Full-Scale Integrated Kinetic Simulations of Laser-Plasma Interactions on the multi-picosecond scale

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Twenty-Second International Conference on Numerical Simulation of Plasmas

September 9 2011

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344

LLNL-PRES-497281

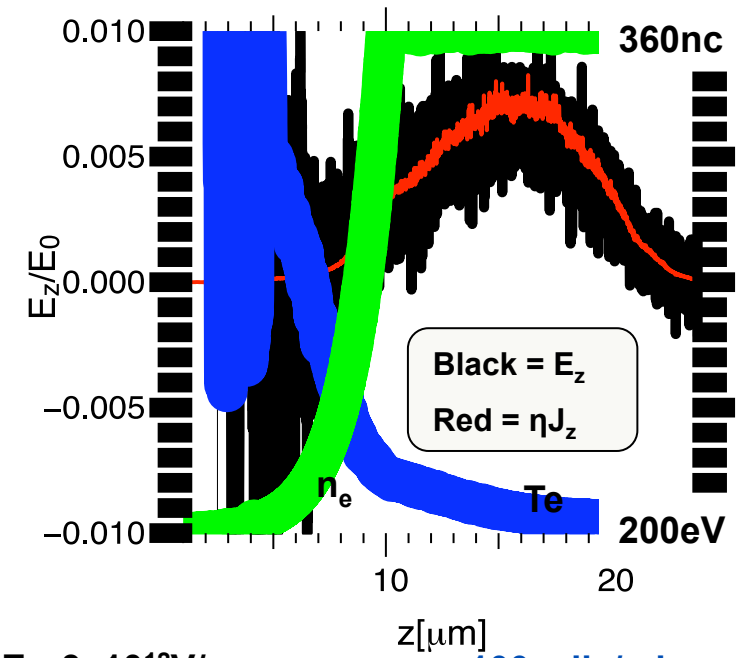
Outline

- Validation of Code and Concepts
  - Combination of explicit PIC and MHD model
  - Titan experiment @ 100TW / 1ps-fwhm laser pulses
- Simulation Studies at the Fast-Ignition Scale
  - @ PW power / 5ps / 40mu diameter flat-top pulses
- Modeling of electron transport in solid matter
  - Transfer from PIC-Hybrid to particle transport code ZUMA

We have developed an efficient algorithm for simulations of short-pulse LPI and electron transport in dense matter

Solving MHD equations in dense plasma yields >>100x speed-up

Electric field, temperature and density in collisional 1D PIC vs Ohm's law



E_0=3x10^{12}V/m

100cells/micron

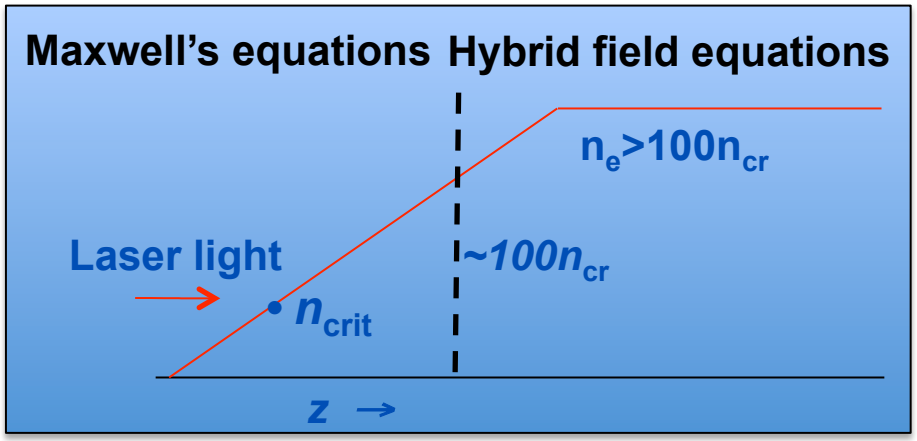
Resolution requirements relaxed by $\left(\frac{n_{peak}}{a_0 n_{crit}}\right)^{\frac{N+1}{2}}$

where N is dimension of simulation

Collisional PIC reproduces Ohm's law in dense plasma

- Takizuka-Abe binary collision operator
- Compare to Ohm's law with Spitzer-Braginskii type resistivity

$$\eta_{\parallel,\perp} = \alpha_{\parallel,\perp}(Z^*, B) \times \frac{m_e}{n_e e^2 \tau_{ei}}$$



B.I. Cohen, A. Kemp and L. Divol, J. Comp. Phys (2010)

Validation of PIC-Hybrid Code

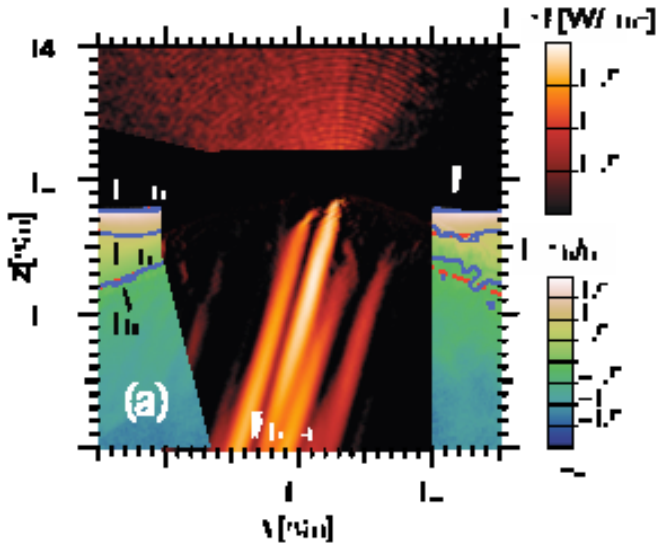
- **Physics motivation: 1D PIC simulations (Kemp et al, PRL2008) predict steepening of pre-plasma density gradient and cooling of laser-generated hot electrons, both over picosecond time scale.**

- **Experiment measures motion of the critical surface dynamically**

- **Implications for Fast Ignition**

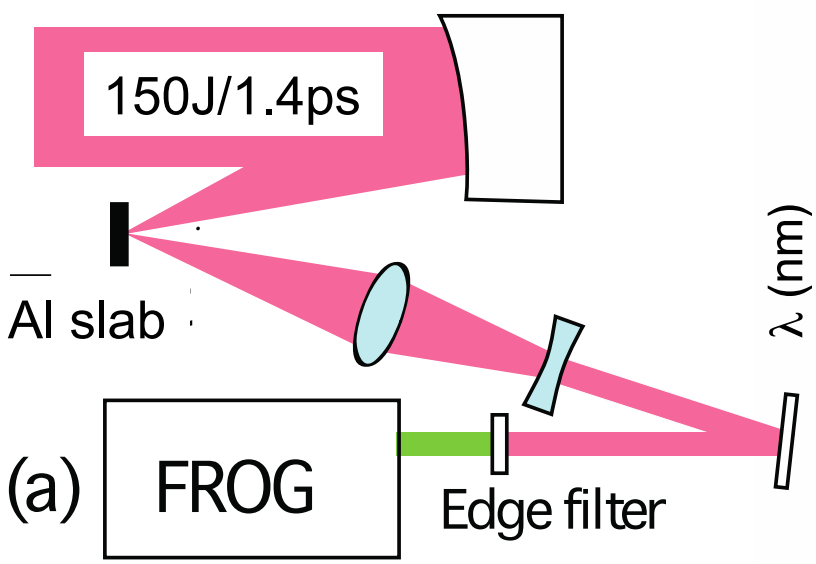
- **Provides a source of hot electrons**

- **Tests our PIC-Hybrid code and ability to model LPI**

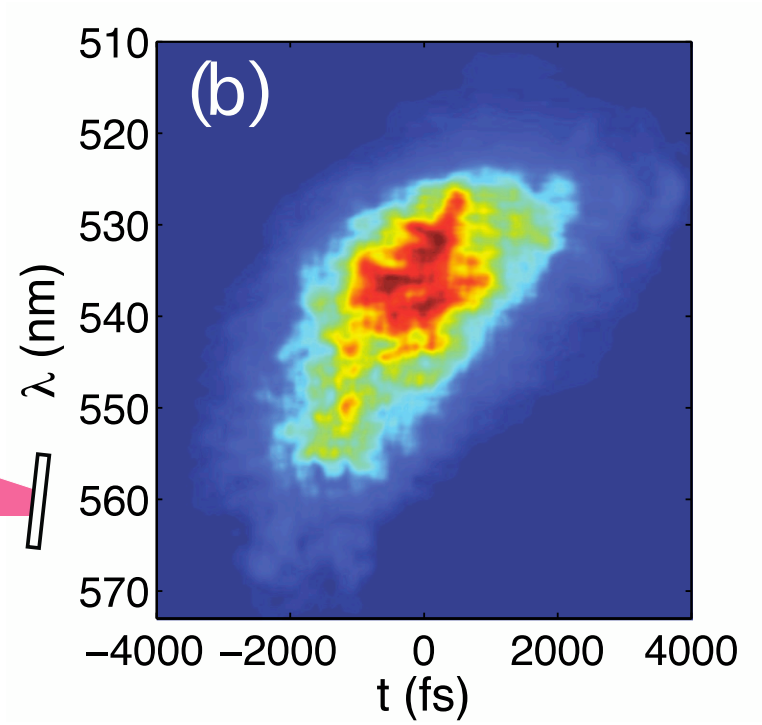


LLNL-Titan experiment: Specular FROG diagnostics records time-resolved spectra of 2ω light

Set-up on LLNL's Titan laser



Recorded FROG image

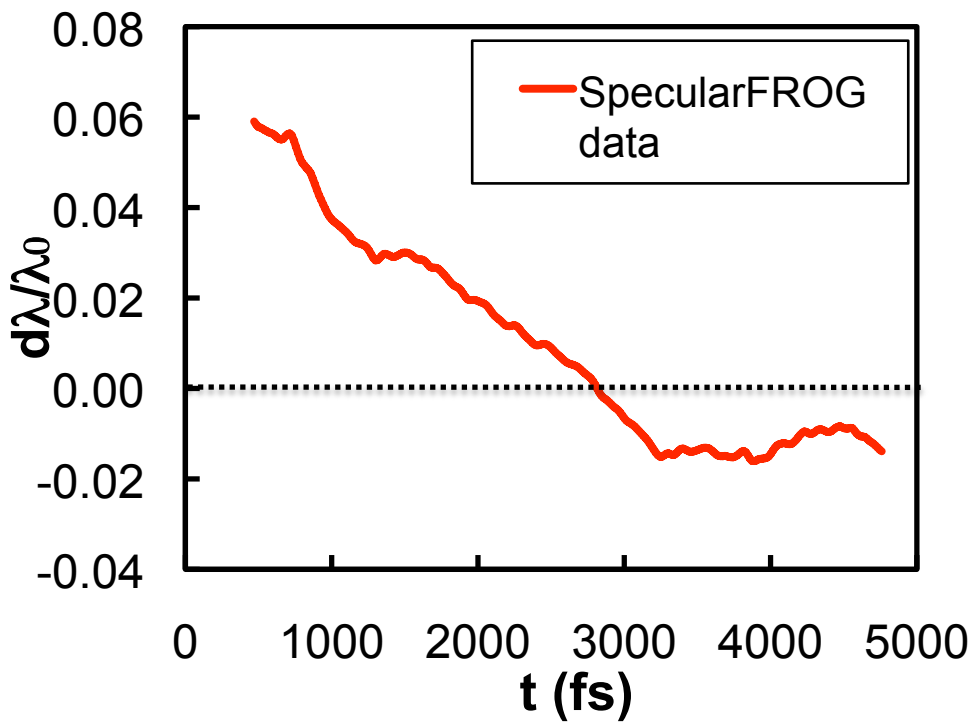


FROG=Frequency Resolved Optical Gating for time-resolved spectrum with resolution ~100fs

Experiment performed by Y.Ping et al., submitted to Phys.Rev.Lett.

