# Modeling of Electron-Driven Fast Ignition at Ignition Scale

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Anomalous Absorption meeting
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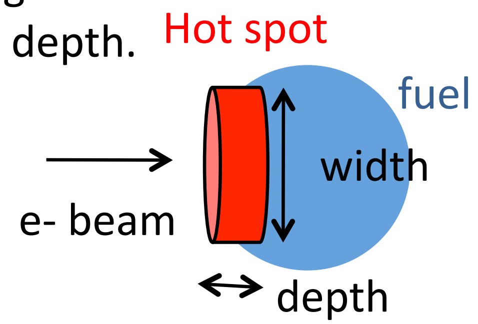
# Summary: Divergent electron source pushes us to width > depth hot spots, large beam energies; need to try focusing tricks

- **Electron source:** from full PIC LPI simulations [A. Kemp, L. Divol]:
  - Angle spectrum: highly divergent, hard to hit small hot spot.
  - Energy spectrum: modified two-temperature, ponderomotive scaling with laser intensity. Large fraction of energetic electrons don't fully stop in hot spot.

- **Width > depth ignition:** to lower laser intensity, and subtend divergent beam, we consider larger radius beams and hot spots with width > depth. Requires more deposited energy than small hot spot, but we can't hit a small spot!



- **Ignition-scale transport simulations:** with implicit PIC code LSP.
  - Ignition condition met with 85 kJ of e- beam energy, for 527 nm laser, 20 ps pulse, and *unrealistic* angular spectrum.
  - Realistic angular spectrum reduces energy in hot spot by ~50%; ~310 kJ needed for ignition.

- **Magnetic focusing** shows promise – Aluminum plug on-axis in C cone improves coupling.

# Electron source from full-PIC LPI simulations with PSC code[1]

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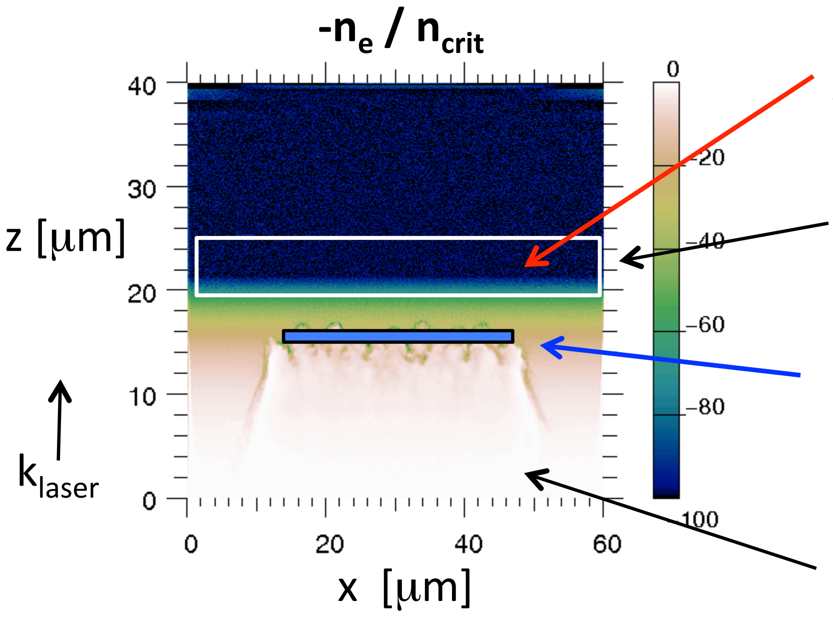
- 3D Cartesian run, 1 μm wavelength, pre-plasma with $n_e \sim \exp[\, z / 3.5\ \mu\mathrm{m}\,]$.
- Peak dens = 100 $n_{crit}$. Particle data taken at time 365 fs.
- Intensity at best focus: $I_{las}(r) = I_0 \exp[-(r/18.3\ \mathrm{um})^8]$
  $I_0$=1.37 E20 W/cm$^2$. Ponderomotive $T_{pond}$ = 4.63 MeV.
- Absorption = (incident – reflected) light ~ 90% with pre-plasma.
- No pre-plasma has somewhat cooler spectrum, but lower absorption.



Forward-going e- with kinetic energy > 0.5 MeV taken in white box

Outward radial drift naturally develops in wings; mapped uniform source matched PIC results

Equivalent e- source: matches white-box contents under free motion (no forces)

Pre-plasma – due to pre-pulse in short-pulse laser, or compression hydro (x-ray pre-heat, shock breakout)

[1] M. Bonitz et al., Introduction to Computational Methods in Many Body Physics (Rinton Press, Princeton, NJ, 2006), Vol. ISBN 1-58949-009-6, Chap. 2.

# Angle spectrum is very divergent! Pushes us toward larger {laser energy, beam spots, hot spot radius}

PIC data (white box)
mapped source (white box)
initial source (blue box)

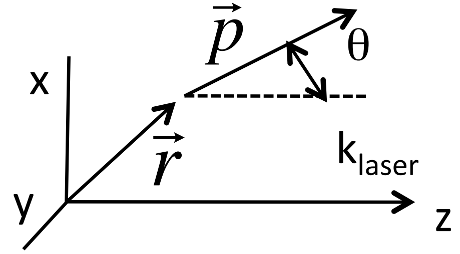
Spectrum in white box well-fit by azimuthally uniform source:

$$\frac{dN}{d\theta} = 2\pi \sin\theta \frac{dN}{d\Omega}$$

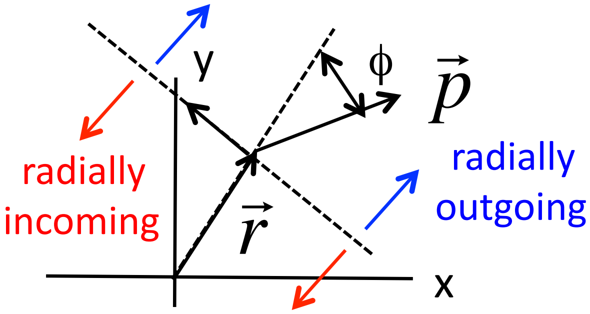
$$\frac{dN}{d\Omega} = \exp\left[-(\theta/\Delta\theta)^5\right]$$

