2D Modelling of Fast Electron Transport

Imperial College London

(and other IFE activities at Imperial College Plasma Group)

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Simon Bland
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Zulf Najmudin
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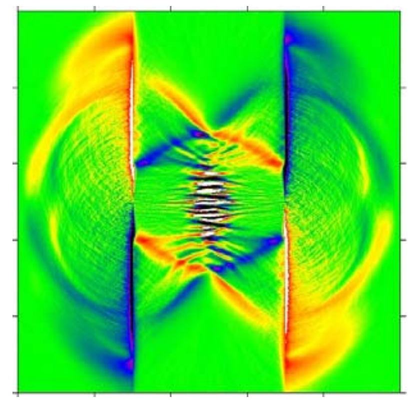
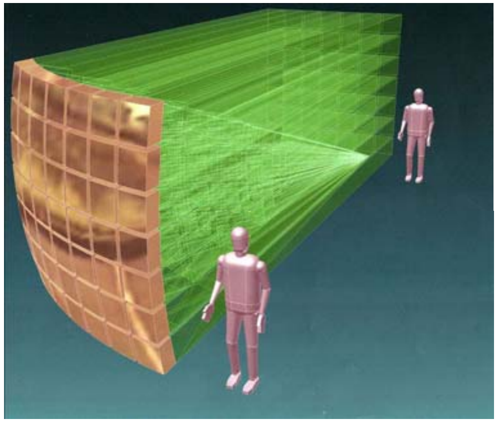
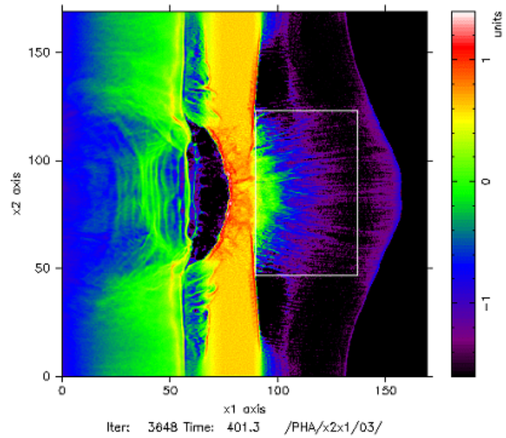
Chris Ridgers

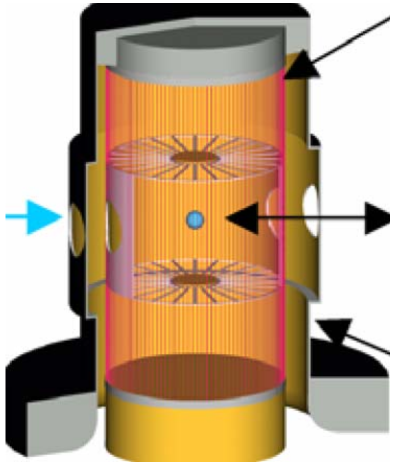
Malcolm Haines
Bucker Dangor

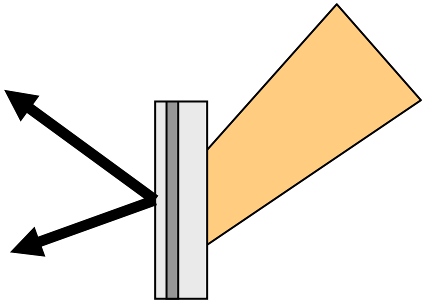
+ PhD Students





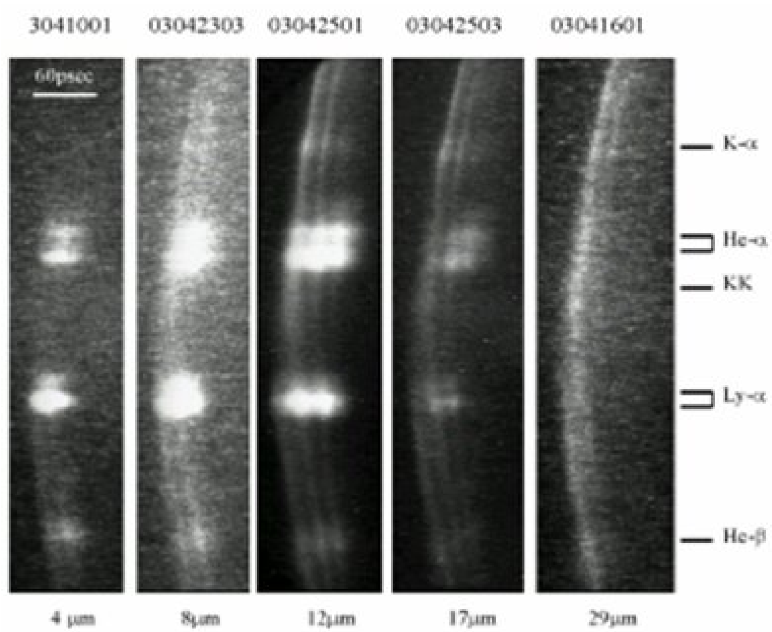


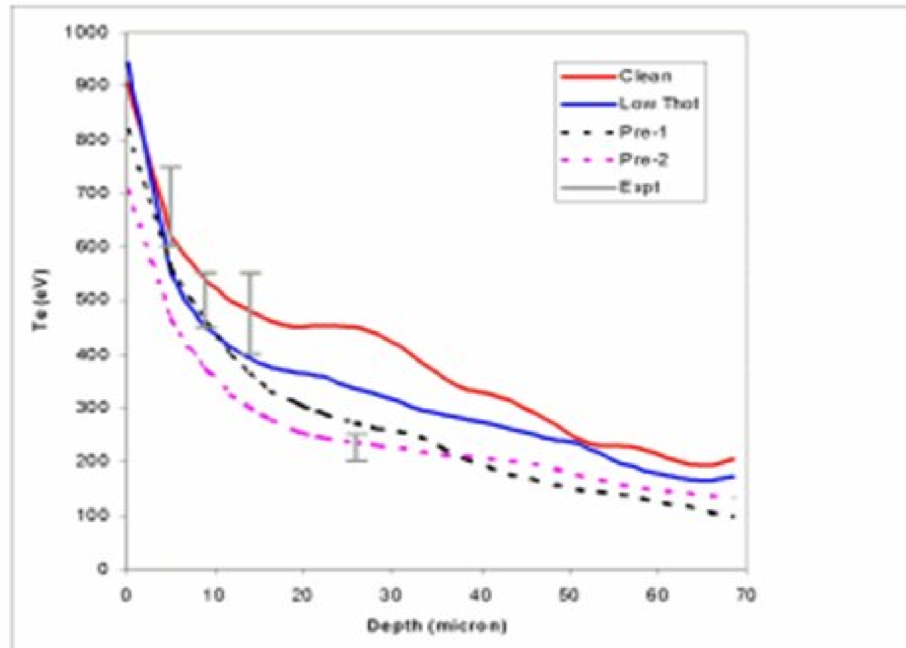




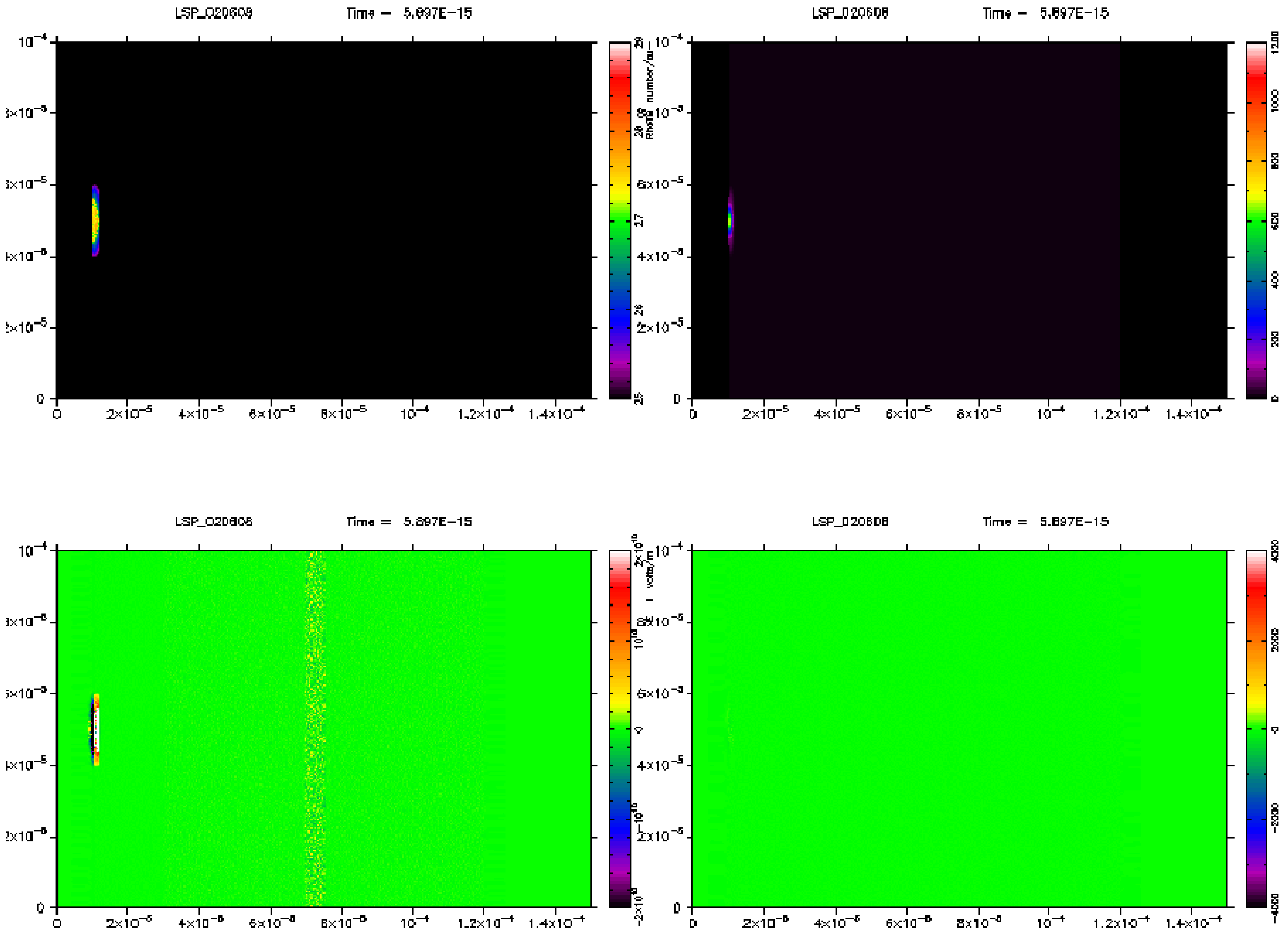
Buried Layer Heating – AWE expt on Vulcan