Experimental results show that reflected 2ω light is red- and later blue-shifted

Measured wavelength shift vs time



Early reflected light is red-shifted

Late reflected light is blue-shifted

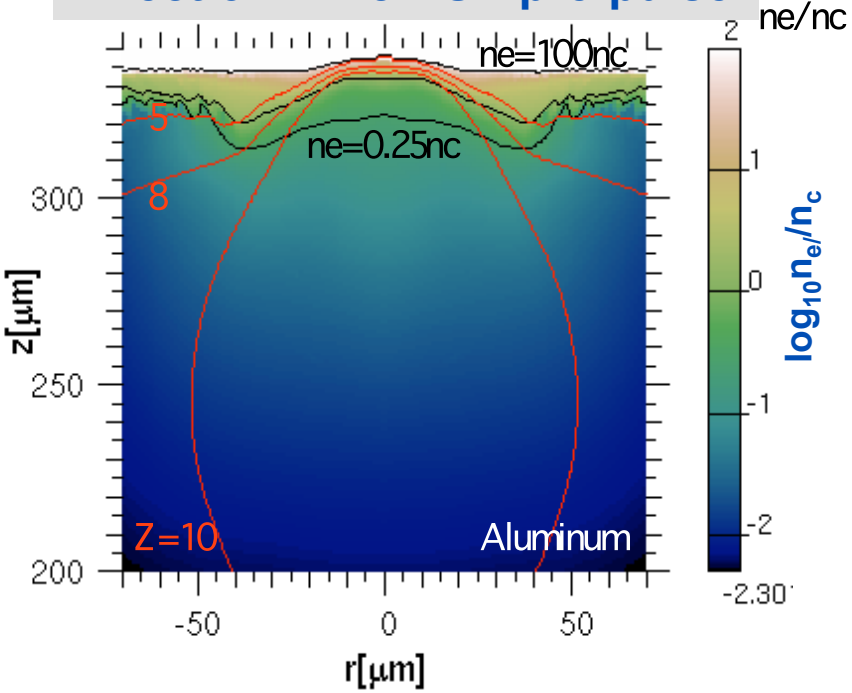
Shift reverses near peak intensity

$$\frac{\Delta\lambda}{\lambda_0} = -\frac{2\mathrm{v}(ncrit)}{c}$$

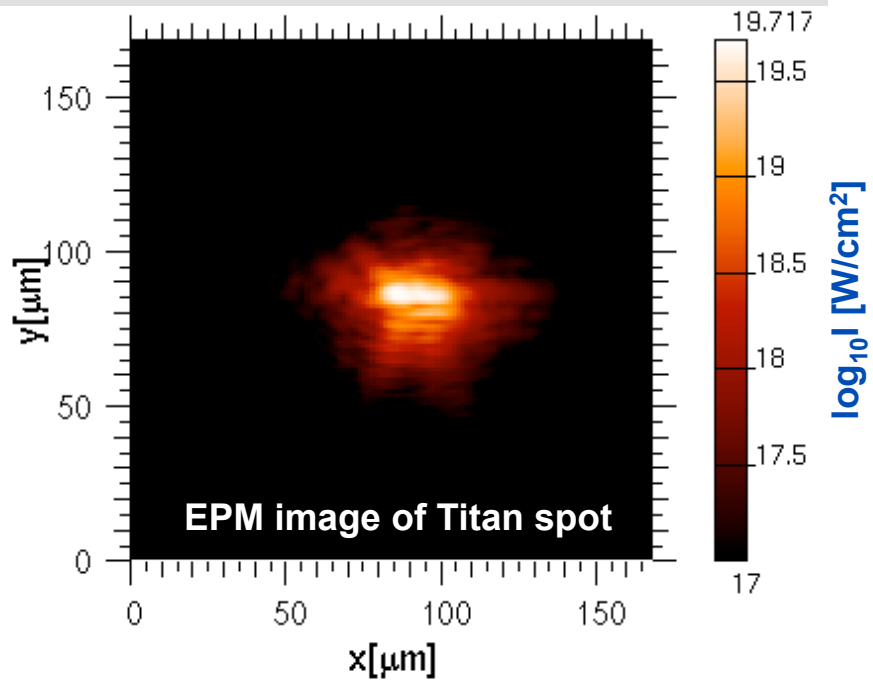
From wavelength shift we can infer the motion of the critical surface

2D PIC simulations are initialized with HYDRA generated maps of plasma density

Effect of 17mJ ASE pre-pulse



Intensity distribution in focal spot



Ionization physics / plasma motion play no role

Relativistic self-phase modulation not important

Change in relativistic critical density not important

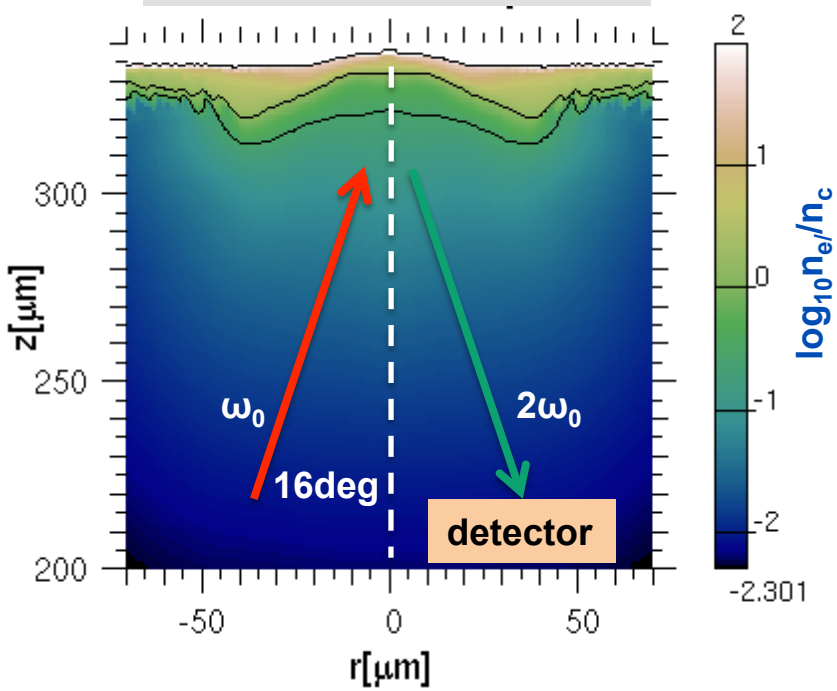
2D representation w/ similar power dist.

Peak intensity 8.6×10^{19} W/cm^2, start at e^{-8}

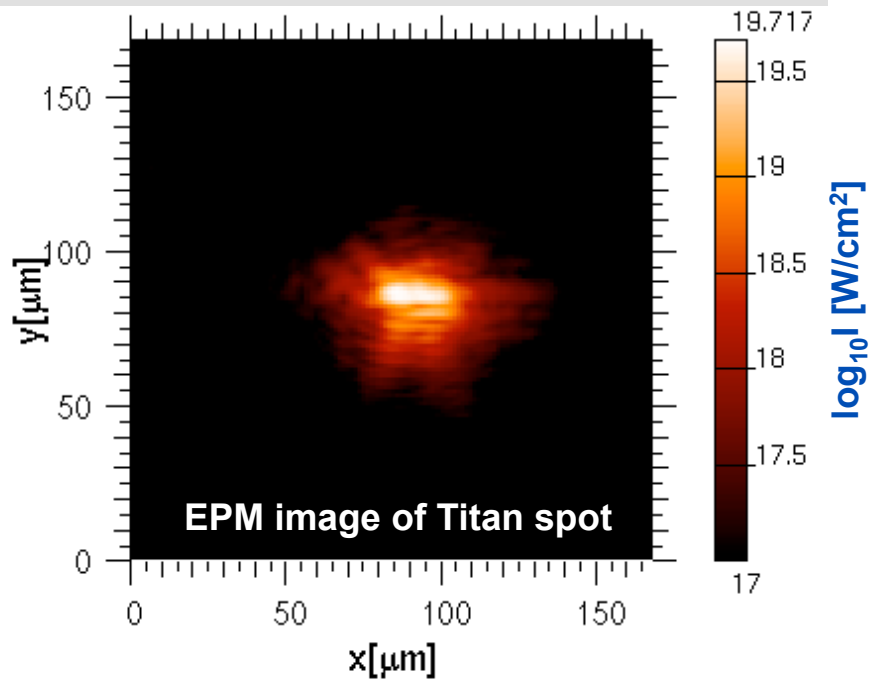
150J at λ=1μm over 1400fs fwhm

In our PIC Simulations we determine the spectrum of reflected light in a 'detector' at the injection plane

