Electron-Driven Fast Ignition Modeling with Realistic Electron Source

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Summary: Realistic beam is divergent, gives large ignition energy; need to study focusing schemes like imposed magnetic field

- **Electron source:** from full PIC LPI simulations [A. Kemp, L. Divol]:
  - Energy spectrum: modified two-temperature, ponderomotive intensity scaling.
  - Angle spectrum: highly divergent, avg. polar angle 50 deg.

- **Integrated Zuma-Hydra Modeling:**
  - HYDRA rad-hydro code (M. Marinak et al.) coupled to hybrid-PIC transport code ZUMA (D. Larson).
  - Electron beam excited (no laser) – distribution chosen to replicate full PIC.

- **Realistic beam divergence:** did not ignite even for 352 kJ of electrons - hopeless!

- **Initial axial magnetic field** and realistic divergence:
  - 40 field MG ignites with 44 kJ.

- **Co-authors:** M. Tabak, A. J. Kemp, L. Divol, D. Larson, M. Marinak, D. P. Grote, M. H. Key, D. R. Welch, B. I. Cohen, R. P. J. Town.
- Supprted by LDRDs 08-SI-001 and 11-SI-002.

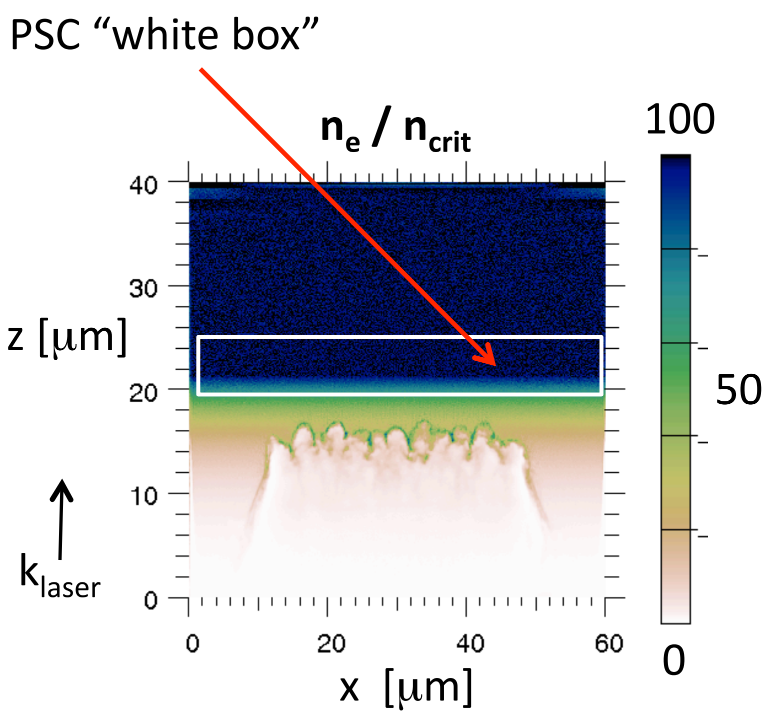
We directly compare electrons in full-PIC “white box” with an LSP run with an excited electron beam

