Cone-Guided Fast Ignition with Imposed Magnetic Fields

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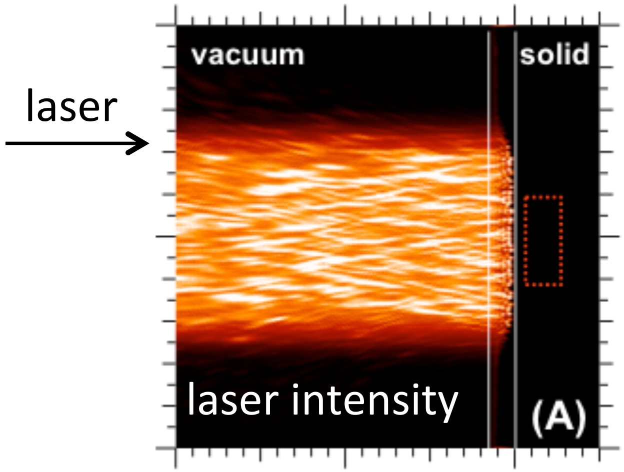
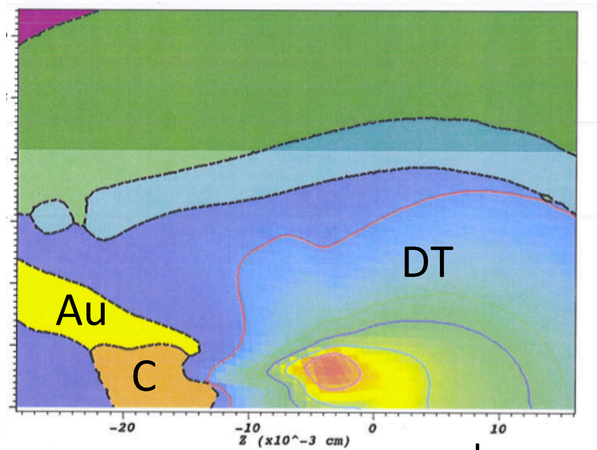
Our fast ignition modeling approach

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



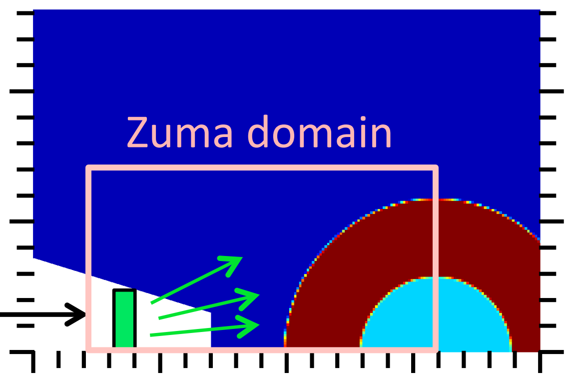
Rad-hydro: fuel assembly in hohlraum, around cone: H. D. Shay, M. Tabak, D. Ho



fast electron injected source

plasma conditions at time of ignitor pulse

Transport modeling of fast electron heating: hybrid PIC code Zuma coupled to Hydra



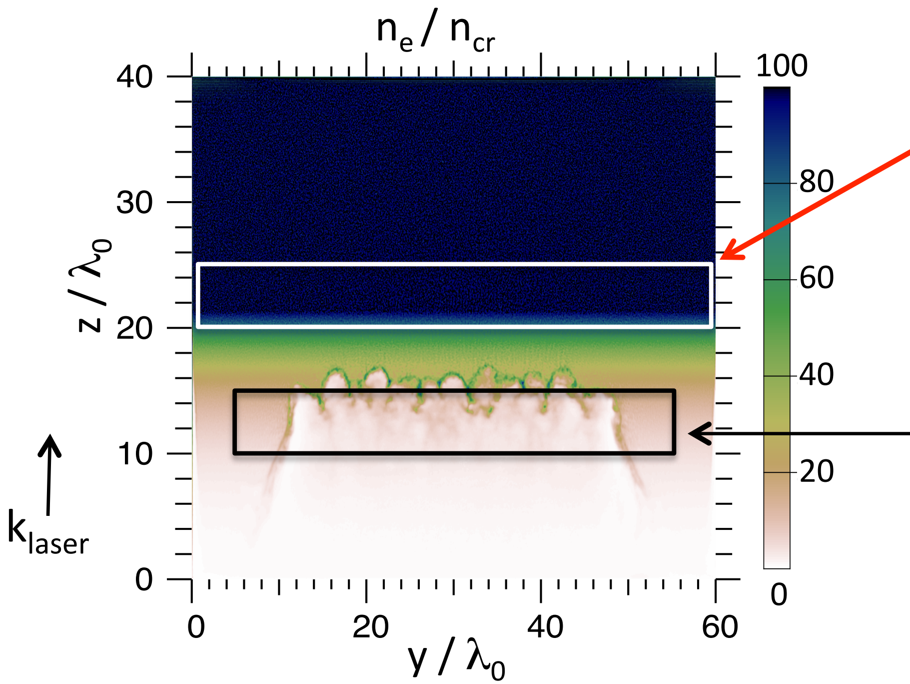
Subject of this talk

Some trick, like imposed magnetic fields, is needed to achieve fast ignition with a realistic, divergent fast electron source

- Fast electron source generated by short-pulse laser – characterized by PIC sims:
  - 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 Hydra rad-hydro code
- Imposed uniform axial magnetic fields > 30 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
- Hollow magnetic pipe can prevent mirroring

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

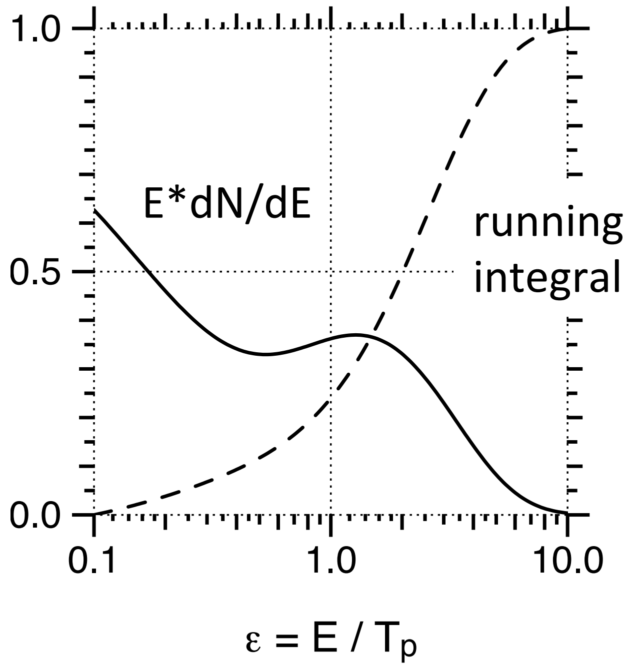
Source box: fast electrons excited here in equivalent transport simulation

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

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

- 3D Cartesian run, 1 μm laser wavelength, pre-plasma with $n_e \sim \exp[z / 3.5\ \mu m]$
- Intensity at vacuum focus (z = 10 μm): $I_{las}(r) = I_0 \exp[-(r/18.3\ um)^8]$
- I_0=1.37 E20 W/cm^2

PIC fast electron energy spectrum is quasi two-temperature



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

We scale dN/dE with ponderomotive temperature [S. C. Wilks et al., Phys. Rev. Lett. (1992)]

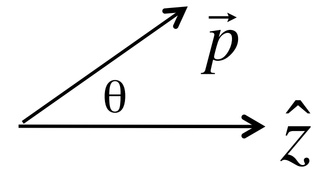
$$\frac{T_{\mathrm{pond}}}{m_e c^2} \equiv \left[1 + a_0^2\right]^{1/2} - 1 \ \sim a_0 \equiv \mathrm{sqrt}\left[\frac{I_{las}\lambda^2}{1.37\cdot 10^{18}\ \mathrm{W\ cm^{-2}}\mu\mathrm{m}^2}\right]$$

