Magnetically Assisted Ignition on NIF

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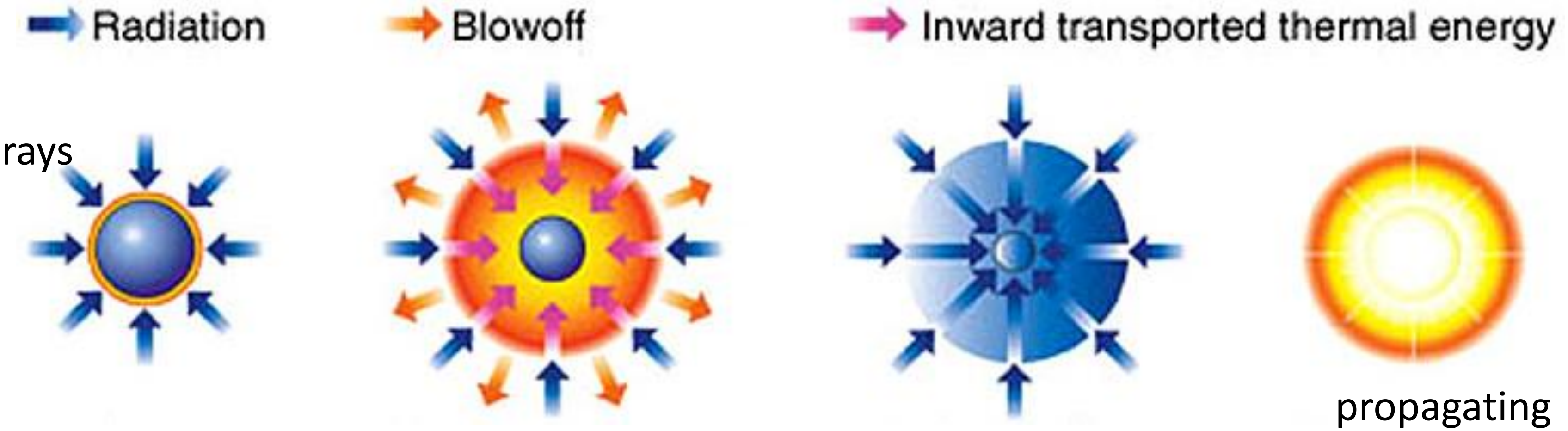
Lawrence Livermore National Laboratory

NIF 101: ICF and hohlraums

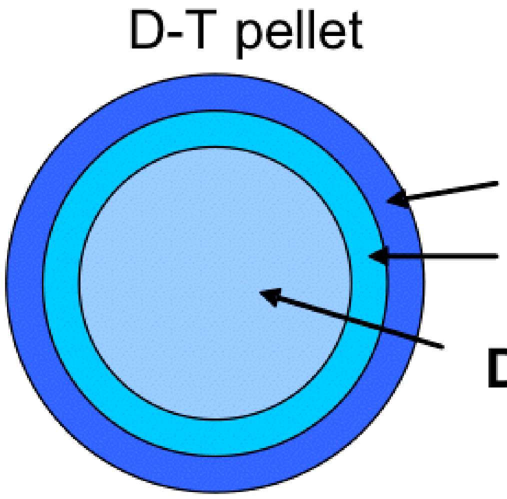


lasers, x-rays

ablation, compression

central hot-spot ignites

propagating burn wave

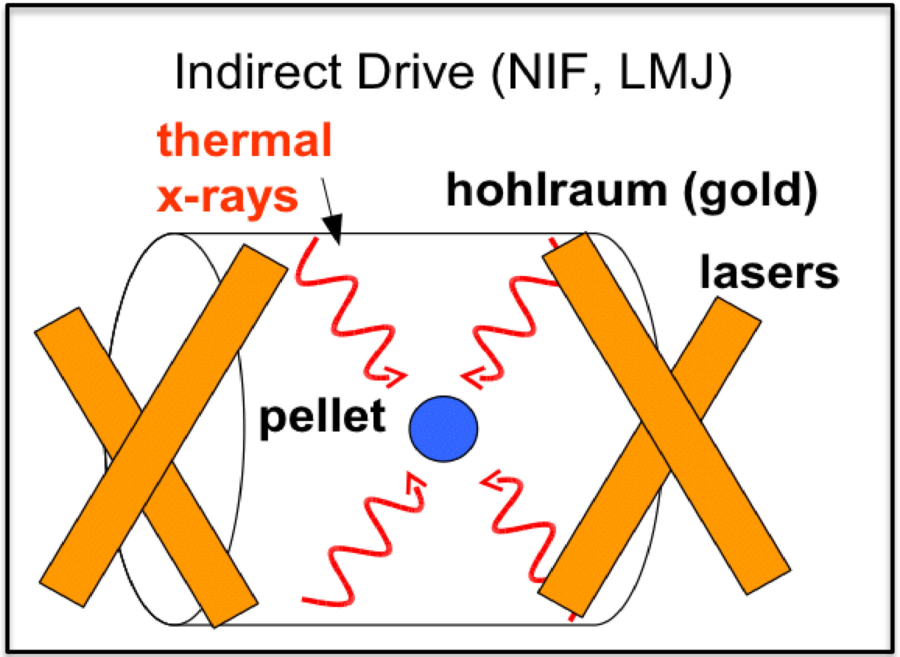


D-T pellet

ablator
(plastic, Be, HDC)

D-T ice

D-T vapor



Indirect Drive (NIF, LMJ)

thermal x-rays

hohlraum (gold)

lasers

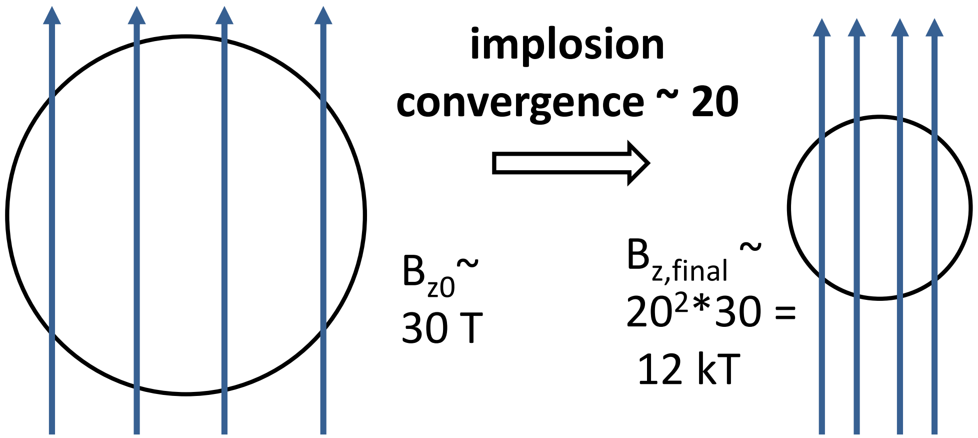
pellet

Magnetically-assisted ignition on NIF adds a B-field to a high-performing hohlraum implosion

Introduction

- Start with high-performing cryo-layered hohlraum implosion
- ~30 T seed B-field to magnetize capsule

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



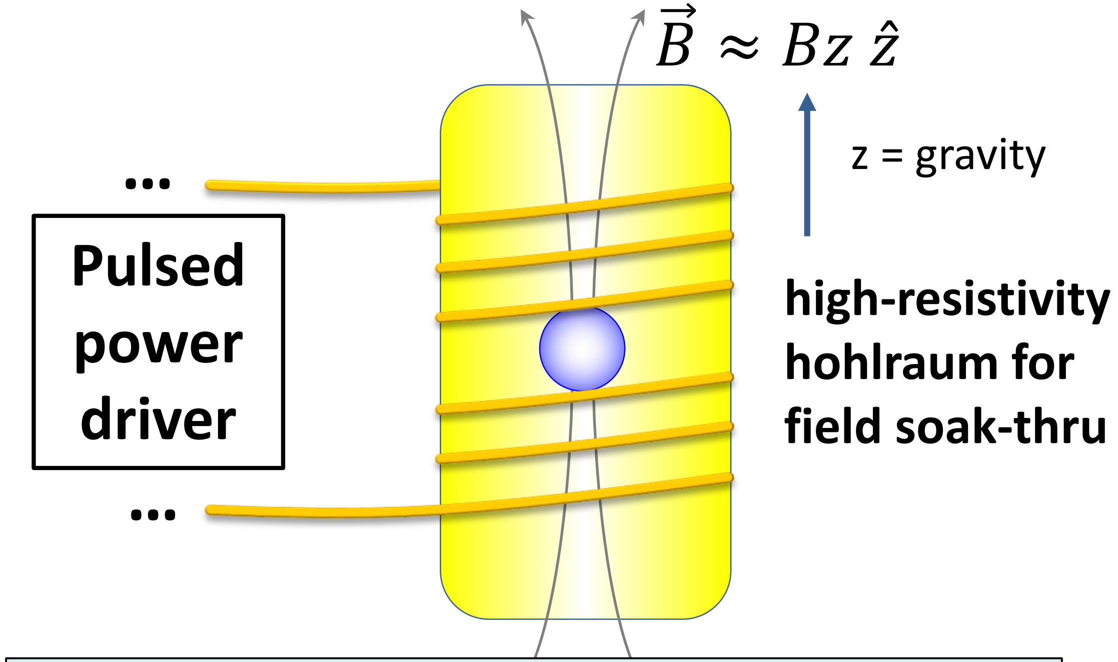
implosion convergence ~ 20

B_{z0}~ 30 T

$B_{z,final}$ ~ 20^2*30 = 12 kT

Magnetic flux conserved:

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



$\vec{B} \approx Bz\,\hat{z}$

z = gravity

Pulsed power driver

high-resistivity hohlraum for field soak-thru

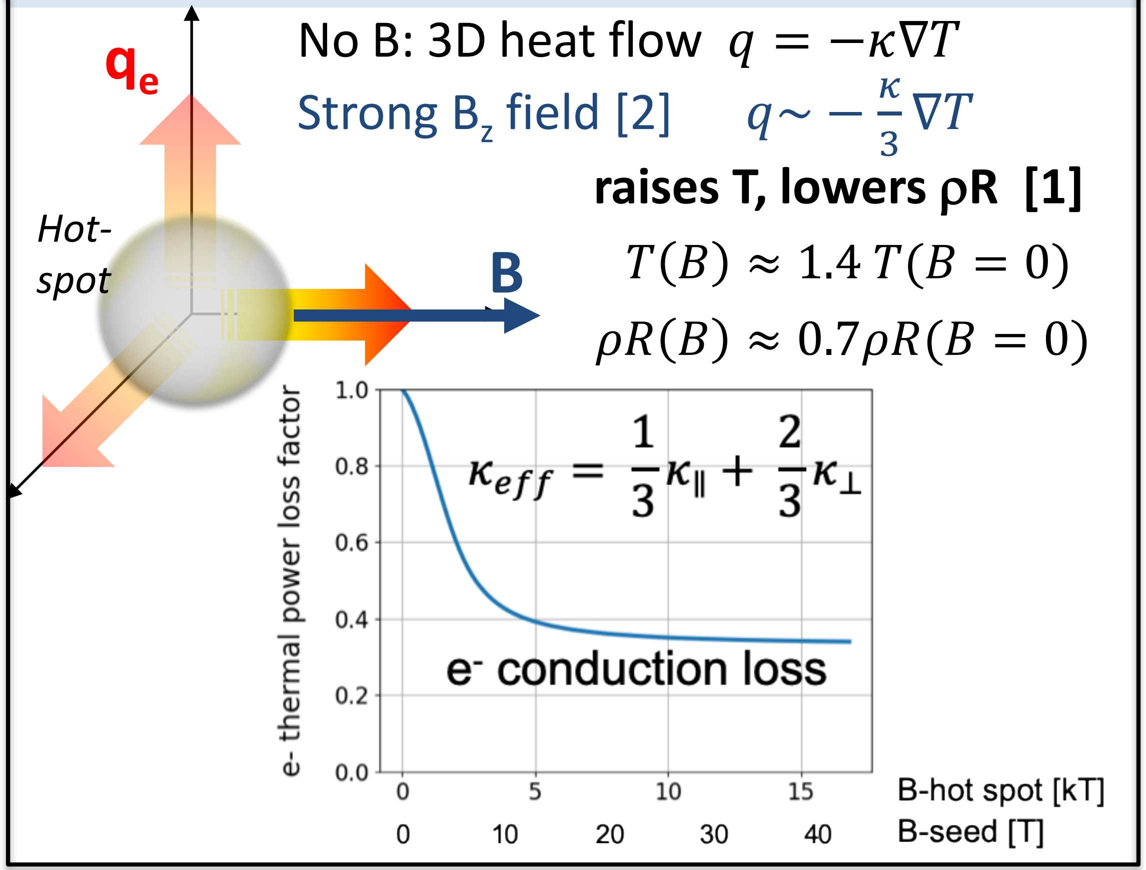
Expectations for current NIF high performers:

- Capsule:
  - ~ 2 keV T_{ion} increase: 5 → 7 keV
  - ≥ 2x yield increase
- Hohlraum: little change to x-ray drive, laser-plasma interaction

B-field can reduce electron thermal conduction and increase hot-spot alpha heating

Introduction

B-field reduces e- conduction ⊥ B: “magnetic insulation”