$$\Delta\theta = 90 \text{ deg}$$

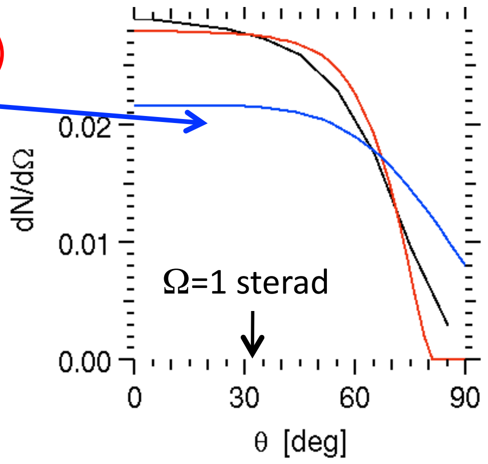
**Polar angle:**



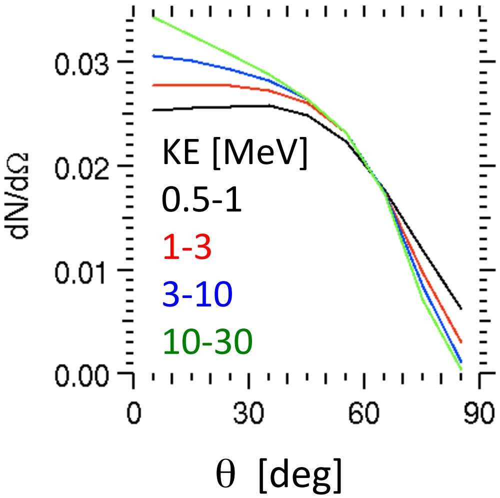
**Azimuthal angle:**



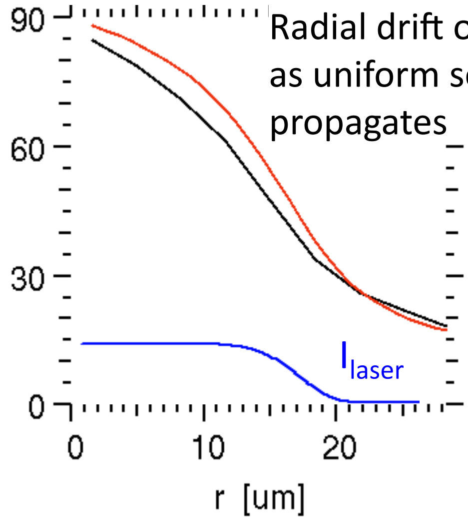
**Solid angle spectrum (all radii)**



**e- in white box: slightly more forward-going at higher energy; we neglect this**

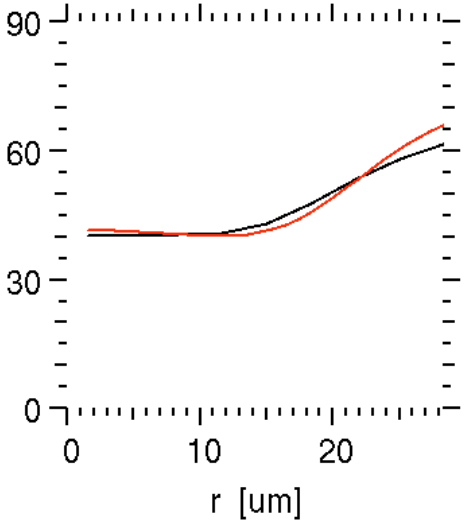


**Avg. azimuthal |ϕ| [deg]**



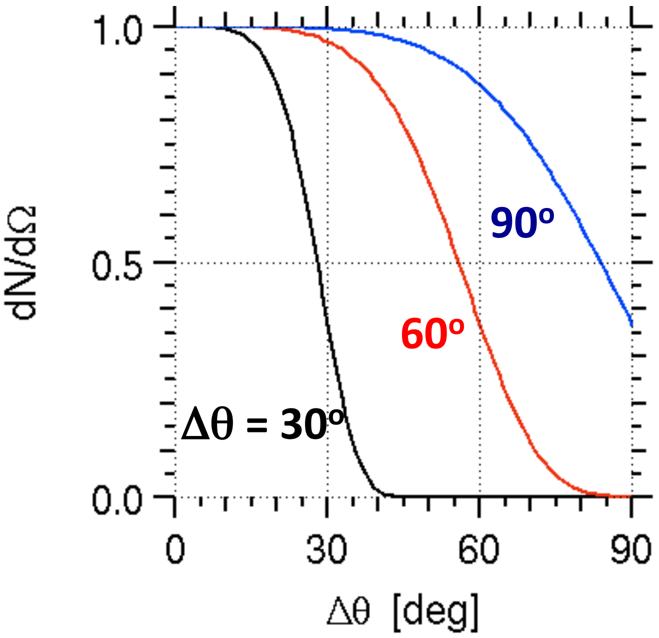
Radial drift occurs as uniform source propagates

