Investigating the Physics of Burning Thermonuclear Plasmas

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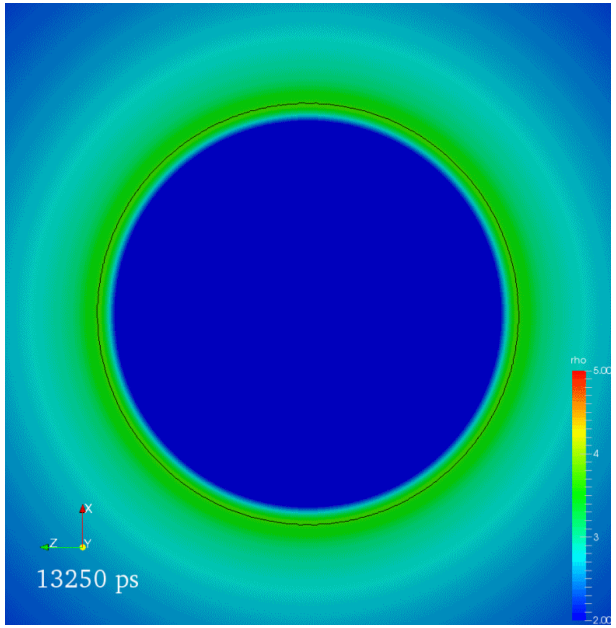
CIFS

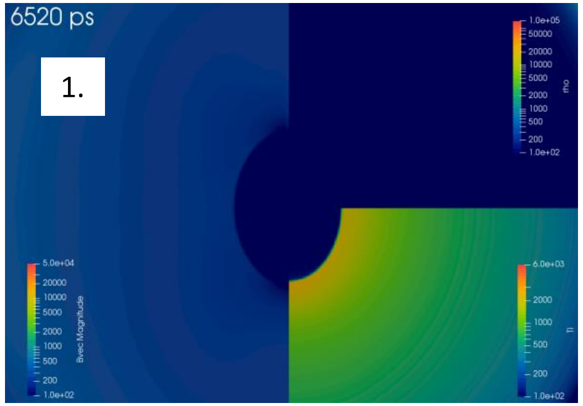
- Theoretical & computational research of ICF & HEDP physics
- Based at Imperial College London, jointly funded with AWE
- Directors – Prof J Chittenden & Prof S Rose, ~10 researchers (RA & PhD)
- 3D Radiation-Hydrodynamic & Magnetohydrodynamic simulations (Chimera & Gorgon)
- Synthetic nuclear diagnostics for ICF
- Atomic & radiation physics
- Vlasov-Fokker-Planck Modelling

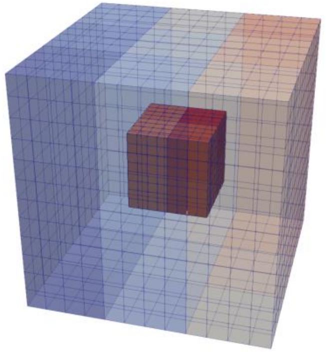
3D CHIMERA simulation

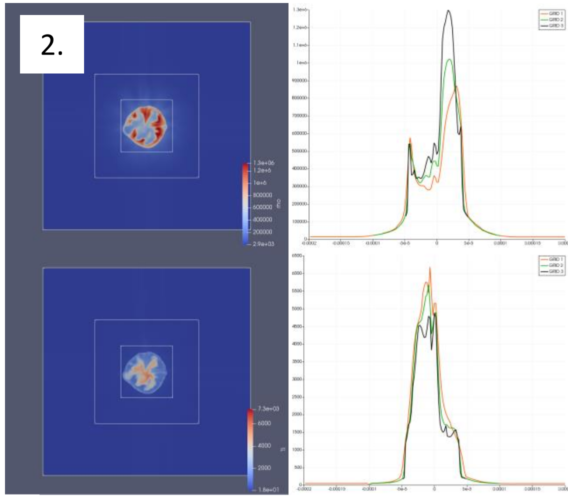


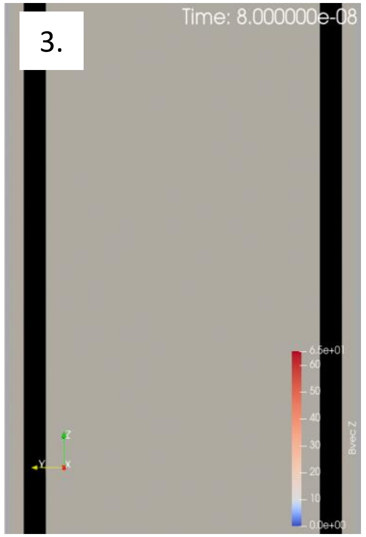
CIFS – Current Activities

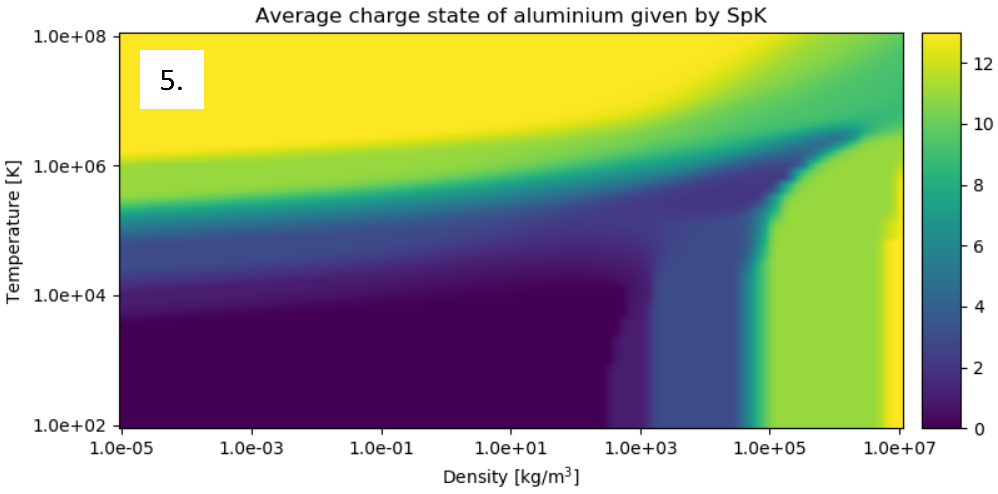
1. MHD modelling of MagNIF (S. O' Neill)
2. Extended-MHD modelling of MagLIF (A. Boxall)
3. AMR grid development (N. Chaturvedi)
4. 3D CBET modelling (P. Moloney)
5. Self-consistent EOS & opacity modelling (A. Fraser)

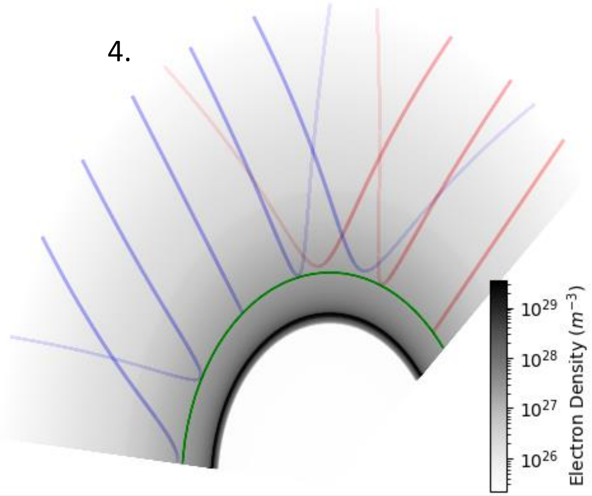












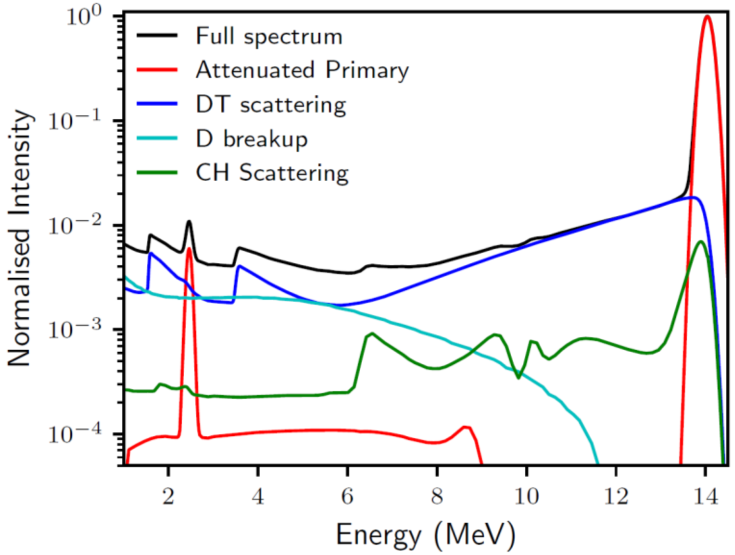
CIFS – Current Activities

Nuclear synthetic diagnostics
(A. Crilly & B. Appelbe)

nT backscatter edge
O. Mannion, C. Forrest (LLE)

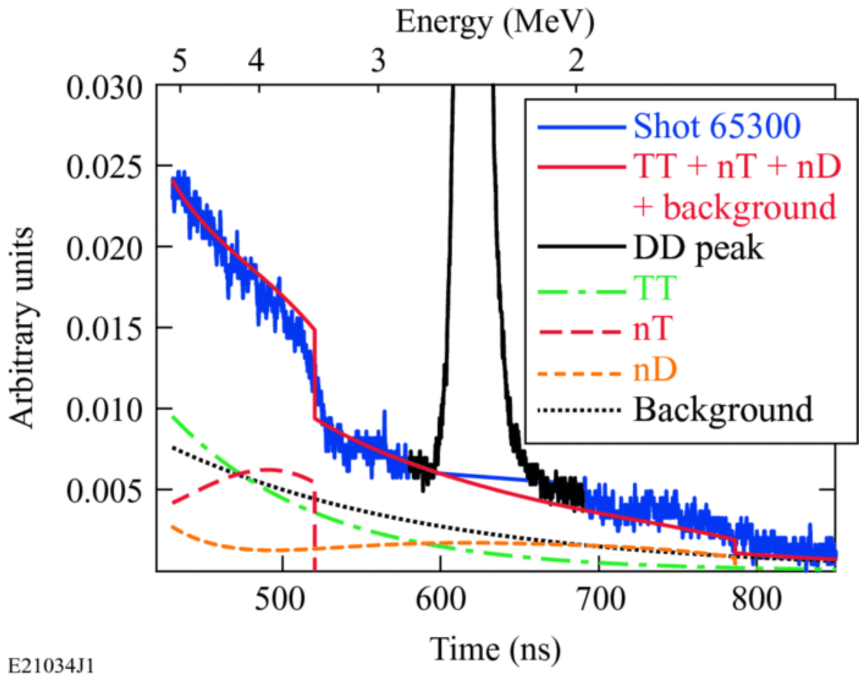
Transport model

Hydro simulation data

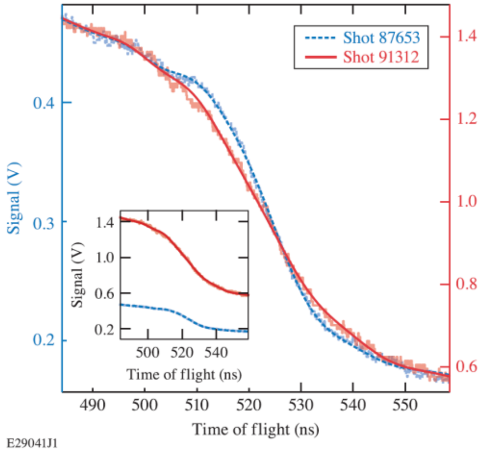


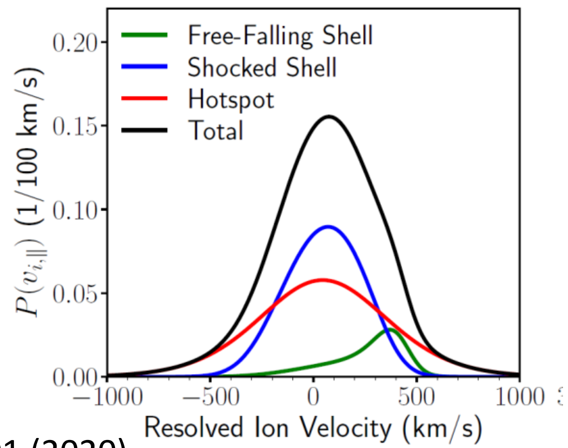
Instrument model

Experimental data



Analysis models





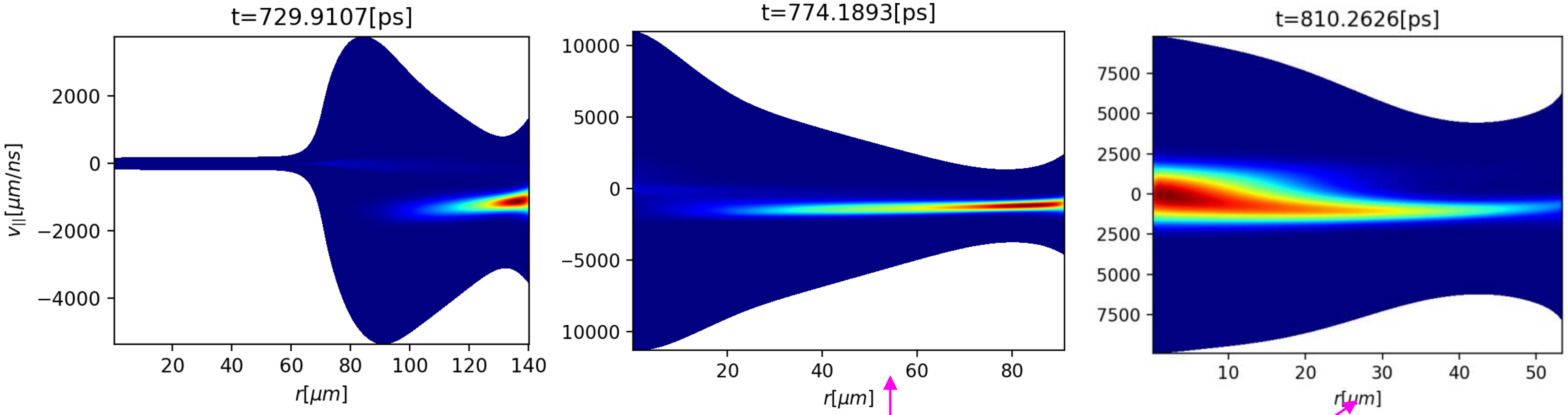
Physical parameter

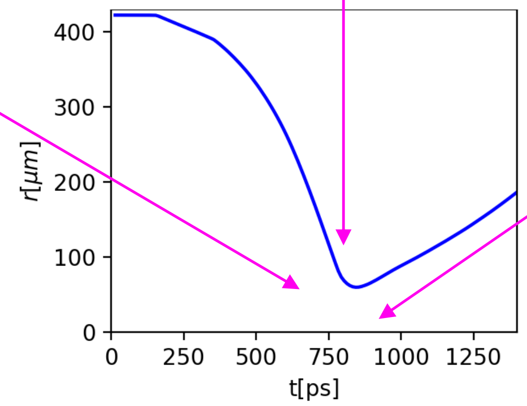
[1] Crilly et al, POP **27**, 012701 (2020)

CIFS – Current Activities

Nuclear synthetic diagnostics
(A. Crilly & B. Appelbe)

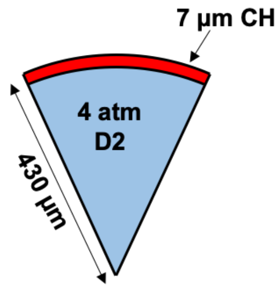
Distribution of $v_{\parallel}$ component





Trajectory of outer boundary

Primary neutron spectra in shock driven capsules
W. Taitano, B. Keenan (LANL)
O. Mannion (LLE)
M. Gatu Johnson (MIT)



	Experiment	iFP (kinetic)	iFP (Maxwell)	HYADES
Tion (keV)	10.74	14.8	13.9	21

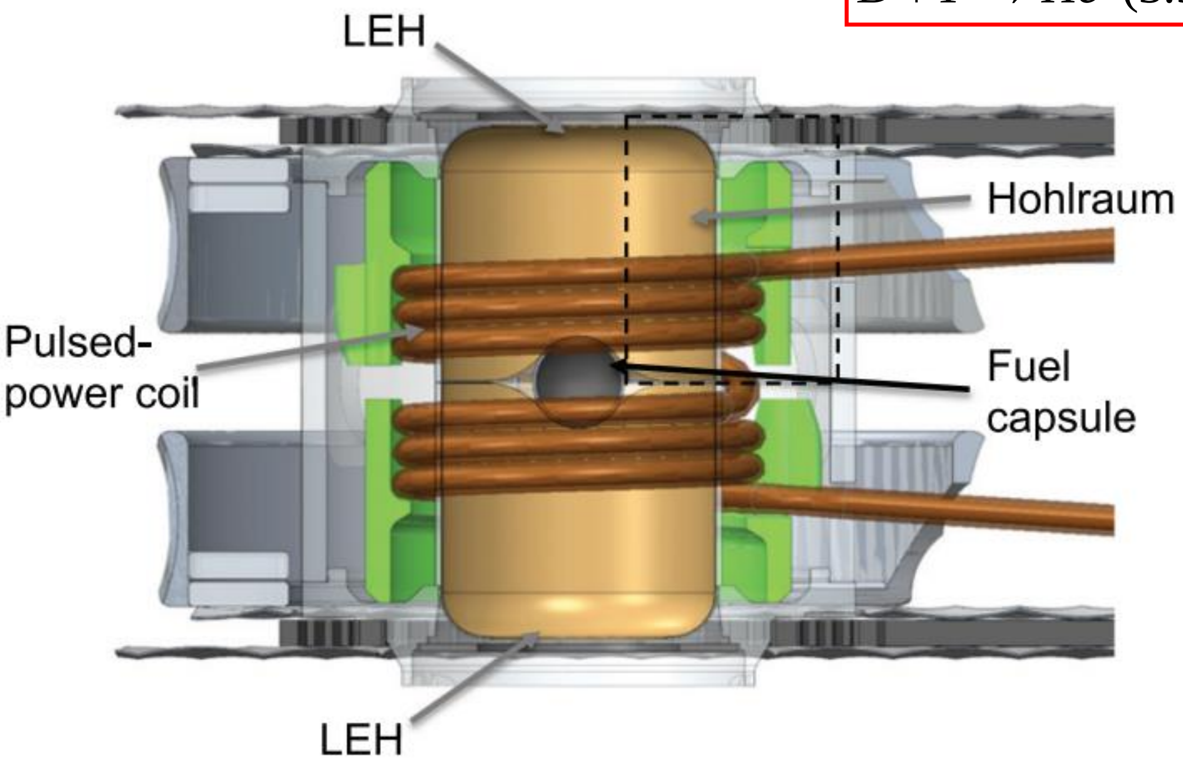
CIFS – Current Activities

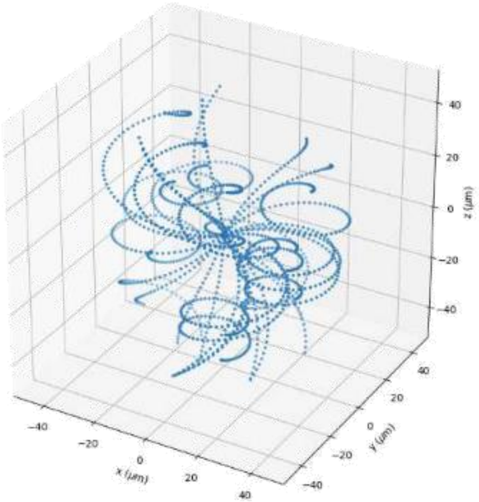
Nuclear synthetic diagnostics
(A. Crilly & B. Appelbe)

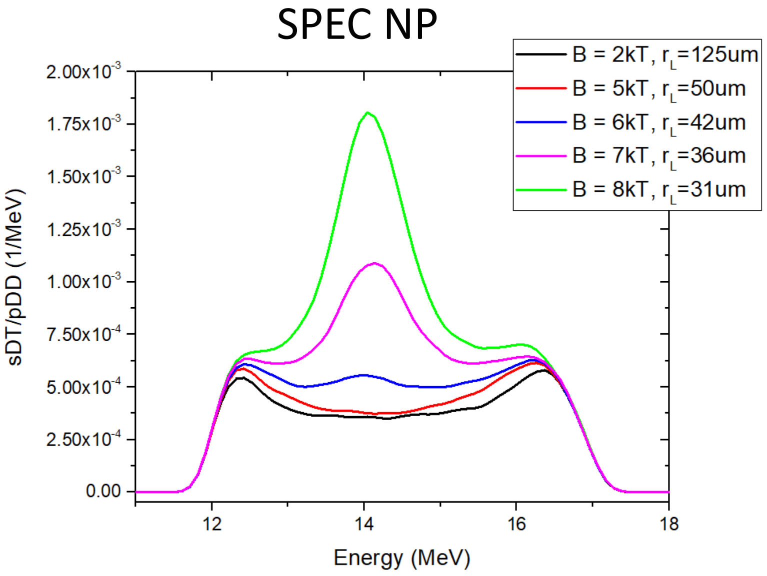
$$D+D \rightarrow \begin{cases} T(1.01MeV)+p(3.02MeV) \\ He^3(0.82MeV)+n(2.45MeV) \end{cases}$$

$$D+T \rightarrow He^4(3.5MeV)+n(14.1MeV)$$

Secondary neutron spectra for magnetized ICF
J. Moody, H. Sio (LLNL)







[4] Moody et al, POP **27**, 112711 (2020)
[4a] Schmit et al, PRL **113**, 155004 (2014)

