The effects of electron divergence on the point design

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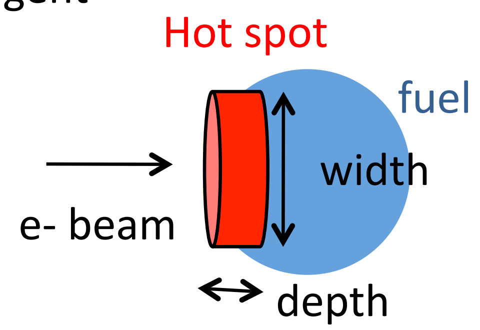
Summary: Divergent electron source pushes us to width > depth hot spots, large beam energies; need to try focusing tricks

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

- **Width > depth ignition:** to lower laser intensity, and subtend divergent beam, use large radius beams and hot spots with width > depth.
  - Requires more deposited energy than small hot spot, but we can't hit a small spot!
  - Look for ignition w/ low hot-spot temperatures (4-6 keV).



- **Ignition-scale transport simulations:** with implicit PIC code LSP.
  - Comparison with Atezni's ignition condition.
  - Burn calculations in HYDRA on LSP final conditions.

- **Magnetic focusing** shows promise – resistivity gradients, external B fields – not discussed further here.

We directly compare electrons in PSC "white box" with an LSP "white box" in a test run with an excited electron beam (forces are included)

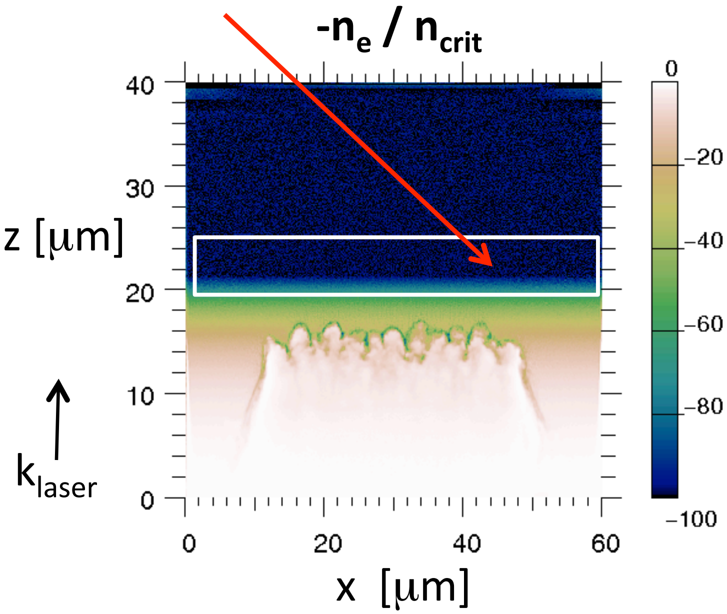
PSC run "3Dpre":

- 3D Cartesian, 1 μm wavelength.
- pre-plasma $n_e \sim \exp[z / 3.5\ \mu\text{m}]$.
- Peak dens = 100 n_{crit}. Data at time 365 fs.
- 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 run "source5":

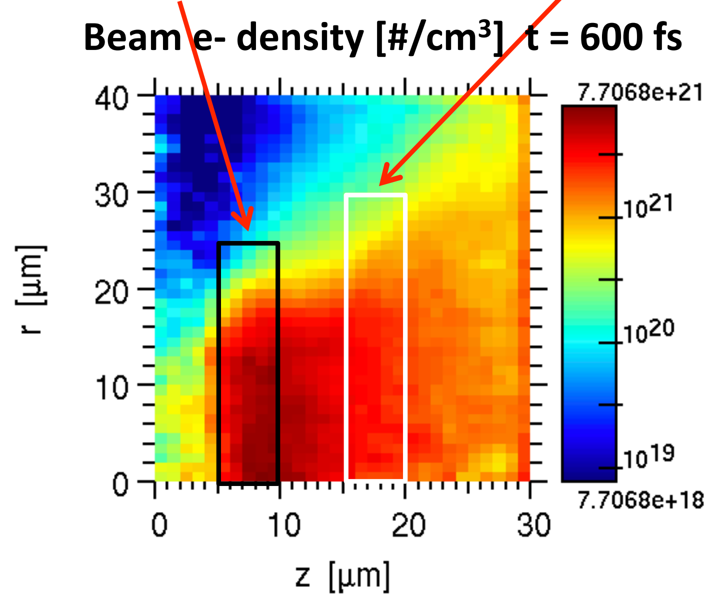
- 10 g/cc, 100 eV, Z=6 carbon.
- Beam radial profile same as laser intensity I_{las}.
- Forces from E/B fields included.
- No dE/dx or scattering since not in PSC run, and would be larger at LSP's high density.

