Towards magnetically-assisted ignition on NIF

Z Fundamental Science Workshop

14 August 2019

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LLNL-CONF-786817

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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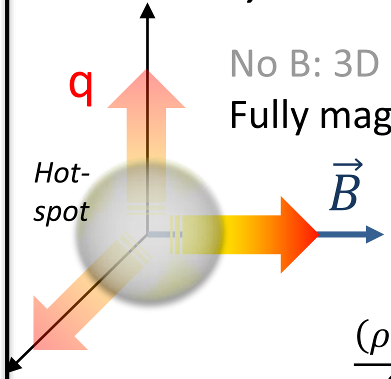
Disclaimer

Goal – magnetize DT layered implosion to reach ignition on NIF

Imposed B field reduces electron conduction loss, increases alpha heating

B-field reduces e- conduction ⊥ B: *increases* T, lowers ρR

"Magnetic insulation"



No B: 3D heat flow $q = -\kappa \nabla T$

Fully magnetized [2] $q \sim -(\kappa/3)\nabla T$

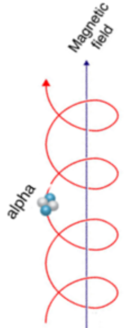
$$\frac{T_{hs}(B)}{T_{hs}} = 3^{1/3} = 1.44$$

$$\frac{(\rho R)_{hs}(B)}{(\rho R)_{hs}} = 3^{-1/3} = 0.69$$

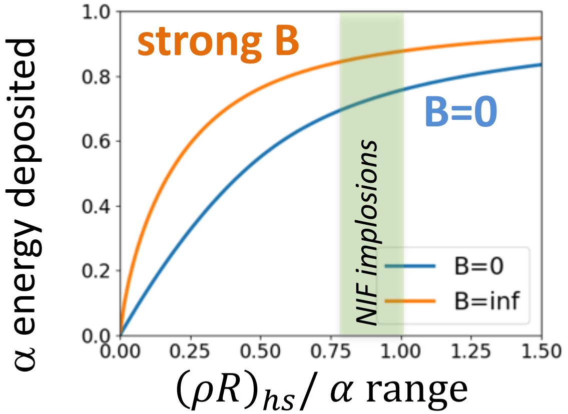
[1]

Strong B: $\omega_{ce}\tau_{ei} \gg 1$

B-field increases hotspot alpha heating



Guskov et al., Sov. JQE 1984



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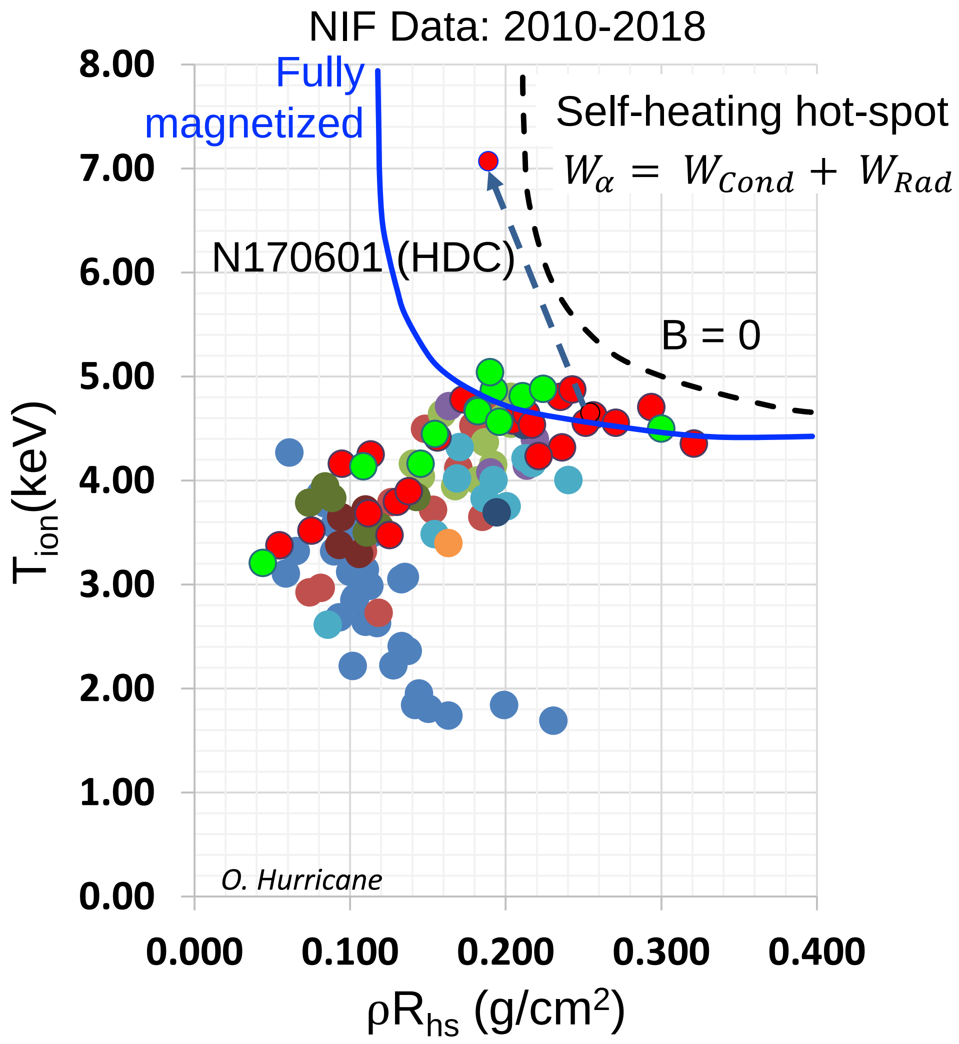


