Transport Simulations for Fast Ignition on NIF

D. J. Strozzi, M. Tabak, D. P. Grote, B. I. Cohen,
H. D. Shay, R. P. J. Town, A. J. Kemp, M. Key
Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550, USA

Talk NO5.00005
APS-DPP 2009 Meeting
Atlanta, GA, USA
4 November 2009

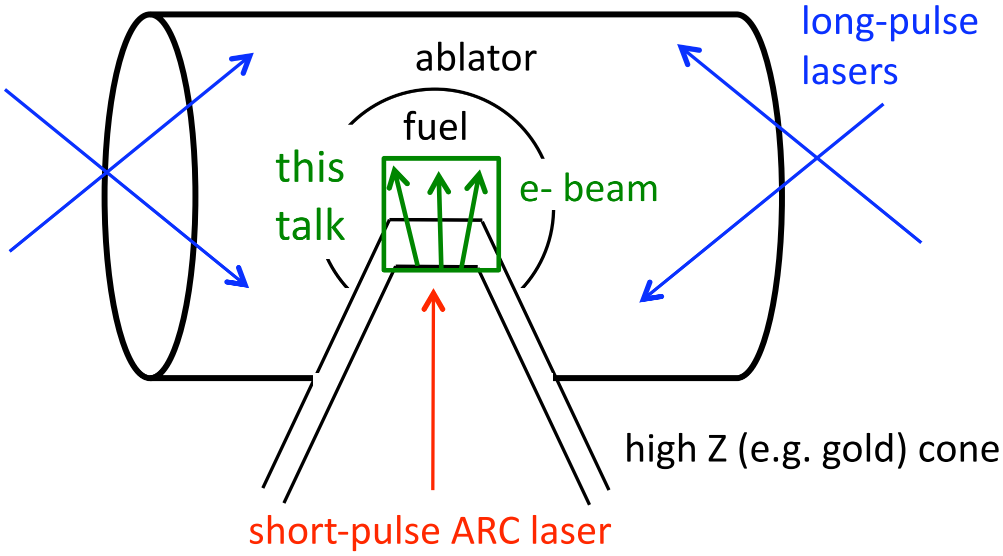
Fusion Energy Program
Physics Division, Physical and Life Sciences Directorate
Lawrence Livermore National Laboratory

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Partially supported by LDRD funds, tracking number 08-SI-001. Release number: LLNL-CONF-418747.

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



ablator

fuel

this talk

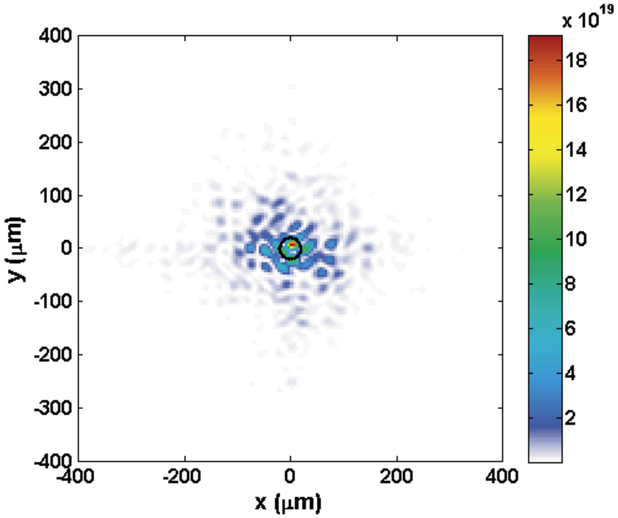
e- beam

long-pulse lasers

high Z (e.g. gold) cone

short-pulse ARC laser

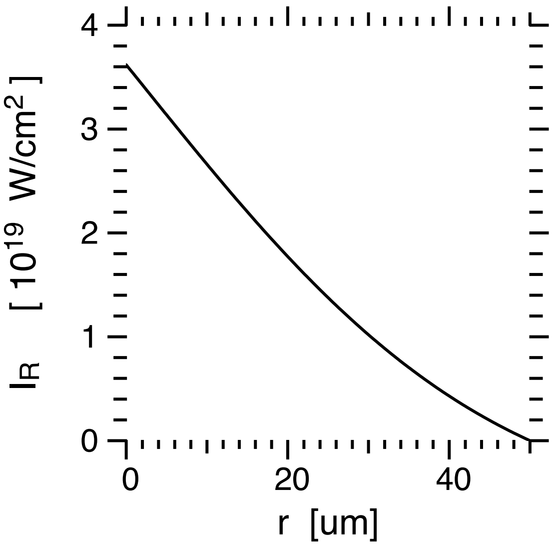
Electron beam based on short-pulse laser specs for one quad of NIF-ARC with FIDO optics upgrade



Courtesy D. Homoelle

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

Electron beam intensity profile



Total energy to r = 50 um:
Laser = 5 kJ
e- beam = 3.5 kJ
70% conversion efficiency (assumed)

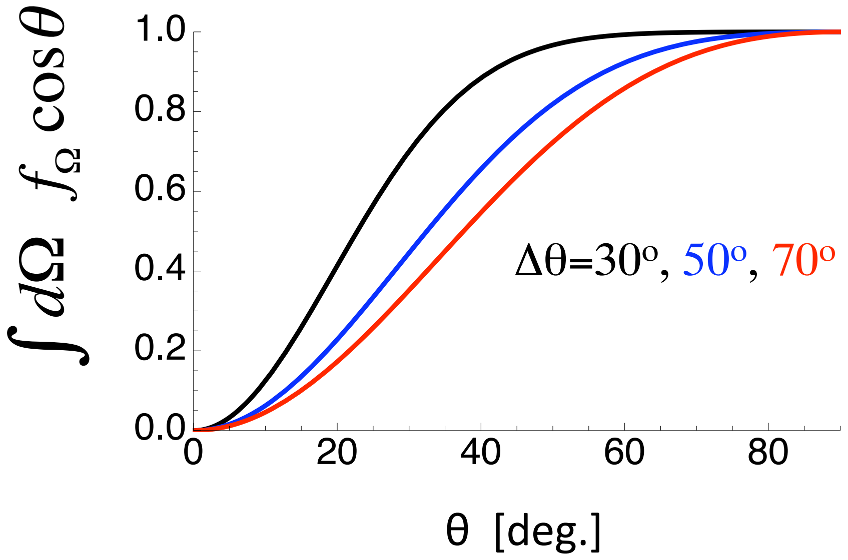
Temporal pulse: 10 ps duration,
Gaussian, FWHM = 5 ps

