Magnetic Guiding for Electron Fast Ignition

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Magnetic pipes can guide electrons to fast-ignition hot spot

NOTE: talk essentially same as my Anomalous Absorption 2012 talk

*R. Magritte

- **Fast electron source:**
  - too energetic to stop in DT hot spot
  - large angular divergence
- **Imposed axial magnetic field** ~50 MG overcomes divergence
  - Magnetic mirroring: increasing field reflects electrons back to source
  - Magnetic pipe: hollow field inside beam radius – prevents mirroring
- **Azimuthal pipe** better than axial pipe, if sign right:
  - Agrees with expectation from orbits
- **Sign of axial pipe matters!**
  - Not based on orbits, or resistive Ohm's law $E = \eta J_{return}$
  - Non-resistive terms in Ohm's law gives different field evolution

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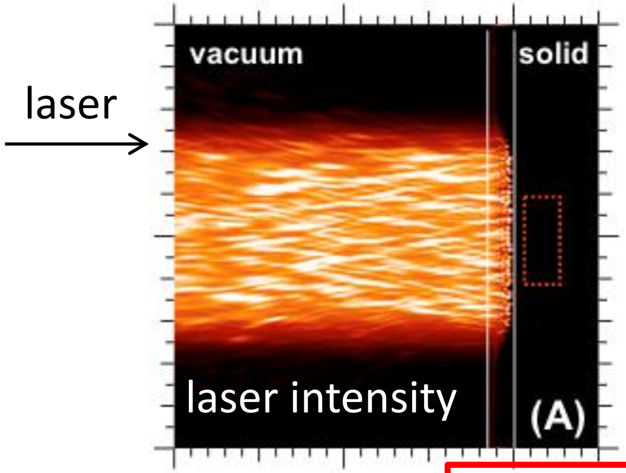
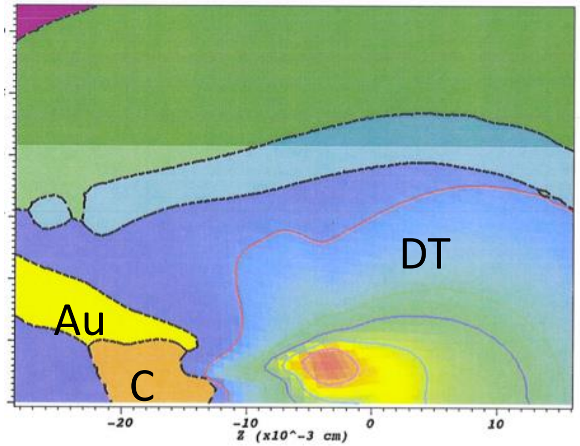
Phys. Plasmas 2012

Fast ignition modeling at LLNL: vintage 2012

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

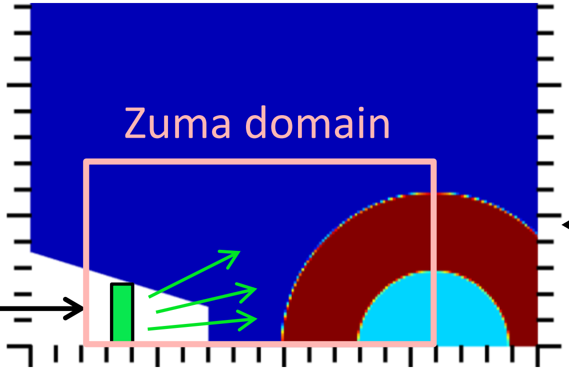


Rad-hydro: fuel assembly in hohlraum, around cone: H. D. Shay, M. Tabak, D. Ho



Transport modeling

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



This talk

fast electron injected source

plasma conditions at time of ignitor pulse

Zuma: D. J. Larson: Hybrid PIC code for fast electron transport in collisional plasmas

- RZ cylindrical (this talk) or 3D Cartesian geometries
- Reduced dynamics: no light, Langmuir waves: $\omega \ll \omega_{pe}, \omega_{laser}$ $k \ll k_{laser}, \lambda^{-1}_{Debye}$
- $\vec{J}_{\mathrm{return}} = -\vec{J}_{\mathrm{fast}} + \mu_0^{-1}\nabla\times\vec{B} + \cancelto{0}{\epsilon_0\partial_t\vec{E}}$
- Electric field from Ohm's law = massless background e- momentum eq:

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

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

full-Braginskii Ohm's law

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

Resistive Ohm's law: $\vec{E} = \eta\vec{J}_{\mathrm{return}}$

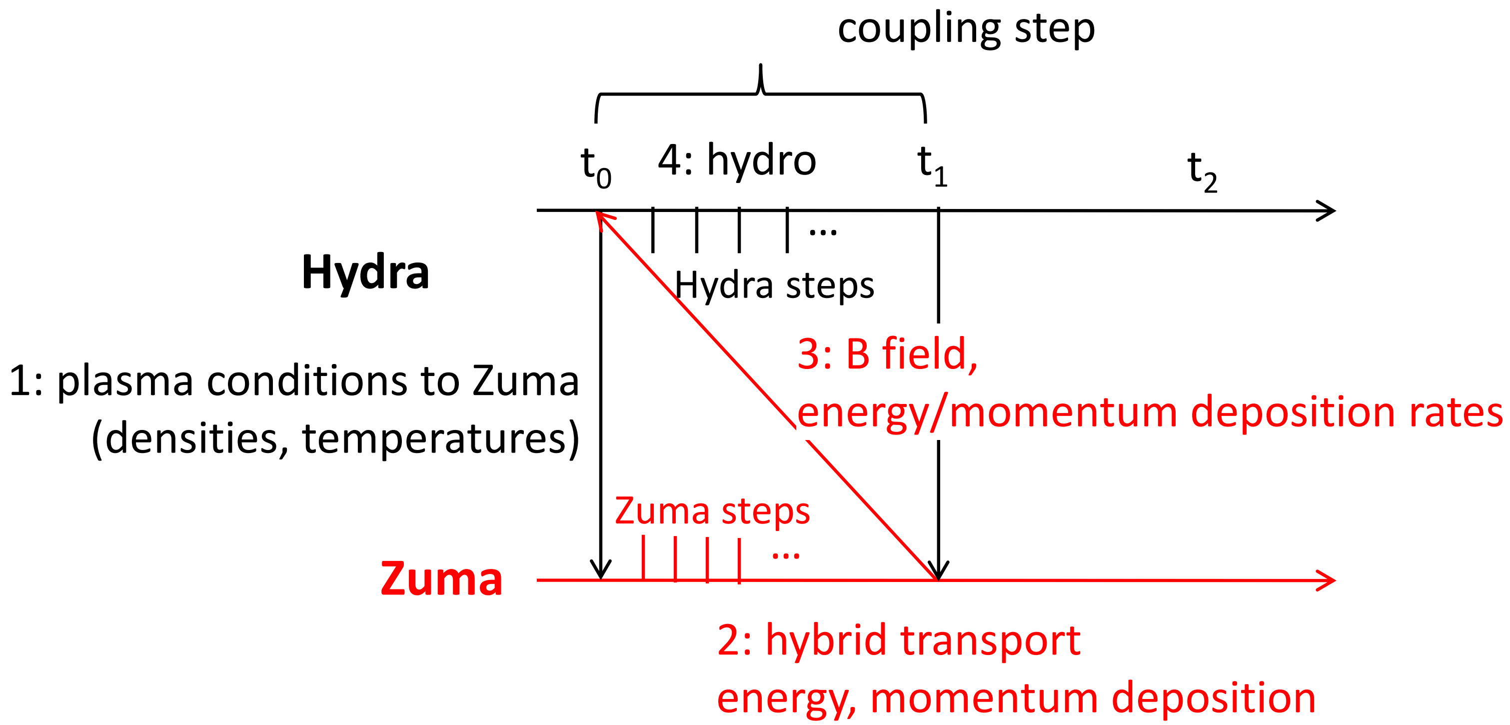
- Relativistic fast electron advance: $\vec{F} = -e\left(\vec{E} + \vec{v}\times\vec{B}\right)$
- Fast e- energy loss, angular scatter [Solodov, Davies]
- $\vec{J}_{\mathrm{return}}\cdot\vec{E}_C$ collisional heating
- $\partial_t\vec{B} = -\nabla\times\vec{E}$ Faraday