[1] O. A. Hurricane et al, PPCF 61 (2019); [2] D. Ho, APS 2016

Imposed B field moves DT implosions closer to ignition

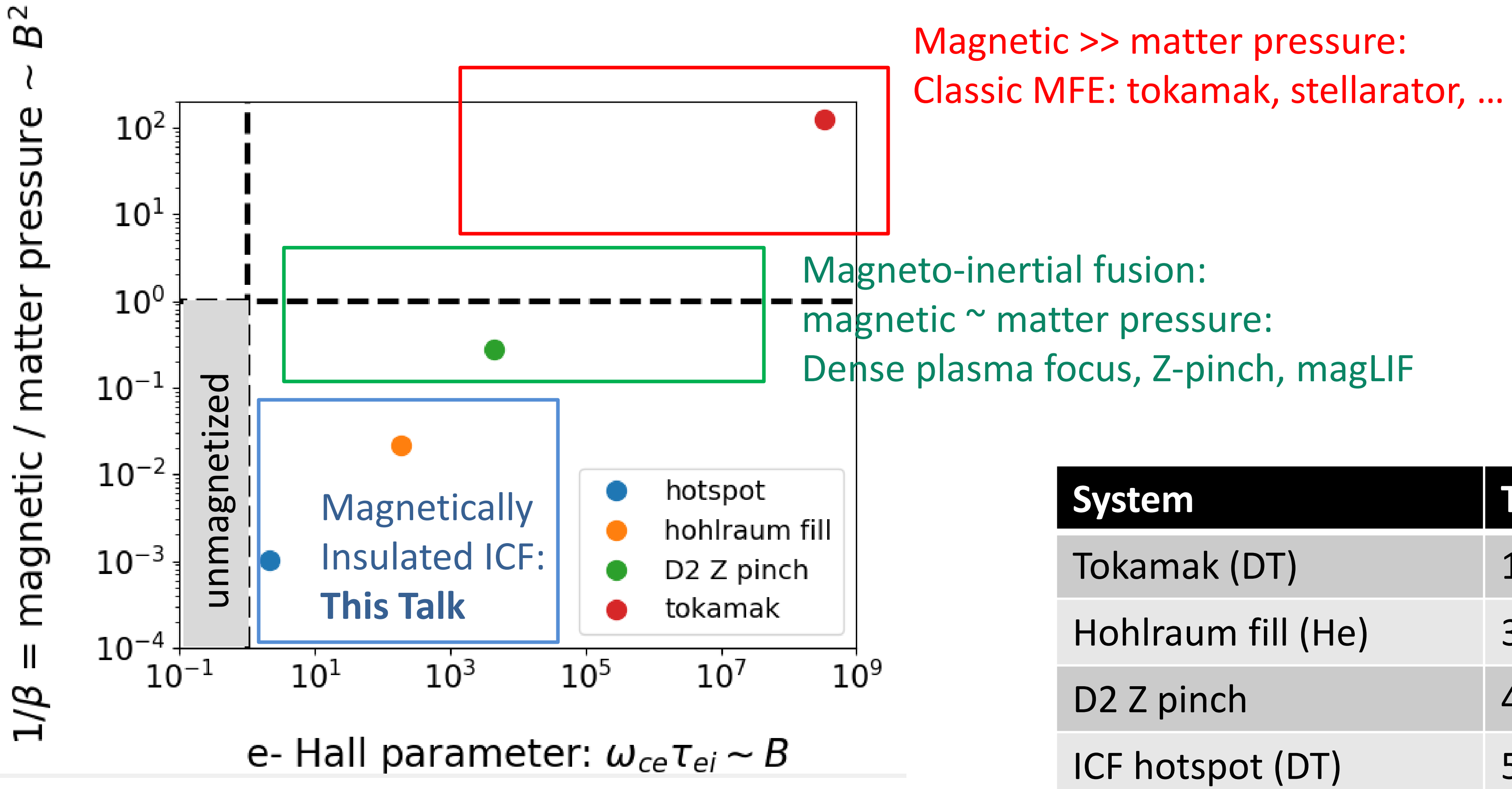
Hotspot of best NIF DT performer (BigFoot shot N180128):

