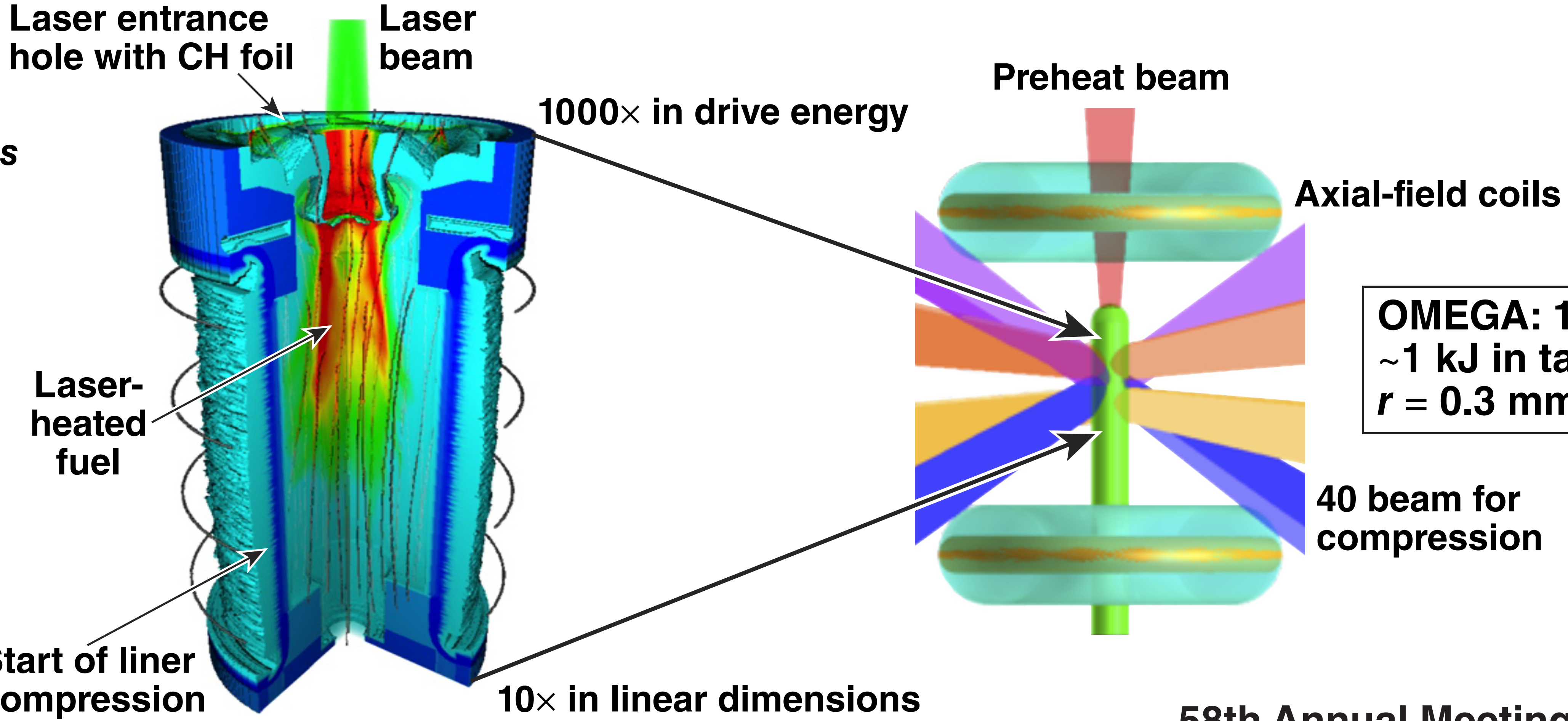
Temperature Scaling for Magnetized Liner Inertial Fusion

Axial-field coils not shown

Z: 19 MA
~1 MJ in target
r = 3 mm



OMEGA: 14.5 kJ
~1 kJ in target
r = 0.3 mm

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Summary

Laser-driven magnetized liner inertial fusion (MagLIF) using a target 10× smaller than Z is being developed on OMEGA to provide the first data on scaling*

- Thermal losses increase as dimensions are reduced
- A simple model shows the final temperature scale as $(C\rho_0 r_0 v)^{2/5}$
  - C is fuel convergence ratio, ρ_0 is initial fuel density, r_0 is initial fuel radius, and v is implosion velocity of the fuel
- Maintaining a sufficient final temperature on OMEGA requires the implosion velocity to be at least double that on Z

*D. H. Barnak, KI2.00004, this conference (invited).

