Electron Transport Studies of Annular Exploders

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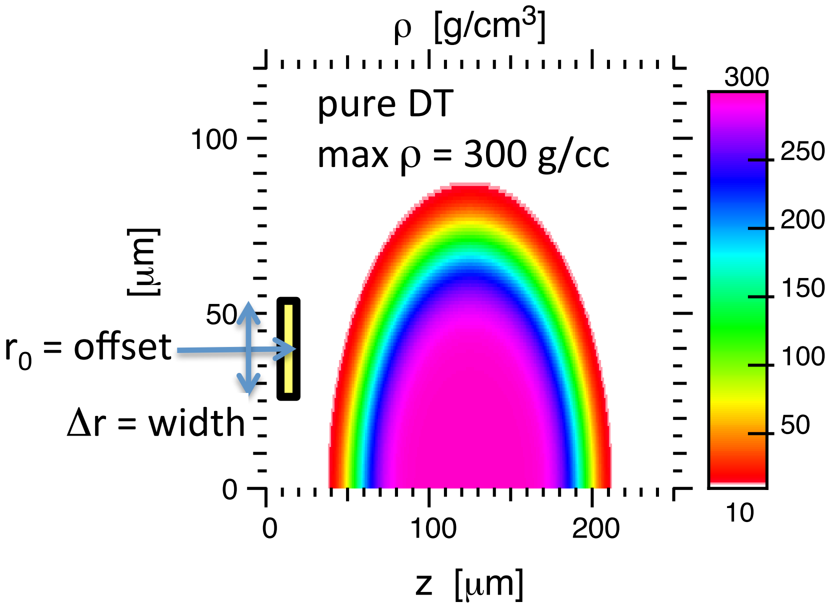
Coupled fast-electron & rad-hydro simulations demonstrate benefit of annular source

fast electron source:

$$I(r) = I_0 \exp\left[-\frac{1}{2}\left(\frac{r-r_0}{\Delta r}\right)^8\right]$$



- Zuma-Hydra simulations: fast-electron transport coupled to rad-hydro
- What spot offset r_0 minimizes ignition energy? Nonzero: annulus better than on-axis spot
- True for 1.5 MeV and PIC-based fast-electron energy spectrum

Zuma[1]: D. J. Larson: Ohmic-hybrid PIC code for fast electron transport in collisional plasmas

- Ohmic-hybrid model: no displacement current, E field from Ohm's law
  - Reduced dynamics: no light, plasma waves
- $\vec{J}_{\text{return}} = -\vec{J}_{\text{fast}} + \mu_0^{-1}\nabla\times\vec{B}$ ~~$+\varepsilon_0\partial_t\vec{E}$~~ Ampere w/o displacement current
- Ohm's law = massless momentum eq. for background electrons:

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

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

$\vec{\eta}$, $\vec{\beta}$: Lee-More-Desjarlais + Epperlein-Haines

- Fast e- energy loss and angular scattering [Solodov, Davies]
- $\vec{J}_{\text{return}}\bullet\vec{E}_C$ collisional heating
- $\frac{\partial\vec{B}}{\partial t} = -\nabla\times\vec{E}$ Faraday

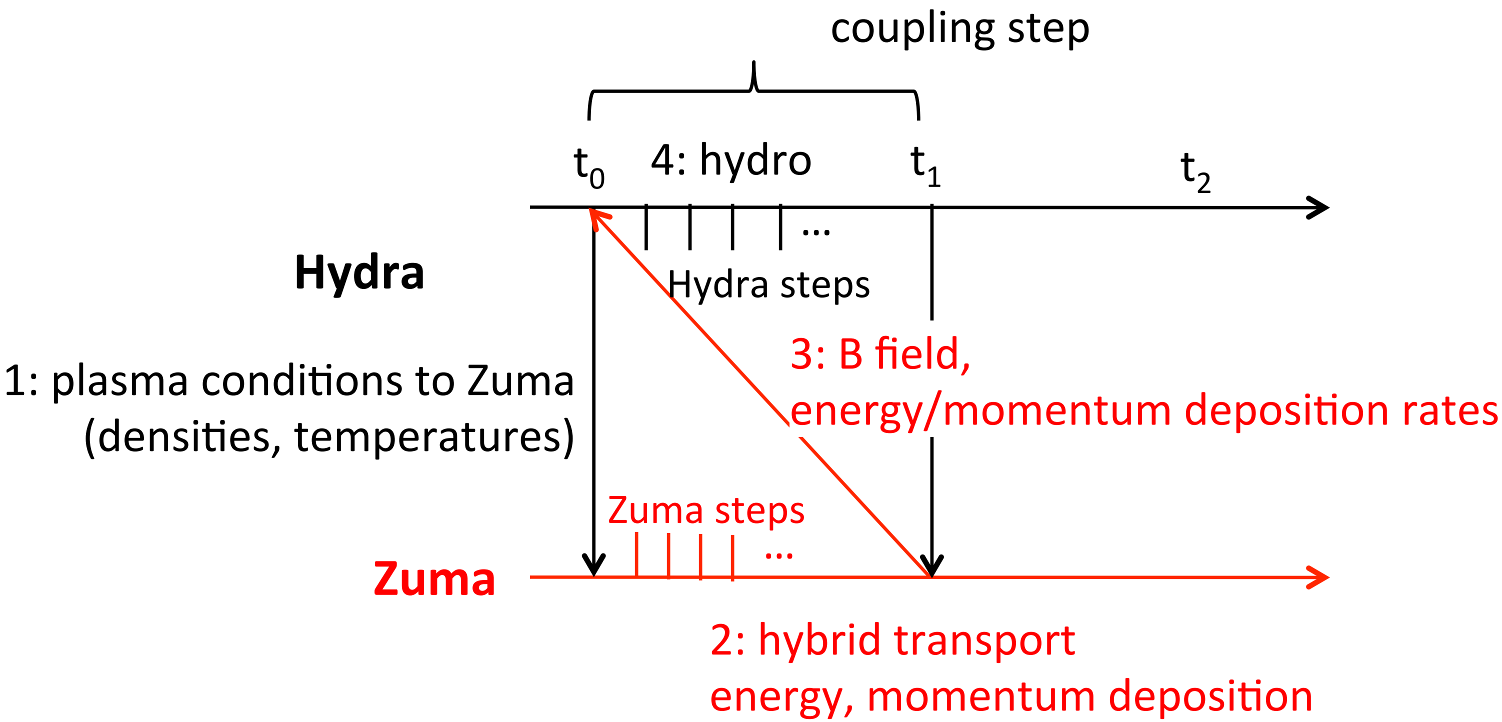
> Extended Ohm's law results differ from $E = \eta * J_{\text{return}}$
>
> Nicolai et al., APS DPP 2010, Phys Rev E **84**, 016402 (2011)
> Strozzi et al., IFSA 2011 (submitted)

