Magnetic Guiding for Electron Fast Ignition

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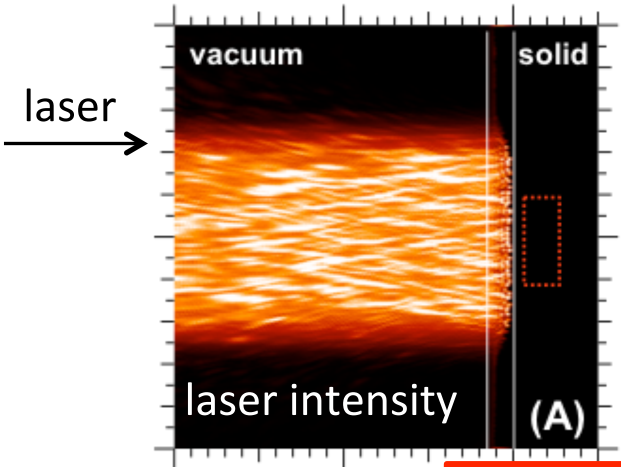
Magnetic pipes can guide electrons to fast-ignition hot spot

- 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 of right sign works better than axial pipe:
  - 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
- Co-authors: M Tabak, D Larson, H Shay, L Divol, A Kemp, C Bellei, M Marinak, M Key

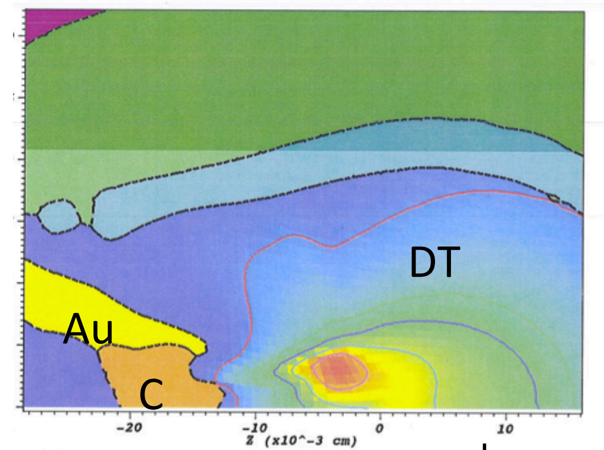
D Strozzi et al., submitted: Phys. Plasmas, arxiv.org/abs/1205.1594; IFSA 2011 proceeding

Fast ignition modeling at LLNL

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



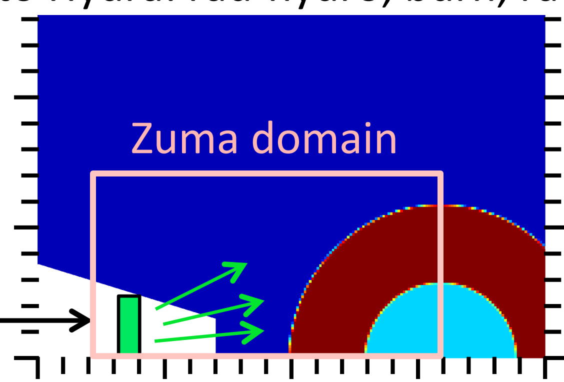
Rad-hydro: fuel assembly in hohlraum, around cone: H. D. Shay, M. Tabak, D. Ho



fast electron injected source

Transport modeling

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



plasma conditions at time of ignitor pulse

Subject of this talk

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, plasma waves: $\omega \ll \omega_{pe}, \omega_{laser}$ $k \ll k_{laser}, \lambda^{-1}_{Debye}$
  - Electric field from Ohm's law = massless momentum eq. for background electrons:

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

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

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

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

Relativistic fast electron advance: $\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B})$

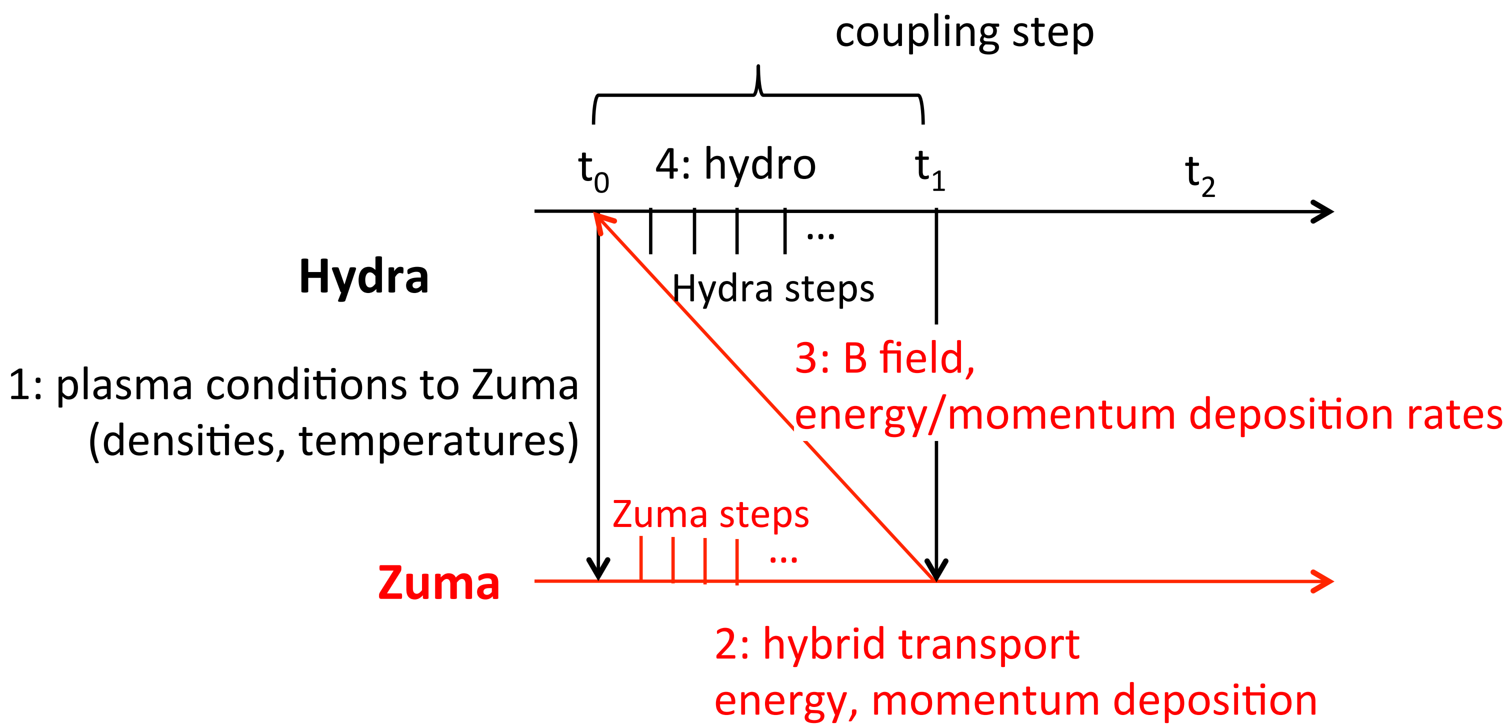
- Fast e- energy loss and angular scattering [Solodov, Davies]
- $\vec{J}_{\mathrm{return}} = -\vec{J}_{\mathrm{fast}} + \mu_0^{-1} \nabla \times \vec{B}$ — Ampere w/o displacement current
- $\vec{J}_{\mathrm{return}} \bullet \vec{E}_C$ — collisional heating
- $\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$ — Faraday

