Design of Magnetized, Room-Temperature Capsule Implosions for NIF

48th Anomalous Absorption Conference

Bar Harbor, Maine

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11 July 2018

LLNL-CONF-754318

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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Disclaimer

"Warm", Bigfoot-based platform: show capsule field compression and yield enhancement

Main effect of B field: reduce e- heat conduction perpendicular to B: $\omega_{ce}\tau_{ei} > 1$
Magnetic pressure << matter pressure: $\beta >> 1$

HYDRA MHD simulations:
Imposed axial field, "Biermann battery" fields, Nernst advection

	Hohlraum	Capsule
Biermann fields (self-generated)	Like Farmer PoP 2017[1] • Hotter fill • Nernst advection reduces B • Modest effect on drive, shape	• B < 20 T for symmetric x-ray drive • Modest effect: yields ~ same
Imposed field: axial 30 Tesla	Like Strozzi JPP 2015[2,3] • Frozen-in law holds: B field compressed or rarified w/ plasma • ***Slightly*** hotter fill	• B ~ 5 kT: ~ frozen-in • Gas-filled capsule yields up ~50% • For range of gas densities

1 W. A. Farmer et al., Phys. Plasmas 2017
2 D. J. Strozzi et al., J. Plasma Phys. 2015
3 L. J. Perkins et al., LLNL LDRD final report

"Bigfoot"[1] platform: starting point for warm magnetized design

"Bigfoot" campaign on NIF

- Robust hotspot: High rho*R, high velocity
  - Price: high adiabat, lower convergence
- Shock overtaking in ablator
- HDC capsule: short pulse, smooth capsules
- Simple hohlraum: low gas fill, low LPI
- Highest yield on NIF

1 C. Thomas, APS-DPP invited talk, 2016

Equivalent DT yield: agrees with Lasnex
13-15 MeV neutrons from DD, D3He, …

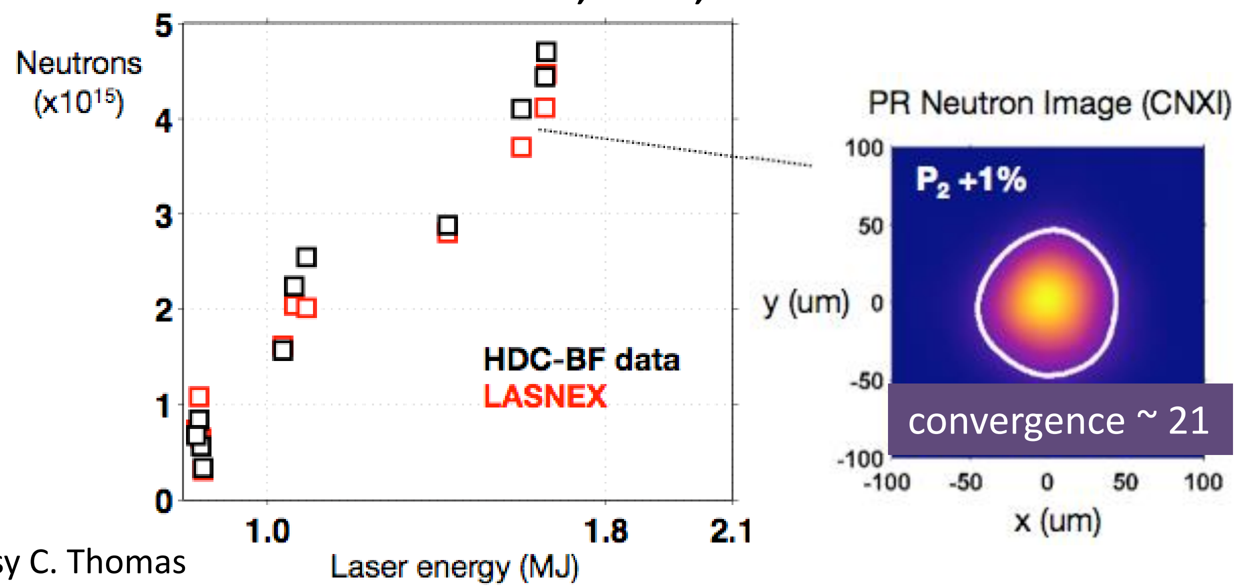


Figure courtesy C. Thomas

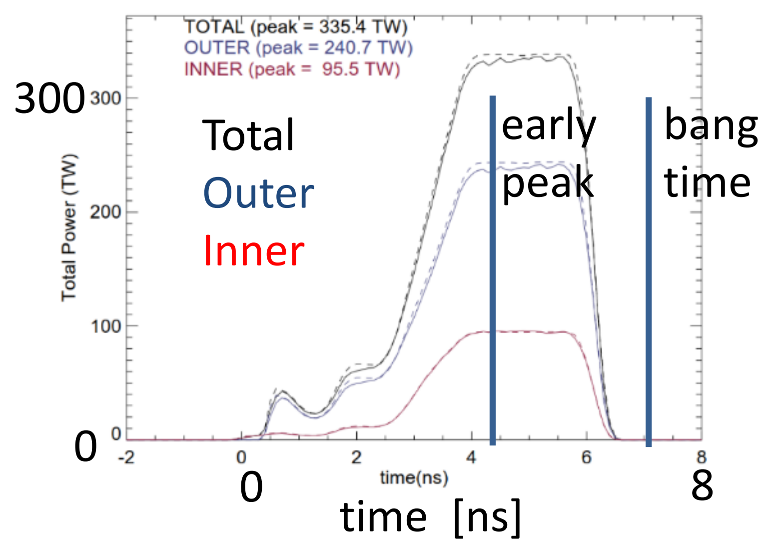
Why Bigfoot for warm magnetized design?

- Don’t re-invent wheel
- Nice features: predictable, tunable, low LPI
- Not so nice to be irrelevant!
    - Enough convergence to amplify B field, reduce e- conduction
    - Connection to existing, high-yield cryo platform
- Vary convergence via capsule gas density

N161204: bigfoot NIF shot

- “Subscale” target: less taxing on laser:
    - 1.1 MJ, 340 TW
- Low hohlraum gas fill density: 0.3 mg/cc He4
- Symcap: gas-filled capsule: D[30%]-He3[70%]
    - 6.5 mg/cc
    - no DT ice layer
- HDC capsule, W dopant
- Au hohlraum

Laser power [TW]



HYDRA MHD model: Full single-fluid Braginskii

Bulk momentum

$$\rho \frac{D\vec{v}}{Dt} = -\nabla p + \vec{J} \times \vec{B}$$

Magnetic force: pressure + tension

$$\vec{J} \times \vec{B} = (\hat{\mathrm{b}}\hat{\mathrm{b}} - 1) \cdot \nabla \left(\frac{B^2}{2\mu_0} \right) + \frac{B^2}{\mu_0} \hat{\mathrm{b}} \cdot \nabla \hat{\mathrm{b}}$$

Maxwell

$$\partial \vec{B} / \partial t = -\nabla \times \vec{E}$$

$$\vec{J} = \mu_0^{-1} \nabla \times \vec{B}$$

Ohm's law : Generalized

$$\vec{E} = -\vec{v} \times \vec{B} + \frac{1}{n_e e} \vec{J} \times \vec{B} - \frac{\nabla p_e}{n_e e} + \overleftrightarrow{\eta} \cdot \vec{J} - e^{-1} \overleftrightarrow{\beta} \cdot \nabla T_e$$

advection / induction term; Hall term; Biermann battery — collisionless

resistivity; thermal force — collisional

Ohm's law: This talk

$$\vec{E} = -\vec{v} \times \vec{B} + \eta \vec{J} - \frac{\nabla p_e}{n_e e} - e^{-1} \overleftrightarrow{\beta} \cdot \nabla T_e$$

always; Biermann

Nernst: advect B to lower T_e
No Righi-Leduc in energy eq.

- Plus analogs in electron energy equation
- No nonlocal limiting of Nernst: Brodrick, Sherlock

→ **Biermann fields, no imposed**

Imposed 30 T axial field

Varying capsule gas density

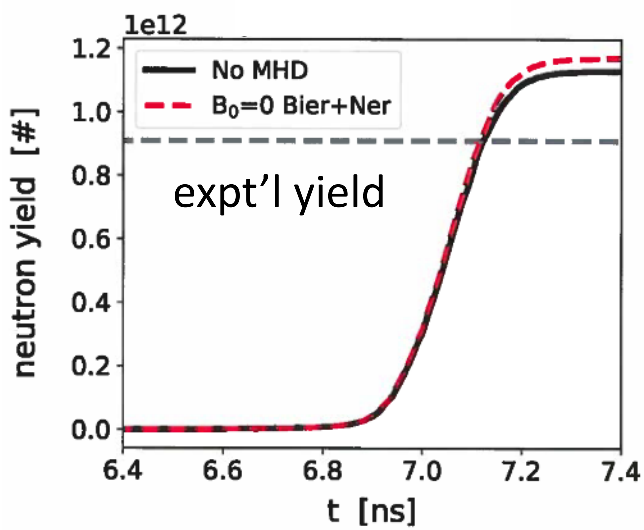
N161204 "post-shot" sims: no imposed B field: Close on bangtime and yield

BIGFOOT doesn't believe in you either.

