Electron Transport Simulations for Fast Ignition on NIF

D. J. Strozzi, D. P. Grote, M. Tabak, R. P. J. Town, A. J. Kemp
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550, USA

Poster 3.10.017
IFSA 2009 Meeting
San Francisco, CA, USA
9 September 2009

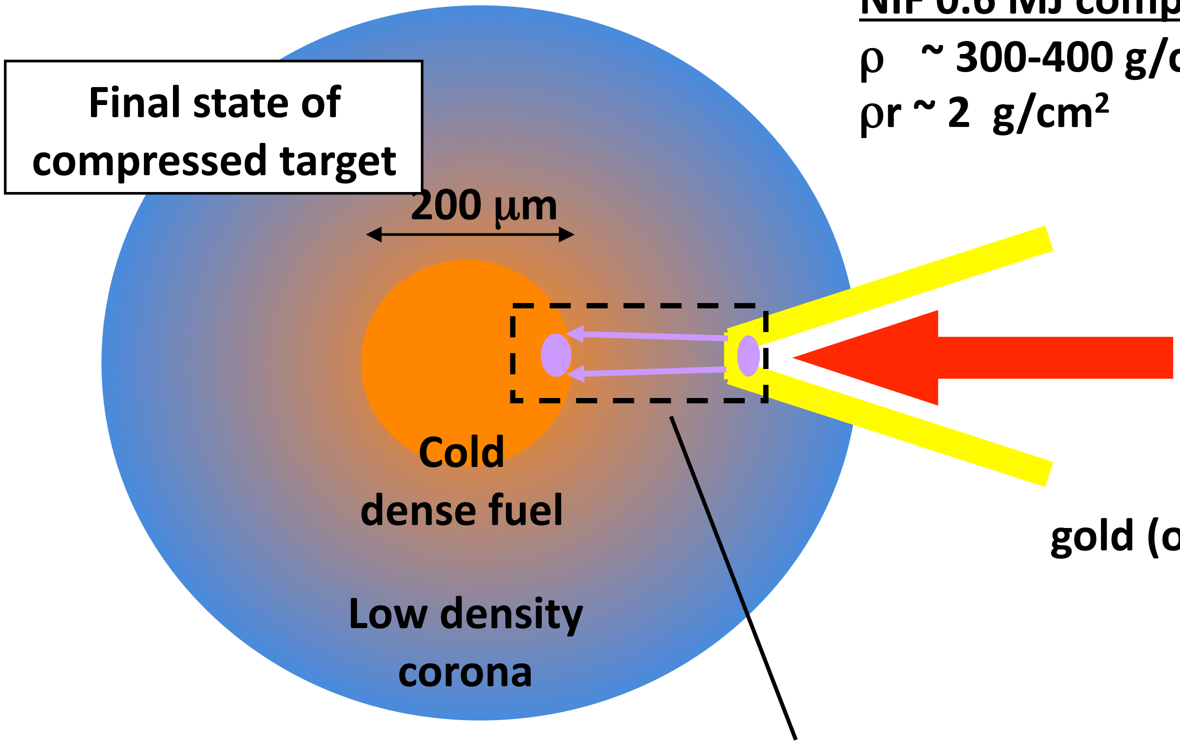
Fusion Energy Program
Physics Division, Physical and Life Sciences Directorate
Lawrence Livermore National Laboratory

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.
Release number: LLNL-POST-416536

Summary: LSP hybrid-PIC code used for "core" transport; role of B fields, materials, beam distribution explored

- Overview of fast ignition and our modeling approach.
- Fast electron energy loss and angular scattering: algorithm and formulas.
- Characterizing explicit PIC electron source: energy and angular distributions.
- Results on a NIF-ARC toy problem: role of B field, beam characteristics, background materials.

Fast ignition conditions



Final state of compressed target

200 μm

Cold dense fuel

Low density corona

NIF 0.6 MJ compression

ρ ~ 300-400 g/cm^3

ρr ~ 2 g/cm^2

NIF ARC Quad

9kJ ,5ps

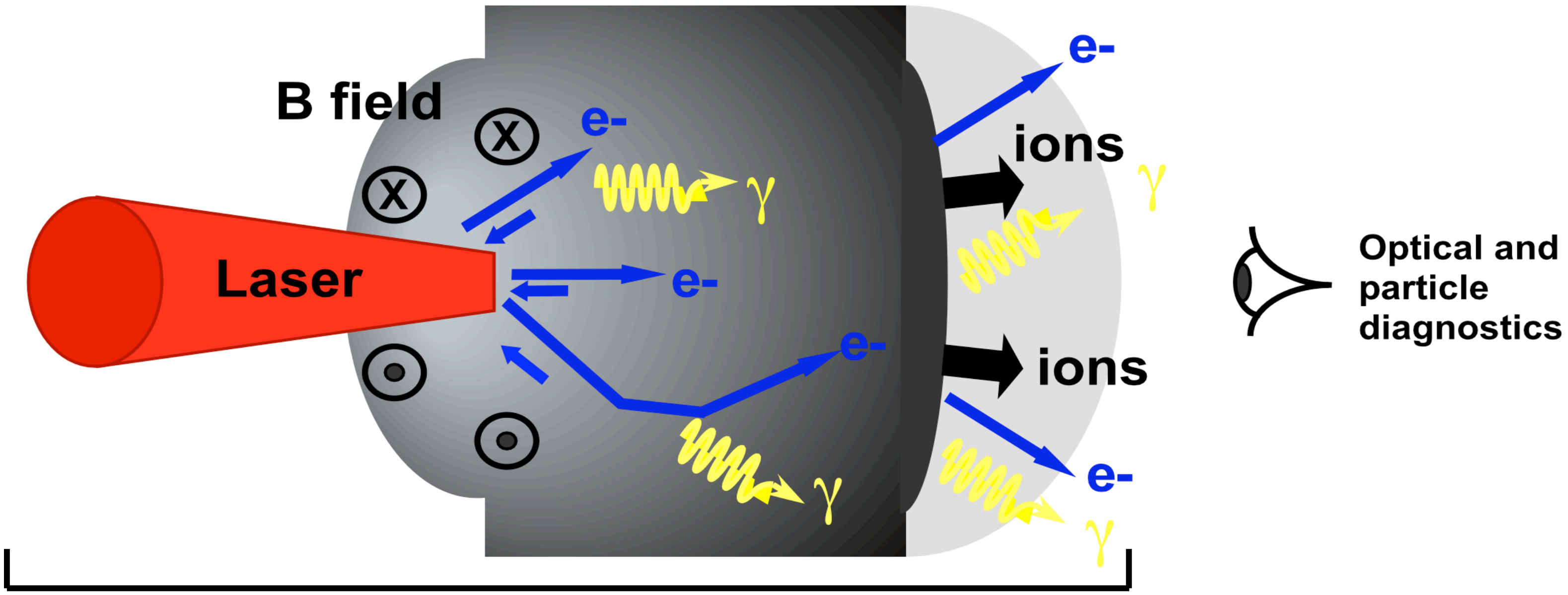
40 μm focal spot (~ FWHM)

Coupling expt, not ignition

gold (or other mid/high Z) cone

“Transport region:” ~50-100 μm;
we wish to minimize standoff to fuel.