Full Ohm's law results differ from $E = \eta^* J_{return}$

Nicolai et al., APS DPP 2010,
Phys Rev E **84**, 016402 (2011)
Strozzi et al., IFSA 2011 (submitted)

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)

Energy spectrum

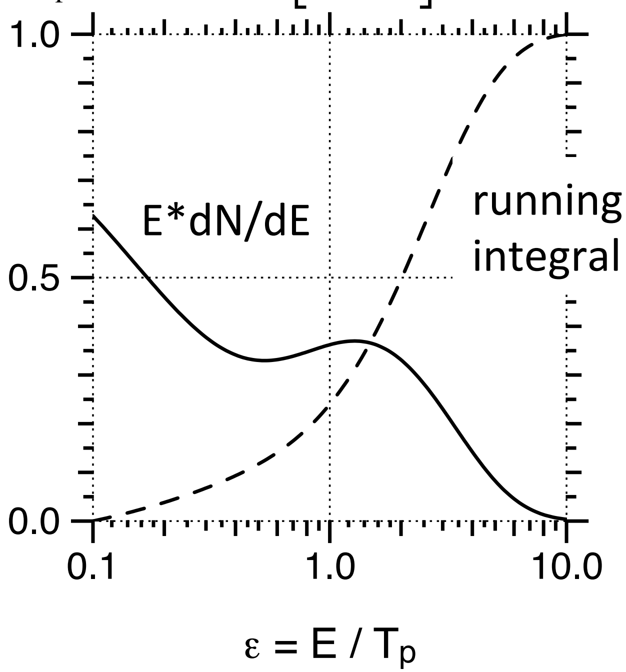
source: $f_E(E)*f_\theta(\theta)$

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

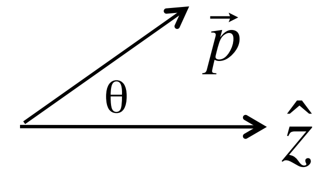
"hot:" from pre-plasma — "cold:" from n_{crit}

$$\varepsilon = \frac{E}{T_{pond}} \qquad \langle\varepsilon\rangle = 1.02$$

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



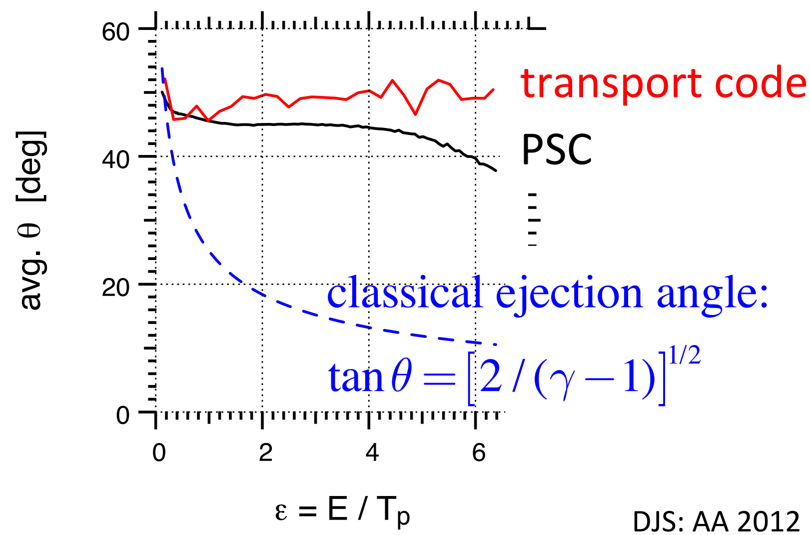
Angle spectrum



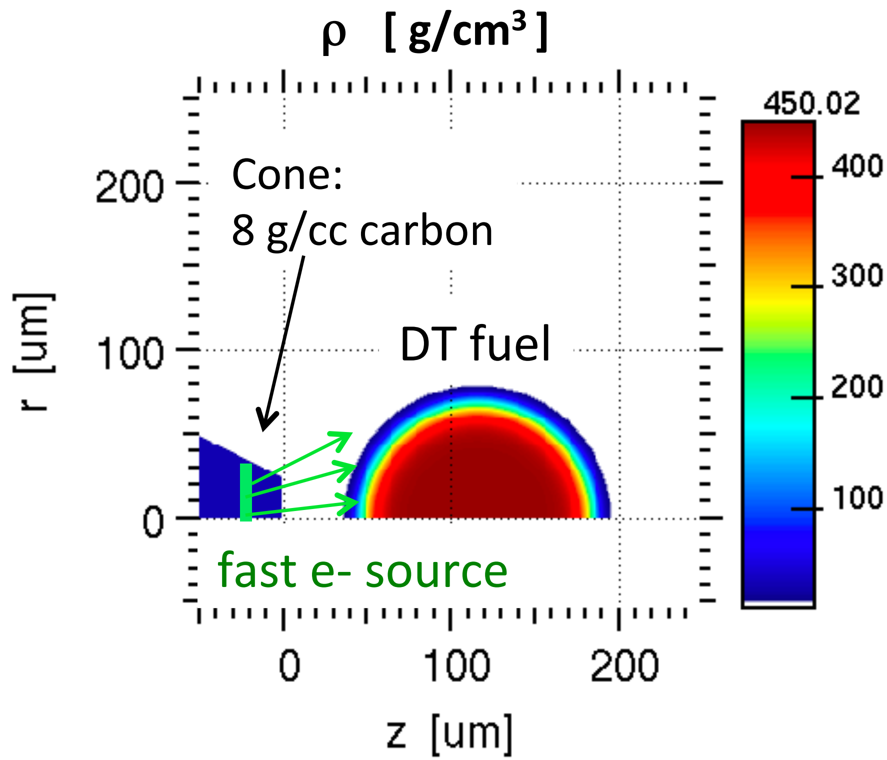
$$\frac{dN}{d\Omega} = \exp\left[-(\theta/\Delta\theta)^4\right] \qquad \Omega = \text{solid angle}$$