**Avg. polar angle [deg]**

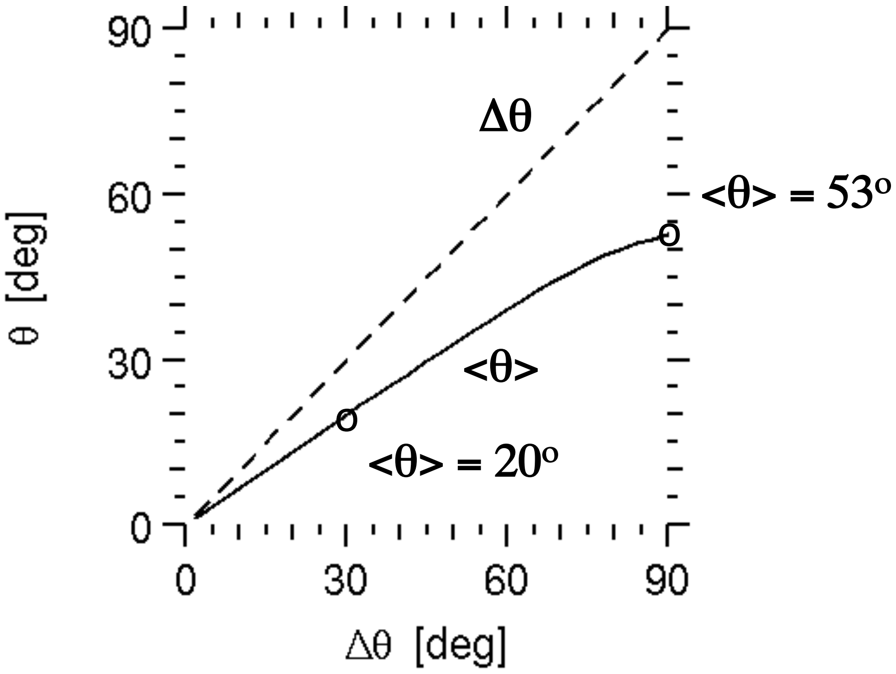


# Properties of super-Gaussian angle spectrum

**Polar angle spectrum (max=1)**

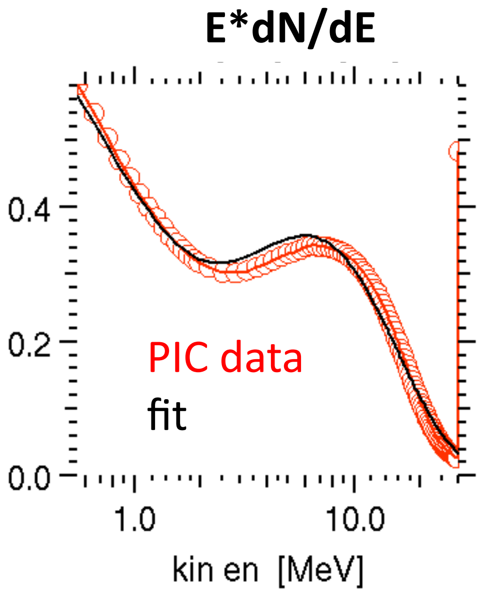


**Avg. polar angle: less than Δθ**



$$\frac{dN}{d\Omega} = \exp\left[-(\theta/\Delta\theta)^5\right]$$

# PIC energy spectrum: modified two-temperature; scaled ponderomotively

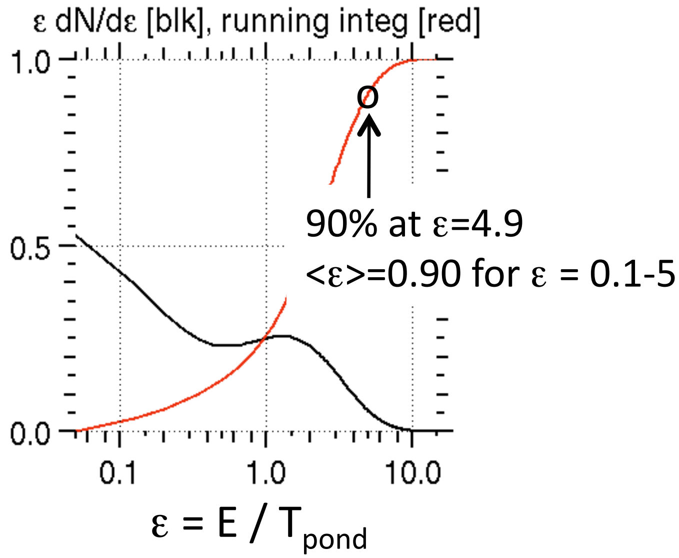


$$dN/dE = \frac{1}{E}\exp[-E/T_1] + \frac{n_2}{T_2}\exp[-E/T_2]$$

Note asymmetry in the two terms!

Plotted fit: $n_2 = 1.06$, $T_1 = 0.87$ MeV, $T_2 = 6.03$ MeV

In transport runs, we excite electrons w/ energies from $(0.1 - 5)T_{pond}$; assume 90% laser energy absorption.



90% at ε=4.9

<ε>=0.90 for ε = 0.1-5

**We scale dN/dE ponderomotively**

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

$$\varepsilon = E/T_{\text{pond}} \qquad \tau_i = T_i/T_{\text{pond}}$$

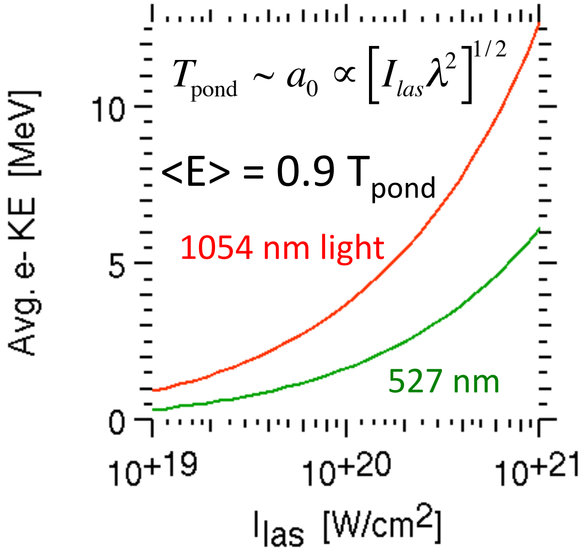
$$\tau_1 = 0.19 \qquad \tau_2 = 1.3 \qquad b_2 = \frac{n_2}{\tau_2} = 0.82$$

$$dN/d\varepsilon = \frac{1}{\varepsilon}\exp[-\varepsilon/\tau_1] + b_2\exp[-\varepsilon/\tau_2]$$

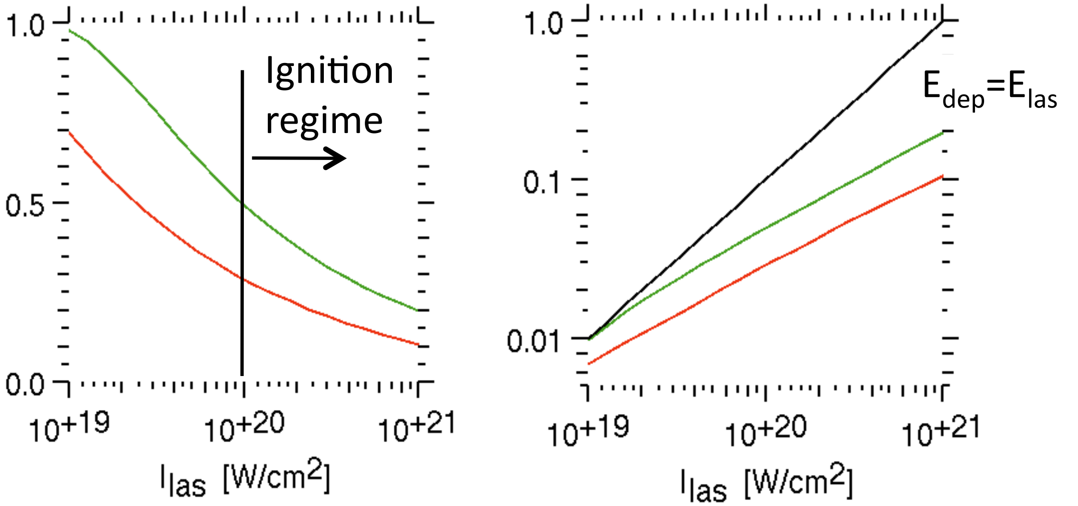
Normalize dN/dε to unity over desired ε interval.

# Usefulness of energy spectrum descreases with laser intensity, but energy deposited still increases; green light better than red

**Avg. e- energy in our spectrum**



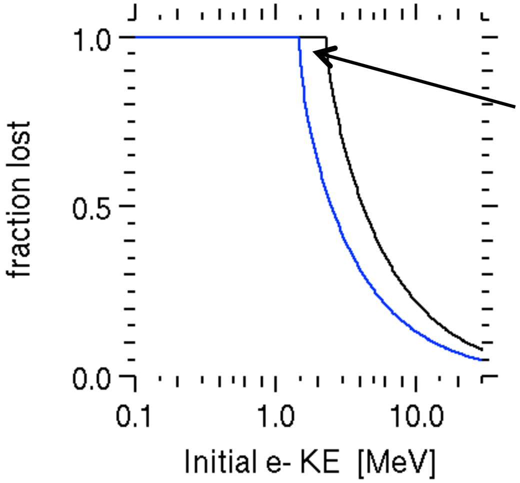
**Energy deposited by spectrum in 1.2 g/cm² of 300 g/cm³ DT**



**Fraction of energy deposited**

**Total deposited energy if $I_{las} \sim E_{las}$**

**Fraction of energy deposited DT, 300 g/cm³ (for one e-)**



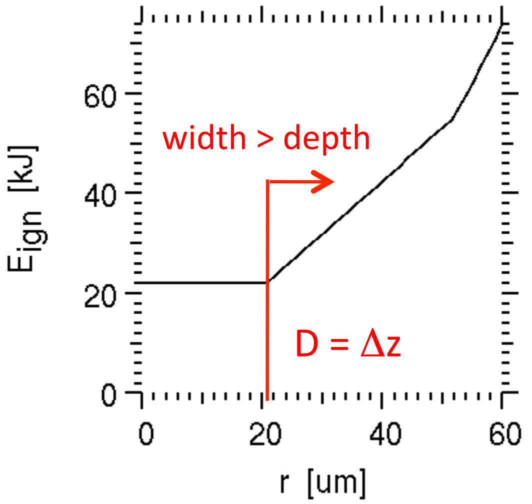
$E_{crit}$ [MeV] ~ 1.2 $\rho\Delta x$ [g/cm$^2$]

$\rho\Delta x$ = 2 g/cm$^2$
1.2

# Ignition requirements for fast ignition: width > depth mode

- **Fuel:** $\rho$~300 g/cm$^3$, $\rho r$>2 g/cm$^2$ – should give energy gain ~ 100 w/ ~1 MJ compression laser.
- **Ignition energy:** TN burn not yet in our transport simulations. We rely on 2D rad-hydro studies by Atzeni et al.[1]: Collimated, mono-energetic beam into spherical fuel.