We use rad-hydro, explicit-PIC and hybrid-PIC codes for FI design studies



HYDRA / LASNEX: hydro evolution (ns / mm)

“LPI” **n_e ~ 10-100 n_{crit}** **“Transport”**

Hot e- generation (ps / 100μm):

PSC: A. Kemp, L. Divol, B. Cohen
Z3: B. Lasinski, B. Langdon, C. H. Still

Hot e- propagation and deposition (10ps /100μm):

LSP: D. Strozzi, M. Tabak, R. Town, D. Grote
Hybrid PSC
ZUMA: D. Larson

Hybrid PIC code LSP[1] can model larger, more dense plasmas for longer times than explicit PIC

- We run LSP for “core transport” with:
  - An implicit particle push and electromagnetic field solution:

    Numerically damps fast oscillations like light waves and plasma waves when

    $\Delta t \gg \omega_{plasma}^{-1}, \omega_{light}^{-1}$; $\Delta x \gg \lambda_{Debye}, \lambda_{light}$.
  - Hybrid treatment: Background plasma of “fluid” particles (carry temperature, internal energy).
  - Inter-and intra-species collisions with Spitzer, Lee-More-Desjarlais, or other rates.
  - Fast electron stopping and angular scattering formulas of J. R. Davies.
  - R-Z cylindrical geometry.
  - Fixed ionization states, ideal gas EOS.

- We are currently working on:
  - Fast electron collisions with bound electrons.
  - Time- and space-dependent ionization.
  - Non-ideal EOS.

---

[1] D. R. Welch, et al, Phys. Plasmas 13, 063105 (2006).

“Loss” of fast electrons off background plasma: grid-based algorithm, energy loss and angular scattering included

- Grid-based algorithm: test particles off field particles; field density, drift, temperature found on each spatial grid cell.
- Polar momentum coordinates: like Lemons[2]; Manheimer[1] presented similar method in Cartesians with drag and diffusion.
- Collisions of background plasma off fast electrons: updating background energy and momentum in each cell to conserve what the fast electrons lost.

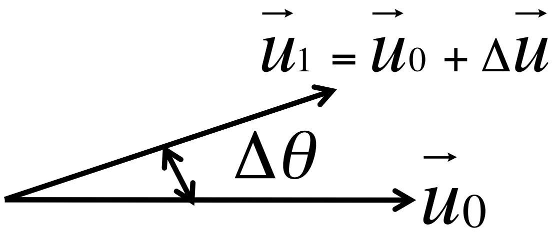
Momentum change in one timestep:

$$\Delta u = \overbrace{-\nu_\beta \Delta t}^{\text{deterministic slowing down}} \quad + \quad \overbrace{[\nu_\delta \Delta t]^{1/2} N_u}^{\text{stochastic heating (zero for cold bkgd)}}$$

$$\Delta\theta = [\nu_\gamma \Delta t]^{1/2} N_\theta \longleftarrow \text{stochastic angular scattering}$$

$$\Delta\phi = 2\pi \cdot U_\phi \longleftarrow \text{random azimuth}$$

N = normal deviate, mean 0 variance 1
U = uniform deviate from 0 to 1



$\vec{u} = \gamma\vec{\beta}$ in drift frame

1. W. Manheimer et al, Journ. Comp. Phys. **138**, 563 (1997); 2. Lemons et al., Journ. Comp. Phys., **228**, 1391 (2009).

Electron energy loss calculation of J. R. Davies: Finding "log lambda"

- Fast electrons lose energy to *electrons*, not ions.

$$\frac{dE}{dx} = -n_e \left[\int_0^{W_c} + \int_{W_c}^{\infty} \right] dW \, \frac{d\sigma}{dW} W$$

W = energy transfer.

The cutoff energy transfer W_c appears in logarithmic terms in both results, but cancels when we add!

low-energy, long range:
motion in a dielectric
(e.g. Langmuir-wave emission)

high-energy, short range:
binary collisions (Møller scattering)

$$\frac{d\gamma}{dx} = -4\pi r_e^2 \frac{n_e}{\beta^2} L_{stop}$$

$$L_{stop} = \ln\left[\frac{m_e c^2}{\hbar\omega_p}\beta[\gamma-1]^{1/2}\right] + \frac{9}{16} + \frac{\ln 2 + 1/8}{\gamma}\left(\frac{1}{2\gamma} - 1\right)$$

$$\omega_p = \left[n_e e^2/\varepsilon_0 m_e\right]^{1/2} = \text{plasma frequency}$$

This is for free e-; for bound e-, $\hbar\omega_p \to \hbar\langle\omega\rangle = I$ "excitation energy"

Range: $$\Delta\gamma = -f(n_e,\gamma)\cdot n_e \Delta x = -f \cdot \frac{\bar{Z}}{\bar{A} m_p} \rho \Delta x \qquad f = 4\pi r_e^2 \frac{L_{stop}}{\beta^2}$$

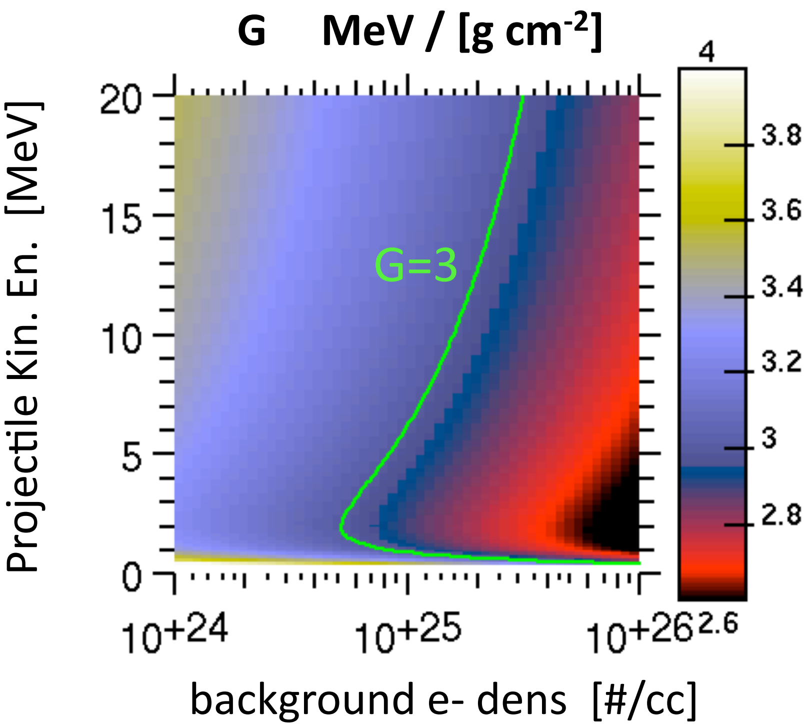
1. J. R. Davies, invited talk, APS DPP 2008.
2. S. Atzeni et al., Plasma Phys. Contol. Fusion **51**, 015016 (2009).
3. International Commission on Radiation Units and Measruements (ICRU) Report 37 (1984) .

