Electron Transport Simulations for Fast Ignition on NIF

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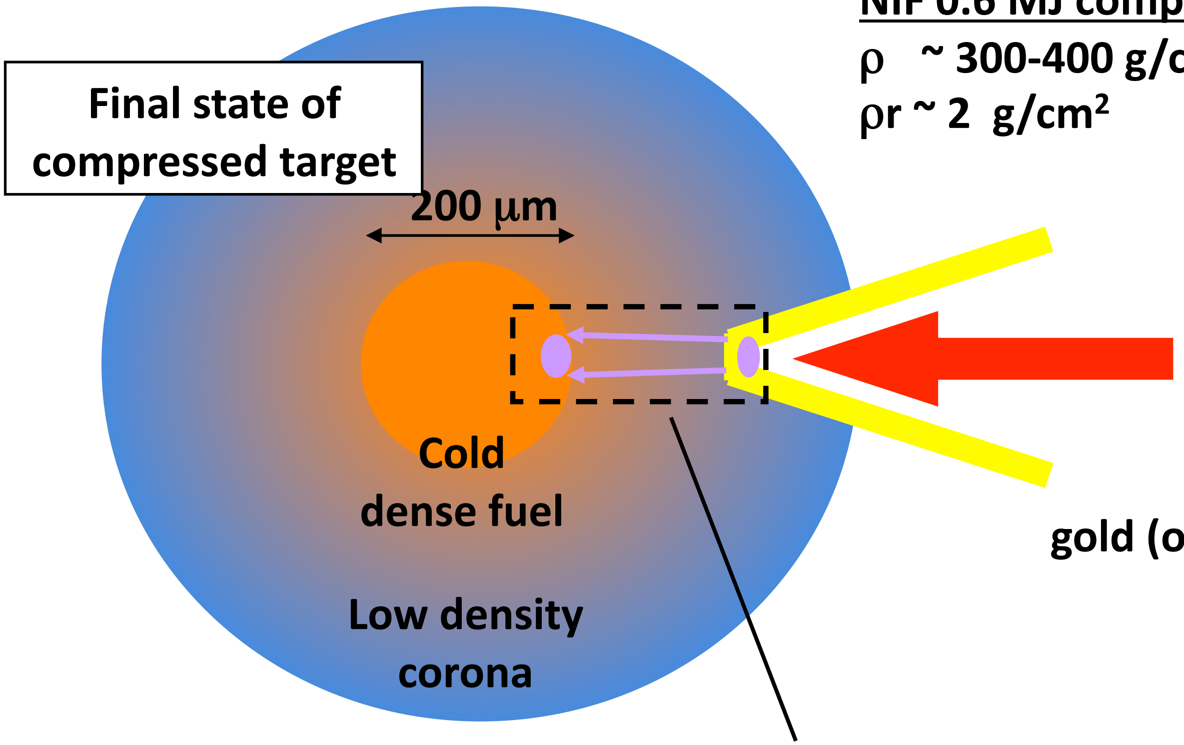
Summary: LSP hybrid-PIC code used for “core” transport; work in progress on high-Z, partially-ionized, non-ideal EOS materials

- Overview of fast ignition and our modeling approach.
- Fast electron energy loss and angular scattering.
- Characterizing explicit PIC electron source: energy and angular distributions.
- Results on a plastic (CD), NIF-ARC toy problem.

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

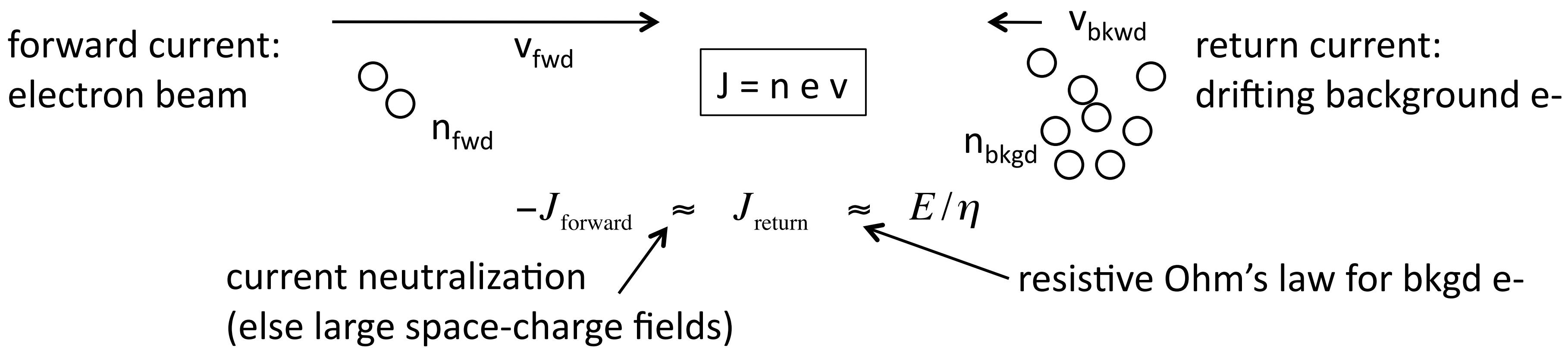
40 μm focal spot (~ FWHM)

Coupling expt, not ignition

gold (or other mid/high Z) cone

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

Electron beam transport physics: current neutralization



forward current:
electron beam

v_{fwd}

n_{fwd}

$\boxed{J = n\,e\,v}$

v_{bkwd}

return current:
drifting background e-

n_{bkgd}

$$-J_{\text{forward}} \approx J_{\text{return}} \approx E/\eta$$

current neutralization
(else large space-charge fields)

resistive Ohm's law for bkgd e-

- Un-neutralized forward current cannot exceed roughly the Alfvén limit $I_A = \gamma\beta * 17$ kA.
- Strong return current is drawn, allowing $I_{fwd} >> I_A$.

Beam-plasma instabilities:

- Weibel, two-stream, filamentation, ion acoustic drift, Haines (thermo-electric).
- Less important as $n_{bkgd} >> n_{fwd}$.

Electron beam transport physics: heating and B fields

Resistivity: $$\begin{aligned} \eta &\sim Z T^{-3/2}, \qquad T > 100\ \text{eV} \quad \text{(plasma)} \\ &\sim T, \qquad T < 10\ \text{eV} \quad \text{(metal)} \end{aligned}$$

Background heating:

- Low density: Ohmic J•E.
- High density: collisional dE/ds loss.

