Progress in Vlasov-Fokker-Planck simulations of laser-plasma interactions

C. P. Ridgers, M. W. Sherlock, R. J. Kingham, A.Thomas, R. Evans

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Outline

Part 1 – simulations of long-pulse laser-plasma interactions.

(1) The interplay of magnetic field dynamics and non-locality.

(2) Magnetic field generation

Part 2 – Vlasov-Fokker-Planck simulations of short-pulse laser-plasma interactions relevant to fast ignition. The importance of rear-surface effects.

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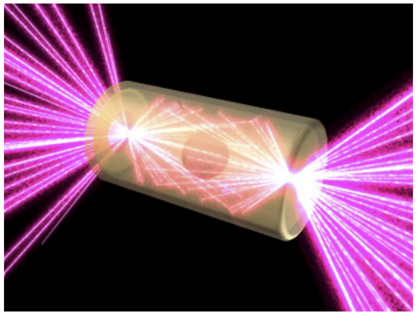
Background – inertial fusion

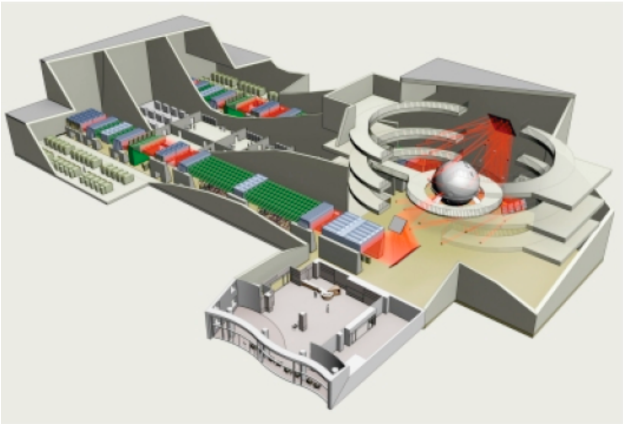


NIF - National Ignition Facility

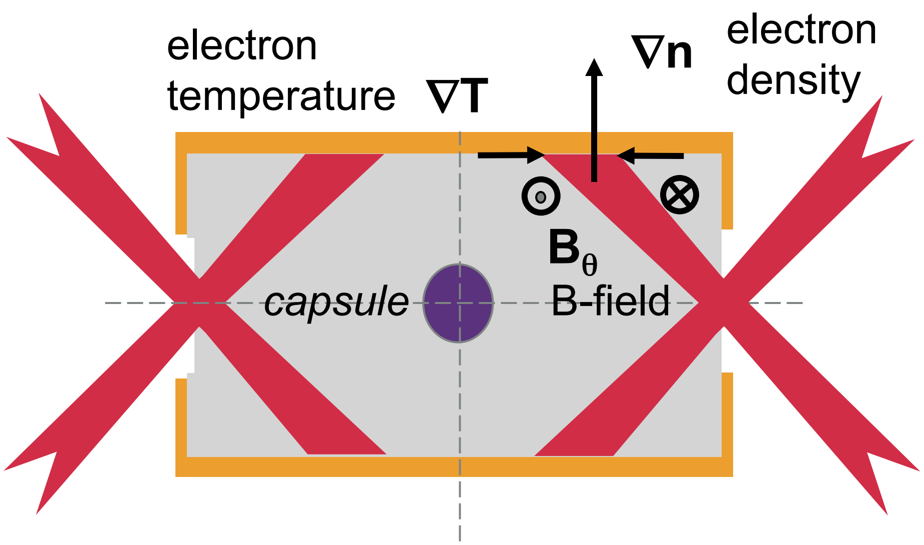
- 1.8 MJ in UV
  based at LLNL
- Partially working now…
  Ignition in 2011

HiPER

- High Power Exper. Research facility
- Proposed European academic facility, with 200--400 kJ
- Site: TBD… UK ?



Indirect drive ICF[1,2]



Gradients in T_e, n_e large enough so that classical diffusive transport (e.g. Spitzer) not valid.

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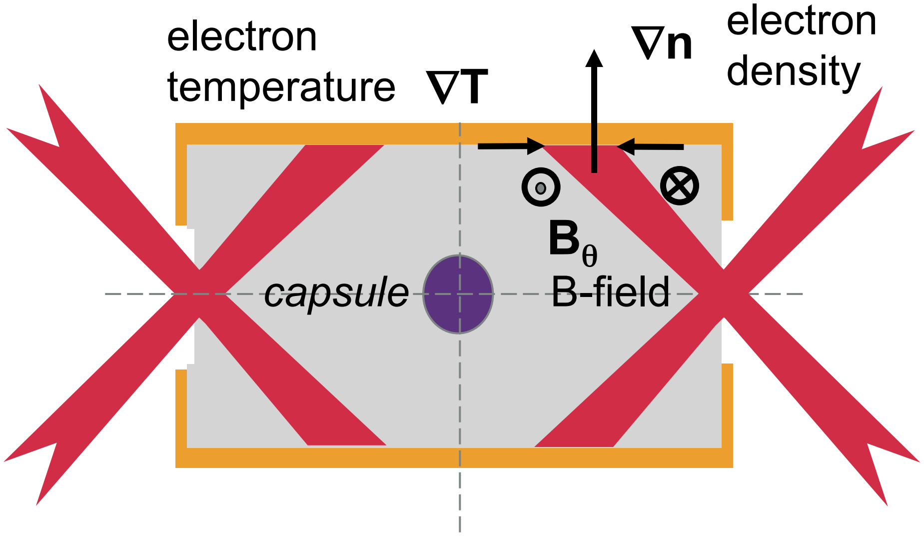

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1) Does the heat-flow obey classical theory? (non-locality)

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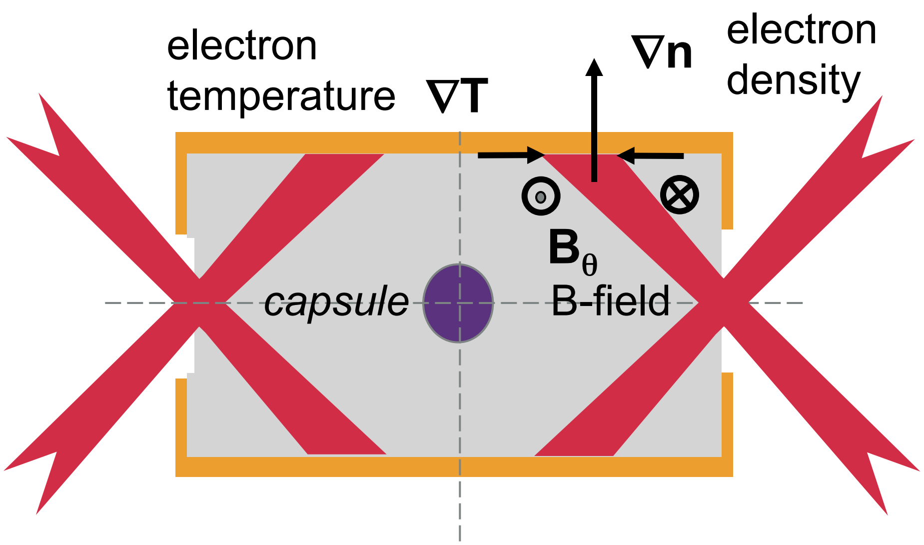
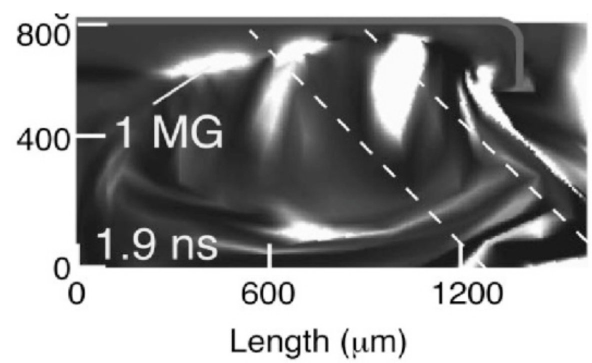


1) Does the heat-flow obey classical theory? (non-locality)

2) Interplay between non-locality and B-fields.

Gradients in T_e, n_e large enough so that classical diffusive transport (e.g. Spitzer) not valid.

B-field



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First part of talk will examine these three points:

1) Does the heat-flow obey classical theory? (non-locality)

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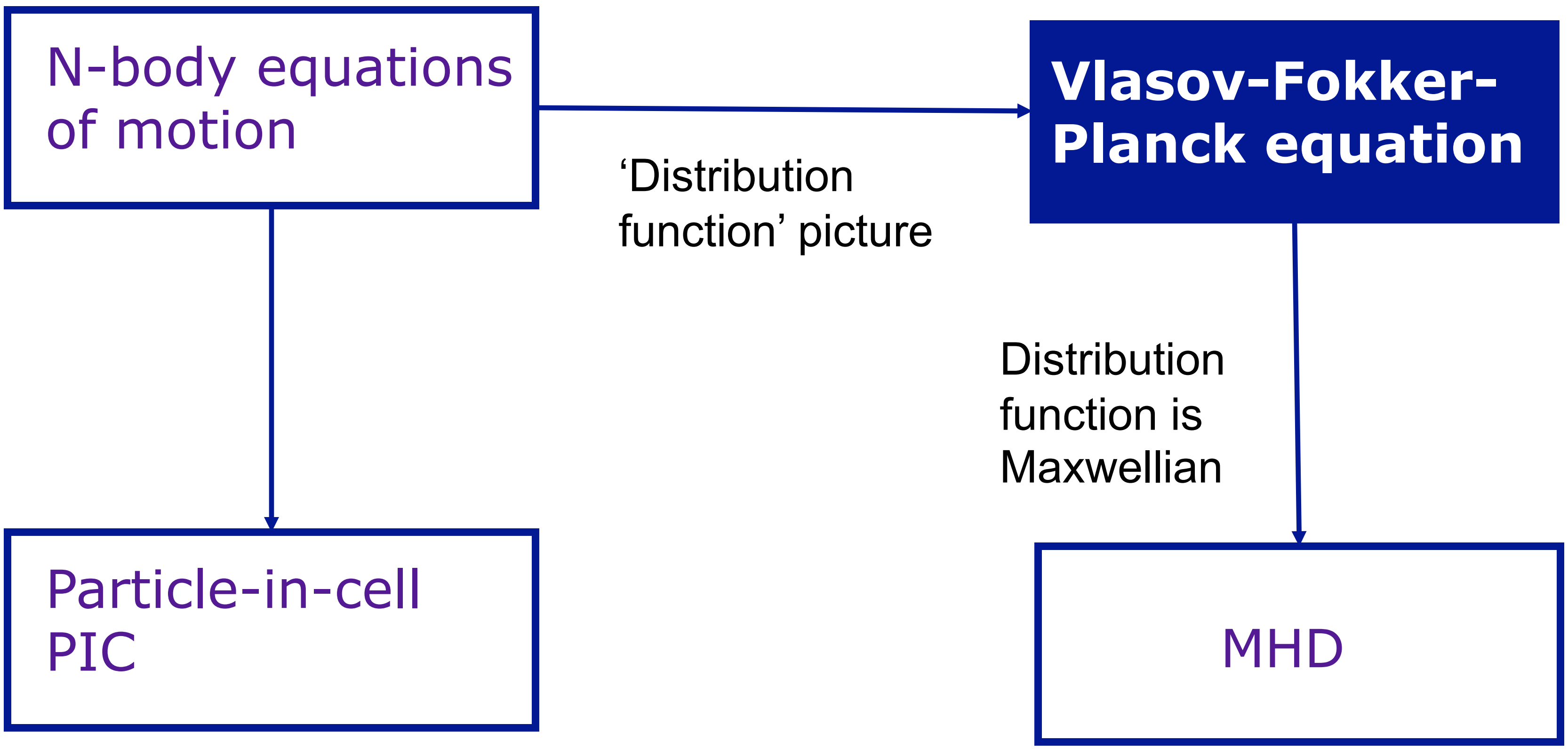
Modelling long-pulse LPI



The Vlasov-Fokker-Planck equation

Distribution function - density of particles in 6D phase space

$$dN = f(\mathbf{v},\mathbf{r},t)\,d^3\mathbf{r}\,d^3\mathbf{v}$$

The VFP equation is the appropriate kinetic equation for a plasma:

$$\frac{\partial f}{\partial t} + \nabla_r \cdot (f\mathbf{v}) + \nabla_p \cdot (f\mathbf{F}) = \left(\frac{\partial f}{\partial t}\right)_{coll}$$

$$\mathbf{v} = \frac{d\mathbf{r}}{dt} \qquad \mathbf{F} = \frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + \mathbf{v}\times\mathbf{B})$$

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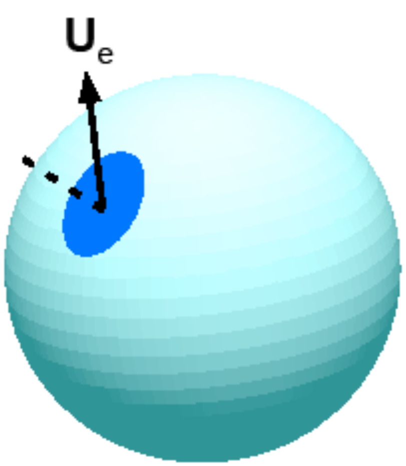
VFP equation is continuity is 6D phase space. Compare to:

$$\frac{\partial n_e}{\partial t} + \nabla_{\mathbf{r}} \cdot \left(n_e \mathbf{U}_e\right) = 0$$



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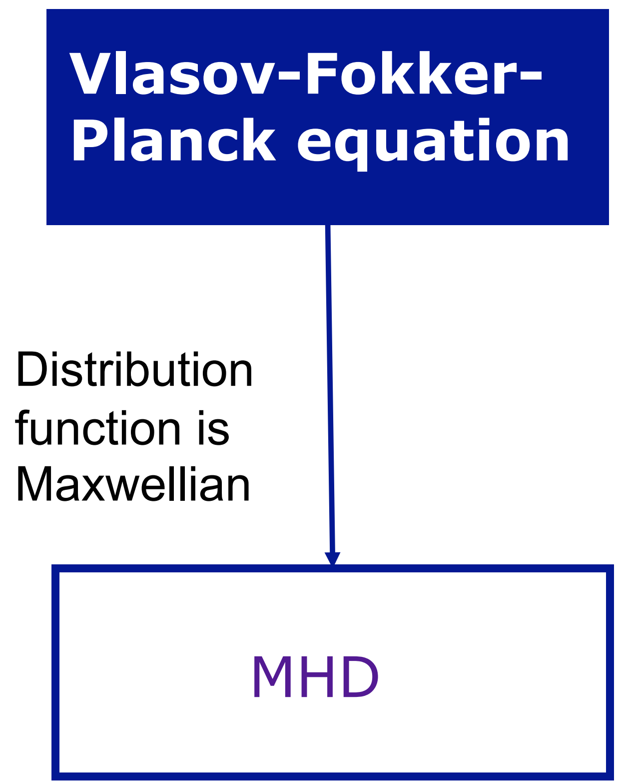

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Modelling long-pulse LPI

Distribution function is Maxwellian:

$$f(\mathbf{v},\mathbf{r},t) = n_e\left(\frac{m_e}{2\pi T_e}\right)^{3/2}\exp\left(-\frac{m_e v^2}{2k_B T_e}\right)$$

Vlasov-Fokker-Planck equation

↓ Distribution function is Maxwellian

MHD

Modelling long-pulse LPI

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MHD requires closure - classical heat flow equation:

$$\mathbf{q} = -\kappa^c \nabla T$$

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MHD requires closure - classical heat flow equation:

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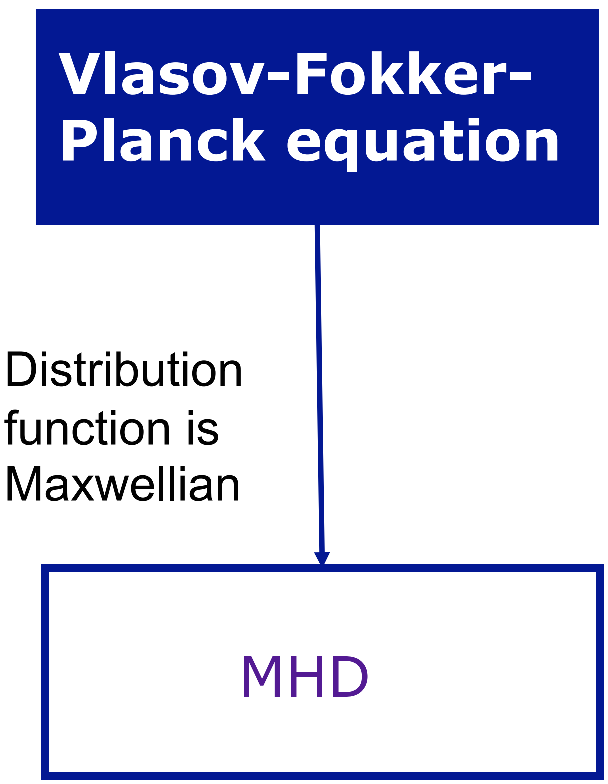
VFP - **Distribution function is NOT Maxwellian**

$$\mathbf{q} = \frac{m_e}{2}\int \mathbf{d}v\,\mathbf{v}v^2 f$$



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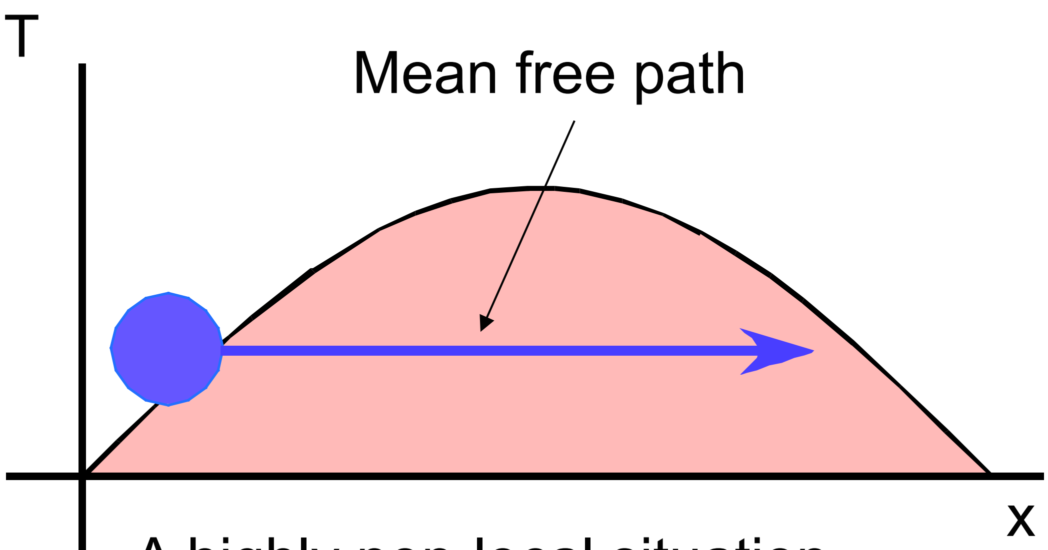
What causes the break-down of classical transport?