"white box": Forward-going e- with kinetic energy between 0.5 and 30 MeV



black box: e- beam excited

LSP white box



- beam $f(E,\theta) = f_E(E) * f_\theta(\theta)$; could add several together.
- number (not just energy) flux important: controls currents, B

Beam energetics, and two-temperature energy spectrum

Energy spectrum: quasi two-temperature, scaled ponderomotively

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

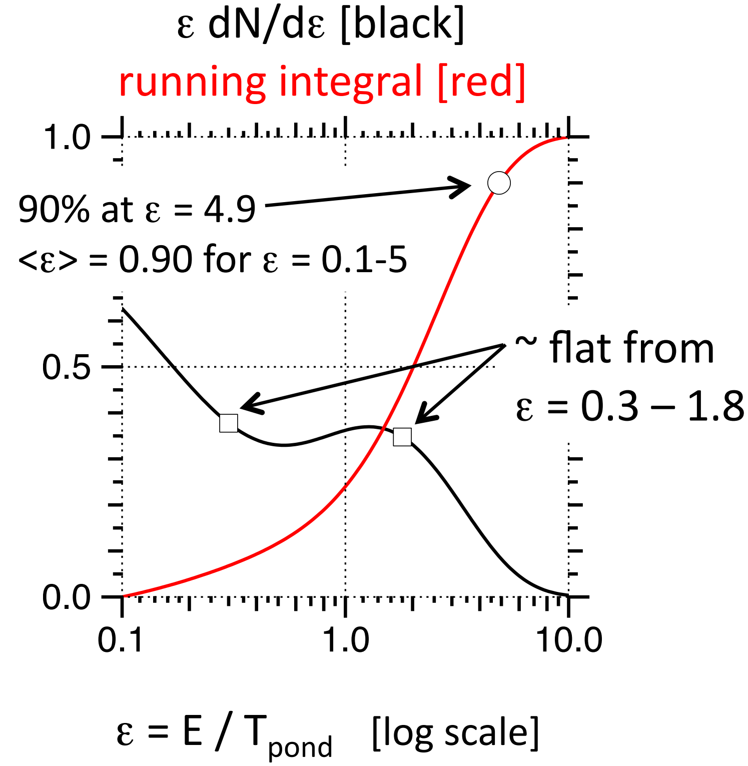
Note asymmetry in the two terms!

$$\frac{T_{\mathrm{pond}}}{m_e c^2} := \left[1 + a_0{}^2\right]^{1/2} - 1$$

$$\sim \quad a_0 := \mathrm{sqrt}\left[\frac{I_{las}\lambda^2}{1.37\cdot 10^{18}\ \ \mathrm{W\ cm^{-2}}\mu\mathrm{m}^2}\right]$$

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

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

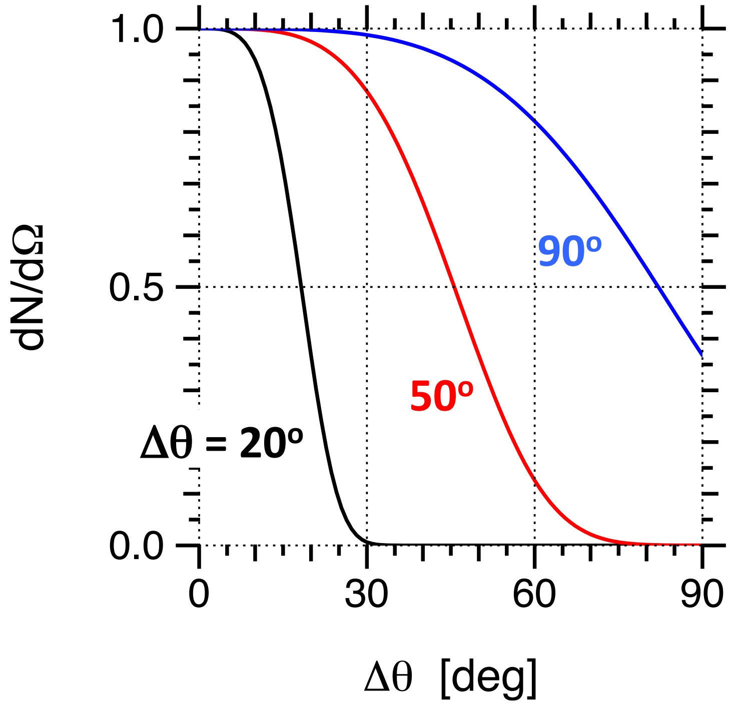


- PSC run "3Dpre": Laser power = 1.3 PW.
- LSP beam power = 0.68 PW = 52% of laser power; sets absolute rate e-beam energy added.
- Total laser absorption is higher ~80-90%, but some is parasitic: expanding plasma,
- return current, ions, etc.