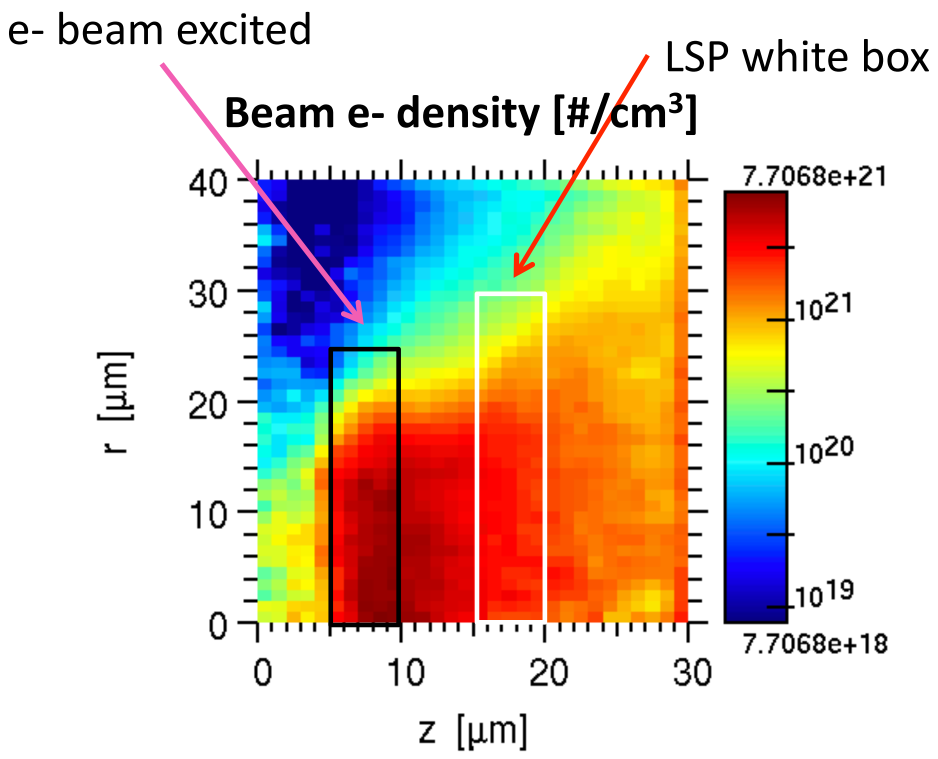
PSC full-PIC run with laser:

- 3D Cartesian, 1 μm wavelength.
- pre-plasma $n_e \sim \exp[\, z / 3.5\ \mu\text{m}\,]$.
- best focus: $I_{las}(r) = I_0 \exp[-(r/18.3\ \text{um})^8]$
  I_0=1.37 E20 W/cm^2. T_{pond} = 4.63 MeV.

LSP hybrid implicit-PIC run with excited electron beam:

- 10 g/cc, 100 eV, Z=6 carbon.
- RZ Cylindrical.
- No dE/dx or angle scattering (not in PSC run).





Beam energetics, and two-temperature energy spectrum

Energy spectrum: quasi two-temperature, scaled ponderomotively

$$dN / dE = \frac{1}{E}\exp[-E / T_{\text{cold}}] + \frac{b_2}{T_{\text{pond}}}\exp[-E / T_{\text{hot}}]$$

Note asymmetry in the two terms!

Parameters to fit with full-PIC:

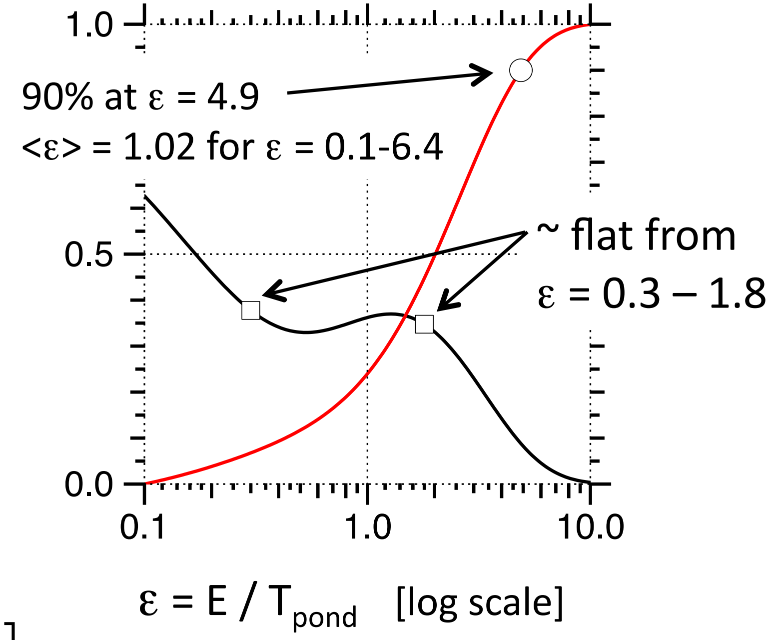
$T_{\text{cold}} = 0.19\ T_{\text{pond}}$ $\quad T_{\text{hot}} = 1.3\, T_{\text{pond}}$ $\quad b_2 = 0.82$

Ponderomotive scaling [Wilks et al., PRL 1992]

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

E dN/dE [black]

running integral [red]



