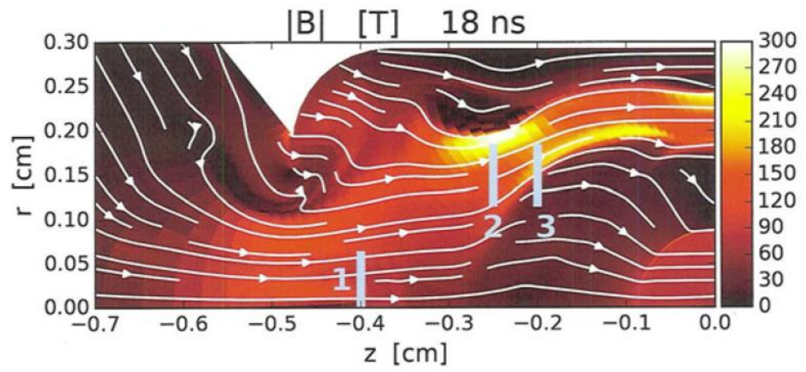


Hot Electron Propagation with B field

Picket: window hots guided to capsule

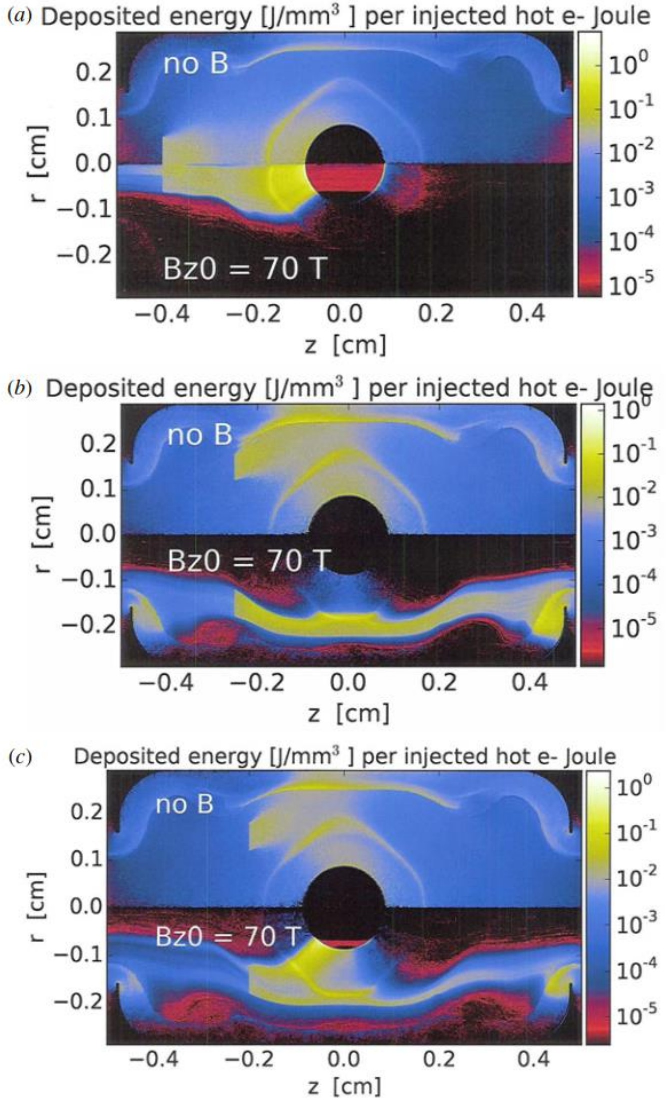


Peak power: SRS hots: depends on birth location



Region	PICKET, no B	PICKET, $B_z = 70$ T	SRSPEAK 1, no MHD	SRSPEAK 1, $B_{z0} = 70$ T
DT gas	6.56×10^{-5}	1.06×10^{-3} (16x)	4.32×10^{-6}	6.26×10^{-5} (14x)
DT layer	2.20×10^{-3}	0.0261 (12x)	3.58×10^{-4}	2.89×10^{-3} (8.1x)
CH ablator	0.0749	0.696 (9.3x)	0.406	0.804 (2.0x)
He gas	0.0566	0.0646 (1.1x)	0.223	0.117 (0.52x)
Au	0.366	4.14×10^{-4} ($1.1 \times 10^{-3}x$)	0.250	1.01×10^{-4} ($4.0 \times 10^{-4}x$)
DU	0.428	4.02×10^{-4} ($9.4 \times 10^{-4}x$)	0.0990	1.61×10^{-5} ($1.6 \times 10^{-4}x$)
Total	0.927	0.789 (0.85x)	0.979	0.925 (0.94x)

