Cone-Guided Fast Ignition with Imposed Magnetic Fields

D. J. Strozzi

Lawrence Livermore National Laboratory

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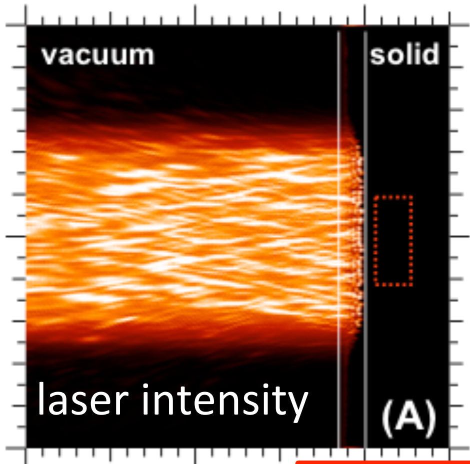
LLNL-CONF-497131

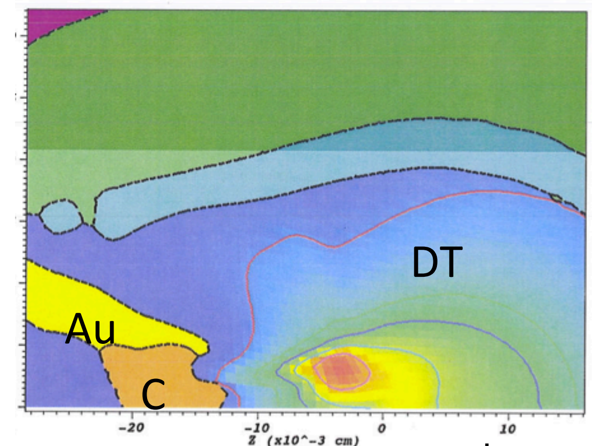
Fast ignition modeling at LLNL

Explicit PIC for short-pulse laser-plasma interaction: A. J. Kemp, L. Divol

laser

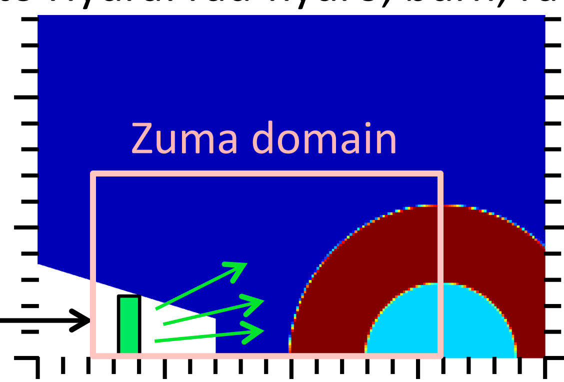


Rad-hydro: fuel assembly in hohlraum, around cone: H. D. Shay, M. Tabak, D. Ho



Transport modeling

hybrid PIC code Zuma fast electrons, E/B fields coupled to Hydra: rad-hydro, burn, radiation



fast electron injected source

plasma conditions at time of ignitor pulse

Subject of this talk

A device is needed to achieve fast ignition with a realistic, divergent electron source – we explore imposed magnetic fields

- Fast electron source from PIC sims of short-pulse laser-plasma interaction:
  - Energy spectrum has two temperature components, many electrons too energetic to stop in DT hotspot
  - Angle spectrum is divergent – serious challenge!

- Transport modeling: hybrid PIC code Zuma coupled to rad-hydro code Hydra

- Imposed uniform axial magnetic fields 30-50 MG mitigate divergence
  - Can be produced in an implosion with seed field ~ 50 kG

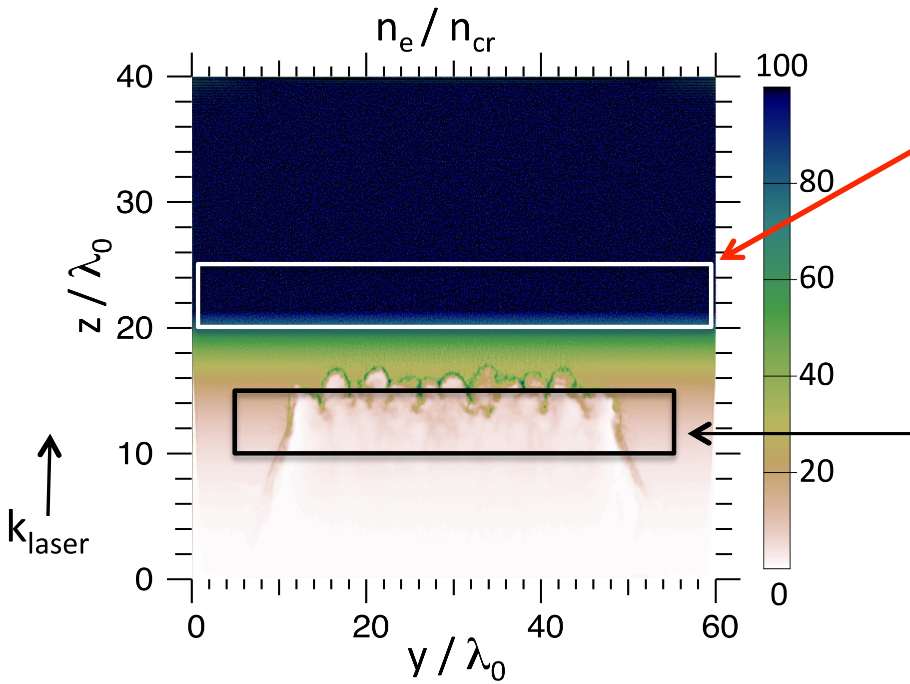
- Magnetic mirroring in non-uniform field prevents fast electrons from reaching fuel
  - Especially if fast electrons generated in uncompressed seed field

- Hollow magnetic pipe can prevent mirroring: no field within spot radius

- Co-authors: M. Tabak, D. J. Larson, M. M. Marinak, M. H. Key, L. Divol, A. J. Kemp, C. Bellei, H. D. Shay

Fast electron source distribution found from explicit PIC laser-plasma simulations with PSC code (A. Kemp, L. Divol)

Electron density (ripples due to laser absorption)