Collaborators

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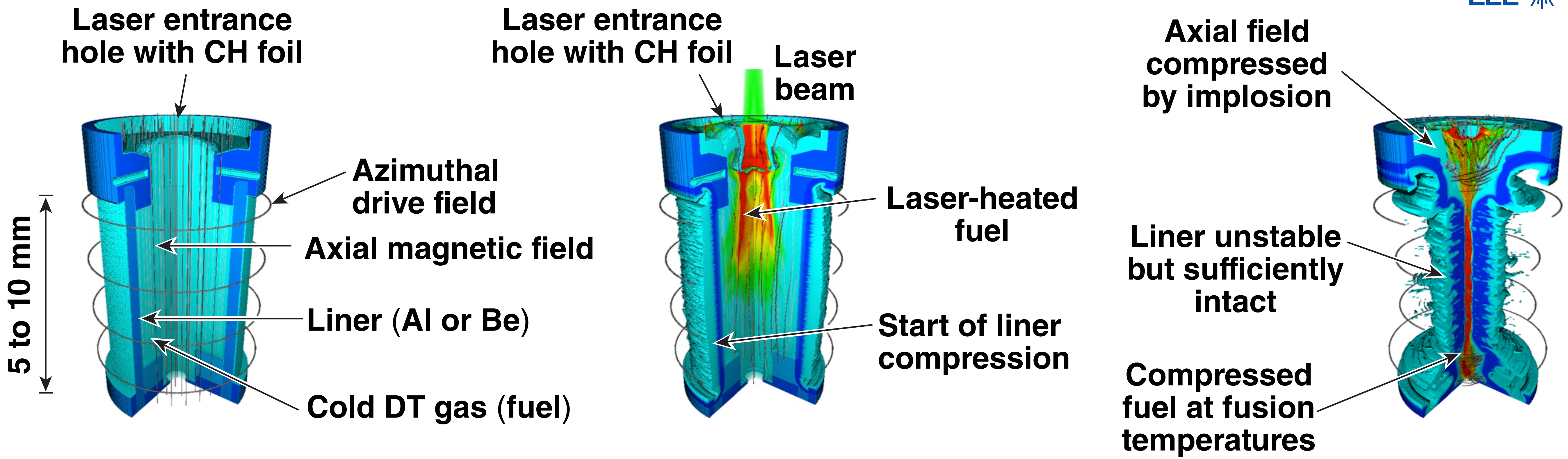
MagLIF is an inertial confinement fusion (ICF) scheme using magnetized, preheated fuel to allow for cylindrical implosions with lower velocities and lower convergence ratios than conventional ICF*



- An axial magnetic field lowers electron thermal conductivity allowing a near-adiabatic compression at lower implosion velocities and confines alpha particles if BR > 0.6 T-m, allowing a lower areal density
- Preheating to ~100 eV makes it possible for >1 keV to be reached at a convergence ratio <30

I2185e

*S. A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

MagLIF is now being considered as a possible route to fusion ignition in the laboratory by the NNSA (National Nuclear Security Agency) along with indirect and direct drive

- DD fusion yields of 3.2×10^{12}, neutron-averaged ion temperatures of 2.5 keV, and magnetic confinement of charged fusion products (BR ~ 0.4 T-m) have been obtained in Z experiments*
- Z is the only pulsed-power facility capable of carrying out MagLIF experiments; at least ~7 MA is required and Z cannot measure yields at lower currents
- OMEGA can carry out laser-driven MagLIF experiments because it has a magnetic-field generation capability [magneto-inertial fusion electrical discharge system (MIFEDS)]

Laser-driven MagLIF on OMEGA will provide the first data on scaling and more shots with better diagnostic access than Z.

