Computational capabilites and needs for Fast Ignition

IPAM

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Max Tabak

Lawrence Livermore National Laboratory

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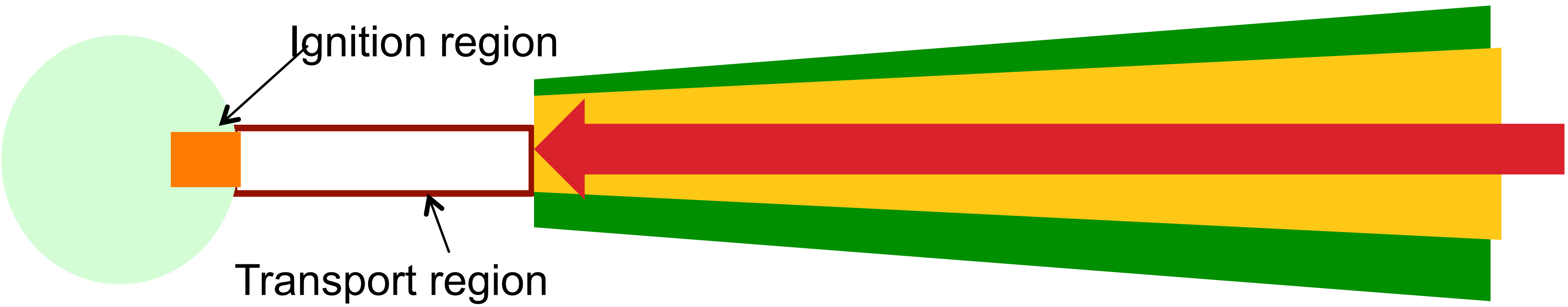
Collaborators

- D. Strozzi
- D. Larson
- A. Kemp
- L. Divol
- B. Cohen
- C. Thomas
- C. Chen
- A. Link
- M. Marinak
- P. Patel

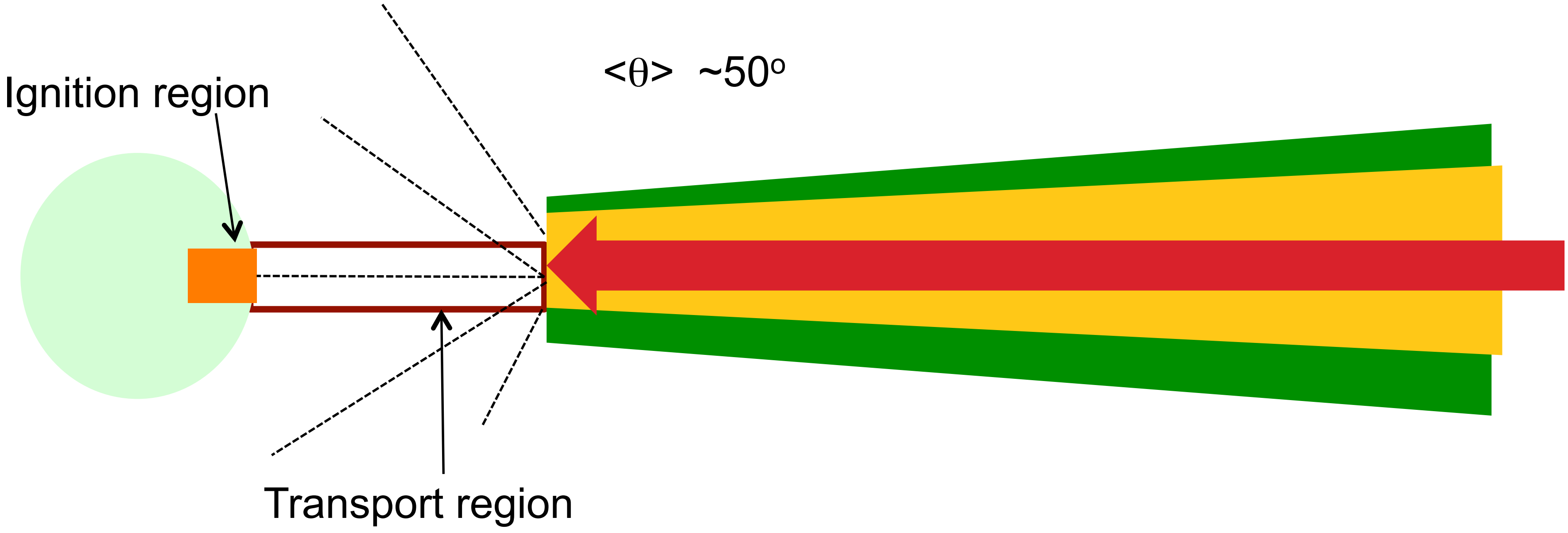
Innovations in modeling have changed our understanding of Fast Ignition and required innovations in design

- Increases in processing power of supercomputers and changes in algorithms enable calculation of integrated Fast Ignition targets from capsule implosion to laser injection to thermonuclear burn
- Hot electrons produced in the laser-plasma interaction populate a larger phase space than earlier experiments and calculations suggested
- Ideas for channeling electrons and increasing the coupling of electrons are being developed

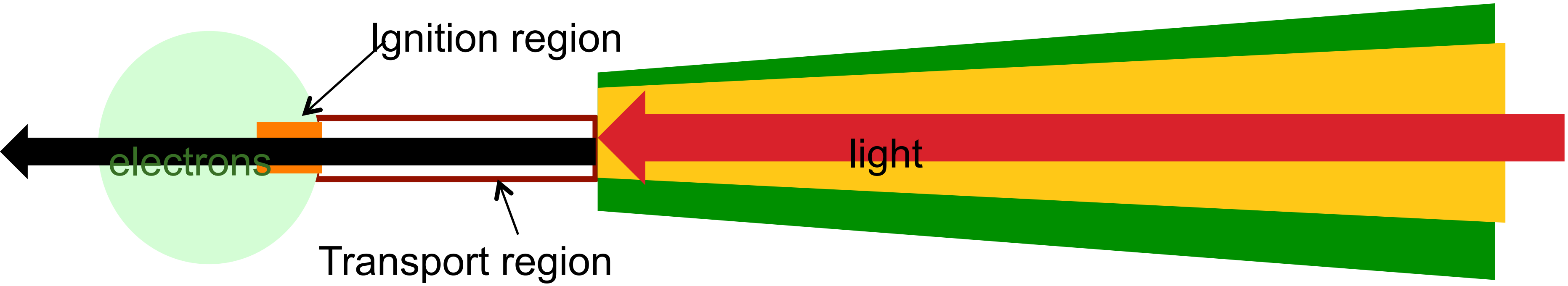
Fast Ignition first precompresses fuel and then heats a fuel region to ignition conditions with a fast driver(laser or particle beams)



But the laser plasma interaction produces a divergent source



And the electron range can become much longer than optimum



Want to heat $\rho\delta z$ ~< 1.2g/cm^2 from burn dynamics
Electron range(g/cm^2) ~ 0.8 E(MeV)
For 300g/cm^3 want to deposit 20kJ in 20ps in 20μm radius

=>$I_{electron}$ ~ 9e19W/cm^2

But laser -> electron coupling only 25-50%

=>I_{laser} ~2e20W/cm^2 => E~6MeV for 1ω light

$\Rightarrow$Range ~4.8g/cm^2 or 4 optimal ranges

Required laser energy grows rapidly with coupling inefficiency

- In relativistic regime particle range,R ~ $E_{particle}$ ~$(I\lambda^2)^{1/2}$
- $E_{laser} \sim E_{req}/(\eta_{geo}\eta_{LPI}\eta_{range}) \sim E_{req}/(\eta\, R_{wanted}/R)$

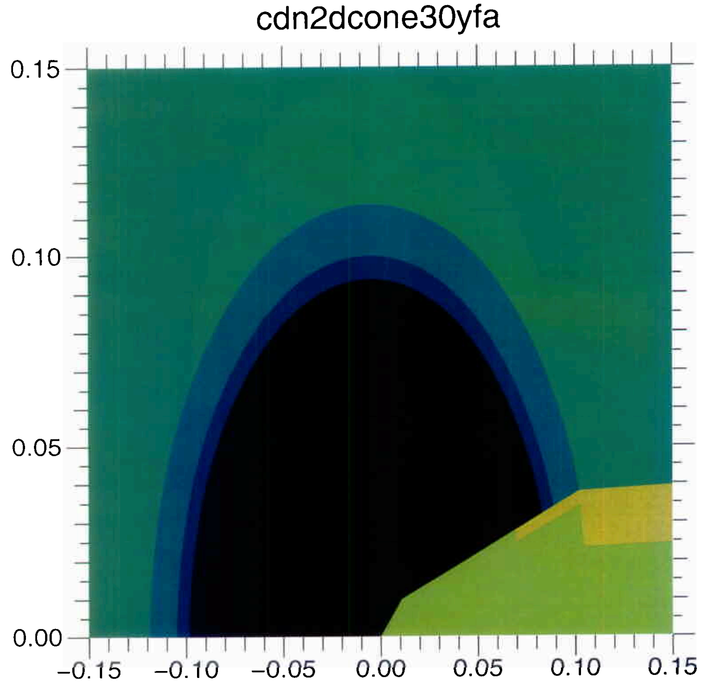
  $\sim E_{req}/\eta/(I\lambda^2)^{1/2} \sim E_{req}E_{laser}{}^{1/2}/\eta$

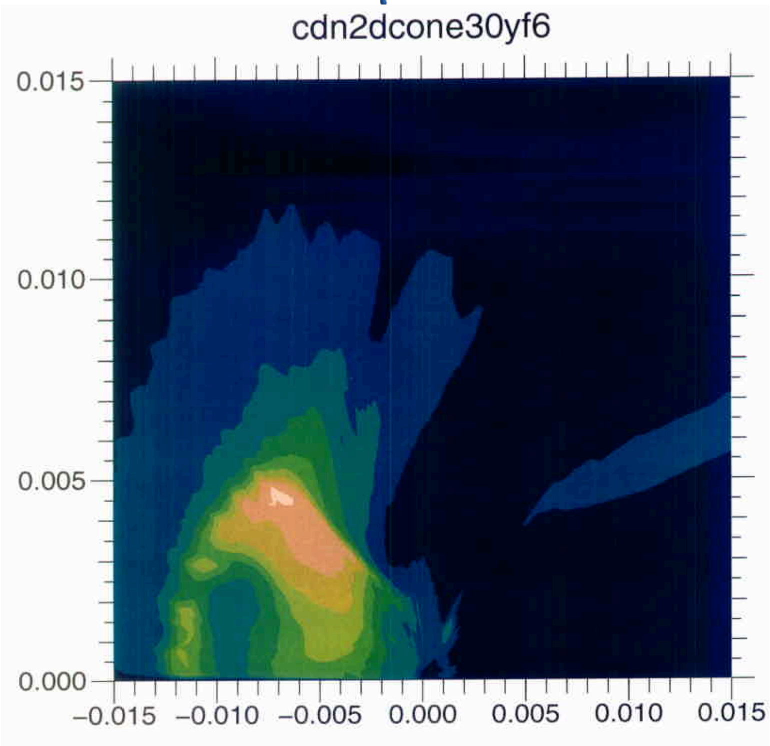
  => $E_{laser} \sim (E_{req}/\eta)^2$
- 20 kJ grows to 320 kJ laser even with perfect transport and optimum fuel assembly
- Requirements: good fuel assembly, efficient transport
- Possible improvements: smaller λ, innovative ways to soften spectrum(reduce I), targets that capture bigger fraction of range

Integrated Fast Ignition calculations have several important parts

- Assemble fuel with standard radiation hydrodynamics codes(e.g.,Lasnex or Hydra)
- Couple short pulse laser to matter with PIC code
- Transport hot electrons from critical surface to ignition region
- Thermonuclear burn and disassembly (Hydrocode coupled to transport code)

Radiation-hydrodynamic calculations that result in fuel-laser separation ~50μm exist





It is unlikely that the separation between laser and fuel will be much less than 50 μm

Integrated Fast Ignition calculations have several important parts

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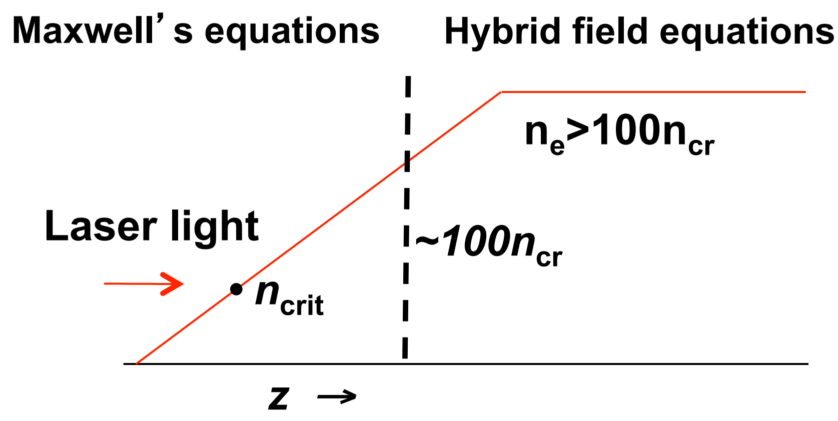
A hybrid code that combines collisional PIC with a particle based solver for resistive MHD was used to calculate LPI at high density and long durations

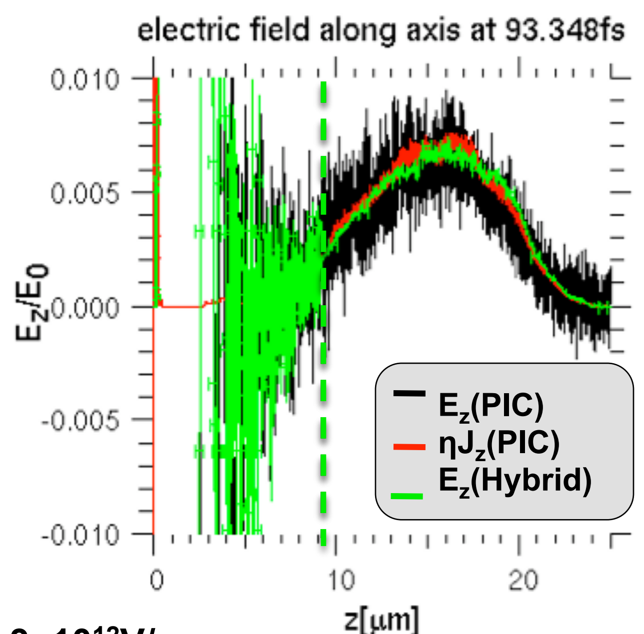
- Remove light waves and electron plasma waves in background by dropping displacement current & electron inertia in Ohm's law
  - ➔ relaxes constraints set by plasma frequency, Debye length & skin-depth in the high-density region where waves are heavily damped
- Conductivity tensor determined from Braginskii expression



Cohen, Kemp, Divol, JCP **229**, 4591 (2010).