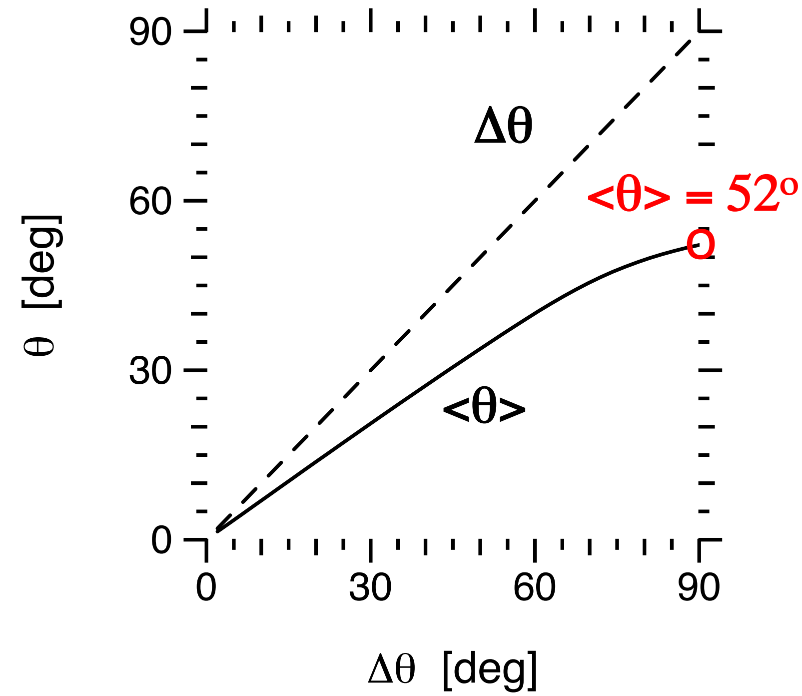
Source polar angle spectrum: super-Gaussian, large opening angle

$$\frac{dN}{d\Omega} = \exp\left[-(\theta/\Delta\theta)^4\right] \qquad \Delta\theta = 90 \text{ deg for LSP source to match PSC}$$

Solid angle spectrum (max=1)



Avg. polar angle: less than Δθ



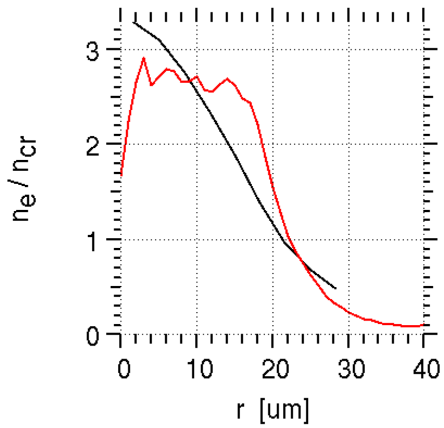
- "The opening angle" is ill-defined: should specify $\langle\theta\rangle$, θ_{rms}, θ enclosing 90% of e-, etc.
- "The intrinsic source" is also ill-defined: my goal is LSP black-box source for transport sims that replicates e- in PSC white box. Different questions (e.g. K-alpha spot size) have different answers.
- Only fwd-going e- excited. LSP bug recently fixed, which gave bad angle spectrum when exciting > 1 ptcl / cell /step. My Anomalous 2010 talk suffered from this bug.

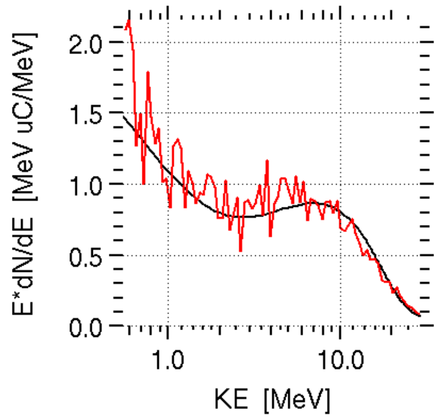
PSC (black) and LSP (red) e- in white boxes are similar – adequate for transport and design studies

e- energy in white box [Joules]: 14.9 PSC, 15.0 LSP. 0.6% error!

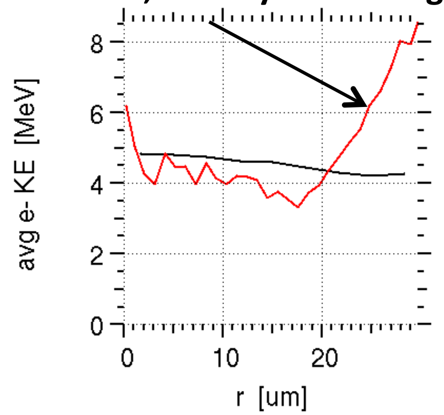
Avg. polar angle theta [deg]: 46.8 PSC, 48.6 LSP, 3.7% error. Smaller than 52 deg in source region.