λ = 1 μm, I_0=1.37 E20 W/cm^2 -> T_{pond} = 4.63 MeV

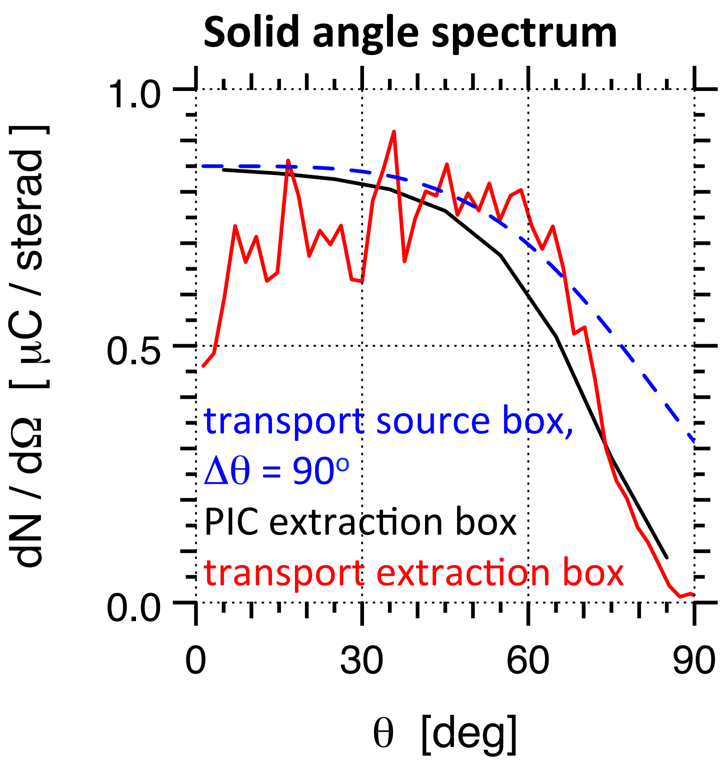
- Same spectrum in source and extraction box
- Ignition DT hot spot: $\rho\Delta z$ ~ 1.2 g/cm^2. Removes ~ 1.4 MeV from a fast electron (neglecting angular scatter)
  - Spectrum is too energetic to stop in hot spot

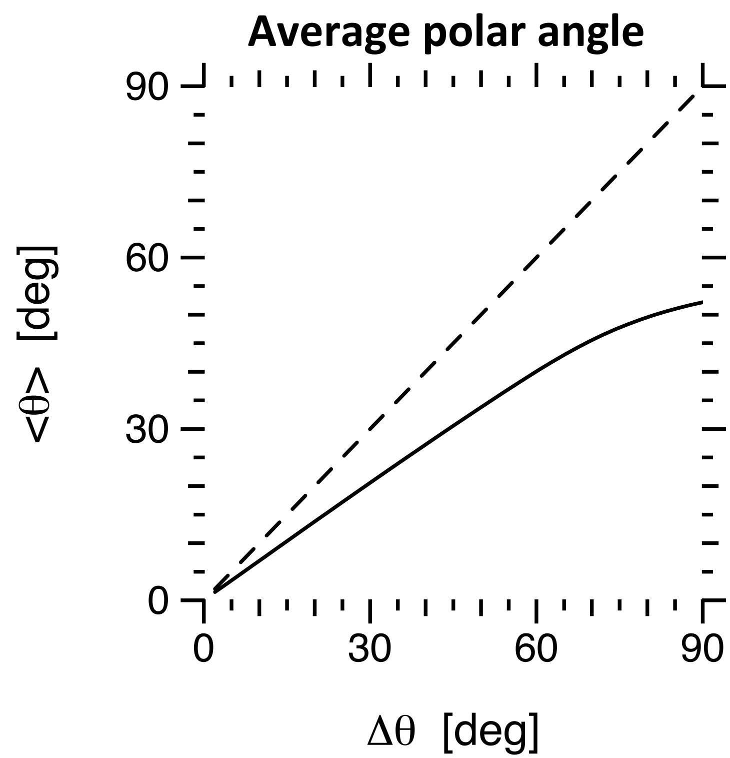
PIC fast electron angle spectrum is very divergent

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



Δθ = 90° needed to agree with PIC results





Δθ	<θ>	Zuma-Hydra runs used for
10°	6.9°	artifically collimated source
90°	52°	realistic PIC source

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

- Field and background dynamics simplified to eliminate light and plasma waves:
  valid for $\omega \ll \omega_{plasma}, \omega_{laser}$ $k \ll k_{laser}, 1/\lambda_{Debye}$

- Relativistic fast electron particle push: $\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B})$
- Fast e- energy loss (drag) 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:

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

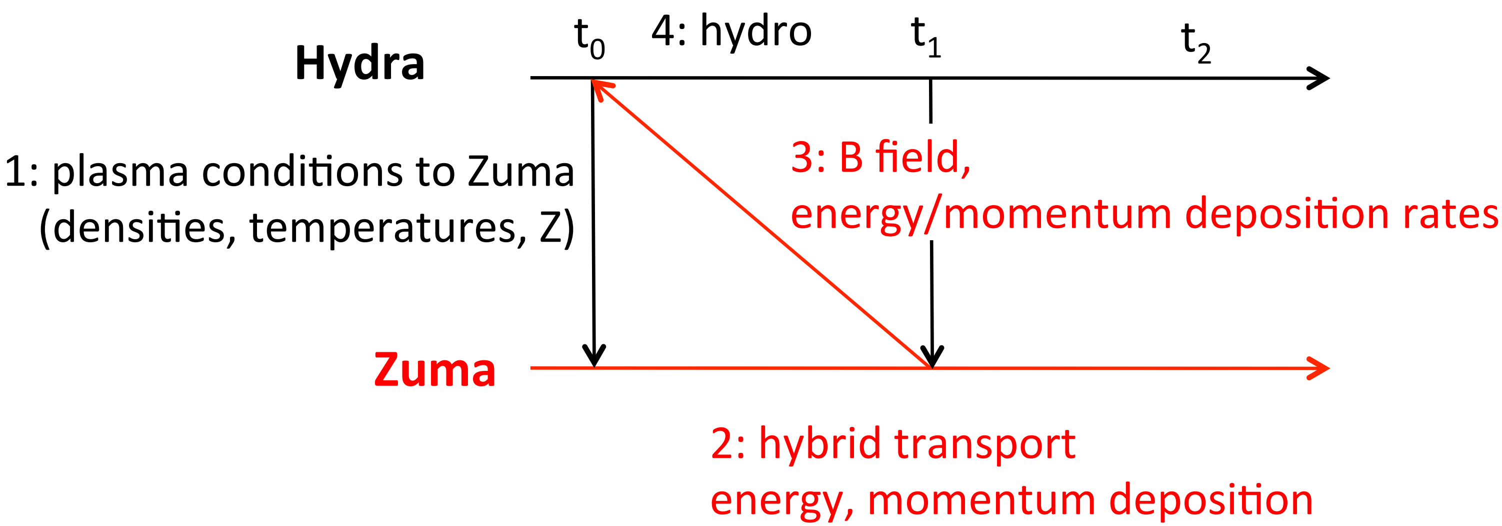
$$\rightarrow \vec{E} = \vec{\vec{\eta}} \bullet \vec{J}_{\text{return}} - e^{-1}\vec{\vec{\beta}} \bullet \nabla T_e - \frac{\nabla p_e}{e n_{eb}} - \vec{v}_{eb} \times \vec{B}$$

$\eta =$ resistivity from Lee-More-Desjarlais

- $\vec{E} = \eta \vec{J}_{\text{return}}$ Simple Ohm's law, used for this talk's runs
- $\vec{J}_{\text{return}} \bullet \vec{E}$ Ohmic heating
- $\frac{\partial \vec{B}}{\partial t} = -\nabla \times E$ Faraday's law