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

Strong B_z field [2] $q \sim -\frac{\kappa}{3}\nabla T$

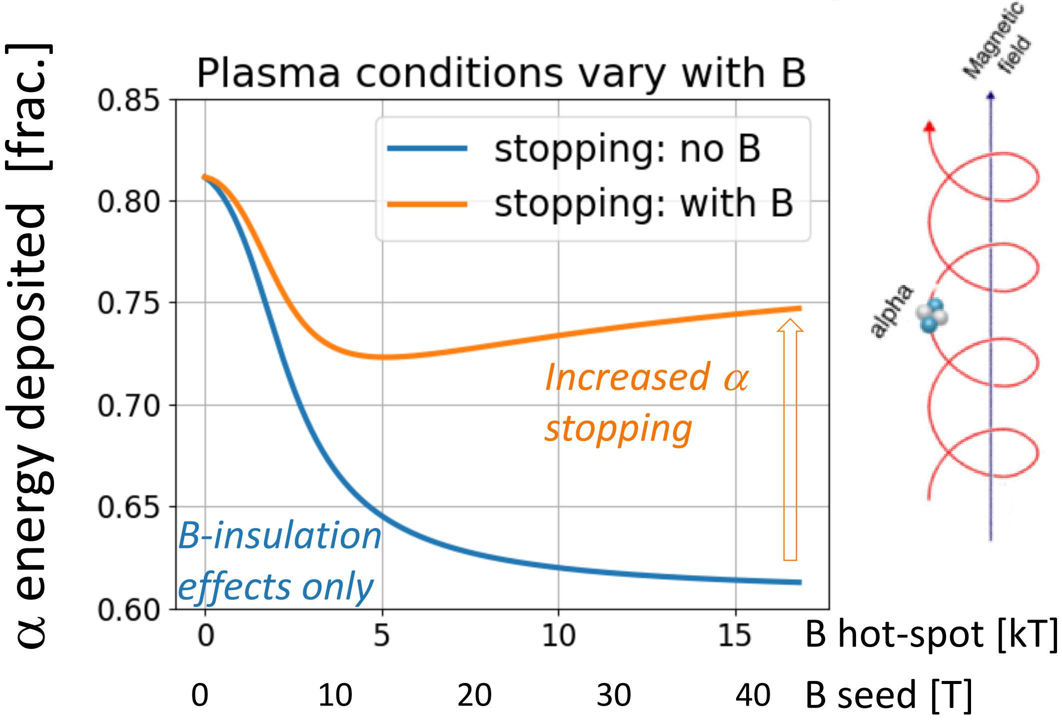
raises T, lowers ρR [1]

$$T(B) \approx 1.4\, T(B=0)$$

$$\rho R(B) \approx 0.7 \rho R(B=0)$$

B-field increases hotspot alpha heating [3]

Mostly compensates reduced ρR

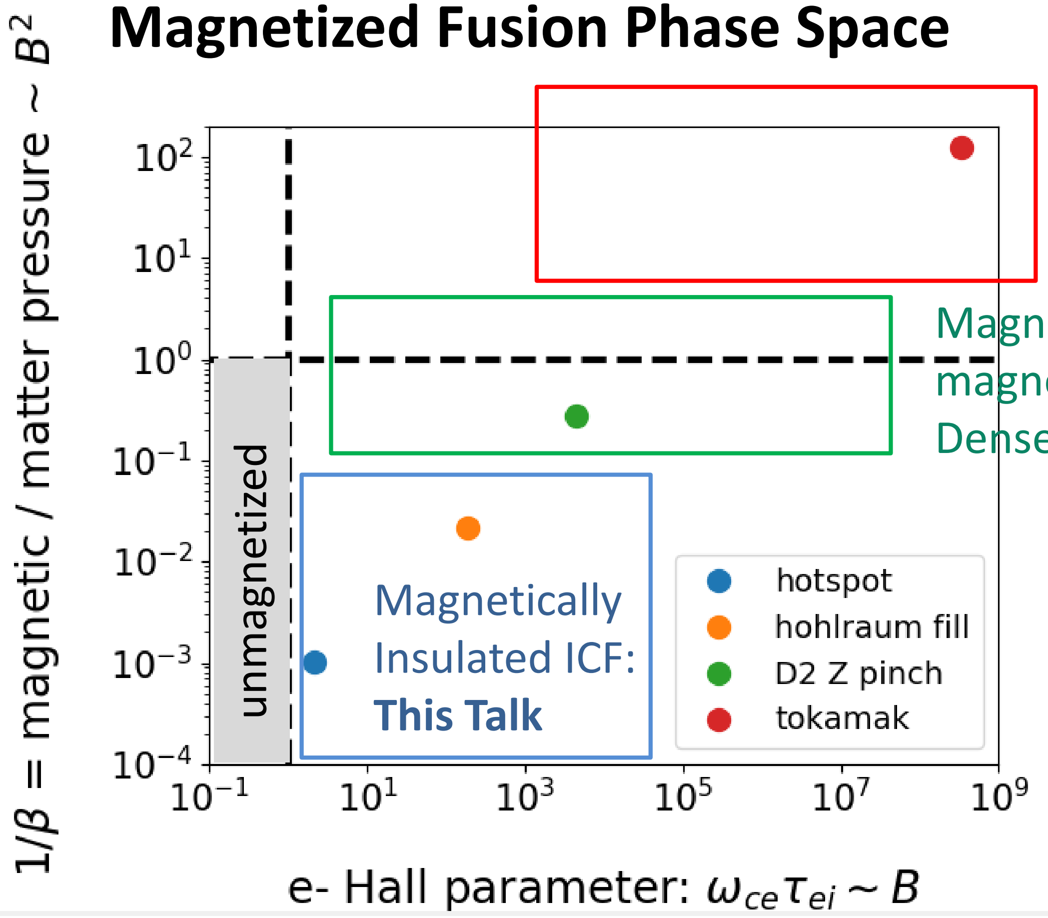


[1] O. A. Hurricane+, PPCF 2019; [2] D. Ho, APS 2016; [3] S. Yu. Gus’kov+, Sov. J. Quantum Electron. 1984

“Magnetically Insulated ICF (this project):” e- conduction reduced, magnetic pressure unimportant

Introduction

Magnetized Fusion Phase Space



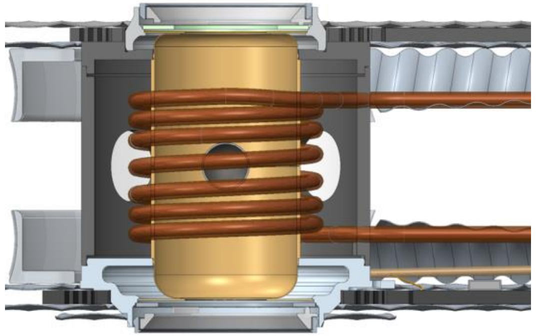
Magnetic >> matter pressure:
Classic MFE: tokamak, stellarator, …

Magneto-inertial fusion:
magnetic ~ matter pressure:
Dense plasma focus, Z-pinch, magLIF

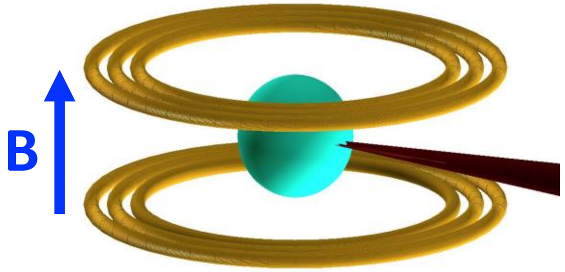
e- conduction suppressed: $\frac{\kappa_{\perp}}{\kappa_{||}} \sim \frac{1}{(\omega_{ce}\tau_{ei})^2}$ or $\frac{1}{(\omega_{ce}\tau_{ei})^1}$

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	100	10,000

Outline: Magnetized Ignition on NIF LDRD

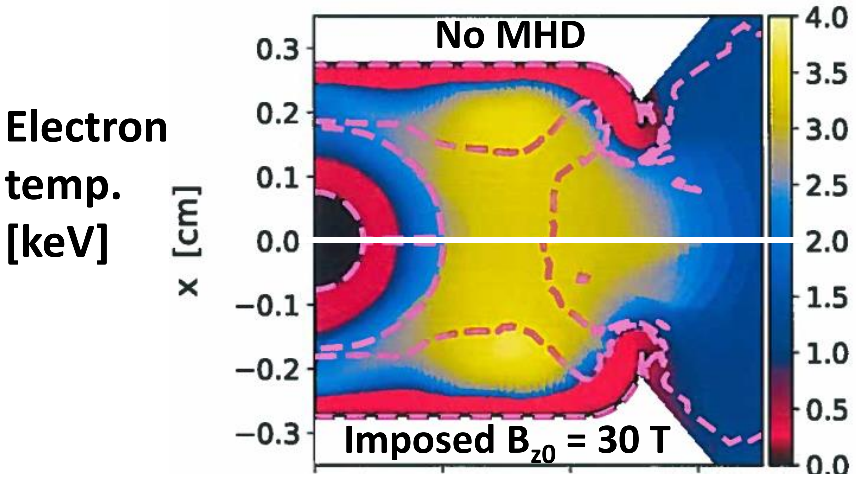


- **Project overview and goals**
    - Hohlraum + gas-filled capsule experiments: temperature + yield increase
    - Direct-drive “compression pusher” experiments: magnetic confinement of DD-produced 1 MeV tritons
        - Next talk, Hong Sio



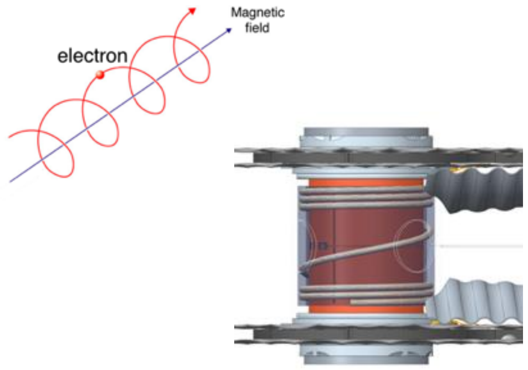
- **MHD modeling:** magnetized hohlraums + “BigFoot” gas capsule
    - Little effect of imposed field

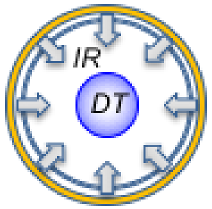
- **High-resistivity hohlraum** material for field soak-thru: Au+Ta alloys promising

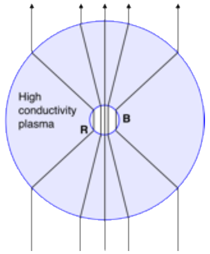


LDRD to demonstrate key elements for magnetized ignition on NIF

- **Lab-funded LDRD “Strategy Initiative” (SI): John Moody PI**
  - Started Oct. 2019
  - $2M/year for 3 years
  - Experimentalists, target designers, target fab, cryo team, NIF engineers
- **Magnetized room-temperature gas-filled capsule on NIF:**
  - Hot-spot temperature increase with B-field
- **Get B-field into hohlraum and capsule**
  - High resistivity hohlraums
- **Magnetized cryo layered targets**
  - Cryo field generator: limited target positioner “real estate”
  - Ice layering method: thermal control, acceptable preheat
- **Experimental platform for magnetized HED / high field science**

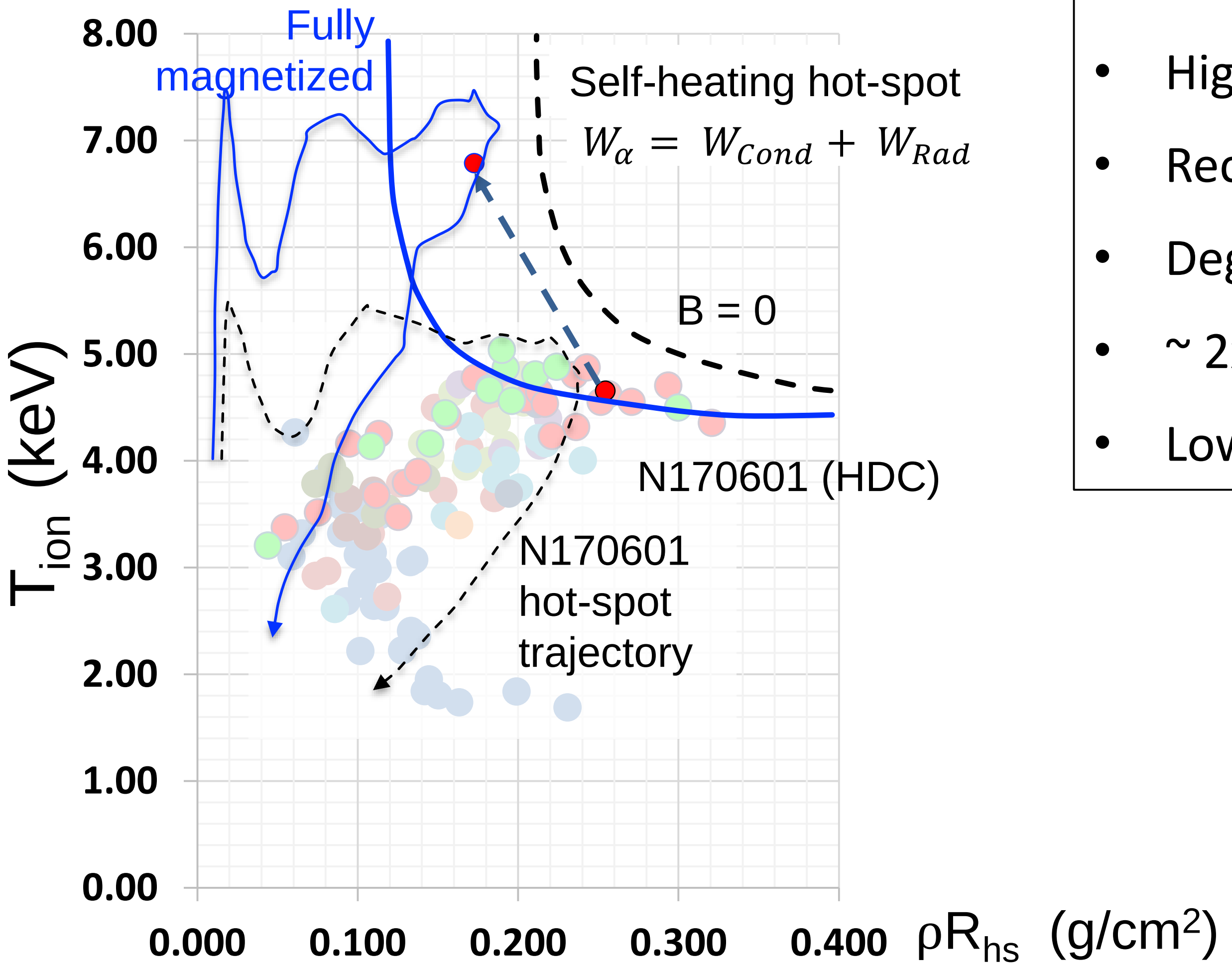






B-field can move current NIF hotspots into ideal self-heating regime; 2x yield realistic

