

Transport Simulations for Fast Ignition on NIF

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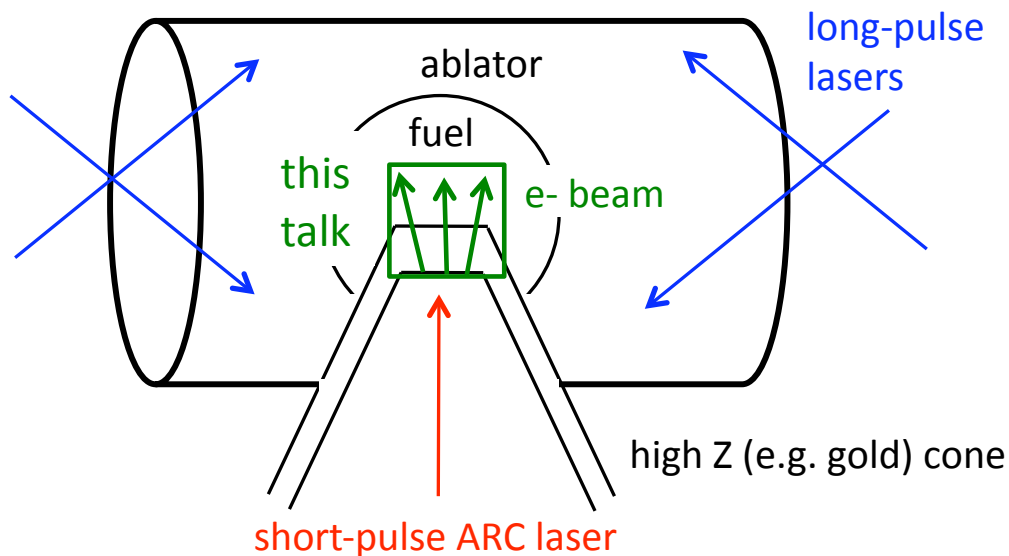
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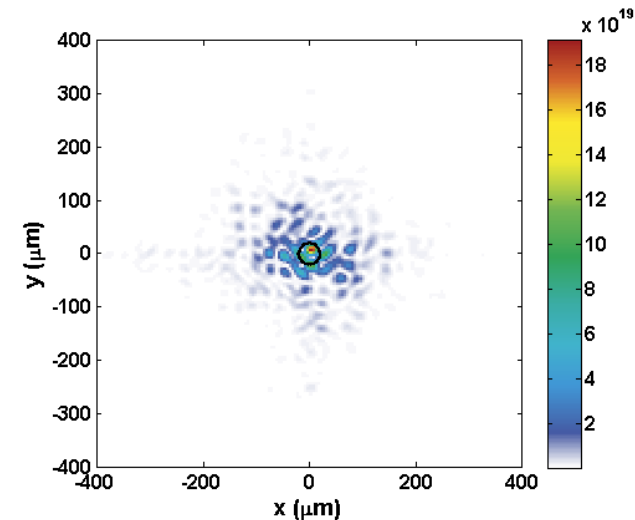
We simulate fast ignition relevant electron beam transport in compressed plasma for future experiments on NIF-ARC

- Modeling with implicit PIC using LSP code.
- Results for NIF-ARC generated e-beam parameters:
 - role of B field: increases coupling considerably
 - background materials: pure D vs CD: surrogacy of warm plastic to cryogenic target
 - electron beam temperature and divergence angle

Profiles from rad-hydro for cone-guided, indirect-drive fast ignition on NIF



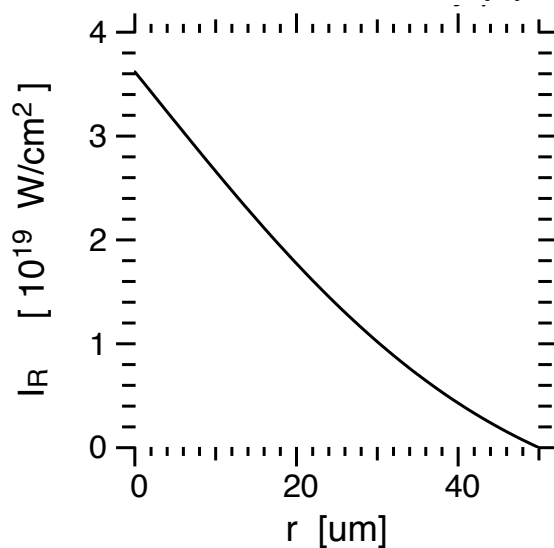
Electron beam based on short-pulse laser specs for one quad of NIF-ARC with FIDO optics upgrade



Courtesy D. Homoelle

We excite an electron beam, based on current ARC laser specs

Electron beam intensity profile



Total energy to $r = 50 \mu\text{m}$:
 Laser = 5 kJ
 e- beam = 3.5 kJ
 70% conversion efficiency (assumed)

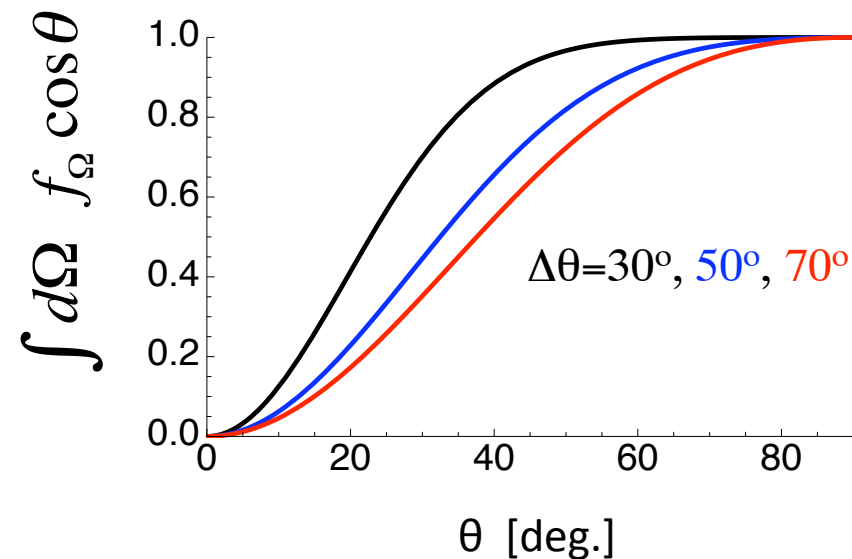
Temporal pulse: 10 ps duration,
 Gaussian, FWHM = 5 ps