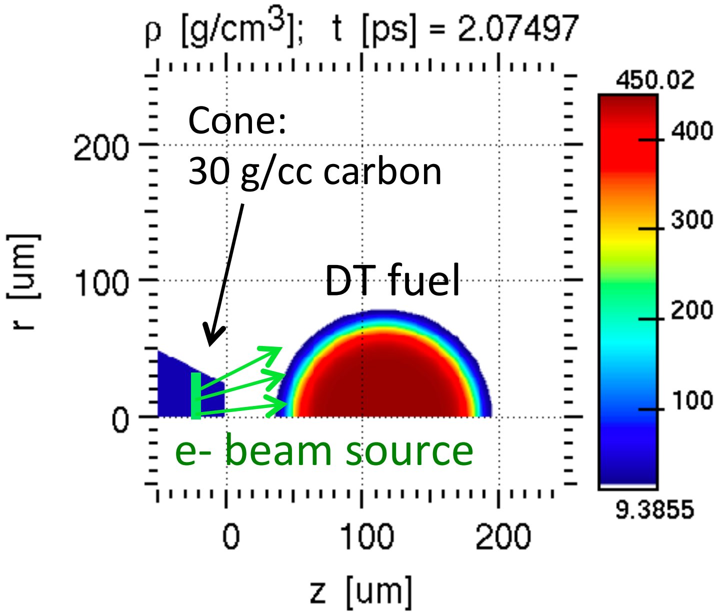
Hybrid PIC transport code Zuma coupled to rad-hydro code Hydra (M. M. Marinak, D. J. Larson, L. Divol)

- Both codes run in cylindrical R-Z geometry on fixed Eulerian meshes (which can differ)
- Data transfer done via files generated by Overlink code [J. Grandy et al.]
- Typical run: 20 ps transport (Zuma + Hydra), then 180 ps burn (just Hydra)
  - 2-3 wall-time hours on 40 cpu's

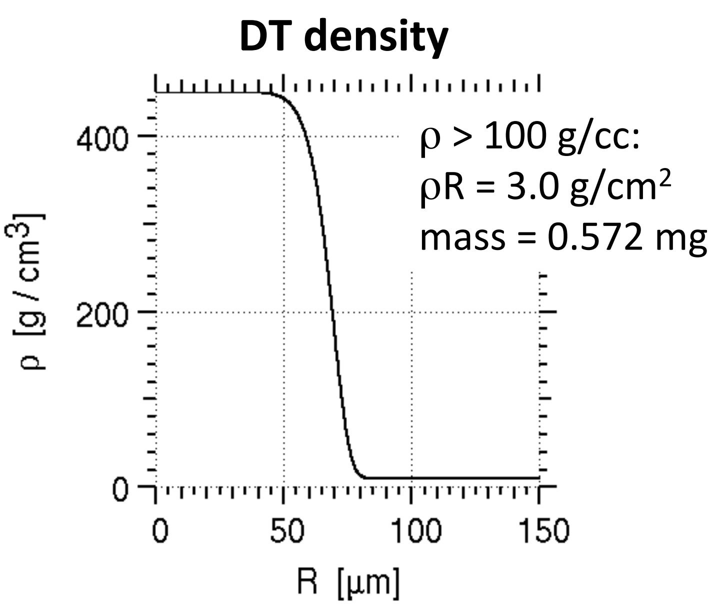


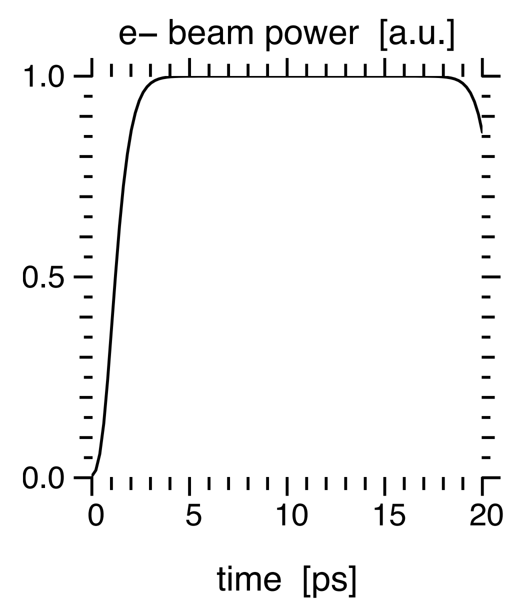
- Hydra details: IMC photonics, neutron deposition turned off, no MHD package used

ignition-scale toy target with carbon cone

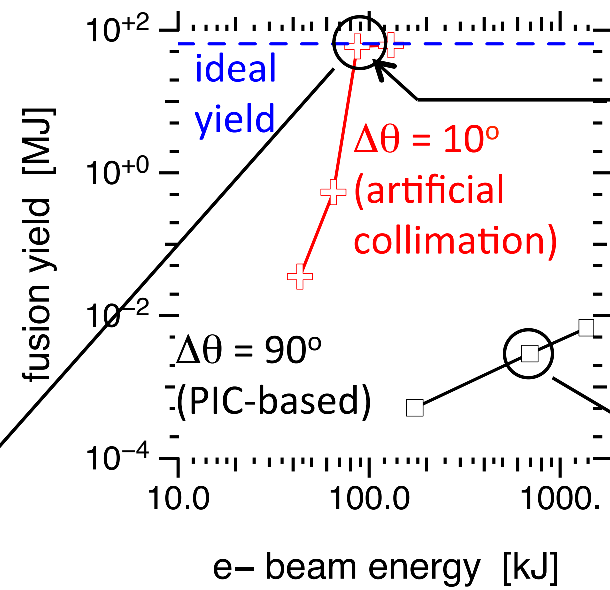


- Ideal burn-up fraction $f = \rho R/(\rho R+6) = 1/3$
- Ideal fusion yield = 338 MJ * Mass [mg] * f = 64.4 MJ
- Optimal e-beam ignition energy [Atzeni et al., PoP 2007]
  140 kJ / $(\rho/100\ \mathrm{g/cc})^{1.85}$ = 8.7 kJ
- Beam intensity = $I_0 \exp(-0.5*(r/23)^8)$
  HWHM: r = 24 μm
- 527 nm (2ω) wavelength laser: lowers $T_{pond} \sim \lambda$

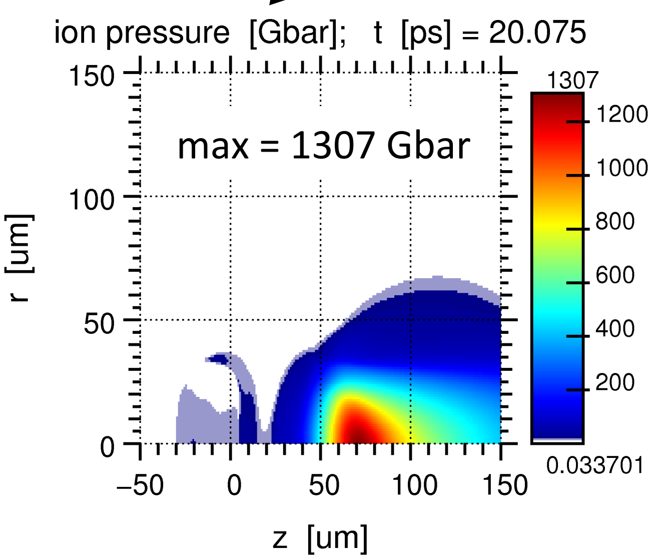


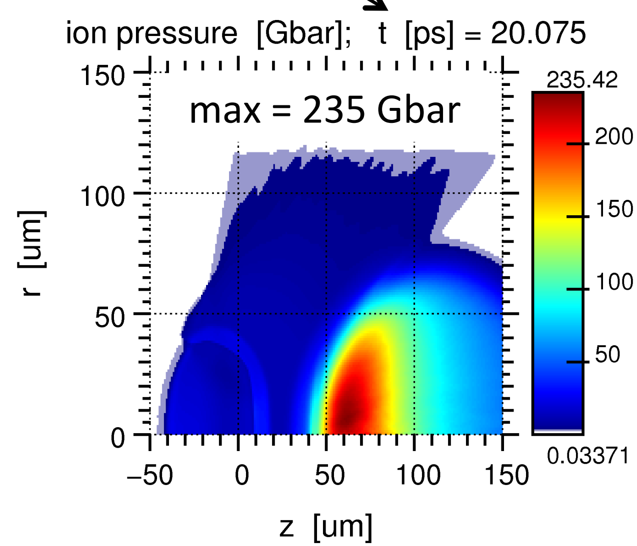


PIC-based source divergence gives prohibitive ignition energies; dramatically reduced if source is artifically collimated