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

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

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

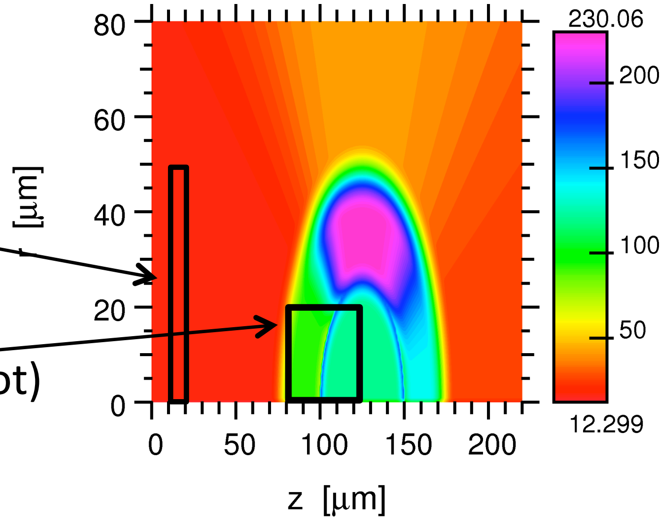
Enclosed Forward Current J_z



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_{hot} = 2.5 MeV, $\Delta\theta$ = 30 deg.

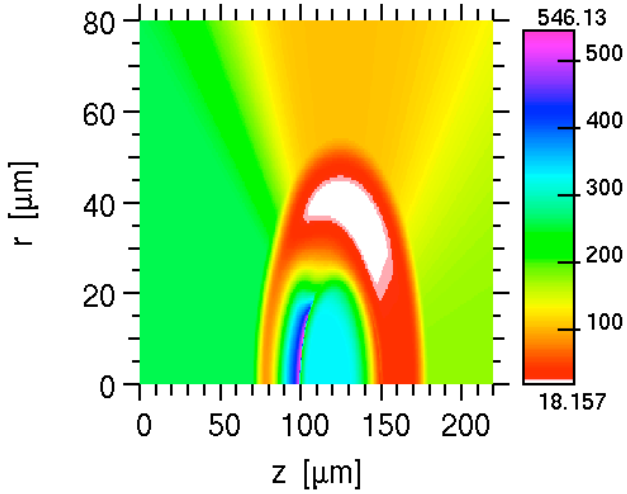
Initial mass density [g/cc]



beam excited:
z = 10-20 um

coupling region
(ignition hot spot)

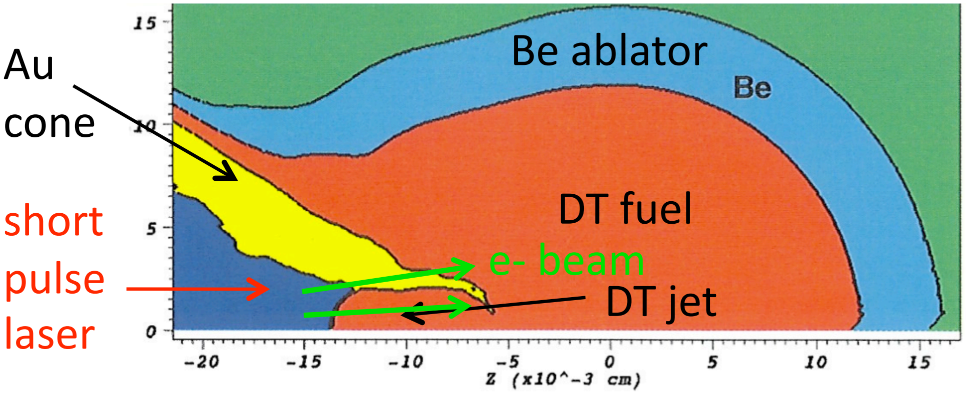
Initial temperature [eV]



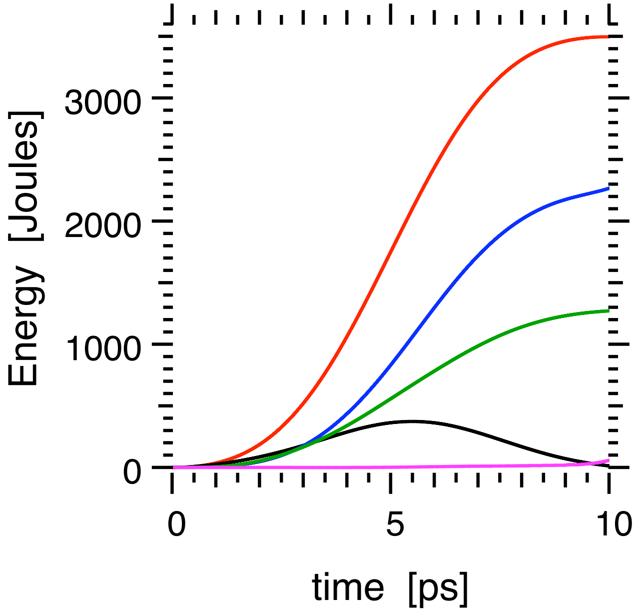
- Profiles we used can be produced at NIF with survival of the cone tip (design result).
- Adequate for coupling experiment: fluor yield will show pressure rise.