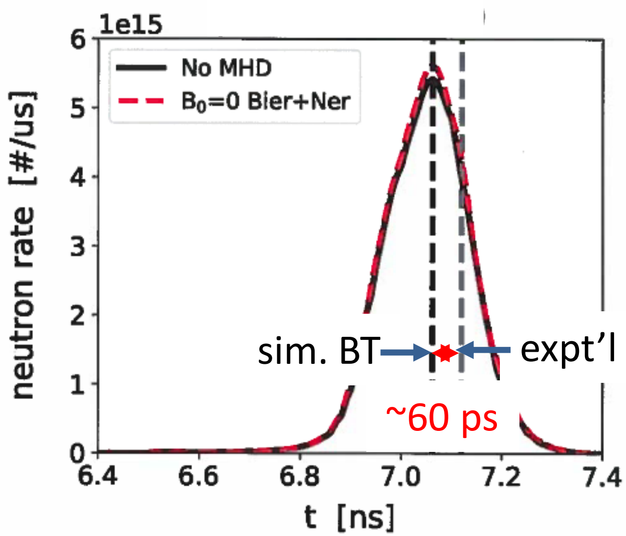
HYDRA methodology
- 2D R-Z axisymmetric
- "HyPyD": Pythonic framework:
  J. Koning, J. Salmonson
- DCA non-LTE: Sept. 2017 model: H. Scott
- Electron heat flux limit f = 0.15 (high)
- X-rays on capsule artificially symmetrized

Without hand tuning
- Sim. bangtime slightly early ~ 60 ps
- Sim. yield 25% above measured
- Biermann fields: little effect

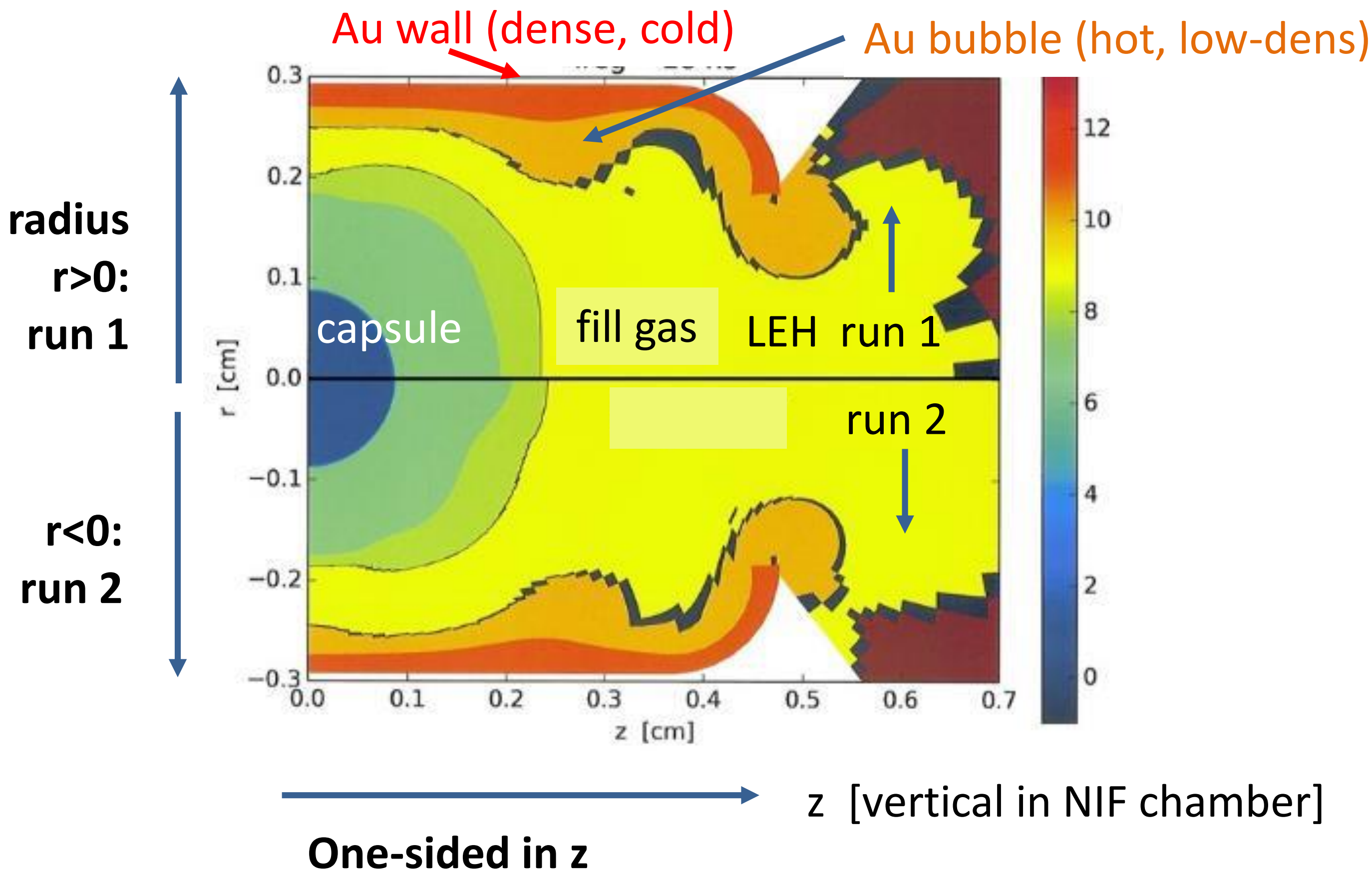
neutron yield



neutron burn rate



Hohlraum map legend



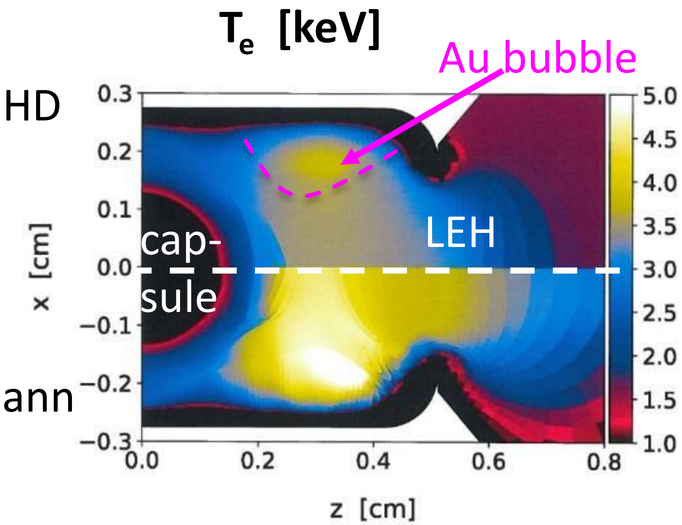
Biermann fields increase T_e, Nernst advection reduces the effect