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1. Overview of Burning Plasmas

2. The interaction of α particles with electrons

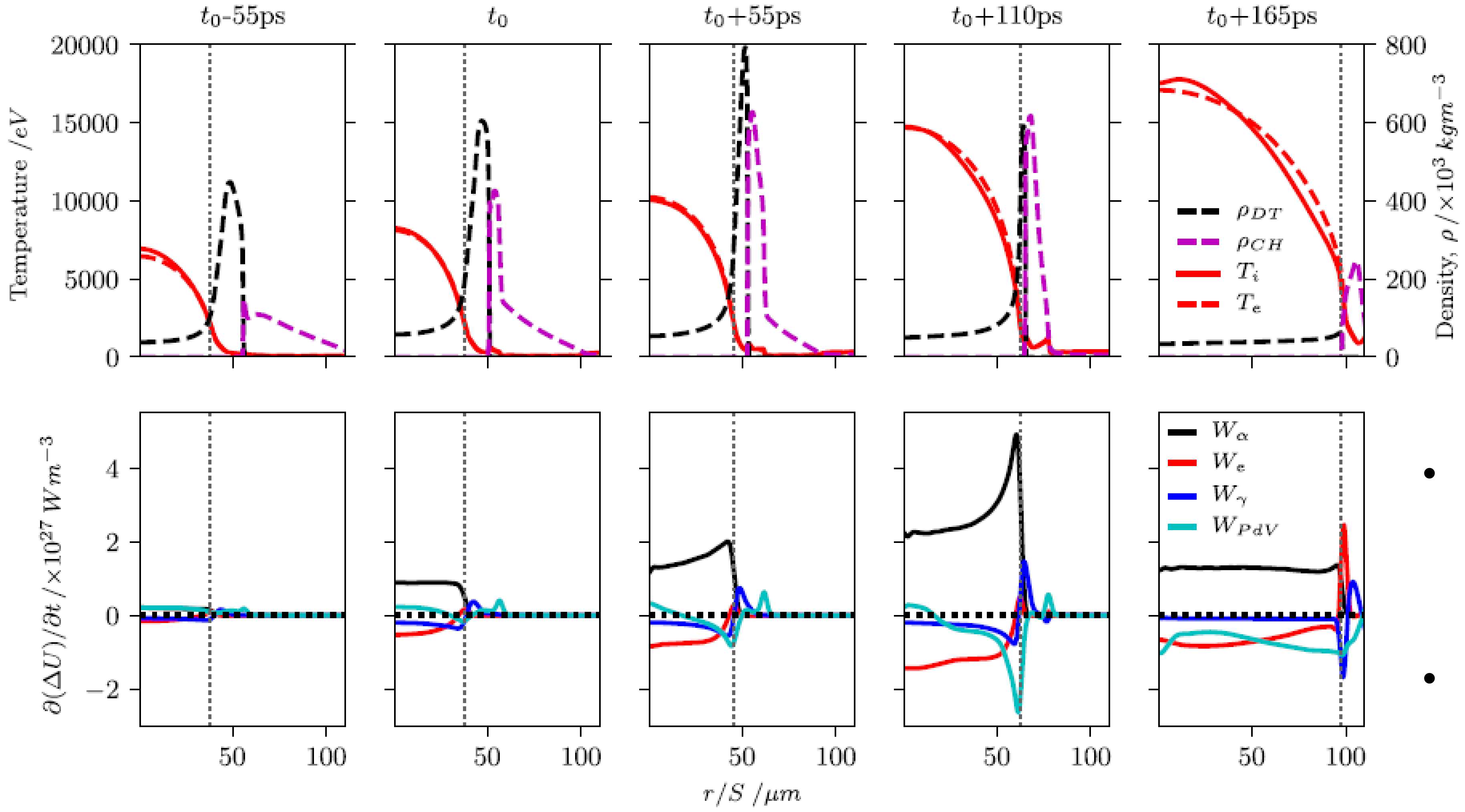
   - Appelbe et al, *Physics of Plasmas* **26**, 102704 (2019)

3. Magnetic field transport in propagating thermonuclear burn

   - Appelbe et al, *Physics of Plasmas* **28**, 032705 (2021)

4. Conclusions

Burning DT – Macroscopic Picture

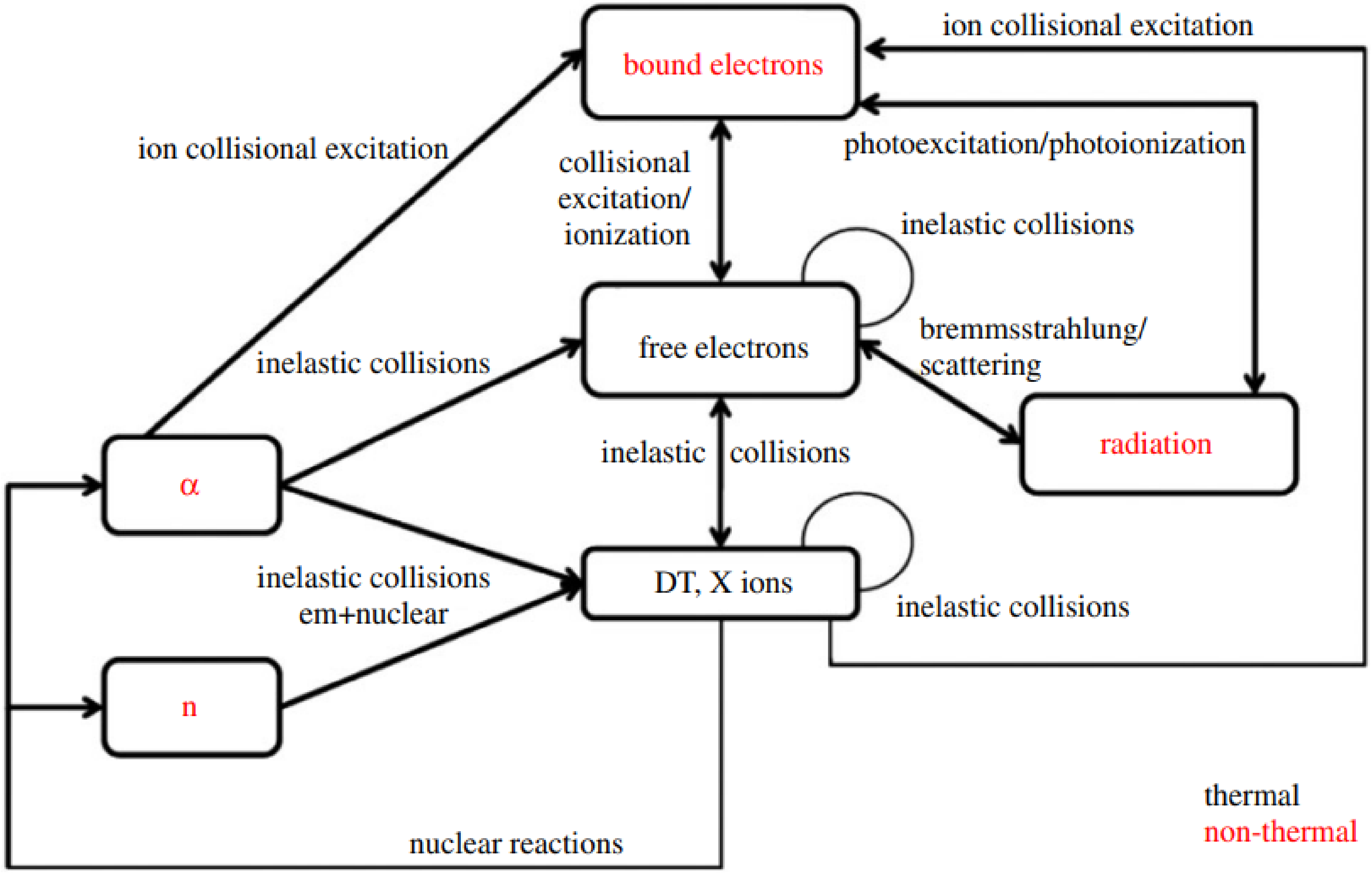


1D rad-hydro (Chimera) simulation of igniting ICF capsule

- *Physical quantities have extreme gradients in time & space*
- *Significant energy exchange processes*

[2] Tong et al, NF **59**, 086015 (2019)

Microphysics of Burn



Do we understand these processes with sufficient precision to ensure macroscopic models are accurate?

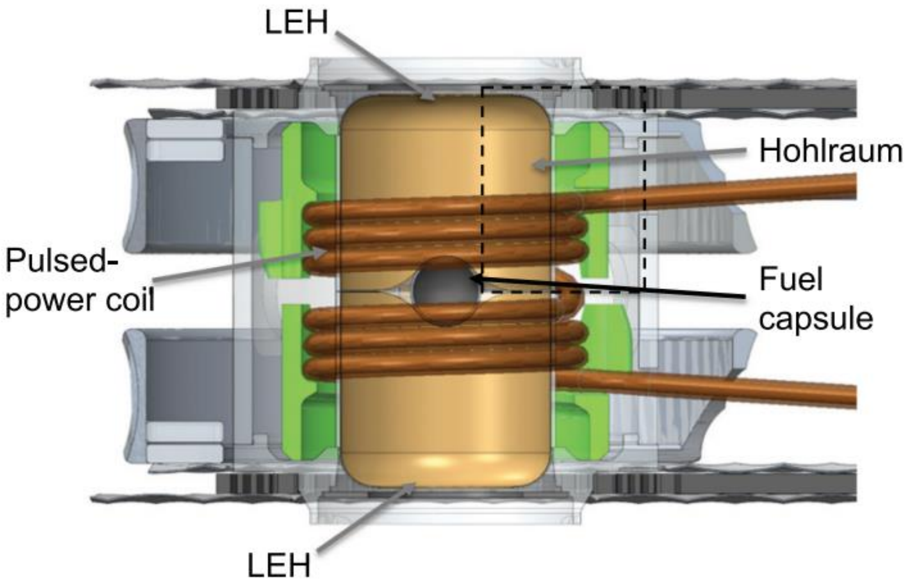
[3] Rose et al, PTRSA **378**, 20200014 (2020)

Microphysics of Burn - Challenges

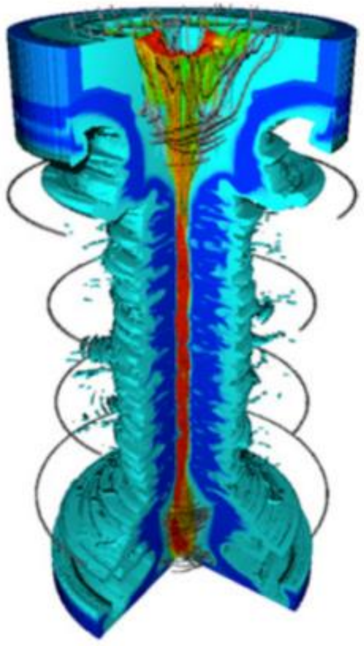
- High ρr - Compton scattering in lines and continuum
- High ρ – continuum lowering
- High I(v) – photoionisation / non-LTE with line transport, e+e- pair production, photonuclear processes, non-equilibrium $f_e(v)$, continuum lowering, double Compton scattering
- High T_e - non-LTE populations, relativistic corrections to rates, relativistic correction to e-i exchange
- High T_i - ion excitation rates
- High α flux - $\boxed{\text{non-equilibrium } f_e(v),}$ $f_i(v)$, non-equilibrium e-i exchange, α-excitation rates, α-nuclear reactions
- High n flux - non-equilibrium $f_i(v)$, n-nuclear reactions.
- Extreme gradients in space and time
- Magnetic Fields

[3] Rose et al, PTRSA **378**, 20200014 (2020)

$\boldsymbol{B}$ fields & ignition



Magnetically-assisted ignition



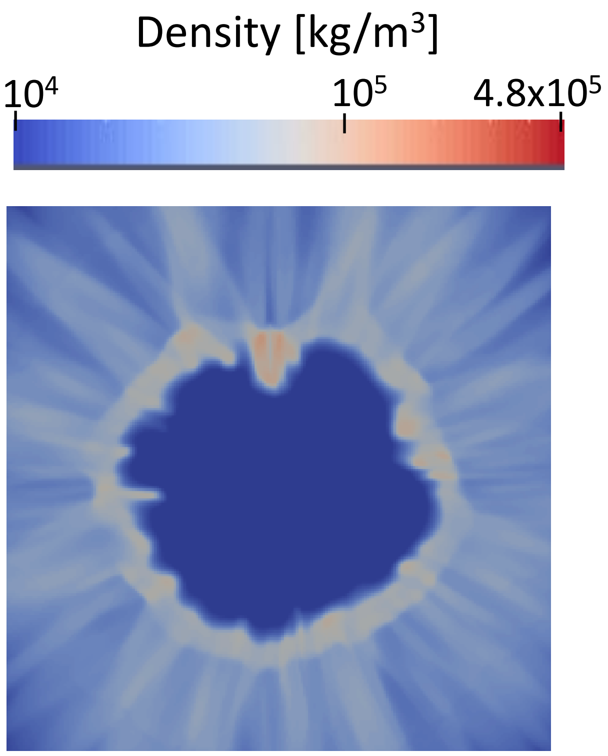
Magneto-Inertial Fusion

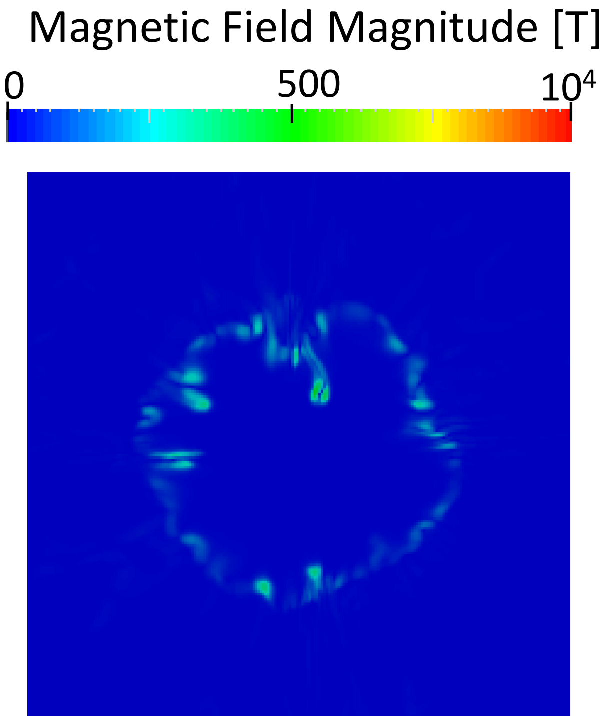
Effects of $\boldsymbol{B}$ field:

- Reduce electron thermal conduction losses from hot fuel
- Magnetically confine α particles (for very high $\boldsymbol{B}$ fields)

[4] Moody et al, POP **27**, 112711 (2020)
[5] Gomez et al, PRL **125**, 155002 (2020)

B fields in ICF





Biermann Battery

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{en} \nabla T \times \nabla n$$

[6] Walsh et al, PRL **118**, 155001 (2017)

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4. Conclusions

Collaborators

A. L. Velikovich

Naval Research Laboratory

M. Sherlock, C. Walsh

Lawrence Livermore National Laboratory

O. El-Amiri

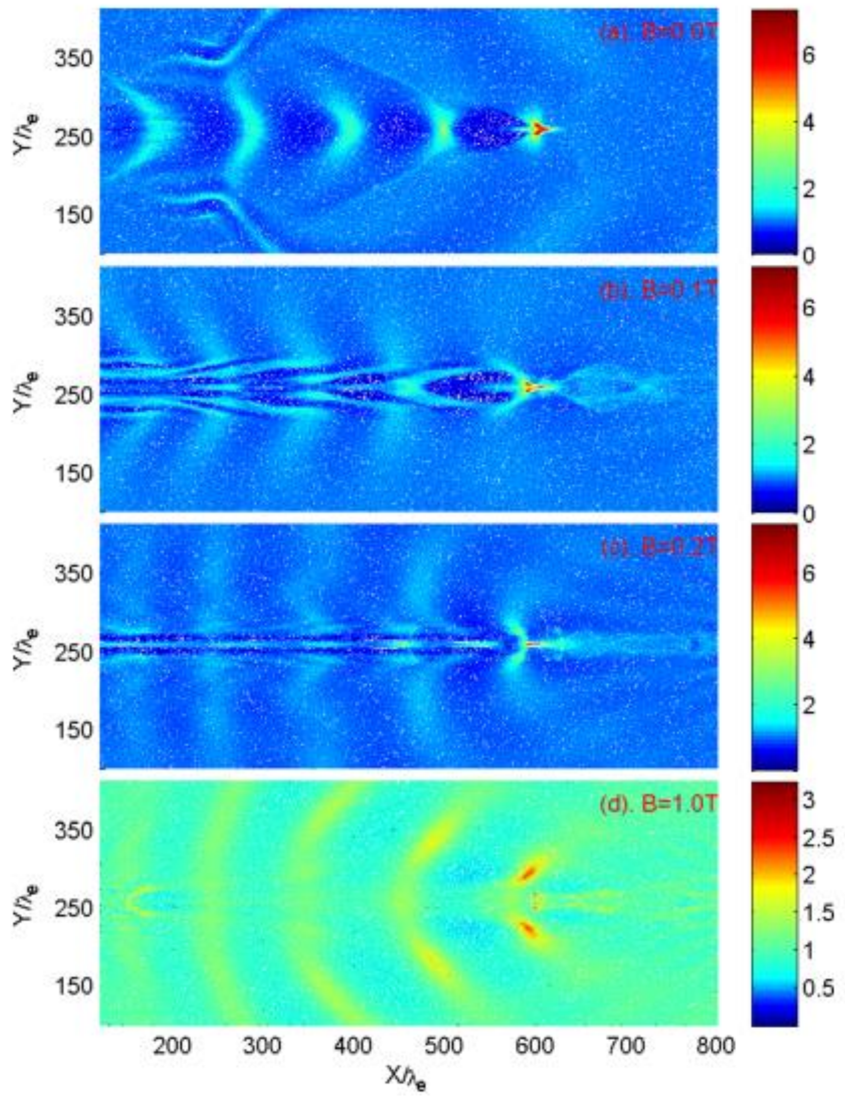
University of Warwick

S. O' Neill, A. Crilly, A. Boxall, J. P. Chittenden

Imperial College London

Electron response to α particles

- MD & PiC models show fast ions generate rich electron dynamics (e.g. wakes)
- Such effects usually not included in integrated simulations of ICF/MIF experiments since $\tau_{ee}\ ,\tau_{ei}\ \ll\ \tau_{e\alpha}$
- Instead, stopping power model is used to conserve energy & momentum between fast ions and fluid
- Is this ok?



What about ions?