Numerical parameters:
- dr=dz=0.5 um; dt = 0.7 fs = 0.42 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)

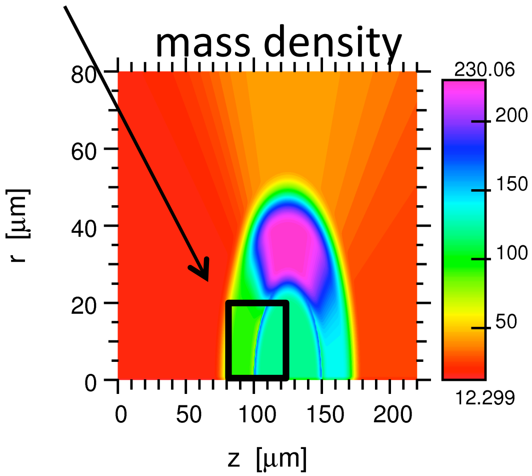
Change in background energy

Beam energy escaping from boundaries

Beam energy (instantaneous)

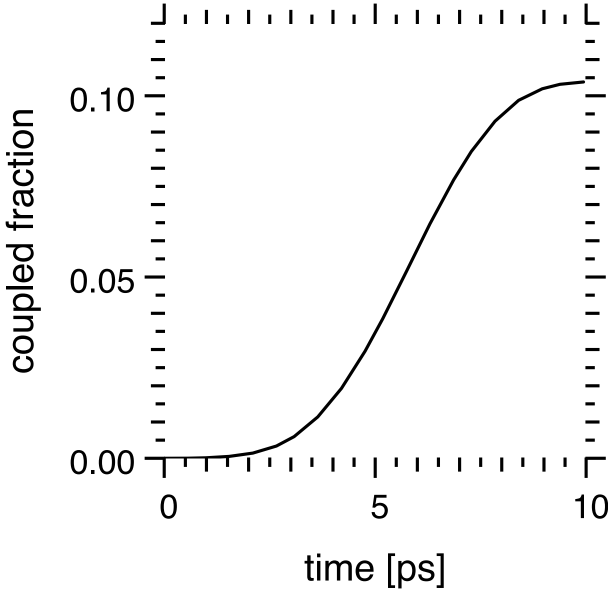
"Net energy:" numerical error (small)

coupling region



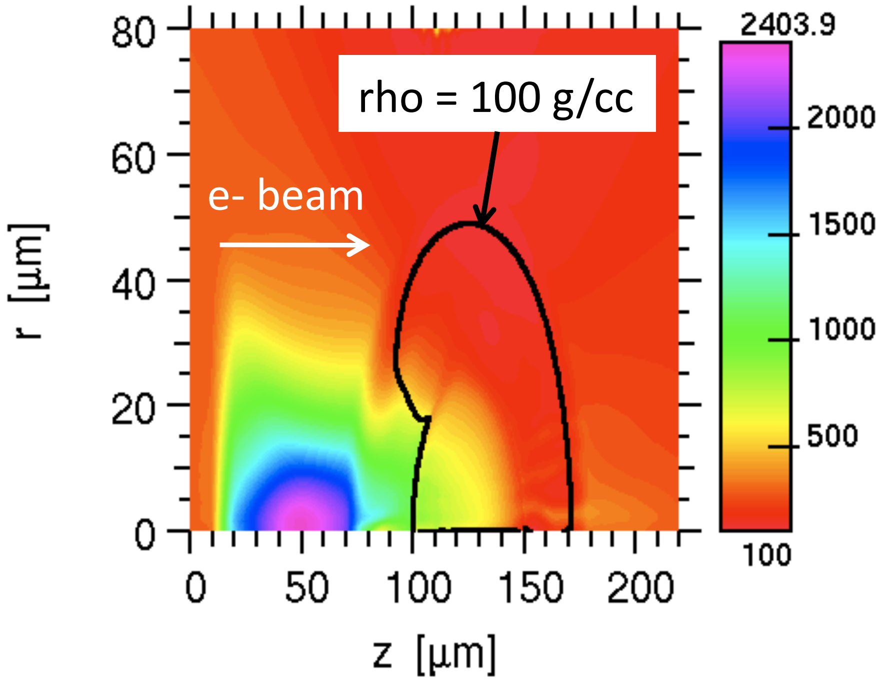
11% of beam energy deposited in coupling region.

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

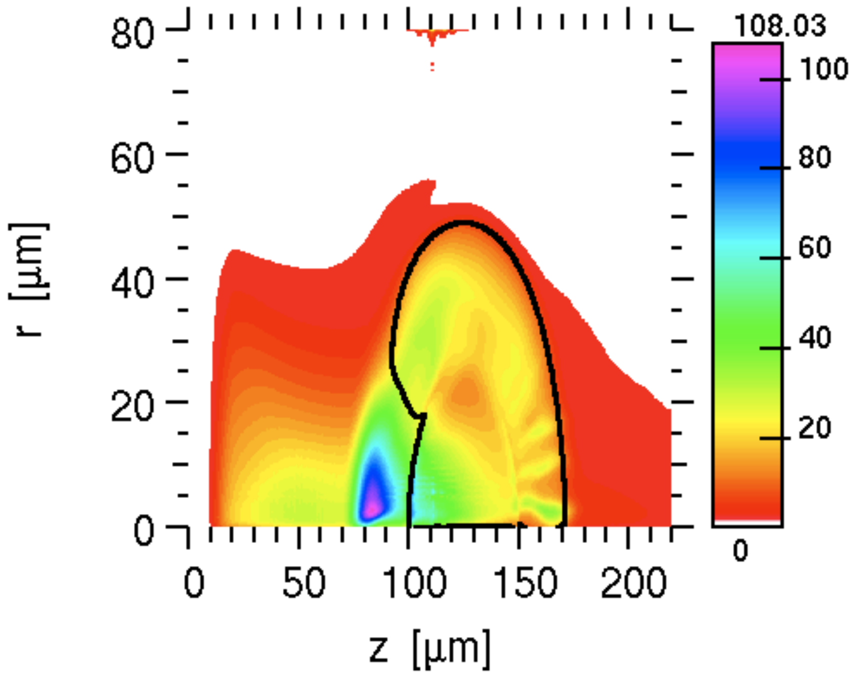


NIF-ARC base case run: heating: lots in low-density region (Ohmic plus collisional)