Irradiation geometry



Intensity distribution in focal spot



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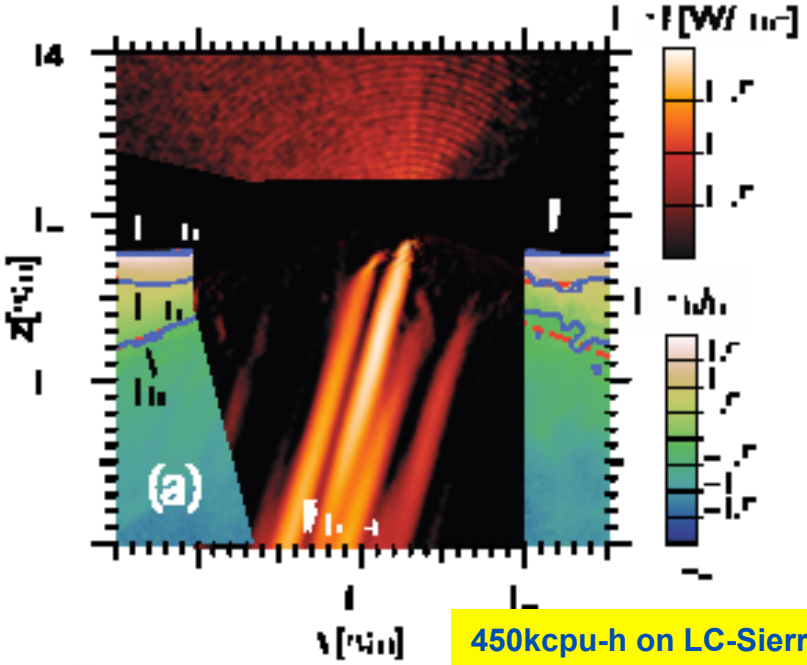
Peak intensity 8.6×10^{19} W/cm^2, start at e^{-8}

150J at λ=1μm over 1400fs fwhm

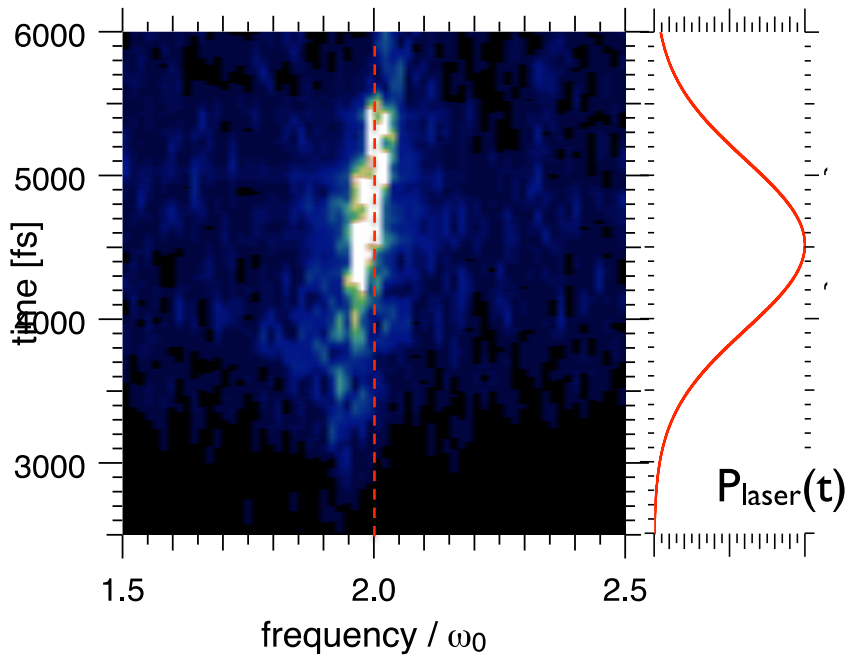
Our PIC Simulation captures Doppler shift of 2ω light

Laser and electron flux @ peak power



450kcpu-h on LC-Sierra

FFT of 2ω light in specular dir.



Simulation box 180x140um

32cells/micron 50particles/cell

74time steps / laser cycle

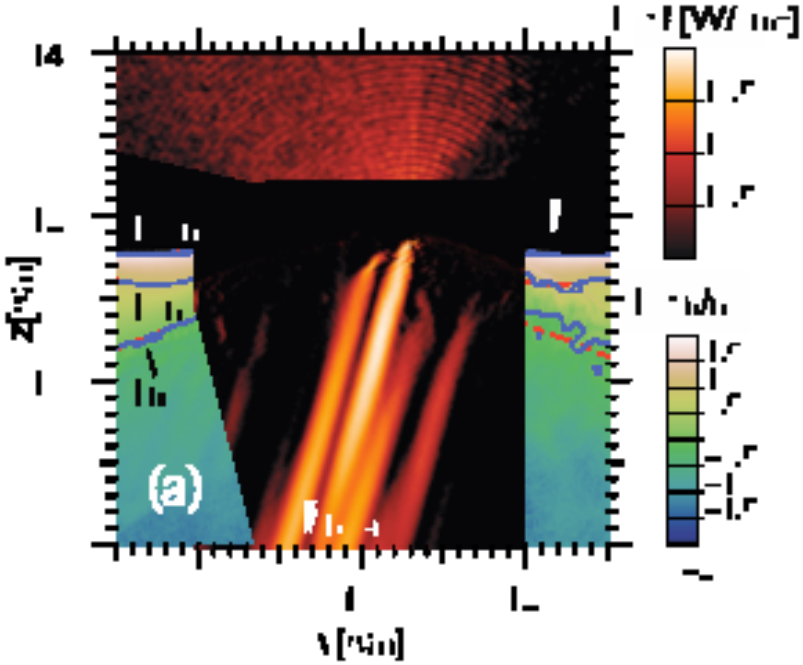
Absorbing b.c. (z); periodic in y

200fs windowed Fourier-transform of light for z=0 & y=100-150um

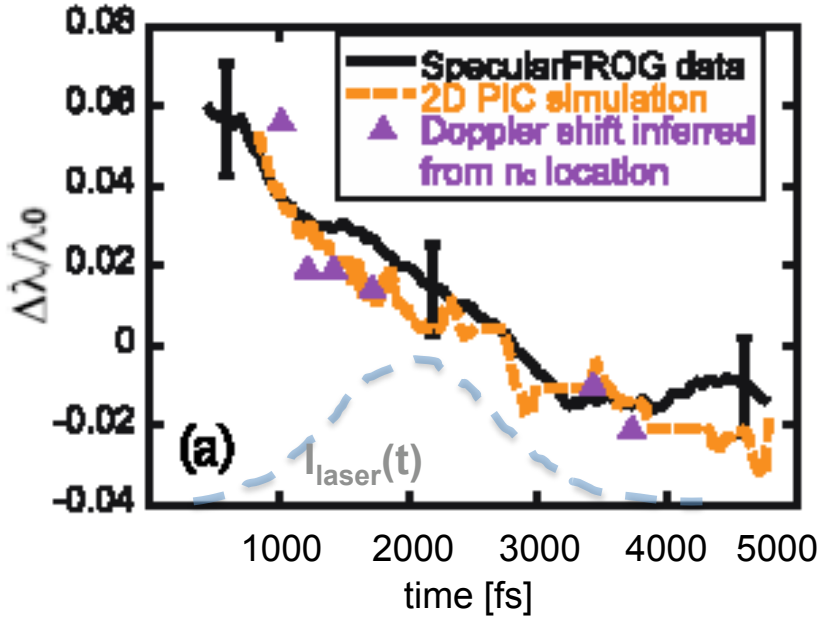
PIC-Hybrid code: Cohen, Kemp, Divol,JCP(2010)

Doppler shift of reflected light in our simulations agrees with experimental result

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)

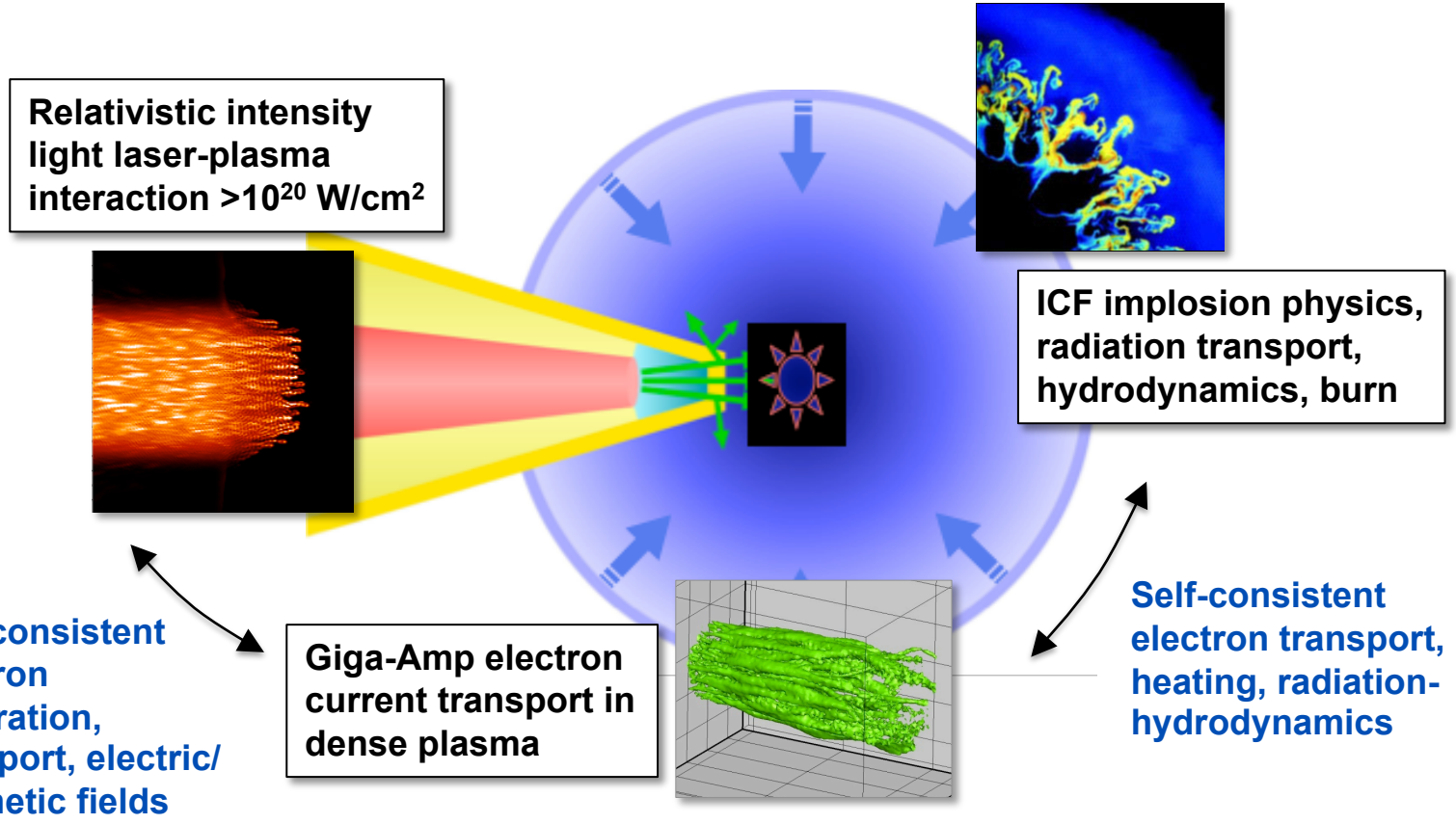
Conclusions from Y.Ping's experiment

- **Specular FROG diagnostics provides time-resolved spectra of 2ω light with a 100fs resolution**