electron beam distribution: $f_e(E, \theta) = F_E(E) * F_\theta(\theta)$

$$F_E = dN/dE \sim \exp[-E / T_{\text{hot}}]$$

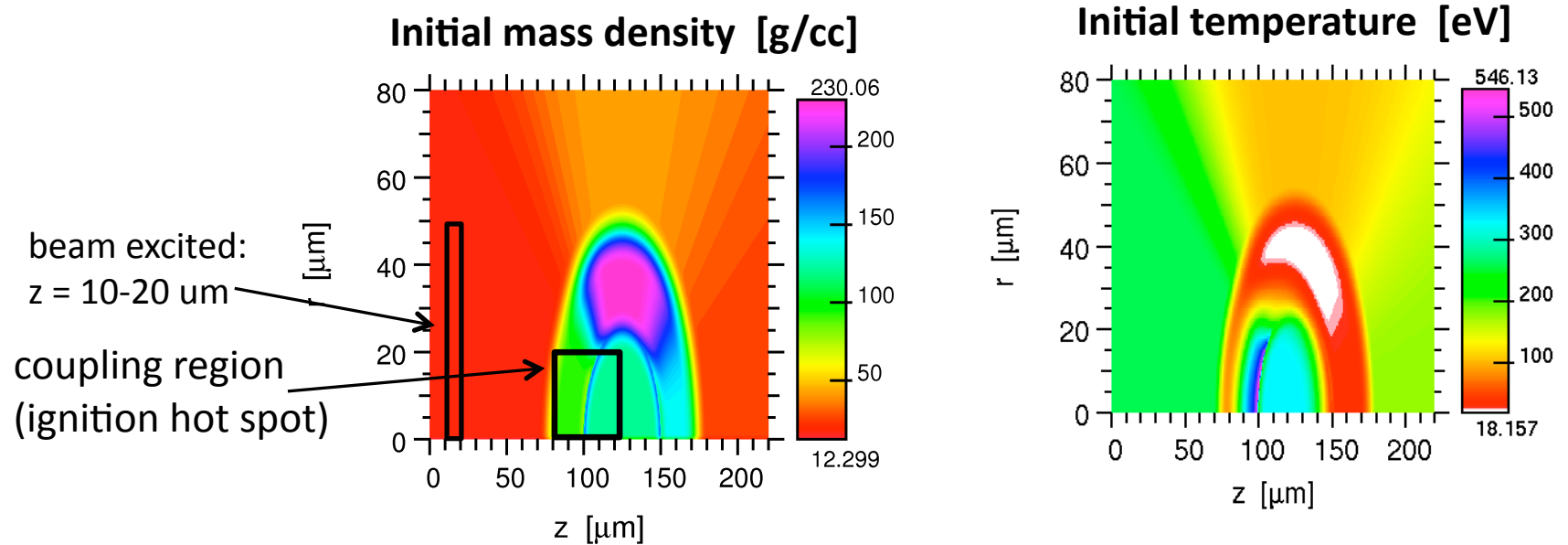
$$F_\theta = 2\pi \sin\theta F_\Omega; F_\Omega = dN/d\Omega \sim \exp[-(\theta/\Delta\theta)^2]$$

Enclosed Forward Current J_z



Explicit-PIC modeling of short-pulse LPI:
 see A. J. Kemp, 4:30pm Thursday, UI2.6

NIF-ARC “base case” run: pure D plasma, $T_{\text{hot}} = 2.5 \text{ MeV}$, $\Delta\theta = 30 \text{ deg.}$

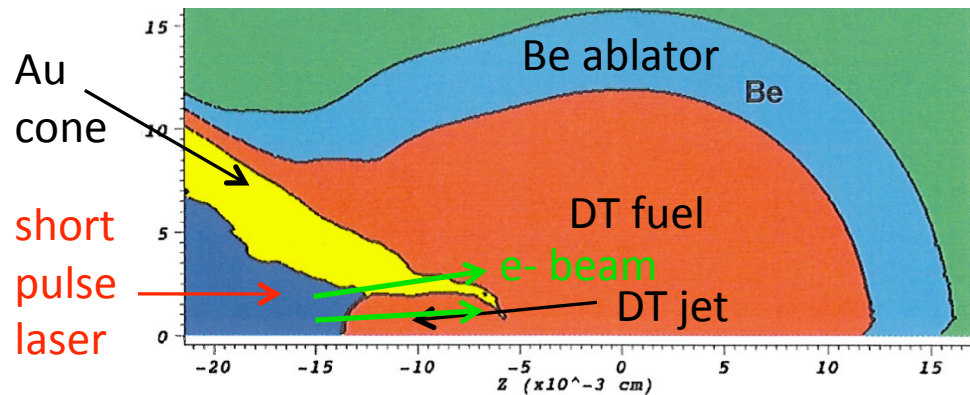


- Profiles we used can be produced at NIF with survival of the cone tip (design result).
- Adequate for coupling experiment: fluor yield will show pressure rise.

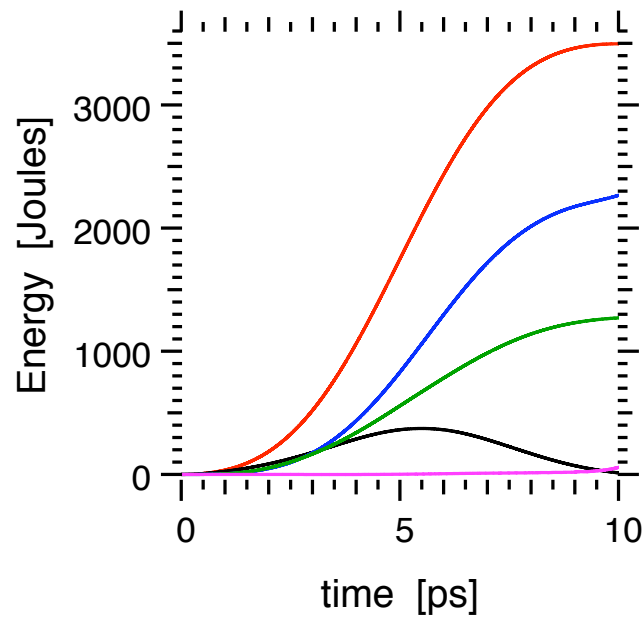
Numerical parameters:

- $dr=dz=0.5 \text{ μm}$; $dt = 0.7 \text{ fs} = 0.42 \text{ dr}/c$
- run wall time for 10 ps = 5.7 hours on 64 opteron cpu's