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

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]:

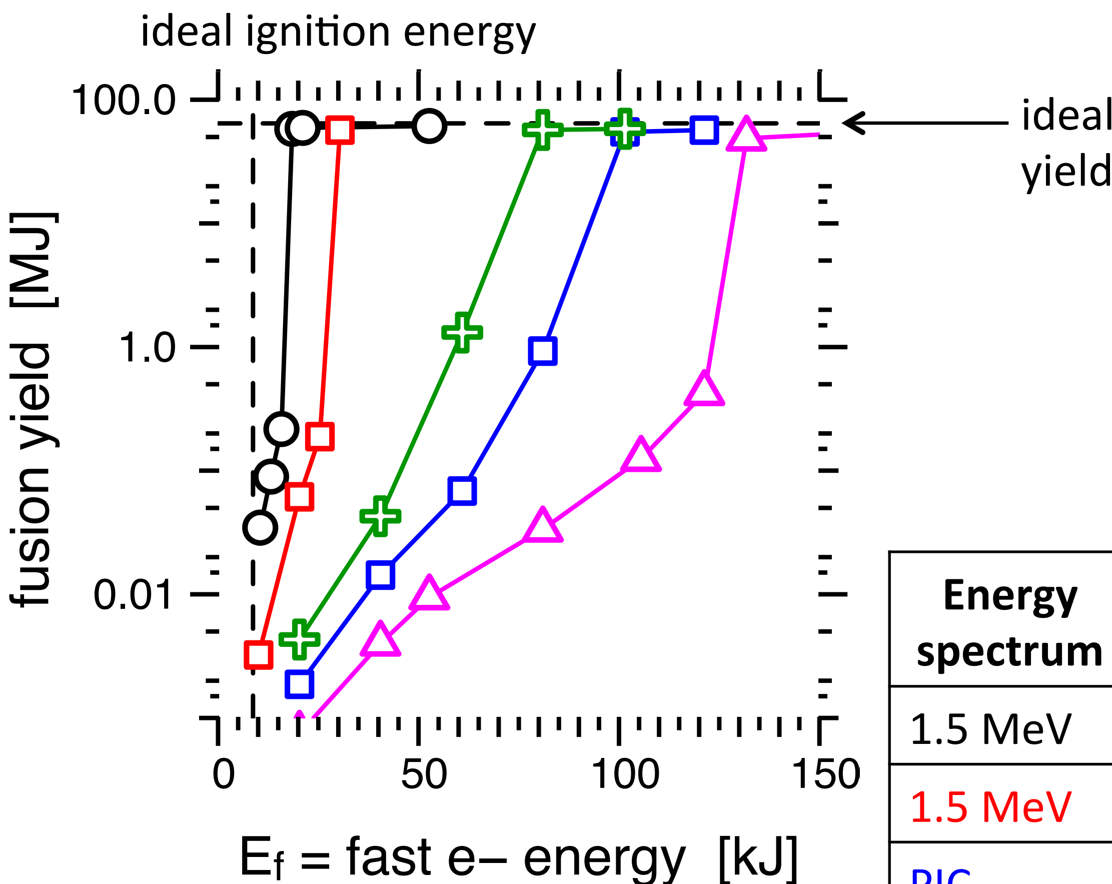
- 2D rad-hydro, no cone, cylindrical beam heat source