Extraction box: all fwd-going electrons with kin. en. > 0.5 MeV

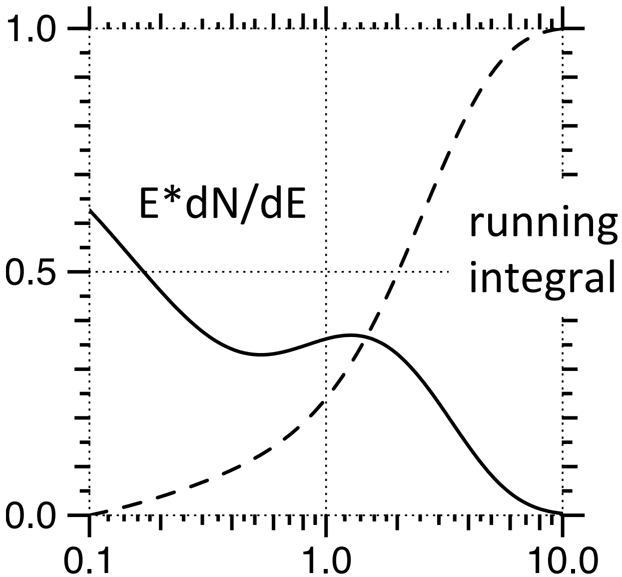
Source box: fast electrons excited here in equivalent Zuma simulation

$f(E,\theta) = f_E(E) * f_\theta(\theta)$ factorized

$I_{fast}(r,t) = 0.52 * I_{las}(r,t)$

- 3D Cartesian run, pre-plasma with $n_e \sim \exp[z / 3.5 \lambda_0]$
- Big run: 600 million cells, 10 billion particles, 160,000 cpu*hrs!
- Intensity at vacuum focus ($z = 10 \lambda_0$): $I_{las}(r) = I_0 \exp[-(r/18.3 \lambda_0)^8]$
- Normalized vector potential: $a_0 = 10$

PIC fast electron energy spectrum is quasi two-temperature



$$\frac{dN}{d\varepsilon} = 0.82\exp[-\varepsilon/1.3] + \frac{1}{\varepsilon}\exp[-\varepsilon/0.19] \qquad \varepsilon = \frac{E}{T_p}$$

"hot:" from pre-plasma

"cold:" from critical density

We scale dN/dE with ponderomotive temperature[1]

$$\frac{T_{\text{pond}}}{m_e c^2} \equiv \left[1 + a_0^2\right]^{1/2} - 1 \sim a_0 \equiv \text{sqrt}\left[\frac{I_{las}\lambda^2}{1.37\cdot 10^{18}\ \text{W cm}^{-2}\mu\text{m}^2}\right]$$

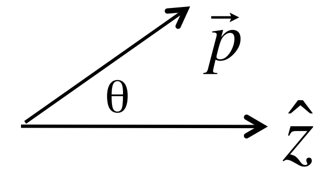
For our PIC run: $a_0 = 10$, $T_{pond} = 4.63$ MeV

- DT hot spot: $\rho\Delta z \sim 1.2$ g/cm^2 removes 1.4 MeV from a fast electron (neglecting angular scatter)
  - Spectrum is too energetic to stop in hot spot

[1]S. C. Wilks et al., Phys. Rev. Lett. (1992)

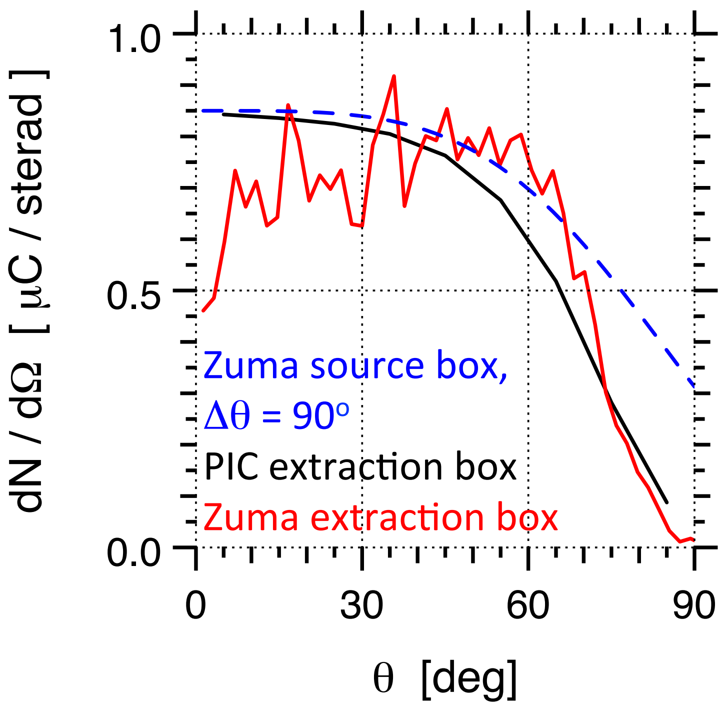
PIC fast electron angle spectrum is divergent

source solid-angle spectrum: $\frac{dN}{d\Omega} = \exp\left[-(\theta / \Delta\theta)^4\right]$

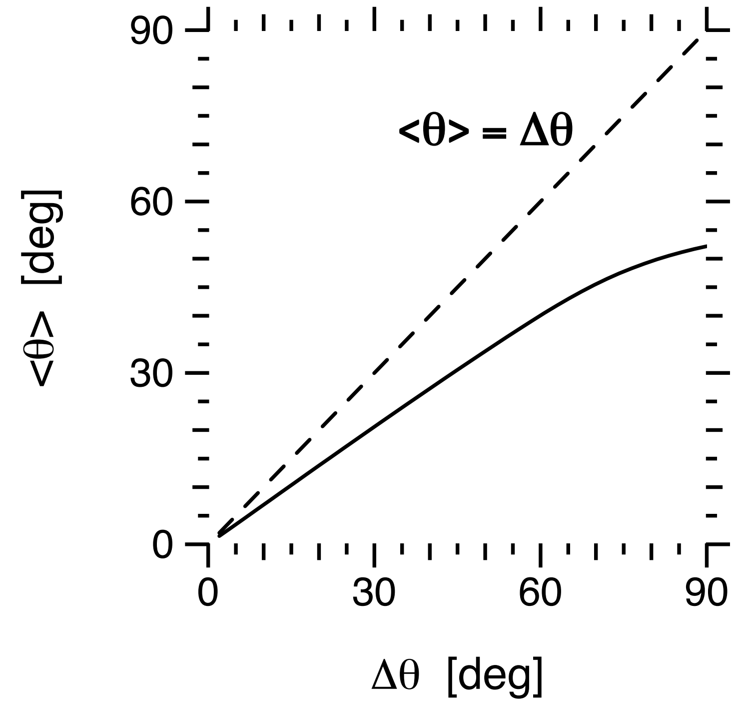


$\Delta\theta = 90^o$ agrees with PIC results

Solid angle spectrum



Average polar angle



$\Delta\theta$	$\langle\theta\rangle$	**Zuma-Hydra runs used for**
10^o	6.9^o	artificially collimated source
90^o	52^o	realistic PIC source