Full Ohm's law results differ from E = η*J_{return}

Nicolai et al., APS DPP 2010, Phys Rev E 2011
Strozzi et al., EPJ Web Conf. 2013, IFSA 2011

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

- This talk:
  - both codes in R-Z geometry, fixed Eulerian meshes
  - 20 ps transport (Zuma + Hydra), then 180 ps burn (just Hydra)



Electron spectra from PSC full-PIC sims (A. J. Kemp, L. Divol)

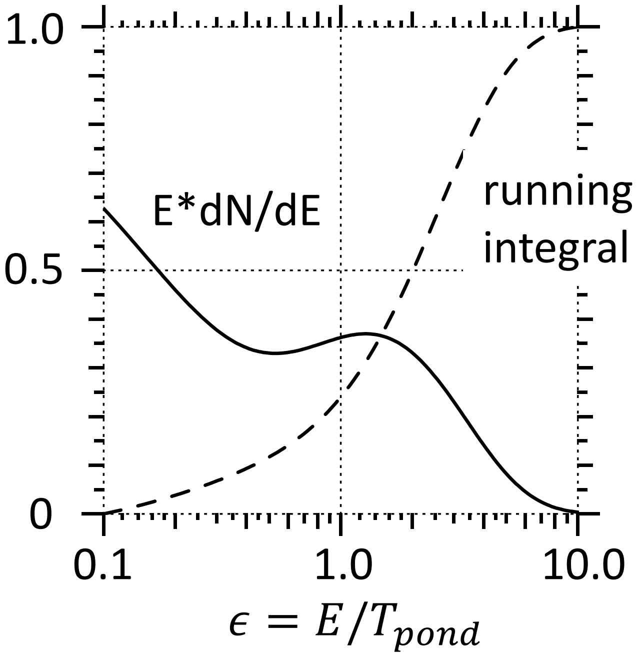
source: $f_E(E)*f_\theta(\theta)$

Energy spectrum

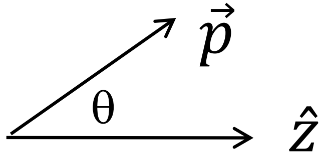
$$\frac{dN}{d\epsilon} = \underbrace{0.82\exp[-\epsilon/1.3]}_{\text{“hot:” from pre-plasma}} + \underbrace{\frac{1}{\epsilon}\exp[-\epsilon/0.19]}_{\text{“cold:” from } n_{crit}}$$

$$\epsilon = E/T_{pond} \qquad \langle\epsilon\rangle = 1.02$$

$$T_{\mathrm{pond}}/m_e c^2 \equiv [1+a_0^2]^{1/2} - 1 \sim a_0$$



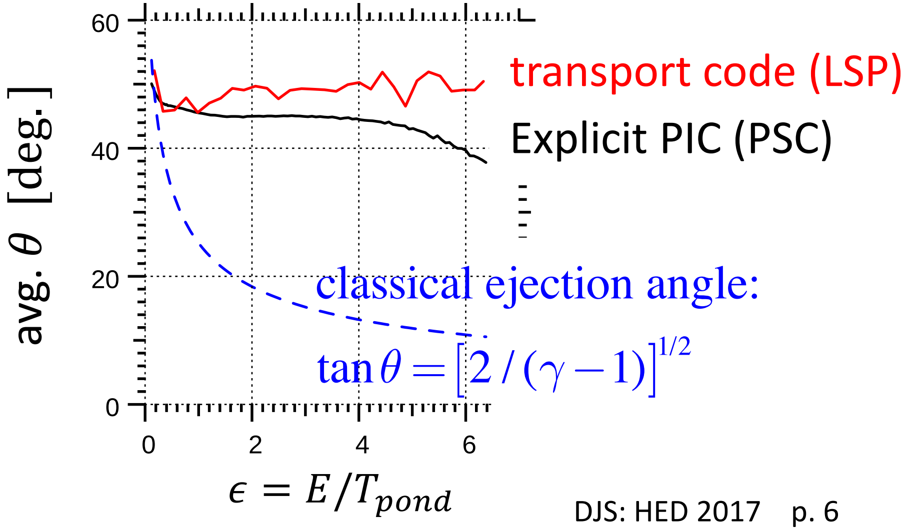
Angle spectrum



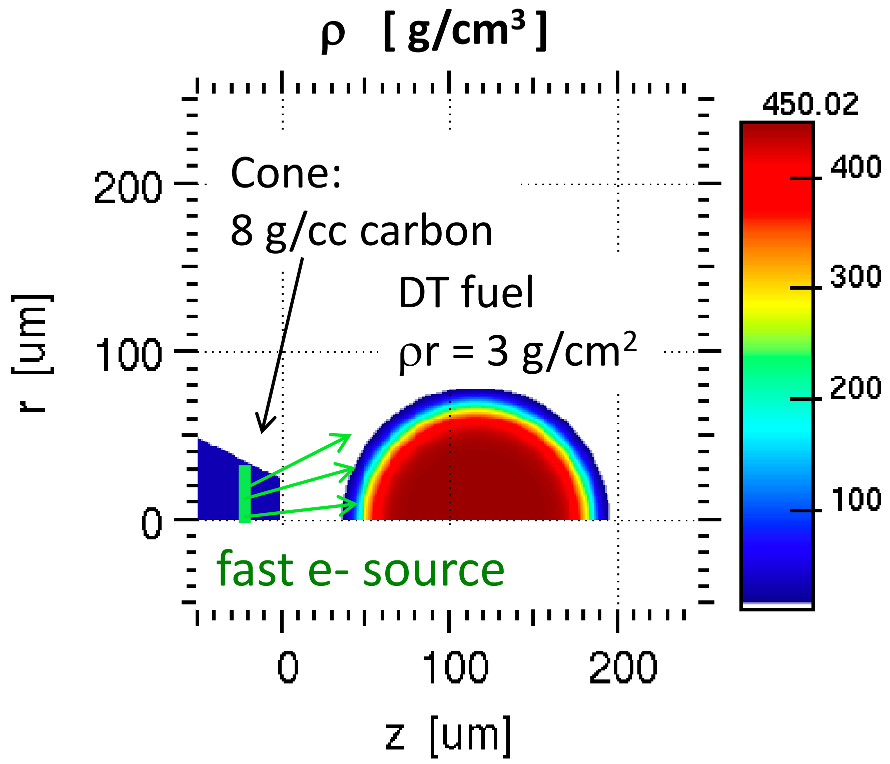
$$\frac{dN}{d\Omega} = \exp\left[-(\theta/\Delta\theta)^4\right] \qquad \Omega = \text{solid angle}$$

$$\langle\theta\rangle \approx 0.69\Delta\theta$$

Δθ	<θ>	runs used for
10°	6.9°	artificially collimated source
90°	52°	matches PSC; realistic source



Idealized high-gain target: carbon cone, ideal ignition energy of 8.7 kJ



- Ideal burn-up fraction: $\rho R/(\rho R+6) = 1/3$
- Ideal fusion yield = 64 MJ

Ideal e- ignition energy [Atzeni et al., PoP 2007]:

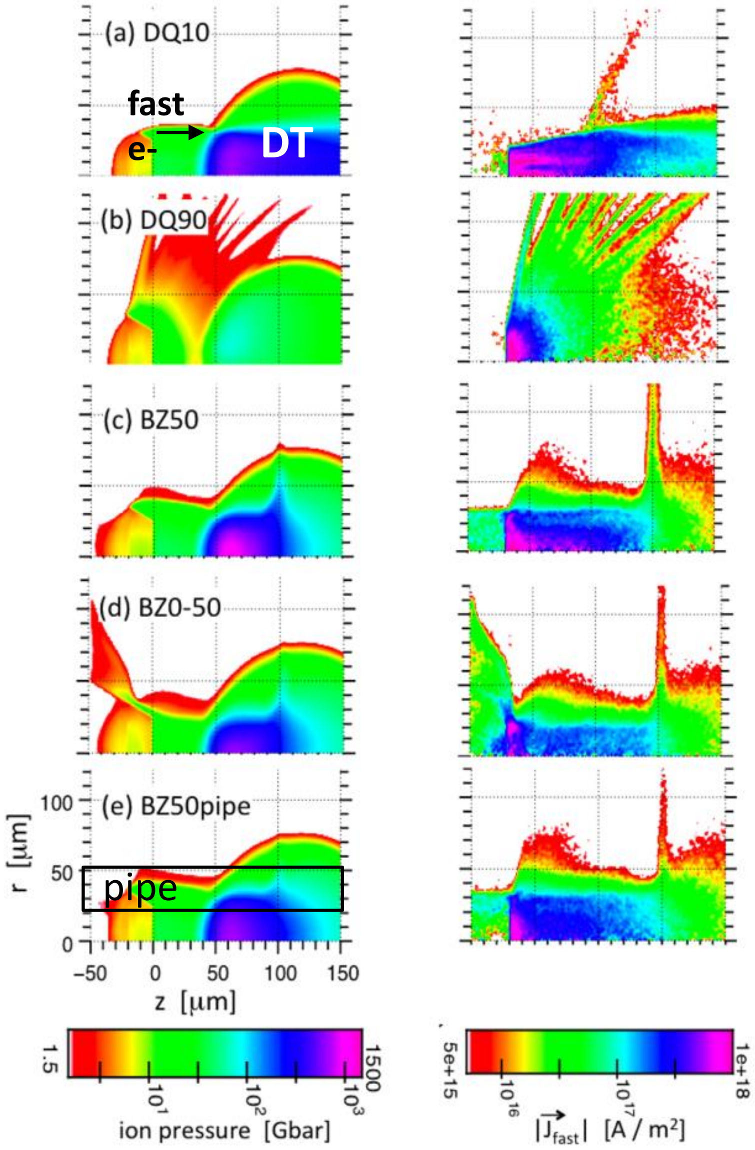
- 2D rad-hydro, no cone, cylindrical beam heat source

  $E_{ig} = 140\text{ kJ} / (\rho/100\text{ g/cc})^{1.85}$

  $= 8.7\text{ kJ}$ ← minimum goal

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

Fast electron coupling helped by axial B field, hurt by mirroring, mitigated by hollow magnetic pipe



Ion pressure

fast e- current

Small source angular spread

Realistic angular spread

Uniform 50 MG axial field to Z = 100 um

0-50 MG ramped field: mirroring

0-50 MG magnetic pipe: mirroring reduced

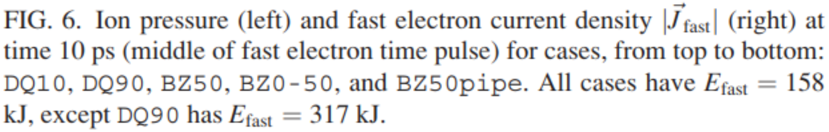
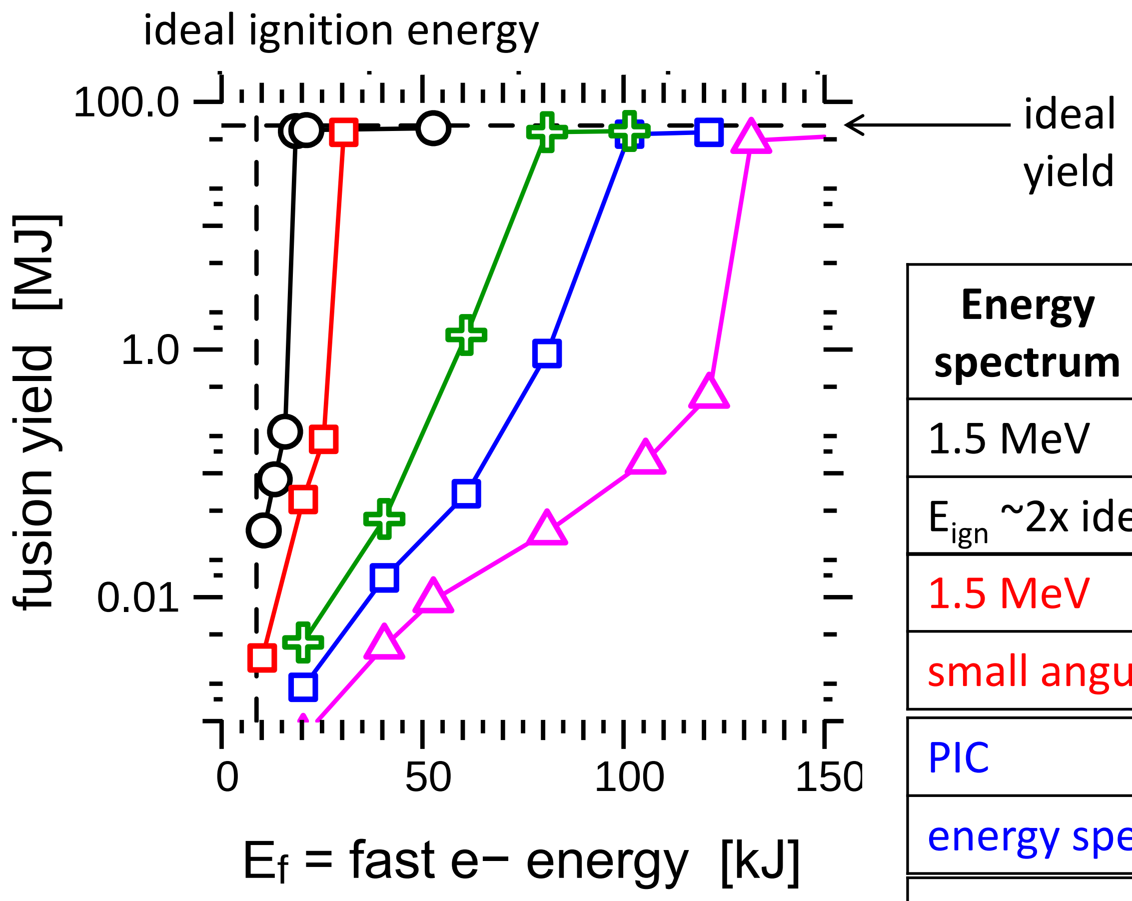


FIG. 6. Ion pressure (left) and fast electron current density $|\vec{J}_{\rm fast}|$ (right) at time 10 ps (middle of fast electron time pulse) for cases, from top to bottom: DQ10, DQ90, BZ50, BZ0-50, and BZ50pipe. All cases have $E_{\rm fast} = 158$ kJ, except DQ90 has $E_{\rm fast} = 317$ kJ.