*M. R. Gomez *et al*., Phys. Rev. Lett. 113, 155003 (2014).
P. F. Schmit *et al*., Phys. Rev. Lett. 113, 155004 (2014).

E25697

OMEGA delivers 1000× less energy than Z so linear dimensions must be reduced by a factor of 10×

- A radius of 0.3 mm versus 2.79 mm on Z experiments was chosen to match existing phase plates
- MIFEDS could provide $B_z \sim 10$ T as used in Z experiments
- In the absence of thermal transport, OMEGA could achieve the same convergence ratio, implosion velocity, and temperature as Z
- Magnetic confinement of charged fusion products will be lost because their Larmor radius remains the same; BR is 10× lower
- Thermal conduction losses will be greater in smaller targets because of the increased surface-area-to-volume ratio and increased temperature gradient—how does this scale?

E25698

Estimate fuel temperature using a "0 D" energy balance with ion thermal conduction to a cold shell and compression at constant velocity

$$\nabla T \sim \frac{T}{r}$$

$$\frac{d}{dt}\left(3neT\pi r^2\right) \sim -K_0 T^{5/2} \frac{T}{r} 2\pi r - 2neT \frac{d}{dt}\left(\pi r^2\right)$$

$$\frac{T}{T_c} = \frac{0.7^{2/5} C^{4/3}}{\left[C^{7/3} - 1 + 0.7\left(T_c / T_0\right)^{5/2}\right]^{2/5}}$$

$$T_c = \left(\frac{2en_0 r_0 v}{K_0}\right)^{2/5} \text{eV}$$

r **is fuel outer radius, not radial coordinate**

E25699

Estimate fuel temperature using a "0 D" energy balance with ion thermal conduction to a cold shell and compression at constant velocity

$$\nabla T \sim \frac{T}{r}$$

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E25699a

UNIVERSITY of ROCHESTER

Estimate fuel temperature using a "0 D" energy balance with ion thermal conduction to a cold shell and compression at constant velocity

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$$\frac{T}{T_c} = \frac{0.7^{2/5} C^{4/3}}{\left[C^{7/3} - 1 + 0.7\left(T_c/T_0\right)^{5/2}\right]^{2/5}}$$

$$T_c = \left(\frac{2en_0 r_0 v}{K_0}\right)^{2/5} \text{eV}$$

***r* is fuel outer radius, not radial coordinate**

E25699b

Estimate fuel temperature using a "0 D" energy balance with ion thermal conduction to a cold shell and compression at constant velocity

$$\nabla T \sim \frac{T}{r}$$ Ion thermal conduction

$$\frac{d}{dt}\left(3neT\pi r^2\right) \sim \boxed{-K_0 T^{5/2} \frac{T}{r} 2\pi r} - 2neT\frac{d}{dt}\left(\pi r^2\right)$$

$$\frac{T}{T_c} = \frac{0.7^{2/5} C^{4/3}}{\left[C^{7/3} - 1 + 0.7\left(T_c / T_0\right)^{5/2}\right]^{2/5}}$$

$$T_c = \left(\frac{2en_0 r_0 v}{K_0}\right)^{2/5} \text{eV}$$

r is fuel outer radius, not radial coordinate

E25699c

Estimate fuel temperature using a "0 D" energy balance with ion thermal conduction to a cold shell and compression at constant velocity