Electron energy loss: off electrons, not ions

$$\Delta E\ [\mathrm{MeV}] = \frac{\overline{\mathrm{Z}}}{\overline{\mathrm{A}}} \cdot G \cdot \rho \Delta x\ [\mathrm{g/cm^2}]$$

$$G = 4\pi r_e^{\,2} \frac{m_e c^2}{m_p} \frac{L_{stop}}{\beta^2}$$

- G blows up at low energy due to $1/\beta^2$.
- Other than that, varies weakly.



$$L_{stop} = \ln\left[\frac{m_e c^2}{\hbar\omega_p}\beta[\gamma-1]^{1/2}\right] + \frac{9}{16} + \frac{\ln 2 + 1/8}{\gamma}\left(\frac{1}{2\gamma} - 1\right)$$

1. J. R. Davies, invited talk, APS DPP 2008;
2. S. Atzeni et al., Plasma Phys. Contol. Fusion **51**, 015016 (2009);
3. International Commission on Radiation Units and Measruements (ICRU) Report 37 (1984)

Angular scattering: fast electrons off electrons and ions

$$\text{RMS}:\ \left[\left\langle \Delta\theta\right\rangle^2\right]^{1/2} = F_\theta \cdot \left[\frac{\overline{Z}}{\overline{A}}\rho\Delta s\right]^{1/2} \sim \left[1+Z_{eff}\right]^{1/2}$$

- Weak dependence on plasma conditions.
- Grows like mad as energy decreases.

$$F_\theta{}^2 = \frac{8\pi r_e{}^2}{\gamma^2\beta^4 m_p}\left(L_{sc,\,e} + Z_{eff}L_{sc,\,I}\right)$$

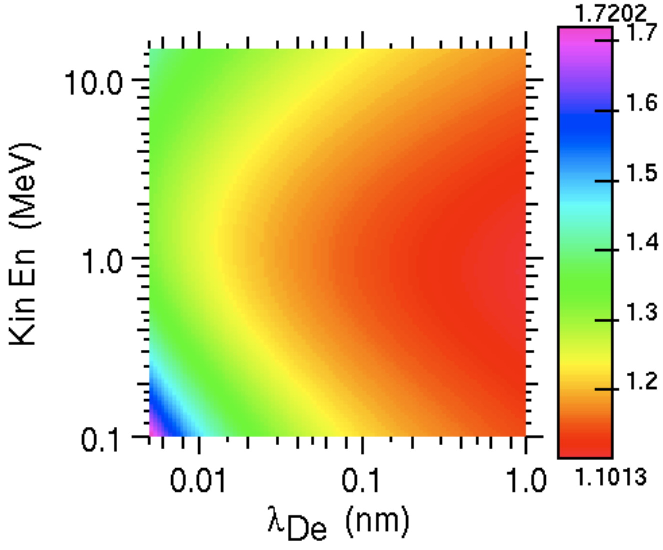
$$L_{sc,\,e} = \ln\Lambda - \tfrac{1}{2}(1+\ln[2\gamma+6]) \qquad \text{electrons}$$

$$L_{sc,\,I} = \ln\Lambda - \tfrac{1}{2}(1+\beta^2) \qquad \text{ions}$$

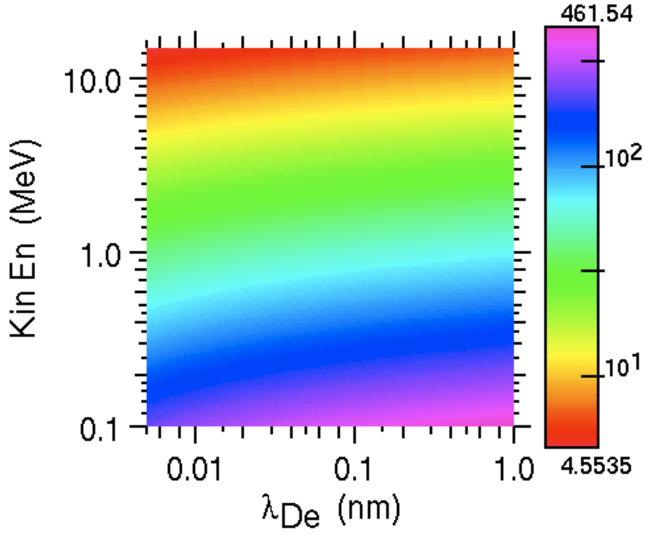
$$\Lambda = 2\lambda_{De}\frac{m_e c}{\hbar}\gamma\beta \sim \frac{\lambda_{De}}{\lambda_{deBroglie}}$$

$$\lambda_{De} = \text{bkgd e - Debye length}$$

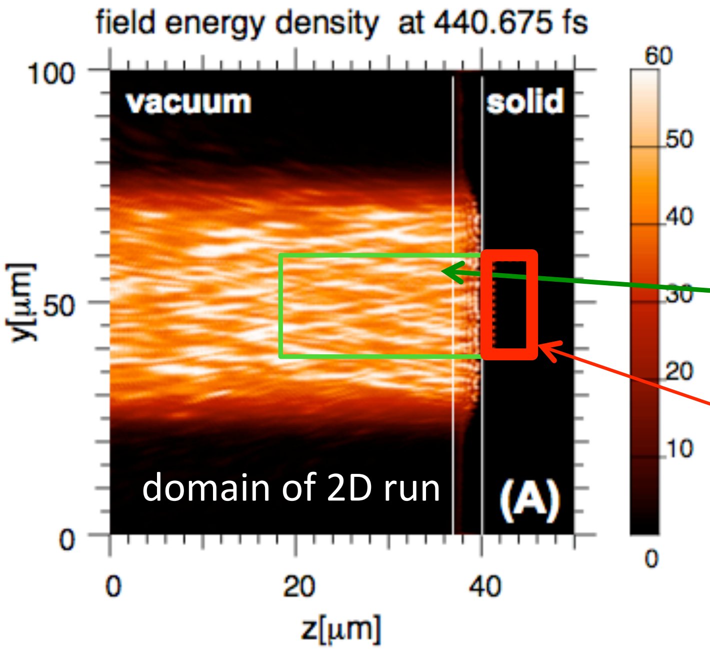
$L_{sc,i}$ / $L_{sc,e}$ (comparable)

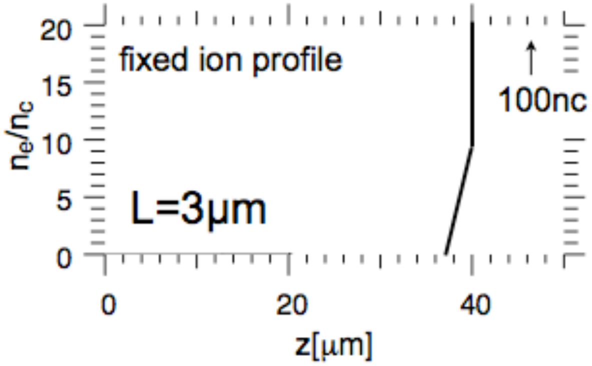


F_θ , Z_{eff}=1 [deg • $(cm^2/g)^{1/2}$]



Electron beam source distribution from a 3D explicit PIC calculation by A. J. Kemp





Run ‘point 3.4’:

- 3D run over small volume
- Laser linearly polarized in y
- Immobile ions – no profile modification
- Peak laser intensity 5E19 W/cm^2

3D run domain

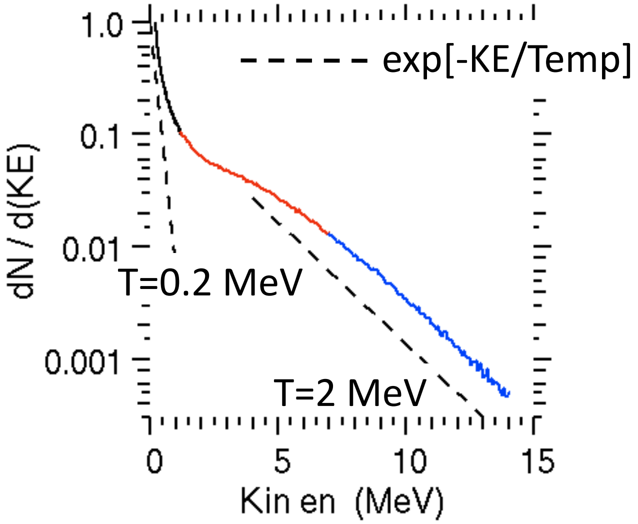
We select all electrons:

- In red spatial box (laser gone by then)
- Kinetic energy between 0.2 and 14 MeV
  (low energy e- stopped before transport region)
- Moving forward in z.