Region	SRSPEAK 2, no B	SRSPEAK 2, $B_{z0} = 70$ T	SRSPEAK 3, no B	SRSPEAK 3, $B_{z0} = 70$ T
DT gas	1.75×10^{-6}	8.95×10^{-9} ($5.1 \times 10^{-3}x$)	1.44×10^{-6}	5.96×10^{-6} (4.1x)
DT layer	1.37×10^{-4}	3.44×10^{-6} (0.025x)	1.19×10^{-4}	1.26×10^{-3} (11x)
CH ablator	0.272	0.105 (0.39x)	0.327	0.576 (1.8x)
He gas	0.229	0.499 (2.2x)	0.182	0.248 (1.4x)
Au	0.335	0.220 (0.66x)	0.328	0.101 (0.31x)
DU	0.133	0.0421 (0.032x)	0.131	5.56×10^{-3} (0.042x)
Total	0.969	0.866 (0.89x)	0.968	0.932 (0.96x)



D J Strozzi +,
Journ. Plasma Phys. 2015

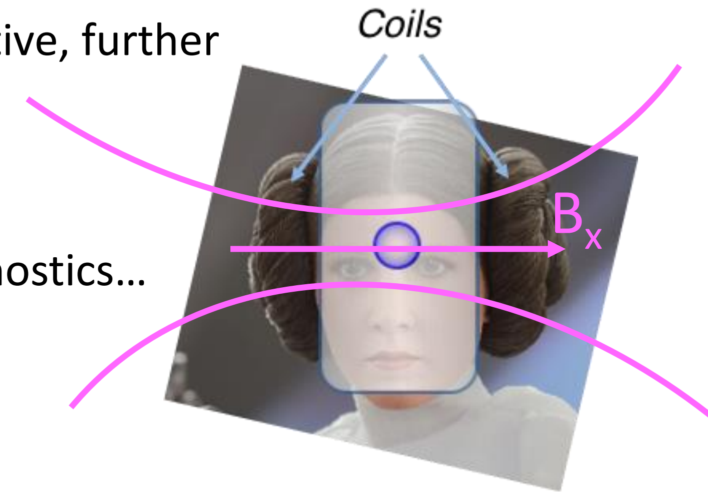
Hot Electron Mitigation

- **Concern: B field can guide hot e-'s to capsule**

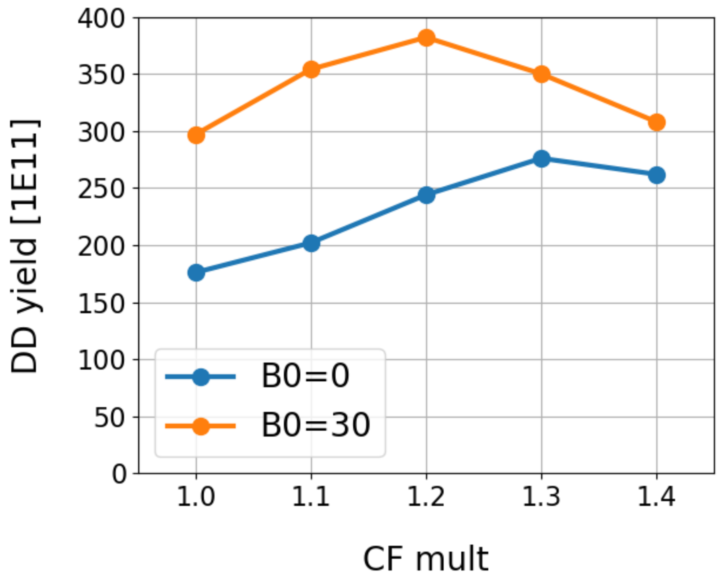
- **BigFoot shots** {low hohlraum fill, short pulse, HDC capsule}:
  - Hot e-'s generally much lower than older high foot {high hohlraum fill, long pulse, CH capsule}

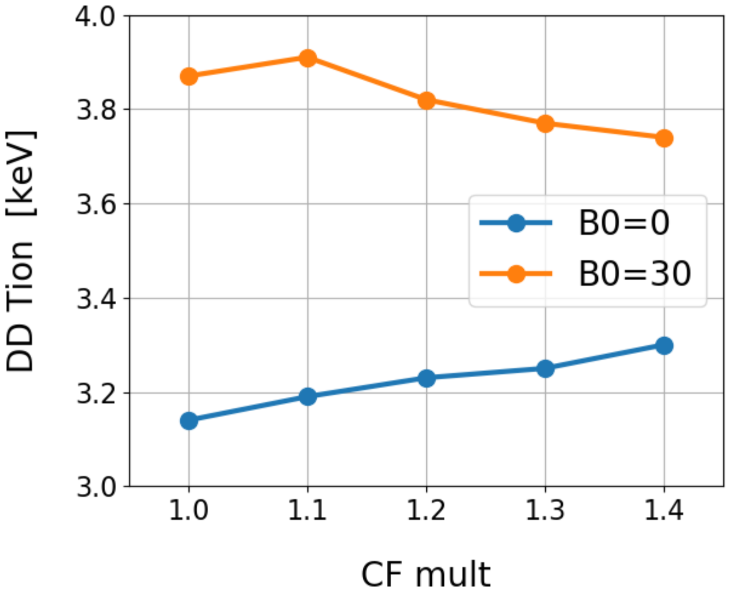
- **Experimental evidence of hot e- problem:**
  - Symcaps probably insensitive
  - Need layered DT, or re-emit ball?