90% at ε = 4.9

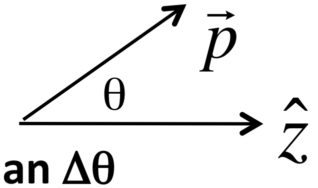
<ε> = 1.02 for ε = 0.1-6.4

~ flat from ε = 0.3 – 1.8

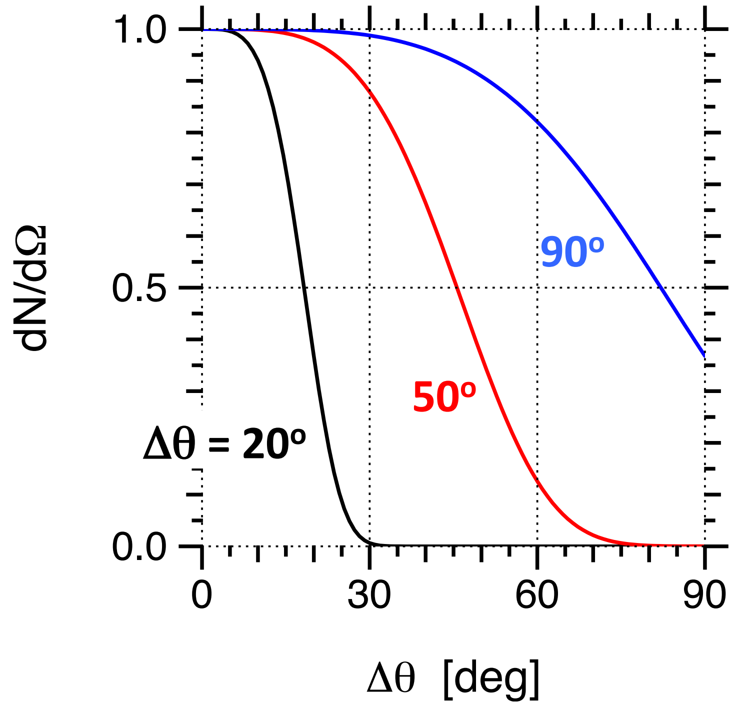
- LSP beam power = 52% of PSC laser power.
- Total laser absorption is higher ~80-90%, but some is parasitic: expanding plasma, return current, ions, etc.

Beam angle spectrum: super-Gaussian, large divergence

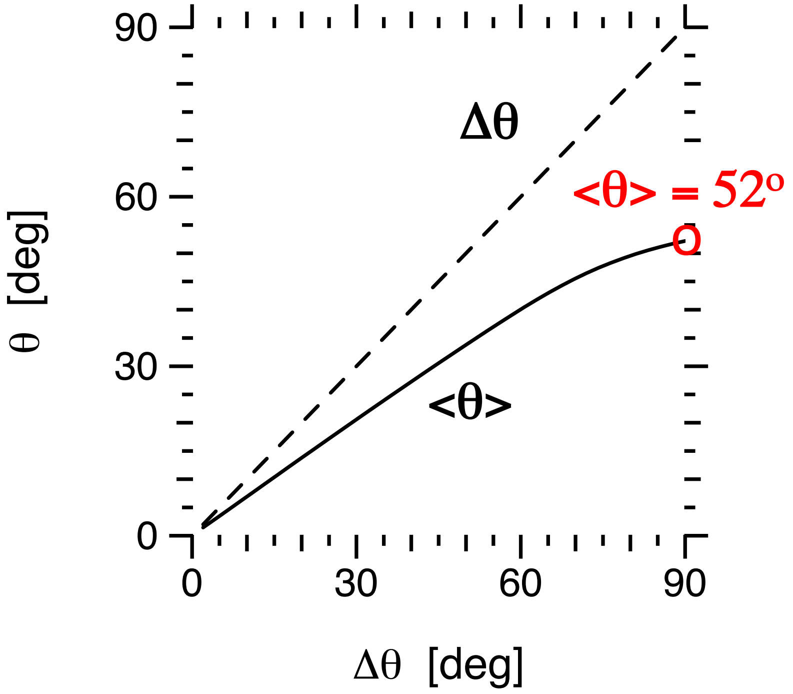
$$\frac{dN}{d\Omega} = \exp\left[-(\theta / \Delta\theta)^4\right] \qquad \theta = \text{polar angle} \qquad \Delta\theta = 90^\circ \text{ matches full-PIC}$$



Solid angle spectrum (max=1)