Like Farmer PoP 2017

4.25 ns: early peak power

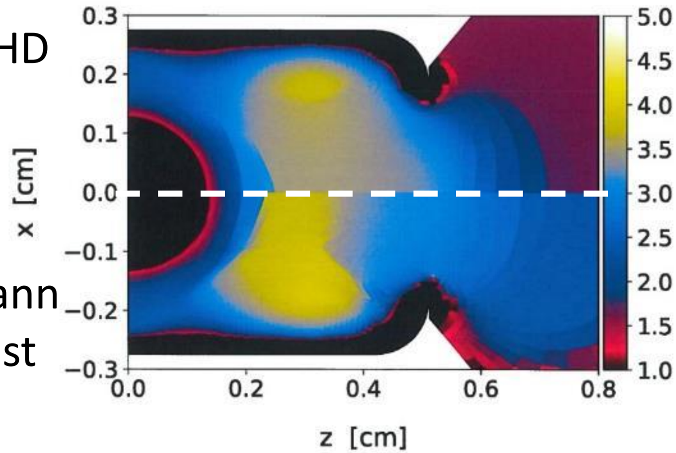
no MHD

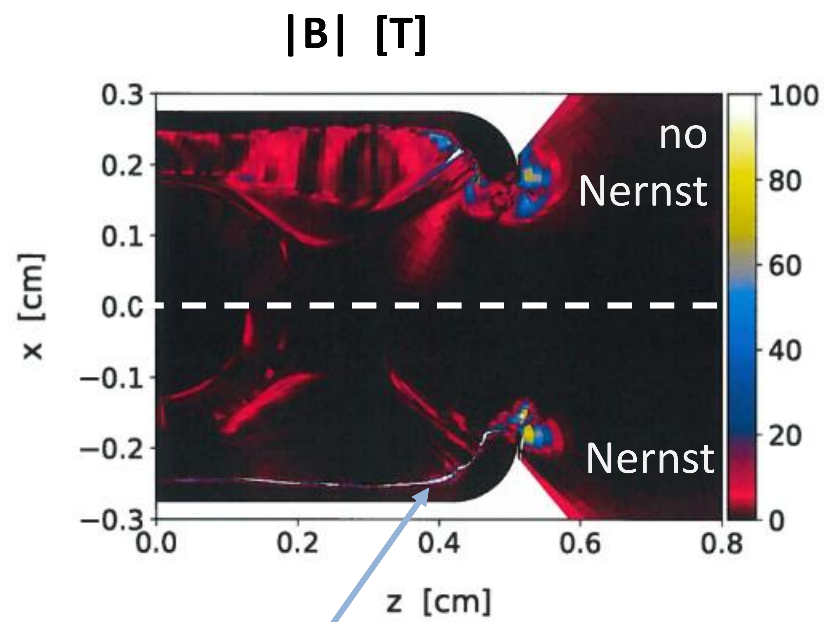
Biermann



no MHD

Biermann
+ Nernst





Nernst:
- Advects B in to cold Au wall
- “Erases” much of Biermann field

Biermann fields, no imposed

→ **Imposed 30 T axial field**

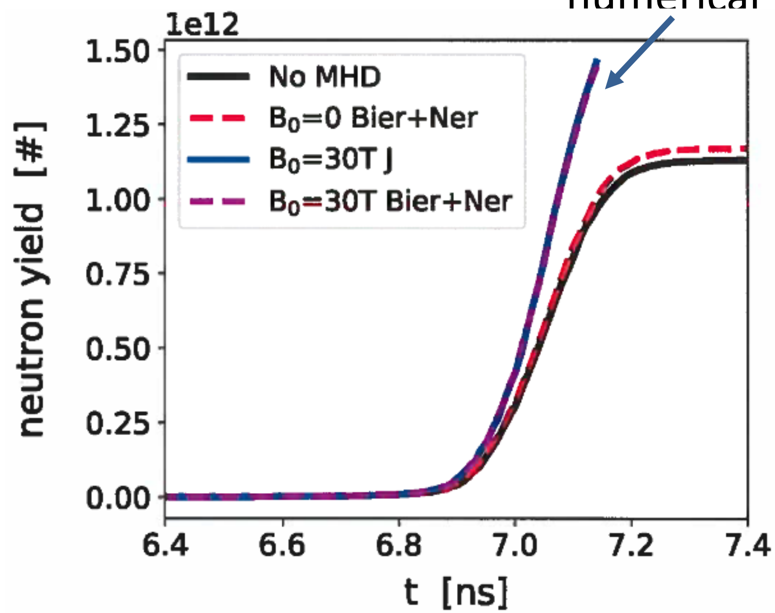
Varying capsule gas density

Imposed B_{z0} = 30 T: yield increase ~ 50%

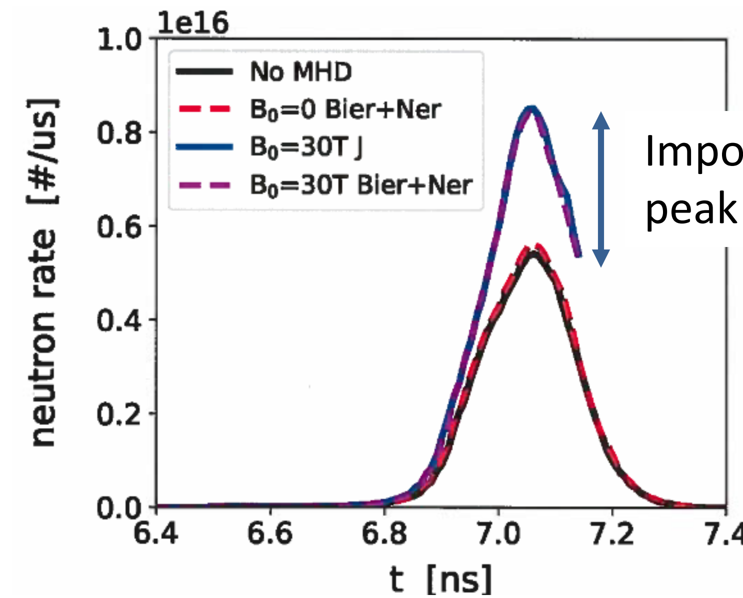
N161204

Neutron yield

Imposed B runs: numerical issues at end



Neutron production rate



Imposed B: peak 1.55x

Layered-DT vs. DHe3-gas capsules

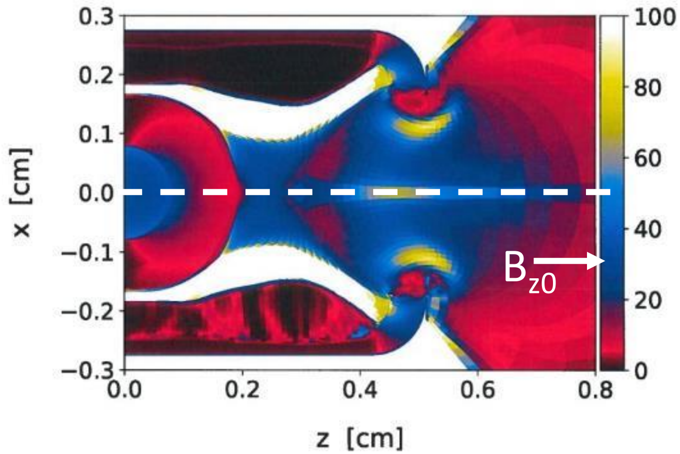
- Yield increased mainly by reduced e- conduction
- Not enough alpha's to matter

Imposed B_{z0} = 30 T: field "adds" with Biermann in bubble / LEH

|B| [T] @ 4.25 ns: early peak power

B_{z0} = 30 T

E = vxB + eta*J



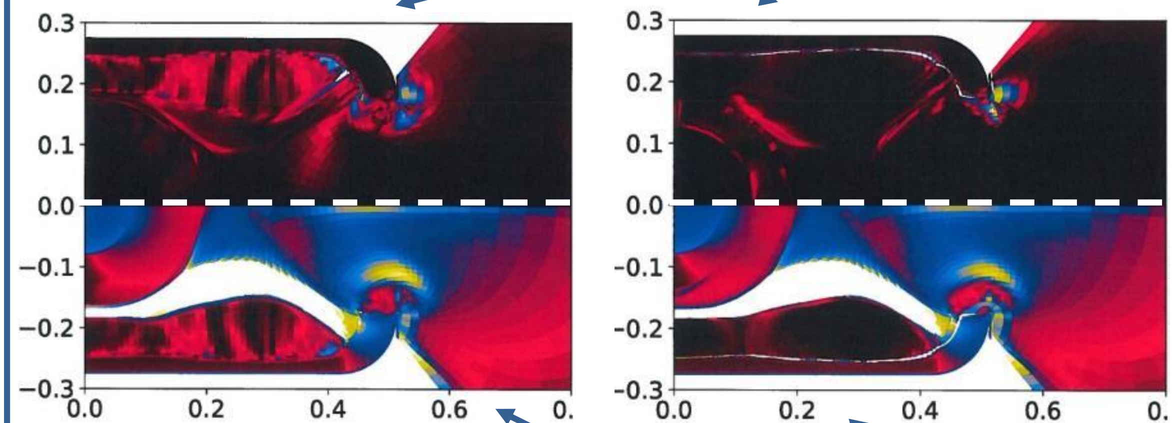
E + Biermann

No imposed vs. B_{z0} = 30 T

E + Biermann

E + Biermann + Nernst

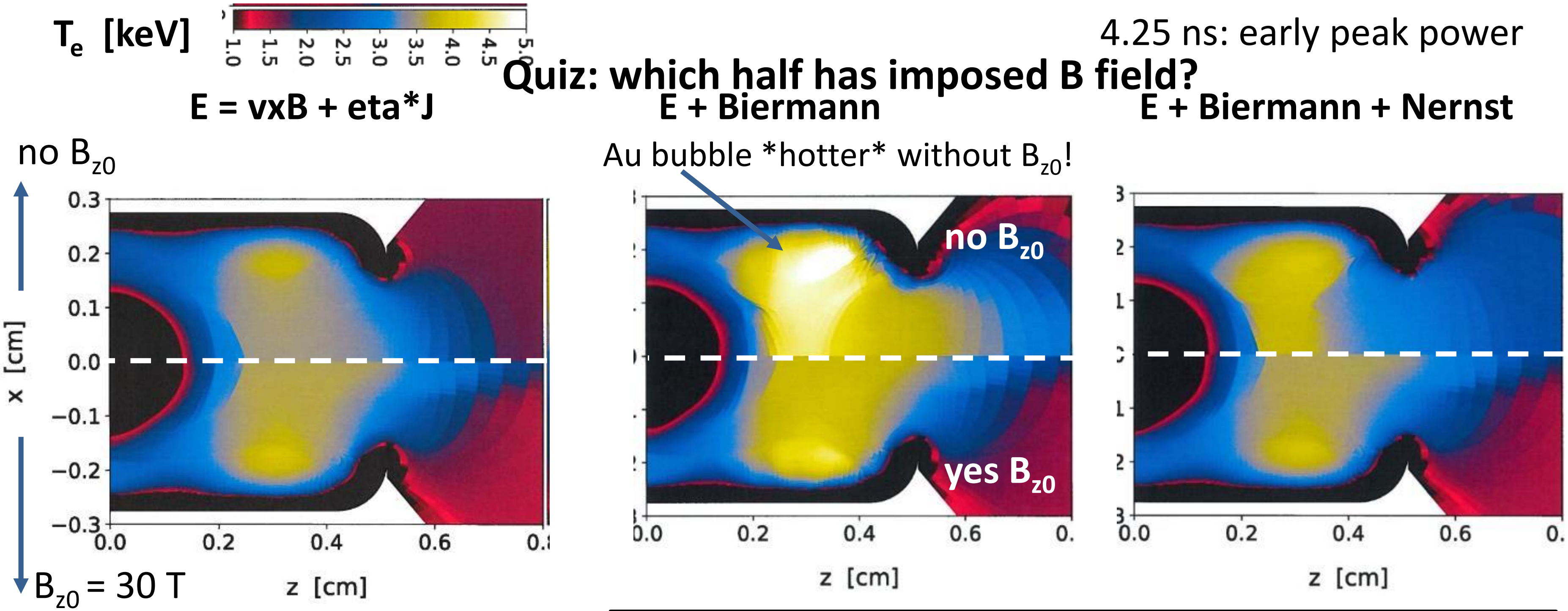
no B_{z0}



B_{z0} = 30 T

- Imposed-field dynamics unchanged by Biermann or Nernst
- Biermann fields unchanged by imposed – at least by eye

Imposed B_{z0} = 30 T: effect on hohlraum fill vs. Biermann fields



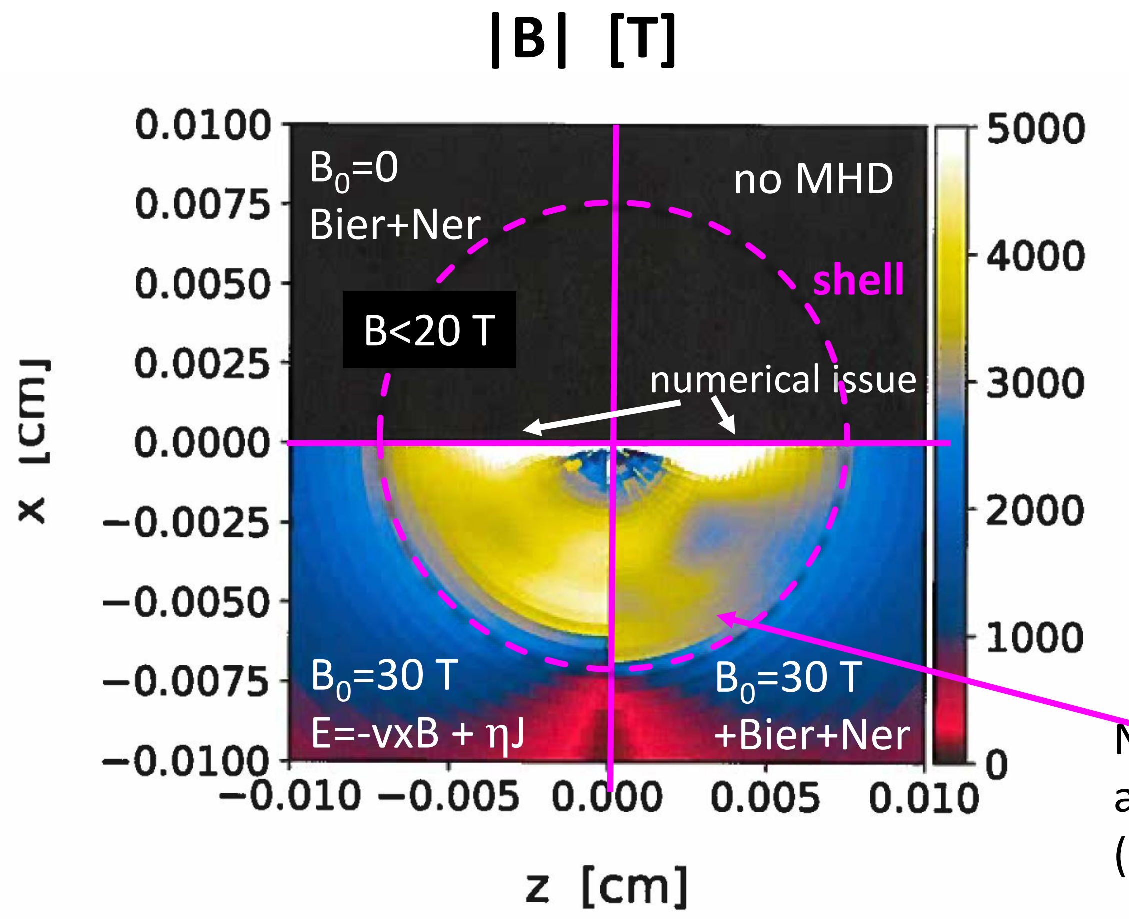
D Montgomery et al., PoP 2015:
T_e increase on Omega gas hohlraums

Why small effect from B_{z0}?
- B inside Au to increase T_e
- Biermann yes, imposed no

