Electron acceleration and Transport in the Context of Fast Ignition

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Why ... What .... Where ...???

Why have we studied electron generation and transport?

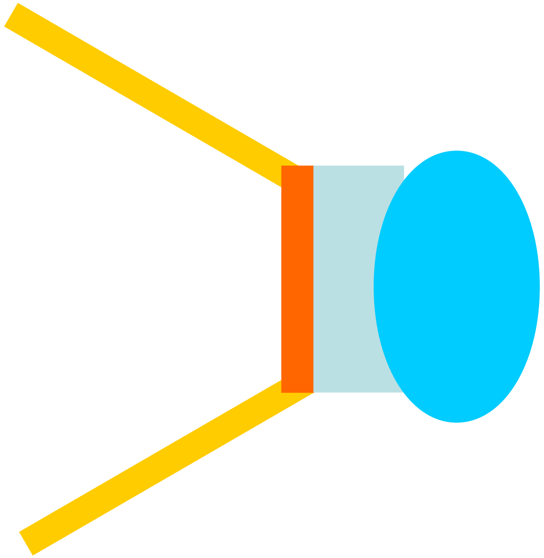
Interesting physics
Application to Fast Ignition
Ion acceleration, isochoric heating, other applications

What have we learned?

Excellent qualitative understanding
Predictive capability is limited by eg
lack of detailed knowledge of laser pulses,
transport coefficients in WDM and non-equilibrium plasmas
enormous computing requirements - multi-scale

Where do we go next?

Fast Ignition Core



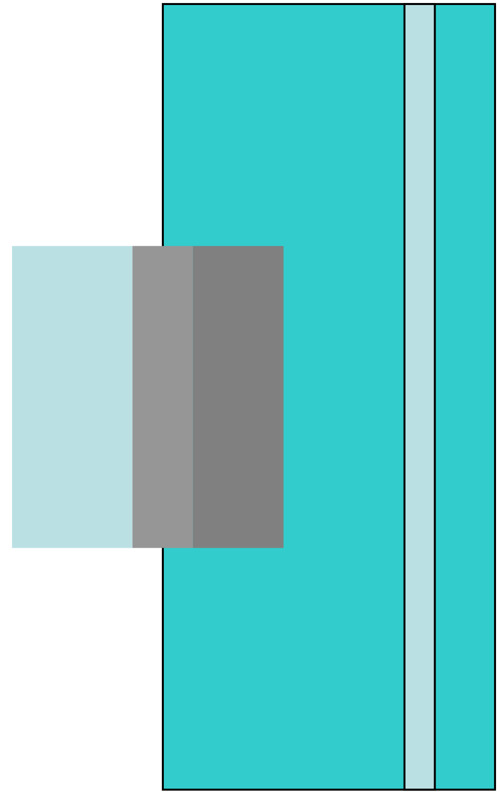
Cone, dense, Au

End wall, low Z, DLC?

Moderate density DT

Compressed DT core
$300 gcm^{-3}$

Current Experiments



Low density plasma $n_e < n_c$

Interaction layer $n_e \sim \gamma n_c$

Transport layer $n_e \ll$ solid

Diagnostic layers

HiPER serves (served!) to concentrate the mind

Design study proposal late 2006

Several x 10 MEuro

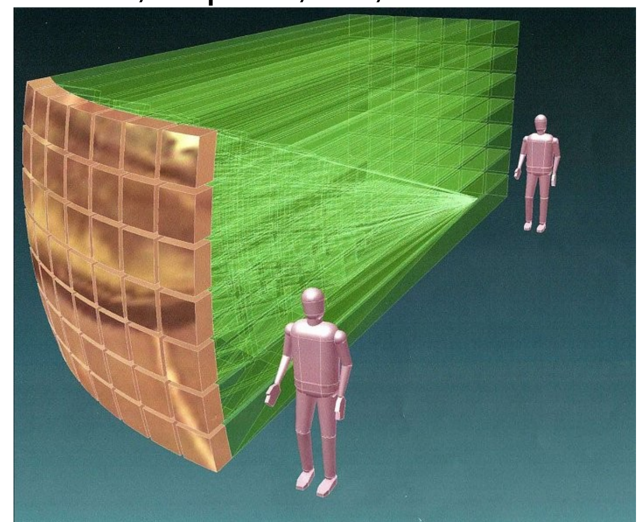
Important decisions for full proposal
- cost and risk elements

Demonstrate our competence to spend the money wisely

Need to get the best out of theory, modelling and experiments on existing facilities.

Establish confidence in our predictions

70kJ, 10psec, 1ω, 2ω or 3ω



200-300kJ, 5nsec, 3ω

Choice (?)of Wavelength for the Ignitor Beam

Energy deposited must heat fuel to ignition	E
Pulse duration τ determined by hydro confinement	$P=E/\tau$
Fuel hot spot size determines laser spot size	$I=P/A$
Electron range determined by $I\lambda^2$ λ is not a free parameter	

2ω or 3ω is expensive and transfers risk to the laser builders

How well do we understand transport and stopping?

Are there any tricks that could improve the margins for 1ω?

Key *et al.*

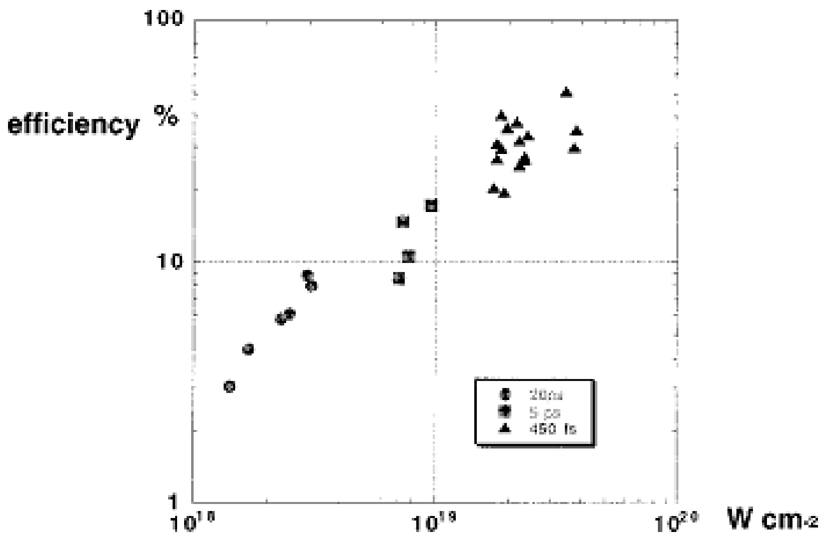


FIG. 3. Ordinate efficiency $E_{elec.}/E_{laser}$ plotted against intensity on target in W cm^{-2}. The 20 and 5 ps data are for high energy (200–400 J) and 450 fs data are for 15–20 J pulses.

Absorption Processes

Brunel / vacuum absorption

steep gradient / short pulse

j x B acceleration

forward going electrons

Pukhov / Direct Laser Acceleration

phase slippage

More generally any non-adiabatic process eg beam edge, interference with reflected beam, small scale structures in focal spot / RT / bubbles

Absorption fraction is not our biggest problem or unknown

The return current problem

Power flux in laser (Poynting Vector) $= \frac{E.B.c}{4\pi} = \frac{E^2 c}{4\pi}$

Energy of laser accelerated electrons
~ ponderomotive energy $= a_0 mc^2 ; a_0 = \frac{eE}{m\omega c}$

Density of laser accelerated electrons
~relativistically corrected critical density $= \frac{a_0 m \omega^2}{4\pi e^2}$

Power flux in electrons =
density x energy x velocity $= \frac{a_0^{\ 2} m^2 \omega^2 c^3}{4\pi e^2} = \frac{E^2 c}{4\pi}$

50% absorption requires half the electrons near critical density
The other half form a return current also moving at velocity c
At 30 x critical the return current drift velocity is equivalent to 500eV

Apparent coincidence is due to v_{group}=0 at turning point

Whatever the 'source' properties they are rapidly modified by the transport instabilities:

Weibel, collisional Weibel, resistive filamentation (transverse)
Two stream (longitudinal)

Full treatment in papers by Bret, Gremillet et al

Adam et al and Ren et al have suggested strong influence of instabilities on beam divergence

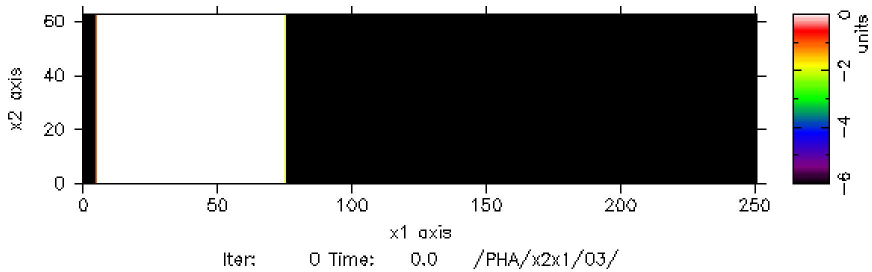
OSIRIS 2D-3V simulations:

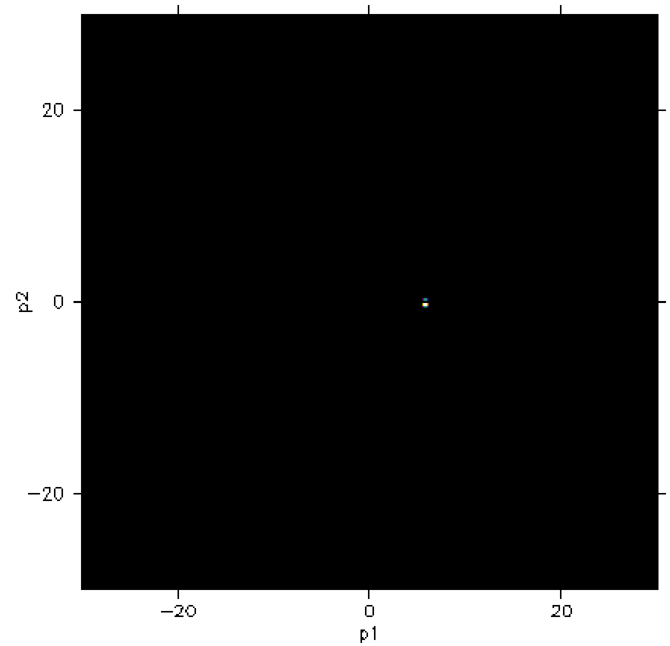
Beam
fraction α,
velocity γ

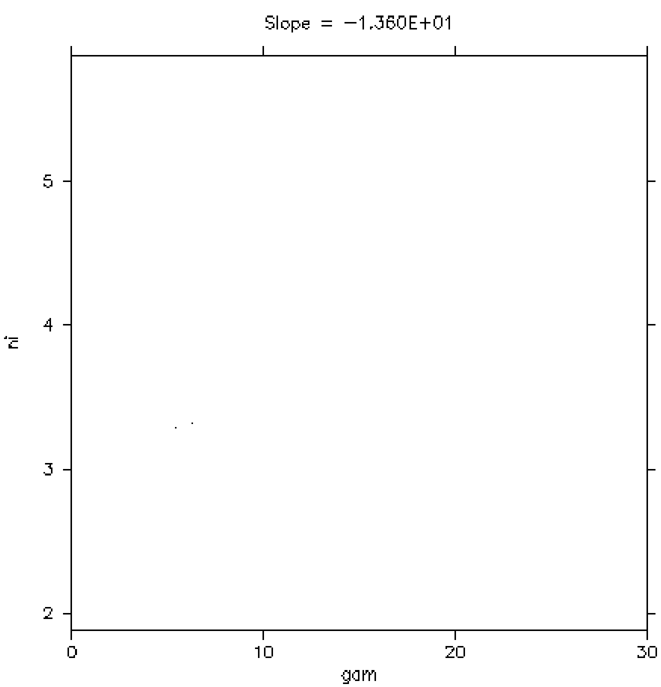
Uniform thermal
background plasma

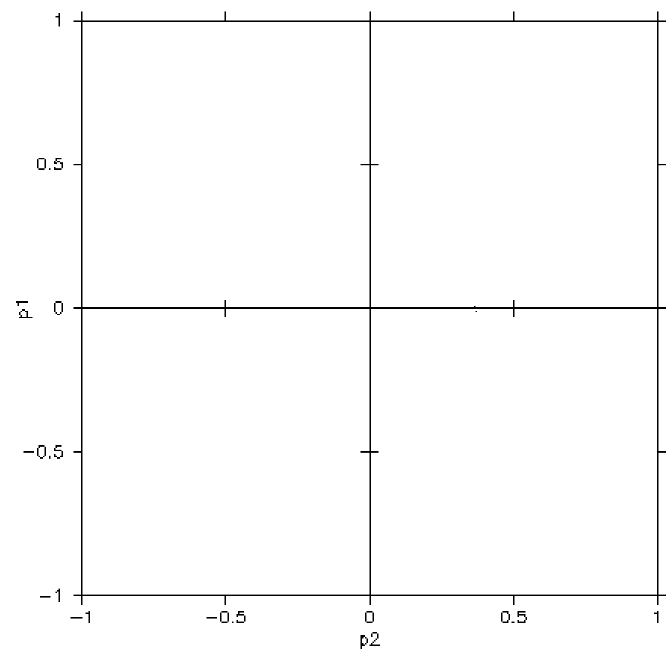
Initially charge neutral and field free

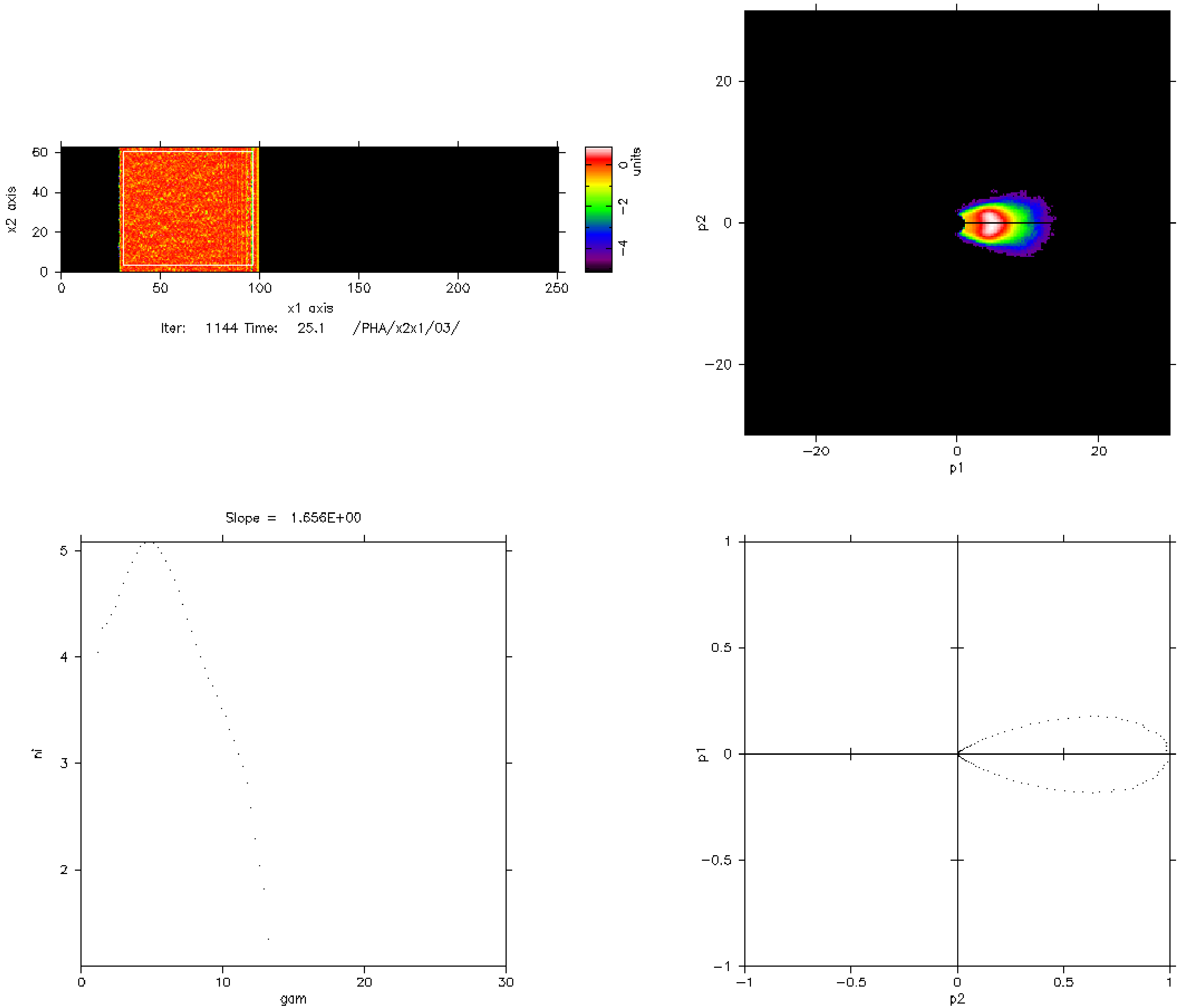
Initial spatial and momentum distribution of beam species: γ=6







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x1 axis
units
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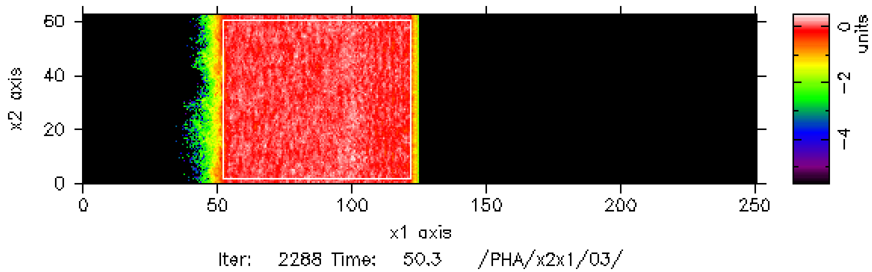
p2
p1
Slope = 1.656E+00
ni
gam
p1
p2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x1 axis
units
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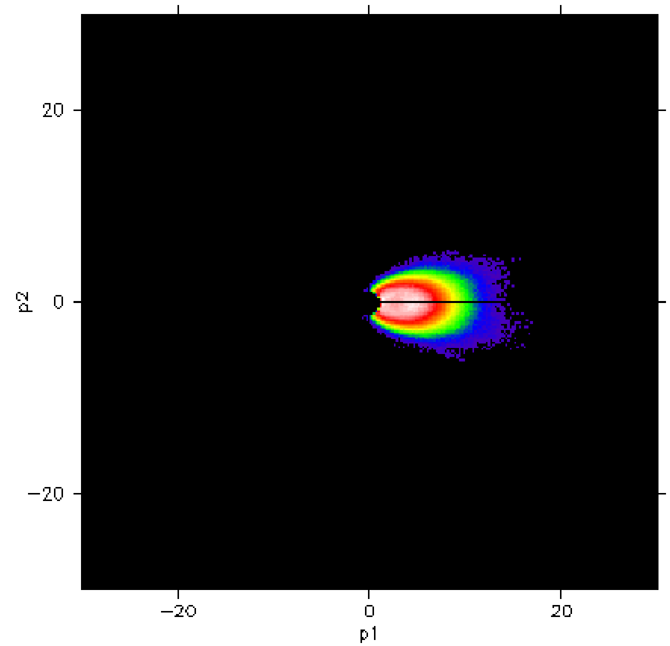
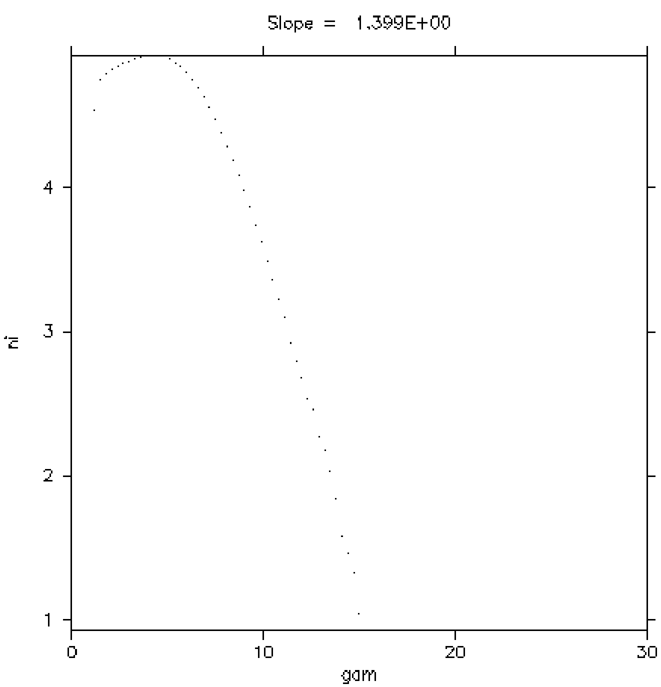

p2
p1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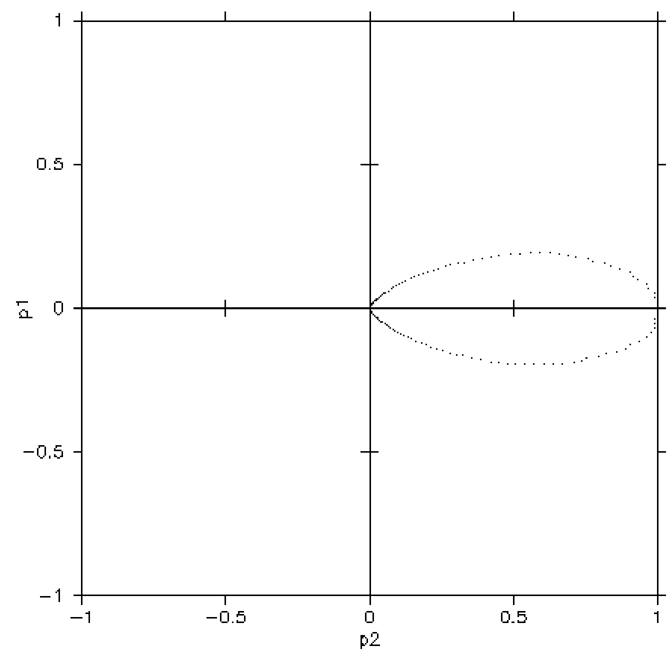
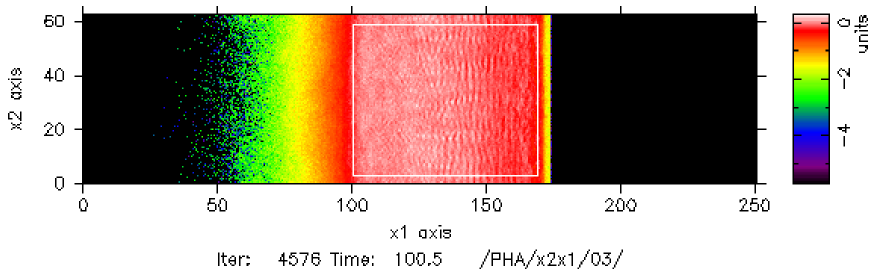
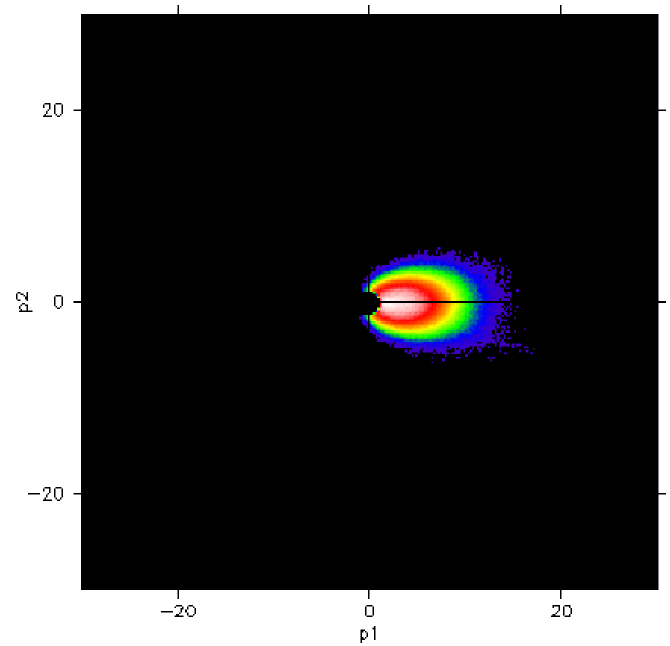
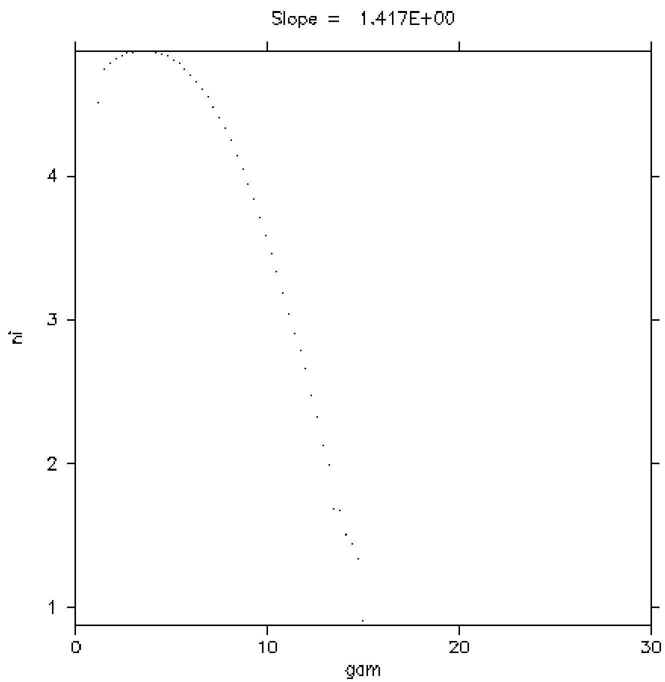
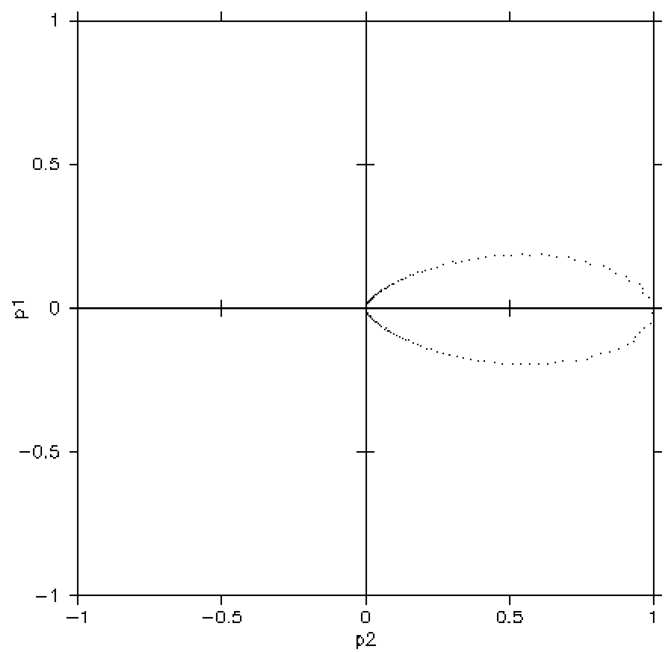

p1
p2

Unstable modes have $k_{//}$ larger than k_{perp}
(Gremillet et al PoP 14 040704 2007)









