Magnetically Assisted Ignition on NIF

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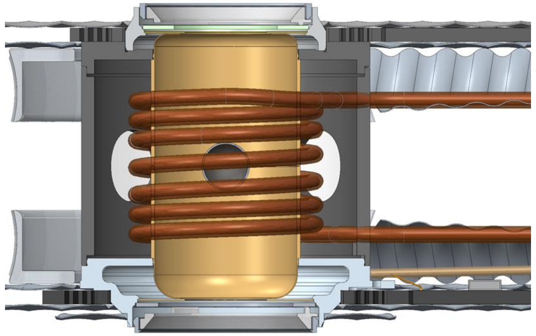
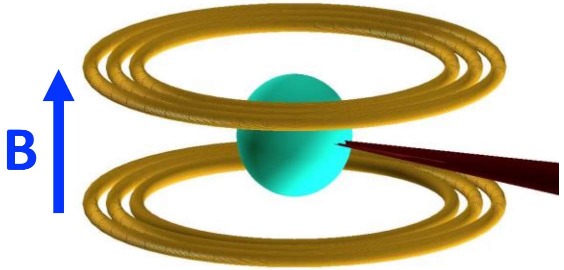
Outline: Magnetized Ignition on NIF LDRD

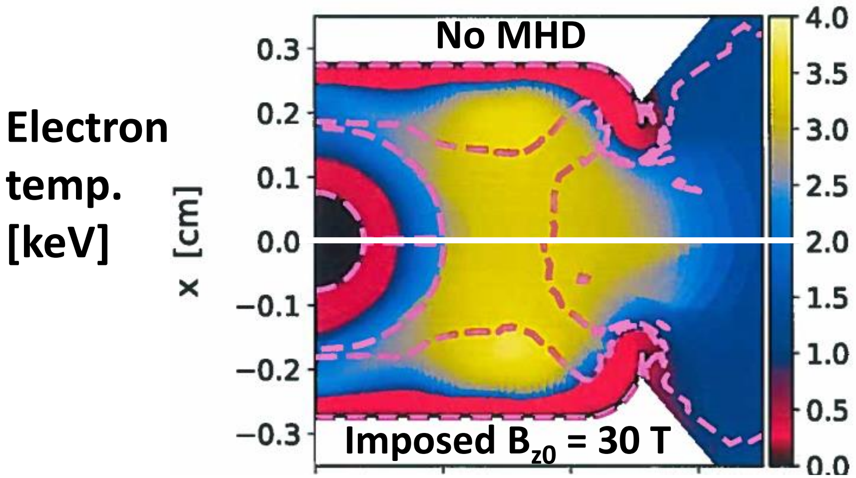
- **Project overview and goals**
  - Hohlraum + gas-filled capsule experiments: temperature + yield increase
  - Direct-drive “compression pusher” experiments: magnetic confinement of DD-produced 1 MeV tritons
    - Hong Sio, PI



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



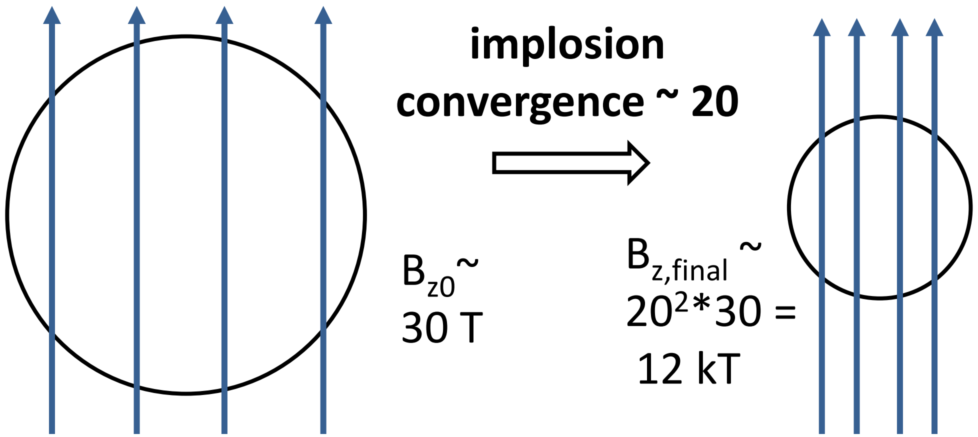
- **High-resistivity hohlraum** material for field soak-thru: Au+Ta alloys promising



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

- 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)



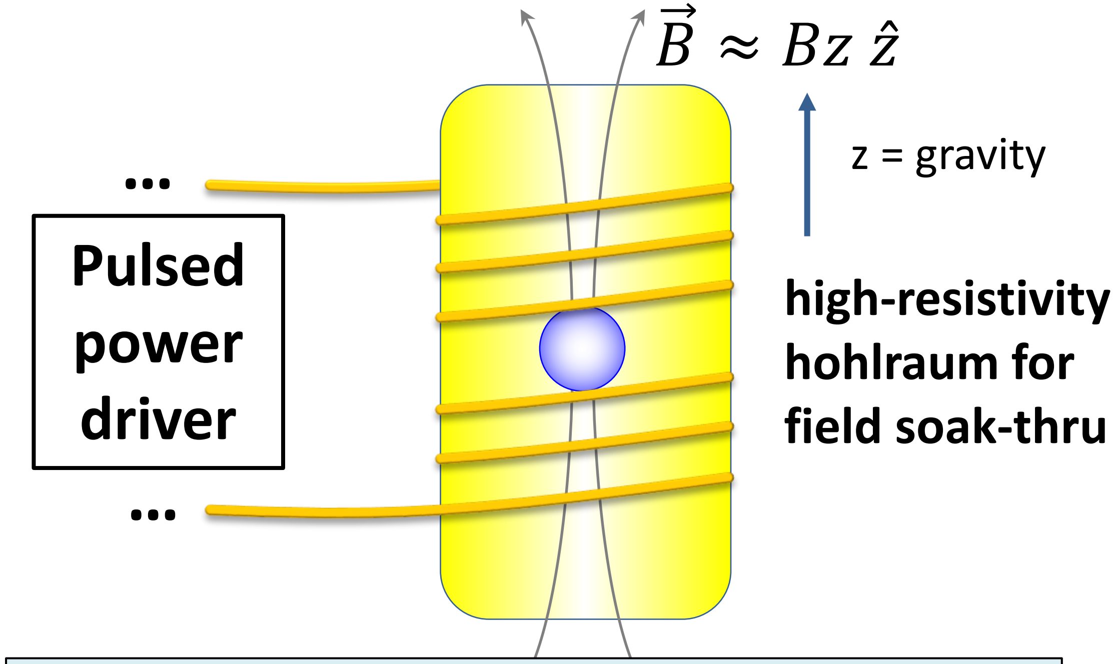
implosion convergence ~ 20

B_{z0}~ 30 T

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

Magnetic flux conserved:

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



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

z = gravity

Pulsed power driver

high-resistivity hohlraum for field soak-thru

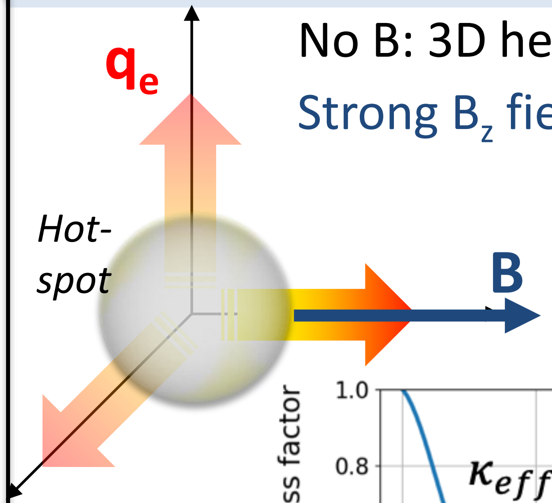
Expectations for current NIF high performers:

- 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"



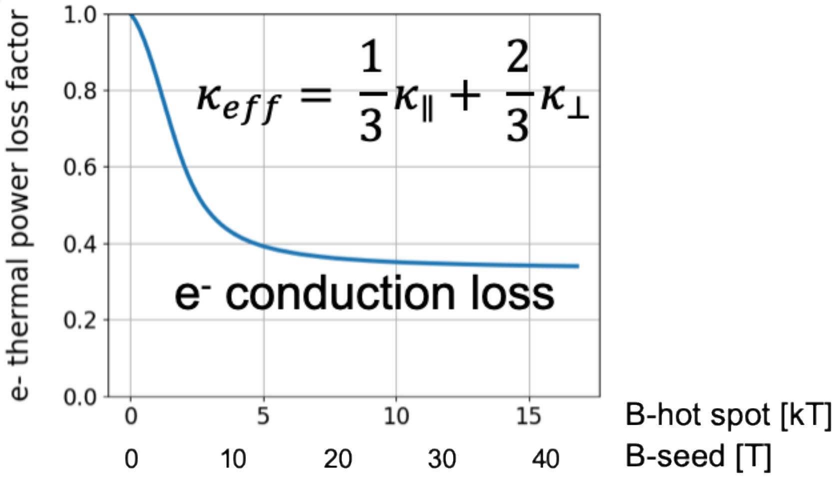
No B: 3D heat flow $q = -\kappa \nabla T$

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

raises T, lowers ρR [1]

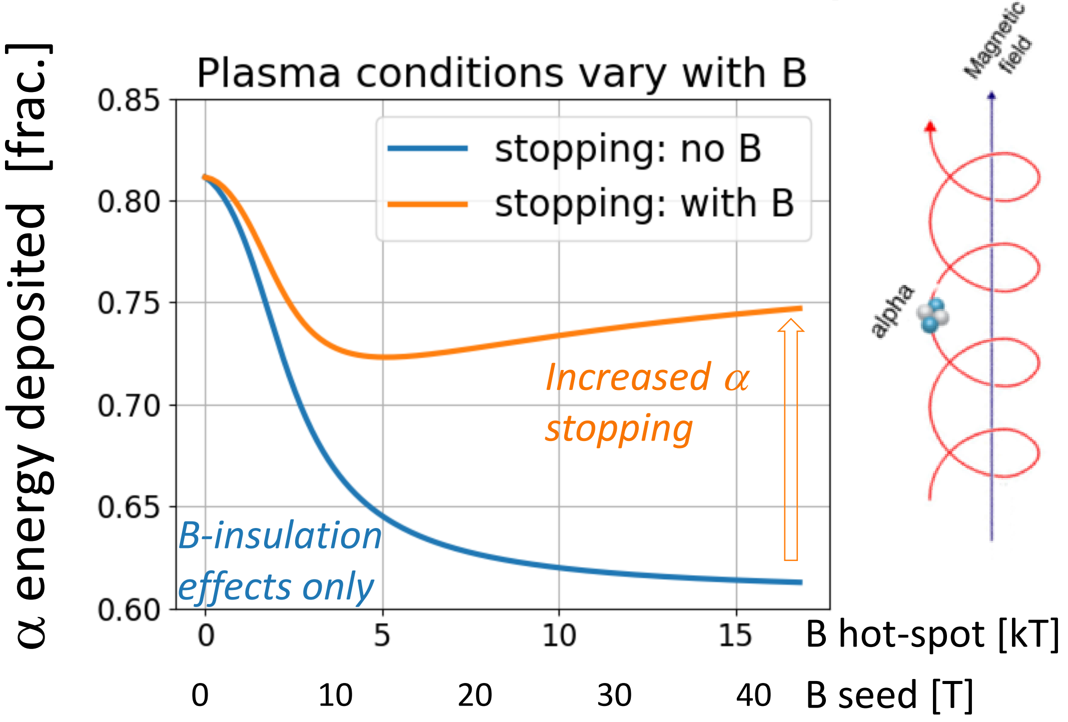
$$T(B) \approx 1.4\, T(B = 0)$$

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



B-field increases hotspot alpha heating [3]

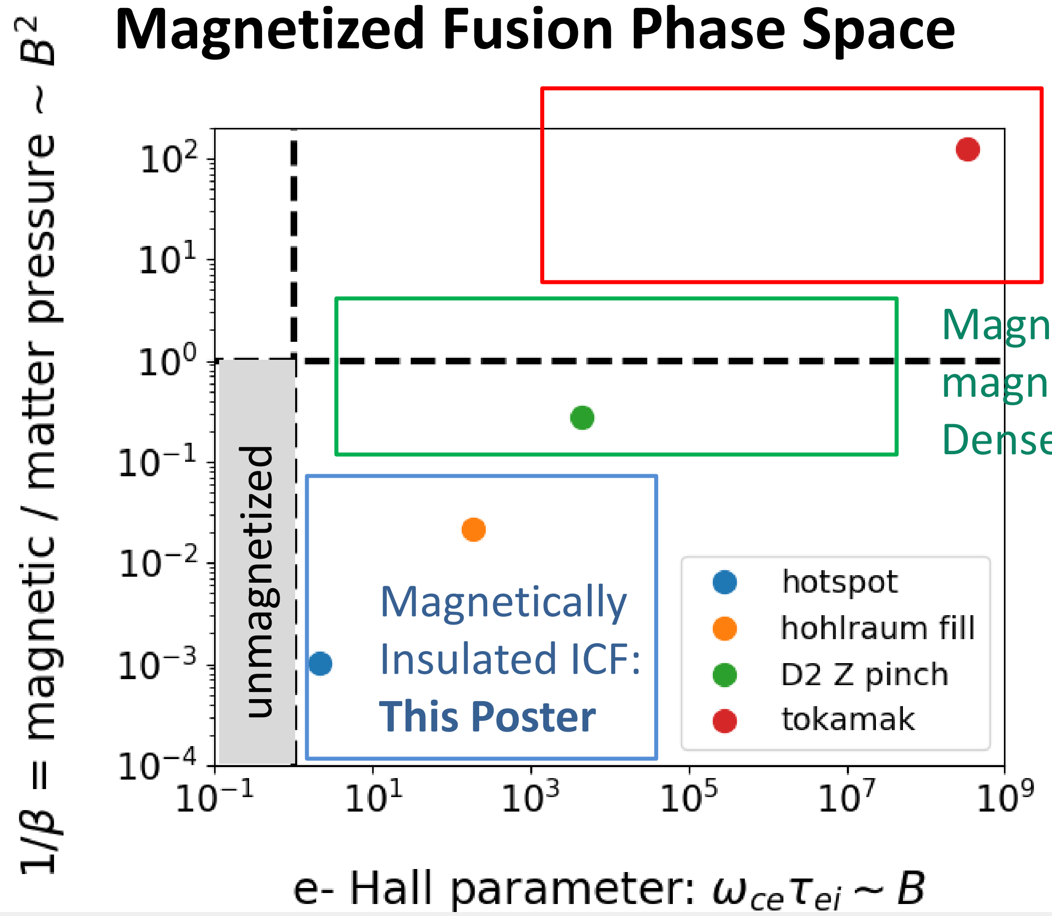
Mostly compensates reduced ρR



[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



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

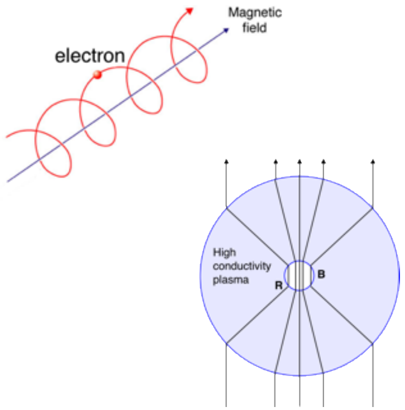
Magneto-inertial fusion:
magnetic ~ matter pressure:
Dense plasma focus, Z-pinch, magLIF