Agreement with experiment





Rapid Heating of Solid Density Material By a Petawatt Laser
R G Evans, E L Clark, R T Eagleton, A M Dunne, R D Edwards, W J Garbett, T J Goldsack, S James, C C Smith, B R Thomas, R Clarke, D J Neely, S J Rose
Applied Physics Lett 86, 191505 (2005)


LSP_020608 Time = 5.897E-15
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FIDO Simulation Code

•Vlasov-Fokker-Planck Equation

•Maxwell's Equations

$$\frac{\partial f}{\partial t} + \nabla_r.(\mathbf{v}f) + \nabla_p.(\mathbf{F}f) = C_{ei} + C_{ee}$$

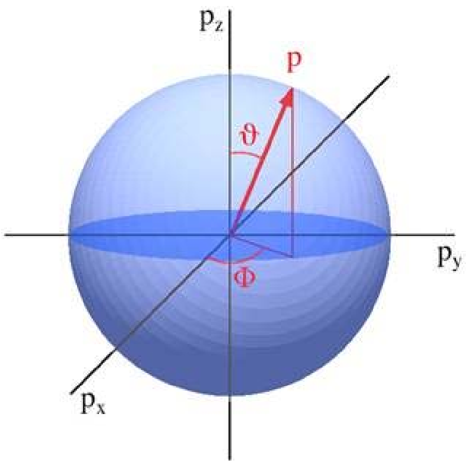
•Cartesian or Spherical grid in configuration space

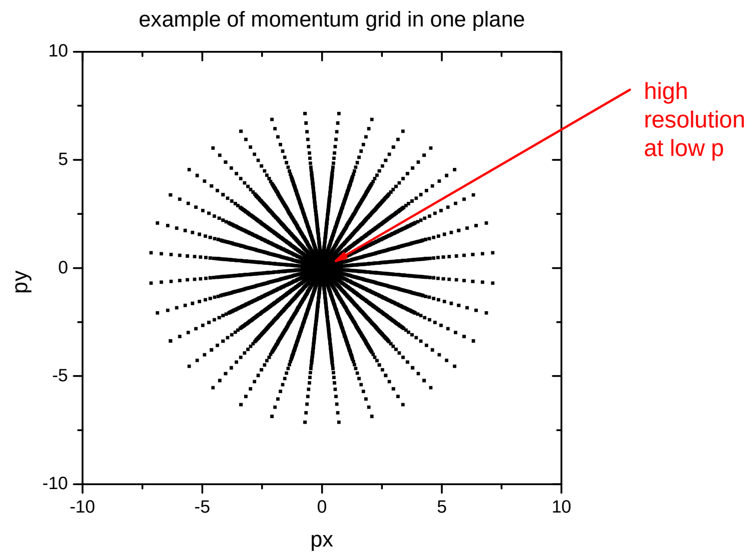
•Spherical grid in momentum space (makes collision algorithms fast and simple, naturally allows for the effect of magnetic fields and p is natural coordinate to stretch if you want to study two populations)

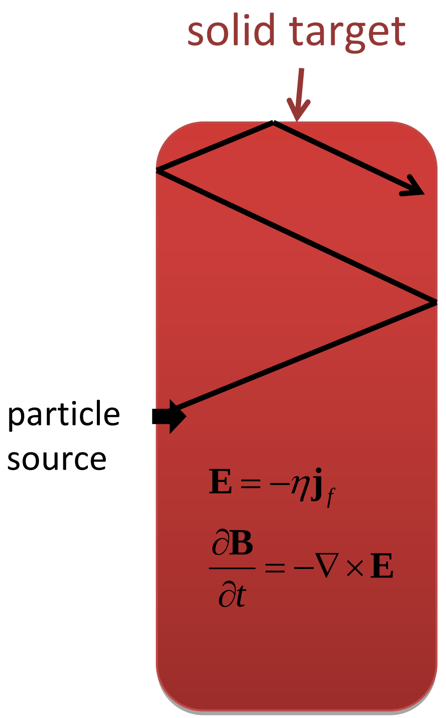
•Piecewise-Parabolic Interpolation for advection

•Solve for collisions and fields implicitly

•Coupled to a background MHD fluid



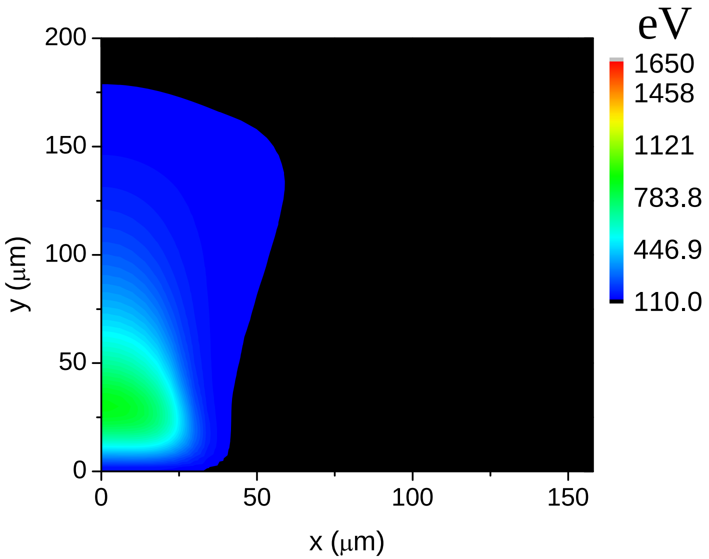




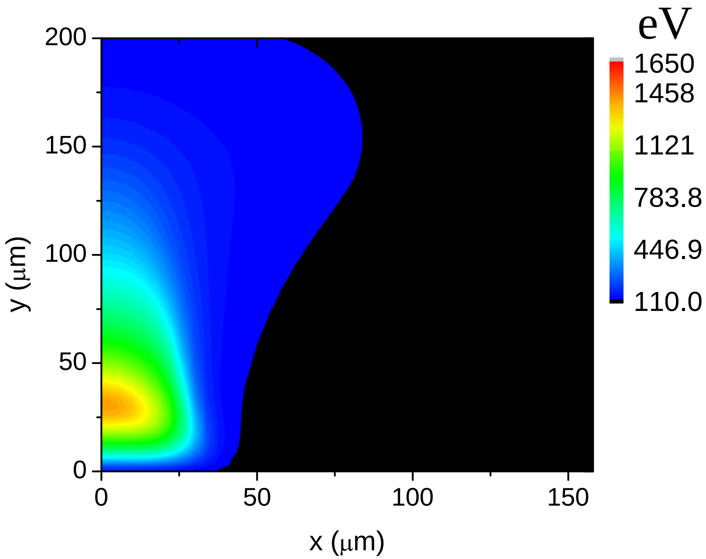
•In hybrid mode only the fast electrons are evolved with the VFP equation