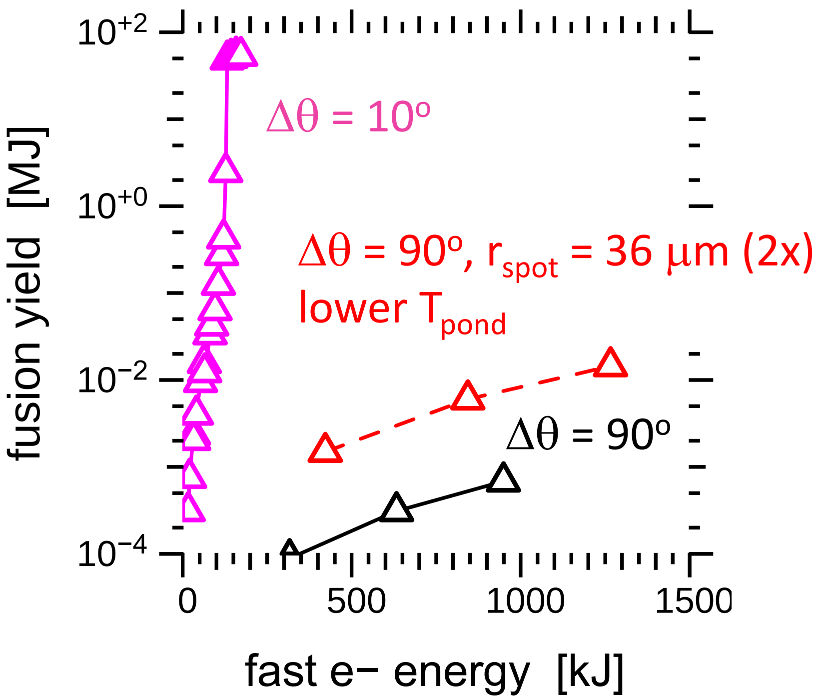
D. Strozzi et al, PoP 2012

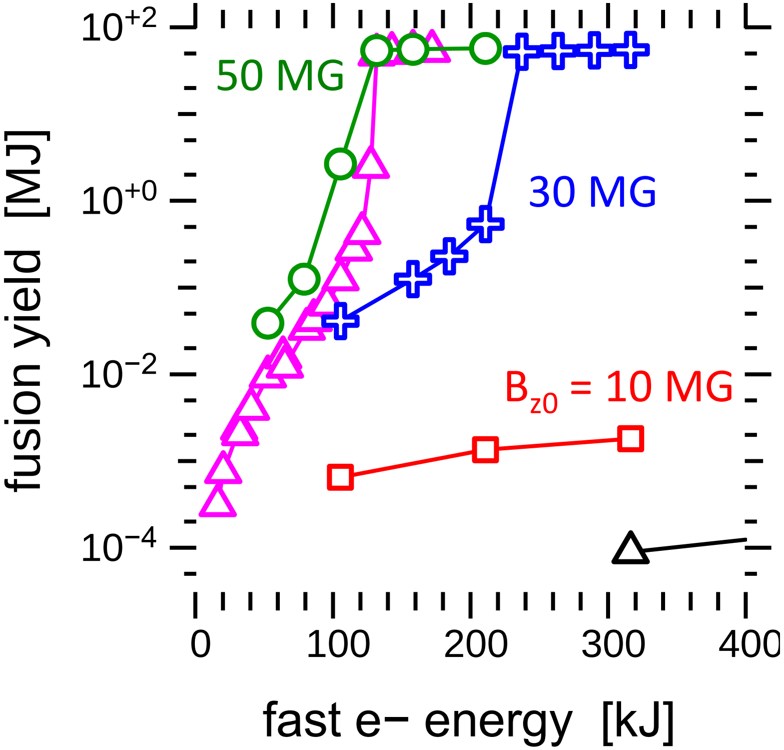
Ignition energy 15x ideal value *with collimated electron source*



Energy spectrum	**initial $\Delta\theta$**	**angular scatter**	**E/B fields**
1.5 MeV	0	no	none
E_{ign} ~2x ideal			
1.5 MeV	10°	yes	none
small angular spread E_{ign} ~ 1.5x			
PIC	10°	yes	none
energy spectrum E_{ign} ~ 3.3x			
PIC	10°	yes	$E = \eta J_{return}$
Resistive self-guiding E_{ign} ~ 0.8x			
PIC	10°	yes	full Ohm's
non-resistive fields E_{ign} ~ 1.6x			

Realistic divergence greatly increases ignition energy; axial magnetic field 30-50 MG mitigates divergence





- Omega implosion experiments: compressed 50 kG seed field to:
  30-40 MG (cylindrical[1]), 20 MG (spherical[2])

- Rad-hydro-MHD studies of B field compression have begun: H. D. Shay, M. Tabak

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[1] J. P. Knauer, Phys. Plasmas 2010

[2] P. Y. Chang et al., Phys. Rev. Lett. 2011

Axial magnetic field that increases in z leads to mirror force, reflects fast electrons

$$\nabla \cdot \vec{B} = 0 \quad \rightarrow \quad B_r = -\frac{1}{r}\int_0^r dr' r' \frac{\partial B_z}{\partial z}$$

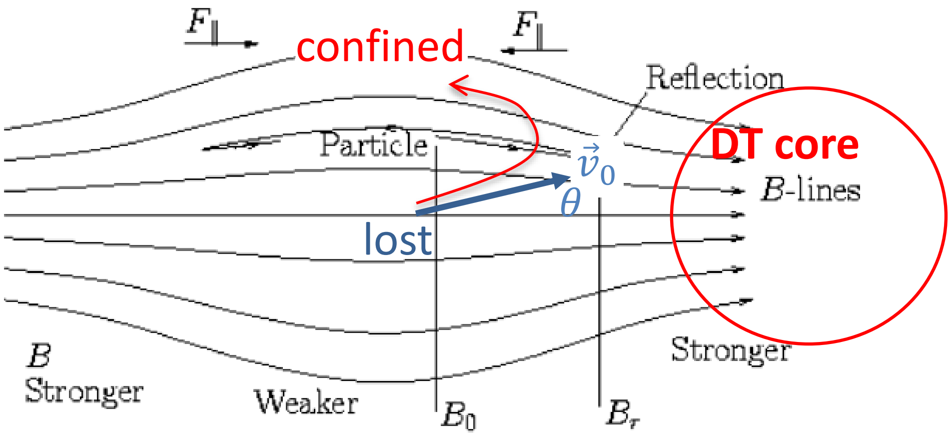
$$\vec{F} = q\vec{v} \times \vec{B} \quad \rightarrow \quad F_z = -q v_\phi B_r$$

Static, non-uniform $\vec{B}$; $\vec{E}$=0

Kinetic energy conserved: $v_\perp^2 + v_{||}^2 = v_{\perp 0}^2 + v_{||0}^2$

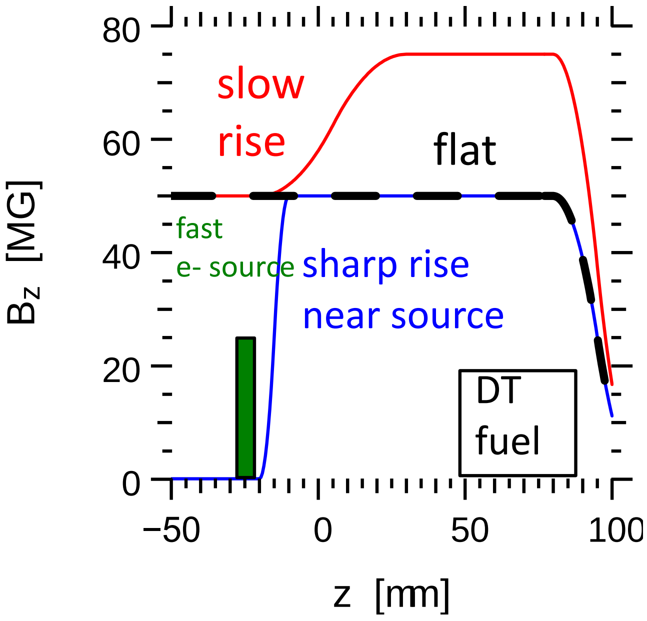
Magnetic moment adiabatic invariant: $\frac{v_\perp^2}{B} = \frac{v_{\perp 0}^2}{B_0}$

Magnetic mirror: turning point: $v_{||} = 0$ → $\frac{B_{mir}}{B_0} = 1 + \frac{v_{||0}^2}{v_{\perp 0}^2}$

