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Use of External Magnetic Fields in Hohlraum Plasmas to Improve Laser-Coupling

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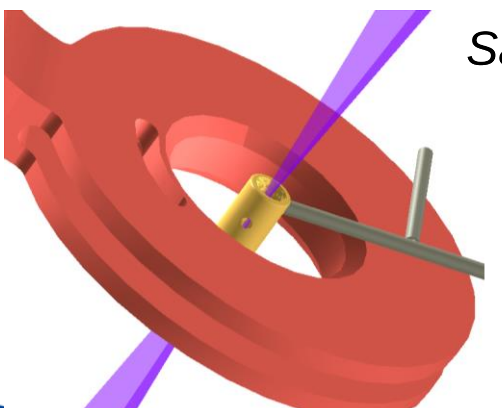
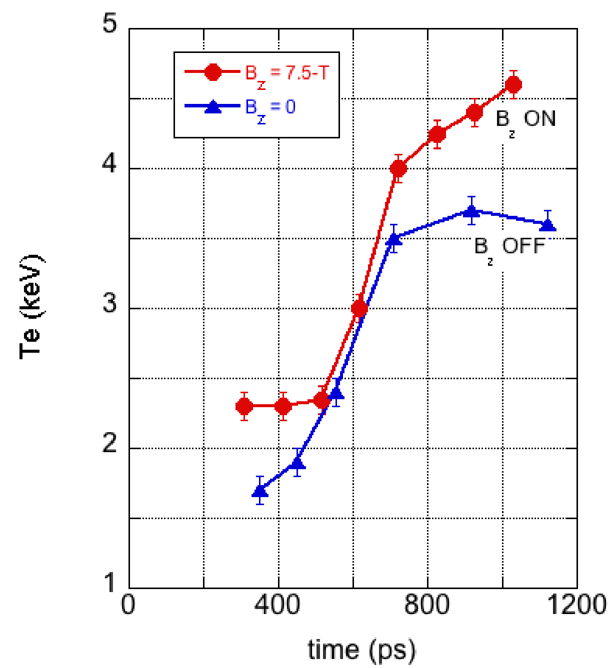
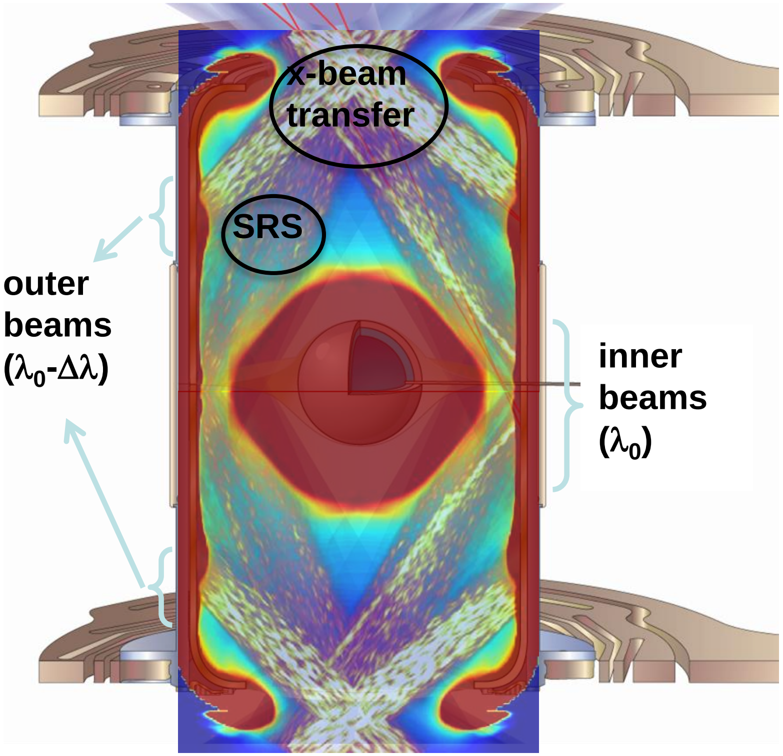




Use of External Magnetic Fields in Hohlraum Plasmas to Improve Laser-Coupling

- **Increased underdense plasma temperatures are desirable for NIF ignition hohlraums**
  - improve laser propagation through long-scale-length low-Z plasma (less inverse bremsstrahlung absorption)
  - possibly mitigate LPI with higher T_e (higher $k\lambda_D$, more Landau damping)
- **Magnetic insulation can increase the plasma temperature with $B_z \geq 10$-T in gas-filled hohlraums**
- **Omega experiments using gas-filled hohlraums demonstrate an increased plasma temperature with $B_z = 7.5$-T**
  - plasma conditions measured with 4ω Thomson scattering
- **2-D HYDRA simulations are in good agreement with experimental results**

Adequate coupling of the laser is required for indirect drive ignition



- laser-hohlraum coupling affects:
  - radiation drive (implosion velocity)
  - radiation symmetry
  - preheat

- lower than expected T_e is inferred [1] in the underdense plasma for NIF ignition hohlraums:
  - significant collisional absorption in cooler, low-Z plasma (symmetry)
  - substantial SRS on inner beams (drive, symmetry, preheat, …)

Higher coronal plasma temperatures can improve laser-plasma coupling in hohlraum targets

1. M.D. Rosen *et al.*, *HEDP* **7**, 180 (2011)

SRS reflectivity decreases with increasing $k\lambda_D$ (increasing electron temperature T_e)

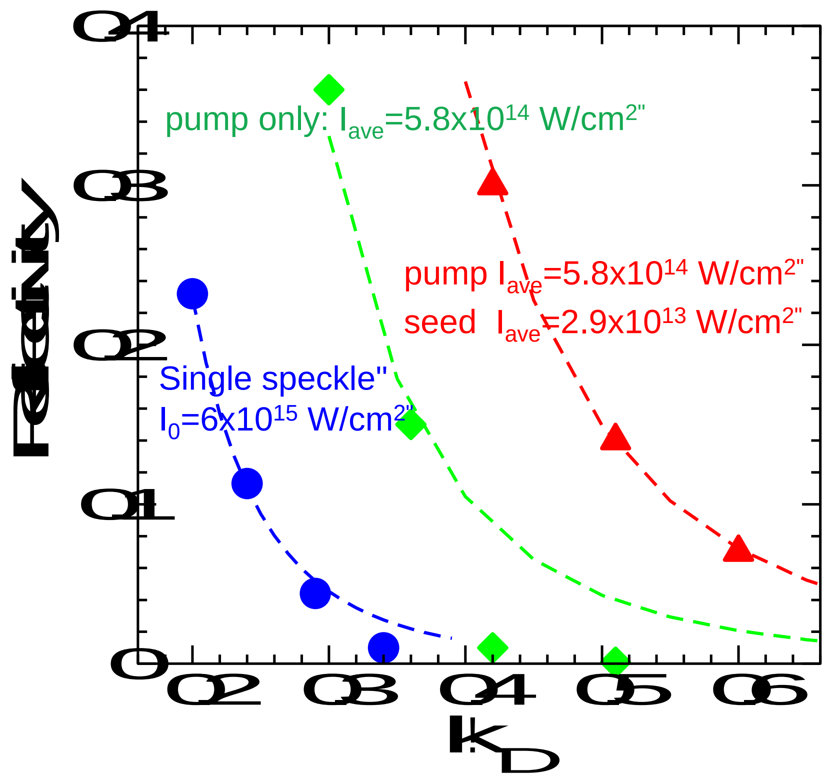
- The daughter EPW saturates when the trapped e- bounce frequency is comparable to the side loss rate for a trapped electron

$$\frac{\omega_b}{\omega_{pe}} = k\lambda_D \sqrt{\frac{e\phi}{T_e}} \sim \frac{\omega_{sl}}{\omega_{pe}}$$