Hotspot quantity	No B value	Strong B value	Comment
T_{ion} [keV]	4.9	7.1	First > 5 keV hotspot
ρ [g/cm^3]	74	52	
R [um]	31	Same	
ρR [g/cm^2]	0.23	0.16	
CR	22	Same	DT convergence ratio: initial / final DT-ablator interface
α energy dep. in HS	0.82	0.85	B effect on α's over-compensates ρR reduction

B_{z0} = 40 T and strong-B values:

B_z final = B_{z0} CR^2	19 kT	MHD frozen-in law
beta = matter pressure / magnetic pressure	190	
e- Hall parameter: $\omega_{ce}\tau_{ei}$	11.5	e-'s magnetized, $\perp$ heat flux strongly reduced
α Hall parameter: $\omega_{c\alpha}\tau_{\alpha e}$	4.1	

"Magnetically Insulated ICF:" e- conduction reduced, magnetic pressure unimportant



e- conduction suppressed: $\frac{\kappa_\perp}{\kappa_{||}} \sim \frac{1}{(\omega_{ce}\tau_{ei})^2} - \frac{1}{(\omega_{ce}\tau_{ei})^1}$

System	T_e [keV]	Rho [g/cc]	B [T]
Tokamak (DT)	10	4.2e-10	10
Hohlraum fill (He)	3	1E-3	100
D2 Z pinch	4	3.3E-4	300
ICF hotspot (DT)	5	3100	1E4

Talk Outline

- Prior magnetically-insulated HEDP work
- Proposed LDRD SI overview: J. Moody, PI
- MHD hohlraum simulations: modest effect on hohlraum conditions
- MHD capsule simulations: optimal imposed B_{z0} = (>20, 30-50) T for (gas-filled, layered DT) implosions

Labs worldwide pursuing Magnetically Insulated HEDP

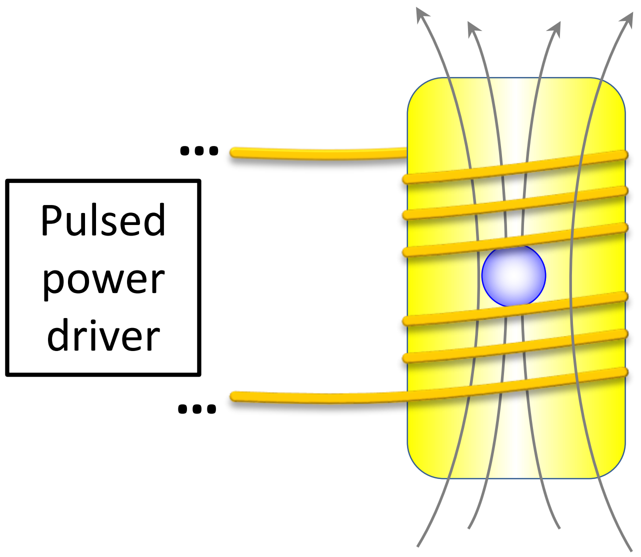
Time period	Description	Results
2006	JLF: magnetically insulated gasjet w/ 12 T (Froula + Pollock)	Quenching of nonlocal heat transport
2011	Omega (MIFEDS): room-temp. D2 implosion, 8 T seed	Direct drive; low seed; modest effect
2019 - on	Omega: <= 30 T and cryo implosions	marginal for ignition assist
2013 - on	Sandia Z machine: MagLIF and other experiments	Promising results w/ D2 fuel
2019 – on	LLNL/SNL: Laser preheat of magnetized gaspipe on NIF (RT)	First imposed B-field at NIF (room temp)
2014 – 2017	LLNL: John Perkins' LDRD: magnetized ICF	Capsule and hohlraum simulations; Prototype hohlraum coil tested offline
Plus Japanese magnetized fast ignition (ILE Oaska), Chinese magnetized ICF + Z machine, …		