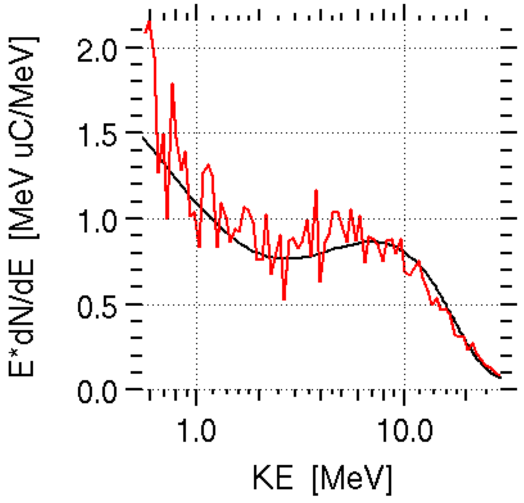
Avg. polar angle: less than Δθ



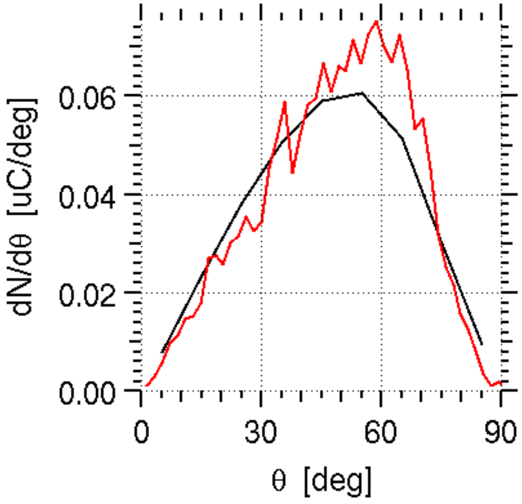
- "Opening angle" is ill-defined: should specify <θ>, θ_{rms}, θ enclosing 90% of e-, etc.
- Only fwd-going e- excited.

PSC (black) and LSP (red) e- in white boxes are similar enough for transport and design studies

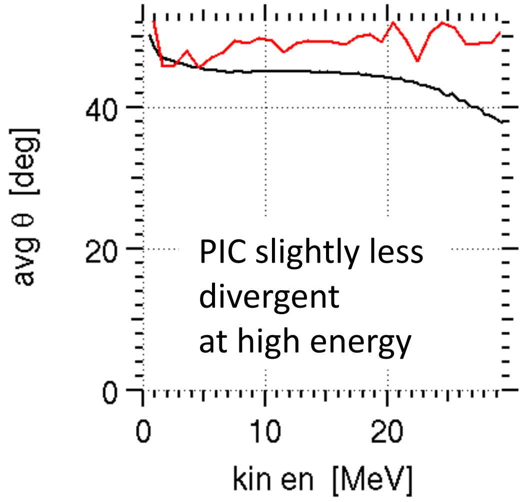
Energy spectrum



Polar angle spectrum

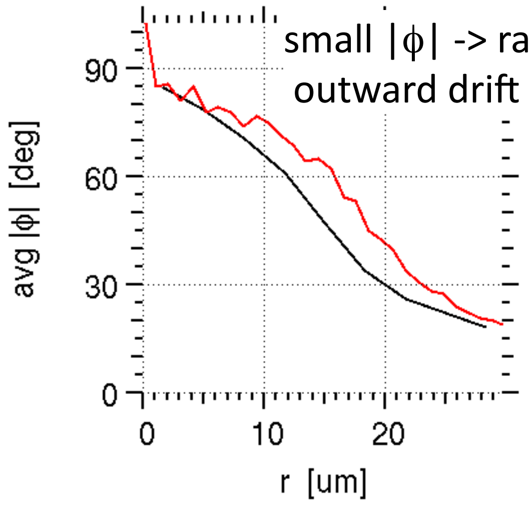


Avg. polar angle vs energy



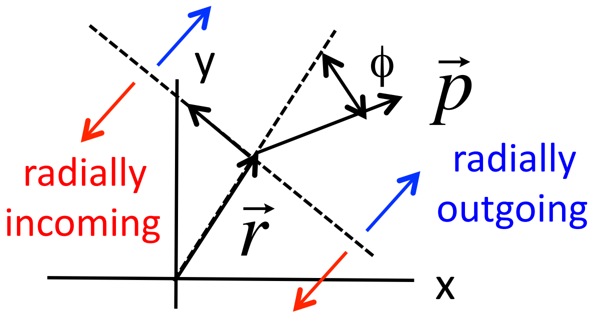
PIC slightly less divergent at high energy

Transverse angle b/t r and p



small |ϕ| -> radial outward drift

Azimuthal angle in transverse plane:



radially incoming

radially outgoing

A. Debayle et al, IFSA 2009 Proceedings: radial outward drift w/ Gaussian laser spot; azimuthally uniform LSP source develops outward drift as it propagates.