* "Extended" and not "full" since we neglect, e.g., off-diagonal pressure tensor, collisions of fast and background e-, advection

[1]D. Larson, M. Tabak, T. Ma, APS-DPP 2010; D. J. Strozzi et al., Phys. Plasmas 2012

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
  - ~25 ps transport (Zuma + Hydra), then 180 ps burn (just Hydra)



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

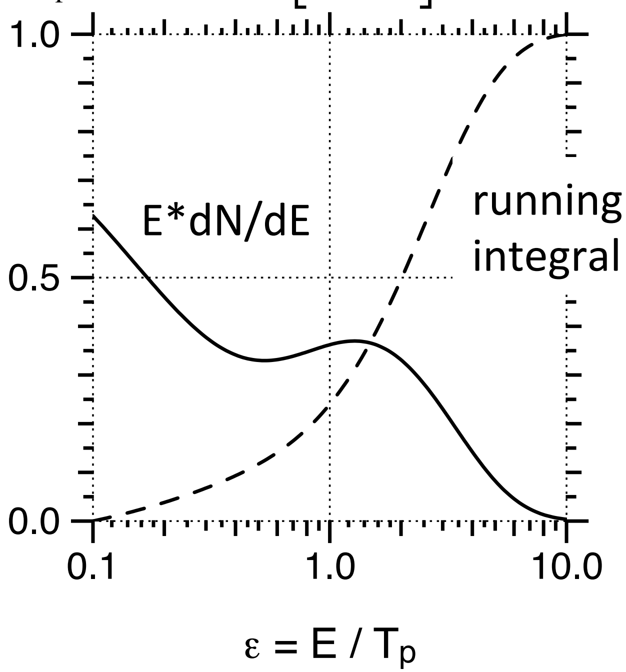
Energy spectrum source: $f_E(E)*f_\theta(\theta)$ **Angle spectrum**

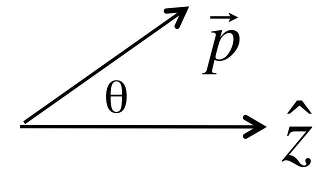
$$\frac{dN}{d\varepsilon} = \underbrace{0.82\exp[-\varepsilon/1.3]}_{\text{"hot:" from pre-plasma}} + \underbrace{\frac{1}{\varepsilon}\exp[-\varepsilon/0.19]}_{\text{"cold:" from } n_{crit}}$$