NIF Data: 2010-2018 [1]



Lasnex 2D MHD Simulations of N170601 [D. Ho]

- High design adiabat ~ 3.0
- Record yield at the time
- Degraded by preheat to match measured yield
- ~ 2x yield with imposed B-field
- Lower design adiabat ~ 2.0 could give ~> 5x yield [2]

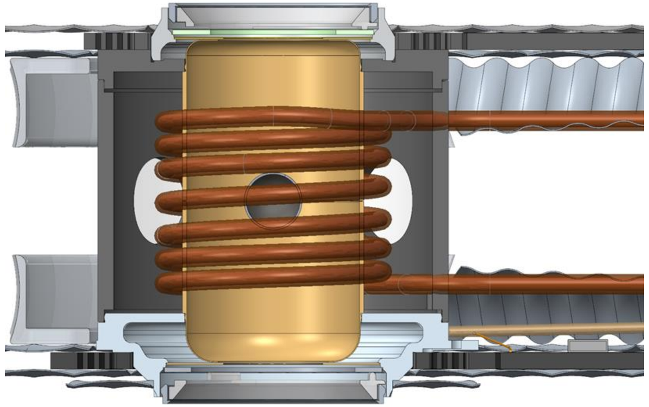
[1] O. A. Hurricane+, PPCF 2019

[2] L. J. Perkins+, Phys. Plasmas 2017

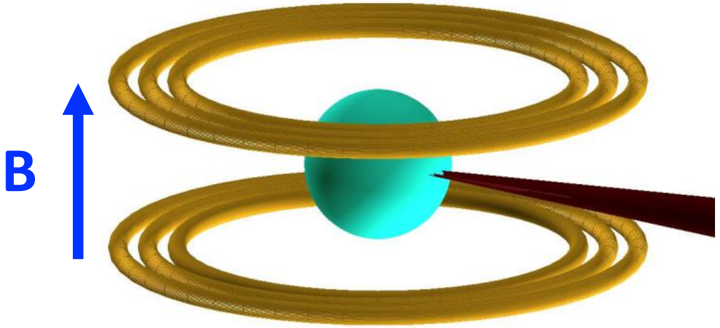
We are planning room-temperature, “subscale” (E_{laser} ~ 1 MJ) hohlraum expt’s, evaluating direct-drive

B_{z0} = 30 T

Magnetized hohlraum



Magnetized direct-drive :
Hong Sio, next talk



Starting NIF Platform /shot	**“BigFoot” symcap / N161204**	**“compression pusher” / N190227**
Laser pulse	3 shocks, adiabat ~ 4	Shock + compression yield
Capsule	HDC, 844 um, D_2 @ 3-5 mg/cc	CH, 2000 um, D_9 + $3He_1$ @ 1.3 mg/cc
Convergence ratio: R_{init}/R_{fin}	15-20	~8
Main B-field effect	hotspot T_{ion} up 1.5 keV DD yield up 90%	Magnetically confine 1 MeV T’s from DD rxn DD yield up 50%

- Project overview and goals
  - Hohlraum + gas-filled capsule experiments: temperature + yield increase
  - Direct-drive “compression pusher” experiments: magnetic confinement of DD-produced 1 MeV tritons

→
- MHD modeling for magnetized hohlraums with “BigFoot” gas-filled capsule
  - Little effect of imposed field

- High-resistivity hohlraum material for field soak-thru: Au+Ta alloys promising

"BigFoot"[1] NIF shot N161204: subscale gas-filled capsule

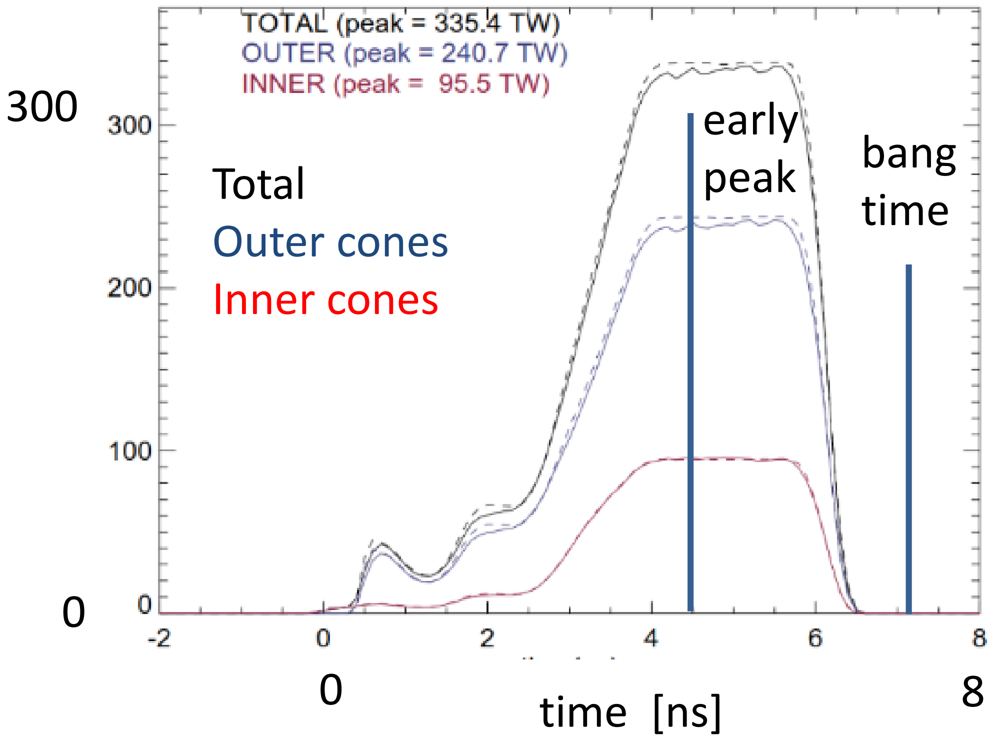
Why BigFoot?
- Don't re-invent wheel: use existing high-yield cryo platform
- Nice features: predictable, tunable, low LPI
- "Goldilocks convergence":
  - Enough to amplify B field, reduce hotspot e- conduction
  - Not so much for significant hydro instabilities or mix

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
  - Symcap: no DT ice layer

- Low backscatter
  - 1.2% of laser energy

Laser power [TW]



[1] C. Thomas, APS-DPP invited talk, 2016; K. Baker+, PRL 2018

HYDRA MHD Model: Full Single-Fluid Braginskii Implemented

Bulk momentum

$$\rho\left(\partial_t + \vec{V}\cdot\nabla\right)\vec{V} = -\nabla p + \vec{J}\times\vec{B}$$

Magnetic force: pressure + tension

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

Maxwell

$$\partial_t\vec{B} = -\nabla\times\vec{E}$$

$$\vec{J} = \mu_0^{-1}\nabla\times\vec{B} - \cancelto{0}{\epsilon_0\partial_t\vec{E}}$$

Generalized Ohm's law:
$dv_e/dt = 0$

$$\vec{E} = \underbrace{\underbrace{-\vec{v}\times\vec{B}}_{\text{advection / induction term}} + \underbrace{\frac{1}{n_e e}\vec{J}\times\vec{B}}_{\text{Hall term}} - \underbrace{\frac{\nabla p_e}{n_e e}}_{\text{Biermann battery}}}_{\text{collisionless}} \underbrace{+ \underbrace{\overleftrightarrow{\eta}\cdot\vec{J}}_{\text{resistivity}} - \underbrace{e^{-1}\overleftrightarrow{\beta}\cdot\nabla T_e}_{\text{thermal force e.g. Nernst}}}_{\text{collisional}}$$

Joe Koning,
talk this morning

Electron heat equation

$$C_V\left(\partial_t + \vec{v}_e\cdot\nabla\right)T_e = \xi_{ei}\left(T_i - T_e\right) - \nabla\cdot\vec{q}_e + W_e - p_e\nabla\cdot\vec{v}_e + \cdots$$

$$\vec{q}_e = -e^{-1}T_e\overleftrightarrow{\beta}\cdot\vec{J} - \overleftrightarrow{\kappa}\cdot\nabla T_e$$ heat flux

$$W_e = \vec{J}\cdot\overleftrightarrow{\eta}\cdot\vec{J} - e^{-1}\vec{J}\cdot\overleftrightarrow{\beta}\cdot\nabla T_e$$ frictional heating

Simplifications in this work:
due to numerical issues

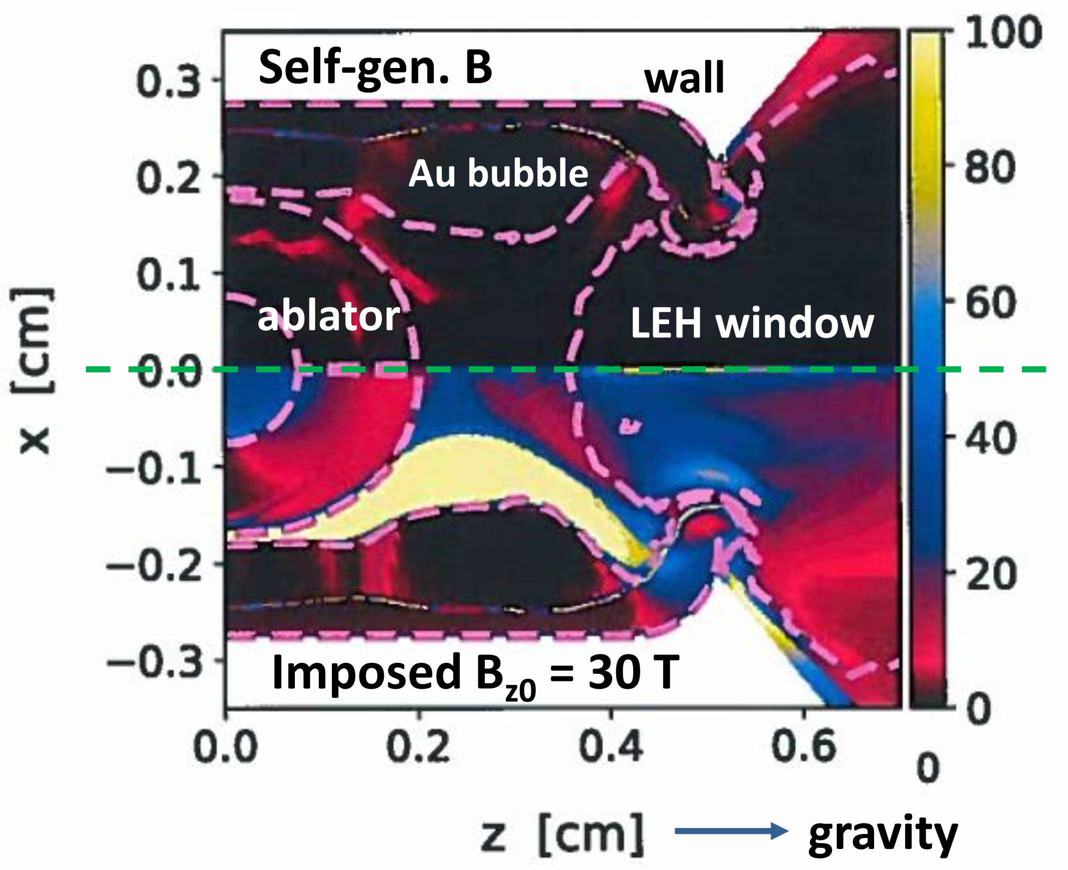
- No Seebeck physics: $\beta_{||} = \beta_{\perp} = 0$
- Scalar resistivity η
- No Hall term in Ohm's law
- No Righi-Leduc heat flow: $\kappa_{\wedge} = 0$