Experimental measurements: T_{hot} and f_{abs}

K-α emission versus thickness

needs mid Z fluor to avoid absorption
angular scattering increases with Z
measures all electrons above 10keV
needs careful modelling

Rear surface temperature

needs modelling input

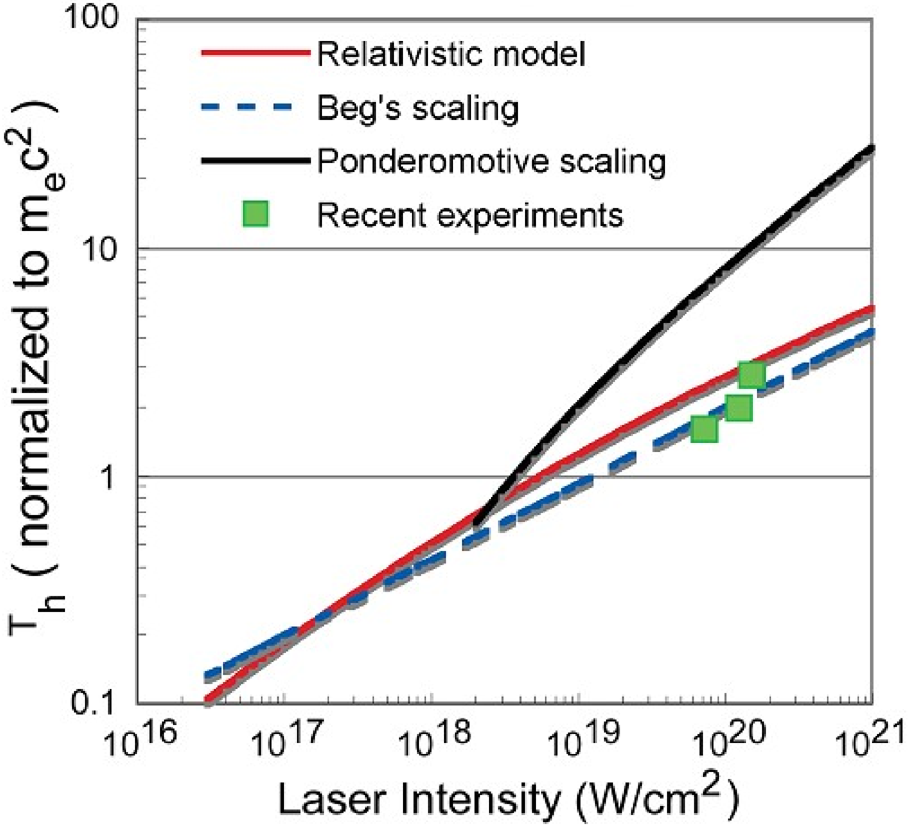
TNSA Ion emission

reasonable estimate of electrons > 10MeV

Hot buried layers

Most relevant for DT heating but complex modelling

Some dependence on material and pre-pulse / scale length



Wilkes' ponderomotive scaling

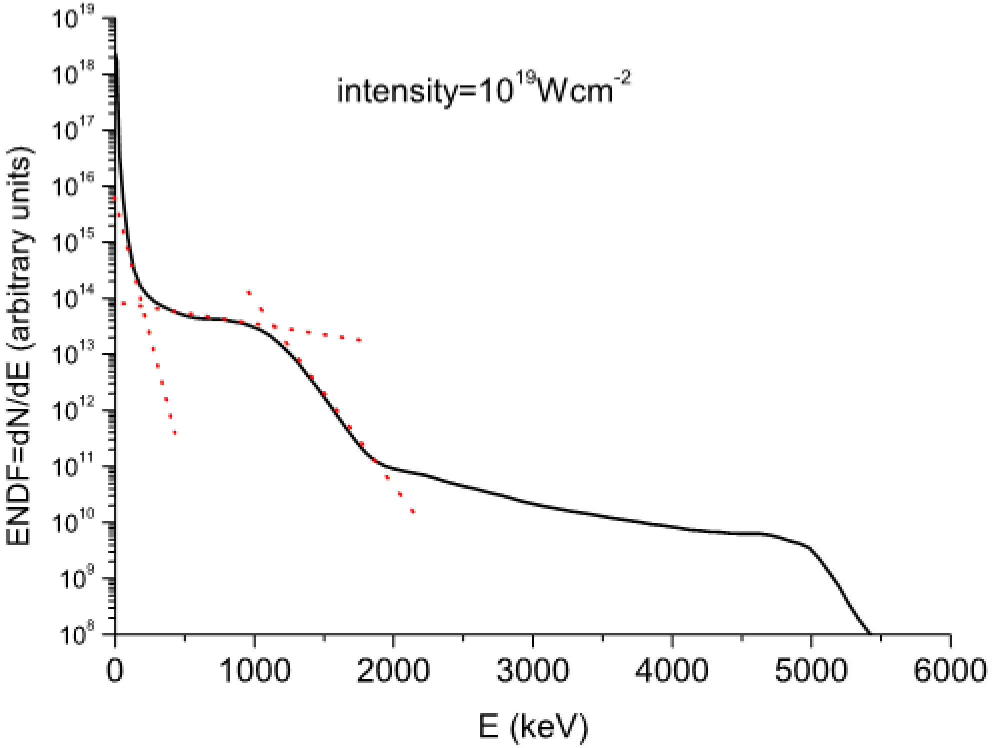
$T_h/mc^2=(1 + a_0^2)^{1/2} - 1$

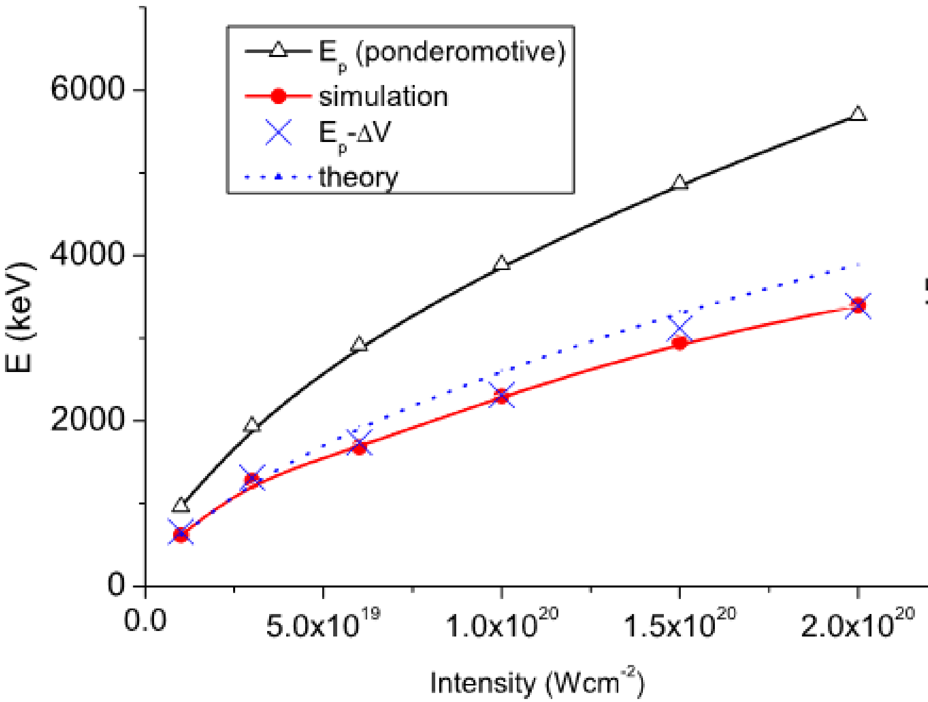
Beg's Law

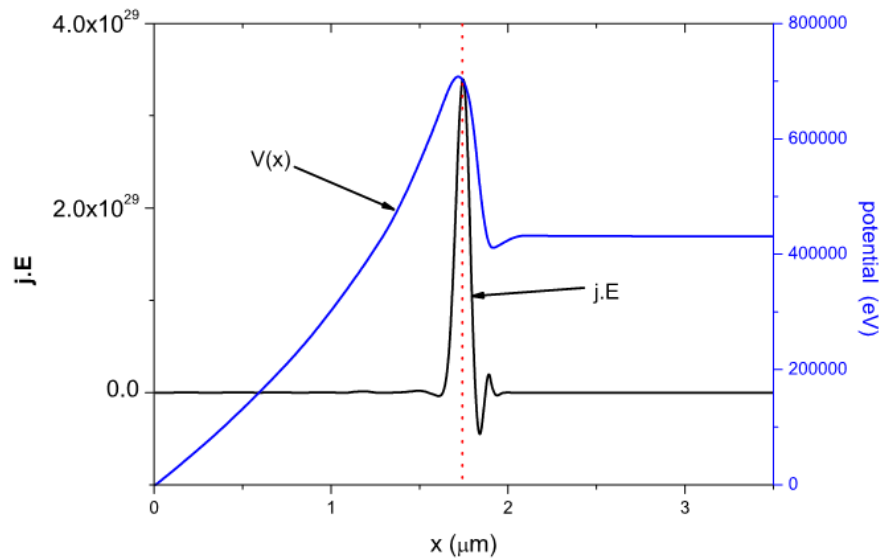
$T_h/mc^2 = 0.47\ a_o^{1/3}$

Haines et al PRL 2009

103101-2 M. Sherlock




E (keV)
6000
4000
2000
0
0.0
5.0x10^19
1.0x10^20
1.5x10^20
2.0x10^20
Intensity (Wcm^-2)
E_p (ponderomotive)
simulation
E_p-ΔV
theory


4.0x10^29
2.0x10^29
0.0
j.E
V(x)
j.E
800000
600000
400000
200000
0
potential (eV)
0
1
2
3
x (μm)

Angular Divergence

K-α spot size vs thickness

needs very careful interpetation

Coherent transition radiation

straightforward but only measures most energetic electrons

Incoherent transition radiation

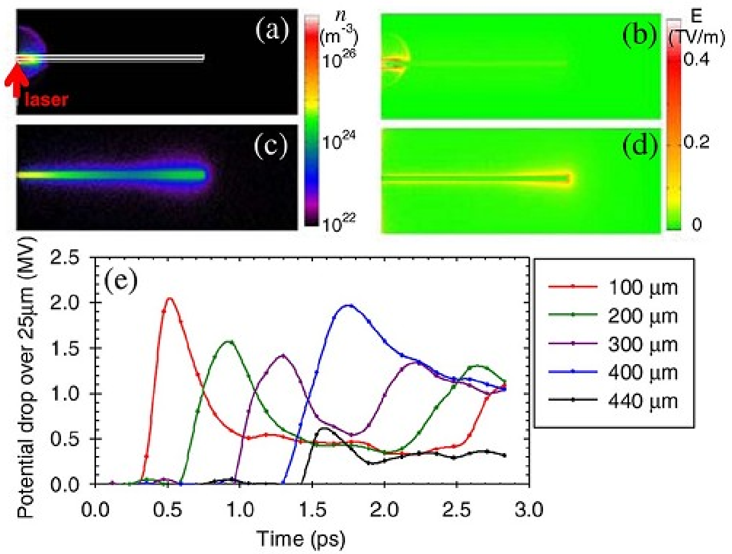
more difficult measurement

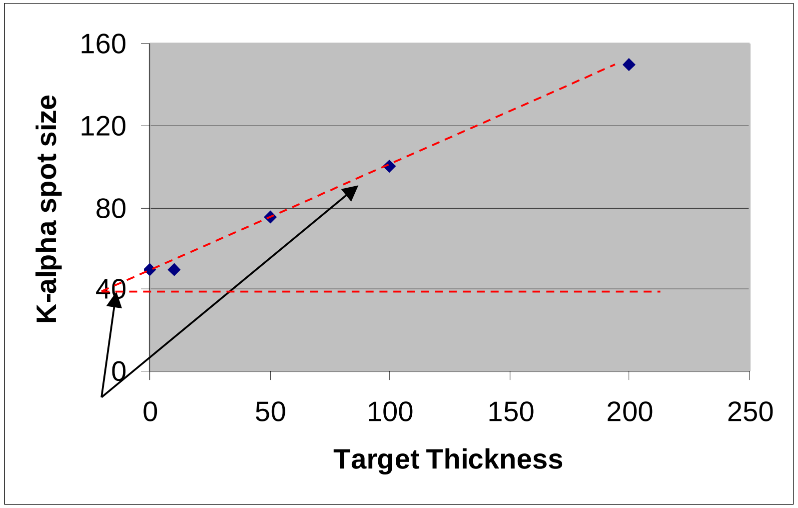
Rear surface temperature profile

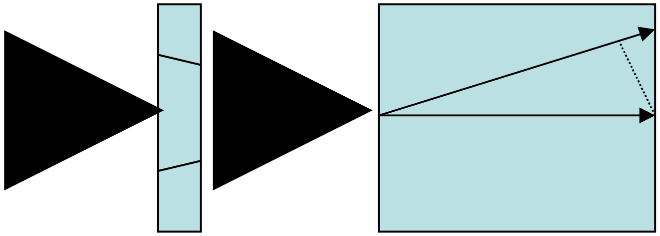
must include refluxing electrons

Ion emission spot size

very large overestimate due to rapid lateral transport at surface







Thin target measures electron range

Thick target has extra path length off axis and only sees high energy electrons

Makes isotropic distribution look like a beam!