Non-Locality: Scale-length of physical variables becomes comparable to mean-free-path



A highly non-local situation

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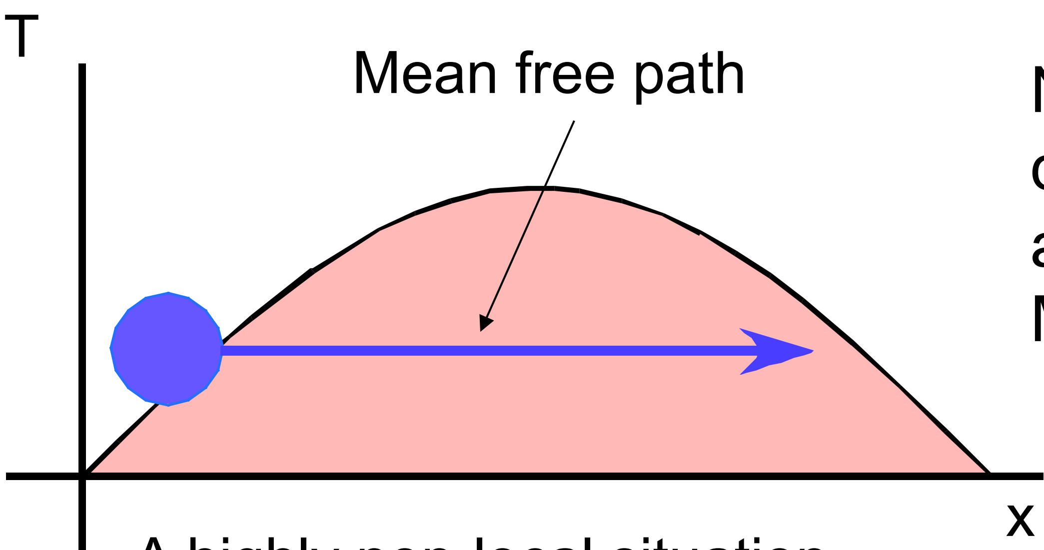

A highly non-local situation

Non-locality causes distribution to move away from Maxwellian

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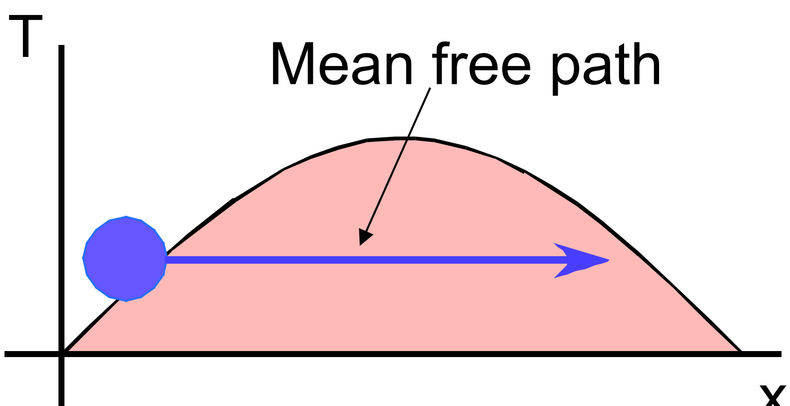
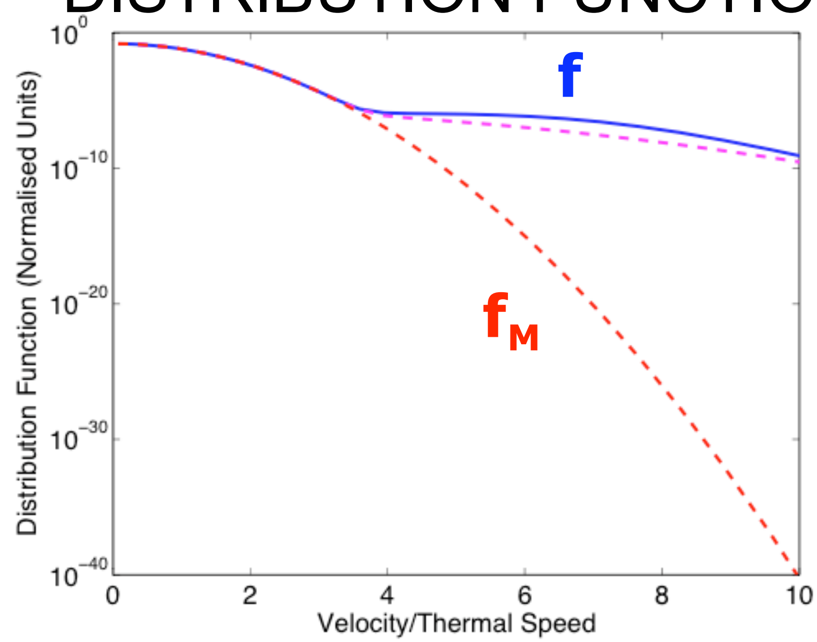


A highly non-local situation

DISTRIBUTION FUNCTION



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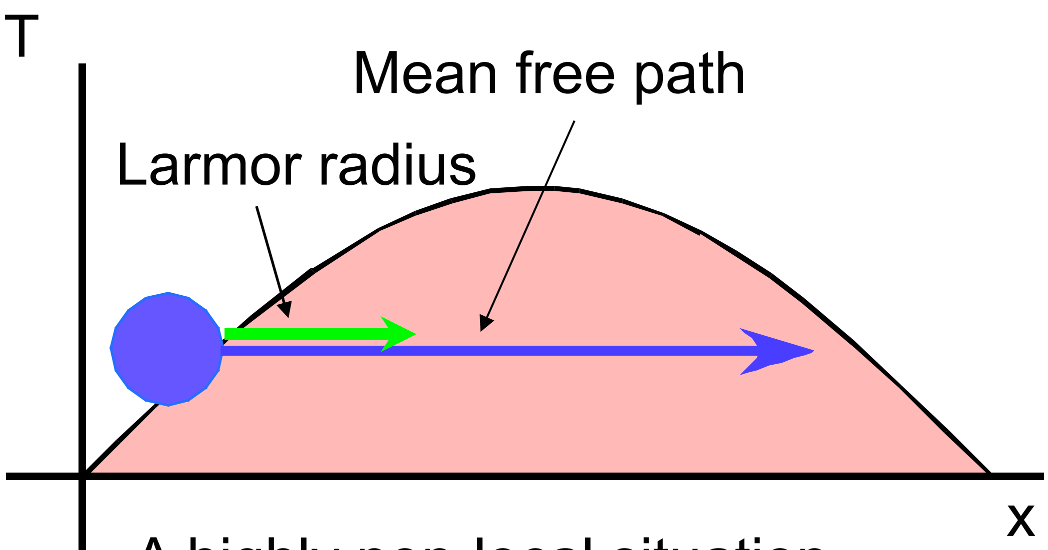

A highly non-local situation

Effect on B-field on non-locality?

IMPACT - Implicit Magnetised Plasma And Collisional Transport[5]

- Solves the VFP Equation (and Maxwell's equations) with hydrodynamic ion flow
- Expands distribution function in spherical harmonics so can only deal with weakly anisotropic distributions
- Implicit finite-differencing - very robust + large Δt (e.g. **~ps** for Δx~1μm vs **3fs**)
- Valid when collisions important (unlike PIC)
- 2D (3V) VFP code with self consistent B_z-fields

[5]*Kingham R.J. & Bell A.R., Journal of Computational Physics* ***194,*** *1, 2004*

IMPACT - Implicit Magnetised Plasma And Collisional Transport[5]

What's new?

FIRST 2D VFP code to be able to simulate long-pulse laser-plasma interactions with self-consistent magnetic fields

Ideal for studying interaction between non-local transport and magnetic fields

[5] *Kingham R.J. & Bell A.R., Journal of Computational Physics* ***194,*** *1, 2004*

Indirect drive ICF[1,2]

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1) **Does the heat-flow obey classical theory? (non-locality)**

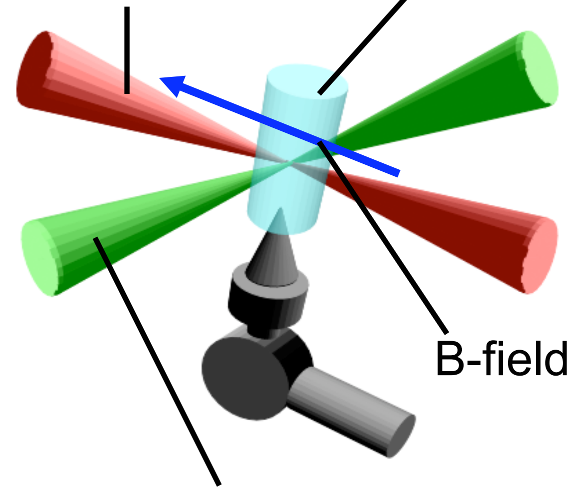
2) Interplay between non-locality and B-fields.

B-Field and Non-Locality: Experimental Measurement[6]

Gas jet:
Initial temperature - 20eV
Number density- $1.5x10^{19}cm^{-3}$

Laser:
Energy - 100J
Spot size - 100μm
Intensity - $1x10^{15}W/cm^2$
Wavelength - 1.053μm
Pulse duration - 1ns

Magnetic field:
Non-local case - 0T
Local case - 12T



Strong B-field expected to "localize" transport

[6] *Froula D.H. et al, Physical Review Letters,* ***98****, 135001, 2007*

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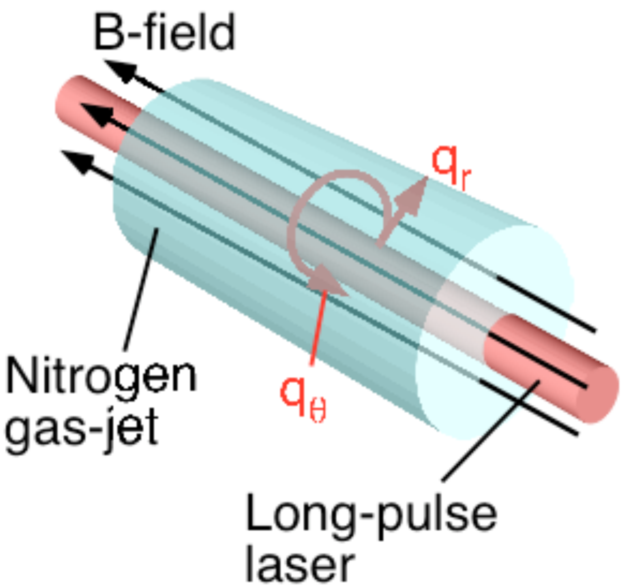
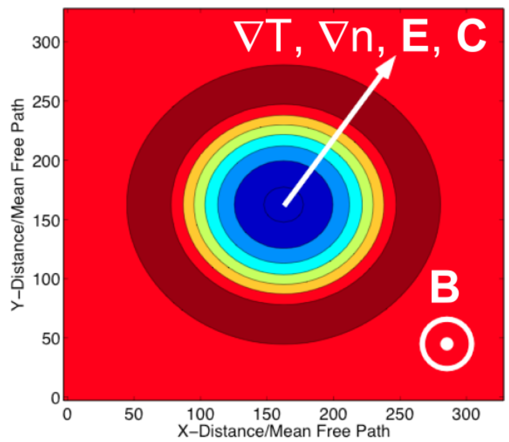
Using IMPACT with MHD to model magnetized transport experiments



Simulation geometry:



IMPOSE A RANGE OF FIELDS B=0-12T

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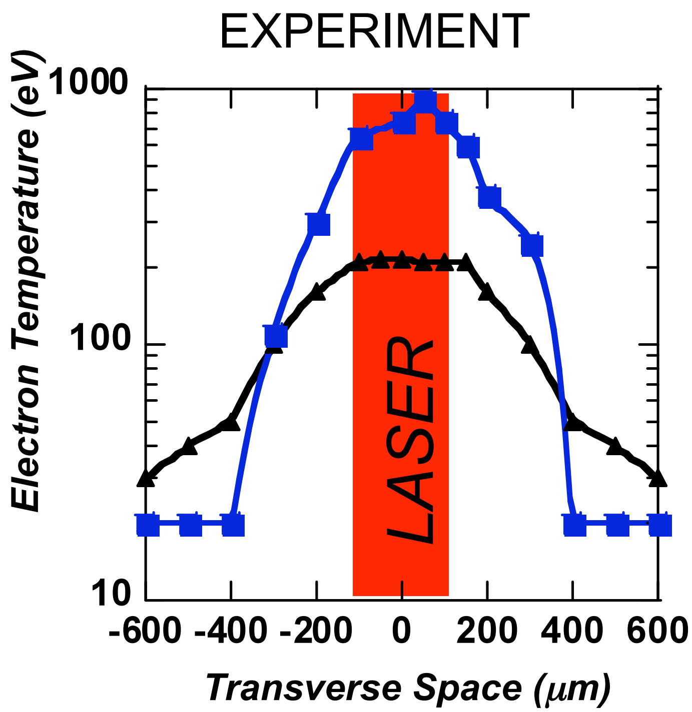
Simulation results - pre-heat

TEMPERATURE PROFILE ACROSS LASER BEAM



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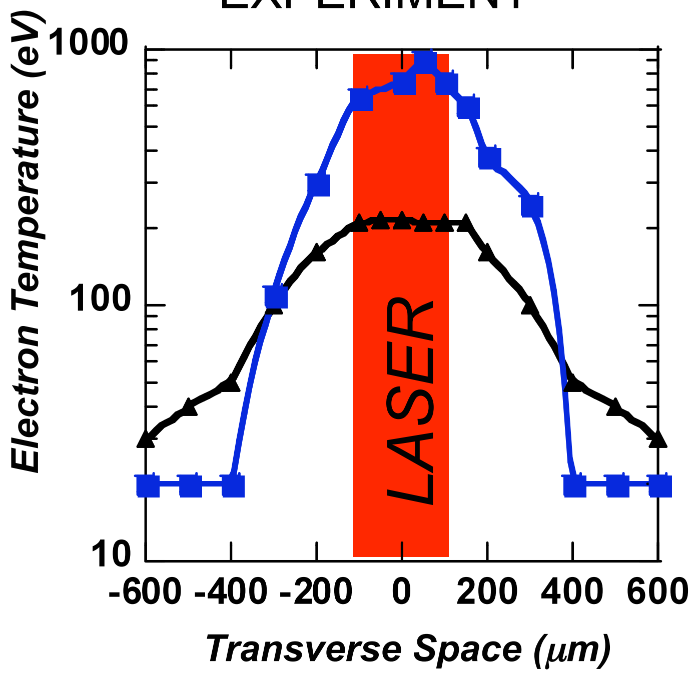
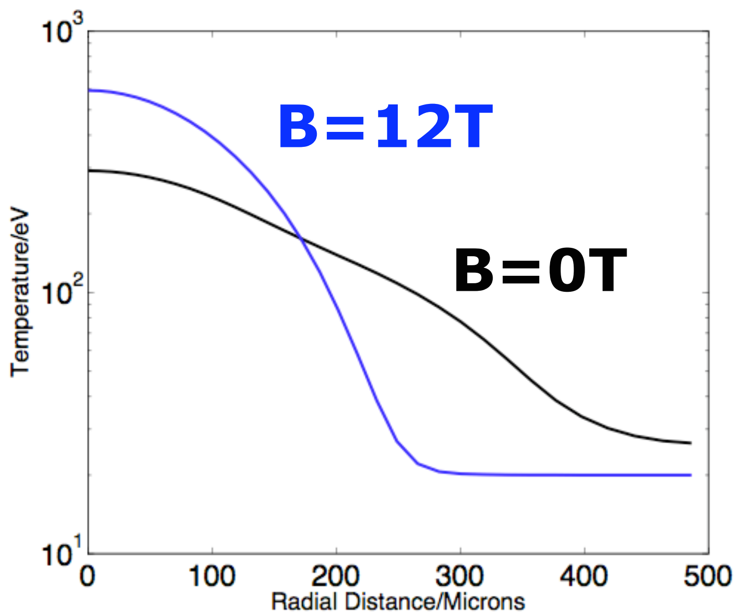
Simulation results - pre-heat[7]

TEMPERATURE PROFILE ACROSS LASER BEAM

EXPERIMENT



IMPACT SIMULATION (After 440ps)



[7]*Ridgers C.P., Kingham R.J. & Thomas A.G.R., Phys Rev Lett,* ***100****, 075003, 2008*

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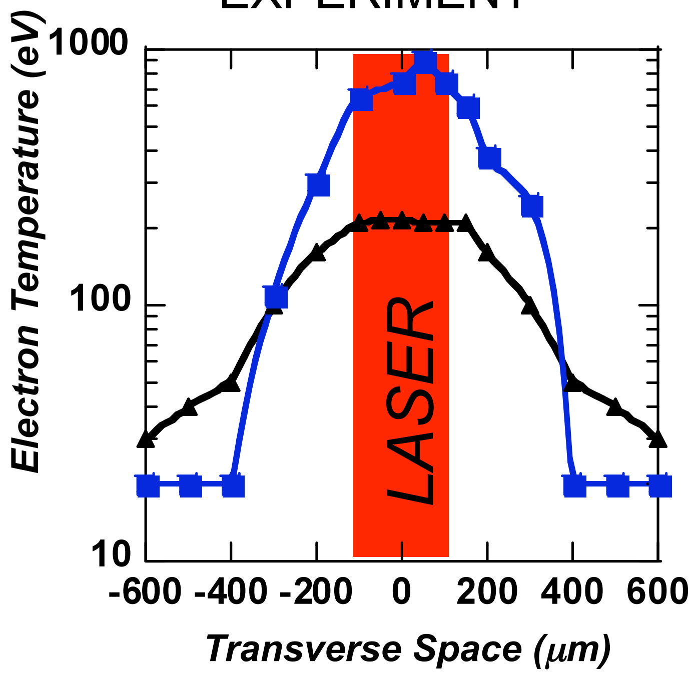

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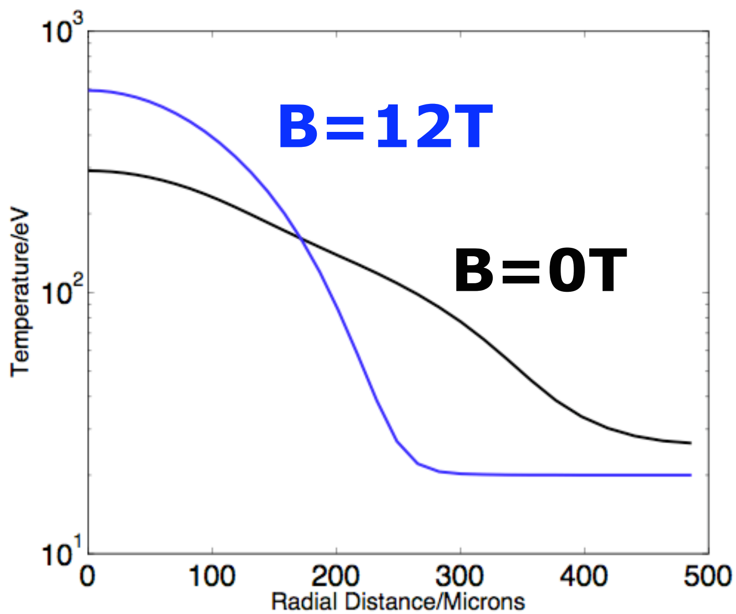
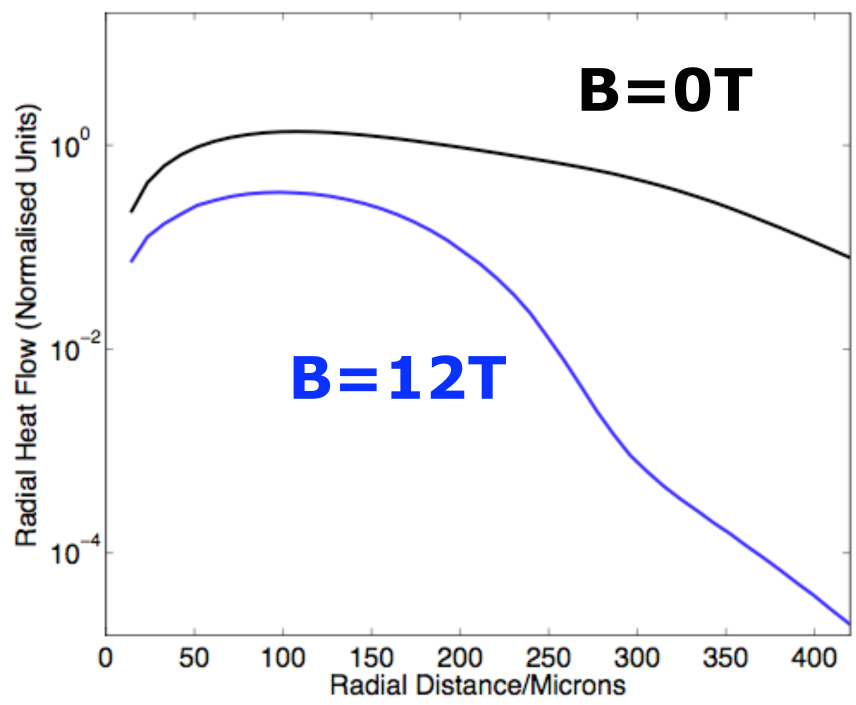


We do see less pre-heat in un-magnetized case - but is it non-local?