Zuma: Hybrid PIC code (D. J. Larson)

- Reduced dynamics removes light, plasma waves: $\omega \ll \omega_{plasma}, \omega_{laser}$ $k \ll k_{laser}, 1/\lambda_{Debye}$
- Relativistic fast electron advance: $\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B})$
- Fast e- energy loss and angular scattering: formulas of Solodov, Davies
- $\vec{J}_{\text{return}} = -\vec{J}_{\text{fast}} + \mu_0^{-1} \nabla \times \vec{B}$ Ampere's law without displacement current

- Electric field given by massless momentum equation for background electrons:

$$m_e \frac{d\vec{v}_{eb}}{dt} = -e\vec{E} + \ldots = 0 \quad \rightarrow \quad \vec{E} = \vec{E}_C + \vec{E}_{NC}$$

$$\vec{E}_C = \vec{\eta} \bullet \vec{J}_{\text{return}} - e^{-1} \overleftrightarrow{\beta} \bullet \nabla T_e \qquad \vec{E}_{NC} = -\frac{\nabla p_e}{e n_{eb}} - \vec{v}_{eb} \times \vec{B}$$

$\vec{\eta}$, $\overleftrightarrow{\beta}$ from Lee-More-Desjarlais and Epperlein-Haines

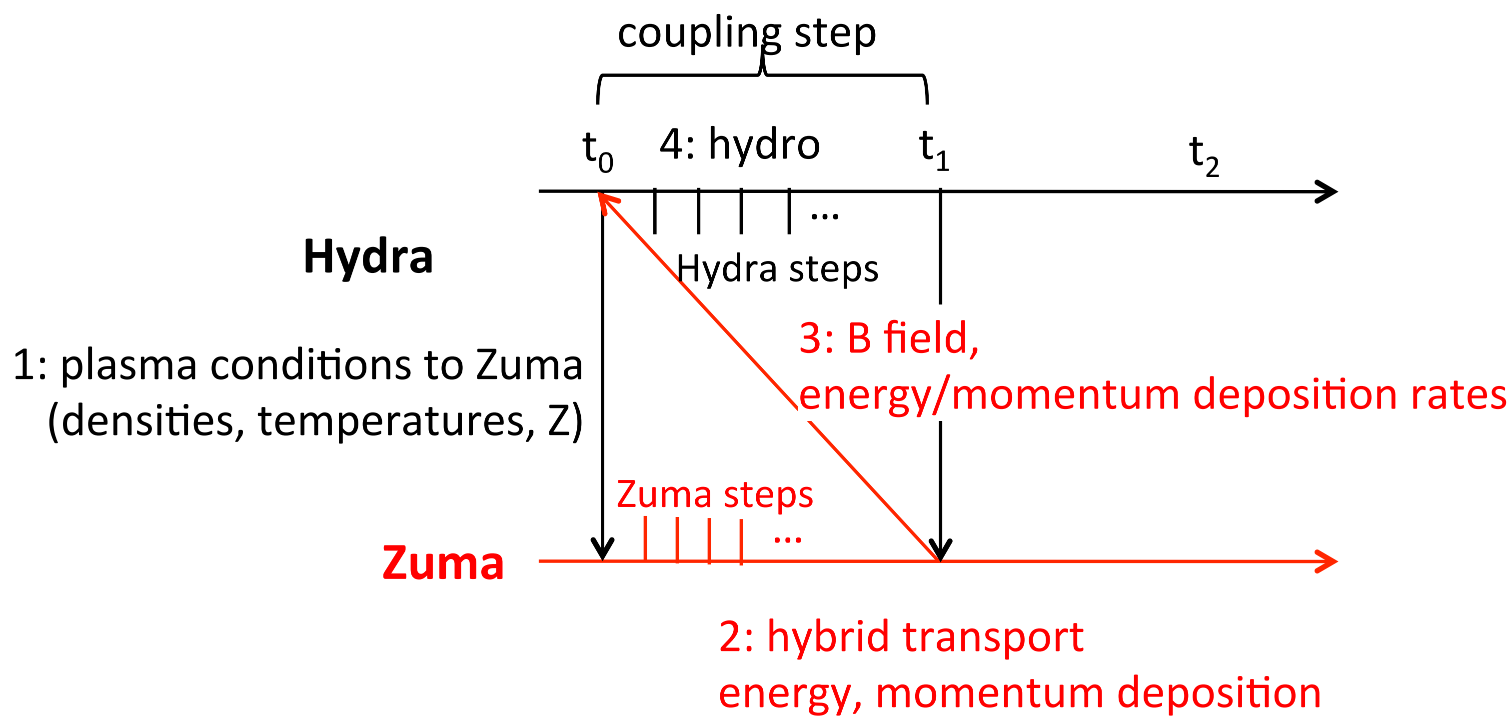
- $\vec{J}_{\text{return}} \bullet \vec{E}_C$ collisional heating
- $\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$ Faraday's law

Complete E field results can differ from $E = \eta * J_{\text{return}}$ (c.f. Nicolai et al., APS DPP 2010)

Hybrid PIC code Zuma coupled to rad-hydro code Hydra (M. M. Marinak, D. J. Larson, L. Divol)

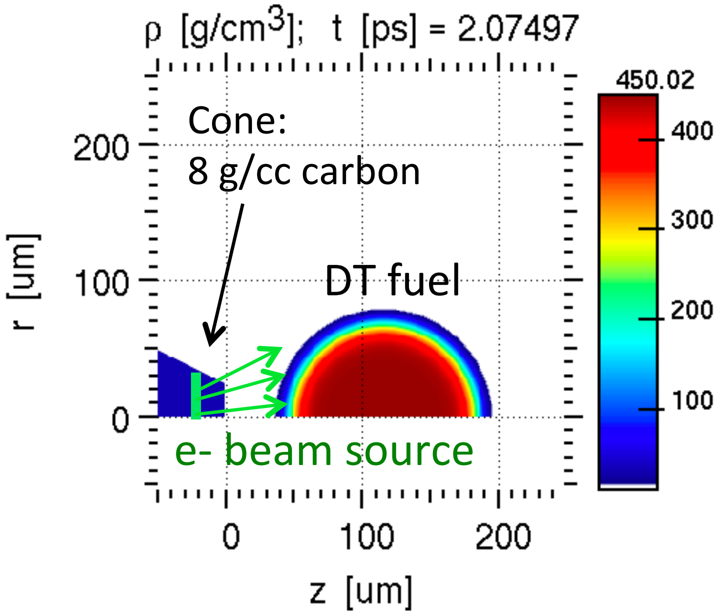
- Both codes run in cylindrical R-Z geometry on fixed Eulerian meshes (which can differ)

- Typical run: 20 ps transport (Zuma + Hydra), then 180 ps burn (just Hydra)
  - 2-3 wall-time hours on 48 cpu's



- Hydra details: IMC photonics, no MHD used yet.