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

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

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





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

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

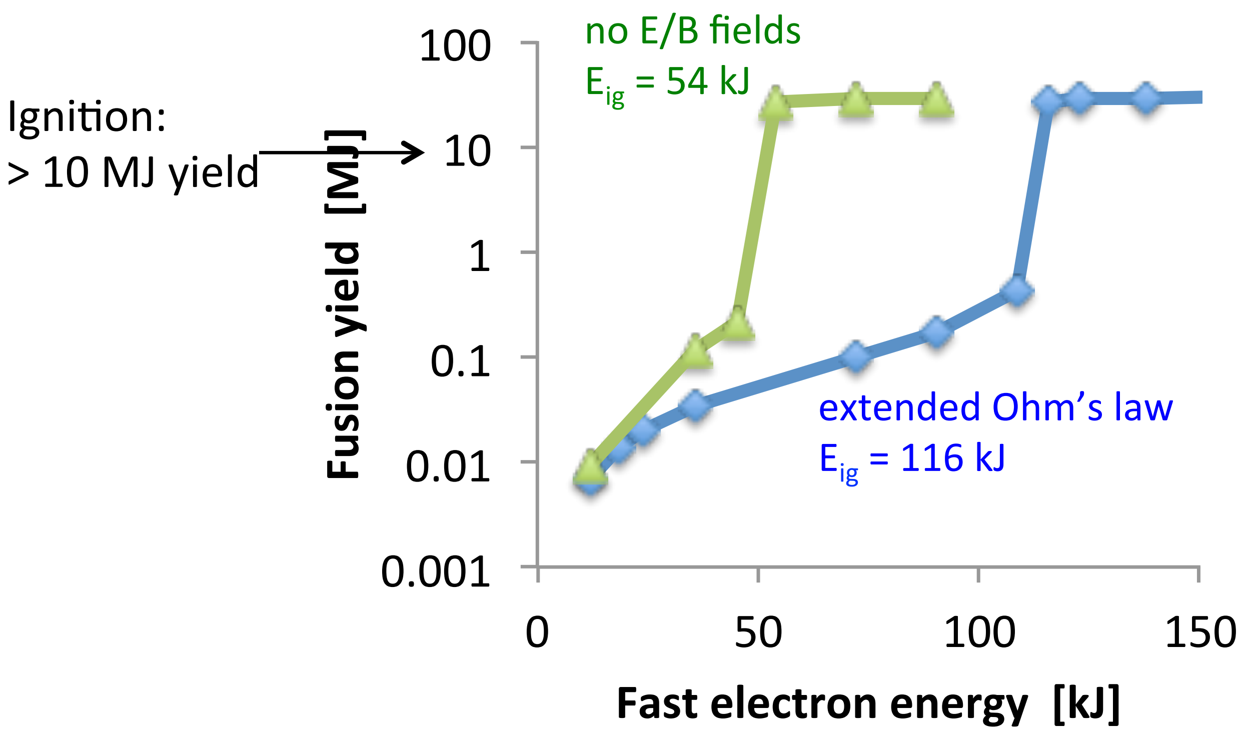
Δθ	**<θ>**	
10°	6.9°	artificially collimated source; used in this talk
90°	52°	matches PSC; realistic source

Assume divergence problem solved, study resulting hydro:

Is annular better than on-axis source?

On-axis source: extended Ohm's law reduces coupling compared to no E and B fields

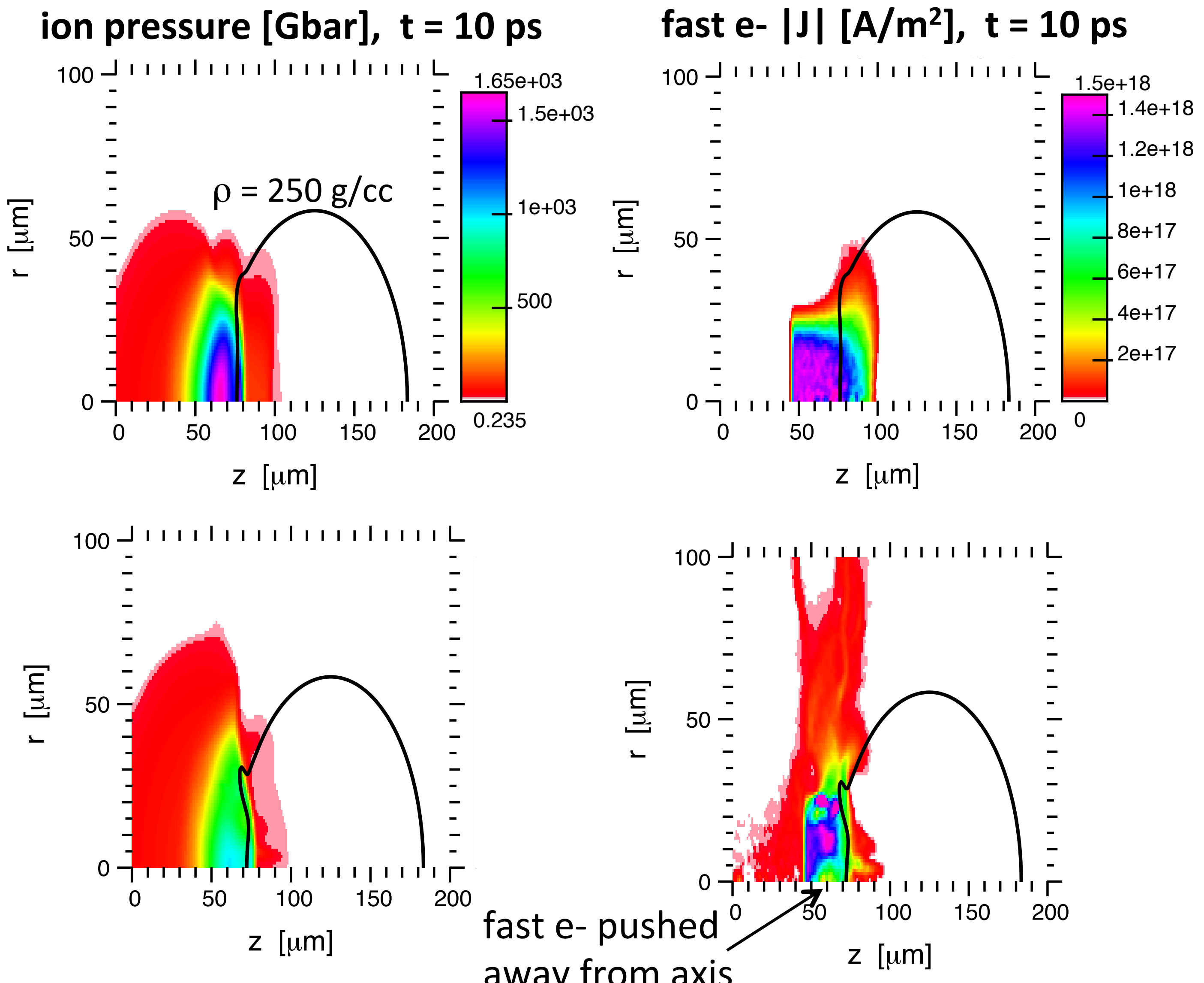
- On-axis source: $r_0 = 0$, $\Delta r = 22$ um
- Energy spectrum: mono-energetic, 1.5 MeV – stops in roughly ideal hot-spot depth