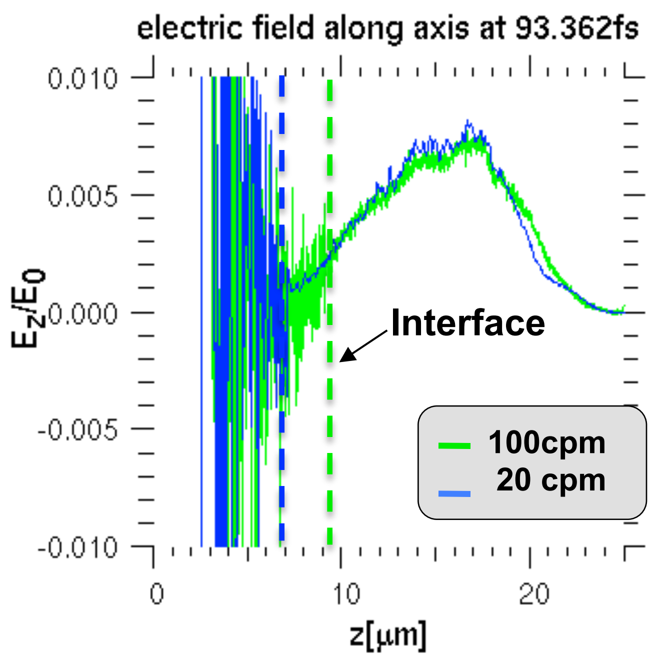
The hybrid approach reproduces highly-resolved PIC results at 5x lower resolution – resulting in significant speed-up

(A) agreement with Collisional PIC at 100 cells per micron



$E_0=3\times10^{12}$V/m

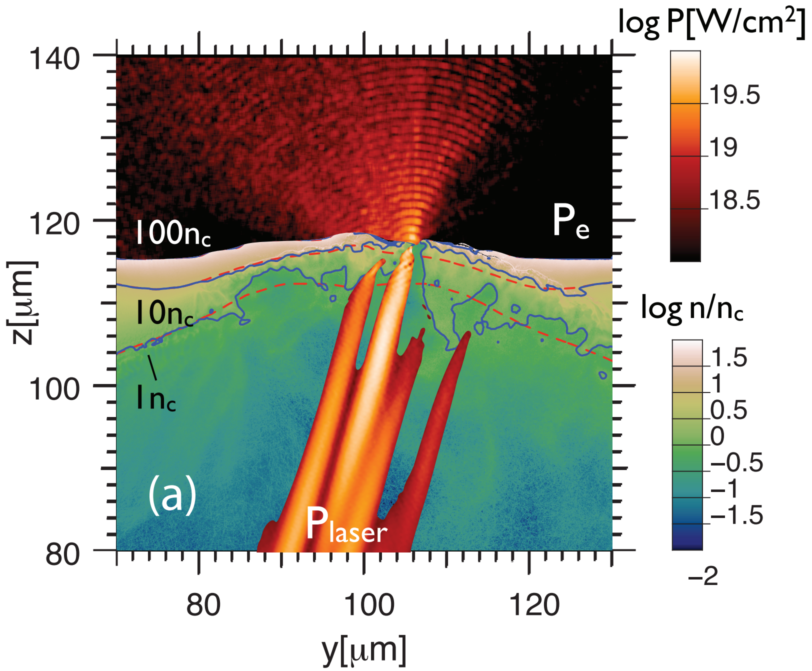
(B) consistency of results at 100 and 20 cells per micron



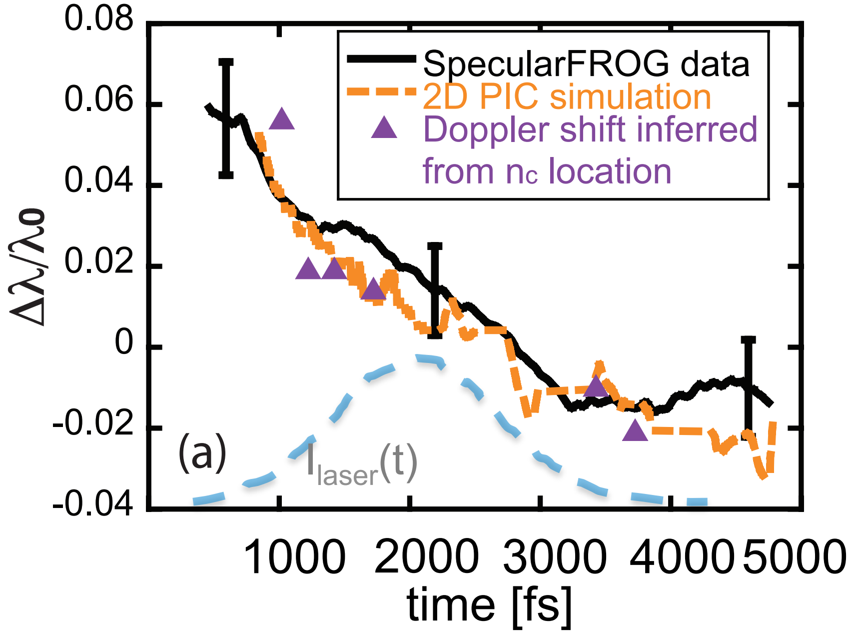
PIC-Hybrid allows us to model cold solid-density plasma in 2D with a speed-up factor 125

The hybrid code explained the time-dependent Doppler shift of reflected light in experiments

Laser and electron flux @ peak power



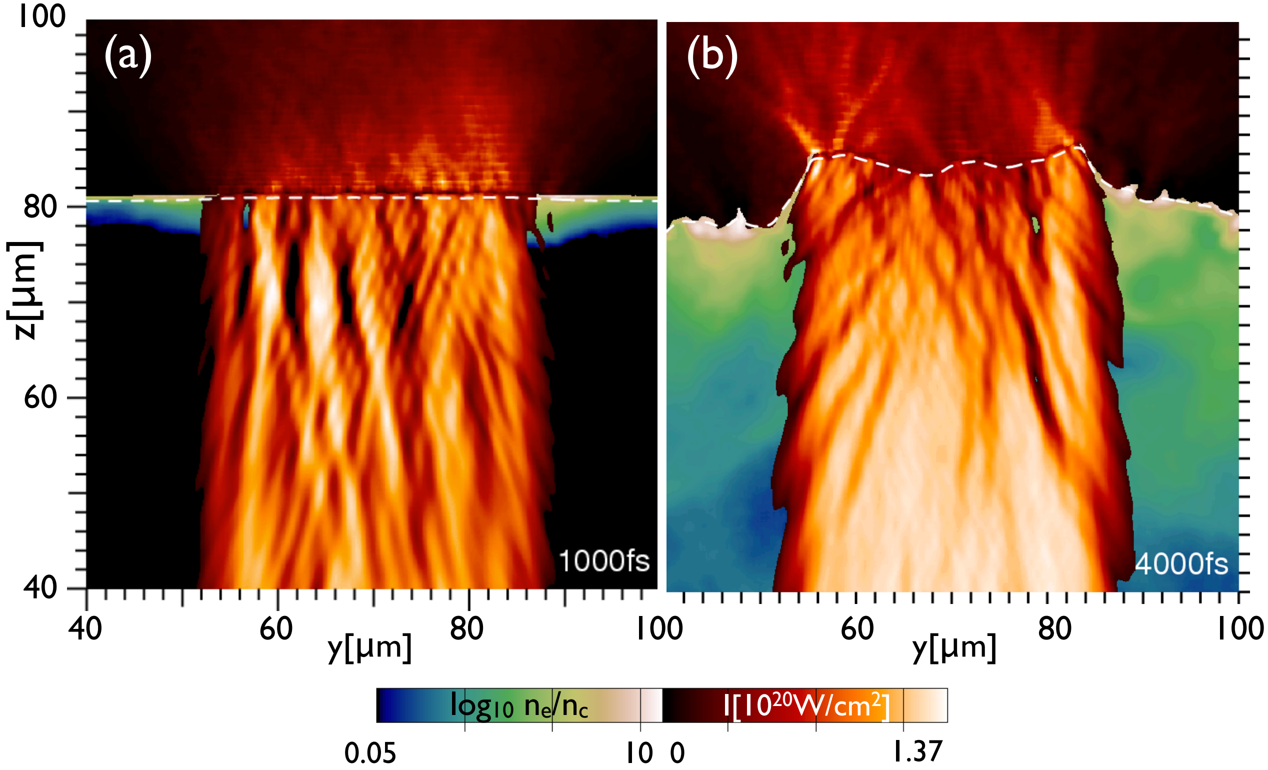
Line-out of FROG / PIC spectra



Simulation box 180x140um
32cells/micron 50particles/cell
74time steps / laser cycle
Absorbing b.c. (z); periodic in y

Wavelength shift compares well to FROG
Consistent with Doppler shift from
motion of critical surface (in 2D PIC)

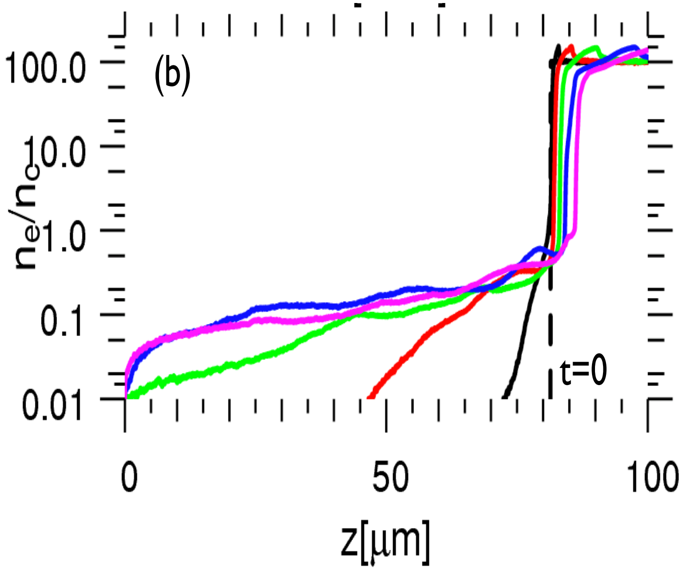
The hybrid approach allows simulation of ignition scale plasmas for long times

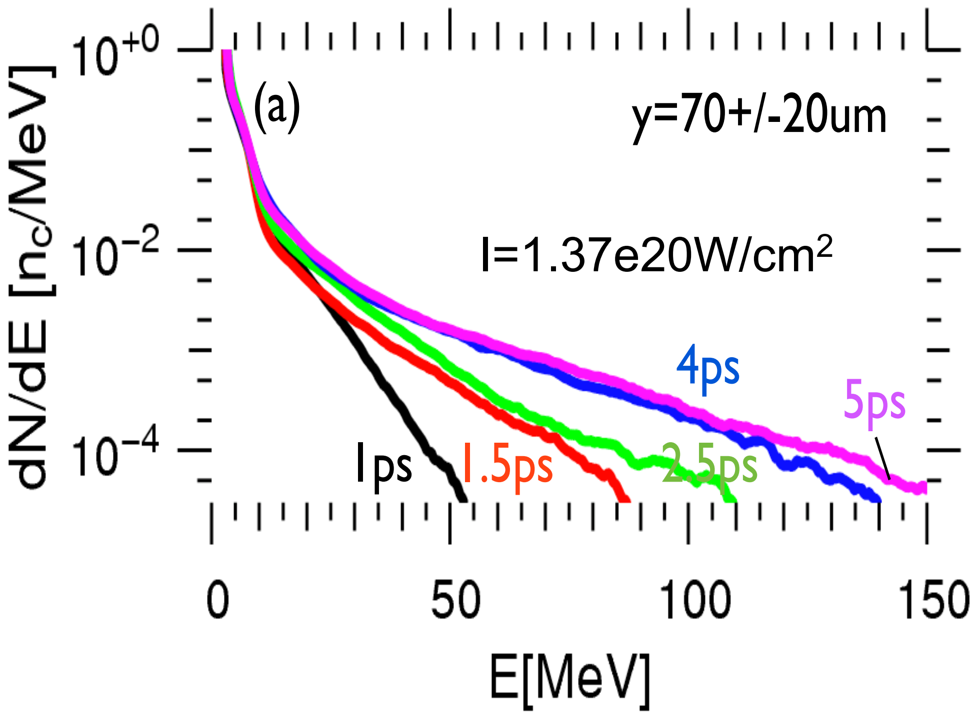


Grid Δy=Δz=(1/50) μm, time step ΔT=0.03fs
120electrons and 40ions per cell
Box size 140x120micron