Problem 2: background T_e

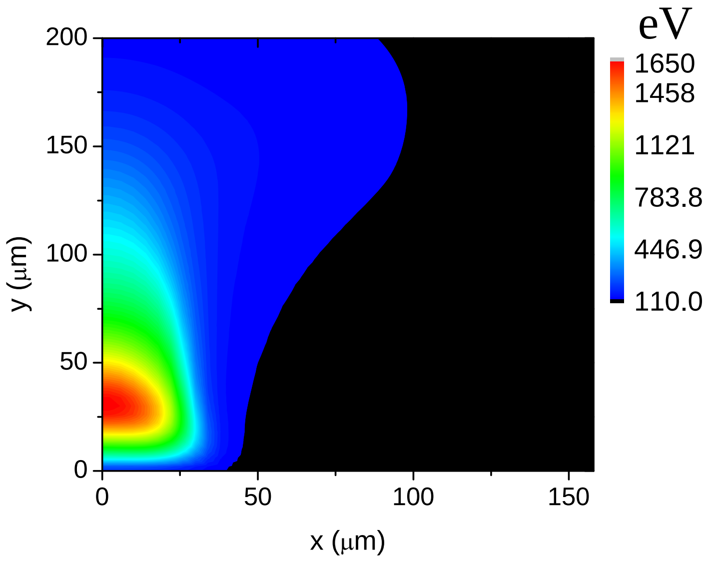
t=2ps

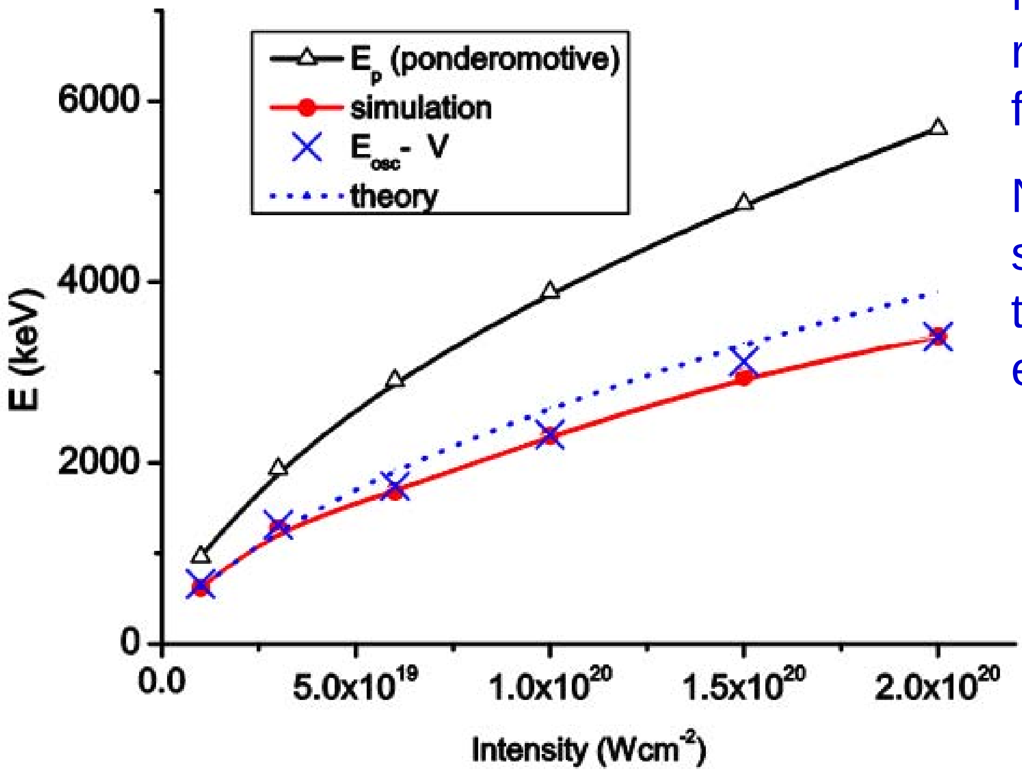


t=4ps



t=6ps





VF-P simulations using 'FIDO' by Mark Sherlock show only moderate reduction of ponderomotive scaling for T_{hot}.

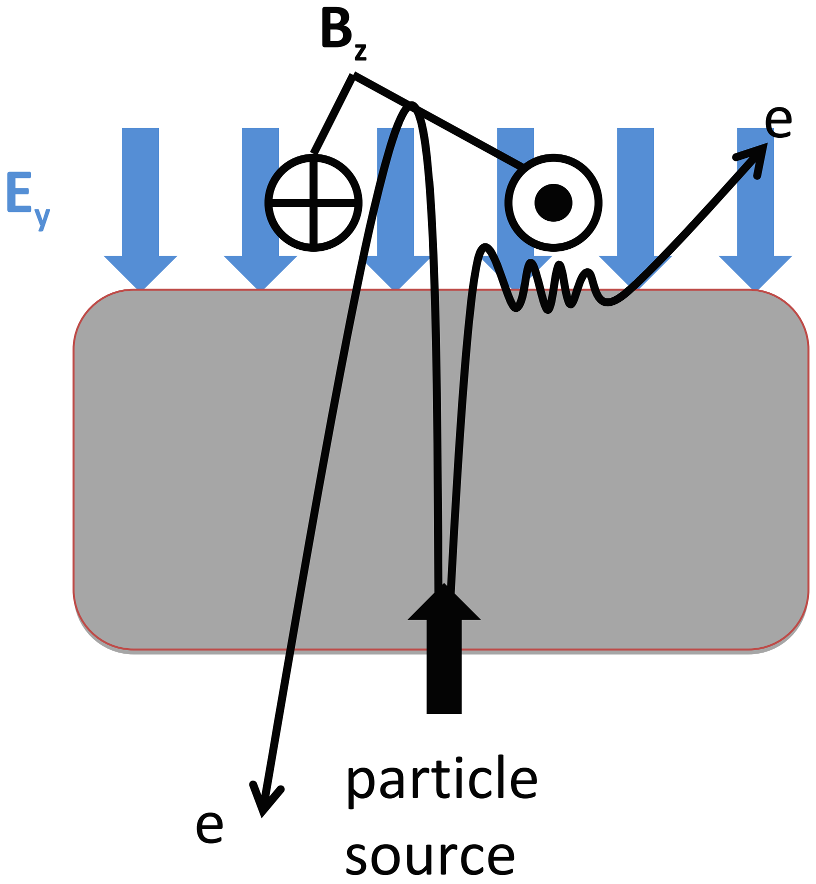
Note that the often quoted $I^{1/3}$ scaling from Haines et al is for transverse temperature not mean energy.

Fig. 5. The average energy as a function of laser intensity (filled-circles). The vacuum oscillatory energy (triangles) and theoretical estimate (crosses) are also plotted. The dashed line refers to the theoretical value based on a reduction of the oscillatory energy by the electric field set up to maintain quasineutrality.

‘Improved’ hybrid mode

Improved hybrid:

B-fields lead to more complicated motion of electrons at rear-surface.

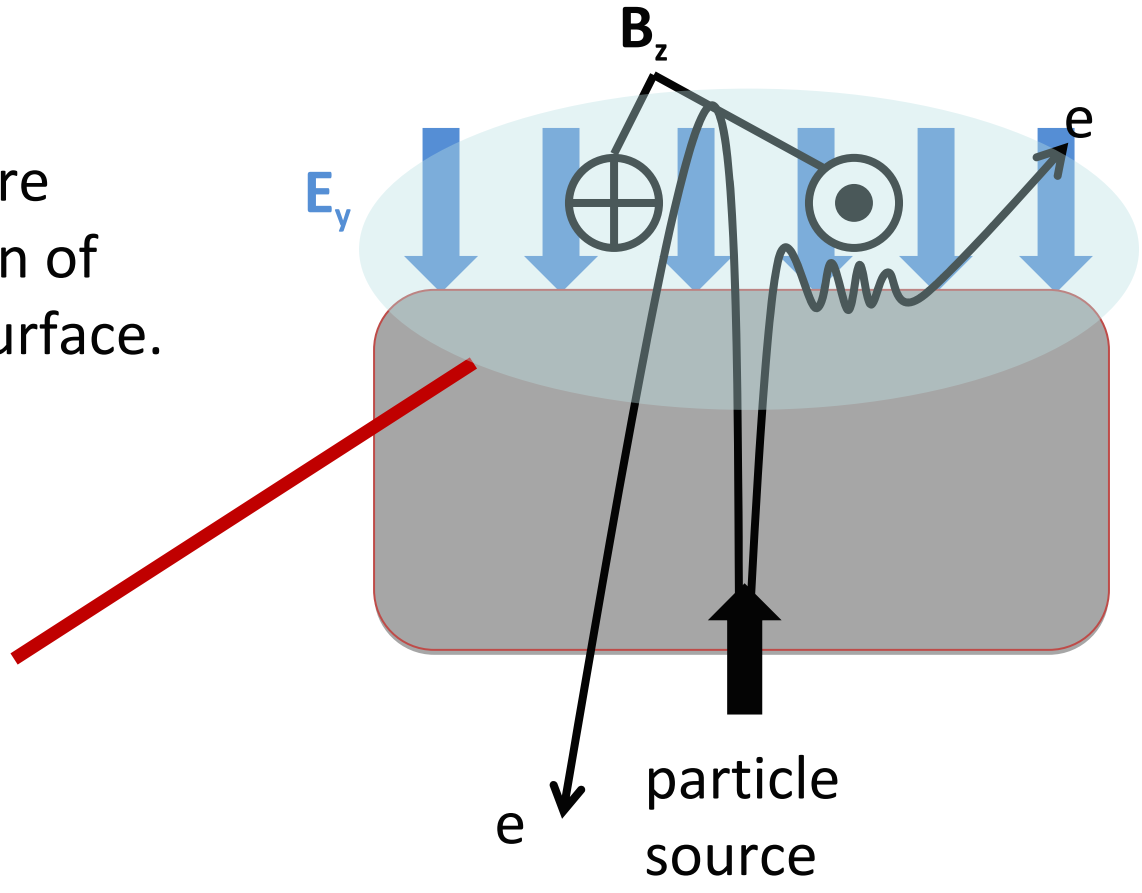


‘Improved’ hybrid mode

Improved hybrid:

B-fields lead to more complicated motion of electrons at rear-surface.