Zuma: Hybrid PIC transport code (D. Larson)

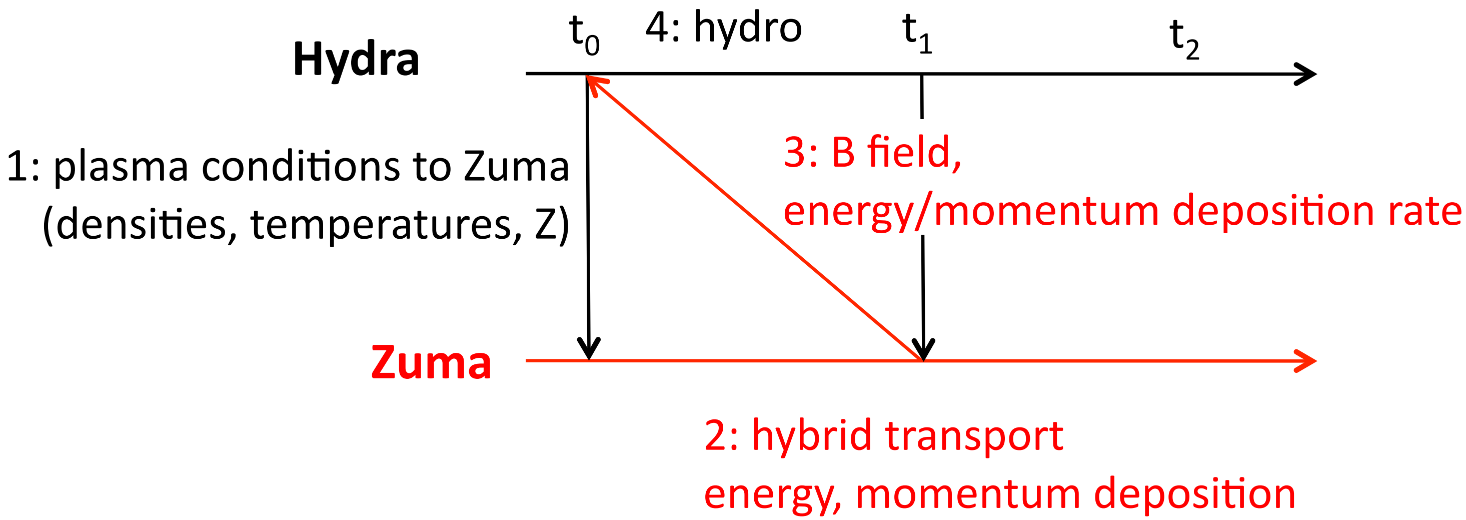
- Fast electrons treated as relativistic PIC particles.
- Field and background dynamics simplified to eliminate light and plasma waves.

Zuma time step :

- Relativistic push of fast electrons' $\vec{x}$ and $\vec{p}$: $\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B})$
- Fast e- energy loss (drag) and angular scattering: formulas of Solodov, Betti, Davies
- Collect $\vec{J}_{\mathrm{fast}}$
- $\vec{J}_{\mathrm{return}} = -\vec{J}_{\mathrm{fast}} + \mu_0^{-1} \nabla \times \vec{B}$ no displacement current
- $\vec{E} = \eta \vec{J}_{\mathrm{return}}$ $\eta =$ resistivity from Lee-More-Desjarlais
- $\vec{J}_{\mathrm{return}} \bullet \vec{E}$ background heating, momentum deposition
- $\dfrac{\partial \vec{B}}{\partial t} = -\nabla \times E$

Hybrid PIC transport code Zuma coupled to rad-hydro code Hydra

- Both codes run in cylindrical R-Z geometry on fixed Eulerian meshes.