[7]*Ridgers C.P., Kingham R.J. & Thomas A.G.R., Phys Rev Lett,* ***100****, 075003, 2008*

Simulation results - is it non-local?[7]

RADIAL HEAT FLOW



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Simulation results - is it non-local?[7]

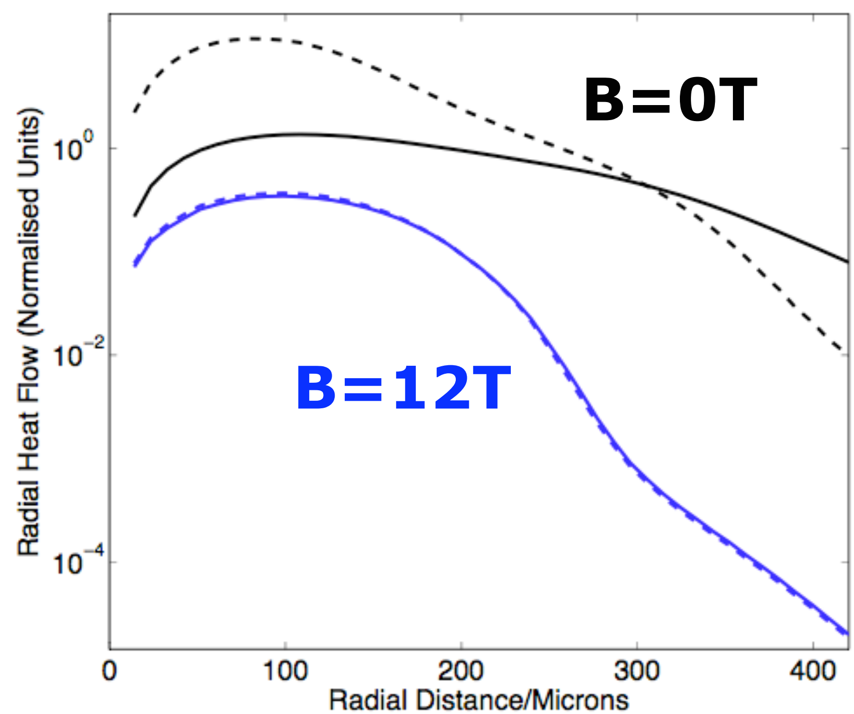
Braginskii heat flow:

$$\mathbf{q} = -\kappa^{c}\nabla T$$

q from instantaneous temperature profile.

12T field suppresses non-locality

RADIAL HEAT FLOW



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Indirect drive ICF[1,2]

First part of talk will examine these three points:

1) Does the heat-flow obey classical theory? (non-locality)

   A: Non-locality causes classical theory to break down BUT transport can be relocalised by a strong B-field, in which case classical theory applies.

2) Interplay between non-locality and B-fields.

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2) **Interplay between non-locality and B-fields.**

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The Nernst effect[8,9]

First moment of VFP equation gives Ohm's law:

$$\frac{e}{m_e}\left(\mathbf{E}+\mathbf{v}\times\mathbf{B}\right)=-\frac{\nabla P_e}{n_e m_e}+\underline{\underline{\alpha}}^c\cdot\frac{\mathbf{j}}{n_e e}-\underline{\underline{\beta}}^c\cdot\frac{\nabla T_e}{m_e}$$

[8] *Nishiguchi A. et al, Physics of Fluids, **28**, 3683, 1985*

[9] *Haines M.G., Plasma Physics and Controlled Fusion, **28**, 1705, 1986*

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Put this into Faraday's law (and simplify!): $\frac{\partial B}{\partial t}=-\nabla\times\mathbf{E}$

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$$\boxed{\frac{\partial B}{\partial t}+\nabla\cdot\left[\left(\mathbf{U}+\mathbf{v}_\mathrm{N}\right)B+\eta\nabla B\right]=0 \qquad \mathbf{v}_\mathrm{N}=\frac{\mathbf{q}_e}{5/2n_eT_e}}$$

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Frozen-in flow

Nernst effect

Resistive diffusion

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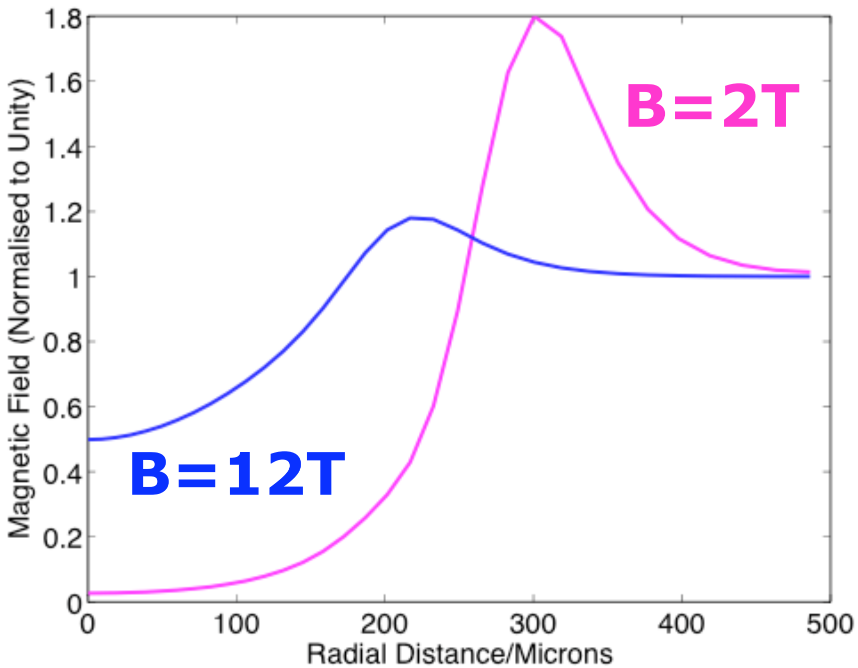
Nernst Advection dominates over Frozen-in-Flow[7]

B-FIELD ACROSS BEAM



Solid lines -

full B-field calculation

Dashed lines -

frozen-in flow only

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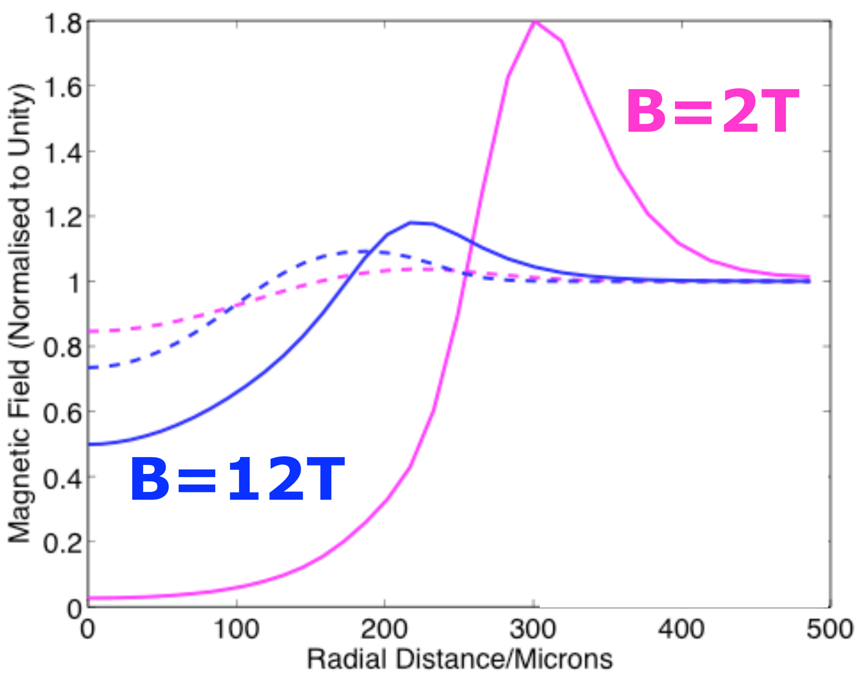

Solid lines -

full B-field calculation

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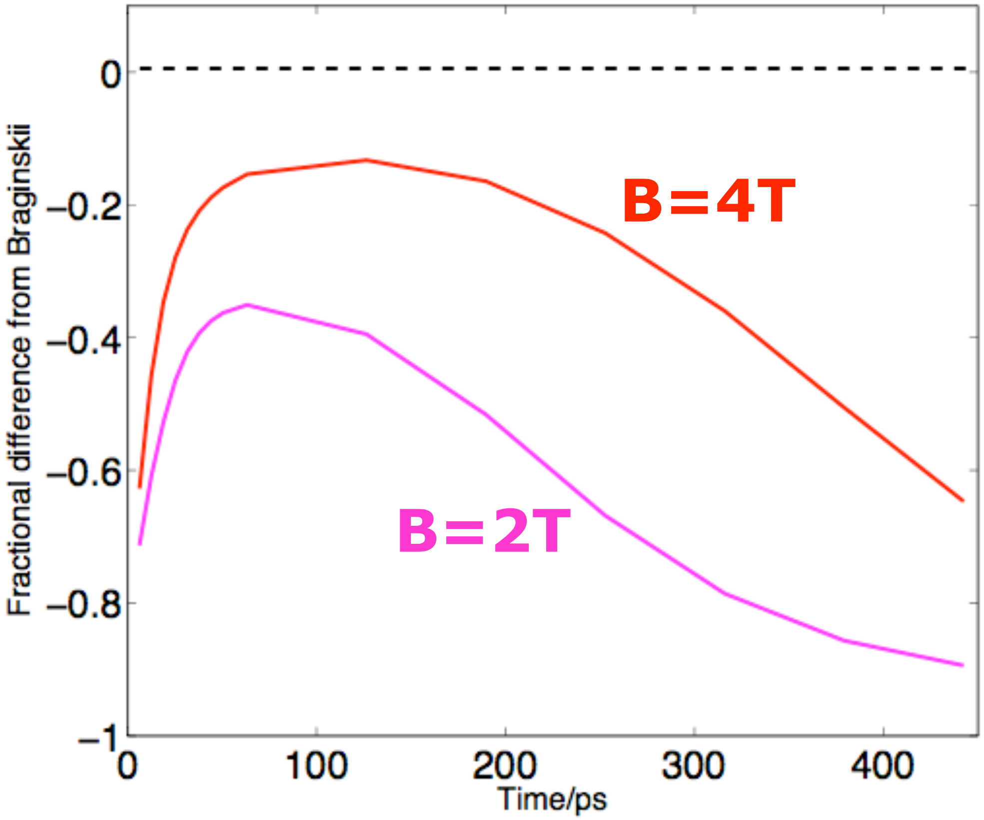
Evolution of non-locality

$$\frac{\mathbf{q}_r - \mathbf{q}_r^{BRAG}}{\mathbf{q}_r^{BRAG}}$$ **VS TIME**



Degree of non-locality increases with time

Indirect drive ICF[1,2]

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2) Interplay between non-locality and B-fields.

A: Enhanced B-field advection, caused by the Nernst effect, causes B to drop so that even if it were initially sufficient to localise transport, non-locality can re-emerge in time

Summary - non-locality & B-fields

- Magnetic field advection can be dominated by the Nernst effect which therefore should be included.
- Enhanced B-field advection can lead to the re-emergence of non-locality, even if the initial B-field suppresses it.
- MAGNETIC FIELD EVOLUTION AND NON-LOCALITY COUPLED

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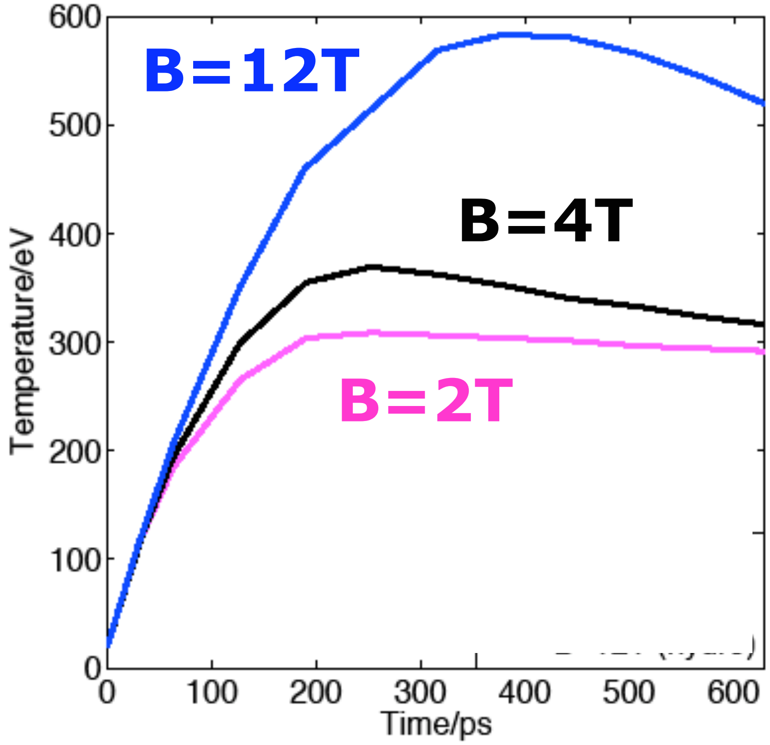
Can these effects be measured experimentally?

The Nernst effect leads to cooling in the laser heated region when the laser is still on at full power

TEMPERATURE VS TIME



Nernst cooling

Equilibrium:	Heating from laser	=	Cooling by thermal conduction

Nernst cooling

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Thermal conduction rate controlled by Hall parameter.

$$\omega\tau \propto \frac{B}{n_e} T_e^{3/2}$$

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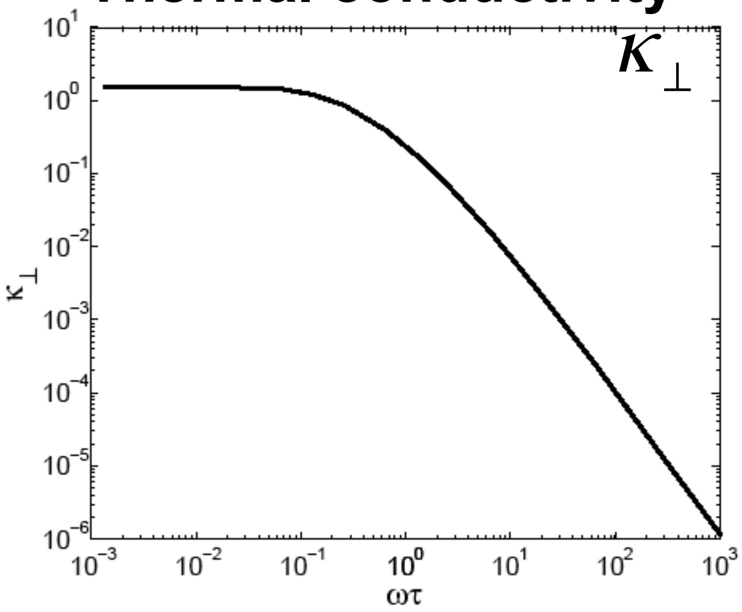
Thermal conductivity



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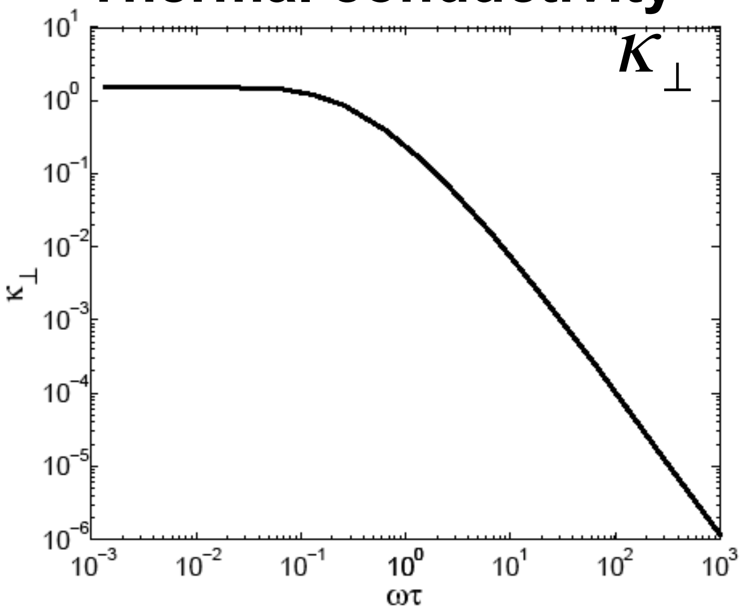