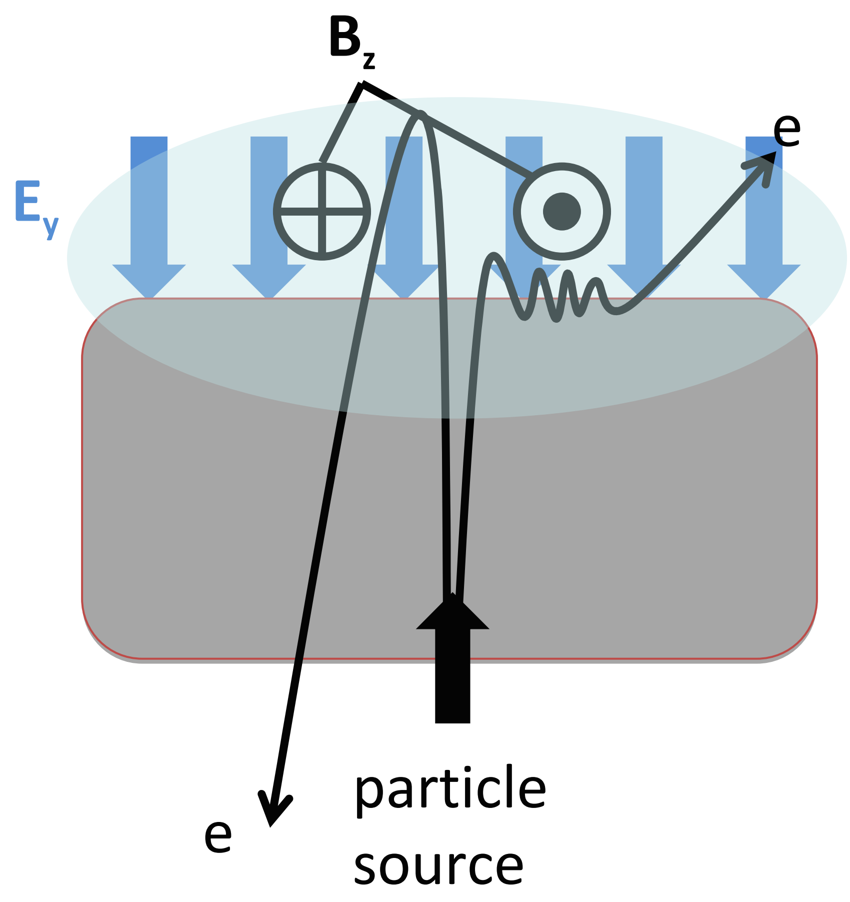
I will simulate rear-surface effects



‘Improved’ hybrid mode

What’s new?

FIRST continuum VFP hybrid simulation of fast-electron transport in solids to include target edge effects



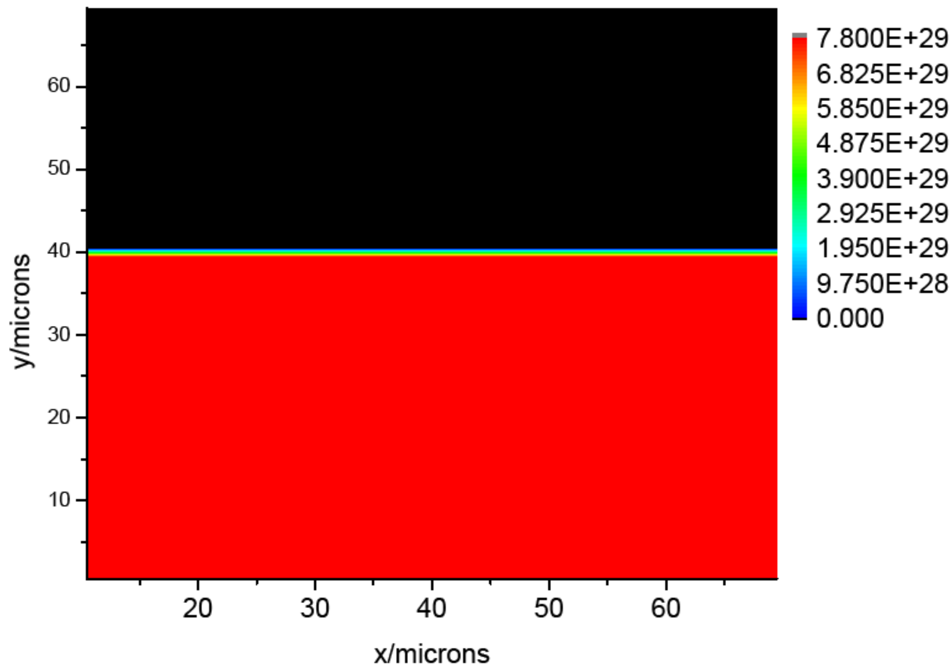
Solid-target simulations

BACKGROUND PROPERTIES:

Background electron number density n_e=7.8x10^{23}cm^{-3}

Ionic charge – Z=13 (Aluminium)

Initial temperature T_e=50eV (somewhat arbitrary)



BACKGROUND ELECRON NUMBER DENSITY

Solid-target simulations

LASER AND ELECTRON INJECTION:

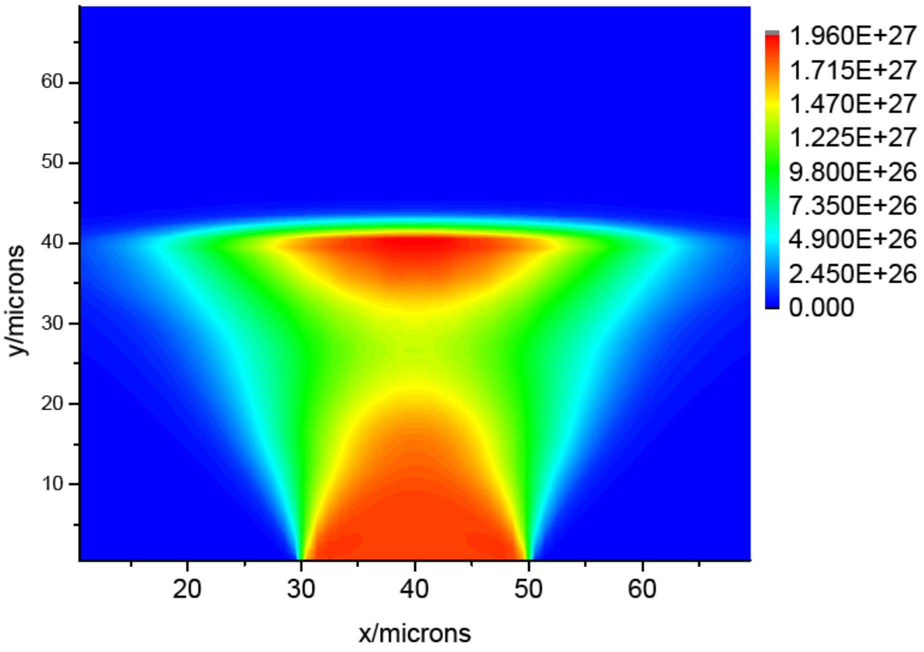
Laser intensity
$I=5x10^{19}Wcm^{-2}$

Absorption fraction η=0.3

Injection region 8μm x 1μm
using square mask

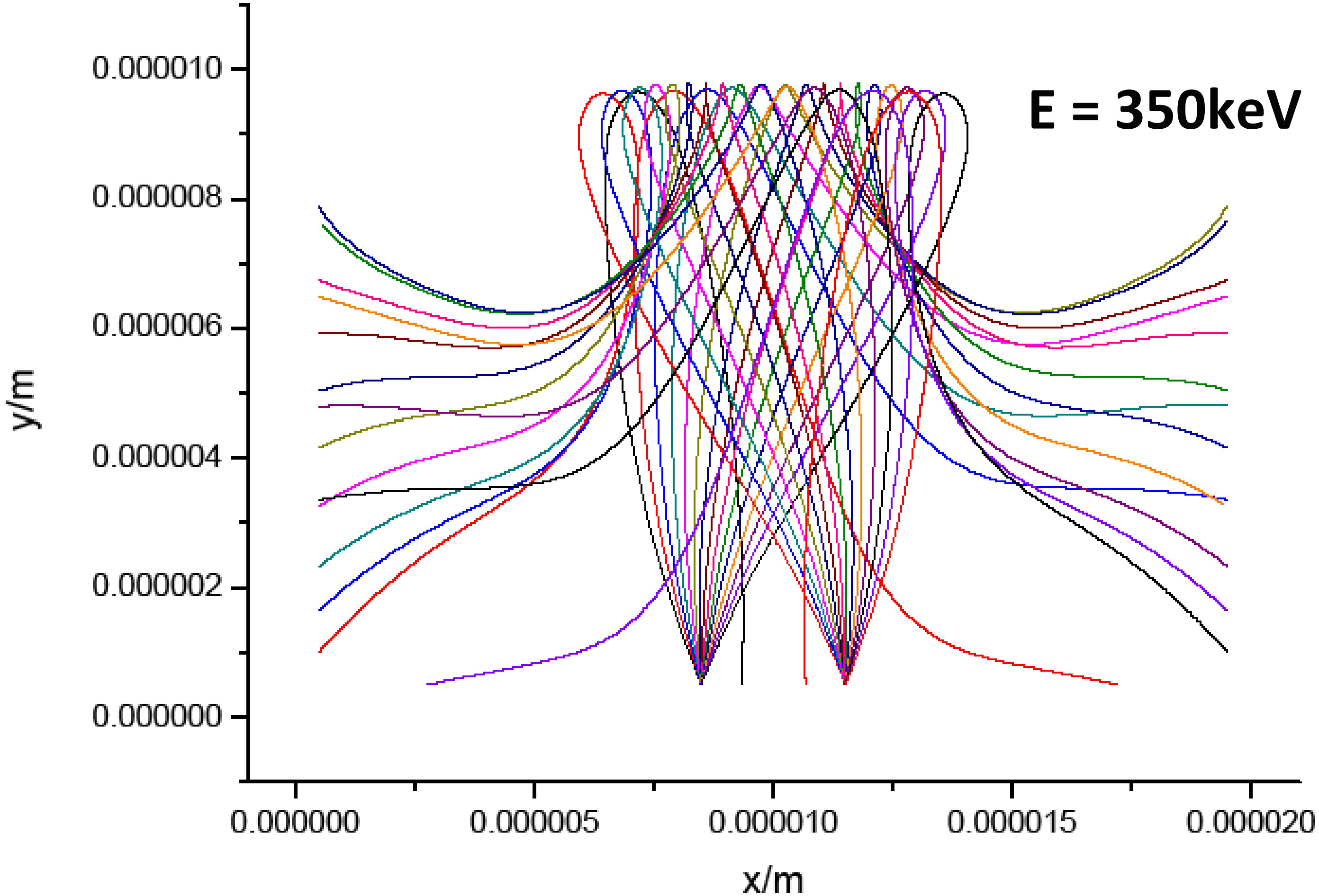
Max injection angle $\theta=28^o$

INJECTED ELECTRON DENSITY (after 200fs)