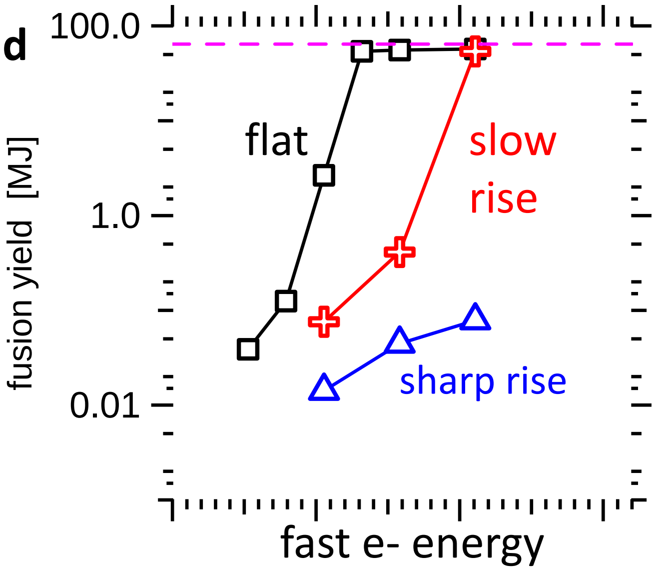


Mirroring reduces effectiveness of axial guide field

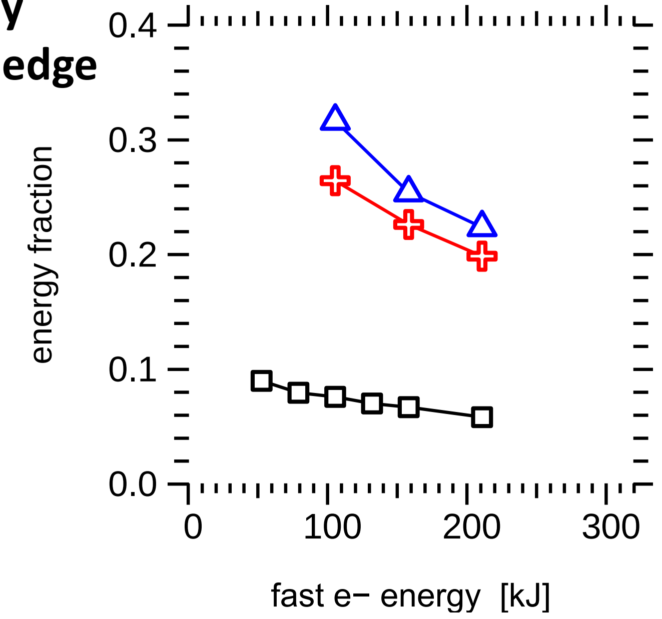
Initial B_z profiles



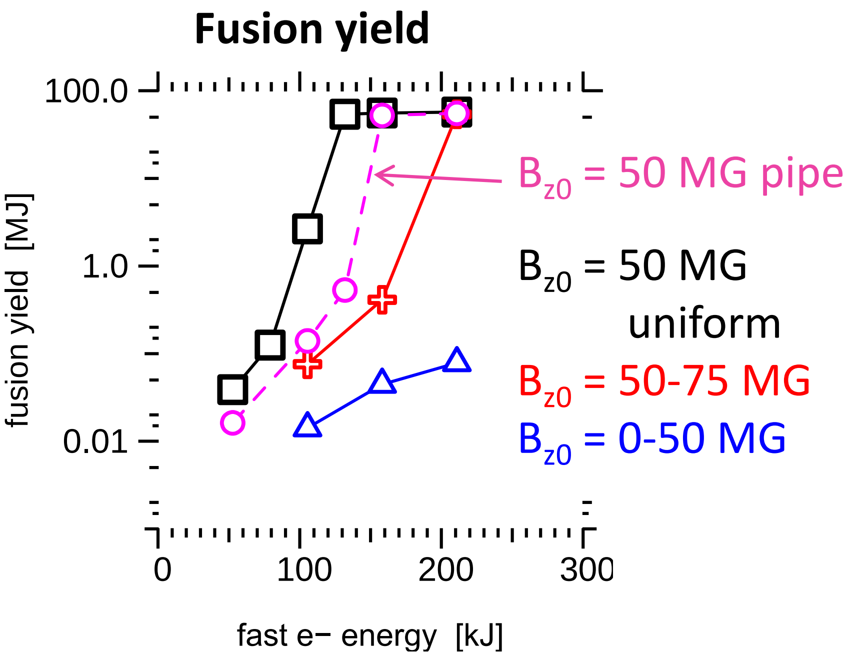
Fusion yield

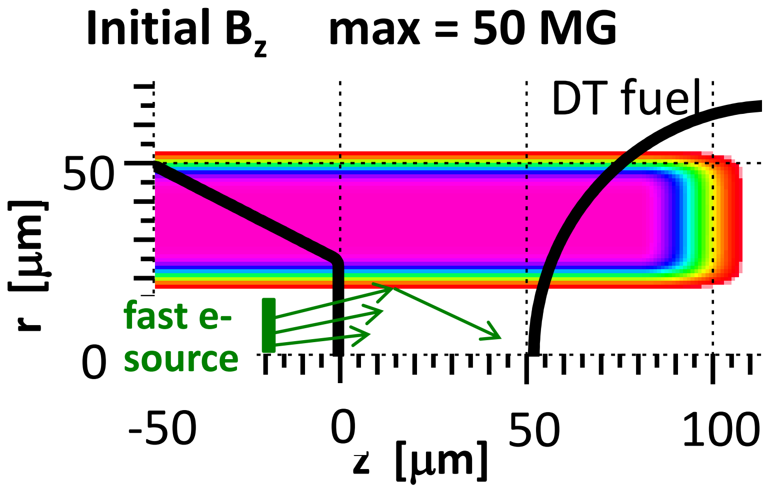


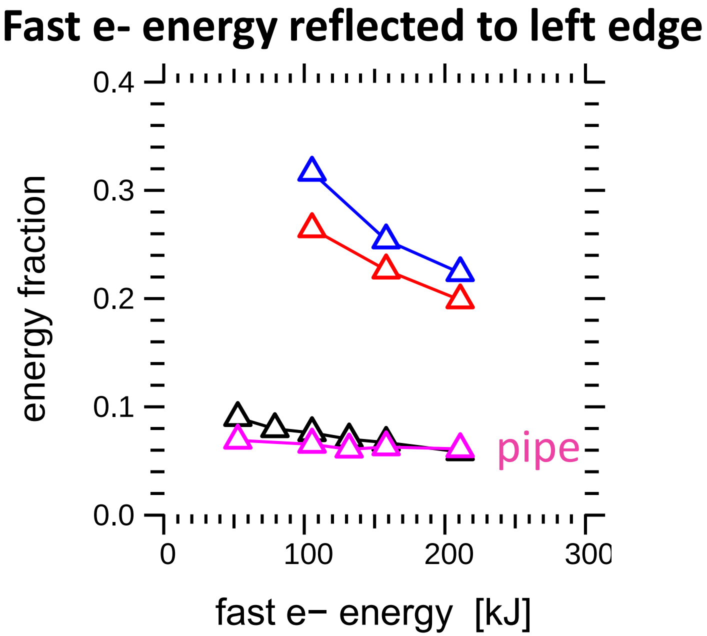
Fast e- energy reflected to left edge



Magnetic pipe: hollow inside spot radius, avoids mirroring

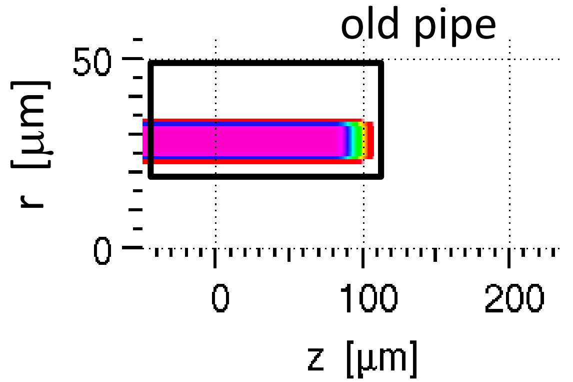


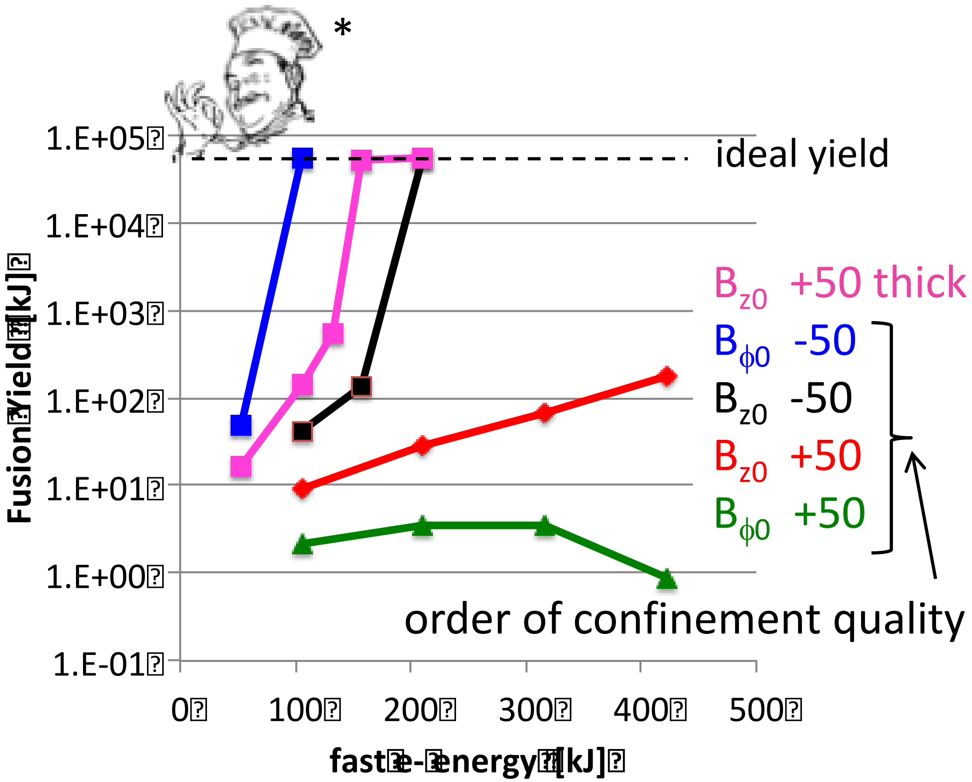




Magnetic pipes: sign and direction (axial vs. azimuthal) matters

Thinner pipe: easier to assemble