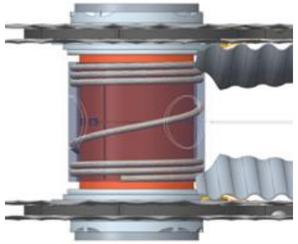
e- conduction suppressed: $\frac{\kappa_\perp}{\kappa_{||}} \sim \frac{1}{(\omega_{ce}\tau_{ei})^2}\ or\ \frac{1}{(\omega_{ce}\tau_{ei})^1}$

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

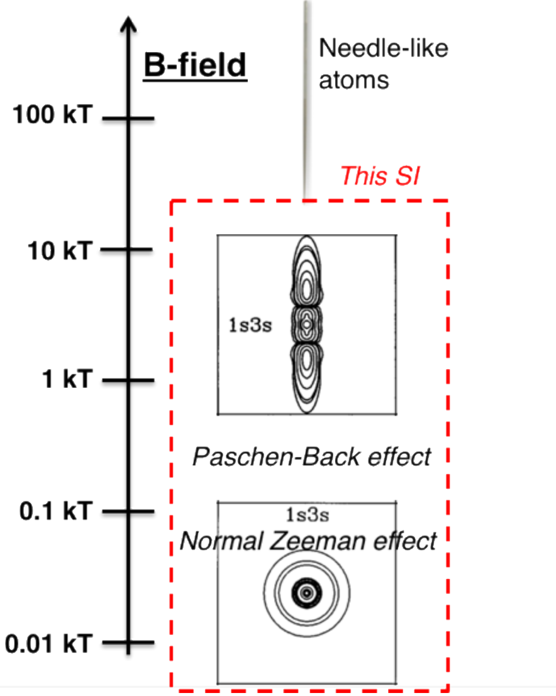
LDRD to demonstrate key elements for magnetized ignition on NIF

- **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**



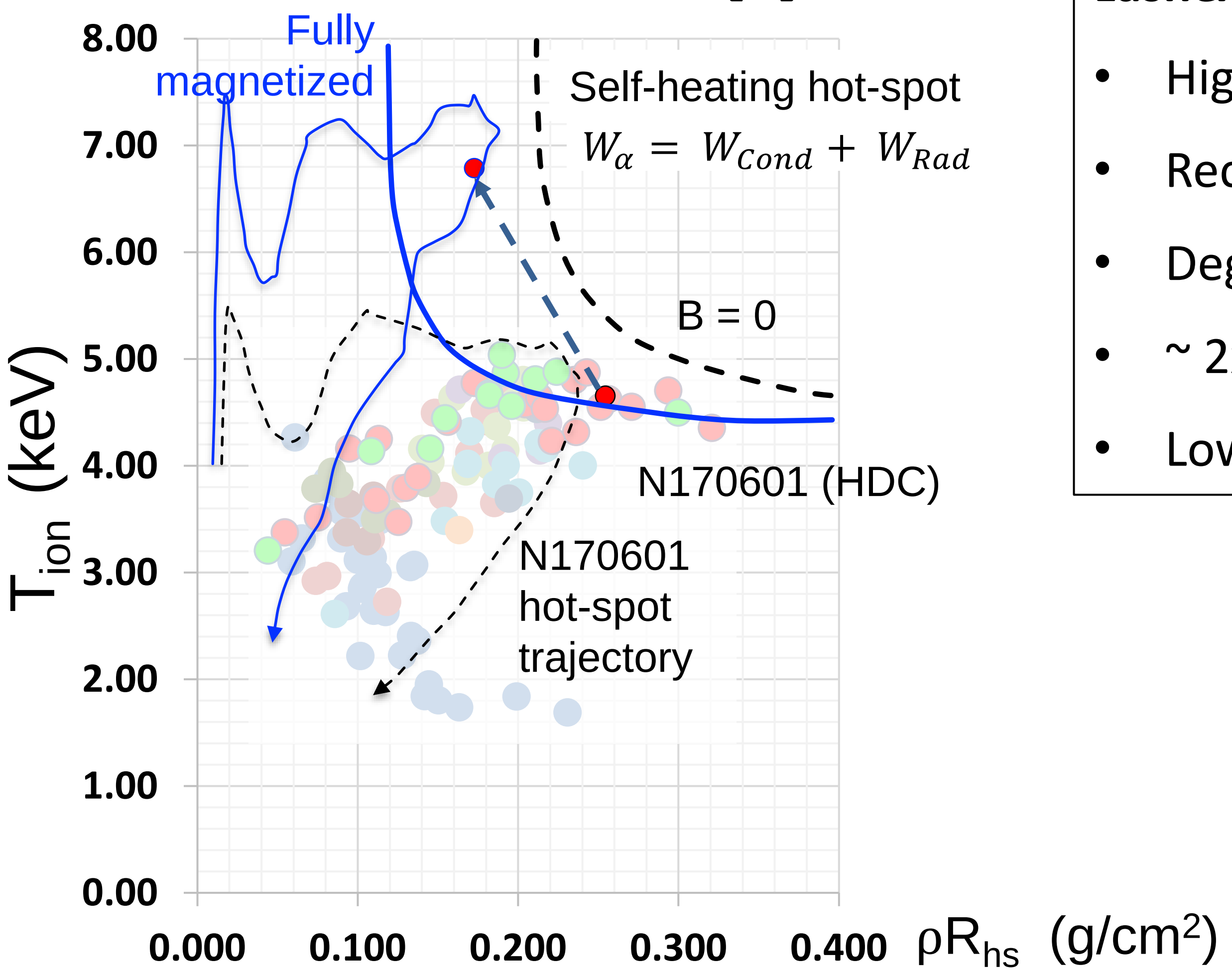


Enables new atomic physics regimes



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]

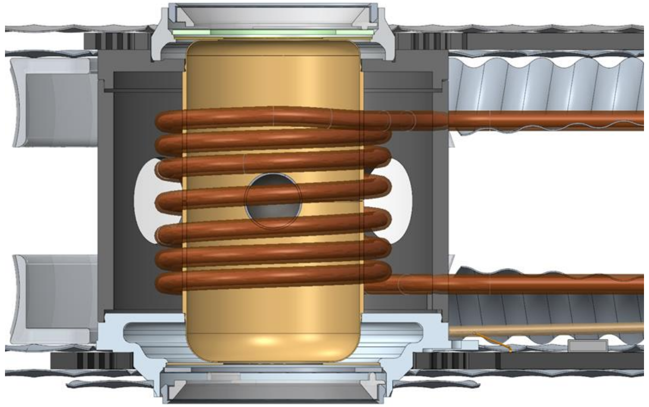
- High design adiabat ~ 3.0
- Record yield at the time
- Degraded by preheat to match measured yield
- ~ 2x yield with imposed B-field
- Lower design adiabat ~ 2.0 could give ~> 5x yield [2]

[1] O. A. Hurricane+, PPCF 2019
[2] L. J. Perkins+, Phys. Plasmas 2017

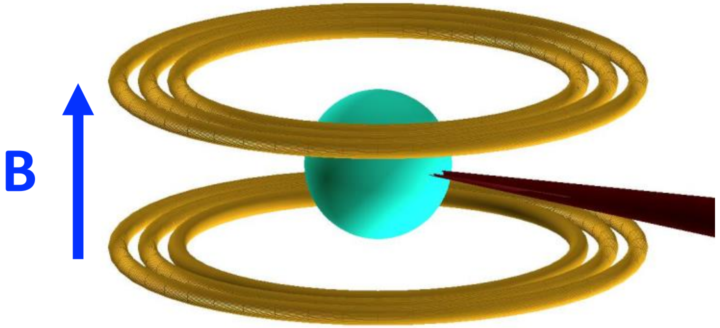
We are planning room-temperature, "subscale" (E_{laser} ~ 1 MJ) hohlraum expt's, evaluating direct-drive