Background e- Temp (eV) at 10 ps



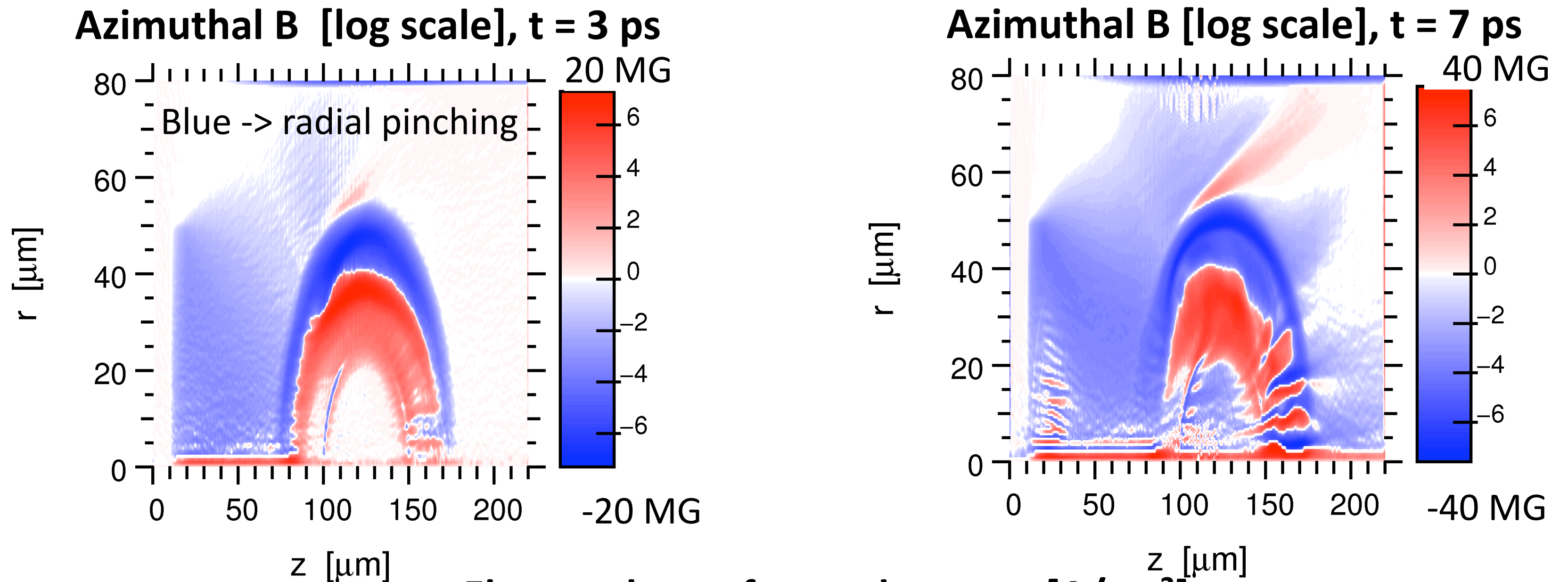
Pressure increase (Gbar) at 10 ps



Initial peak pressure: 38 Gbar.

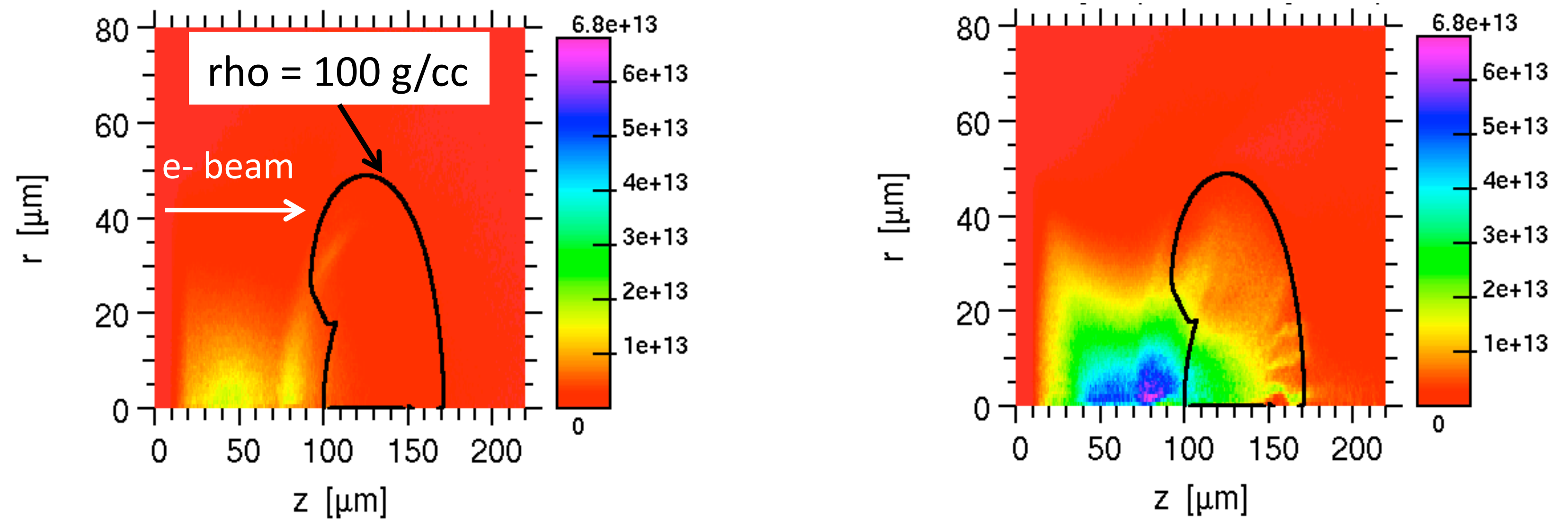
Imaging of K-alpha fluorescence will show local pressure rise in experiments.