Future LLNL work toward magnetized ignition		
2019	LDRD feasibility study: low electrical conductivity hohlraums	Address B-field soak-thru
2019 – on	NIF IPT: magnetized cryo layered implosions	Scoping of technical challenges and ideas
FY20 – 22	LDRD SI (proposed): magnetized ignition: John Moody PI	Room-temp magnetized gas-filled capsules; research for magnetized cryo-layered shots

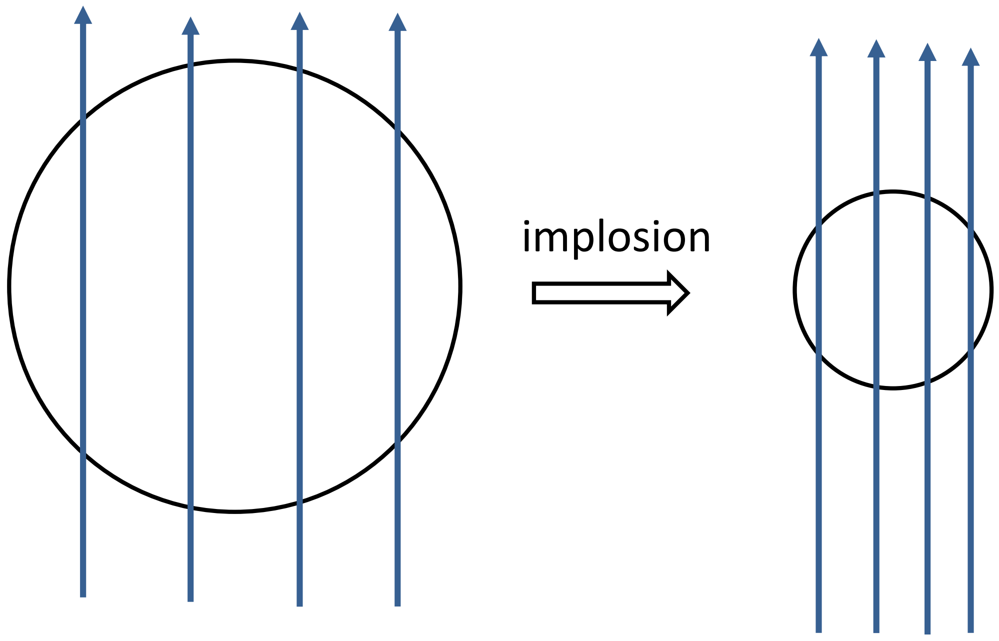
Magnetized Ignition SI (Proposed): Magnetically-assisted ignition adds a B-field to a high-performing hohlraum implosion

Slide Courtesy J. Moody

- Take high-performing cryo-layered hohlraum implosion experiment
- Add B-field to magnetize the capsule



MHD Frozen-in law: assumes no flux loss (e.g. resistive, Nernst)



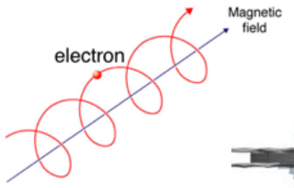
Magnetic flux conserved:
B*area = constant → $B \sim 1/R_{final}^2$

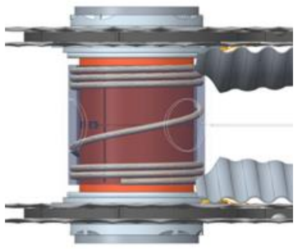
Expectations

- Significant capsule magnetization, performance improvement
- Modest changes in hohlraum behavior

Magnetized Ignition SI (Proposed): John Moody PI: Demonstrate key elements for magnetized ignition on NIF

Slide Courtesy J. Moody



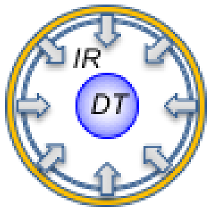


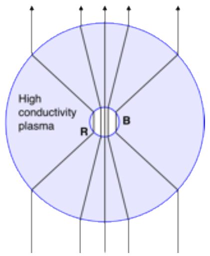
1. **Magnetized room-temperature gas-filled capsule on NIF:** hot-spot temperature increase with embedded B-field

2. **Get B-field into hohlraum and capsule** consistent with NIF constraints

3. **DT ice layering method** that works with B-field hardware

4. **Experimental platform for magnetized HED / high field science**





This SI addresses key research elements needed for a demonstration of a magnetized cryo implosion on NIF; final implementation is follow-on programmatic work