Nernst drives out B-field faster than central hot-spot drives out plasma hydrodynamically, Hall parameter decreases

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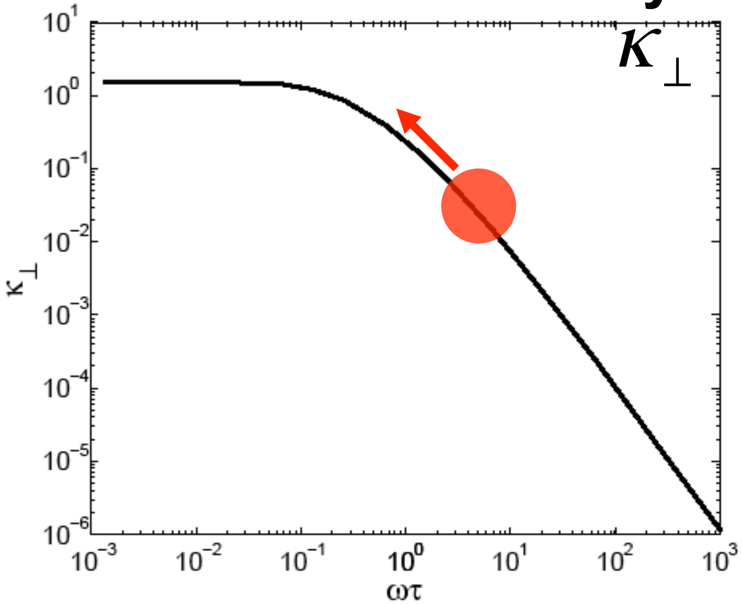

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Conductivity increases

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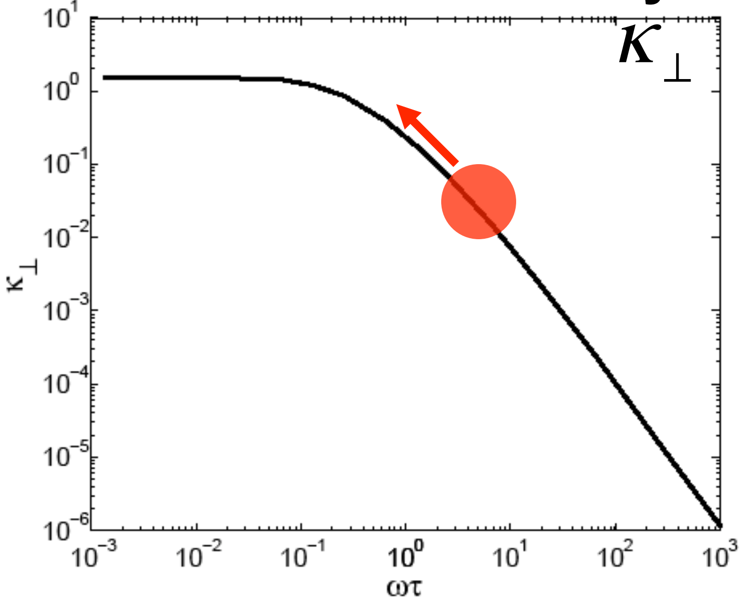
Thermal conductivity



Nernst drives out B-field faster than central hot-spot drives out plasma hydrodynamically, Hall parameter decreases

Conductivity increases

Central temperature decreases – Nernst cooling

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Nernst cooling

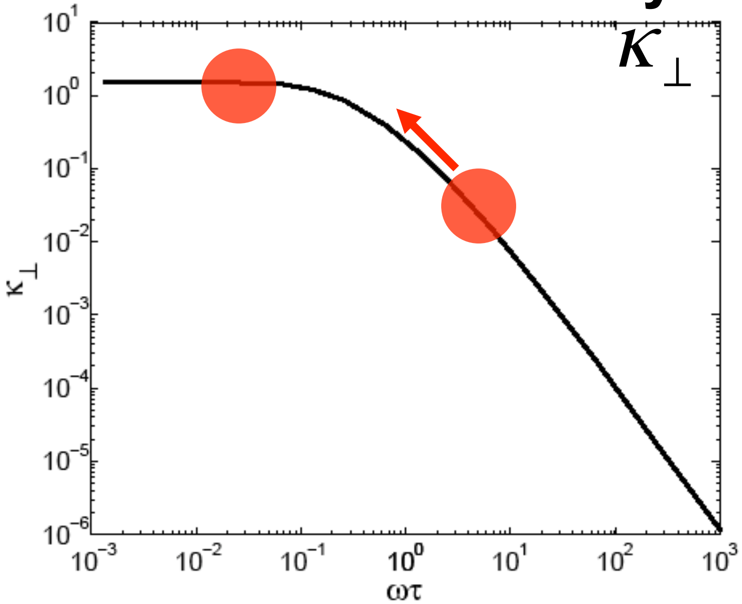
Equilibrium:

Heating from laser = Cooling by thermal conduction

Thermal conduction rate controlled by Hall parameter.

$$\omega\tau \propto \frac{B}{n_e} T_e^{3/2}$$

Thermal conductivity

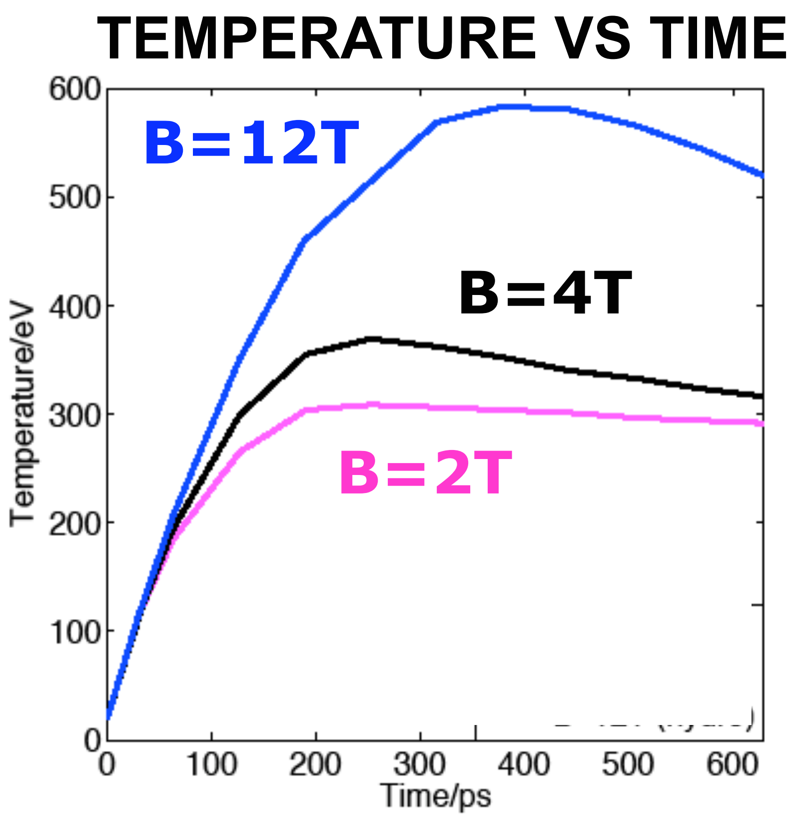


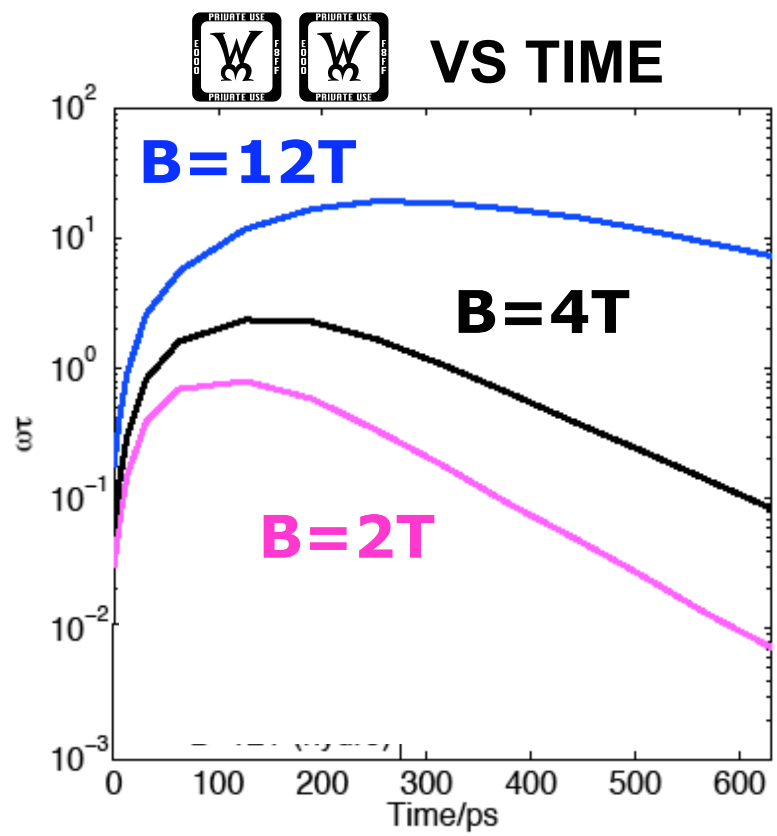
Nernst drives out B-field faster than central hot-spot drives out plasma hydrodynamically, Hall parameter decreases

Conductivity increases

Central temperature decreases – Nernst cooling

Can these effects be measured experimentally?





Nernst cooling

Equilibrium: Heating from laser = Cooling by thermal conduction

Thermal conduction rate controlled by Hall parameter.

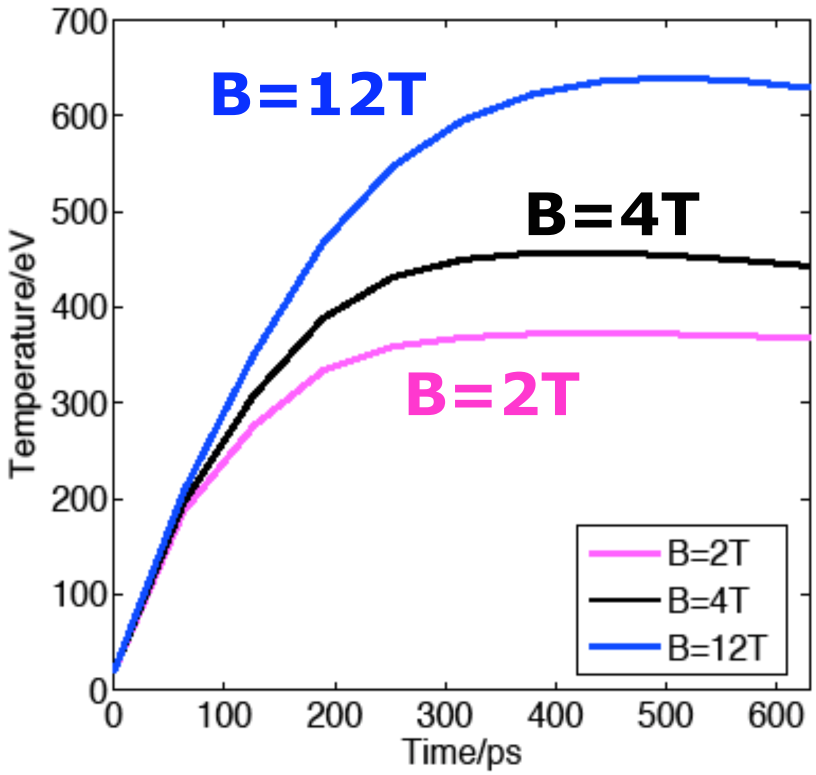
$$\omega\tau \propto \frac{B}{n_e} T_e^{3/2}$$

Frozen-in flow – ratio B/n_e constant
– Hall parameter constant

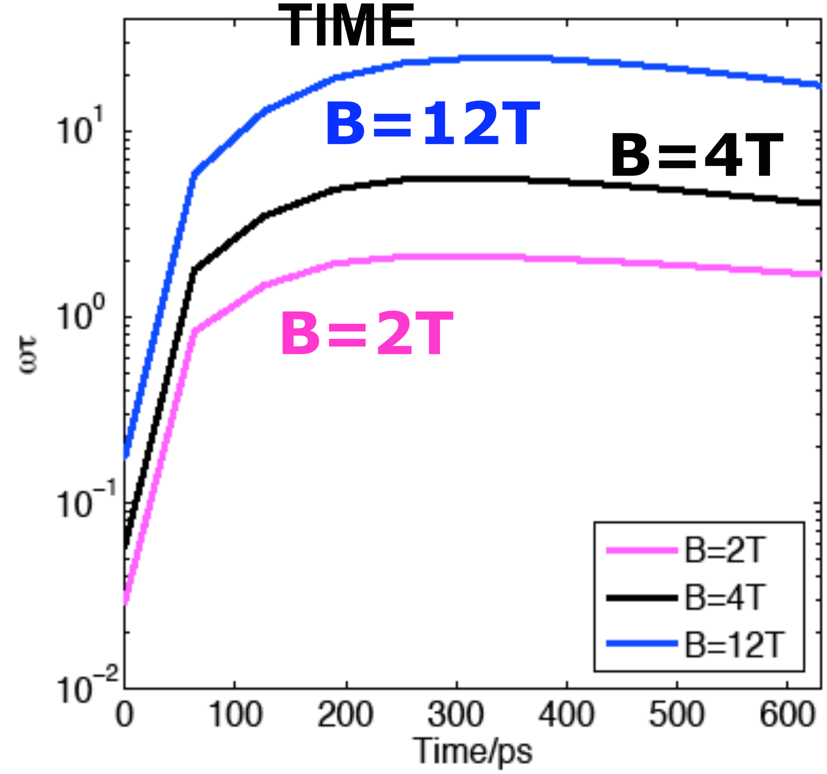
COOLING OF CENTRAL LASER-HEATED REGION DOES NOT OCCUR

Cooling can't happen for frozen-in-flow

TEMPERATURE VS TIME



VS TIME



Outline

Part 1 – simulations of long-pulse laser-plasma interactions.

(1) The interplay of magnetic field dynamics and non-locality.

(2) Magnetic field generation

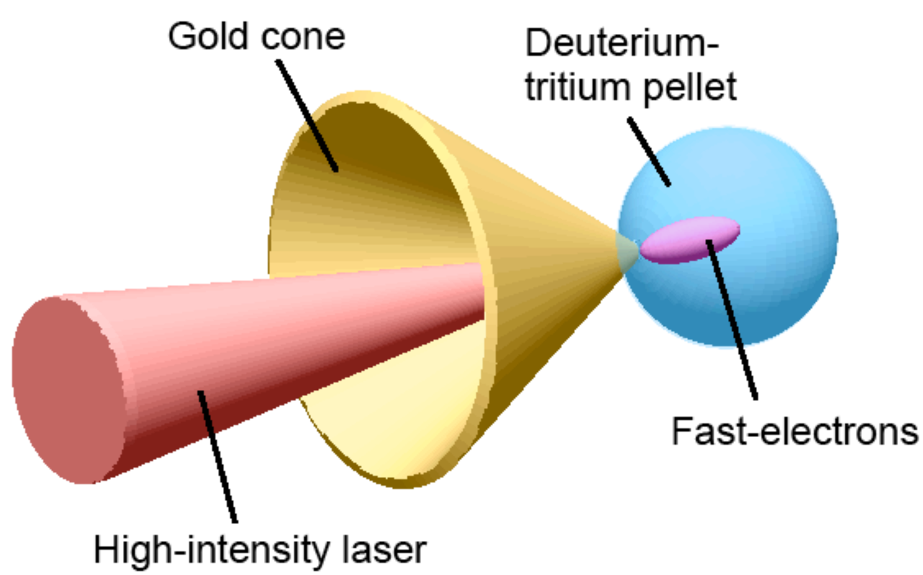
Part 2 – Vlasov-Fokker-Planck simulations of short-pulse laser-plasma interactions relevant to fast ignition. The importance of rear-surface effects.

Short-pulse modelling

Fast ignition[13] – decouple compression and heating phase.