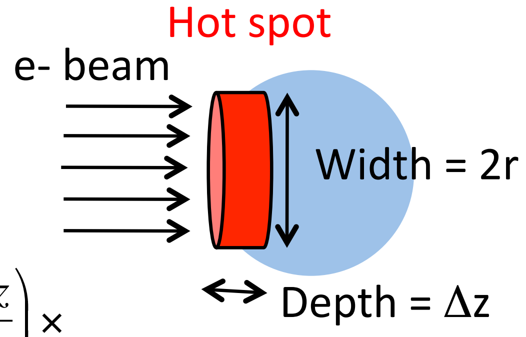
**Ignition energy criterion**
**$\rho$ = 300 g/cm$^3$ DT, $\rho\Delta z$ = 1.2**



$$E_{opt} = 140\left(\frac{\rho}{100\ \text{g/cm}^3}\right)^{-1.85}$$

width > depth penalty

$$E_{ign} \geq E_{opt}(\rho) \times \max\left(1, \frac{\rho\Delta z}{1.2}\right) \times \begin{cases} \max\left(1, \dfrac{\rho r}{0.6}\right), & \rho r < 1.5 \\ 2.5\left(\dfrac{\rho r}{1.5}\right)^2, & \rho r \geq 1.5 \end{cases}$$



$$(\rho r)_{\text{opt}} \approx 0.6, \text{ or}$$

$$(\rho D)_{\text{opt}} = \rho\Delta z = 1.2$$

$\rho X$ in g/cm$^2$

One pays an energy penalty to ignite a width>depth hot spot, but it's the better choice if one's beam is too energetic or divergent – which our e- beams are.

[1] S. Atzeni, A. Schiavi, C. Bellei, Phys. Plasmas 14, 052702 (2007)

# Energy in hot spot vs. ignition energy is our figure of merit for our no-burn simulations

- **Ignition energy:** Atzeni used collimated, mono-energetic beams; we take his ignition energy as the energy one must deposit in the hot spot.

- **Hot-spot energy:** some deposited energy is lost, so we are generous in finding hot-spot energy.

- **Hot spot construction:** $\rho > 200$ g/cm$^3$ and in depth $\rho*\Delta z=1.2$ from cone side.
  - $E_{\text{hot-spot}}$ = thermal + flow energy in all species

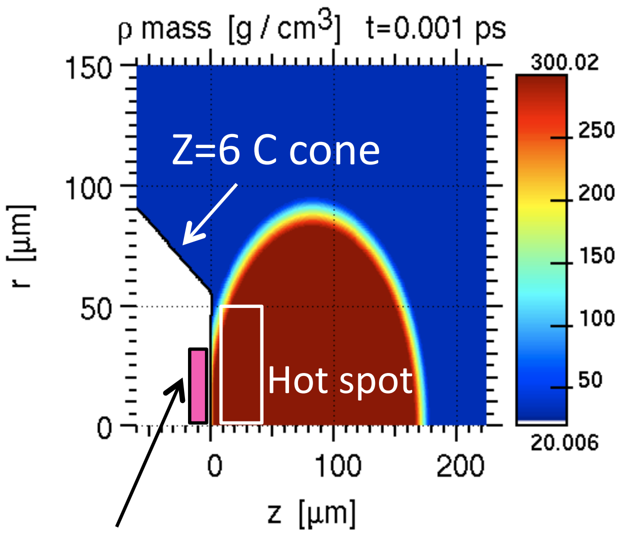
- Darwin Ho is performing Lasnex calculations with electron beam using realistic energy and angle spectra: next talk!

$E_{\text{hot-spot}}$ / $E_{\text{ignition}}$ = figure of merit to compare runs;
accurate ignition assessment requires simulations with burn.

# LSP[1] direct-implicit PIC code for transport modeling: excited electron beam (no laser) propagating to ideal targets, RZ geometry, fluid background

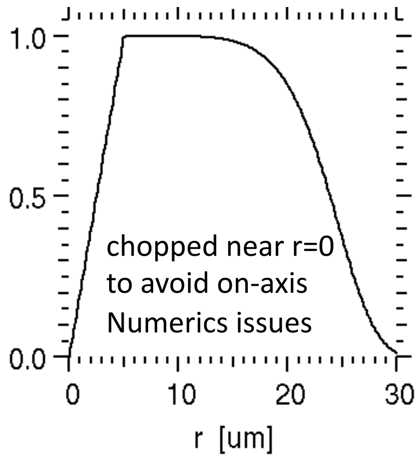
[1] D. R. Welch, D. V. Rose, M. E. Cuneo, R. B. Campbell, T. A. Mehlhorn, Phys. Plasmas 13, 063105 (2006)

# No-standoff target, carbon cone, ~ 85 kJ beam energy, Δθ=30 deg (magic collimation): ignites with green light and 20 ps pulse

