LLNL-CONF-447431

The effects of electron divergence on the point design

D. J. Strozzi, A. J. Kemp, L. Divol, M. Tabak, M. M. Marinak, D. R. Welch, D. P. Grote, M. H. Key

August 4, 2010

Fusion Science Center Annual Meeting
Livermore, CA, United States
August 4, 2010 through August 6, 2010

The effects of electron divergence on the point design

D. J. Strozzi[1], A. J. Kemp[1], L. Divol[1], M. Tabak[1], M. M. Marinak[1], D. R. Welch[2], D. P. Grote[1], M. H. Key[1]

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FSC Meeting on Electron Divergence
5 August 2010

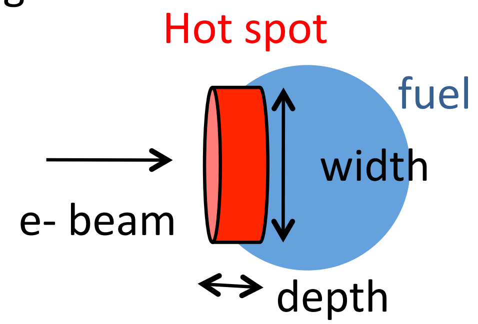
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Release No. LLNL-CONF-447431.

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)

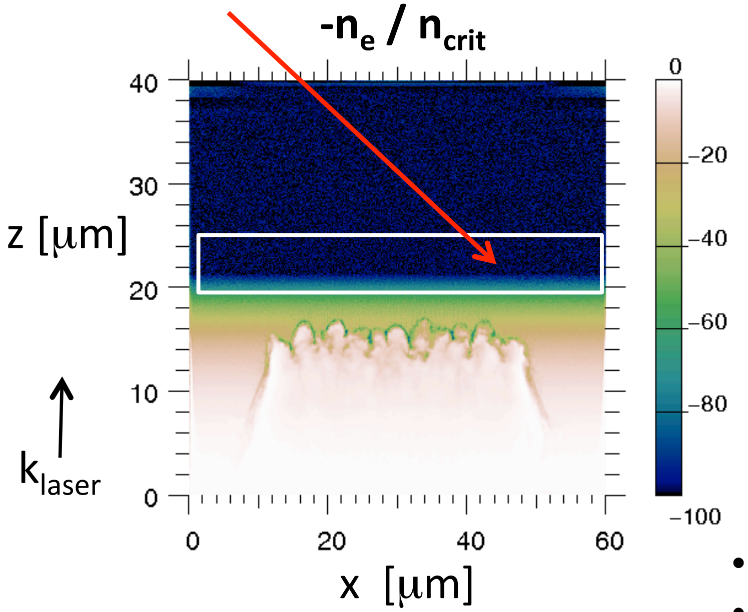
PSC run "3Dpre":

- 3D Cartesian, 1 μm wavelength.
- pre-plasma $n_e \sim \exp[z / 3.5\ \mu m]$.
- Peak dens = 100 n_{crit}. Data at time 365 fs.
- best focus: $I_{las}(r) = I_0 \exp[-(r/18.3\ um)^8]$
  I_0=1.37 E20 W/cm^2. T_{pond} = 4.63 MeV.

LSP run "source5":

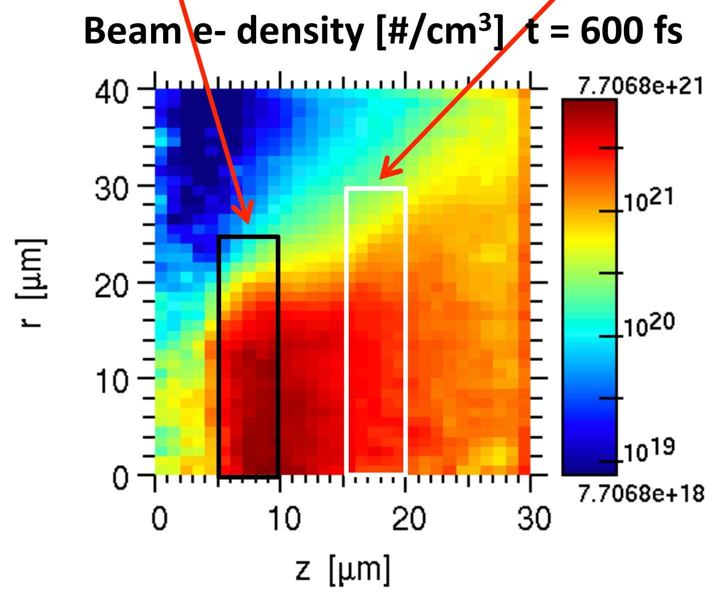
- 10 g/cc, 100 eV, Z=6 carbon.
- Beam radial profile same as laser intensity I_{las}.
- Forces from E/B fields included.
- No dE/dx or scattering since not in PSC run, and would be larger at LSP's high density.