Typical rad-hydro design (more jetting than in design this talk is based on)



NIF-ARC base case run: energetics



Total added beam energy (final: 3.5 kJ)

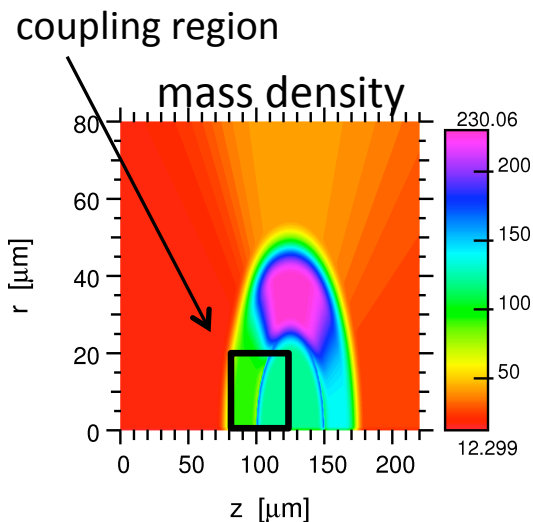
Change in background energy

Beam energy escaping from boundaries

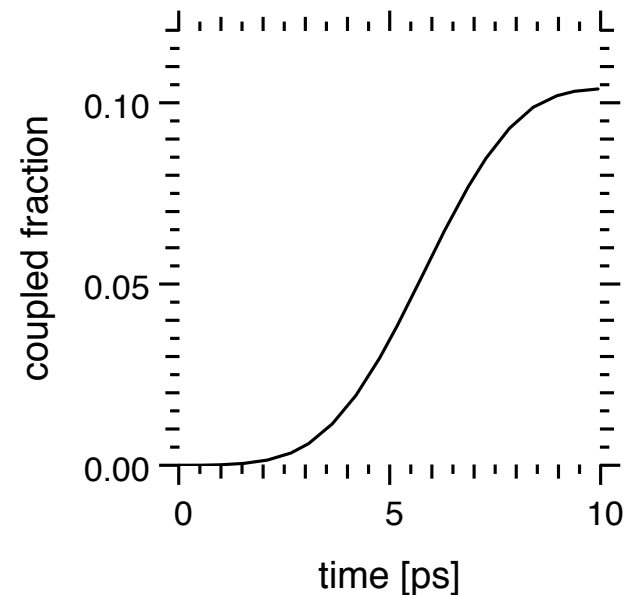
Beam energy (instantaneous)

"Net energy:" numerical error (small)

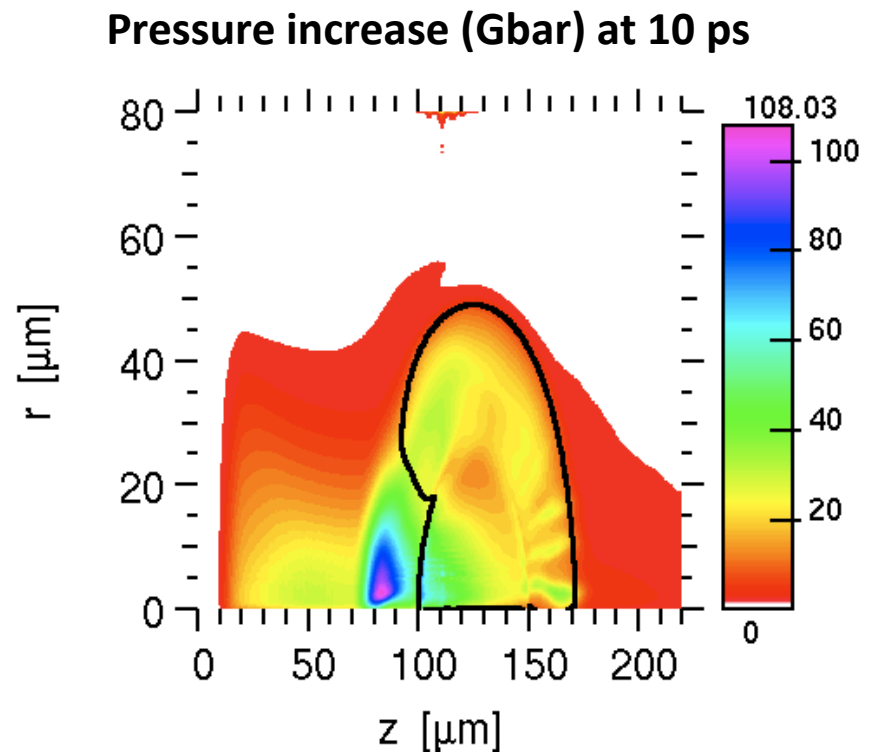
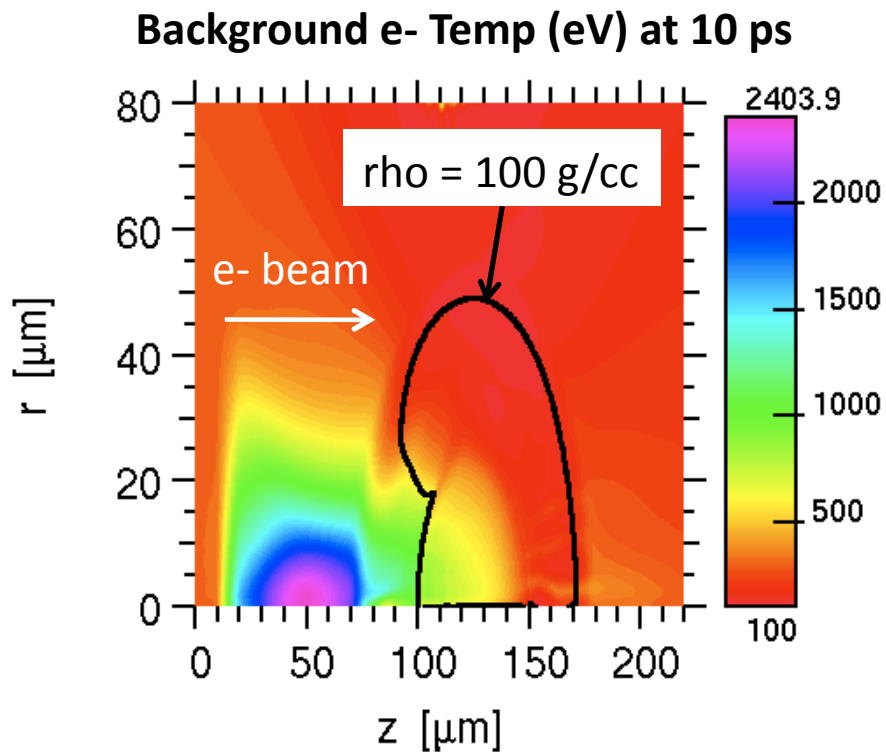
Energy vs. time in coupling region,
scaled by 3.5 kJ (total added energy)



11% of beam energy
deposited in coupling
region.