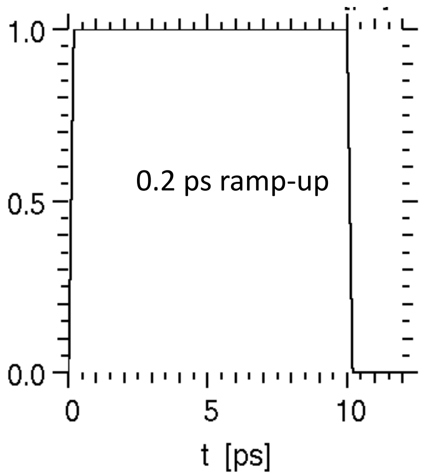


Beam excited: z = -15 to -5 um

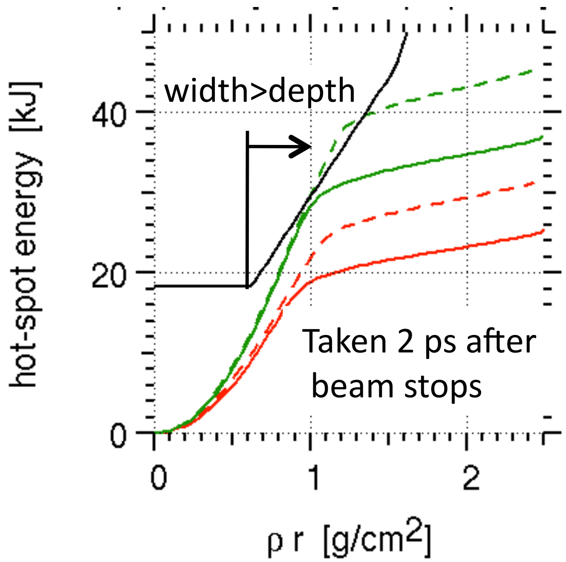
**Beam profile: exp[-(r/25 um)$^8$]**



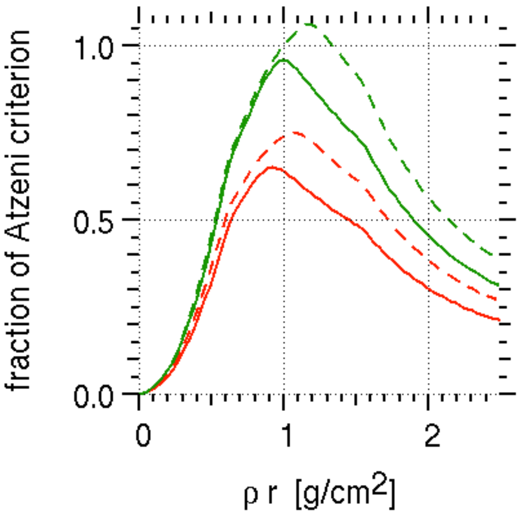
**Beam pulse (10 ps length)**



**Energy in hot spot [kJ]**



**Fraction of ignition conditon: $E_{\text{hot spot}} / E_{\text{ignition}}$**



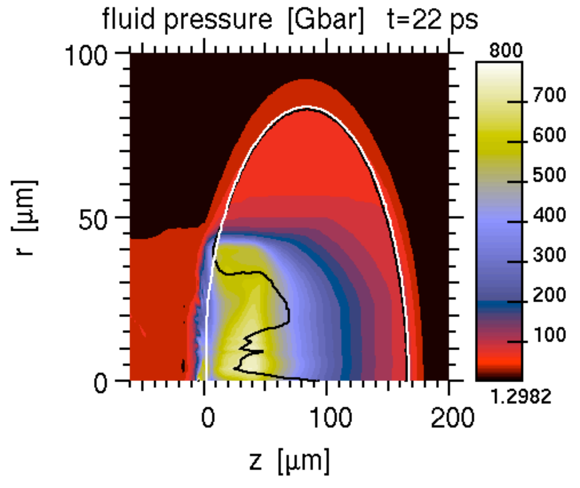
——— 1054 nm laser, 10 ps pulse
——— 527 nm laser, “
- - - - 1054 nm laser, 20 ps pulse
- - - - 527 nm laser, “
——— Ignition condition

Beam intensity [x$10^{20}$ W/cm$^2$] =
4.9, 2.5 for T = 10, 20 ps

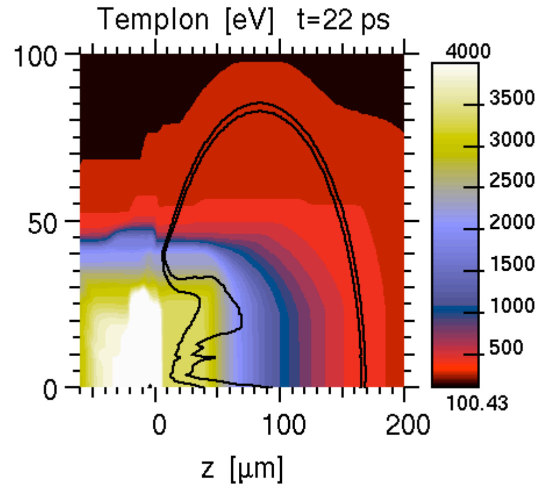
- Green is good – cooler spectrum
- Long pulse helps – cooler spectrum overcomes more hot-spot loss
- Peak fraction for $\rho$*r = 0.9-1.2 g/cm$^2$

# 527 nm light, 20 ps pulse cases: profiles at run end (22 ps) for $\Delta\theta$ = 30, 90 deg

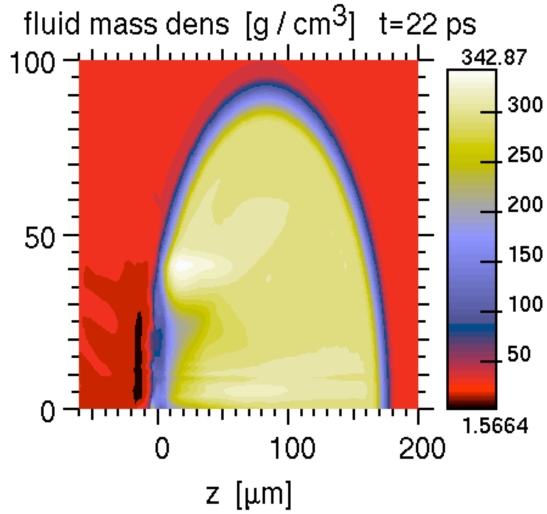
**$\Delta\theta$=30: non-isobaric -> p*dV work, mass motion; hot spot $T_{ion}$ = 3-4 keV**


fluid pressure [Gbar] t=22 ps

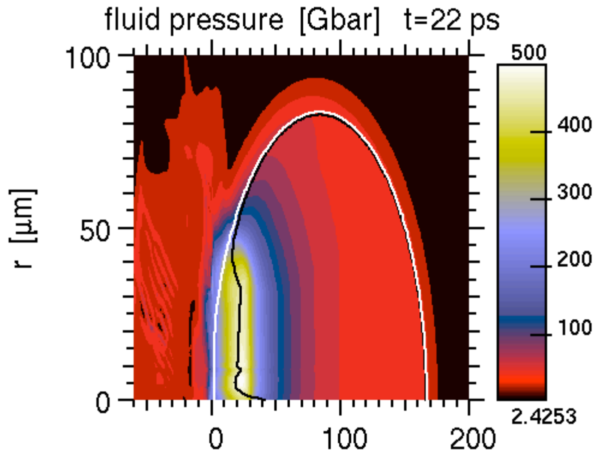
(white, black): (initial, final) rho=290