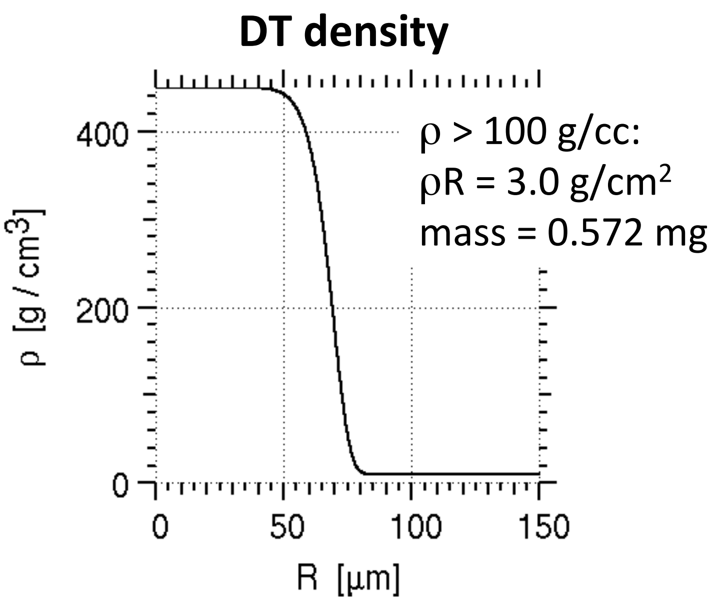
ignition-scale idealized target with carbon cone

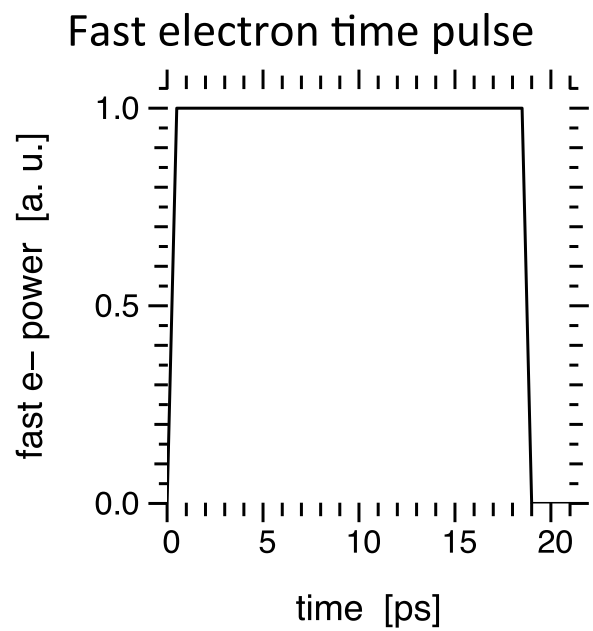


- Ideal burn-up fraction $f = \rho R/(\rho R+6) = 1/3$
- Ideal fusion yield = 338 MJ * Mass [mg] * f = 64.4 MJ

- Optimal e-beam ignition energy [Atzeni et al., PoP 2007]:
  $E_{ig} = 140 \text{ kJ} / (\rho/100 \text{ g/cc})^{1.85}$
  $= 8.7$ kJ in $\rho r = 0.6$, or $r = 13.3\ \mu$m

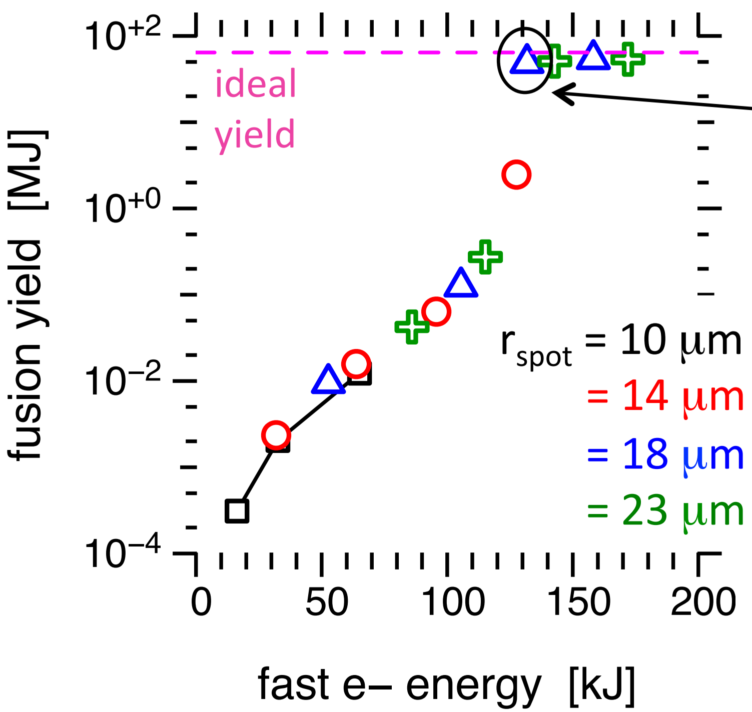
- 527 nm (2ω) wavelength laser: lowers $T_{pond} \sim \lambda$





Artificially collimated source ignites with 132 kJ of fast electrons; PIC-based divergence gives prohibitive ignition energies

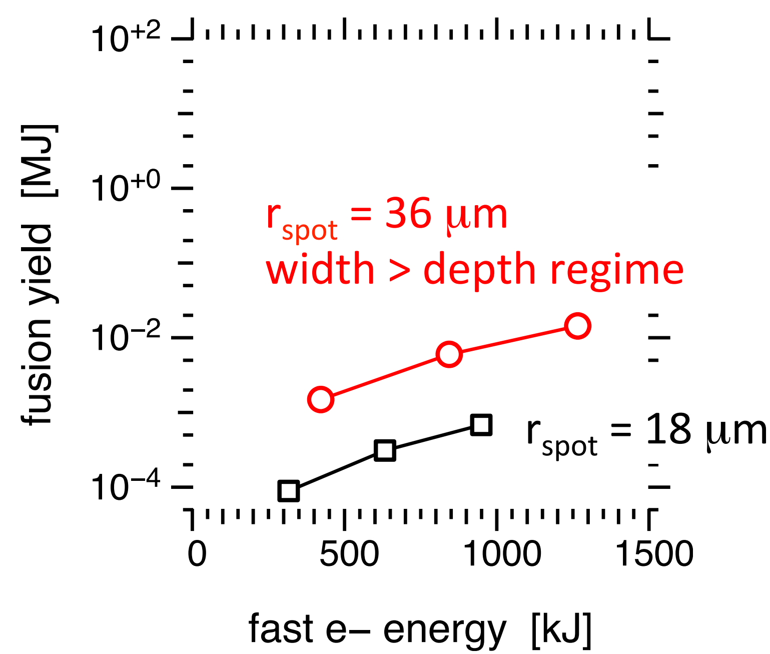
Artificially collimated source: Δθ=10º



E_{fast} = 132 kJ:
15x ideal value: spectrum too energetic to stop in hot spot; further optimization may lower