Run “point 3.4”

Kemp PIC run electron source: “two-temperature” energy spectrum; transversely somewhat isotropic

Number Distribution

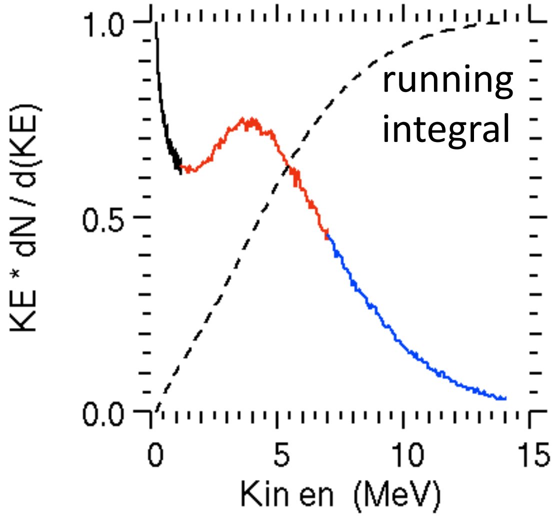


0.2-1.2 MeV

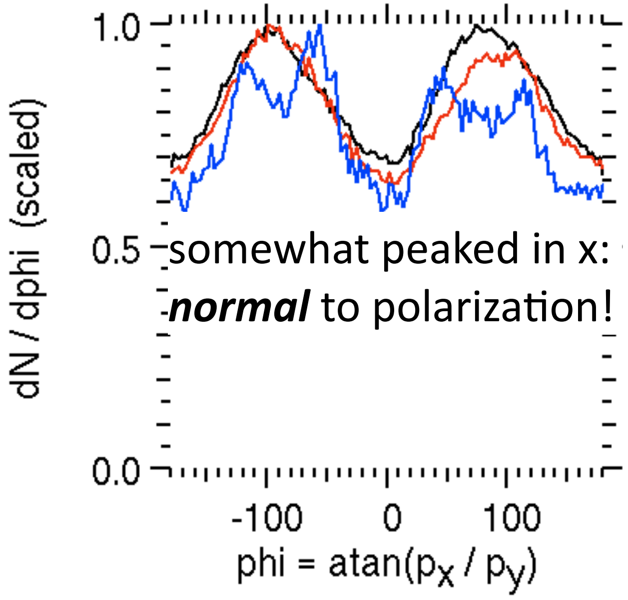
1.2 – 7 MeV

7 – 14 MeV

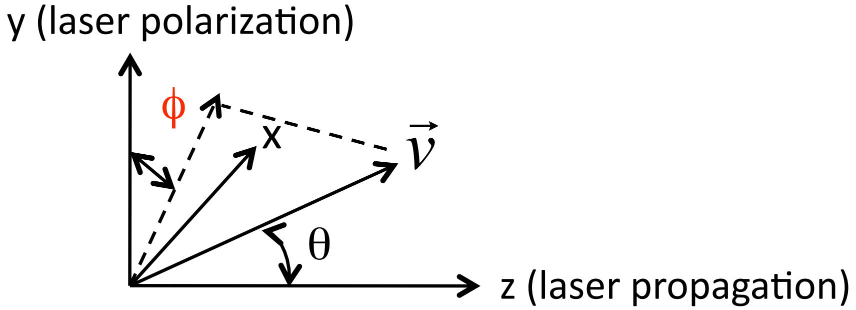
Energy Distribution



Transverse distribution similar in the 3 energy bins



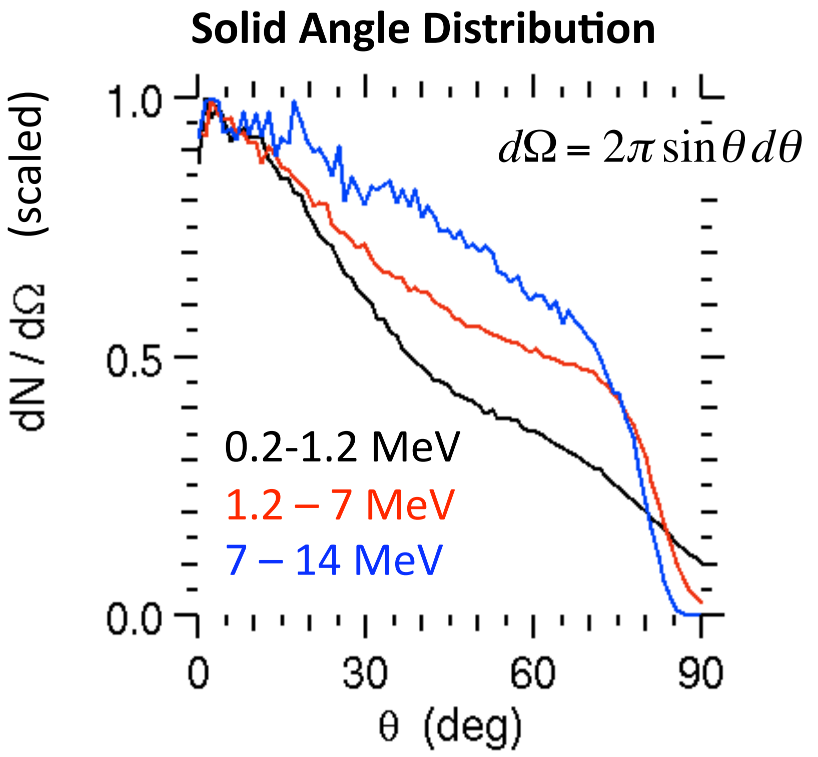
somewhat peaked in x: ***normal*** to polarization!



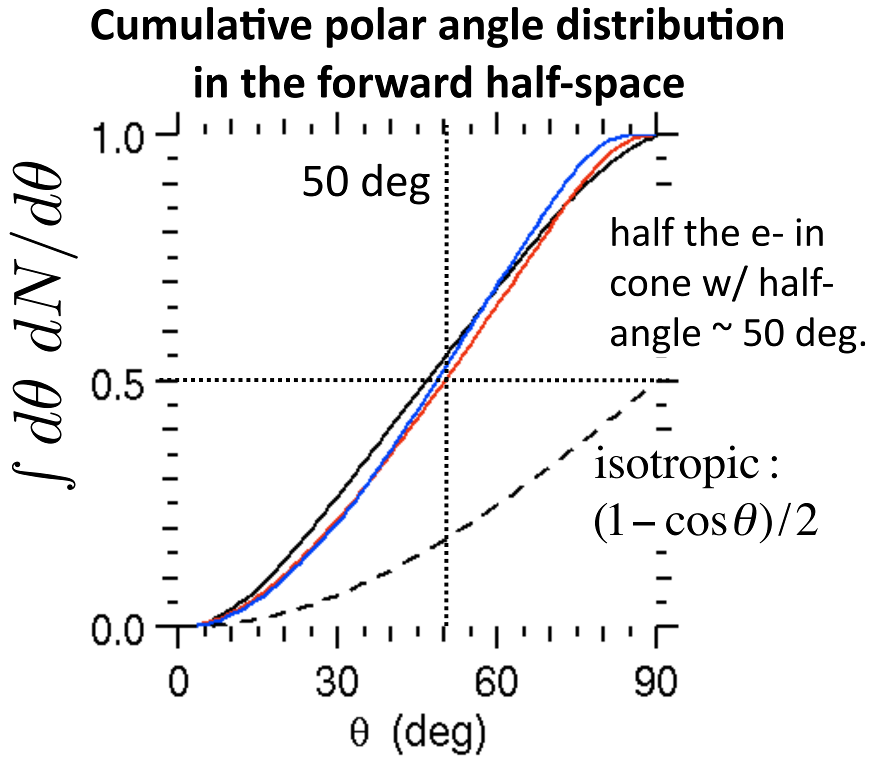
Cylindrical R-Z LSP simulations treat distribution as transversely isotropic.

