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Cone-Guided Fast Ignition with Imposed Magnetic Fields

D. J. Strozzi, M. Tabak, D. J. Larson, M. M. Marinak, M. H. Key, L. Divol, A. J. Kemp, H. D. Shay

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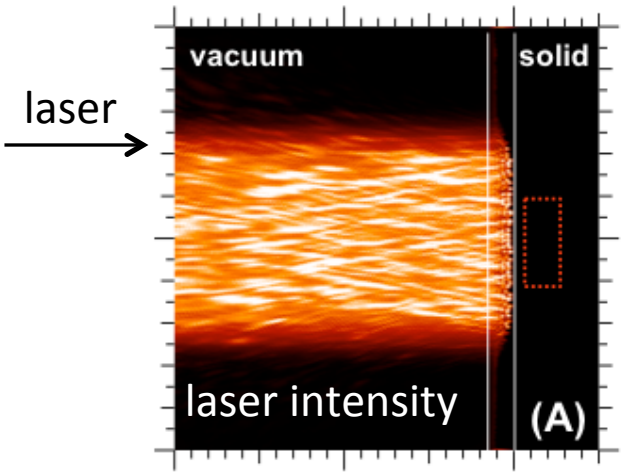
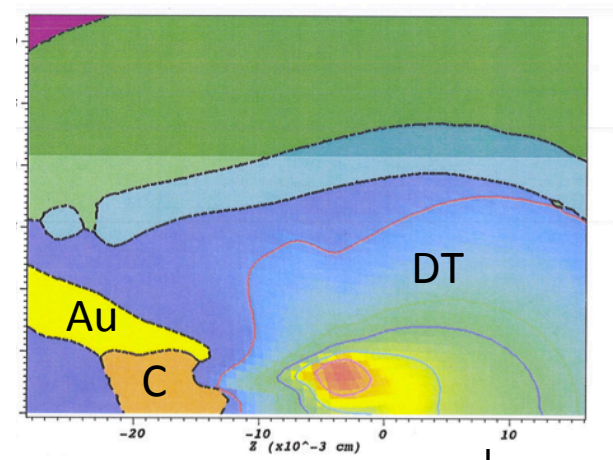
Our fast ignition modeling approach

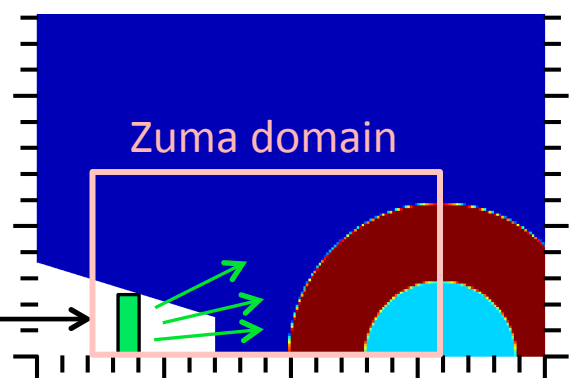
Explicit PIC modeling of short-pulse laser-plasma interaction: A. J. Kemp, L. Divol



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



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



fast electron injected source

plasma conditions at time of ignitor pulse

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

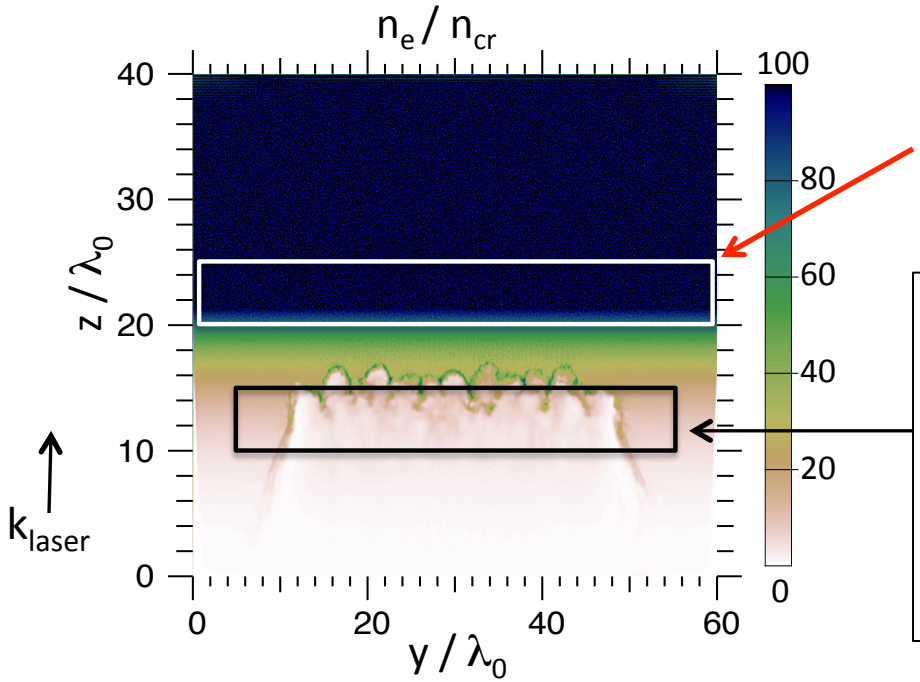
- Imposed uniform axial magnetic fields > 30 MG mitigate divergence
  - Can be produced in an implosion with seed field ~ 50 kG

- 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

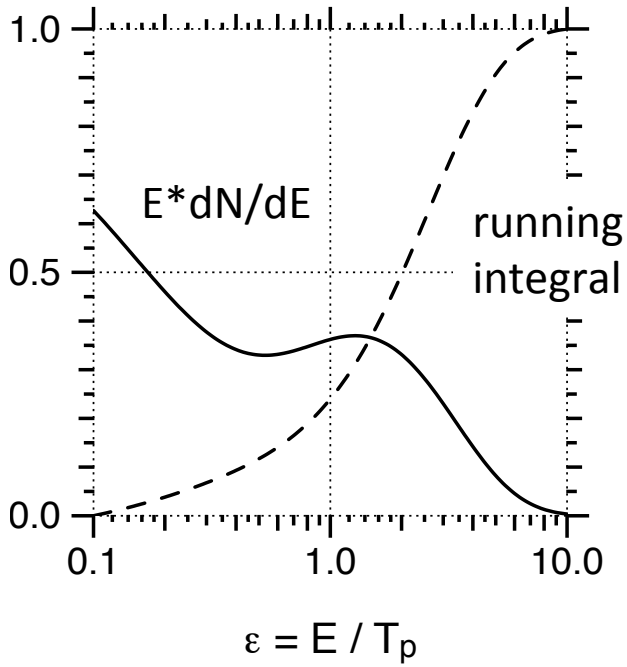
Source box: fast electrons excited here in equivalent transport simulation

$f(E,\theta) = f_E(E) * f_\theta(\theta)$ 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): $I_{las}(r) = I_0 \exp[-(r/18.3\ \mathrm{um})^8]$
- 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)]

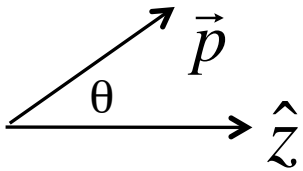
$$\frac{T_{\text{pond}}}{m_e c^2} \equiv \left[1 + a_0^2\right]^{1/2} - 1 \sim a_0 \equiv \text{sqrt}\left[\frac{I_{las}\lambda^2}{1.37\cdot 10^{18}\ \text{W cm}^{-2}\mu\text{m}^2}\right]$$