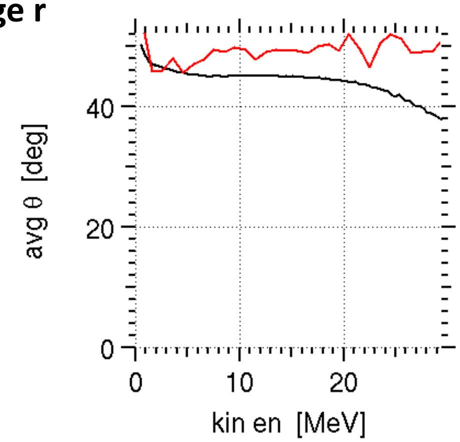
All LSP e-, not just some KE range

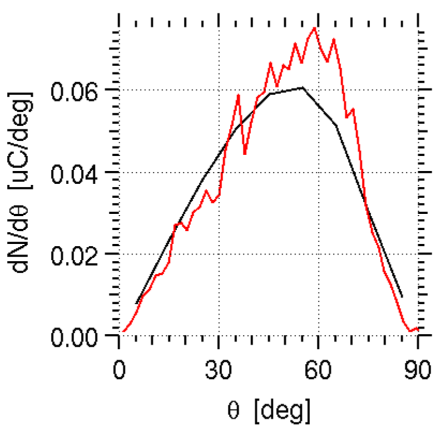




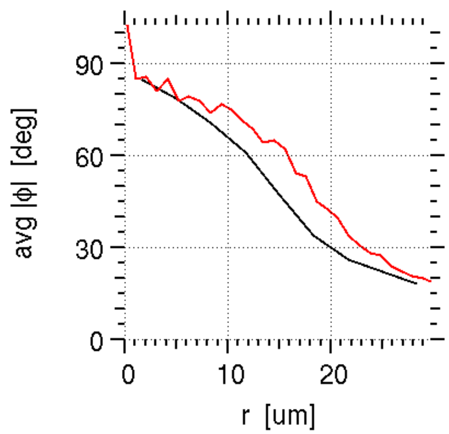
resistive B in LSP may deflect low-KE e-; density low at large r

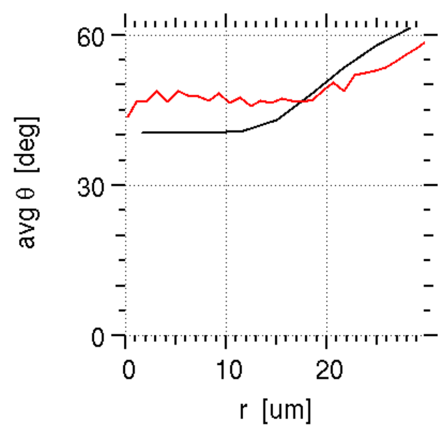




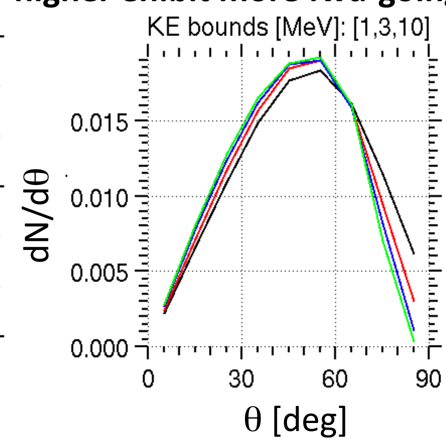


ϕ = angle b/t r and p, in xy plane[1]
small |ϕ| -> radial outward drift





PSC dN/dθ in en. bins: higher en.bit more fwd-going



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

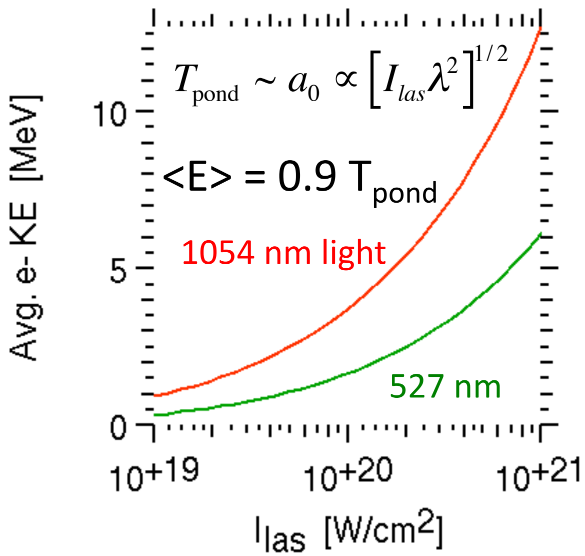
- **Electron source**

- **Width > depth ignition**

- **Ignition-scale transport simulations**

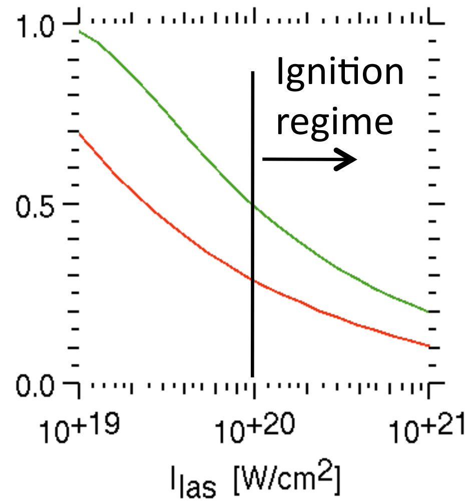
Usefulness of energy spectrum decreases with laser intensity, but energy deposited still increases; green light better than red