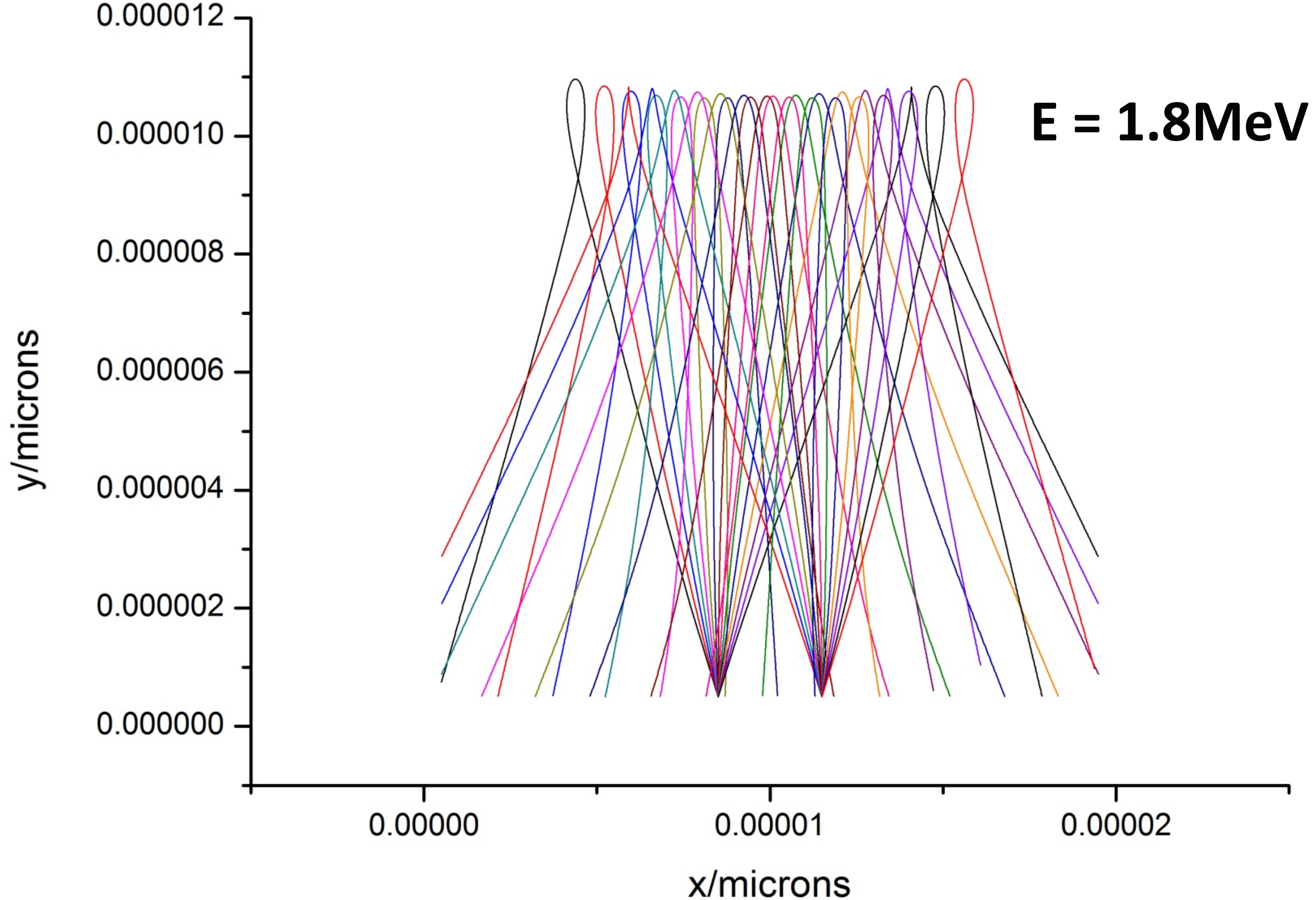
Particle-tracking

Particles injected at 350keV affected by $\mathbf{E}$ and $\mathbf{B}$ fields



Particle-tracking

Particles injected at 1.8MeV affected by $\mathbf{E}$ and $\mathbf{B}$ fields



IMPACT – **Parallel** Implicit VFP code

<u>First</u> 2-D FP code for LPI with self consistent B-fields

Kingham & Bell , J. Comput. Phys. ***194,*** *1 (2004)*

- Implicit finite-differencing $\Rightarrow$ very robust + large Δt (e.g. **~ps** for Δx~1μm vs **3fs**)

- $$\frac{\partial f_0}{\partial t} + \frac{v}{3}\nabla_r.\mathbf{f}_1 - \frac{e}{m_e}\frac{1}{3v^2}\frac{\partial}{\partial v}\left(v^2\mathbf{E}.\mathbf{f}_1\right) = \frac{\nu' \ln\Lambda_{ee}}{v^2}\frac{\partial}{\partial v}\left[C f_0 + D\frac{\partial f_0}{\partial v}\right]$$

$$\frac{\partial \mathbf{f}_1}{\partial t} + v\nabla_r f_0 - \frac{e\mathbf{E}}{m_e}\frac{\partial f_0}{\partial v} - \frac{e}{m_e}(\mathbf{B}\times\mathbf{f}_1) = -\nu'\frac{Z^2 n_i \ln\Lambda_{ei}}{v^3}\mathbf{f}_1$$

$$\nabla\times\mathbf{B}(\mathbf{r},t) = \mu_o\mathbf{j} + \frac{1}{c^2}\frac{\partial\mathbf{E}}{\partial t}$$

$$\nabla\times\mathbf{E}(\mathbf{r},t) = -\frac{\partial\mathbf{B}}{\partial t}$$

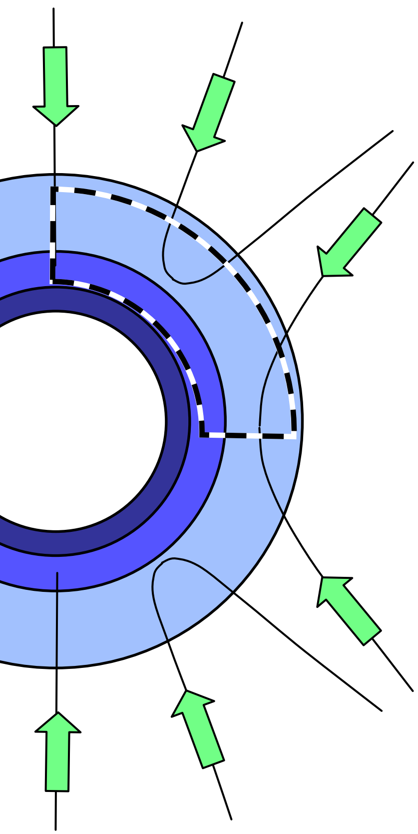
f_o can be non-Maxwellian

$\rightarrow$ get non-local effects

IMPLICT LAGGED EXPLICIT

Simulation set up – region from $0.25\, n_{cr} < n_e < 4\, n_{cr}$

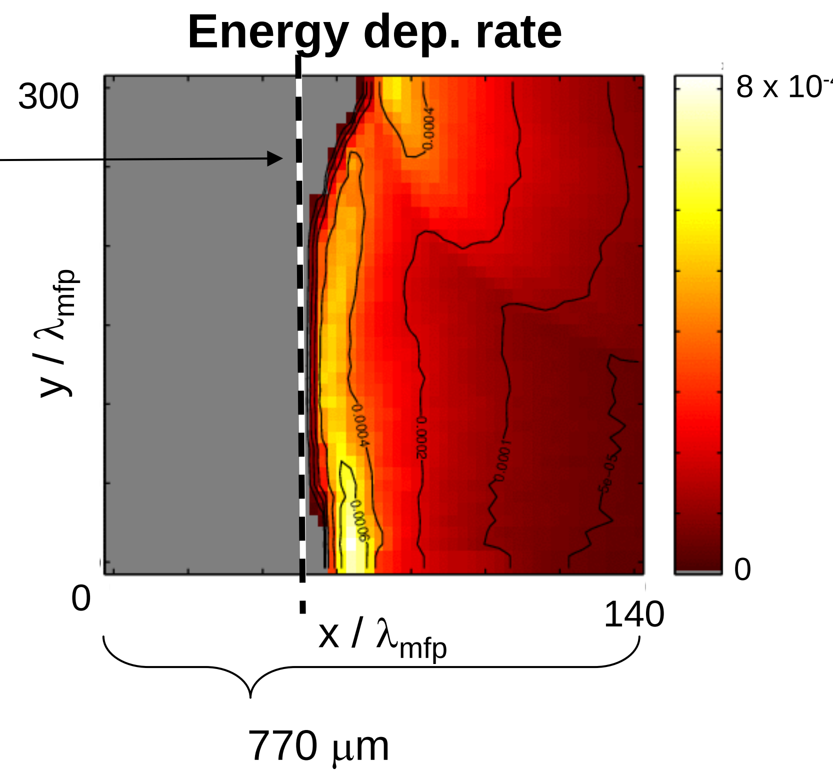
- Took a 'snapshot' of $n_e(r,\theta)$, $T_e(r,\theta)$, $dU(r,\theta)/dt$ from DRACO (2D-ALE code)