- **Experiment finds early red and late blue-shift, consistent with compression followed by expanding motion of critical surface.**

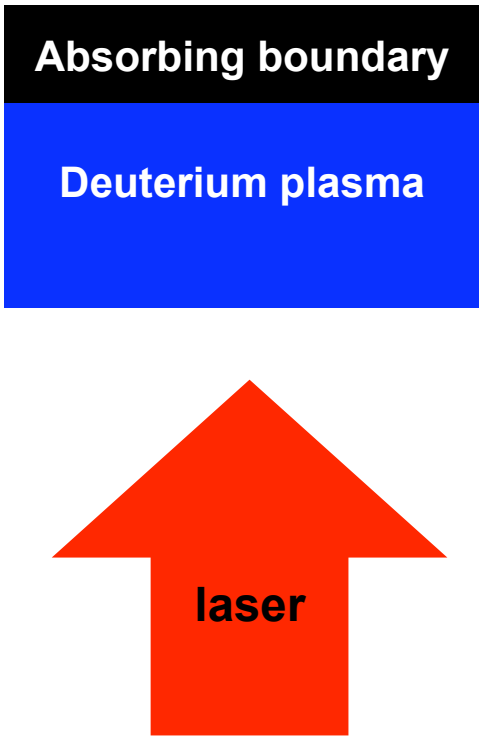
- **2D PIC-Hybrid simulations with careful set-up and boundary conditions reproduce wavelength shift <u>quantitatively</u>**

Fast Ignition presents a scientific and computational grand challenge in high-energy-density physics

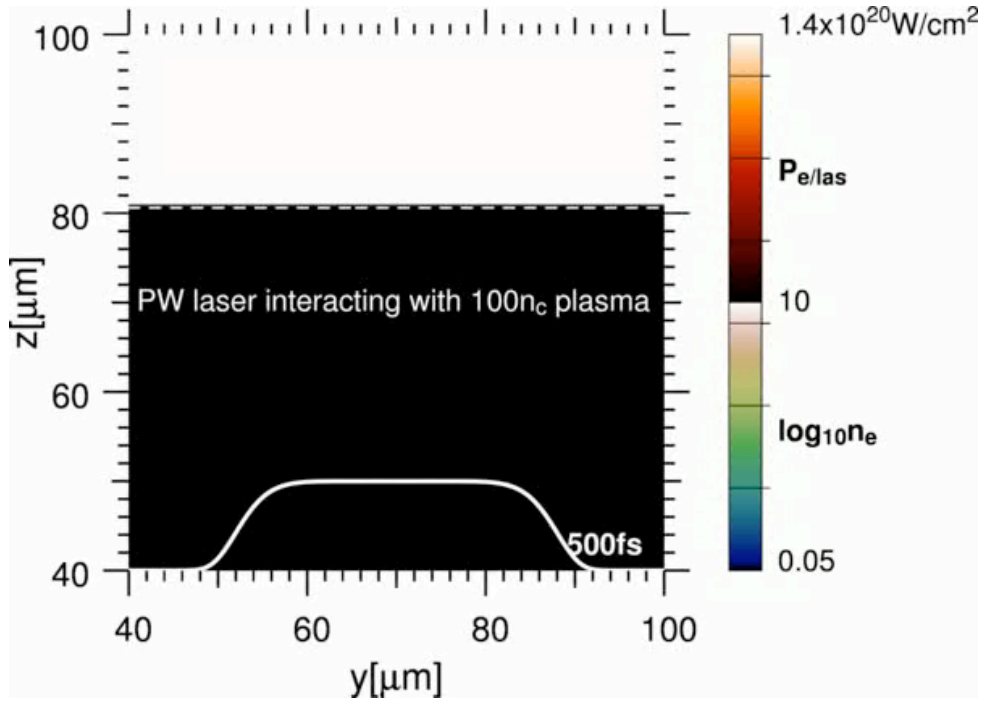


FI offers the potential for high gain ignition, but its scientific underpinning is a formidable multi-scale, multi-physics problem

We study the interaction of a Petawatt laser pulse with a plasma density step over 5ps

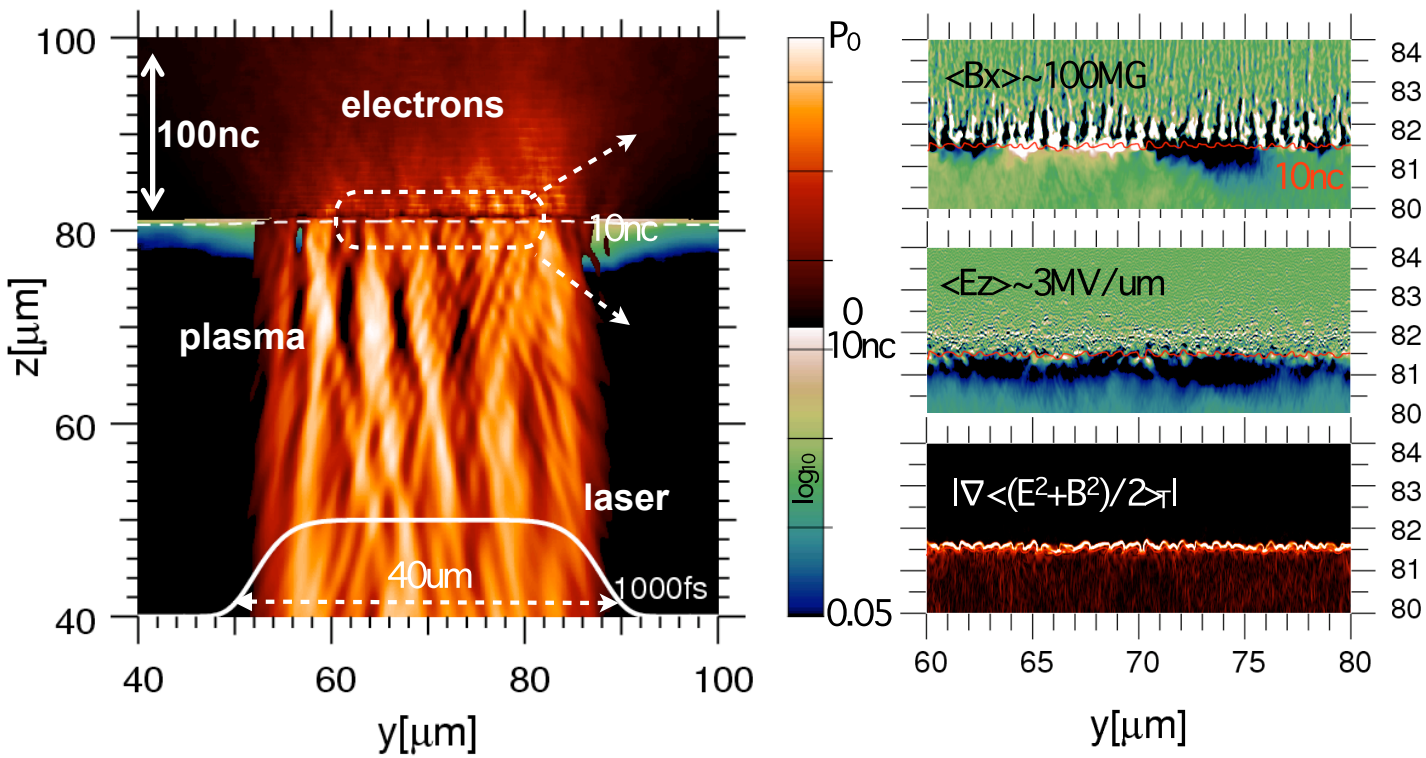


Poynting flux & Electron energy flux



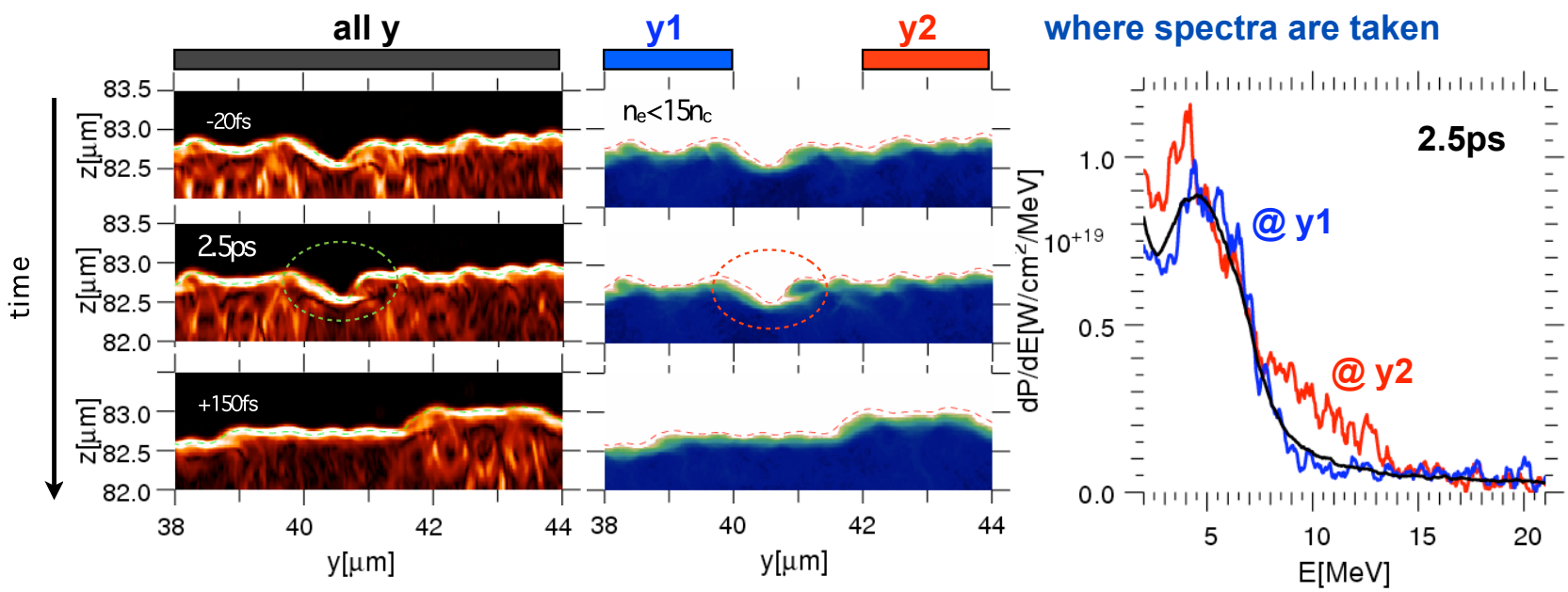
300kcpu-h on LC-Sierra

The early stage of interaction is dominated by laser beam filamentation in under-dense plasma