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

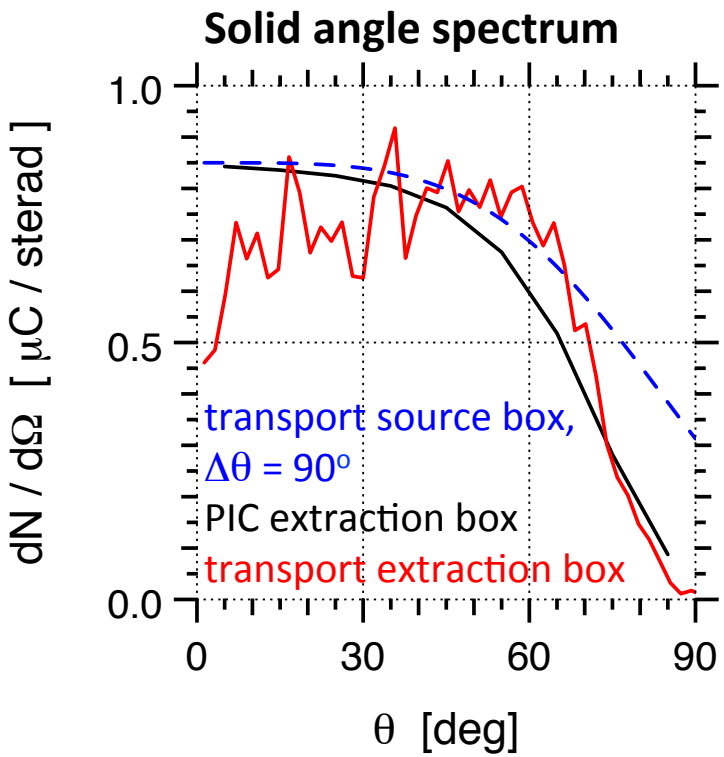
- Same spectrum in source and extraction box
- Ignition DT hot spot: $\rho\Delta z$ ~ 1.2 g/cm^2. Removes ~ 1.4 MeV from a fast electron (neglecting angular scatter)
  - Spectrum is too energetic to stop in hot spot

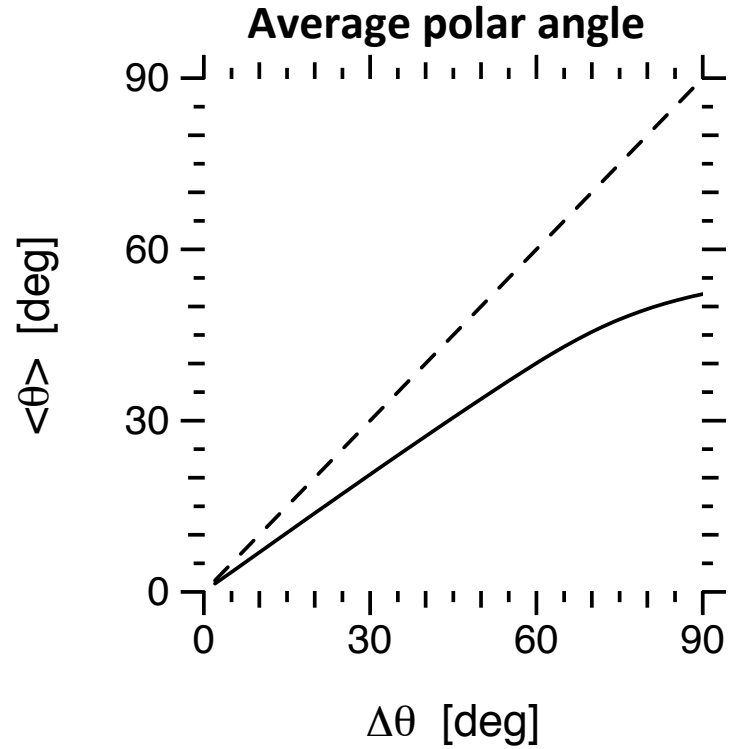
PIC fast electron angle spectrum is very divergent

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



$\Delta\theta = 90^o$ 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 $\omega << \omega_{plasma}, \omega_{laser}$ $k << k_{laser}, 1/\lambda_{Debye}$

- 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
- $\vec{J}_{return} = -\vec{J}_{fast} + \mu_0^{-1} \nabla \times \vec{B}$ Ampere's law without displacement current
- Electric field given by massless momentum equation for background electrons:

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

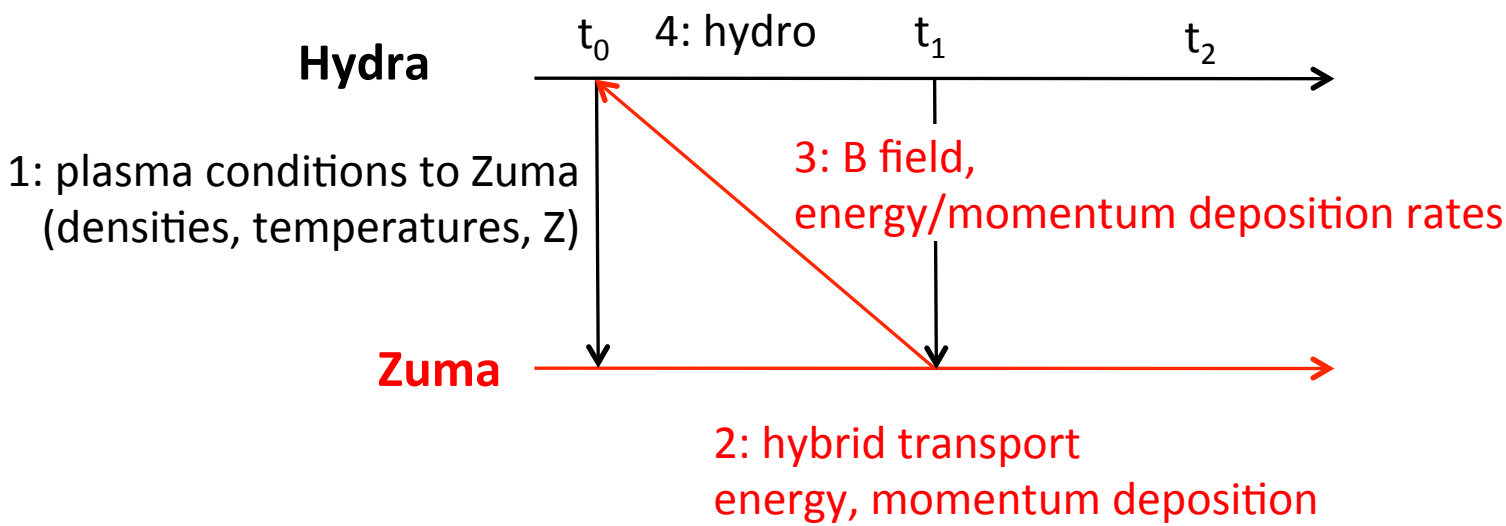
$$\rightarrow \vec{E} = \overleftrightarrow{\eta} \bullet \vec{J}_{return} - e^{-1} \overleftrightarrow{\beta} \bullet \nabla T_e - \frac{\nabla p_e}{e n_{eb}} - \vec{v}_{eb} \times \vec{B}$$