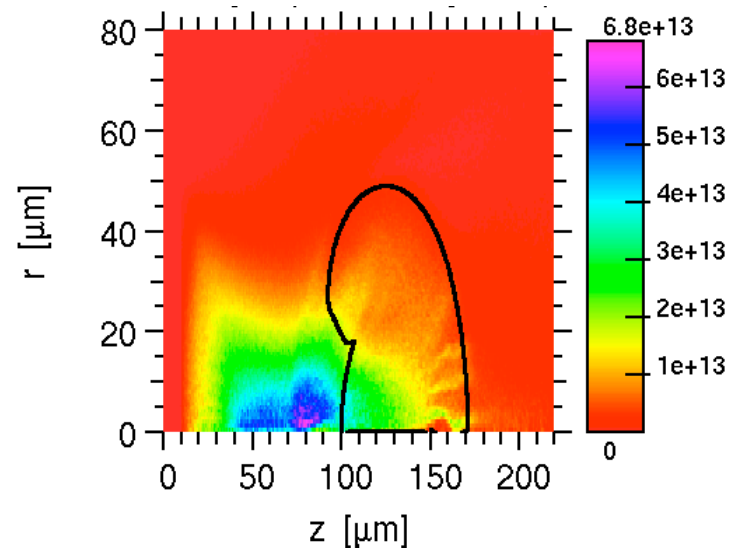
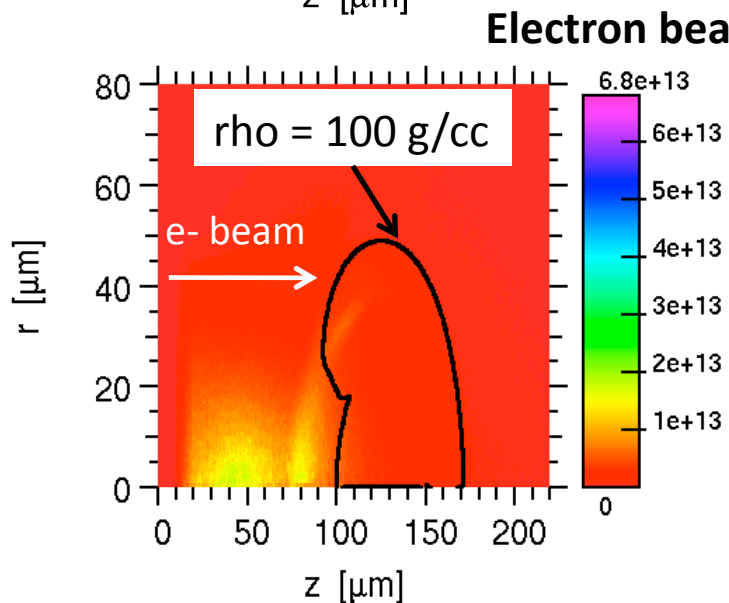
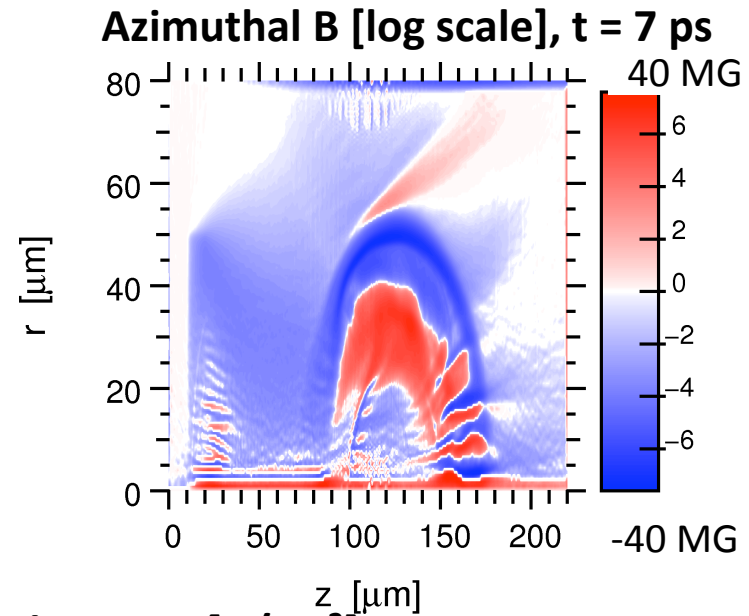
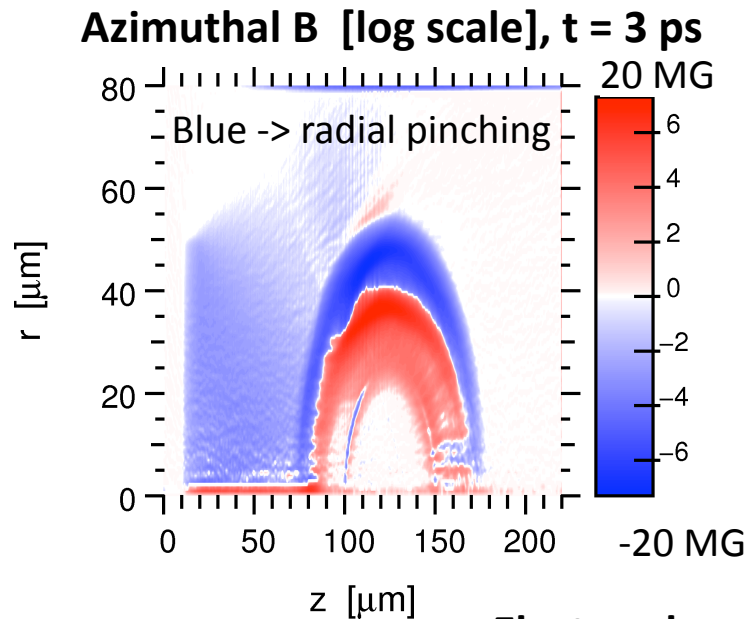
NIF-ARC base case run: heating: lots in low-density region (Ohmic plus collisional)



Initial peak pressure: 38 Gbar.

Imaging of K-alpha fluorescence will show local pressure rise in experiments.