- For $T_i\ ,T_e\!\sim 1-10\ keV$ α particles lose most energy in *e*-α collisions
- Various ion kinetic studies have shown moderate perturbation of ions by α particles

[7] Grabowski et al, PRL **111**, 215002 (2013)
[8] Hu et al, PRE **82**, 026404 (2010)
[9] Zhao et al, POP **22**, 093114 (2015)
[10] Michta et al, POP **17**, 012707 (2010)
[11] Sherlock et al, HEDP **5**, pp.27-30 (2009)
[12] Peigney et al, POP **21**, 122709 (2014)

The Electron VFP Equation

- Weakly-coupled, non-degenerate plasmas

Electron-electron collisions

Electron-α collisions

$$\frac{\partial f_e}{\partial t} + \mathbf{v} \cdot \nabla f_e - \frac{e}{m_e}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_v f_e = \mathcal{C}_{ee}(f_e) + \mathcal{C}_{ei}(f_e, f_i) + \mathcal{C}_{e\alpha}(f_e, f_\alpha)$$

Electron-ion (thermal) collisions

$T_i \approx T_e$

- Impose a fast ion flux
- Assume $\tau_{ei} \ll \tau_{\alpha e}$ and $v_\alpha \tau_{ei} \ll L_H$ steady-state, local behaviour of electrons
- Seek perturbative solutions to VFP equation (Chapman-Enskog Theory)

Electron gyro-frequency

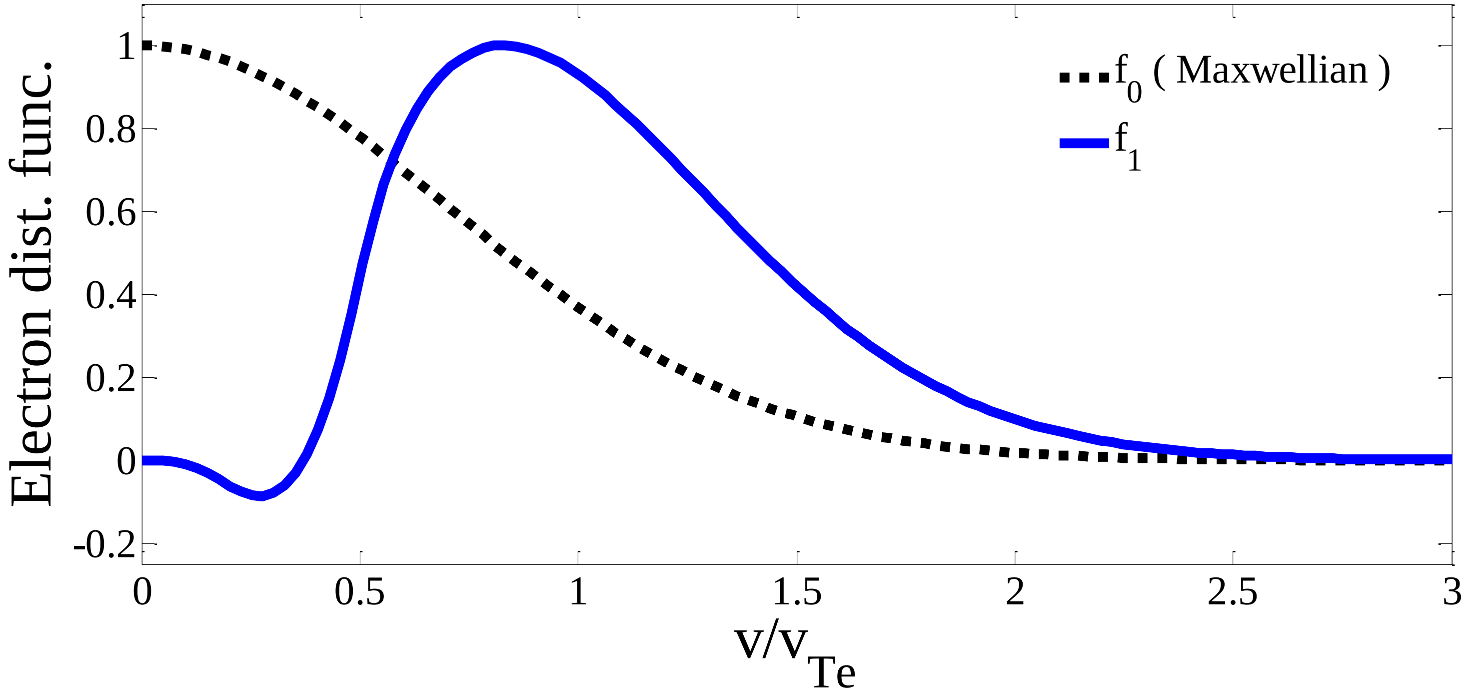
$$\boldsymbol{\omega} = \frac{e}{m_e}\mathbf{B}$$

$$\mathbf{a} = \frac{e}{m_e}\mathbf{E}$$

$$v f_0 \left[\frac{\nabla n_e}{n_e} + \frac{2}{v_{Te}^2}\mathbf{a} + \frac{\nabla T_e}{T_e}\left(\frac{v^2}{v_{Te}^2} - \frac{3}{2} \right) \right] + \mathbf{C}_{e\alpha 1}^{01} = \boldsymbol{\omega} \times \mathbf{f_1} + \mathbf{C}_{ee1} + \mathbf{C}_{ei1} + \mathbf{C}_{e\alpha 1}^{10}$$

Driving terms *Electron response terms*

Electron f_1 – unmagnetized case



$$T_e = 2\ keV$$

$$E_\alpha = 3.45\ MeV$$

$$\frac{v_\alpha}{v_{Te}} = 0.48$$

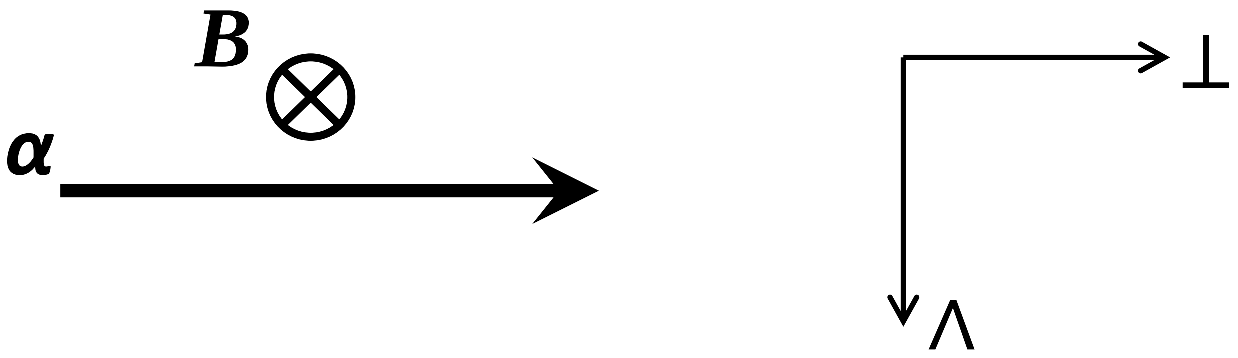
$$\langle v_\alpha \rangle = 4 \times 10^6\ ms^{-1}$$

- Max f_1 occurs at velocities close to electron thermal velocity
- Magnitude of f_1 is proportional to n_α
- f_1 is directed parallel to α flux

These effects are independent of the α heating of electrons and ions

Electron f_1 – magnetized case

Co-ordinate system



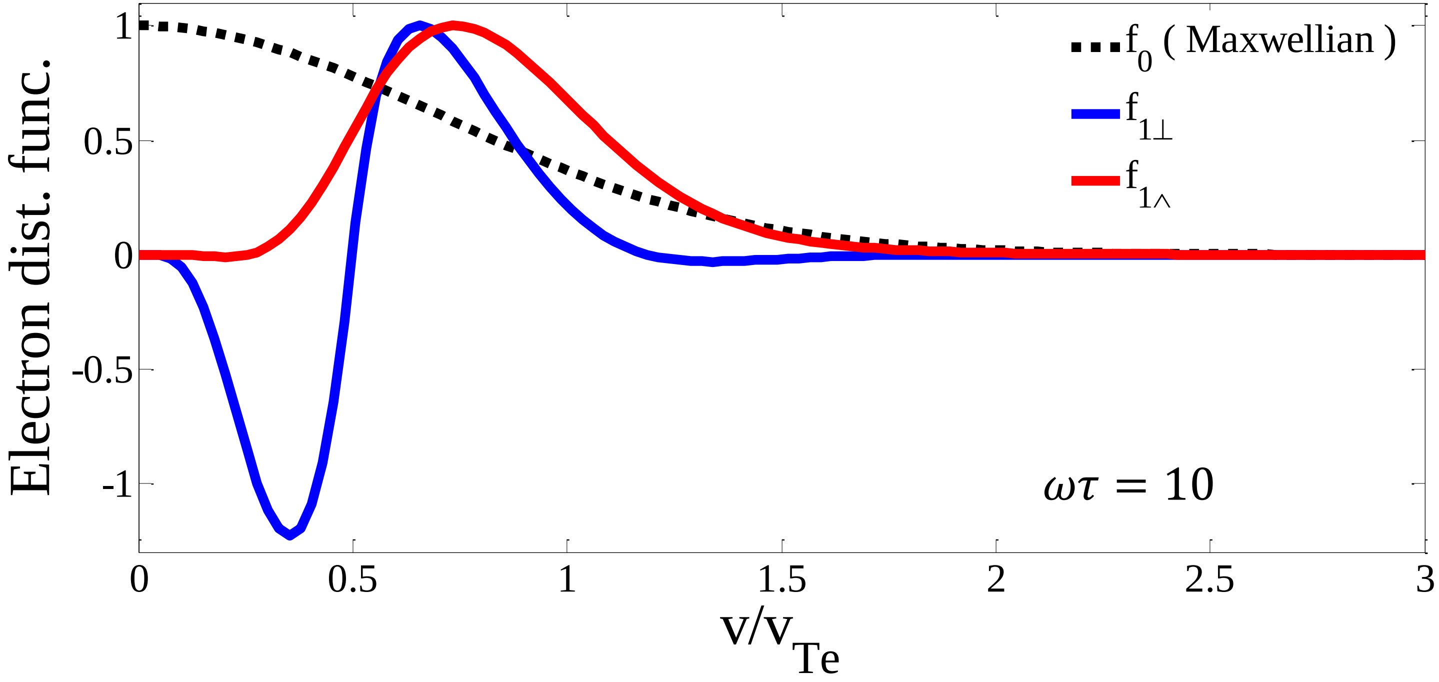
- $\perp$ is parallel to α flux
- $\wedge$ is orthogonal to α flux and $\boldsymbol{B}$ field

Parameterization of $\boldsymbol{B}$ *field*

χ , $\omega\tau_{ei}$ - electron Hall parameter

- Small $\omega\tau_{ei}$ - collisions dominate
- Large $\omega\tau_{ei}$ - $\boldsymbol{B}$ field dominates

Electron f_1 – magnetized case



$T_e = 2\ keV$

$E_\alpha = 3.45\ MeV$

$\frac{v_\alpha}{v_{Te}} = 0.48$

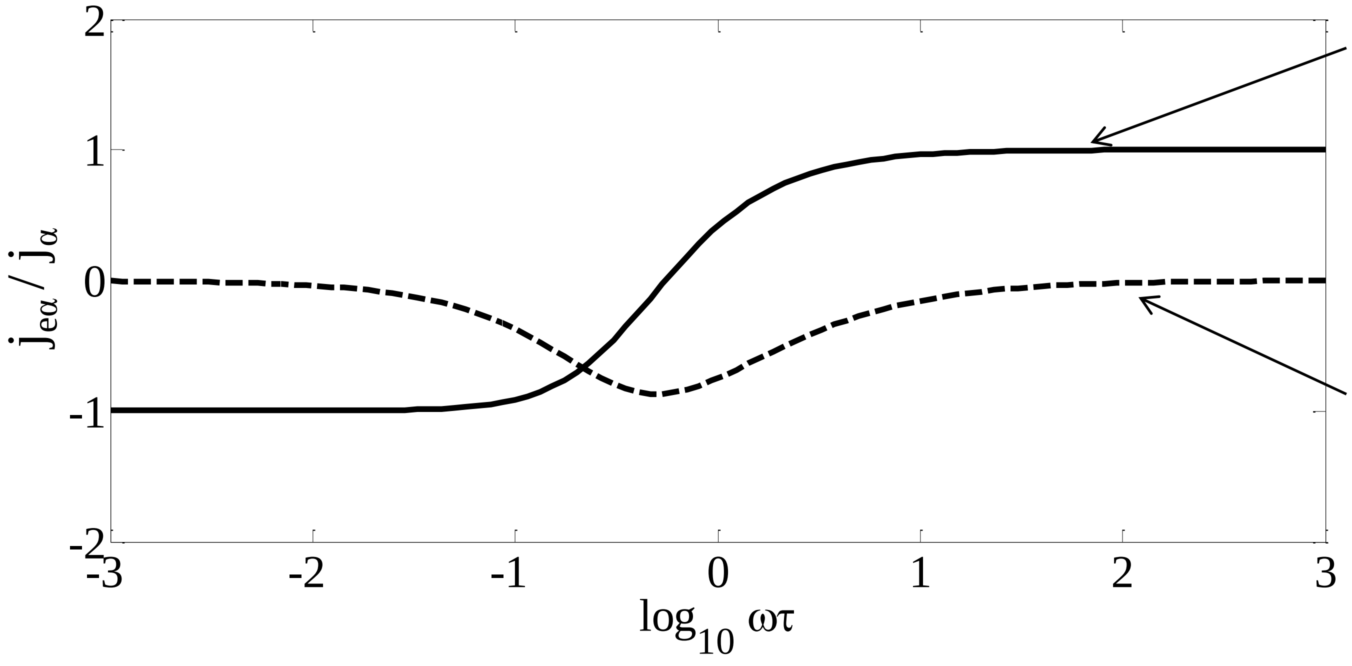
$\langle v_\alpha \rangle = 4 \times\ 10^6\ ms^{-1}$

e current moment: $$\boldsymbol{\xi}_{\boldsymbol{e\alpha}} = -\frac{4\pi e}{3}\int_0^\infty v^3 \mathbf{f_1} dv$$

e heat flow moment: $$\boldsymbol{\zeta}_{\boldsymbol{e\alpha}} = \frac{2\pi m_e}{3}\int_0^\infty v^5 \mathbf{f_1} dv$$

Collisionally-induced current

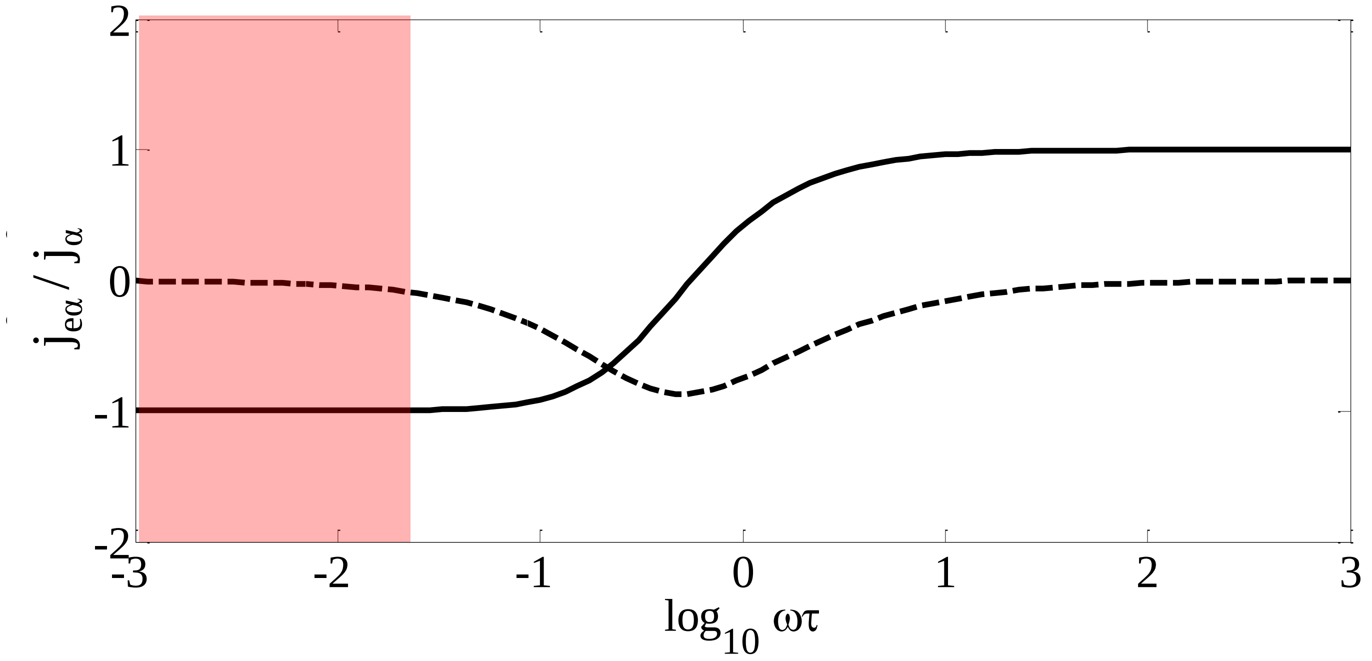
Sum of α current and electron current moment divided by α current

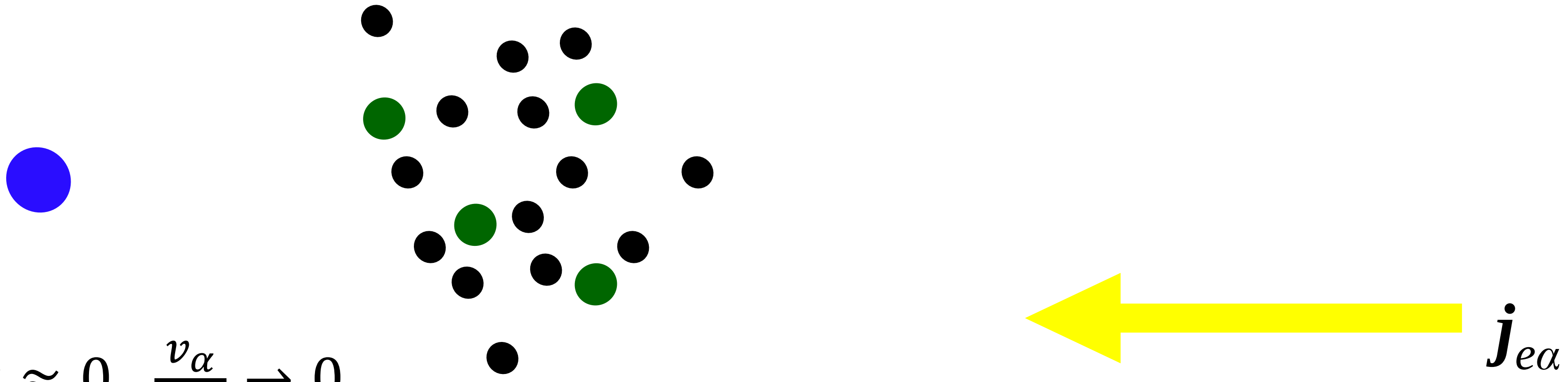


⊥ - parallel to α flux

Λ - orthogonal to **B** field and α flux

Collisionally-induced current

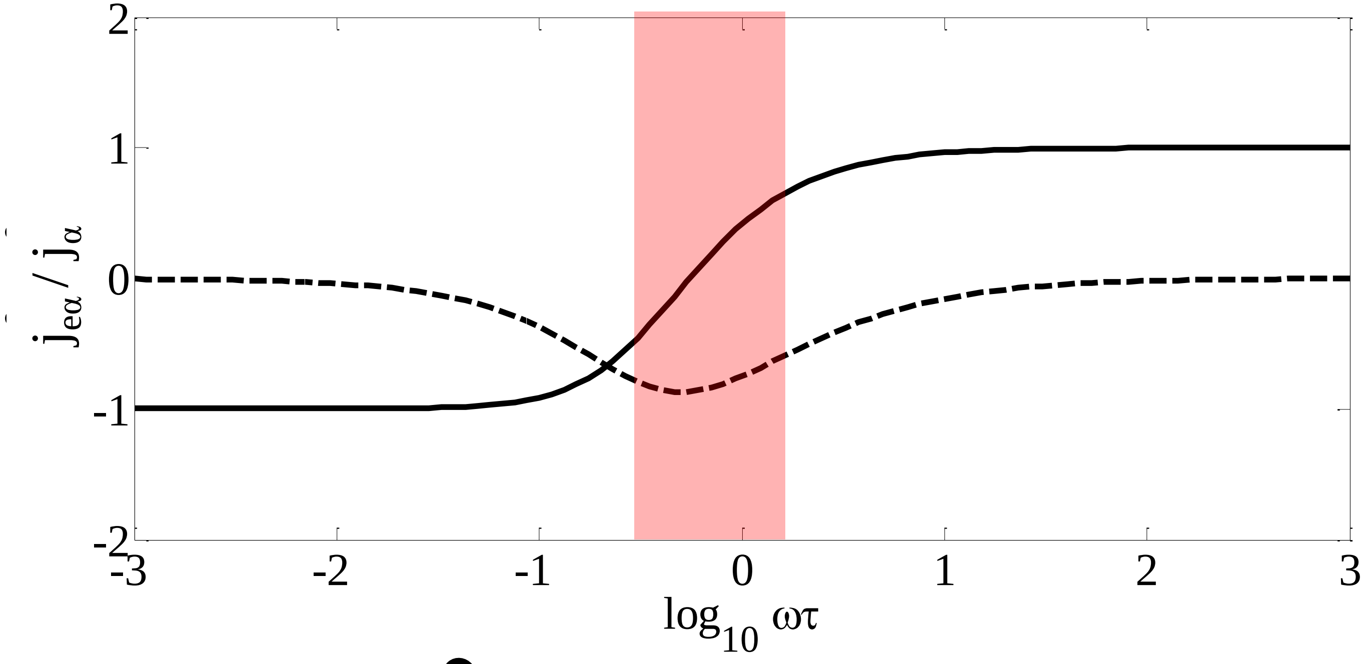


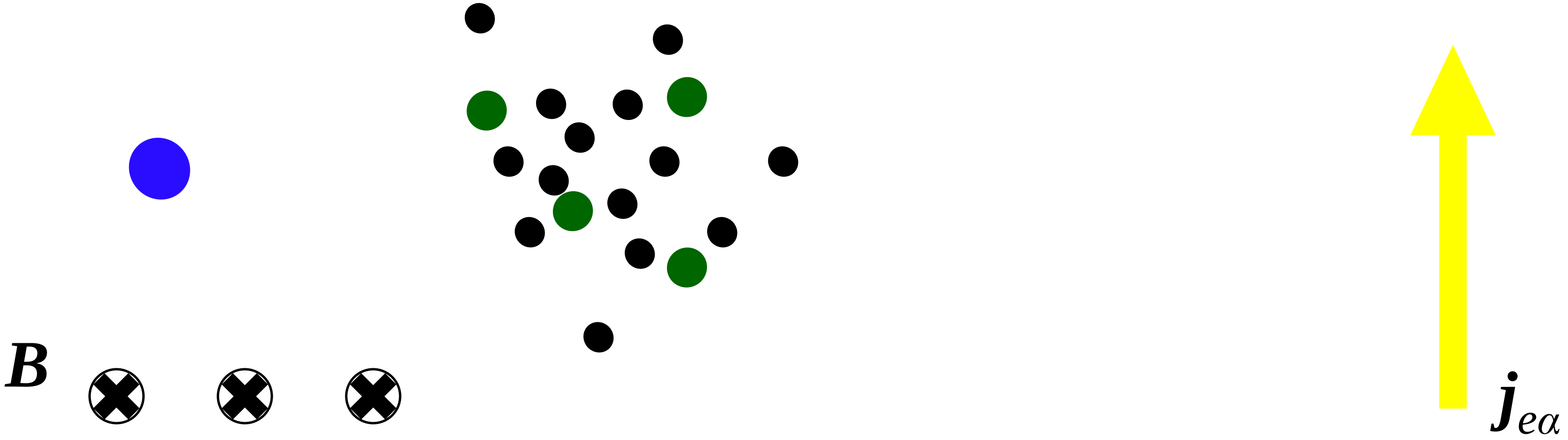


$$\frac{j_{e\alpha}}{j_\alpha} \approx 1 - \frac{Z_\alpha}{Z_i} \text{ for } \omega\tau \approx 0\,, \frac{v_\alpha}{v_{Te}} \to 0$$

[13] Fisch, RMP **59**, pp. 175-234 (1987)