PSC predicts that the high energy tail grows with time along with the underdense plasma

On a picosecond time scale the vacuum in front of target fills with under-dense plasma, leading to acceleration up to 150MeV



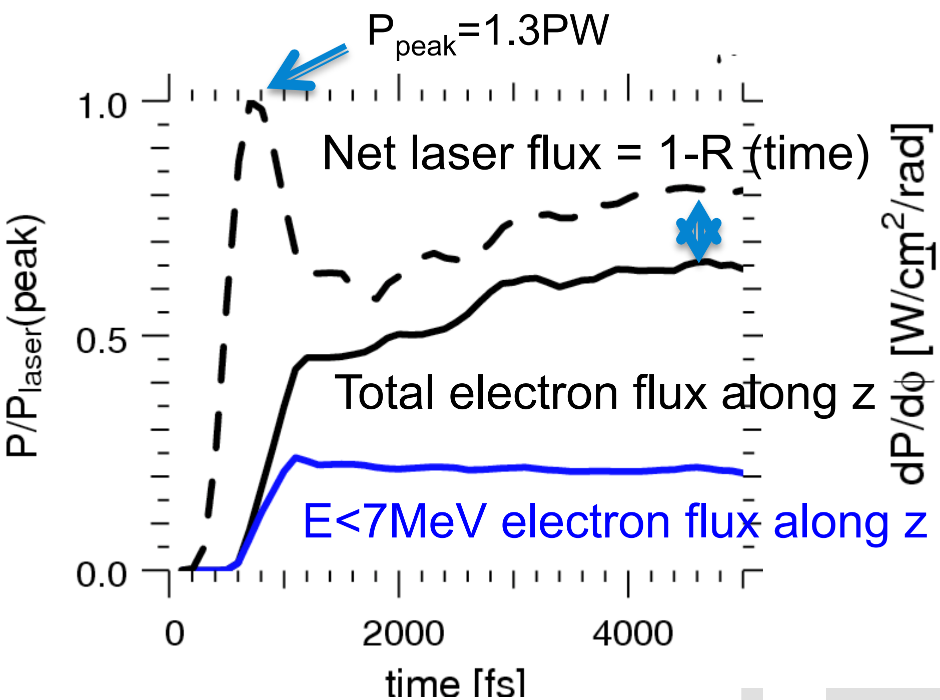


Extraction from over-dense; $E \sim 1.5E_p$
Acceleration in under-dense; T_{eff}=f(time)
Acceleration near interface; $E \sim 3E_p$

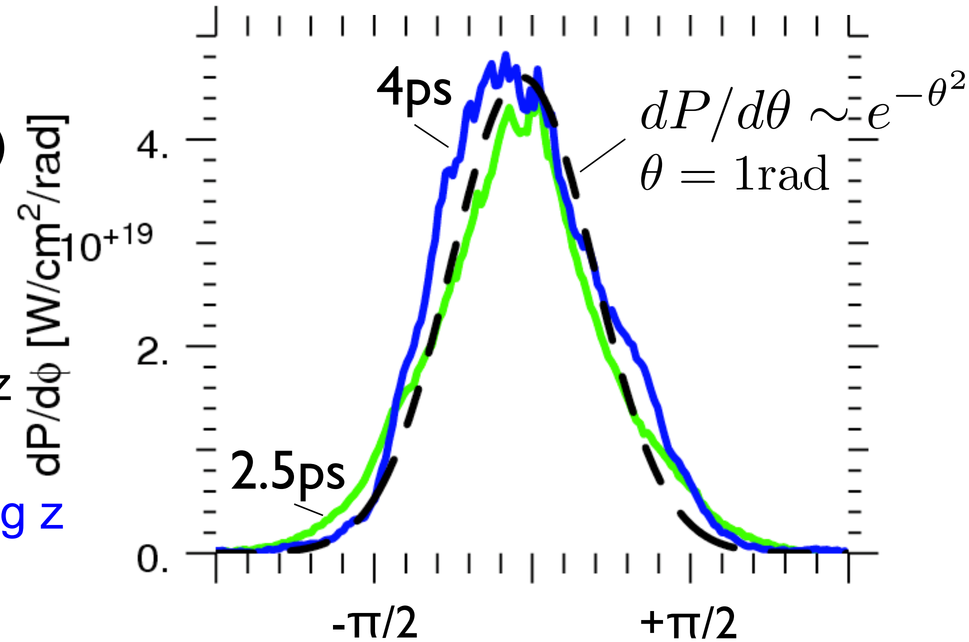
Open question: how do these distributions scale with intensity?

About 1/3 of the laser power is absorbed into hot electrons in a 'ponderomotive' group with energies <7MeV

Electron energy partition:
energy flux along z

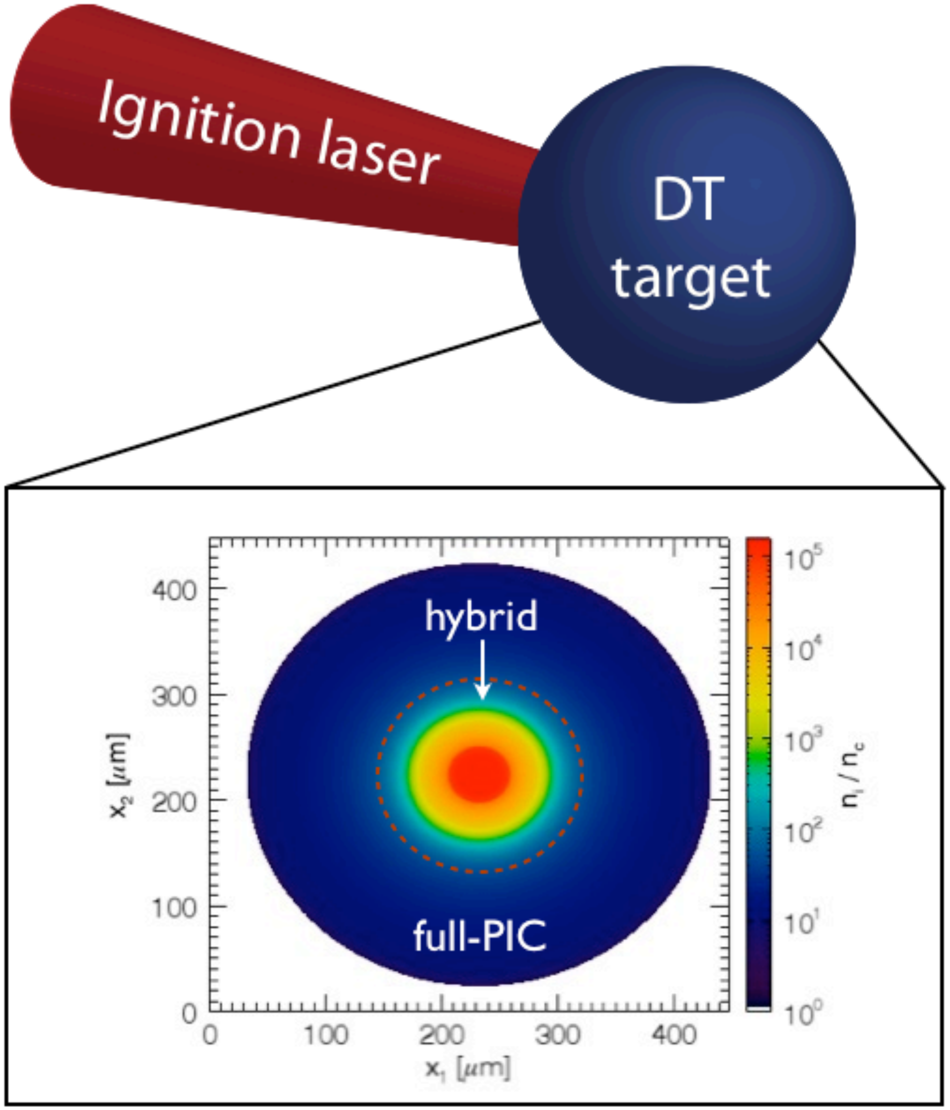


Angular distribution
of energy flux behind spot



Angular divergence consistent with absorption / electron energy flux along z

The hybrid model has been ported into OSIRIS and allows full-scale modeling of FI up to ignition densities



Physical Parameters

Laser

- λ_0 = 1 μm
- $I_0 = 2\times10^{20}$ Wcm^{-2} (100 kJ)
- W_0 = 30 μm
- **τ_0 = 15 ps**

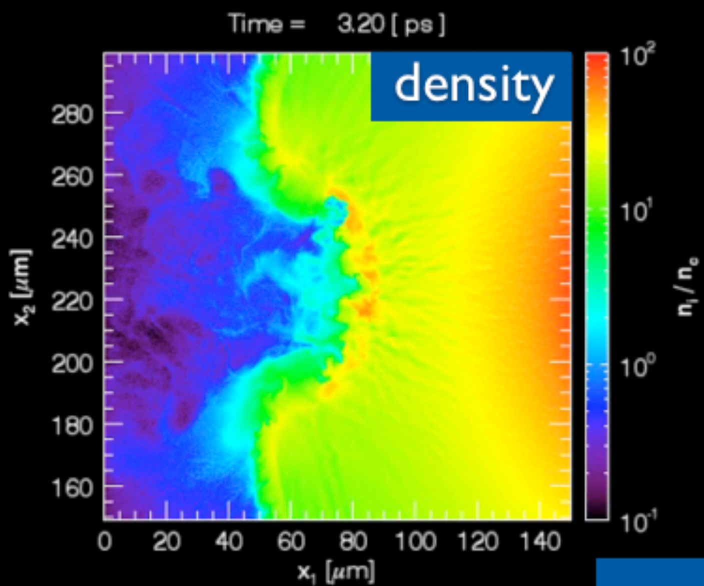
Plasma

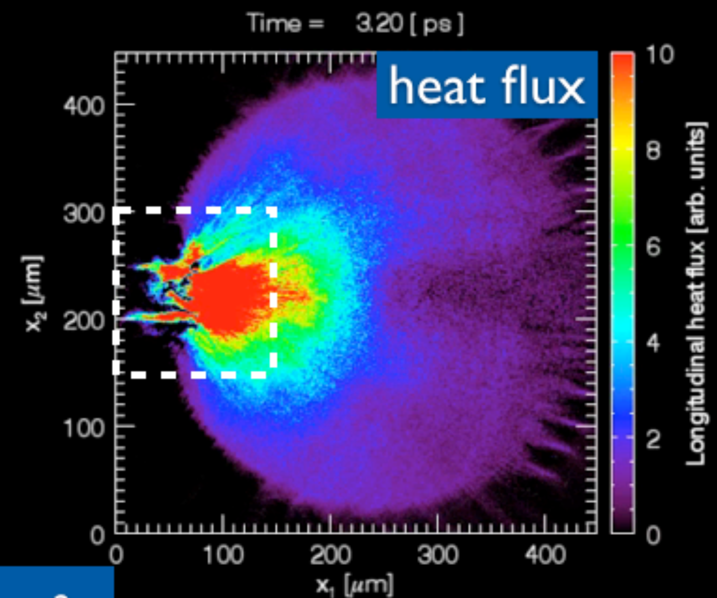
- **L = 450 x 450 μm^2**
- **n_{e0} = 1 n_c - 2×10^5 n_c**
- m_i/m_e = 3672

Numerical Parameters

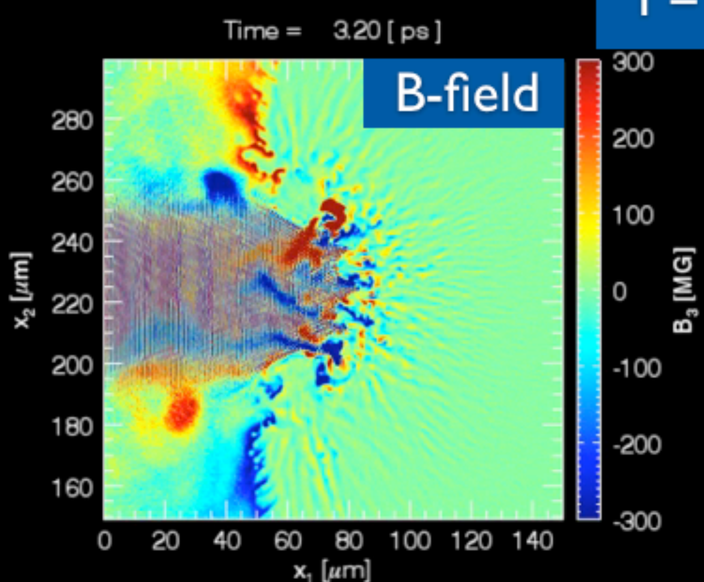
- 42 cells/μm
- hybrid/full-PIC transition = 100 n_c
- Particles per cell = 64
- # time steps = 10^5
- cubic interpolation

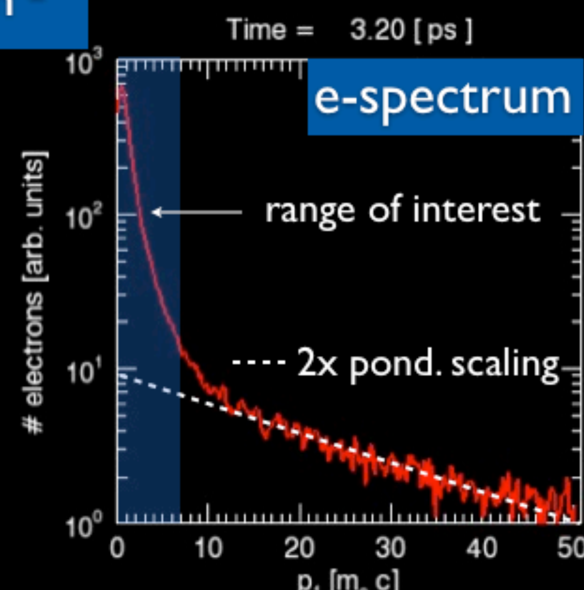
Stable interaction for multi-picoseconds