Hydra

t_0 4: hydro t_1 t_2

1: plasma conditions to Zuma
(densities, temperatures, Z)

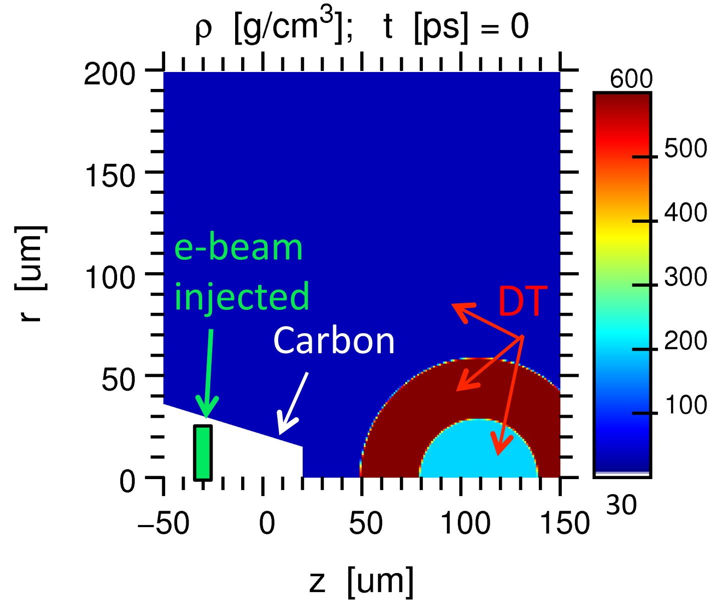
3: B field,
energy/momentum deposition rate

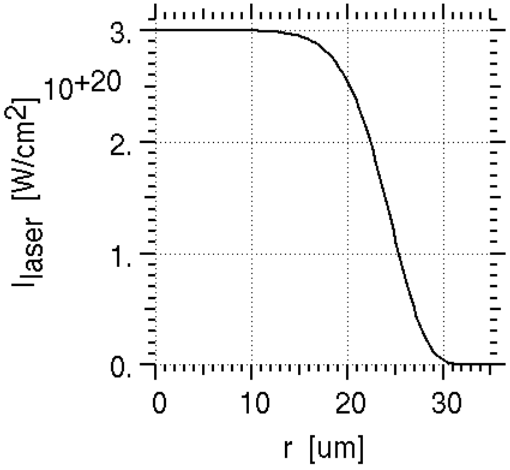
Zuma

2: hybrid transport
energy, momentum deposition

Tues. afternoon posters:
M. Marinak JP9.106: Zuma-Hydra
D. Larson JP9.119: Zuma modeling of wire experiments

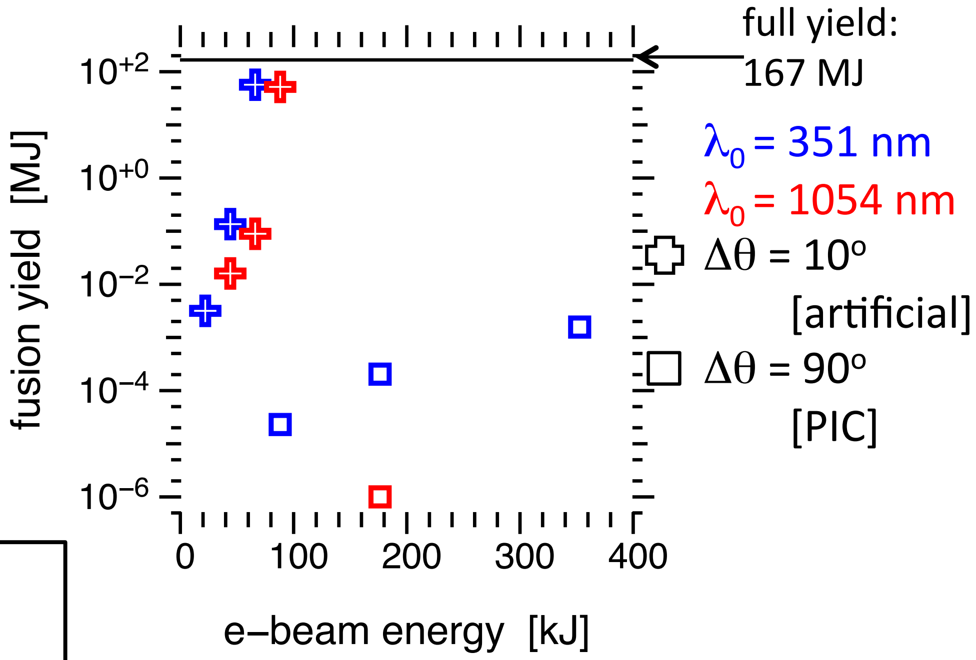
Zuma-Hydra modeling shows beam divergence has large effect on ignition energy