Long-pulse laser
compresses target

Short-pulse laser interacts
with cone and
generates fast
electrons, whose
absorption in the core
heats target like a
spark-plug



[13]*M. Tabak et. al., Physics of Plasmas,* ***1****, 1626 (1971)*

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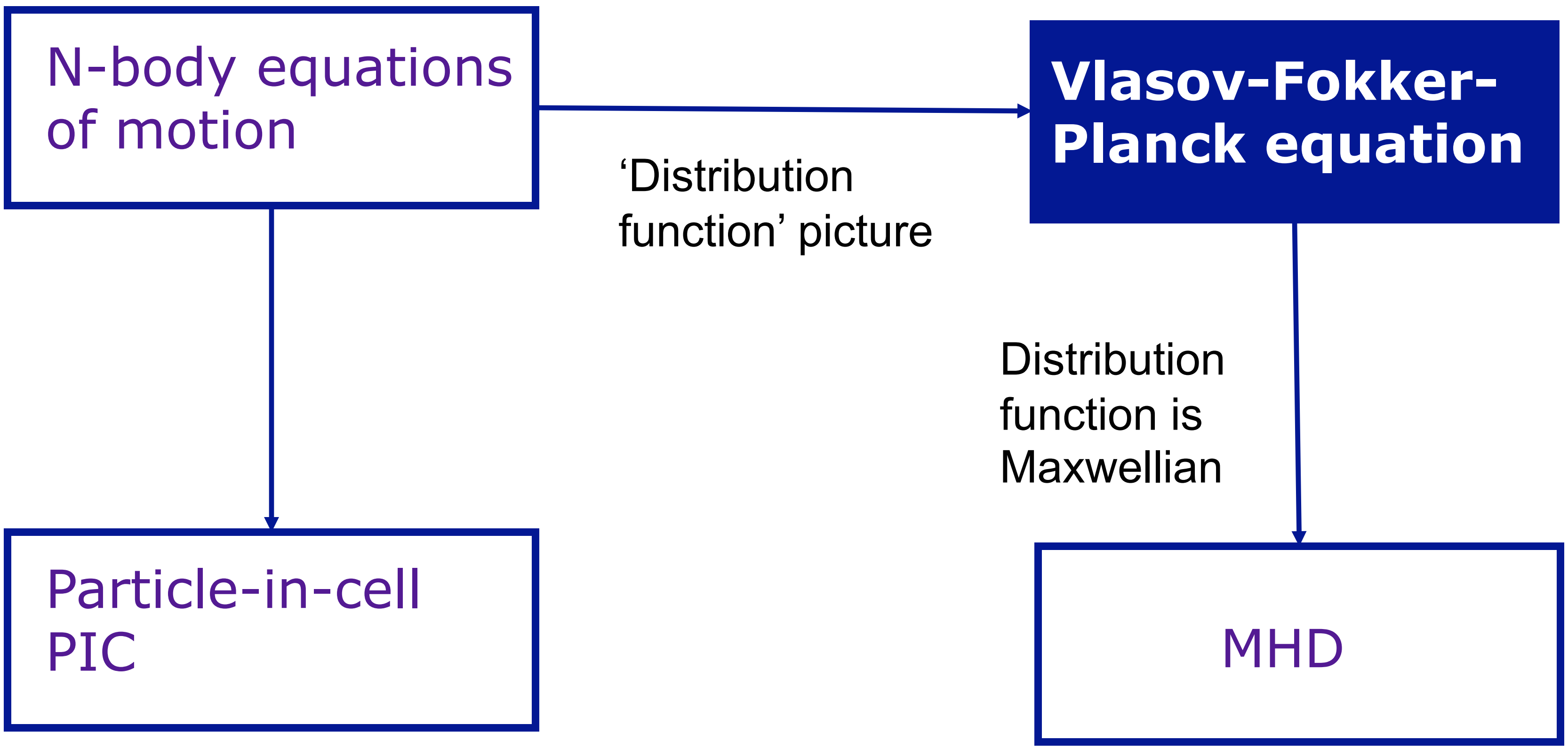
Modelling long-pulse LPI



Modelling long-pulse LPI

N-body equations of motion

'Distribution function' picture

Vlasov-Fokker-Planck equation

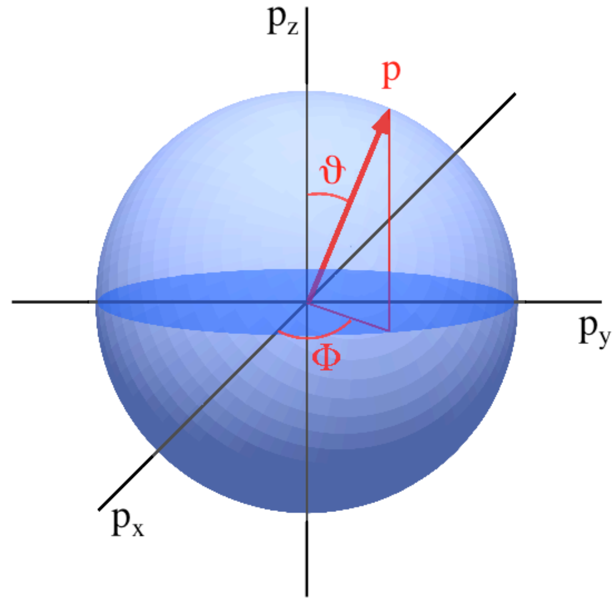
Particle-in-cell PIC

VFP handles collisions much better than PIC. PIC prone to noise

FIDO[14]

- Solves the VFP Equation (and Maxwell's equations) without expanding distribution function

- Implicit EM solve but explicit momentum space solve limits Δt to 3fs
- Can deal with very anisotropic distribcutions - beams



- Runs in hybrid mode or full VFP mode

- 2D (3V) VFP code with self consistent E_x, E_y and B_z-fields

[14]*Sherlock M.W. submitted to PRL*

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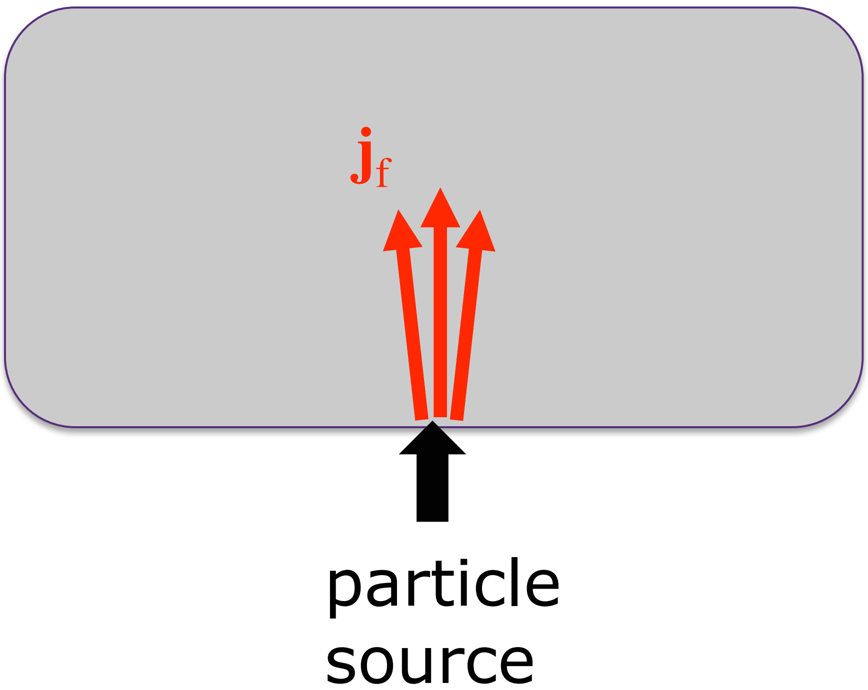
Short-pulse modelling

Usual model:

Fast electrons treated kinetically

Background electrons treated as fluid



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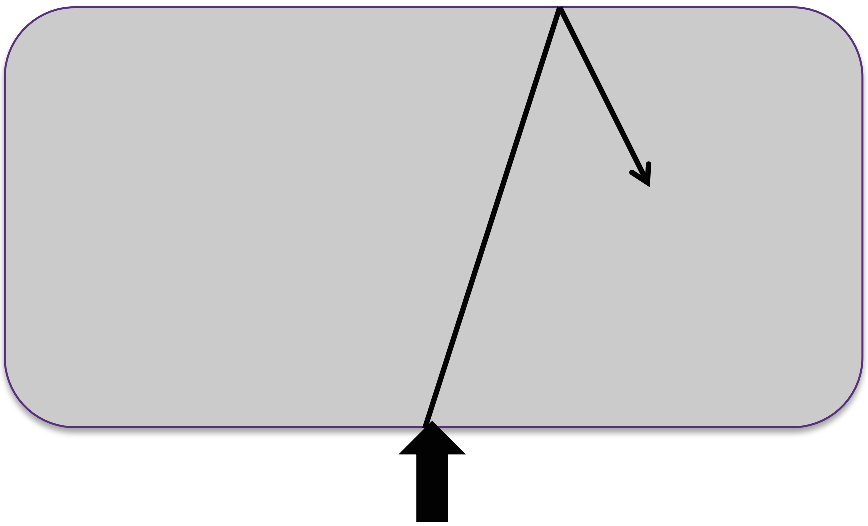
‘Standard’ hybrid mode

Standard hybrid usually uses reflective boundary conditions



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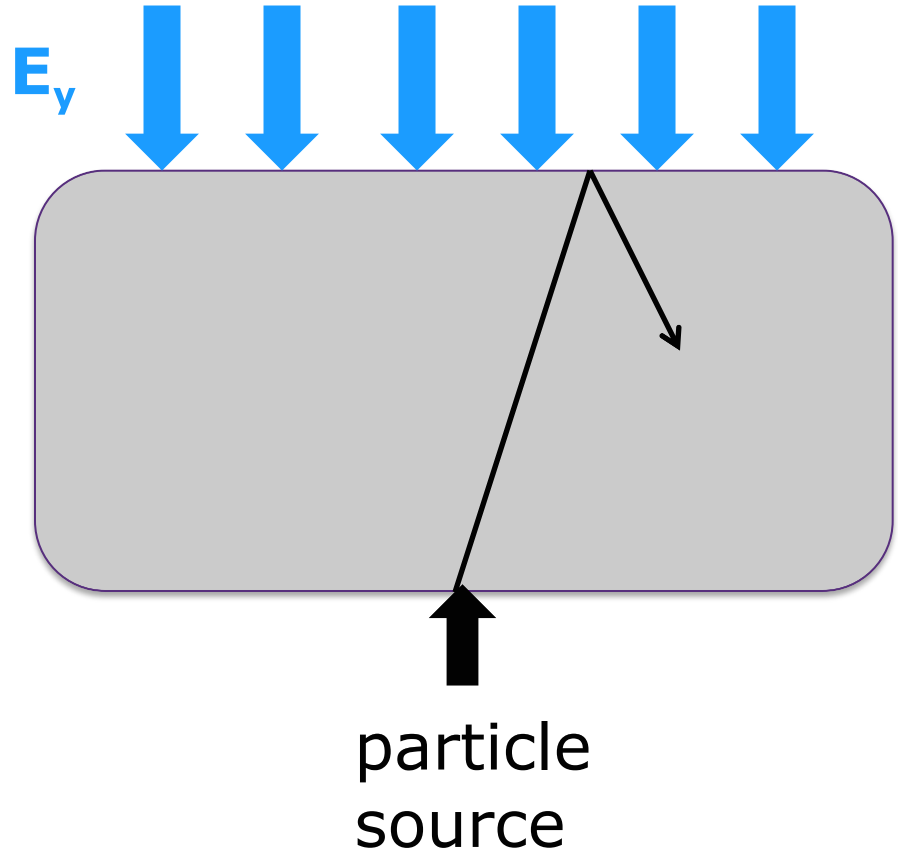
‘Standard’ hybrid mode

Standard hybrid usually uses reflective boundary conditions

Justified by large sheath field at rear surface – reflects particles. But ….



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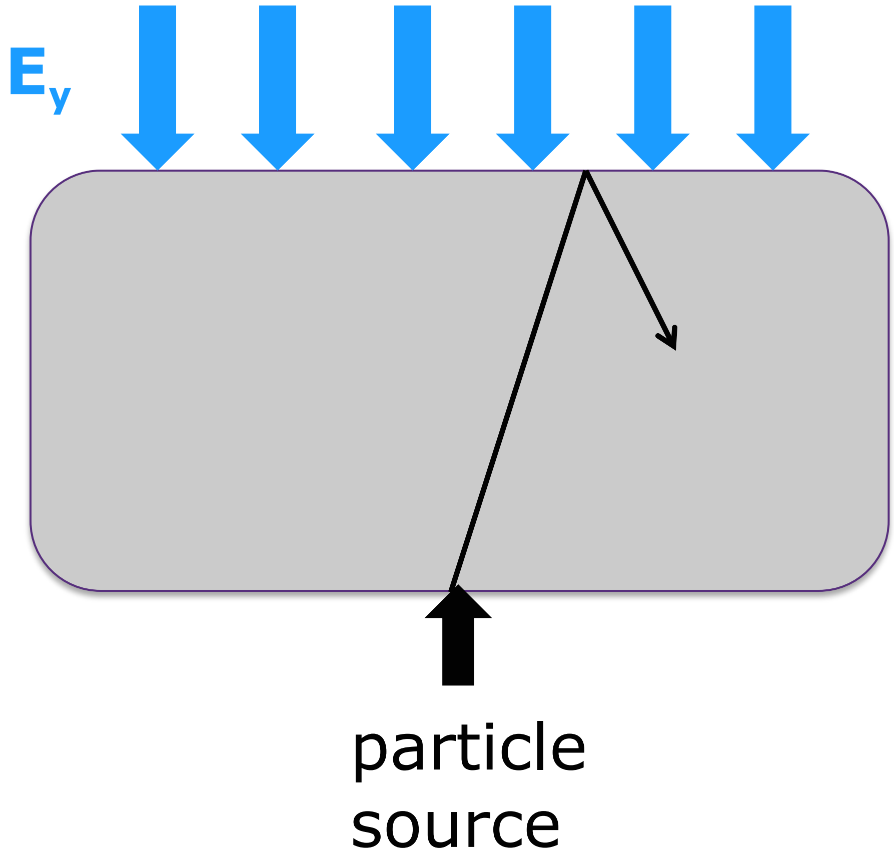
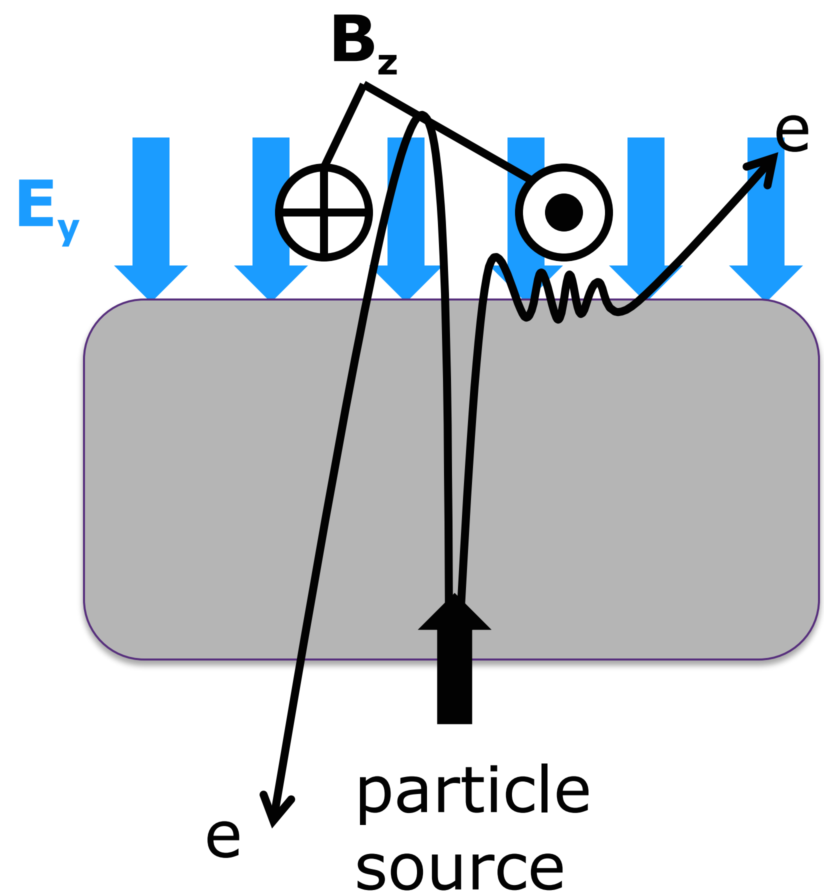


… only if there is no magnetic field

'Improved' hybrid mode

Improved hybrid:

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

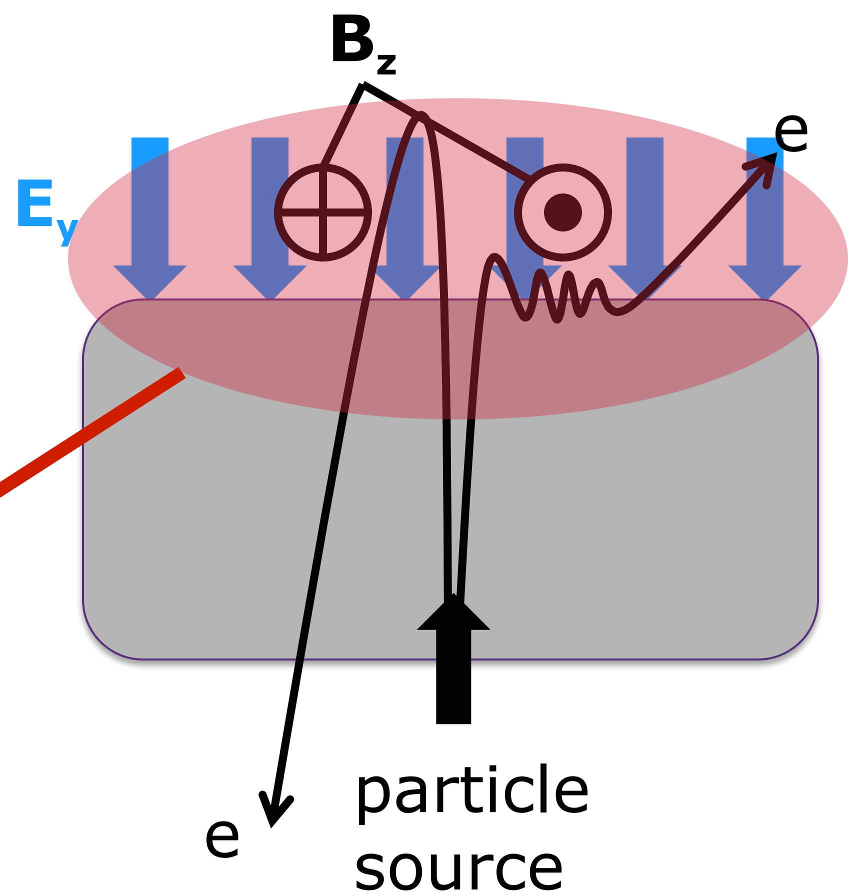


‘Improved’ hybrid mode

Improved hybrid:

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

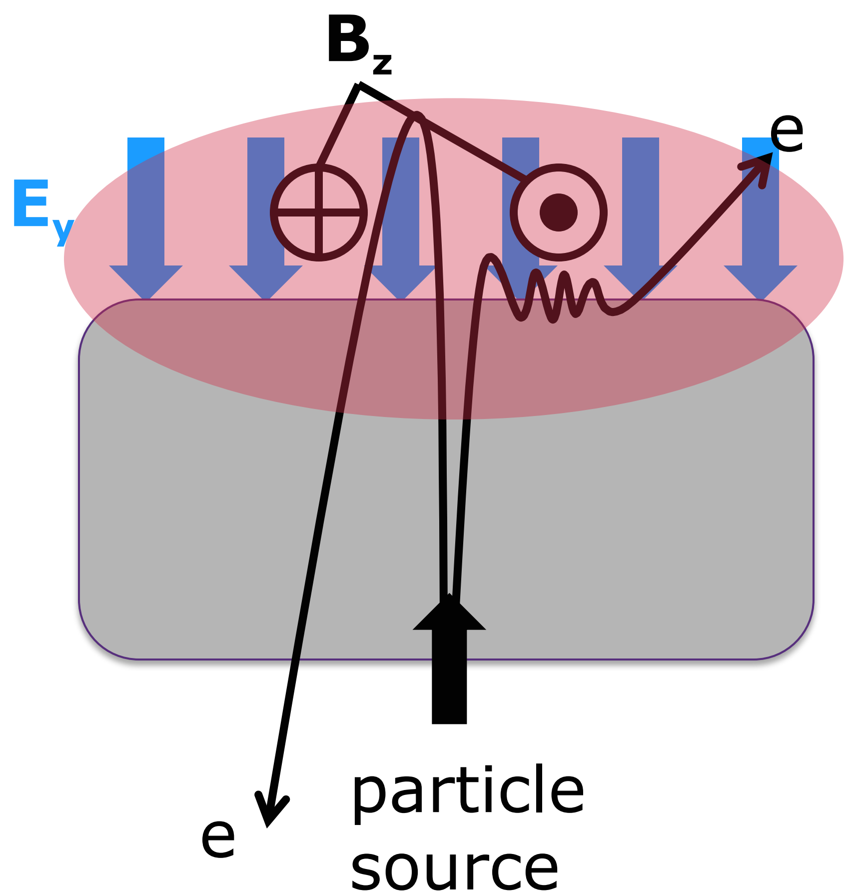
I will simulate rear-surface effects



‘Improved’ hybrid mode

What’s new?