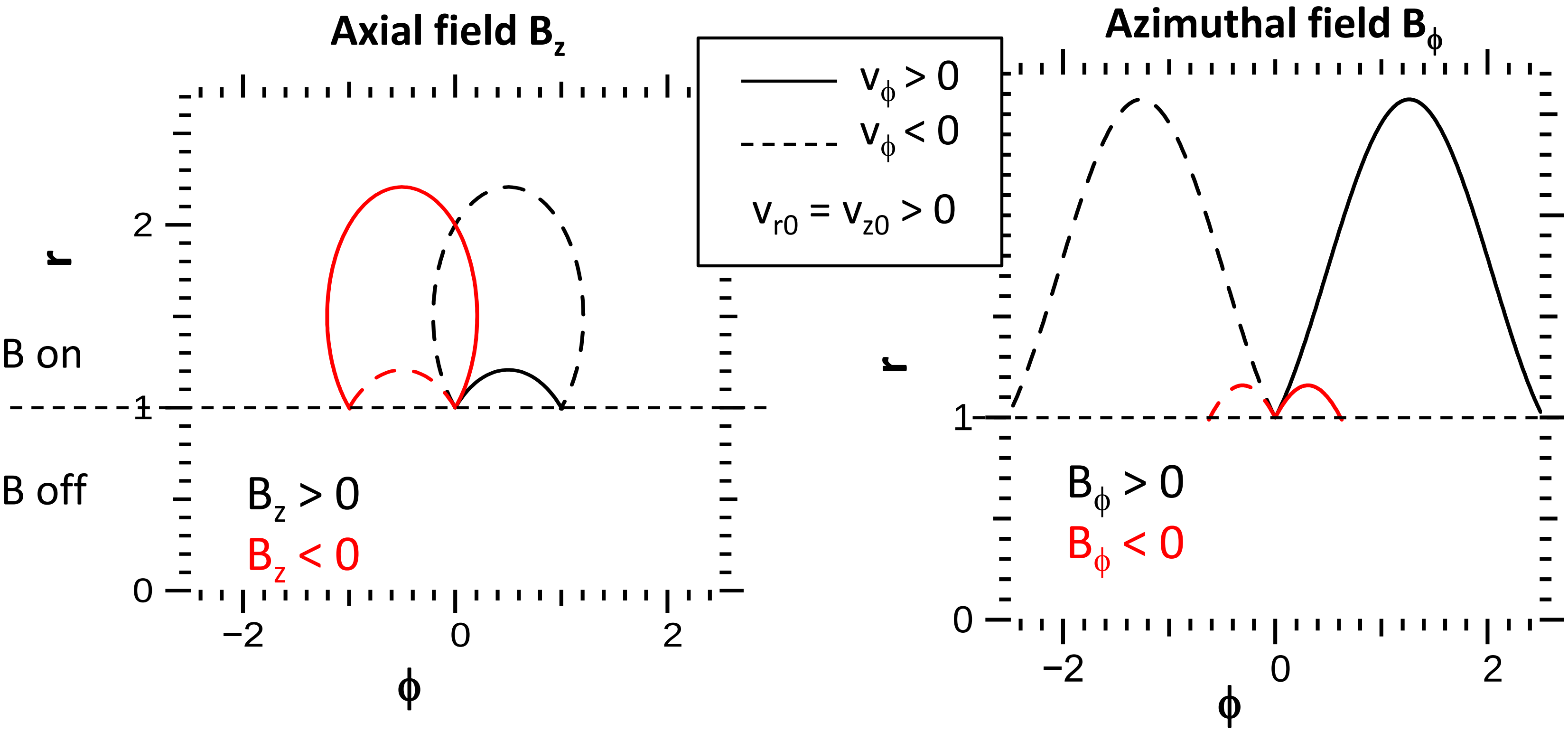


- So far I've used $B_z > 0$, the wrong sign – sorry!

- Fast electrons self-generate azimuthal field in radial resistivity gradient:
  Robinson and Sherlock, Phys. Plasmas 2007

* Courtesy C. Bellei

Orbits of electrons in magnetic pipe fields



Orbit-based quality of pipe confinement:

$B_\phi < 0$

$B_z < 0$ and $B_z > 0$ same

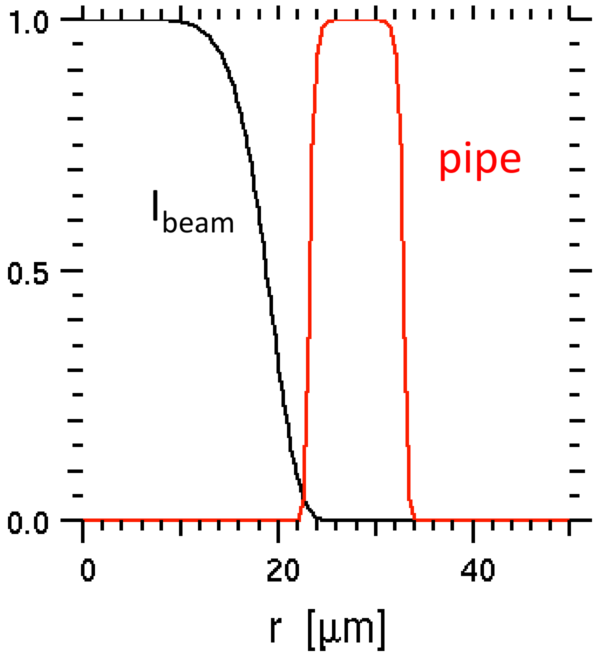
$B_\phi > 0$

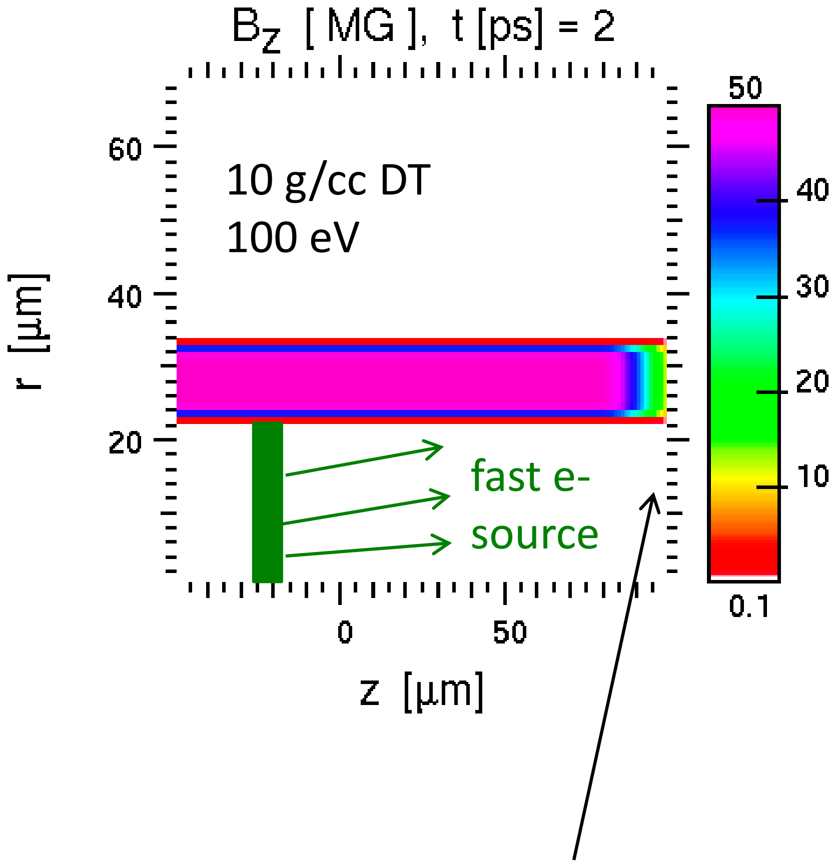
Orbits explain performance of B_ϕ signs, and B_ϕ vs B_z – but not role of sign(B_z)