B_{z0} = 30 T

Magnetized hohlraum



Magnetized direct-drive : Hong Sio



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%

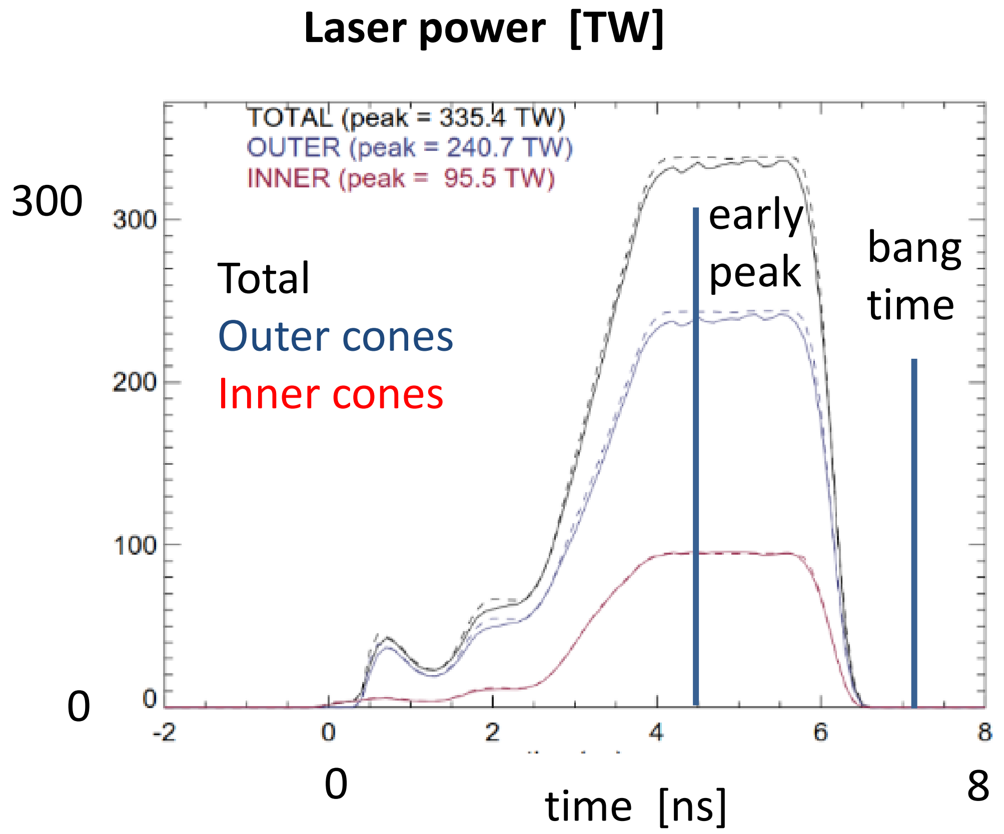
“BigFoot”[1] NIF shot N161204: subscale gas-filled capsule

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



[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: $dv_e/dt = 0$

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

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

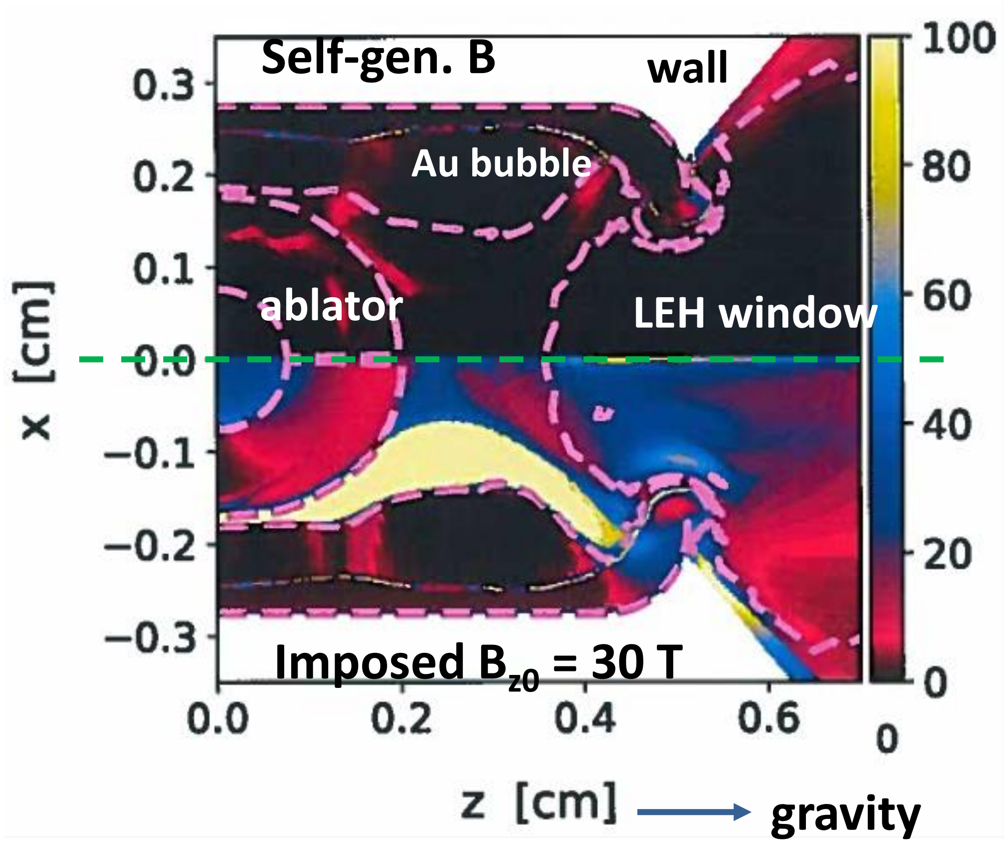
Simplifications in this work:
due to numerical issues