- Used as initial conditions & heating rate in VFP transport sim
  - "IMPACT" B-fields, 2D-Cartesian, static density

$n_{cr} = 10^{22}\ cm^{-3}$

(Radius = 1.08mm)



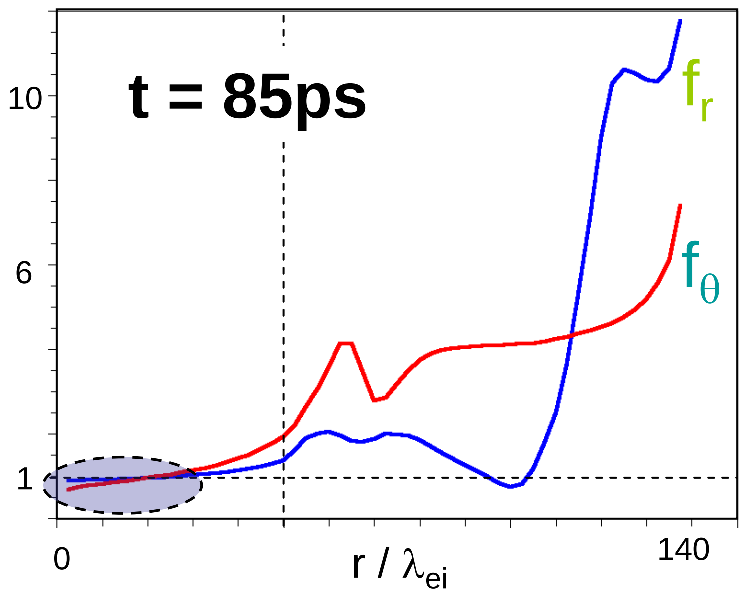
<u>Peak heating rate</u>:

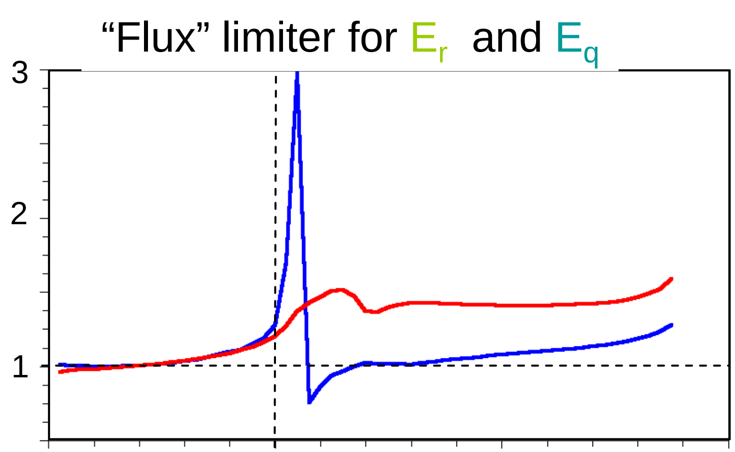
~ 1.5 keV / ns at n_{cr}

I ~ $3 \times 10^{14}\ W/cm^2$

~ $8 \times 10^{-4}\ (n_e T_{eo} / \tau_{ei})_{cr}$

Flux limiter for q_θ and q_r not generally the same





- Flux limiter measure: *RMS ave. in θ*

$$f_r = \frac{\left\langle (q_r)_{Brag} \right\rangle_{rms-\theta}}{\left\langle (q_r)_{VFP} \right\rangle_{rms-\theta}}$$

- Implied flux limiter for q_θ **larger** than that for q_r where heating occurs

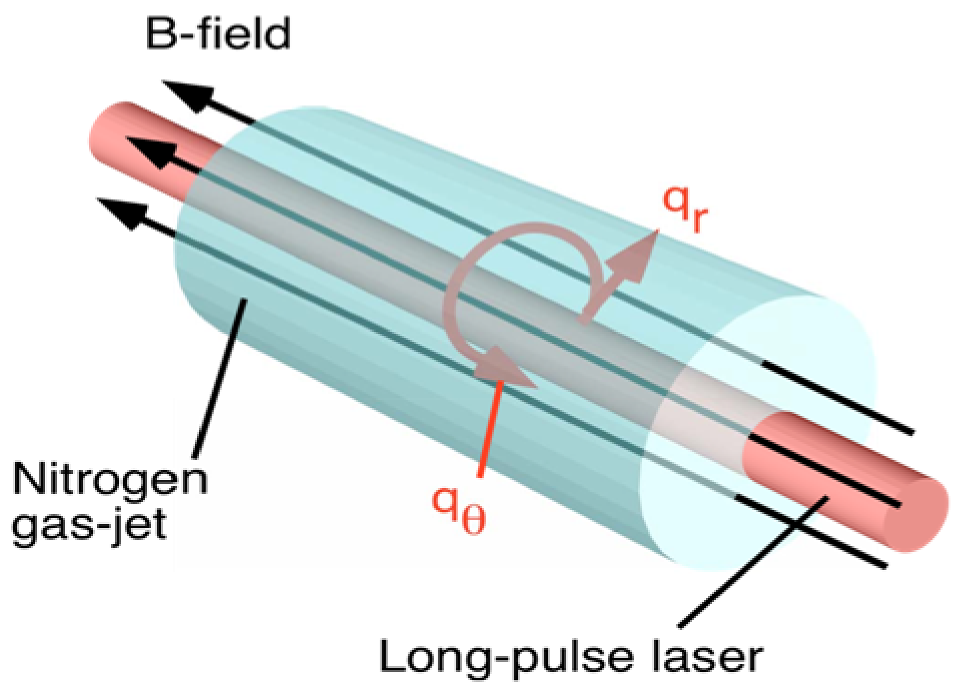
c.f. [*Rickard, Epperlein & Bell., PRL* ***62,*** *(1989)*]

- q_θ "diffuses" toward ablation surface
  - Braginskii underestimates q_θ here!
  - Analogous effect to Nernst (?)

- E_r & E_θ also show departures from locality

PART 2 — Effect of Inverse-Bremsstrahlung heating on transport & B-field phenomena

- **Theoretical:** Better understanding of **B**-fields and transport
- **Practical**: Inertial Confinement Fusion and other experiments



1μm, 100J, 1ns laser

I~ 4×10^{14} W/cm^2 ϕ ~ 150 μm

$n_e \sim 1.5 \times 10^{19}$ cm^{-3}

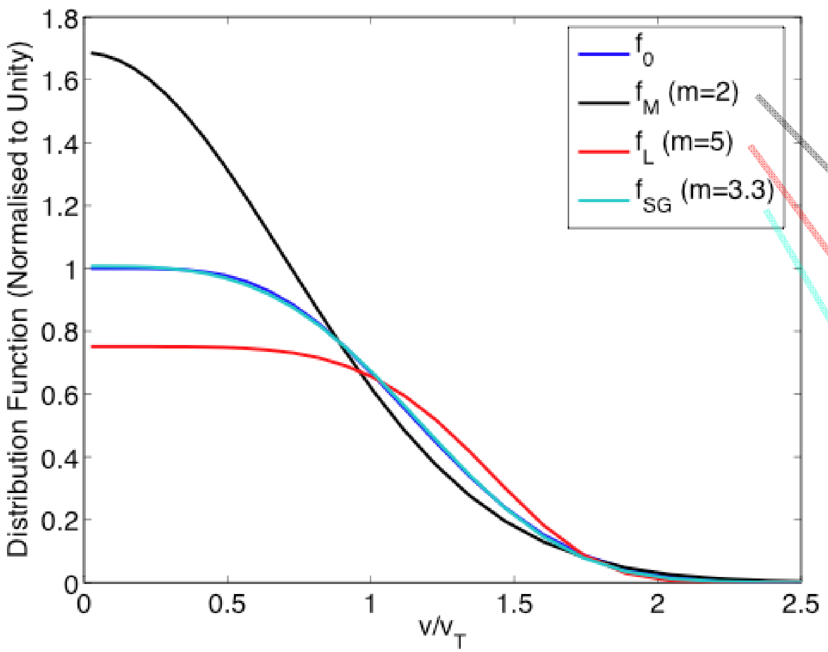
20 < T_e < 800eV

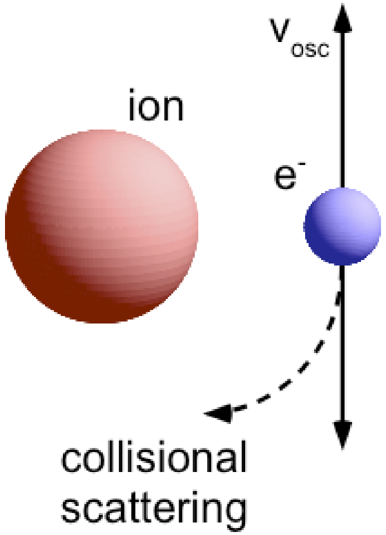
$B_{applied}$ up to 120 kG (12 T)

D.H. Froula *et al.*, PRL 98, 085001 (2007)

Super-Gaussian electron distribution function
Breakdown of Maxwellian Assumption

- **A. B. Langdon, PRL 44, 9 (1980):**
  EDF $f_0(\mathbf{r},v,t)$ tends to Super-Gaussian due to I.B.