Run “point 3.4”

Electron source: Angular spectrum fairly broad


Solid Angle Distribution

$d\Omega = 2\pi \sin\theta \, d\theta$


Cumulative polar angle distribution in the forward half-space

half the e- in cone w/ half-angle ~ 50 deg.

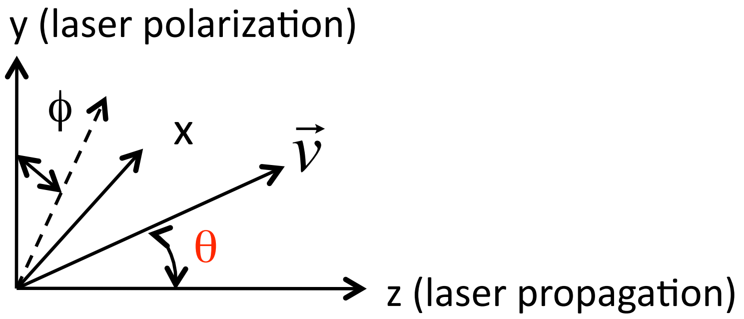
isotropic : $(1-\cos\theta)/2$

- In LSP, we write the electron source as a sum of a function of energy times one of angle:

$$\boxed{f(E,\theta) = \sum_{i=1}^{3} f_{E,i}(E) f_{\theta,i}(\theta)}$$

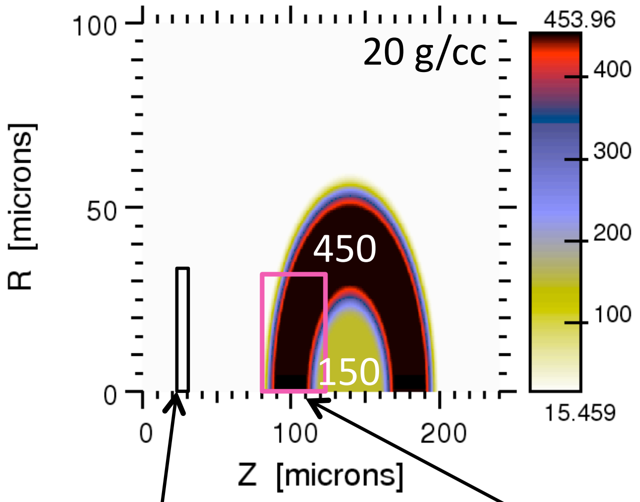
i = for each energy bin

- We can use energy and angle spectra taken from PIC.

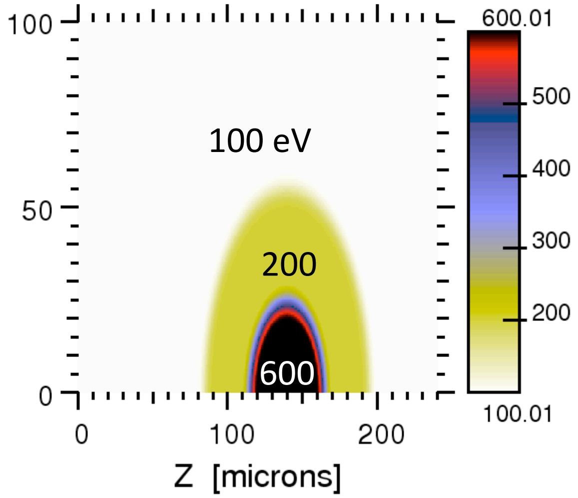


NIF-ARC "toy" problem

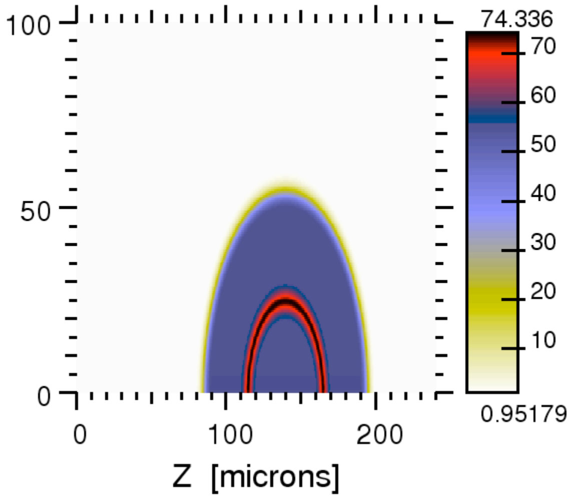
Initial mass density [g/cc]



Initial temperature [eV]



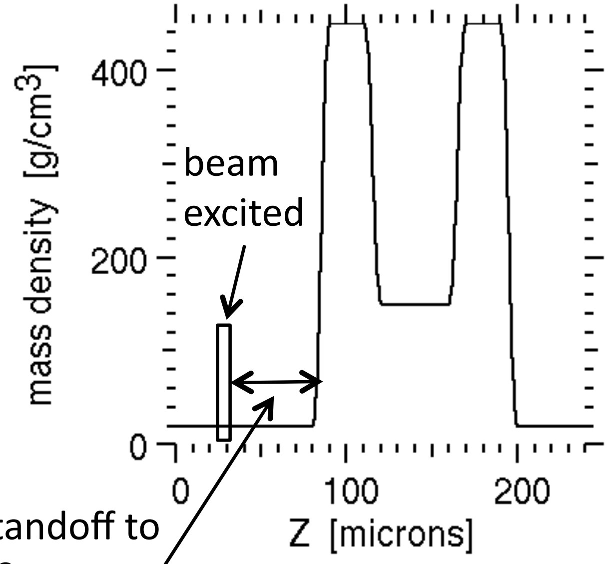
Initial pressure [Gbar]



beam excited:
z = 25-30 um

ignition region
(for diagnostics)

Initial mass density near r=0

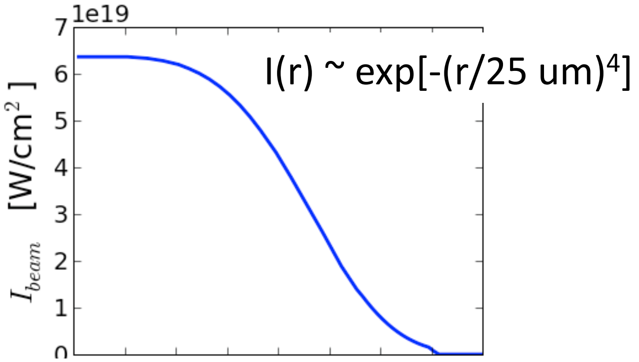


beam standoff to
fuel ~ 50 um

- Plastic CD (50-50 atomic) material, fully ionized; as considered for warm ARC expt's on coupling.
- High-Z cone (e.g., gold) not included; doing "core" transport.
- Little mass b/t beam and fuel. Work ongoing for a hydro design w/o high-pressure "jet" from core to cone (could trash cone).