- 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

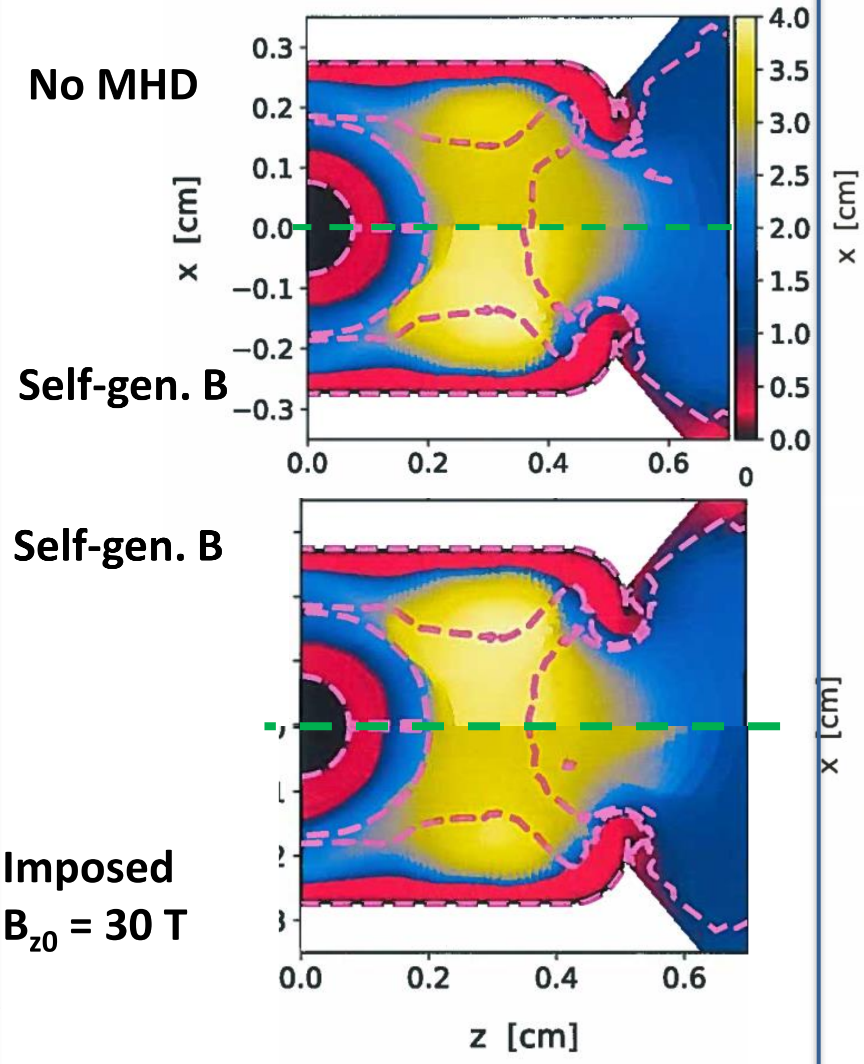
4.5 ns: early peak power

| Magnetic field | [T]

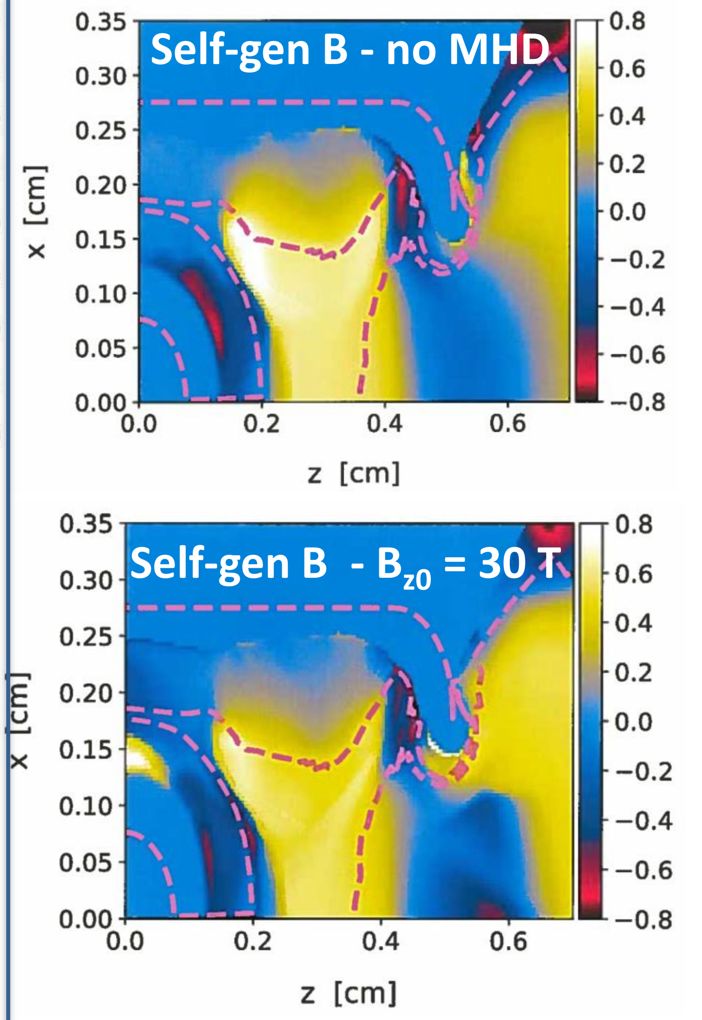


BigFoot Symcap

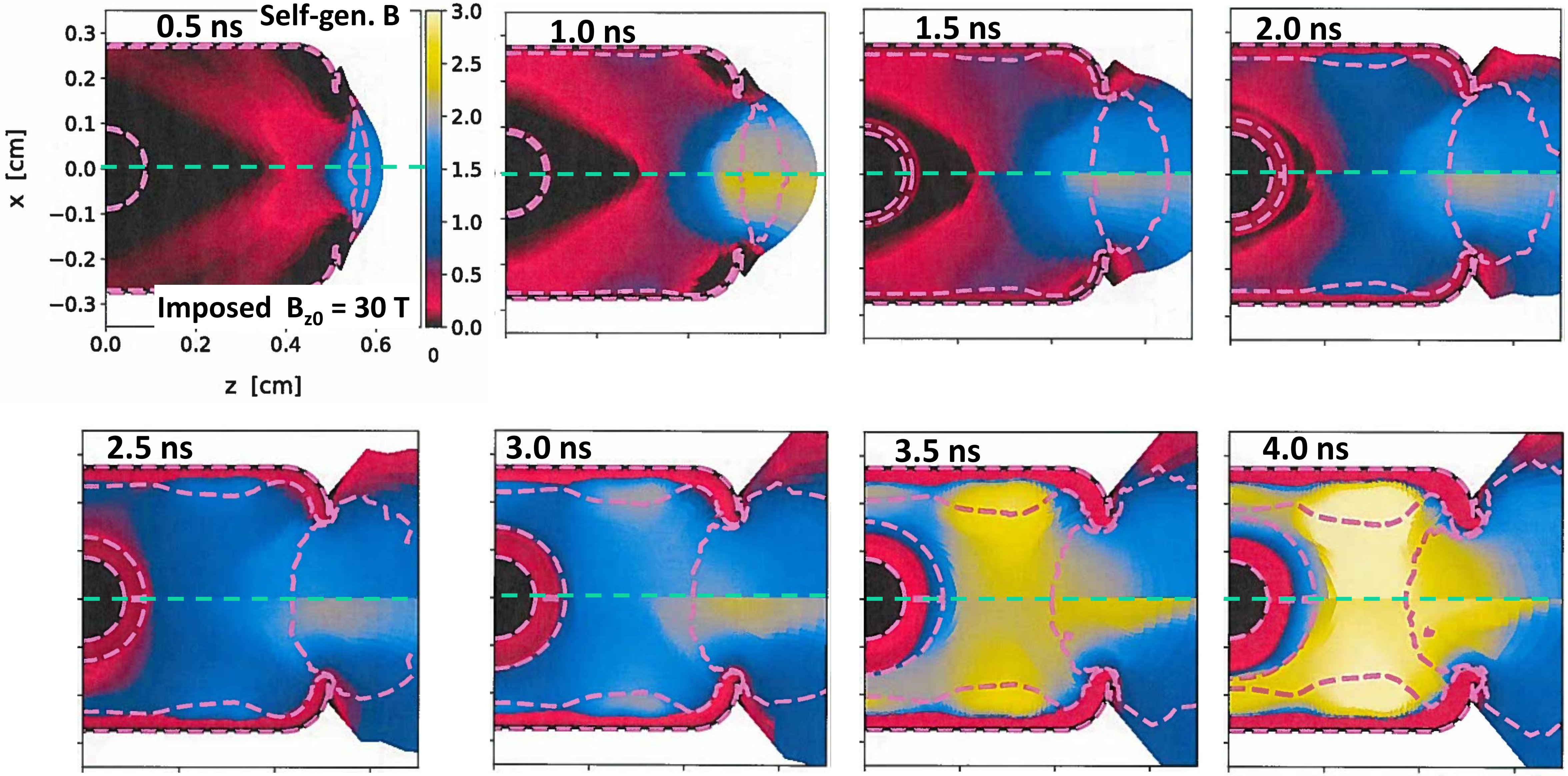
e- temperature [keV]