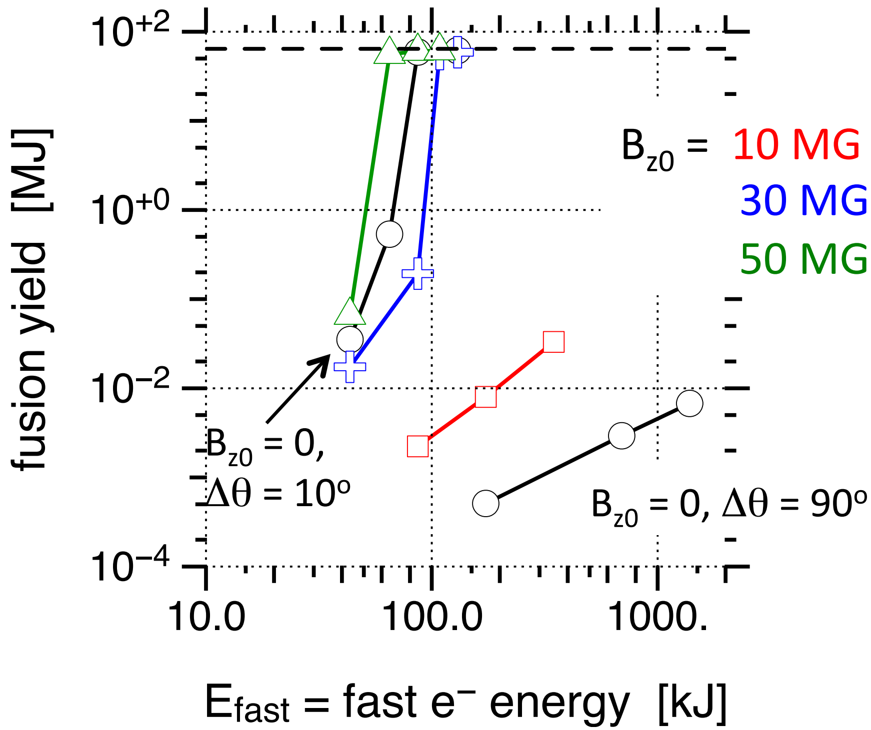


87 kJ ignition energy
10x ideal value:
divergence, spectrum too energetic, pulse and spot un-optimized





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



e- Larmor radius:

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

For a 2 MeV e- (roughly optimal to deposit energy in hot spot), r_{Le} = 82 um / B [MG]

r_{Le} = spot radius (24 um) for B = 3.4 MG: lower bound on when B fields matter

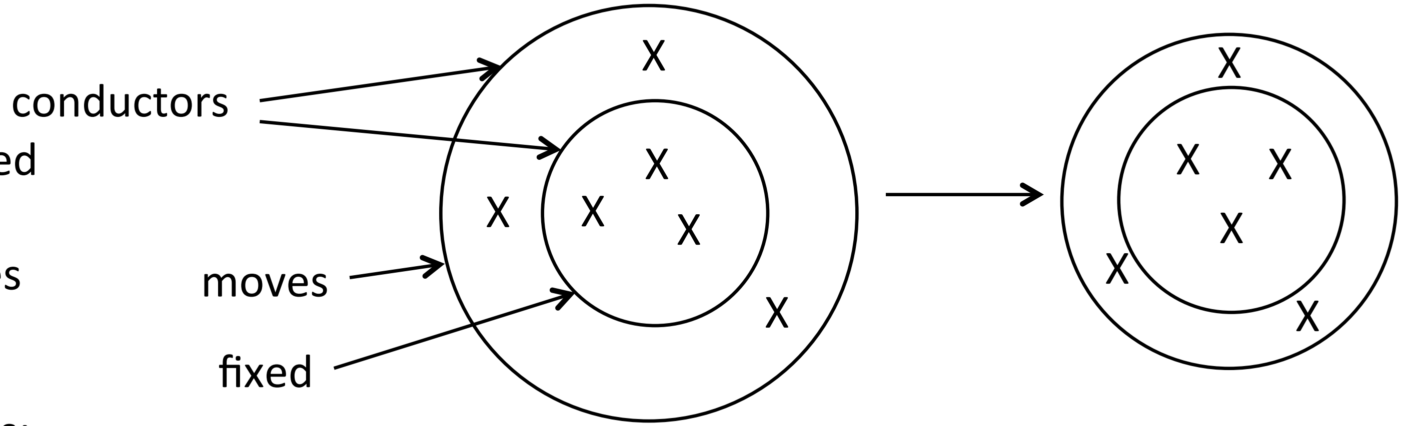
Rad-hydro-MHD studies of B field compression have been started by H. D. Shay, M. Tabak

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., talk J05-2, APS-DPP 2010

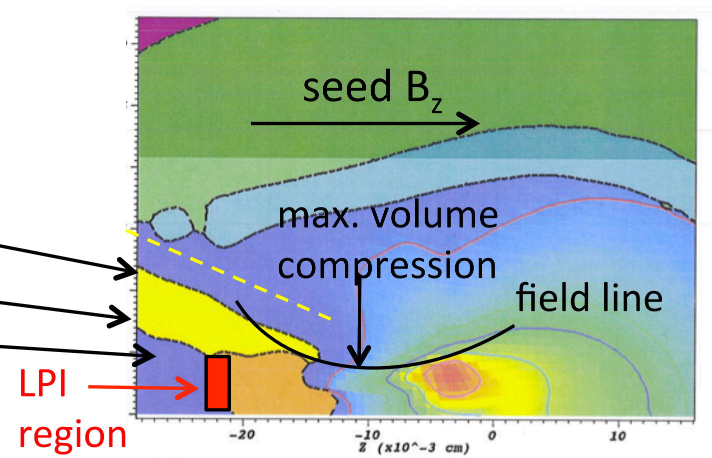
Implosion can compress magnetic field in DT, but short-pulse LPI will likely happen in the seed field

Flux B_z*r^2 conserved inside conductor, unless field diffuses due to resistivity



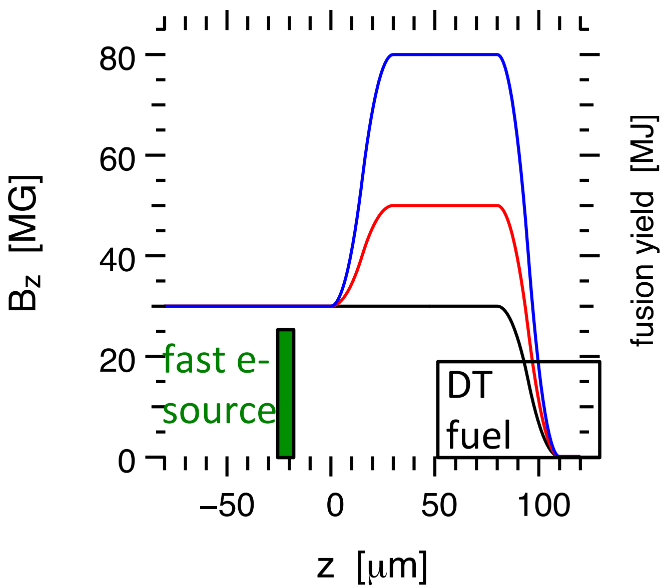
Nested conductors:
Field compressed between conductors, but not inside inner one

- Cone outer surface compressed
- Cone inner surface doesn't move – shock break-out would fill cone
- B field in vacuum region is uncompressed; may increase over seed field due to diffusion