- **Imposed B_{z0}**
  - Hall parameter > 1 in fill: not small
  - Reduced B in Au bubble: Frozen-in expansion
  - B in R-Z plane: heat flow reduced in 1 direction
- **Biermann field**
  - Azimuthal → 2 directions reduced

Imposed B_{z0} = 30 T: capsule B field ~ 5 kT; Biermann fields small

7.05 ns: bangtime
x-ray flux on capsule
artificially symmetrized



Frozen-in estimate of field increase

- Gas convergence ~ 14
- Increase ~ (R_initial / R_final)^2 = 200x : 30 T → 6000 T

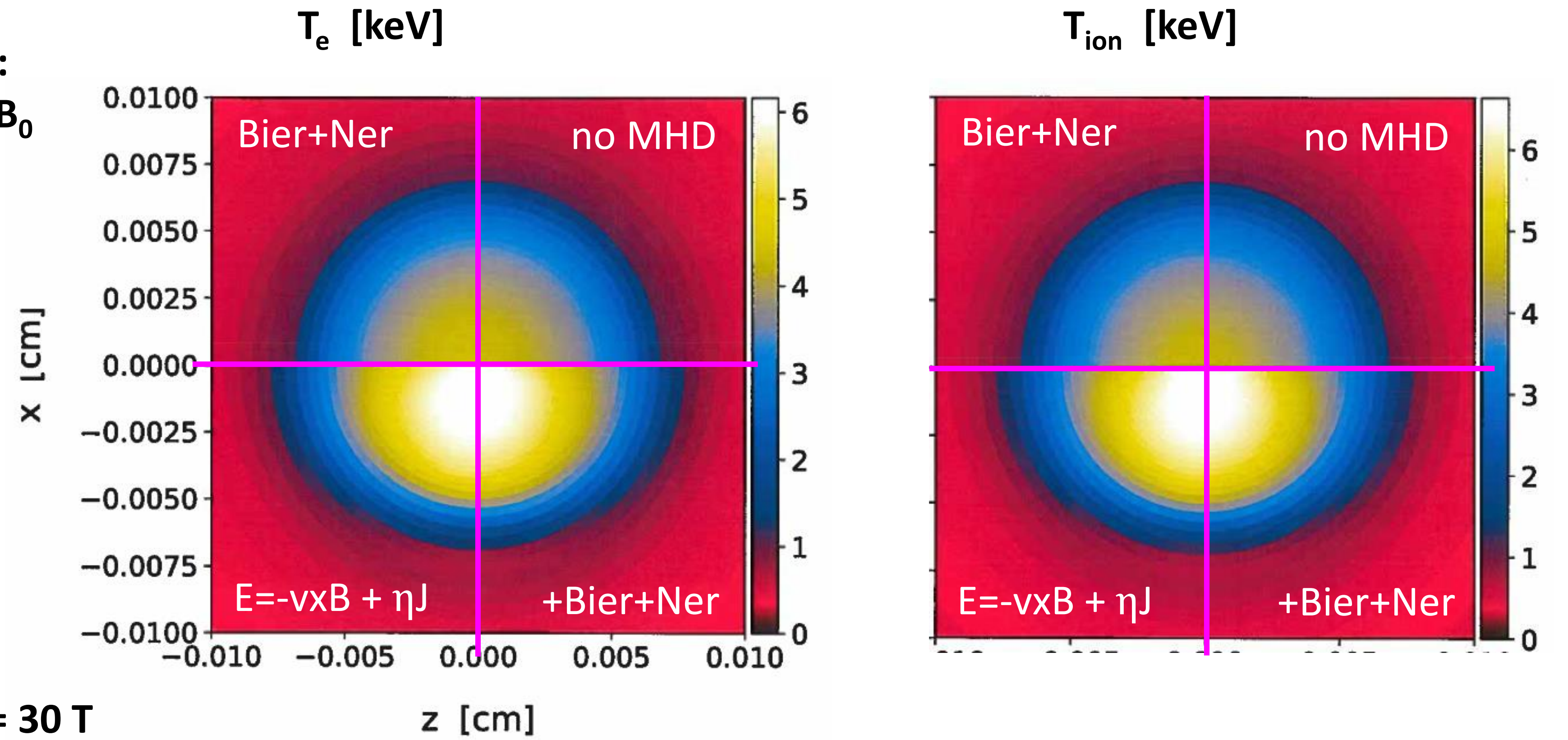
Nernst de-magnetization:
also seen by C. Walsh in CHIMERA (Imperial College)

Imposed B_{z0} = 30 T: capsule hotter for all MHD models

7.05 ns: bangtime
x-ray flux on capsule artificially symmetrized

Top: No B_0

Bot: B_{z0} = 30 T

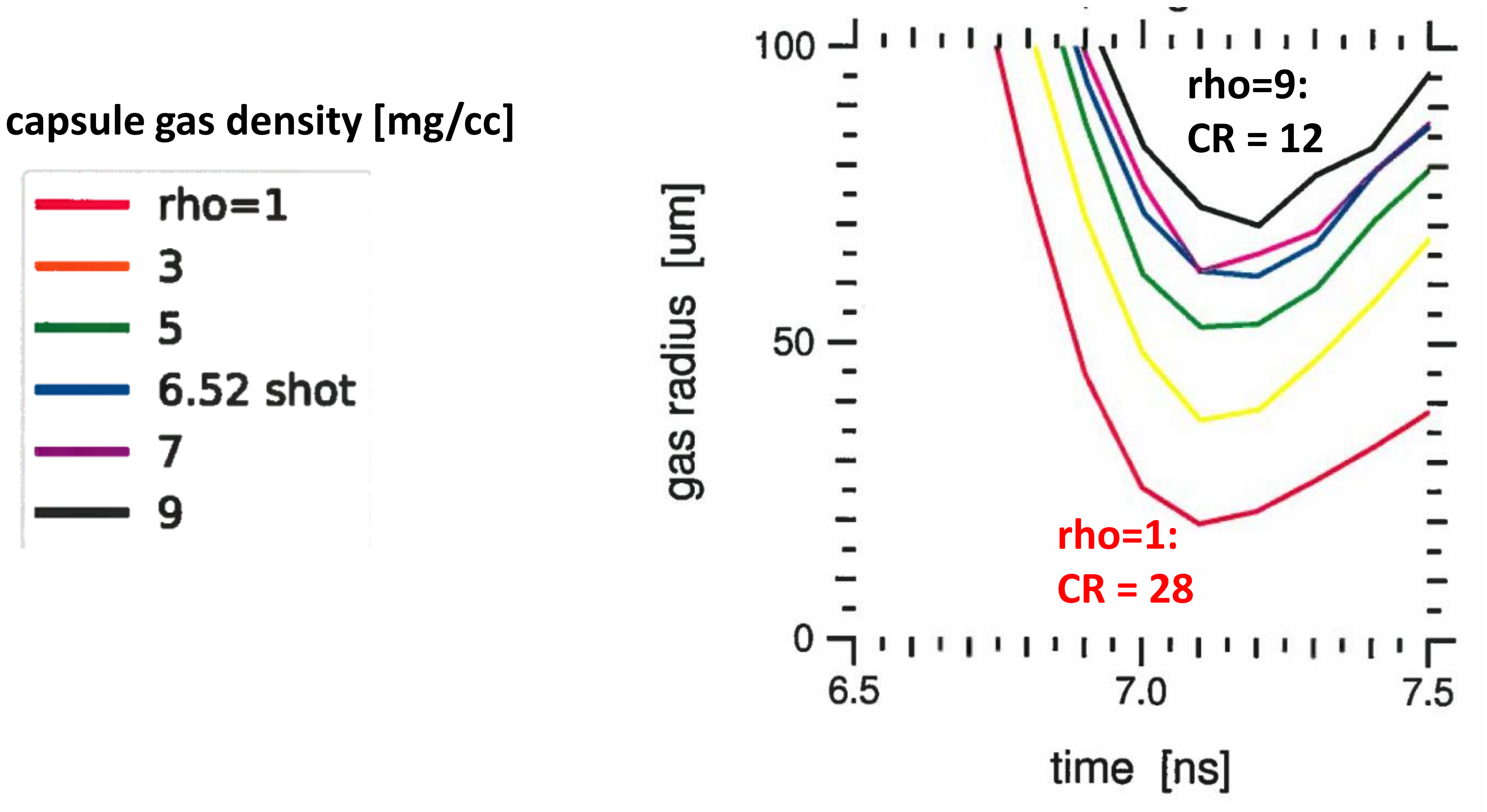


Biermann fields, no imposed

Imposed 30 T axial field

→ **Varying capsule gas density**

Gas capsules: vary convergence and yield via gas density

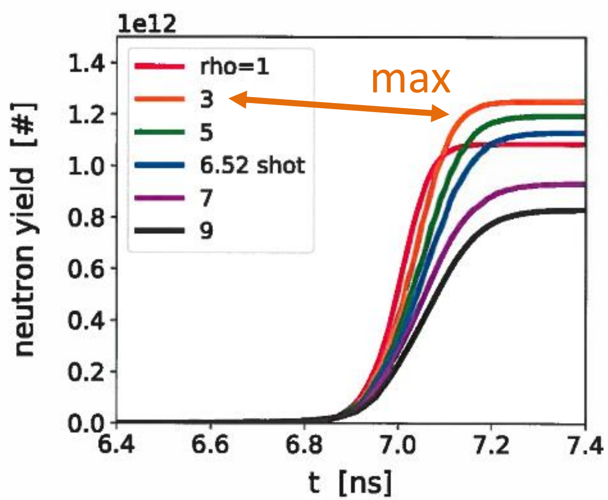


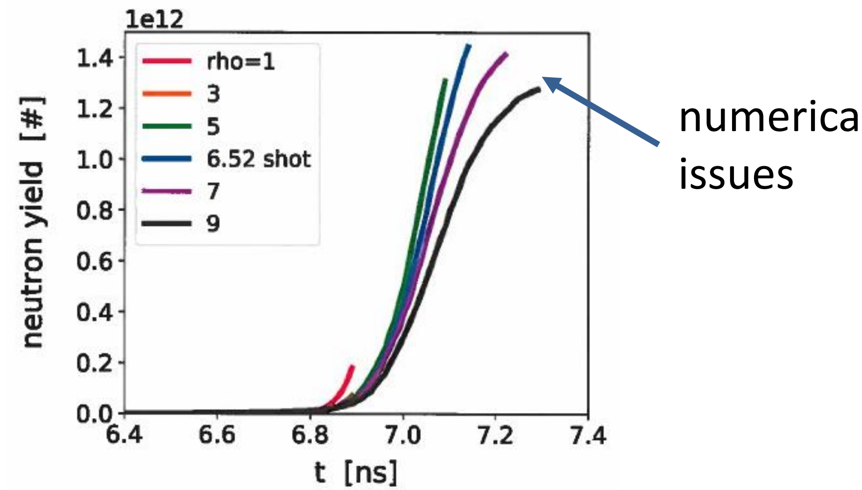
Gas capsules: vary convergence and yield via gas density