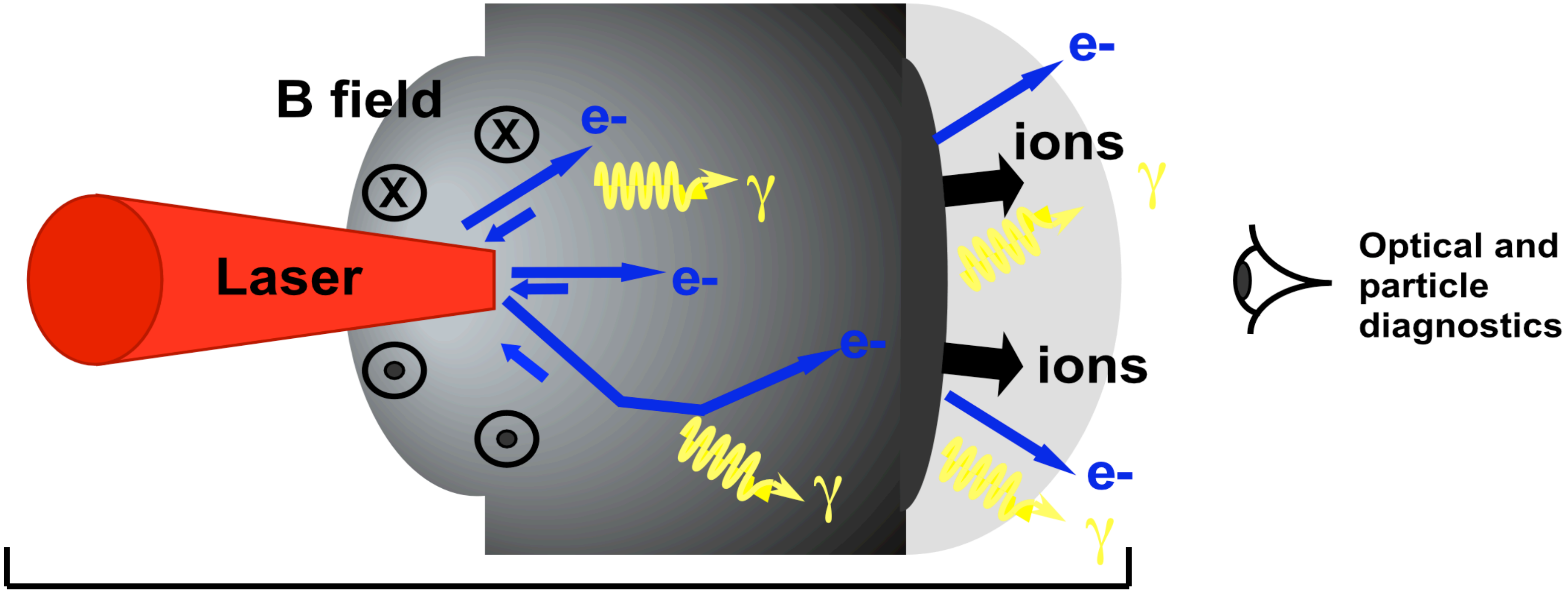
Magnetic fields can help:

- Collimate forward e- beam (pinching).
- Roll up orbits in fuel, increase dE/ds energy loss.
- More B growth in more resistive (cold, high-Z) regions.
- B-field engineering: pre-pulses, mid-Z “lenses”, ... (future work).

$$\partial_t \vec{B} = -\nabla \times \vec{E} \approx \nabla \times (\eta J_{fwd})$$

$$\rightarrow \partial_t B_\theta = -\partial_r (\eta J_{fwd})$$

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



HYDRA / LASNEX: hydro evolution (ns / mm)

$n_e \sim 10\text{-}100\ n_{crit}$

"LPI"

Hot e- generation (ps / 100μm):

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

"Transport"

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

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

Integrated simulations

- Hydrodynamics:
  - Profiles generated at ignition laser time.

- Laser-plasma interaction (LPI): laser into fast electrons:
  - PSC , Z3 for electron distribution (1D reduced distributions or functional fits, not raw particles).
  - Hand-off to transport after “steady-state” source achieved in density 10-100 n_{crit}.

- Electron transport: fast electron propagation and deposition
  - LSP in implicit mode with “fluid particles” for background plasma.
  - Calculate energy deposited in fuel.

- Future options:
  - LSP (or hybrid PSC) to self consistently perform LPI and transport.
  - ZUMA (Larson’s Davies/Honrubia model, resistive background) for quick answers.

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

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

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[1] D. R. Welch, et al, Nucl. Inst. Meth. Phys. Res. A 242, 134 (2001).

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

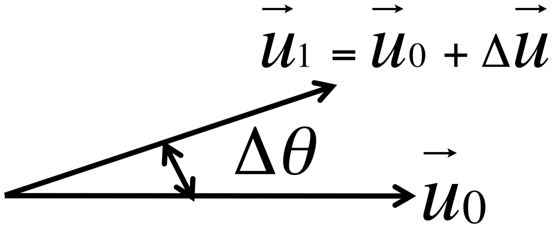
- Grid-based algorithm: test particles off field particles; field density, drift, temperature found on each spatial grid cell.
- Polar momentum coordinates: like Lemons[2]; Manheimer[1] presented similar method in Cartesians with drag and diffusion.
- Collisions of background plasma off fast electrons: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

Momentum change in one timestep:

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

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

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



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

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

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

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

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

W = energy transfer.

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

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

low-energy, long range:
Langmuir-wave emission

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

$$\frac{d\gamma}{dx} = -4\pi r_e^{\,2} \frac{n_e}{\beta^2} L_{stop} \qquad L_{stop} = \ln\left[\frac{m_e c^2}{\hbar\omega_p} \beta[\gamma - 1]^{1/2}\right] + \frac{9}{16} + \frac{\ln 2 + 1/8}{\gamma}\left(\frac{1}{2\gamma} - 1\right)$$

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

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

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

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) .

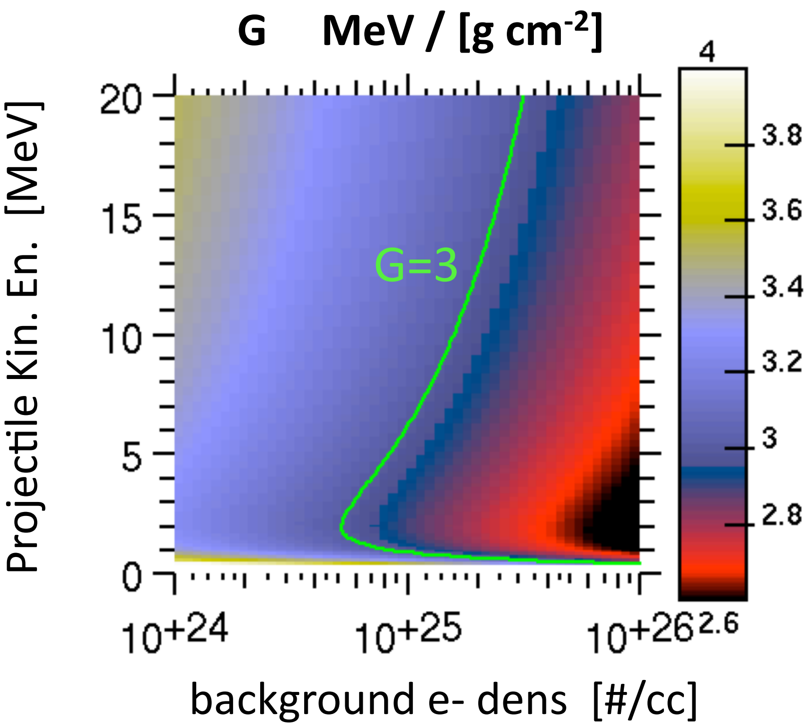
Electron energy loss: off electrons, not ions