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

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

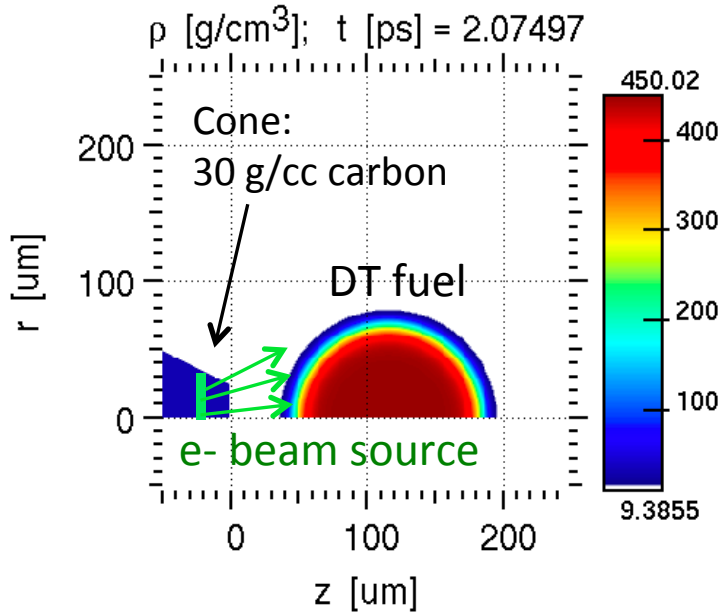
Hybrid PIC transport code Zuma coupled to rad-hydro code Hydra (M. M. Marinak, D. J. Larson, L. Divol)

- 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

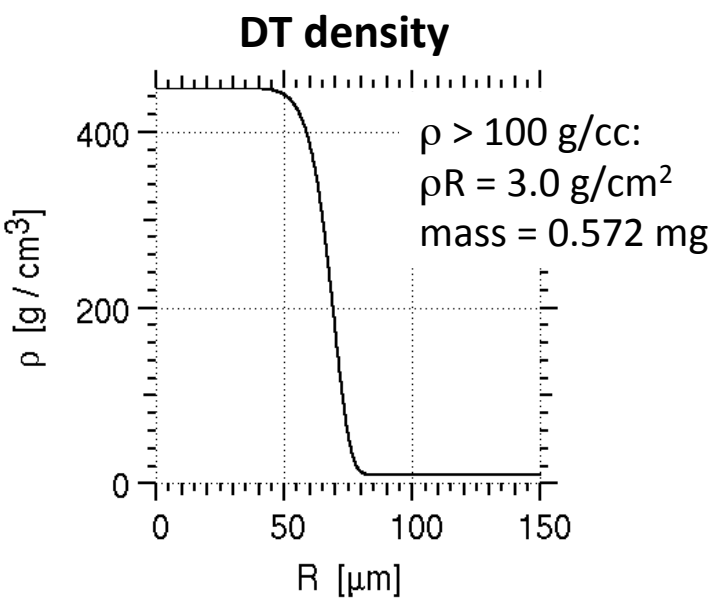


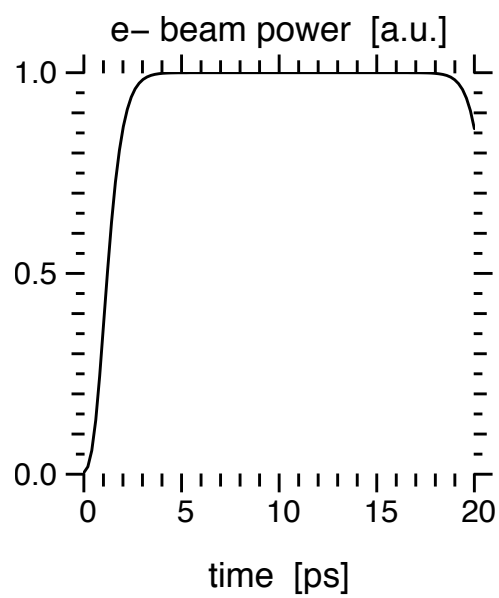
- Hydra details: IMC photonics, neutron deposition turned off, no MHD package used

ignition-scale toy target with carbon cone

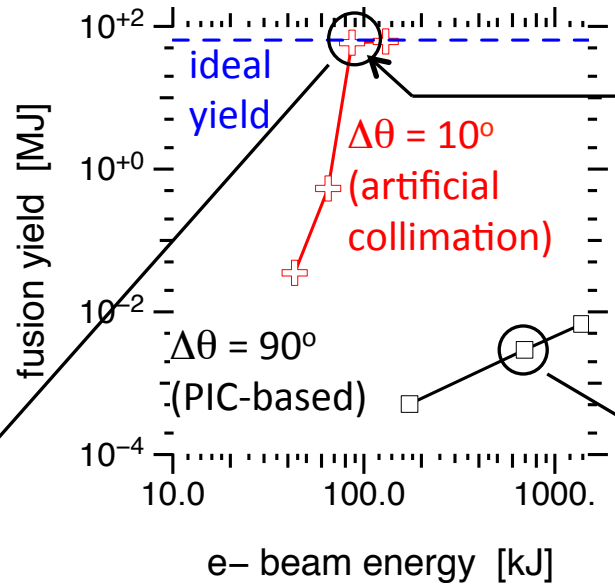


- Ideal burn-up fraction $f = \rho R/(\rho R+6) = 1/3$
- Ideal fusion yield = 338 MJ * Mass [mg] * f = 64.4 MJ
- Optimal e-beam ignition energy [Atzeni et al., PoP 2007]
  $140\ \text{kJ} / (\rho/100\ \text{g/cc})^{1.85} = 8.7\ \text{kJ}$
- Beam intensity = $I_0 \exp(-0.5*(r/23)^8)$
  HWHM: r = 24 μm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

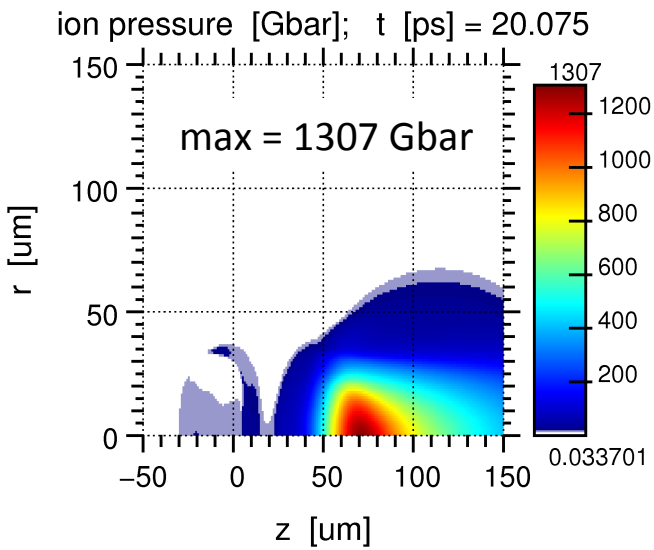


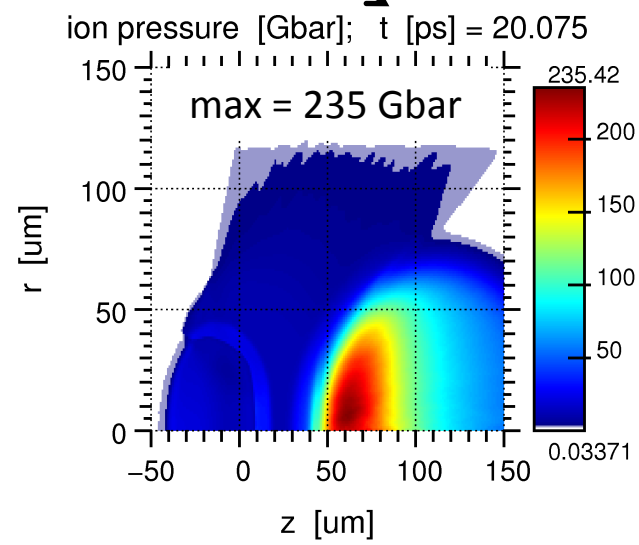


PIC-based source divergence gives prohibitive ignition energies; dramatically reduced if source is artifically collimated