Maxwellian (m=2)

Langdon (m=5)

Super-Gaussian fit (m=3.3)

General m

- **Involved in transport**

$$f \approx f_0 + \delta f$$

$$f_0(\mathbf{r},v,t) \propto \exp(-V^m)$$

Transport Relations
Extension to Super-Gaussian EDF

- **Braginskii:** **valid m=2** ($f_0 = f_M$)

$$\mathbf{E} = -\frac{\nabla P_e}{en_e} - \underline{\underline{\alpha}} \cdot \mathbf{j} - \frac{1}{e}\underline{\underline{\beta}} \cdot \nabla T_e + \frac{1}{en_e}\mathbf{j} \times \mathbf{B}$$

$$\mathbf{q} = -\underline{\underline{\kappa}} \cdot \nabla T_e - \underline{\underline{\beta}} \cdot \mathbf{j}\frac{T_e}{e}$$

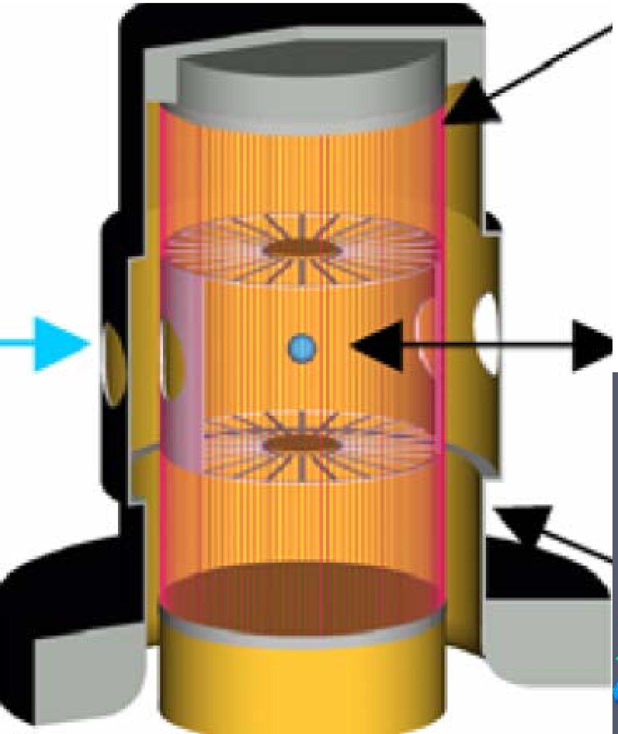
- **Dum (1978) & Ridgers (2008)**: transport theory for **$2 \leq m \leq 5$**

$$\mathbf{E} = -\frac{1}{en_e}\underline{\underline{\gamma}} \cdot \nabla P_e - \underline{\underline{\alpha}} \cdot \mathbf{j} - \frac{1}{e}\underline{\underline{\beta}} \cdot \nabla T_e + \frac{1}{en_e}\mathbf{j} \times \mathbf{B}$$

$$\mathbf{q} = -\underline{\underline{\kappa}} \cdot \nabla T_e - \underline{\underline{\psi}} \cdot \mathbf{j}\frac{T_e}{e} - \underline{\underline{\phi}} \cdot \nabla P_e$$

- New coefficients , old ones changed , Onsager symmetry broken

MHD simulation of indirect drive using wire array Z-pinches



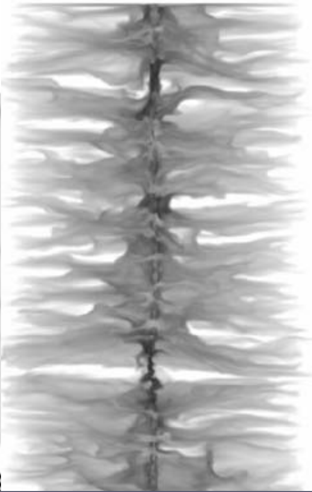
Double ended vacuum hohlruam approach

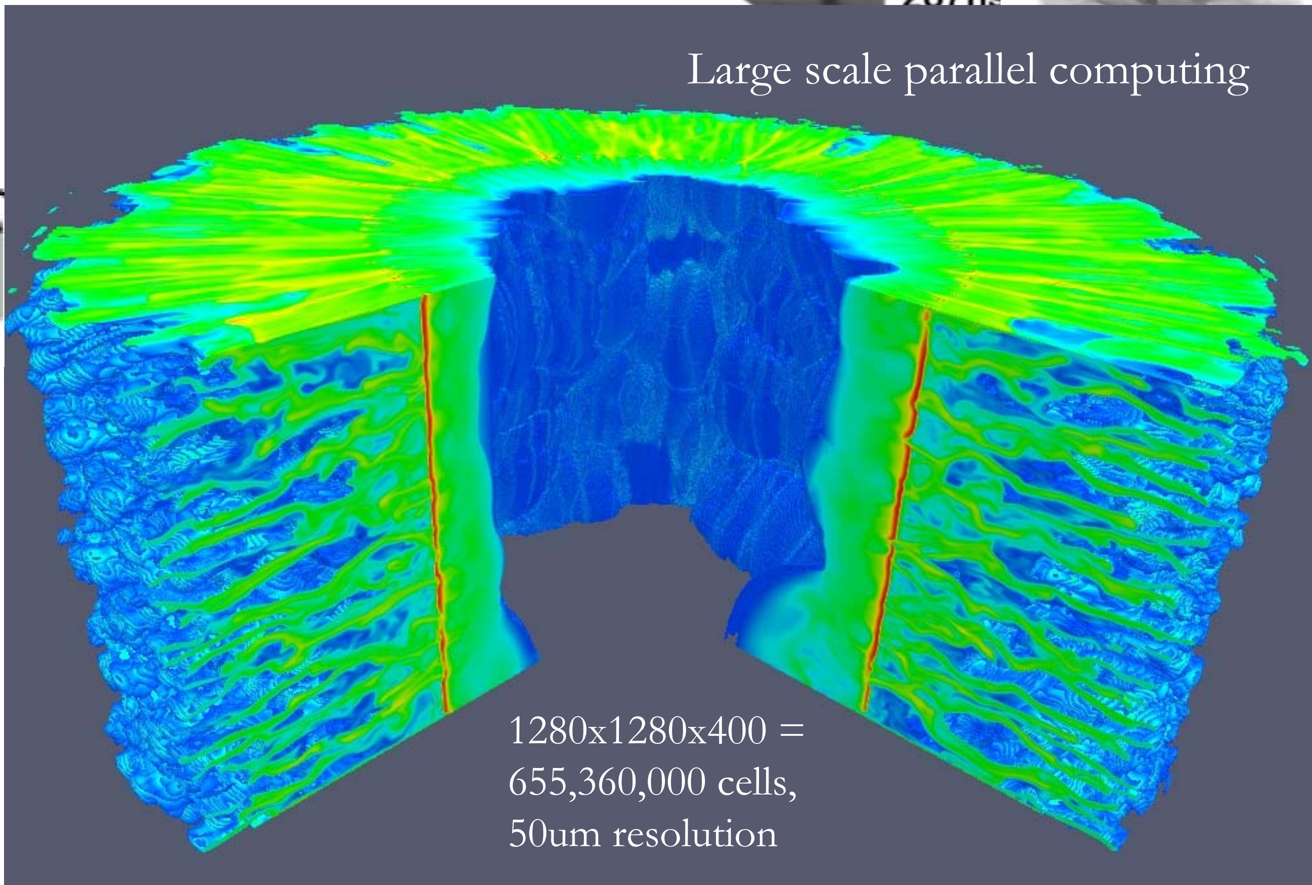
Simulations using Gorgon 3D radiative resistive MHD code

Benchmark testing against MAGPIE data

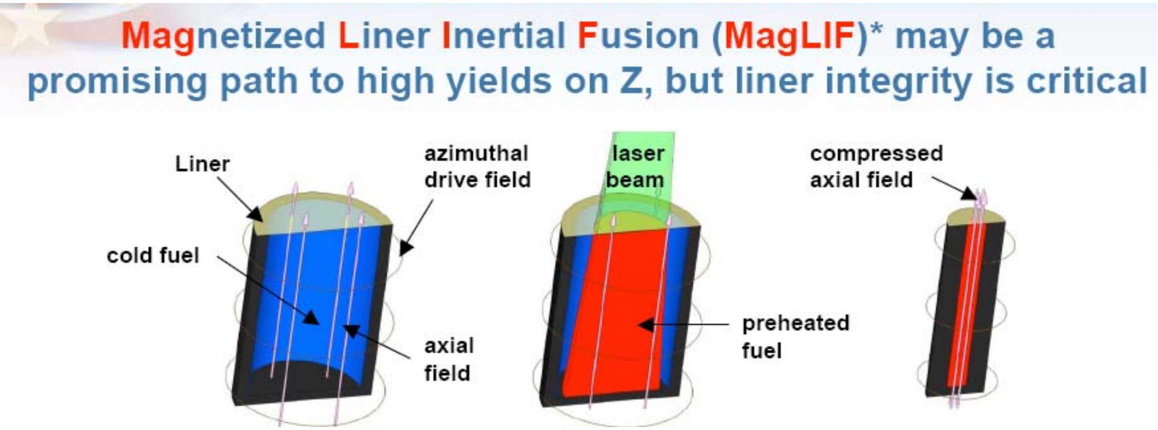
Experiment

Simulation



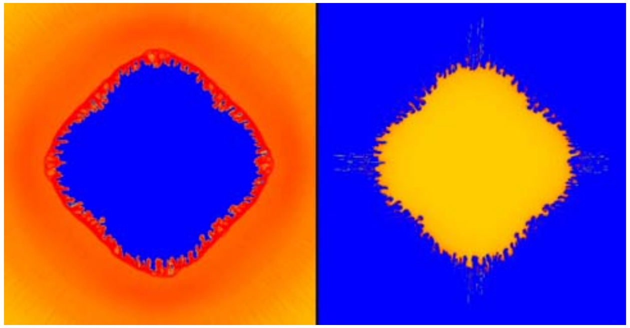


MHD simulation of magnetised liner fusion concepts, a three-way collaboration between SNL, IC and AWE