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

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

- 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;
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3. International Commission on Radiation Units and Measruements (ICRU) Report 37 (1984)

Angular scattering: fast electrons off electrons and ions

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

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

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

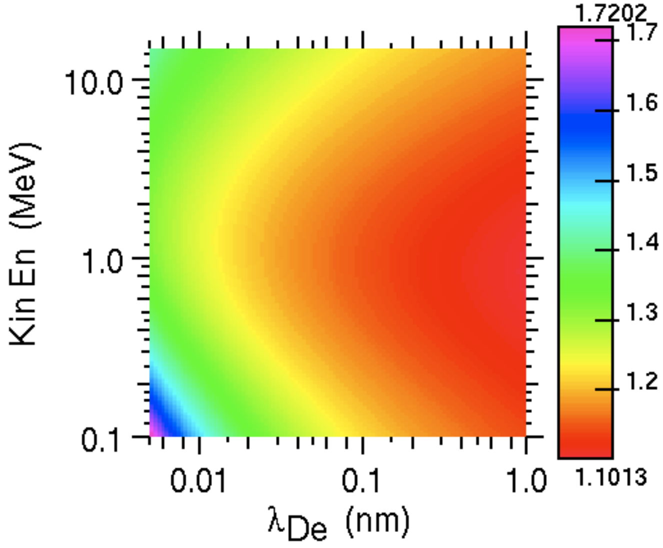
$$L_{sc,\,I} = \ln\Lambda - \tfrac{1}{2}\left(1+\beta^2\right) \qquad \text{ions}$$

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

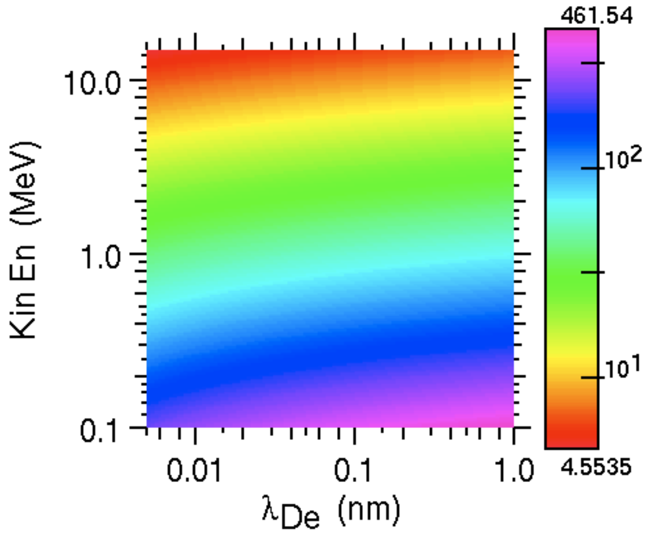
$$\lambda_{De} = \text{bkgd e - Debye length}$$

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

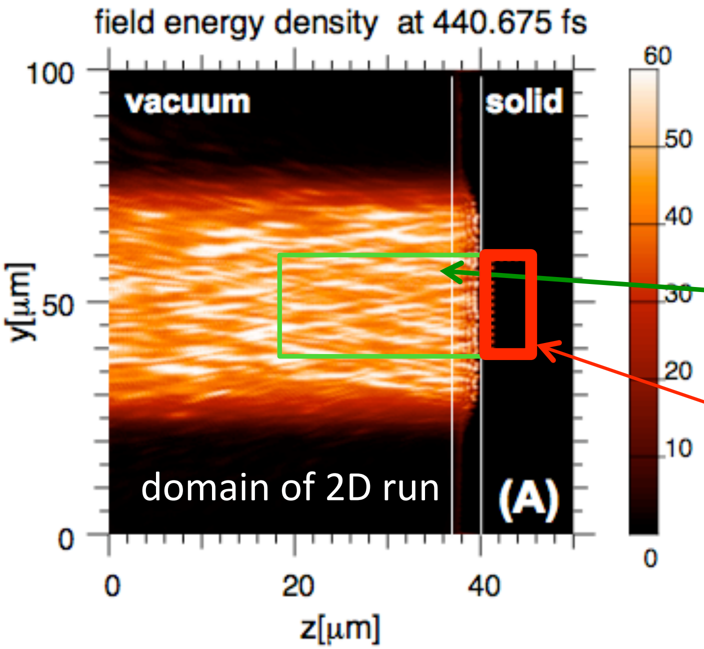
$L_{sc,I}$ / $L_{sc,e}$ (comparable)

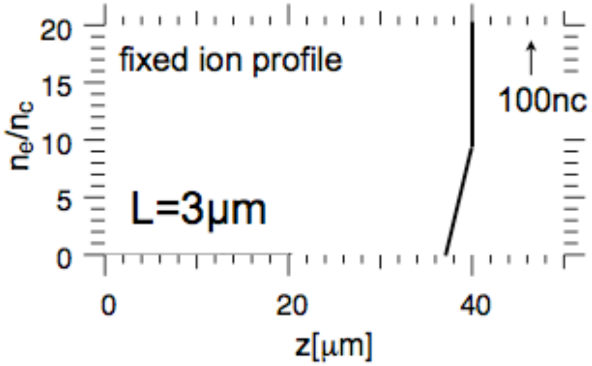


F_θ , Z_{eff}=1 [deg • (cm^2/g)$^{1/2}$]