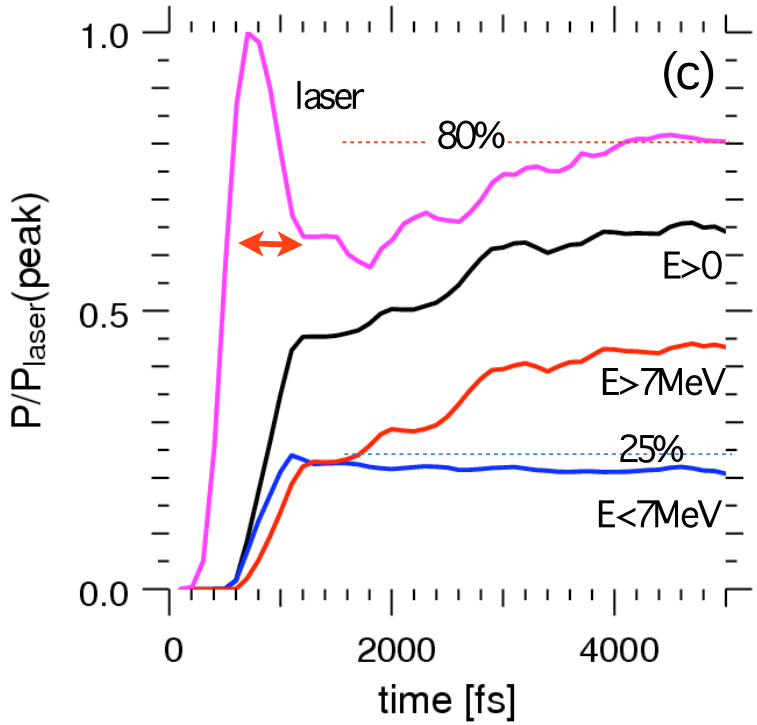
- Electrostatic field near absorption interface permeable to return currents, follows laser filaments: unlike 1D
- Electron beam filaments in over-dense plasma

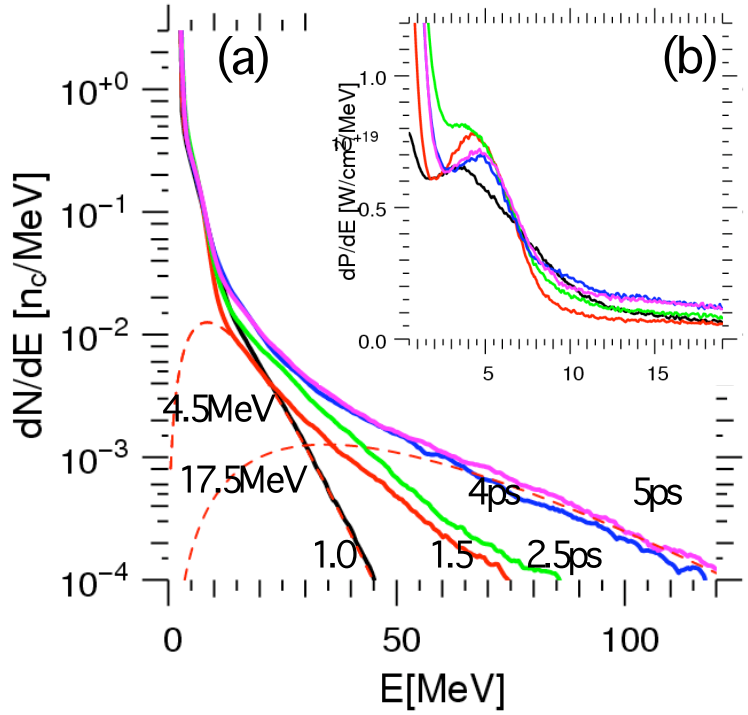
We have identified key physics elements of energy partition and plasma expansion on the ps time scale



- Ponderomotive push-on-dense-plasma resembles Rayleigh-Taylor instability
- Plasma release modifies spectrum: more 'hot' absorption
- Drives plasma expansion into vacuum

After 5ps, 80% of laser power is absorbed; 65% of energy flux is coupled to an electron beam at roughly 35deg half-angle





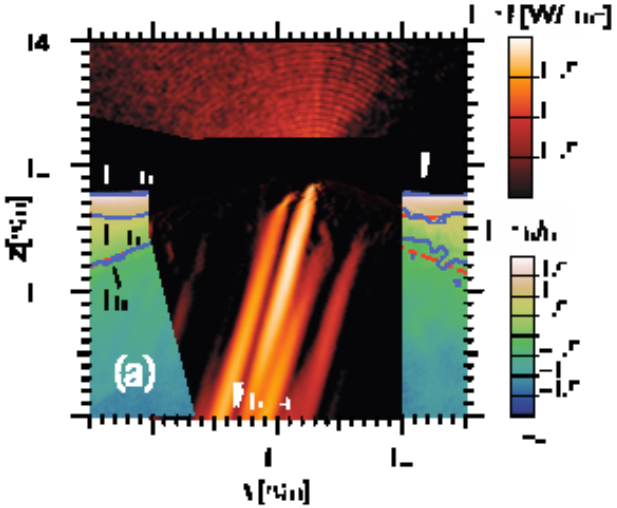
- **Difference between net laser- and forward electron power is due to beam divergence, i.e. <cos θ>**
- **Plasma expansion causes growing population of hots**

We want to use PIC-generated electron distributions as source for pure transport simulations

- For modeling large targets over tens of picoseconds, we want to use pure transport codes instead of PIC-Hybrid

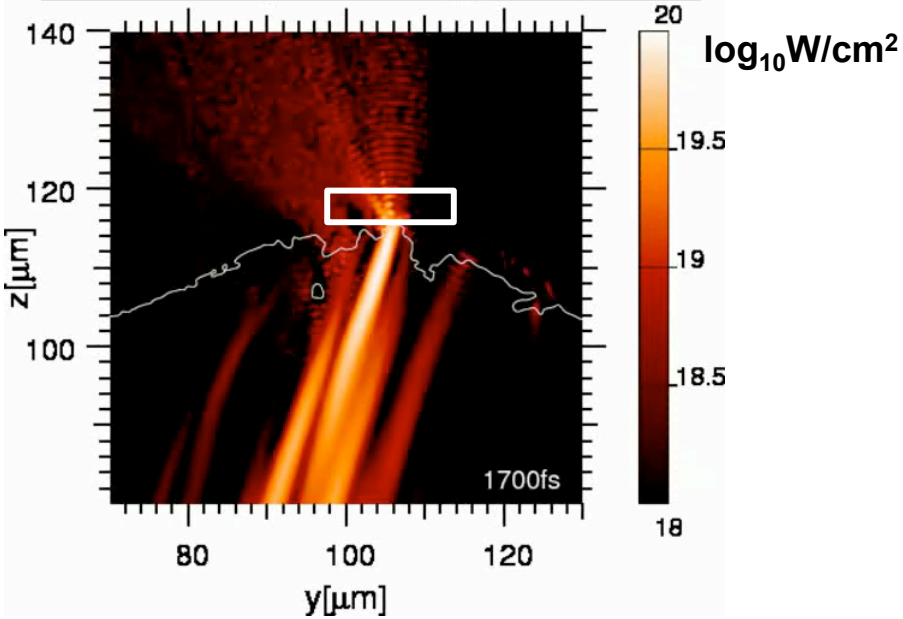
- We use our 2D PIC model of Y.Ping's experiment, where we have validated reflected light spectra and absorption, as a basis for a demo

- We translate PIC-generated electron spectra into electron sources for transport simulations

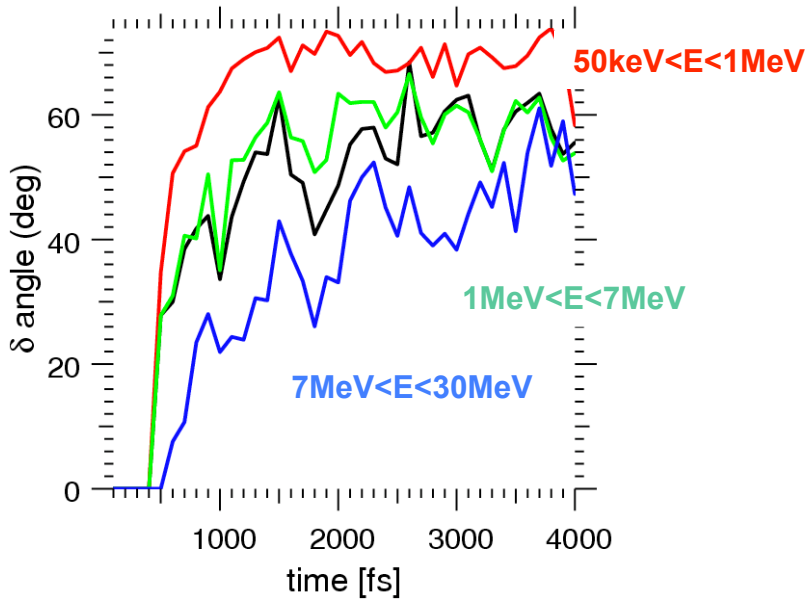


We characterize the laser-generated electron distribution vs. angle & energy for transport codes like ZUMA*

Energy flux density along z



Divergence angle vs time



- 60% of incident laser flux coupled to electron flux through box
- 30% coupled into wide 'wings'
- Electron 'slope temperature' varies, but near peak ~7MeV (multi-sloped)