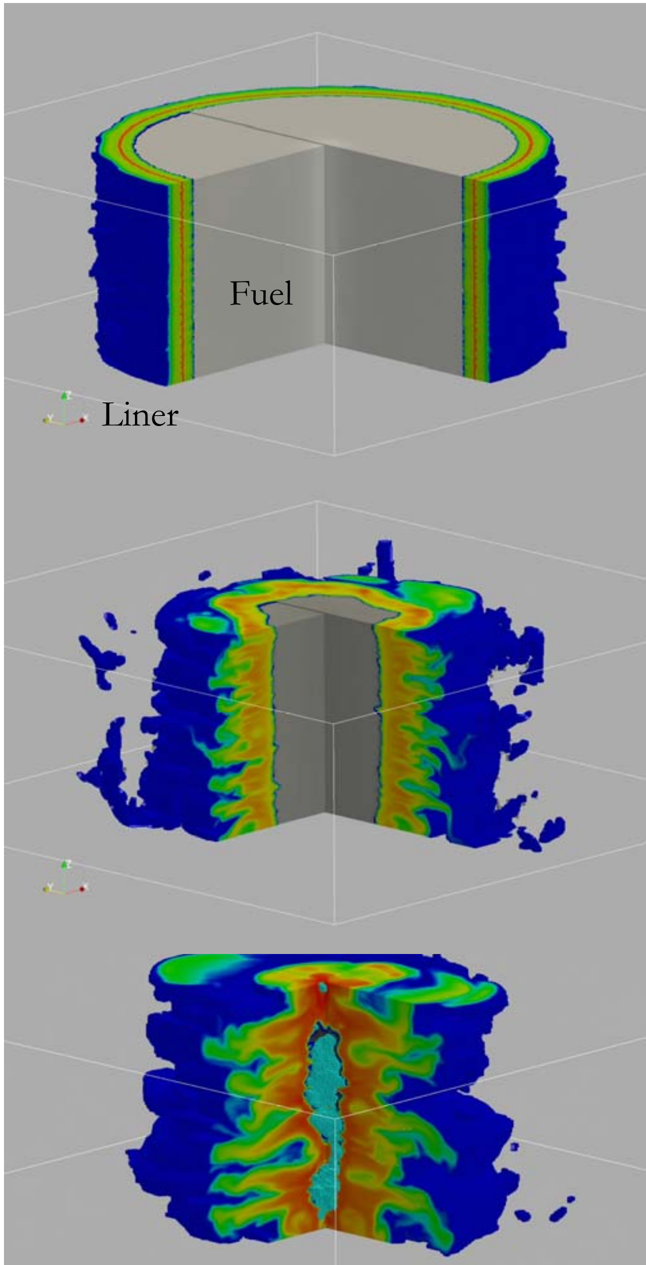


S.A. Slutz and M.C Herrmann

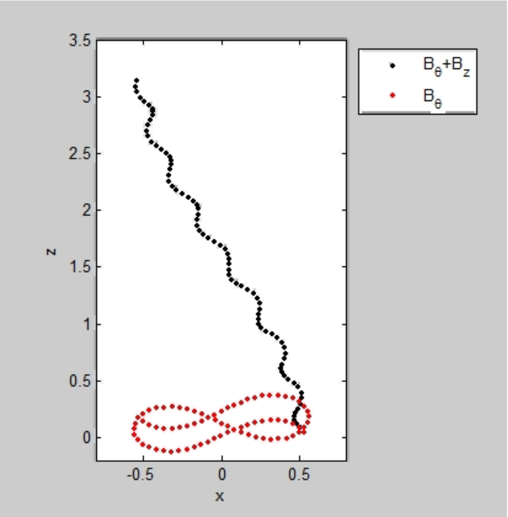
APS-DPP 2009



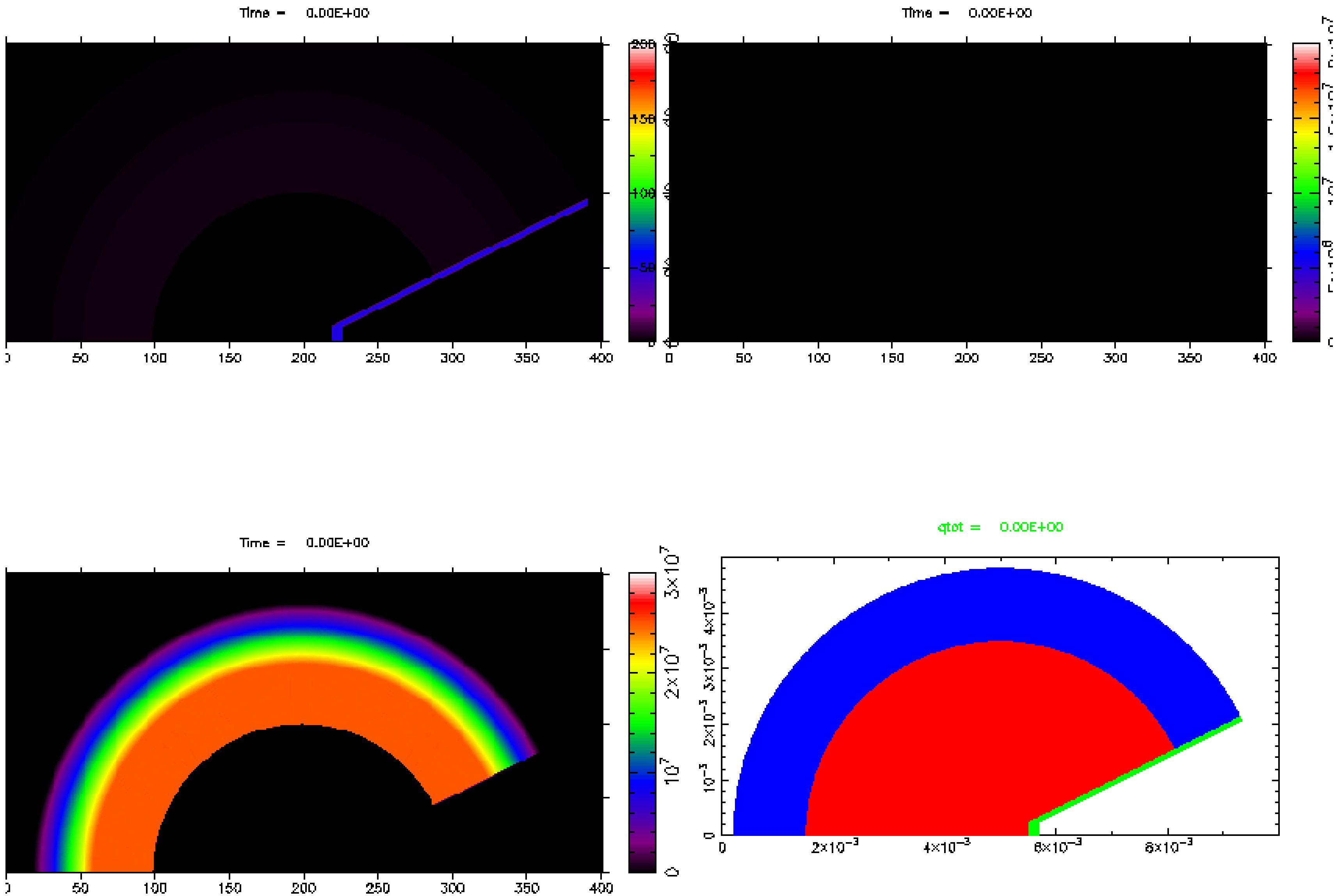
Grid based mix model for liner-fuel separation



Gorgon 3D simulations of MagLIF



3D EM PIC code for alpha particle heating in burning magnetized plasma – under development



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Time = 0.00E+00
Time = 0.00E+00
qtot = 0.00E+00
0 50 100 150 200 250 300 350 400
0 50 100 150 200
0 10^7 2×10^7 3×10^7
0 2×10^-3 4×10^-3 6×10^-3 8×10^-3
0 10^-3 2×10^-3 3×10^-3 4×10^-3

Other Activities

Kinetic modelling of α transport and thermonuclear burn
(Mark Sherlock, Steve Rose, Jerry Chittenden)

PIC code development for future HPC applications
(with Warwick and Oxford)

Experiments on magnetic field generation and transport
- new results on enhanced advection due to Nernst effect

Experiments on fast electron source and transport

Experiments on ion emission as a transport diagnostic
(with Strathclyde and RAL)

Atomic physics calculations for diagnostics and opacity

Conclusions

There are many academically interesting challenges related to IFE physics.

Now is a good time to tackle them!

There is a good mix of skills between AWE and universities