Avg. e- energy in our 2-T spectrum

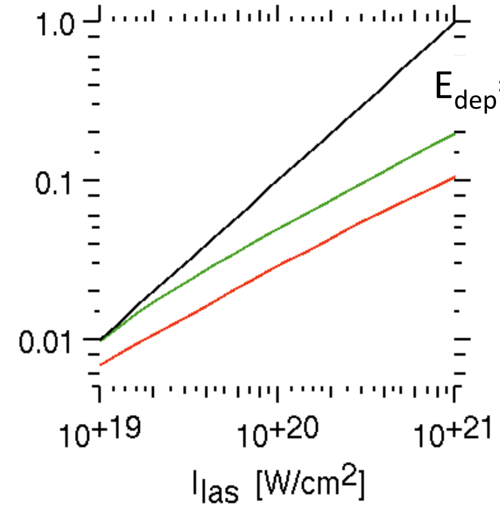


Energy deposited by 2-T spectrum in 1.2 g/cm^2 of 300 g/cm^3 DT

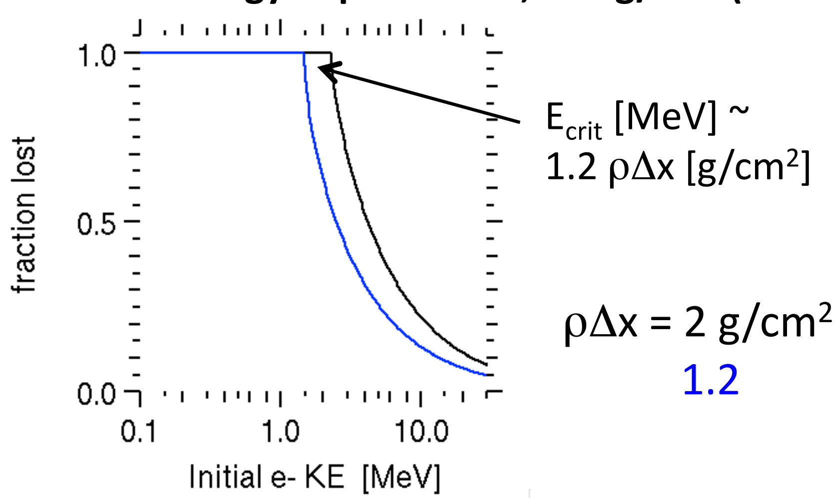
Fraction of energy deposited



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



Fraction of energy deposited DT, 300 g/cm^3 (for one e-)



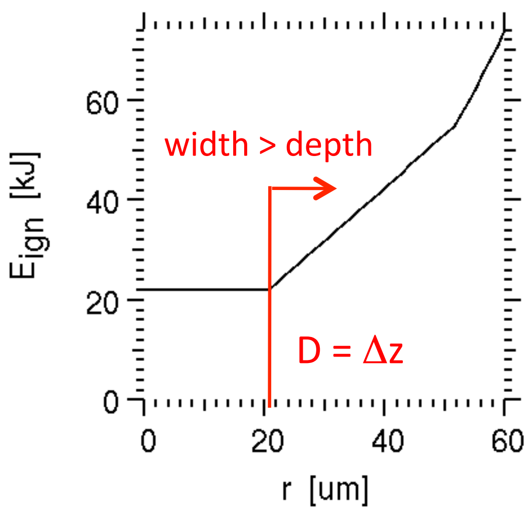
You still win as you increase laser energy (for fixed spot and pulse), but slower than linearly.

Ignition requirements for fast ignition: width > depth mode

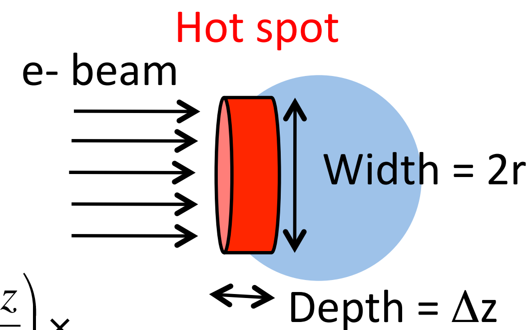
- **Fuel:** ρ~300 g/cm³, ρr>2 g/cm² – should give energy gain ~ 100 w/ ~1 MJ indirect-drive compression laser.

- **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
ρ = 300 g/cm³ DT, ρΔz = 1.2



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



width > depth penalty

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

$$(\rho r)_{opt} \approx 0.6, \text{ or}$$
$$(\rho D)_{opt} = \rho\Delta z = 1.2$$

ρX in g/cm²

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.
  - $E_{hot\text{-}spot}$ = thermal + flow energy in all species.

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

- **Electron source**

- **Width > depth ignition**

- **Ignition-scale transport simulations**

LSP[1] direct-implicit PIC code for transport modeling

• Excited electron beam (no laser) propagating to ideal targets.

• RZ geometry.

• Eulerian multi-species fluid background.

• Ideal gas EOS, fixed ionization.

• Unmagnetized Lee-More-Desjarlais background transport (e.g. electrical and thermal conductivities).

• Solodov/Davies stopping and scattering of fast e- by Lemons-like algorithm.

  • Fast electrons collide with both free and bound background electrons! Only differ in “log lambda”.