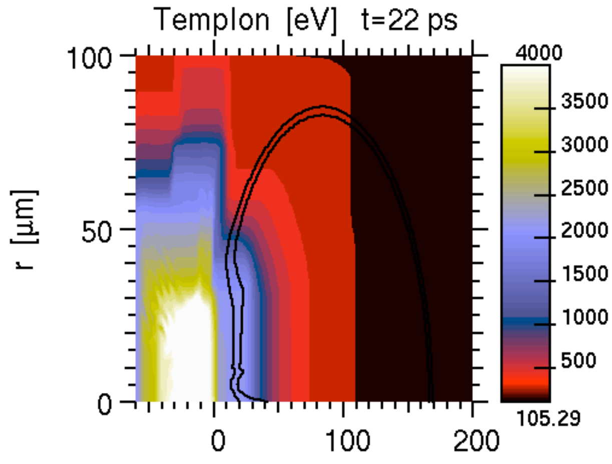

TempIon [eV] t=22 ps

contours: final rho = 250, 290

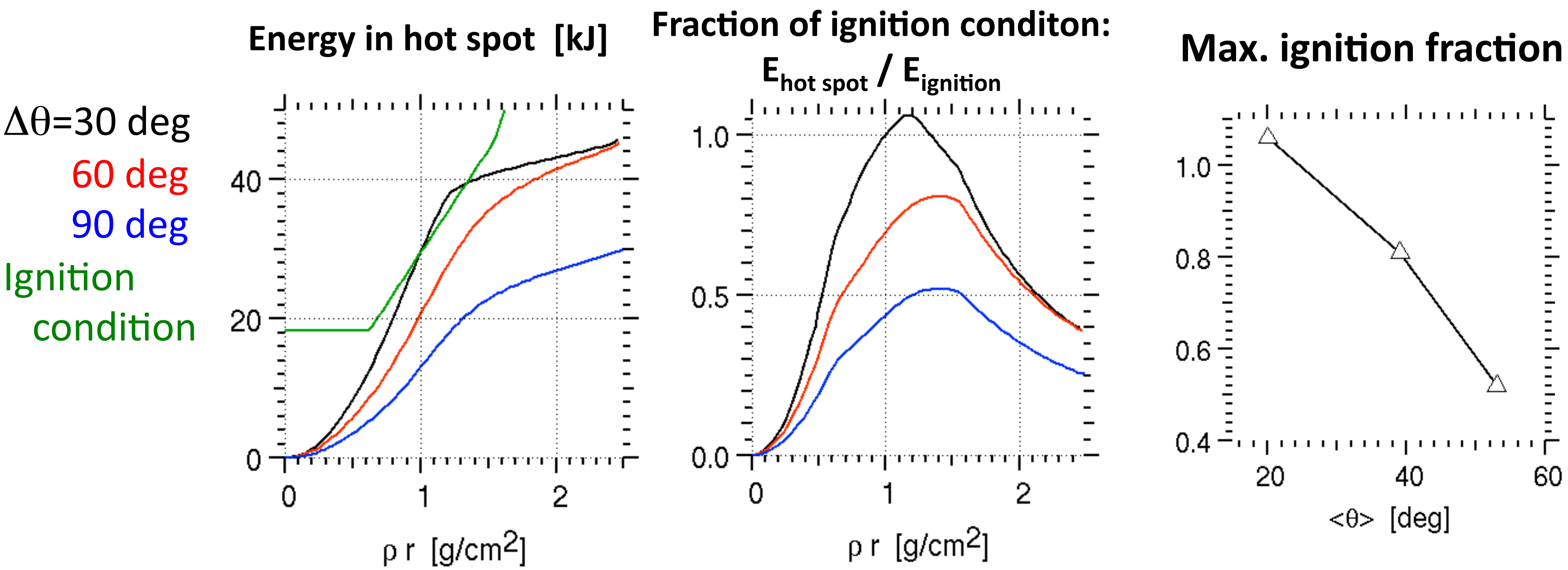

fluid mass dens [g / cm$^3$] t=22 ps

**$\Delta\theta$=90: bigger hot spot radius, less deep heating; beam hits fuel at glancing blow**


fluid pressure [Gbar] t=22 ps


TempIon [eV] t=22 ps

# Effect of angular spread Δθ, on green light (527 nm), 20 ps pulse case



$$dN/d\Omega \propto \exp\left[-(\theta/\Delta\theta)^5\right]$$

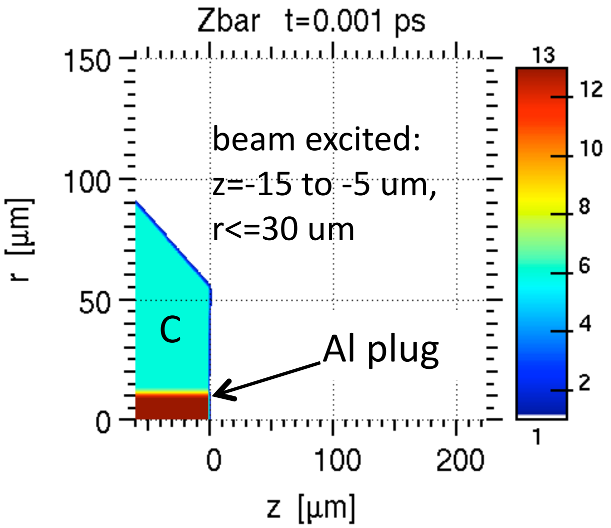
- Angular spread severely degrades coupling to hot spot.
- To recover ignition, need to add more energy, increase spot…
- Or figure out ways to collimate beam!
  Beam profile or resistivity gradients[1]

$$\vec{J}_{\text{ret}} \approx \vec{J}_{\text{fwd}}, \qquad \vec{E} = \eta \vec{J}_{\text{ret}},$$

$$\partial_t \vec{B} = -\nabla \times \vec{E} = \eta \nabla \times \vec{J}_{\text{fwd}} + \nabla \eta \times \vec{J}_{\text{fwd}}$$

[1] A. P. L. Robinson, M. Sherlock, Phys. Plasmas 14, 083105 (2007)

# Aluminum plug on axis, 10 μm radius gives some collimation

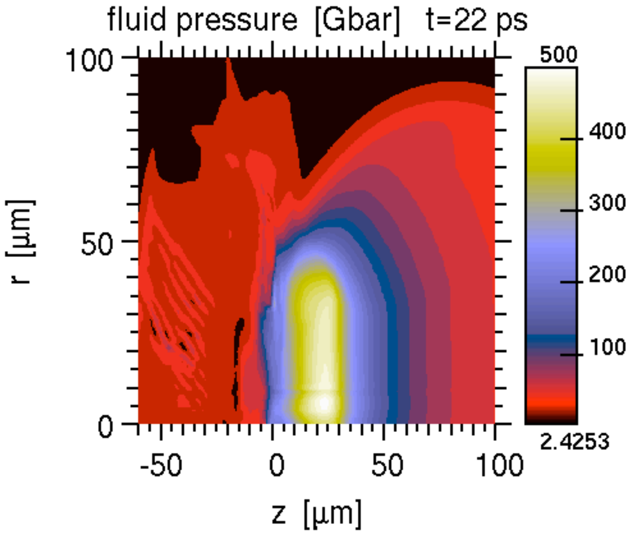


527 nm laser,
20 ps pulse,
$\Delta\theta$ = 90 deg

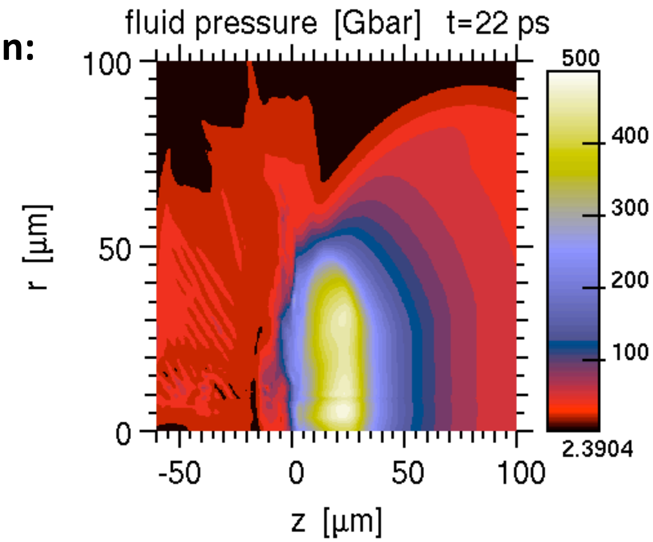
All fully ionized

Resistivity gradient transverse to beam generates collimating B fields.