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

  = 8.7 kJ ← minimum goal

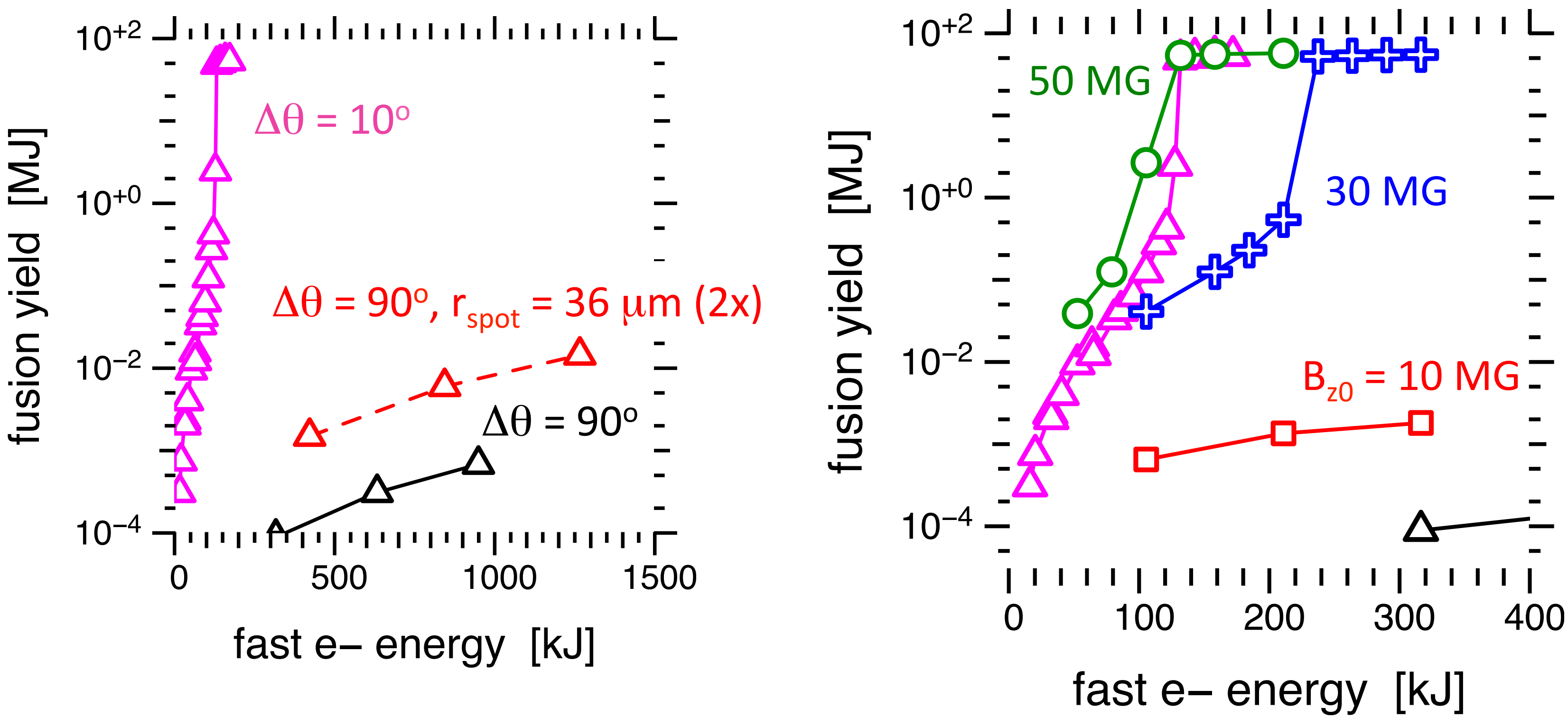
- 527 nm (2ω) wavelength laser: lowers $T_{pond} \sim \lambda$

Ignition energy is 15x ideal value with collimated electron source



Energy spectrum	initial $\Delta\theta$	angular scattering	E/B fields
1.5 MeV	0	no	none
1.5 MeV	10°	yes	none
PIC	10°	yes	none
PIC	10°	yes	$E = \eta J_{return}$
PIC	10°	yes	full Ohm's

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

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

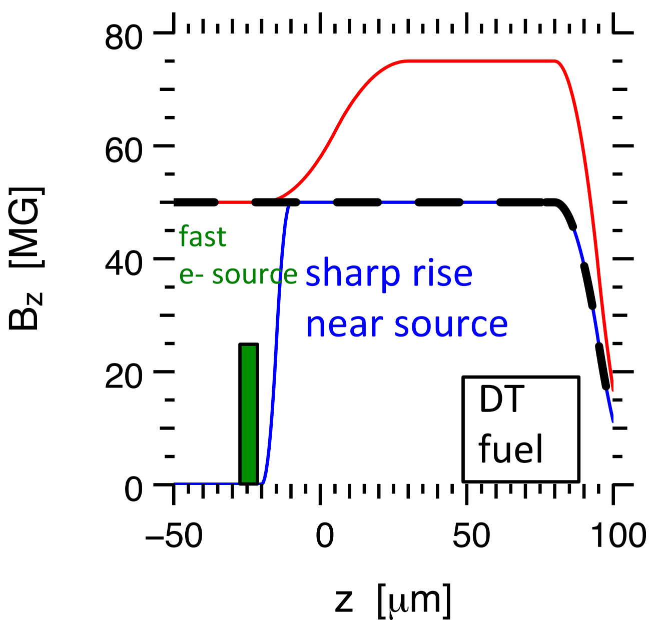
Axial magnetic field that increases in z leads to mirror force, reflects fast electrons

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

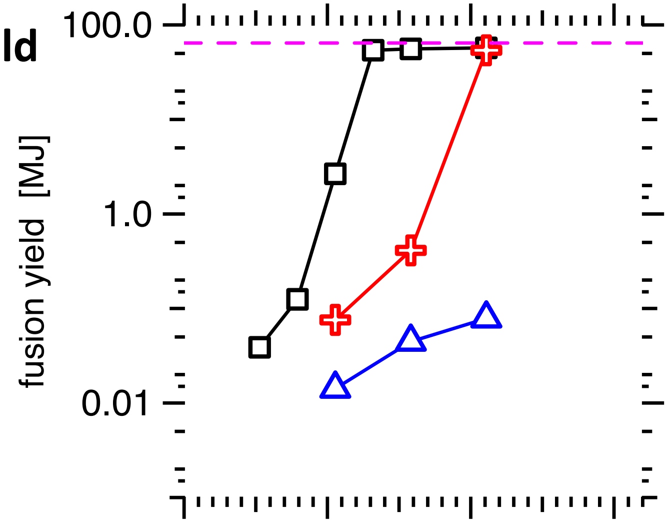
$$\vec{F} = q\vec{v} \times \vec{B} \quad \rightarrow \quad F_z = -q v_\phi B_r$$