Cartesian geometry: $(r,\phi,z) = (x,y,z)$

Magnetic pipes in simplified, uniform plasma

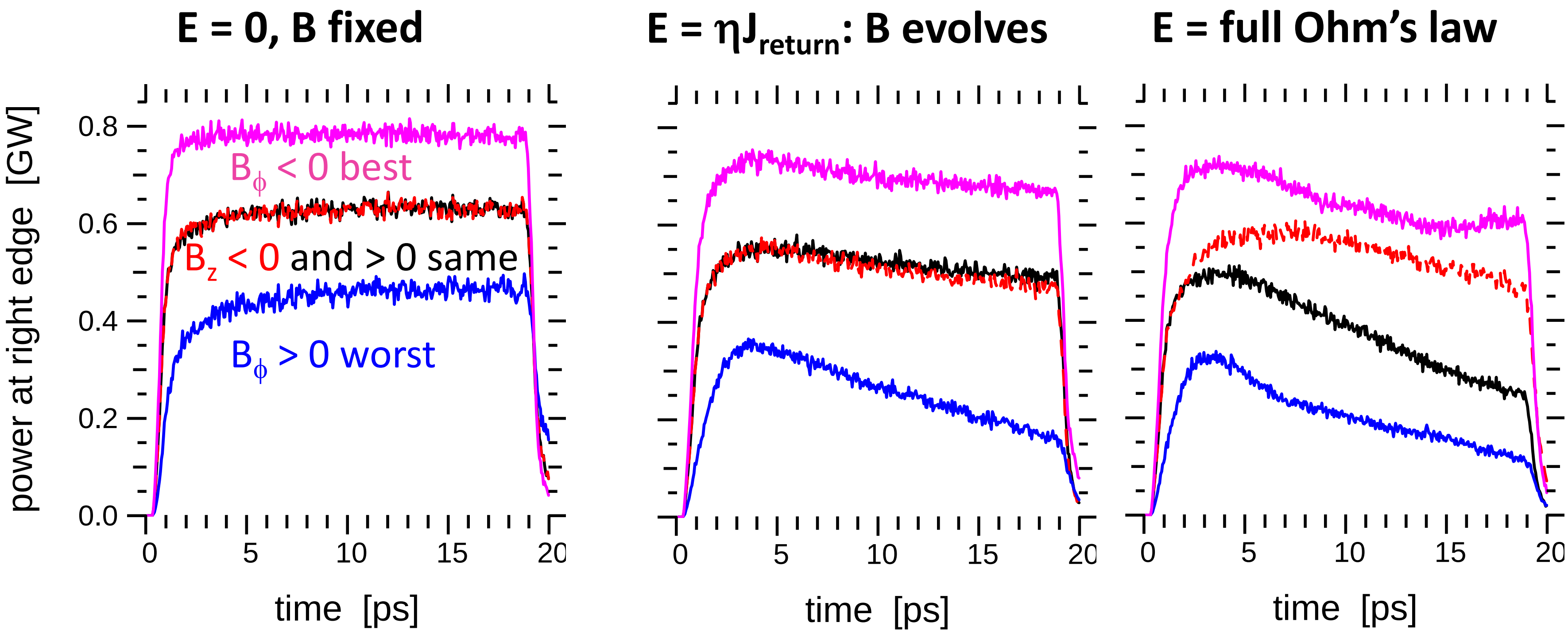
Zuma runs, no Hydra, no cone or dense fuel





Next page: delivered power = rate energy exits at right, r < 20 µm, at most 1.3 MeV per electron (~ stopping in hot spot)

Full Ohm's law gives different confinement based on sign(B_z):



E = 0, B fixed

E = ηJ_{return}: B evolves

E = full Ohm's law

Coupling as expected
from orbits

coupling drops:
plasma diamagnetic

ordering unchanged

B_z < 0 better than B_z > 0!

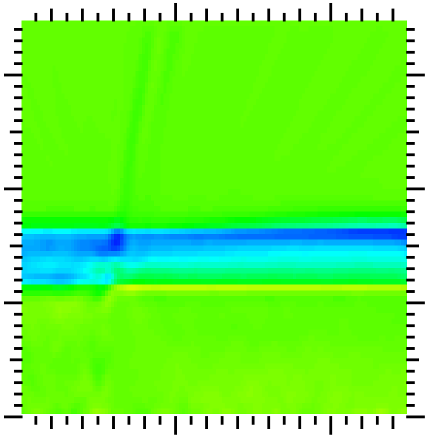
Delivered power = rate energy exits at right, r < 20 μm, at most 1.3 MeV per electron (~ stopping in hot spot)

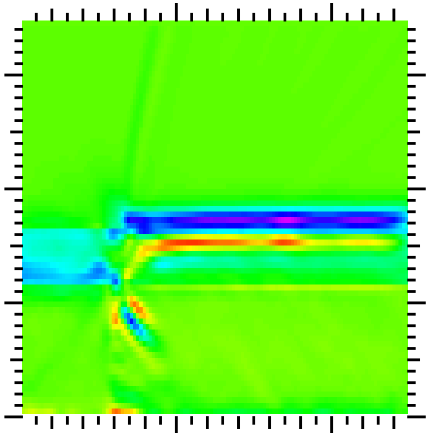
Full Ohm's law: magnetic fields evolve differently than with $E = \eta J_{return}$, and for each sign (B_z)

$E = \eta J_{return}$

E = full Ohm's law

$B_{z0} > 0$
$+B_z$ plotted

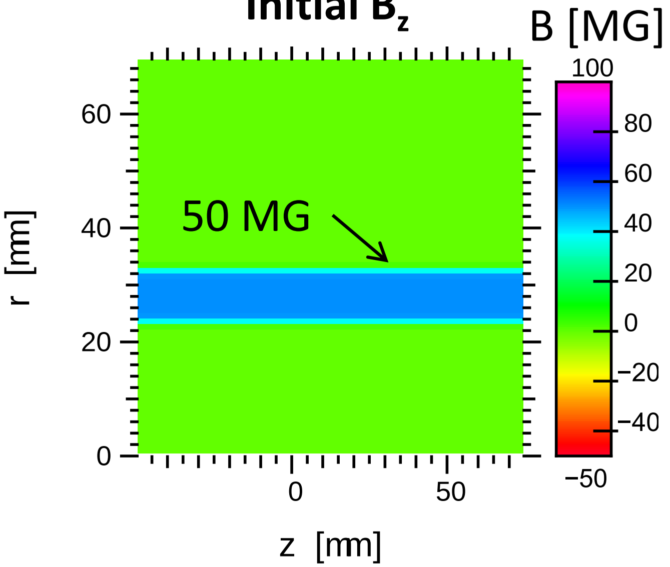




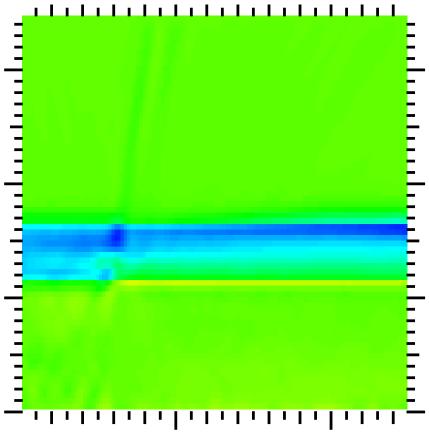
plasma diamagnetic: reduces pipe, similar for both sign(B_z)

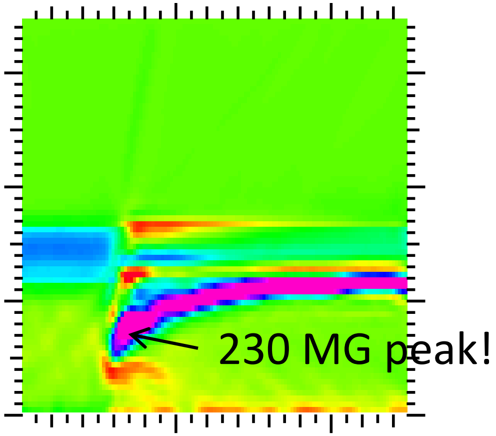
More change in B field, different for each sign(B_z)!