1.5 MeV fast electrons: B fields push fast electrons away from fuel - under study

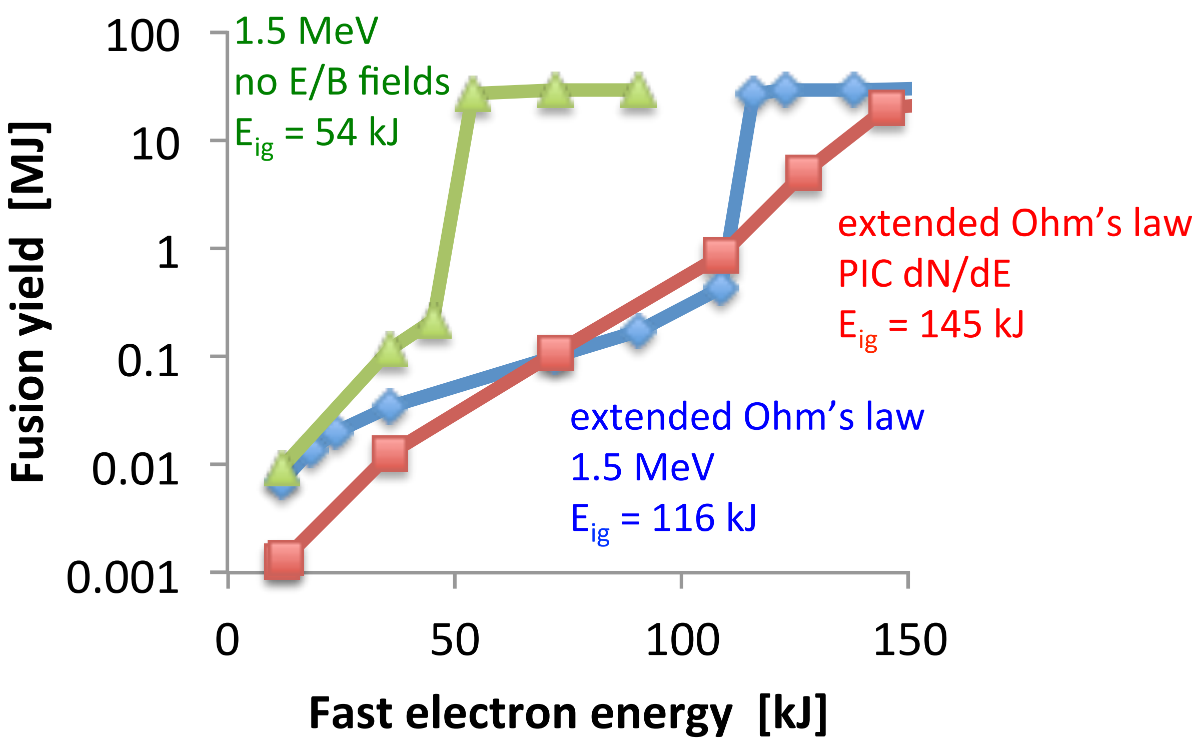
no E/B
E_{fast} = 72 kJ
ignites

yes E/B
E_{fast} = 72 kJ
does not ignite

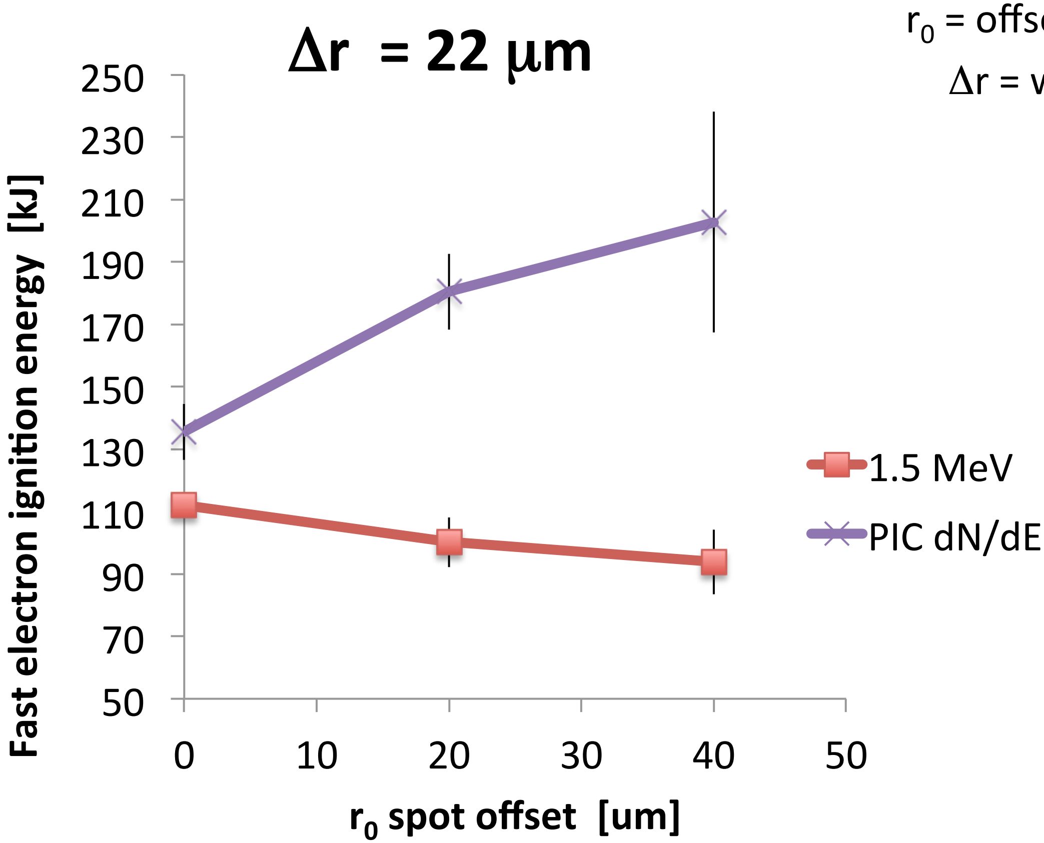


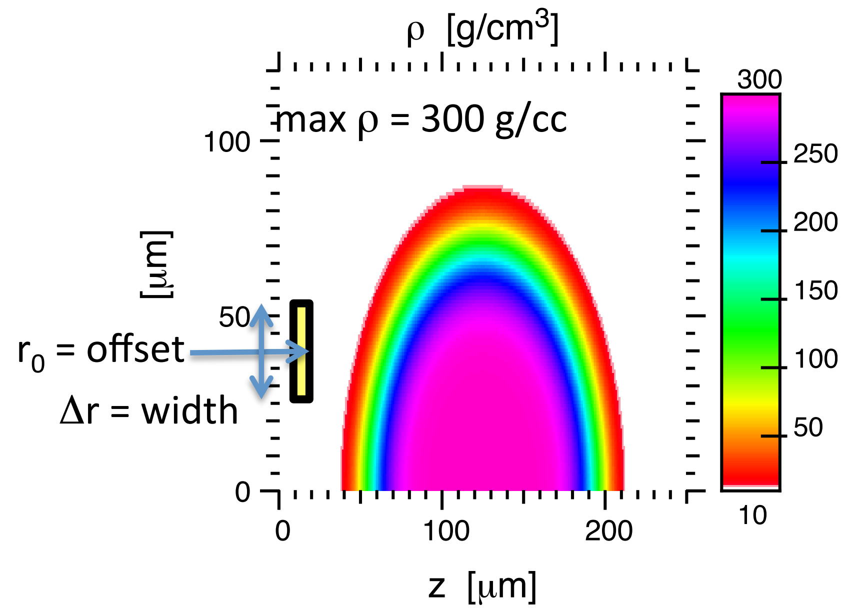
PIC-based energy spectrum has slightly higher ignition energy than mono-energetic 1.5 MeV electrons

- On-axis source: $r_0 = 0$, Δr = 22 um
- PIC spectrum for 527 nm laser light, 52% laser to electron conversion efficiency