no MHD

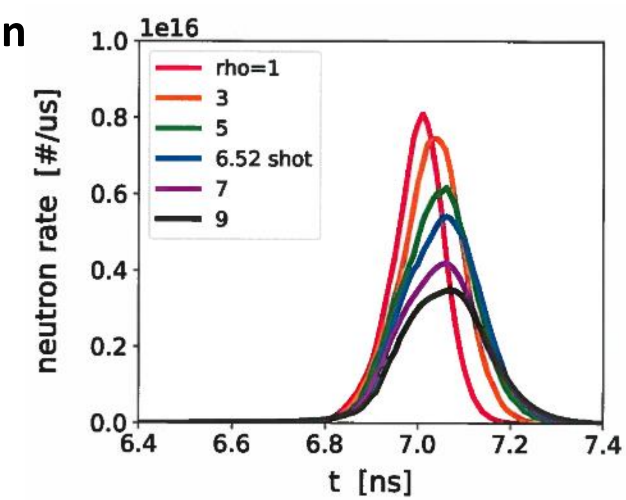
B_{z0} = 30 T, Biermann + Nernst

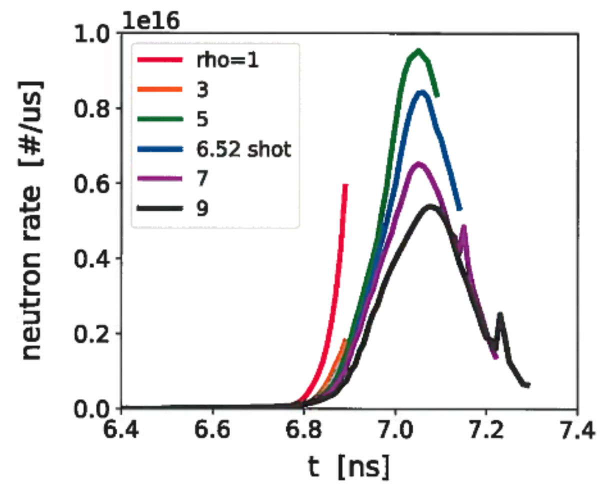
Neutron yield





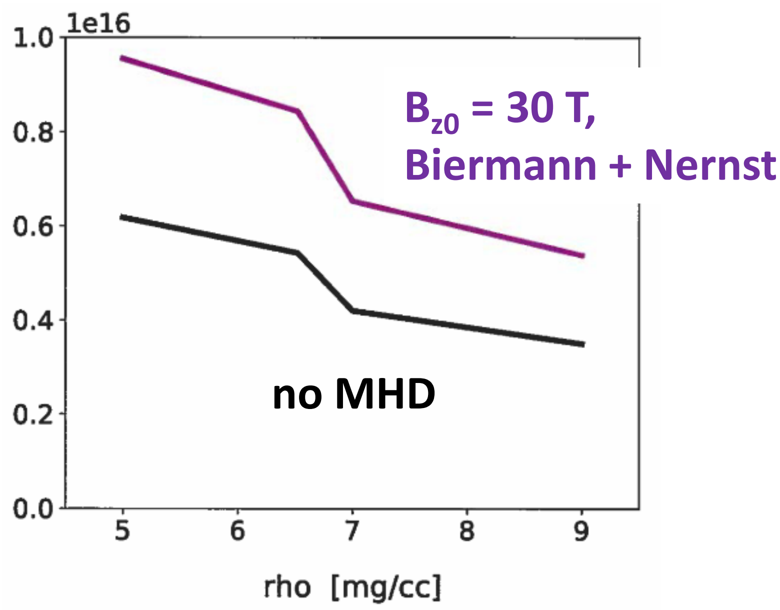
Neutron production rate



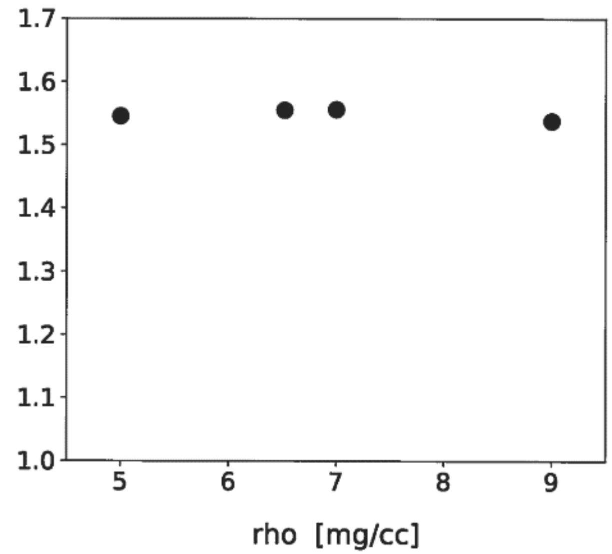


Gas capsules: yield increase ~55% for all gas densities

Max. neutron production rate



Max. neutron production rate: With B_{z0} / without



Magnetized ICF on NIF

Short term: Warm bigfoot-like magnetized gas capsules: B_{z0} = 30 T

- Field generator available for warm targets ~ Dec. 2018
- Validate:
  - Field compression[1] in NIF-scale capsule
  - Good hohlraum performance, low LPI
  - MHD modeling
- Yield enhancement ~50%: reduced e- conduction
- Other B field signatures: pole vs. waist 2ndary DT neutrons

[1] Already done at Omega scale:
Hohenberger PoP 2012
Chang PRL 2011
Knauer PoP 2010

Long-term: Make non-igniting targets ignite: B_{z0} = 40-50 T

- Cryo field generator needs engineering work
- Yield enhancement: alpha confinement
- Recover ignition [Perkins[2]]
  overcome e.g. hydro instabilities
- Relax Lawson condition [Ho[3]]
  Ignite when impossible w/o imposed B

[2] L J Perkins et al., PoP 2017

[3] D D Ho, APS DPP 2016

Hotspot self-heating condition

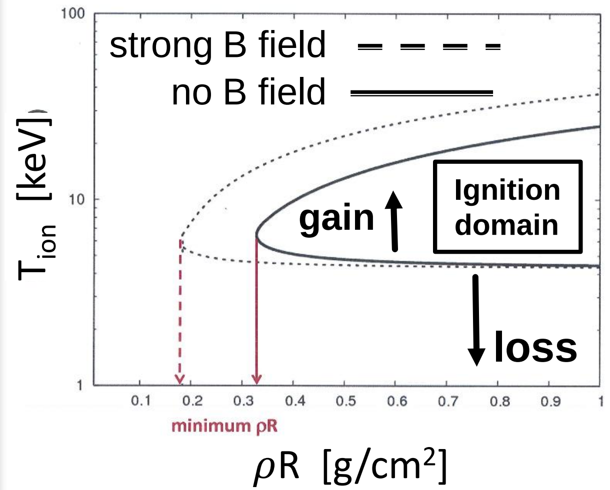


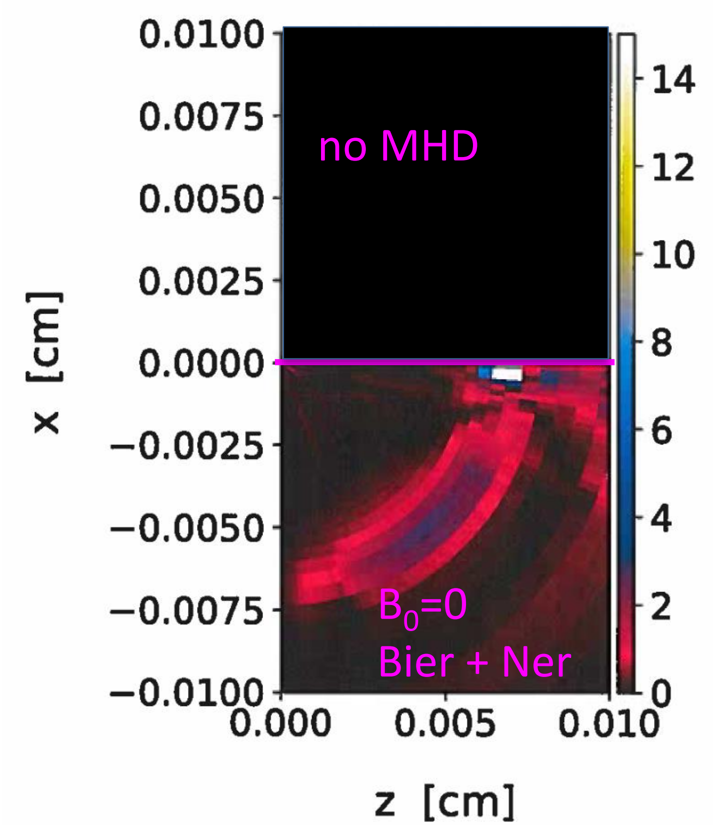
Figure from D. Ho

BACKUP BELOW

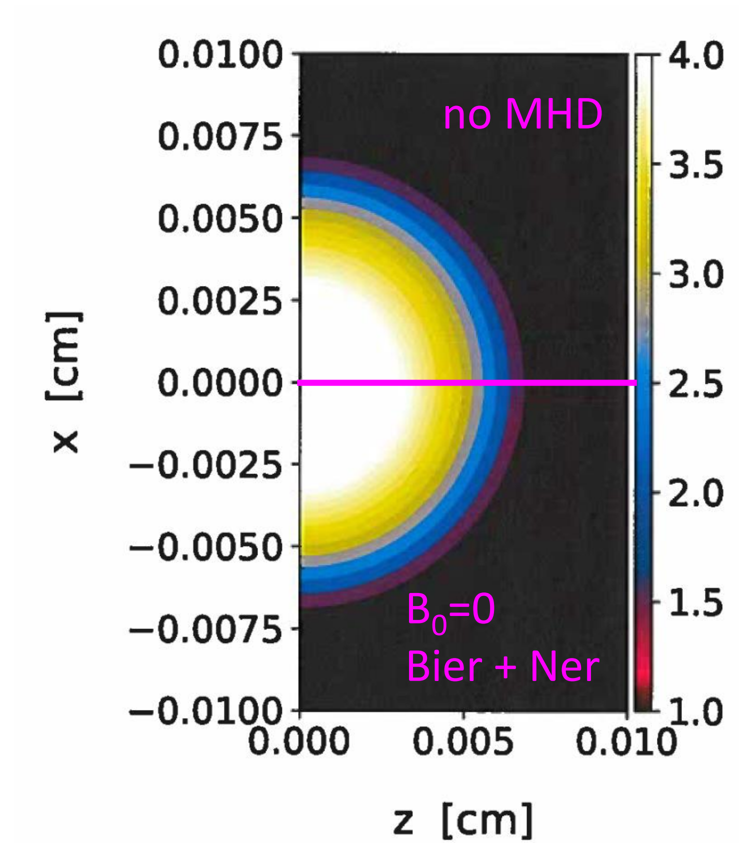
Biermann fields unimportant in capsule

7.05 ns: ~ bangtime

|B| [Tesla]