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

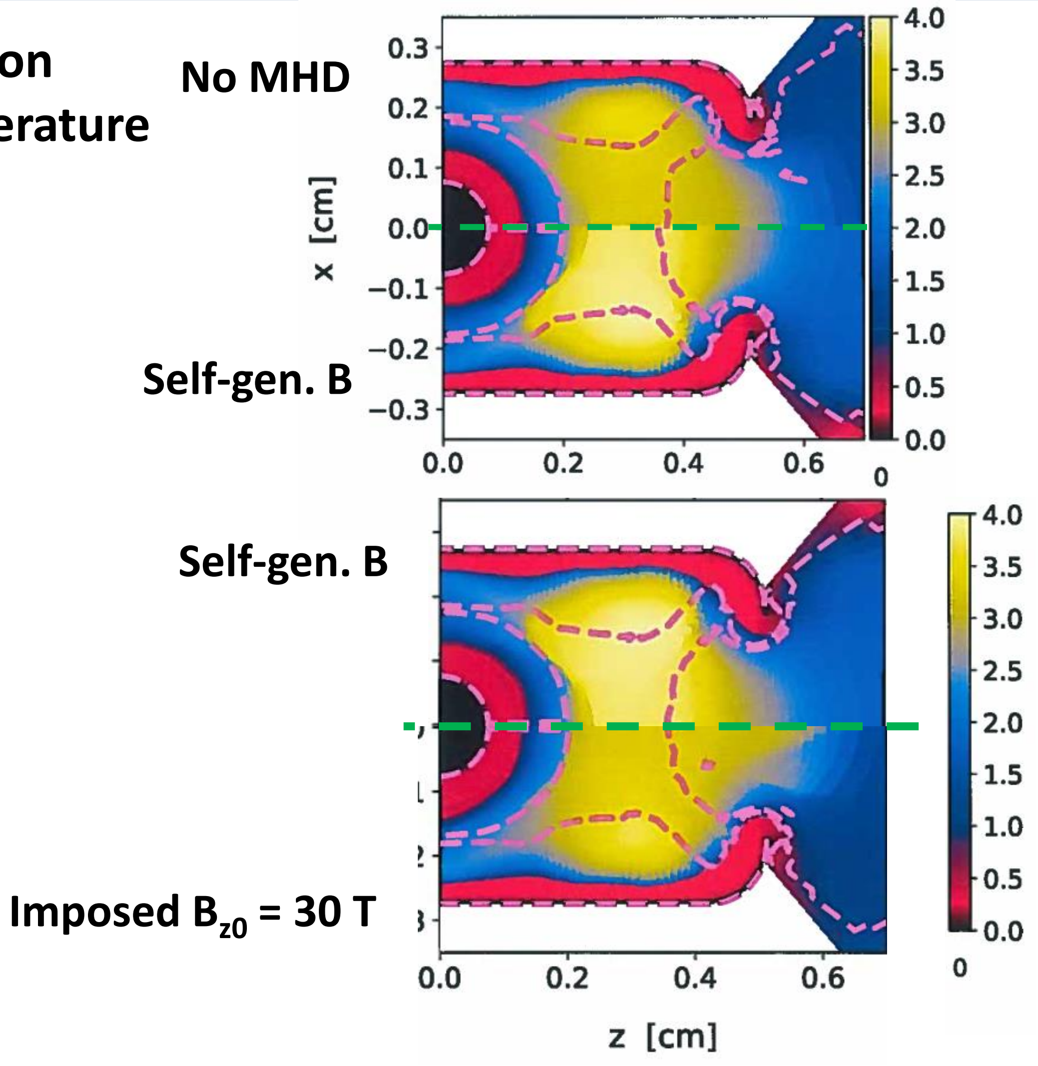
BigFoot Symcap

4.5 ns: early peak power

| Magnetic field | [T]



Electron temperature [keV]

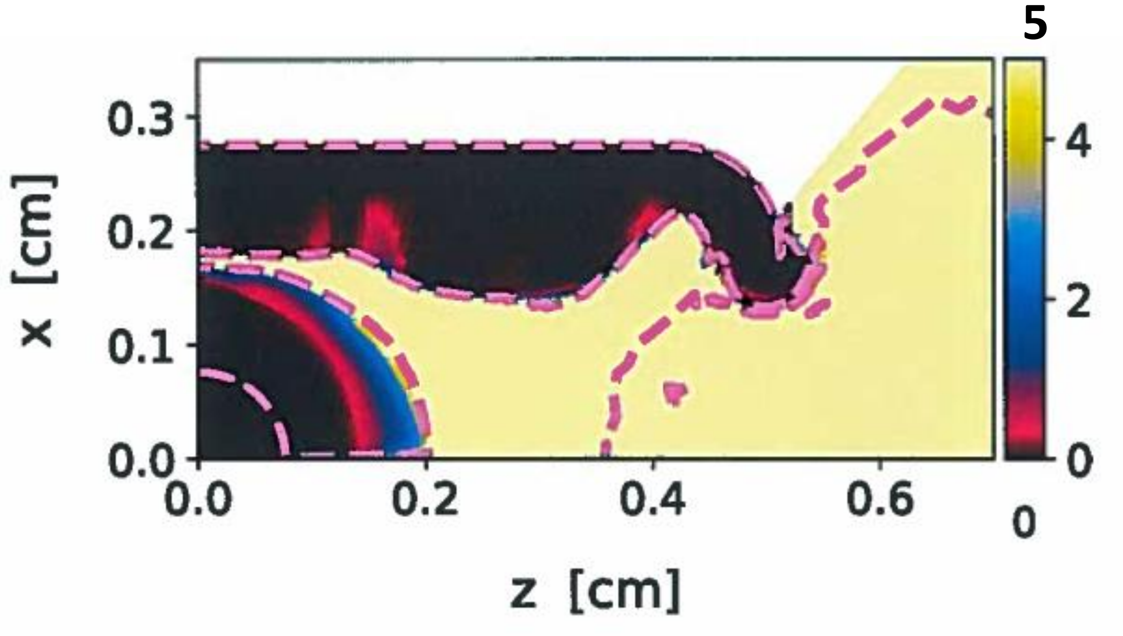


Hohlraum dynamics with imposed B_{z0} = 30 T: e- Hall parameter large in fill, magnetic pressure unimportant

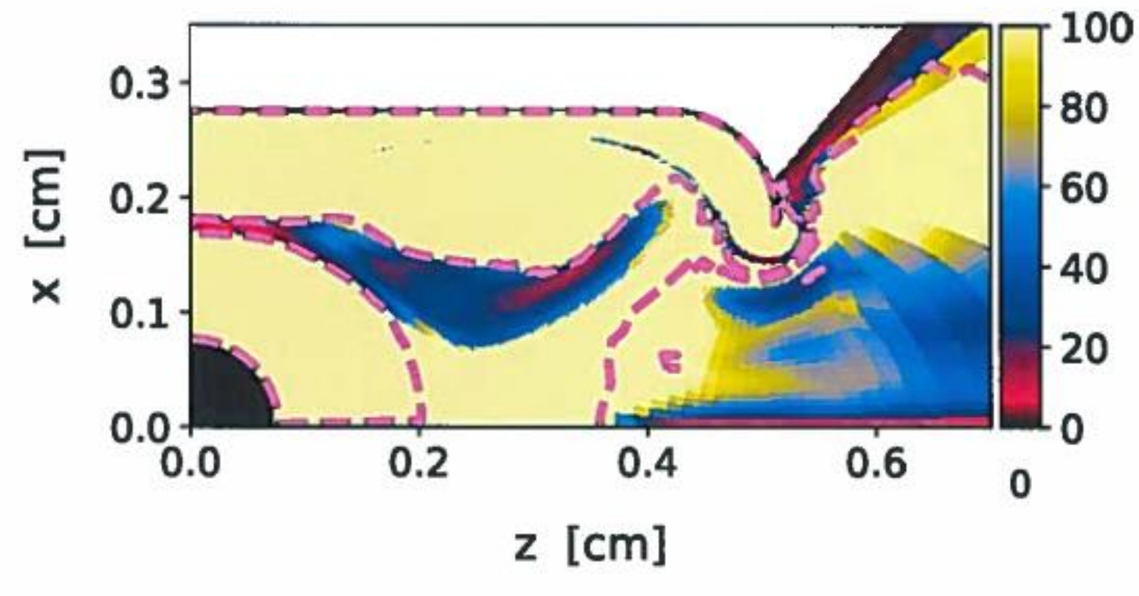
4.5 ns: early peak power

BigFoot Symcap

e- Hall parameter: $\omega_{ce}\tau_{ei}$



beta: plasma / magnetic pressure

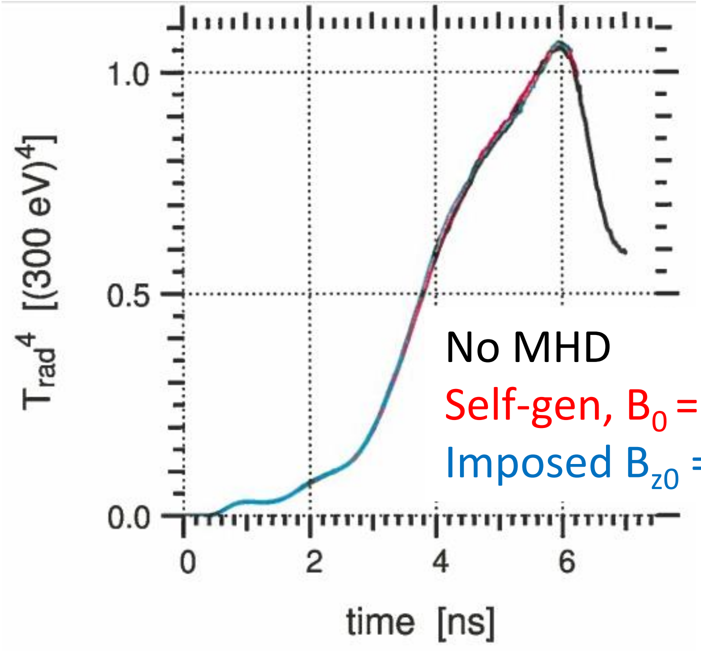


Prior work on MHD in hohlraums

- D. Strozzi+, JPP 2015 – imposed B_z in high-gas-fill hohlraum
- W. Farmer+, PoP 2017 – self-generated B

X-ray flux on capsule: small effect of B fields on drive

Drive: total x-ray flux

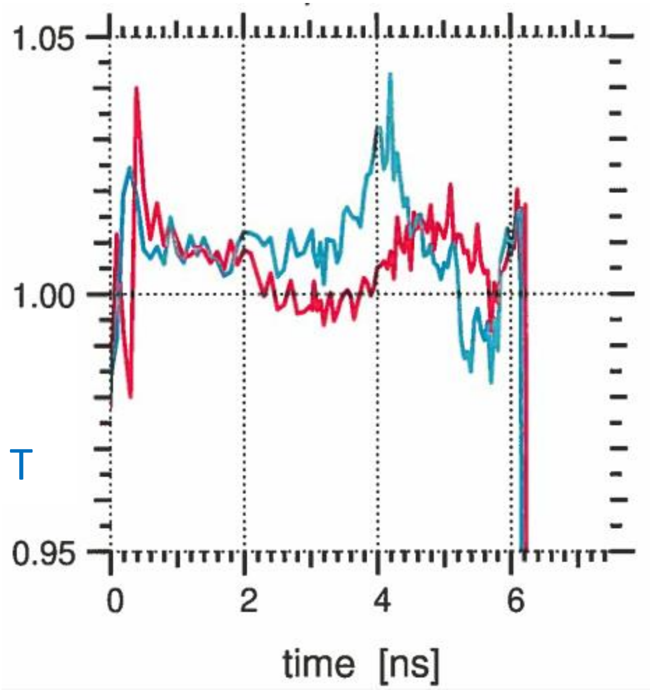


No MHD

Self-gen, $B_0 = 0$

Imposed B_{z0} = 30 T

Flux ratio to no-MHD run



Yes, there are 3 curves

- Project overview and goals
    - Hohlraum + gas-filled capsule experiments: temperature + yield increase
    - Direct-drive “compression pusher” experiments: magnetic confinement of DD-produced 1 MeV tritons

- MHD modeling for magnetized hohlraums with “BigFoot” gas-filled capsule
    - Little effect of imposed field

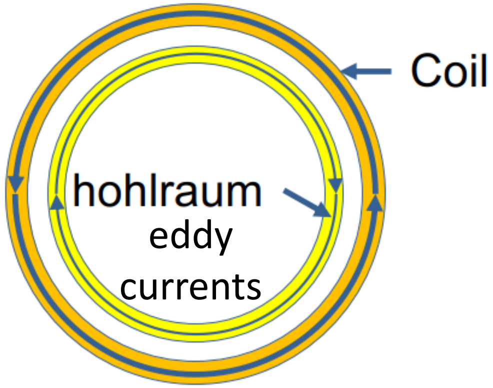
- **High-resistivity hohlraum** material for field soak-thru: Au+Ta alloys promising

Hohlraum material must meet field soak-thru and x-ray drive constraints

soak-thru: want high resistivity ρ

Want high Z

Constraint	Requirement	Notes
$\vec{J} \times \vec{B}$ wall motion	< 50 μm	Beam pointing, symmetry, backscatter
Wall Joule heating	< 2000 K gas capsule < 700 K (est.) DT layer	Limit $\Delta T_{ablator}$ Limit ΔT_{ice}
Field soak-thru time	~0.1's μs	Not issue for our ~ 2 μs current pulses
X-ray flux	>= 95% of pure Au	Retain yield increase



Target fab hohlraum team:
S. O. Kucheyev, A. Engwall, L.B. Bayu Aji, J. Bae, S. Shin, A. Baker, and S. McCall.

