Design of Magnetized, Room-Temperature Capsule Implosions for NIF

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

<table>
<thead>
<tr>
<th>Biermann fields (self-generated)</th>
<th>Hohlraum</th>
<th>Capsule</th>
</tr>
</thead>
</table>
| Like Farmer PoP 2017¹ | • 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 2015²,³ | B ~ 5 kT: ~ frozen-in  
• Gas-filled capsule yields up ~50%  
• For range of gas densities |
| • Frozen-in law holds: B field compressed or rarified w/ plasma  
• *Slightly* hotter fill | |

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

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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”\textsuperscript{1} platform: starting point for warm magnetized design

“Bigfoot” campaign on NIF
- Robust hotspot: High \( \rho \cdot R \), 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

Equivalent DT yield: agrees with Lasnex
13-15 MeV neutrons from DD, D\textsubscript{3}He, ...

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\caption{Figure courtesy C. Thomas}
\end{figure}

\textsuperscript{1} C. Thomas, APS-DPP invited talk, 2016

convergence ~ 21
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
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**
\[
\vec{J} \times \vec{B} = (B\hat{\beta} - 1) \cdot \nabla \left( \frac{B^2}{2\mu_0} \right) + \frac{B^2}{\mu_0} \hat{\beta} \cdot \nabla \hat{\beta}
\]

**Maxwell**
\[
\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} \\
\vec{J} = \mu_0^{-1} \nabla \times \vec{B}
\]

**Ohm’s law: Generalized**
\[
\vec{E} = -\vec{v} \times \vec{B} + \frac{1}{n_ee} \vec{J} \times \vec{B} - \frac{\nabla p_e}{n_ee} + \eta \vec{J} - e^{-1} \hat{\beta} \cdot \nabla T_e
\]
- Advection / induction term
- Hall term
- Biermann battery
- Resistivity
- Thermal force
- Collisional

**Ohm’s law: This talk**
\[
\vec{E} = -\vec{v} \times \vec{B} + \eta \vec{J} - \frac{\nabla p_e}{n_ee} - e^{-1} \hat{\beta} \cdot \nabla T_e
\]
- 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
HYDRA methodology

- 2D R-Z axisymmetric
- "HyPyD": Pythonic framework: J. Koning, J. Salmonson
- 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

Sim. bangtime slightly early ~ 60 ps

Neutron burn rate

Sim. BT ~ 60 ps

Expt’l BT ~ 60 ps
Hohlraum map legend

radius

r>0:
run 1

r<0:
run 2

Au wall (dense, cold)

Au bubble (hot, low-dens)

One-sided in z

z [vertical in NIF chamber]
Biermann fields increase $T_e$, Nernst advection reduces the effect

Like Farmer PoP 2017

$T_e$ [keV]

4.25 ns: early peak power

no MHD

Biermann

no MHD

Biermann + Nernst

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

|B| [T]

Au bubble

LEH

no Nernst

Nernst
Biermann fields, no imposed

→ Imposed 30 T axial field

Varying capsule gas density
Imposed $B_{z0} = 30$ T: yield increase $\sim 50\%$

**Neutron yield**

- No MHD
- $B_0=0$ Bier+Ner
- $B_0=30T$ J
- $B_0=30T$ Bier+Ner

**Neutron production rate**

- No MHD
- $B_0=0$ Bier+Ner
- $B_0=30T$ J
- $B_0=30T$ Bier+Ner

Imposed B runs: numerical issues at end

**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

**No imposed vs. $B_{z0} = 30$ 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**

**E = vxB + eta*J**

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 $\rightarrow$ 2 directions reduced

**Quiz: which half has imposed B field?**

- **no $B_{z0}$**
  - Au bubble *hotter* without $B_{z0}$!

- **yes $B_{z0}$**

4.25 ns: early peak power

$E + \text{Biermann}$

$E + \text{Biermann} + \text{Nernst}$
Imposed $B_{z0} = 30 \text{ T}$: capsule $B$ field $\sim 5 \text{ kT}$; Biermann fields small

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

Frozen-in estimate of field increase
• Gas convergence $\sim 14$
• Increase $\sim (R_{\text{initial}} / R_{\text{final}})^2$
  $= 200x : 30 \text{ T} \rightarrow 6000 \text{ T}$

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

capsule gas density [mg/cc]
- rho=1
- 3
- 5
- 6.52 shot
- 7
- 9

rho=1: CR = 28
rho=9: CR = 12
Gas capsules: vary convergence and yield via gas density

**Neutron yield**

- **no MHD**
  - $B_{z0} = 30$ T, Biermann + Nernst

- **$B_{z0} = 30$ T, Biermann + Nernst**
  - Numerical issues

**Neutron production rate**
Gas capsules: yield increase ~55% for all gas densities

Max. neutron production rate

- $B_{z0} = 30$ T, Biermann + Nernst
- no MHD

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 \(2^{nd}\)ary 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

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**Hotspot self-heating condition**

- strong B field
- no B field

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\(T_{\text{ion}} \, [\text{keV}]\)
\(\rho R \, [\text{g/cm}^2]\)

Figure from D. Ho
BACKUP BELOW
Biermann fields unimportant in capsule

7.05 ns: ~ bangtime

\[ |B| \text{ [Tesla]} \]

\[ T_e \text{ [keV]} \]

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

• 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

azimuthal B [MG]

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

MHD: Biermann + Nernst
Highly localized
~ 100 T fields

$r$ (cm)

$z$ (cm)

$r$ (cm)

$z$ (cm)

Plots at 5 ns:
late peak power

$T_e$ [keV]

Farmer ‘17

No MHD

MHD

$T_e$ MHD – no MHD [keV]
Hohlraums, no imposed B: Nernst advection reduces effect of B field

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

MHD no Nernst
MHD with Nernst

“What Biermann giveth, Nernst taketh away”
– M. D. Rosen
Hohlraums, no imposed field: MHD slightly reduces “drive deficit”, implosion less oblate

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

Bangtime: measured – simulated reflects total x-ray drive

\[ \frac{P_2}{P_0}: \text{hotspot emission shape} \]

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

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

Wider equator channel with $B$

Less $n_e$ w/ $B$

Higher $T_e$ w/ $B$, esp. on equator


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

$B_{z0} = 70$ T
Imposed B field: 10 T similar effect in hohlraum as 70 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.
Imposed B: improved inner beam propagation, less pancaked implosion

Low-foot shot N120321\textsuperscript{1}
B\textsubscript{z0} = 70 T
21.5 ns: end of pulse

High-foot shot N121130\textsuperscript{2}
B\textsubscript{z0} = 10 T
15.2 ns: peak power


\textsuperscript{2}L. J. Perkins et al., LDRD final report
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

<table>
<thead>
<tr>
<th>$B_0$ (T)</th>
<th>$\omega \tau_e$</th>
<th>$\alpha$-B-orbits</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>on</td>
<td>on</td>
</tr>
<tr>
<td>50</td>
<td>on</td>
<td>off</td>
</tr>
<tr>
<td>50</td>
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<td>on</td>
</tr>
<tr>
<td>50</td>
<td>off</td>
<td>off</td>
</tr>
<tr>
<td>0</td>
<td>n.a</td>
<td>n.a</td>
</tr>
</tbody>
</table>

Fusion yield (kJ) vs. DT gas fill density (mg cm$^{-3}$)

Burn-off ($B=0$)