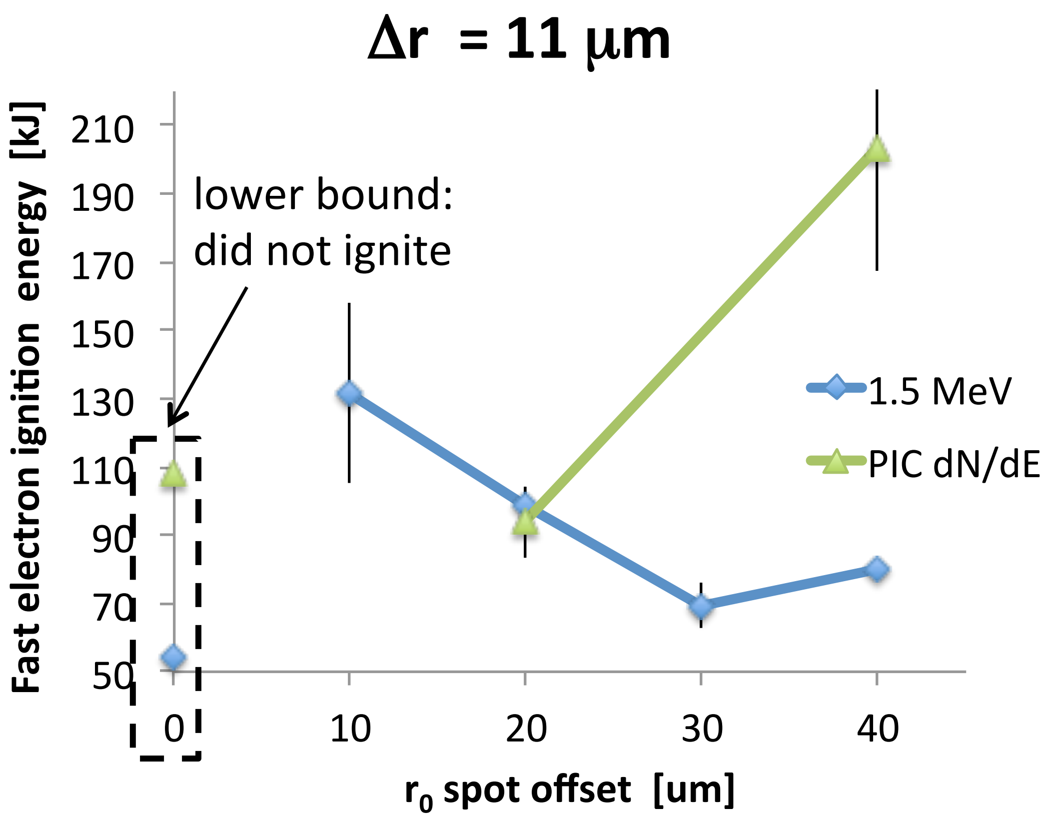


Wide source: slight annular benefit for mono-energetic spectrum, not yet found for PIC-based dN/dE