- $E_{SRS} \sim f\, E_{laser}$; $R_{SRS} = (E_{SRS}/E_{laser})^2$, so

$$R_{SRS} \sim \frac{1}{(k\lambda_D)^4} \quad \text{(or } R_{SRS} \sim T_e^{-2}\text{)}$$

- This simple scaling[1] agrees well with both single- and multi-speckle VPIC simulations over a range of conditions



[1] Yin, Albright, Rose et al. *Phys. Plasmas* 19, 056304 (2012)

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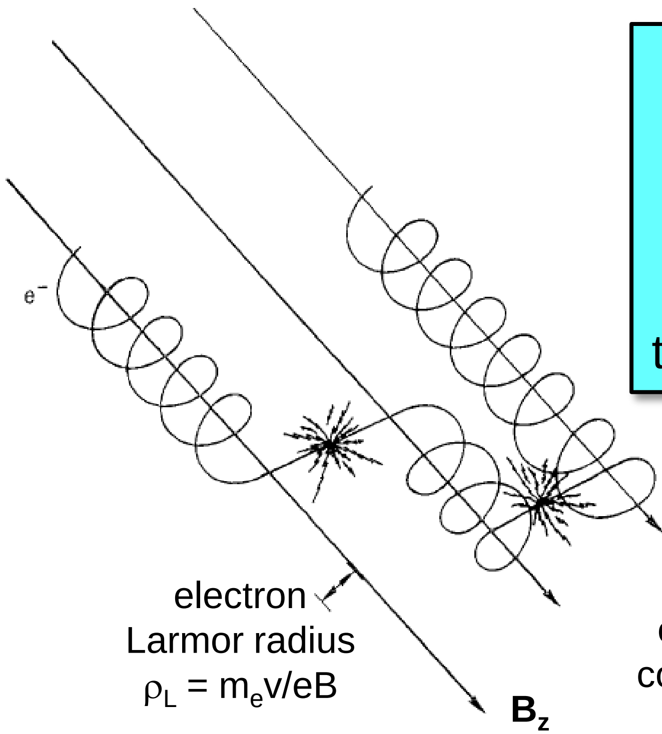
Magnetic insulation can lead to increased hohlraum plasma temperatures



when $\rho_L < \lambda_{ei}$ transport across magnetic field is reduced since ρ_L sets the transport step size

adapted from "Physics of Laser Fusion, Vol. 1", C.E. Max, UCRL-53107 (1982)

Braginskii heat flux†

$$Q_B \approx -\kappa_\parallel \nabla_\parallel T_e - \kappa_\perp \nabla_\perp T_e$$

$$\kappa_\parallel \approx \gamma_0 \frac{n_e T_e \tau_{ei}}{m_e}$$

$$\kappa_\perp \approx \gamma_1' \frac{n_e T_e \tau_{ei}}{m_e \omega_{ce}^2 \tau_{ei}^2}$$

"insulation" occurs when:

$$\frac{\kappa_\perp}{\kappa_\parallel} \approx \left(\frac{1}{\omega_{ce}\tau_{ei}}\right)^2 \ll 1$$

† ignoring cross-terms

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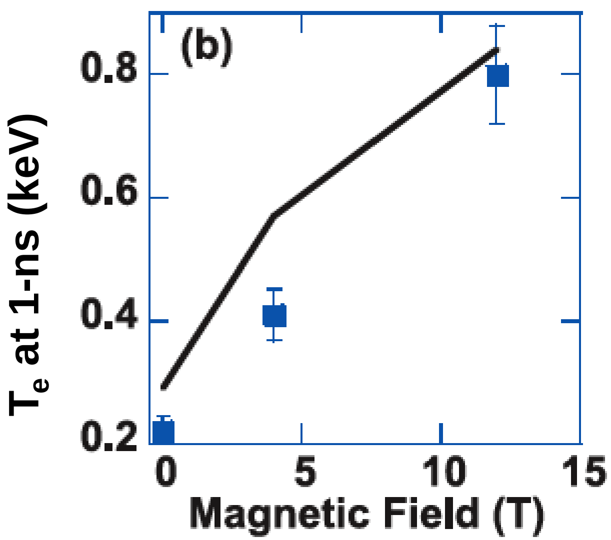
Scaling from previous experiments suggests B_z ~ 10-T may increase T_e in gas-filled hohlraums

Magnetized Gasjet Experiments*



* Froula *et al.*, *PRL* (2007)

	gasjet parameters	NIF parameters
T_e	250 eV	2 – 2.5 keV
n_e	1.5e19 e/cm^3	1e21 e/cm^3
Z	~ 5 (N_2)	2 – 3.5 (He or CH)
B_z	10 T	10-12 T
$\frac{1}{\omega_{ce}^2 \tau_{ei}^2}$	$\frac{k_\wedge}{k_\parallel} » \frac{1}{15}$	$\frac{\kappa_\perp}{\kappa_\parallel} \approx \frac{1}{10} - \frac{1}{15}$