BigFoot[1] platform: starting point for room-temp. magnetized design

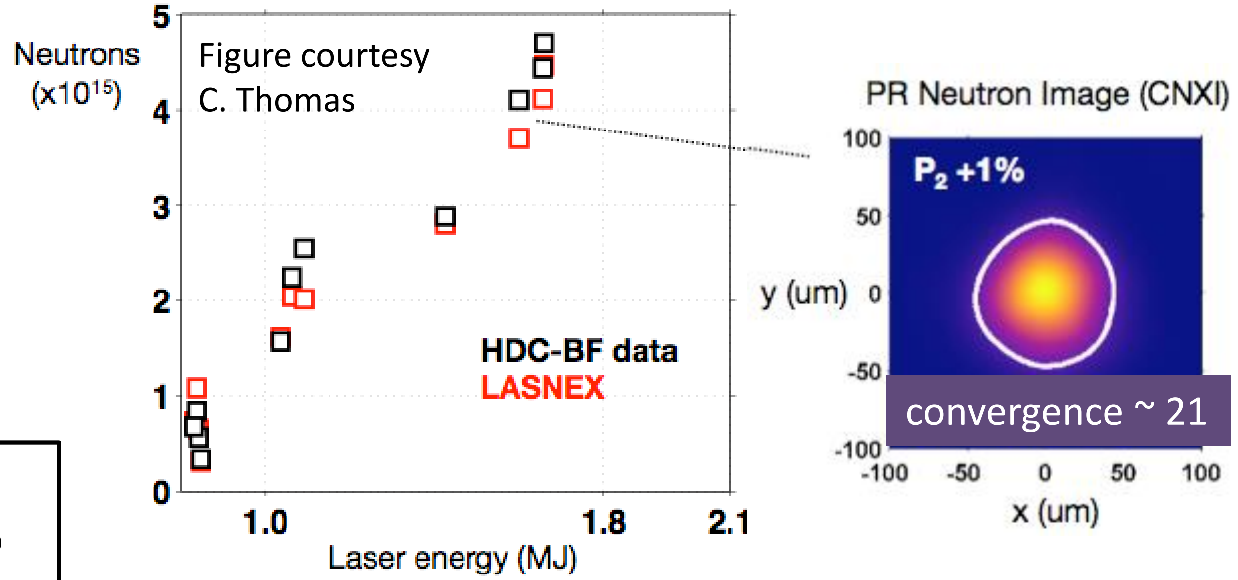
“Bigfoot” campaign on NIF

- Robust hotspot: High rho*R, high velocity
  - Price: high adiabat, lower convergence
- Shocks 1 and 2 overtake in ablator
- HDC capsule: short pulse, smooth capsules
- Simple hohlraum:
  - Low gas fill density: 0.3 mg/cc He
  - Low LPI: CBET + backscatter
  - Au: low flakes / meteors vs. DU
- Highest yield on NIF

Why BigFoot?

- Don’t re-invent wheel: connect to existing, high-yield cryo platform
- Nice features: predictable, tunable, low LPI
- “Goldilocks convergence”:
  - Enough to amplify B field, reduce e- conduction
  - Not so much for significant hydro instabilities or mix

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

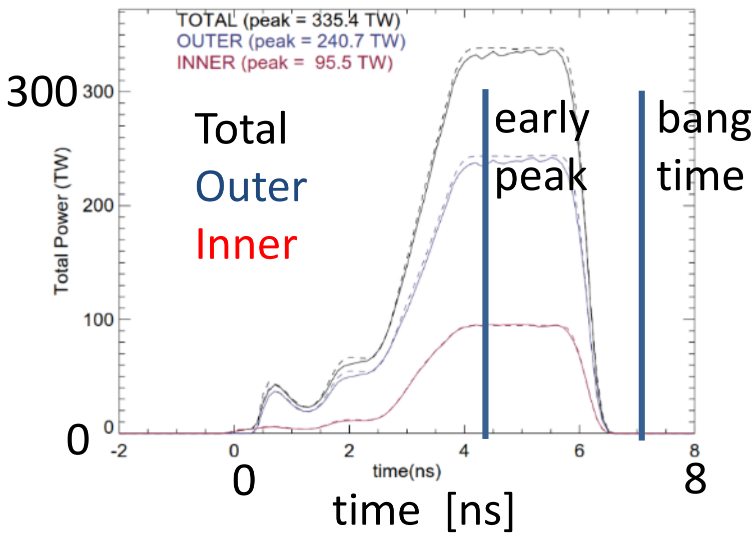


1 C. Thomas, APS-DPP invited talk, 2016

Room-temp. magnetized design: subscale BigFoot gas-filled capsule

N161204: BigFoot subscale gas-filled capsule
- Less taxing on laser and optics:
  - 1.1 MJ, 340 TW
- Capsule fill: D[30%] + He3[70%]
  - 6.5 mg/cc
  - no DT ice layer