mirroring: F_z towards decreasing B_z

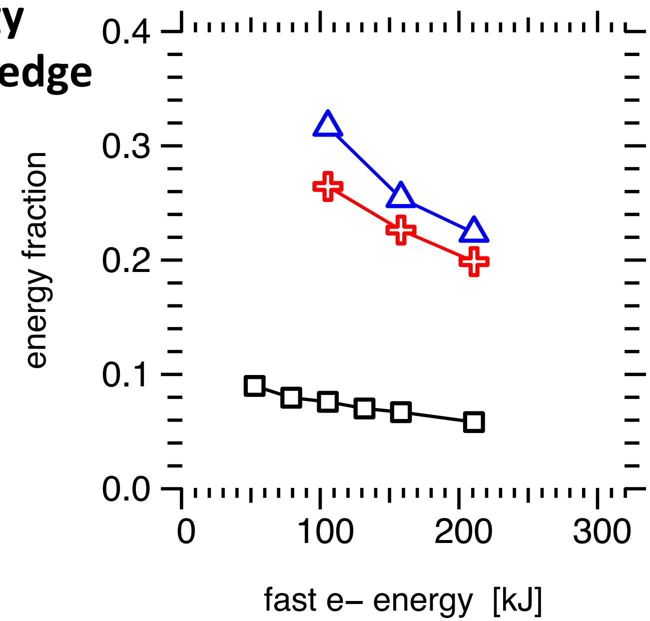
Initial B_z profiles



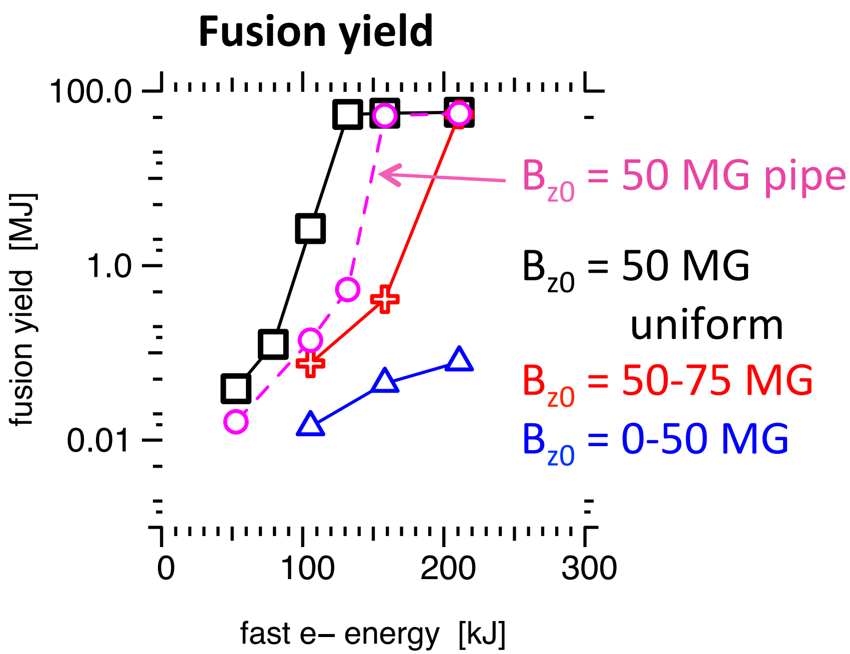
Fusion yield

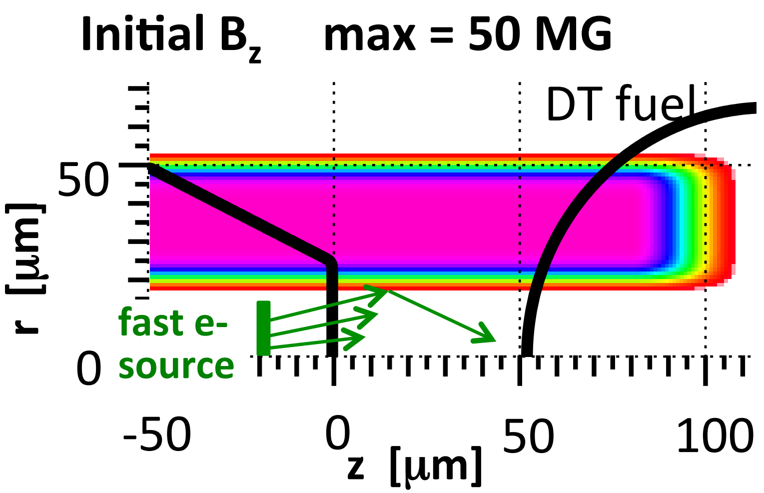


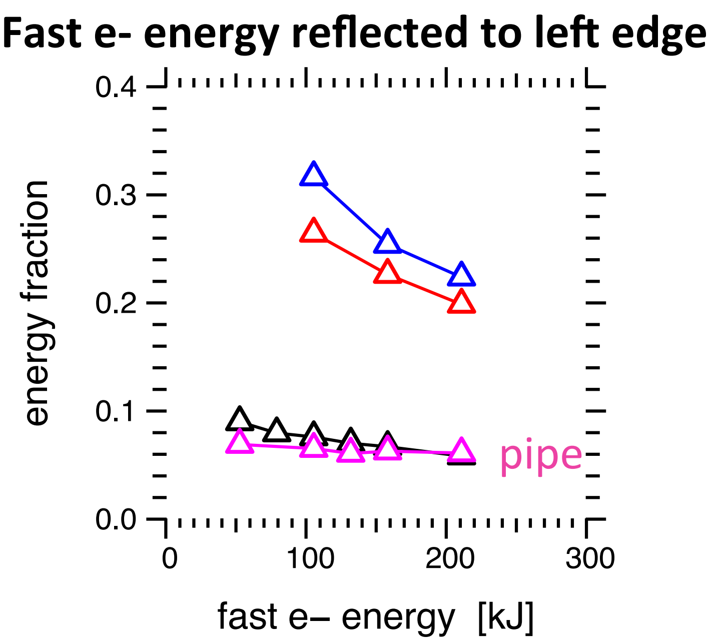
Fast e- energy reflected to left edge



Magnetic pipe: hollow inside spot radius, avoids mirroring

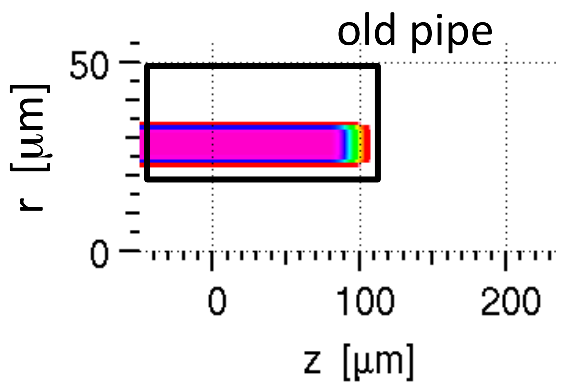