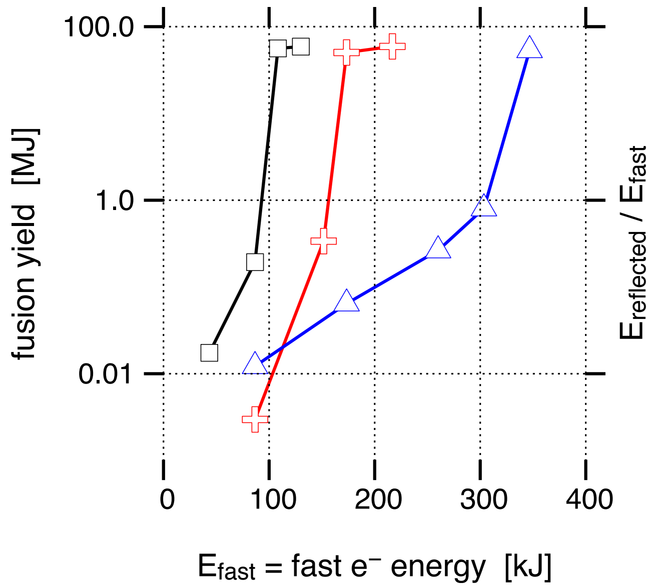


Axial variation in magnetic field strength reduces hot-spot heating due to magnetic mirroring

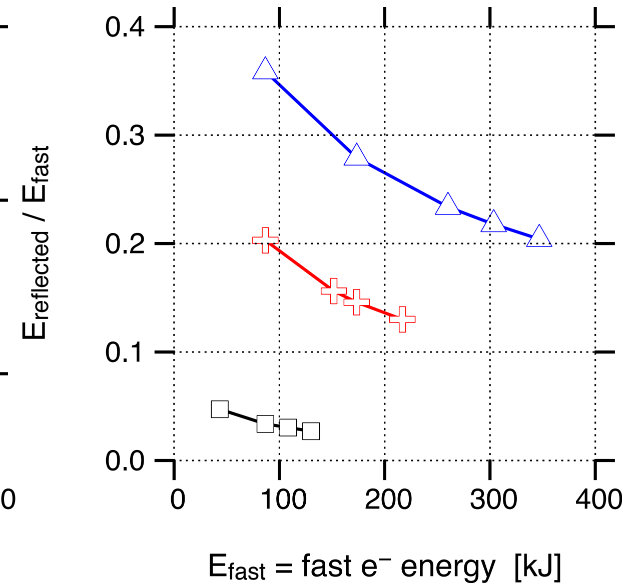
Initial Bz profiles



fusion yield



Fast e- energy reflected to left boundary



$$B_z(r,z) = B_{z0} + (B_{z1} - B_{z0})G(r)H(z)$$

$$H(z) = \left(1 + \left(\frac{z - z_0}{\Delta z}\right)^2\right)^{-1}$$

$$G(r) = \exp\left[-(r/50\ \mu\text{m})^8\right]$$

$$B_r(r,z)\ \text{from}\ A_\phi\ \text{to ensure}\ \nabla \cdot \vec{B} = 0$$

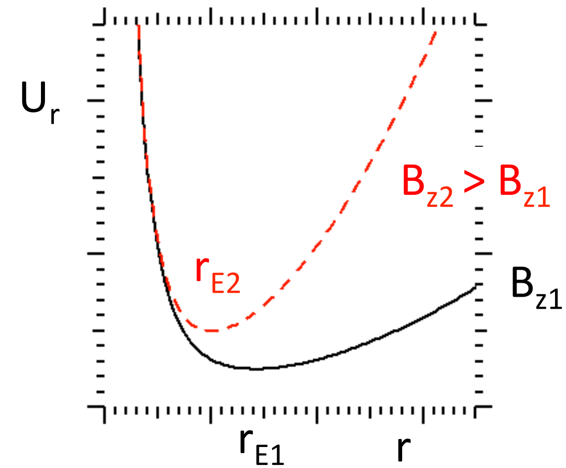
Axial variation in B_z gives rise to B_r, to satisfy div B = 0.
Leads to mirror force in z direction.

Magnetic mirroring in cylindrical B field

$$\frac{d\vec{p}}{dt} = q\vec{v}\times\vec{B} \qquad \vec{B} = B_z(z)\hat{z} + B_r(r,z)\hat{r} \qquad \omega_{cz} = \frac{qB_z}{\gamma m} \qquad \nabla\cdot\vec{B} = 0 \quad \rightarrow \quad B_r = -\frac{r}{2}\frac{\partial B_z}{\partial z}$$

constants of motion: γ and canonical

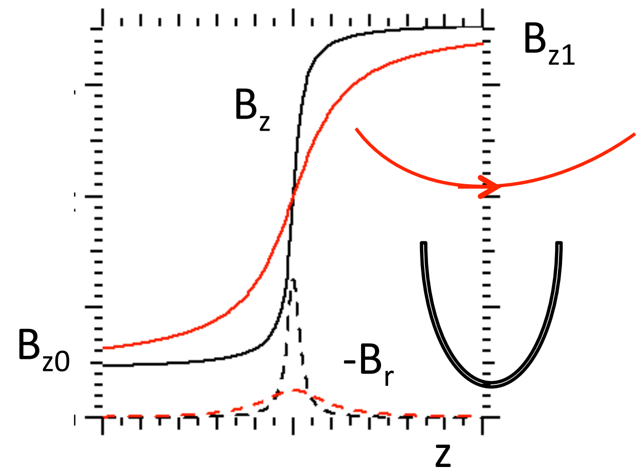
angular momentum $l_0 = r^2(\dot{\phi} + \omega_{cz}/2)$



Radial motion: $$\frac{d^2r}{dt^2} = -\frac{d}{dr}U_r \qquad U_r = \frac{l_0^2}{2r^2} + \frac{r^2}{8}\omega_{cz}^2$$

equilibrium: $$dU_r/dr = 0 \quad \rightarrow \quad r_E = \left|\frac{2l_0}{\omega_{cz}}\right|^{1/2}$$

Axial motion: $$\frac{d^2z}{dt^2} = \frac{1}{8}\left(\sigma r_E^2 - r^2\right)\frac{\partial}{\partial z}\omega_{cz}^2 \qquad \sigma = \mathrm{sign}(l_0\omega_{cz})$$

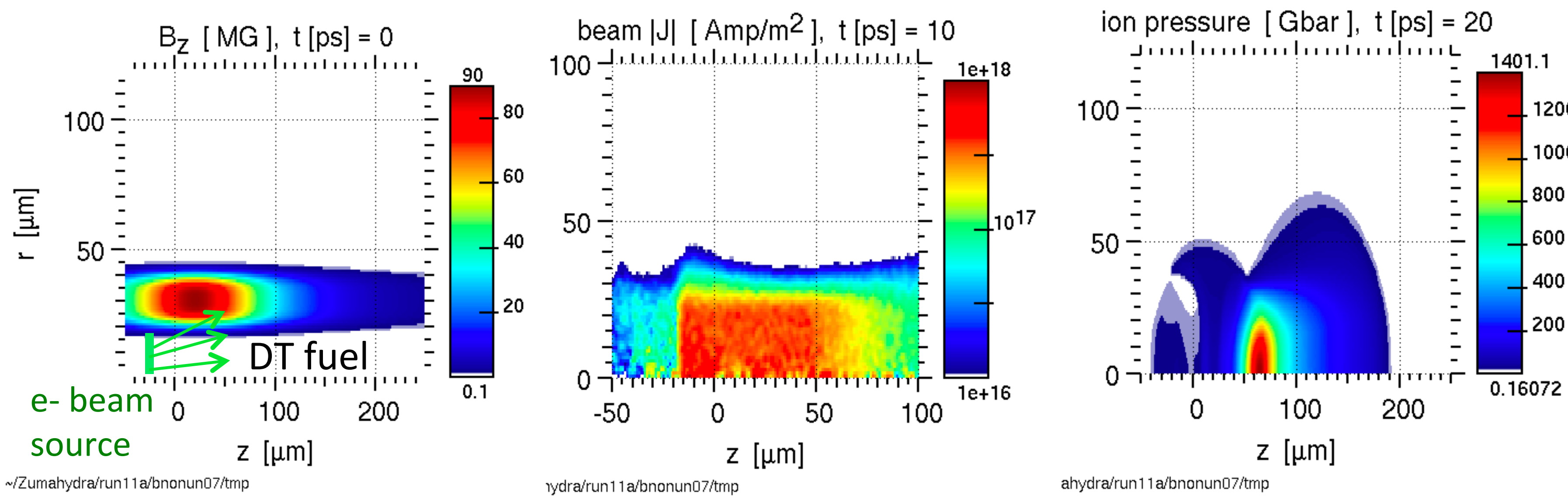


Mirroring in increasing B_z

- Fight between dB_z/dz and decreasing radius
- Adiabatic invariant for slowly changing B_z:
  "loss cone" $\tan^2\theta_L = B_{z0}/(B_{z1}-B_{z0})$
- Loss cone not accurate for rapidly-varying B_z:
  Large B_r can mirror particles with $v_{perp}(t=0) = 0$
  (always in adiabatic loss cone)

We can circumvent mirroring with "magnetic pipe:" B_{z0} peaks off-axis

- Run with B_{z0} = 90 MG, E_{beam} = 87 kJ ignites
- Using B_{z0} = 60 MG, or narrower in z, or E_{fast} = 43.4 kJ all fail (<270 kJ fusion yield).
- Artifically collimated beam ($\Delta\theta$ = 10°) requires E_{fast} = 87 kJ to ignite.