Ridgers et al PRE

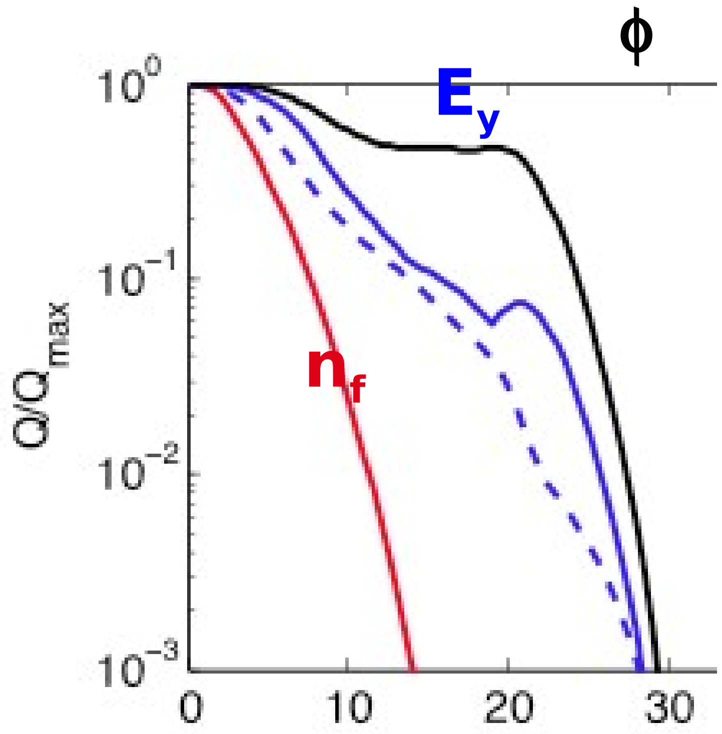
Rear-surface sheath field

Electric field and potential profiles wider than n_f

Sheath:

$$E_y \propto n_f^{1/2}$$

$$\phi \approx const$$



Ion spot POOR indicator of angular divergence

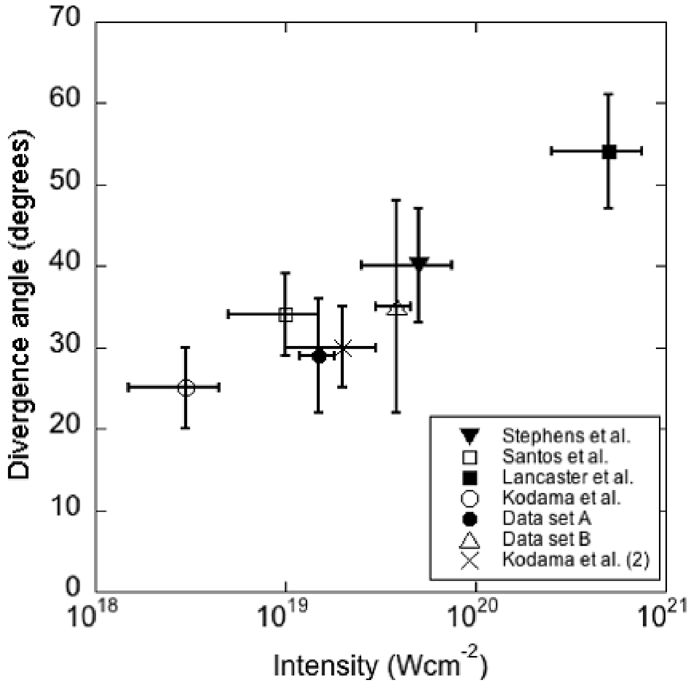


FIG. 2. Electron beam divergence as a function of intensity on target, along with other data published in the literature [5,11–14]. It is assumed that the errors in the other published work are similar, as the techniques employed are comparable.

Divergence is not well understood

Energy dependent, time dependent, pre-pulse dependent ...

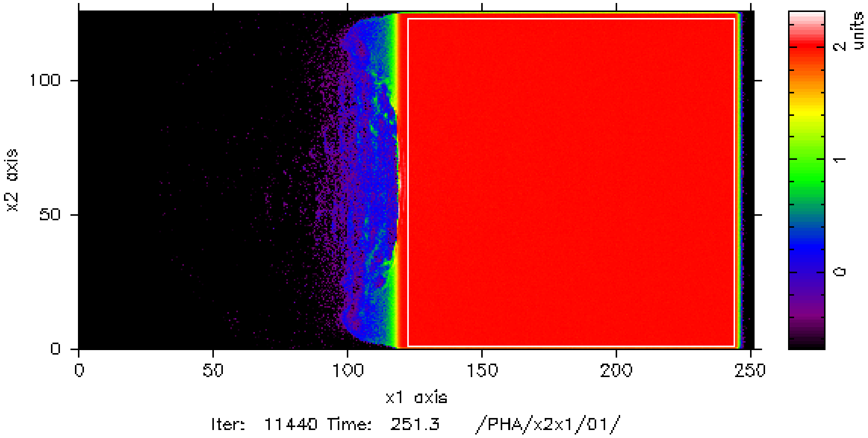
No measurements at FI relevant intensity and pulse durations

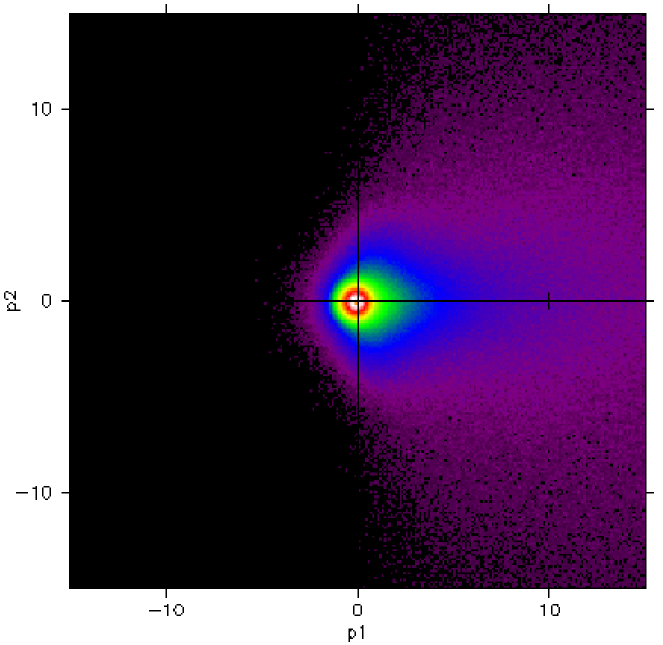
Possibly the most crucial parameter for the viability of Fast Ignition

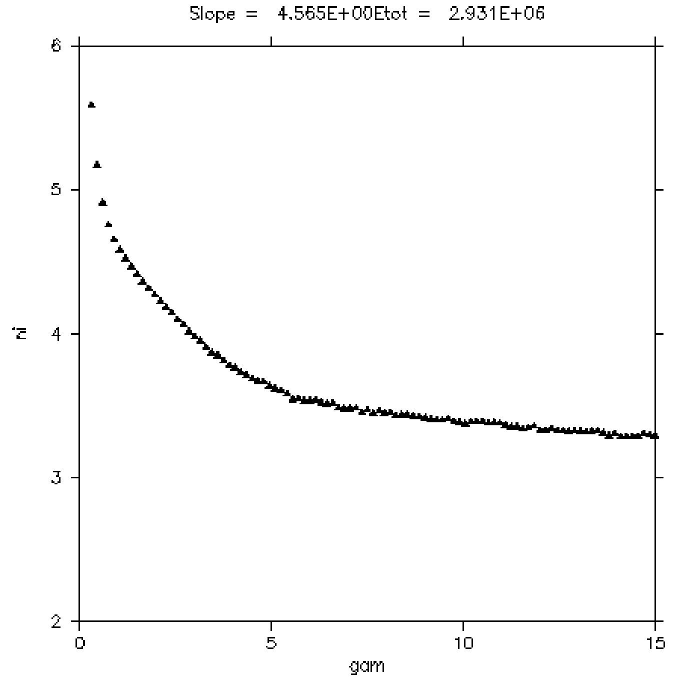
Determines potential for magnetic collimation effects

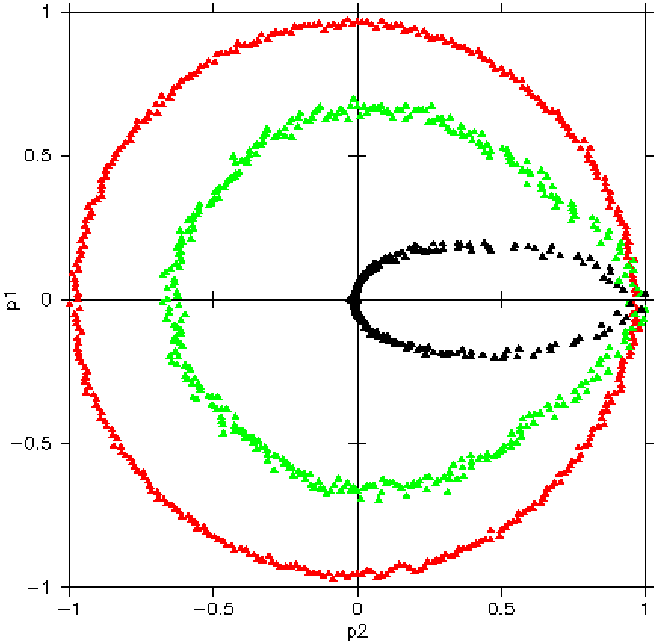
From Green et al PRL 100 015003 (2008)