Au_xTa_{1-x} alloys may be resistive enough for cryo layered shots; $Au_xTa_yO_z$ far exceed minimum

$\rho \ [\mu\Omega \cdot cm]$

10^{10} Ta_2O_5 ceramic insulator: too big x-ray hit

…

5000 $Au_{35}Ta_{30}O_{35}$

>1000 $Ta_{>1}O_1$

$Au_xTa_yO_z$ sputter deposition

280 Au_2Ta_8 Max for Au_xTa_{1-x}

Au+Ta alloys

100 min. for cryo layer: ΔT_{ice}

60 min. for gas capsule: 50 μm wall motion

60 DU from Tfab (2x book value)

13 Ta

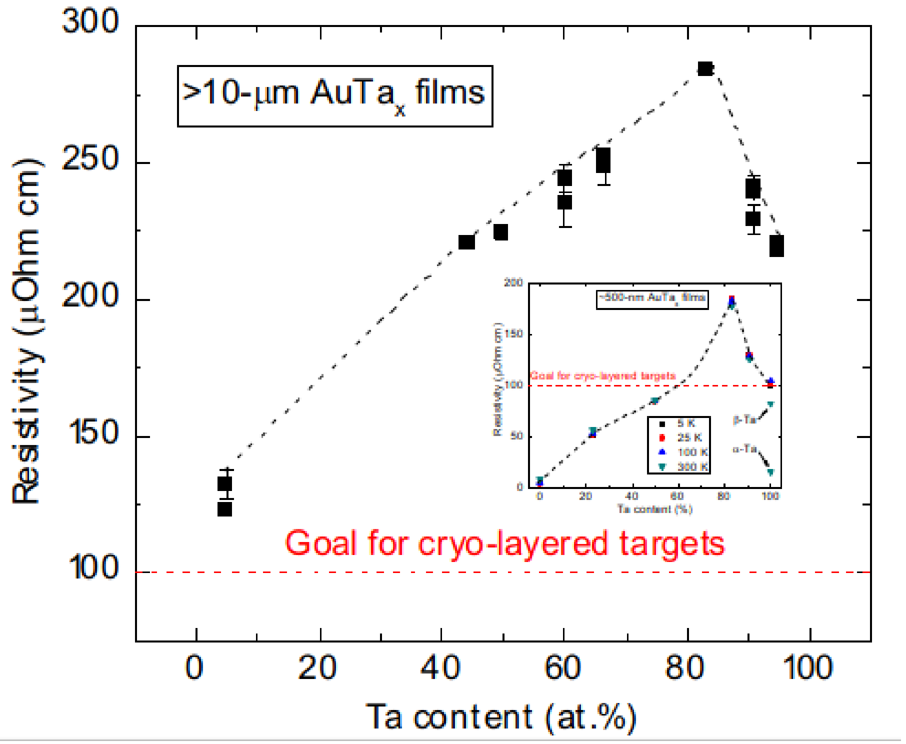
2.2 Au

Pure metals @ 273 K

…

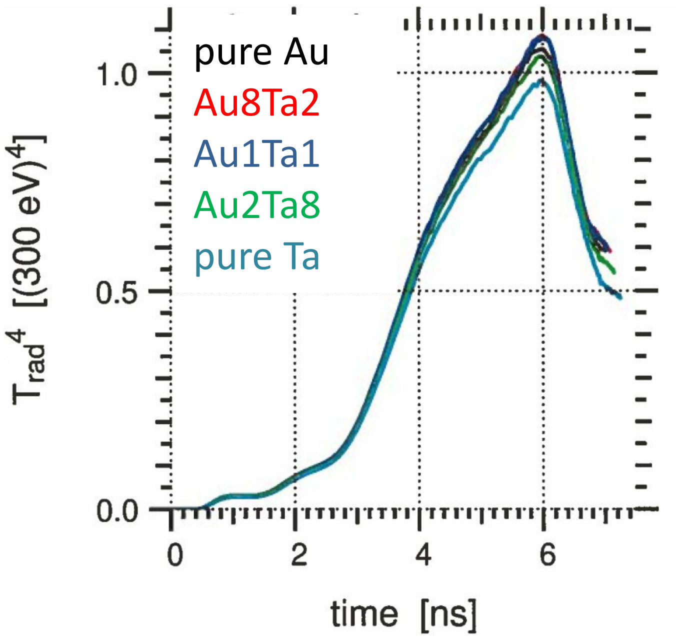
<< 1: Pure {Ta, Au, DU} @ 20 K

AuTa alloy resistivity exceeds cryo goal, peaks for Au2Ta8



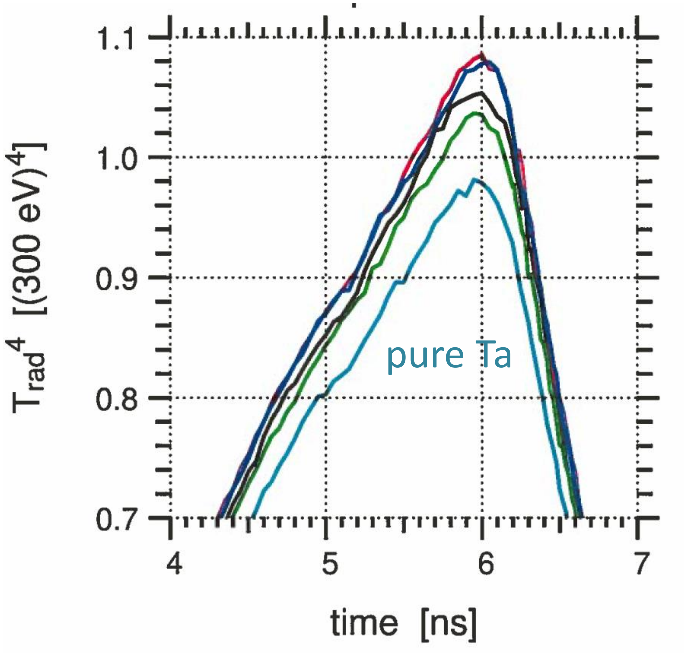
Au+Ta alloys: more resistive than Au, small effect on x-ray drive

x-ray flux on capsule

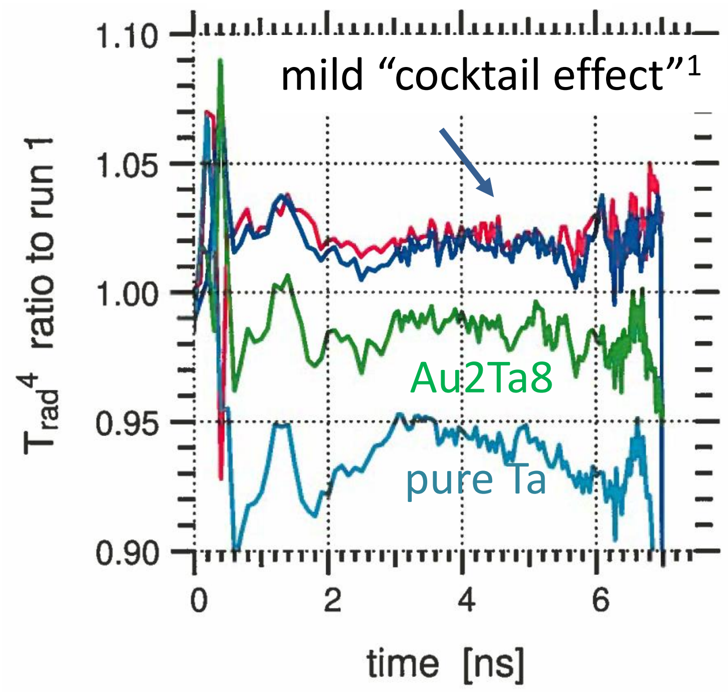


Same atom density as pure Au

Zoom on peak



Ratio to pure Au

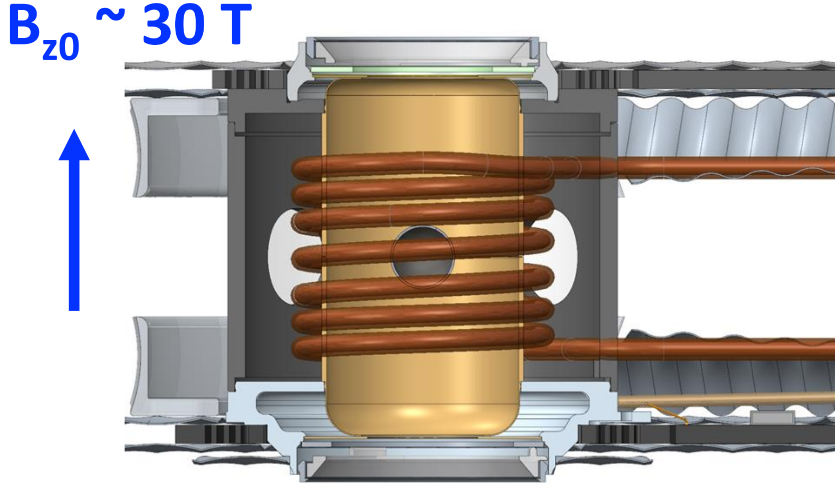


- Ta_2O_5: unacceptable x-ray flux: 15-20% lower than pure Au
- $Au_xTa_yO_z$ may be OK

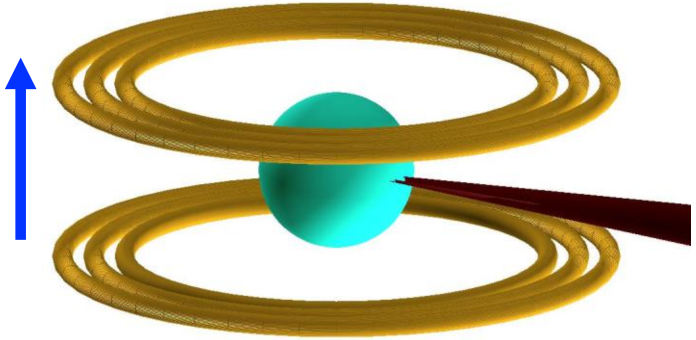
[1] O. Jones, J. Schein, M. D. Rosen +, PoP 2007

Summary: Magnetically-assisted indirect drive could be one path to ignition

Indirect drive: gas-filled capsules



Direct drive: Next talk: Hong Sio



- LDRD project develops the science and addresses the challenges to test B-field effects on a high performing implosion
- First NIF experiments planned for fall 2020
  - Room-temperature: no cryo field generator
  - Hohlraum + gas-filled capsule
  - May include direct-drive capsule

BACKUP

Imposed B field moves DT implosions closer to ignition

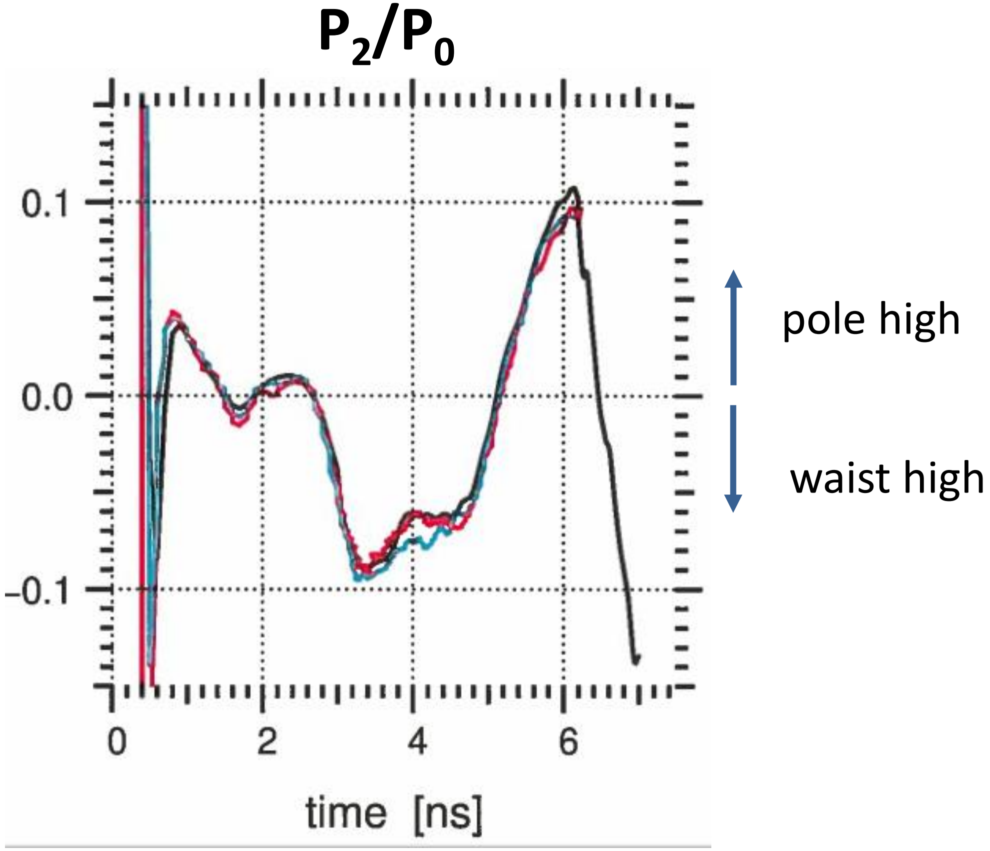
Hotspot of best NIF DT performer (BigFoot shot N180128):