Very little backward-going e-, unlike mirroring cases

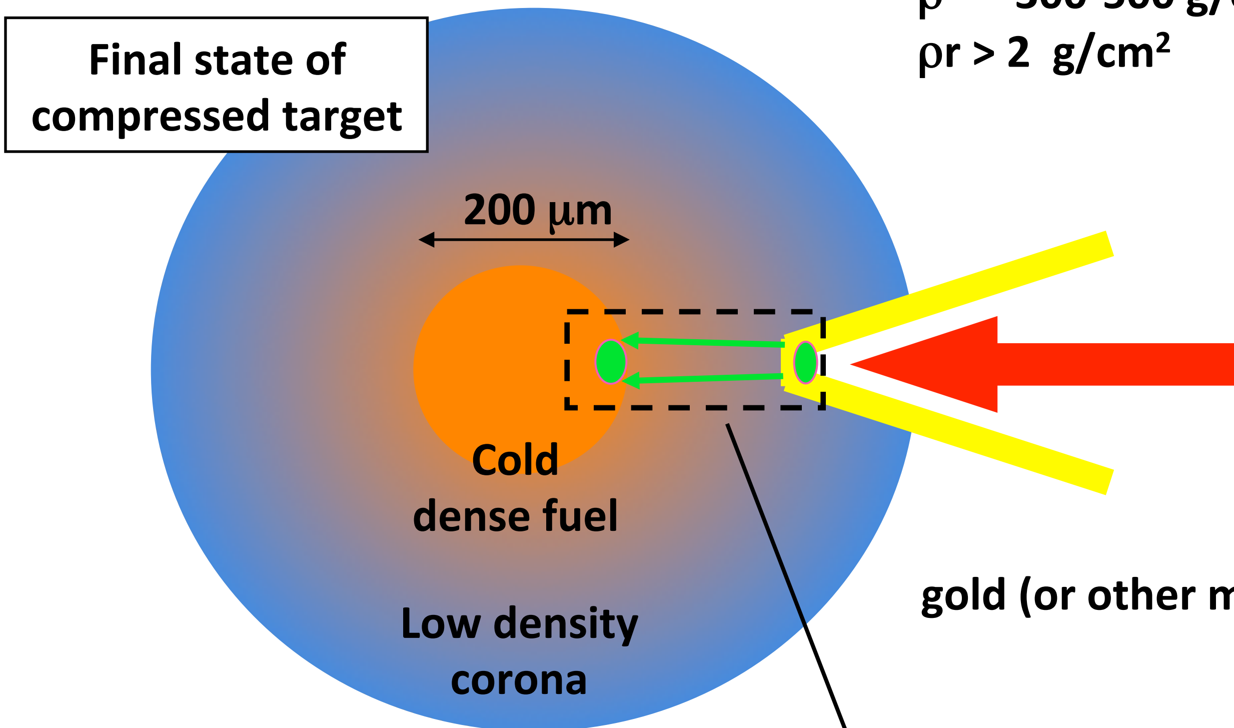
Imposed magnetic fields may circumvent large fast-electron divergence for fast ignition, but mirroring is an issue

- Artificially collimated e- beam: ignition E_{fast} = 87 kJ
- Realistic PIC beam divergence: ignition E_{fast} ~ MJ's
- Uniform initial axial magnetic field > 30 MG: ignition E_{fast} = 100 kJ
- Non-uniform field peaking in fuel: fast e- reflected by mirror force
- Magnetic pipe: hollow radial profile: can recover ignition E_{fast} = 87 kJ

How can we assemble such fields in an implosion?

- **Backup slides beyond here**

We are pursuing fast ignition for high gain and inertial fusion energy



long-pulse compression laser ~ 1 MJ
ρ ~ 300-500 g/cm^3
ρr > 2 g/cm^2

Short-pulse laser produces fast electrons
10-20 ps pulse
< 100 kJ (to ever be built)
power ~ 5-10 PW
~50 μm focal spot (FWHM)

gold (or other mid/high Z) cone

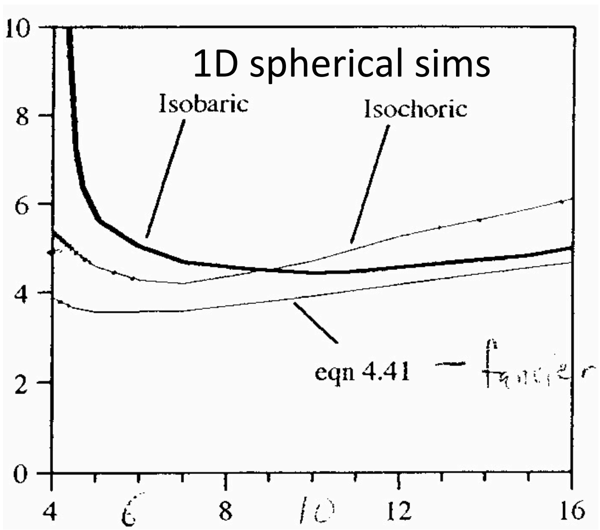
"Transport region:" ~50-100 μm;
Subject of this talk.

M. Tabak, J. Hammer, M. E. Glinsky, et al., *Phys. Plasmas* **1**, 1626 (1994).

Isochoric ignition hot-spot: $T_{ion} > 4$ keV and $\rho * R * T_{ion} > 5$ g cm^{-2} keV

Atzeni and Meyer-ter-Vehn: *The Physics of Inertial Fusion*: p. 85.
X_h = hot-spot value; ρ_c = density of surrounding cold fuel. $\rho_c = \rho_h$ for isochoric.

$\rho_h R_h T_h (\rho_c / \rho_h)^{1/2}$ [g cm^{-2} keV]



T_h [keV]

$(\rho_c / \rho_h)^{1/2}$ = (1, 3-4) for (isochoric, NIC isobaric).

Isobaric ignition requires a smaller hotspot $\rho_h R_h T_h$ but more laser energy to achieve a larger ρ_c.

$\rho * R * T_{ion}$ = max. at end of e- source pulse, centered on peak ion pressure.