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



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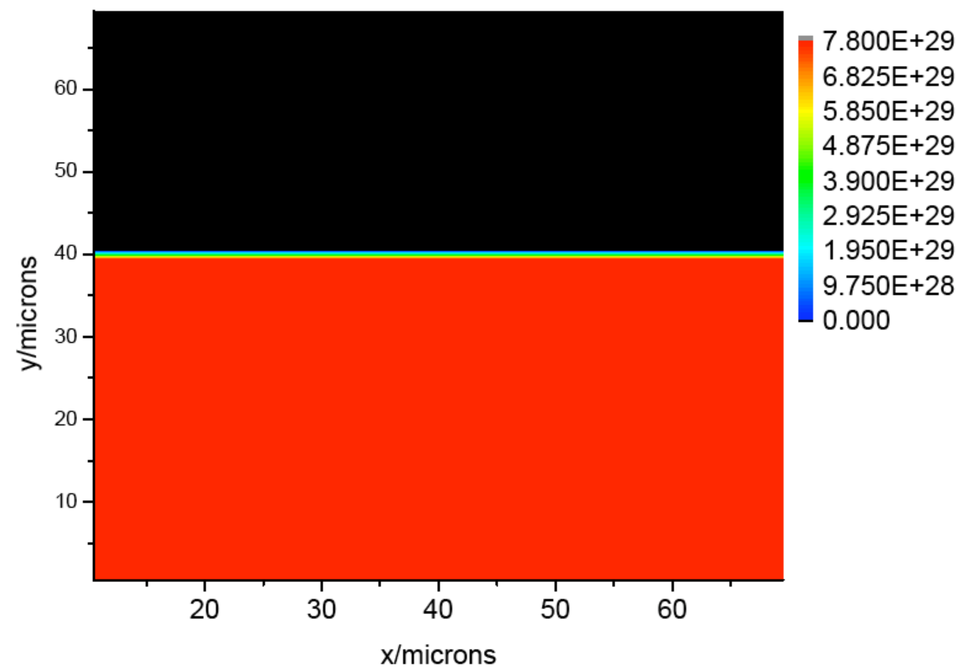
Solid-target simulations

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:

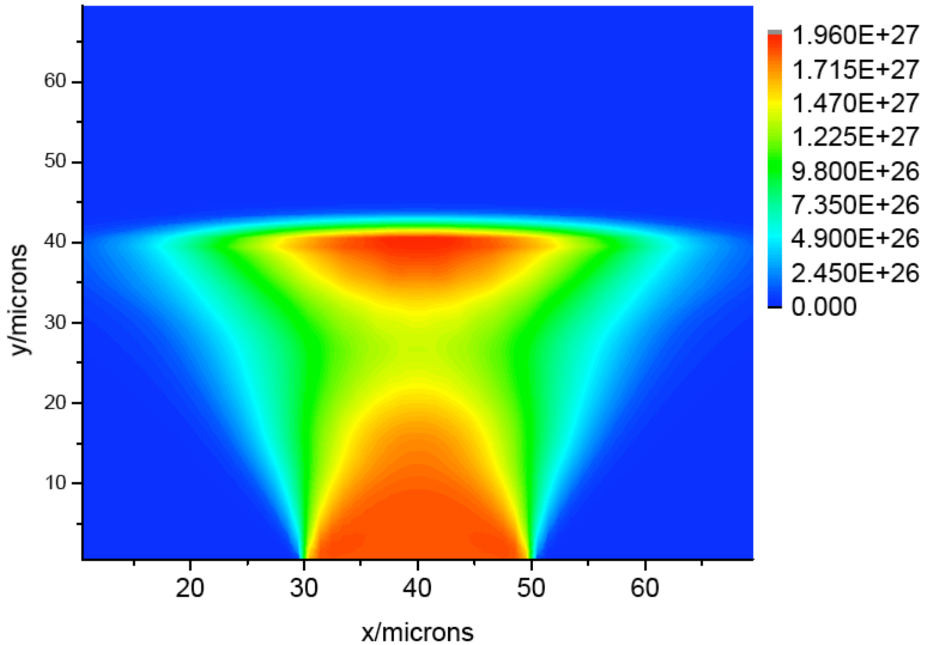
Laser intensity $I=5\times10^{19}\,\mathrm{Wcm}^{-2}$

Absorption fraction $\eta=0.3$

Injection region $8\mu m \times 1\mu m$ using square mask

Max injection angle $\theta=28^{\circ}$

INJECTED ELECTRON DENSITY (after 200fs)



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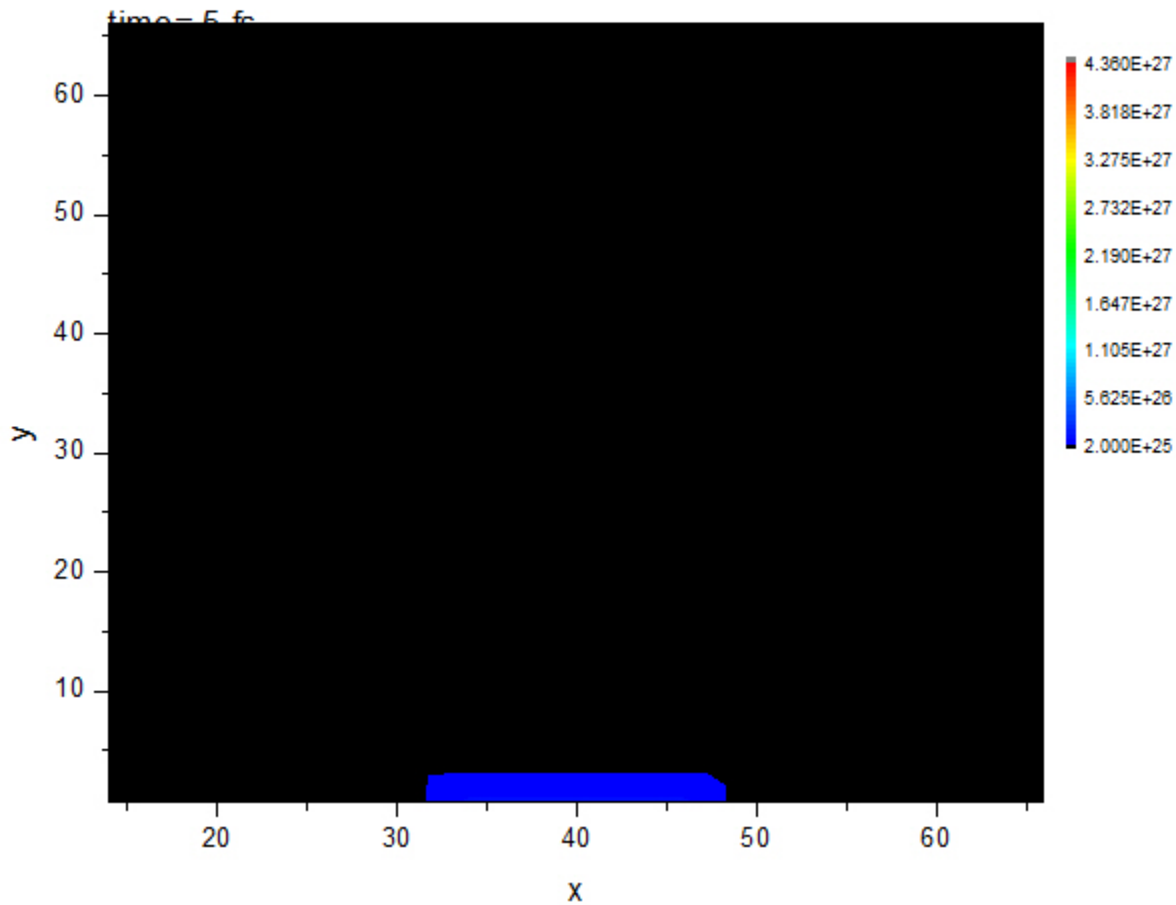
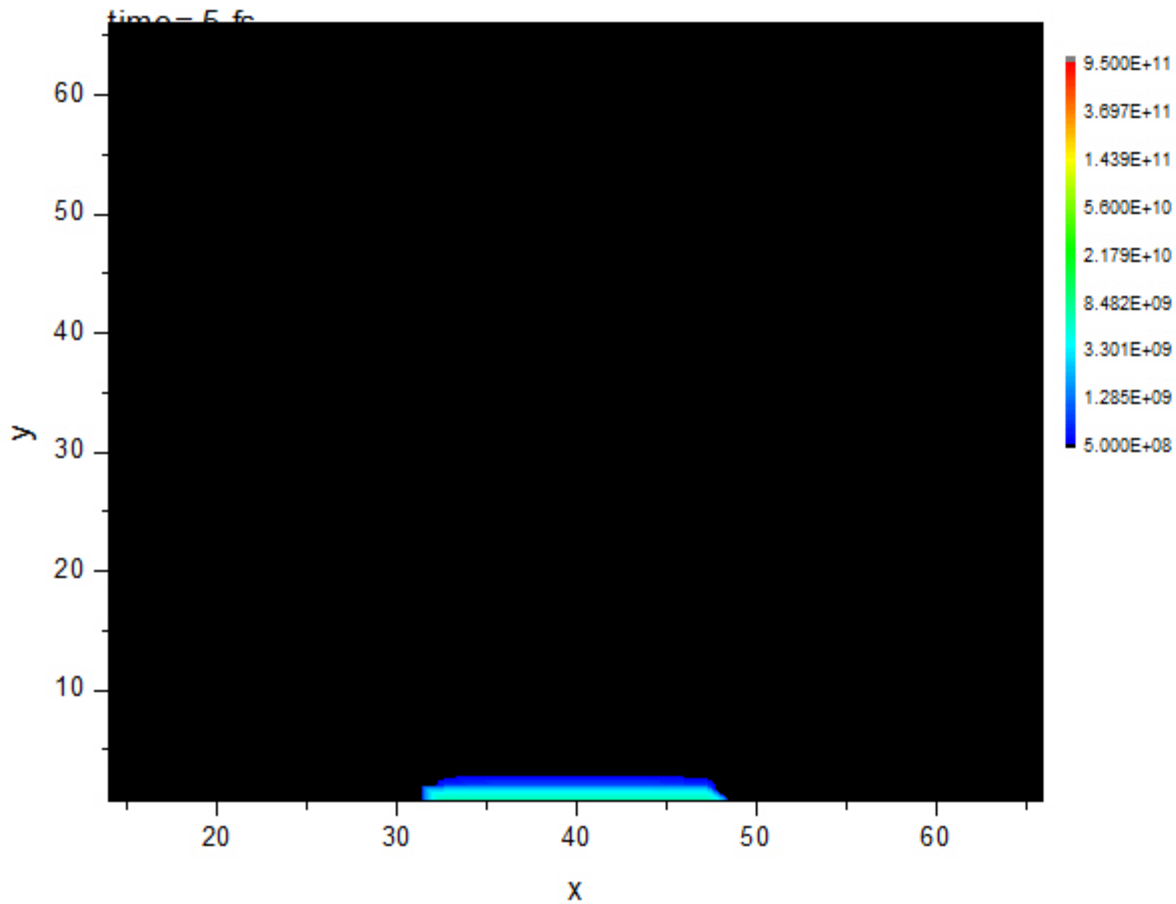
Solid-target simulations