We expect a temperature increase for magnetized NIF hohlraums

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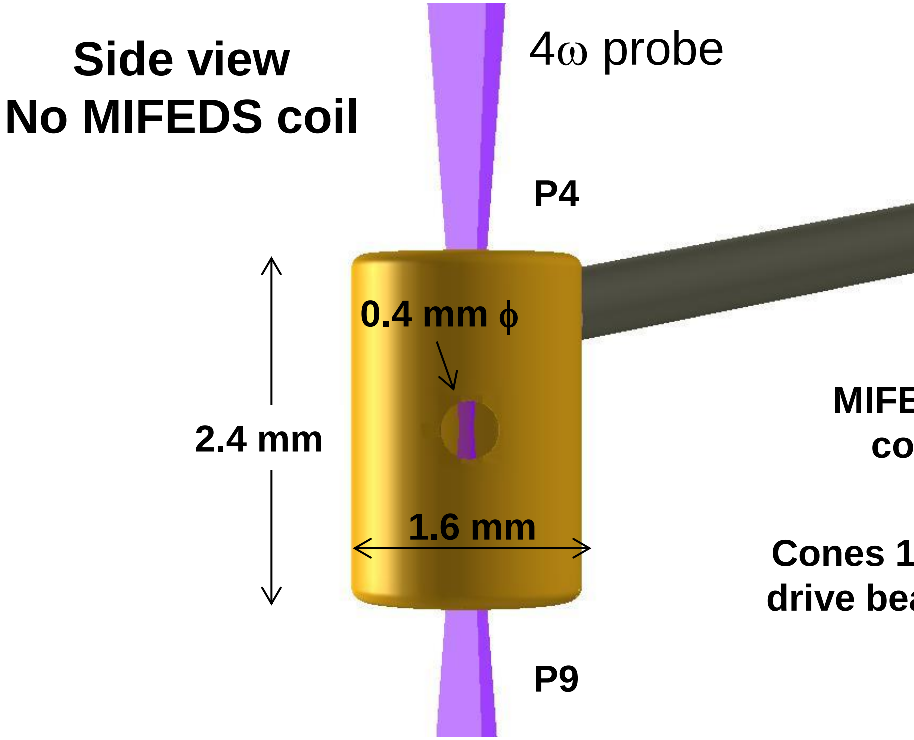
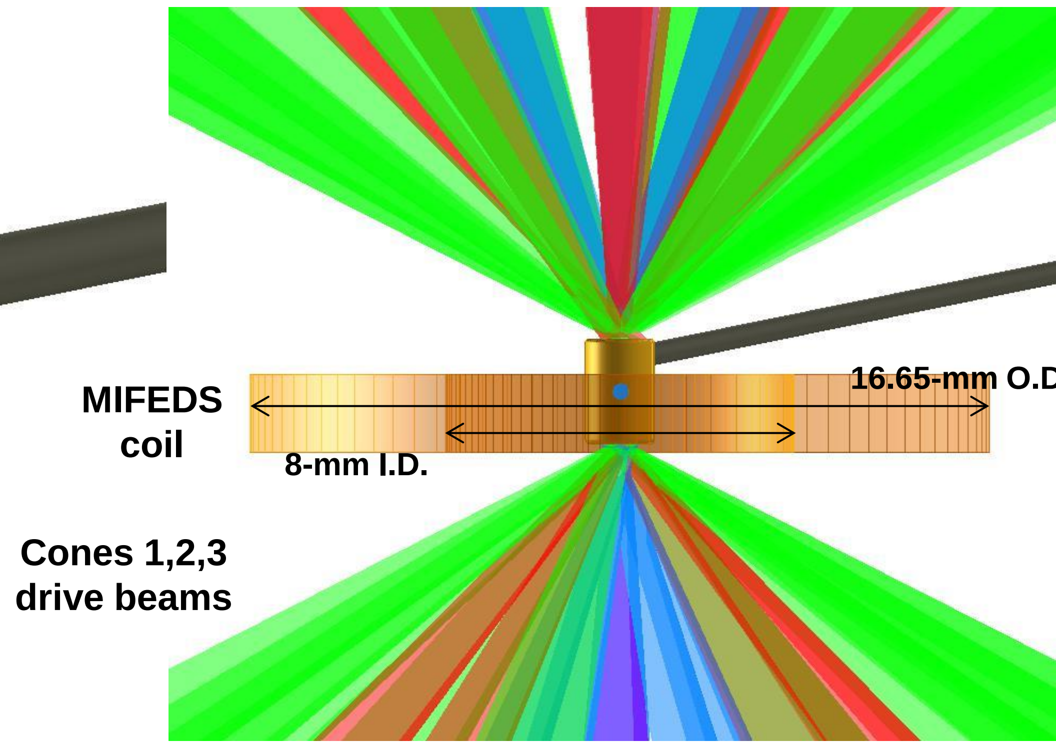
Experiments are performed at Omega using gas-filled hohlraums and an external B-field

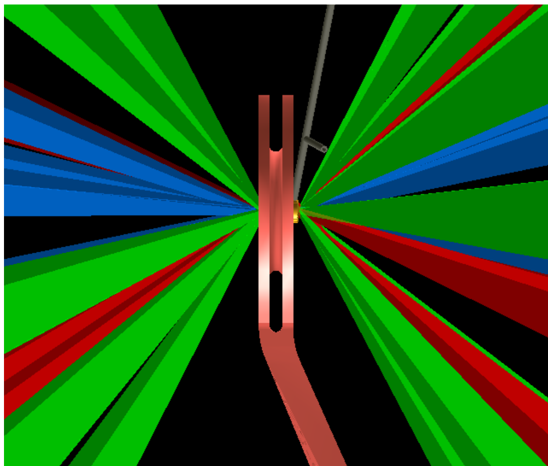


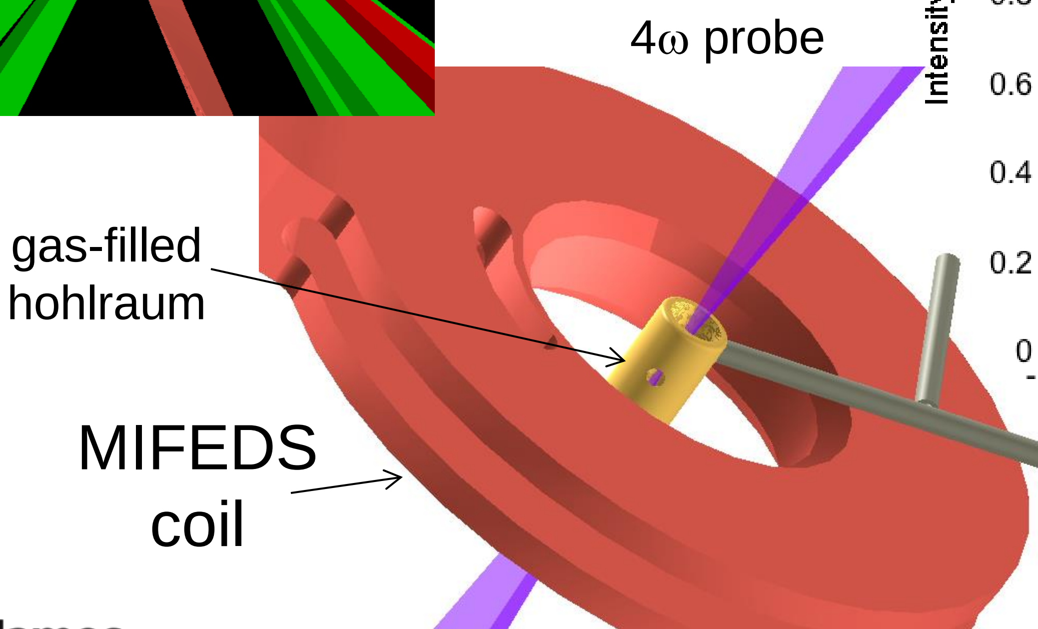


- 19-kJ of 3ω in 1-ns pulse (39 beams, 3 cones), gas-fill 0.95-atm 25% C_5H_{12} + 75% CH_4
- plasma conditions measured using 4ω Thomson scattering, delayed 0.3-ns
- external B_z applied using MIFEDS coil in a 400-ns pulse†