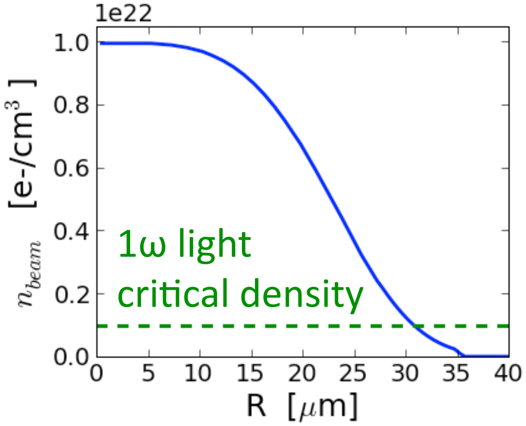
NIF-ARC run: electron beam source

Beam intensity

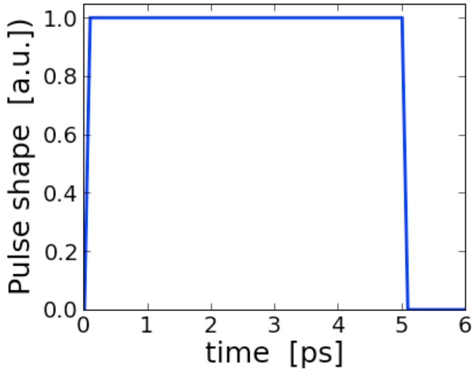


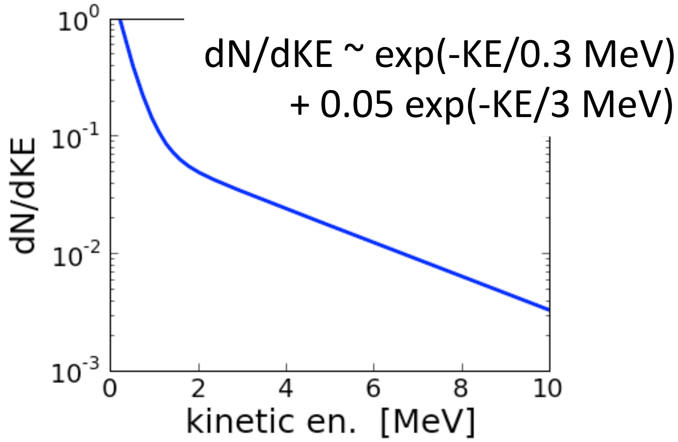
$I(r) \sim \exp[-(r/25\ \mathrm{um})^4]$

Beam density

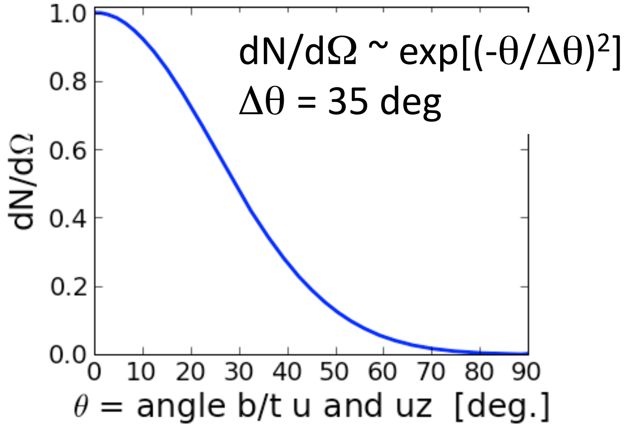


Pulse shape: flattop for 5 ps





$dN/dKE \sim \exp(-KE/0.3\ \mathrm{MeV}) + 0.05 \exp(-KE/3\ \mathrm{MeV})$

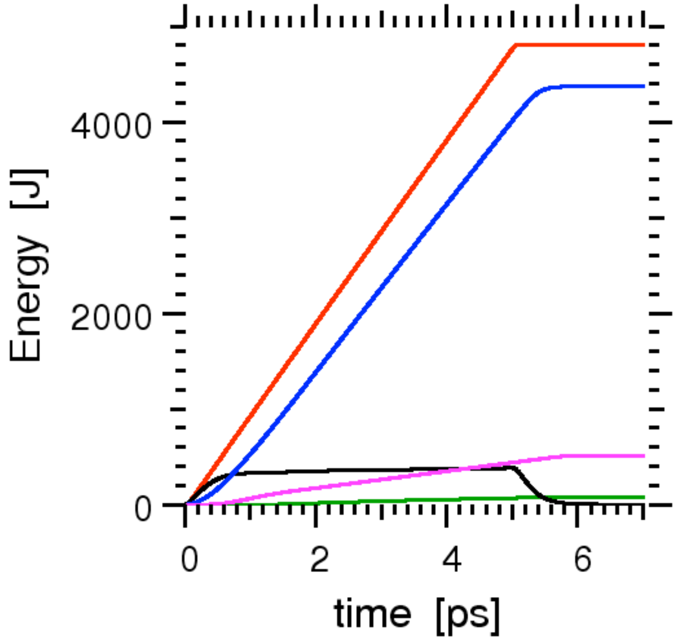


$dN/d\Omega \sim \exp[(-\theta/\Delta\theta)^2]$
$\Delta\theta$ = 35 deg

Total energy: 4.8 kJ Peak power: 960 TW

NIF-ARC should give 9 kJ laser energy; PIC results show ~ 50% conversion into energetic electrons is feasible.

NIF-ARC run: energetics



Total added beam energy (final: 4.8 kJ)

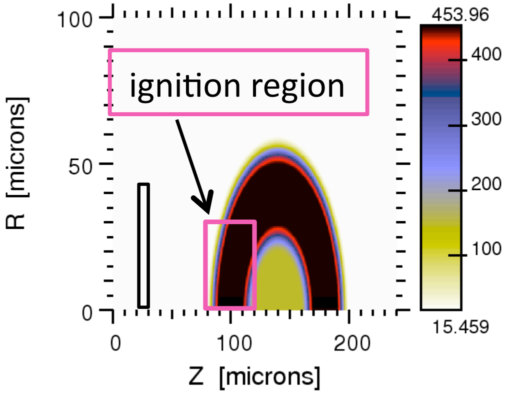
Change in background energy

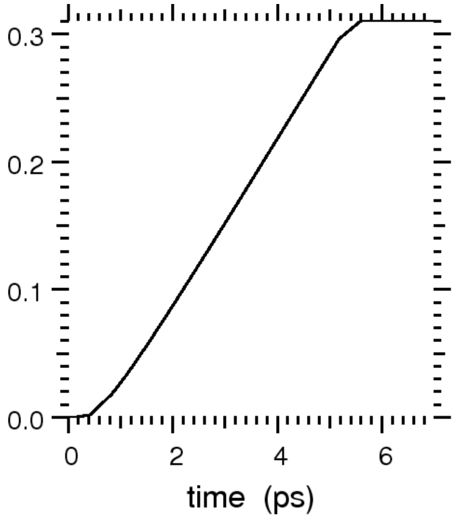
Beam energy escaping from boundaries

Beam energy (instantaneous)

Numerical error (small)

Energy(t) in ignition region / 4.8 kJ (final added energy)