Energy dependence of divergence

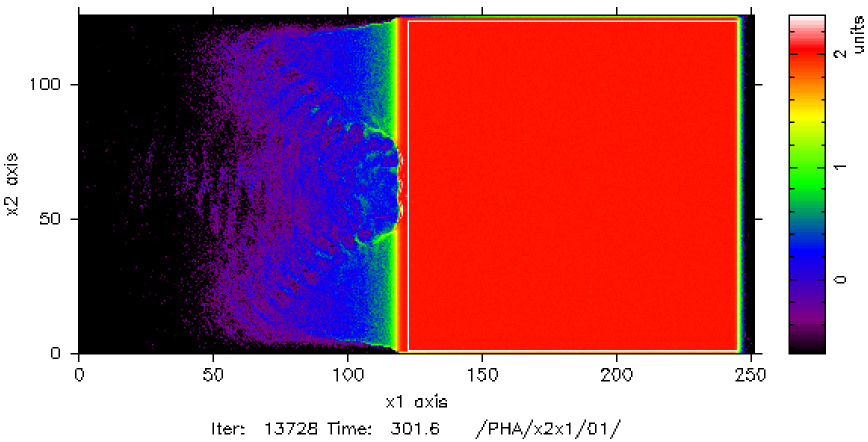


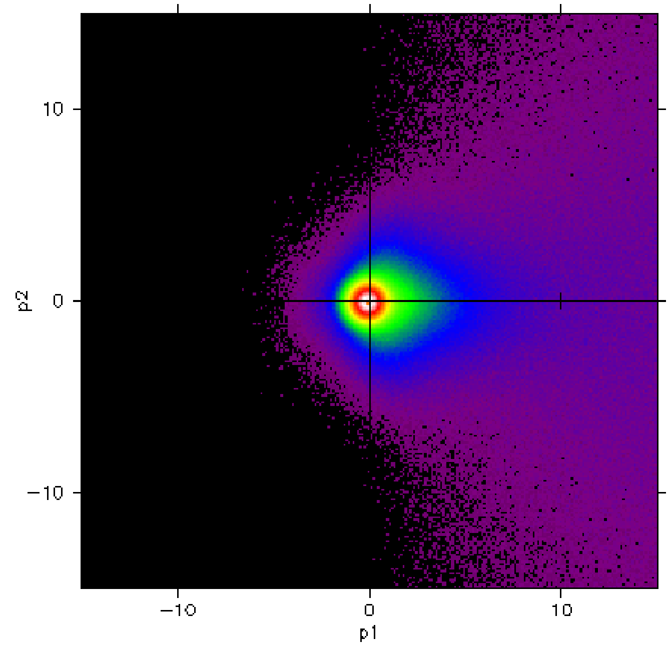


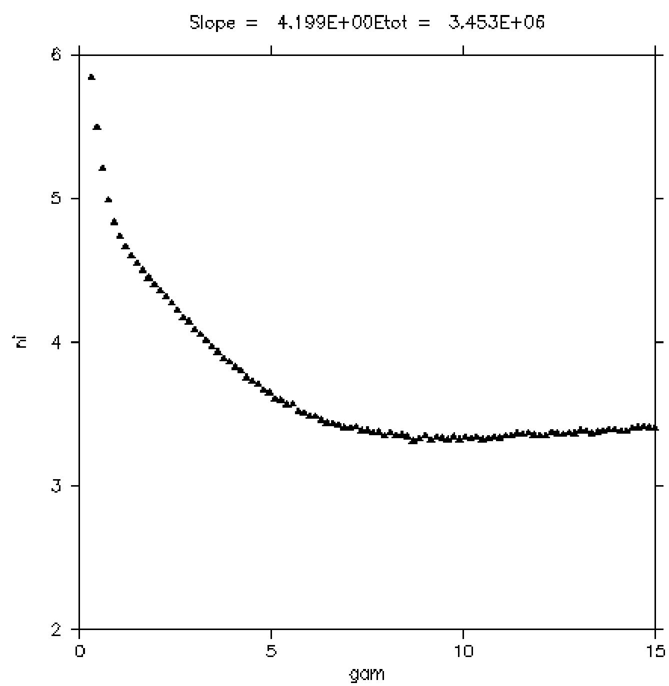


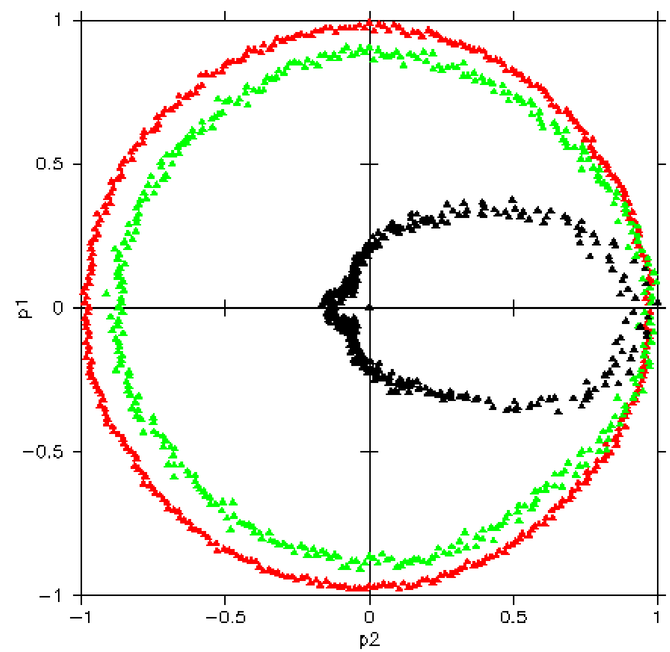


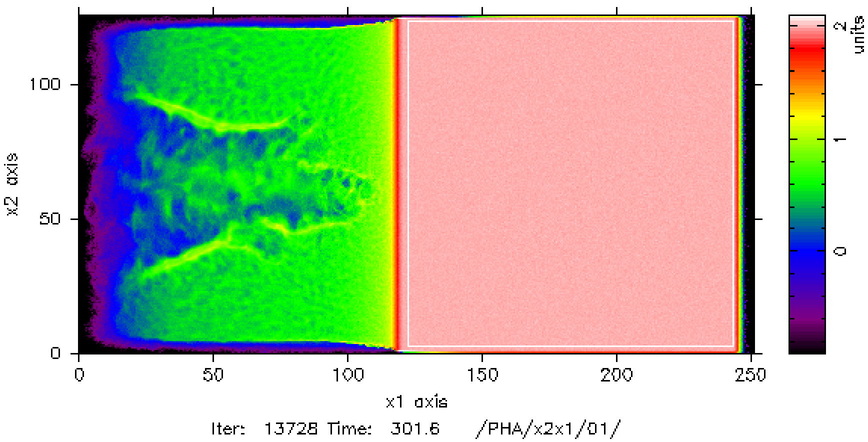
With prepulse - more very energetic electrons










x2 axis
x1 axis
units
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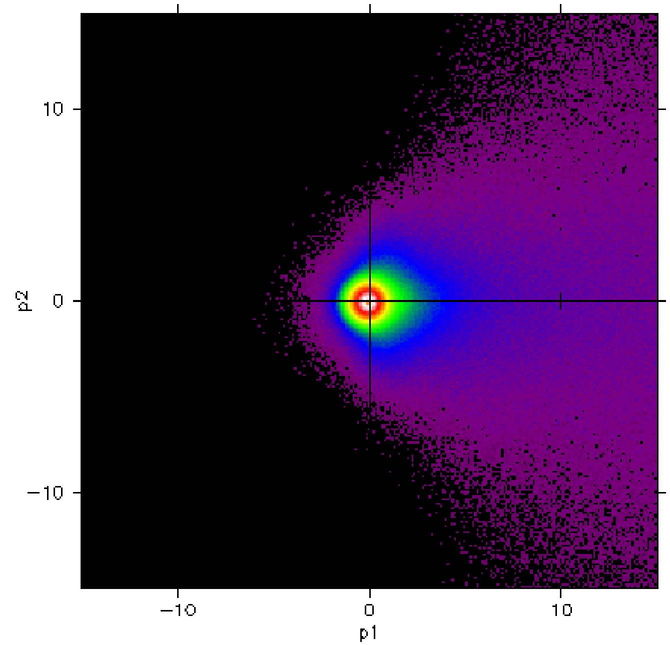
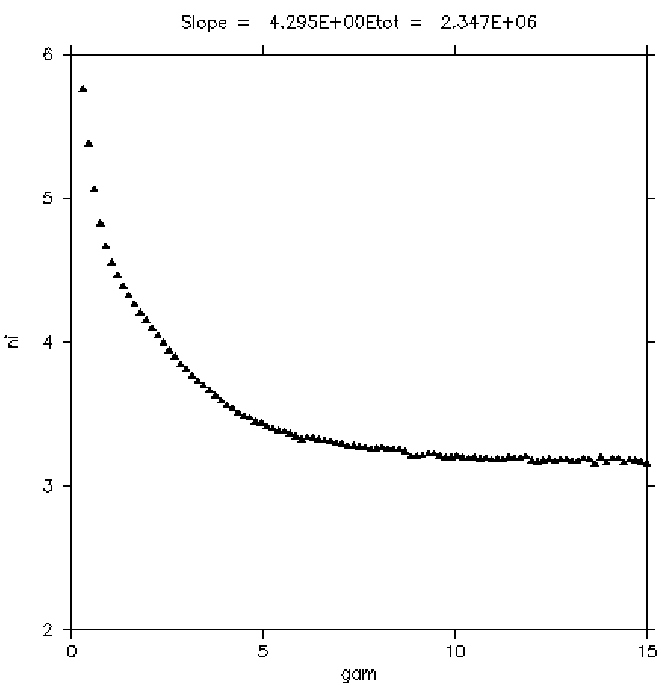

p2
p1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ni
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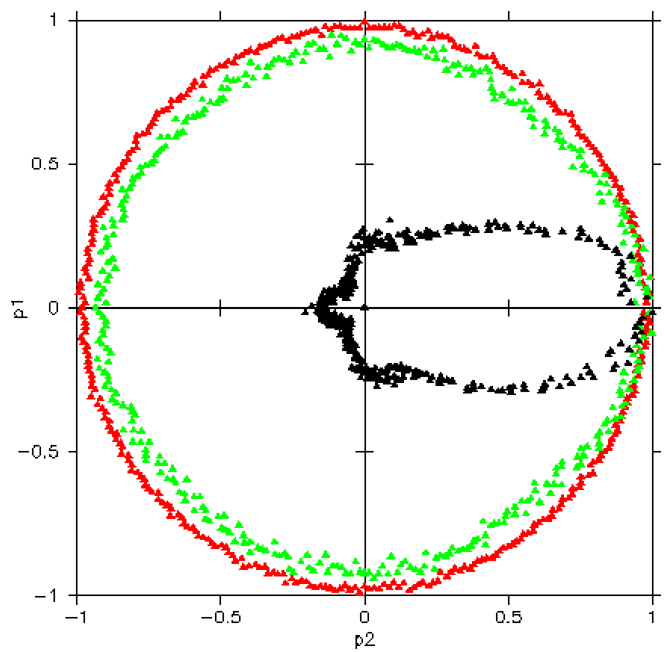
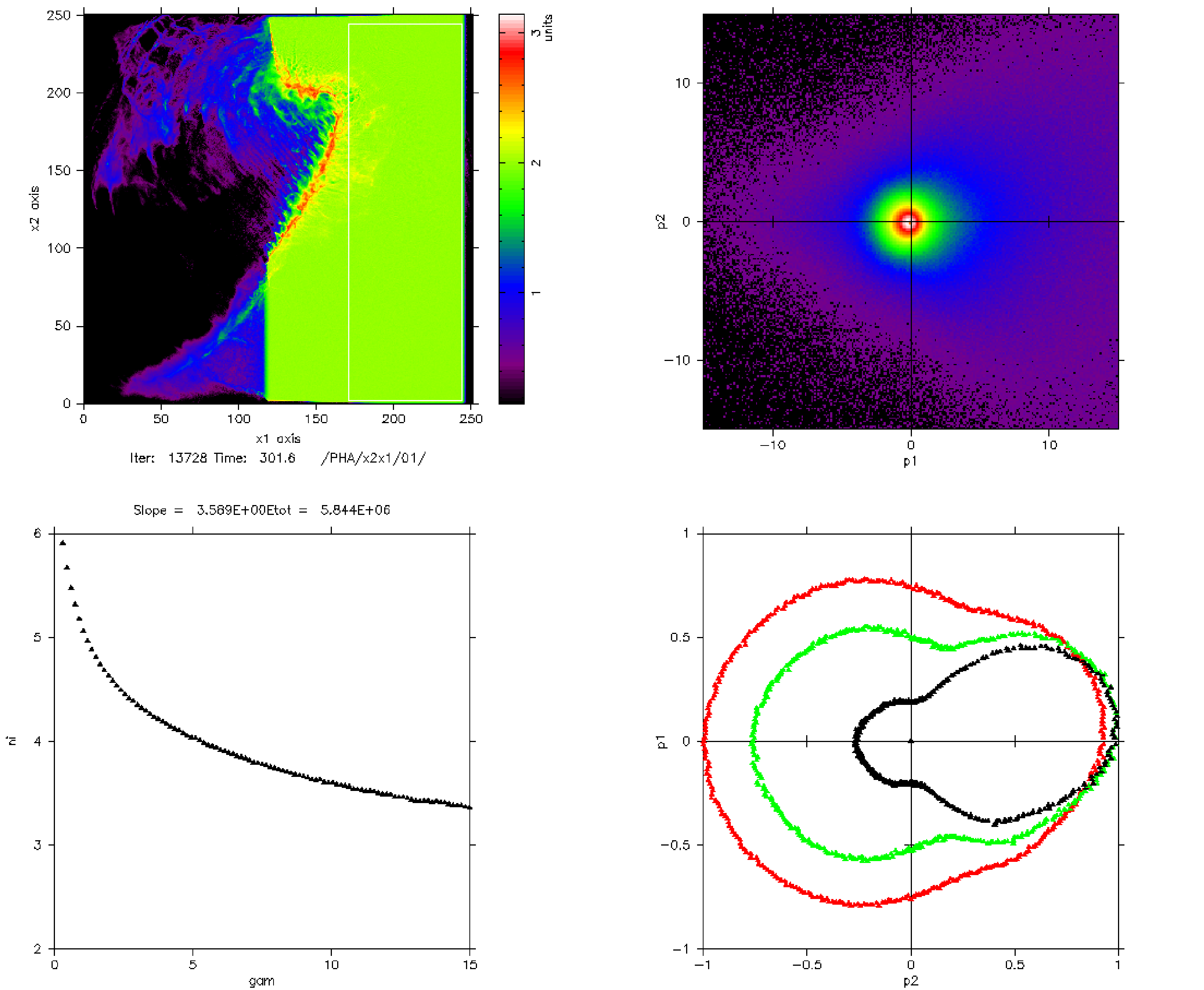
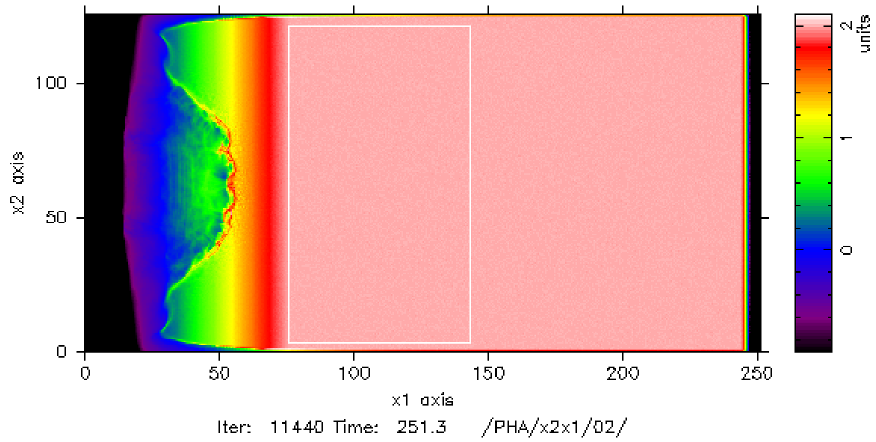
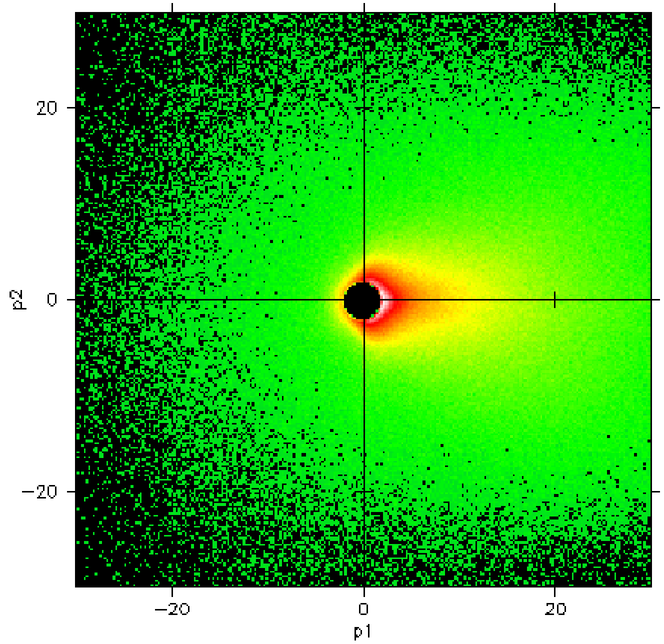