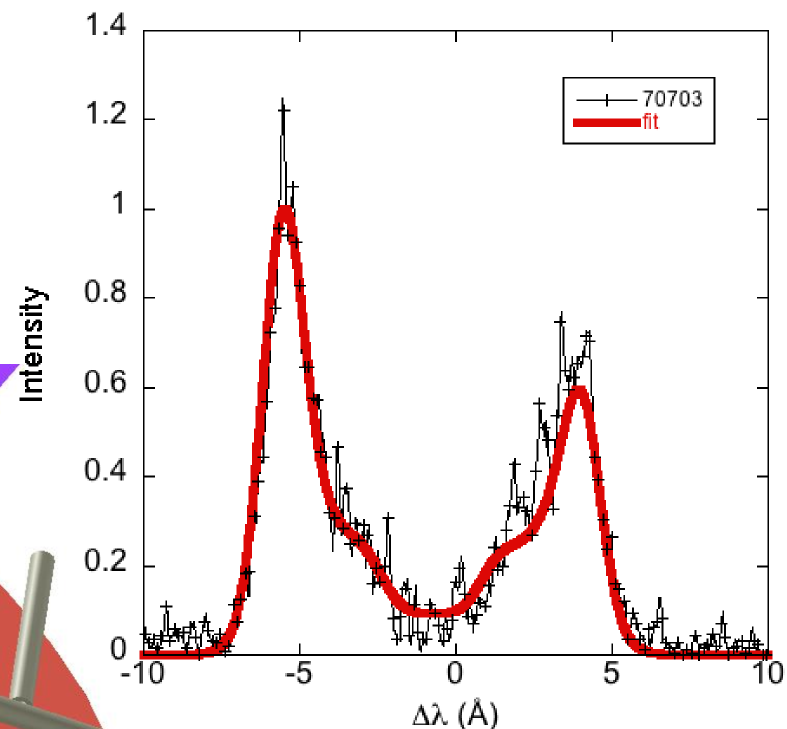
† Gotchev *et al., Rev. Sci. Instrum.* **80**, 043504 (2009).