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

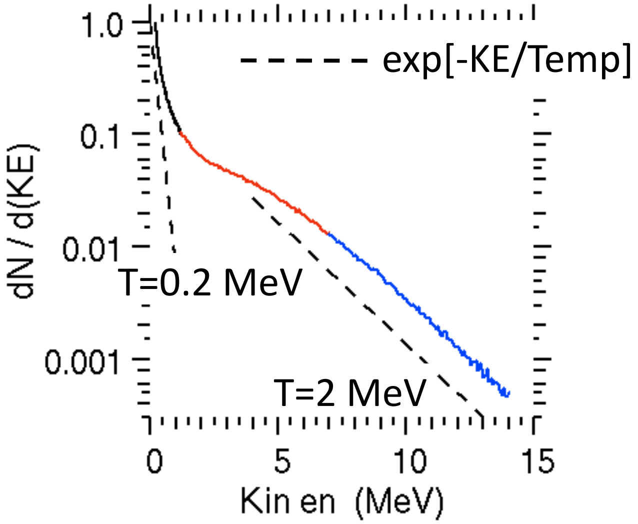
3D run domain

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

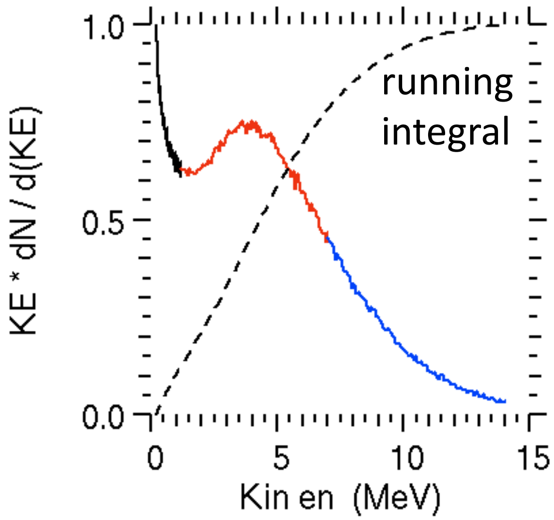


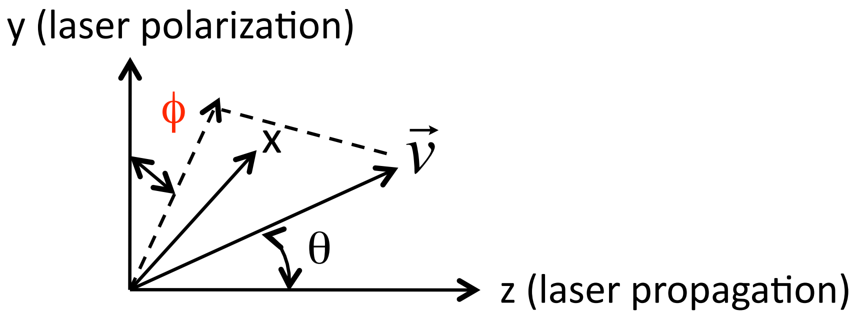
0.2-1.2 MeV

1.2 – 7 MeV

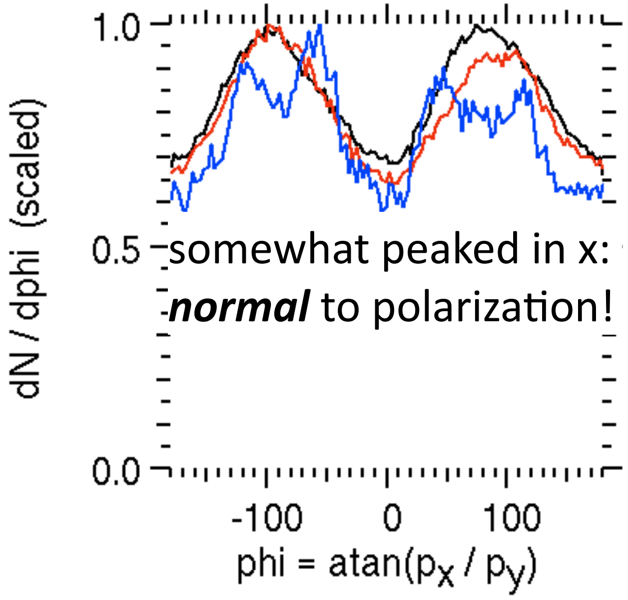
7 – 14 MeV

Energy Distribution





Transverse distribution similar in the 3 energy bins

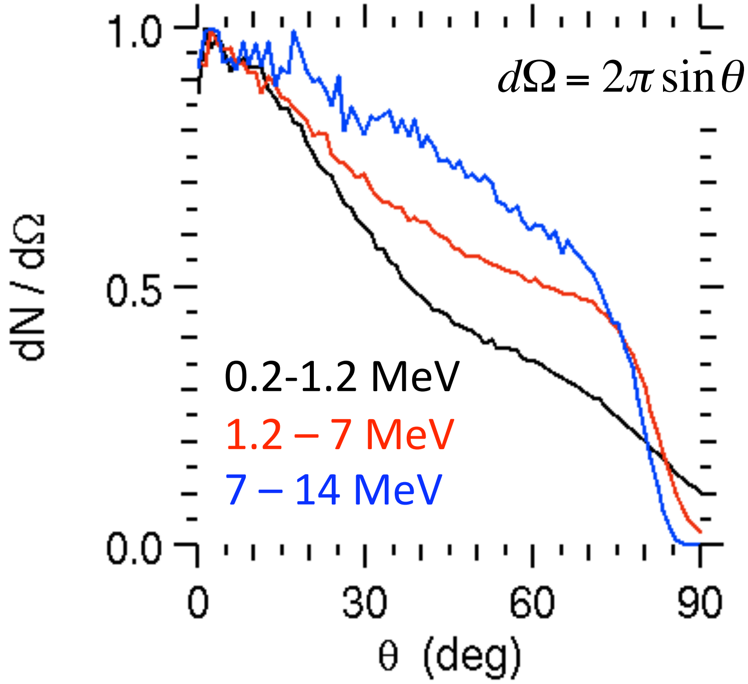


somewhat peaked in x: ***normal*** to polarization!

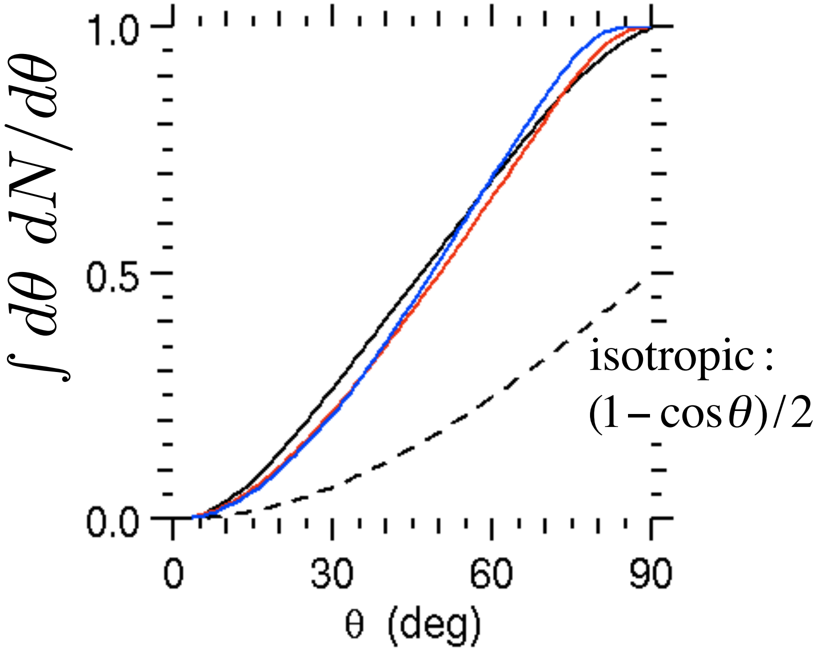
Cylindrical R-Z LSP simulations treat distribution as transversely isotropic.