We can circumvent mirroring with "magnetic pipe:" B_{z0} peaks off-axis

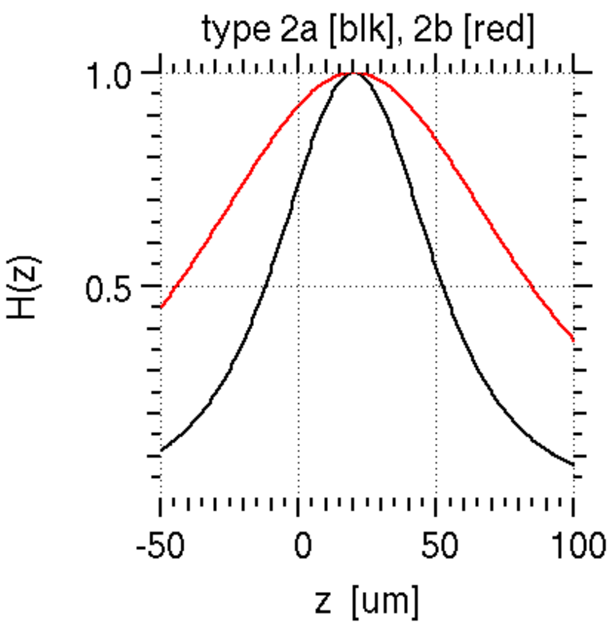
$$B_z(r,z) = B_{z0} + (B_{z1} - B_{z0})G(r)H(z)$$

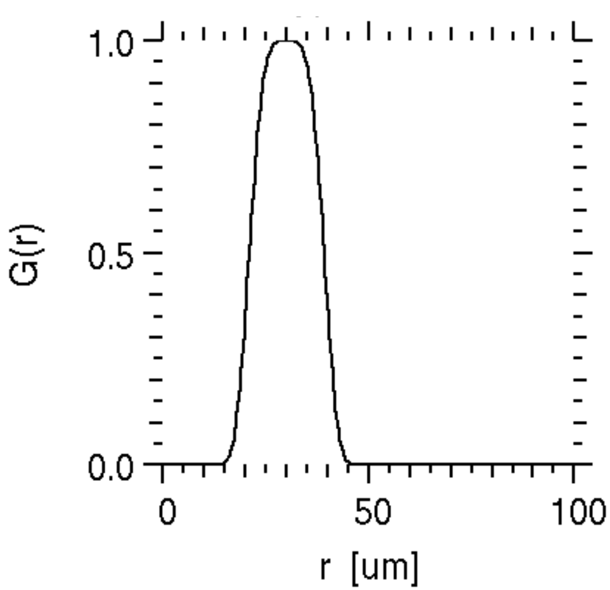
$$G(r) = \exp\left[-\left(\frac{r - r_0}{\Delta r}\right)^4\right]$$

$$H(z) = \left[1 + \left(\frac{z - z_0}{\Delta z}\right)^2\right]^{-2}$$

Field type 2a: B_{z0} = 0.1 MG, B_{z1} varies,
z_0 = 20, Δz = 50, r_0 = 30, Δr = 10

Field type 2b: same as 2a, but Δz = 100





Magnetic field evolution governed by MHD frozen-in law

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

$$\vec{E} = -\vec{v}_e \times \vec{B} + \eta \vec{J}_e$$

$$\nabla \times \vec{B} = \mu_0 \vec{J}_e$$

$$\longrightarrow \quad \frac{\partial}{\partial t} r B_z + \frac{\partial}{\partial r} v_r r B_z = \mu_0^{-1} \frac{\partial}{\partial r}\left[r\eta \frac{\partial B_z}{\partial r} \right]$$

Cylindrical geometry:

$$\vec{B} = B_z(r,t)\hat{z}$$

$$\eta = \eta(r,t)$$

$$\vec{v}_e = v_r(r,t)\hat{r}$$

magnetic flux $\psi \equiv \int_{r_1}^{r_2} da \ \hat{z} \cdot \vec{B} = 2\pi \int_{r_1}^{r_2} dr \ rB_z$

Let $\dfrac{dr_i}{dt} = v_r(r_i, t)$ follows plasma electron flow

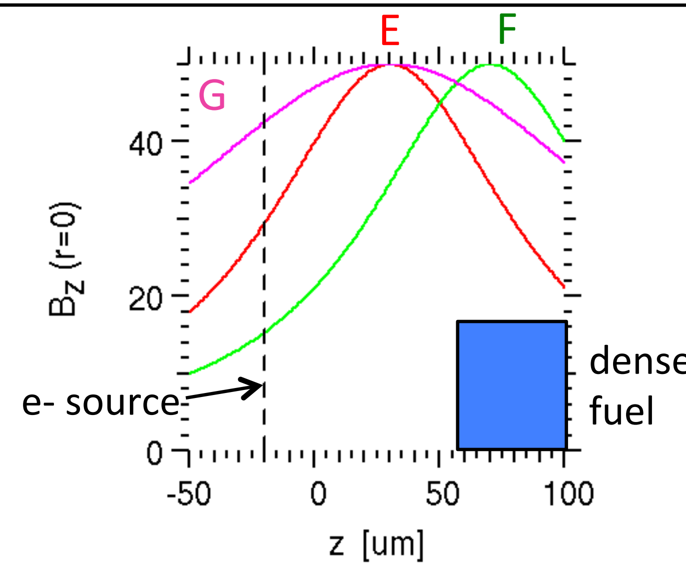
Then $\dfrac{d\psi}{dt} = \dfrac{2\pi}{\mu_0} \left(r\eta \dfrac{\partial B_z}{\partial r} \right) \Bigg|_{r_1}^{r_2}$

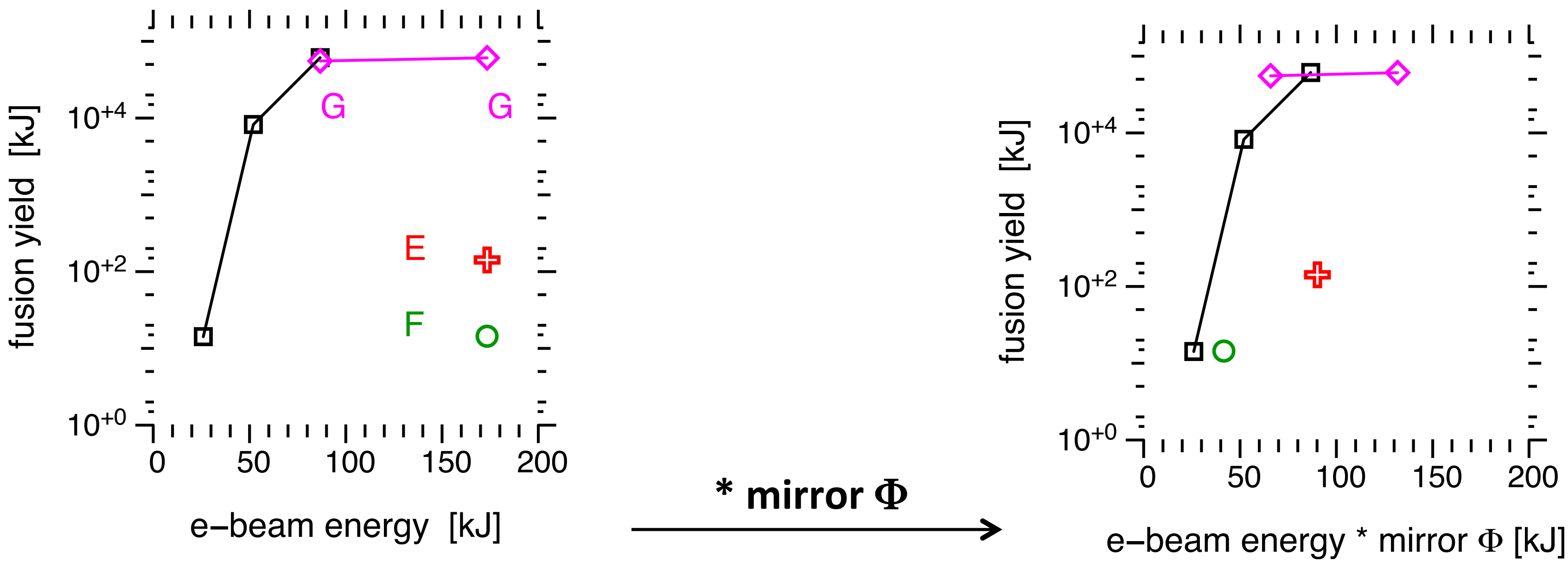
Frozen-in law: magnetic flux between two surfaces moving with the plasma electrons changes only due to magnetic diffusion.