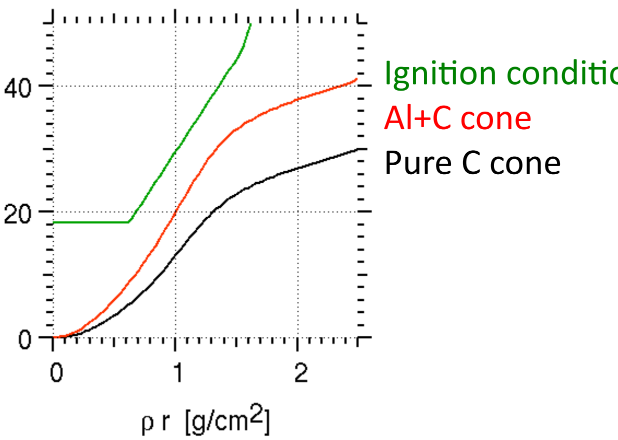
**pure C cone**



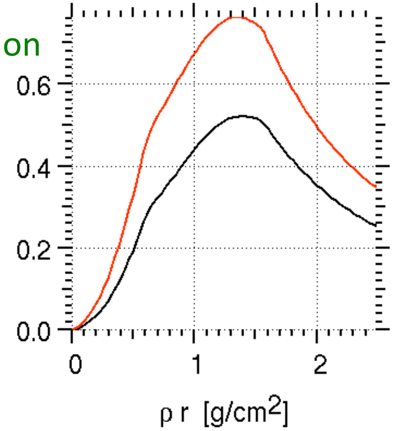
**Al in C cone**



**Energy in hot spot [kJ]**



**Fraction of ignition conditon: $E_{\text{hot spot}} / E_{\text{ignition}}$**

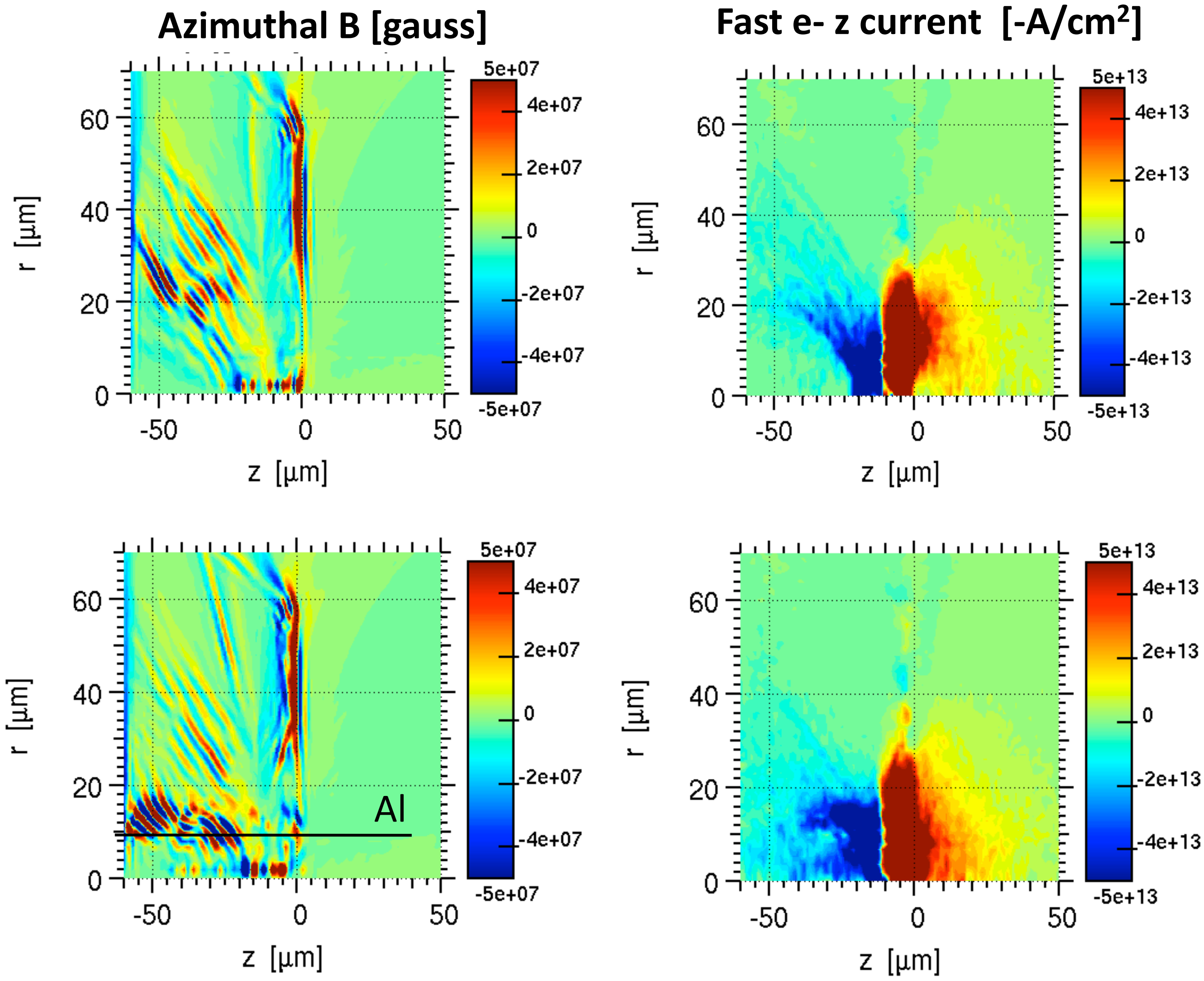


# Azimuthal B fields (<0 is radially confining for $v_z$>0) and currents late in pulse (15 ps)

**pure C cone**

**Al+C cone**

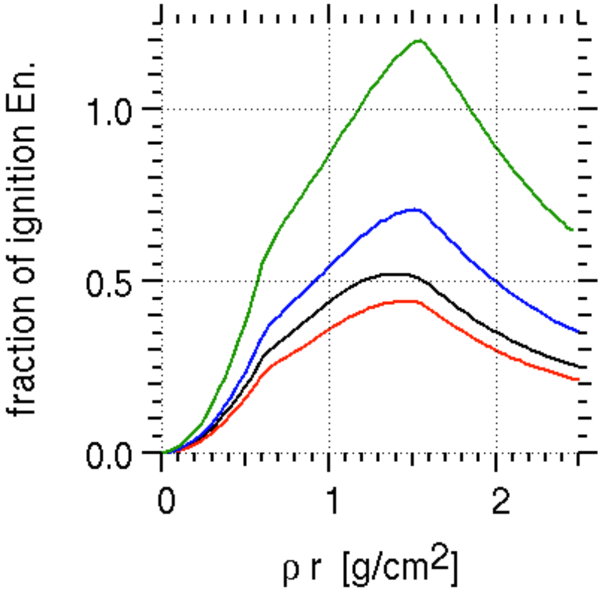
Increased B fields at r=10 $\mu$m Al-C interface; more current near r=0.