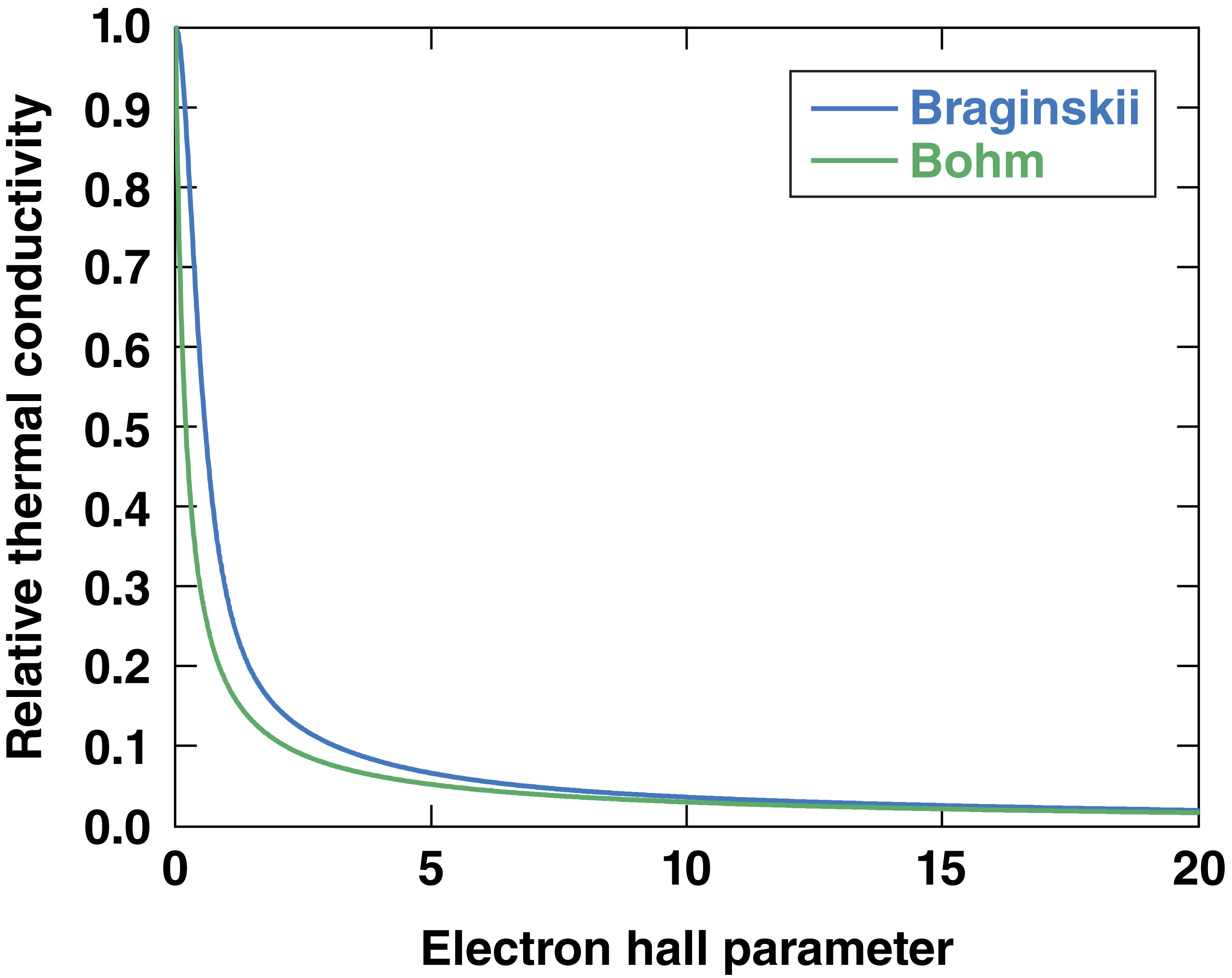
$$\nabla T \sim \frac{T}{r}$$ Ion thermal conduction

$$\frac{d}{dt}\left(3neT\pi r^2\right) \sim \boxed{-K_0 T^{5/2} \frac{T}{r} 2\pi r} - 2neT\frac{d}{dt}\left(\pi r^2\right)$$

$$\frac{T}{T_c} = \frac{0.7^{2/5} C^{4/3}}{\left[C^{7/3} - 1 + 0.7\left(T_c/T_0\right)^{5/2}\right]^{2/5}}$$

$$T_c = \left(\frac{2en_0 r_0 v}{K_0}\right)^{2/5} \text{eV}$$

r is fuel outer radius, not radial coordinate



E25699d

Estimate fuel temperature using a "0 D" energy balance with ion thermal conduction to a cold shell and compression at constant velocity