Run “point 3.4”

Electron source: Angular spectrum fairly broad



Solid Angle Distribution



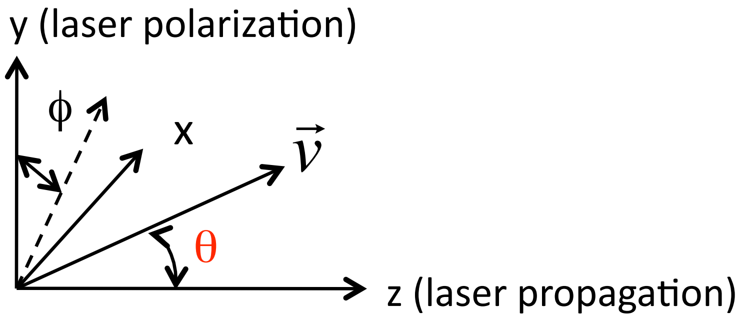
Cumulative Polar Angle Distribution in the forward half-space

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

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

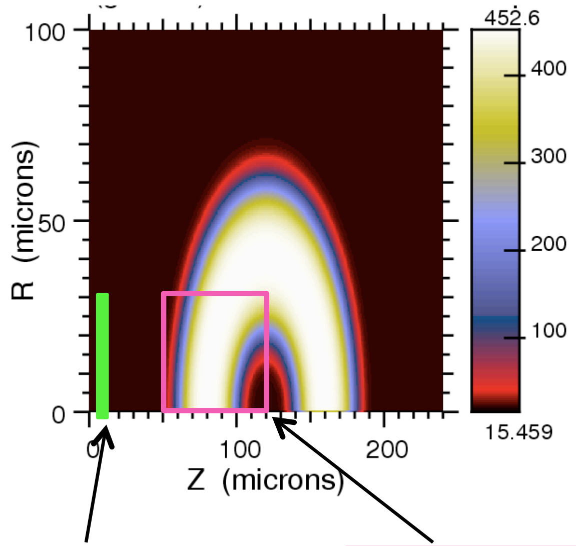
i = for each energy bin

- We use energy and angle spectra taken from PIC.

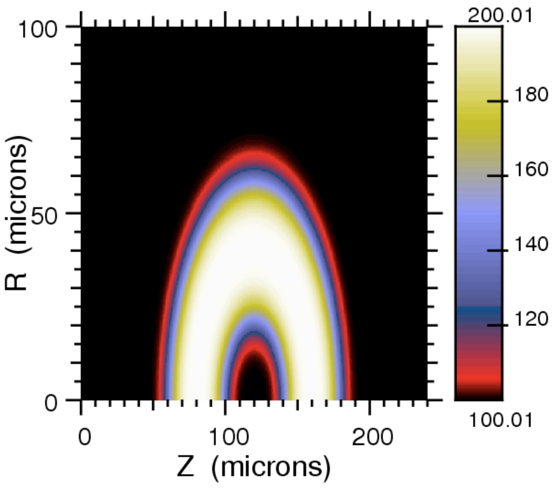


NIF-ARC toy problem: “rev. 1.2” transport profile

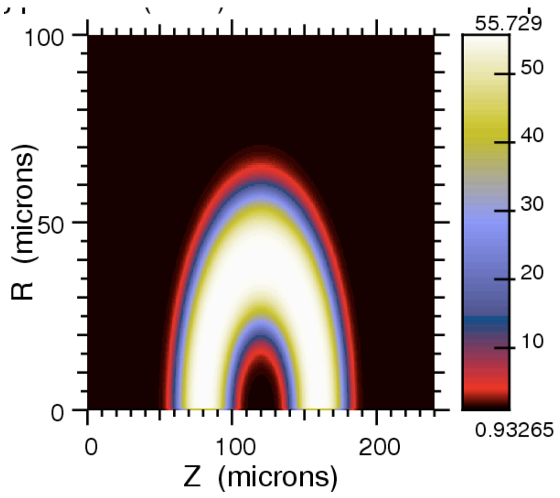
Initial mass density [g/cc]



Initial temperature [eV]



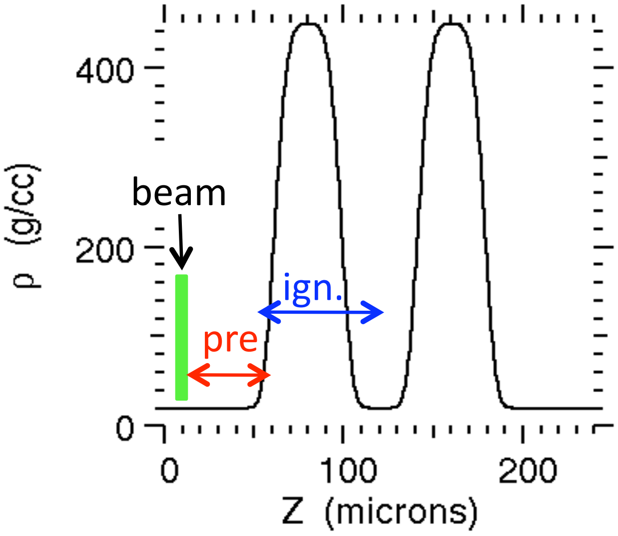
Initial pressure [Gbar]



Electron beam excitation region

Ignition region

- 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).



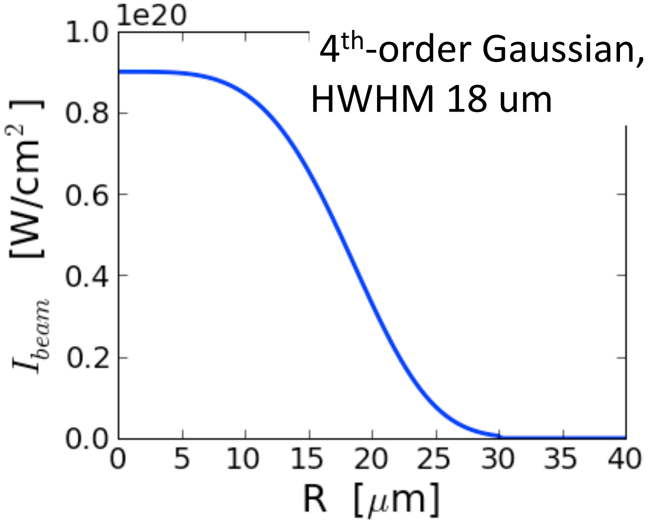
pre-fuel: $\rho r = 0.08$ g/cm^2; $\Delta E \approx -0.12$ MeV