"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

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

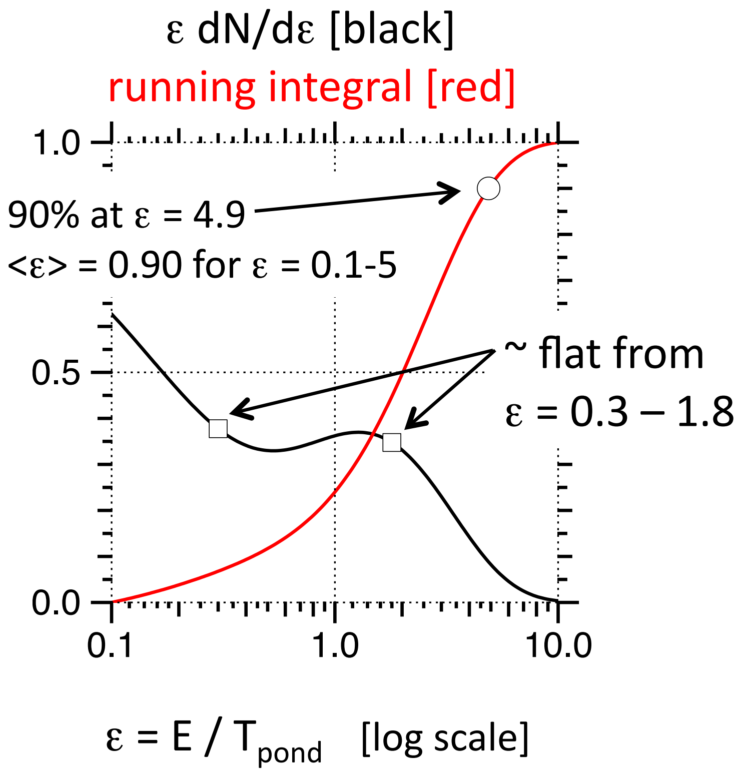
Note asymmetry in the two terms!

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

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

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

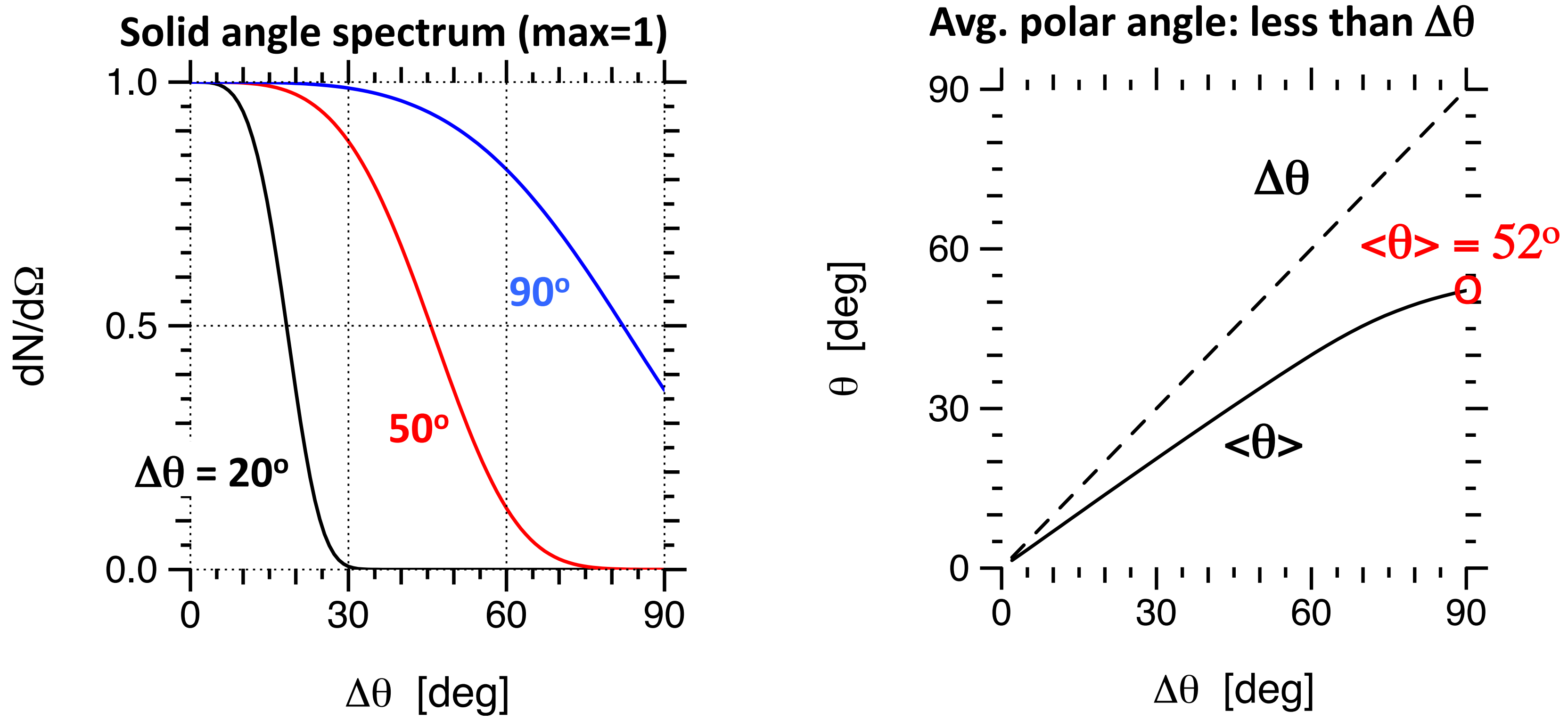
$$\tau_1 = 0.19 \qquad \tau_2 = 1.3 \qquad b_2 = \frac{n_2}{\tau_2} = 0.82$$