$$\nabla T \sim \frac{T}{r}$$

PdV work

$$\frac{d}{dt}\left(3neT\pi r^2\right) \sim -K_0 T^{5/2} \frac{T}{r} 2\pi r \boxed{- 2neT \frac{d}{dt}\left(\pi r^2\right)}$$

$$\frac{T}{T_c} = \frac{0.7^{2/5} C^{4/3}}{\left[C^{7/3} - 1 + 0.7\left(T_c / T_0\right)^{5/2}\right]^{2/5}}$$

$$T_c = \left(\frac{2en_0 r_0 v}{K_0}\right)^{2/5} \text{eV}$$

r **is fuel outer radius, not radial coordinate**

Estimate fuel temperature using a "0 D" energy balance with ion thermal conduction to a cold shell and compression at constant velocity

$$\nabla T \sim \frac{T}{r}$$

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(3neT\pi r^2\right) \sim -K_0 T^{5/2}\frac{T}{r}2\pi r - 2neT\frac{\mathrm{d}}{\mathrm{dt}}\left(\pi r^2\right)$$

$$\frac{T}{T_\mathrm{c}} = \frac{0.7^{2/5}C^{4/3}}{\left[C^{7/3} - 1 + 0.7\left(T_\mathrm{c}/T_0\right)^{5/2}\right]^{2/5}}$$

$$T_\mathrm{c} = \left(\frac{2en_0 r_0 v}{K_0}\right)^{2/5} \mathrm{eV}$$

r **is fuel outer radius, not radial coordinate**

E25699f

Estimate fuel temperature using a "0 D" energy balance with ion thermal conduction to a cold shell and compression at constant velocity

$$\nabla T \sim \frac{T}{r}$$

$$\frac{d}{dt}\left(3neT\pi r^2\right) \sim -K_0 T^{5/2}\frac{T}{r}2\pi r - 2neT\frac{d}{dt}\left(\pi r^2\right)$$

$$\frac{T}{T_c} = \frac{0.7^{2/5} C^{4/3}}{\left[C^{7/3} - 1 + 0.7\left(T_c/T_0\right)^{5/2}\right]^{2/5}}$$