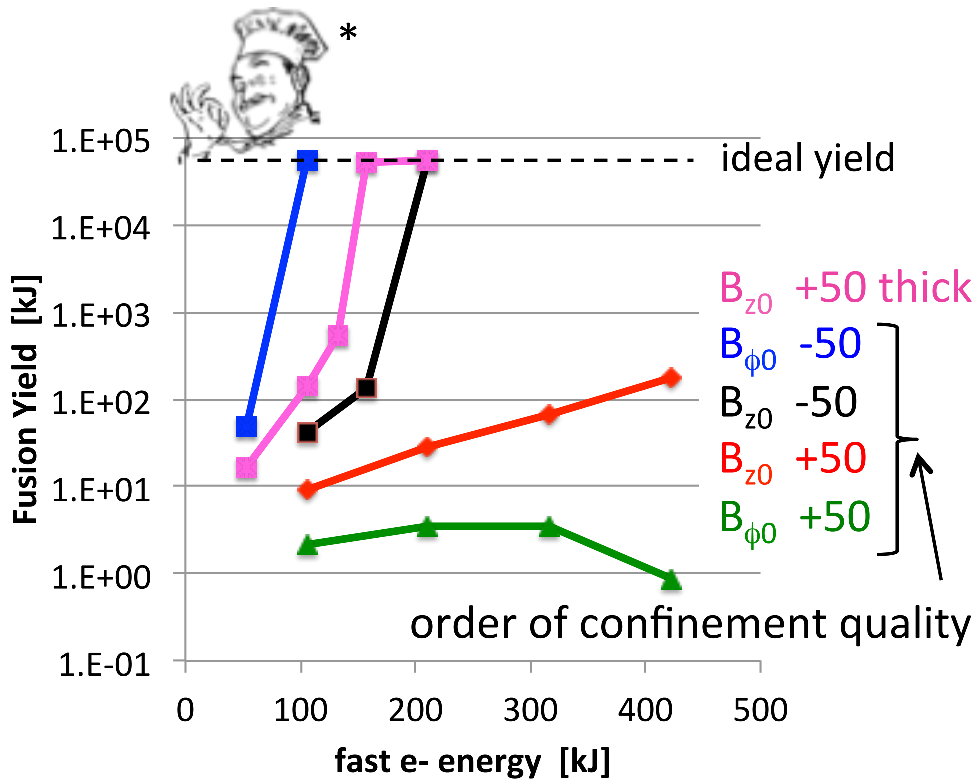




Magnetic pipes: sign and direction (axial vs. azimuthal) matters

Thinner pipe: easier to assemble

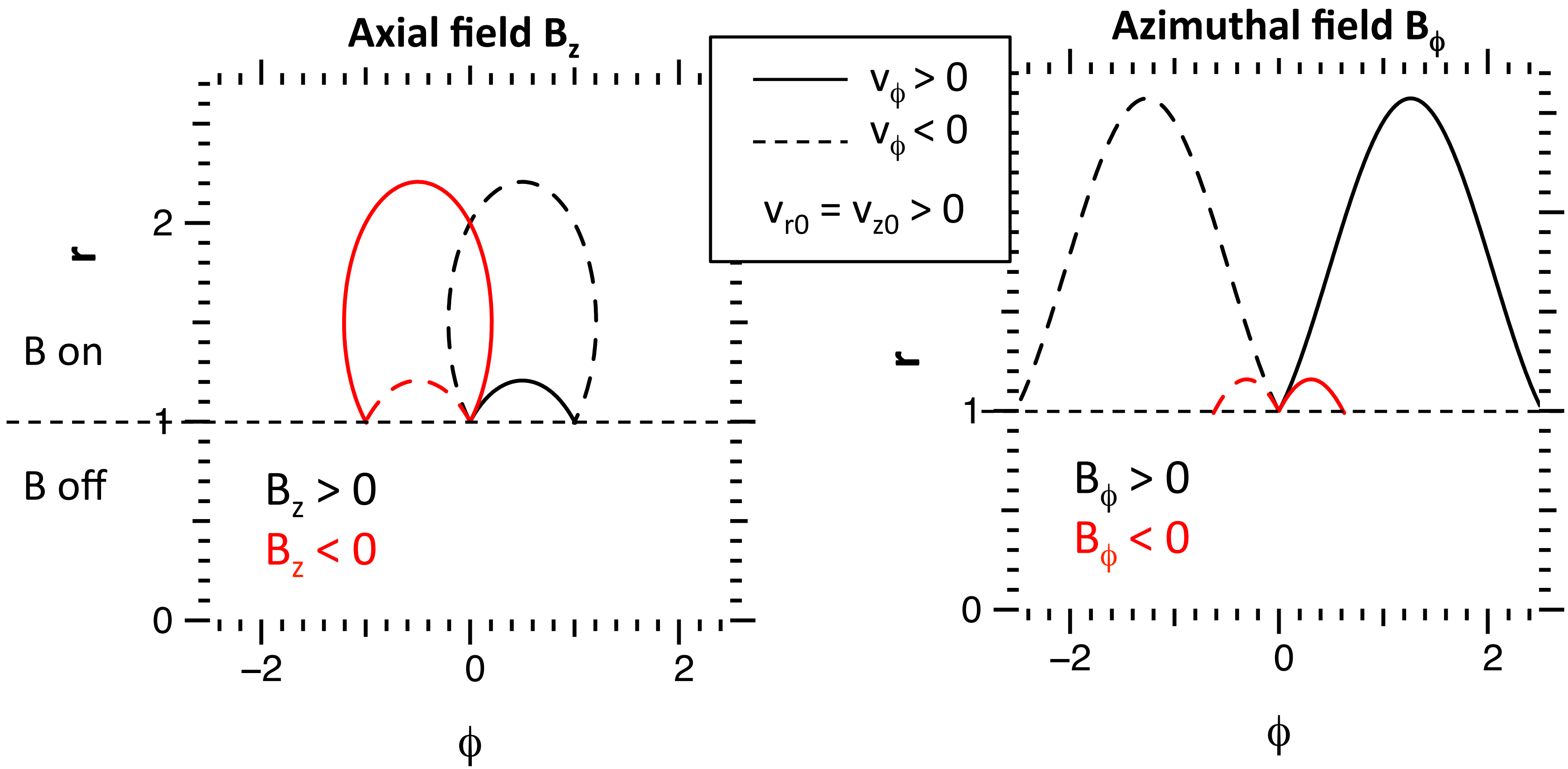




- So far I've used $B_z > 0$, the wrong sign – sorry!
- Fast electrons self-generate azimuthal field in radial resistivity gradient: Robinson and Sherlock, Phys. Plasmas 2007