- 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

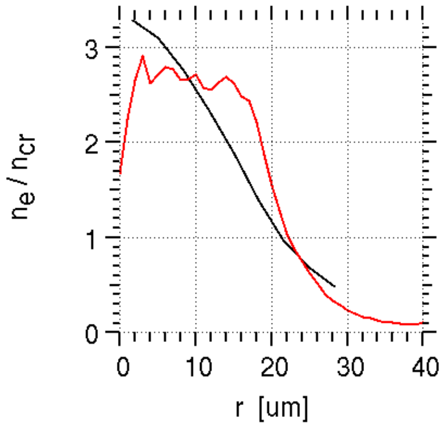
- “The opening angle” is ill-defined: should specify <θ>, θ_{rms}, θ enclosing 90% of e-, etc.
- “The intrinsic source” is also ill-defined: my goal is LSP black-box source for transport sims that replicates e- in PSC white box. Different questions (e.g. K-alpha spot size) have different answers.
- Only 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.

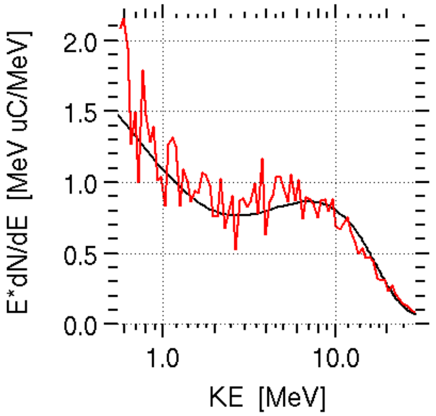
PSC (black) and LSP (red) e- in white boxes are similar – adequate for transport and design studies

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

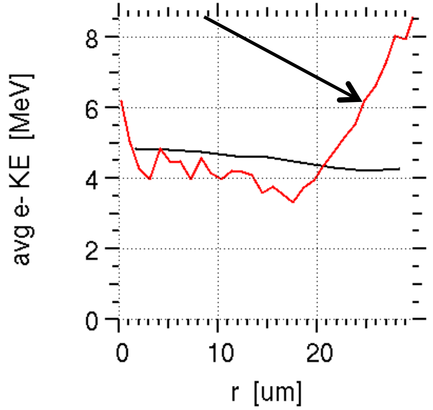
Avg. polar angle theta [deg]: 46.8 PSC, 48.6 LSP, 3.7% error. Smaller than 52 deg in source region.