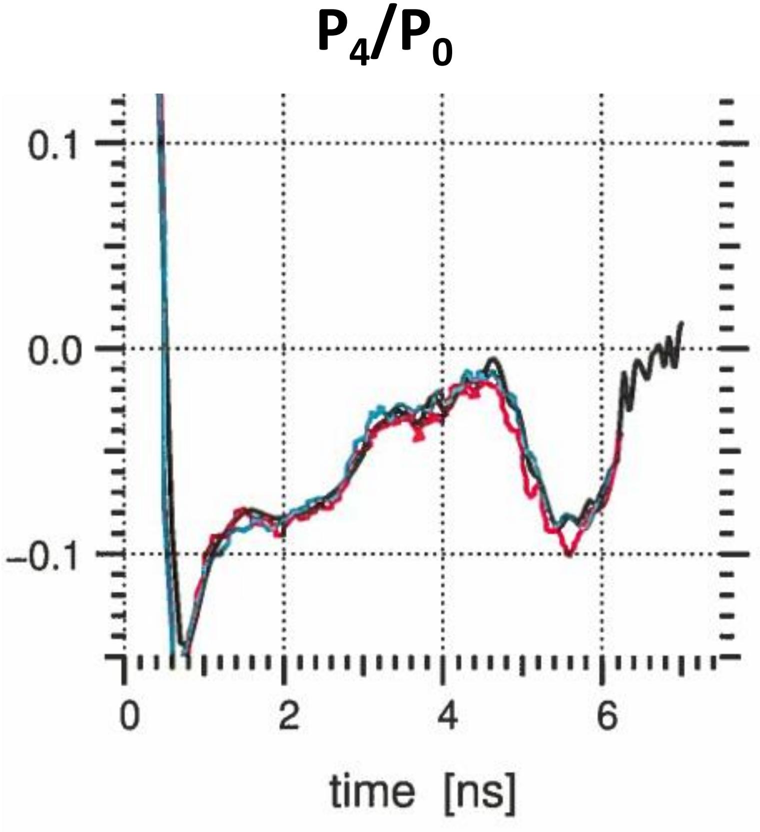
Hotspot quantity	No B value	Strong B value	Comment
T_{ion} [keV]	4.9	7.1	First > 5 keV hotspot
ρ [g/cm^3]	74	52	
R [um]	31	Same	
ρR [g/cm^2]	0.23	0.16	
CR	22	Same	DT convergence ratio: initial / final DT-ablator interface
α energy dep. in HS	0.82	0.85	B effect on α's over-compensates ρR reduction

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	

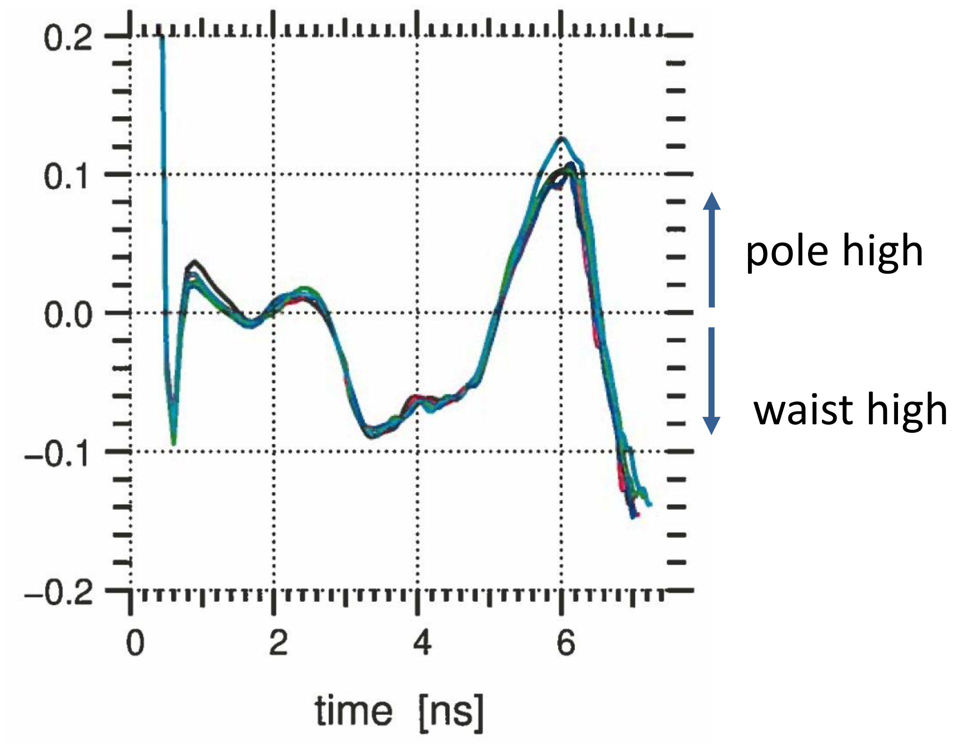
B field has small effect on x-ray flux asymmetry on capsule





x-ray flux asymmetries on capsule: small effect from wall material

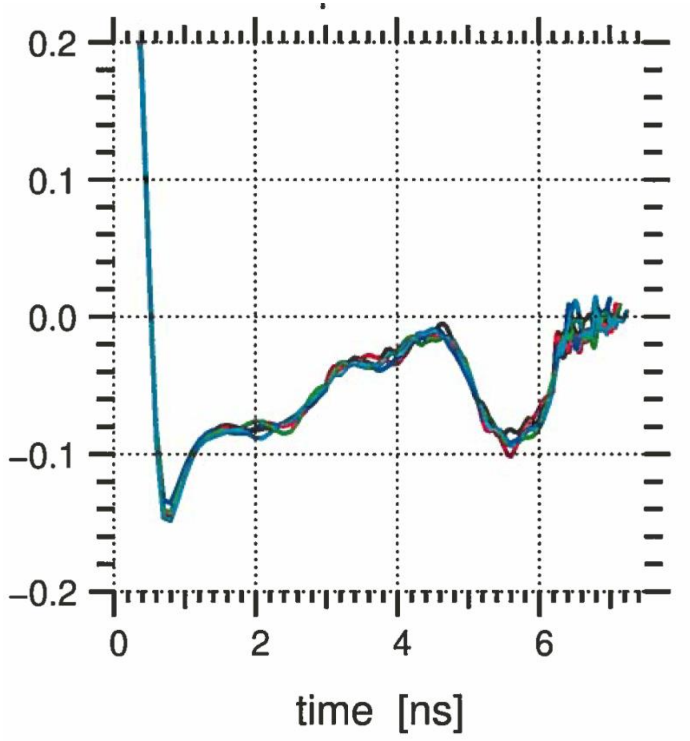
P_2/P_0



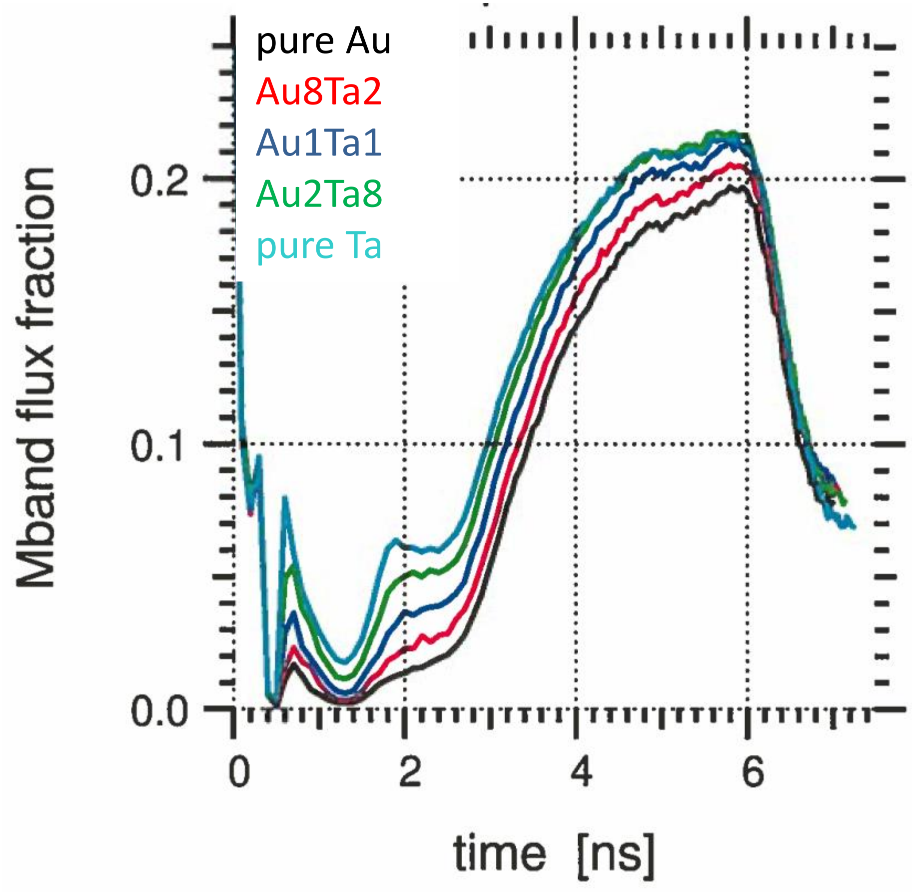
pole high

waist high

P_4/P_0



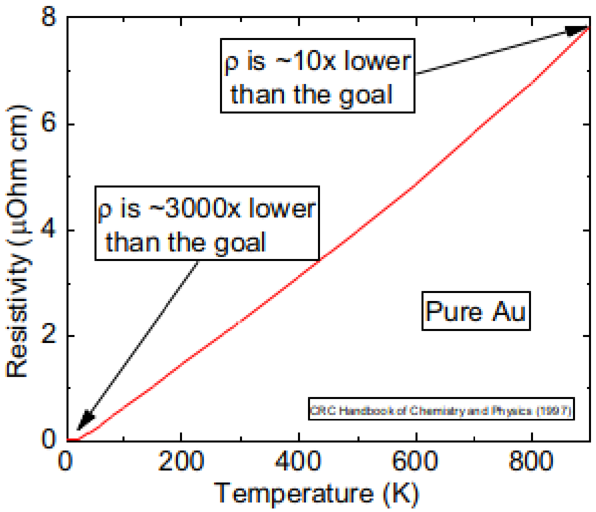
M-band fraction increases w/ Tantalum fraction



Resistivity 101: defects needed for high enough value at cryo conditions; alloys can provide

Matthiessen rule:

$$\rho(T) = \rho_{defect} + \rho_{phonon}(T)$$



ρ is ~10x lower than the goal

ρ is ~3000x lower than the goal

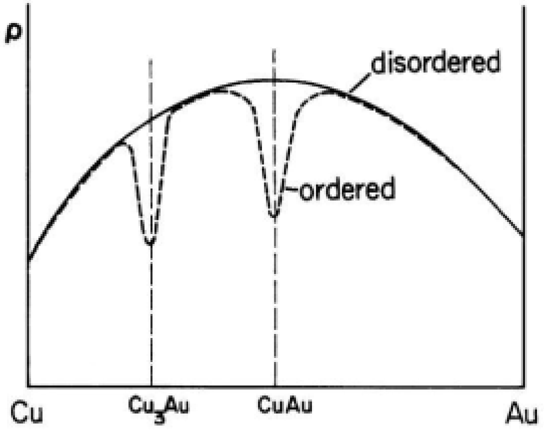
Pure Au

CRC Handbook of Chemistry and Physics (1997)

Gold is an excellent conductor in the entire temperature range

Nordheim rule:

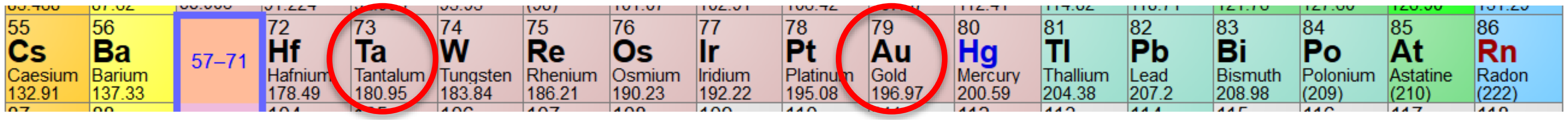
$$\rho_{defect} = x(1 - x)$$



Resistivity depends on microstructure and defects

Norbury-Linde rule: $\rho_{defect} = A + B(\Delta Z)^2$

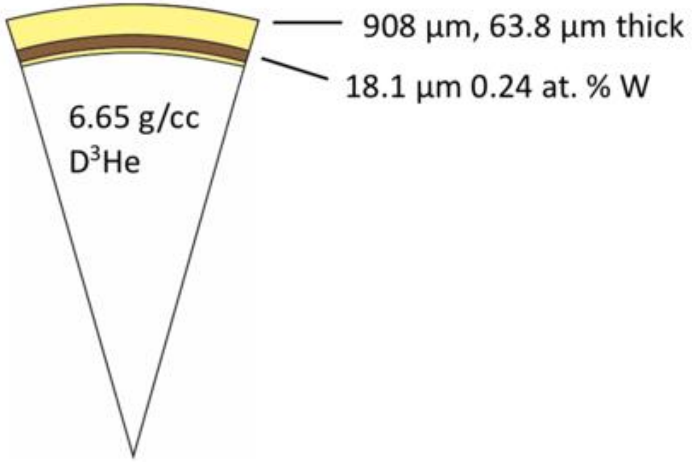
Ta: ΔZ = -6 from Au



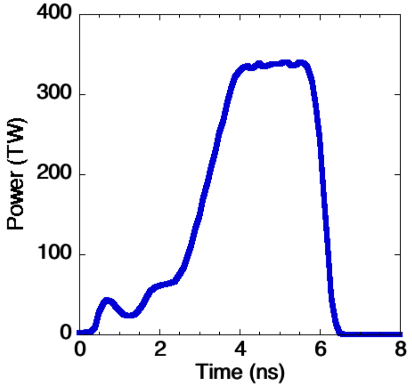
55 **Cs** Caesium 132.91	56 **Ba** Barium 137.33	57–71	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.95	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.21	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.22	78 **Pt** Platinum 195.08	79 **Au** Gold 196.97	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.38	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)