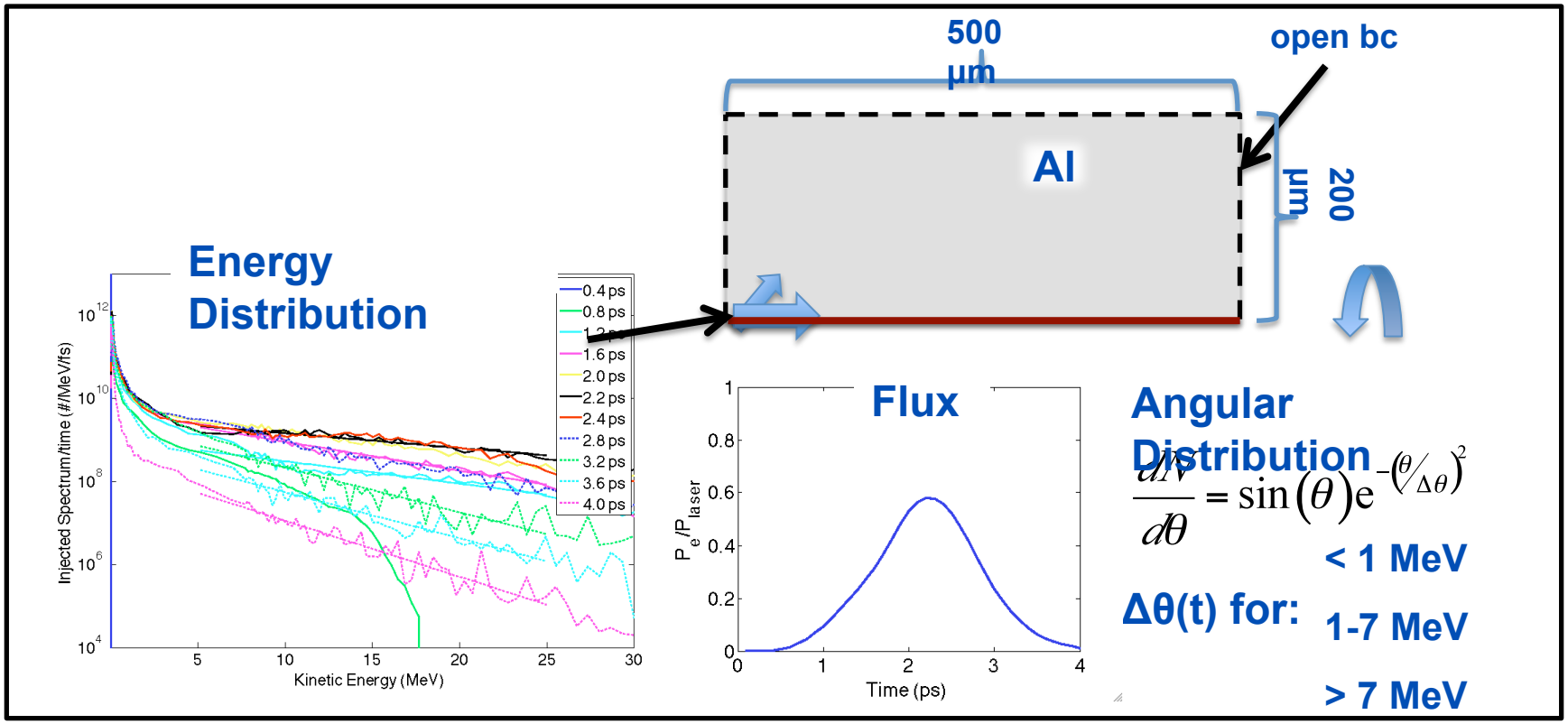
- Divergence for three energy groups as function of time

*ZUMA by D.Larson, LLNL

We inject particles in cylindrical geometry in a demo case: Aluminum slab target

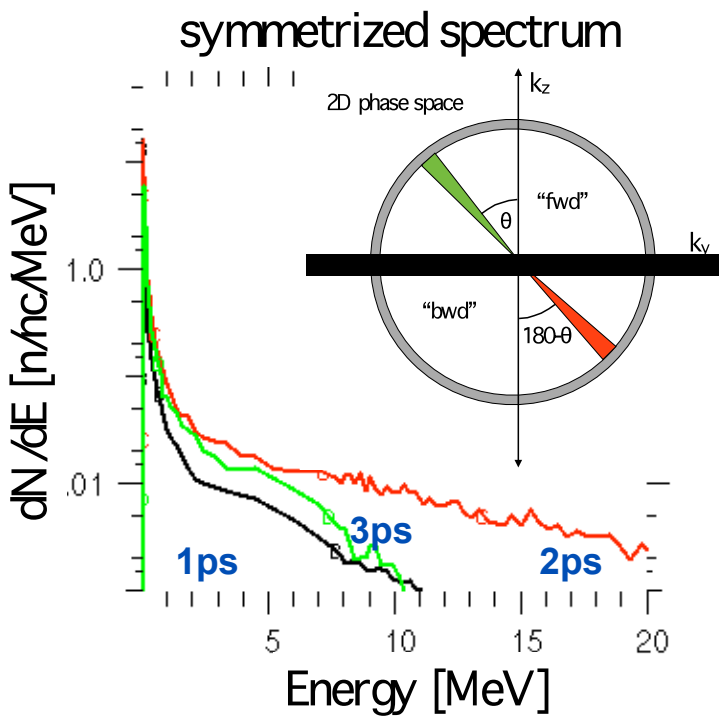
- **Particle Flux, Angular & Energy Distribution time dependent**
- **Spatial Distribution constant in time, made symmetric in cylindrical geometry**

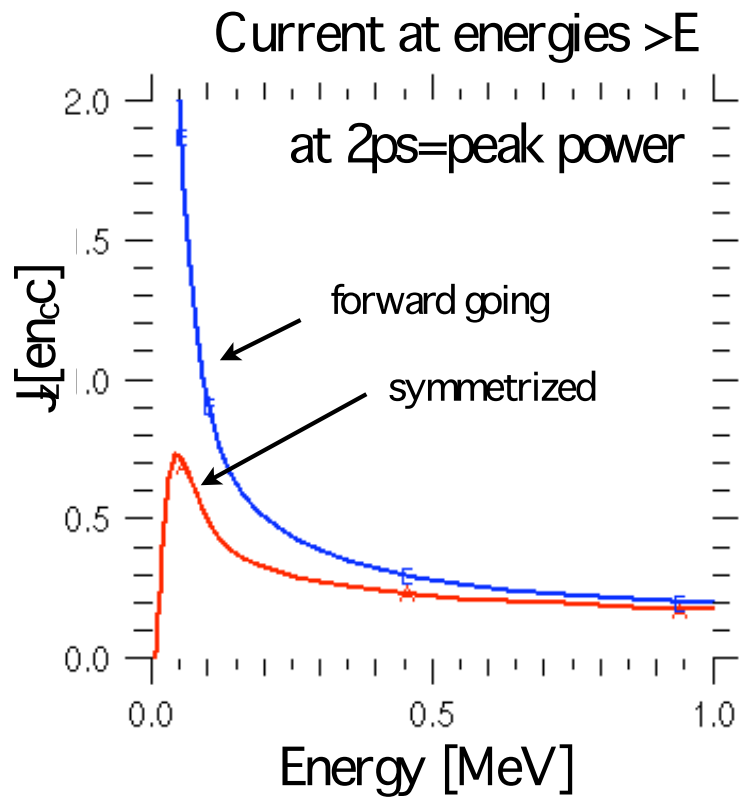
$$f = Spatial(r)\,Flux(t)\frac{dN}{dE}(E,t)\frac{dN}{d\theta}(\theta,t)$$



We remove thermal & return currents from PIC spectra to prevent artificial heating in transport code

Subtracting phase space from particles going in opposite directions means that the net particle current in hybrid code is reduced

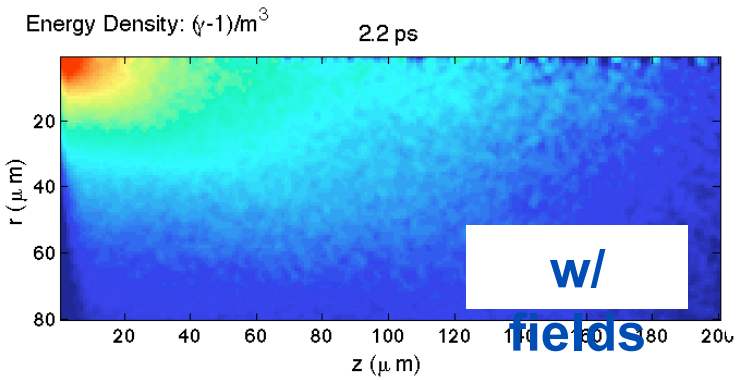


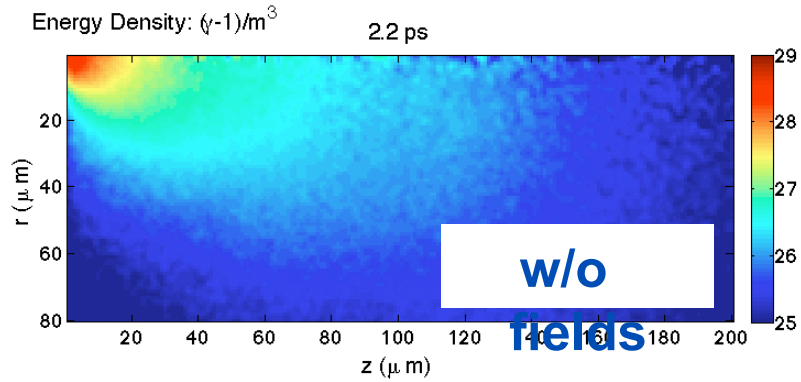


'hotter' spectra have less charge current than 'colder' ones at equal absorption

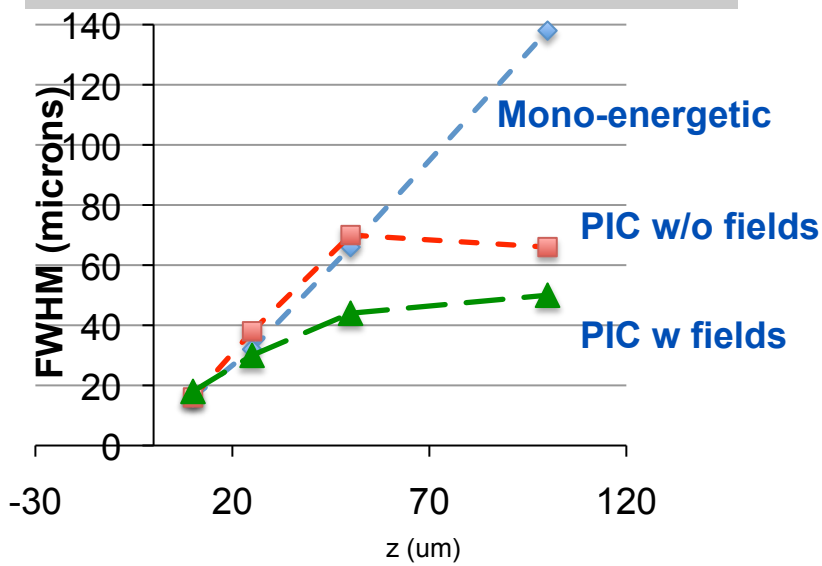
Fusion Energy Sciences

We find up to 15MG magnetic fields inside solid targets that help collimate electron beam