laser intensity:
8^{th}-order Gaussian

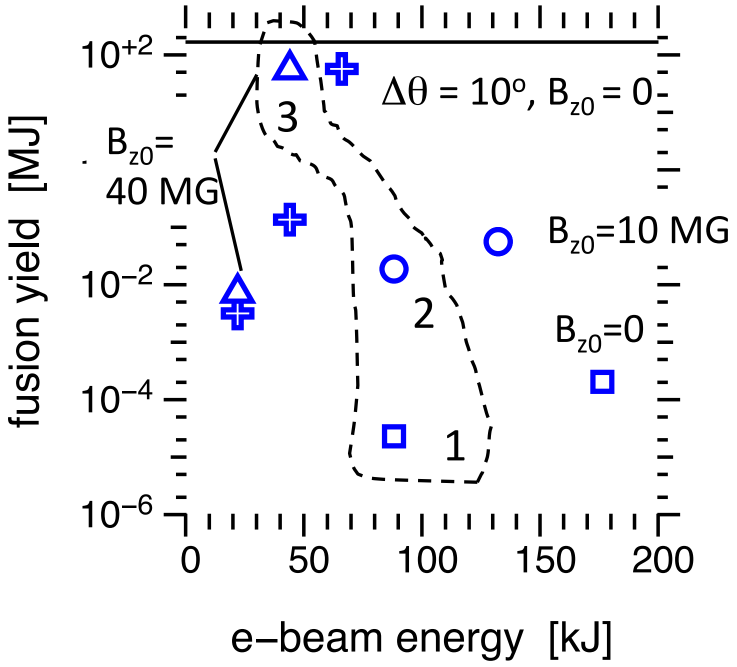
- 50 μm standoff from beam injection to cone tip, 30 μm from tip to dense fuel
- e-beam intensity = 0.52 * laser intensity
- 20 ps flattop pulse in time
- Angle spectrum: $dN/d\Omega = \exp[-(\theta/\Delta\theta)^4]$



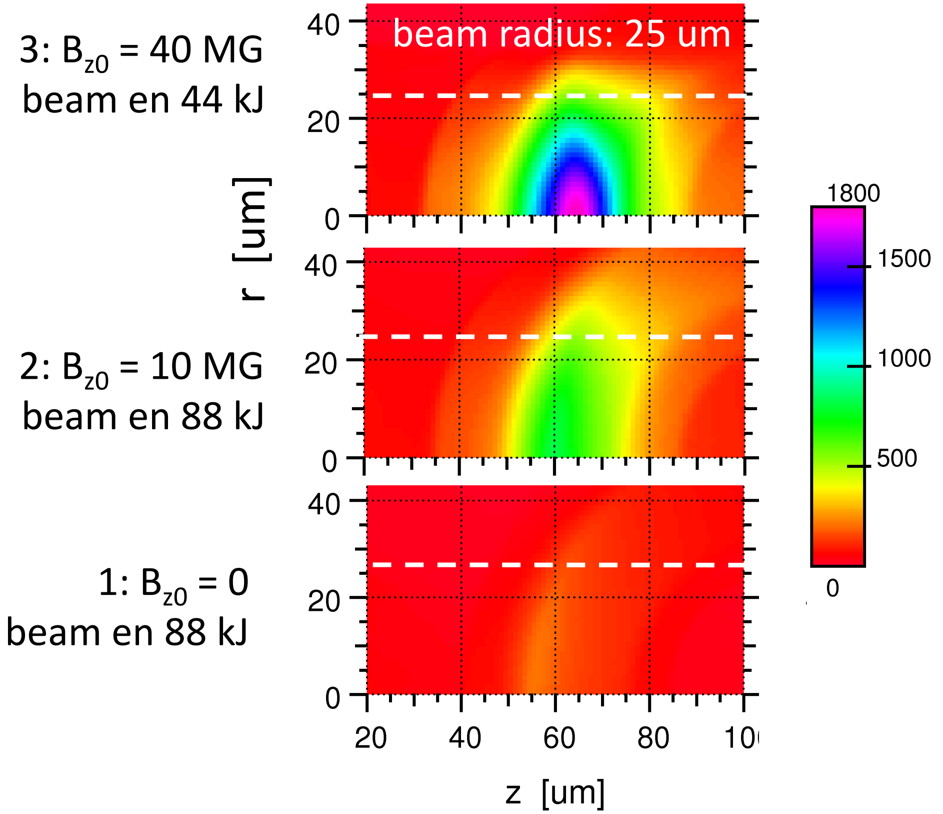
$\Delta\theta$ = 10°: beam ignition energy = (66,88) kJ
for λ_0 = (351, 1054) nm
$\Delta\theta$ = 90°: > 352 kJ for both λ_0: this is a loser!