T_e difference [keV]



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

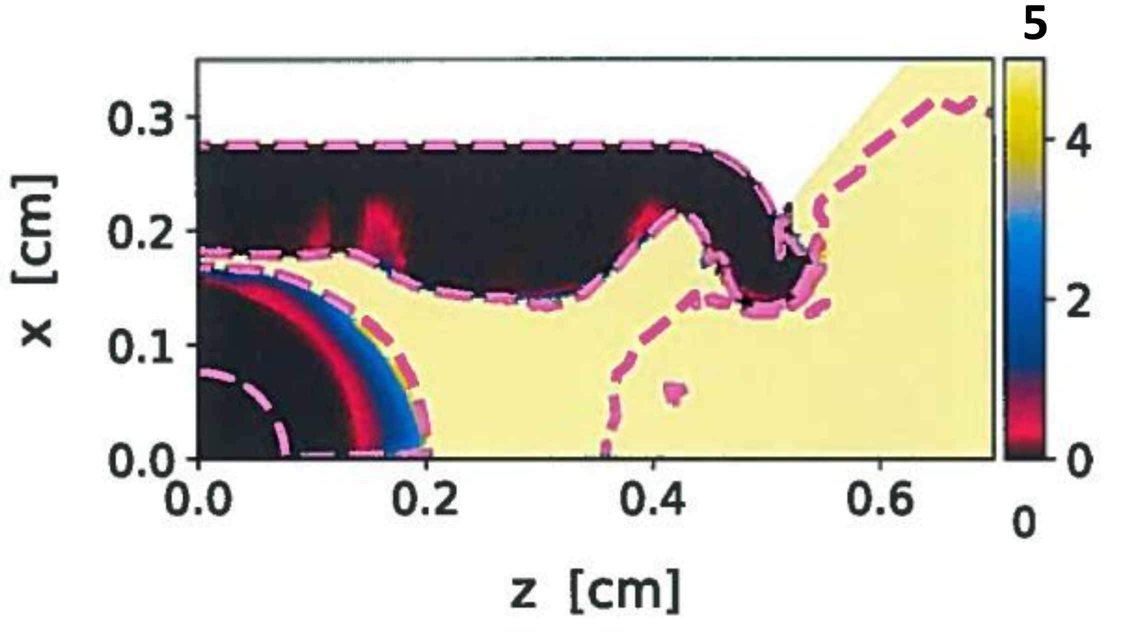


Hohlraum dynamics with imposed B_{z0} = 30 T: e- Hall parameter large in fill, magnetic pressure unimportant

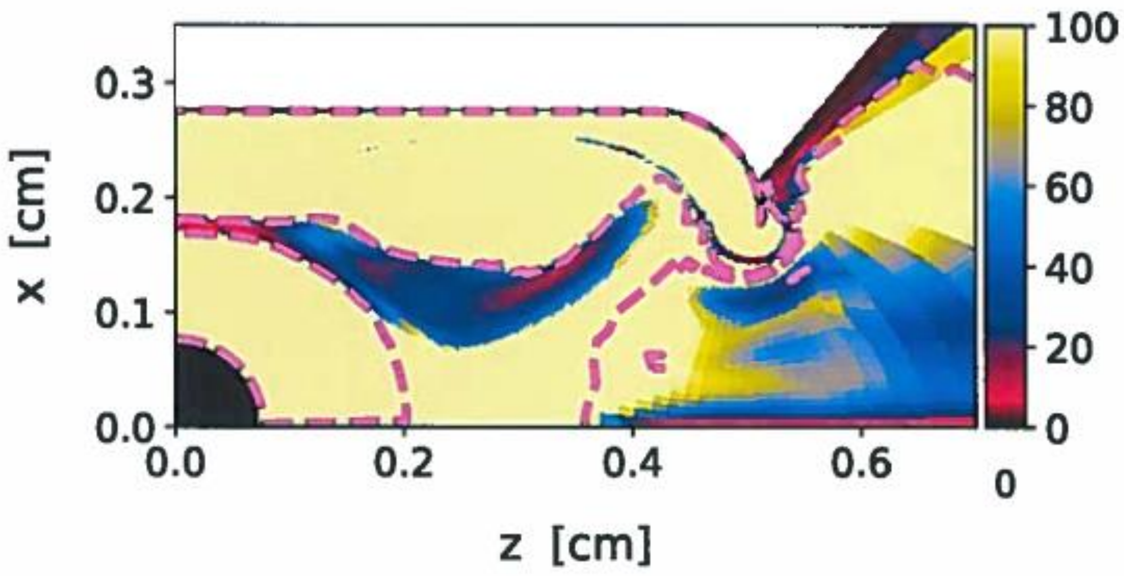
4.5 ns: early peak power

BigFoot Symcap

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



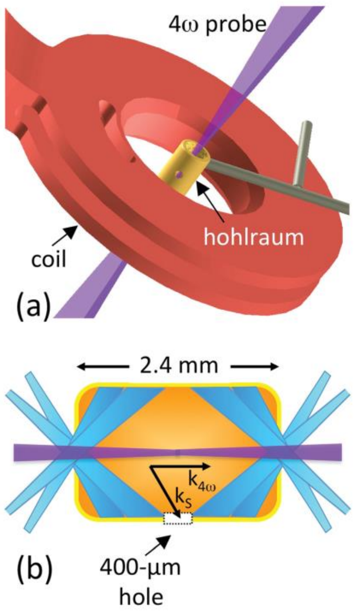
beta: plasma / magnetic pressure



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

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



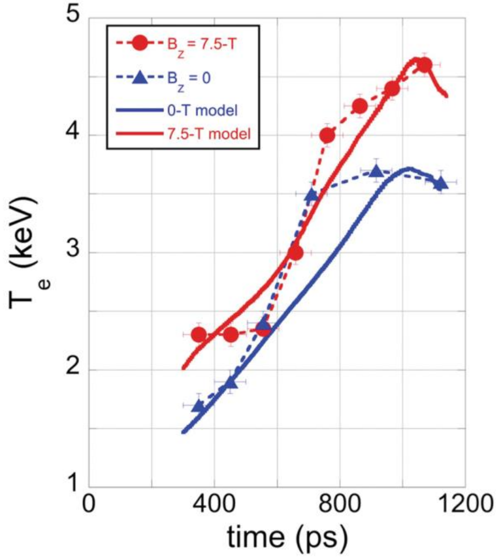


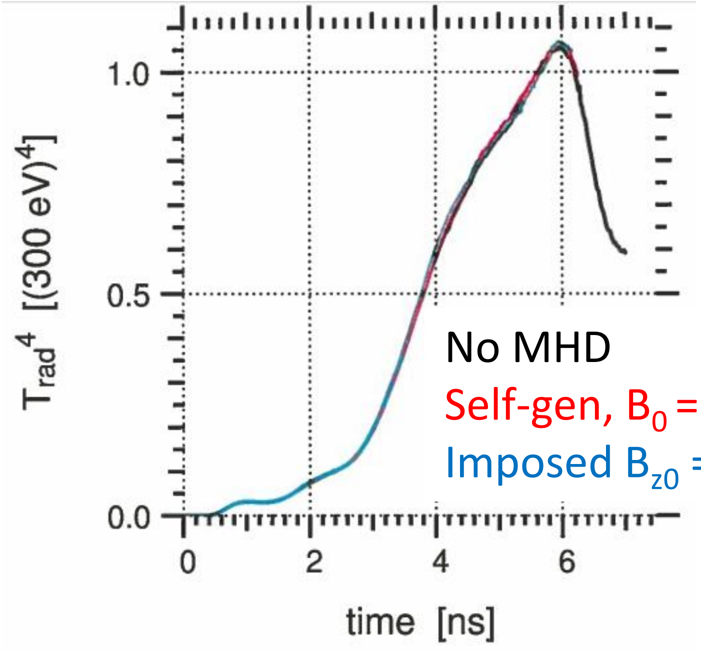
FIG. 3. Measured electron temperature versus time for B = 0 (blue triangles) and B = 7.5-T (red circles). Over-plotted as solid lines are the 2-D HYDRA model for B = 0 (blue) and B = 7.5-T (red).