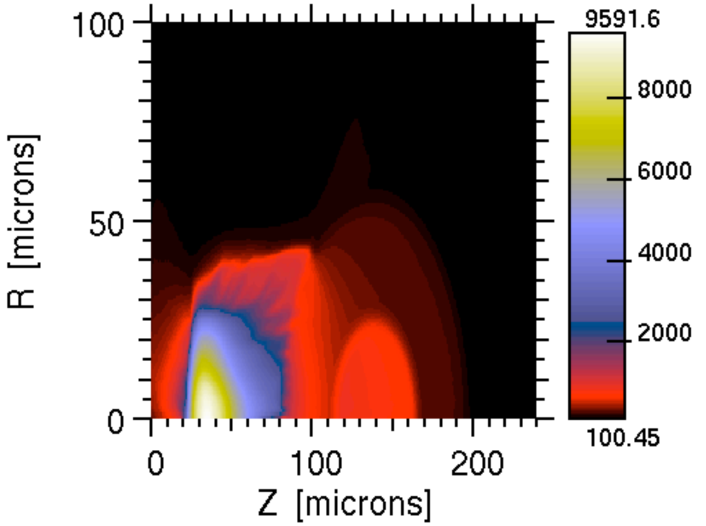




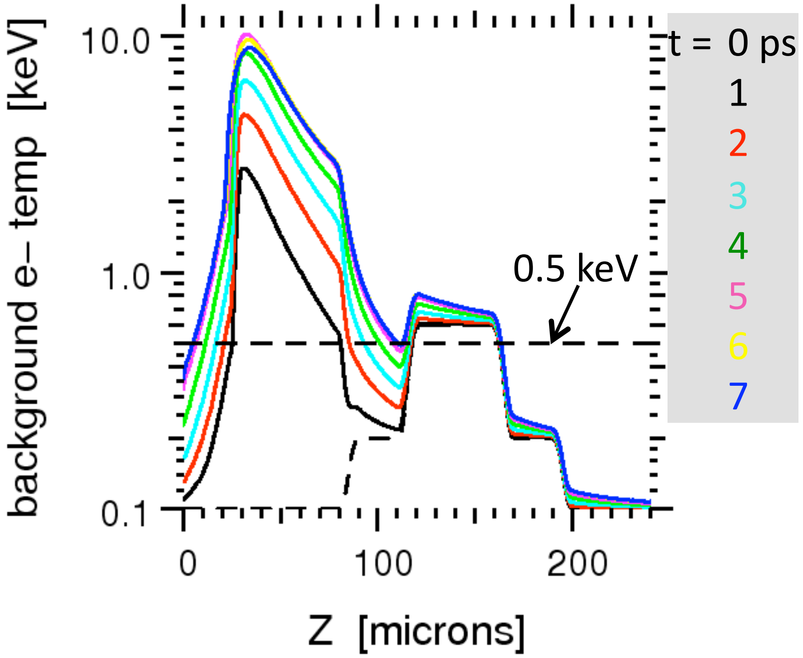
31% of beam energy deposited in ignition region.

NIF-ARC run: heating: lots in low-density region (Ohmic plus collisional), max. fuel pressure increases by 220 Gbar

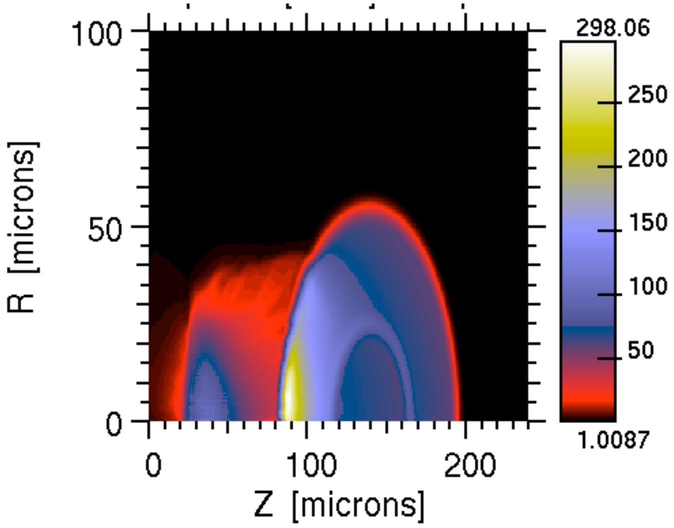
Background e- Temp (eV) at 7 ps



Background e- Temp, averaged over r = 0-5 um

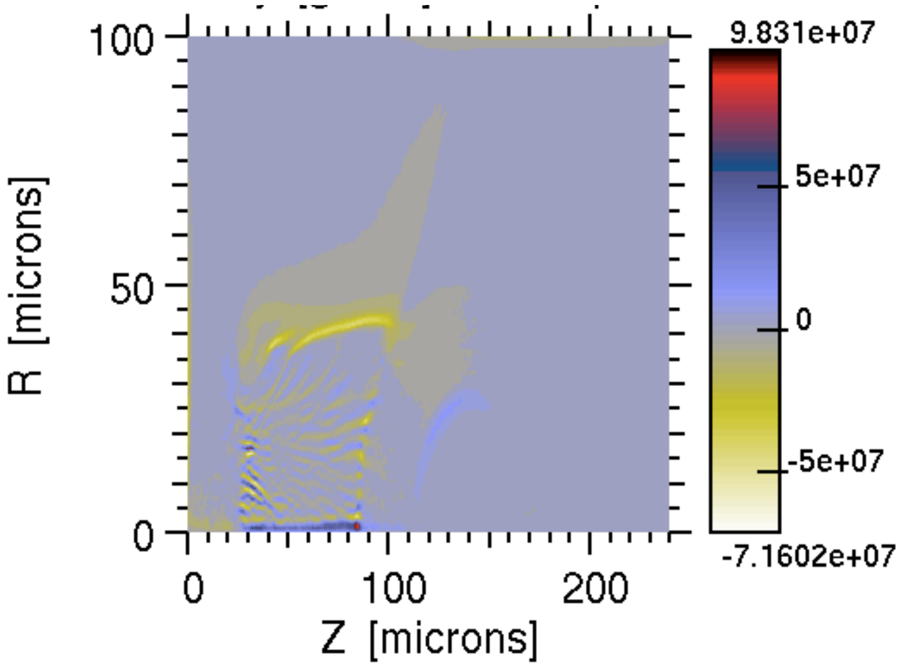


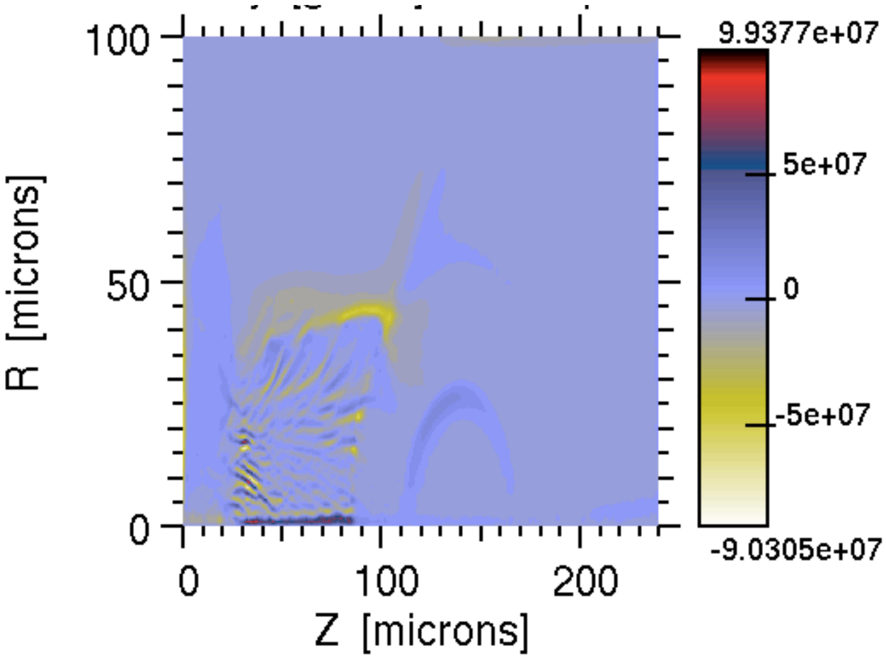
Background pressure (Gbar) at 7 ps



Initial peak pressure: 74 Gbar.