p1
p2

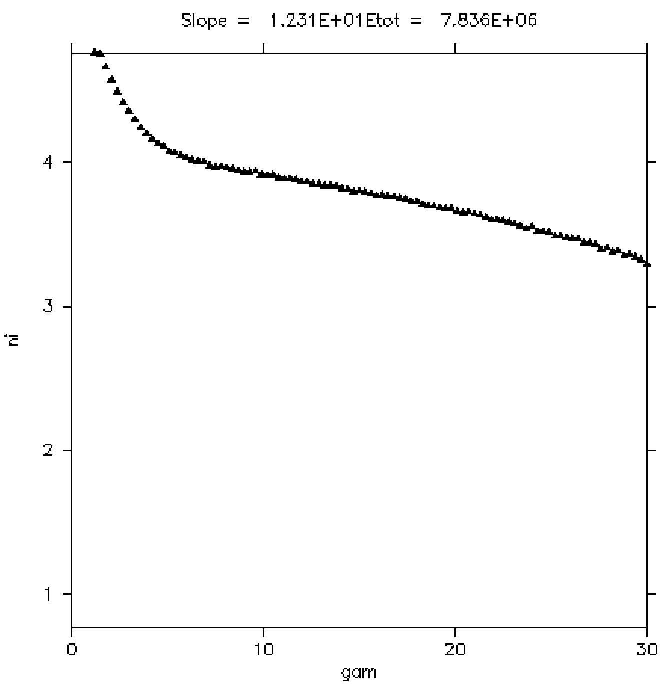
40 degree incidence

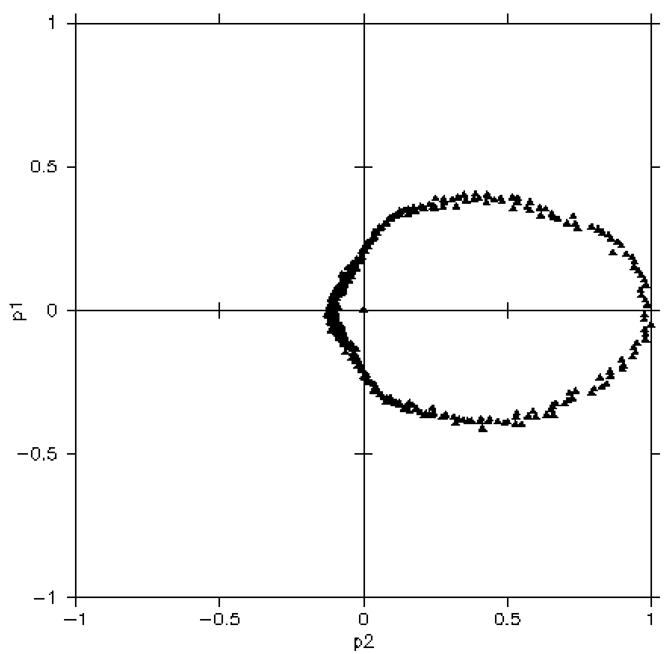


Divergence depends on refluxing from rear
Thick target no refluxing

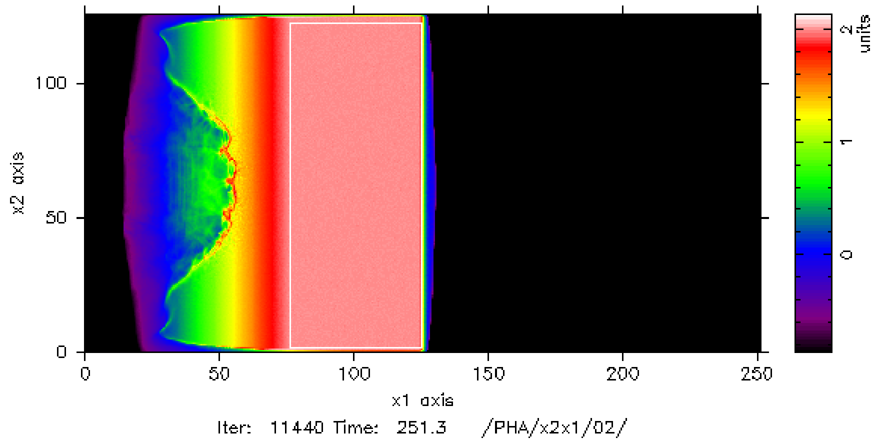


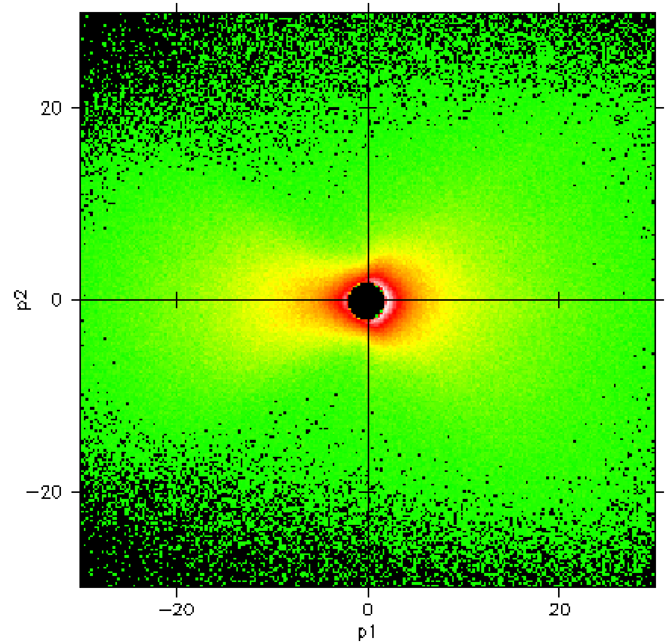


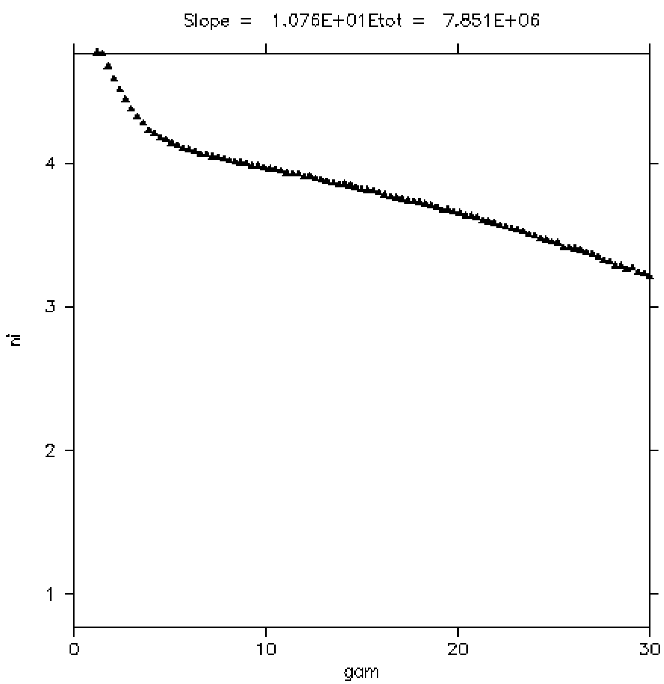


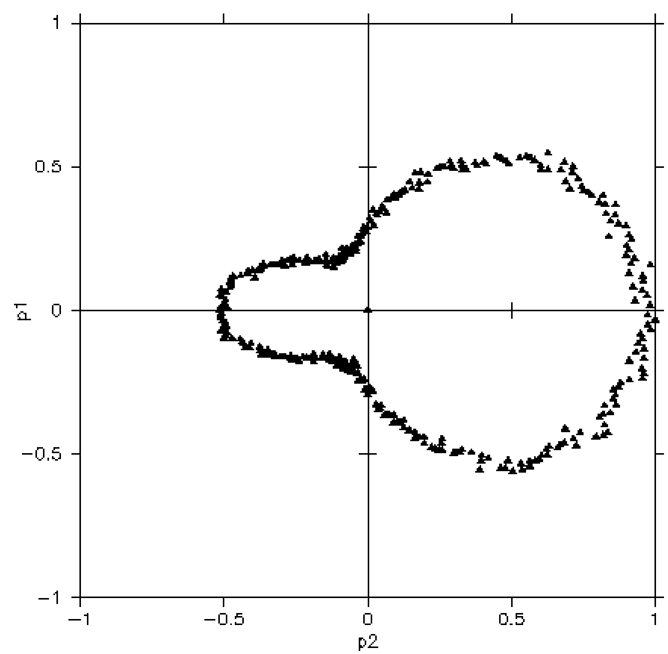


Refluxing from rear of thin target increases divergence of forward component



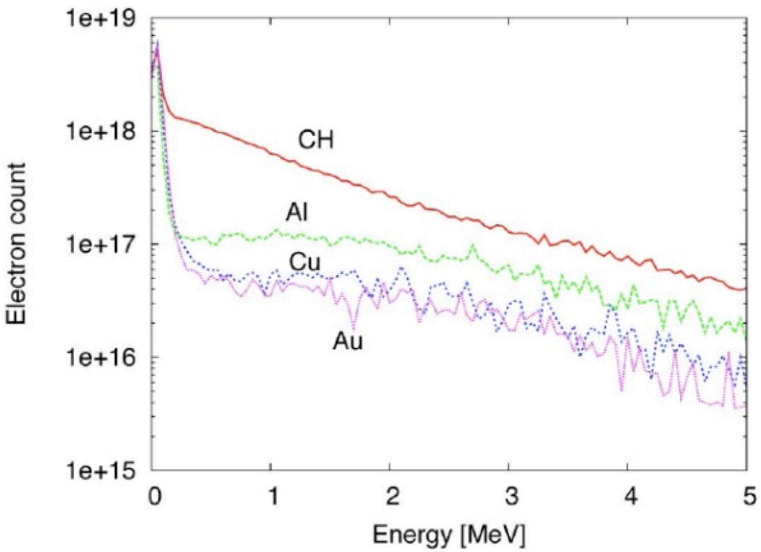


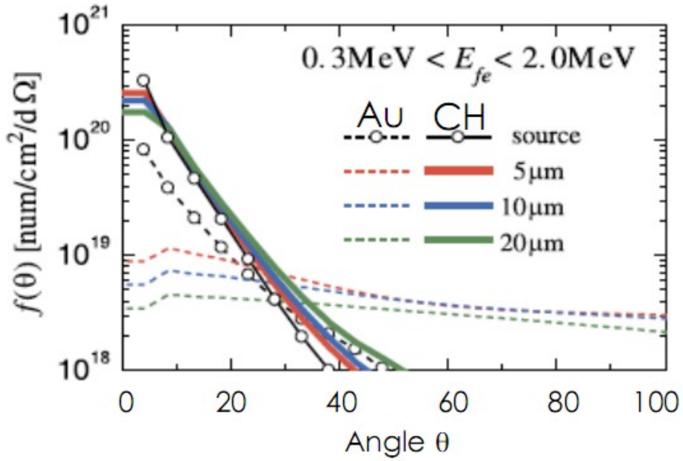




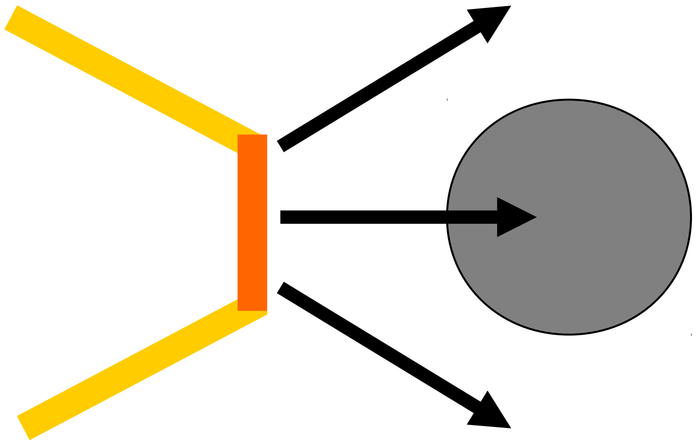
High Z transport layer modifies the fast electron spectrum and angular distribution