Time-dependent plasma temperatures are measured using 4ω Thomson scattering



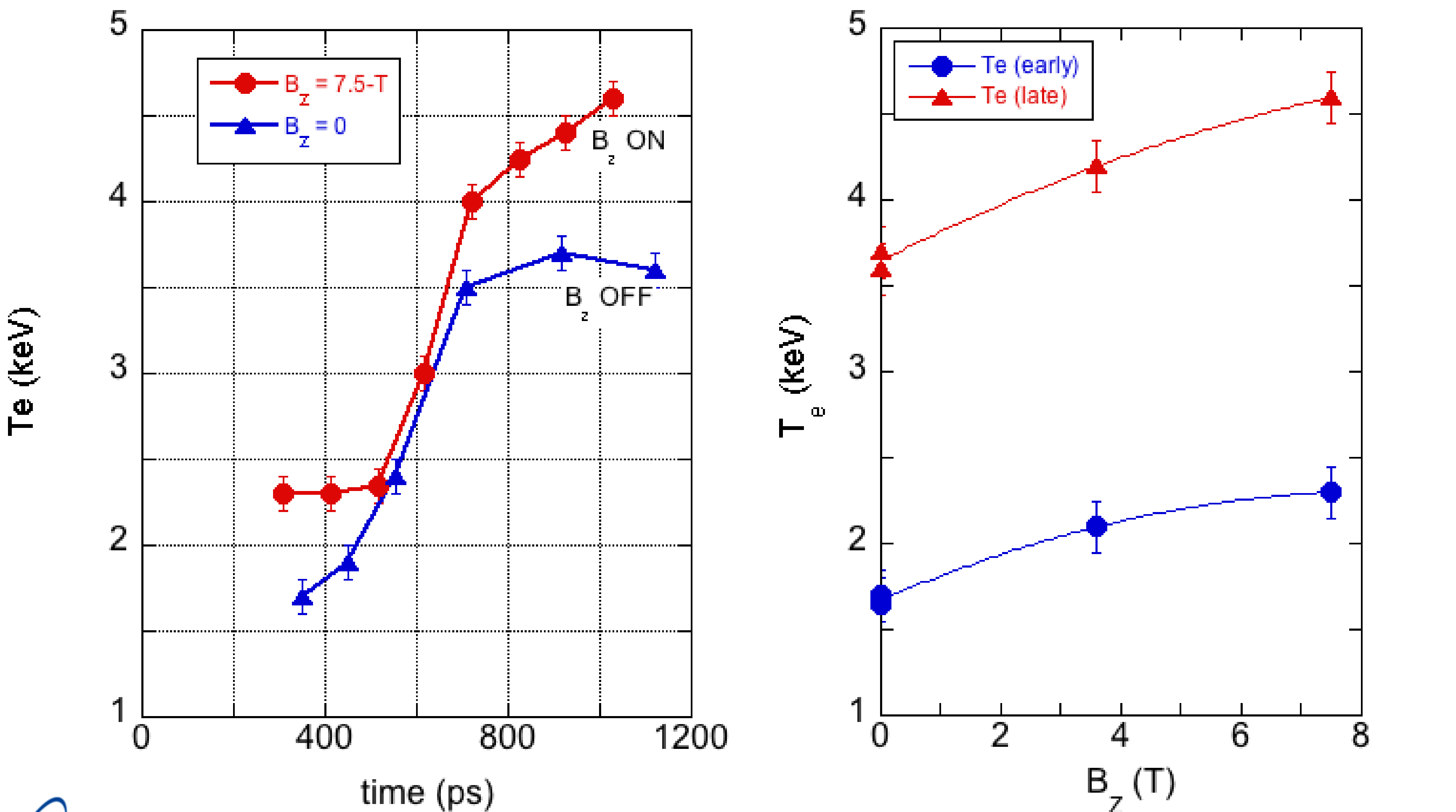


Thomson spectrum at t = 1-ns



multi-species form factor fit: $T_e \pm 0.1$-keV

A substantial increase in plasma temperature is observed with external B-field



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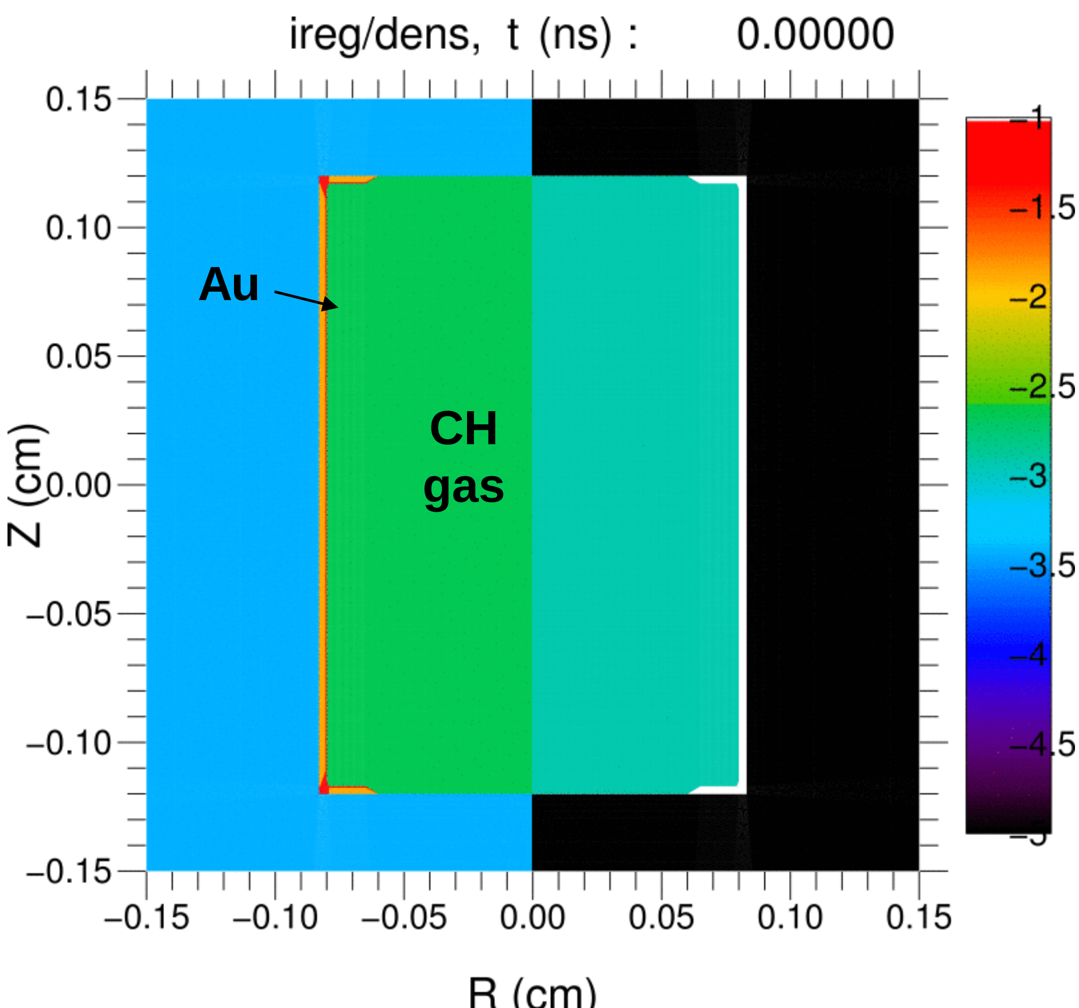
Material regions and log(density) contour plots from 2-D HYDRA simulations - movie



- **Material regions**
  Au (red)
  CH gas (green)
- **Log(density)**
- **Plots very similar with and without B_z**

  (i.e. β >> 1, B-field affects thermal conduction but not hydro)