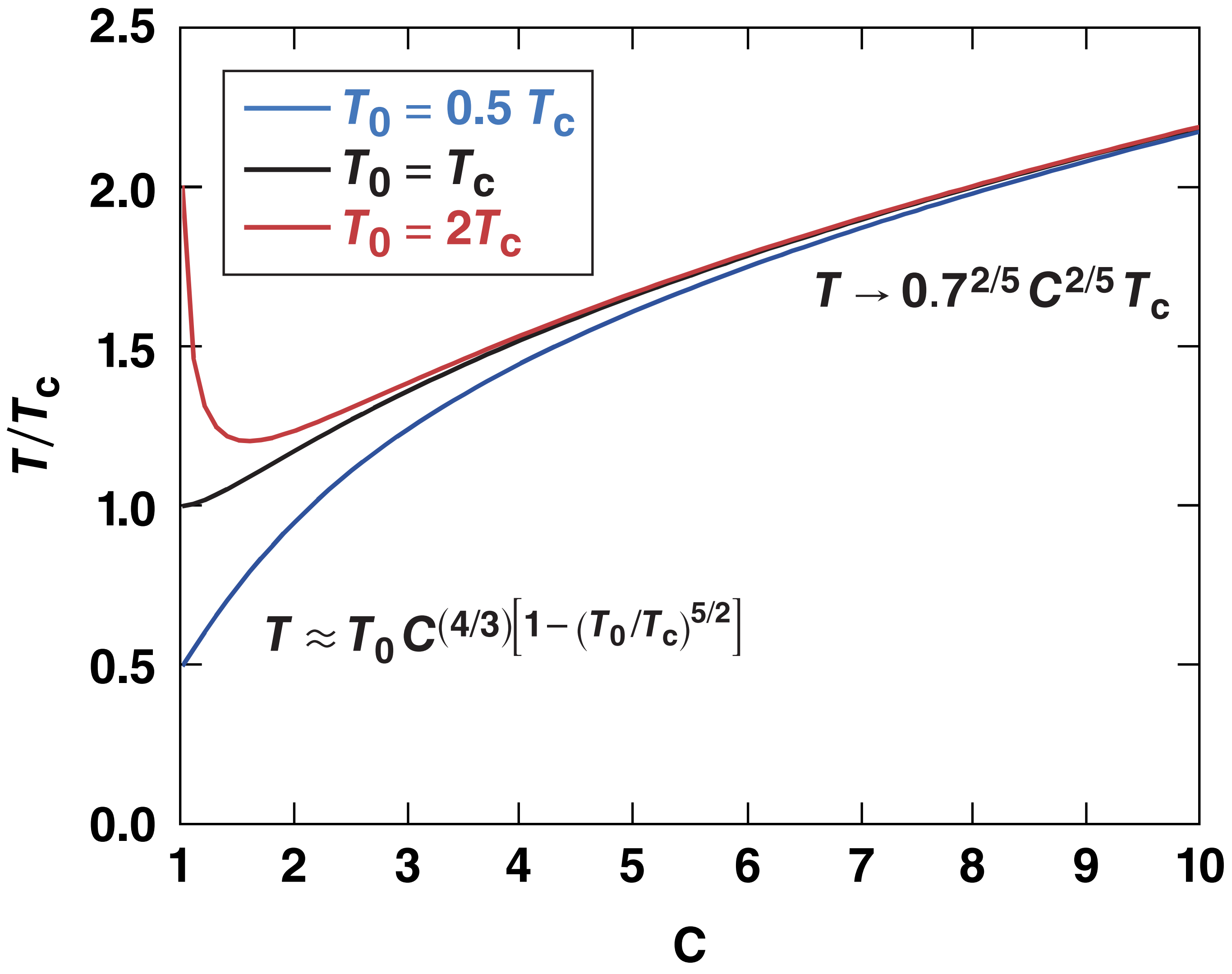
$$T_c = \left(\frac{2en_0 r_0 v}{K_0}\right)^{2/5} \text{eV}$$