Initial imposed axial magnetic field substantially reduces ignition energy for beam with realistic divergence

λ_0 = 351 nm, $\Delta\theta$ = 90° [matches PIC]



ion pressure [Gbar], t = 20 ps (end of pulse)



Tues. afternoon posters:
M. Tabak JP9.105: assembling B-fields

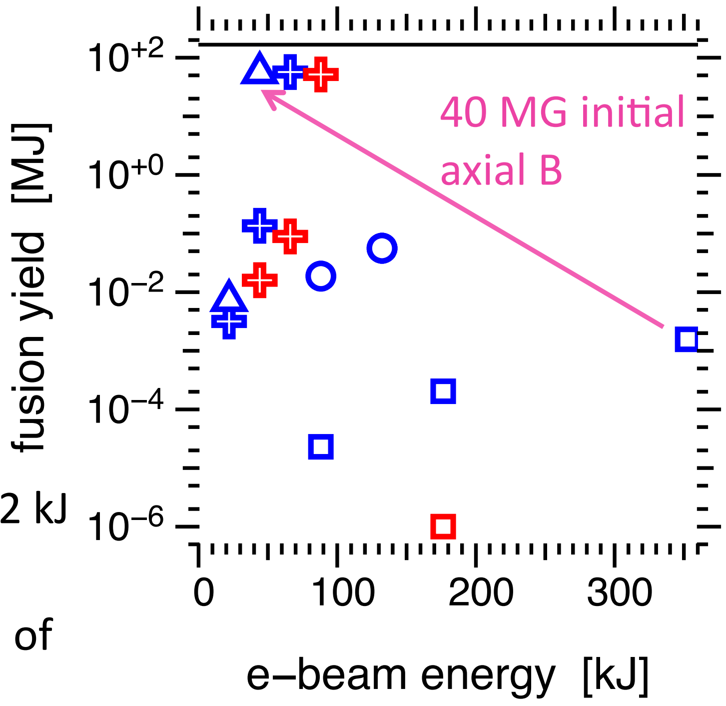
Omega expt's show cylindrical compression of 50 kG seed B field to 30-40 MG [J. P. Knauer, APS 2009, Phys. Plasmas 17, 056318 (2010)]

Symbol	B_{z0} [MG]	Beam ig'n energy [kJ]
□	0	>352
○	10	>132
Δ	40	44

Conclusions

- **Electron source:** full PIC LPI results well replicated by excited e- beam.
  - 52% conversion of laser in e-beam energy
  - Energy spectrum: quasi two-temperature, ponderomotive scaling.
  - Angle spectrum: very divergent supergaussian.
- **Zuma-Hydra integrated ignition studies** with PIC source (not experimentally validated):
  - Realistic divergence doesn't ignite even with 352 kJ of e-beam, or 700 kJ of laser!
  - Imposed axial B field of 40 MG ignites with 44 kJ of e-beam, for 351 nm laser light.
- **Furue work:**
  - Assembling B in implosion.
  - Use of 527 nm or 1054 nm light under study.
  - Recent PIC results of A. Kemp indicate a cooler spectrum than used here after 1-2 ps:

    later this session.



$\lambda_0 = 351$ nm

$\lambda_0 = 1054$ nm

✚ $\Delta\theta = 10$ deg, $B_{z0} = 0$

☐ $\Delta\theta = 90$ deg, $B_{z0} = 0$

○ $\Delta\theta = 90$ deg, $B_{z0} = 10$ MG

Δ $\Delta\theta = 90$ deg, $B_{z0} = 40$ MG