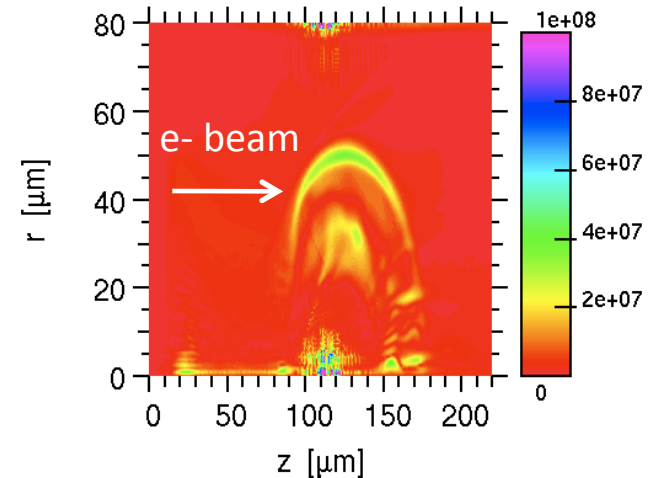
NIF-ARC base case run: magnetic fields: filaments form in excitation region; pinching field due to beam profile



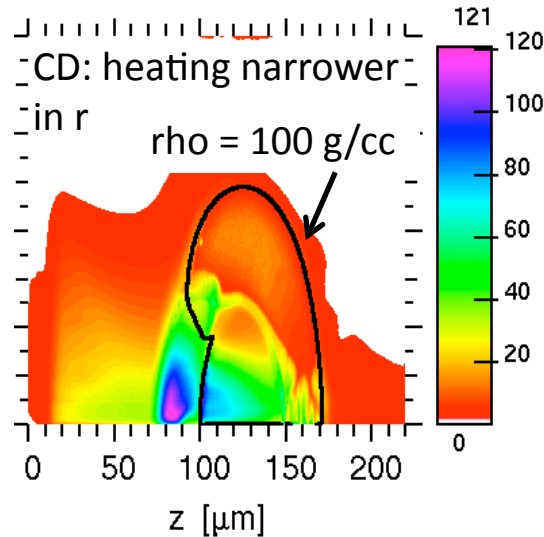
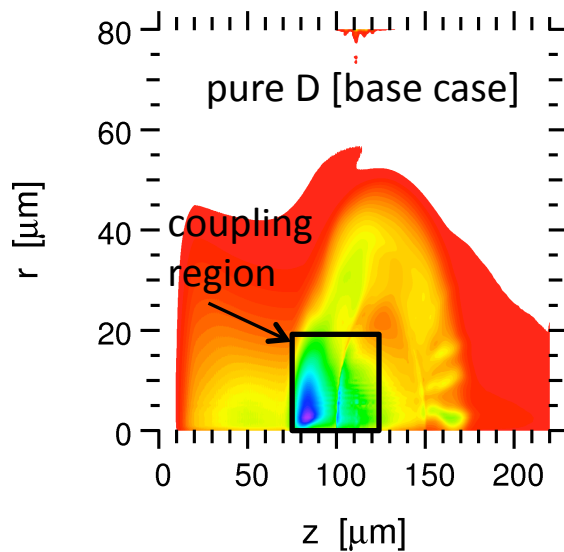
NIF-ARC runs: Magnetic fields improve coupling; plastic (CD) improves coupling by increasing resistive B fields

Run	Beam energy fraction in coupling region
base case: pure D	10.4%
base case, no B fields	2.9%
CD, 50-50 atomic	13.7%

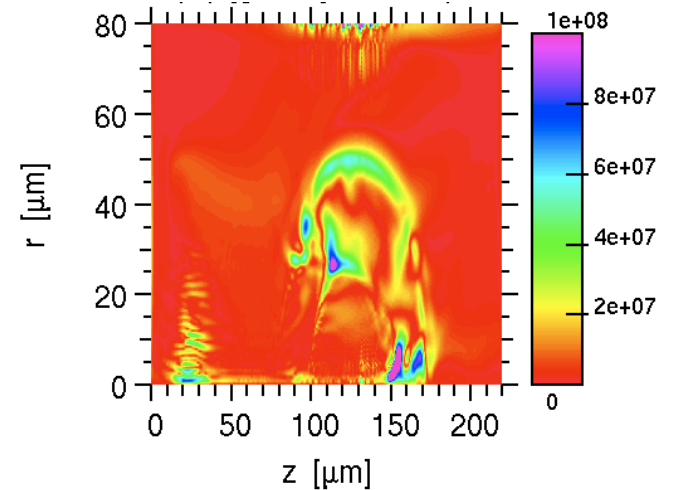
|B| [gauss], pure D run, 10 ps



Background pressure increase [Gbar], time = 10 ps

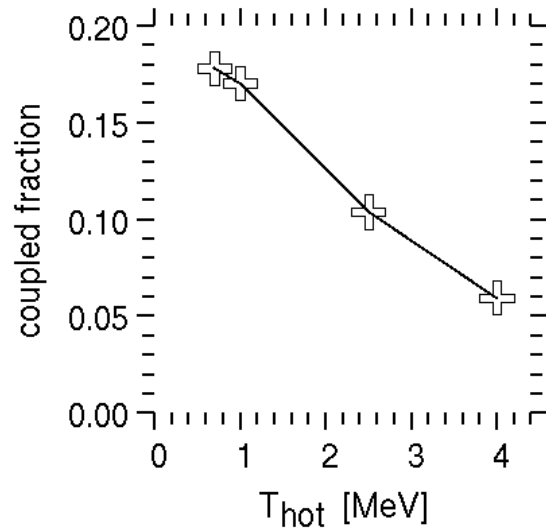


|B| [gauss], CD run, 10 ps



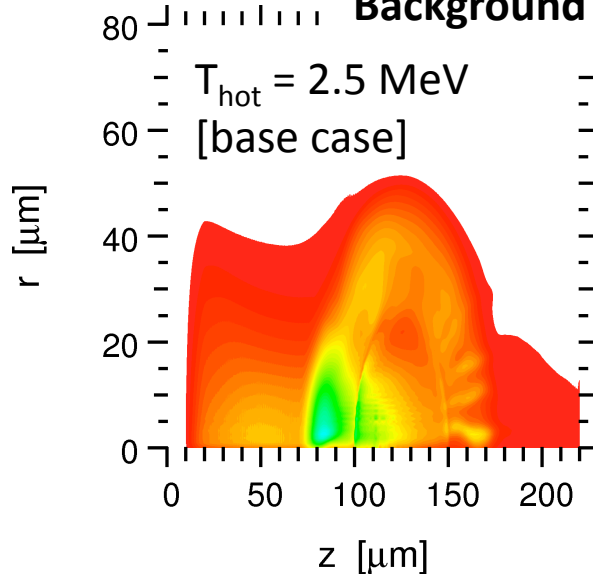
NIF-ARC runs: coupling best at $T_{\text{hot}} < \sim 1 \text{ MeV}$ *for this target*