$I = 2 \times 10^{20}\ \mathrm{Wcm^{-2}}$

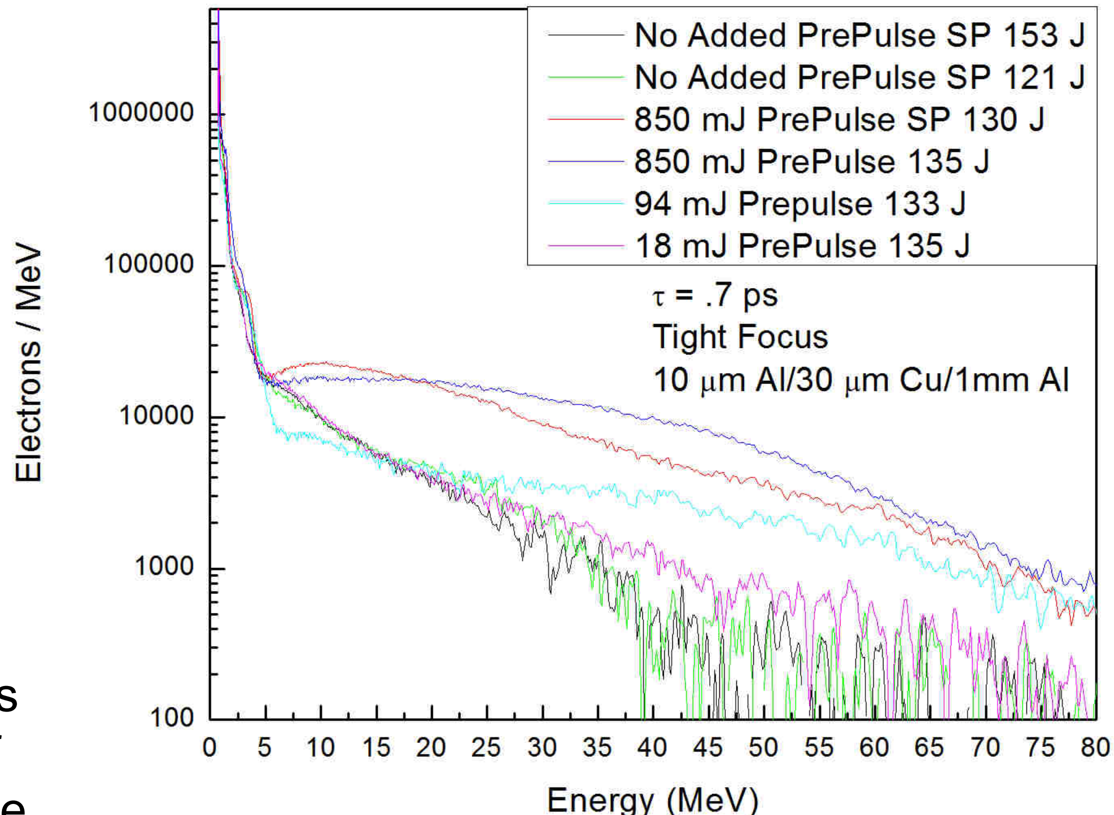




The hard part of the experimental escaping electron spectrum increases with increasing prepulse and preplasma

- Intensity ~9e19
- The ponderomotive part of the spectrum doesn't change much.

- Escaping electrons are affected by self generated fields(shifts birth spectrum to lower energy)but tail shouldn't be very sensitive.
- Growing the plasma scaleheight in longer pulses could increase hardness of spectrum as function of time



The two implementations of the hybrid algorithm differ in some details

- UCLA implementation going to 10^5 n_c uses additional smoothing to defeat anomalous heating in the pure PIC region
- In LLNL simulations, anomalous heating in the pure PIC region:
  - Causes resistivity jump across pure/hybrid interface
  - May cause more plasma blowout into underdense region, possibly leading to hotter electron distributions
- Research in understanding this anomalous heating and what faithful remedies are allowed is ongoing

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The large opening angle the electrons produced in the laser-plasma interaction requires collimating/ focusing forces to guide the electrons to the fuel

$$\frac{dN}{d\Omega} \propto \exp[-\left(\frac{\theta}{90°}\right)^4]$$

B_z and B_r magnetic fields of sufficient magnetic can be produced by compressing uniform 60 kG B_z fields.

Fields of this magnitude can be produced by electromagnets

B_θ fields are produced by the suprathermal electron current via

$$\dot{B} = -c\nabla \times E \approx c\nabla \times (\eta j_{hot})$$

And grow until the resistivity vanishes at high temperatures. The magnetic field will continue to grow as the plasma becomes magnetized, but at lower rate, even for constant resistivity.

We use Zuma (hybrid-only PIC code*) to transport electrons in very overdense plasmas

- Reduced dynamics removes light, plasma waves: $\omega << \omega_{plasma}$,

- Relativistic fast electron advance: $\vec{F} = -e(\vec{E} + \vec{v} \times \vec{B})$
- Fast e- energy loss and angular scattering: formulas of Solodov, Davies
- $\vec{J}_{\text{return}} = -\vec{J}_{\text{fast}} + \mu_0^{-1} \nabla \times \vec{B}$ Ampere's law without displacement current
- Electric field given by massless momentum equation for background electrons:

$$m_e \frac{d\vec{v}_{eb}}{dt} = -e\vec{E} + \ldots = 0 \quad \rightarrow \quad \vec{E} = \vec{E}_C + \vec{E}_{NC}$$

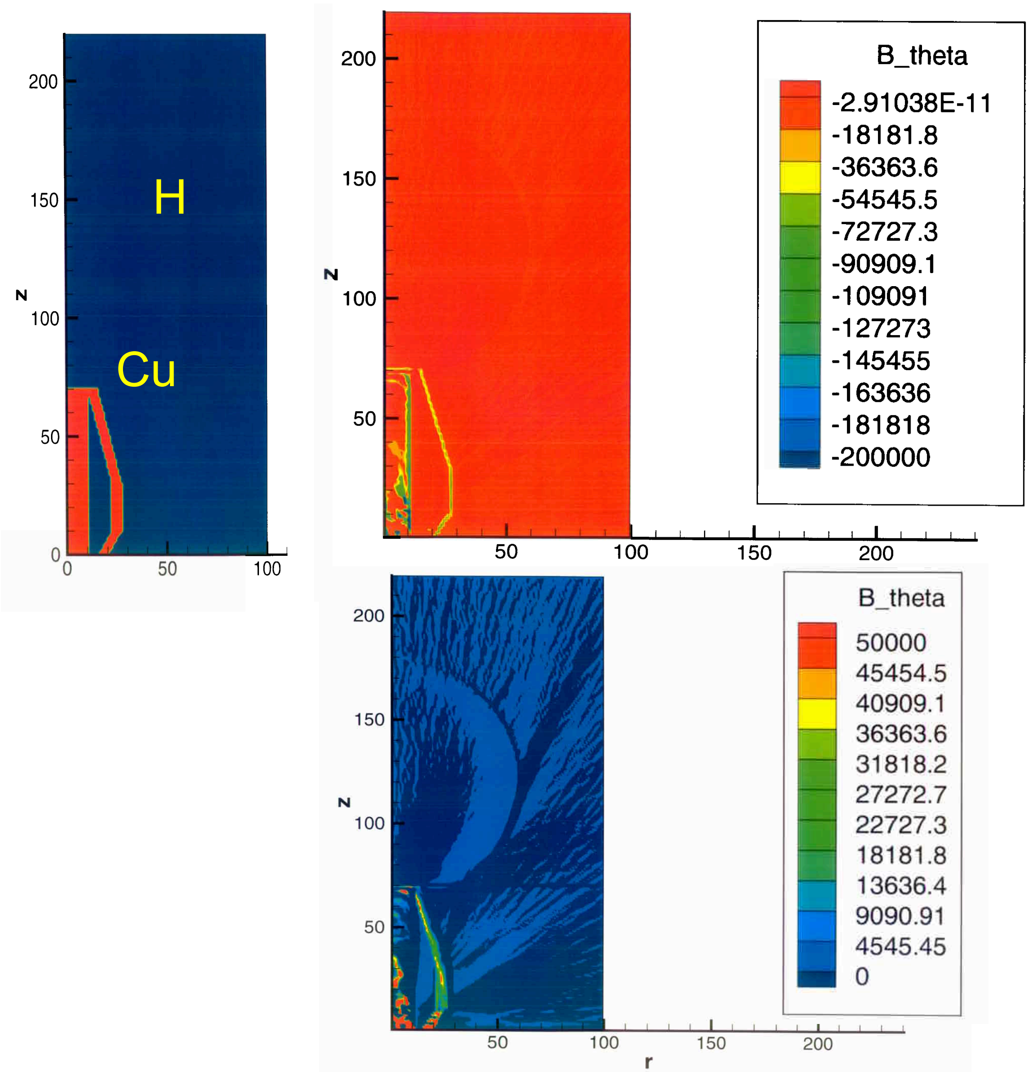
$$\vec{E}_C = \vec{\eta} \bullet \vec{J}_{\text{return}} - e^{-1}\overleftrightarrow{\beta} \bullet \nabla T_e \qquad \vec{E}_{NC} = -\frac{\nabla p_e}{en_{eb}} - \vec{v}_{eb} \times \vec{B}$$

$\vec{\eta}$, $\overleftrightarrow{\beta}$ from Lee-More-Desjarlais and Epperlein-Haines

- $\vec{J}_{\text{return}} \bullet \vec{E}_C$ collisional heating
- $\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$ Faraday's law

Complete E field results can differ from E = η*J_{return} (c.f. Nicolai et al., APS DPP 2010)
*(D. J. Larson)

A Zuma calculation of Cu embedded in H driven with 1 PW of <E>=3 MeV electrons produced peak fields in the 500-1000MG range in 4 ps when θ_e<=1 keV



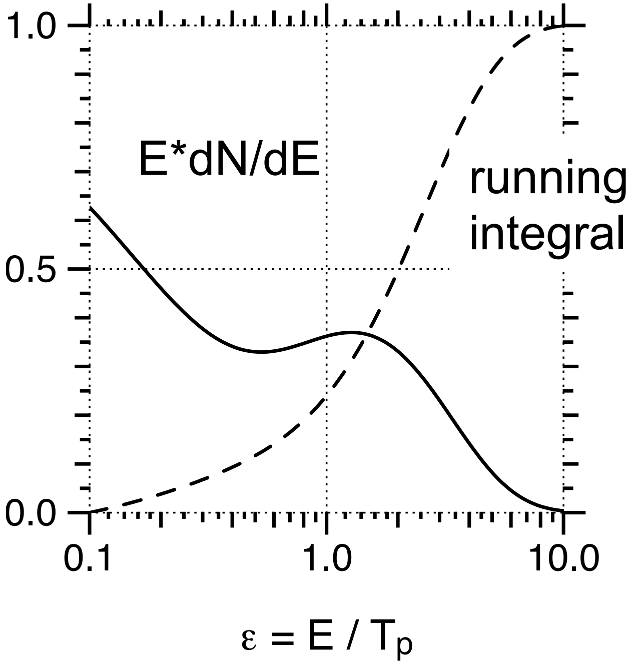
Without temperature constraint , 100 MG fields can be obtained
Low temperatures can be obtained by radiative cooling and/or heat capacity

These large fields can effectively guide the transport of energetic electrons

$$r_L(cm) \approx \frac{E(MeV)}{300B(MG)}$$

What unknown physics can spoil these fields?