Collisionally-induced current





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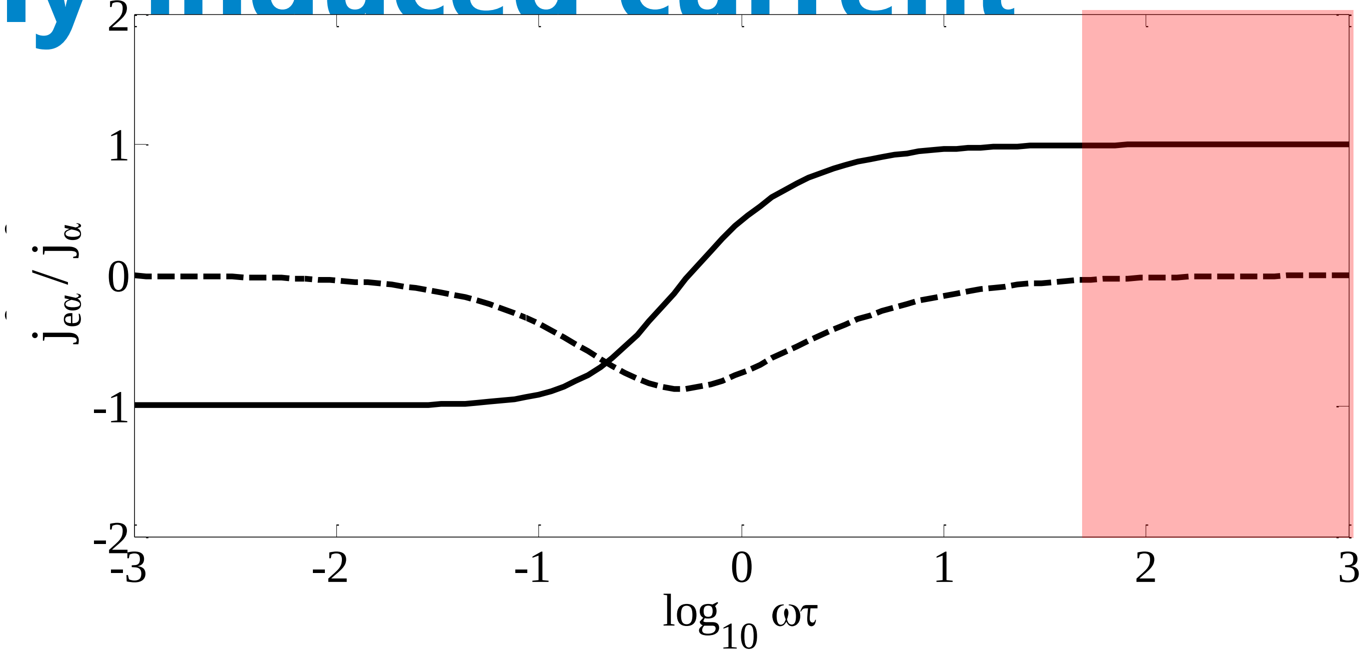
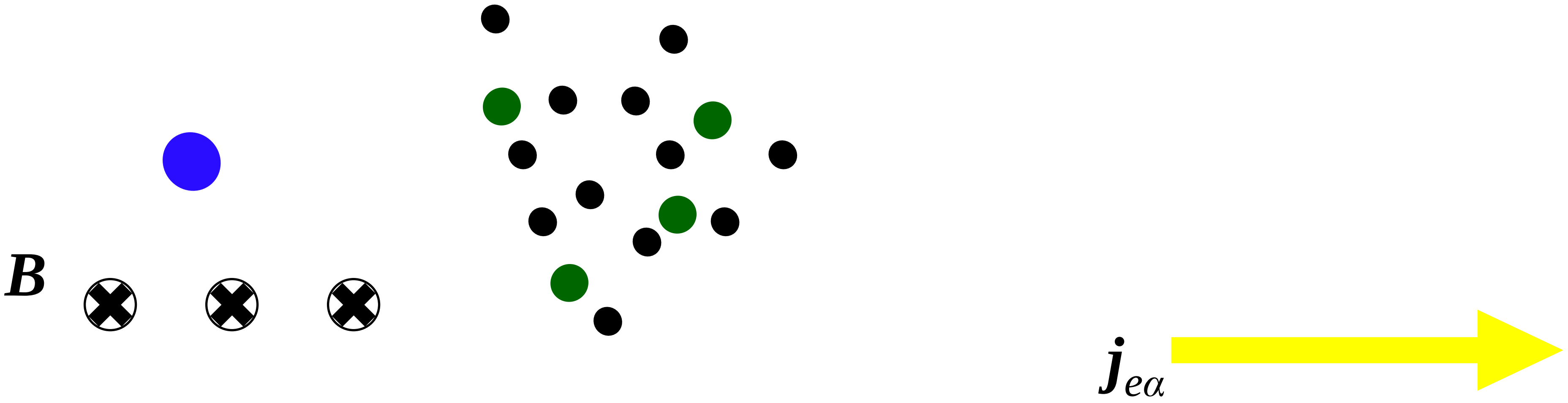
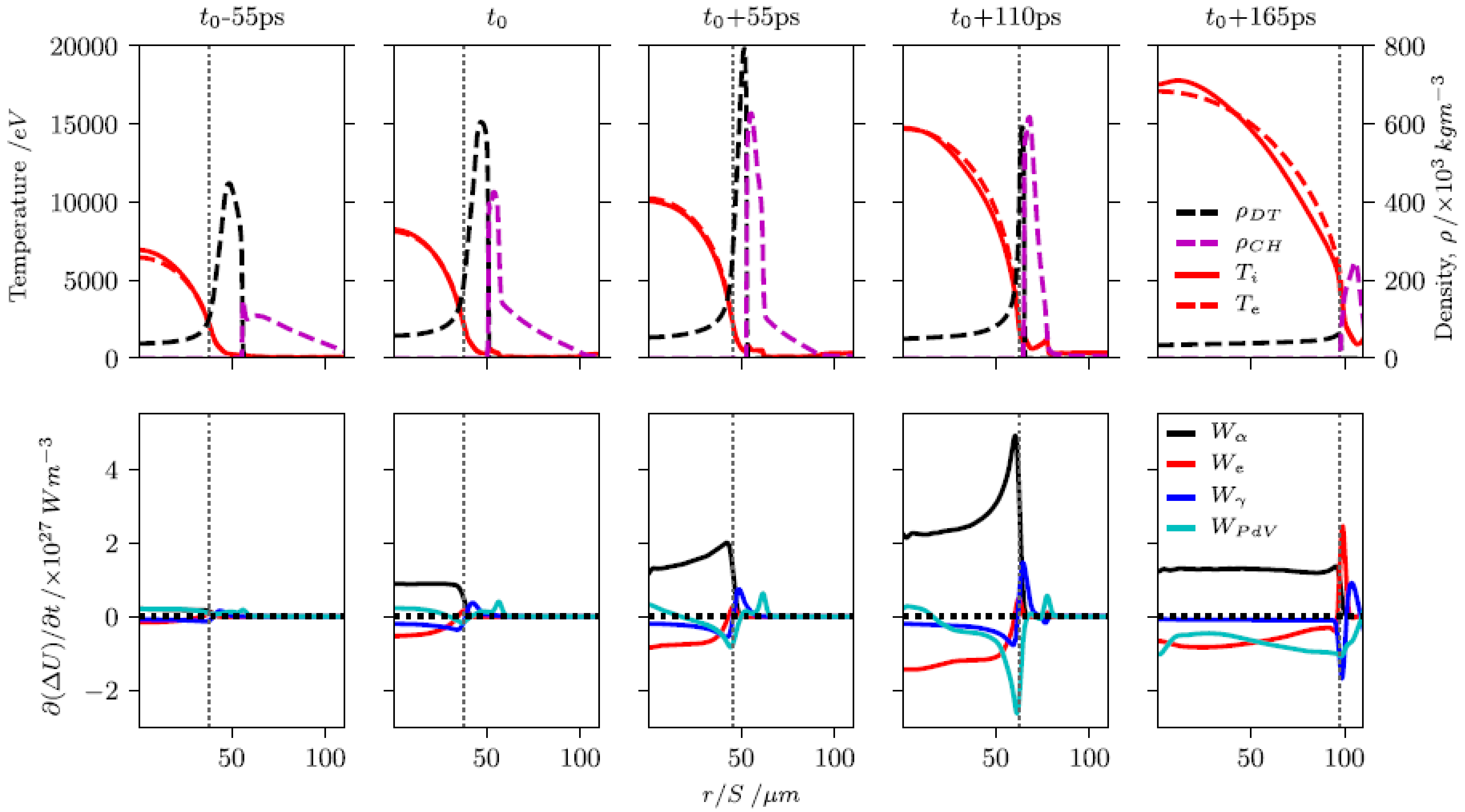




Collisionally-induced current



α flux $\approx 10^{35}\ m^{-2}\ s^{-1}$ → $j_{e\alpha} \approx 10^{16}\ A\ m^{-2}$

This is similar current densities achieved on Z

The Induction Equation

- $\boldsymbol{j_{e\alpha}}$ can be incorporated in fluid models via an induction equation

$$\frac{\partial \mathbf{B}}{\partial t} - \underbrace{\boxed{\nabla \times \mathbf{u} \times \mathbf{B}}}_{\text{Advection with fluid}} = \underbrace{\boxed{\frac{1}{en}\nabla T \times \nabla n}}_{\text{Biermann battery}} + \underbrace{\boxed{\frac{1}{e}\nabla \times \left[\underline{\underline{\beta}} \cdot \nabla T\right]}}_{\text{Thermoelectric effects}} - \nabla \times \frac{1}{en}\left[\underbrace{\boxed{\mathbf{j}_T \times \mathbf{B}}}_{\text{Hall term}} + \underbrace{\boxed{\frac{1}{en}\underline{\underline{\alpha}} \cdot \mathbf{j}_T}}_{\text{Resistive diffusion}}\right] + \underbrace{\boxed{\nabla \times \frac{1}{en}\left[\mathbf{j}_{e\alpha} \times \mathbf{B} + \frac{1}{en}\underline{\underline{\alpha}} \cdot \mathbf{j}_{e\alpha}\right]}}_{\alpha \text{ flux effects}}$$

if $\boldsymbol{B = 0}$ $\quad \dfrac{\partial \mathbf{B}}{\partial t} = \dfrac{1}{en}\nabla T \times \nabla n + \nabla \times \dfrac{\alpha_{||}}{(en)^2}\mathbf{j}_{e\alpha}$

$$j_{e\alpha} \approx 10^{16}\ A\ m^{-2}$$

$$L \sim 10\ \mu m$$

$$T \sim 1 - 10\ keV$$

$$n \sim 10^{31}\ m^{-3}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} \sim 10^{13} - 10^{15}\ T\ s^{-1}$$

[14] Braginskii, Rev Plas Phys **1**, pp. 205- (1965)
[15] Epperlein & Haines, Phys Fluids **29**, pp. 1029=1041 (1986)

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Propagating Burn Model

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$$\frac{\partial n}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}\left(n\hat{u}\right) = 0$$

DT fuel continuity eqn

$$\frac{\partial}{\partial \hat{x}}\left(2nT + \frac{B^2}{2\mu_0}\right) = 0$$

Isobaric condition

$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}\left(\hat{u}B\right) = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}} + \hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}\right)B\right]$$

Induction eqn

$$3n\frac{DT}{D\hat{t}} + 2nT\frac{\partial \hat{u}}{\partial \hat{x}} = \frac{\partial}{\partial \hat{x}}\left[\hat{\kappa}\frac{\partial T}{\partial \hat{x}} + \hat{\beta}\frac{B}{\mu_0}\frac{\partial B}{\partial \hat{x}}\right] + \hat{q}_\alpha - \hat{P}$$

DT fuel energy eqn

$$\frac{D\mathcal{E}_\alpha}{D\hat{t}} + \frac{5}{3}\mathcal{E}_\alpha\frac{\partial \hat{u}}{\partial \hat{x}} = \frac{\partial}{\partial \hat{x}}\left(\hat{\delta}_\mathcal{E}\frac{\partial \mathcal{E}_\alpha}{\partial \hat{x}}\right) - \hat{q}_\alpha + \hat{Q}$$

α energy eqn

Propagating Burn Model

Imperial College London CiFS

$$\frac{\partial n}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}(n\hat{u}) = 0$$

DT fuel continuity eqn

Thermal pressure

Magnetic pressure

$$\frac{\partial}{\partial \hat{x}}\left(\boxed{2nT} + \boxed{\frac{B^2}{2\mu_0}}\right) = 0$$

Isobaric condition

$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}(\hat{u}B) = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}} + \hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}\right)B\right]$$

Induction eqn

$$3n\frac{DT}{D\hat{t}} + 2nT\frac{\partial \hat{u}}{\partial \hat{x}} = \frac{\partial}{\partial \hat{x}}\left[\hat{\kappa}\frac{\partial T}{\partial \hat{x}} + \hat{\beta}\frac{B}{\mu_0}\frac{\partial B}{\partial \hat{x}}\right] + \hat{q}_\alpha - \hat{P}$$

DT fuel energy eqn

$$\frac{D\mathcal{E}_\alpha}{D\hat{t}} + \frac{5}{3}\mathcal{E}_\alpha\frac{\partial \hat{u}}{\partial \hat{x}} = \frac{\partial}{\partial \hat{x}}\left(\hat{\delta}_{\mathcal{E}}\frac{\partial \mathcal{E}_\alpha}{\partial \hat{x}}\right) - \hat{q}_\alpha + \hat{Q}$$

α energy eqn

Propagating Burn Model

$$\frac{\partial n}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}(n\hat{u}) = 0$$

DT fuel continuity eqn

$$\frac{\partial}{\partial \hat{x}}\left(2nT + \frac{B^2}{2\mu_0}\right) = 0$$

Isobaric condition

$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}(\hat{u}B) = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}} + \hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}\right)B\right]$$

Induction eqn

$$3n\frac{DT}{D\hat{t}} + 2nT\frac{\partial \hat{u}}{\partial \hat{x}} = \frac{\partial}{\partial \hat{x}}\left[\boxed{\hat{\kappa}\frac{\partial T}{\partial \hat{x}}} + \boxed{\hat{\beta}\frac{B}{\mu_0}\frac{\partial B}{\partial \hat{x}}}\right] + \boxed{\hat{q}_\alpha} - \boxed{\hat{P}}$$

DT fuel energy eqn

$$\frac{D\mathcal{E}_\alpha}{D\hat{t}} + \frac{5}{3}\mathcal{E}_\alpha\frac{\partial \hat{u}}{\partial \hat{x}} = \frac{\partial}{\partial \hat{x}}\left(\hat{\delta}_\mathcal{E}\frac{\partial \mathcal{E}_\alpha}{\partial \hat{x}}\right) - \hat{q}_\alpha + \hat{Q}$$

α energy eqn

Thermal conductivity

Ettingshausen

α heating

Brems losses

Propagating Burn Model

$$\frac{\partial n}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}(n\hat{u}) = 0$$

DT fuel continuity eqn

$$\frac{\partial}{\partial \hat{x}}\left(2nT + \frac{B^2}{2\mu_0}\right) = 0$$

Isobaric condition

$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}(\hat{u}B) = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}} + \hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}\right)B\right]$$

Induction eqn

$$3n\frac{DT}{D\hat{t}} + 2nT\frac{\partial \hat{u}}{\partial \hat{x}} = \frac{\partial}{\partial \hat{x}}\left[\hat{\kappa}\frac{\partial T}{\partial \hat{x}} + \hat{\beta}\frac{B}{\mu_0}\frac{\partial B}{\partial \hat{x}}\right] + \hat{q}_\alpha - \hat{P}$$

DT fuel energy eqn

Magnetized α energy diffusion

α heating

α energy prod rate

$$\frac{D\mathcal{E}_\alpha}{D\hat{t}} + \frac{5}{3}\mathcal{E}_\alpha\frac{\partial \hat{u}}{\partial \hat{x}} = \frac{\partial}{\partial \hat{x}}\boxed{\left(\hat{\delta}_\mathcal{E}\frac{\partial \mathcal{E}_\alpha}{\partial \hat{x}}\right)} - \boxed{\hat{q}_\alpha} + \boxed{\hat{Q}}$$

α energy eqn

[16] Liberman & Velikovich, JPP **31**, 369-380 (1984)

Propagating Burn Model

- 1D planar geometry
- Semi-infinite hot & cold fuel
- Isobaric, deflagration only
- Dimensionless time & space:
  - $\tau_{\alpha H}$ - slowing time for α in hot fuel
  - L_T - mean α stopping distance (unmagnetized)

$$\frac{\partial n}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}(n\hat{u}) = 0$$

DT fuel continuity eqn

$$\frac{\partial}{\partial \hat{x}}\left(2nT + \frac{B^2}{2\mu_0}\right) = 0$$

Isobaric condition

$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}(\hat{u}B) = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}} + \hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}\right)B\right]$$

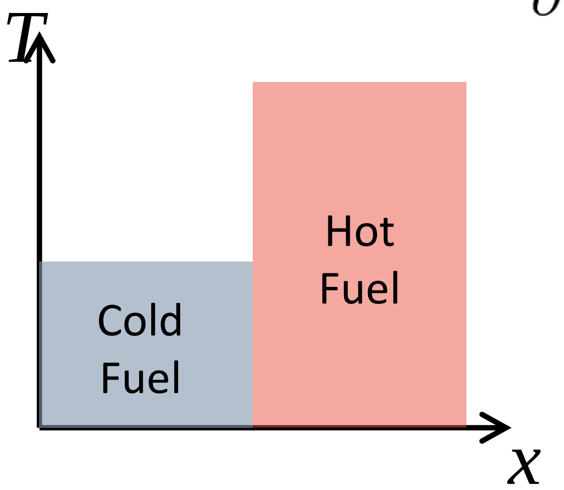
Induction eqn

$$3n\frac{DT}{D\hat{t}} + 2nT\frac{\partial \hat{u}}{\partial \hat{x}} = \frac{\partial}{\partial \hat{x}}\left[\hat{\kappa}\frac{\partial T}{\partial \hat{x}} + \hat{\beta}\frac{B}{\mu_0}\frac{\partial B}{\partial \hat{x}}\right] + \hat{q}_\alpha - \hat{P}$$

DT fuel energy eqn

$$\frac{D\mathcal{E}_\alpha}{D\hat{t}} + \frac{5}{3}\mathcal{E}_\alpha\frac{\partial \hat{u}}{\partial \hat{x}} = \frac{\partial}{\partial \hat{x}}\left(\hat{\delta}_\mathcal{E}\frac{\partial \mathcal{E}_\alpha}{\partial \hat{x}}\right) - \hat{q}_\alpha + \hat{Q}$$

α energy eqn



Induction Equation

$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}\boxed{(\hat{u}B)} = \frac{\partial}{\partial \hat{x}}\left[\boxed{\hat{\alpha}\frac{\partial B}{\partial \hat{x}}} + \left(\boxed{\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}}} + \boxed{\hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}}\right) B\right]$$

advection

Resistive diffusion, $L_m \gg 1$

Nernst effect

α flux effect

Induction Equation

$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}} \underbrace{\boxed{(\hat{u} B)}}_{\text{advection}} = \frac{\partial}{\partial \hat{x}} \left[\hat{\alpha} \frac{\partial B}{\partial \hat{x}} + \left(\underbrace{\boxed{\hat{\beta} \frac{\partial \ln T}{\partial \hat{x}}}}_{\text{Nernst effect}} + \underbrace{\boxed{\hat{\gamma} \frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}}}_{\alpha \text{ flux effect}} \right) B \right]$$

Induction Equation

$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}(\hat{u}B) = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}} + \hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}\right) B\right]$$

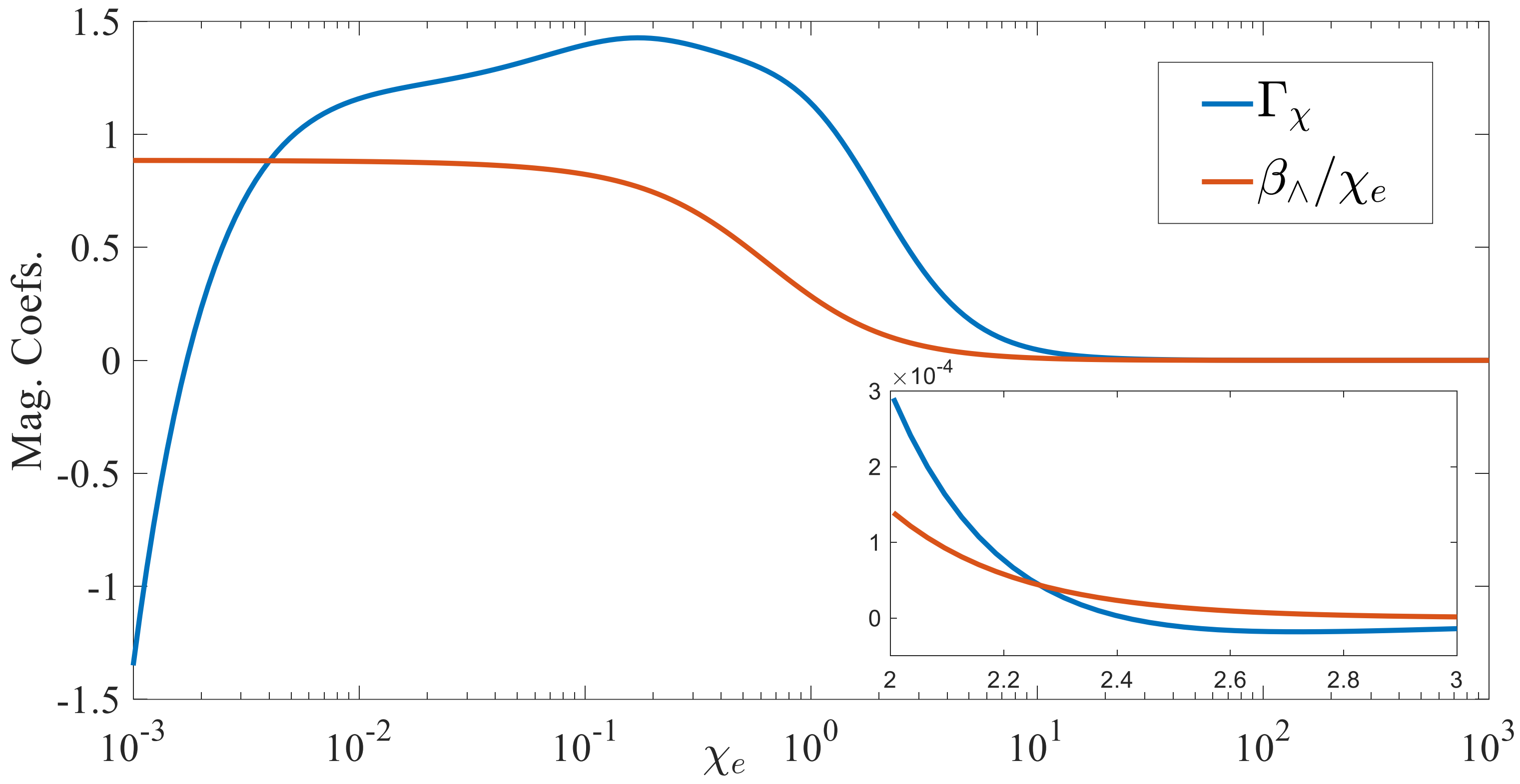
contains $j_{e\alpha}$

$$\frac{\hat{\gamma}}{\hat{\beta}} \sim \frac{E_{\alpha 0}}{6T}\frac{n_\alpha}{n}\frac{\ln \Lambda_{ei}}{\ln \Lambda_{\alpha e}}\Gamma_\chi\left(\frac{\chi_e}{\beta_\wedge}\right)$$