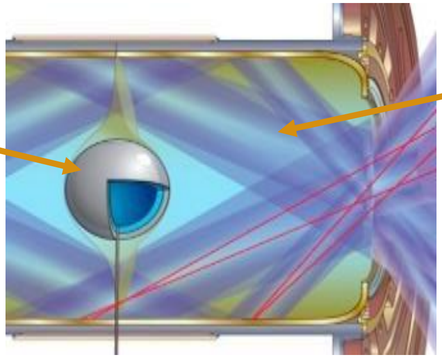
T_e [keV]



x-ray flux on capsule symmetrized: asymmetries will drive Biermann fields

Magnetized "warm" (293 K) gas-filled capsules: established NIF process for cryo analogs

HDC capsule fill
cryo: 5.5 mg/cc D-He3
warm: pure D or D-He3
Magnetized shots from TANDM, can't easily handle T



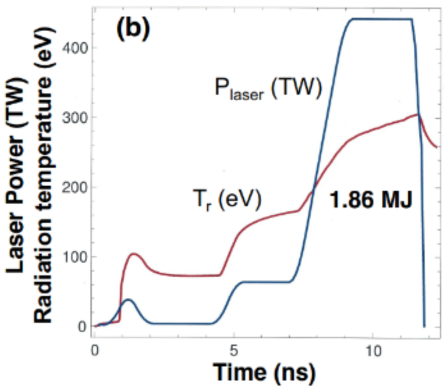
Hohlraum fill
cryo: 0.3 mg/cc He4
warm: C5H12, ~ same e- density
He4 → too much pressure on window

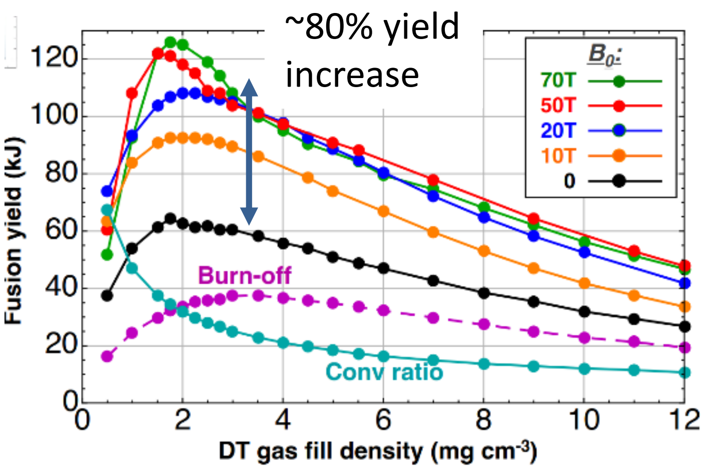
J. E. Ralph, D. J. Strozzi, et al., Phys. Plasmas 2016

- Warm analogs of "low-foot" CH implosions
- Backscatter, x-ray drive, implosion shape similar
- Capsule gas: C3D8 – light species (H, D, …) diffuse through CH –could aluminize
- HDC capsules should hold light species

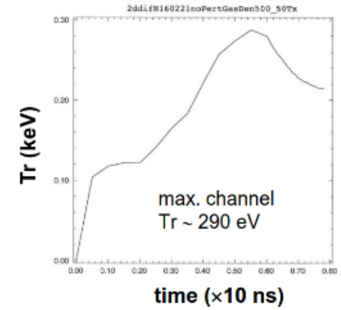
Magnetized gas-filled capsules: up to 2x yield increase with imposed B field

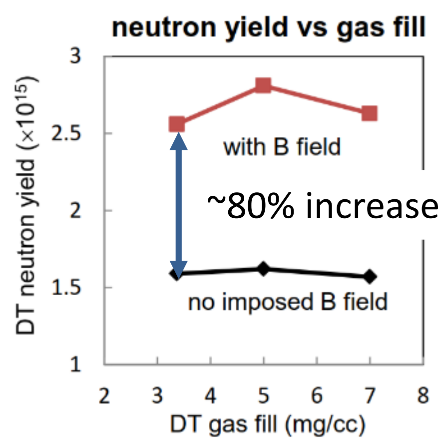
L. J. Perkins [unpublished]: HDC capsule, low adiabat

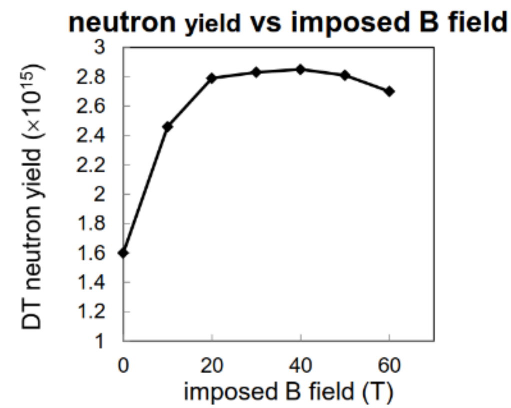




D. D. Ho [APS DPP 2016]: HDC capsule, high adiabat



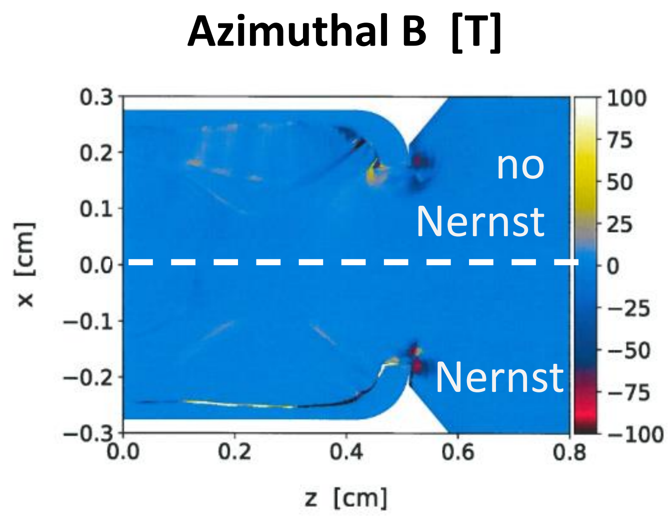




DT vs. DHe3 gas capsules

- Yield increased mainly by reduced e- conduction
- Not enough alpha's to matter
- Warm shots: D-He3 fill: e- conduction reduction should have similar effect

Biermann, no imposed, 4.25 ns



Hohlraums, no imposed field: Farmer PoP 2017

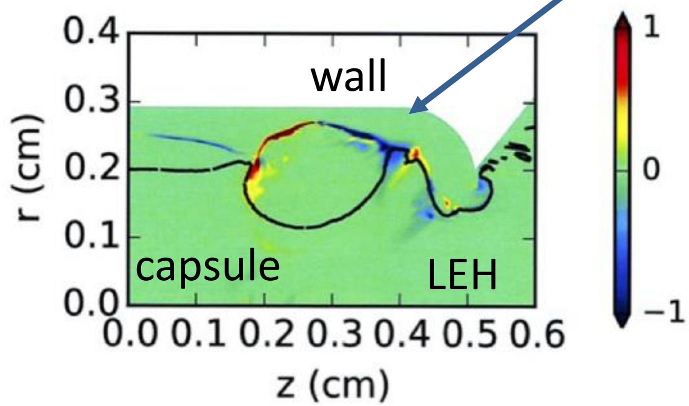
NIF shot N151122
HDC capsule
0.3 mg/cc hohlraum gas fill

MHD: Biermann + Nernst

Farmer ‘17

Highly localized
~ 100 T fields

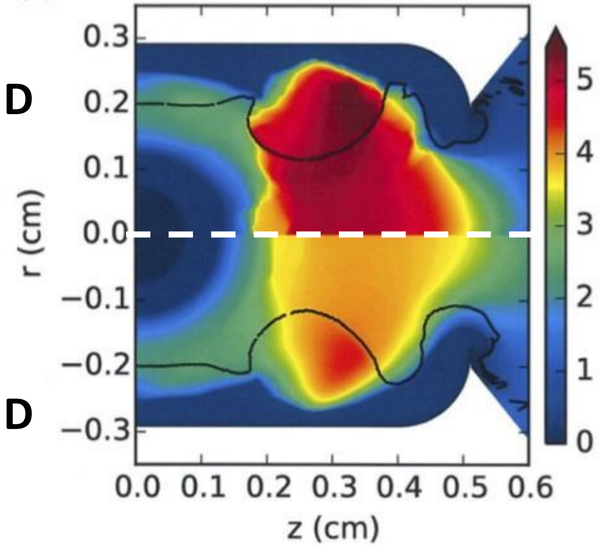
azimuthal B [MG]



T_e [keV]