Zuma calculations used a quasi two-temperature electron energy spectrum coming from earlier PFC runs



$$\frac{dN}{d\varepsilon} = 0.82\exp[-\varepsilon/1.3] + \frac{1}{\varepsilon}\exp[-\varepsilon/0.19] \qquad \varepsilon = \frac{E}{T_p}$$

Ansatz: scale dN/dE with ponderomotive temperature[1]

$$\frac{T_{\text{pond}}}{m_e c^2} \equiv \left[1 + a_0^2\right]^{1/2} - 1 \sim a_0 \equiv \text{sqrt}\left[\frac{I_{las}\lambda^2}{1.37\cdot 10^{18}\ \text{W cm}^{-2}\mu\text{m}^2}\right]$$

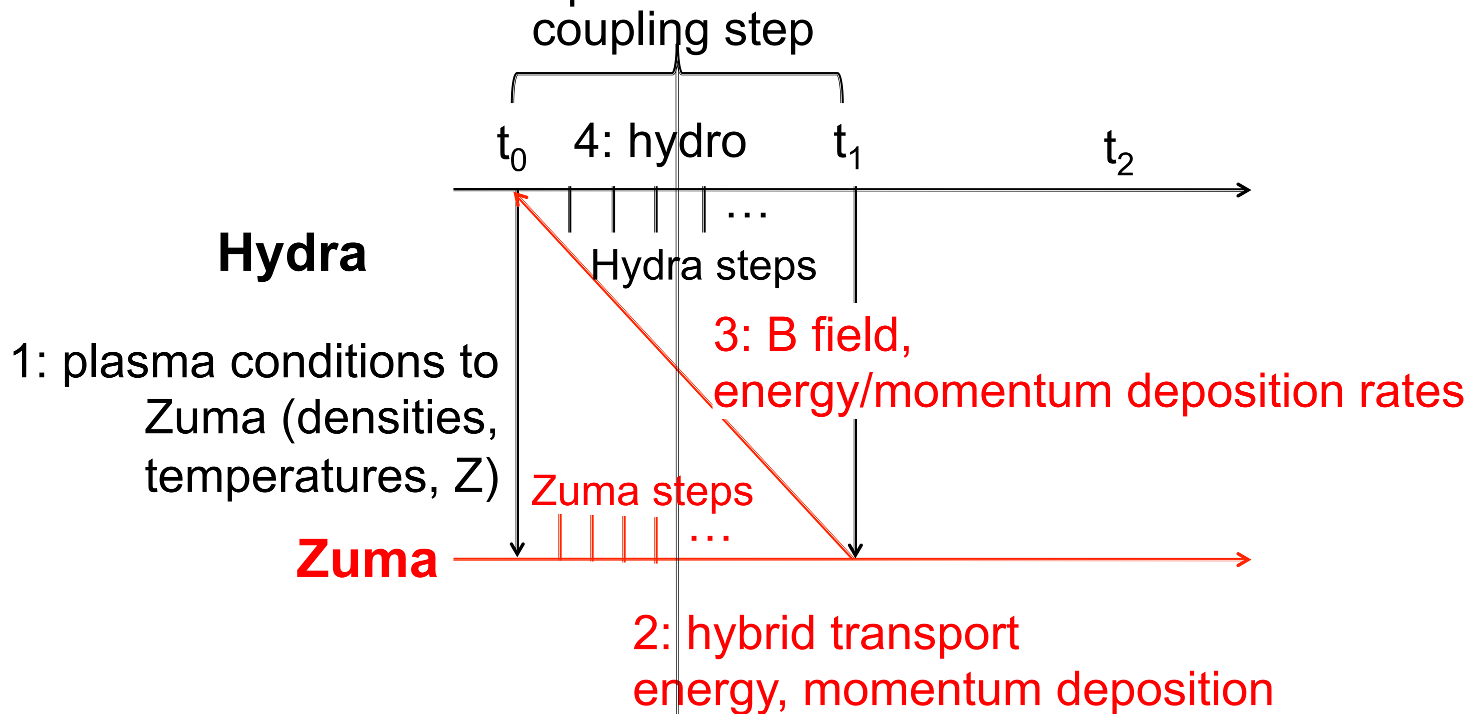
For our PIC run: $a_0 = 10$, $T_{pond} = 4.63$ MeV

- DT hot spot: $\rho\Delta z \sim 1.2$ g/cm^2 removes 1.4 MeV from a fast electron (neglecting angular scatter)
  - Spectrum is too energetic to stop in hot spot

[1]S. C. Wilks et al., Phys. Rev. Lett. (1992)

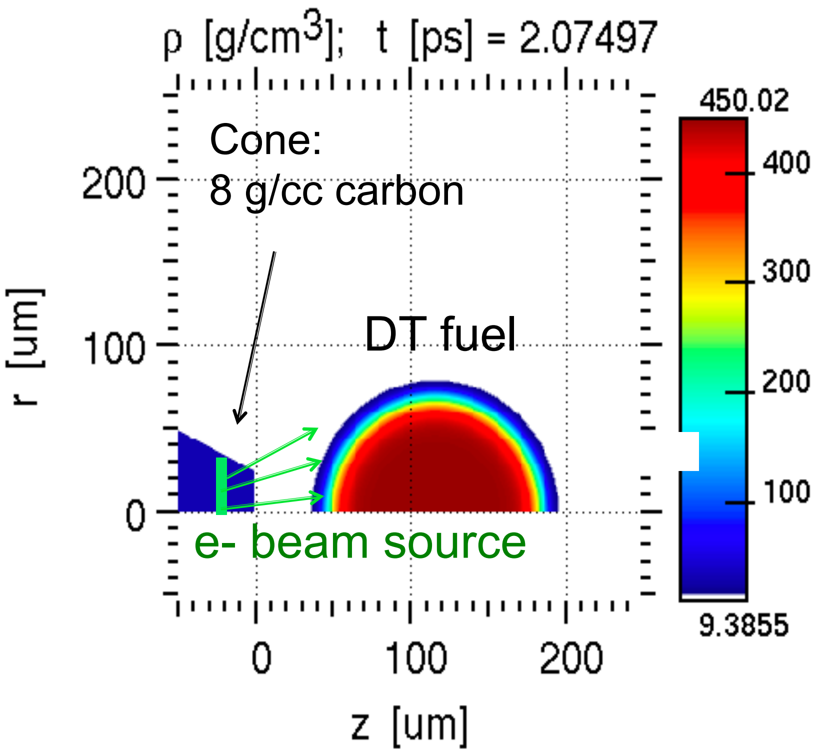
The hybrid PIC code Zuma coupled to the rad-hydro code Hydra is used to calculate short pulse driven burn

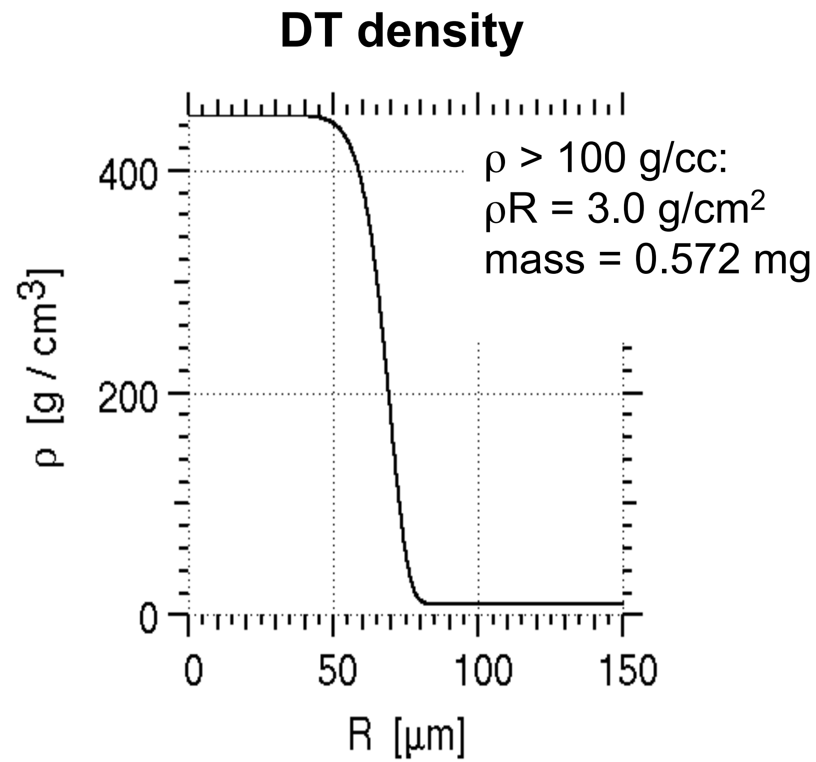
- Both codes run in cylindrical R-Z geometry on fixed Eulerian meshes (which can differ)
- Typical run: 20 ps transport (Zuma + Hydra), then 180 ps burn (just Hydra)
  - 2-3 wall-time hours on 48 cpu's



- Hydra details: IMC photonics, no MHD used yet.

Zuma-hydra was used to model idealized test configurations

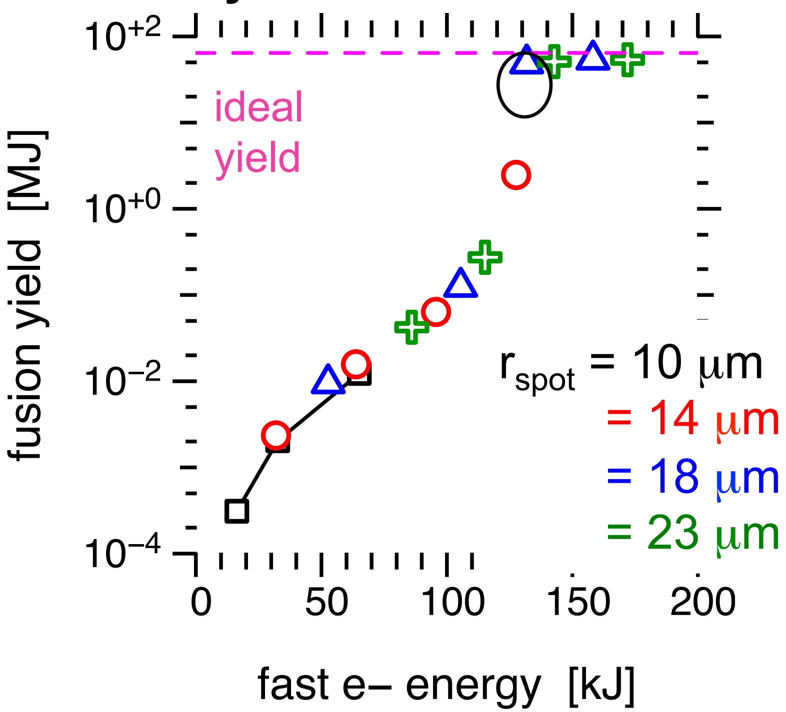




- 527 nm (2ω) wavelength laser: lowers $T_{pond} \sim \lambda$
- Energy delivered in 20 ps
- Beam intensity = $I_0 \exp(-0.5^*(r/r_{spot})^8)$

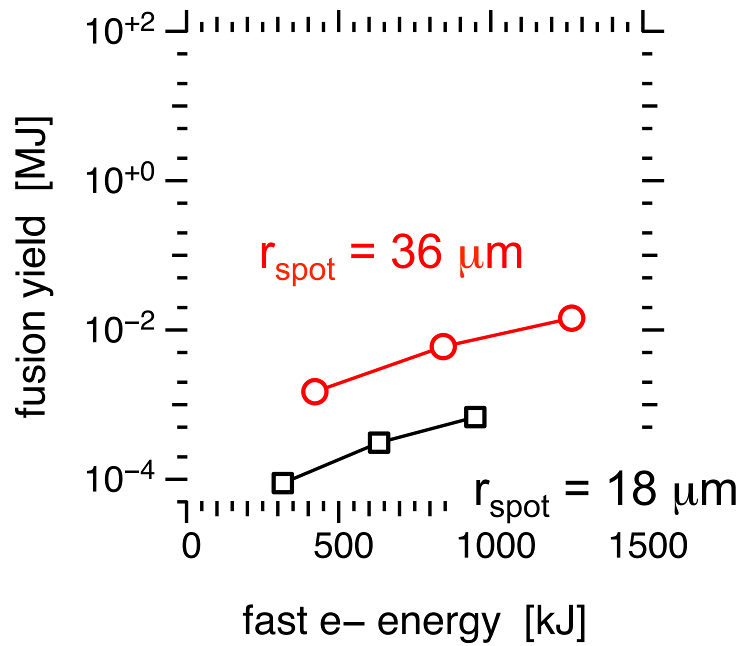
Artificially collimated source ignites with 132 kJ of fast electrons from green laser

Artificially collimated source: Δθ=10°



E_{fast} = 132 kJ:
7x optimum spectrum value:
spectrum too energetic to stop in hot spot

PIC-based source: Δθ=90°

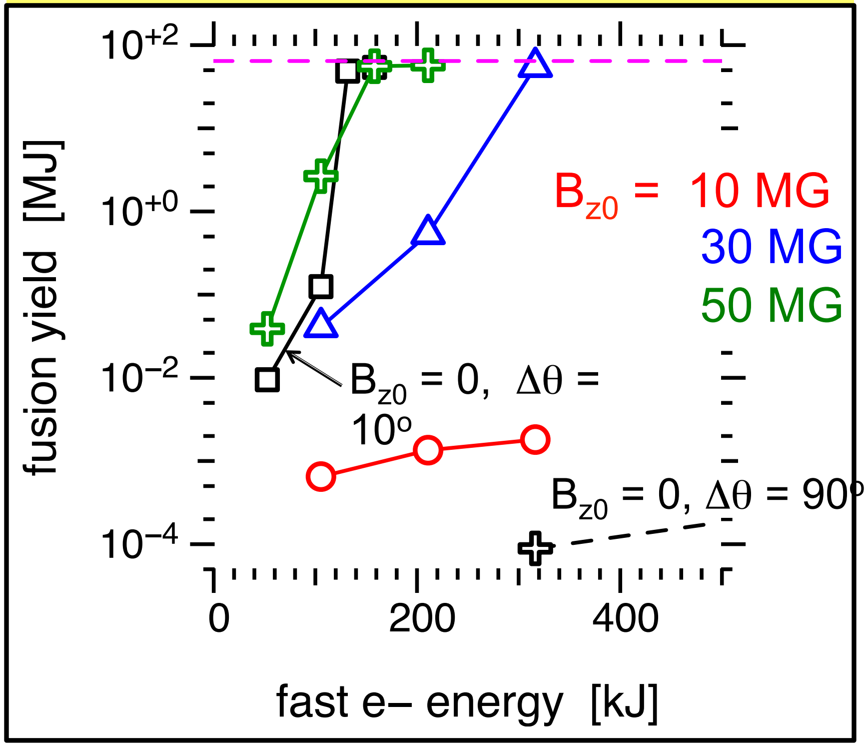


A somewhat narrower source ignited with ~1.5 MJ

PIC-based divergence gives prohibitive ignition energies

Adding an initial, uniform, B_z reduces ignition energy to roughly that of artificially collimated beam