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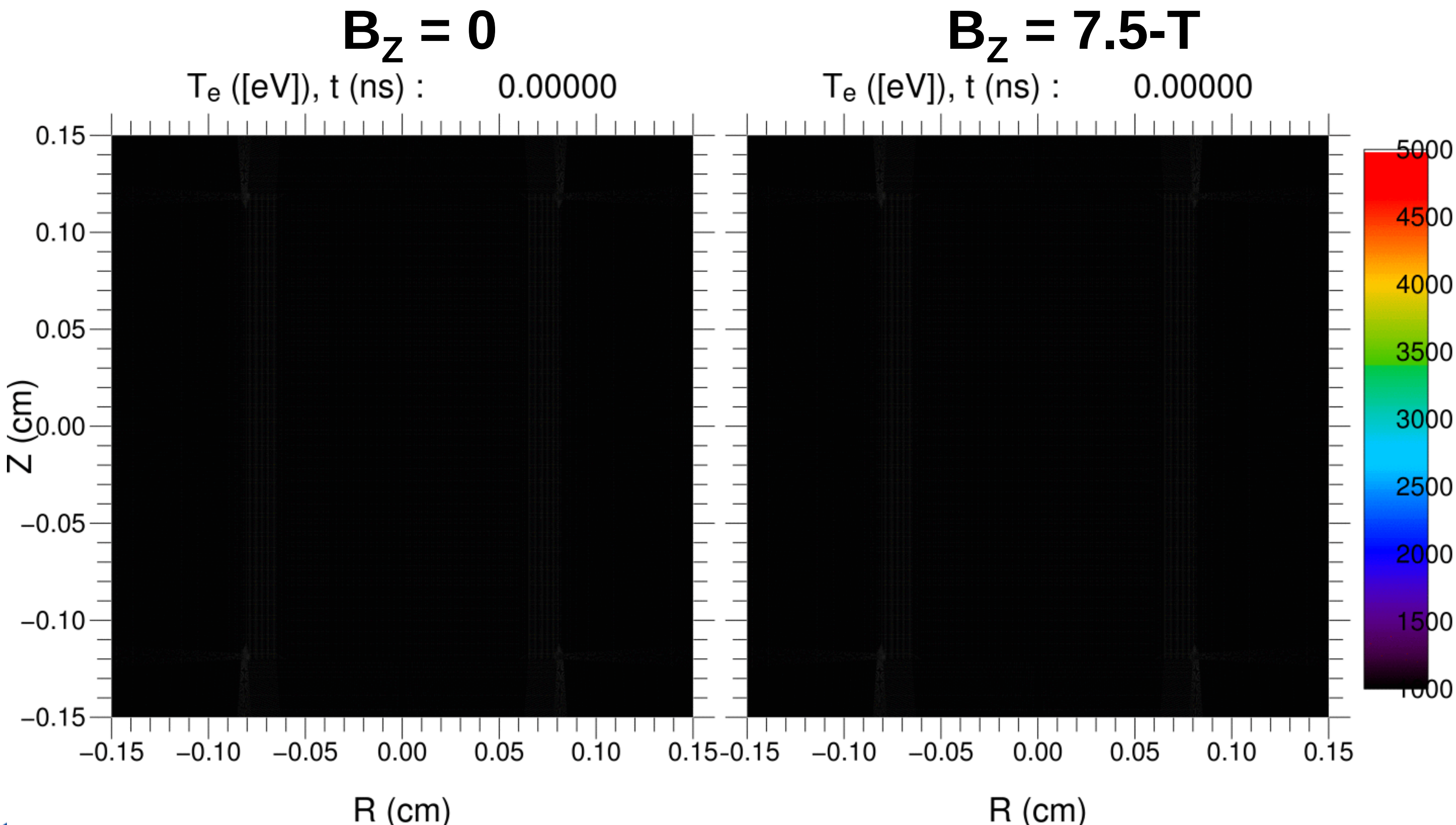
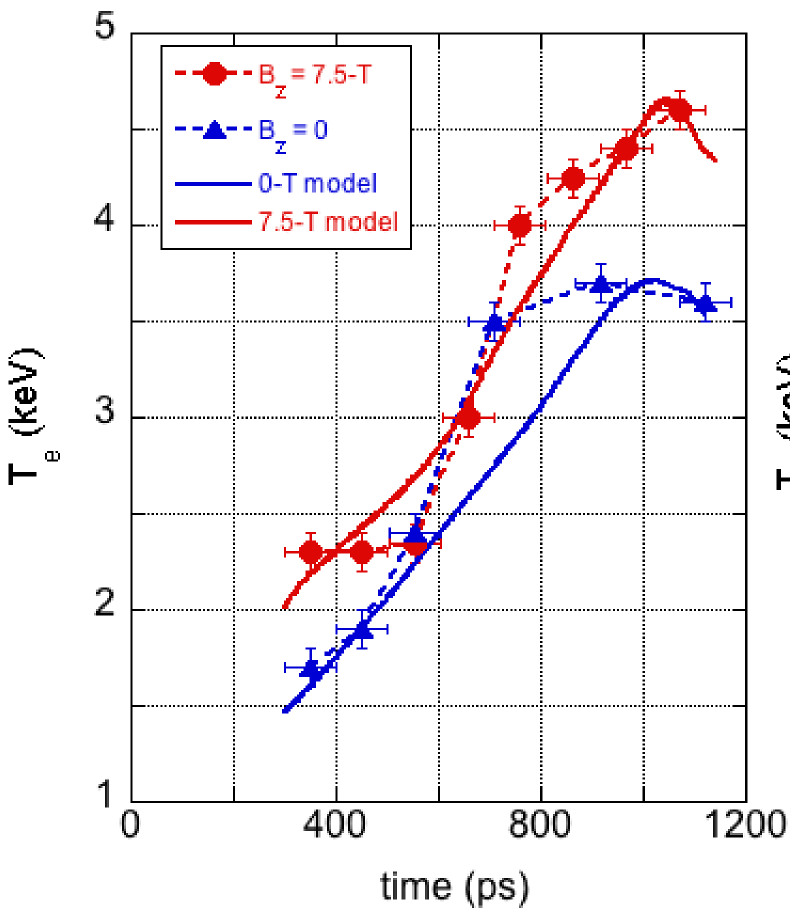
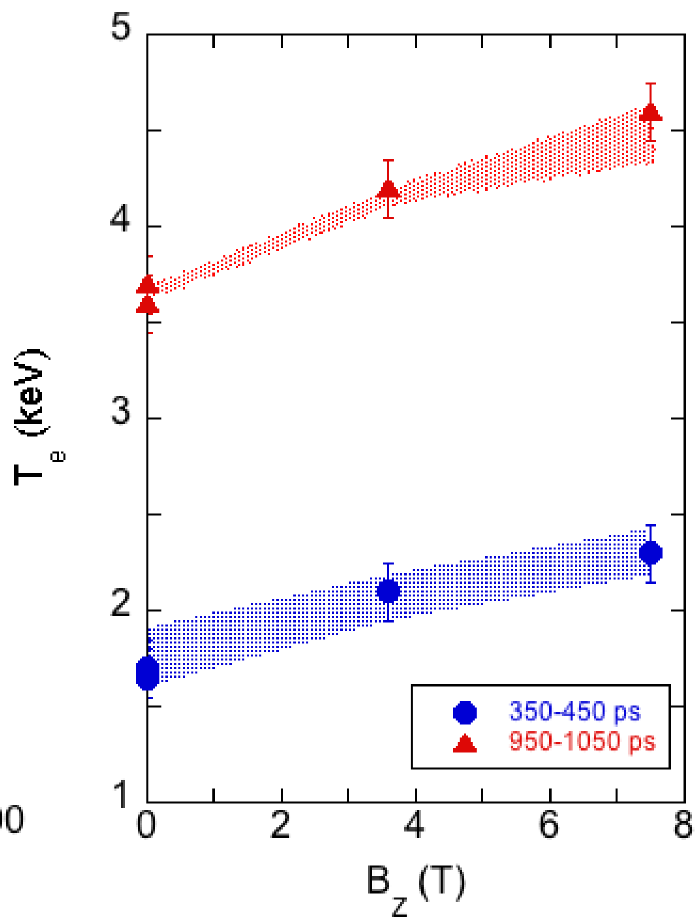
2-D HYDRA simulations show an increase in plasma temperature with external B_z = 7.5-T



movie

2-D HYDRA modeling is in good agreement with measured plasma temperatures†





- **HYDRA model:**
  - used measured laser parameters
  - flux limiter f = 0.05
  - no self-fields
  - overall trends compare well
  - rapid temperature rise not captured at intermediate times (sampling region different between expt & model).

† D.S. Montgomery *et al.*, *Phys. Plasmas* (2015)

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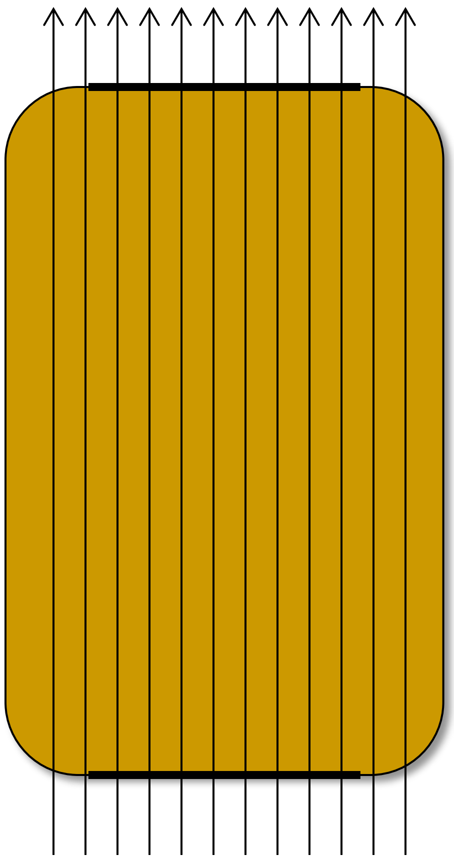
What is the limit for an empty hohlraum with very large B_z?? (conduction only)