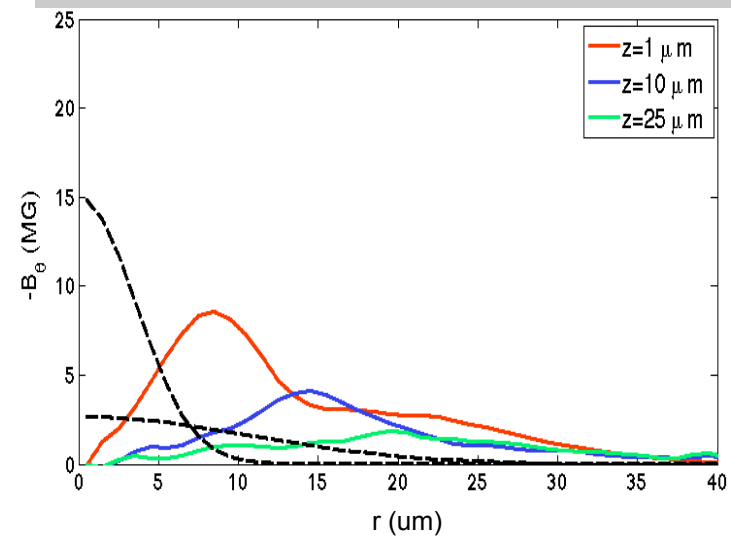




Width of K-alpha image vs z



Azimuthal magnetic field

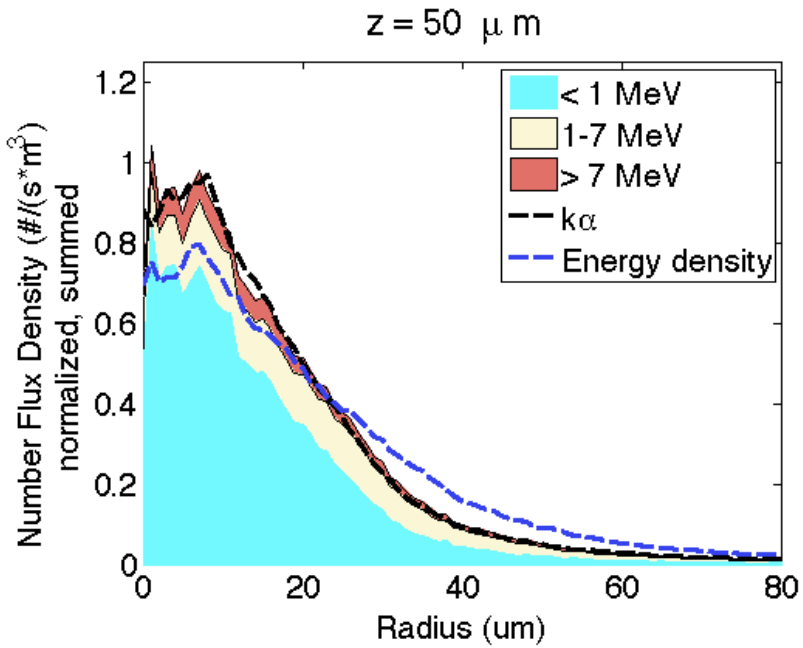


100um location dominated by stopping of fast particles more than by fields..

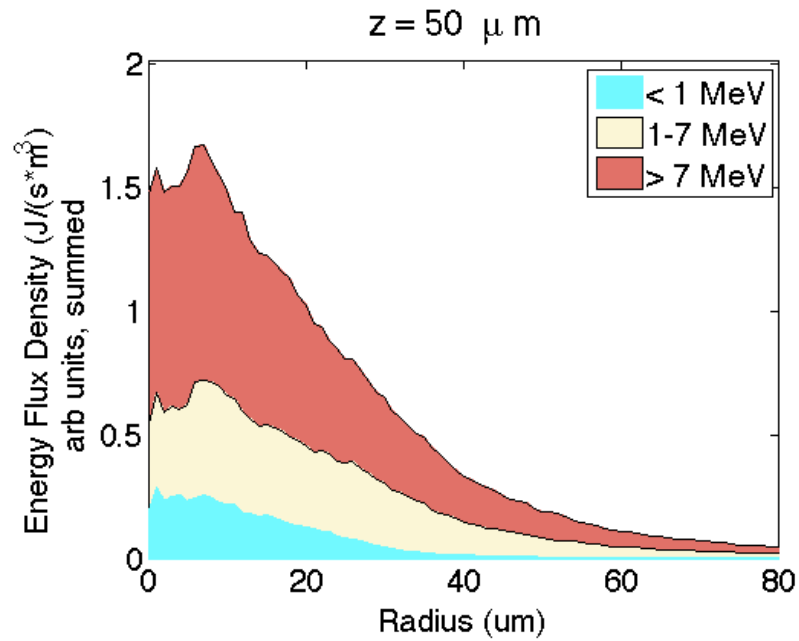
Fusion Energy Sciences

K-alpha mostly due to <1MeV electrons, but energy flux is dominated by >7MeV electrons

Number flux vs. radius



Energy flux vs radius



Interpretation of experimental K-alpha images requires de-convolution under several aspects, including instrument function, target heating

Conclusions from modeling transport

- We consider injection of laser-generated electron spectra into transport codes like ZUMA

- We find ~10MG fields are generated near target surface that affect transport somewhat

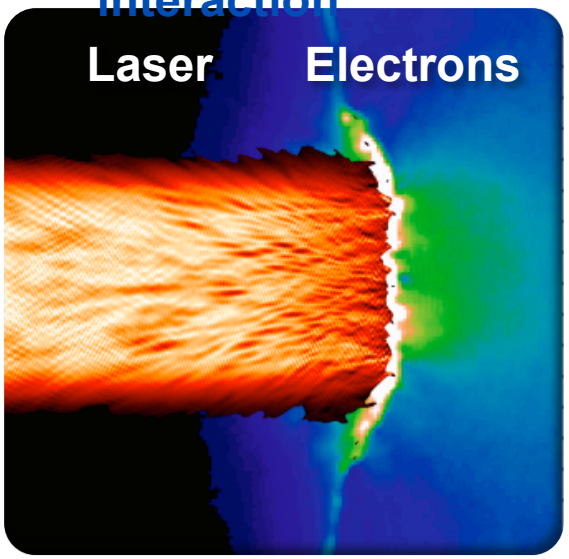
- While K-alpha tracks electron number flux (<1MeV), energy flux is dominated by >7MeV electrons

- Beam hosing and non-symmetric injection requires 3D simulations

Our vision for multi-picosecond integrated simulations of Fast Ignition is to combine PIC-Hybrid with HYDRA

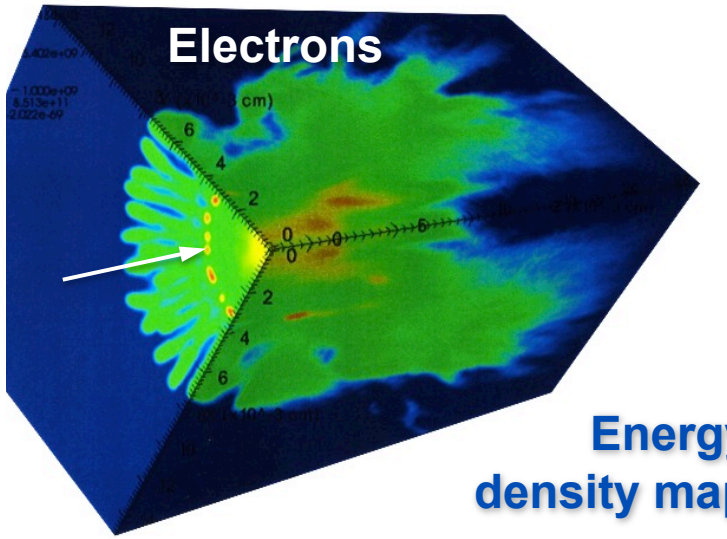
PIC-Hybrid

Relativistic laser-plasma interaction



ZUMA+HYDRA

Implosion, core heating, and burn



Energy density map

PSC-Hybrid - Cohen, Kemp, Divol, J.Comp.Phys.229(2010)

HYDRA+ZUMA-Marinak(2010)

Conclusions

- PIC-Hybrid code properly set-up with HYDRA allow us to simulate short pulse laser experiments on Titan laser to full scale

- We have validated codes and concepts against experiments
  - Y.Ping's FROG diagnostic track motion of critical surface on 100fs scale
  - Simulations reproduce Doppler shift of reflected light quantitatively

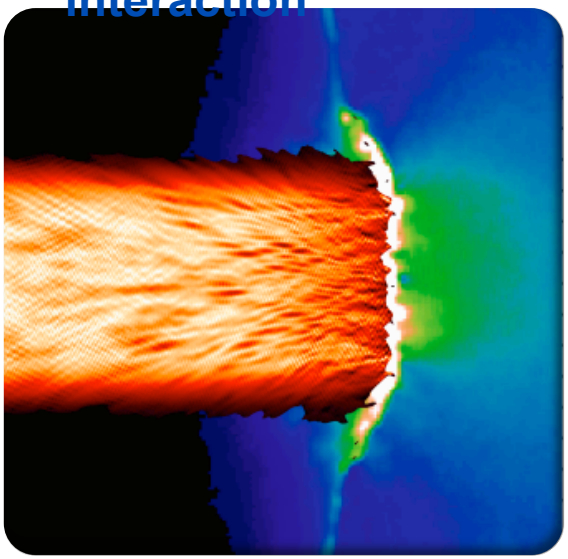
- We have studied Fast-ignition relevant laser pulses to 5ps
  - 80% of laser light is coupled into hot electrons
    ~1/3 of hot-electron flux is <7MeV, with a 35deg half-angle divergence

- We use the electron distribution function from PIC simulations for multi-ps transport simulations (ZUMA-Hydra)