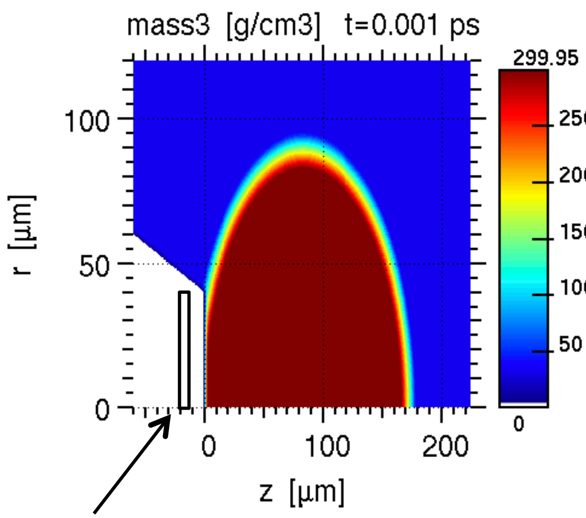
• Energy conservation is excellent (usually better than 1% of beam energy).

• Problems do occur in B (and E) fields near R=0. Thanks to A. Solodov for coding for B-field smoother, which helps.

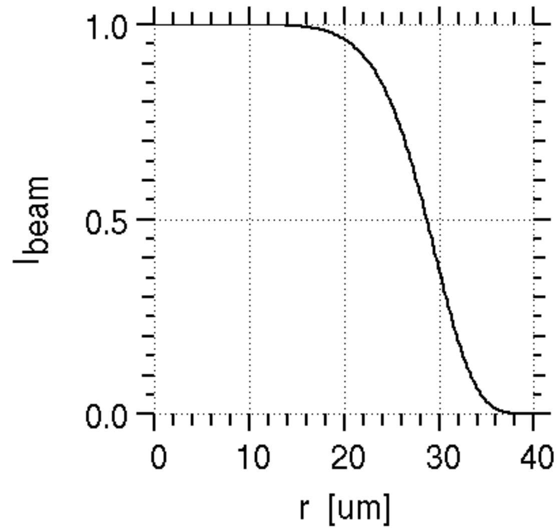
[1]D. R. Welch, D. V. Rose, M. E. Cuneo, R. B. Campbell, T. A. Mehlhorn, Phys. Plasmas 13, 063105 (2006)

LSP run ign02: realistic Δθ = 90 deg

Cone: 20 g/cc, Z=6 carbon; fuel = DT;   total e- beam energy = 127 kJ;   laser energy = 127/0.52 = 244 kJ



beam excited from z=-15 to -10 um

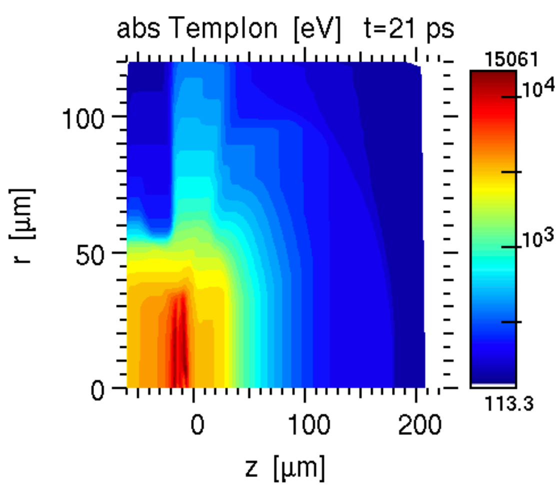


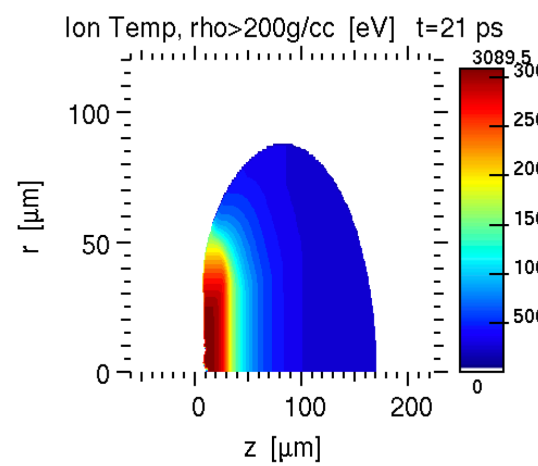
$$P = \int da \ \ I = I_0 A_{\mathrm{eff}}$$

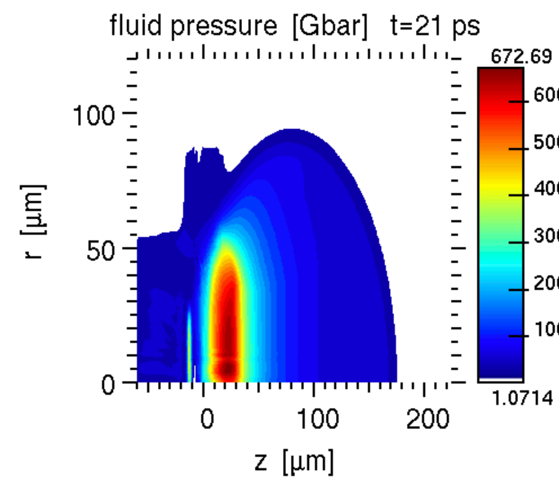
$$A_{\mathrm{eff}} = \int dr \ \ 2\pi r \ \ (I / I_0) = \pi r_{\mathrm{eff}}^{\ 2}$$