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


Azimuthal B [log scale], t = 3 ps

Azimuthal B [log scale], t = 7 ps

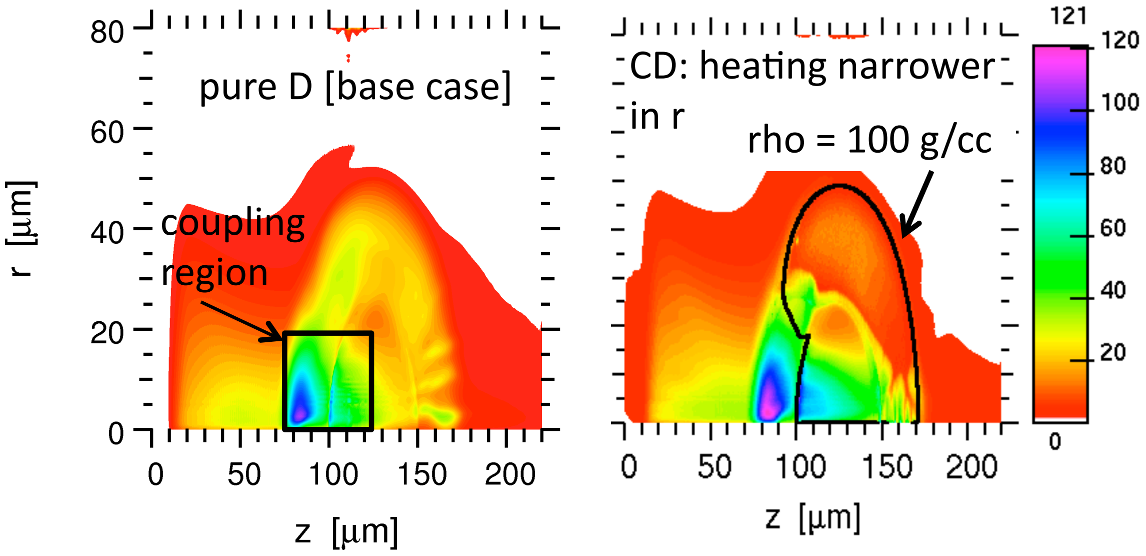
Electron beam forward current [A/cm^2]



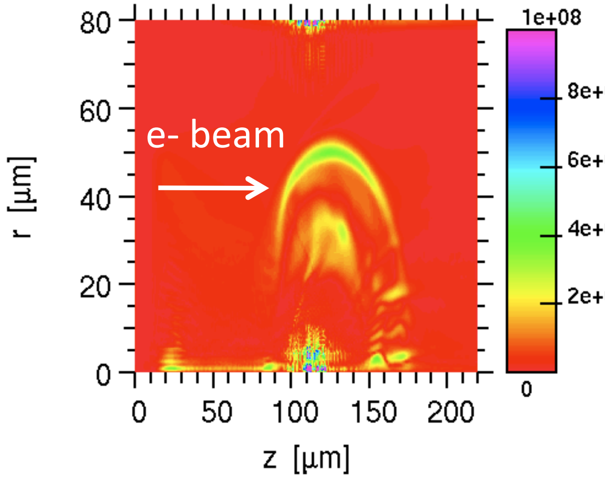
NIF-ARC runs: Magnetic fields improve coupling; plastic (CD) improves coupling by increasing resistive B fields

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%

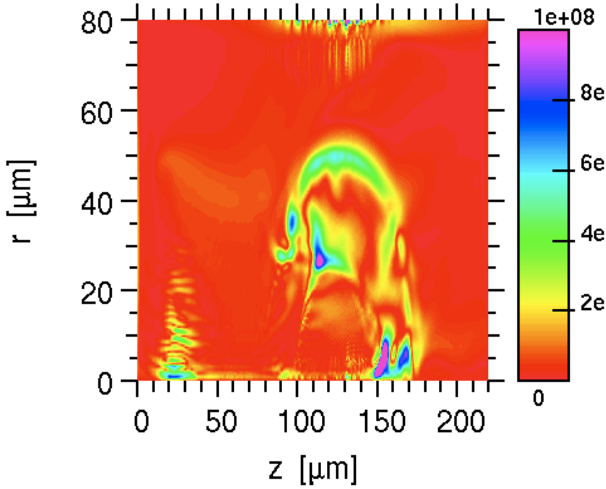
Background pressure increase [Gbar], time = 10 ps