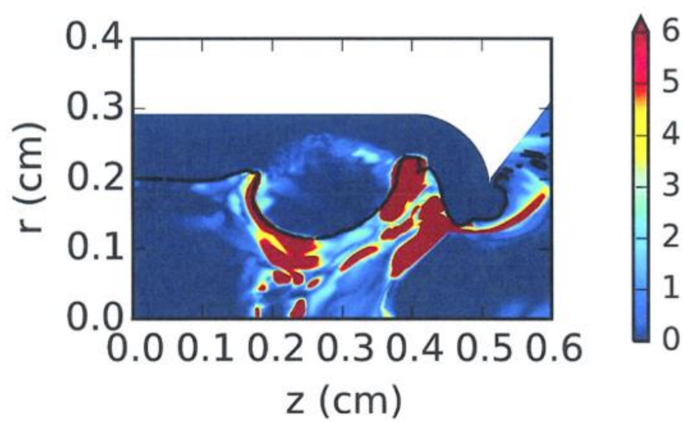
MHD

No MHD

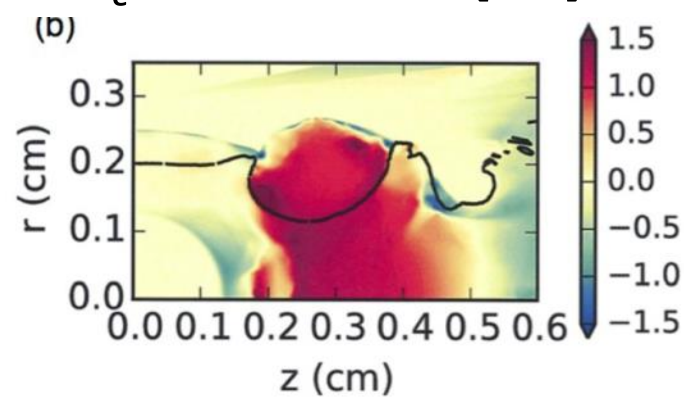


Plots at 5 ns:
late peak power

Hall parameter $\omega_{ce}\tau_{ei}$



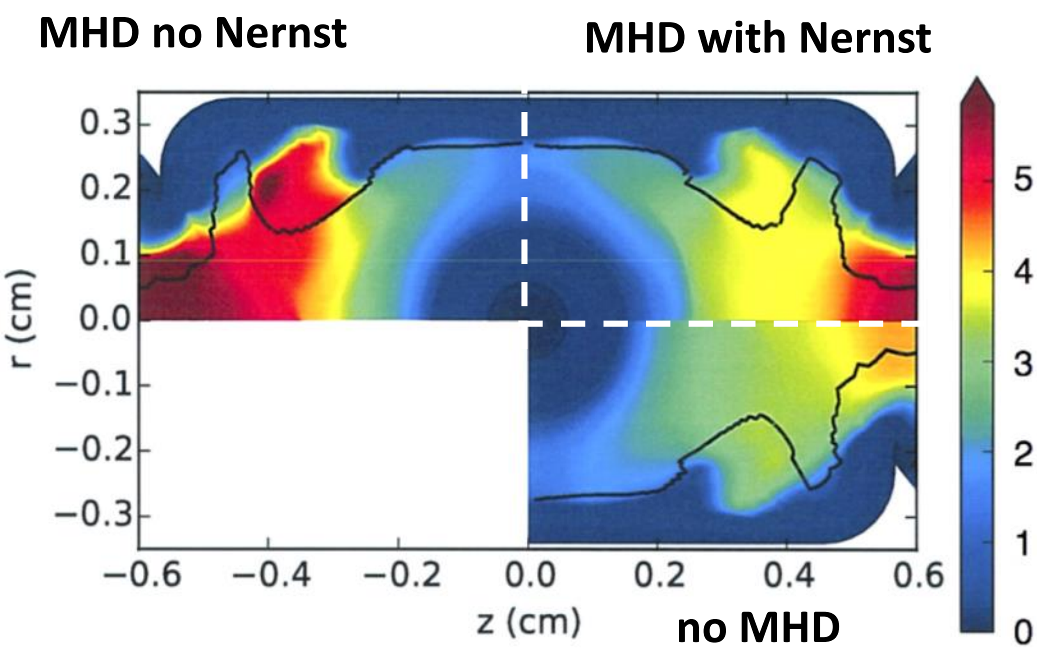
T_e MHD – no MHD [keV]

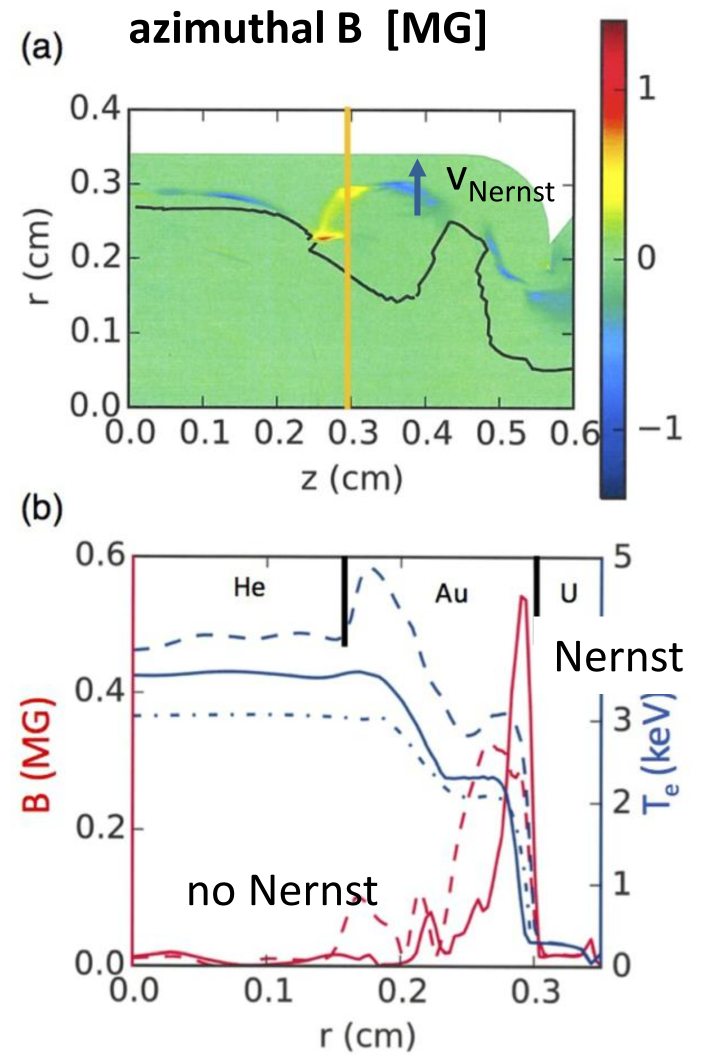


Hohlraums, no imposed B: Nernst advection reduces effect of B field

Farmer ‘17

“High foot” design
CH capsule
0.6 mg/cc hohlraum gas fill





“What Biermann giveth, Nernst taketh away”
– M. D. Rosen

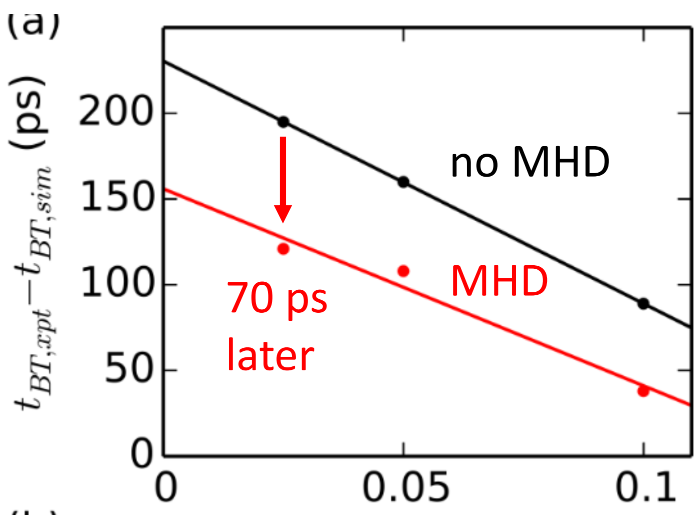
Hohlraums, no imposed field: MHD slightly reduces "drive deficit", implosion less oblate

Farmer '17

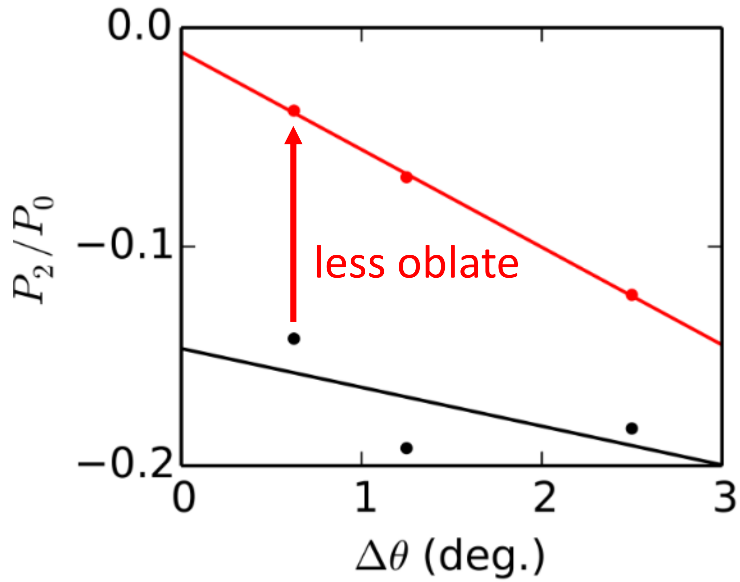
NIF shot N151122
HDC capsule
0.3 mg/cc hohlraum gas fill

W. A. Farmer, J. M. Koning, et al., Phys. Plasmas 2017

Bangtime: measured – simulated reflects total x-ray drive



P_2/P_0: hotspot emission shape



Imposed axial field (70 T) *slightly* raises T_e, improves inner-beam propagation

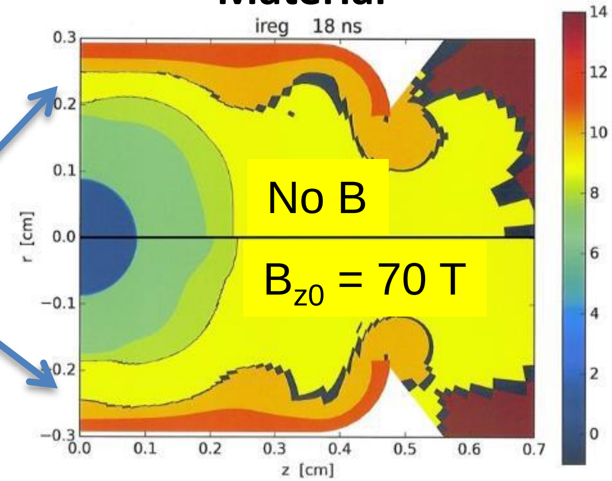
Strozzi '15
B_{z0} = 70 T

"Low-foot" shot N120321
CH capsule
18 ns: early peak power

D J Strozzi, L J Perkins, et al., *J. Plasma Phys.* (2015)

Wider equator channel with B

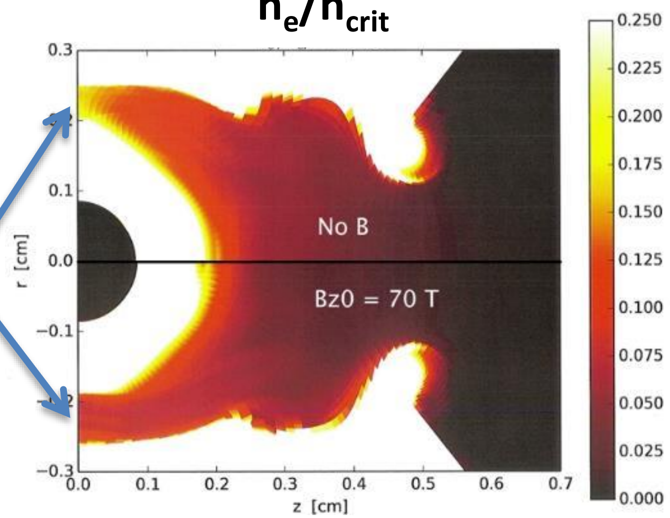
Material



Each figure: hohlraum quadrants with initial B_{z0} = 70 T (top), and without MHD (bottom)