Experiment

A warm NIF magnetized experiment will test the improvements expected in an implosion



Laser: 1.1 MJ, 340 TW



NIF shot N161204

D3He filled symcap at 6.65 mg/cc

Planned shot

Room temperature capsule at 3 - 6 mg/cc of D2 + 0.01% Kr

No B | No B | With B_{z0} = 30 T

Observable	**N161204**	**Hydra / Lasnex**	**Magnetized - prediction**
Yn	9.1e11	8.9e11	17e11
Ti (keV)	3.09	3.45	5.1
Bang-time	7.22	6.96 – 7.16	6.96 – 7.16

Significant challenges are being addressed to get a high B and high performing target

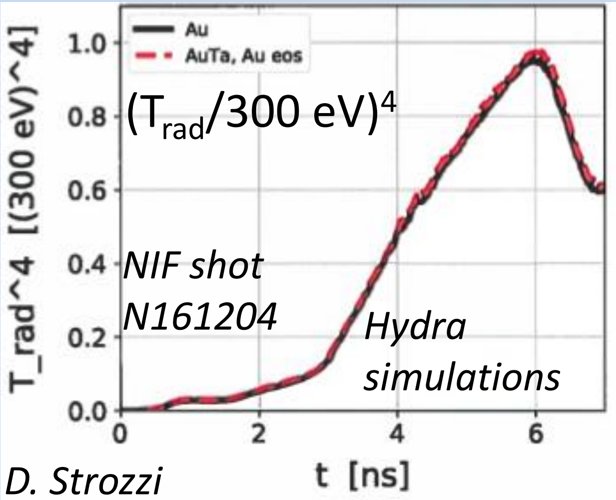
Energizing a B-field coil

E. Carroll

Hohlraum eddy currents due to applied B:

1. Reduce capsule B
2. Heat the hohlraum walls
3. Compress the hohlraum

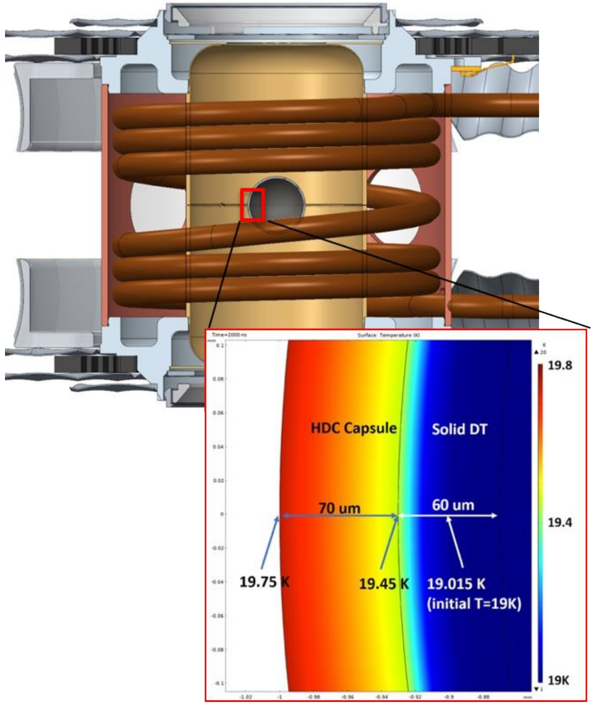
Au and Au-Ta: similar drive



D. Strozzi

Au-Ta alloy has ~ 50-100x higher resistivity than Au

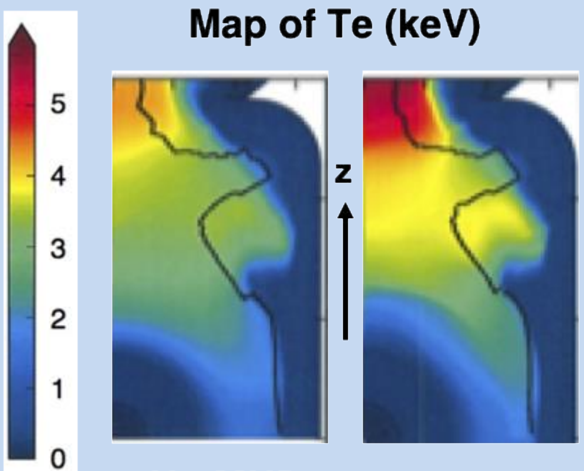
We plan to quantify the rapid ice heating



NIF now has a working pulser – see B. Pollock in this session

B-fields in implosions enables new/novel HED and high field science on NIF

Magnetized HED science



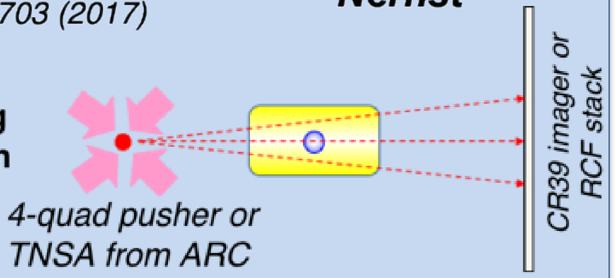
Map of Te (keV)

No MHD

W. A. Farmer, etal, PoP 24,052703 (2017)

MHD with Nernst

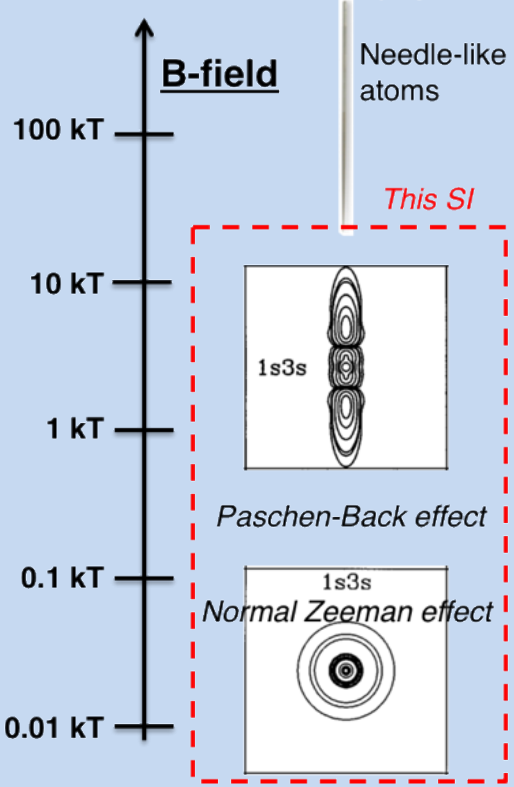
Sensing B fields using laser-driven proton deflection



Tests MHD models in major codes

Ultra-high B-field science

Enables new atomic physics regimes



Laboratory tests of ultra-high field science

Self-generated and imposed magnetic fields: simulated to have minor effect on NIF-scale hohlraums

- **HYDRA MHD model:**
    - Full single-fluid Braginskii equations implemented
    - Partial set used here for numerical reasons

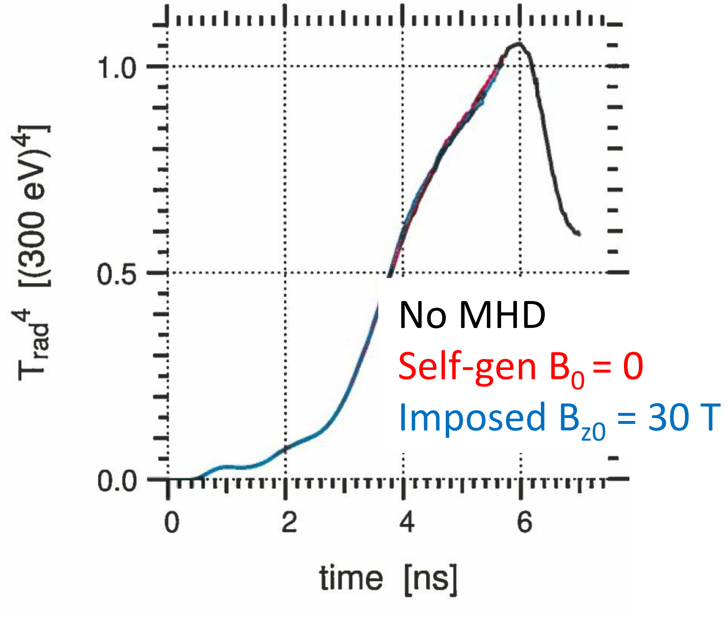
- **BigFoot subscale symcap:** starting point for magnetized design

- **Hohlraum dynamics:**
    - B field follows frozen-in law
    - e- Hall parameter >> 1 in fill: magnetized e- heat flow
    - Plasma pressure >> magnetic: beta >> 1
    - Temperature change: small with B field

- **X-ray flux:** small effect of B field on total drive and asymmetry

- **Wall material:**
    - High resistivity Au+Ta alloy for field soak-thru
    - X-ray drive slightly ***higher*** for Au1Ta1: “cocktail effect[1]”

Total x-ray flux



[1] O. Jones, J. Schein, M. D. Rosen +, PoP 2007

BigFoot[1] platform: starting point for 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

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

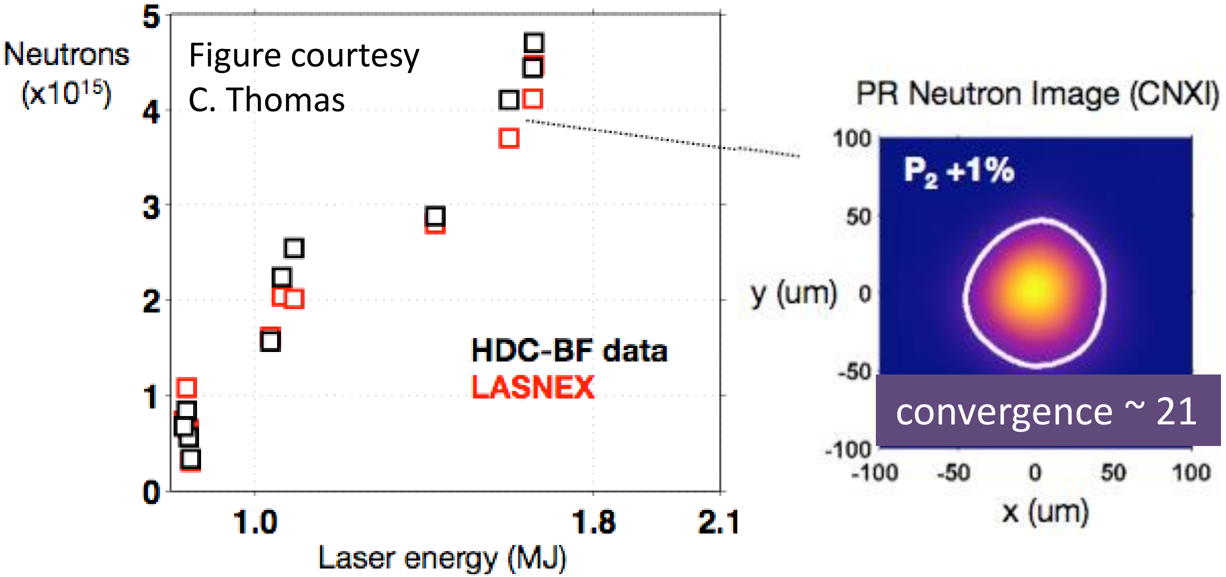
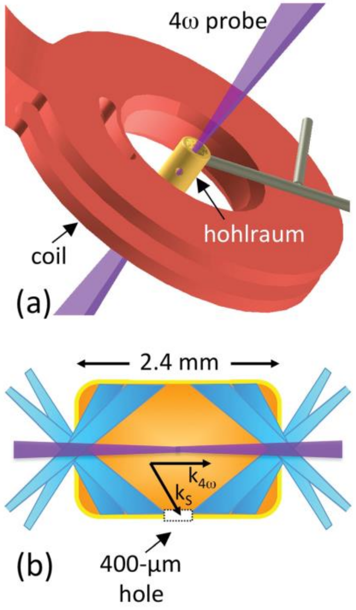


Figure courtesy
C. Thomas

convergence ~ 21

Higher T_e seen in magnetized hohlraum experiments on Omega: Montgomery et al., 2015



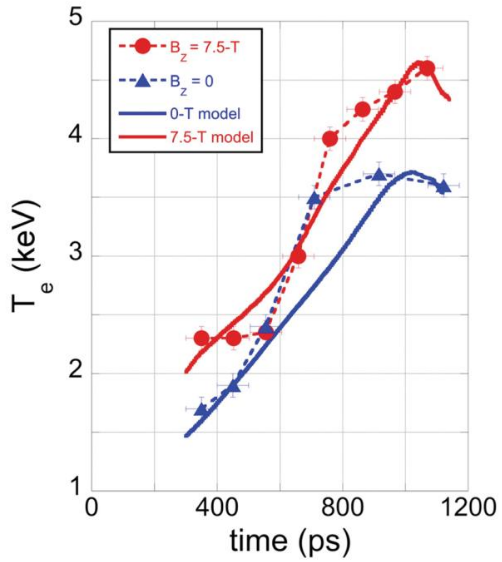


FIG. 3. Measured electron temperature versus time for B = 0 (blue triangles) and B = 7.5-T (red circles). Over-plotted as solid lines are the 2-D HYDRA model for B = 0 (blue) and B = 7.5-T (red).