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

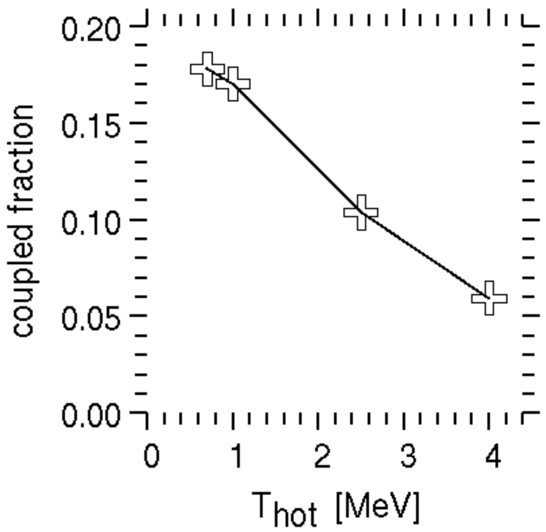


|B| [gauss], CD run, 10 ps

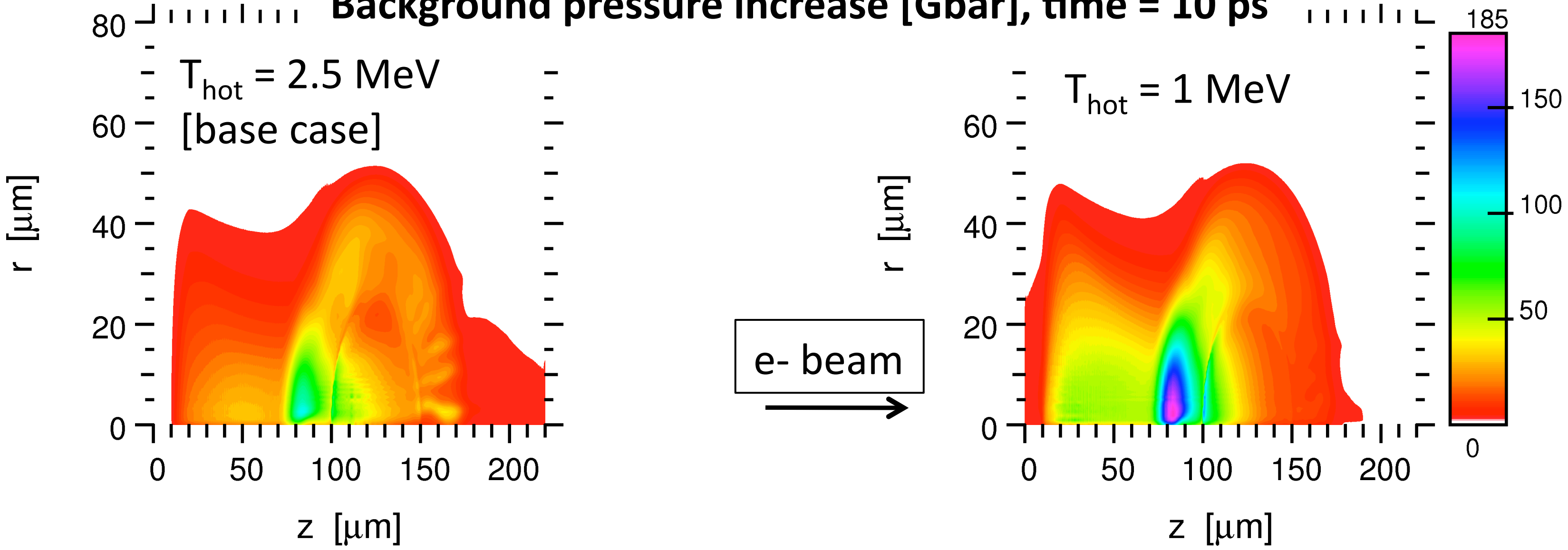


NIF-ARC runs: coupling best at T_{hot} <~ 1 MeV *for this target*

Beam energy fraction in coupling region



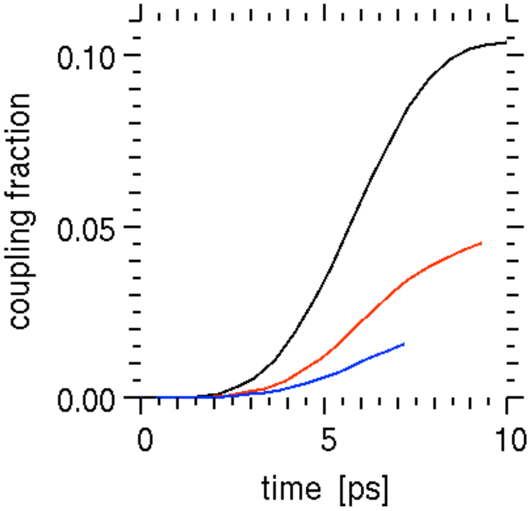
$dN/dE \sim \exp[-E / T_{hot}]$


Background pressure increase [Gbar], time = 10 ps

NIF-ARC runs: Increased beam angular divergence reduces coupling

Beam energy fraction in coupling region

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

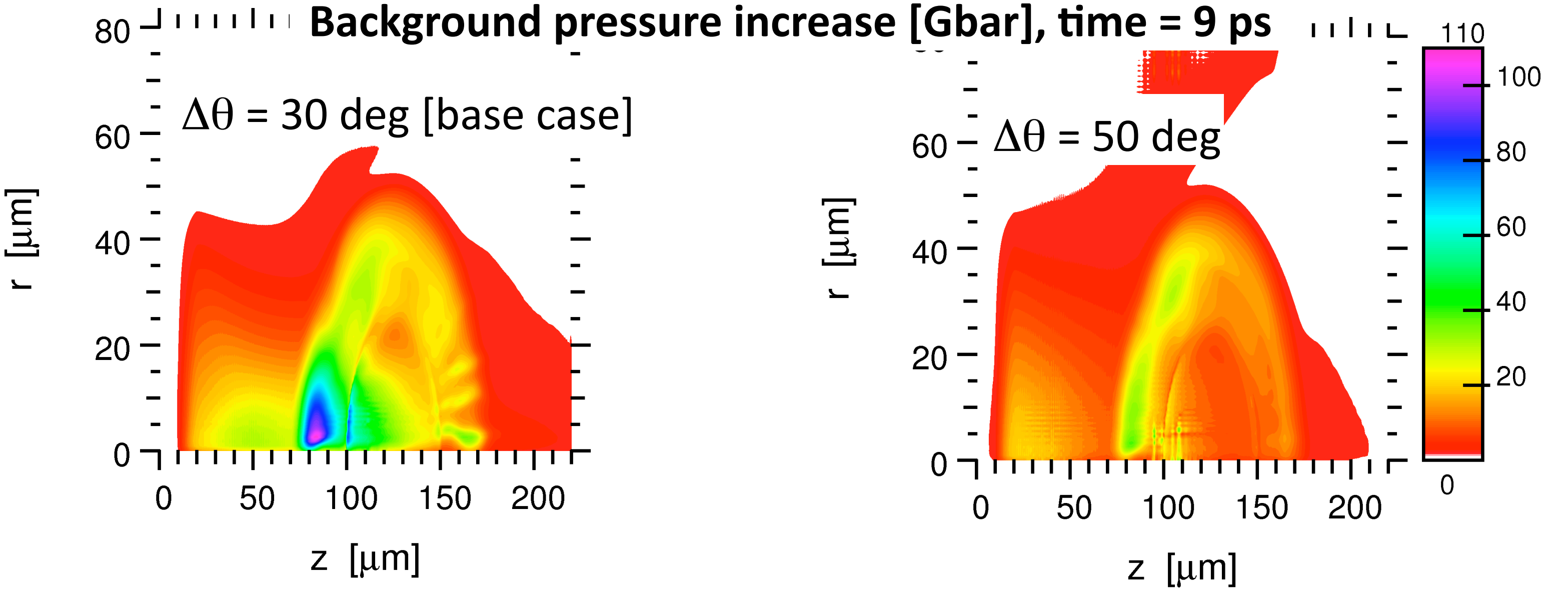


$\Delta\theta$ = 30 deg [base case]

= 50 deg

= 70 deg

Background pressure increase [Gbar], time = 9 ps



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 um 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
    $\Delta t \gg \omega_{\mathrm{plasma}}^{-1}, \omega_{\mathrm{light}}^{-1}$; $\Delta x \gg \lambda_{\mathrm{Debye}}, \lambda_{\mathrm{light}}$.
  - 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.