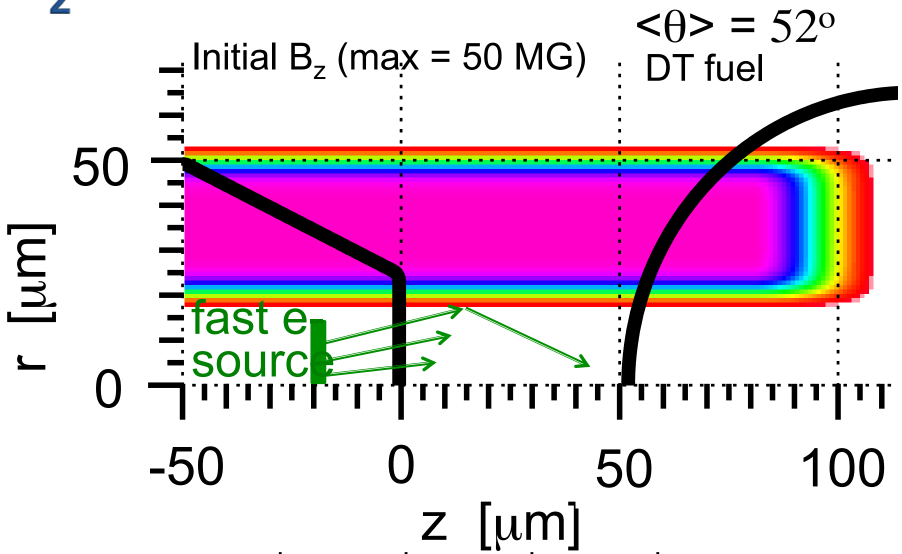
B_{z0} = 50 MG ignites with 158 kJ of fast electrons, similar to $\Delta\theta$=10°

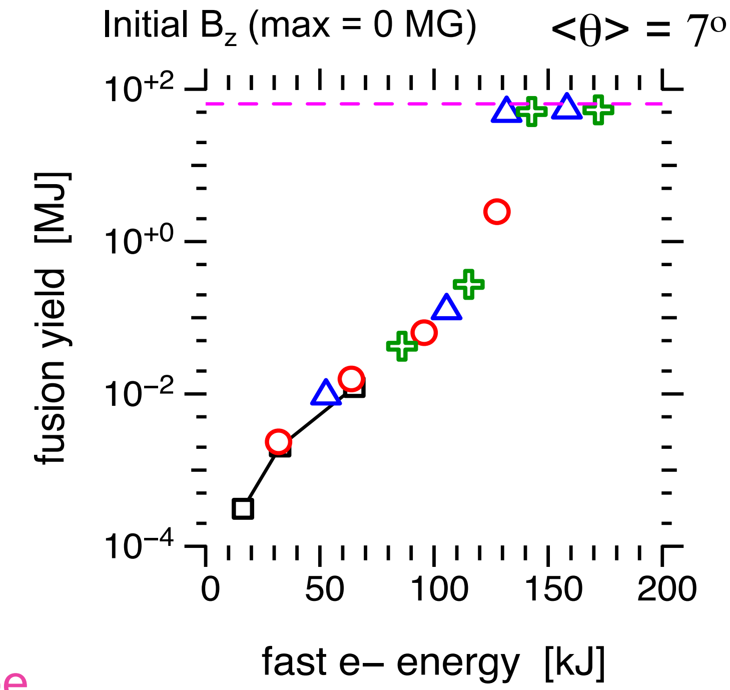


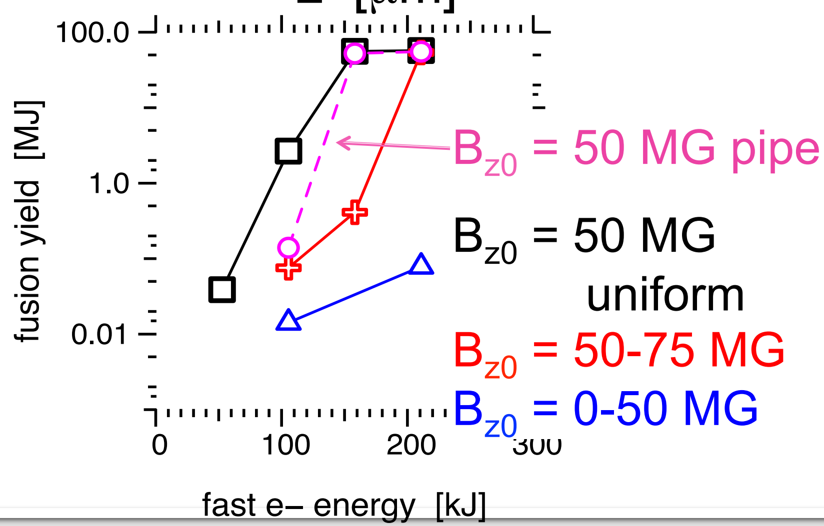
Omega experiments show compression of 50 kG seed B field in cylindrical implosions[1] to 30-40 MG, and in spherical implosions[2] to 20 MG

[1]J. P. Knauer, Phys. Plasmas 17, 056318 (2010) [2]P. Y. Chang et al., Phys. Rev. Lett 107(3):035006 (2011)

A hollow magnetic pipe transports a <θ> = 52° beam almost as efficiently as a 6° beam without an imposed B_z field



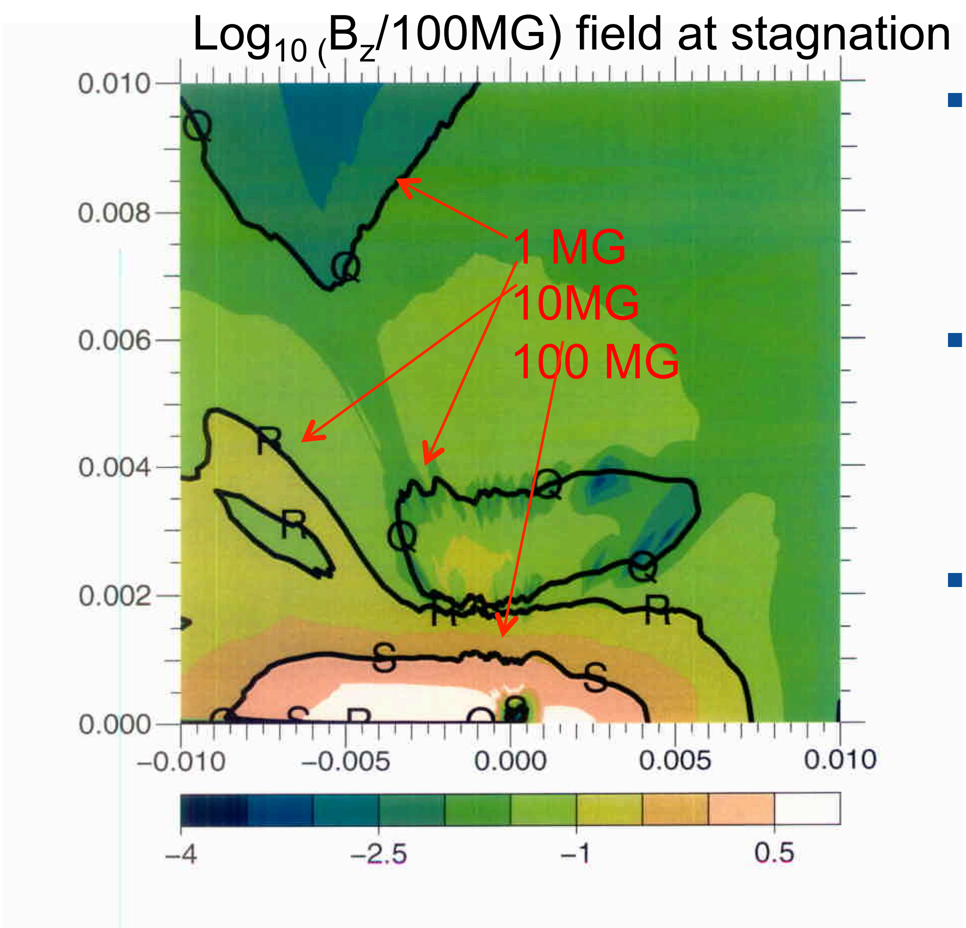




Similar results for B_θ fields generated by Faraday's law from resistivity gradients

But electron energy >130kJ

Capsule implosions can compress a uniform 6 Tesla B_z field to >100MG



- Significant longitudinal gradients will mirror electrons on axis.
- A hollow magnetic pipe will be less sensitive to axial variations
- Assembling magnetic configurations with implosions will require understanding hydro/MHD instabilities and effective conductivities

What are possible ways to overcome excessive particle range

- Couple to “ablator” in longer path around fuel
- Correlated stopping fortuitously increases stopping power
- Focus from larger laser spot to smaller ignition spot
  - Allowed by Liouville theorem, but practical realization not demonstrated

We can increase coupling efficiency of energetic electrons by increasing the path length in the stopping material

- Change the shape
- Increase the multiple scattering
- Changing the shape is a viable strategy if the energy can ultimately be redirected to an ignition region
- The distance before an electron multiple scatters 90^o ~ 1/Z * stopping distance
  — As the particle diffuses, the practical range $\sim(1/Z)^{1/2}$ the straight line range

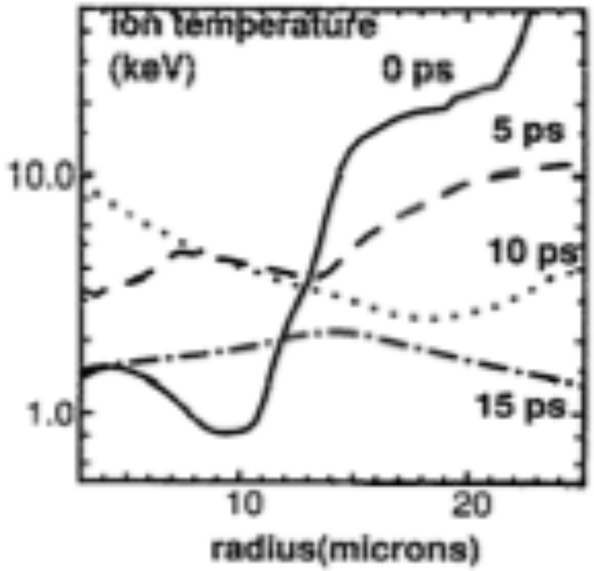
Using ignition energy to drive implosion may be at least as efficient as direct ignition in DT

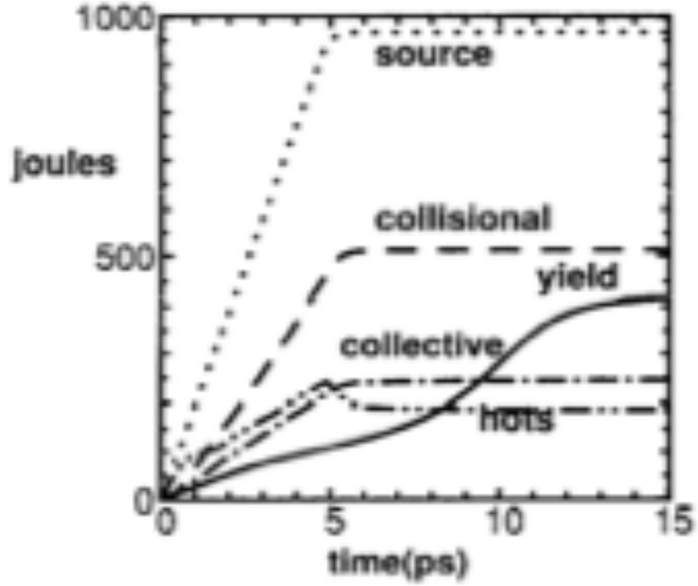
- For conventional ICF, directly heating the fuel would be very inefficient because the ignition energy ~ρ^{-2} so we implode fuel
- Conventional FI has ignition pressure ~Tbar.
  - Used as compression could increase density 10X (0.01X in ignition energy)
  - But must take hydro-efficiency hit
  - And some fraction of drive pressure results in translational energy

A shock ignition scheme was introduced in the first FI paper(1994)+

In order to illustrate FI, a 1D version was described where 1 kJ of 300 keV electrons was injected at critical density(22 micron radius) (after hole-boring) from a ¼ micron laser.