B_z

Assume straight field lines

B_z very large: $k_\perp / k_\parallel \approx 0$, but parallel losses remain

For unmagnetized:

$Q_\parallel \approx \frac{1}{4} Q_\perp$ since the ratio of areas $\left(A_\perp + A_\parallel\right)/A_\parallel \approx 4$

Unmagnetized heat flux: $Q \sim T_e^{7/2}$

Maximum increase: $4^{2/7} \approx 1.48$

2-D HYDRA:

$B_z = 0$	$T_{max} \sim 3.7$ keV
$B_z = 7.5$-T	$T_{max} \sim 4.65$ keV
$B_z = 60$-T	$T_{max} \sim 4.82$ keV

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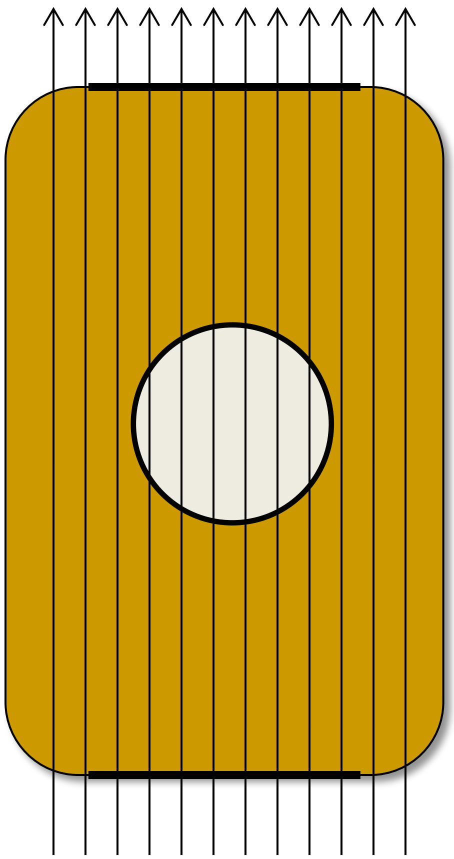
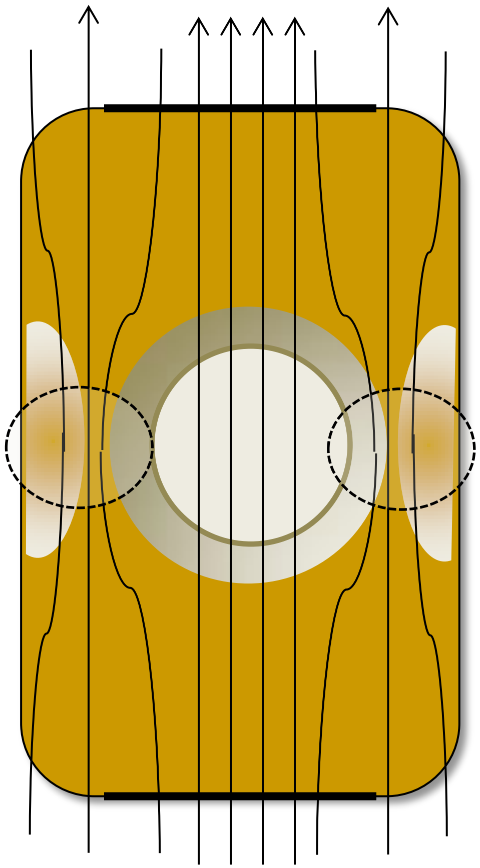
What about a hohlraum with a capsule? (cartoon not a simulation)

t=0



B_z



B_z

t ~ several ns

Magnetic mirror?

T/T_0 much larger?

Will need 2-D HYDRA simulations …

Summary and Conclusions

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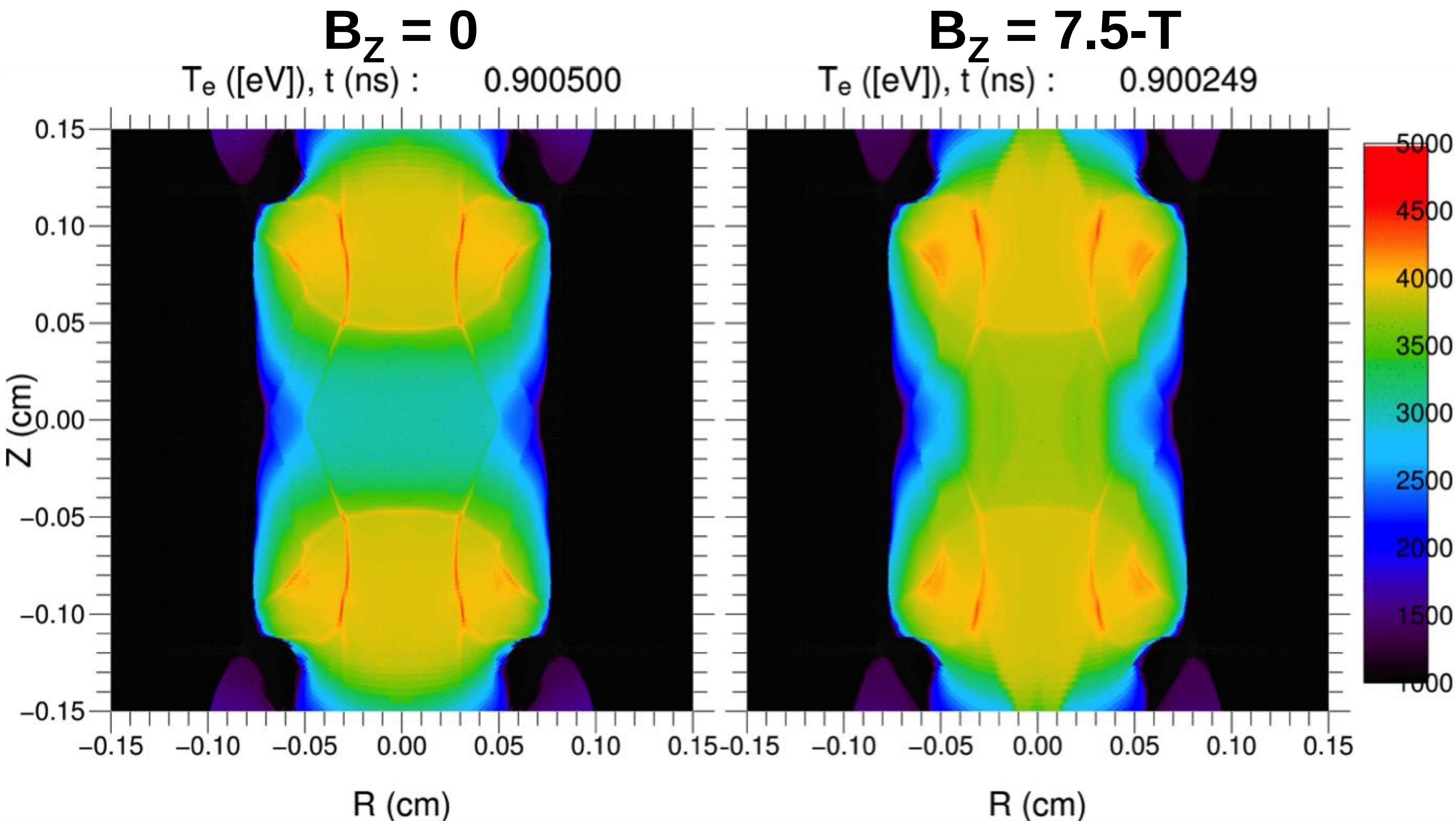
BACKUPS