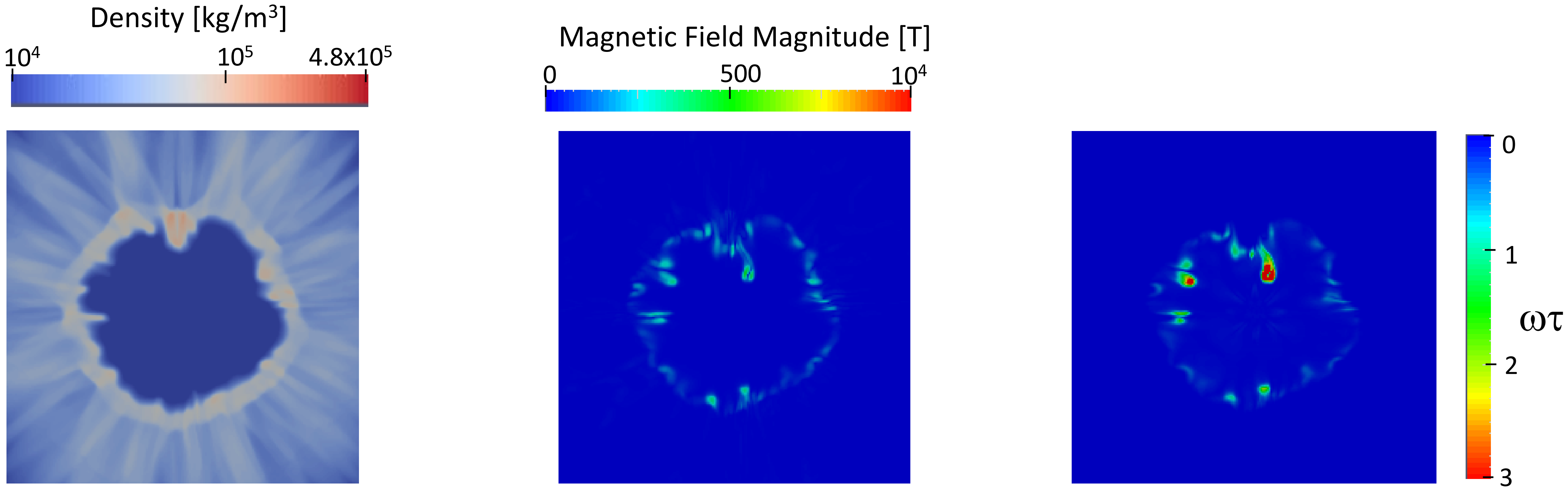
$$T \sim 1 - 10\ keV$$

$$E_{\alpha 0} = 3.45\ MeV$$

$$\hat{\gamma} \geq \hat{\beta} \ \text{ for } \ \frac{n_\alpha}{n} \geq \sim 10^{-2}$$



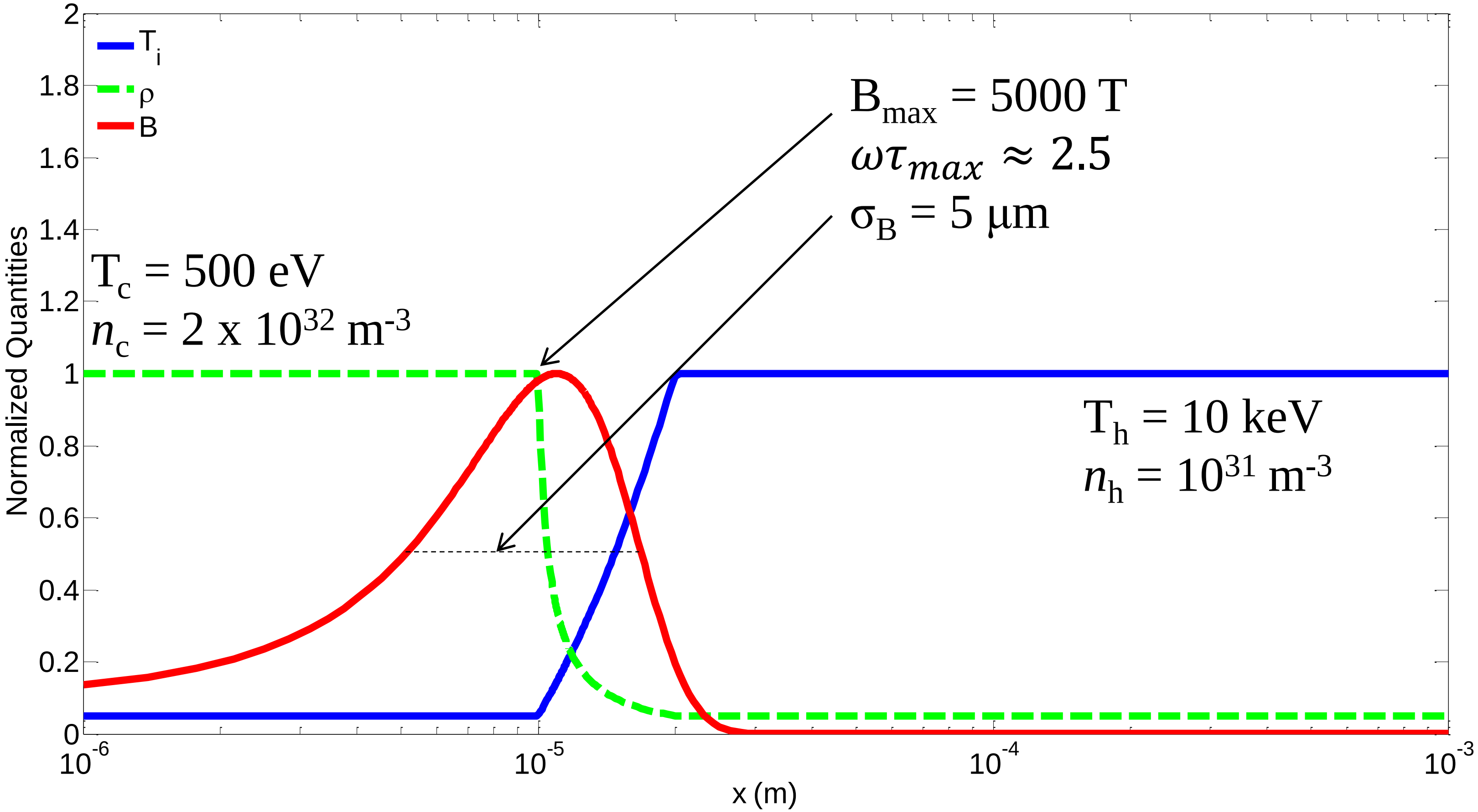
B fields in ICF



Self-generated $\boldsymbol{B}$ fields $\omega\tau > \sim 1$

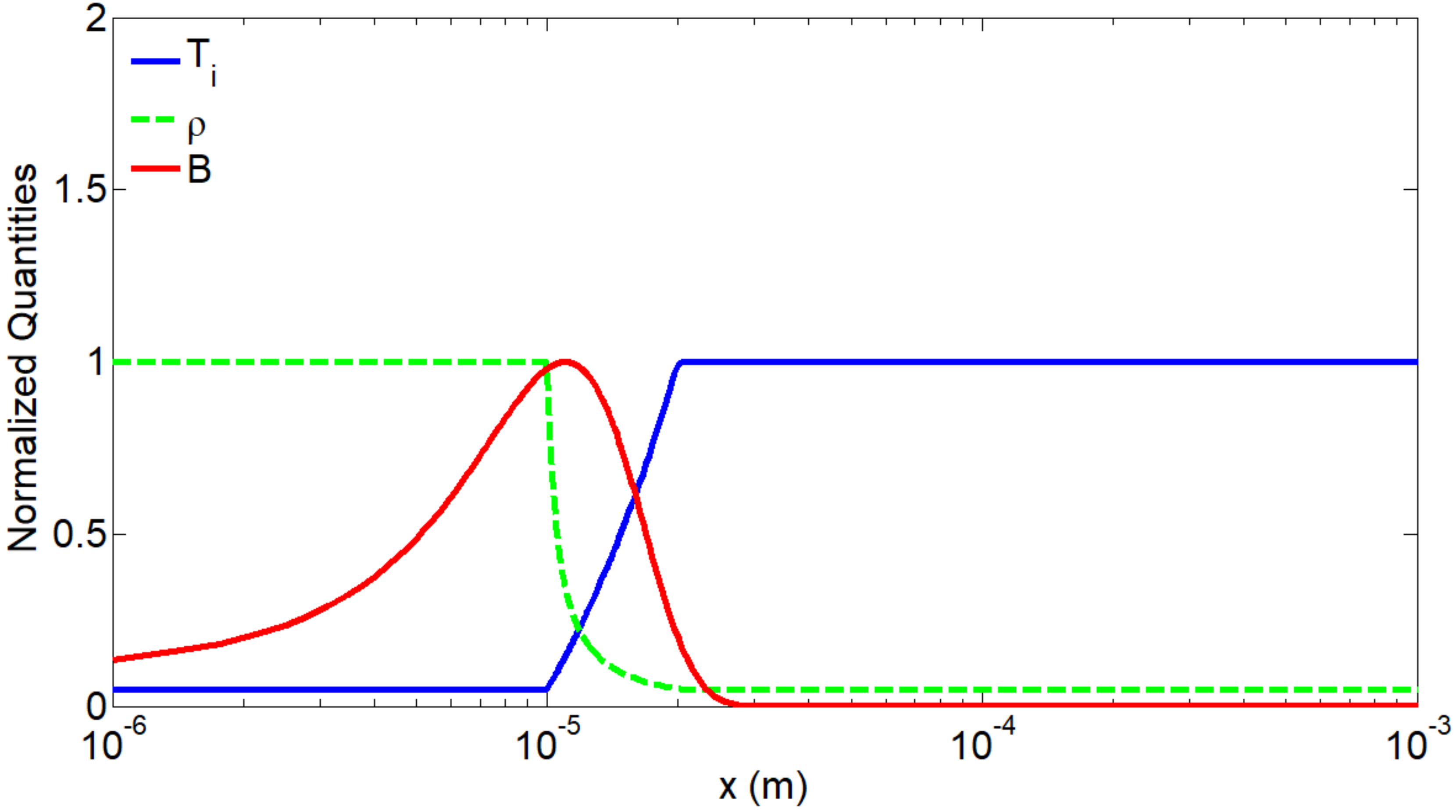
[6] Walsh et al, PRL **118**, 155001 (2017)

Simple Model for Local B field



Burn time = 100 ps

Evolution of B field



Regimes of B field transport

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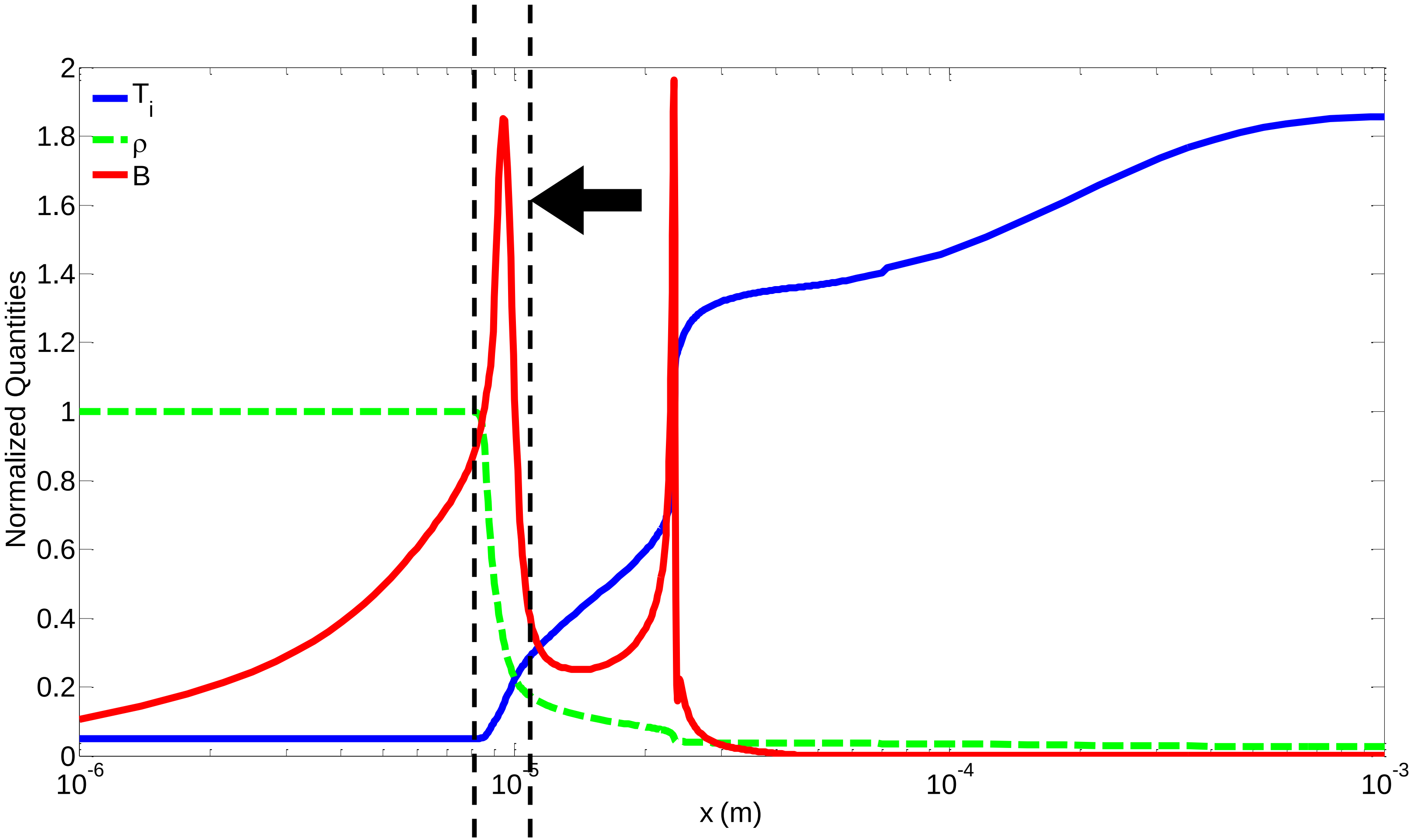
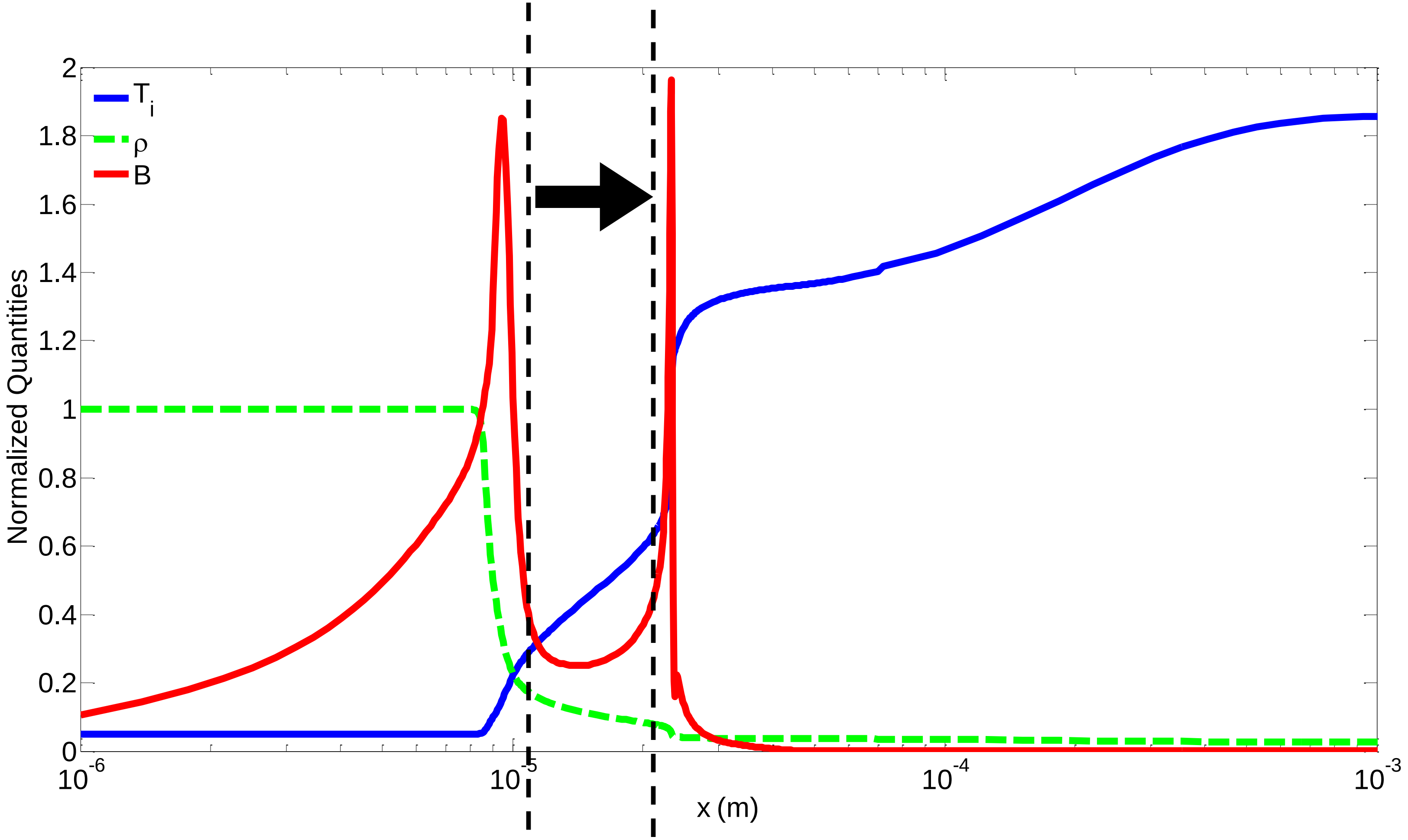


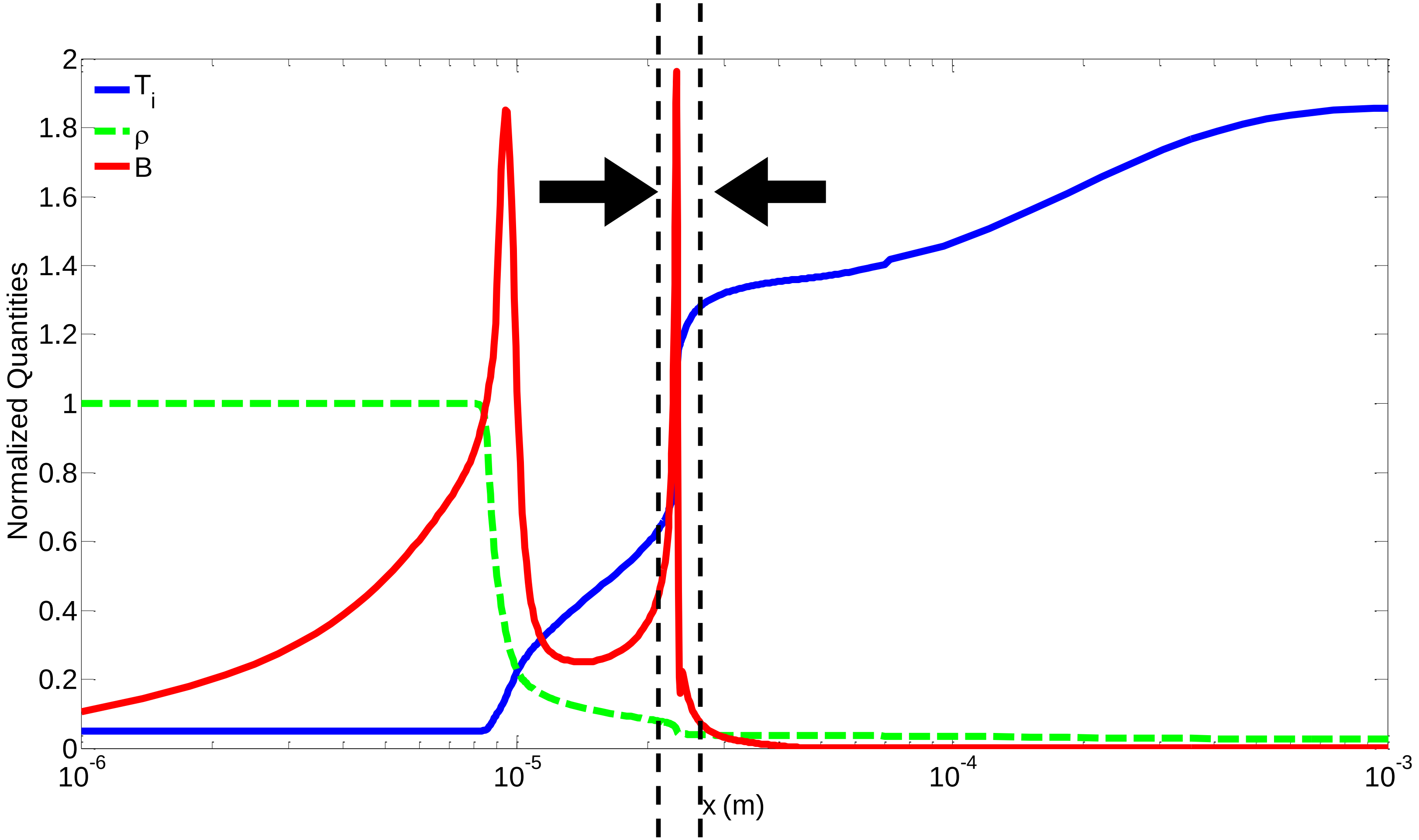
$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}\left(\hat{u}B\right) = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\boxed{\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}}} + \hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}\right)B\right]$$