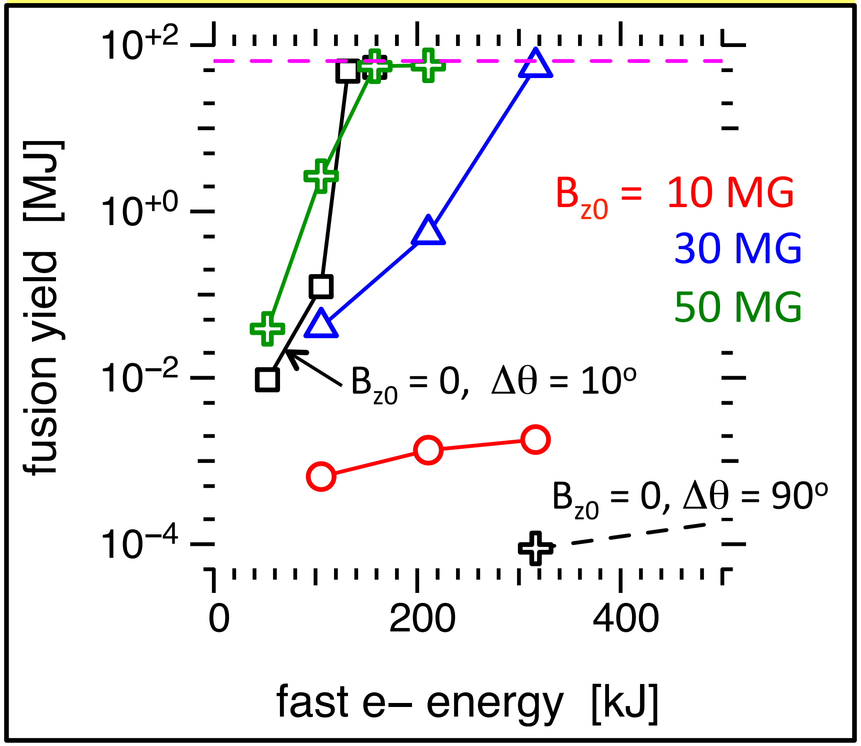
- Beam intensity = $I_0 \exp(-0.5*(r/r_{spot})^8)$

PIC-based source: Δθ=90º



Adding an initial, uniform, axial magnetic field B_z reduces ignition energy to roughly that of artificially collimated beam

B_{z0} = 50 MG ignites with 158 kJ of fast electrons, similar to $\Delta\theta$=10°



e- Larmor radius:

$$r_{Le} \propto \frac{\gamma\beta}{B} = \frac{33.4\ \mu\mathrm{m}}{B_{MG}}\left[W_{MV}^2 + 1.02 W_{MV}\right]^{1/2}$$

For 2 MeV e- (deposits well in hot spot):

r_{Le} = spot radius (18 μm) for B = 4.6 MG: lower bound on when B fields matter

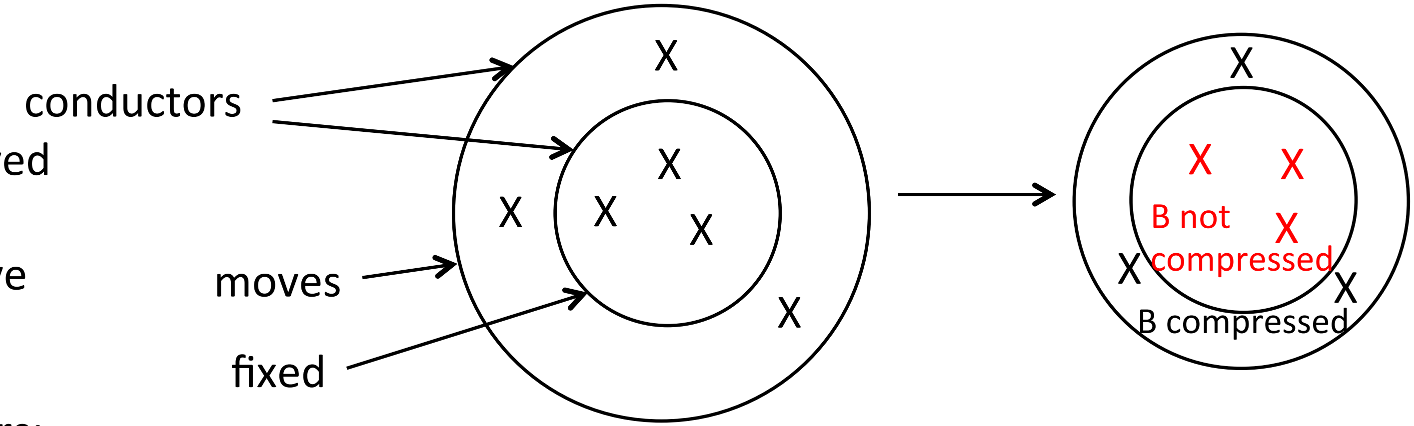
Rad-hydro-MHD studies of B field compression are underway (H. D. Shay, M. Tabak)

Omega experiments show compression of 50 kG seed B field in cylindrical implosions[1] to 30-40 MG, and in spherical implosions[2] to 20 MG

[1] J. P. Knauer, Phys. Plasmas 17, 056318 (2010) [2] P. Y. Chang et al., Phys. Rev. Lett 107(3):035006 (2011)