Initial B_z



$B_{z0} < 0$
$-B_z$ plotted





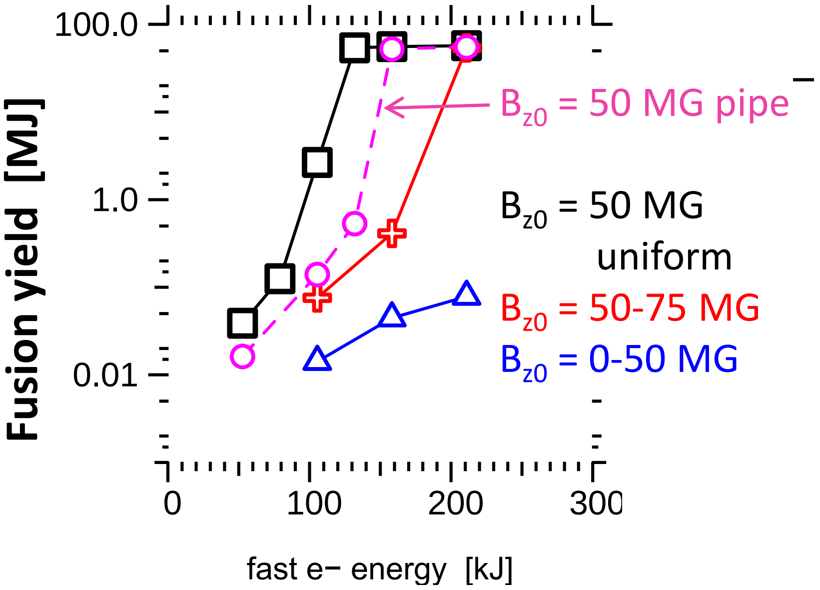
230 MG peak!

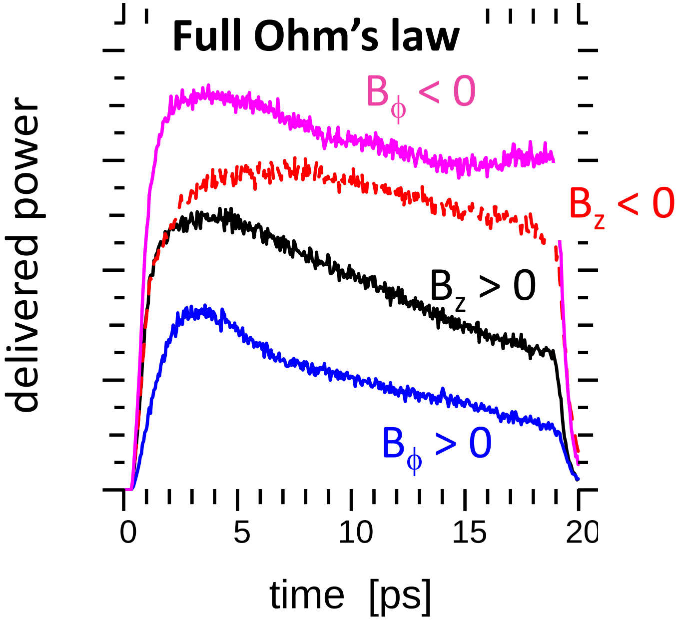
Fields at t = 20 ps

Is fast ignition a pipe dream?

- **Imposed, axial magnetic fields 30-50 MG:**
  - recover ignition energy of collimated electron source
- **Magnetic mirroring** reduces benefit
- **Magnetic pipes** overcome mirroring

- **Azimuthal vs. axial pipes:**
  - $B_\phi < 0$ works best
  - $B_z < 0$ works better than $B_z > 0$
  - Full Ohm's law: B fields evolve differently





D. J. Strozzi et al., Phys. Plasmas 2012; IFSA 2011 proceeding

BACKUP BELOW

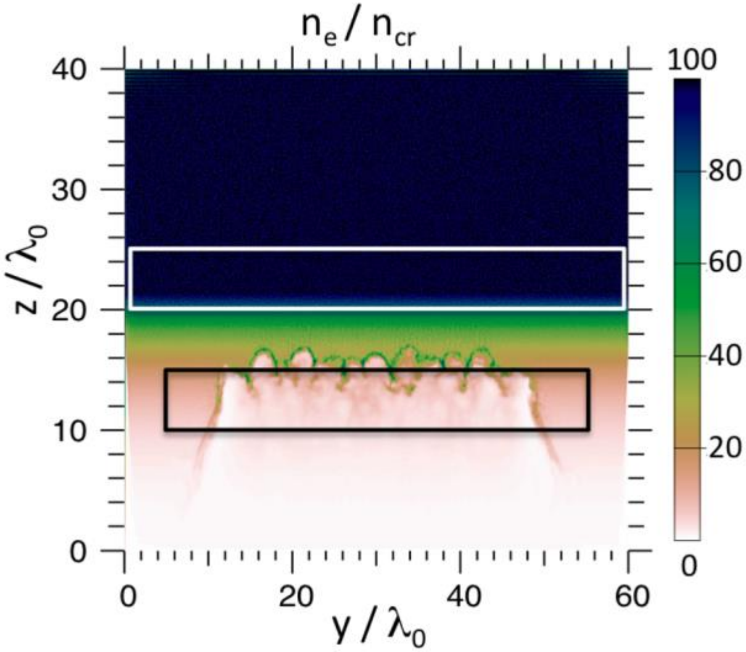


FIG. 1. Electron density at time 360 fs in the PSC run used to characterize the fast electron source. The white box indicates the extraction box, and the black box indicates the source box in the hybrid-implicit LSP run. The laser was incident from $z = 0$ with a vacuum focus at $z = 10$ μm.

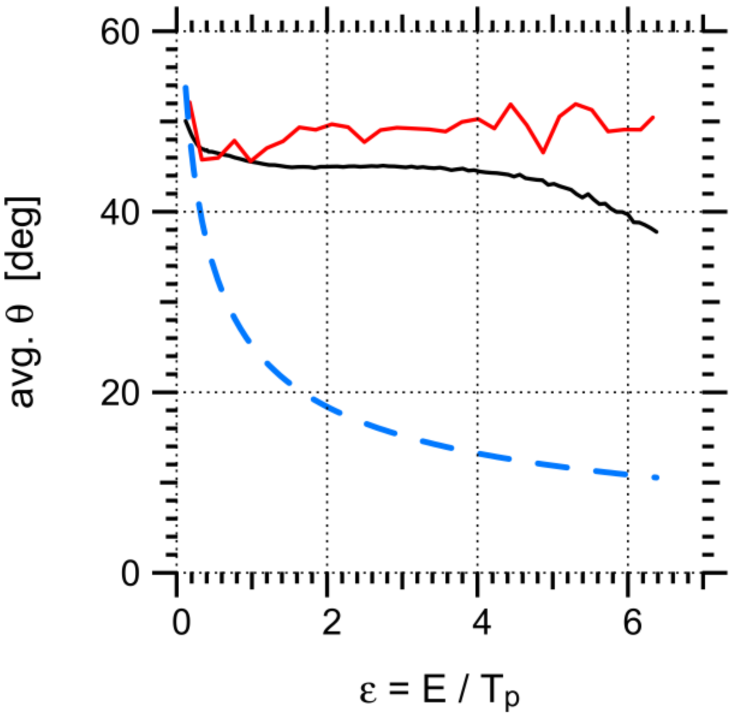


FIG. 2. Average velocity-space polar angle vs. electron kinetic energy in the extraction box for the PSC full-PIC (solid black) and LSP implicit-PIC (solid red) runs. The classical ejection angle θ_c from Eq. (2) is plotted in dashed blue.