2-D HYDRA simulations show an increase in plasma temperature with external B_z = 7.5-T



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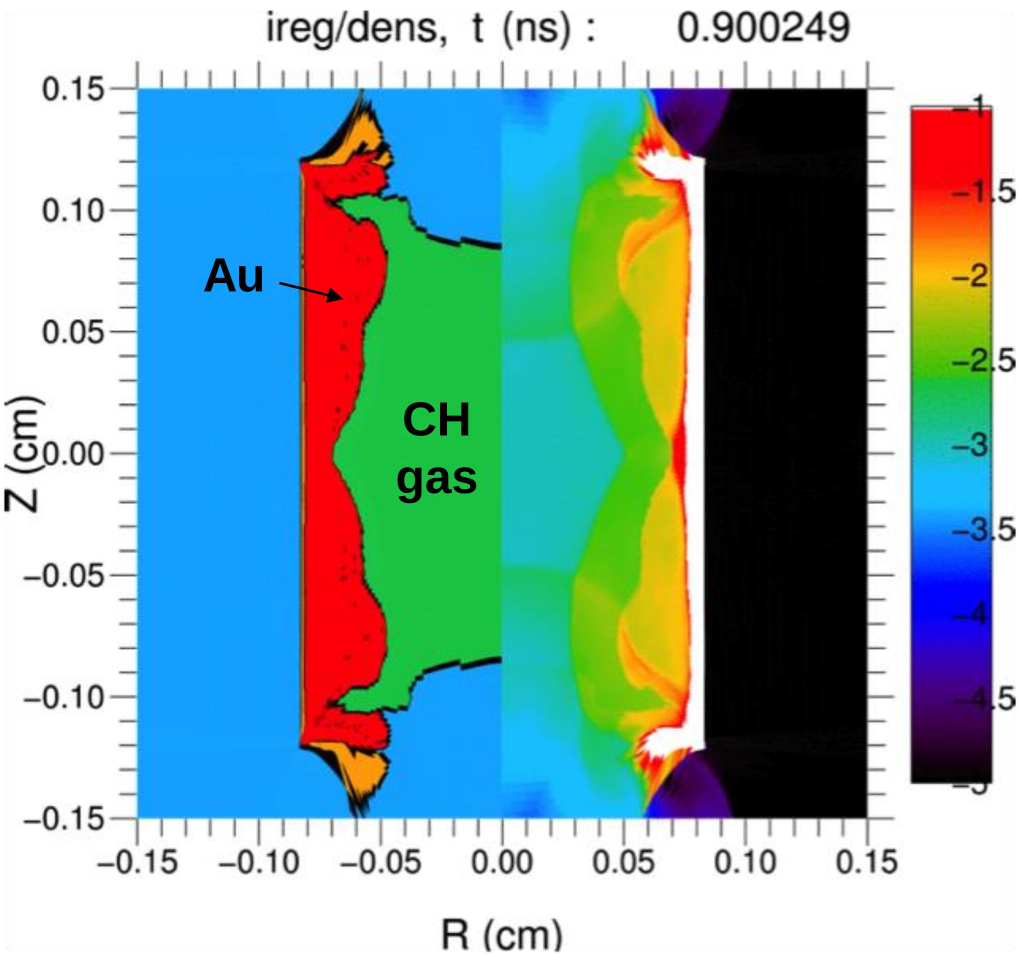
Material regions and log(density) contour plots from 2-D HYDRA simulations at t=0.9-ns



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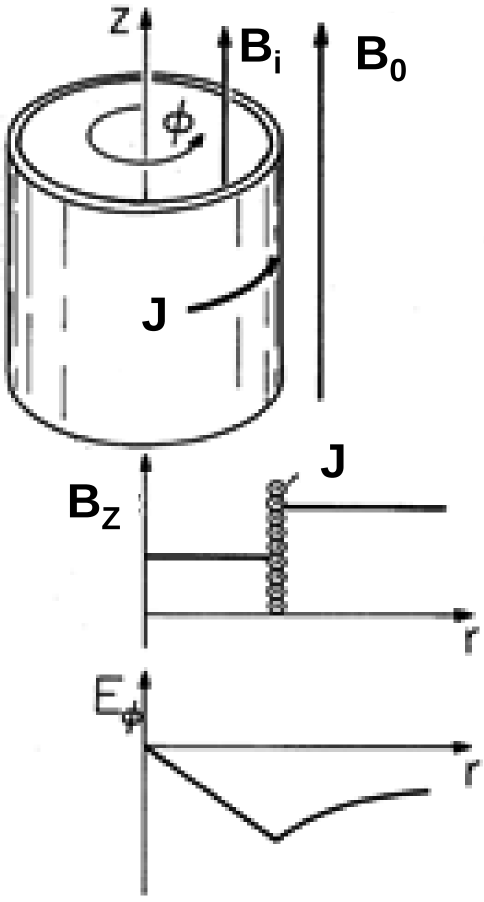
Finite diffusion time for magnetic field into the Au cylindrical hohlraum due to eddy currents



$$\frac{dB_i}{dt} + \frac{B_i}{\tau_m} = \frac{B_0}{\tau_m}$$

B_z turned on instantly at t=0

$$\tau_m = \frac{1}{2}\mu_0 \sigma \Delta a$$

Thin conducting shell of radius *a*, thickness Δ, conductivity σ

$$B_i = B_0\left(1 - e^{-t/\tau_m}\right)$$

Omega Hohlraum	NIF Hohlraum
a = 0.8 mm	a = 2.5 mm
Δ = 5-µm	Δ = 25-µm
σ_{Au} = 4e7 (ohm-m)$^{-1}$	σ_{Au} = 4e7 (ohm-m)$^{-1}$
τ_m ~ 100-ns	τ_m ~ 1.6-µs

σ_{Au} is for 99.9% pure Au at room temperature, consider adding impurities, e.g. 0.5% at. Ti + 99.5% Au decreases σ to 1e7 (ohm-m)$^{-1}$, then τ_m ~ 400-ns.

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