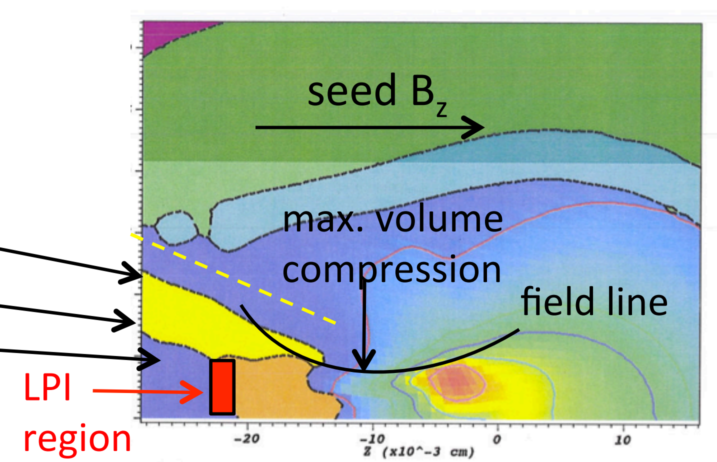
Implosion can compress magnetic field in DT, but short-pulse LPI will likely happen in the seed field

Flux $B_z * r^2$ conserved inside conductor, neglecting resistive diffusion



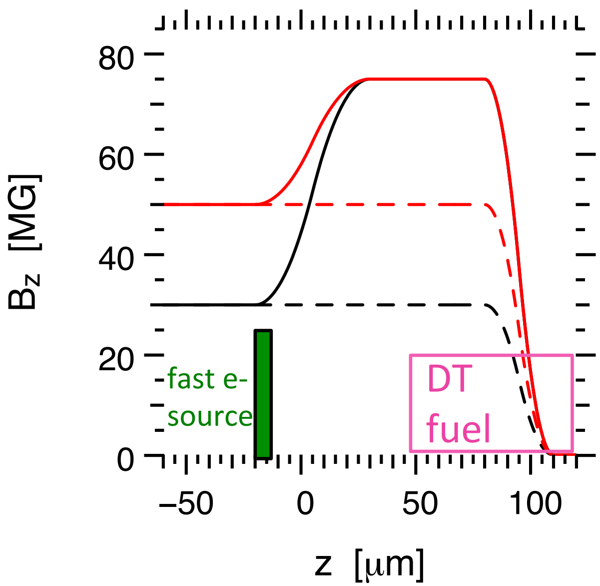
Nested conductors:
Field compressed between conductors, but not inside inner one

- Cone outer surface compressed
- Cone inner surface doesn't move – shock break-out would fill cone
- B field in vacuum region is uncompressed, neglecting diffusion