Temperature at which thermal loss balances compression heating

r **is fuel outer radius, not radial coordinate**

E25699g

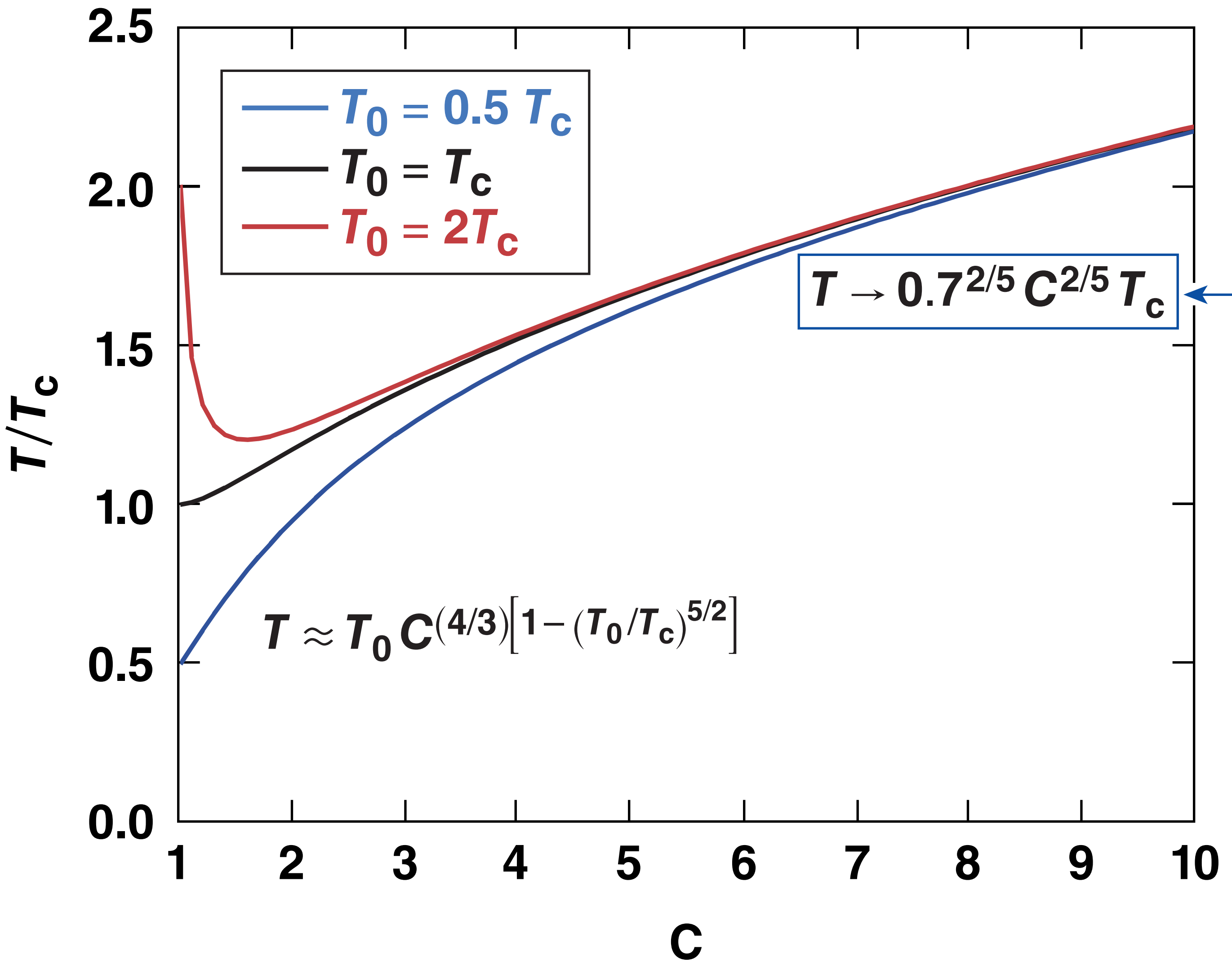
Thermal losses are significant on Z and will be even greater on OMEGA



$$T_c \sim 2\left(\sqrt{\frac{2}{A}}\,\frac{\rho_0}{1\,\text{mg/cm}^3}\,\frac{r_0}{3\,\text{mm}}\,\frac{v}{70\,\text{km/s}}\right)^{2/5}\text{keV}$$

E25700

Thermal losses are significant on Z and will be even greater on OMEGA



Regime of interest for MagLIF

$$T_c \sim 2\left(\sqrt{\frac{2}{A}}\,\frac{\rho_0}{1\,\text{mg/cm}^3}\,\frac{r_0}{3\,\text{mm}}\,\frac{v}{70\,\text{km/s}}\right)^{2/5}\text{keV}$$