$$I_{\mathrm{beam}}(r) = I_0 \exp[-(r/30\mu\mathrm{m})^8]$$

$$\rightarrow r_{\mathrm{eff}} = 28.6 \ \ \mu\mathrm{m}$$

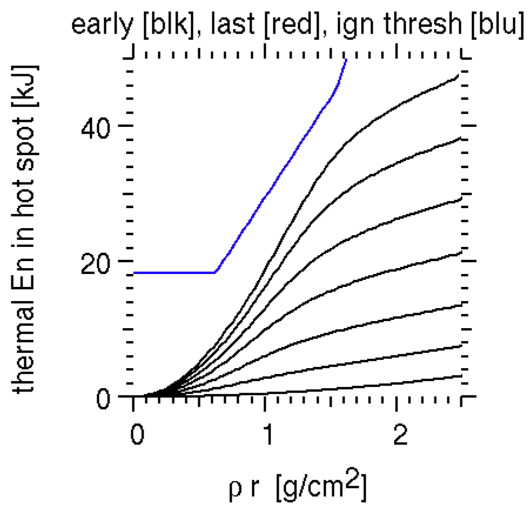


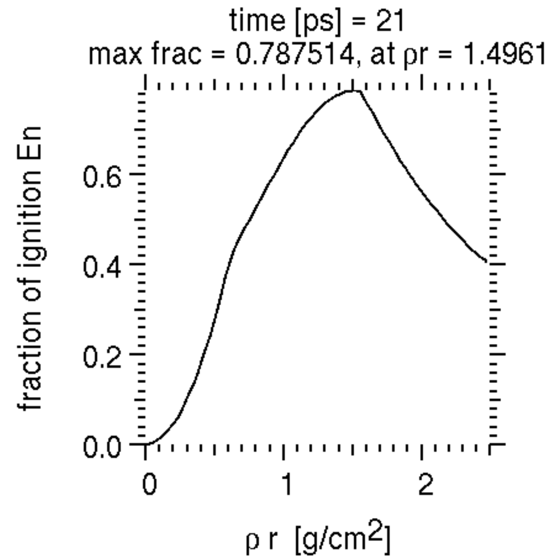




ign02: reached 79% of ignition condition w/ 127 kJ of beam energy (244 kJ laser); ign03 met condition w/ 185 kJ beam

ign02

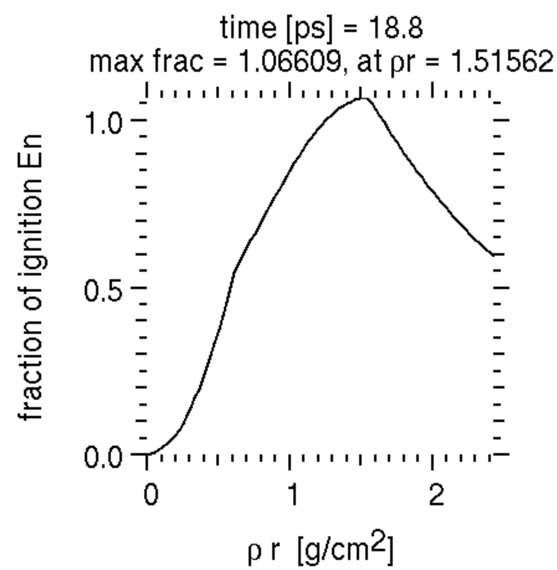




ign03: more beam en.: 185 kJ beam (356 kJ laser) added at 18.8ps, when we meet ignition condition

Have yet to:

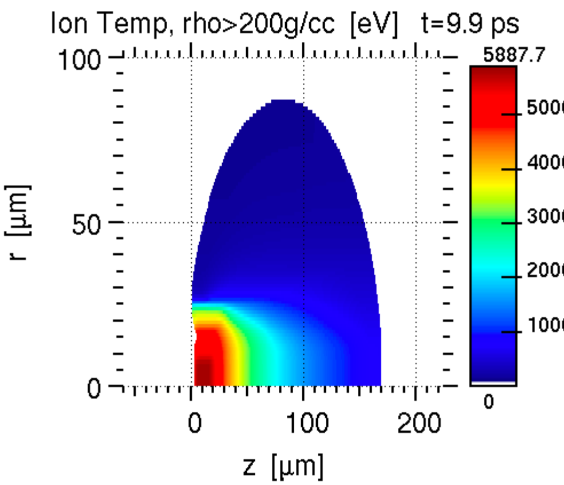
- vary spot size, standoff distance
- compare with Zuma
- try resistivity gradients