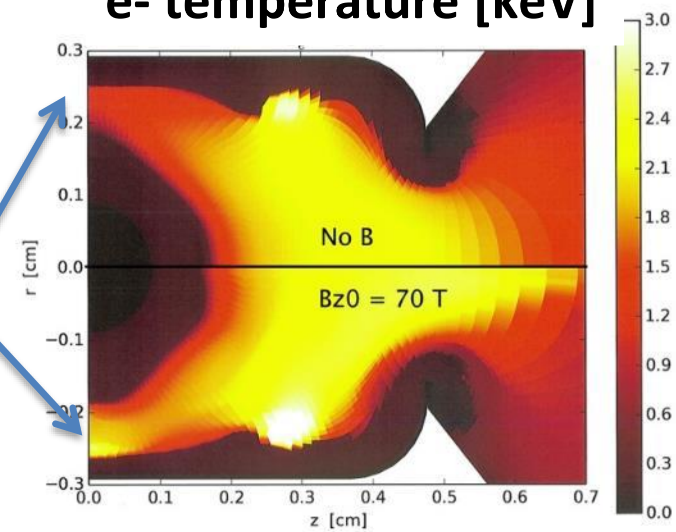
Less n_e w/ B

n_e/n_{crit}



Higher T_e w/ B, esp. on equator

e- temperature [keV]



Imposed B field: 10 T similar effect in hohlraum as 70 T

Strozzi ’15
B_{z0} = 10 T

High-foot shot N121130
B_{z0} = 10 T
15.2 ns: peak power

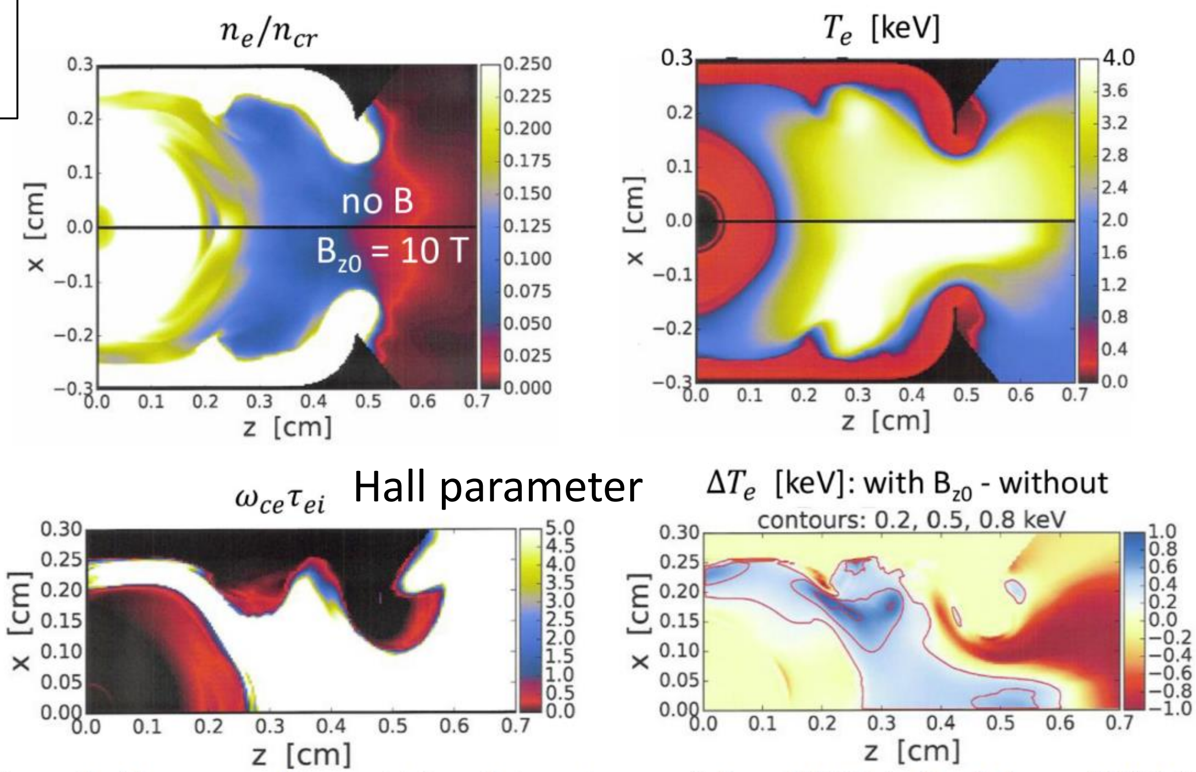


Figure 5. Plasma conditions at 14 ns (late peak power) from HYDRA simulations of NIF shot N121130. For n_e and T_e plots, top half (x>0) has no field, and bottom half (x<0) has B_{z0}=10 T. The Hall parameter $\omega_{ce}\tau_{ei}$ is capped at 5 for clarity.

L. J. Perkins et al., LDRD final report

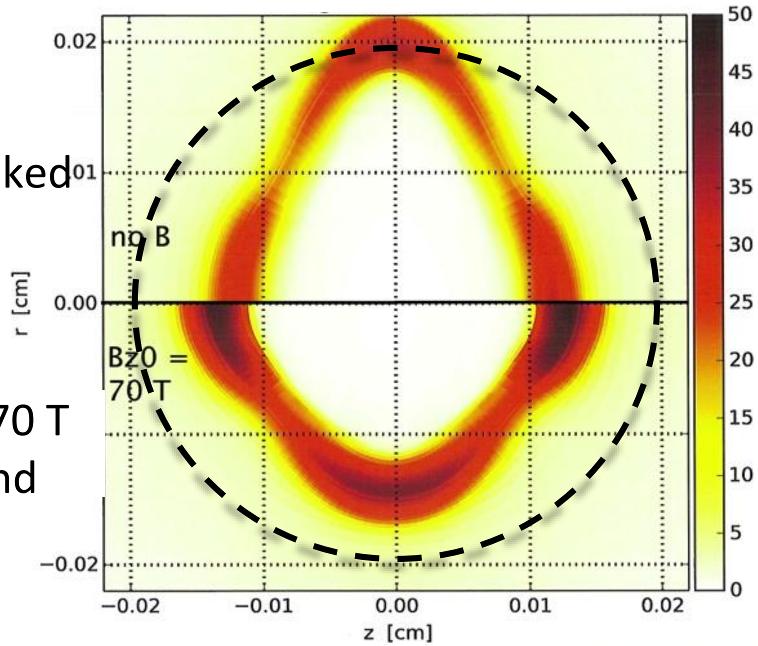
Imposed B: improved inner beam propagation, less pancaked implosion

Strozzi ’15
B_{z0} = 10, 70 T

Low-foot shot N120321[1]
B_{z0} = 70 T
21.5 ns: end of pulse

Capsule density [g/cc]

No B:
pancaked



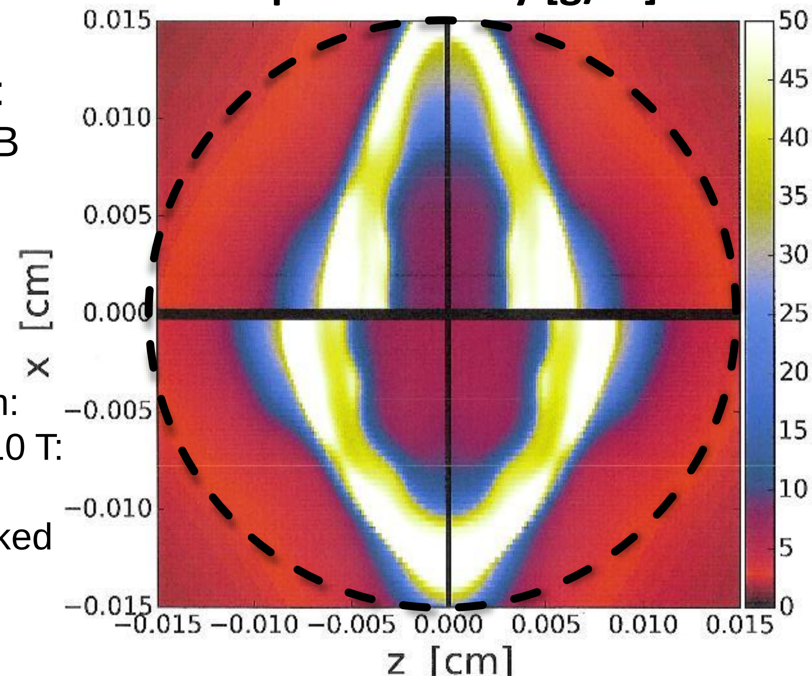
B_{z0} = 70 T
~ round

High-foot shot N121130[2]
B_{z0} = 10 T
15.2 ns: peak power

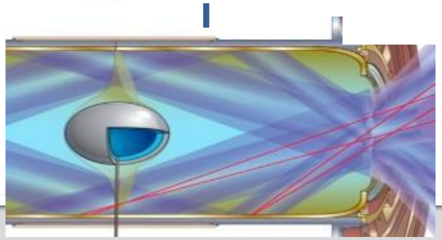
Top:
No B

Bottom:
B_{z0} = 10 T:
less
pancaked

Capsule density [g/cc]



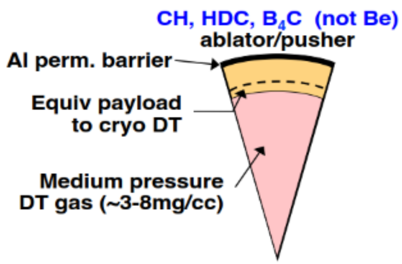
[1]D. J. Strozzi, L. J. Perkins, et al., *J. Plasma Phys.* (2015)

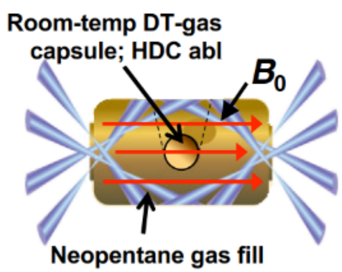


[2]L. J. Perkins et al., LDRD final report

Slide courtesy L. J. Perkins

Room-temperature gas target performance, HDC shell – What's the most important role of the B-field?





Most important effect of B for (non-metal) gas targets is on electron heat conduction as there's few alphas.
⇒ Can get interesting results at low imposed B-fields (~20T) because $\omega\tau_e$ is still very high

B_0 (T)	$\omega\tau_e$	α-B-orbits	
50	on	on	red
50	on	off	blue
50	off	on	green
50	off	off	orange
0	n.a	n.a	black