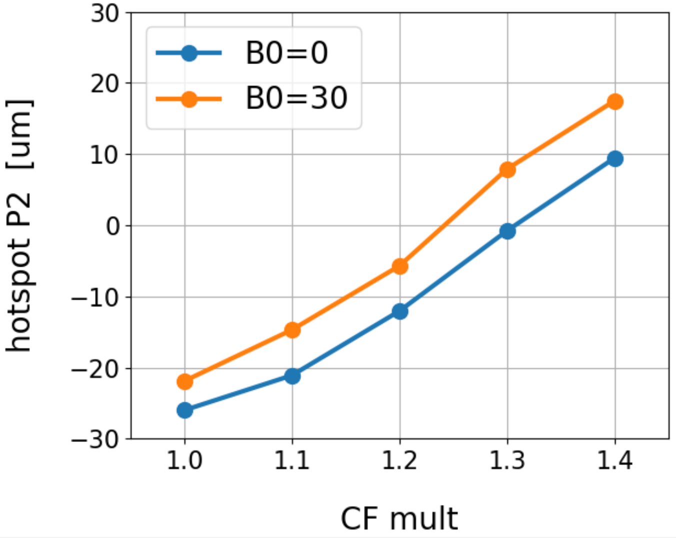
- **If hot e-'s are a problem:**
  - Preferred option: reduce hot e- source
    - Window hots: beam phasing (starting inners before outers) known to be effective, further tuning possible
    - Could try direct-drive techniques, e.g. mid-Z dopant in window
  - Fallback option: orthogonal B field with "Leia coils"
    - Intrinsically 3D: NIF is geared toward axisymmetry: codes, lasers, targets, diagnostics…
    - Would *not* help if hot e-'s born on equator



Varying cone fraction: imposed B increases yield and makes implosion more sausaged

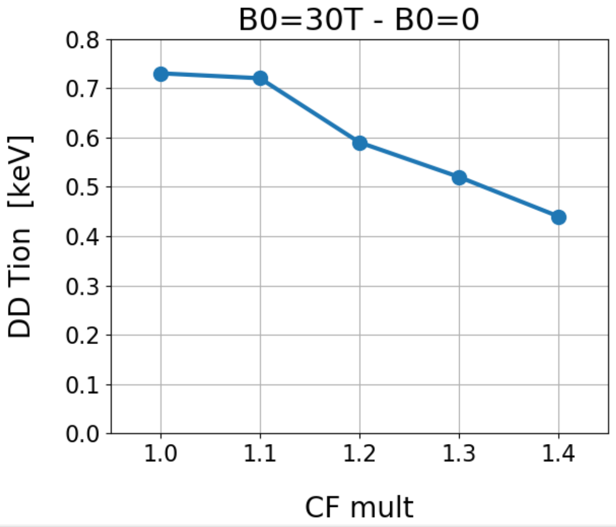


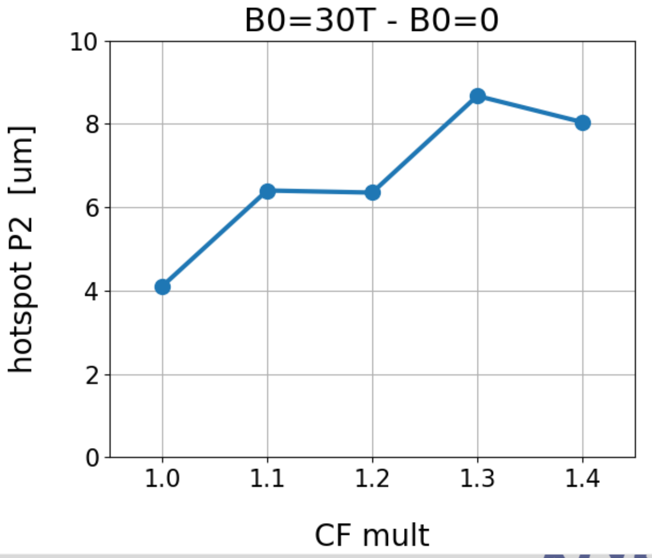




max B0=0 yield: 2.76E13
max B0=30 T yield: 3.82E13 = 1.38x B0=0

CF mult of 1.3 needed
to match N161204 data





Lawrence Livermore National Laboratory