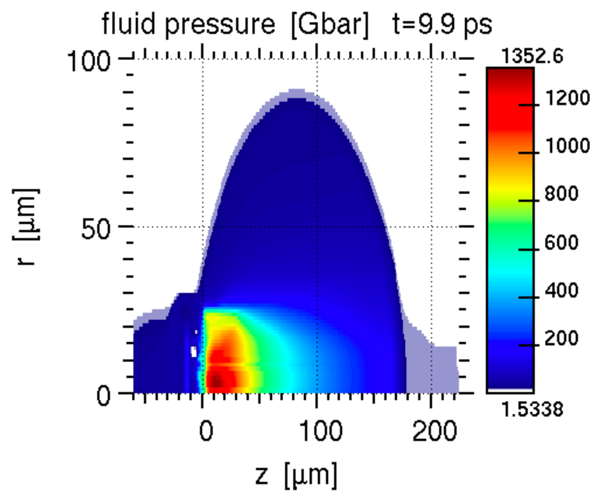


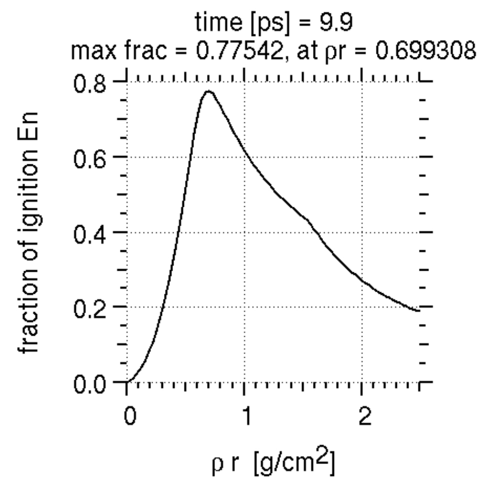
Results of HYDRA burn calculation on LSP output

- LSP run with artifically collimated source: $\Delta\theta$ = 20 deg (90 deg would match PSC).
- Beam intensity profile exp[-(r/21 um)^8] – smaller spot than previously.

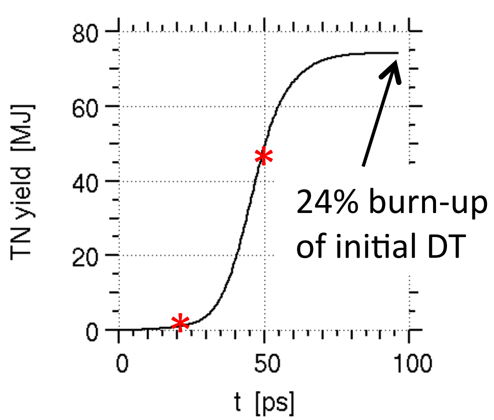
LSP conditions at t = 9.9 ps (73 kJ of e-beam energy added):

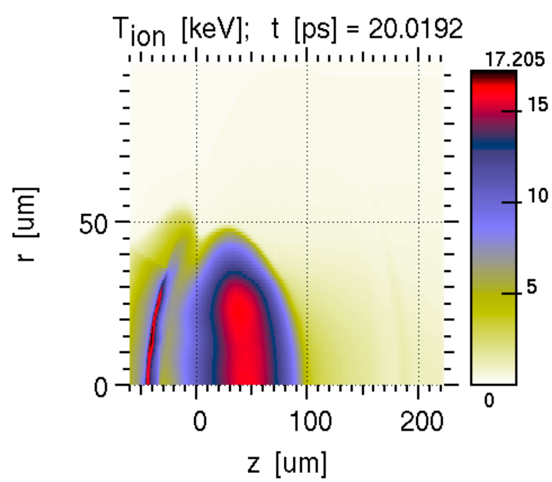


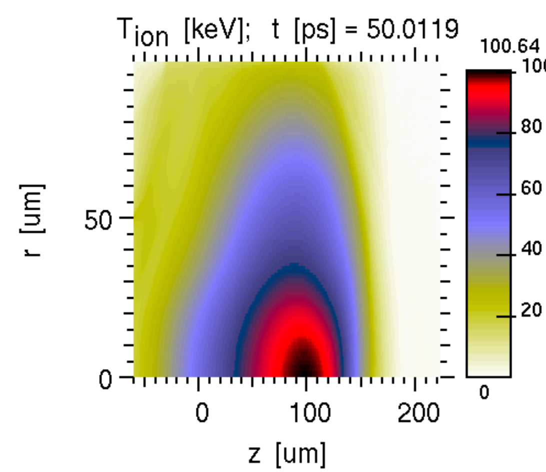




HYDRA run on these conditions didn't ignite, but doubling the temperature (overkill) does:







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 ρ*r = 1-1.5 g/cm^2 and temperatures ~ 4-5 keV.

- **LSP Transport modeling:** Ignition condition can be achieved, with no cone-fuel standoff, with green (527 nm) laser:
  - E_{beam} = 185 kJ for realistic $\Delta\theta$ = 90 deg. Does this large, ~3 keV hot spot burn?
  - E_{beam} ~ 73 kJ in 10 ps and $\Delta\theta$ = 20 deg. obtains 80% of ignition condition.
  - Doesn't ignite in Hydra, but doubling the temperature (probably overkill) does: burn-up fraction of 24%.

- **Magnetic collimation:** may reduce beam divergence, improve coupling.

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

Backup slides after here

LSP run source6: $\Delta\theta$ = 80 deg instead of 90 deg

e- energy in white box [Joules]: 14.9 PSC, 15.0 LSP. 0.5% error!
Avg. polar angle theta [deg]: 46.8 PSC, 47.2 LSP, 0.88% error.