---

[1] D. 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 Lemons[1]: Manheimer[2] 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.

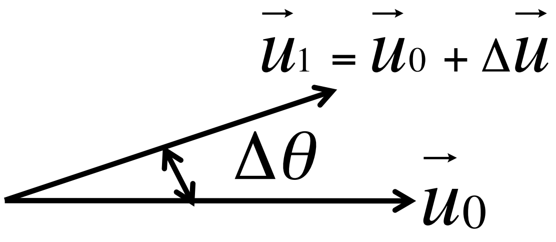
Momentum change in one timestep:

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

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

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

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



$\vec{u} = \gamma\vec{\beta}$ 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

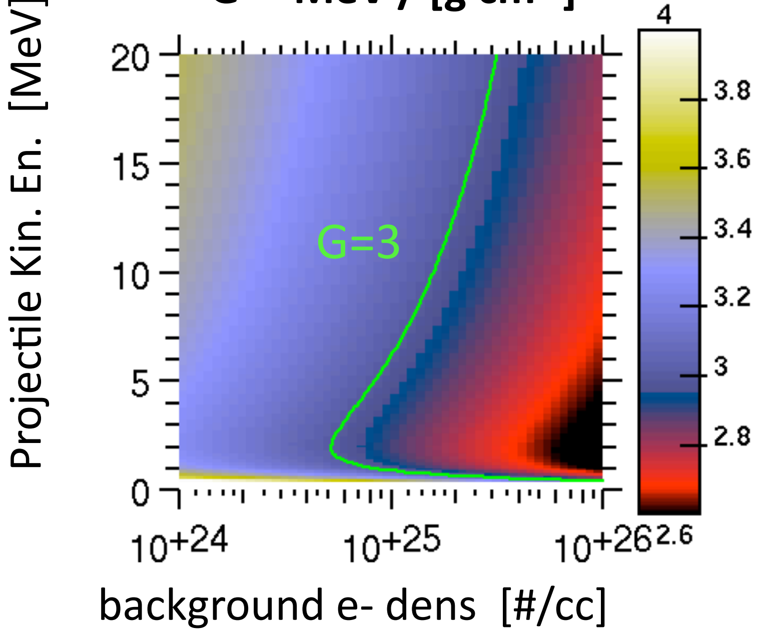
Energy loss

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

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

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

G MeV / [g cm^{-2}]



S. Atzeni et al., Plasma Phys. Contol. Fusion **51**, 015016 (2009);
A. A. Solodov and R. Betti, Phys. Plasmas 15, 042707 (2008)

Angular scatter

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

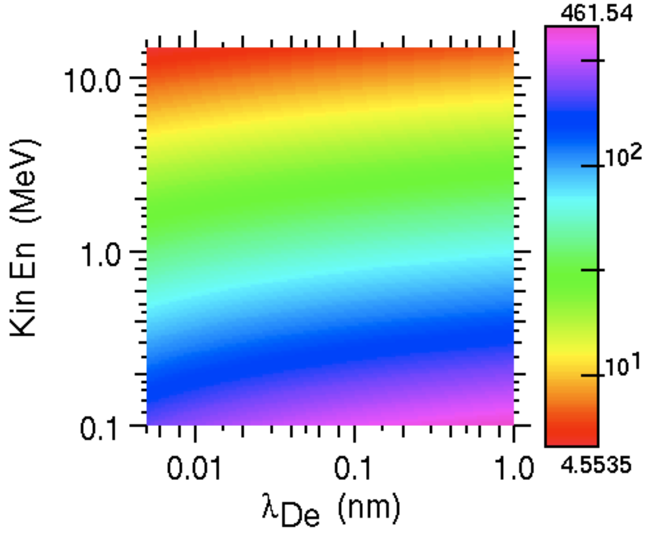
$$F_\theta^{\,2} = \frac{8\pi r_e^{\,2}}{\gamma^2\beta^4 m_p}\left(L_{sc,\,e} + Z_{eff} L_{sc,\,I}\right)$$

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

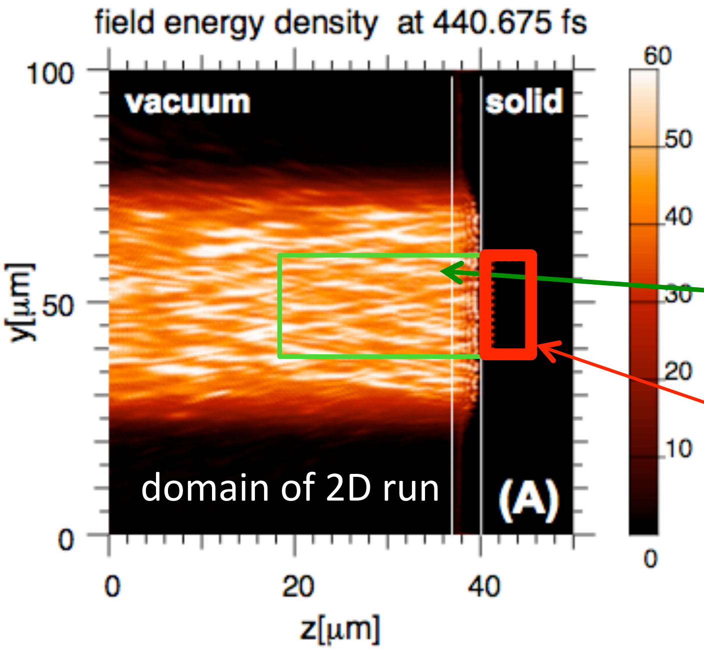
$$L_{sc,\,I} = \ln\Lambda - \tfrac{1}{2}(1 + \beta^2) \qquad \text{ions}$$