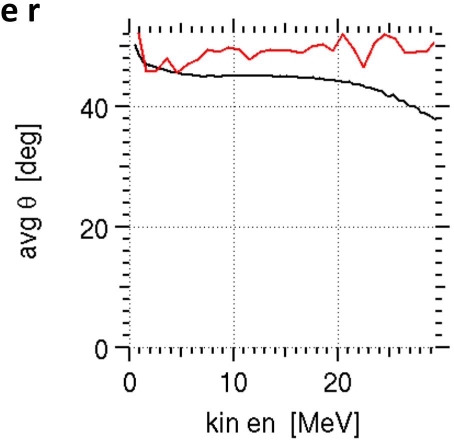
All LSP e-, not just some KE range

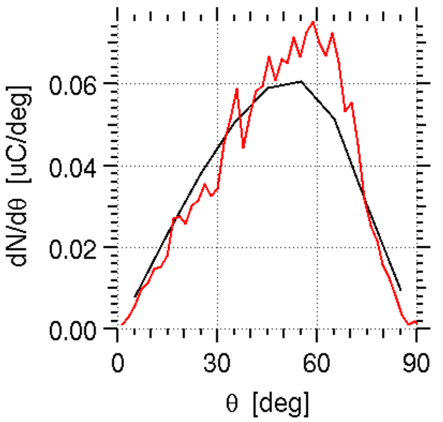




resistive B in LSP may deflect low-KE e-; density low at large r

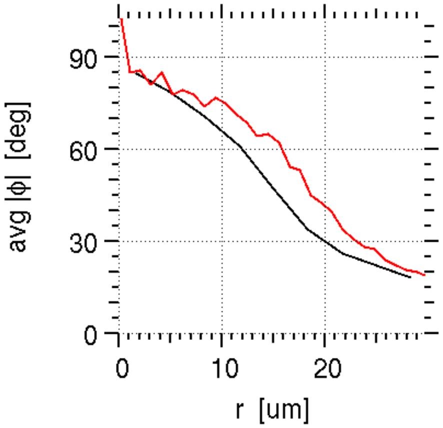


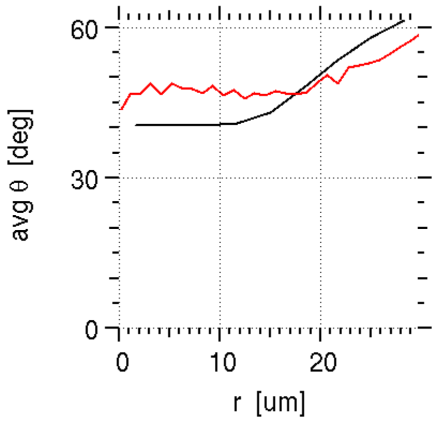




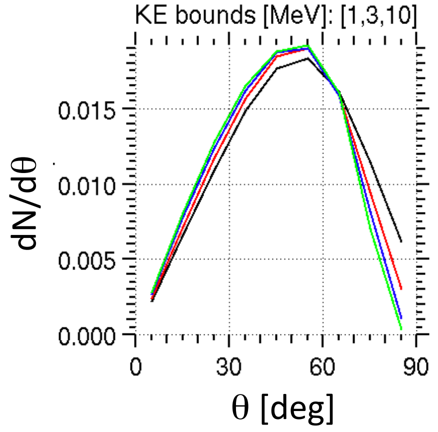
ϕ = angle b/t r and p, in xy plane[1]

small |ϕ| -> radial outward drift





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



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[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.