At 10 ps there is a temperature peak in the center and about ½ the yield is produced then after the shocks converge

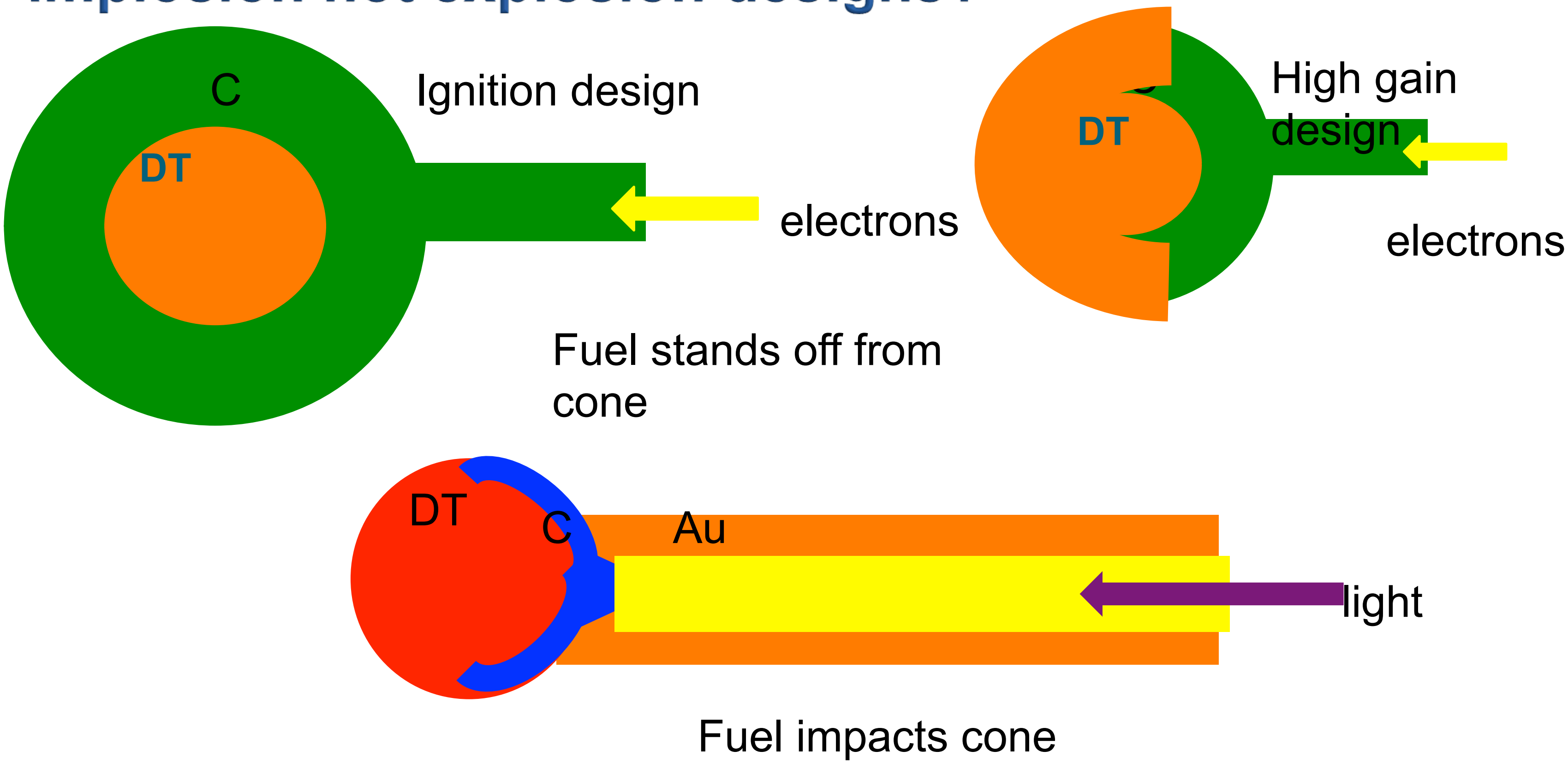




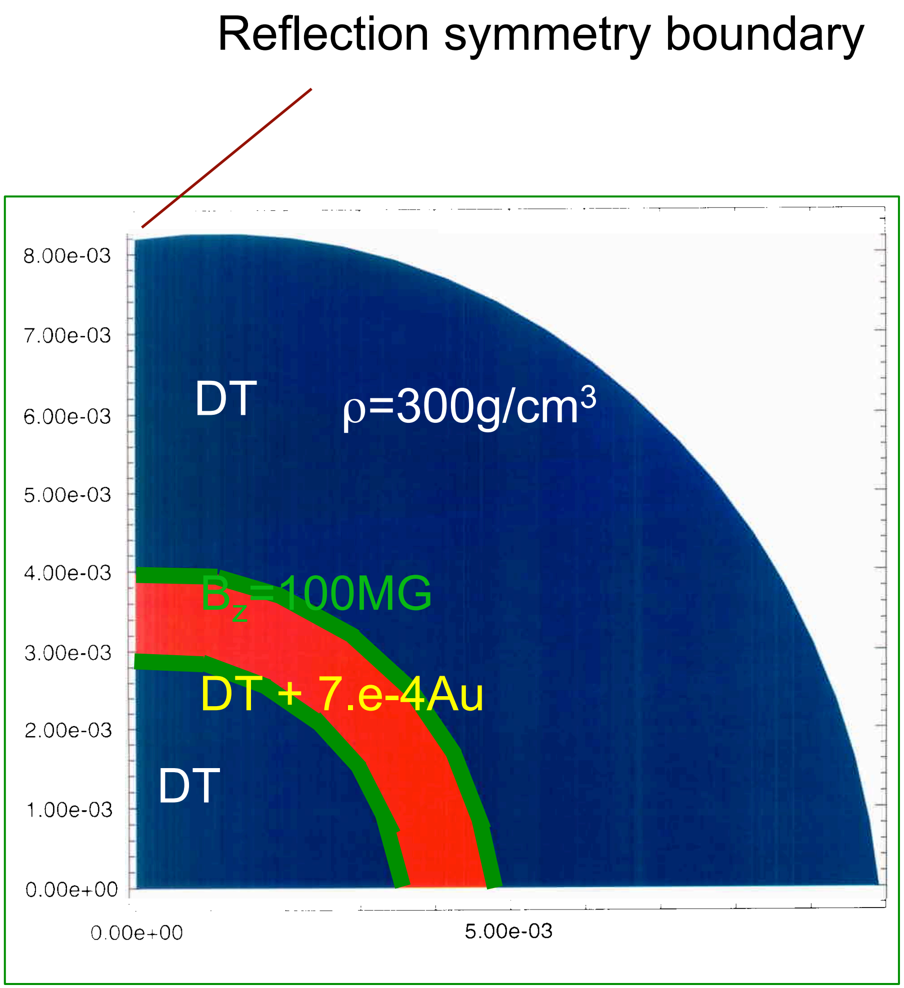
A cylindrical ignition shock reduces ignition energy factor 2*

+Tabak,et.al.,PoP 1,5(1994)1626. * Hatchett,Herrmann and Tabak(2002)

What are possible transport designs for target implosion not explosion designs?



Symmetric designs can ignite and burn through "ablator" to produce high gain for inputs as low as 10 kJ



- Ignites in 1D with 10kJ up to 2.8e-3 Au mix in ablator
- Radiative cooling from ablator not energetically important because of low temperatur
- Depending on initial fuel density, ignition can occur in the Wheeler (high density-low temperature) mode
- Larmor radius of 4 MeV alpha ~20μm so can penetrate field that reflects fast electrons
- Because convergence to hotspot was ~6 a distorted 2D problem was run. Required 20 kJ

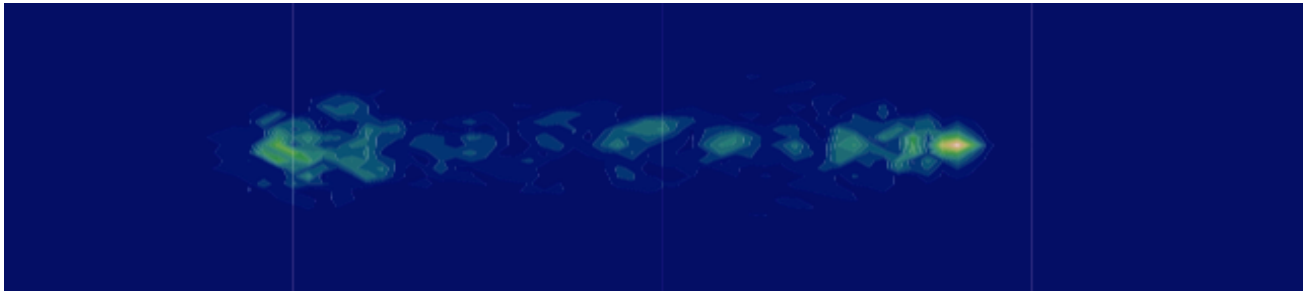
Still need to demonstrate scheme with relativistic electrons

Correlations can significantly increase stopping power

- If a single particle with v,m,q has stopping power
  •$\frac{dE}{dx}$ then n such uncorrelated particles will have stopping power $n\frac{dE}{dx}$
- If totally correlated, the particles appear to be 1 particle with charge nq and mass nm
- The correlated stopping power is $n^2 \frac{dE}{dx}$ with energy nE
- Deutsch and Fromy(PoP 6(1999)3597 find correlated stopping out to >10λ_D ~ λ_C using Fermi treatment
- We study particle constellations in a PIC code

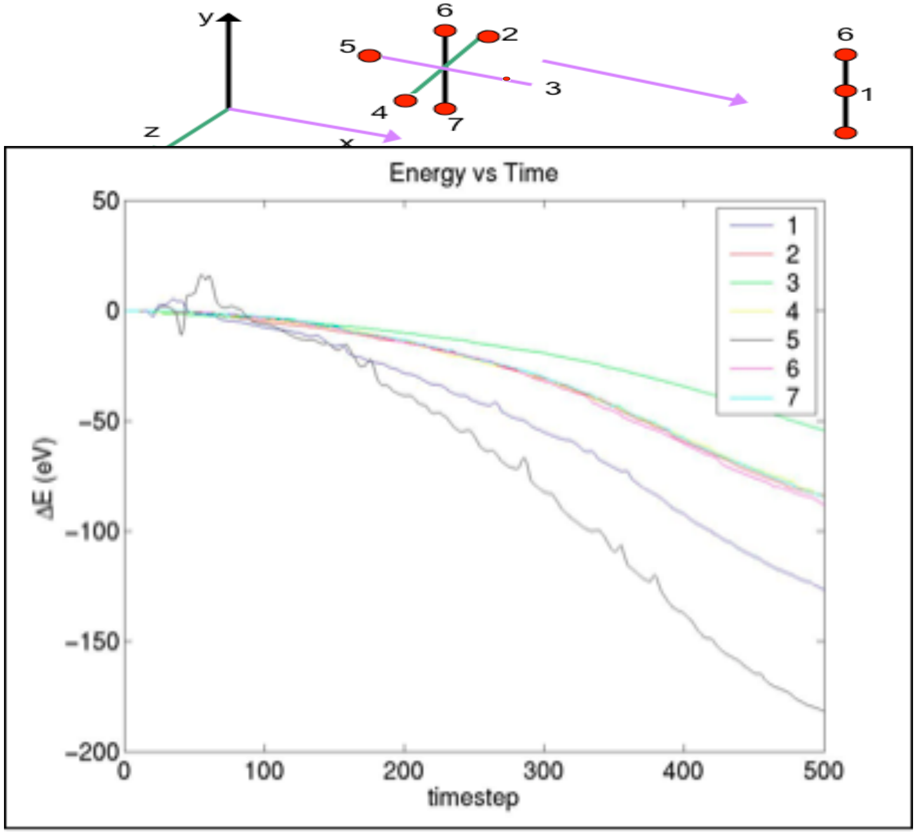
PIC codes(LSP here) can directly simulate stopping power

- Resolve interionic spacing with microparticles
- Remove self-forces
  - Forces are generated on cells by aggregating particle charges and act on particles
  - A particle can act on itself even in vacuum
  - Measure fields in vacuum
  - In problem with plasma subtract vacuum fields from plasma fields before applying to test particle
- For single particle agrees with Jackson <25% depending on plasma density



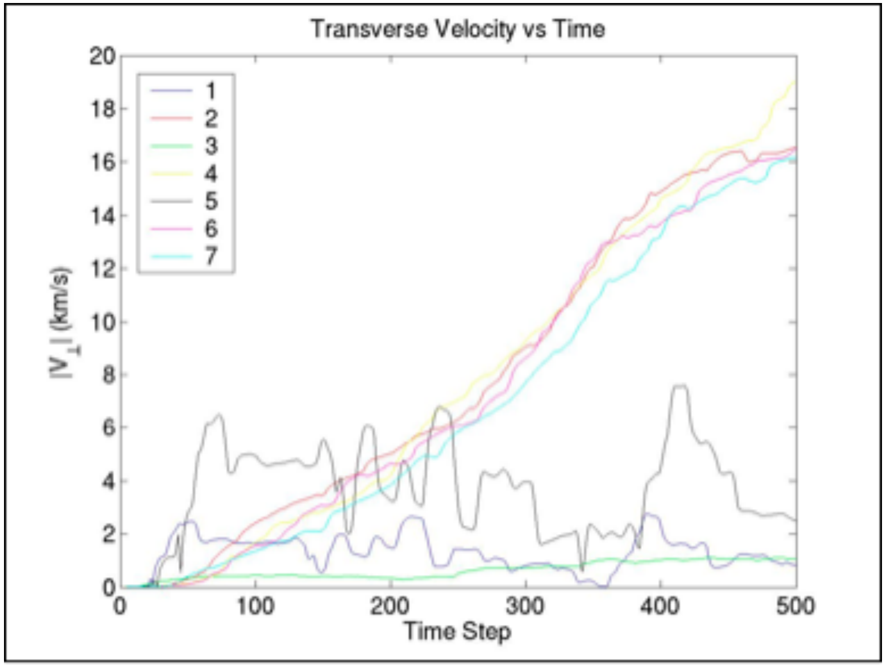
Plasma wake |E|

A relativistic electron beam with $n_b=10^{22}/cm^3$ shows significant correlation effects



$L \approx 5 n_e^{-1/3}$

E^{1-7} = 1MeV, $\Delta x = 5 \times 10^{-12}$ m
$\Delta t = 9.5 \times 10^{-21}$ s, $n_e = 10^{26}$ cm^{-3}



dE/dx 5X uncorrelated

Transverse forces blow up constellations so correlations will change with time

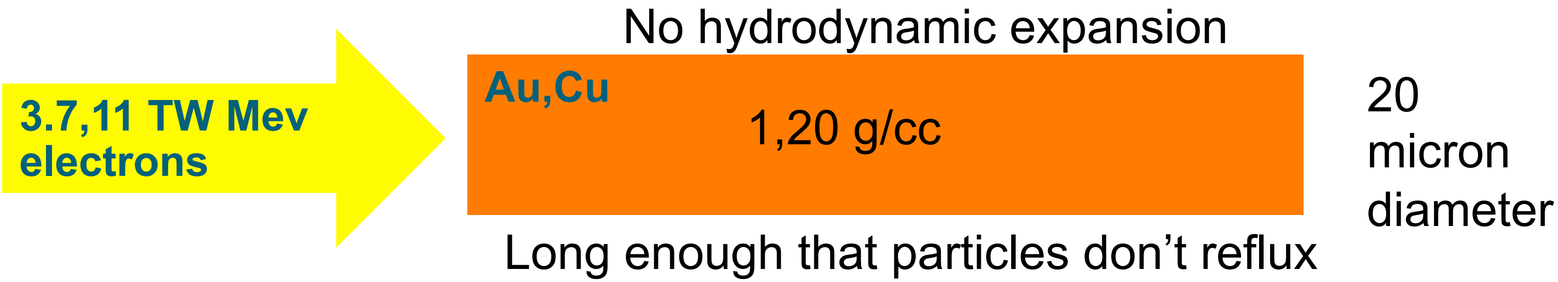
Open questions remain about these correlation effects

- Does the effect survive for the variation in particle positions and velocities expected in a real beam?
- Will particles find correlations on the fly?
- Because effects seem to occur when beam particle separations are of order the background plasma collisionless mfp, should we see stronger effects with shorter wavelength short pulse lasers?