E25700a

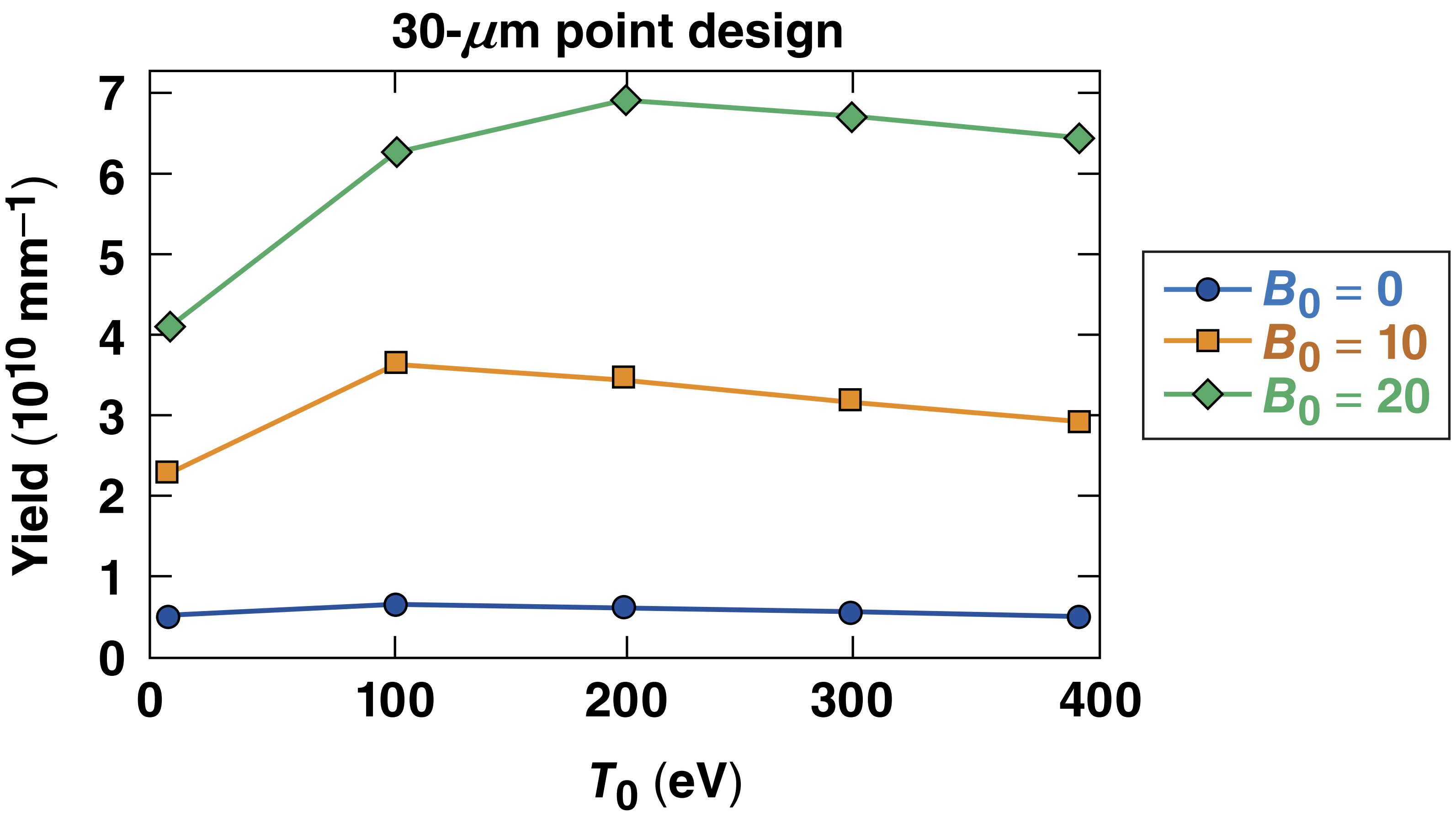
Reducing fuel radius by 10× will lower the final temperature 2.5×

- To maintain the final temperature within a factor of 2 requires an increase in $C\rho_0 v$ of at least 1.75×
- Increasing convergence ratio will increase instability growth and mix
- Increasing initial fuel density will create issues for laser preheating
- Aim for a design with roughly 2× the 70-km/s implosion velocity of the Z point design and experiments by using a relatively thinner shell
  - the current OMEGA point design has a shell aspect ratio (outer radius/thickness) of 15 versus 6 for the Z point design and experiments, giving an implosion velocity of 188 km/s in 1-D simulations
  - the peak ion temperature from 1-D simulations is 4.3 keV versus 8 keV for the Z point design

The model predicts a threshold preheat temperature in agreement with 1-D simulations

- To reach 90% of the limiting temperature requires

$$T_0 > 1.47\frac{T_c}{C^{14/15}} \sim 120\left(\sqrt{\frac{2}{A}}\ \frac{\rho 0}{2.4\ \mathrm{mg/cm^3}}\ \frac{r_0}{0.3\ \mathrm{mm}}\ \frac{v}{140\ \mathrm{km/s}}\right)^{2/5}\left(\frac{C}{25}\right)^{-14/15}\ \mathrm{eV}$$



The Z point-design parameters give $T_0 > 220$ eV

250 eV was chosen

E25702

Laser-driven magnetized liner inertial fusion (MagLIF) using a target 10× smaller than Z is being developed on OMEGA to provide the first data on scaling*

UR LLE

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E25696

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