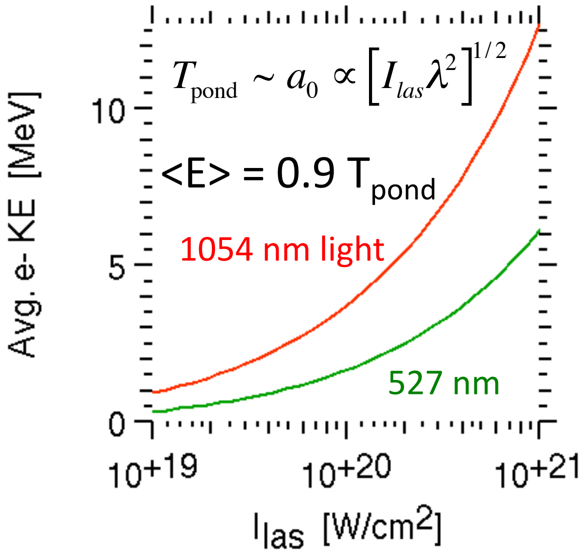
- **Electron source**

- **Width > depth ignition**

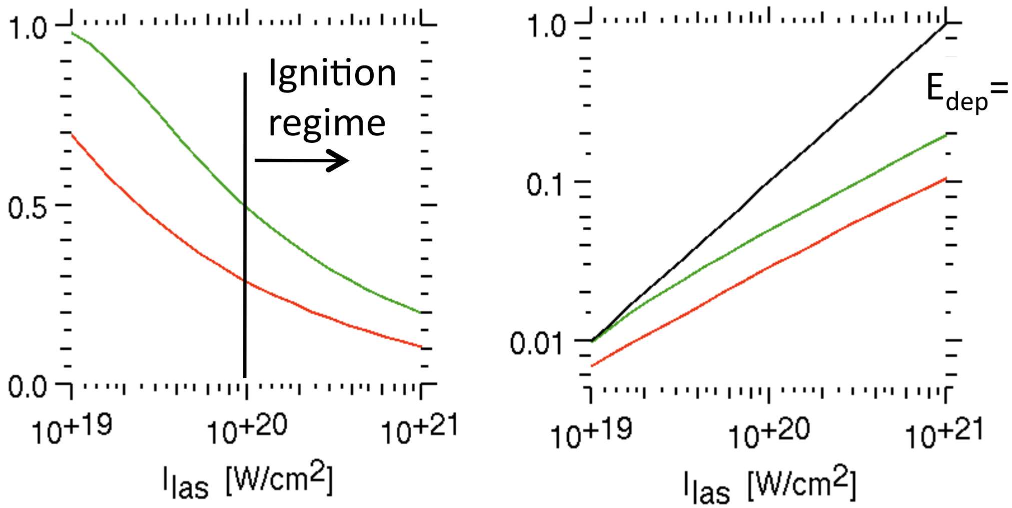
- **Ignition-scale transport simulations**

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

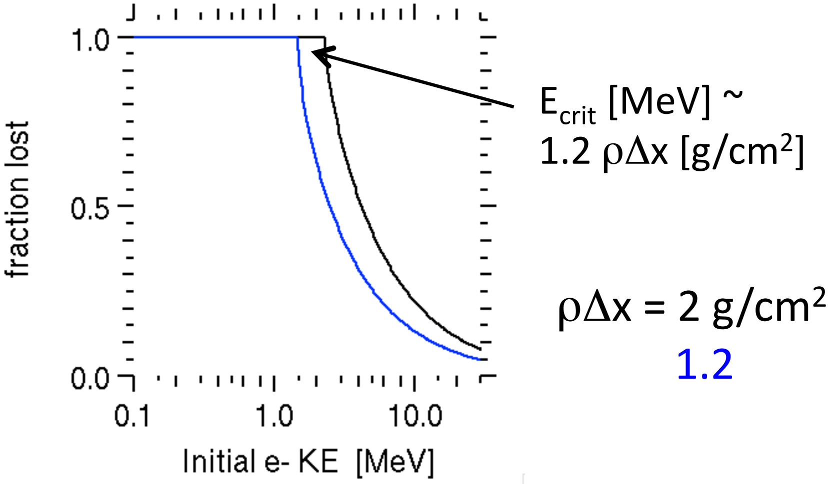


Energy deposited by 2-T spectrum in 1.2 g/cm^2 of 300 g/cm^3 DT


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-)



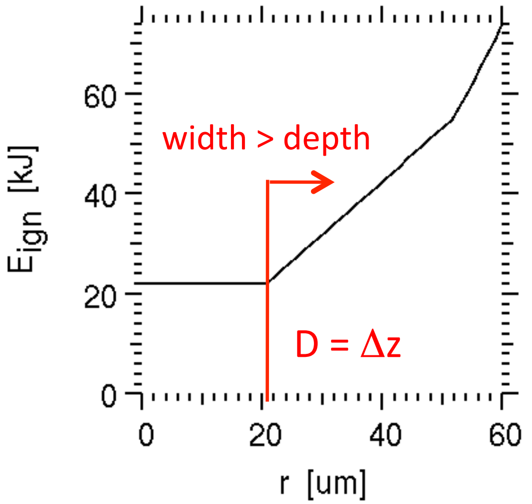
E_{crit} [MeV] ~ 1.2 $\rho\Delta x$ [g/cm^2]

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/cm^3, ρr>2 g/cm^2 – 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.

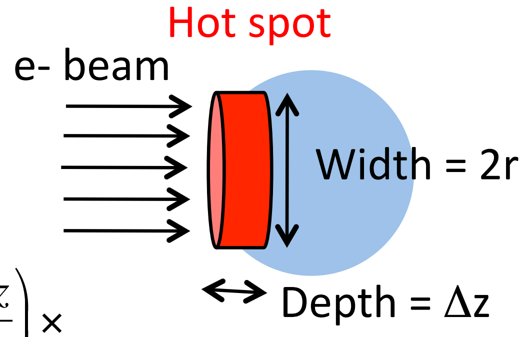
Ignition energy criterion
ρ = 300 g/cm^3 DT, ρΔz = 1.2



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

width > depth penalty

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



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

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

ρX 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.

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[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.