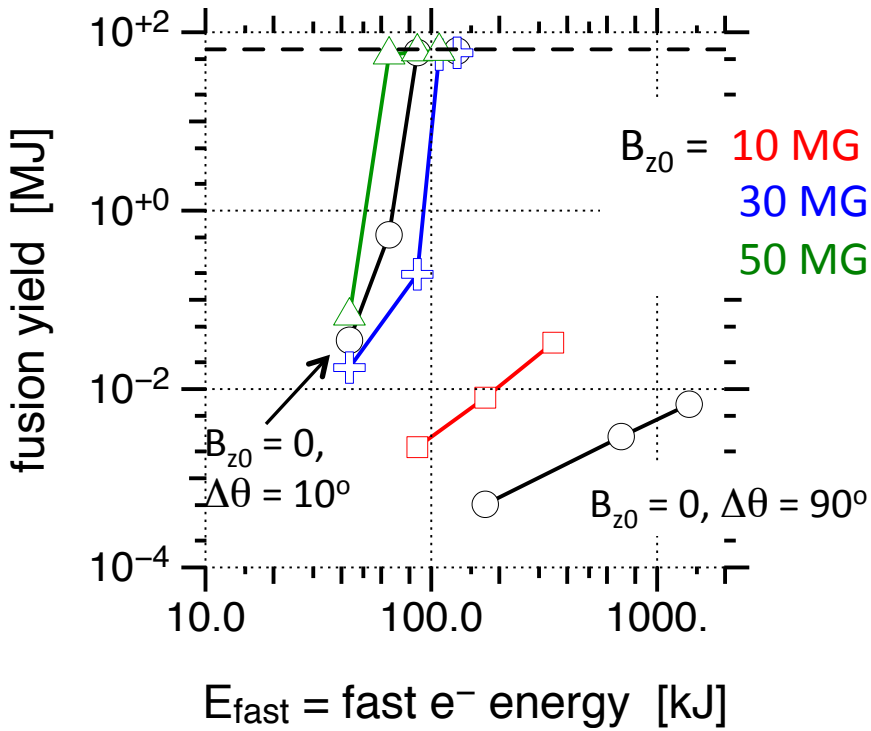


87 kJ ignition energy
10x ideal value:
divergence, spectrum too energetic, pulse and spot un-optimized





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

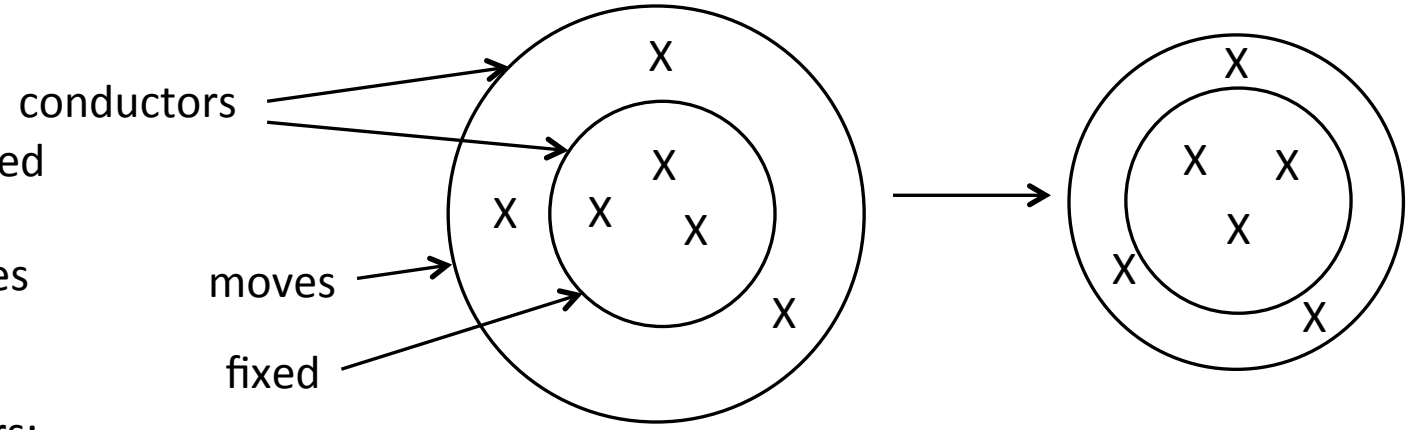
Omega experiments show compression of 50 kG seed B field in cylindrical implosions[1] to 30-40 MG, and in spherical implosions[2] to 20 MG

[1]J. P. Knauer, Phys. Plasmas 17, 056318 (2010)

[2]P. Y. Chang et al., talk J05-2, APS-DPP 2010

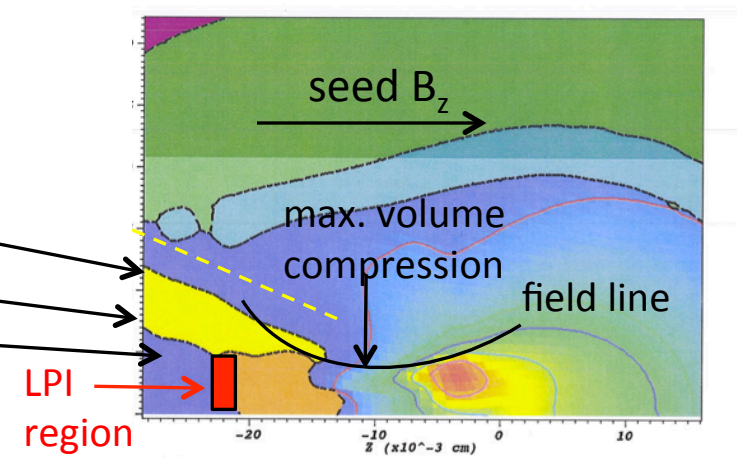
Implosion can compress magnetic field in DT, but short-pulse LPI will likely happen in the seed field

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



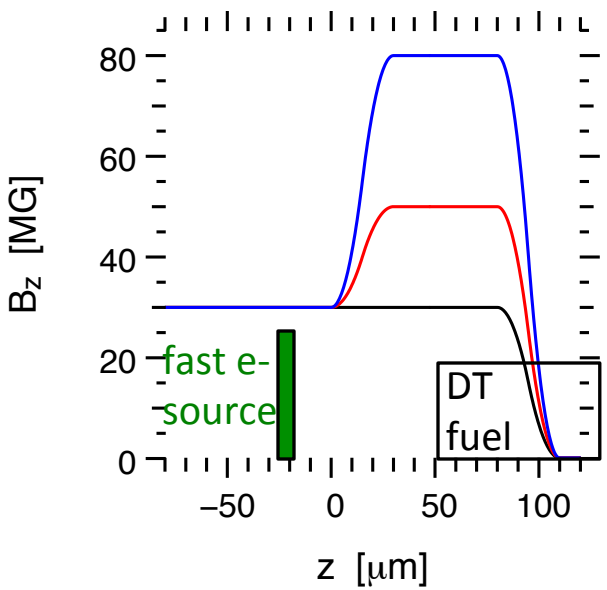
Nested conductors:
Field compressed between conductors, but not inside inner one