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

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

Drive: total x-ray flux



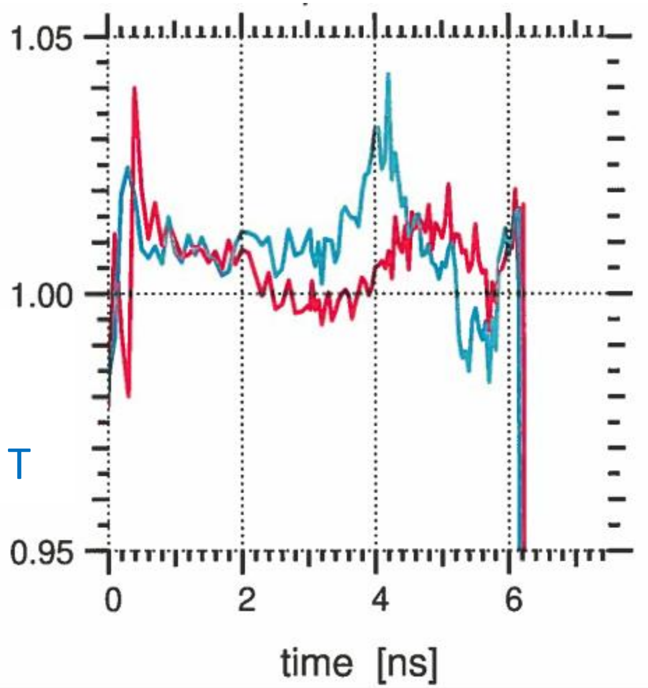
No MHD

Self-gen, $B_0 = 0$

Imposed B_{z0} = 30 T

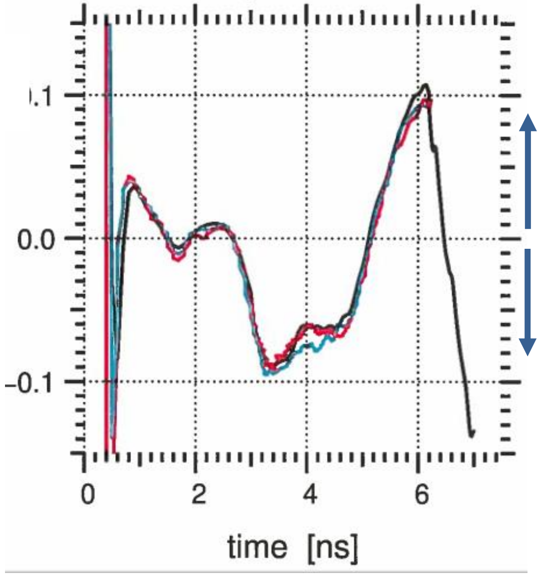
Yes, there are 3 curves

Flux ratio to no-MHD run



x-ray flux asymmetry

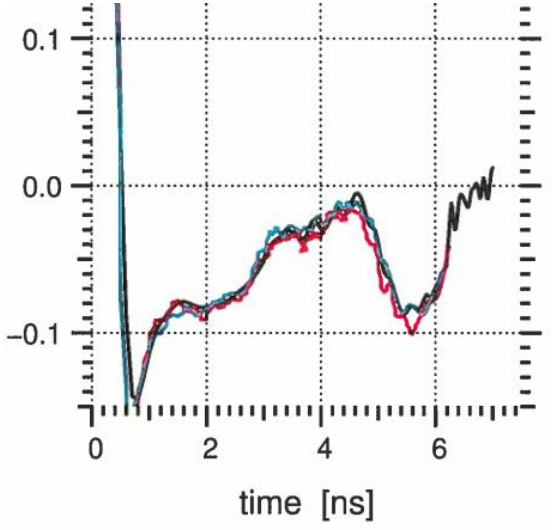
P_2/P_0



pole high

waist high

P_4/P_0

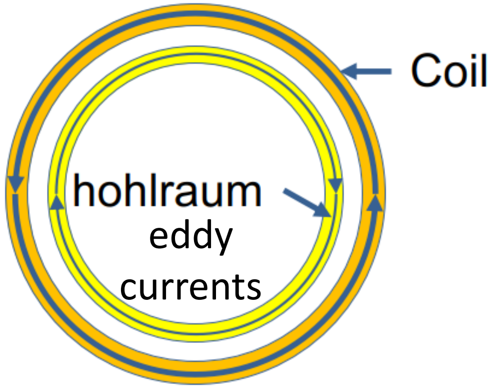


Hohlraum material must meet field soak-thru and x-ray drive constraints

soak-thru: want high resistivity ρ

Want high Z

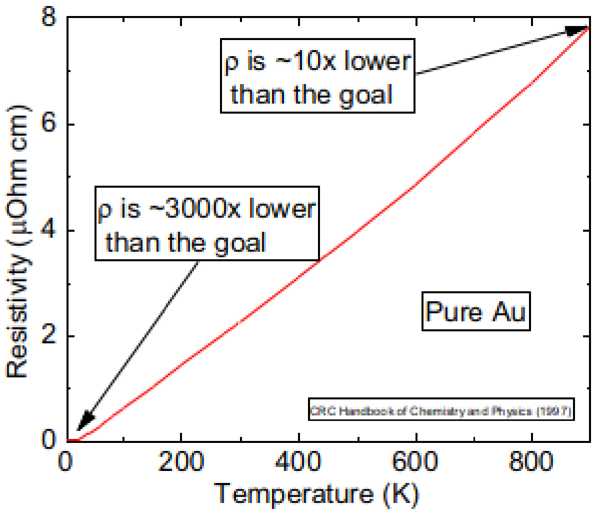
Constraint	Requirement	Notes
$\vec{J} \times \vec{B}$ wall motion	< 50 μm	Beam pointing, symmetry, backscatter
Wall Joule heating	< 2000 K gas capsule < 700 K (est.) DT layer	Limit $\Delta T_{ablator}$ Limit ΔT_{ice}
Field soak-thru time	~0.1's μs	Not issue for our ~ 2 μs current pulses
X-ray flux	>=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

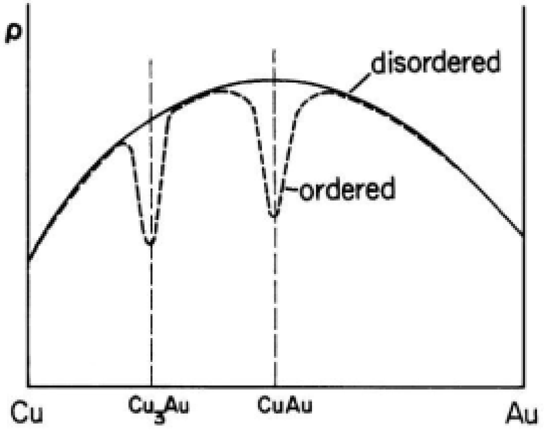
Resistivity 101: defects needed for high enough value at cryo conditions; alloys can provide