Regimes of B field transport



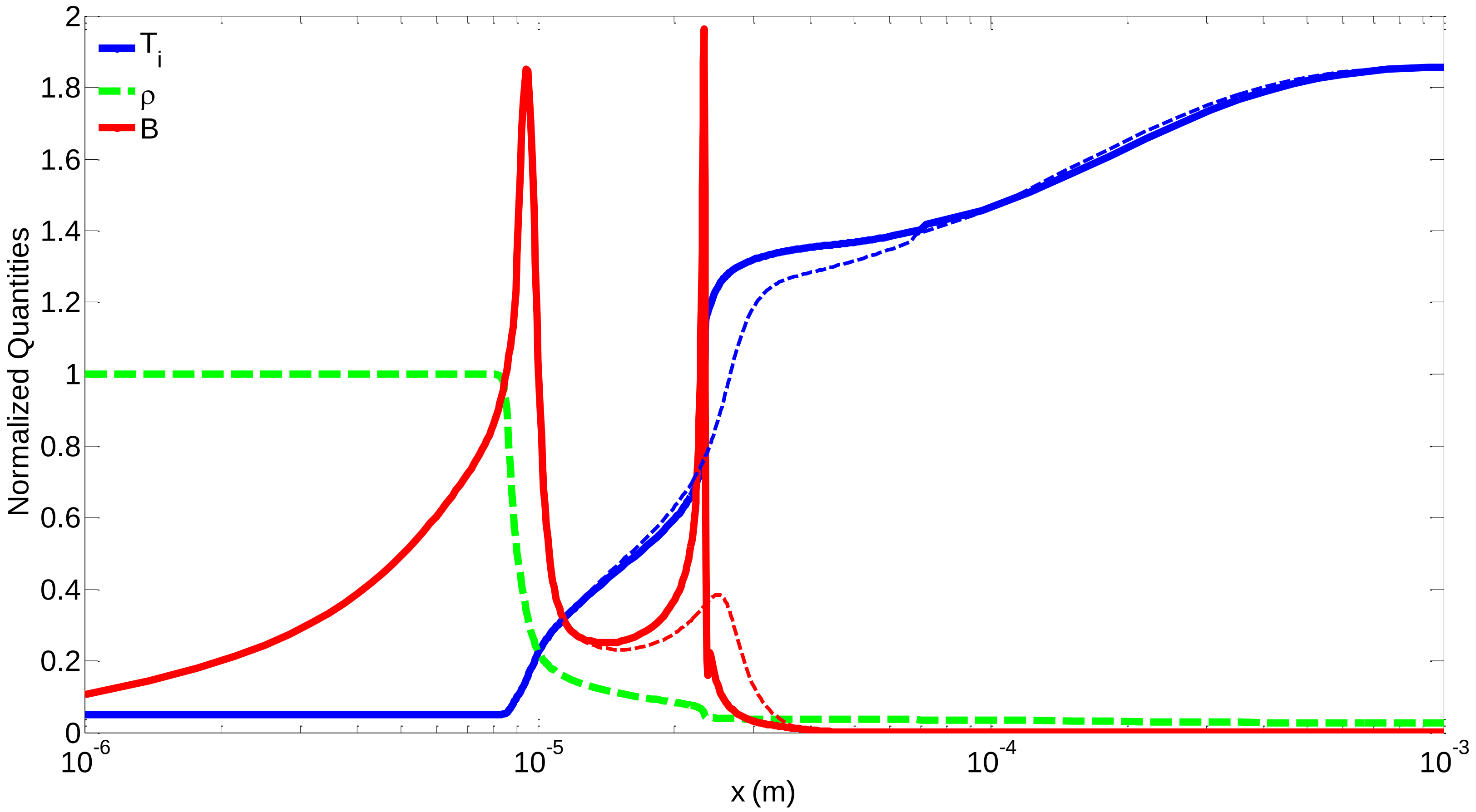
$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}\boxed{(\hat{u}B)} = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}} + \hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}\right) B\right]$$

Regimes of B field transport



$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}(\hat{u}B) = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\boxed{\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}}} + \boxed{\hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}}\right) B\right]$$

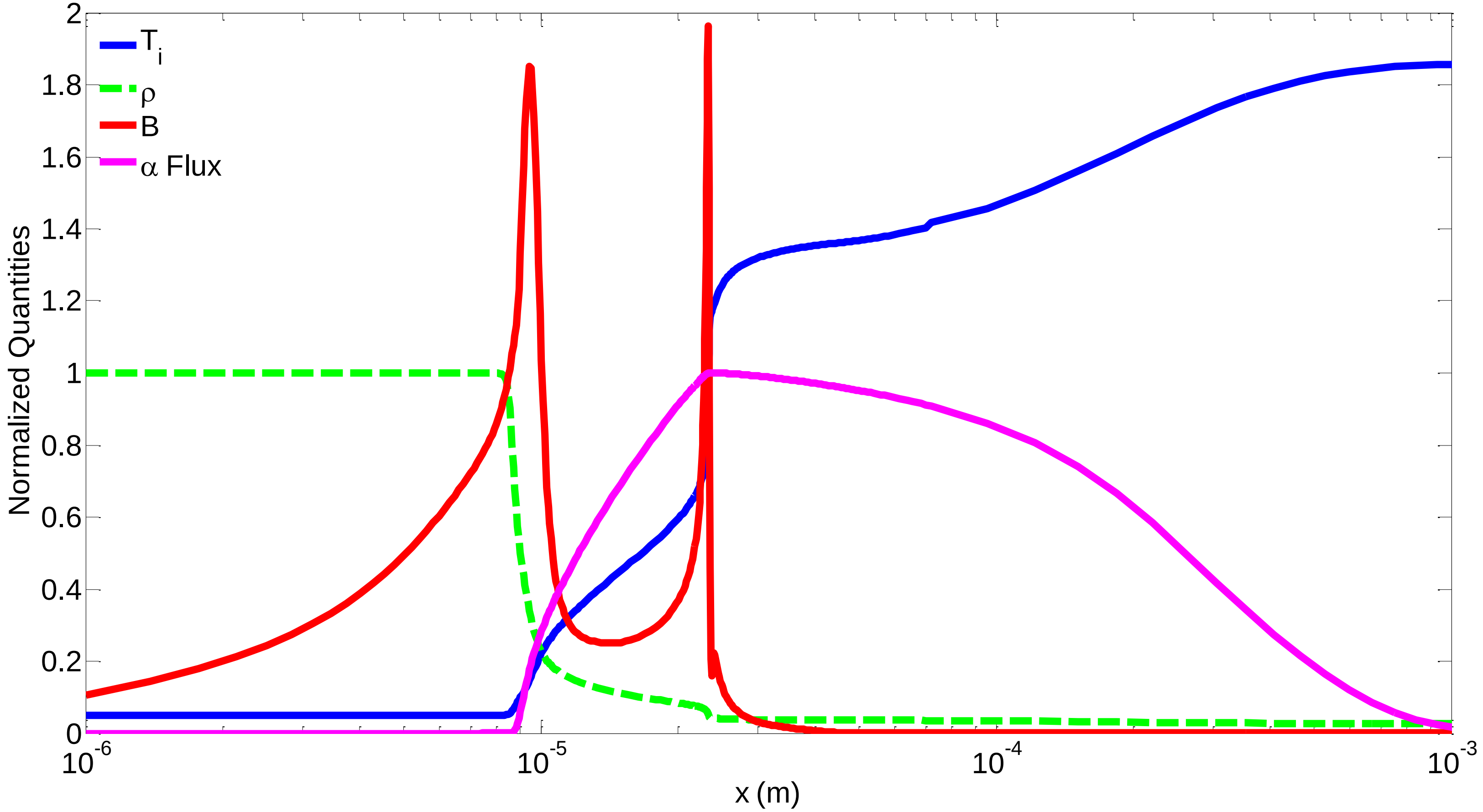
Regimes of B field transport



$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}\left(\hat{u}B\right) = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}} + \hat{\gamma}\cancel{\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}}\right)B\right]$$

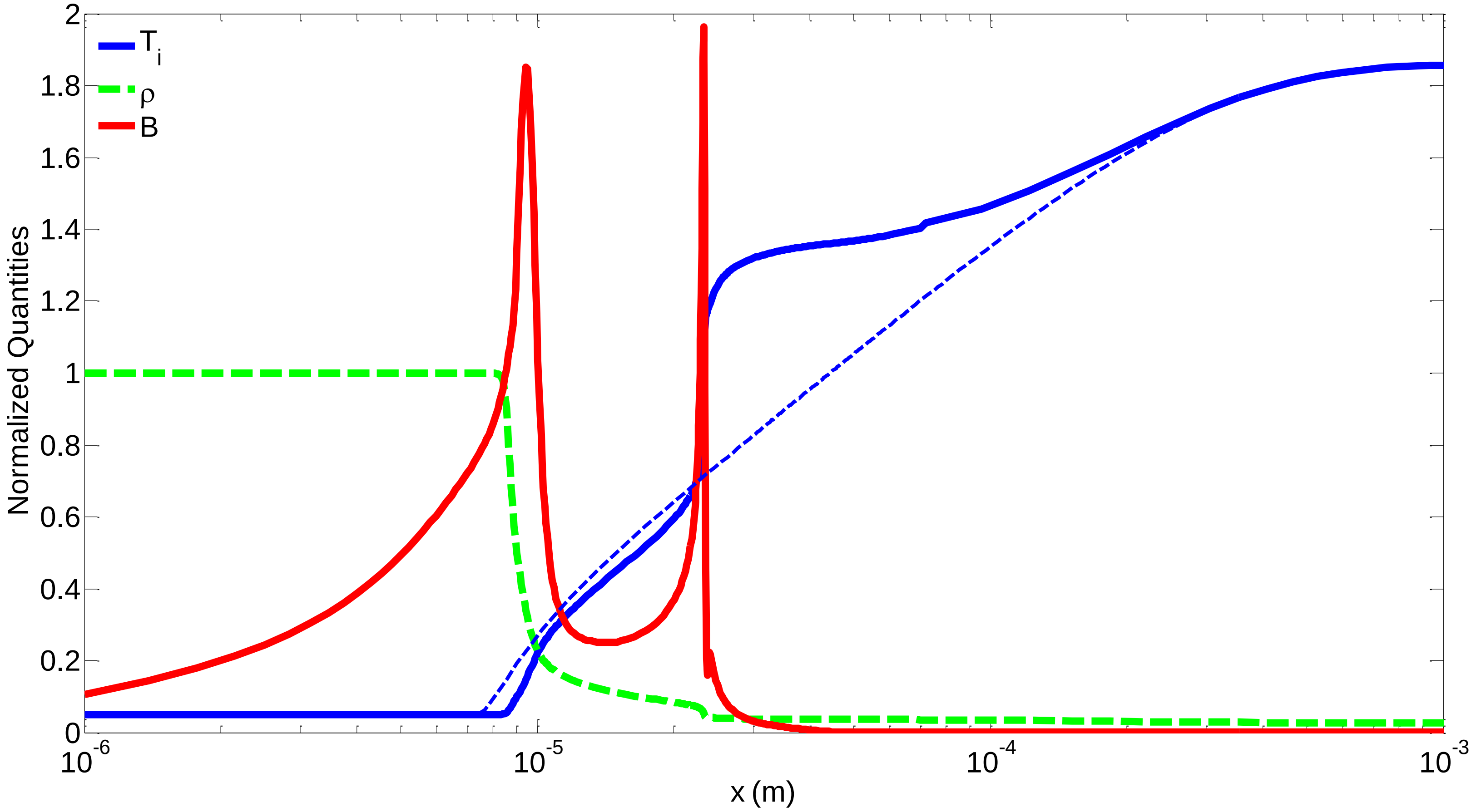
Regimes of B field transport

Imperial College London

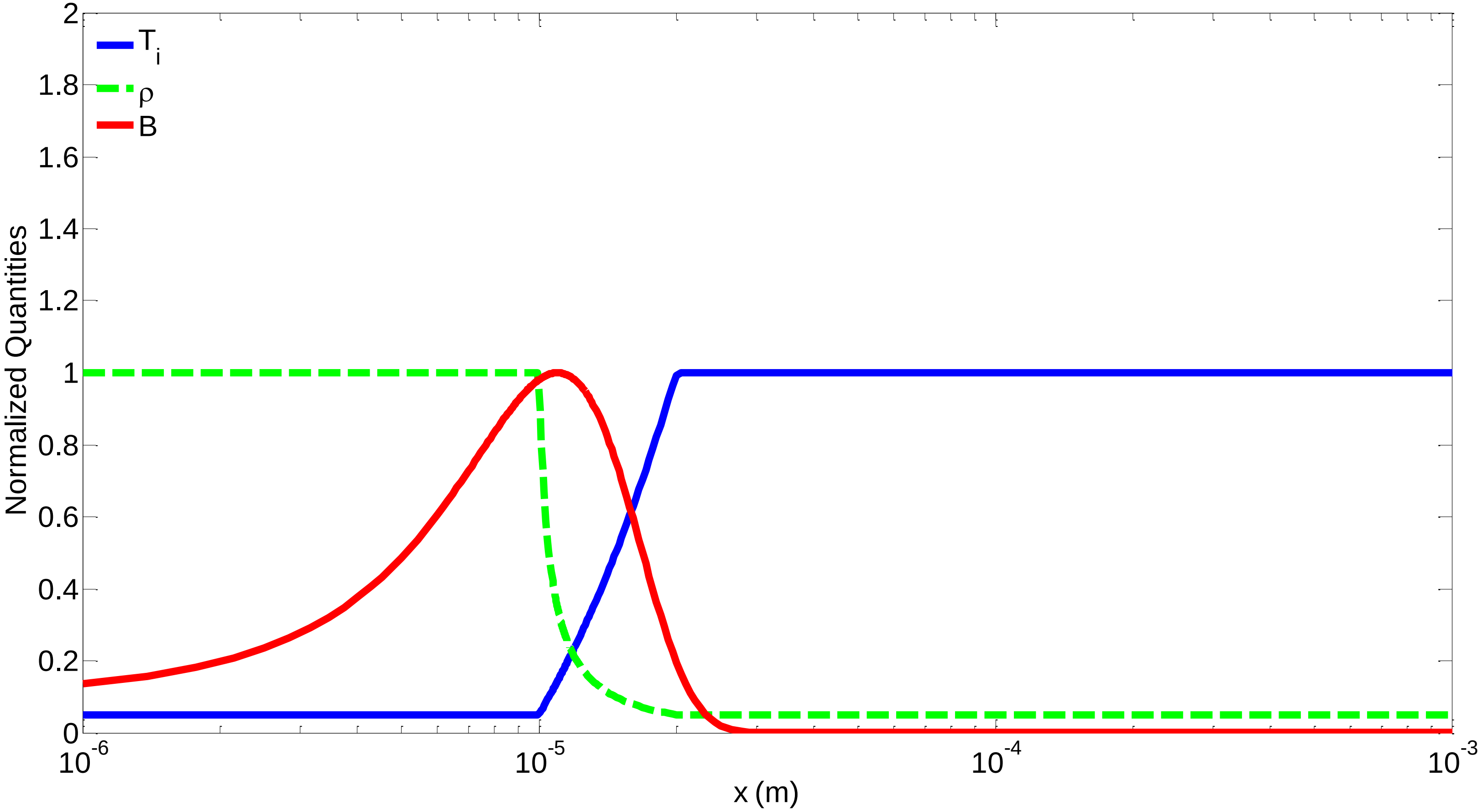


$$\frac{\partial B}{\partial \hat{t}} + \frac{\partial}{\partial \hat{x}}\left(\hat{u}B\right) = \frac{\partial}{\partial \hat{x}}\left[\hat{\alpha}\frac{\partial B}{\partial \hat{x}} + \left(\hat{\beta}\frac{\partial \ln T}{\partial \hat{x}} + \cancel{\hat{\gamma}\frac{\partial \ln \mathcal{E}_\alpha}{\partial \hat{x}}}\right)B\right]$$

Regimes of B field transport



Evolution of Hall parameter



Evolution of Hall parameter

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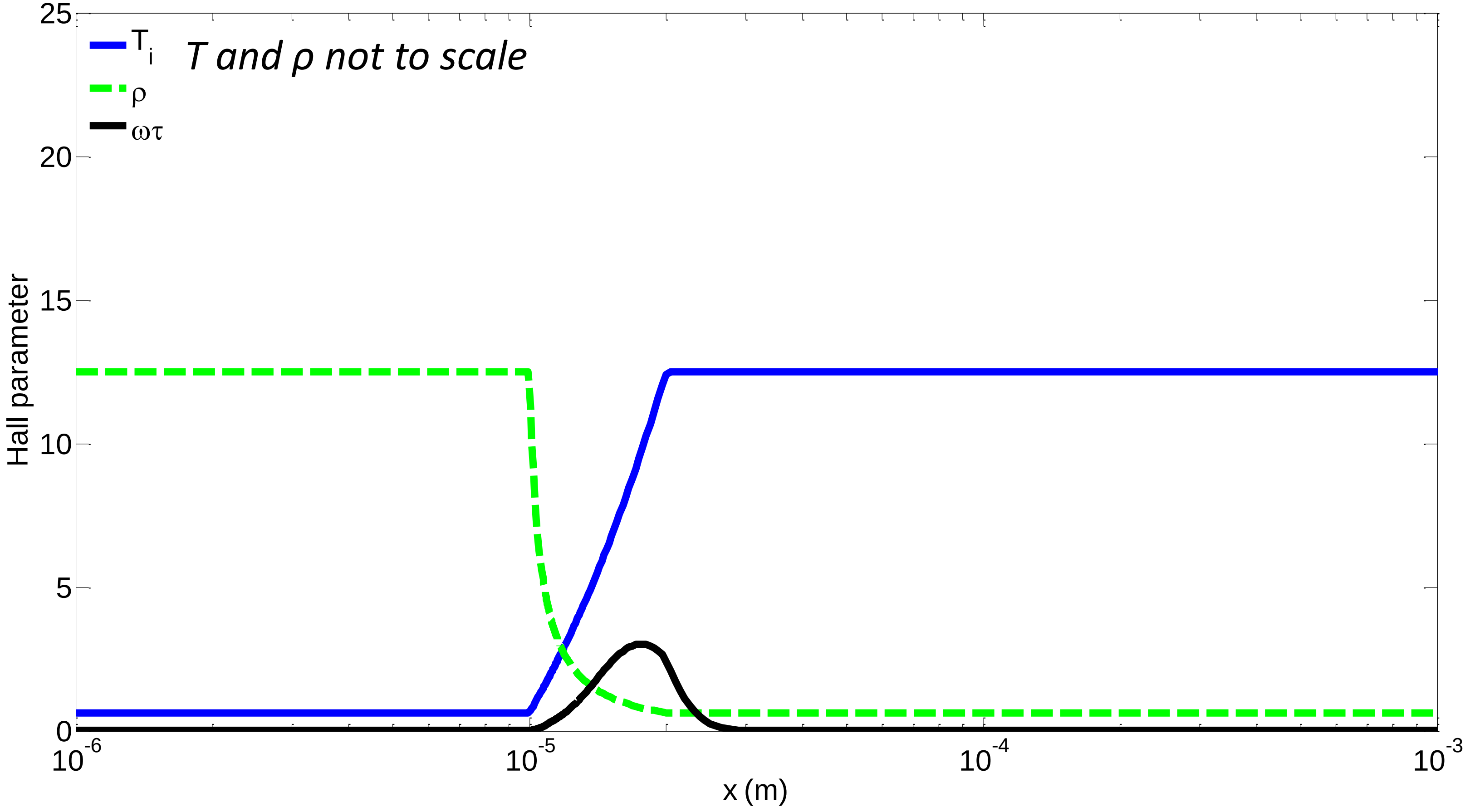