- 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

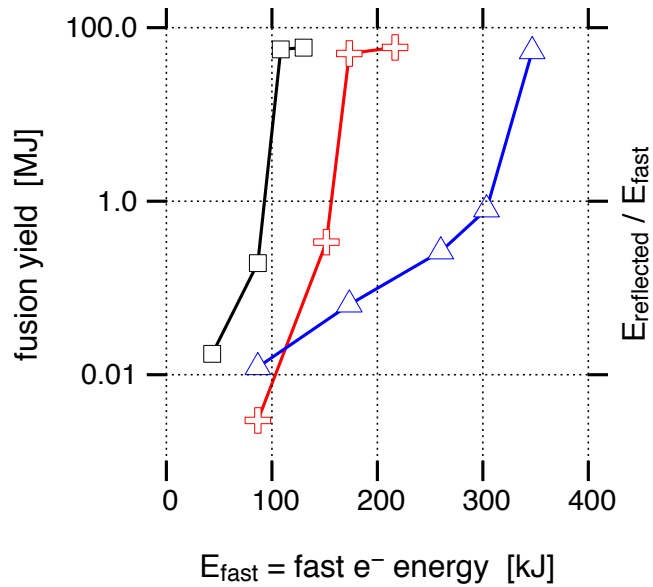


Axial variation in magnetic field strength reduces hot-spot heating due to magnetic mirroring

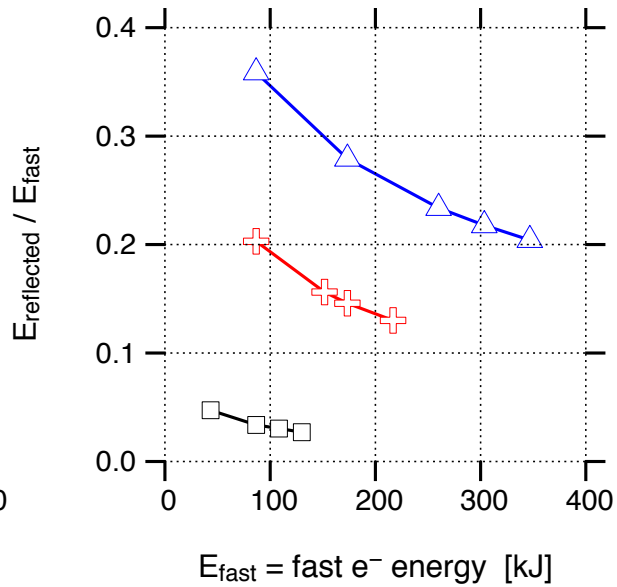
Initial Bz profiles



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

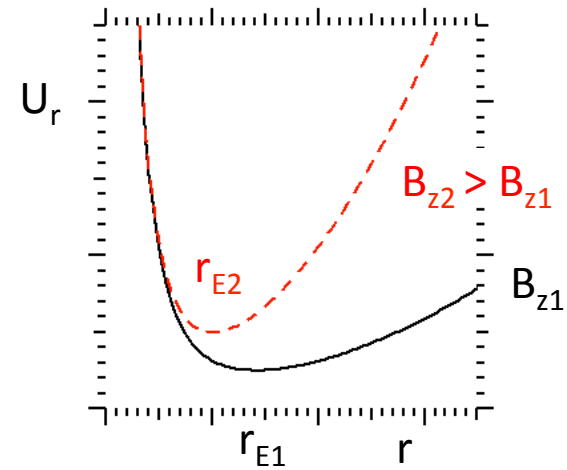
$$\frac{d\vec{p}}{dt} = q\vec{v}\times\vec{B} \qquad \vec{B} = B_z(z)\hat{z} + B_r(r,z)\hat{r} \qquad \omega_{cz} = \frac{qB_z}{\gamma m} \qquad \nabla\cdot\vec{B} = 0 \quad \rightarrow \quad B_r = -\frac{r}{2}\frac{\partial B_z}{\partial z}$$

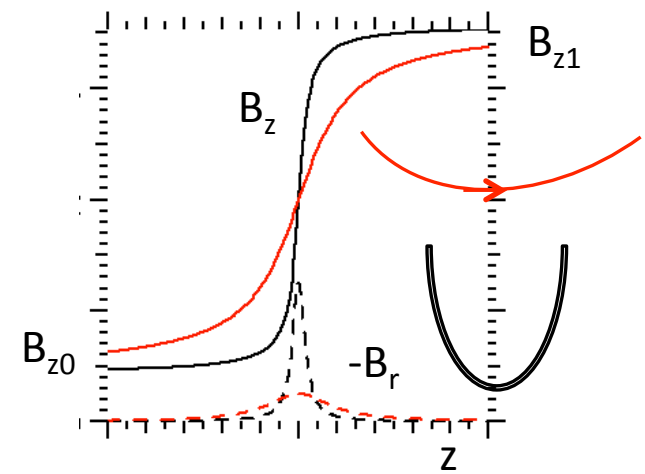
constants of motion: γ and canonical angular momentum $l_0 = r^2(\dot{\phi} + \omega_{cz}/2)$

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



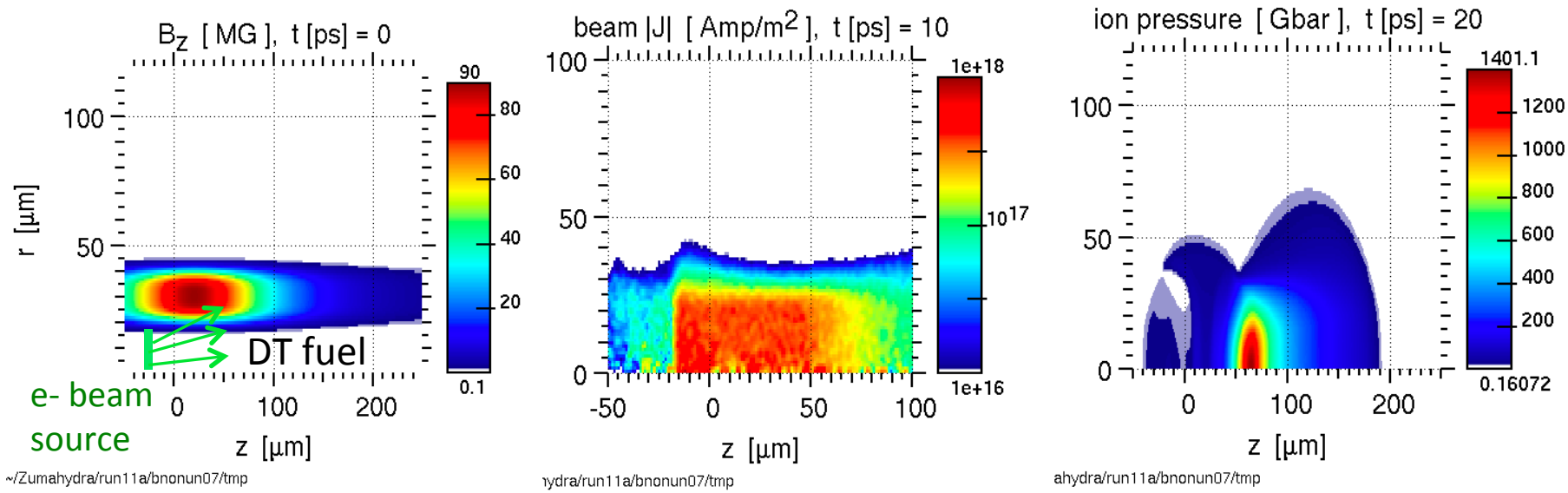


Mirroring in increasing B_z

- 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 ($\Delta\theta = 10^o$) requires E_{fast} = 87 kJ to ignite.