NIF-ARC run: magnetic fields: filaments form in excitation region; pinching field due to beam profile


Azimuthal B [gauss], t = 2.94 ps

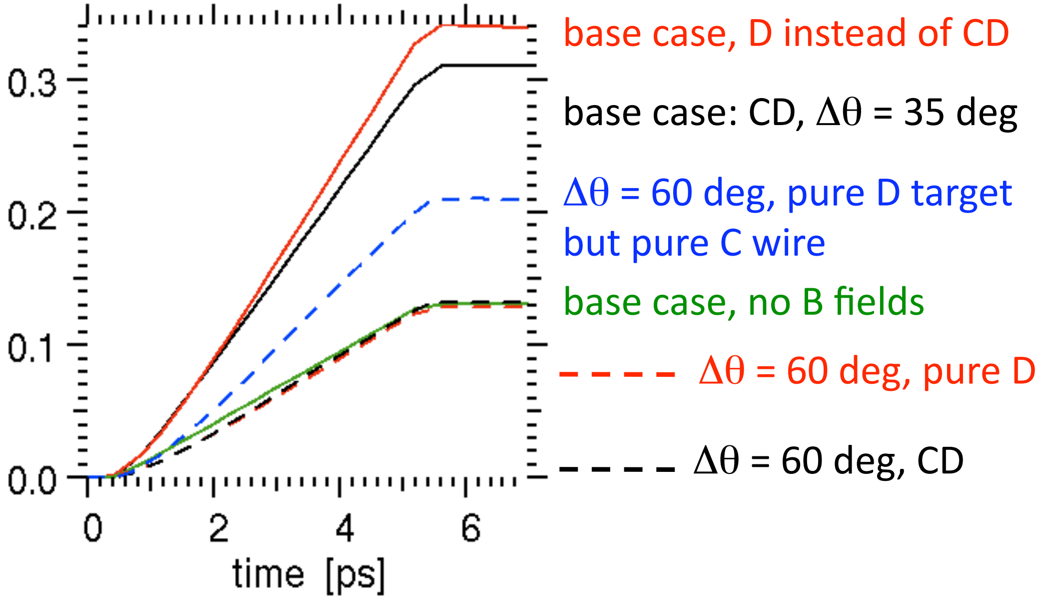

Azimuthal B [gauss], t = 6.02 ps

$$\partial_t B_\theta \approx -\partial_r(\eta J_{z,beam}) \approx e\eta v_{z,beam}\partial_r n_{beam} \quad \rightarrow \quad B_\theta < 0 \text{ due to beam profile}$$

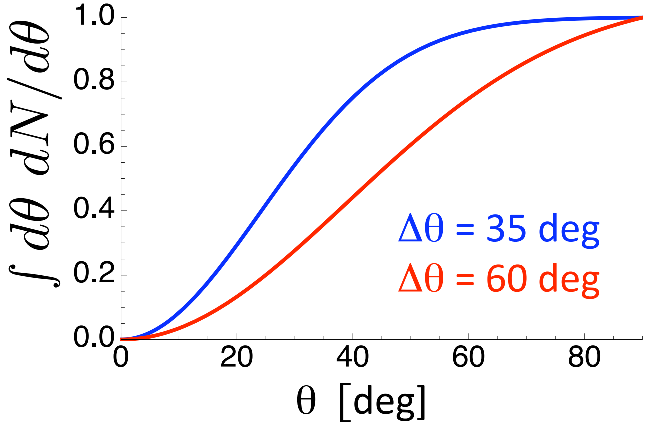
$$\text{pinching}: \quad F_r = e v_{z,beam} B_\theta < 0$$

NIF-ARC toy problem: variations on a theme

fraction of total added energy in ignition region

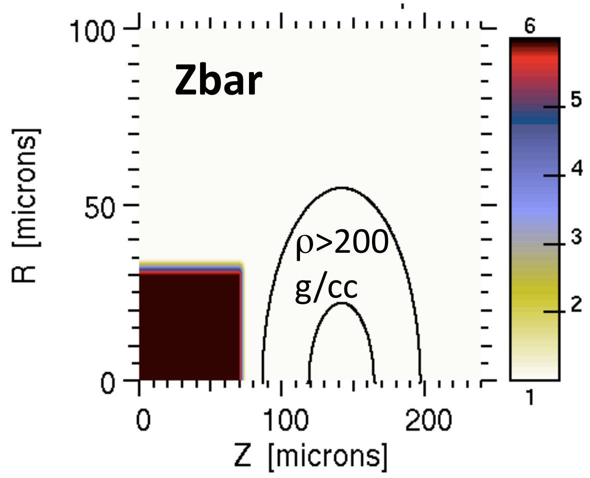


Angular distributions:
dN/dΩ ~ exp[(-θ/Δθ)^2]



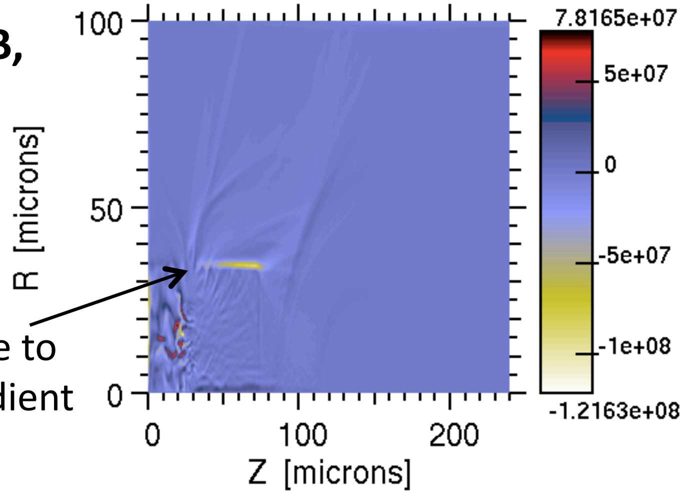
All carbon is fully ionized

C wire: initial mass (and electron) density, temperature same as base case



Azimuthal B, t = 5.04 ps

pinching B due to resistivity gradient



Summary and future prospects

- Hydrid-PIC code LSP, run with the direct-implicit algorithm and background fluid particles, is an effective way to simulate core transport: runs are fast (several hours on ~32 cpu's), energy conservation is good, most physics included.
- Electron beam distributions from explicit PIC show a two-temperature energy distribution, and can have a very wide angular spread.
- LSP simulations, with an excited electron beam propagating thru a simple target with dense fuel, show energy coupling to the ignition region of 10-35%.
- Magnetic fields and smaller angular spreads help considerably.
- A mid-Z "wire" in the transport path improves the coupling.
- In the future, we will model "non-ideal" systems: partially ionized, non-ideal EOS:
  - utilize the equation of state and ionization package in LSP.
  - Account for fast electron stopping and scattering off atomically bound electrons.
  - These issues are crucial for modeling (initially) room-temperature experiments, and high-Z cones.