Beam energy fraction in coupling region

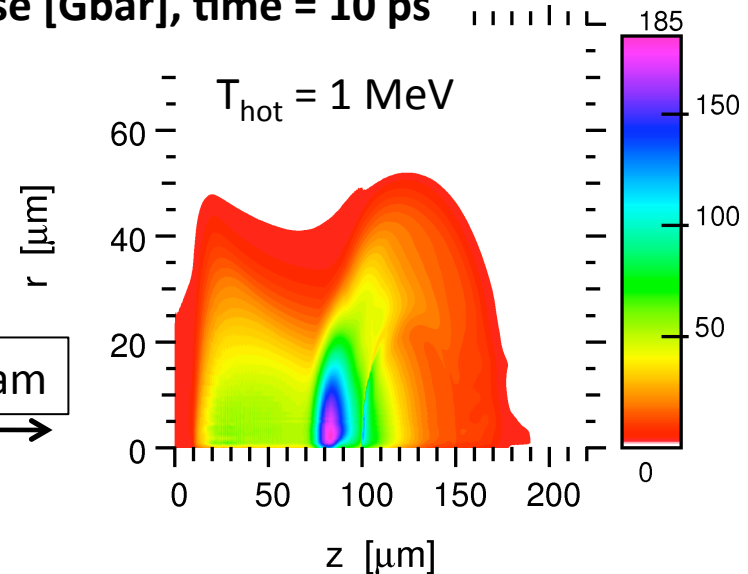


$$dN/dE \sim \exp[-E / T_{\text{hot}}]$$

Background pressure increase [Gbar], time = 10 ps



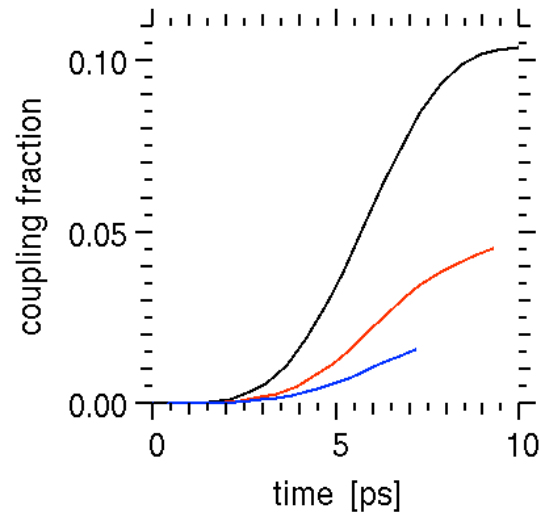
e- beam
→



NIF-ARC runs: Increased beam angular divergence reduces coupling

Beam energy fraction in coupling region

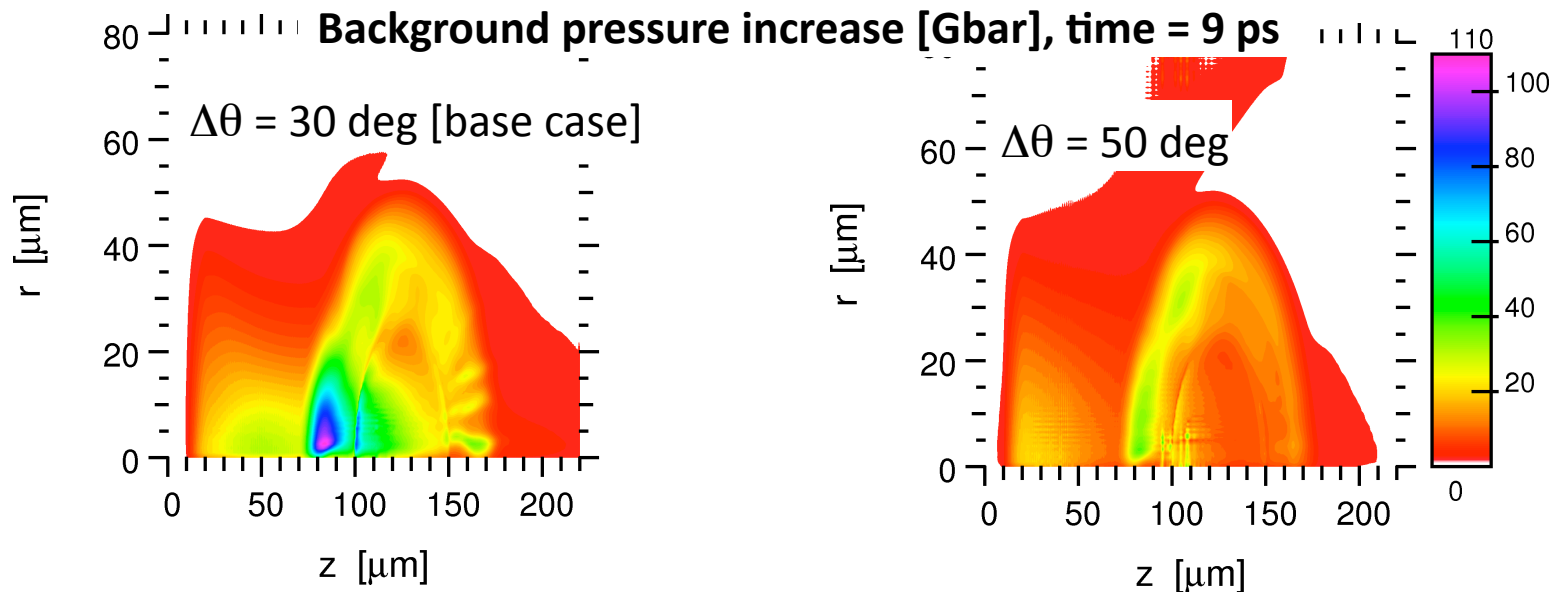
$$F_{\theta} = 2\pi \sin\theta F_{\Omega}; \quad F_{\Omega} = dN/d\Omega \sim \exp[-(\theta/\Delta\theta)^2]$$



$\Delta\theta = 30$ deg [base case]

= 50 deg

= 70 deg



Summary and future prospects

- We are designing a full hydro-scale cone-guided, indirect-drive FI coupling experiment, for NIF, with the ARC-FIDO short-pulse laser.
- Current rad-hydro designs with limited fuel jetting into cone tip are not yet adequate for ignition. Designs are improving.