* 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

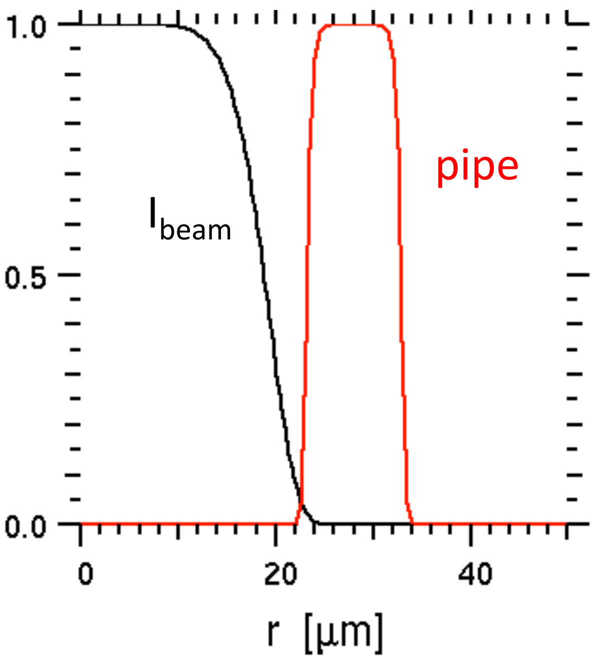
$B_\phi > 0$

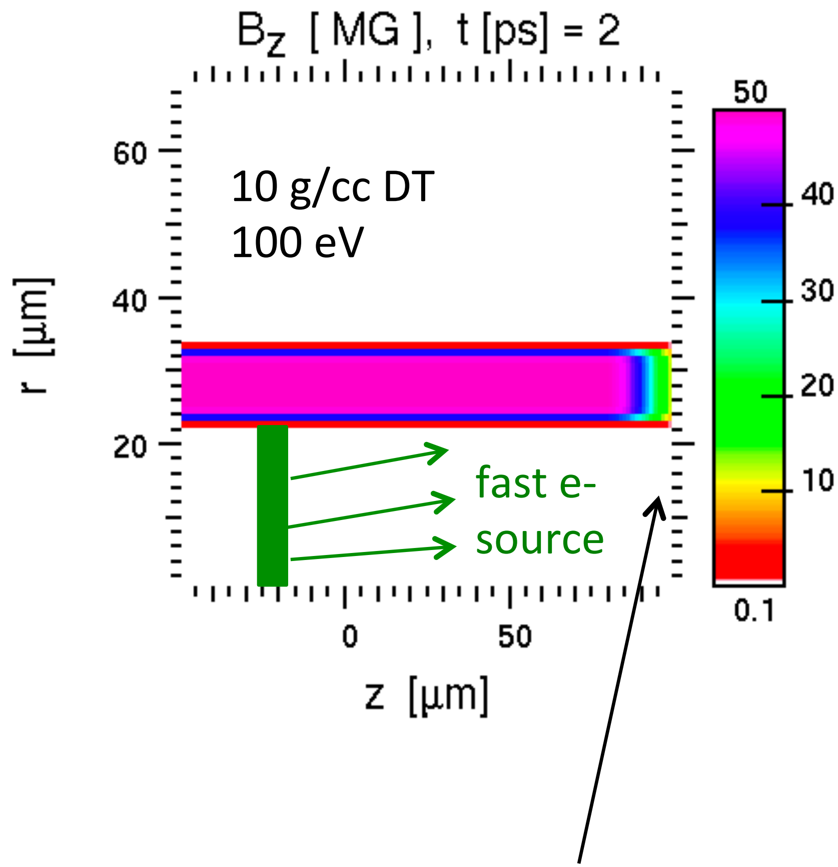
Orbits explain performance of B_ϕ signs, and B_ϕ vs B_z – but not role of sign(B_z)

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

Magnetic pipes in simplified, uniform plasma

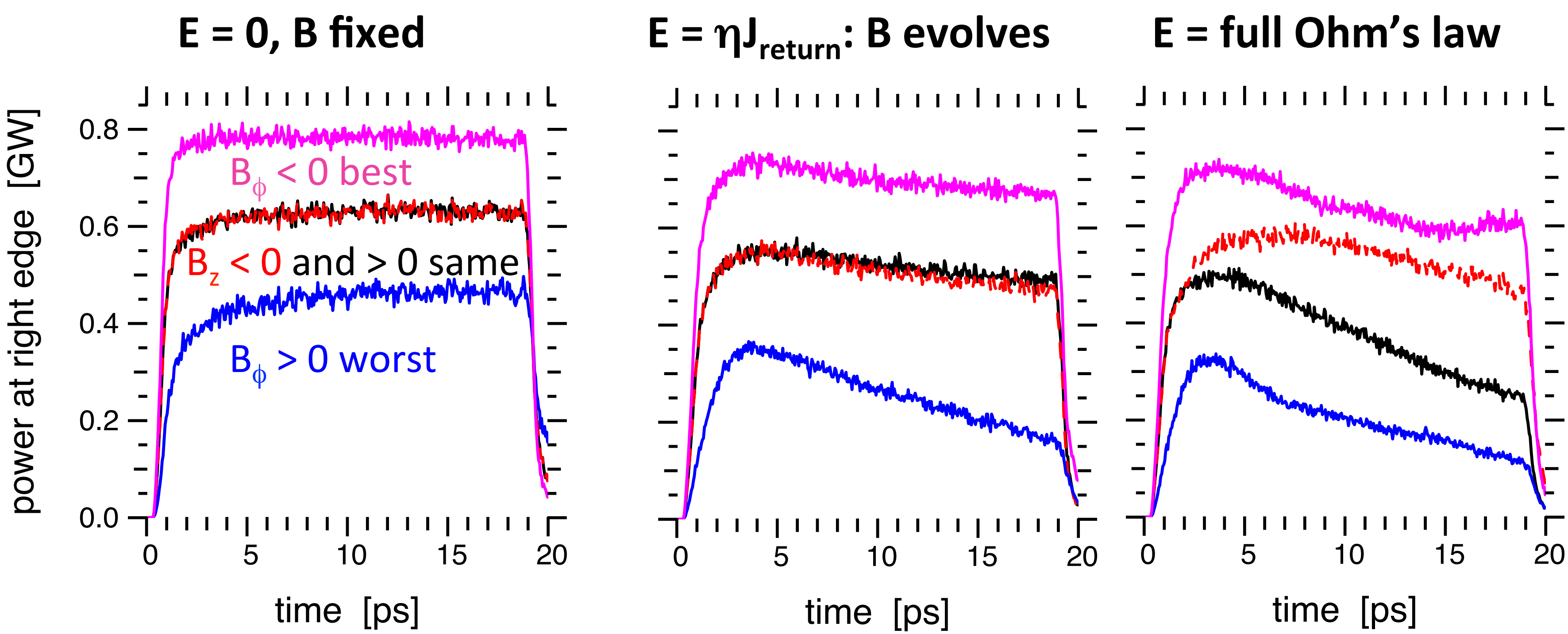
Zuma runs, no Hydra, no cone or dense fuel