Very little backward-going e-, unlike mirroring cases

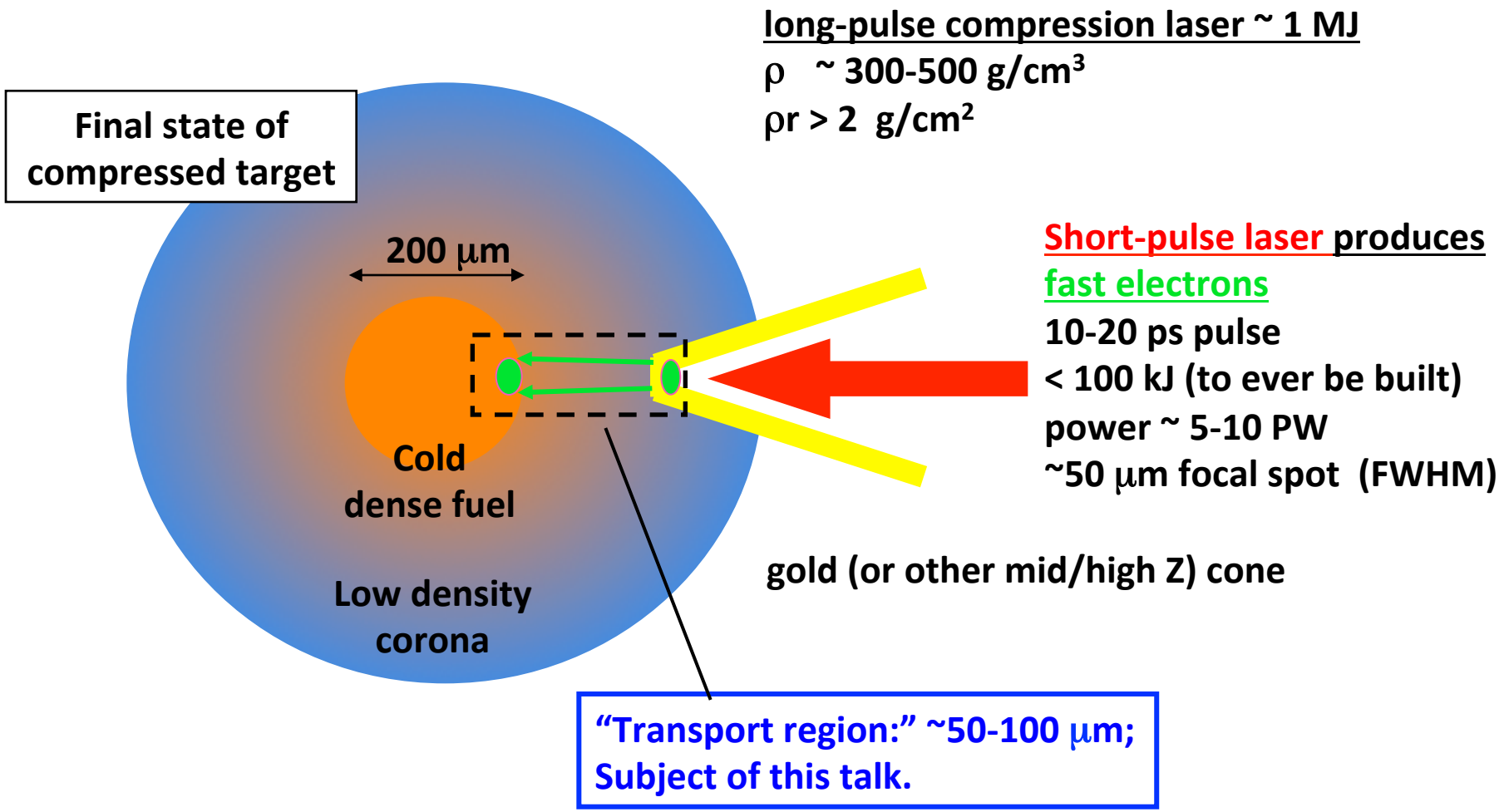
Imposed magnetic fields may circumvent large fast-electron divergence for fast ignition, but mirroring is an issue

- 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

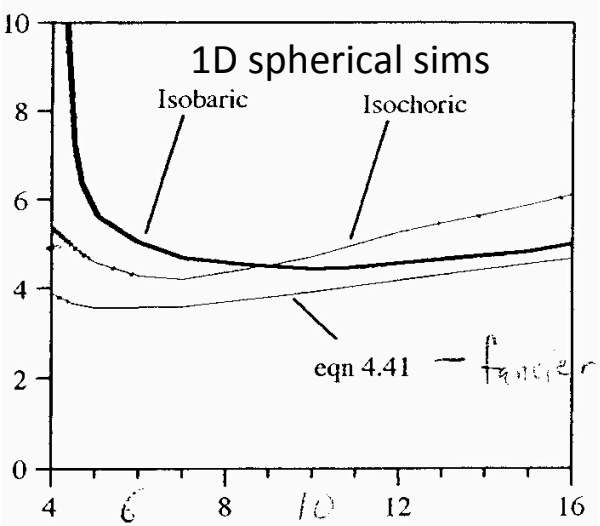


M. Tabak, J. Hammer, M. E. Glinsky, et al., *Phys. Plasmas* **1**, 1626 (1994).

Isochoric ignition hot-spot: T_{ion} > 4 keV and ρ*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.

ρ*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

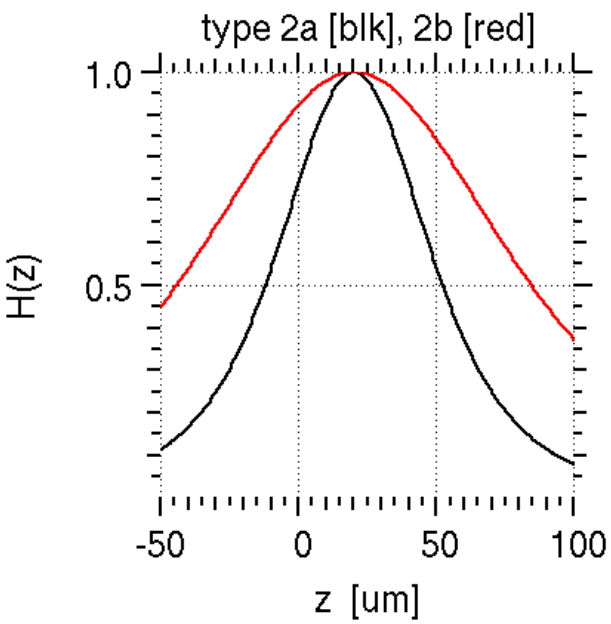
$$B_z(r,z) = B_{z0} + (B_{z1} - B_{z0})G(r)H(z)$$