ignition: $\rho r = 1.7$ g/cm^2; $\Delta E \approx -2.1$ MeV

NIF-ARC run: electron beam source

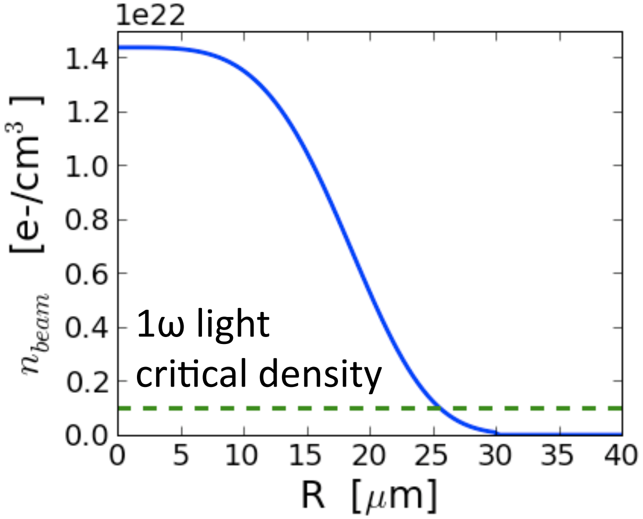
Energy and angle spectrum taken from Kemp point3.4 3D PIC run.

Beam intensity



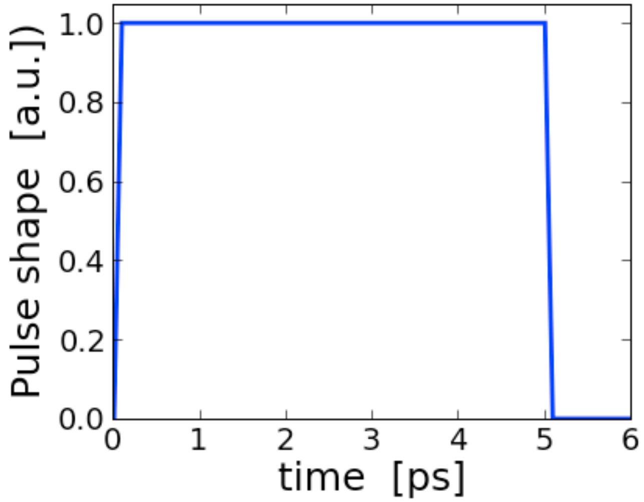
4^{th}-order Gaussian,
HWHM 18 um

Beam density: may be unrealistically high (preliminary PIC shows n_{beam} <= 2 n_{crit})



1ω light
critical density

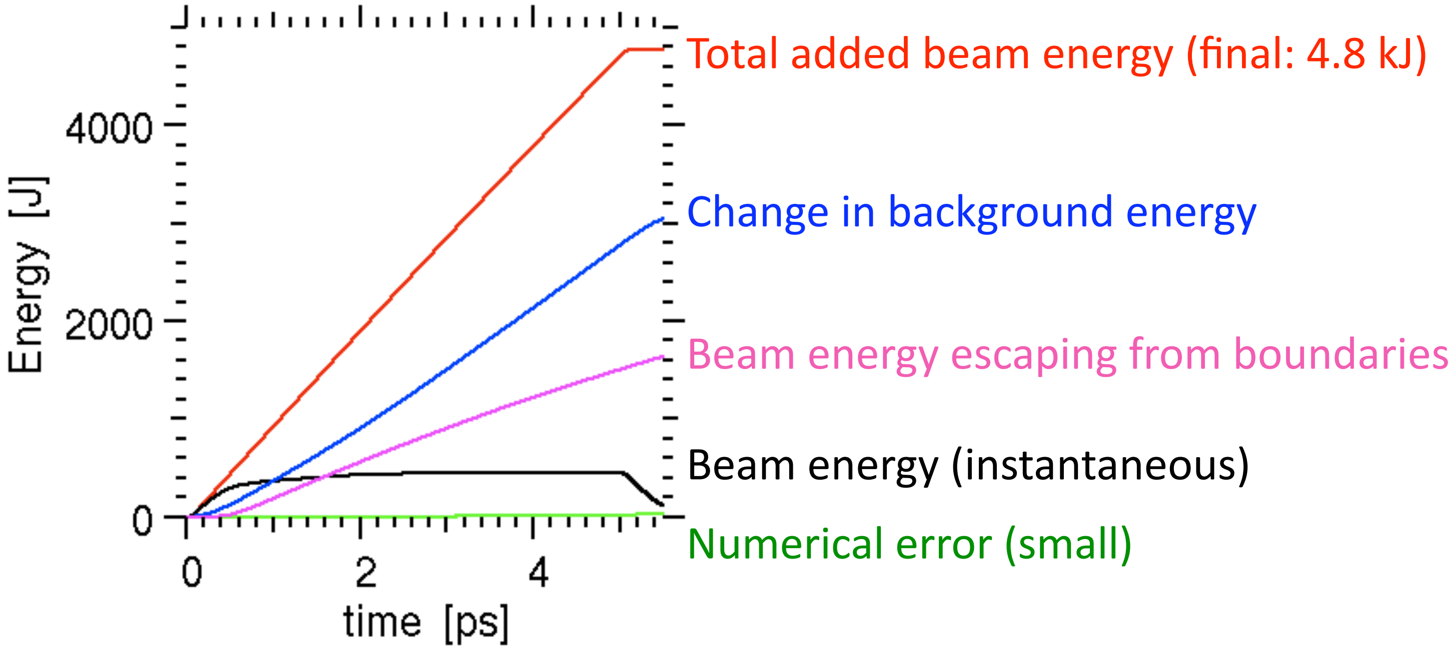
Pulse shape:
flattop for 5 ps



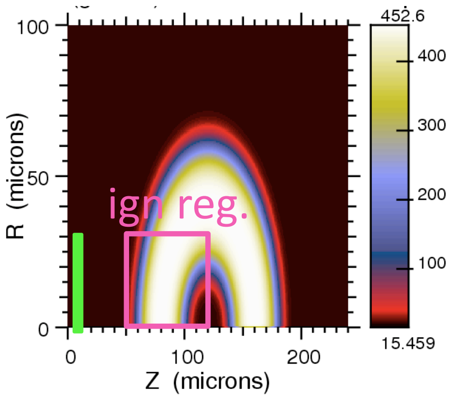
Total energy: 4.8 kJ
Peak power: 960 TW

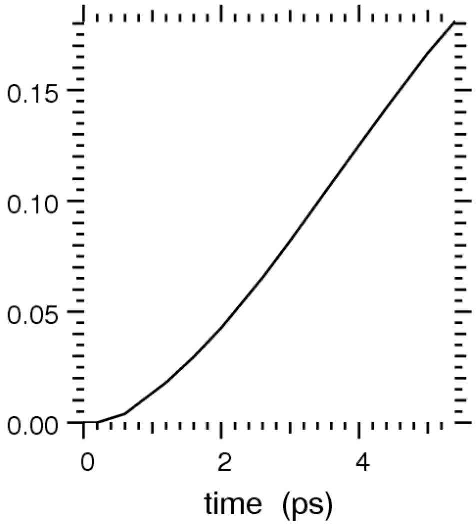
NIF-ARC should give 9 kJ laser energy; PIC rersults show ~ 50% conversion into energetic electrons.