Y. Sentoku et al., J. Comp. Phys. 227, 6846 (2008)
T. Johzaki et al., PPCF 51, 014002 (2009)





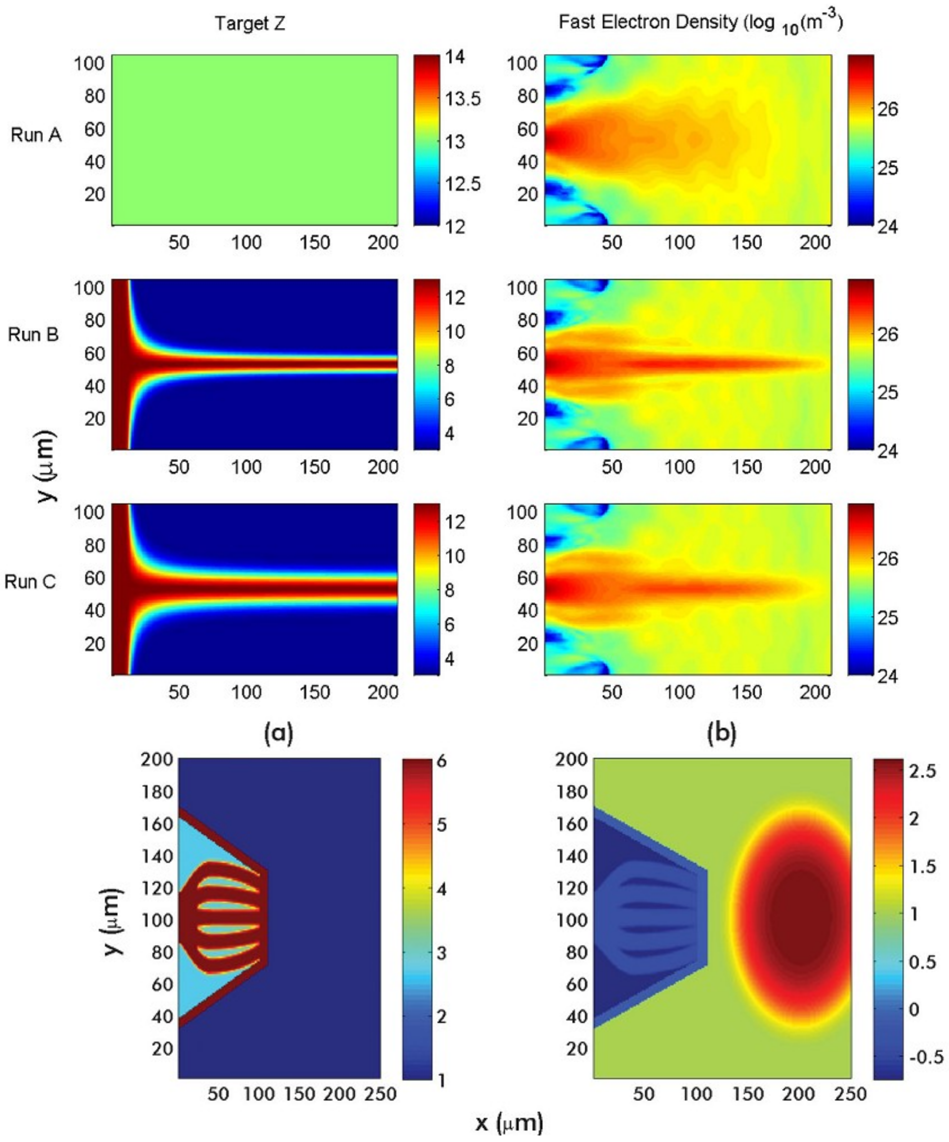
- **Fast electron forward transport is strongly reduced due to large scattering, drag and resistive effects in high Z plasma targets**
- **Broader fast electron angular distribution due to scattering in high Z targets**
  - Source divergence of 5° changes to 60° after 20 μm in gold



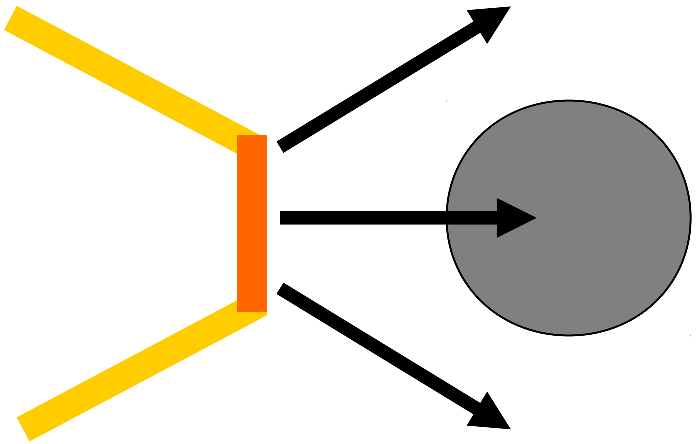
Ballistic transport is very inefficient and fatal to Fast Ignition

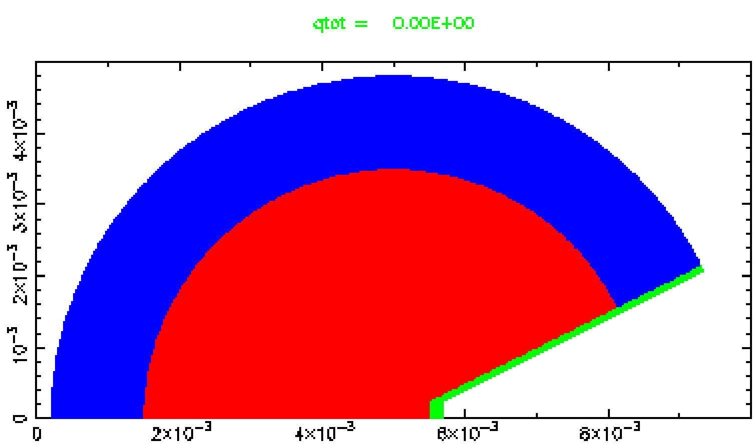
Resistively generated B fields (Davies and Bell) can help, structuring the region between source and core is a large benefit (Robinson, Sherlock et al)

Can micro-structures survive the main implosion?



Cones





Originally to maintain vacuum path for heating beam.

High density reduces deformation due to pressure of imploding fuel

Mixed material from High Z wall severely cools fuel

High Z end of cone scatters and slows fast electrons

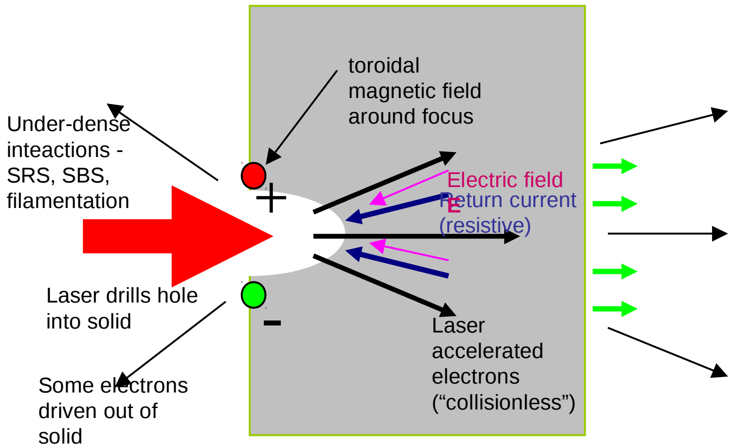
What happens between end wall and high density fuel?

Constrained geometry of cone increases the problem of pre-plasma formation

LLNL prefer Diamond like Carbon to Gold

Increases fabrication cost and alignment complexity for IFE power plant

Simulation of CPA laser - solid target experiments - the problem



MeV electrons are collisionless in the blow off plasma and have mean free paths in the solid comparable to the target size.

Charge separation (ie low frequency) fields and currents are a major factor

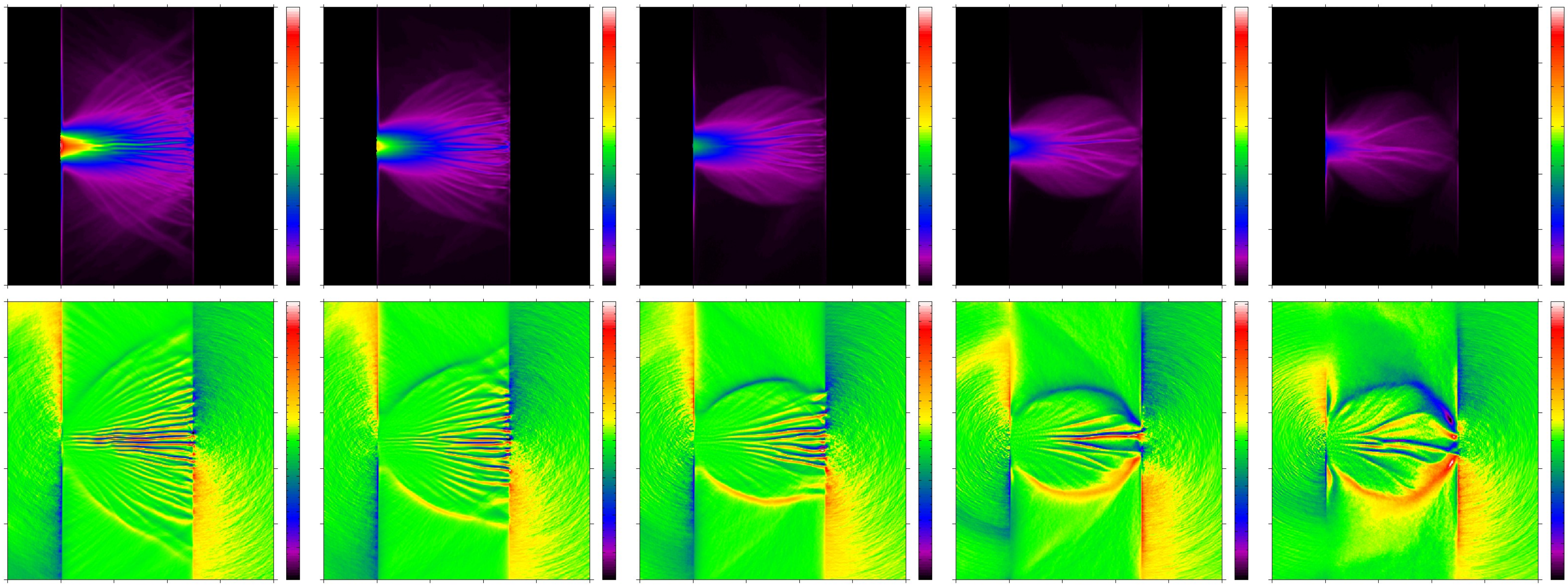
Plasma frequency / Debye lengths in the solid preclude explicit methods

Forward / return current electron distributions are unstable, return current may or may not be collisional, correct collision frequency for thermals is uncertain due to large drift velocity

Problem is very 'stiff' in space and time scales, large density ratios make PIC methods more difficult

Hybrid models typically do not include displacement current or Nernst advection of magnetic fields