Fast electron number density



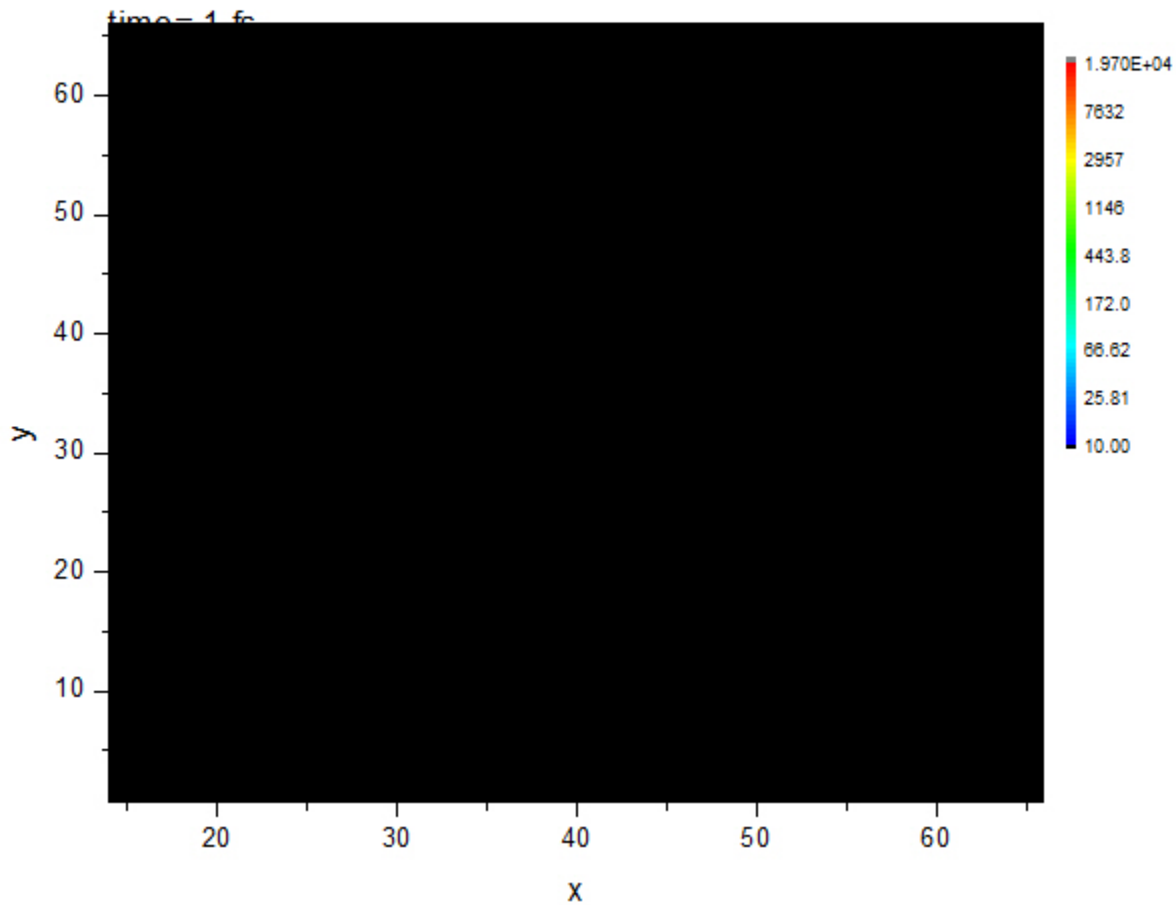
Solid-target simulations

Electric
field



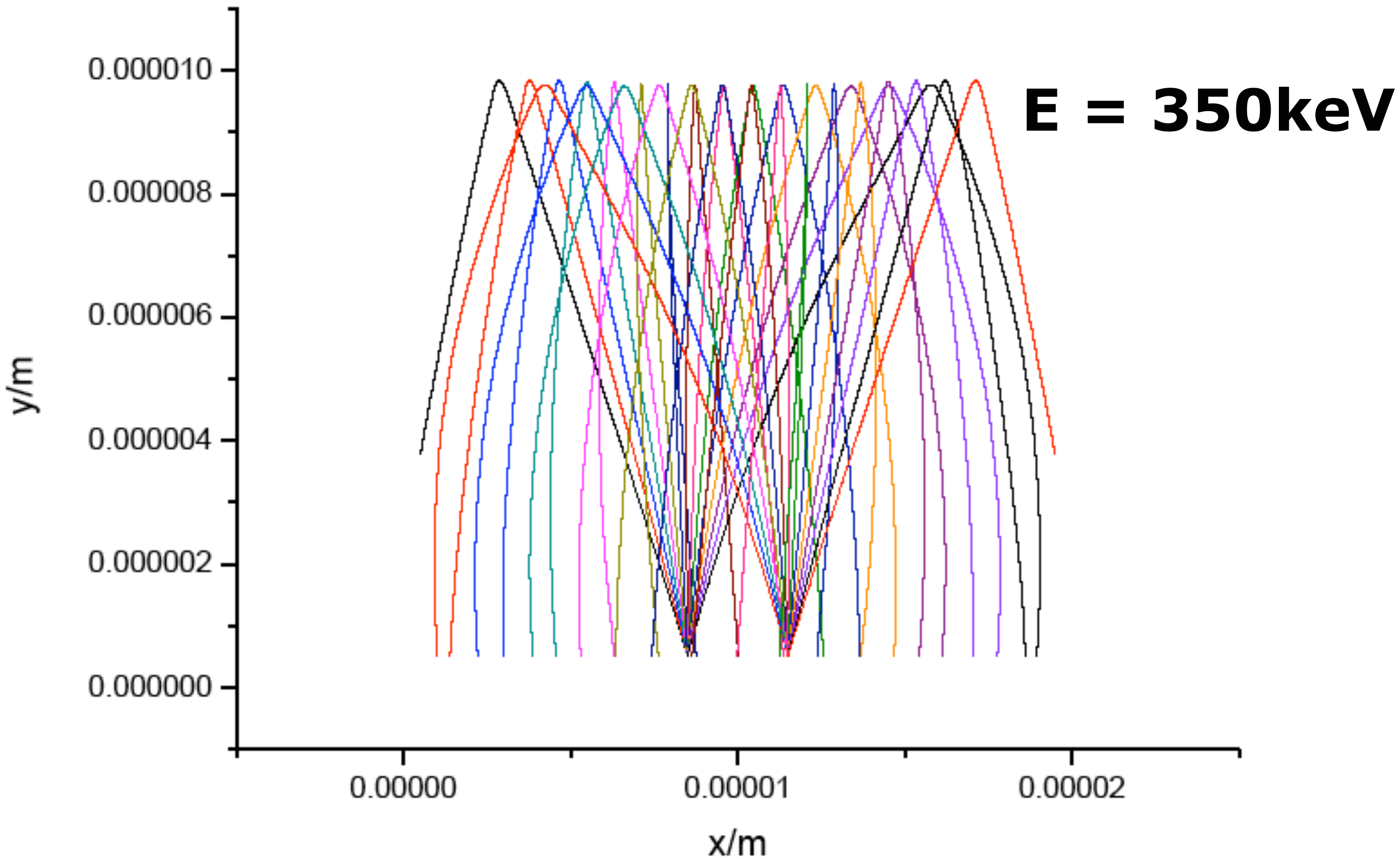
Solid-target simulations

Magnetic field



Particle-tracking

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



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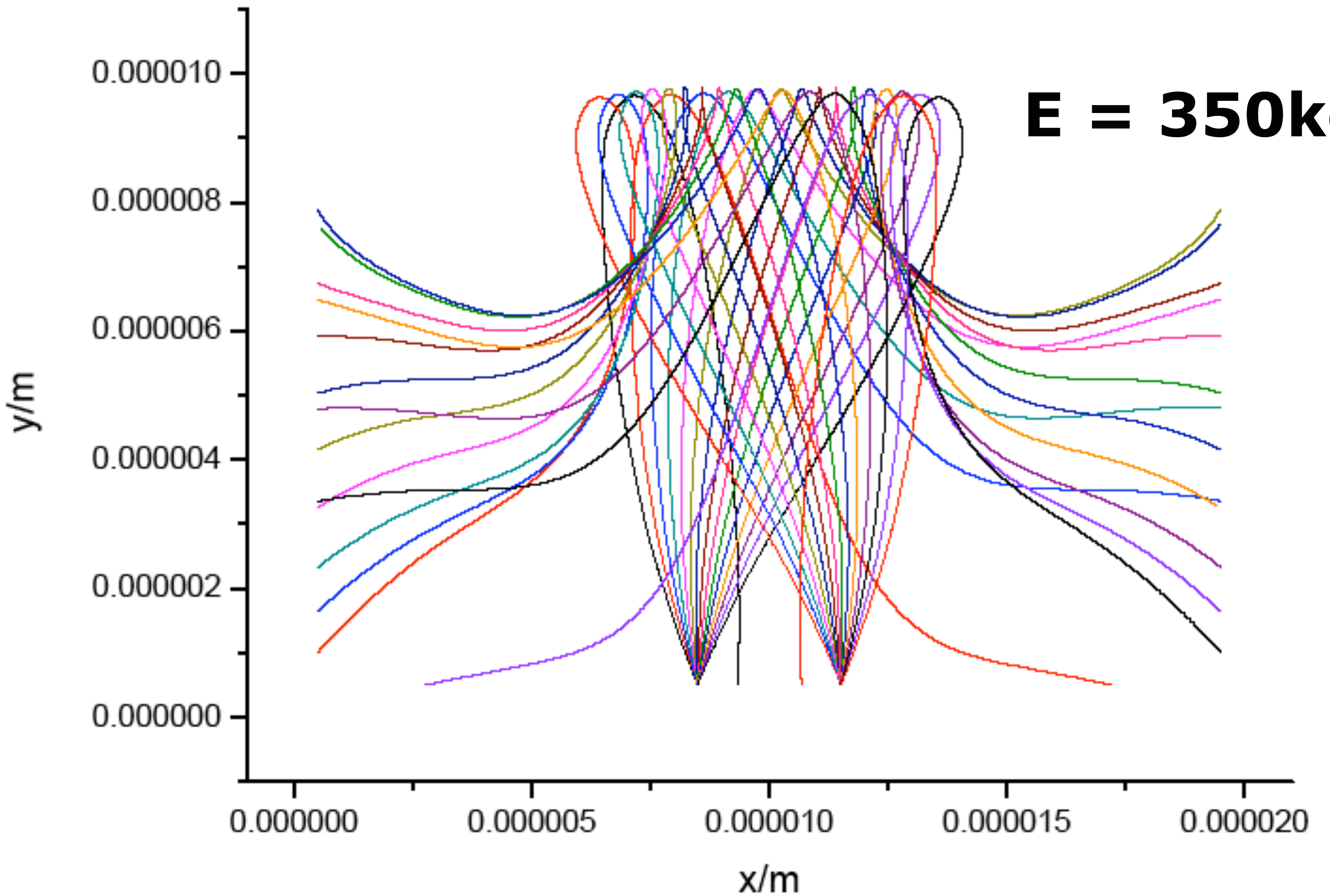
Particle-tracking

Particles injected at 350keV affected by **E** and **B** fields



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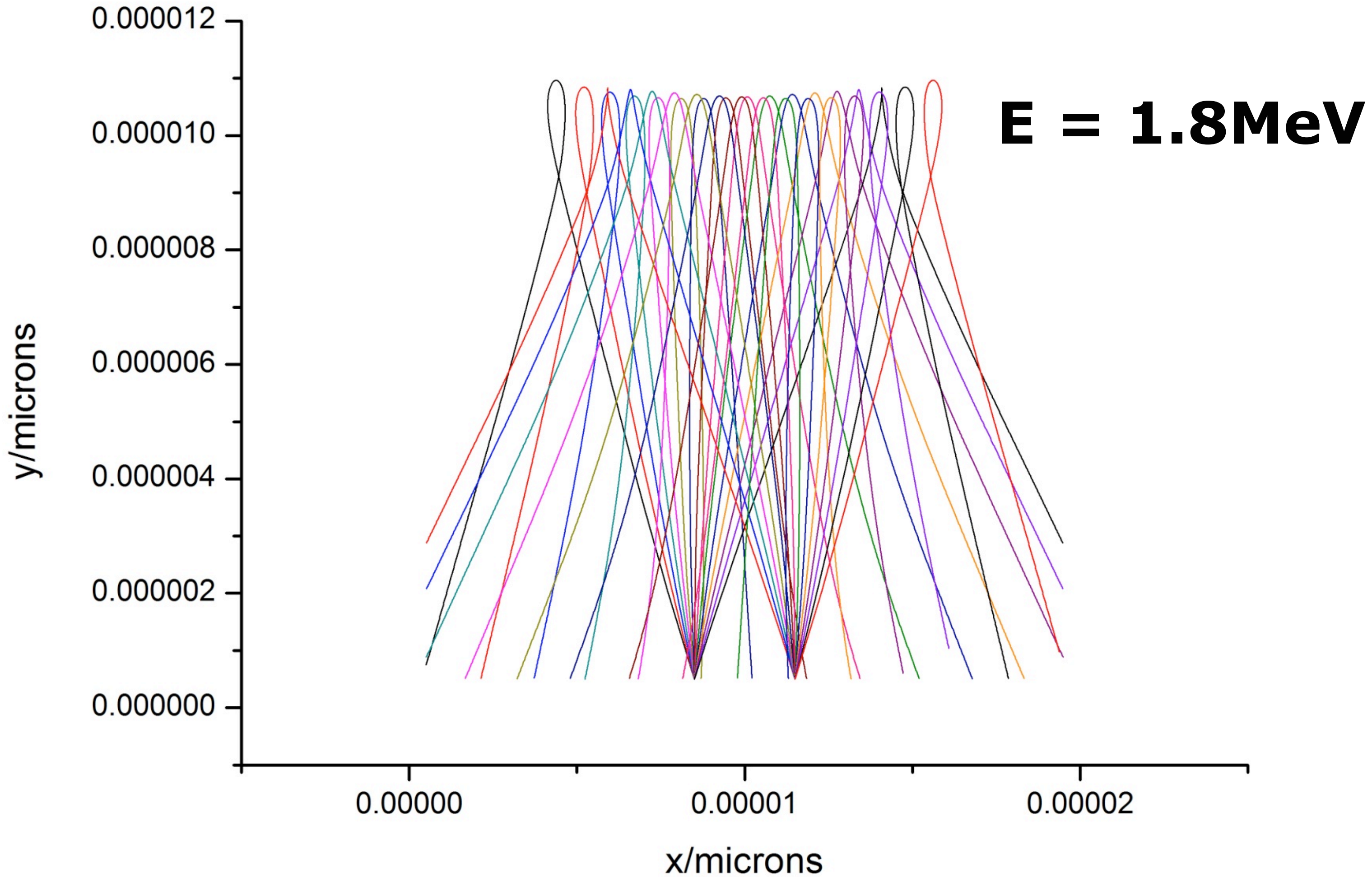
Particle-tracking

Particles injected at 1.8MeV affected by **E** and **B** fields



Experiments?

Proposals for experiments:

(1) Is filamentation inside the target real? – use tracer layers and rear surface measurements to see where it happens

(2) Measure rear surface B and look at effects of scale-length?

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Summary

- Realistic inclusion of rear surface effects is important for the explanation of experiments.
- Large fields develop at the rear surface of the target and dominate the behaviour of electrons as they exit the target (and head towards experimental diagnositics)
- Large magnetic fields develop, necessitating a two dimensional treatment of the rear surface

Conclusions

- Kinetic modelling gives useful insight into both long and short-pulse laser-plasma interactions

- Magnetic field dynamics can only be modelled correctly by using the appropriate Ohm's law…

- …In long-pulse gas-jet interactions this means the inclusion of the Nernst effect…

- …In short-pulse solid-target interactions this means including edge effects by blending the Ohm's law with a full solution of Maxwell's equations

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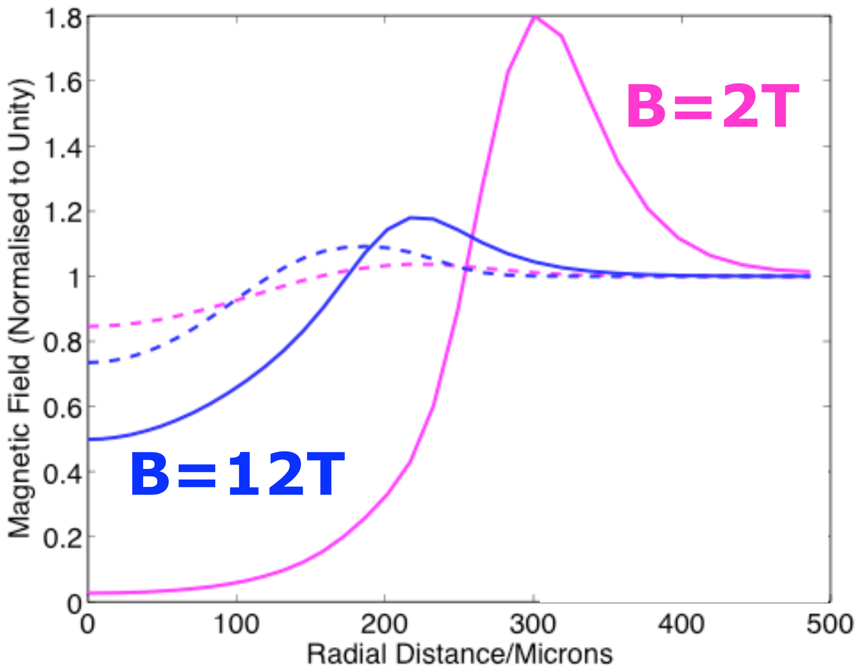
Nernst Advection dominates over Frozen-in-Flow

B-FIELD ACROSS BEAM

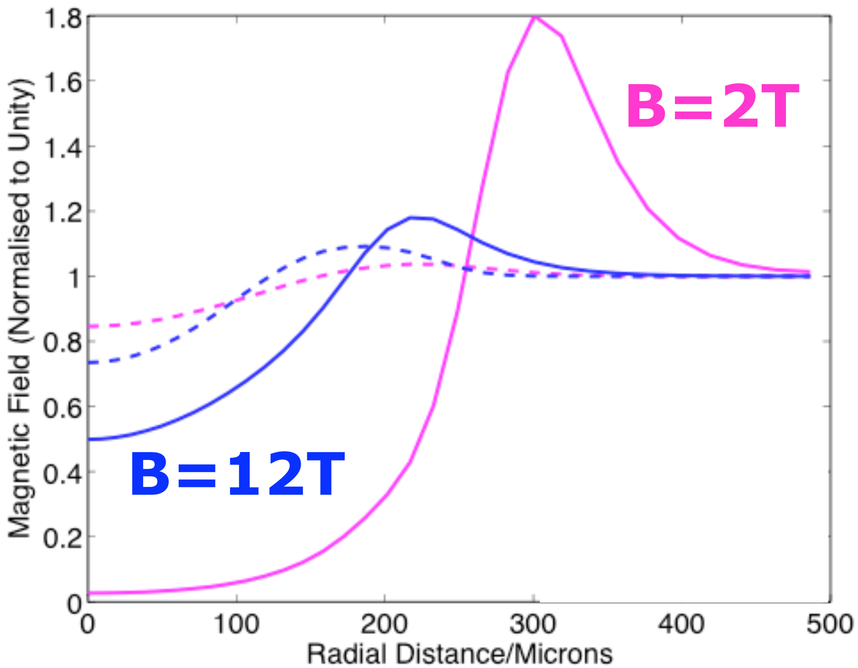


Dimensionless ratio quantifying Nernst vs. Frozen-In-Flow…

$$R_N = \frac{v_N}{U} = \frac{3\,\Delta T_e}{n_e(\omega_e \tau_e)^2 L_T\, U}$$

Nernst Advection dominates over Frozen-in-Flow

B-FIELD ACROSS BEAM



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$$R_N = \frac{v_N}{U} = \frac{3\,\Delta T_e}{n_e(\omega_e \tau_e)^2 L_T\, U}$$

In sims. $R_N = 8 \quad \mathbf{B} = 2\mathrm{T}$

$R_N = 3 \quad \mathbf{B} = 4\mathrm{T}$

$R_N = 0.3 \quad \mathbf{B} = 12\mathrm{T}$

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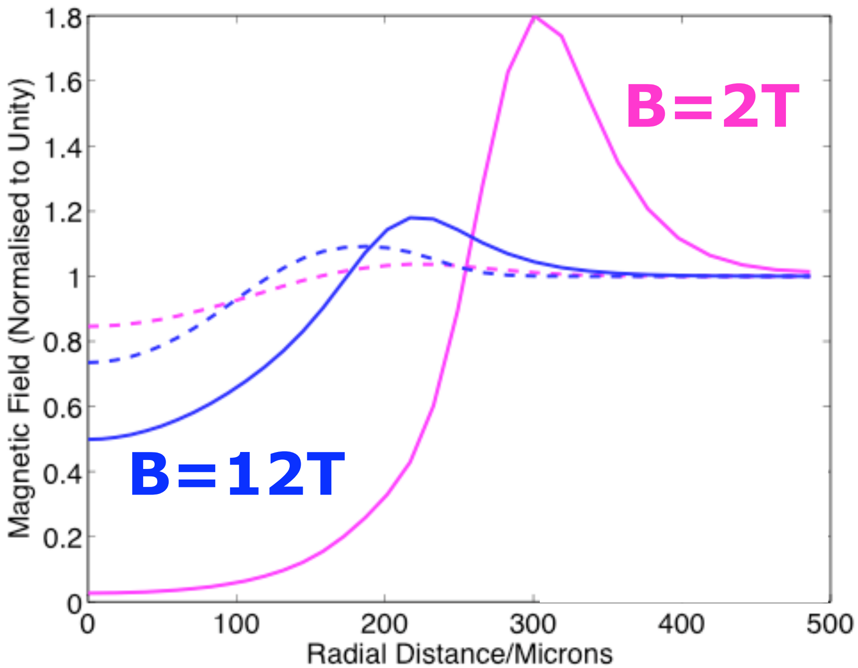
Nernst Advection dominates over Frozen-in-Flow

B-FIELD ACROSS BEAM



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$R_N = 3$ $\mathbf{B} = 4\mathrm{T}$

$R_N = 0.3$ $\mathbf{B} = 12\mathrm{T}$

Importance of Nernst is reduced with larger $\omega\tau$

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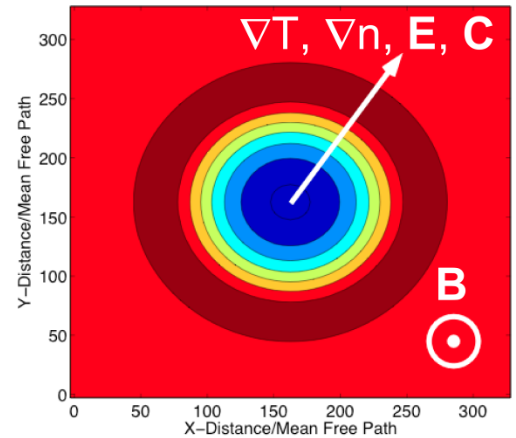
The Nernst effect[8,9]

$$\frac{\partial B_z}{\partial t} = -\frac{\partial}{\partial r}\left(\frac{q_r}{2.5 n_e T_e} B_z\right)$$



[8]*Nishiguchi A. et al, Physics of Fluids,* ***28****, 3683, 1985*

[9]*Haines M.G., Plasma Physics and Controlled Fusion,* ***28****, 1705, 1986*

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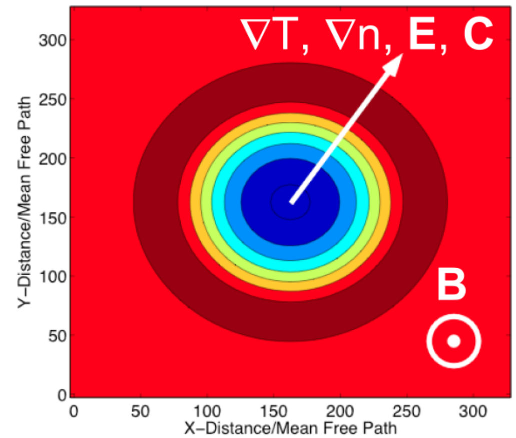

ONLY see Nernst if collision frequency depends on velocity

Hotter (faster) particles carry B-field further

Magnetic field 'frozen' to heat flow

[8] *Nishiguchi A. et al, Physics of Fluids,* ***28****, 3683, 1985*

[9] *Haines M.G., Plasma Physics and Controlled Fusion,* ***28****, 1705, 1986*

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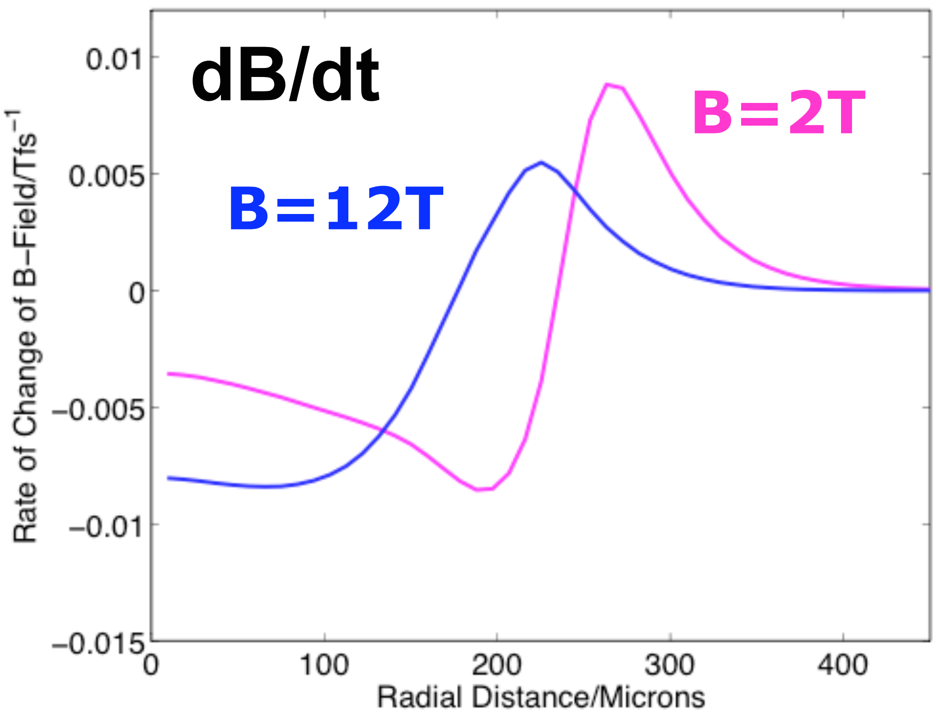
Non-Local Nernst[10]