Laser power [TW]



Room-temp. magnetized design
- Start from N161204
- Target and pulsed-power system fielded on TANDM
- Capsule: HDC: can fill with H, D, He – no T on TANDM
- Capsule fill: D2: less radiative loss than He: hotter, higher yield
- Hohlraum fill gas[1]: C5H12: window can't hold same He density

[1]J. Ralph, D. Strozzi et al., Phys. Plasmas 2016

HYDRA MHD* model: Full single-fluid Braginskii: not all used here

Bulk momentum

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

Magnetic force: pressure + tension

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

Maxwell

$$\partial \vec{B}/\partial t = -\nabla \times \vec{E}$$
$$\vec{J} = \mu_0^{-1} \nabla \times \vec{B}$$

JxB generally not important for us, for $B_{z0} < 50$ T

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

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

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

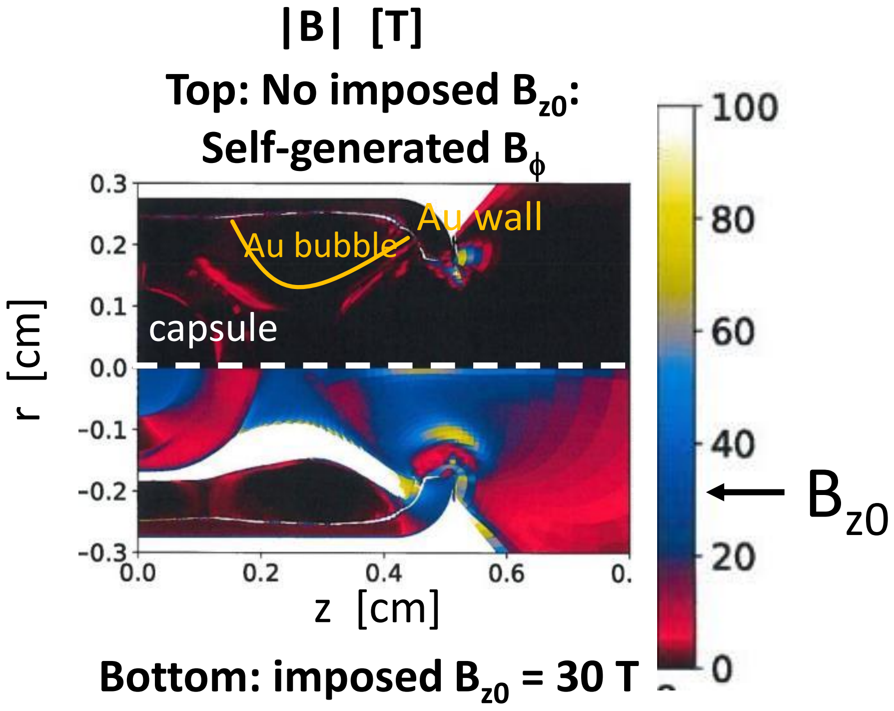
Biermann: Self-generated

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

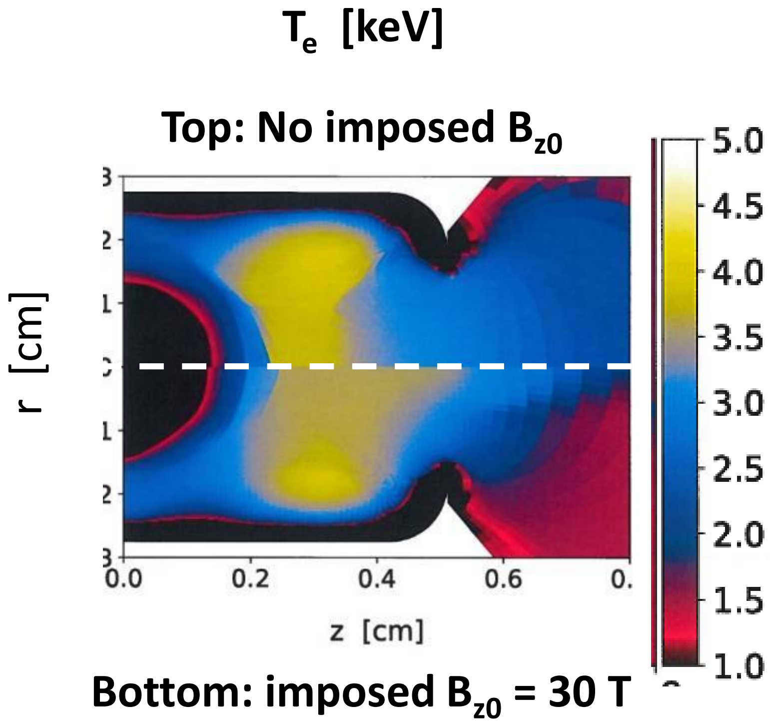
* J. Koning: lead developer

Hohlraum plasma: modest temperature change due to B field

Hydra MHD hohlraum sims **BigFoot N161204 post-shot: 4.25 ns: early peak power**



- Self-generated and imposed fields independent
- Imposed B follows frozen-in law: advects w/ plasma