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



Gold is an excellent conductor in the entire temperature range

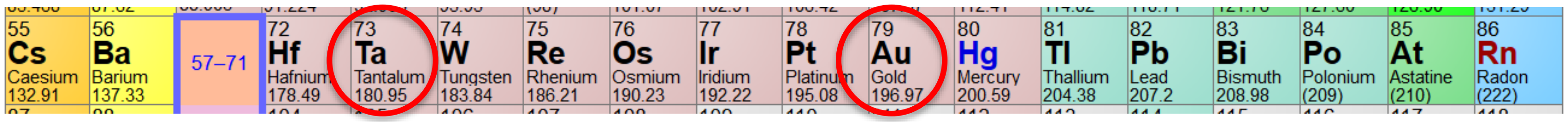
Nordheim rule:
$\rho_{defect} = x(1-x)$



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)

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

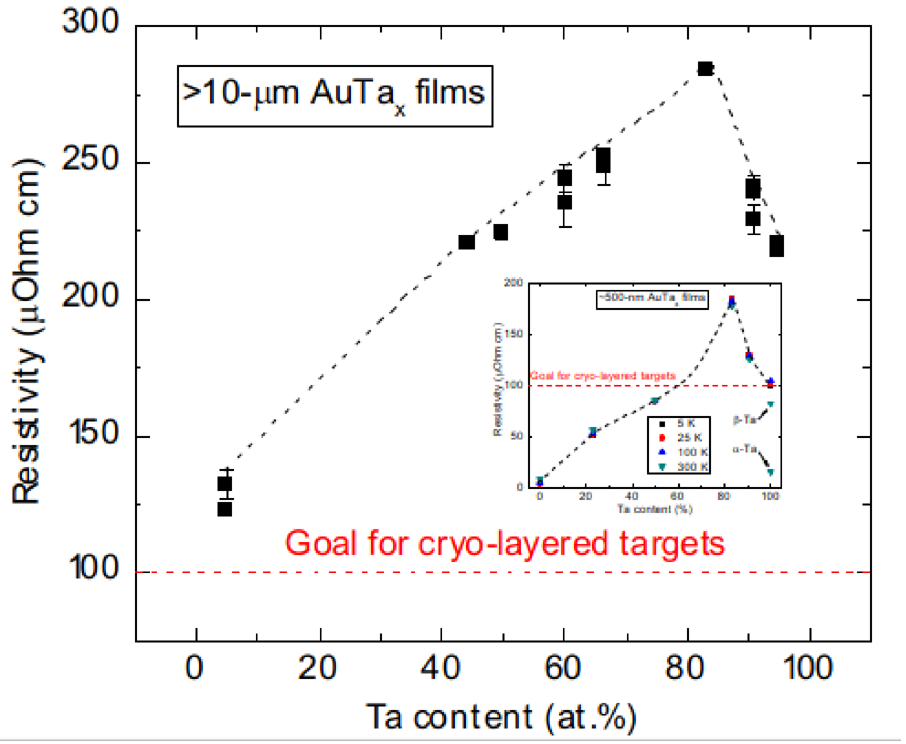
2.2 Au

Pure metals @ 273 K

…

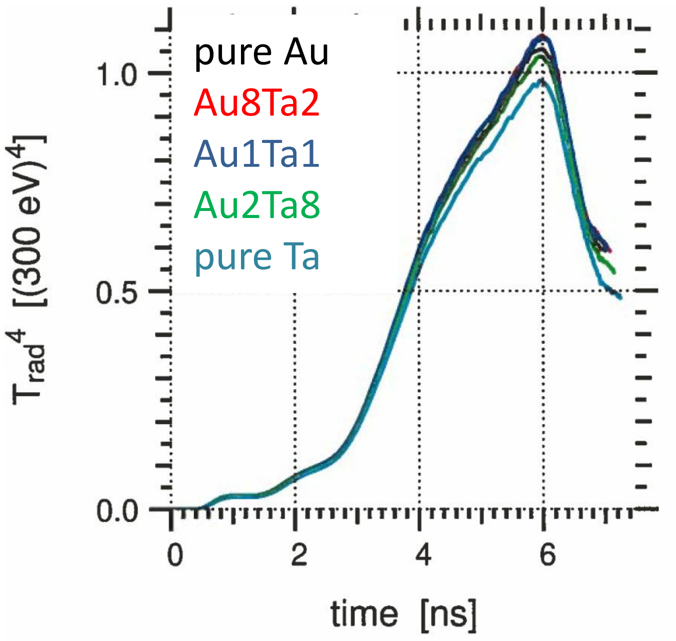
<< 1: Pure {Ta, Au, DU} @ 20 K

AuTa alloy resistivity exceeds cryo goal, peaks for Au2Ta8



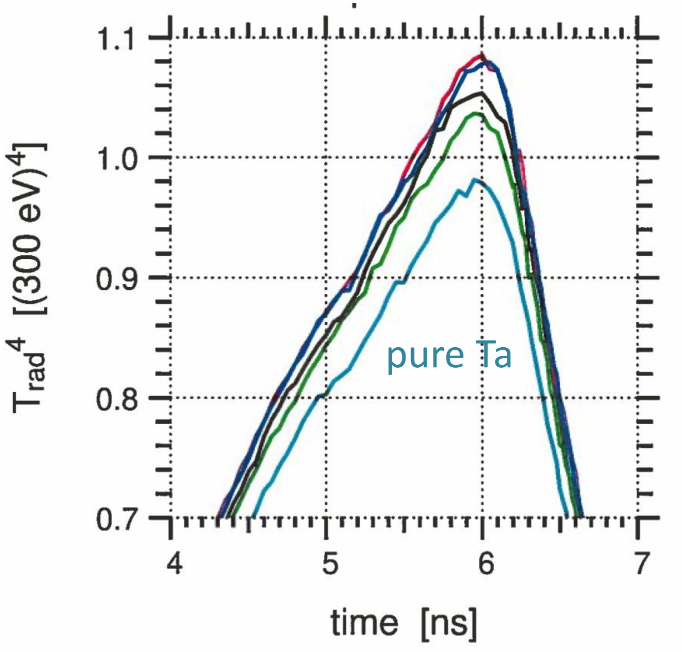
Au+Ta alloys: more resistive than Au, small effect on x-ray drive

x-ray flux on capsule

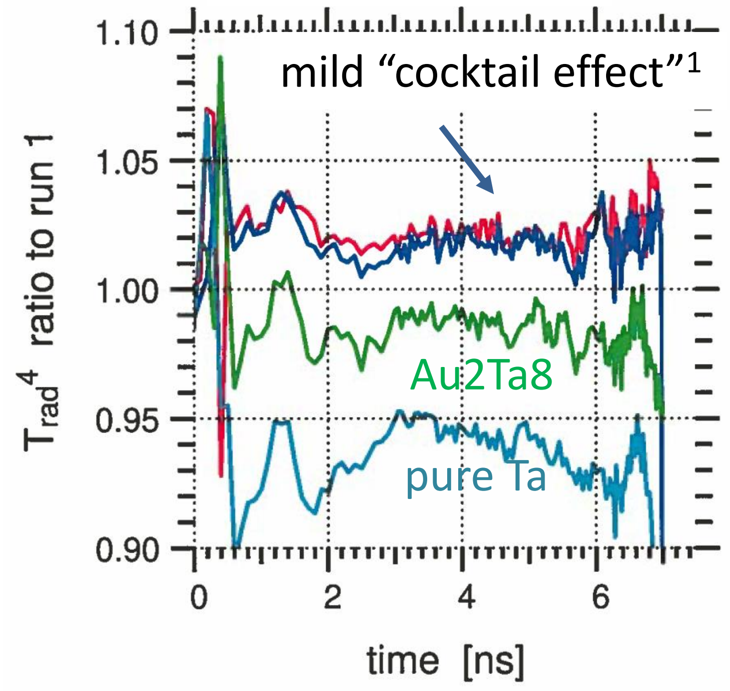


Same atom density as pure Au

Zoom on peak



Ratio to pure Au



mild "cocktail effect"[1]

- 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

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	

Disclaimer