NIF-ARC run: energetics



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

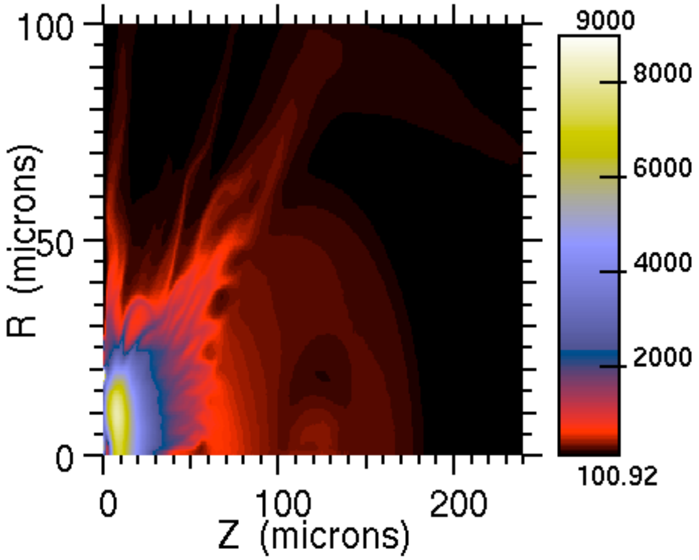




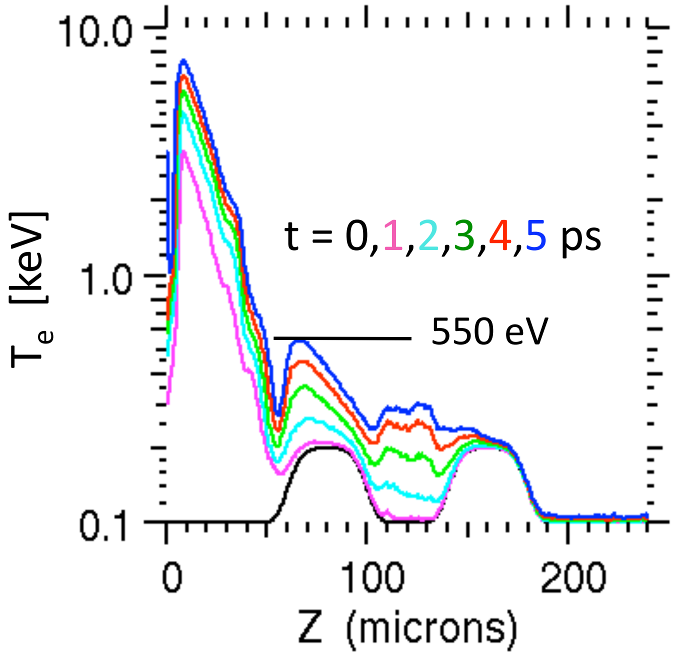
About 20% of beam energy deposited in ignition region.

NIF-ARC run: Heating

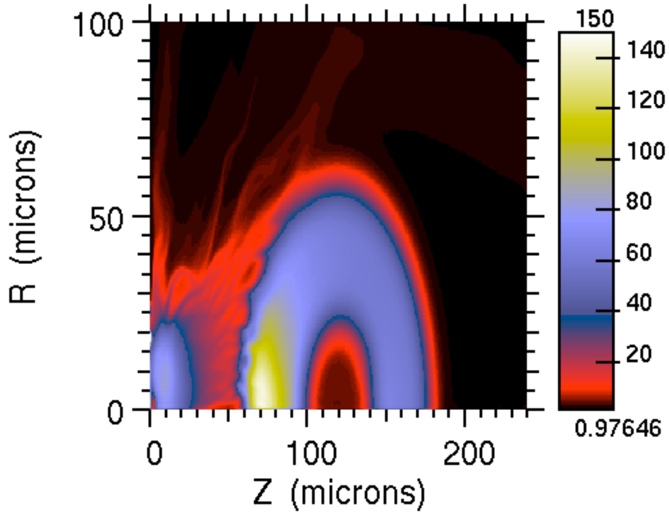
Background e- Temp (eV) at 5.4 ps



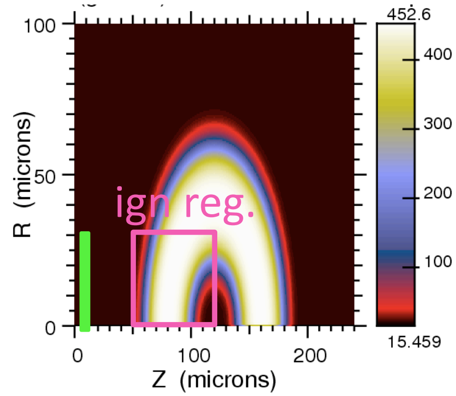
Background e- temp. at r=0



Background pressure (Gbar) at 5.4 ps

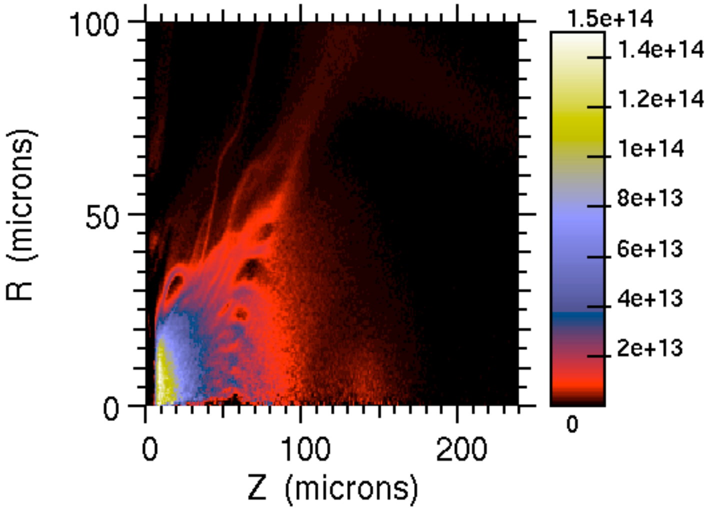


Initial peak pressure: 56 Gbar.