Electron beam transport simulations (implicit-PIC LSP) show:

- Magnetic fields and smaller angular spreads increase coupling to ignition-relevant “hot spot” (20 μm radius).
- Plastic CD (for a warm target) produces somewhat better coupling than pure D (cryogenic target) due to enhanced resistive B fields.
- The optimal T_{hot} for this target is ~ 1 MeV; coupling falls by 3x as T_{hot} rises to 4 MeV.

Hybrid PIC code LSP^{1,2} 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 $\Delta t \gg \omega_{\text{plasma}}^{-1}, \omega_{\text{light}}^{-1}$; $\Delta x \gg \lambda_{\text{Debye}}, \lambda_{\text{light}}$.
 - 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.
 - Energy loss off bound electrons.
 - R-Z cylindrical geometry.
 - Fixed ionization states, ideal gas EOS.
- We are currently working on:
 - Angular scattering off partially ionized ions.
 - Time- and space-dependent ionization: available in official LSP version 9.1.
 - Non-ideal EOS: in LSP 9.1.

¹D. R. Welch, et al, Phys. Plasmas 13, 063105 (2006); D. J. Strozzi et al, IFSA 2009 Proceeding.

Spatial grid-based algorithm for energy loss and angular scattering of fast electrons off background plasma

- **Grid-based algorithm**: test particles off field particles; field density, drift, temperature found on each spatial grid cell.
- **Spherical momentum coordinates like Lemons¹**: Manheimer² 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.

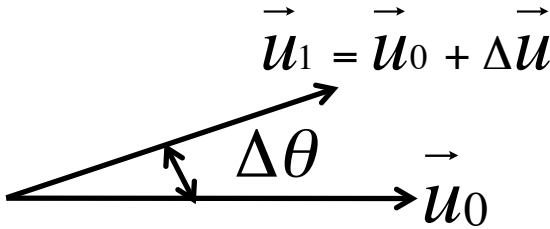
Momentum change in one timestep:

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

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

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

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



$$\vec{u}_1 = \vec{u}_0 + \Delta \vec{u}$$

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

1. Lemons et al., Journ. Comp. Phys. **228**, 1391 (2009)

2. W. Manheimer et al, Journ. Comp. Phys. **138**, 563 (1997)

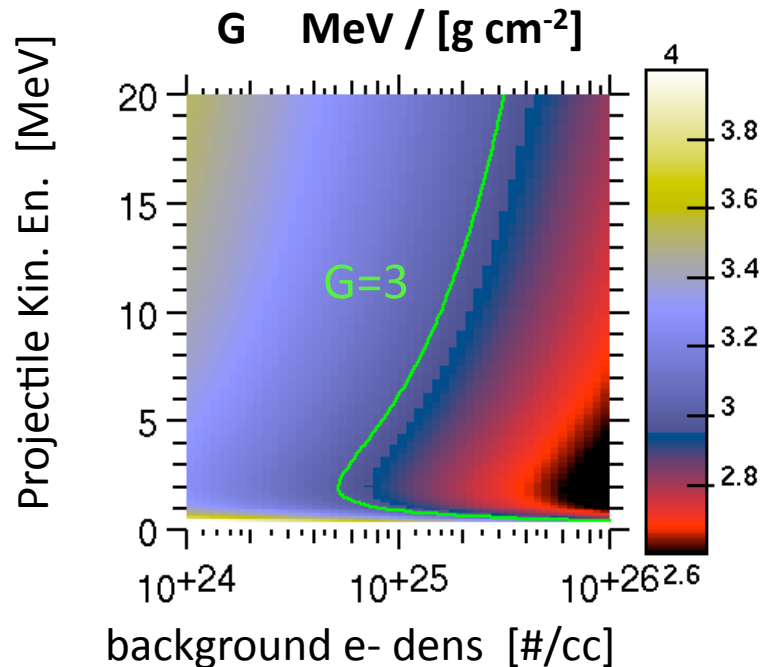
Energy loss and angular scatter: Davies-Solodov formulas

Energy loss

$$\Delta E \text{ [MeV]} = (\bar{Z} / \bar{A}) \cdot G \cdot \rho \Delta x \text{ [g/cm}^2\text{]}$$

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

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



Angular scatter

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

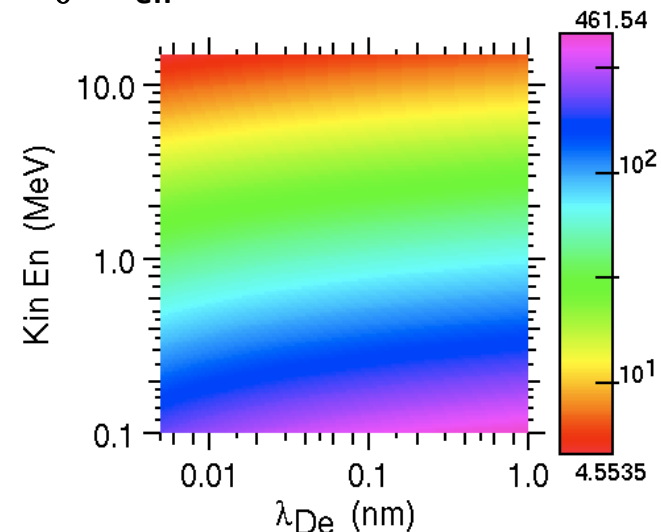
$$F_\theta^2 = \frac{8\pi r_e^2}{\gamma^2 \beta^4 m_p} (L_{sc, e} + Z_{eff} L_{sc, I})$$