Mirroring with non-uniform imposed B-fields: effective beam energy partly follows mirror scaling

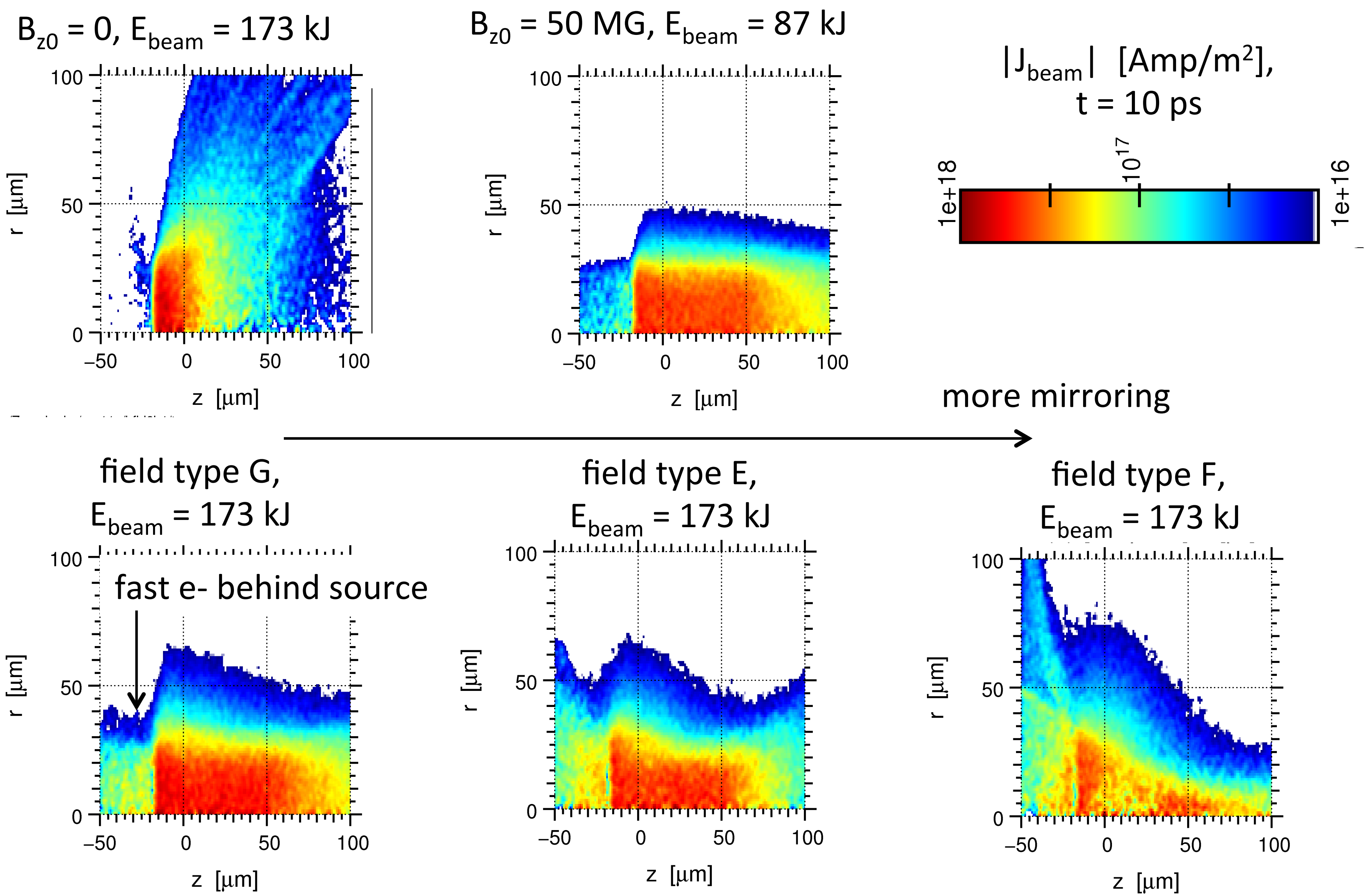
B field type	$B_{z,fuel} / B_{z,exc}$	mirror Φ
E	0.66	0.52 (mid)
F	0.34	0.24 (worst)
G	0.88	0.76 (best)

black: uniform B_{z0}=50 MG; mirror Φ = 1.





Evidence of mirroring with non-uniform imposed B-fields: reflected fast electrons



Magnetic mirroring generalities (fully relativistic)

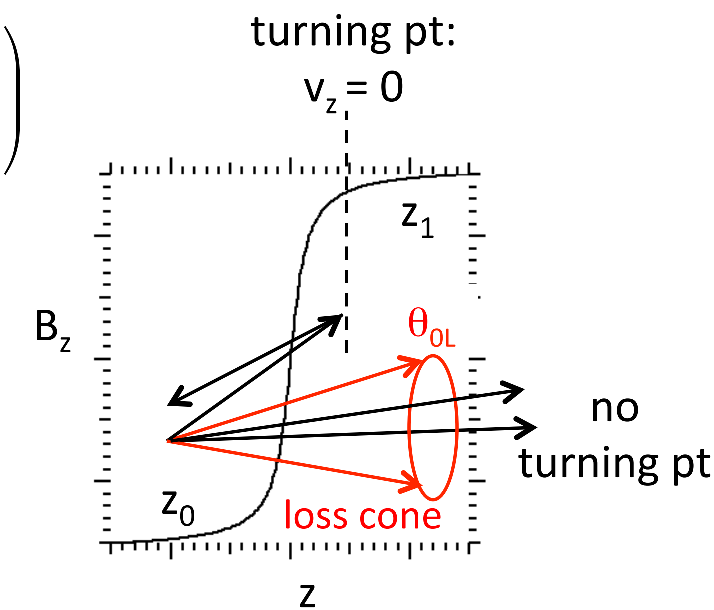
- div B = 0 implies $B_r(r,z) = -(r/2)\, dB_z / dz$
- Mirroring due to z force on a particle: $F_z = q\, v_\perp \times B_r$
- Adiabatic limit: $\left|\frac{1}{B}\frac{dB}{dt}\right| << \text{cyclotron freq.}$
- Magnetic moment = adiabatic invariant: *not* exactly conserved, but change is small

$$\mu = \oint \vec{p}_\perp \cdot d\vec{l} = \pi \frac{c}{e}\frac{p_\perp^2}{B_z} \quad \rightarrow \quad \frac{v_\perp^2}{B_z} = \text{const.}$$

$$v_z^2 + v_\perp^2 = \text{const.} \quad \rightarrow \quad v_z^2 = v_{z0}^2 + v_{\perp 0}^2\left(1 - \frac{B_z}{B_{z0}}\right)$$

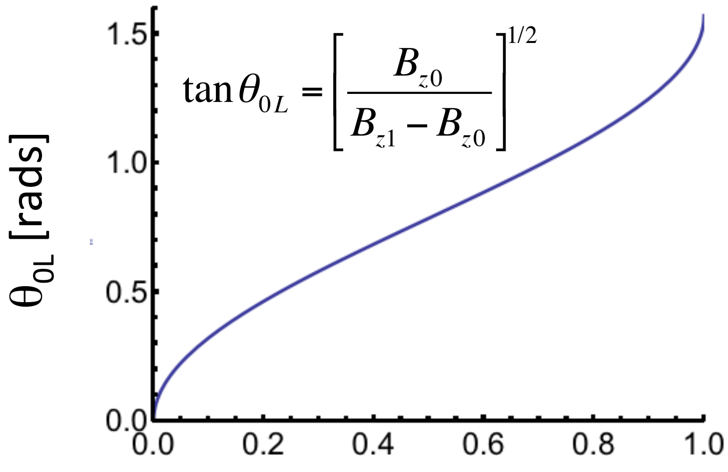
- Loss cone bad in MFE mirror machine,
  but good for us: these e- reach the fuel

$$\text{loss cone: } \tan\theta_{0L} = \frac{v_\perp}{v_z} = \left[\frac{B_{z0}}{B_{z1} - B_{z0}}\right]^{1/2}$$



Mirroring with our electron source

Loss cone angle vs. mirror ratio



mirror ratio = B_{z0} / B_{z1}

- e- source: $\frac{d^2N}{dEd\theta} = \frac{dN}{dE} \cdot \frac{dN}{d\theta}$

$$\frac{dN}{d\theta} = \sin\theta \exp\left[-(\theta / 90 \text{ deg.})^4\right]$$

Number in loss cone: $F(\theta) = \int_0^\theta d\theta \, \frac{dN}{d\theta}$

loss-cone fraction: $\Phi = \frac{F(\theta)}{F(\pi/2)}$

Loss cone fraction of our dN/dθ vs. mirror ratio