Evolution of Hall parameter

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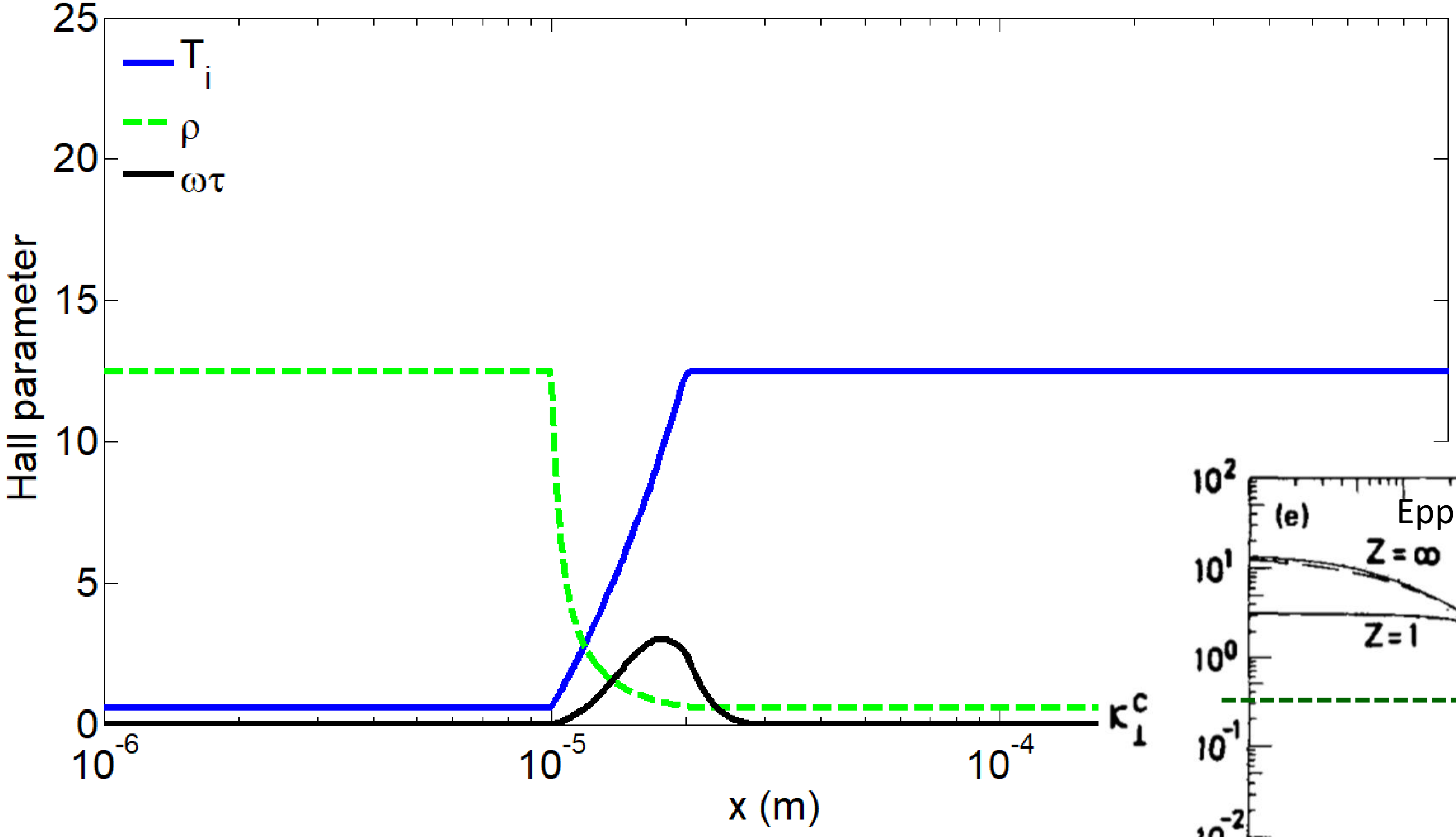
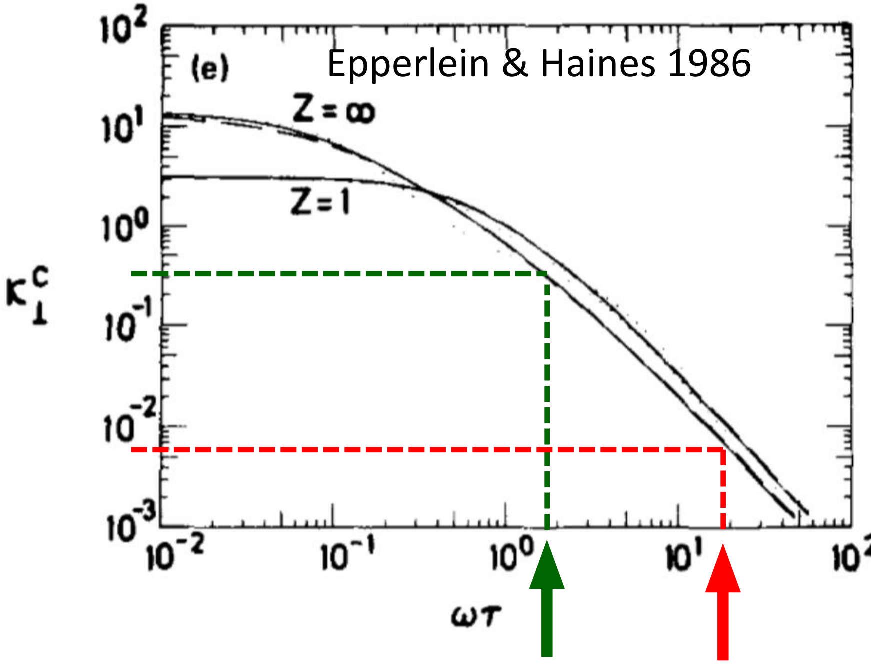
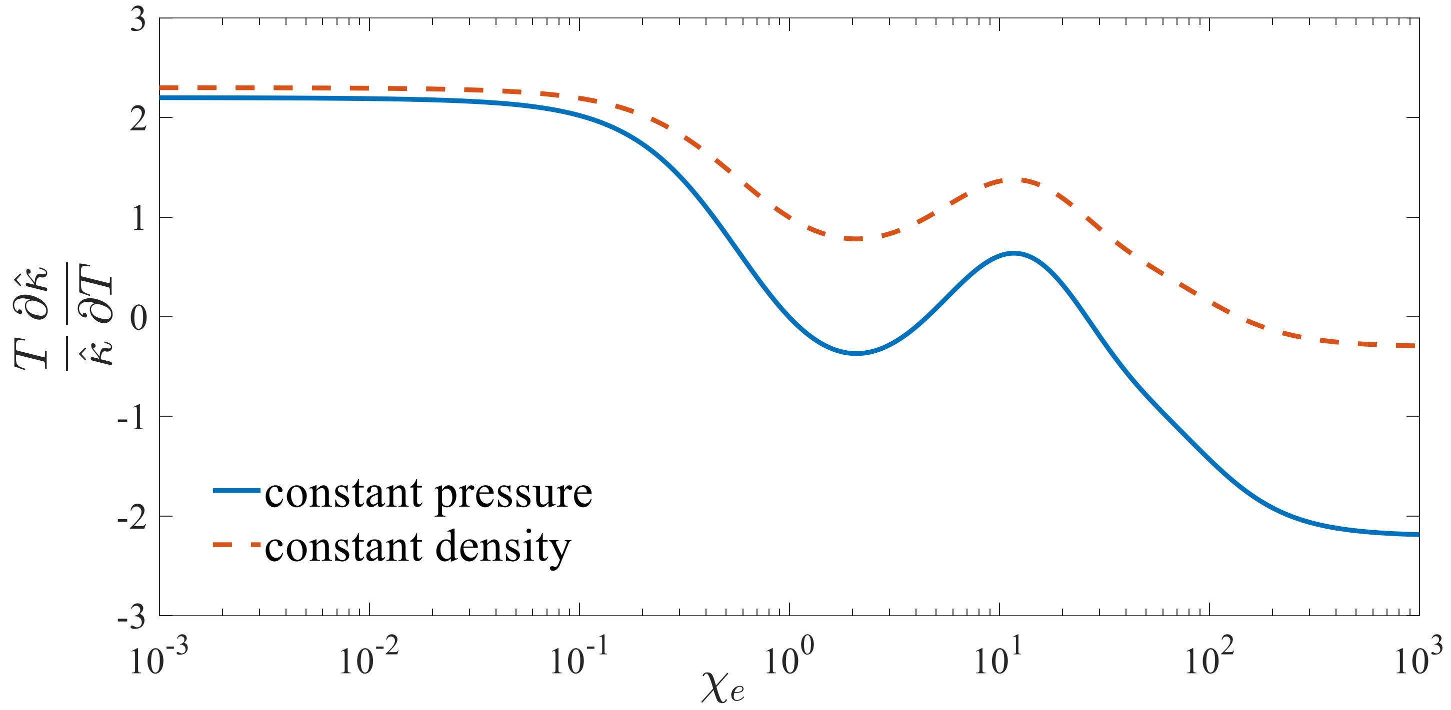


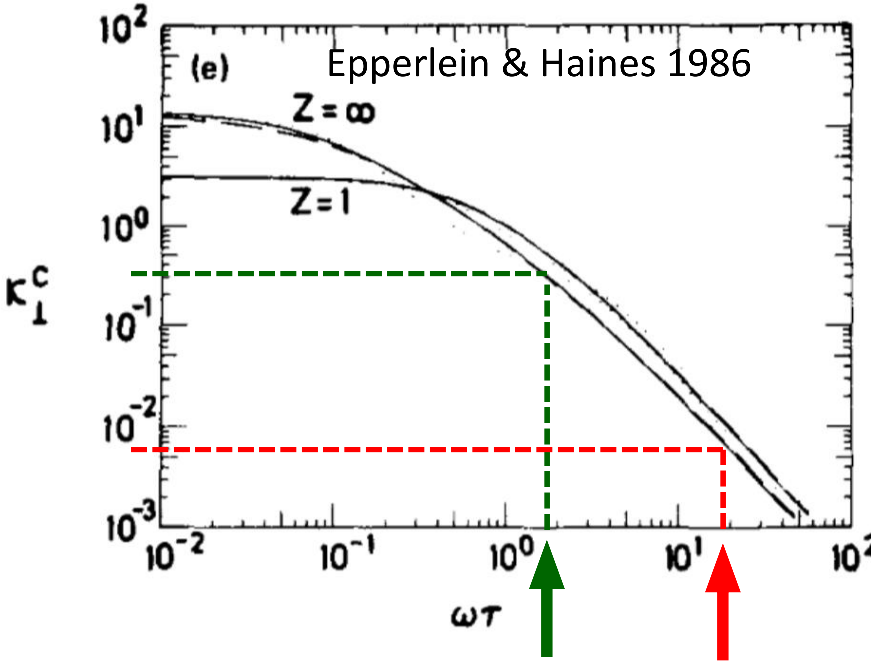


Spike in magnetization forms a narrow insulating layer between hot and cold fuel

Thermal Conductivity



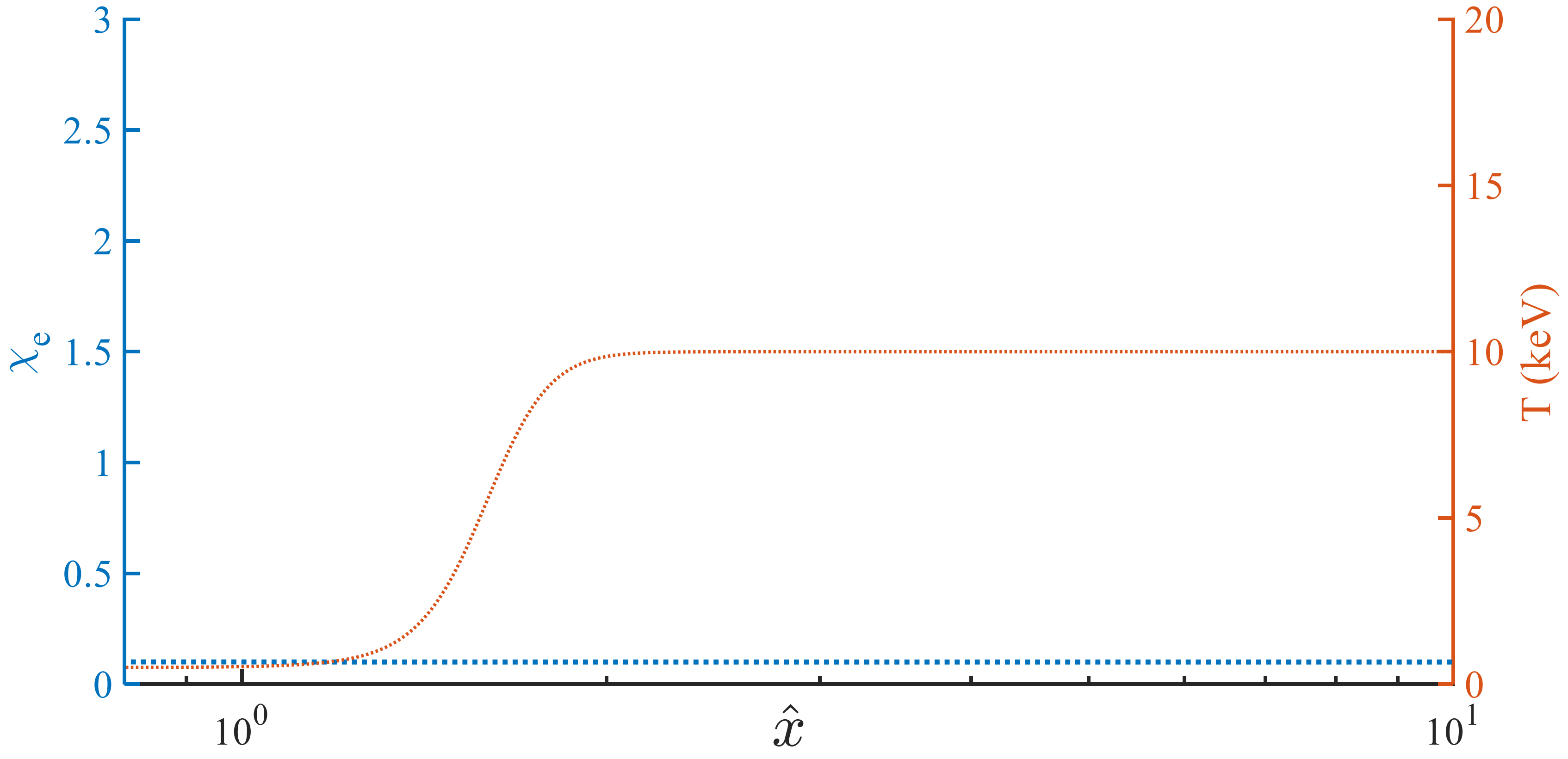
$$\kappa = \frac{nT\tau_{ei}}{m_e}\kappa_\perp^c$$



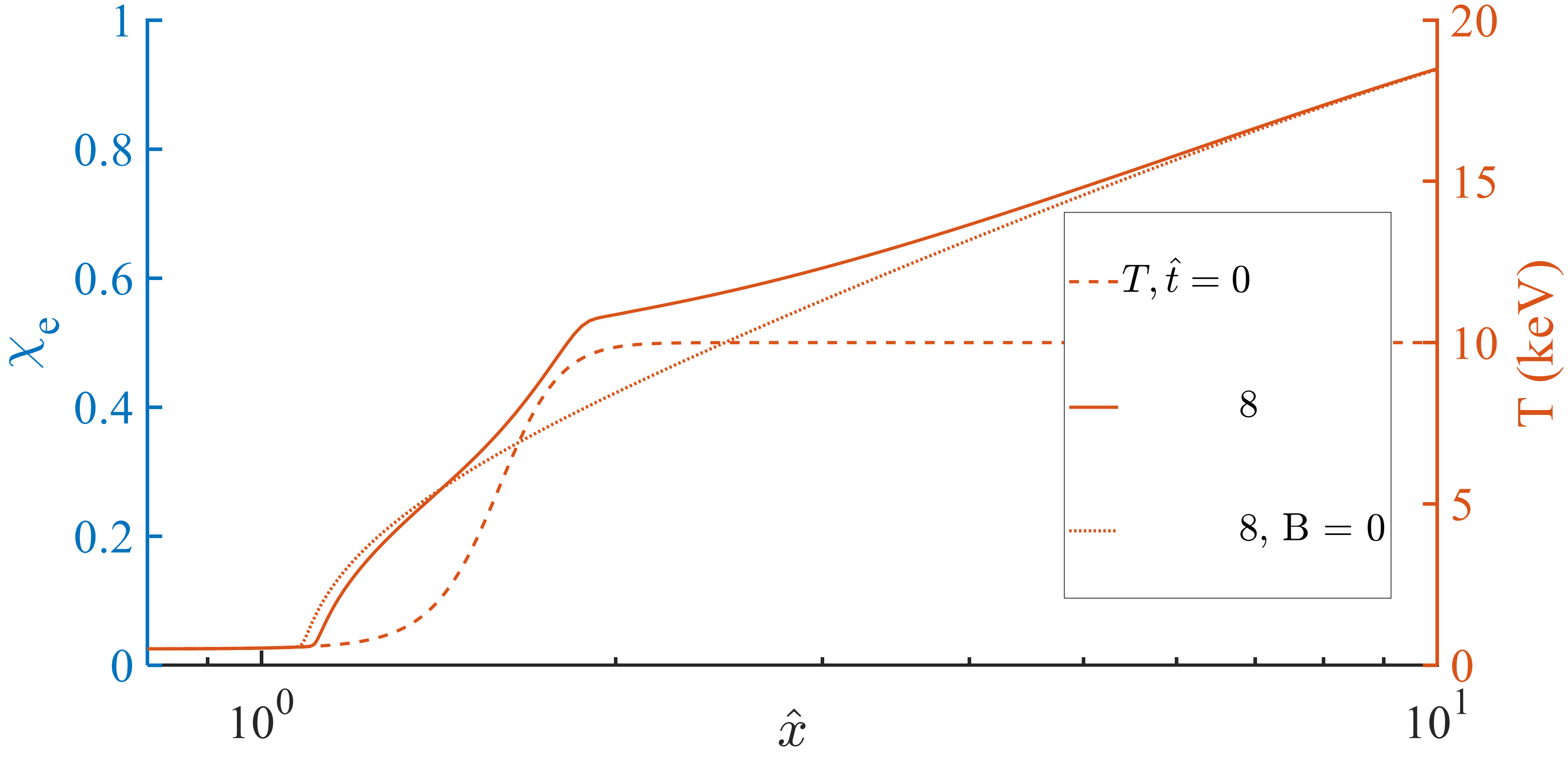
Spike in magnetization forms a narrow insulating layer between hot and cold fuel