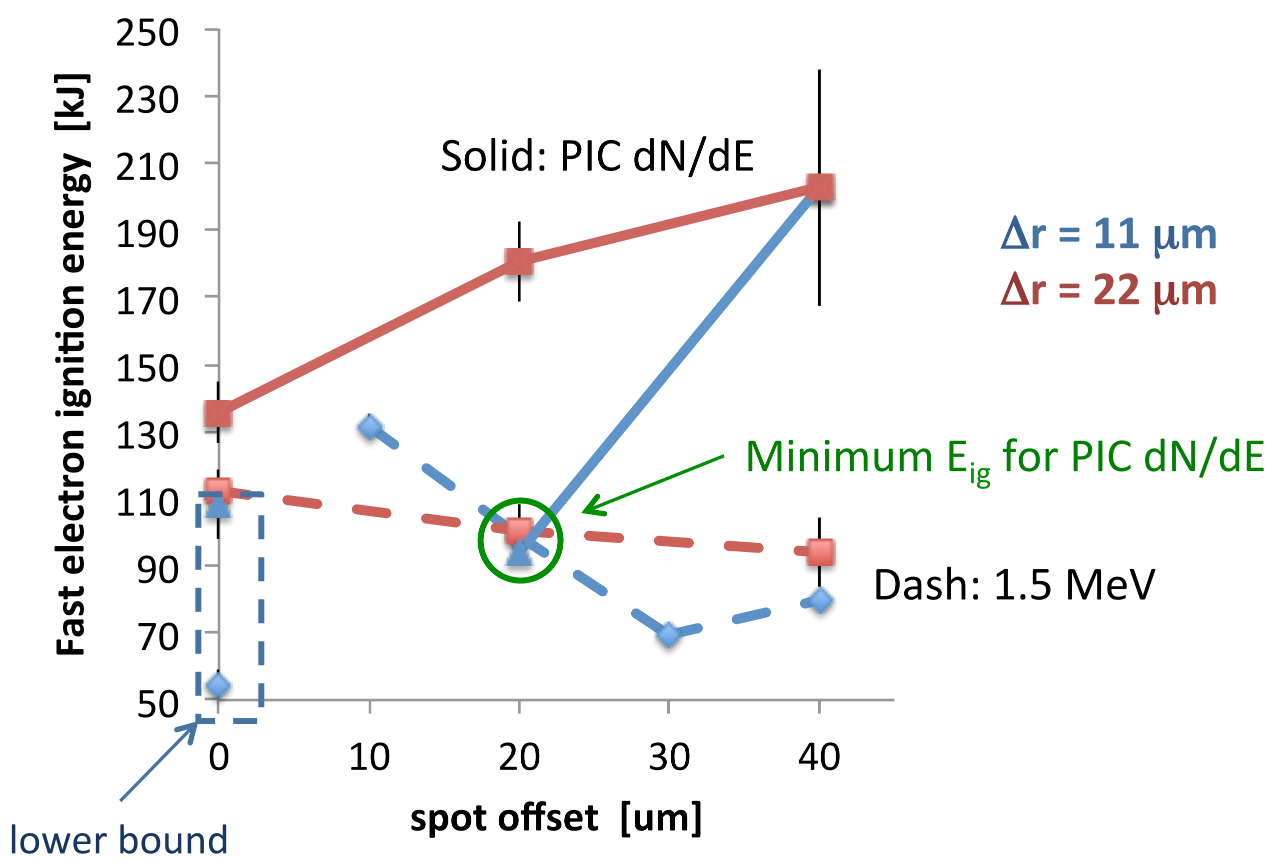




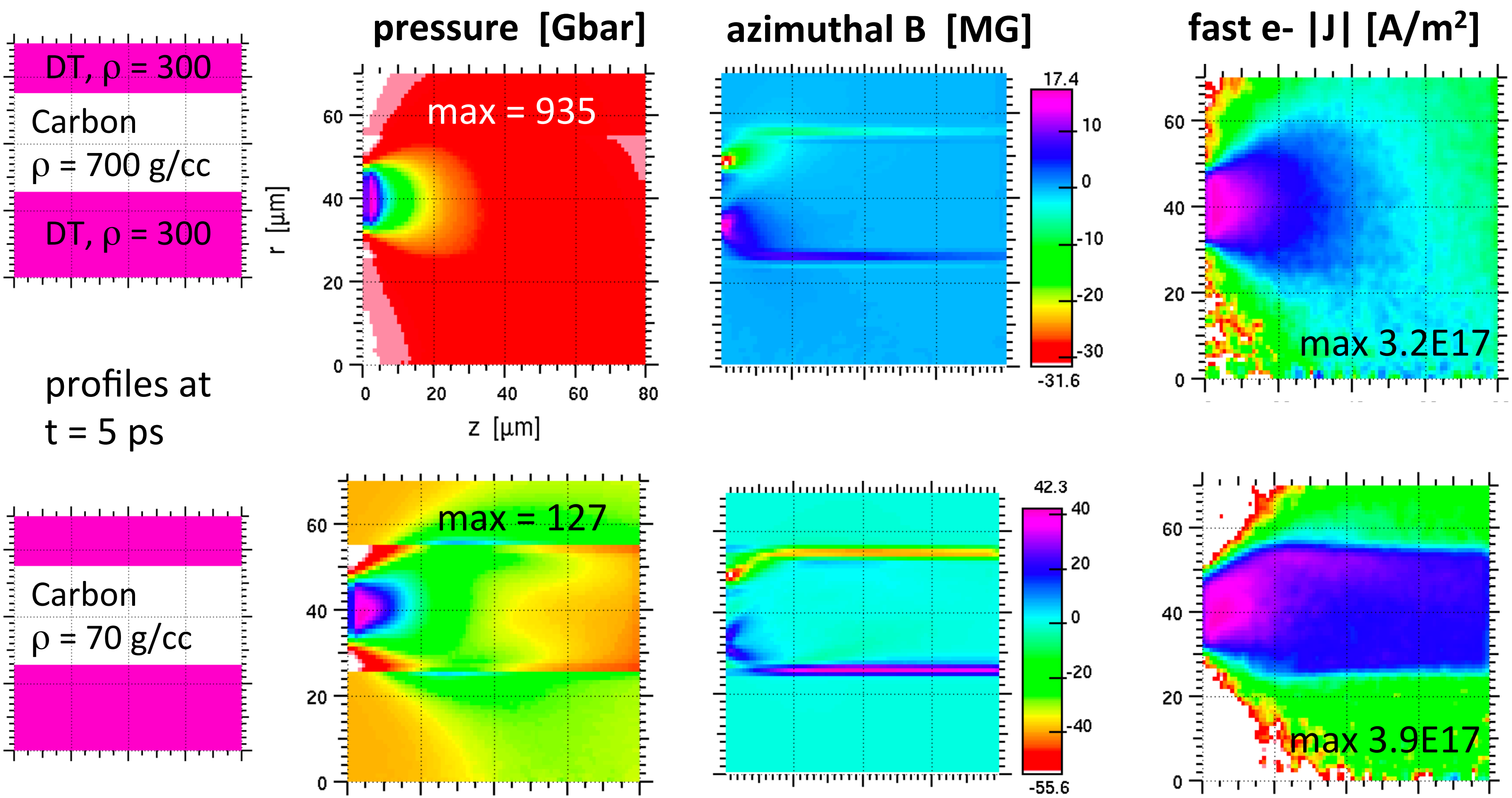
Narrow source: annulus has benefit!



Thinner annulus (Δr = 11 μm) with moderate offset (r_0 = 20 μm) ignites for 94 kJ of fast electrons, with PIC-based dN/dE



Magnetic confinement by mid-Z annulus: resistivity gradient (Robinson et al.)