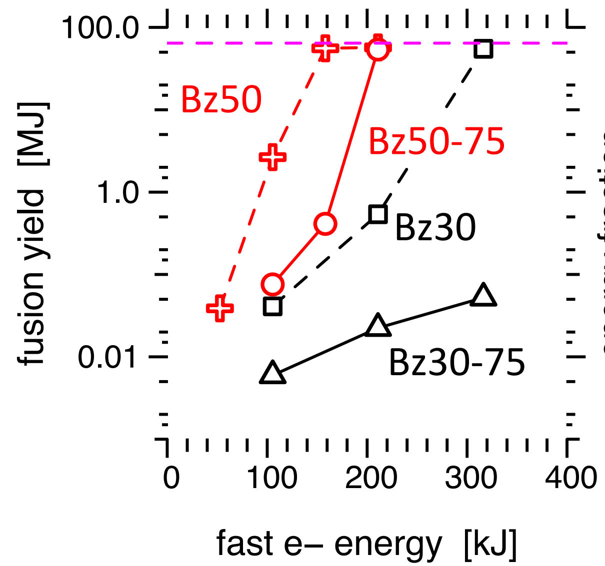


Magnetic mirroring issue 1: axial increase in magnetic field strength

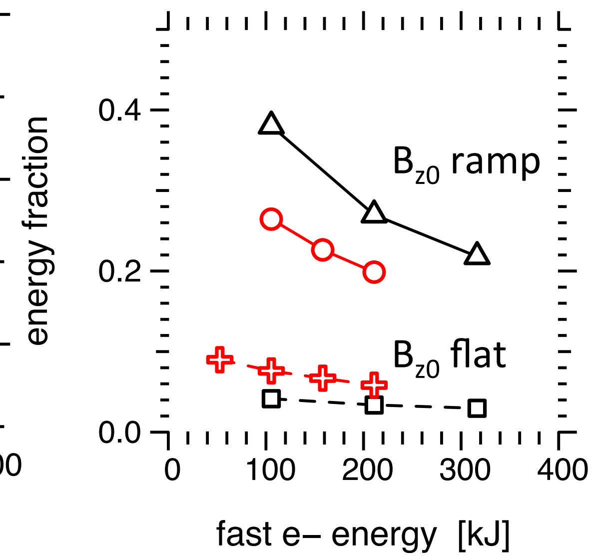
Initial B_z profiles



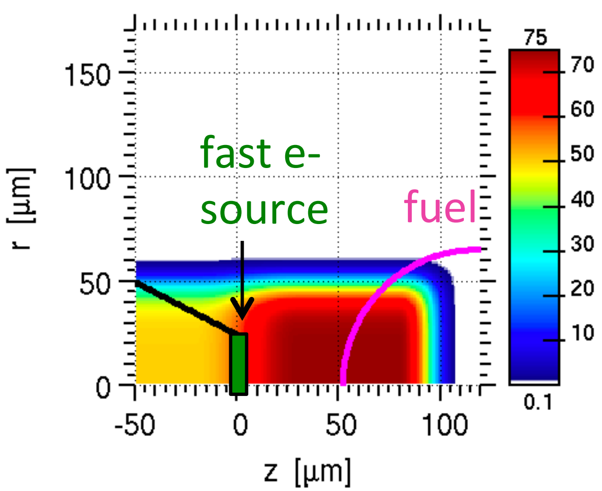
Fusion yield



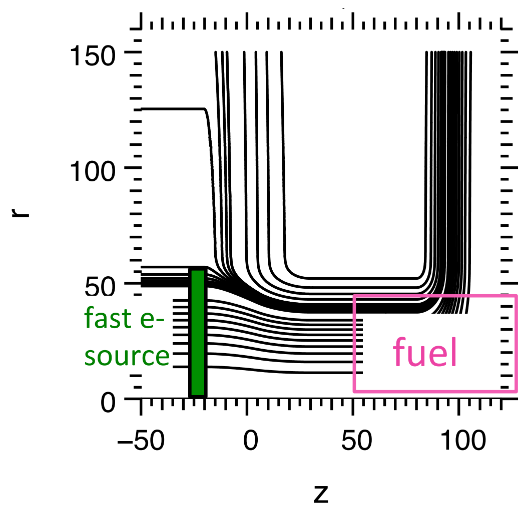
Fast e- energy reflected to left edge



Initial B_z: 50-75 MG

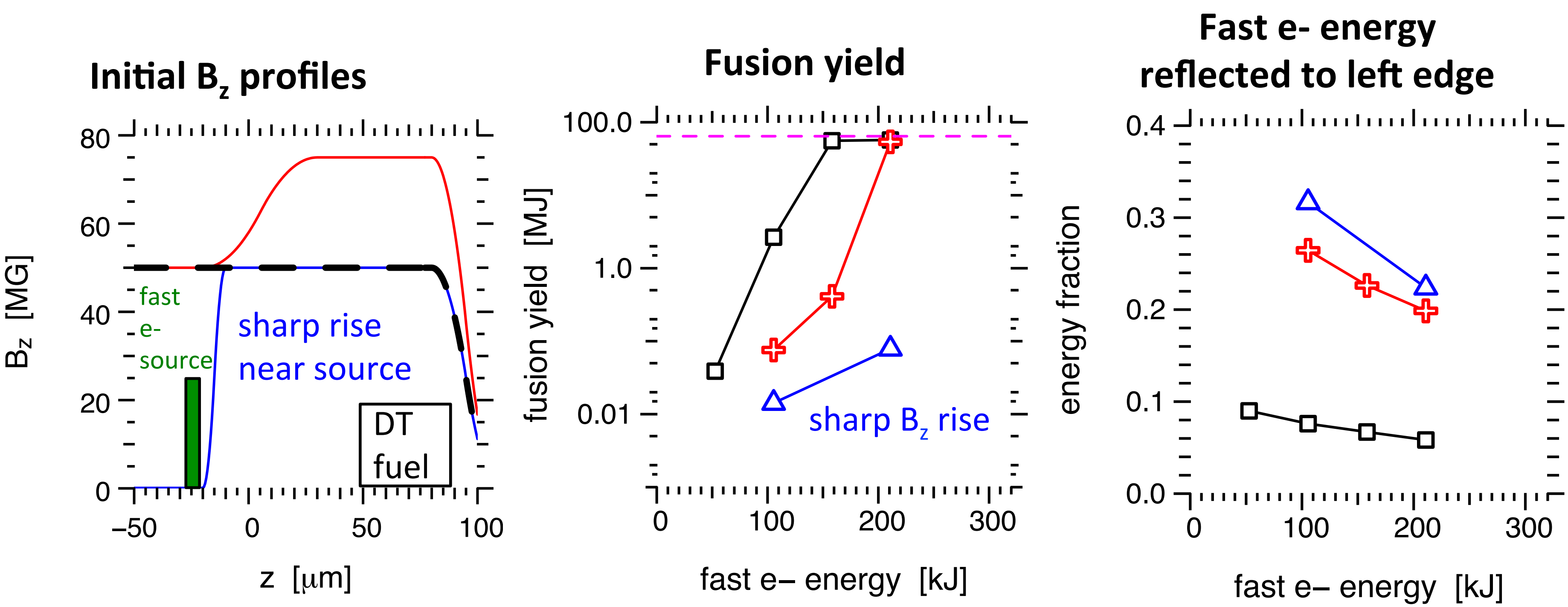


B field lines



- dB_z/dz requires B_r for div B = 0
- mirror force $F_z = e\, v_\phi\, B_r$

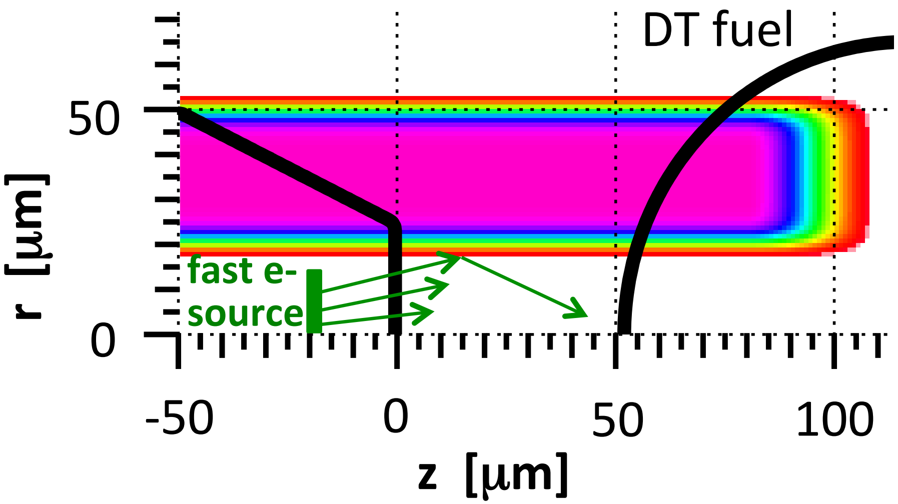
Magnetic mirroring issue 2: field low in electron source region