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

- **Electron source**

- **Width > depth ignition**

- **Ignition-scale transport simulations**

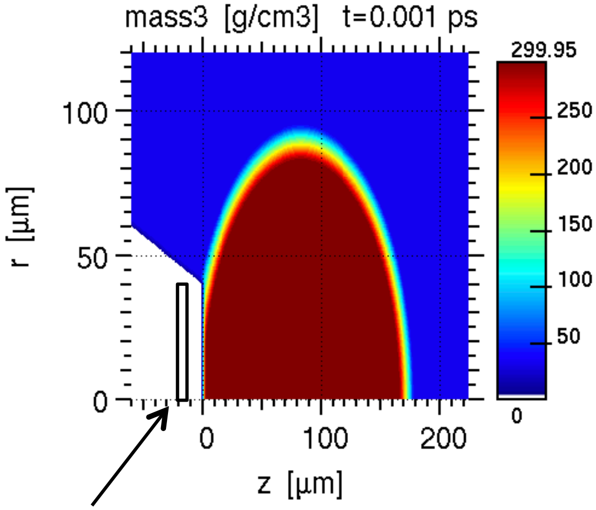
LSP[1] direct-implicit PIC code for transport modeling

- 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.

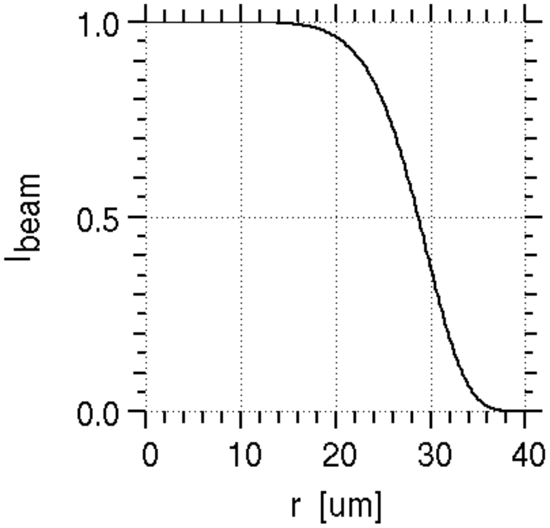
[1] D. R. Welch, D. V. Rose, M. E. Cuneo, R. B. Campbell, T. A. Mehlhorn, Phys. Plasmas 13, 063105 (2006)

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

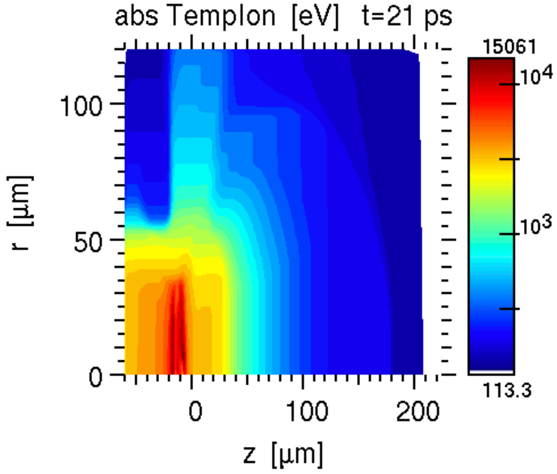


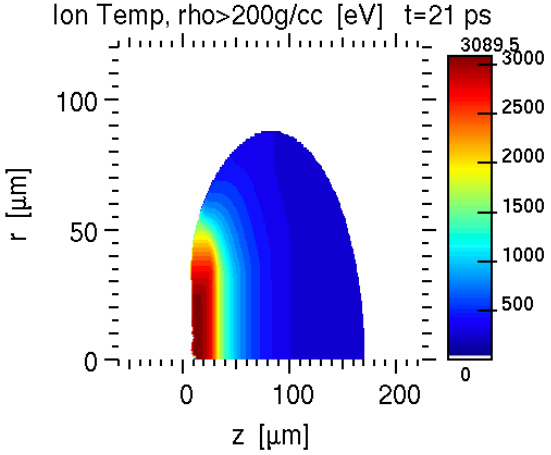
$$P = \int da \;\; I = I_0 A_{\rm eff}$$