Next page: 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):



Coupling as expected from orbits

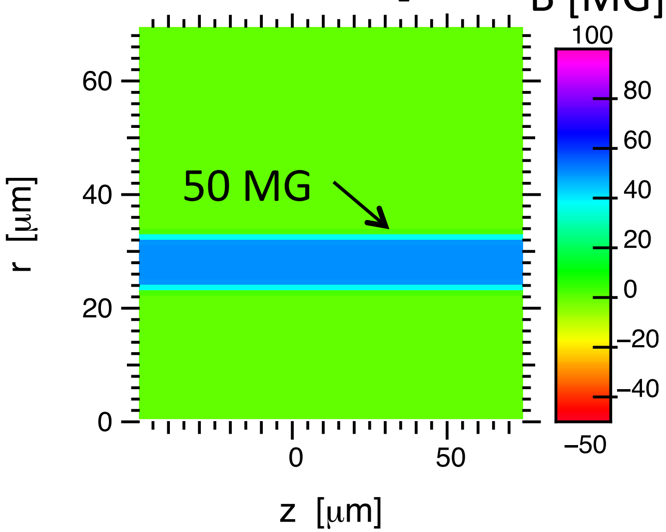
coupling drops: plasma diamagnetic

ordering unchanged

$B_z < 0$ better than $B_z > 0$!

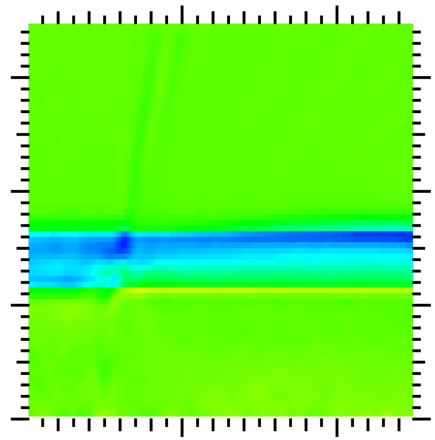
Full Ohm's law: magnetic fields evolve differently than with $E = \eta J_{return}$, and for each sign (B_z)

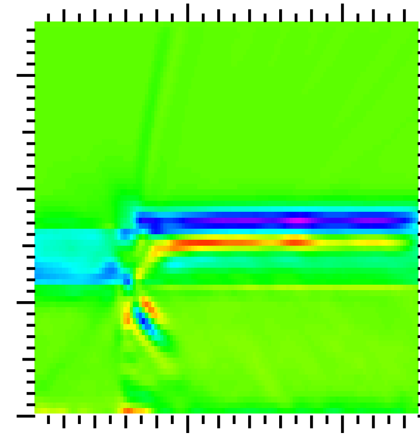
Initial B_z



$E = \eta J_{return}$ | **E = full Ohm's law**

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

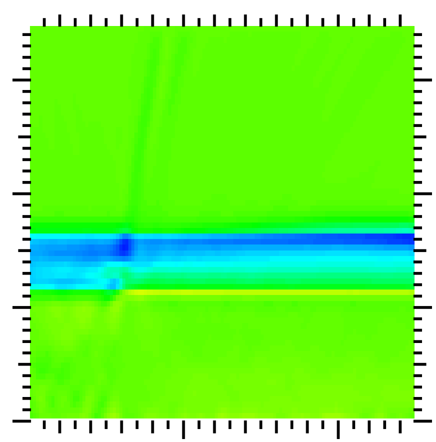


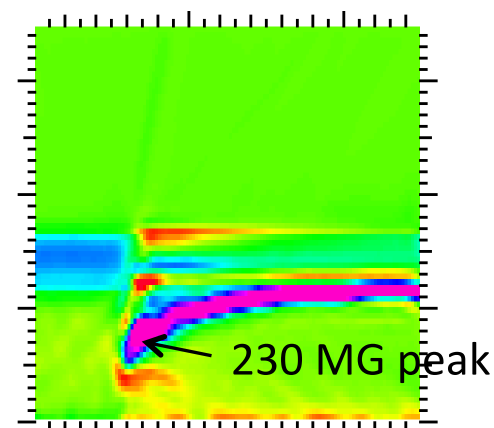


plasma diamagnetic: reduces pipe, similar for both sign(B_z)

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

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





Fields at t = 20 ps

Is fast ignition a pipe dream?

- Imposed, axial magnetic fields 30-50 MG recover ignition energy of artificially-collimated electron source

- Magnetic mirroring in increasing field reduces benefit

- Mirroring overcome with magnetic pipes – hollow out to e- source radius

- Pipe confinement best for one sign of B_ϕ – beats either B_z sign
  - Orbits explain this
  - Fast e- can self-generate in radial resistivity gradient

- $B_z < 0$ pipe confines better than $B_z > 0$
  - Orbits don't explain this!
  - Nor does resistive Ohm's law $E = \eta J_{return}$
  - Full Ohm's law does: B fields evolve differently

D Strozzi et al., submitted: Phys. Plasmas, arxiv.org/abs/1205.1594; IFSA 2011 proceeding