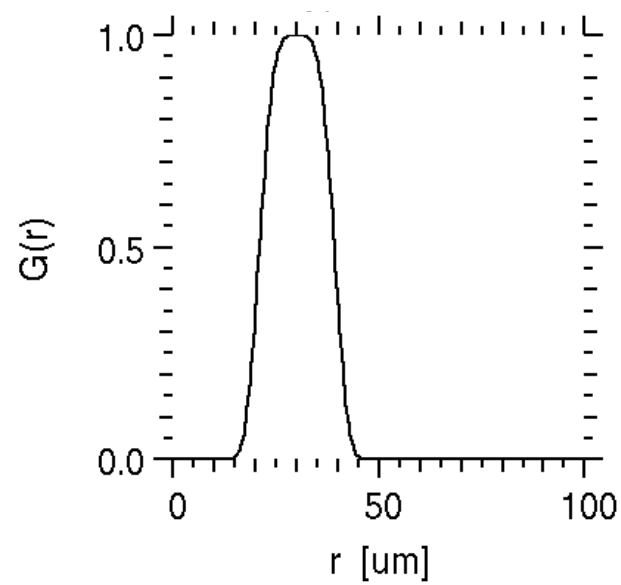
$$G(r) = \exp\left[-\left(\frac{r - r_0}{\Delta r}\right)^4\right]$$

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

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

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

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

$$\nabla \times \vec{B} = \mu_0 \vec{J}_e \longrightarrow \frac{\partial}{\partial t} r B_z + \frac{\partial}{\partial r} v_r r B_z = \mu_0^{-1} \frac{\partial}{\partial r}\left[r\eta \frac{\partial B_z}{\partial r} \right]$$

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 $\psi \equiv \int_{r_1}^{r_2} da \; \hat{z} \cdot \vec{B} = 2\pi \int_{r_1}^{r_2} dr \; r B_z$

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

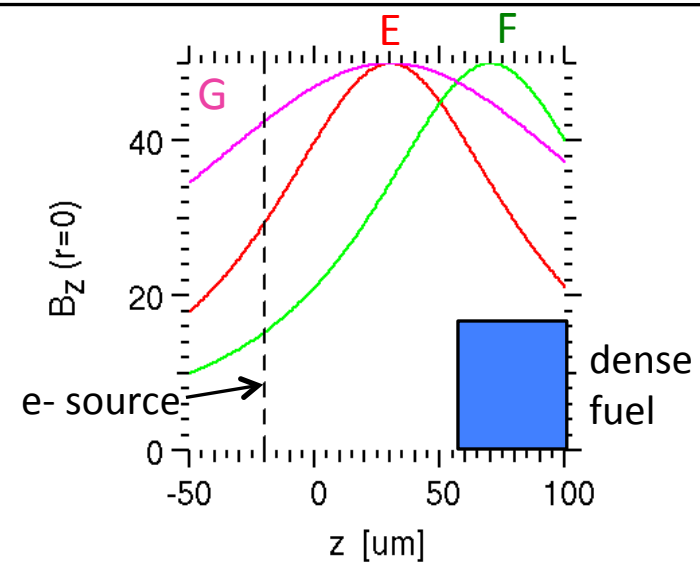
$$\boxed{\text{Then} \quad \frac{d\psi}{dt} = \frac{2\pi}{\mu_0}\left(r\eta \frac{\partial B_z}{\partial r} \right)\Bigg|_{r_1}^{r_2}}$$

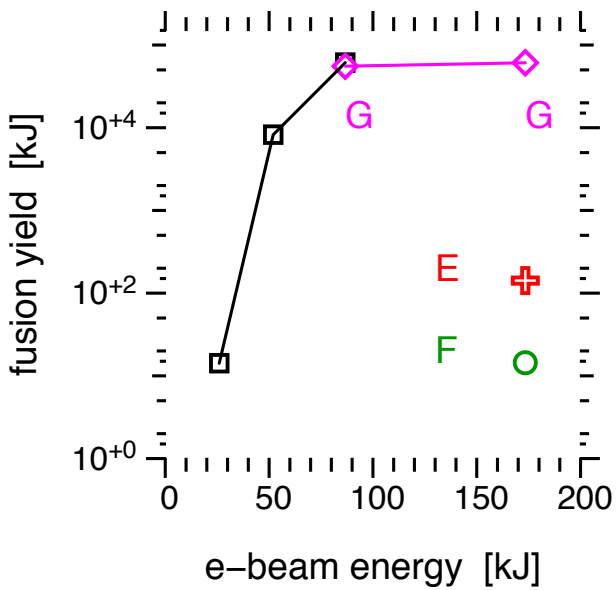
Frozen-in law: magnetic flux between two surfaces moving with the plasma electrons changes only due to magnetic diffusion.

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

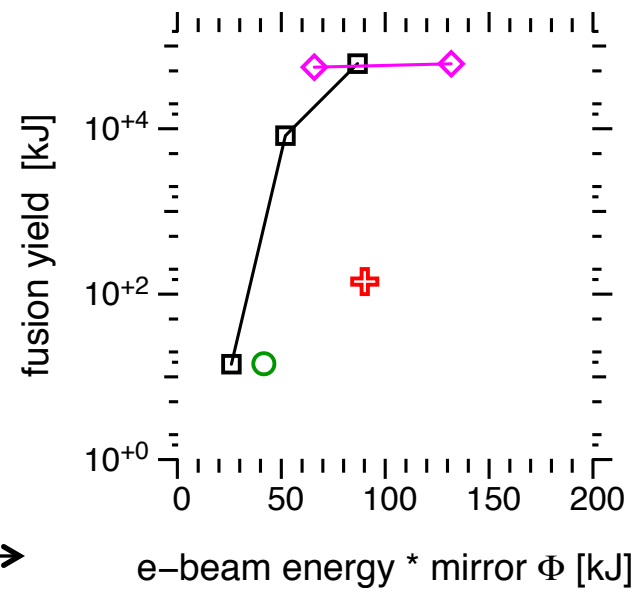
B field type	$B_{z,fuel}$ / $B_{z,exc}$	mirror Φ
E	0.66	0.52 (mid)
F	0.34	0.24 (worst)
G	0.88	0.76 (best)

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



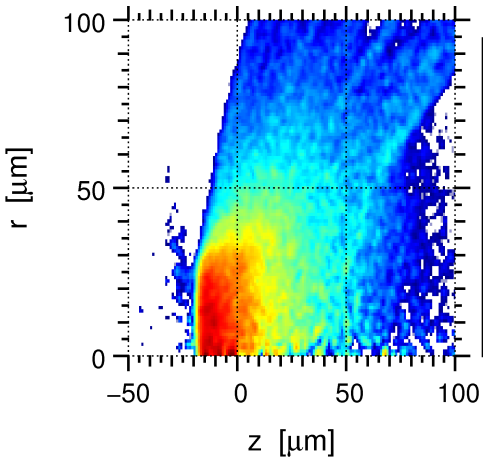


*** mirror Φ**

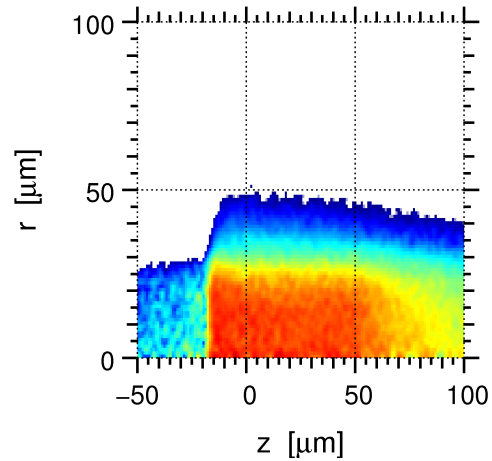


Evidence of mirroring with non-uniform imposed B-fields: reflected fast electrons