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

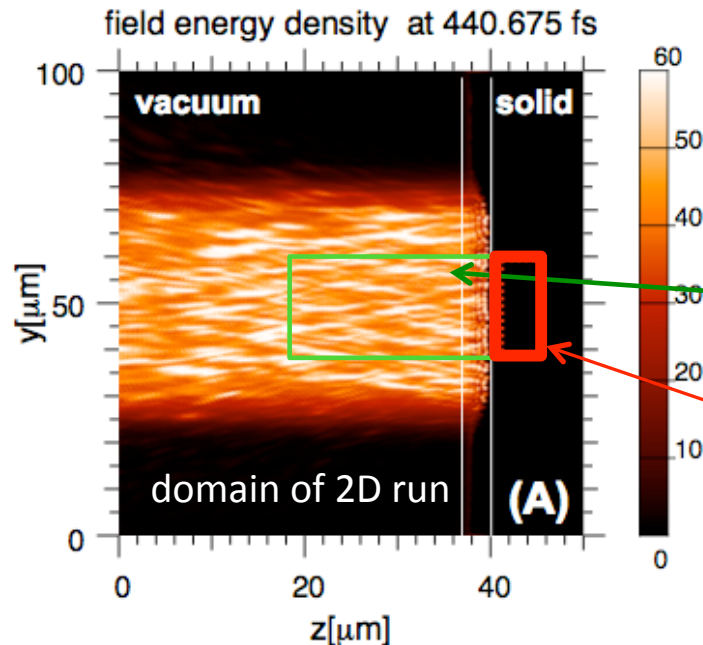
$$L_{sc, I} = \ln \Lambda - \frac{1}{2} (1 + \beta^2) \quad \text{ions}$$

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

$$F_\theta, Z_{eff}=1 \text{ [deg} \cdot \text{(cm}^2\text{/g)}^{1/2}\text{]}$$



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



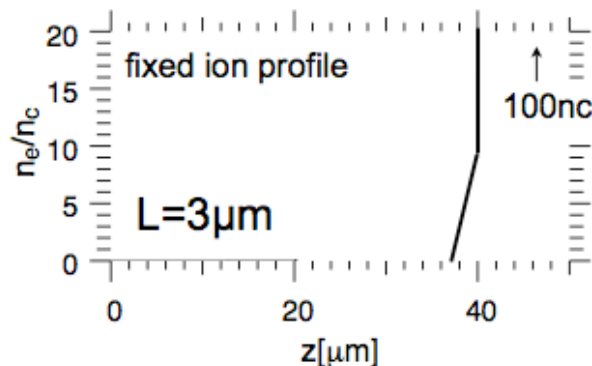
Run 'point 3.4':

- 3D run over small volume
- Laser linearly polarized in y
- Immobile ions – no profile modification
- Peak laser intensity $5\text{E}19 \text{ W/cm}^2$

3D run domain

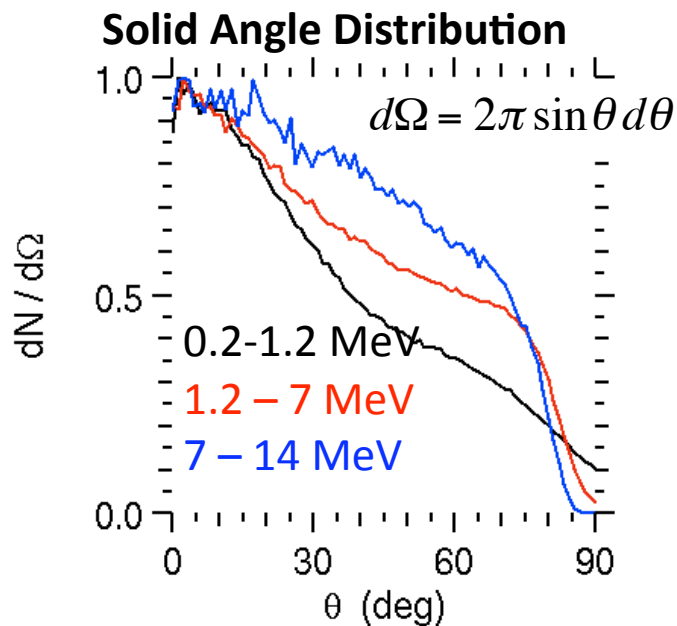
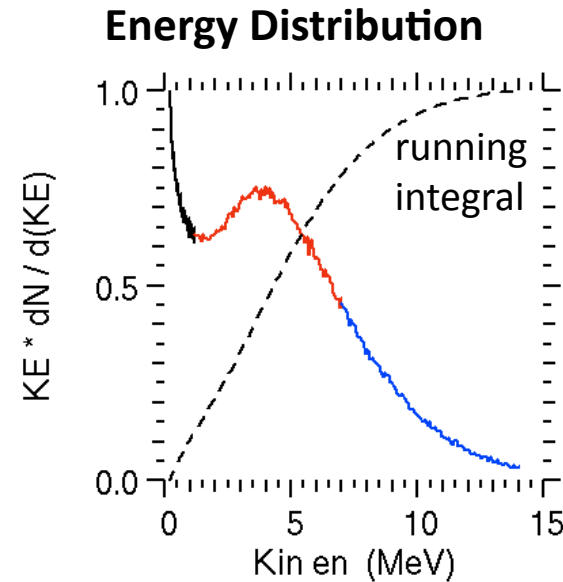
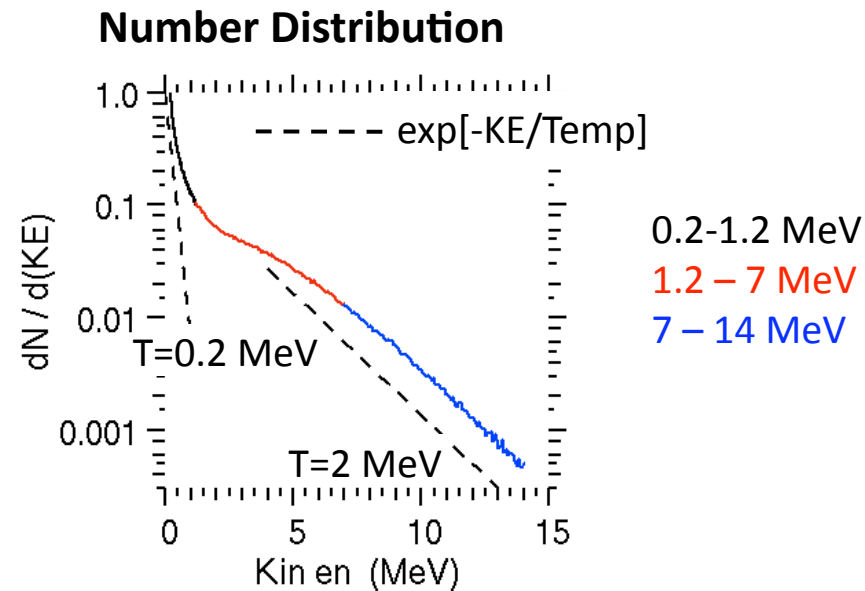
We select all electrons:

- 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



Transverse distribution similar in the 3 energy bins