Comparison with Montgomery+ PoP 2015

- Omega+MIFEDS hohlraum expt’s
  - B_{z0} = 7.5 T, gas-filled, no capsule
- NIF hohlraums: much different scale:
  - Larger, 50x laser energy, 6-7x longer pulse
  - More time to reach quasi-equilibrium

Magnetized hohlraums: path forward

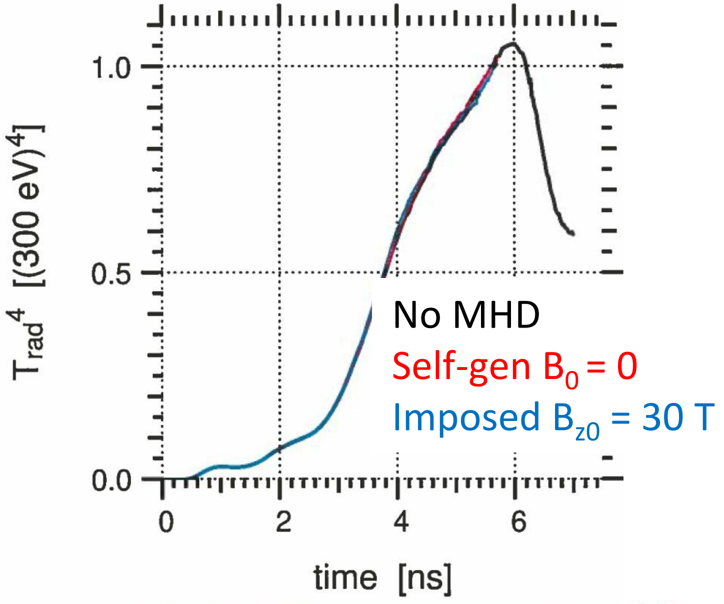
Summary

- BigFoot subscale symcap: starting point for magnetized design
- Hohlraum dynamics:
    - B field follows frozen-in law
    - e- Hall parameter >> 1 in fill: magnetized e- heat flow
    - Plasma pressure >> magnetic: beta >> 1
    - Temperature change: small with B field
- X-ray flux: small effect of B field on total drive and asymmetry
- Wall material:
    - High resistivity Au+Ta alloy for field soak-thru
    - X-ray drive slightly ***higher*** for Au1Ta1: “cocktail effect”

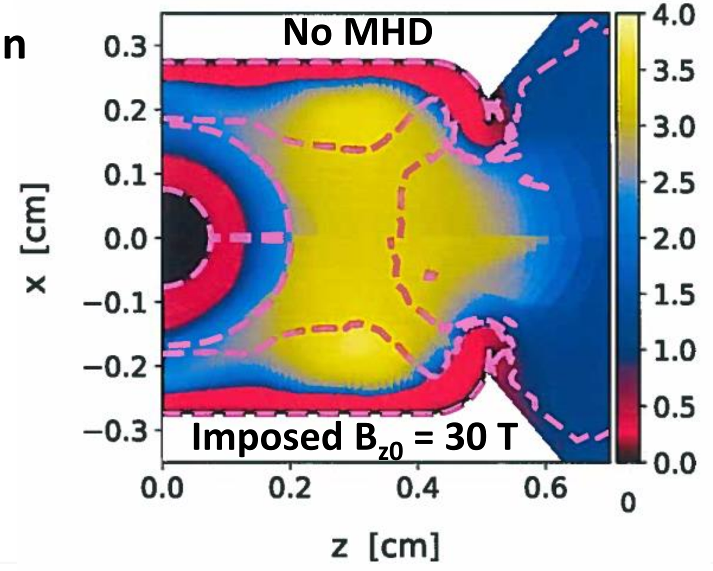
Future Work

- Room-temperature magnetized design for FY20 NIF shots
    - C5H12 hohlraum fill gas
    - High-resistivity wall
- Include full Braginskii MHD
- Nonlocality in e- transport and MHD

Total x-ray flux



Electron temp. [keV]

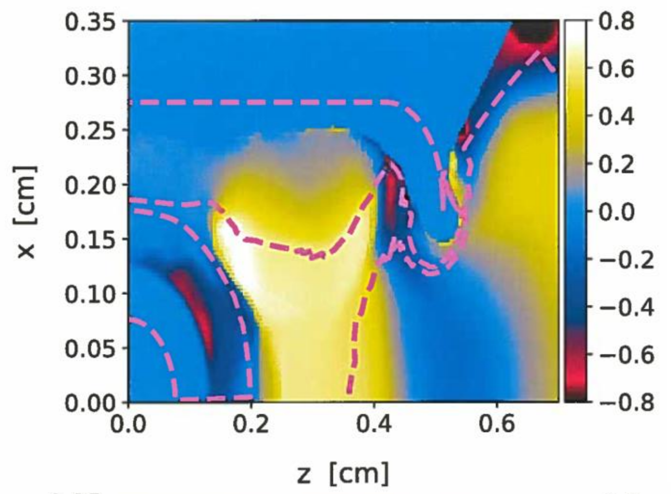


Hohlraum dynamics:
small temperature change from imposed 30 T B_z field

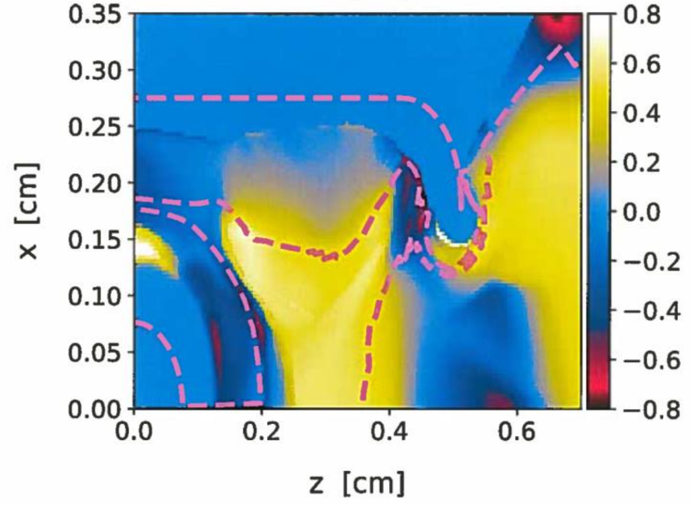
T_e difference [keV]

BigFoot Symcap

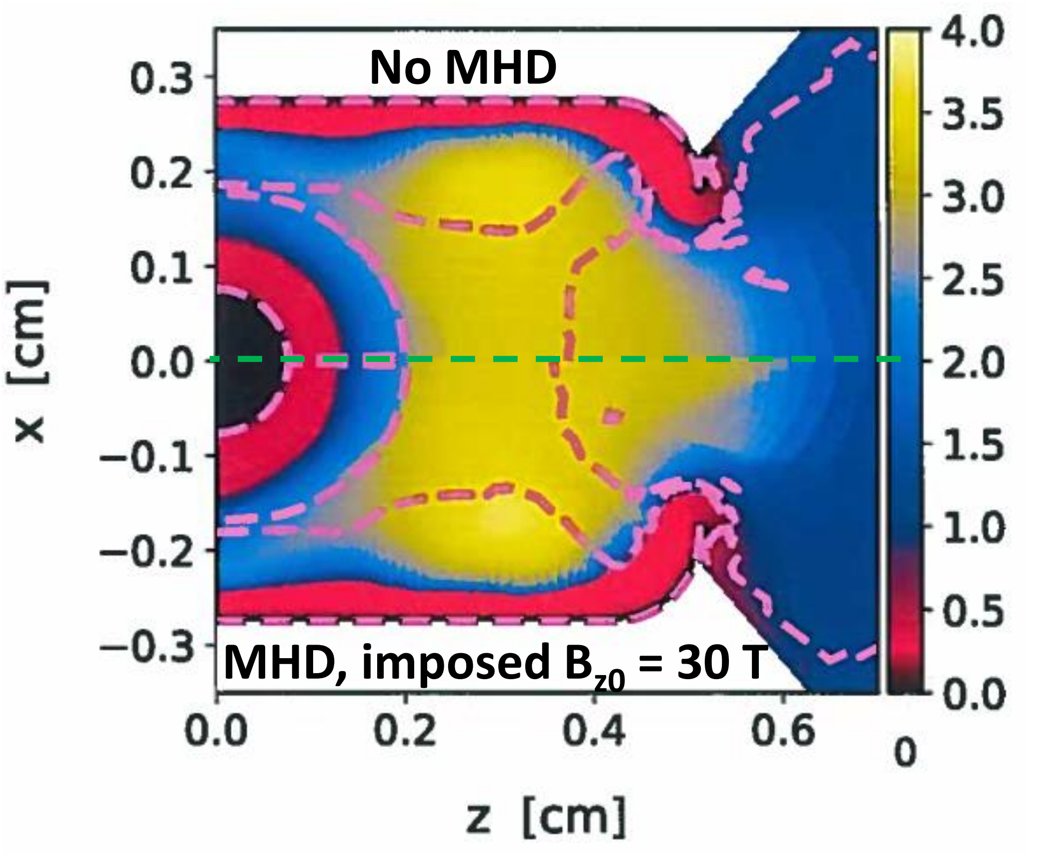
Self-gen B
- no MHD

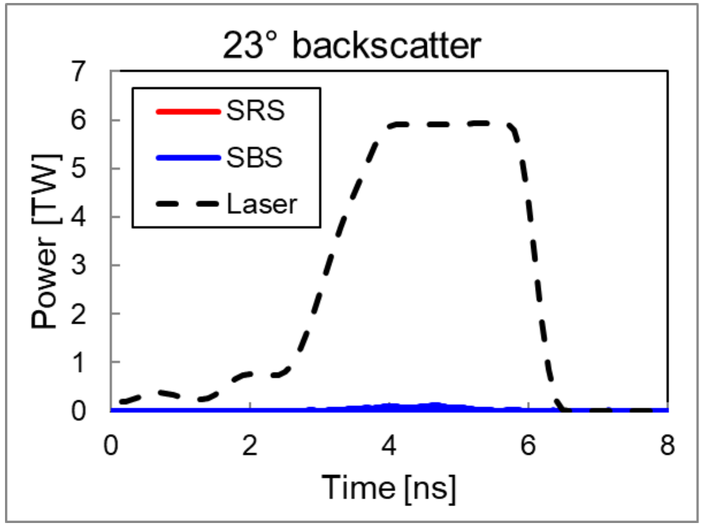


Self-gen B
- B_{z0} = 30 T



Electron temperature [keV]




23° backscatter
Power [TW]
Time [ns]
SRS
SBS
Laser
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1
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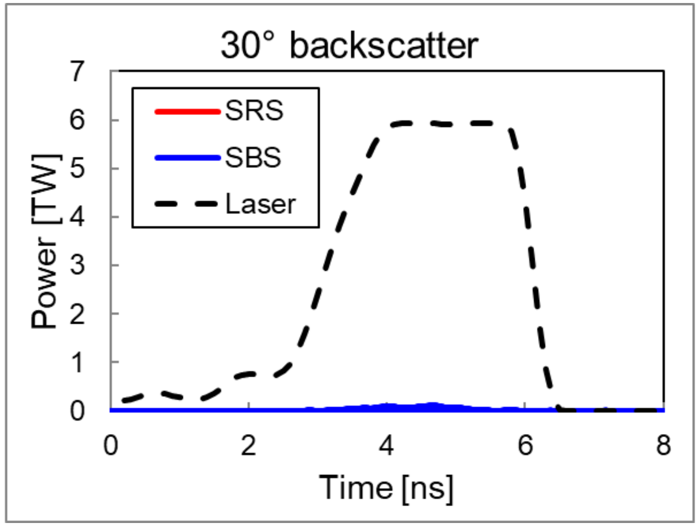
30° backscatter
Power [TW]
Time [ns]
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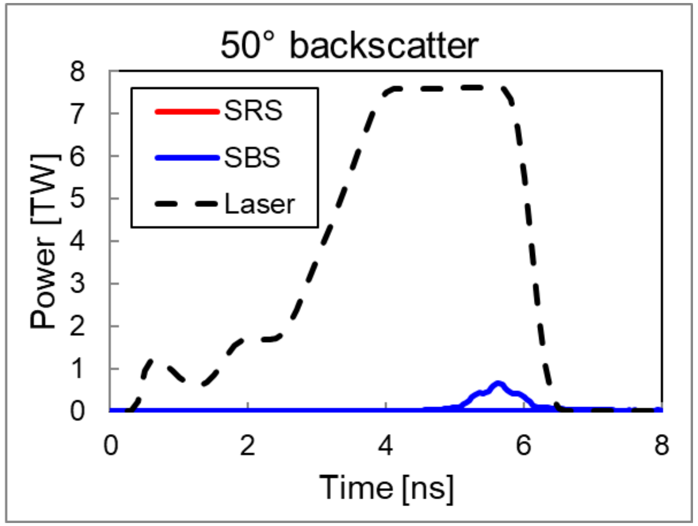
50° backscatter
Power [TW]
Time [ns]
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SBS
Laser
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