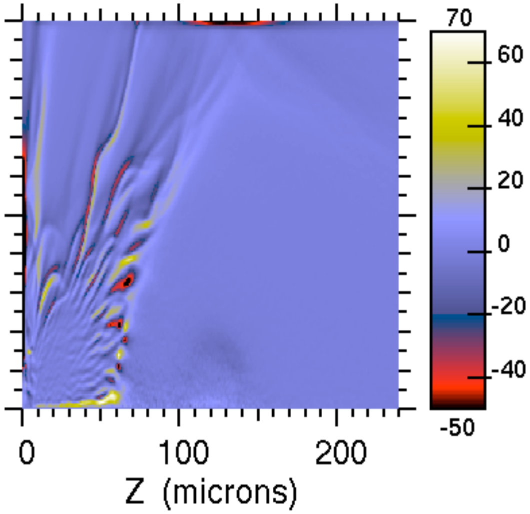


NIF-ARC run: currents and B fields

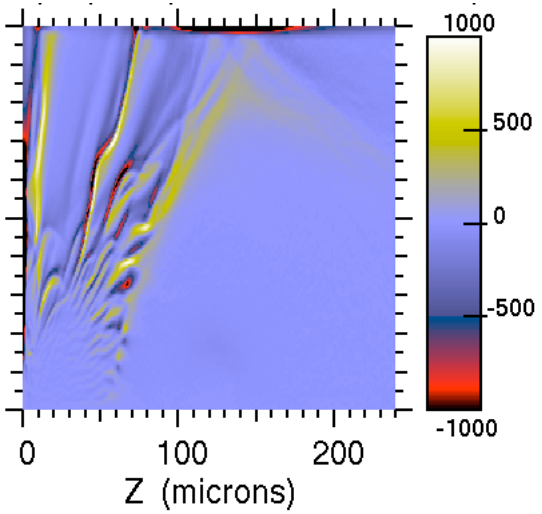
Beam current at 3 ps

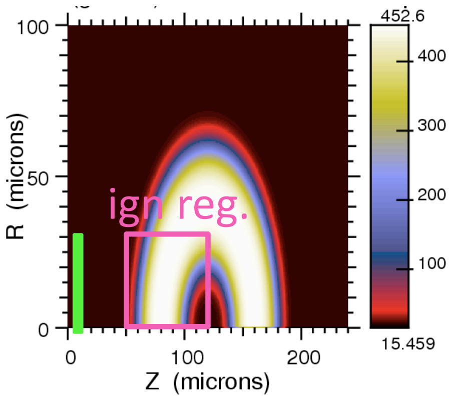


Azimuthal B field (MG) at 3 ps



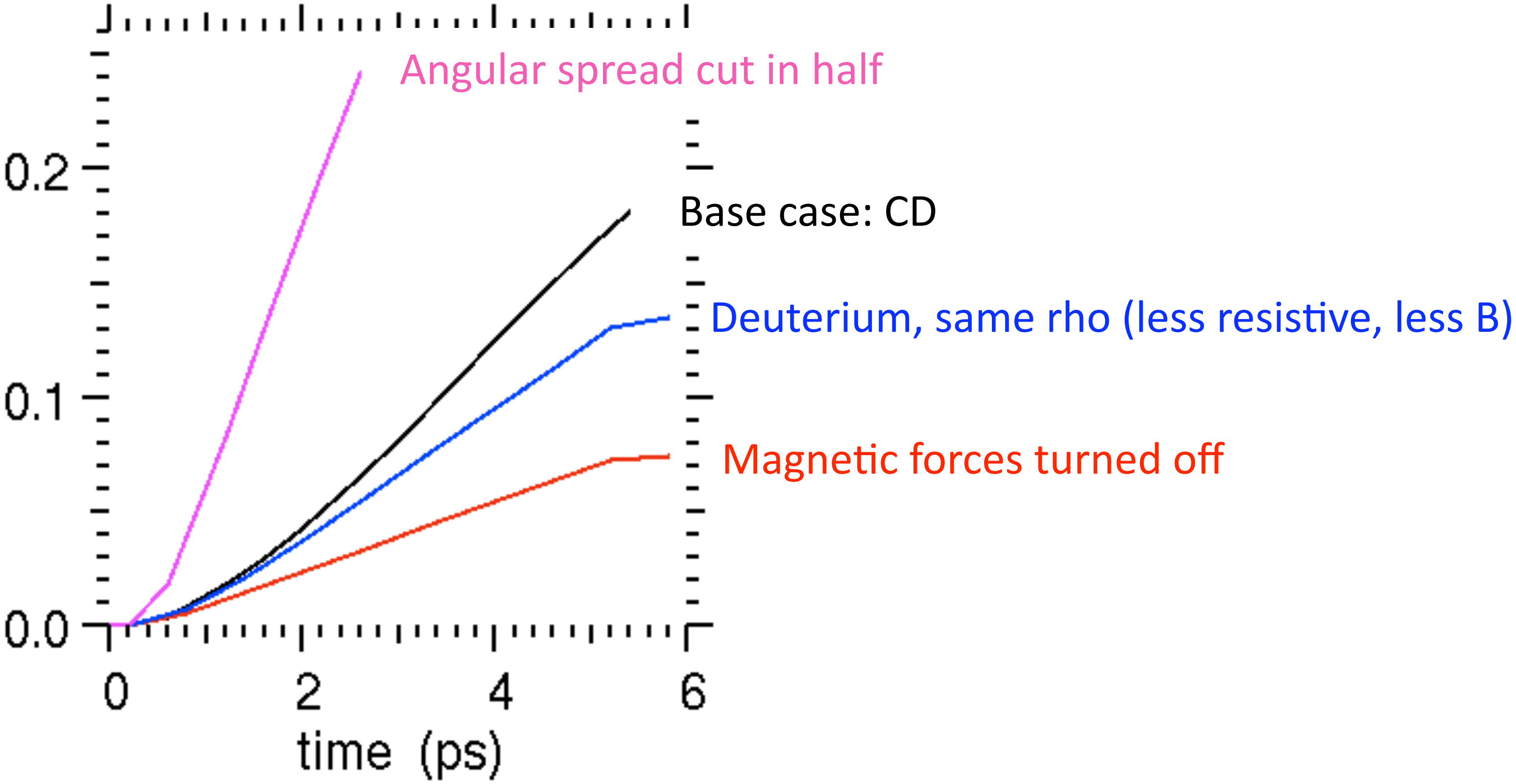
Enclosed net z current (kA) at 3 ps





NIF-ARC runs: B fields, more collimated beam give better coupling

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



Summary and Future Work

In a "best case" NIF-ARC hydro configuration, we couple 20% of the electron beam energy into the ignition region. Magnetic fields and smaller angular spread both help.

- LSP code: improvements to handle ionization, loss off bound electrons, non-ideal EOS.
- Full-scale ignition: can we ignite DT? Surrogacy w/ warm CD target with less beam energy.
- DT jet: some hydro designs have a high-pressure jet that deforms the cone tip. What is transport through this?
- Beam collimation: can we reduce angular spread by growing B fields with low-intensity pre-pulse? Can we make resistive "lenses"?
- Green (2w) light: is this preferable to a 1w short pulse laser?