The Nernst effect is modified by non-locality



Calculate dB/dt from:

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

Solid lines – $\mathbf{E}$ from VFP code

[10] *T.H. Kho & M.G. Haines, Physics of Fluids, Vol. 29, No. 8, 1986*

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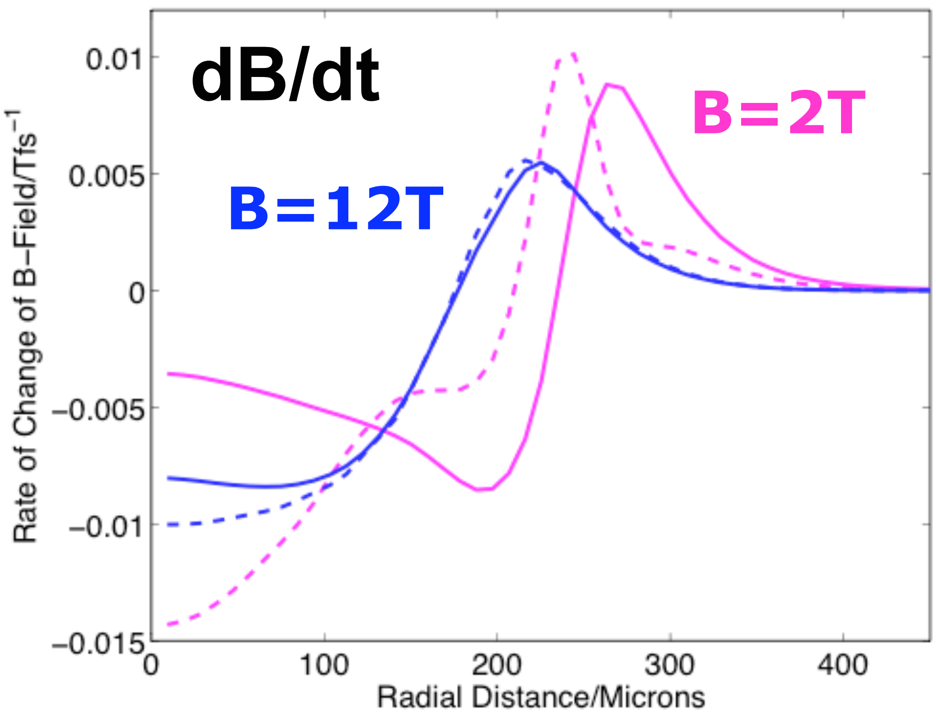


Calculate dB/dt from:

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

Solid lines – $\mathbf{E}$ from VFP code

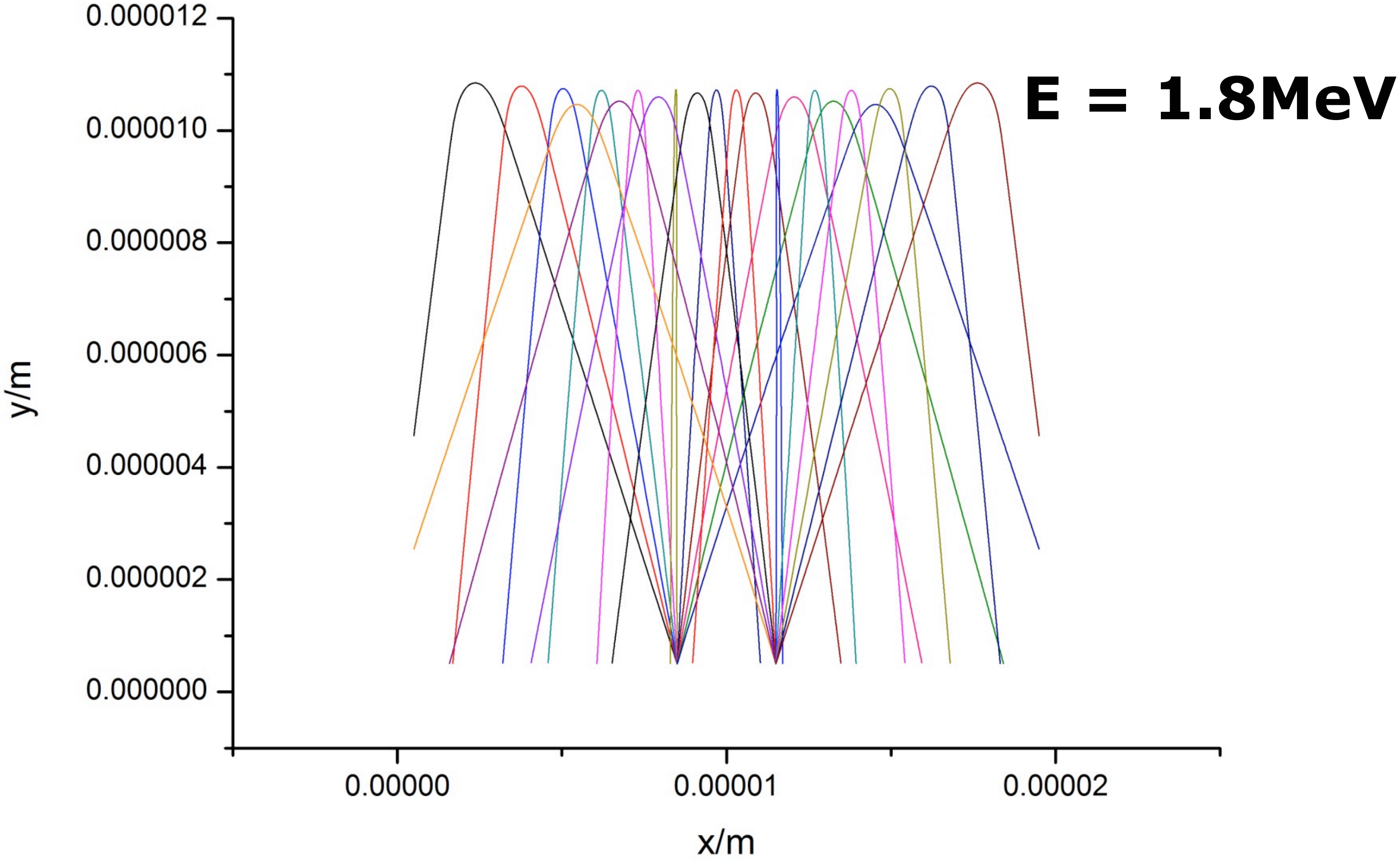
Dashed lines – $\mathbf{E}$ from classical Ohm's law

Nernst not classical

[10] *T.H. Kho & M.G. Haines, Physics of Fluids, Vol. 29, No. 8, 1986*

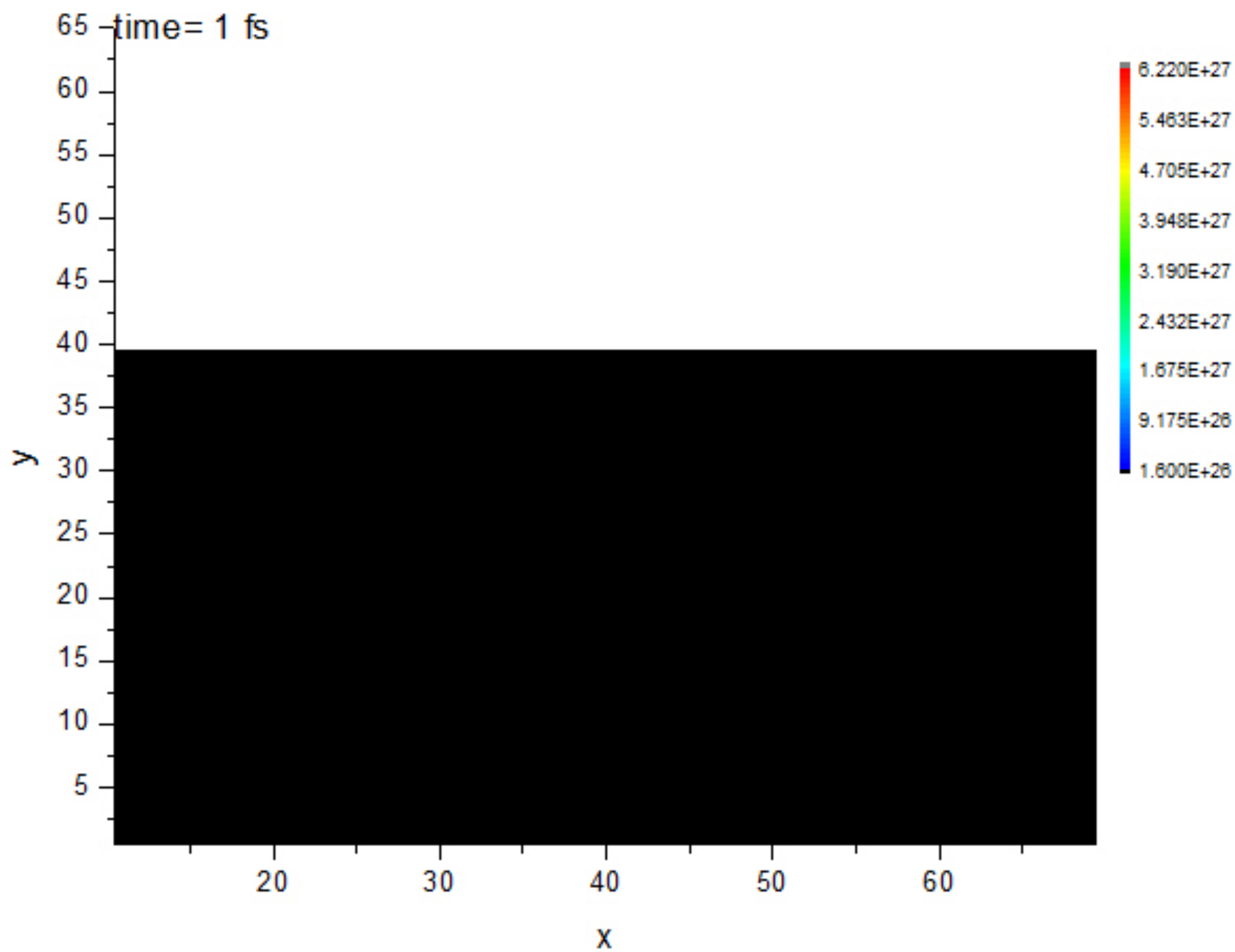
Particle-tracking

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



Reflective boundary conditions

Fast electron number density



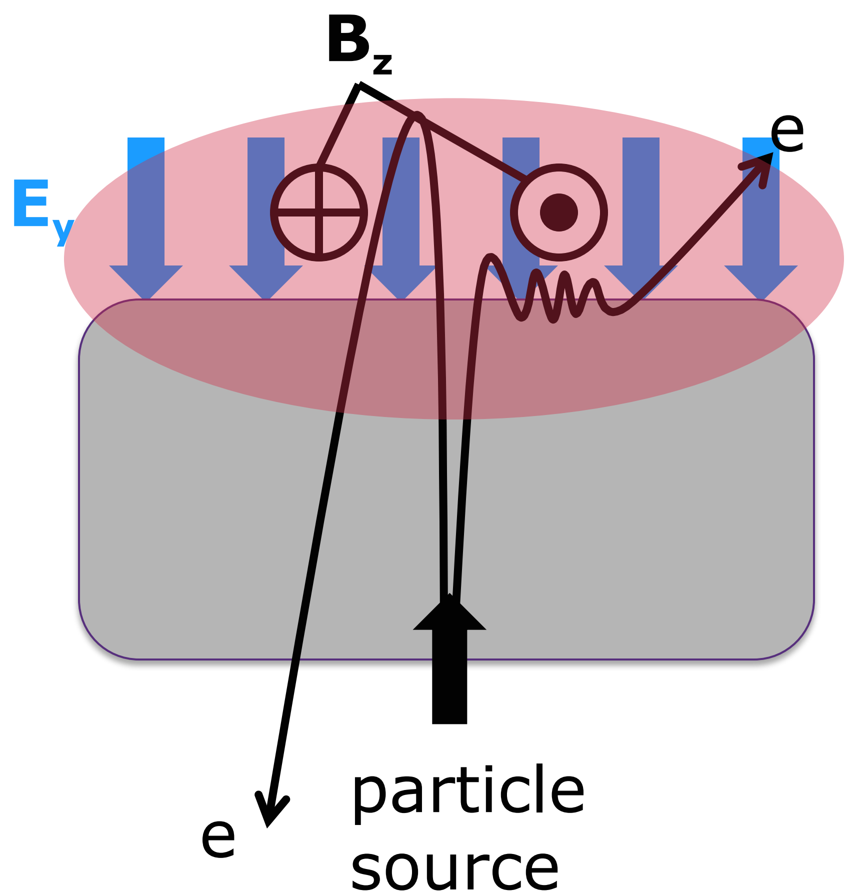
'Improved' hybrid mode

Need to solve Maxwell's equations and Ohm's law.

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

$$\frac{\partial \mathbf{E}}{\partial t} = c^2 \nabla \times \mathbf{B} - \mu_0 \mathbf{j}$$

VFP code must supply current



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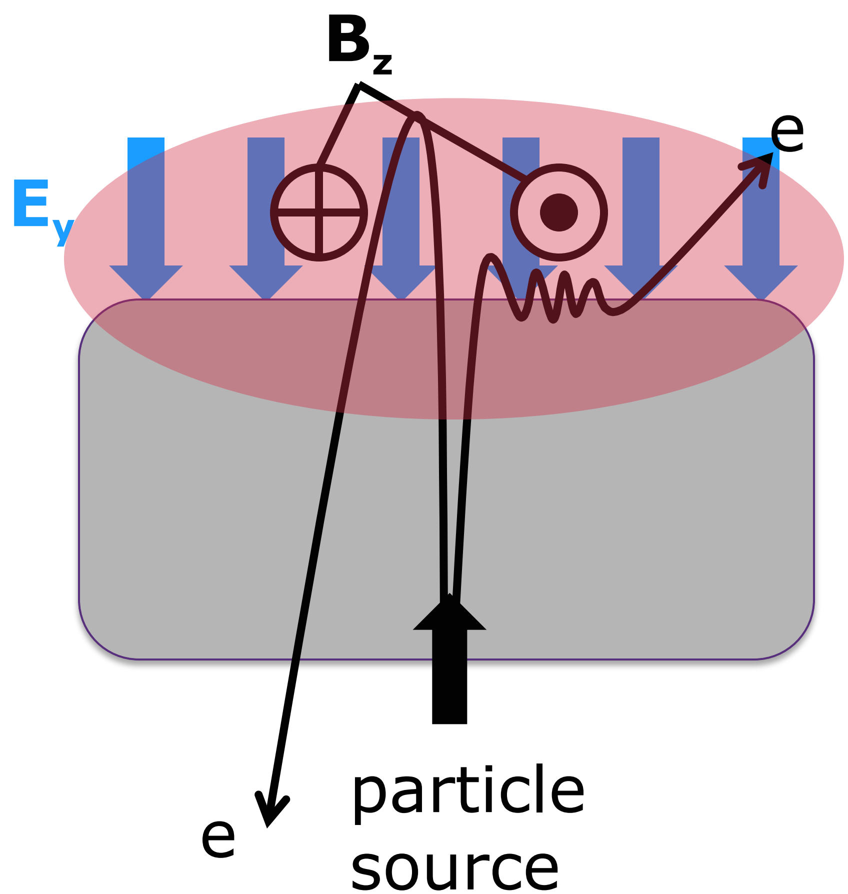
Standard Ohm’s law: $\mathbf{E} = \eta \mathbf{j}_b$



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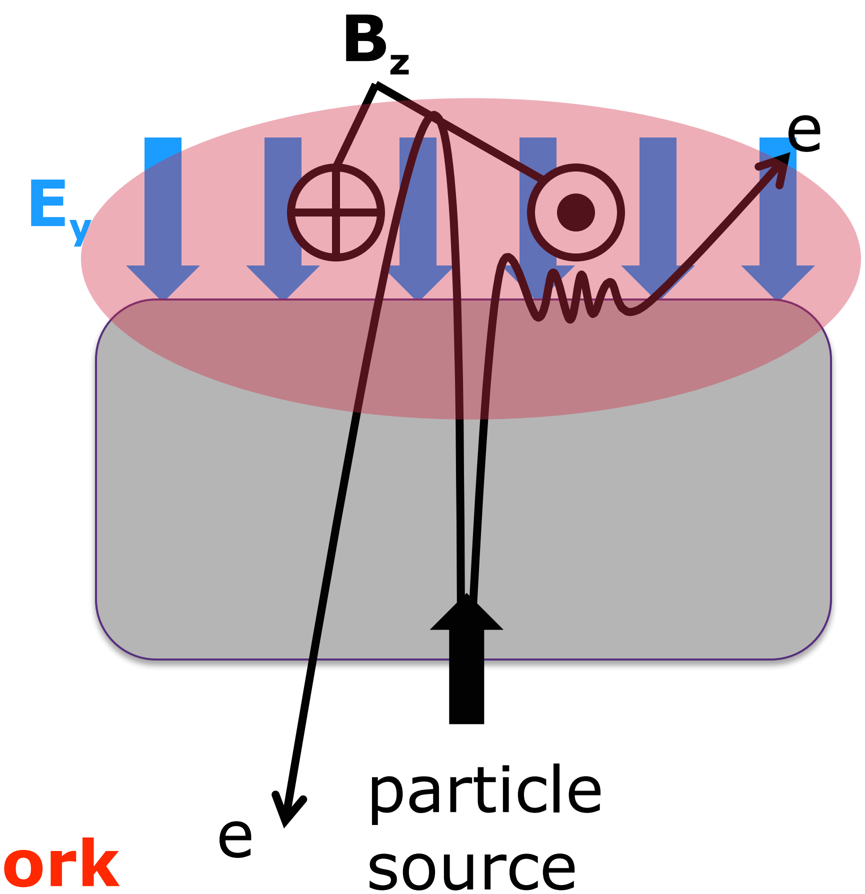
Standard
Ohm’s law: $\mathbf{E} = \eta \mathbf{j}_b$

BUT… This doesn’t work for very low density



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'Improved' hybrid mode

Need to solve Maxwell's equations and Ohm's law.

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

$$\frac{\partial \mathbf{E}}{\partial t} = c^2 \nabla \times \mathbf{B} - \mu_0 \mathbf{j}$$

Standard Ohm's law: $\mathbf{E} = \eta \mathbf{j}_b + \dots$

Include more terms and ensure realistic resistivity in vacuum