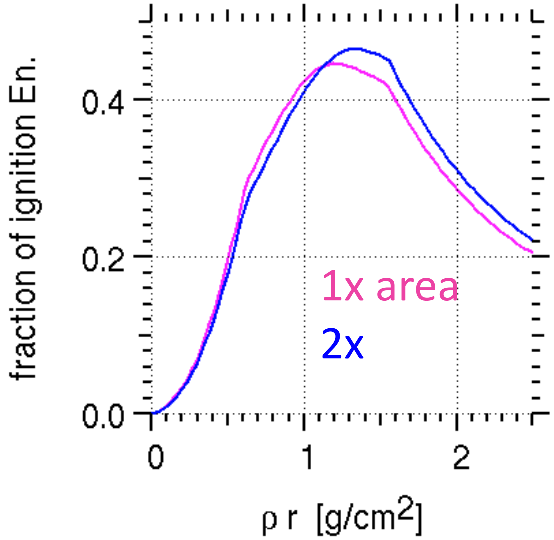
# Reaching ignition with $\Delta\theta = 90$: about 310 kJ needed; weak dependence on beam area

| Beam area | beam energy |
|---|---|
| 1x | 1x |
| 1x | 2x |
| 2x | 1x |
| 2x | 2x |
| 2x | 4x |

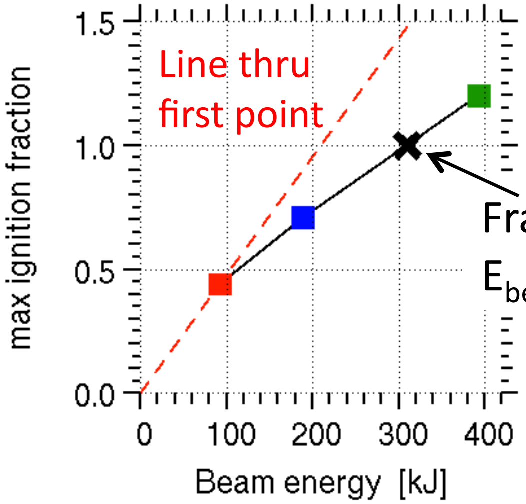
**At run end [22 ps]**



**2x energy runs @ 14 ps [magenta stopped]**



**Energy scaling for 2x area**



Line thru first point

Frac=1: $E_{beam}$ = 310 kJ

# Summary: toward electron-driven fast ignition

- **Electron source:** full-PIC simulations with pre-plasma show highly divergent angular spectra, and a modified two-temperature energy spectrum. Both facts make it hard to deposit energy in a small hot spot.
  - Can no pre-plasma help? Other laser-plasma interaction tricks?

- **Width > depth ignition:** we are pushed towards larger hot spots with $\rho * r = 1\text{-}1.5\ \mathrm{g/cm^2}$ and temperatures ~ 4-5 keV.

- **LSP Transport modeling:** Atzeni ignition condition can be achieved, with no cone-fuel standoff, with green (527 nm) laser:
  - $E_{beam} = 85$ kJ for unrealistic $\Delta\theta = 30$ deg.
  - Coupling to hot spot 50% lower with realistic $\Delta\theta = 90$ deg.
  - $E_{beam} \sim 310$ kJ in 2x area spot with $\Delta\theta = 90$ deg.

- **Magnetic collimation:** may reduce beam divergence, improve coupling.
  - Resistivity gradient: Aluminum plug in cone helps in $\Delta\theta = 90$ deg case.

Collimation should be explored more, but at ignition relevant targets: scales, energies, pulse durations, geometries, etc.

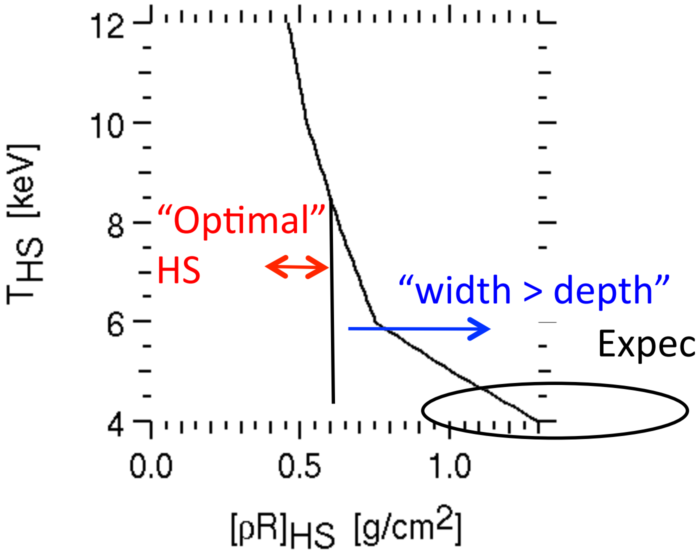
# Width > depth ignition regime

- **Laser intensity:** spectrum too energetic, minimize intensity – flattop time pulse, spatial spot.
- **Temporal pulse:** balance between overcoming hot spot losses and making spectrum too energetic.

$$t_{\text{pulse}} = 54\left[\frac{100\ \text{g/cm}^3}{\rho}\right]^{0.85}\ \text{ps} = 21\ \text{ps for } \rho = \ 300\ \text{g/cm}^3 \qquad \text{Atzeni optimal pulse length}$$

**Ignition condition from isochoric, 1D rad-hydro simulations**

From fig. 4.6 of Atzeni and Meyer-ter-Vehn, "The Physics of Inertial Fusion."



Expected ignition regime:

$\rho r$ = 1-1.5 g/cm$^2$

$T_i$ = 4-5 keV

# LSP[1] implicit PIC code for transport modeling: excited electron beam (no laser) propagating to ideal targets

- Direct-implicit[2] particle push and electromagnetic field solution:
  - Numerically damps fast modes (light, plasma waves) when $\Delta t \gg \omega_{pe}^{-1}, \omega_{light}^{-1}$; $\Delta x \gg \lambda_{De}, \lambda_{light}$.
  - Field solver: Petsc-based matrix inversion.
  - Electromagnetic, but numerical implicit magnetization term not included in LSP.
  - *IF* numerically resolved, allows electromagnetic beam instabilities, full LPI (continuous transition from full-PIC to effectively hybrid model).
- Background plasma: multi-species Eulerian fluid:
  - Collisional transport (unmagnetized): Lee-More-Desjarlais, LSP coefficients recently corrected.
- Fast electron stopping and angular scattering formulas of Solodov-Betti / Davies; energy and momentum lost by fast e- to a background species deposited in each cell (conservative).
- R-Z cylindrical geometry.
- Fixed ionization states, ideal gas EOS.

- Future options:
  - Correct ionization, non-ideal EOS.
  - Fusion reactions, bremsstrahlung emission.
  - Coupling to Hydra rad-hydro code.

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