LSP - implicit PIC, hybrid, includes displacement current



0.25gcm^{-3} 0.5gcm^{-3} 1.0gcm^{-3} 2.0gcm^{-3} 4.0gcm^{-3}

Results from LSP compare well with analytic theory of

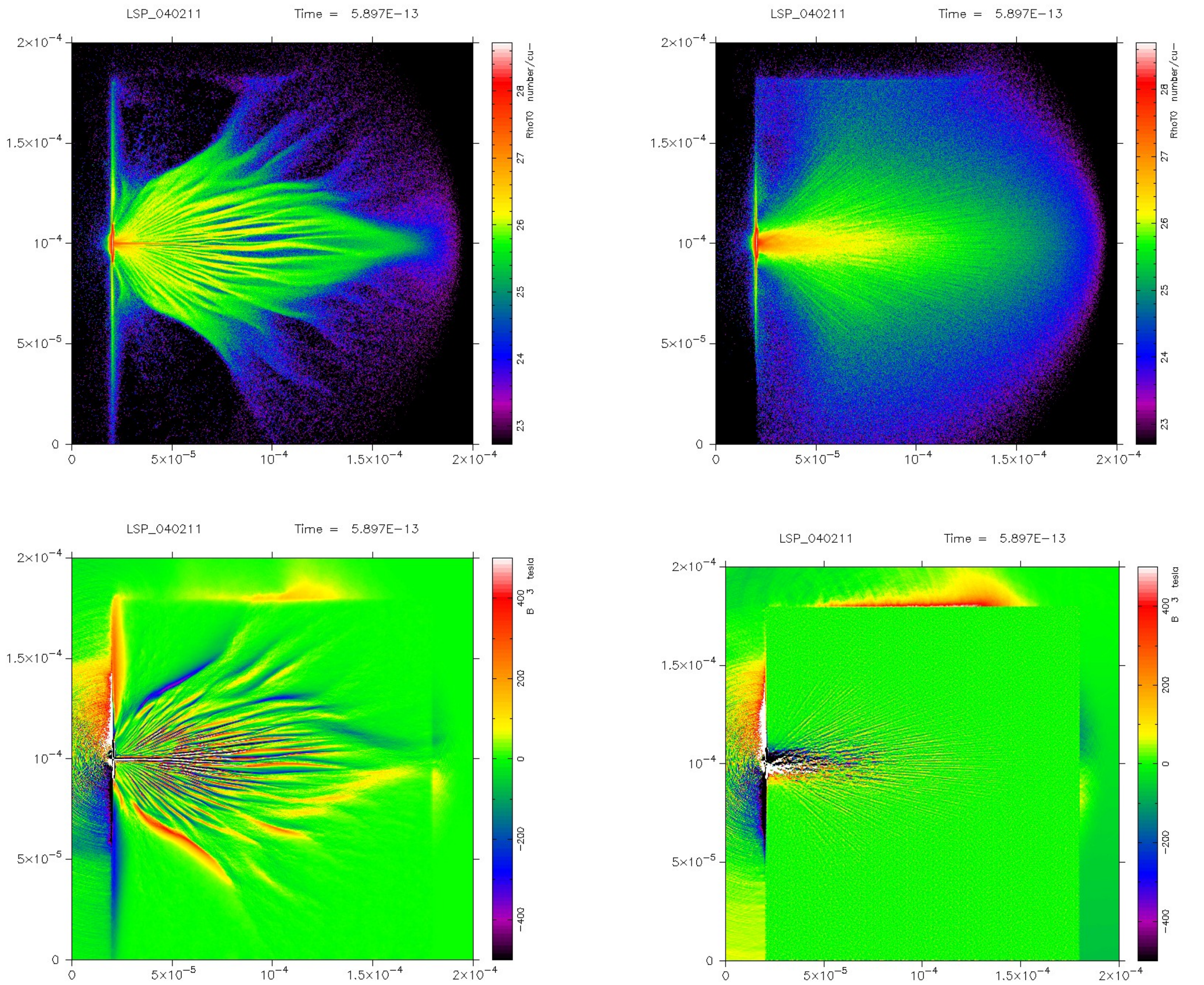
Bell and Kingham Phys. Rev. Lett. **91**, 035003 (2003).

Denser targets take longer to heat and remain longer in the resistive

phase when generation of B is greatest

Nhot

Bz

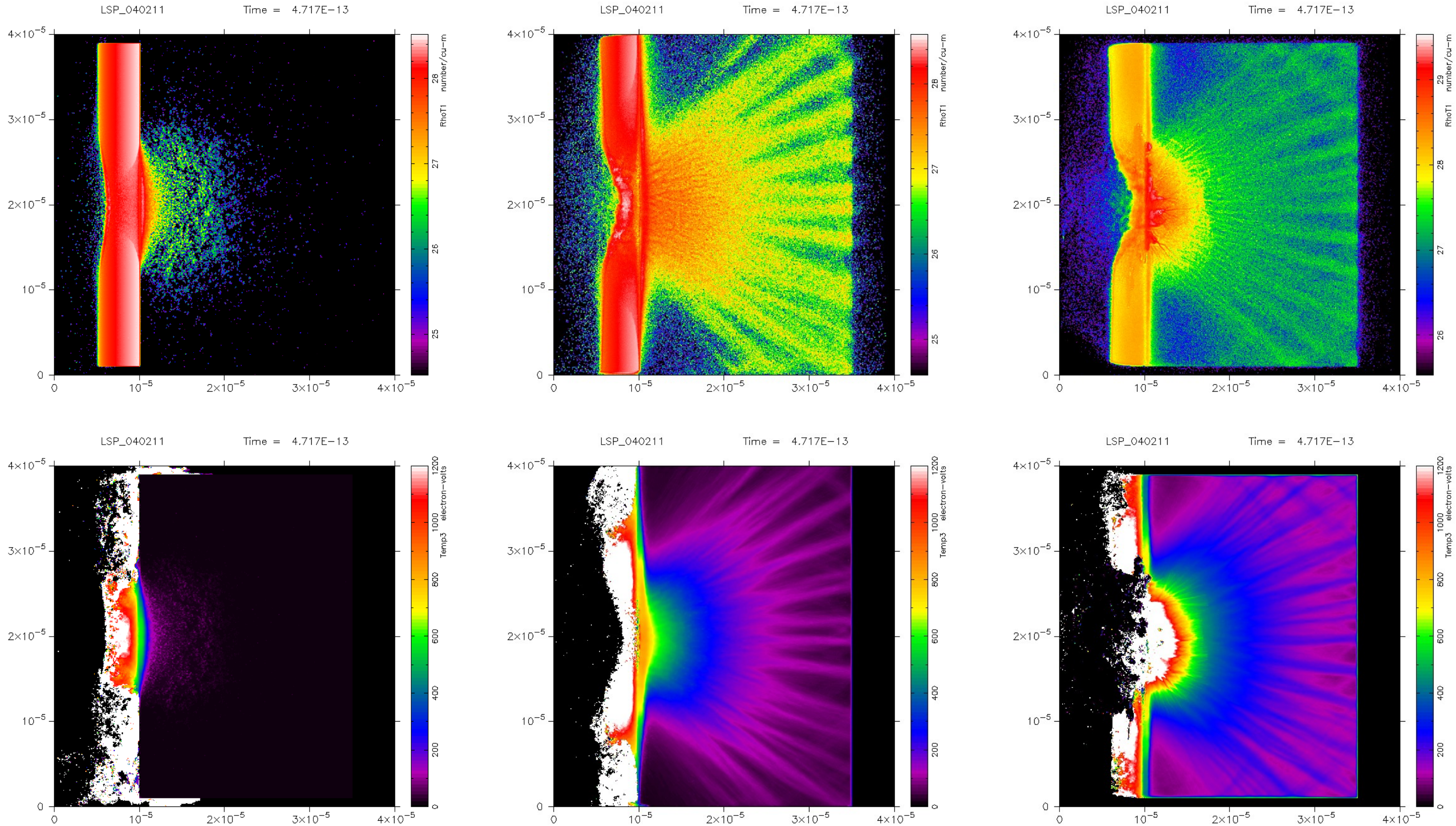


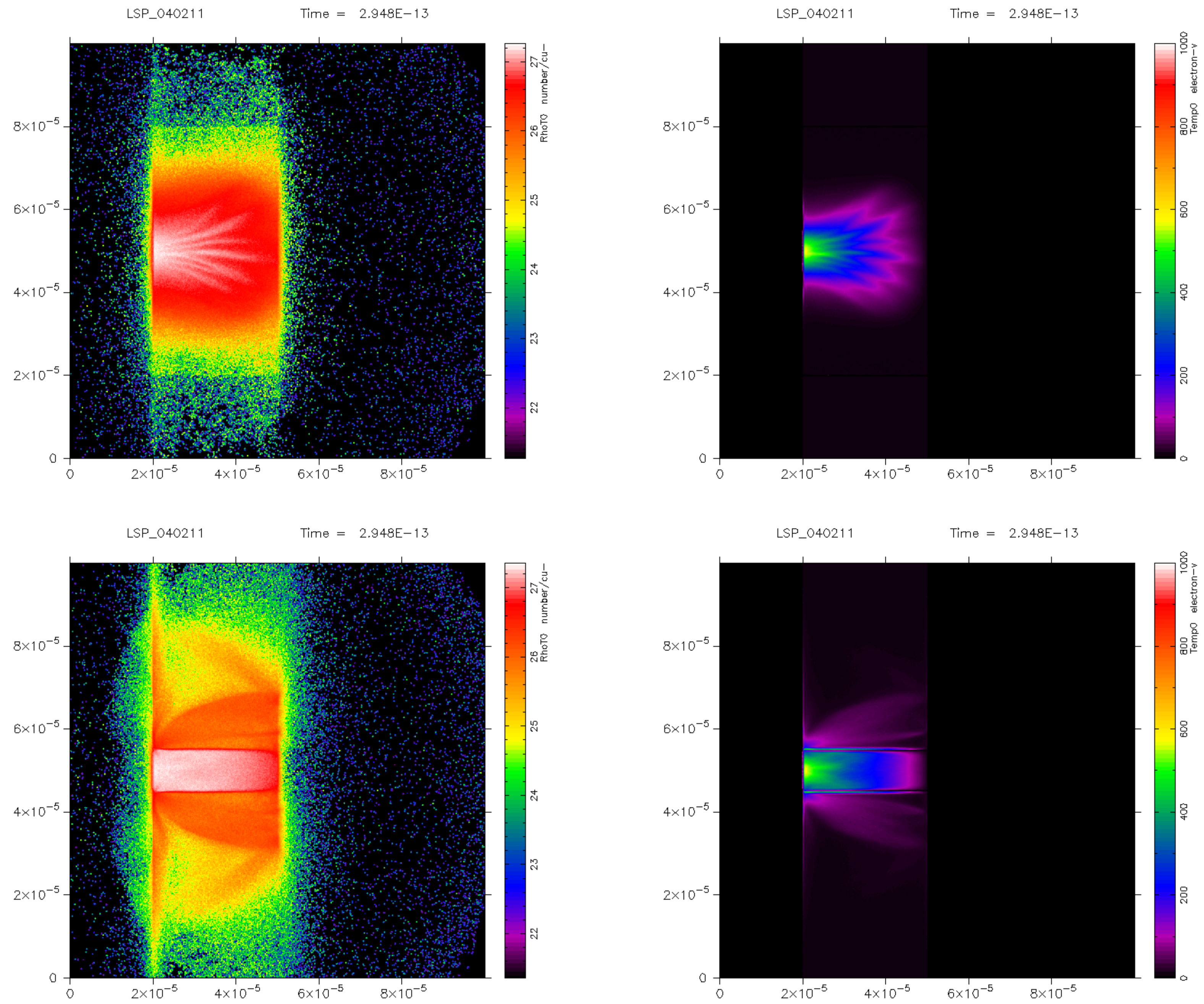
Initial background Te = 10eV

Initial background Te = 1keV

Self-consistent acceleration and transport

10^{19} | $1.5\ 10^{20}$ | $3.0\ 10^{20}$




LSP_040211
Time = 2.948E-13
RhoT0 number/cu-
22
23
24
25
26
27
0
2×10^-5
4×10^-5
6×10^-5
8×10^-5
LSP_040211
Time = 2.948E-13
Temp0 electron-v
0
200
400
600
800
1000
0
2×10^-5
4×10^-5
6×10^-5
8×10^-5
LSP_040211
Time = 2.948E-13
RhoT0 number/cu-
LSP_040211
Time = 2.948E-13
Temp0 electron-v

Collisional PIC should include all physics ...

Binary collision model should be OK above ~50eV

All magnetic effects included

Extensible to very high density using Cohen, Kemp, Divol methods

Full Maxwell below solid density, all propagation instabilities

but

Collision model requires resolution of collision time

Closeness of boundaries limits run duration - J-C Adam

'Only' a problem of computing resources

What ... Why .... Where ...???

Why have we studied electron generation and transport?

Interesting physics

What have we learned?

Excellent qualitative understanding
Predictive capability is limited

Where do we go next?

HiPER? John Collier seeking some funds within UK

France and UK have HEDP interests eg LMJ/PETAL and ORION

Non-IFE applications?

Large scale co-operative supercomputing projects?

Maybe discussion later in this meeting?