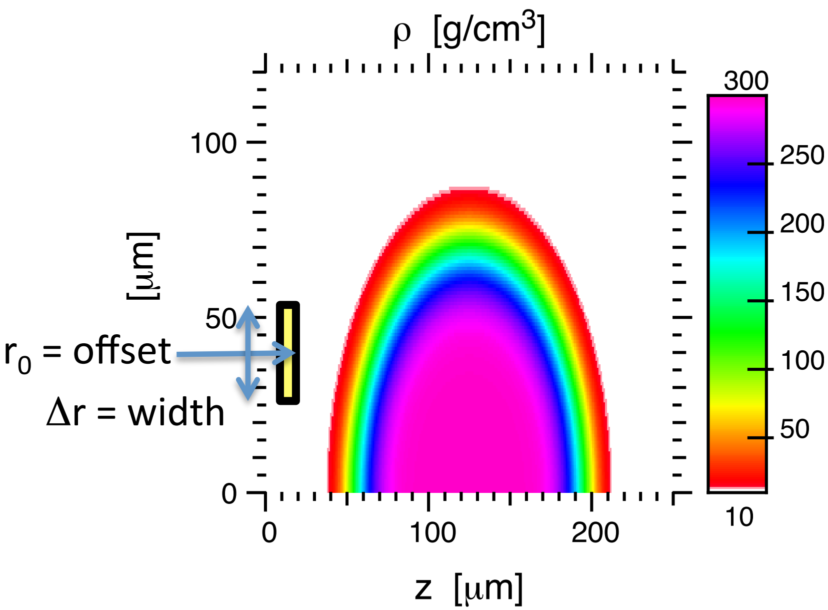
- Low density annulus: large B field, fast e- confined, but stop over larger distance
- High density annulus: less confinement, but stop over shorter distance, higher pressure
- Hydro question: optimal ρ*Δz for heated annulus?