Acknowledgements

PIC-Hybrid

Relativistic laser-plasma interaction



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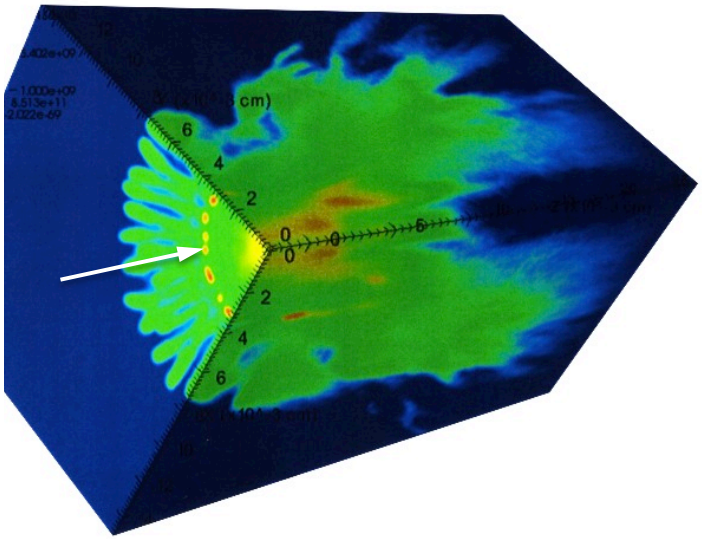


L.Divol, B.Cohen, D.Strozzi

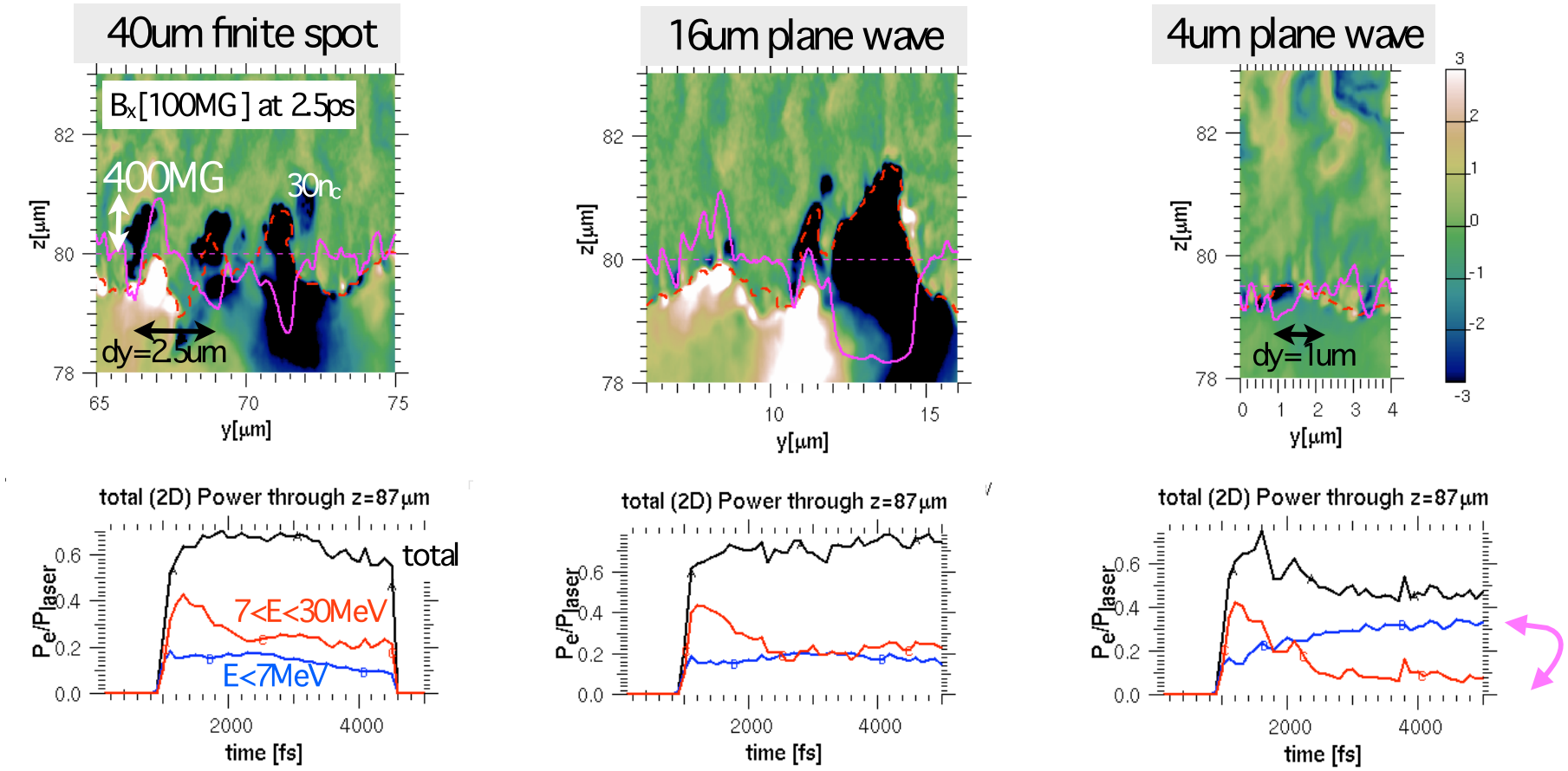
Y.Ping, C.Chen, P. Patel, M.Tabak, M.Key

Y.Sentoku (U.Nevada,Reno), H.Ruhl (LMU Munchen, Germany)

Institutional Computing Grand Challenge Award – 10M cpu-h

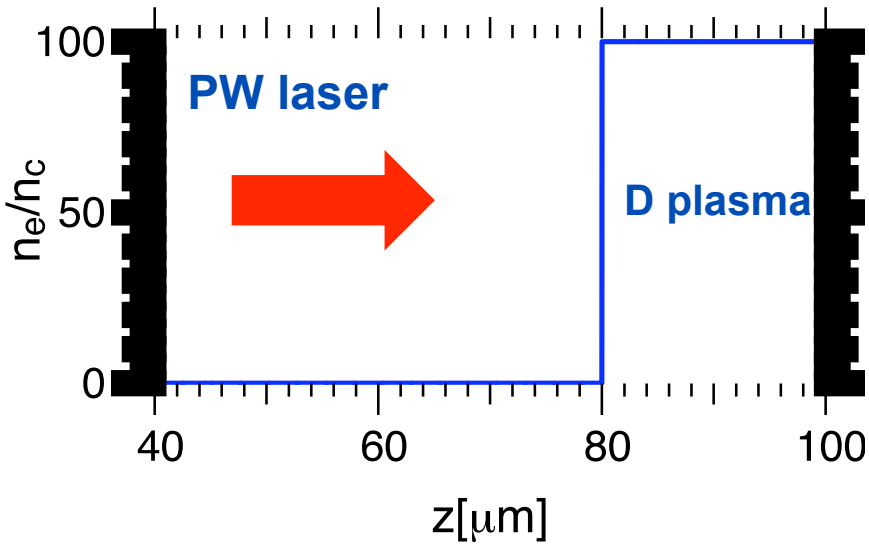
Backup slides

Multi-micron scale magnetic structures evolve near critical interface, affecting coupling and spectrum of hot electrons



Magnetic field scale and -magnitude are consistent with the 'colder' spectra found in small runs, i.e. with Ly<16um and periodic boundary conditions

We study the interaction of a Petawatt laser pulse with plasma over ~5 picoseconds

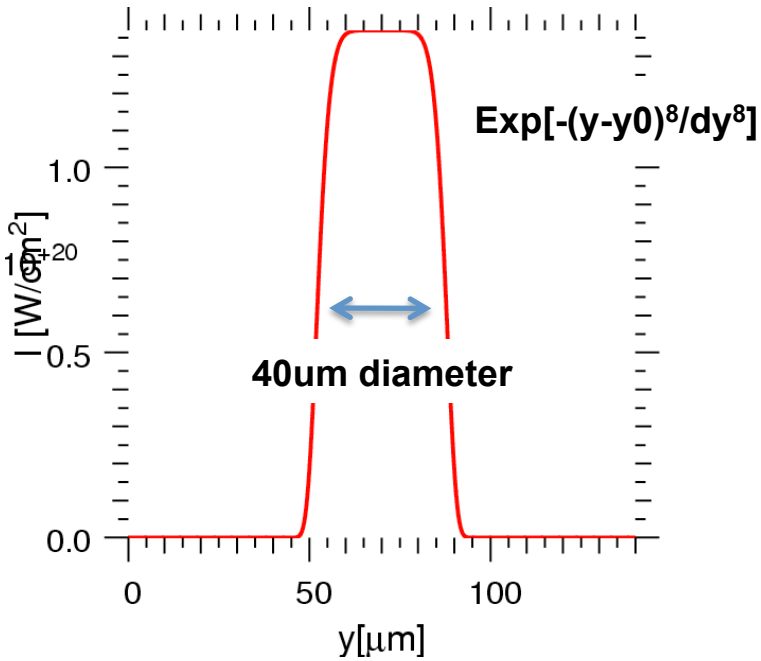


- Target geometry is quasi-1D, 140x120μm box, $2m_p$ ions, no density gradient
- PIC simulation 50cells/micron, 120e+40i particles/cell
- 300kcpu-h @ 2304 cpus on LC-Sierra

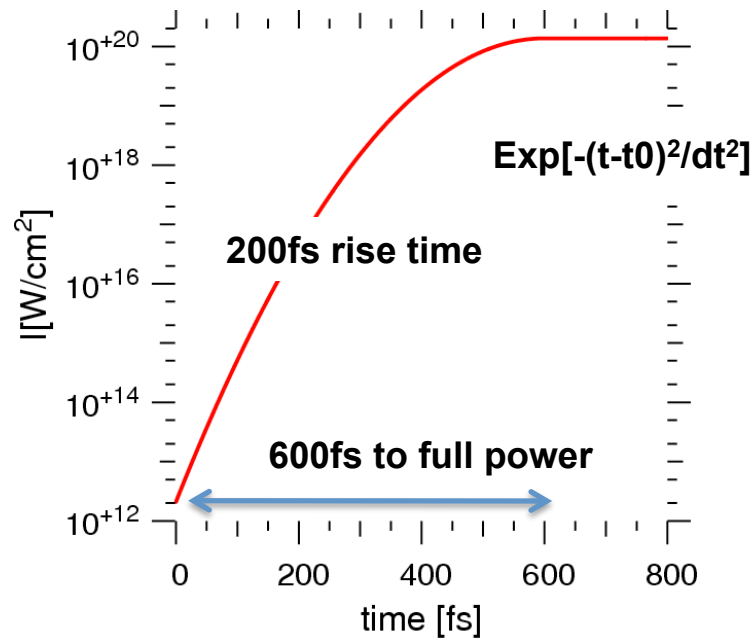
We simplify the set-up by interacting with a steep plasma interface

A 40um diameter, flat-front laser pulse is turned on 'adiabatically' to 1.37×10^{20} W/cm ^{2}

Transverse spot profile



Time history of laser intensity



Laser history has impact on long-term behavior of plasma expansion