Innovations in modeling have changed our understanding of Fast Ignition and required innovations in design

- Increases in processing power of supercomputers and changes in algorithms enable calculation of integrated Fast Ignition targets from capsule implosion to laser injection to thermonuclear burn
- Hot electrons produced in the laser-plasma interaction populate a larger phase space than earlier experiments and calculations suggested
- Ideas for channeling electrons and increasing the coupling of electrons are being developed

We can maintain the resistivity and E field by radiatively cooling the conductor as the current passes through it



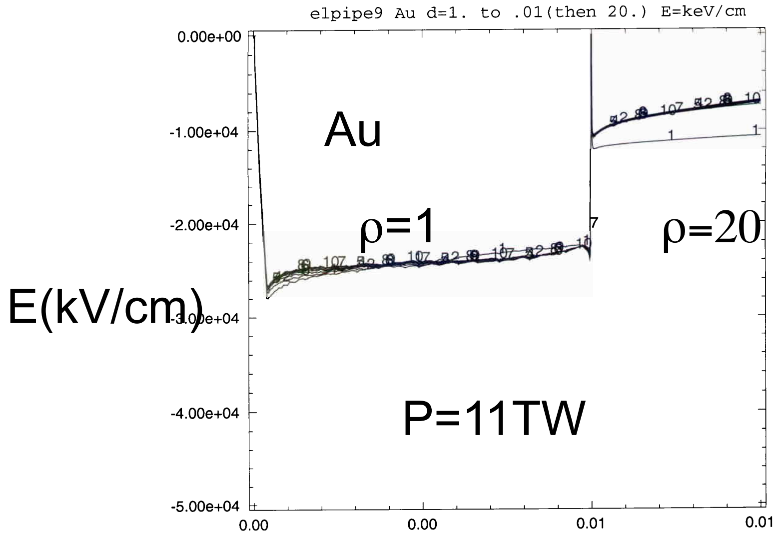
If the wire is a black body radiator with the material and radiation temperatures equal then a steady state occurs when:

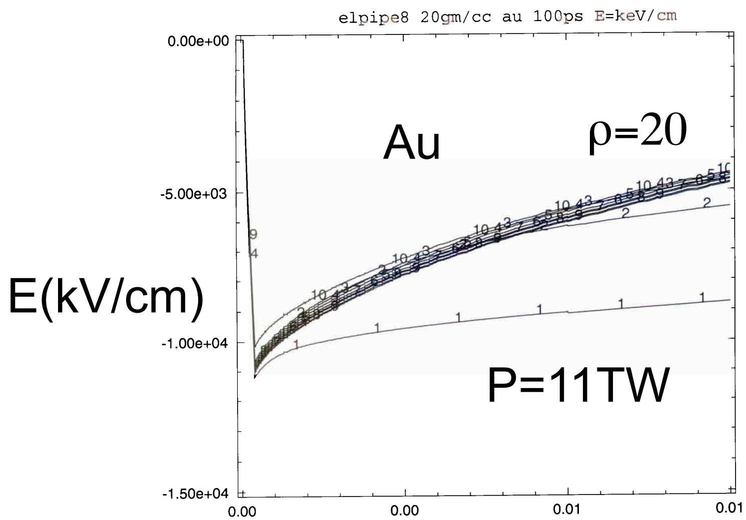
Power_{in} = radiative loss

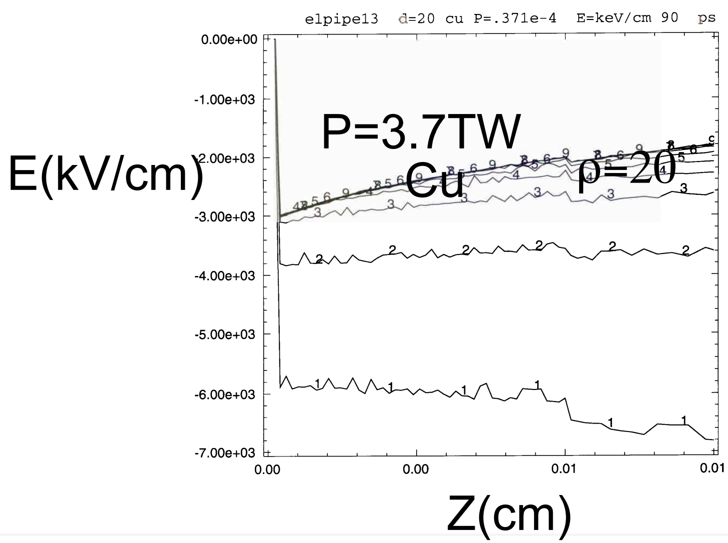
$\pi r^2 I = 2\pi r L\, T^4$

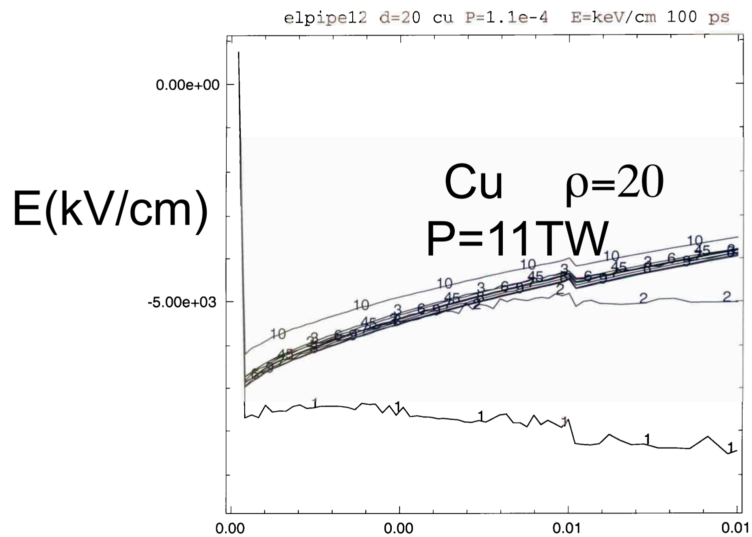
For low enough power and high enough opacity this equilibrium can be found. In hydrogen at high power the radiation can't keep up.

The electric field in the wire reaches a steady state for 100 ps exposures

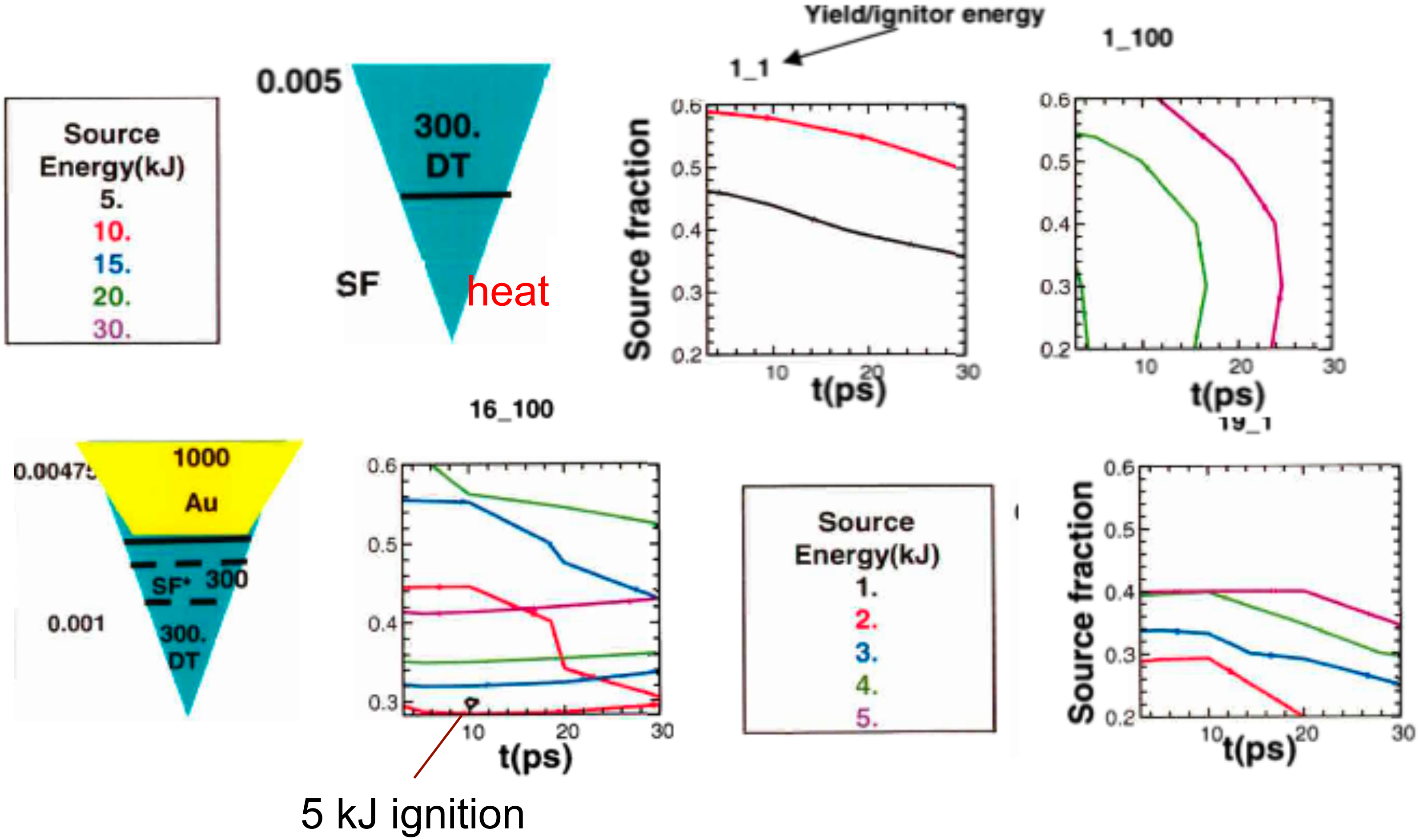








A number of 1D runs show that implosion +tamping can reduce the the ignition energy a factor2-3

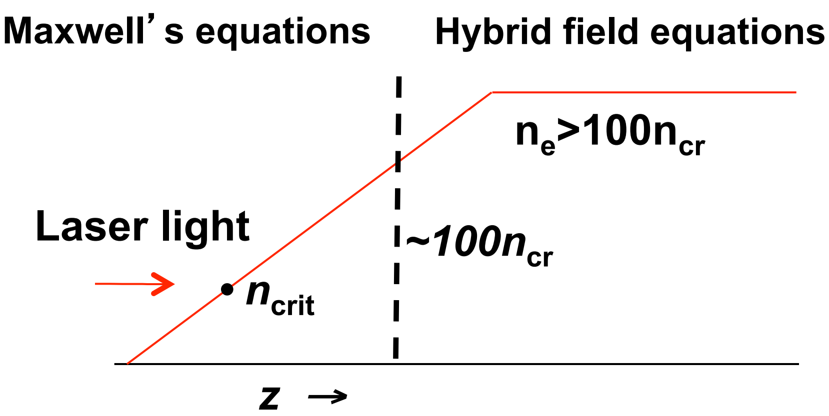


A hybrid code that combines collisional PIC with a particle based solver for resistive MHD was used to calculate LPI at high density and long durations

- **Remove light waves and electron plasma waves in background by dropping displacement current & electron inertia in Ohm's law**

  ➔ relaxes constraints set by plasma frequency, Debye length & skin-depth in the high-density region where waves are heavily damped

- **Conductivity tensor determined from Braginskii expression**



Hybrid Field Equations

$$\vec{J}_{cold,e} + \vec{J}_{ion} = -\vec{J}_{fast,e} + \frac{c}{4\pi}\vec{\nabla}\times\vec{B} - \frac{1}{4\pi}\cancel{\frac{\partial E}{\partial t}}$$

$$\cancel{\left(\frac{\partial}{\partial t} + \vec{v}_e\right.}\cdot\vec{\nabla})\vec{v}_e = -\vec{E} + \vec{\eta}\left(\vec{J}_{cold,e} + \vec{J}_{ion}\right) - (en_e)^{-1}\vec{\nabla}n_e T_e$$

$$-(en_e c)^{-1}\vec{J}_{cold,e}\times\vec{B} + (en_e c)^{-1}\frac{\Delta\vec{P}^{e-efast}_{mom,coll}}{\Delta t}$$

$$\frac{\partial\vec{B}}{\partial t} = -c\vec{\nabla}\times\vec{E}$$

Cohen, Kemp, Divol, JCP **229**, 4591 (2010).