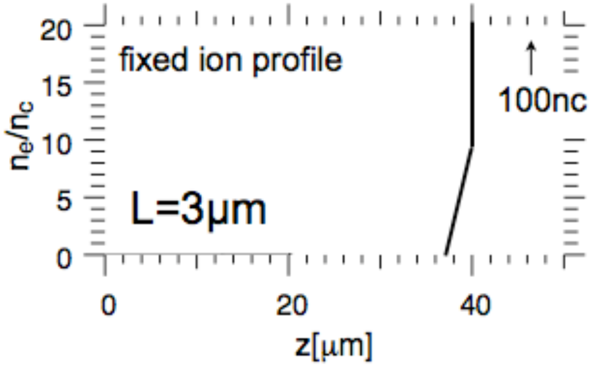
$$\Lambda = 2\lambda_{De}\frac{m_e c}{\hbar}\gamma\beta \sim \frac{\lambda_{De}}{\lambda_{deBroglie}}$$

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

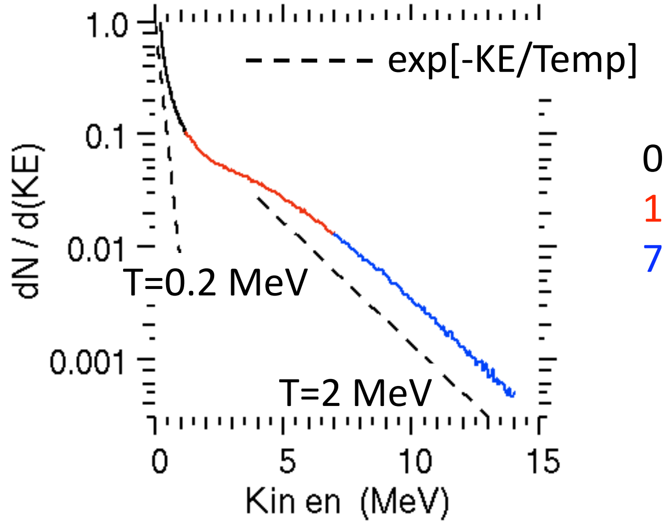
We select all electrons:

- 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”

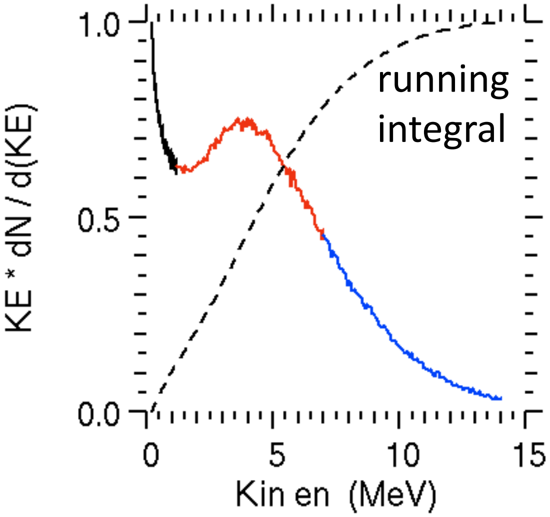
Kemp PIC run electron source: "two-temperature" energy spectrum; transversely somewhat isotropic

Number Distribution

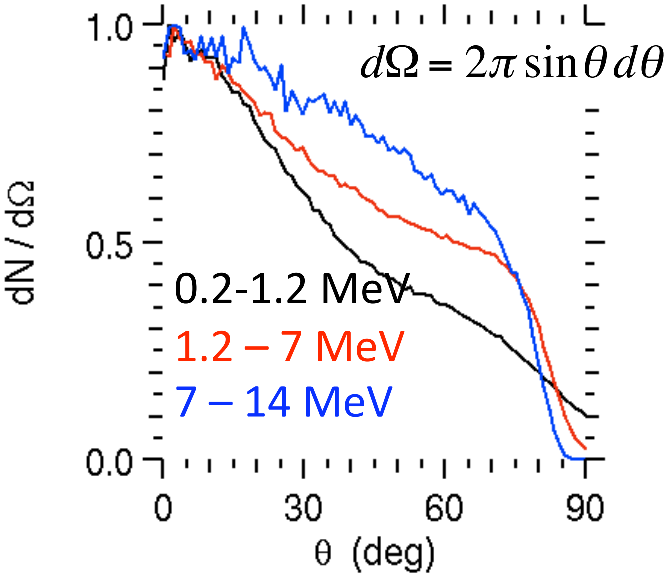


0.2-1.2 MeV
1.2 – 7 MeV
7 – 14 MeV

Energy Distribution



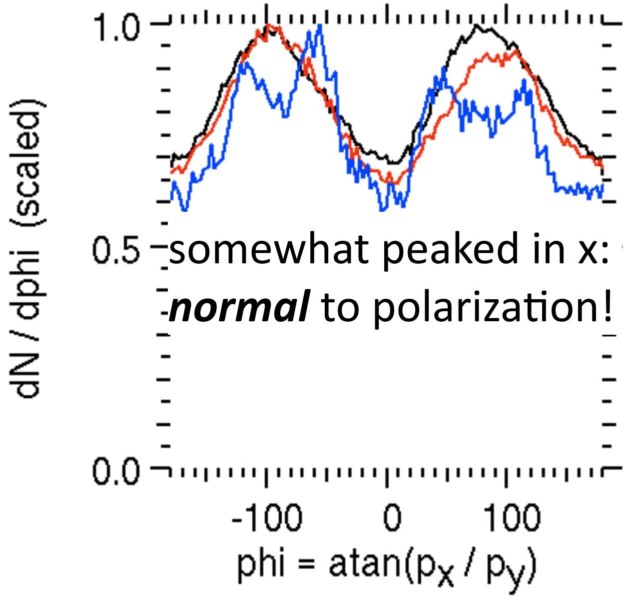
Solid Angle Distribution



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

0.2-1.2 MeV
1.2 – 7 MeV
7 – 14 MeV

Transverse distribution similar in the 3 energy bins



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