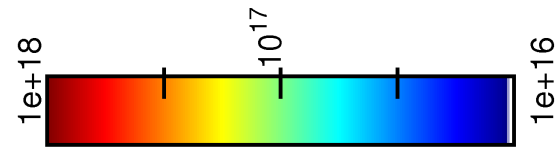
B_{z0} = 0, E_{beam} = 173 kJ



B_{z0} = 50 MG, E_{beam} = 87 kJ

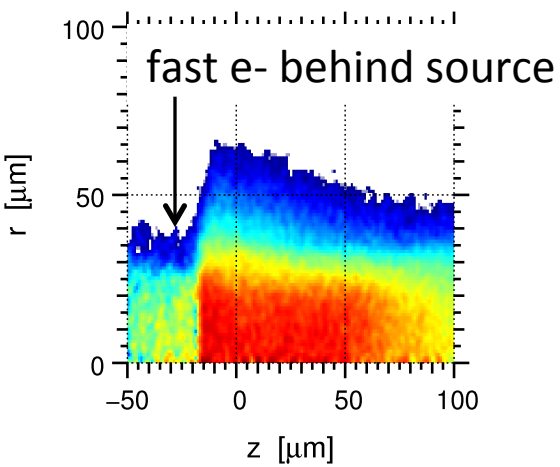


$|J_{beam}|$ [Amp/m^2], t = 10 ps

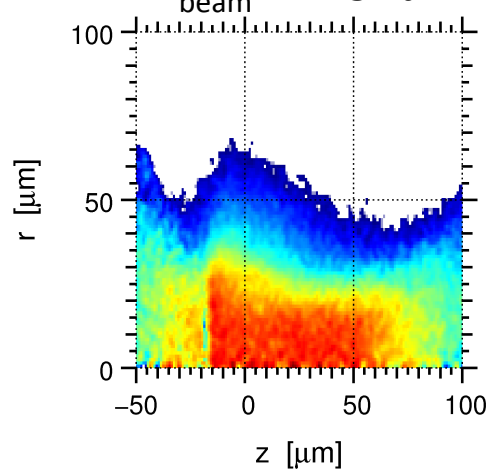


more mirroring

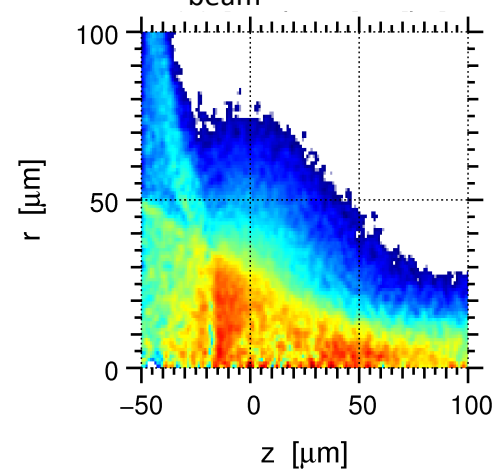
field type G, E_{beam} = 173 kJ



field type E, E_{beam} = 173 kJ



field type F, E_{beam} = 173 kJ



Magnetic mirroring generalities (fully relativistic)

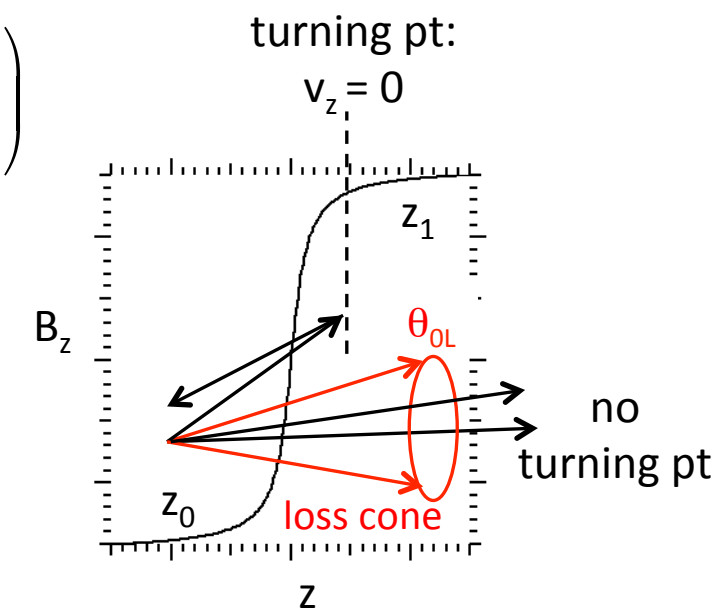
- div B = 0 implies $B_r(r,z) = -(r/2)\, dB_z / dz$
- Mirroring due to z force on a particle: $F_z = q\, v_\perp \times B_r$
- Adiabatic limit: $\left|\frac{1}{B}\frac{dB}{dt}\right| \ll \text{cyclotron freq.}$
- Magnetic moment = adiabatic invariant: *not* exactly conserved, but change is small

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

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

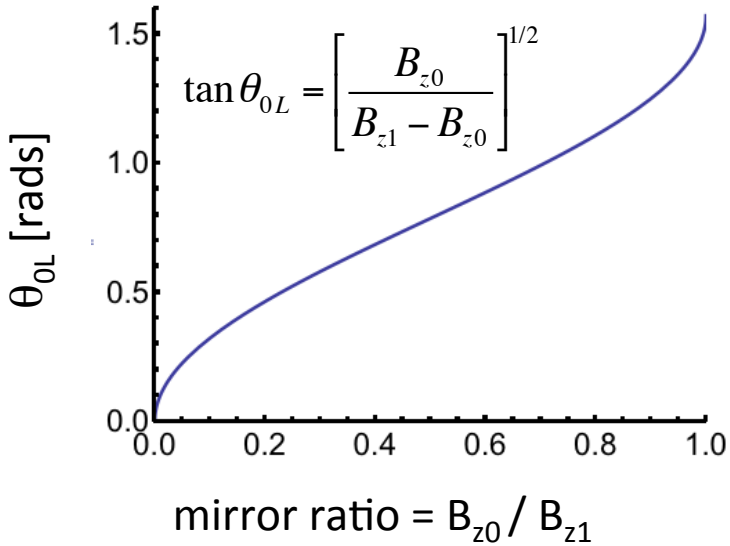
- Loss cone bad in MFE mirror machine,
  but good for us: these e- reach the fuel

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



Mirroring with our electron source

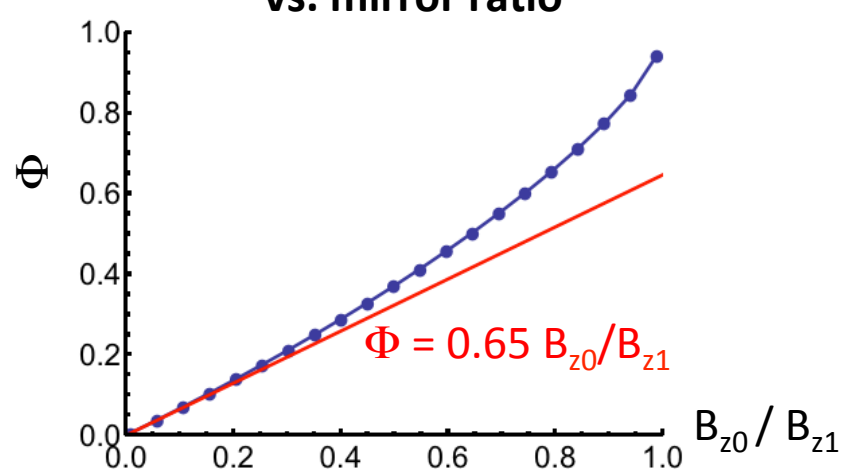
Loss cone angle vs. mirror ratio



- 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