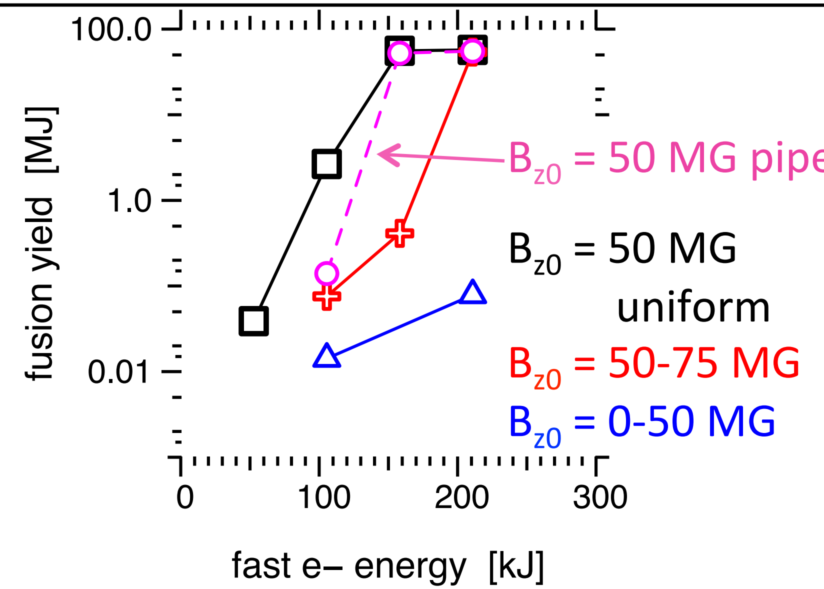


Mirroring avoided with "magnetic pipe:" B_{z0} peaks off-axis

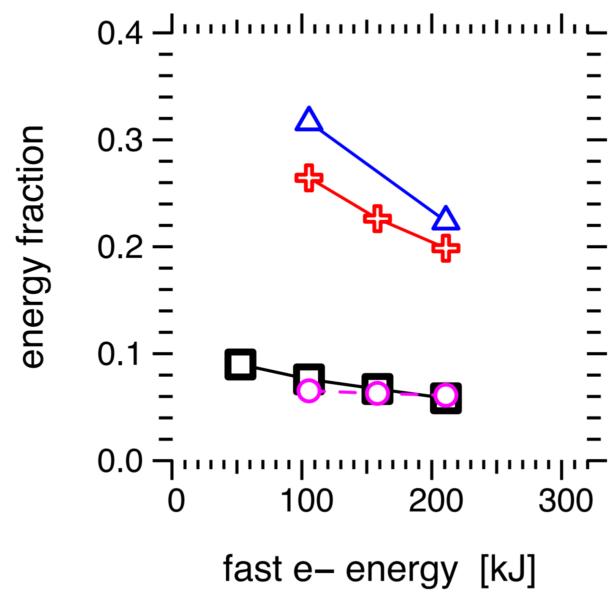
- Pipe with B_{z0} = 50 MG ignites for E_{fast} = 158 kJ
- Artifically collimated beam ($\Delta\theta$ = 10°) ignites for E_{fast} = 132 kJ

Initial B_z (max = 50 MG)



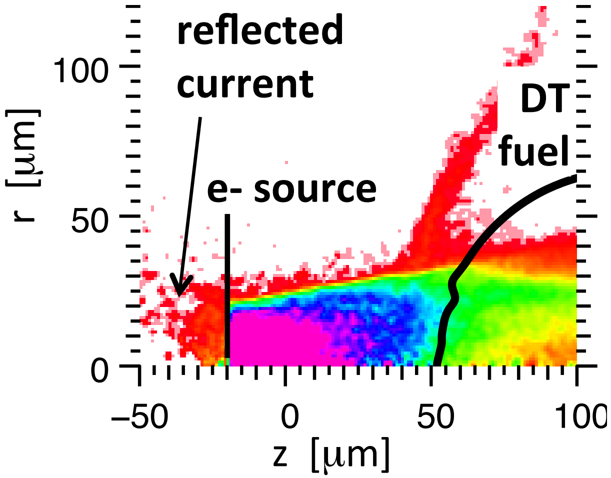


Fast e- energy reflected to left edge

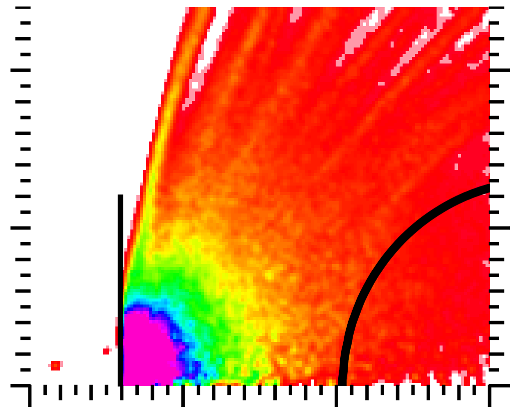


Summary: imposed magnetic fields can overcome electron source divergence; magnetic pipe avoids mirroring in non-uniform field

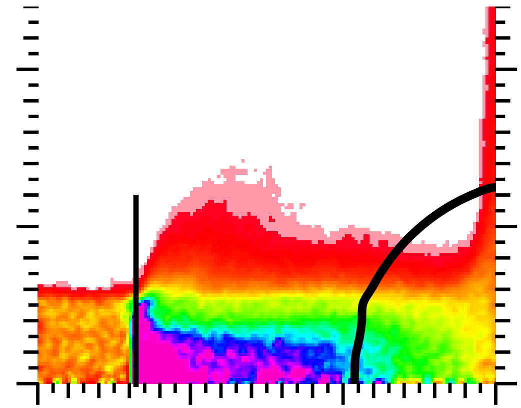
$\Delta\theta = 10^o$: ignition @ 132 kJ e-



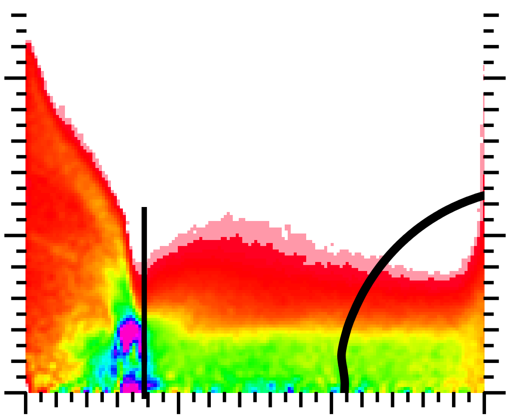
$\Delta\theta = 90^o$: ignition > 1 MJ e-



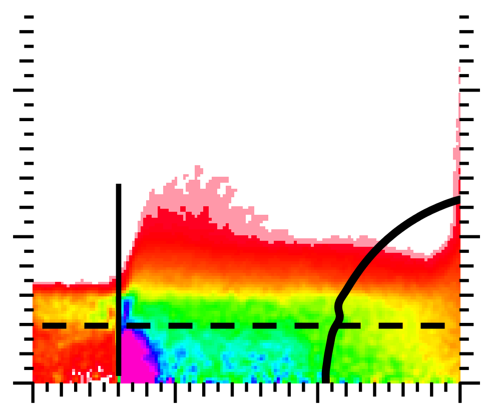
B_{z0} = 50 MG: ignition @ 158 kJ e-



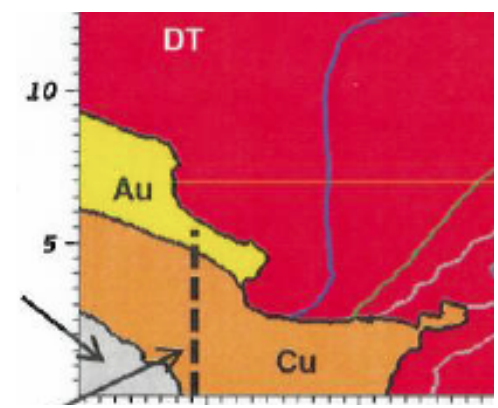
B_{z0} = 0 to 50 MG: ignition > 211 kJ e-



magnetic pipe, 20 μm radius: ignition @ 158 kJ e-



Possible pipe approach: mid-Z wire on axis, not compressed in implosion



|J_{fast}| at 10 ps (mid ignitor pulse) 0  5E17 A/m^2