- Imposed field: Temperature modestly increases or decreases, depending on location

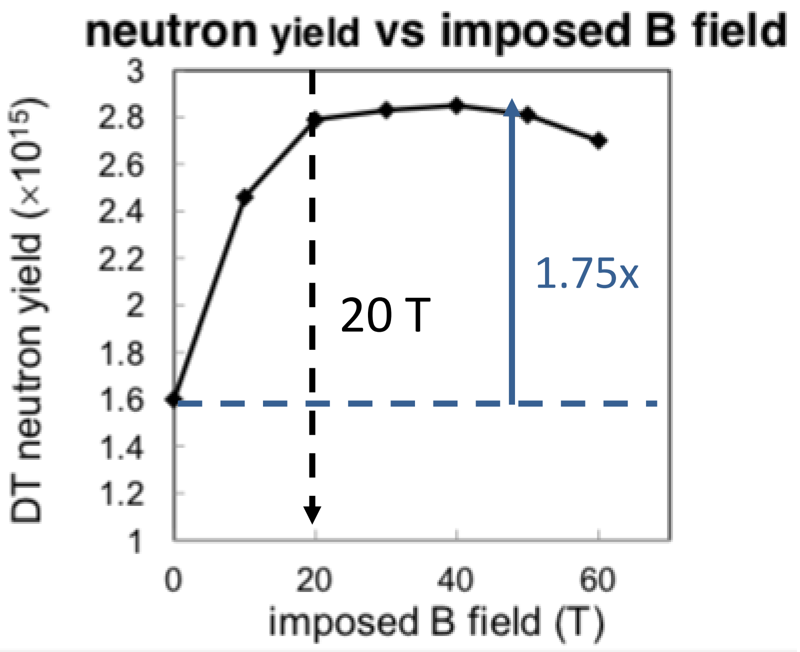
MHD model includes Biermann and Nernst effects

Seed field of 30 T - 50 T optimal DT-layered capsule

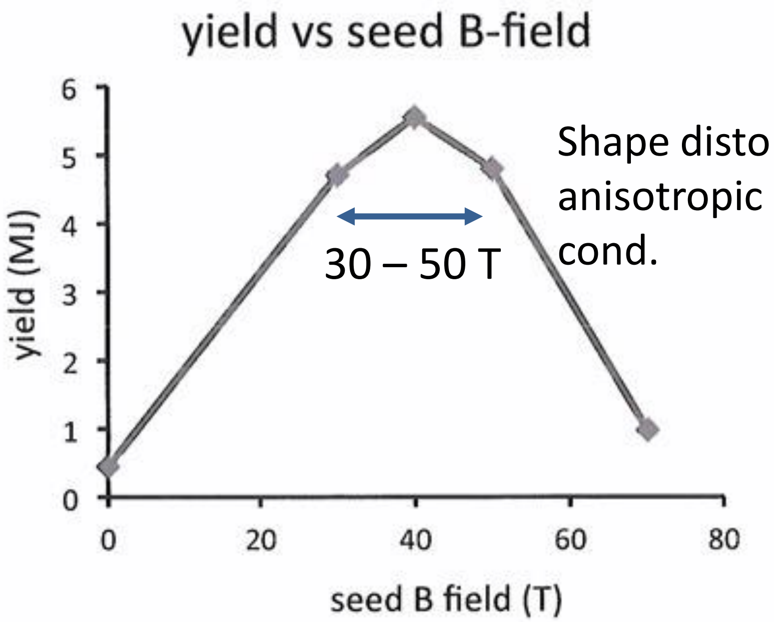
Darwin Ho: 2D Lasnex MHD sims:

- HDC capsule
- 3 shocks
- Slightly degraded simulation

Gas-filled DT implosions:
Optimal B_{z0} > 20 T
Effect mainly on e-'s, not α's



Layered DT implosions:
Optimal B_{z0} = 30-50 T
Effect on e-'s and α's both matter