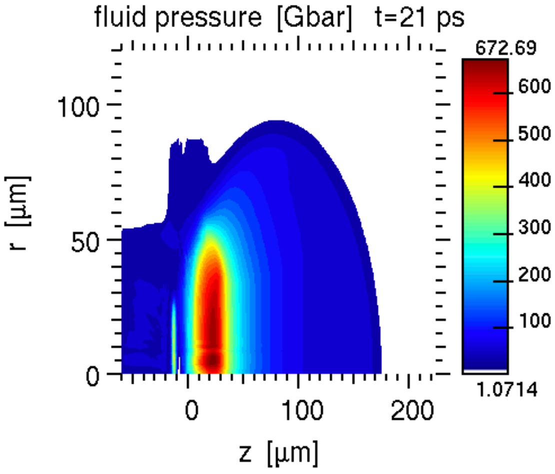
$$A_{\rm eff} = \int dr \;\; 2\pi r \;\; (I/I_0) = \pi r_{\rm eff}^2$$

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

$$\rightarrow r_{\rm eff} = 28.6 \;\; \mu{\rm m}$$

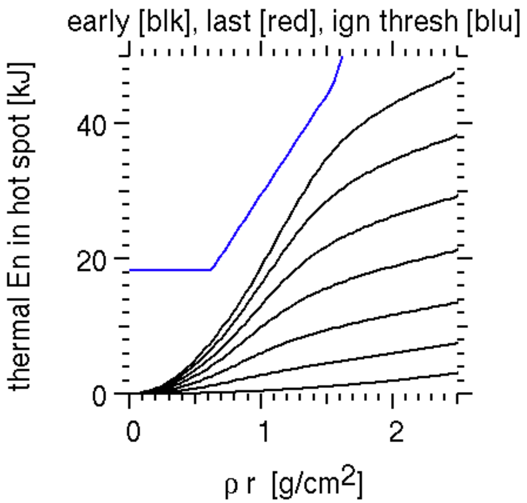


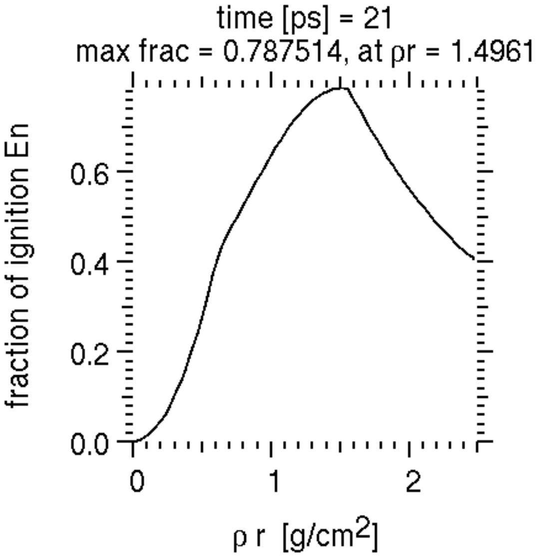




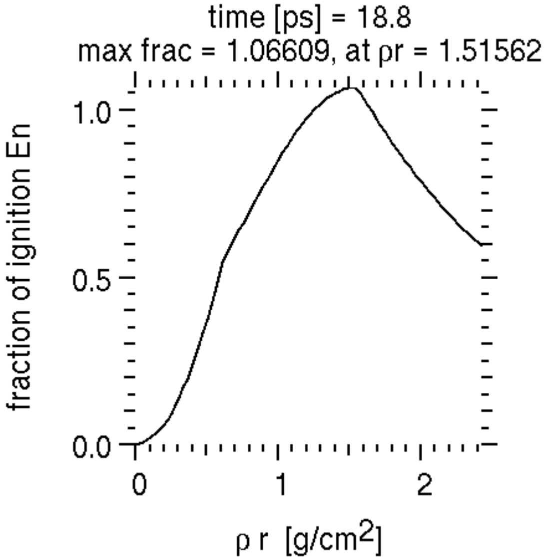
ign02: reached 79% of ignition condition w/ 127 kJ of beam energy (244 kJ laser); ign03 met condition w/ 185 kJ beam

ign02





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



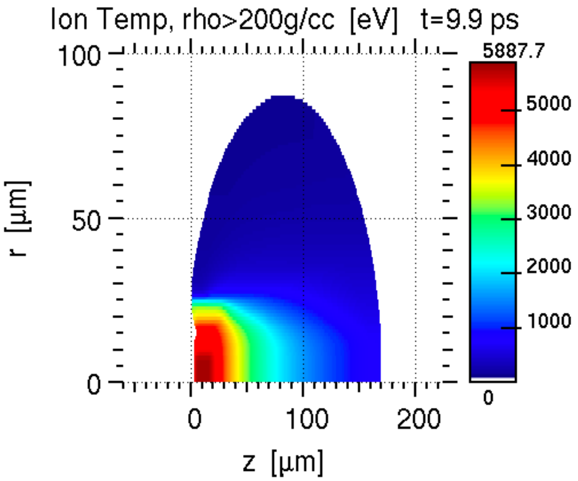
Have yet to:

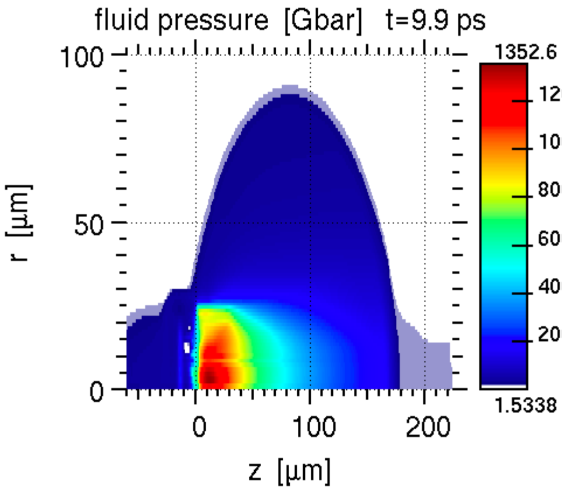
- vary spot size, standoff distance
- compare with Zuma
- try resistivity gradients

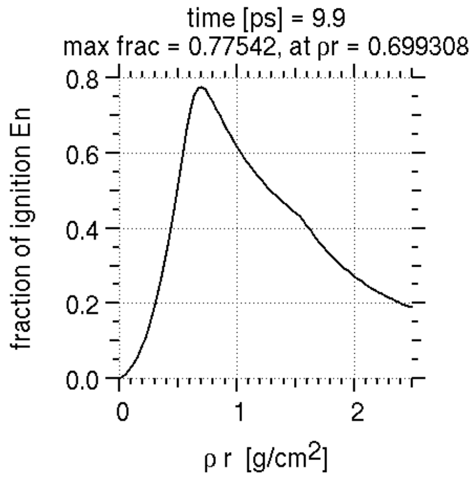
Results of HYDRA burn calculation on LSP output

- 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.

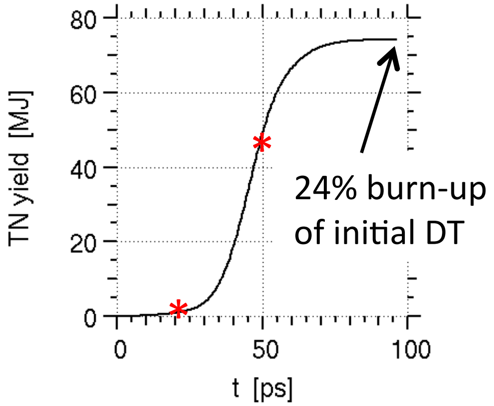
LSP conditions at t = 9.9 ps (73 kJ of e-beam energy added):



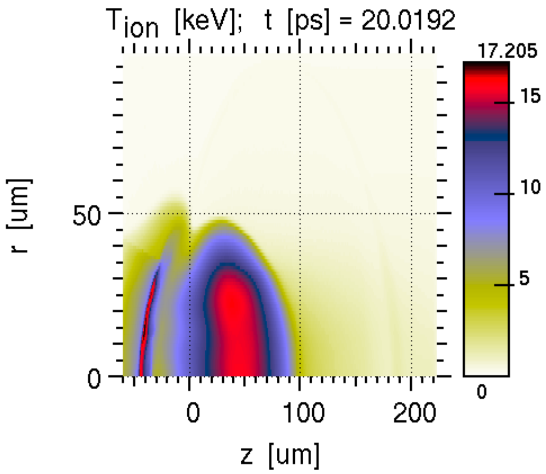


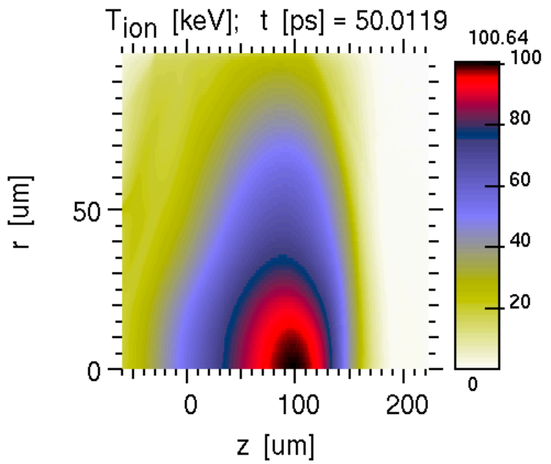


HYDRA run on these conditions didn't ignite, but doubling the temperature (overkill) does:



24% burn-up of initial DT





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.