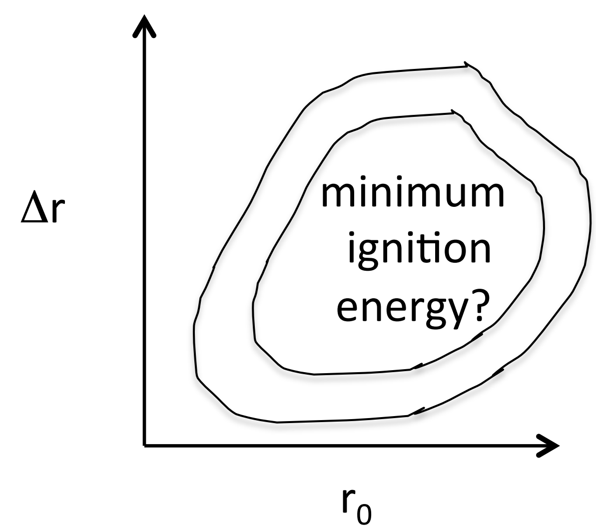
Summary: coupled Zuma-Hydra modeling shows annular sources reduce ignition energy

For an artificially-collimated source (assume divergence solved)…

- E and B fields from extended Ohm's law:
  - Reduced coupling of mono-energetic 1.5 MeV electrons
  - PIC-based ponderomotive and 1.5 MeV spectra have similar ignition energies

- Annular (finite r_0) source lowers ignition energy
  - Optimization in (r_0, Δr) parameter space started
  - Mid-Z annulus allows confining magnetic fields





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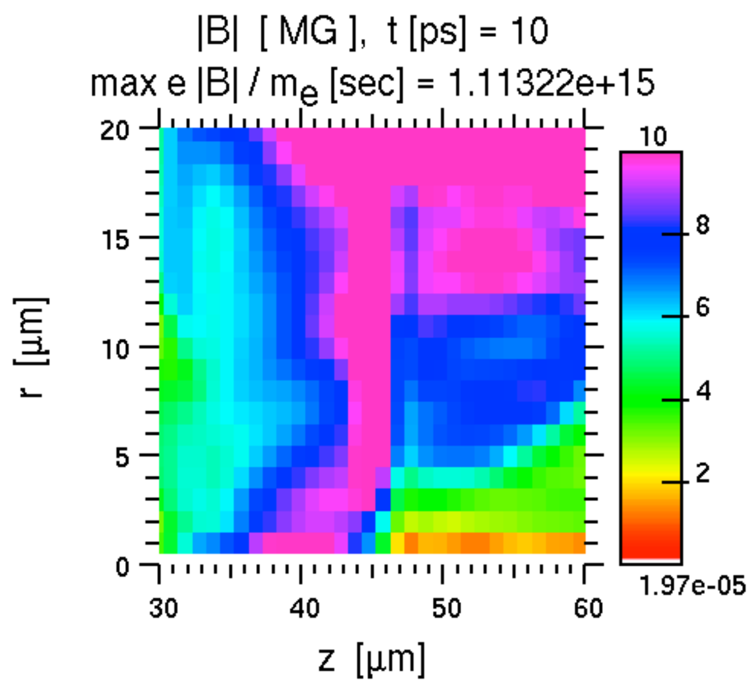

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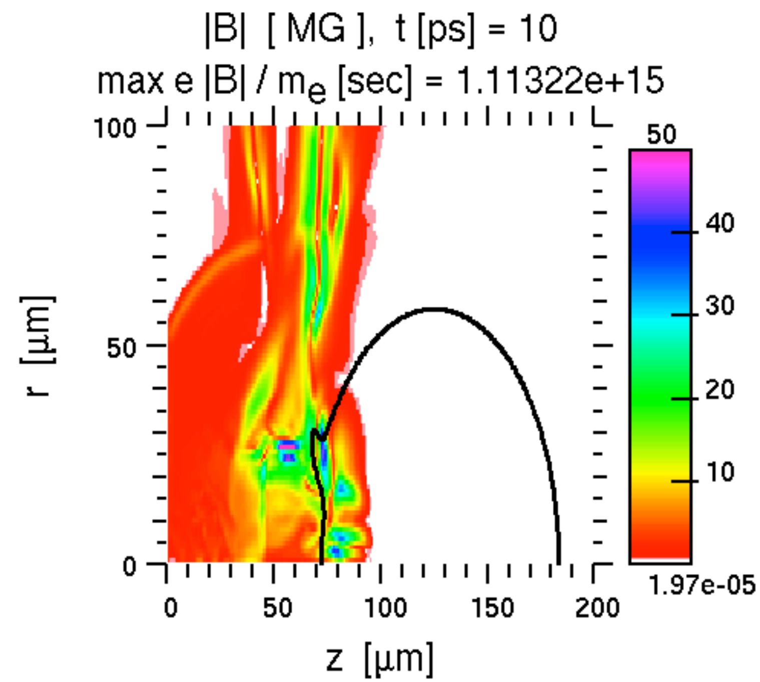

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