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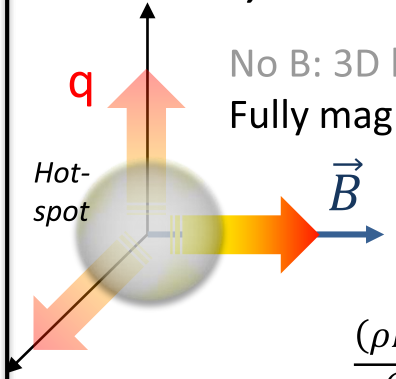

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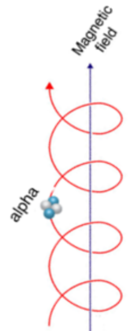

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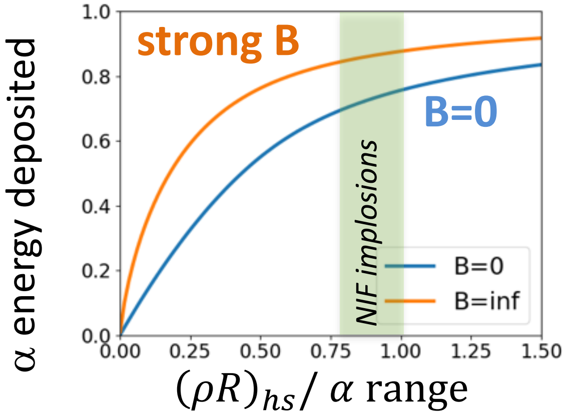

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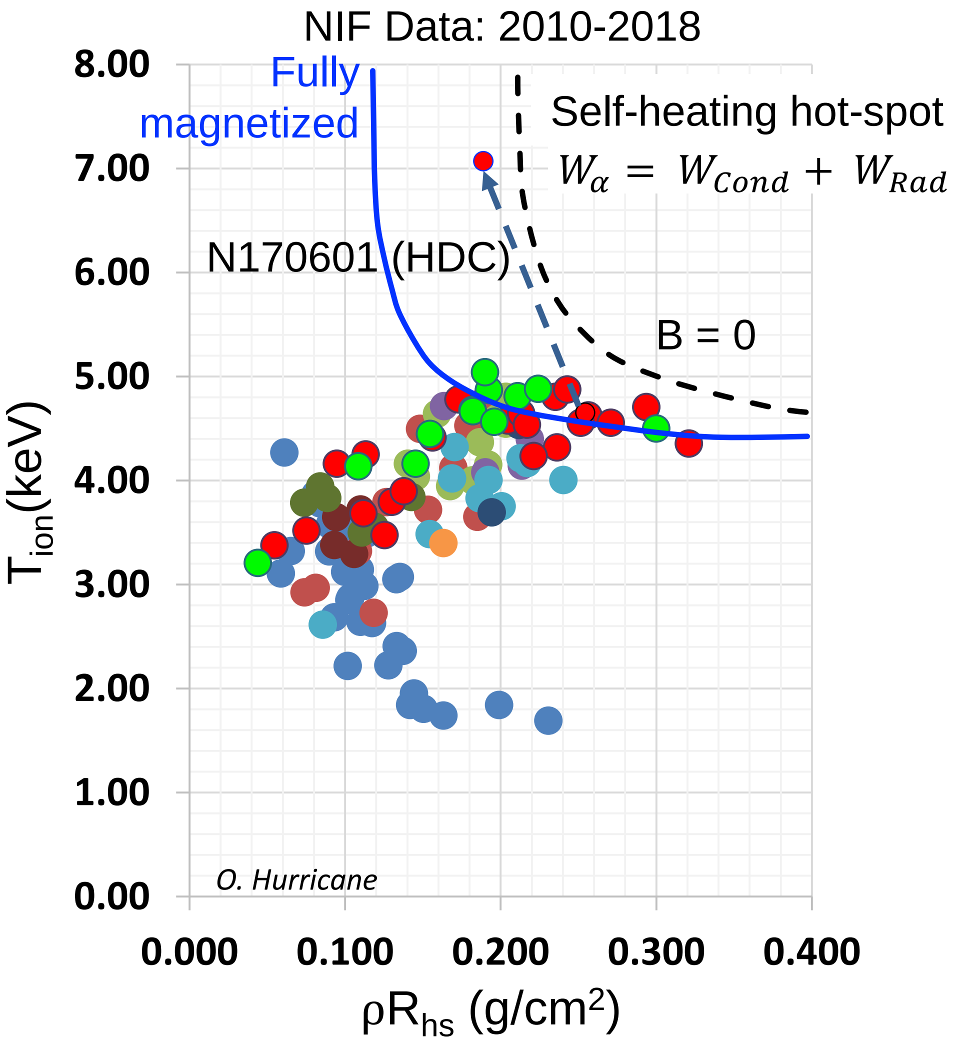

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