Initially uniform χ

T_h = 10 keV
$n_h = 10^{30}$ m^{-3}

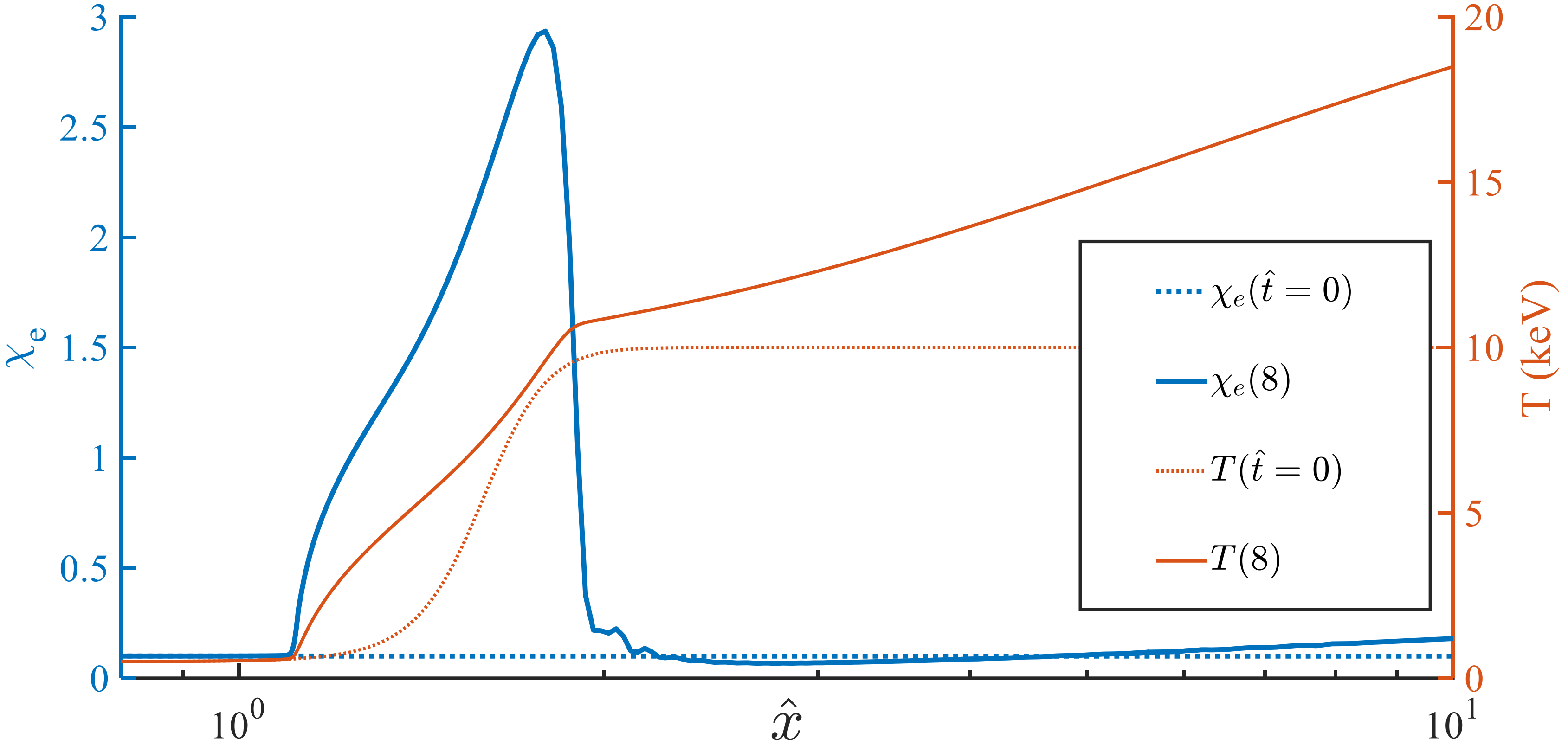


Initially uniform χ

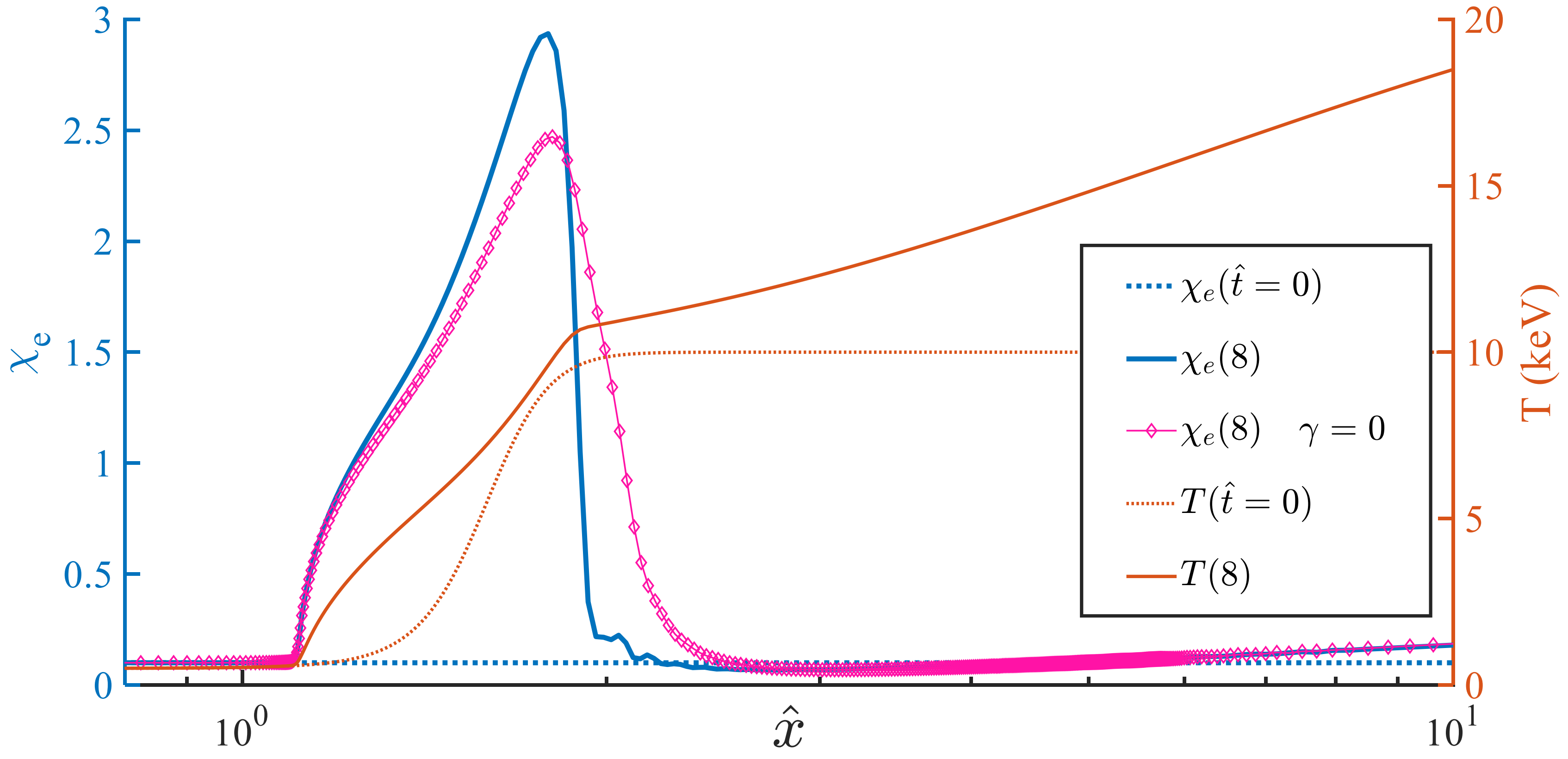


Initially uniform χ

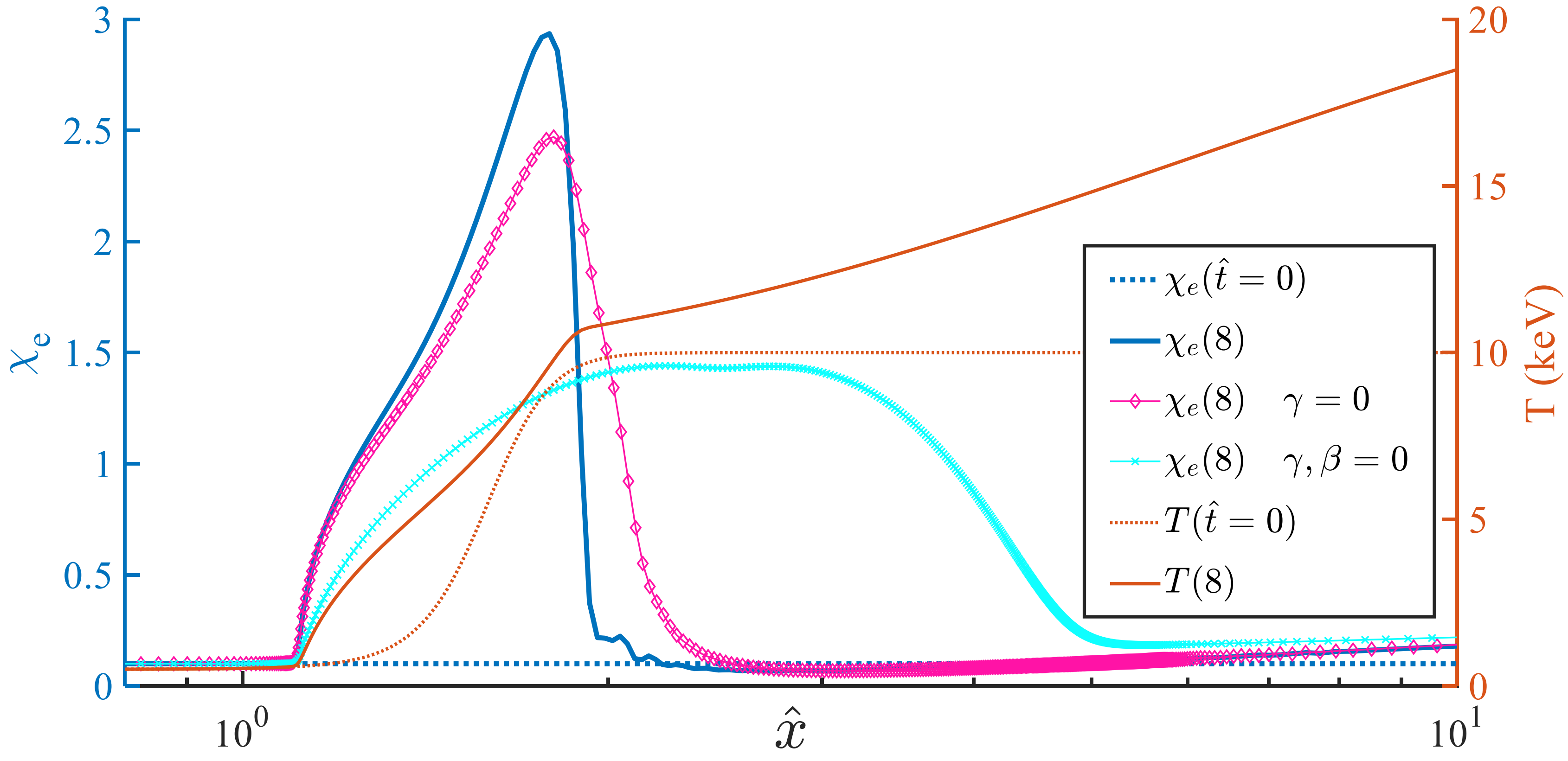
$$\sigma_\chi = \frac{D\ln\chi_e}{D\hat{t}} = \frac{1}{B}\frac{DB}{D\hat{t}} + \frac{g}{T}\frac{DT}{D\hat{t}}$$



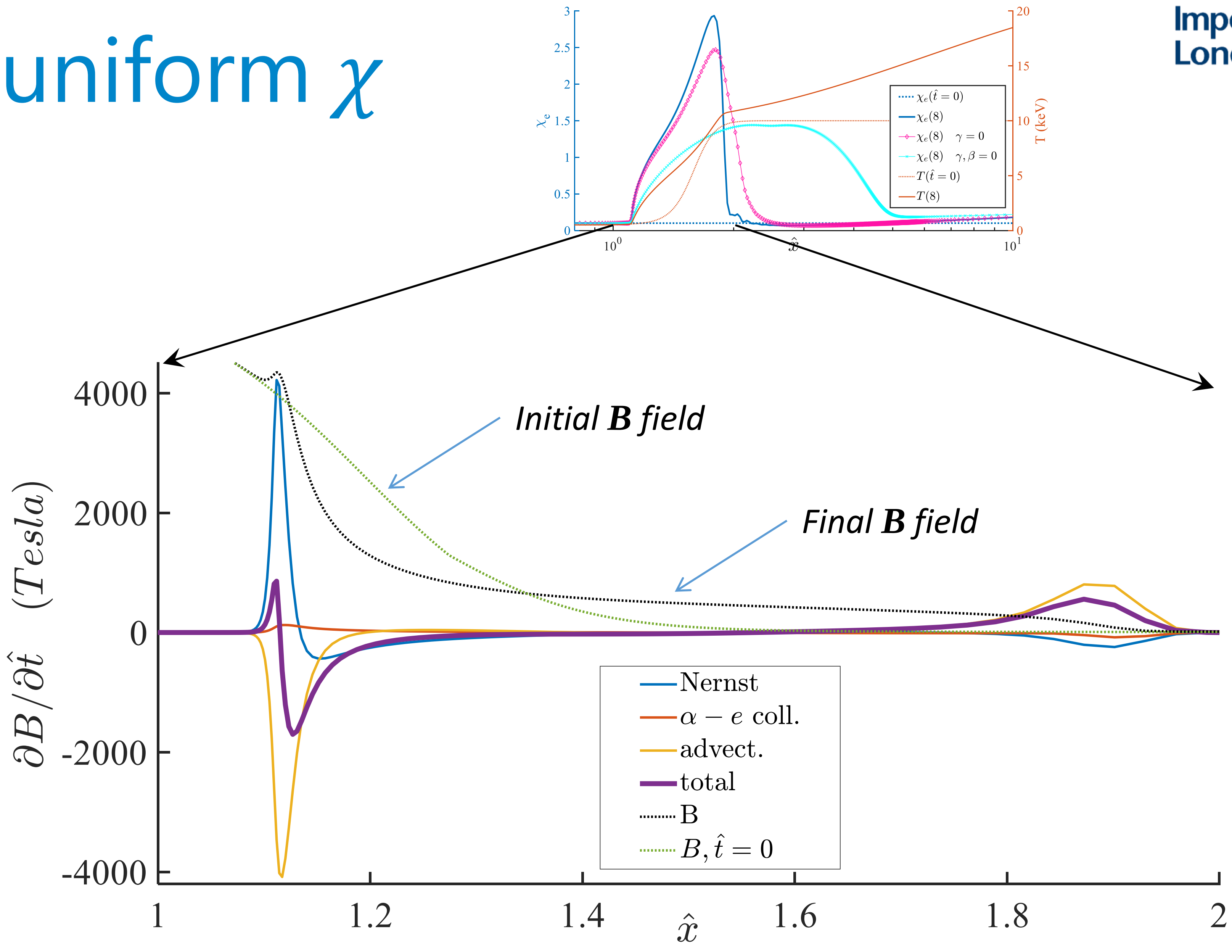
Initially uniform χ



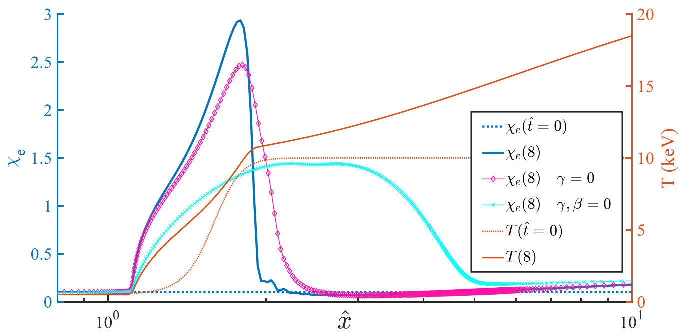
Initially uniform χ

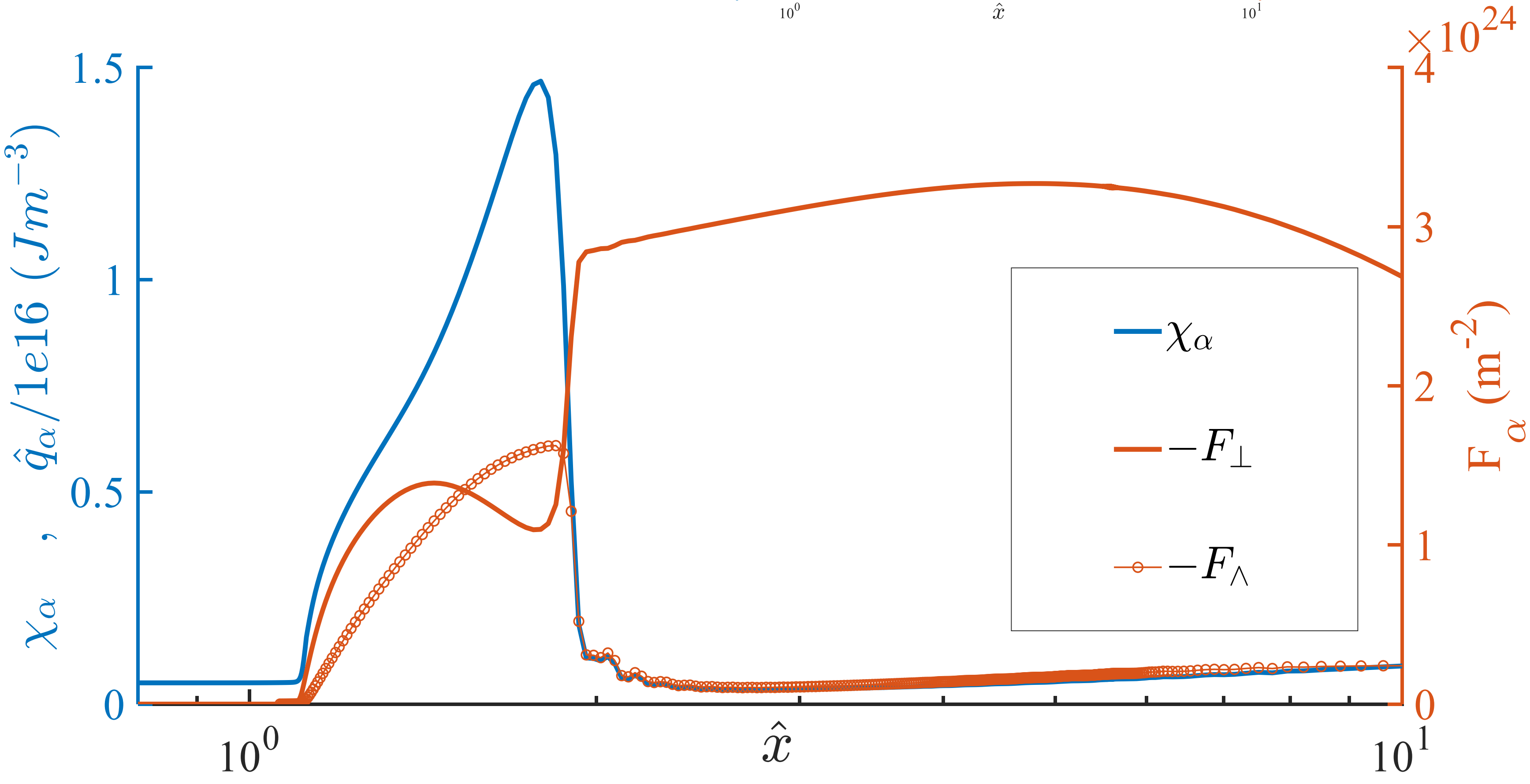


Initially uniform χ

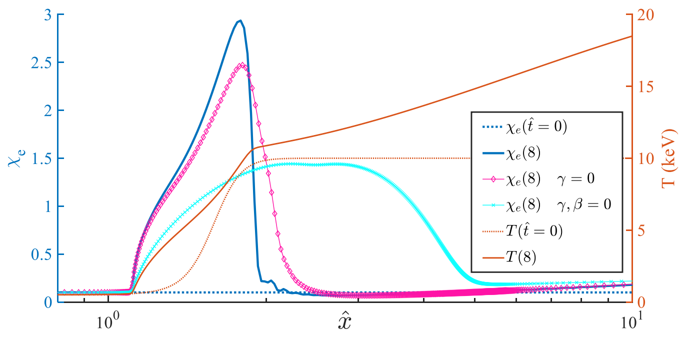


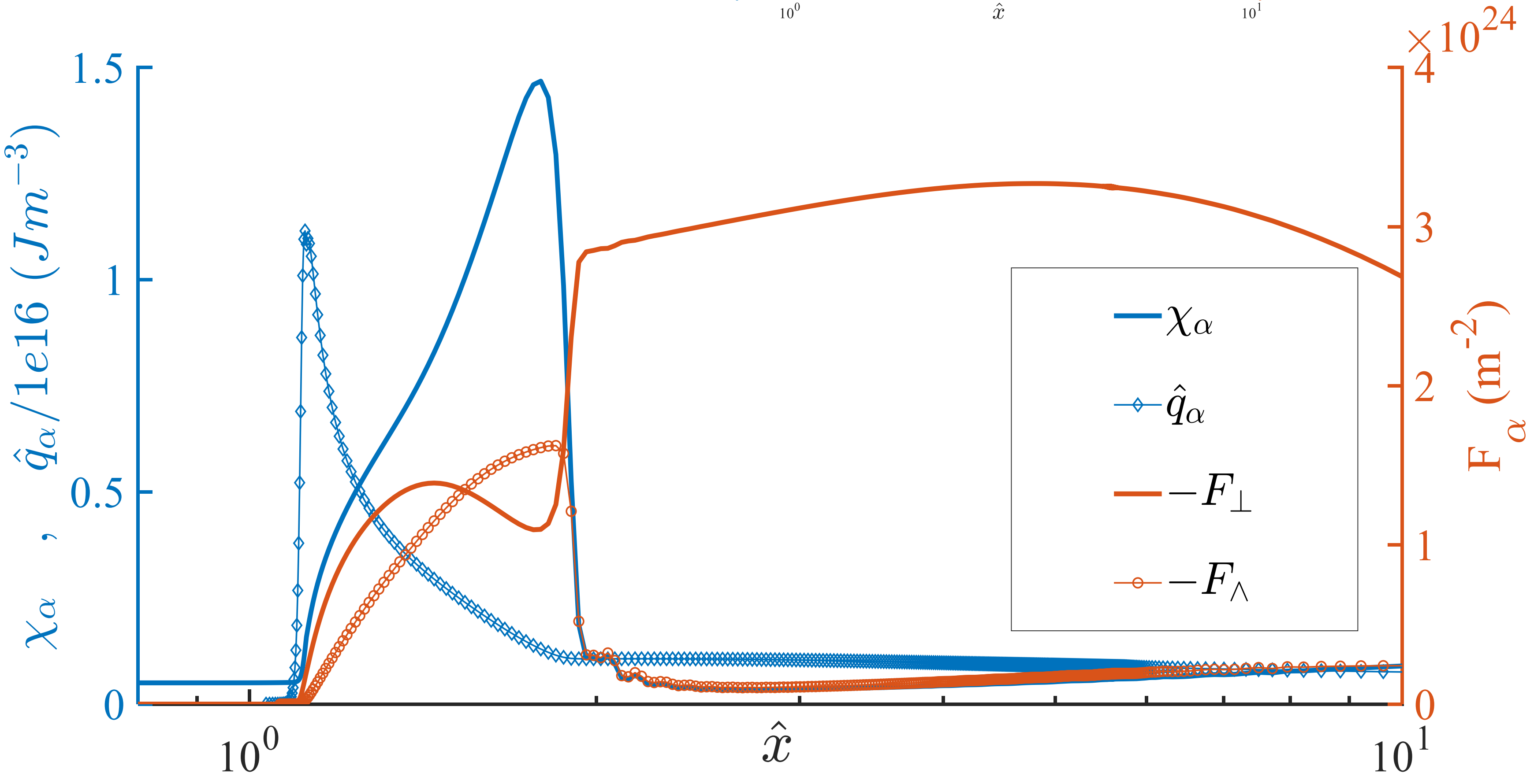
Initially uniform χ



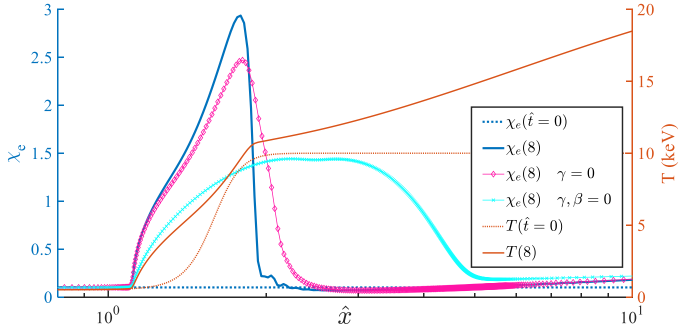


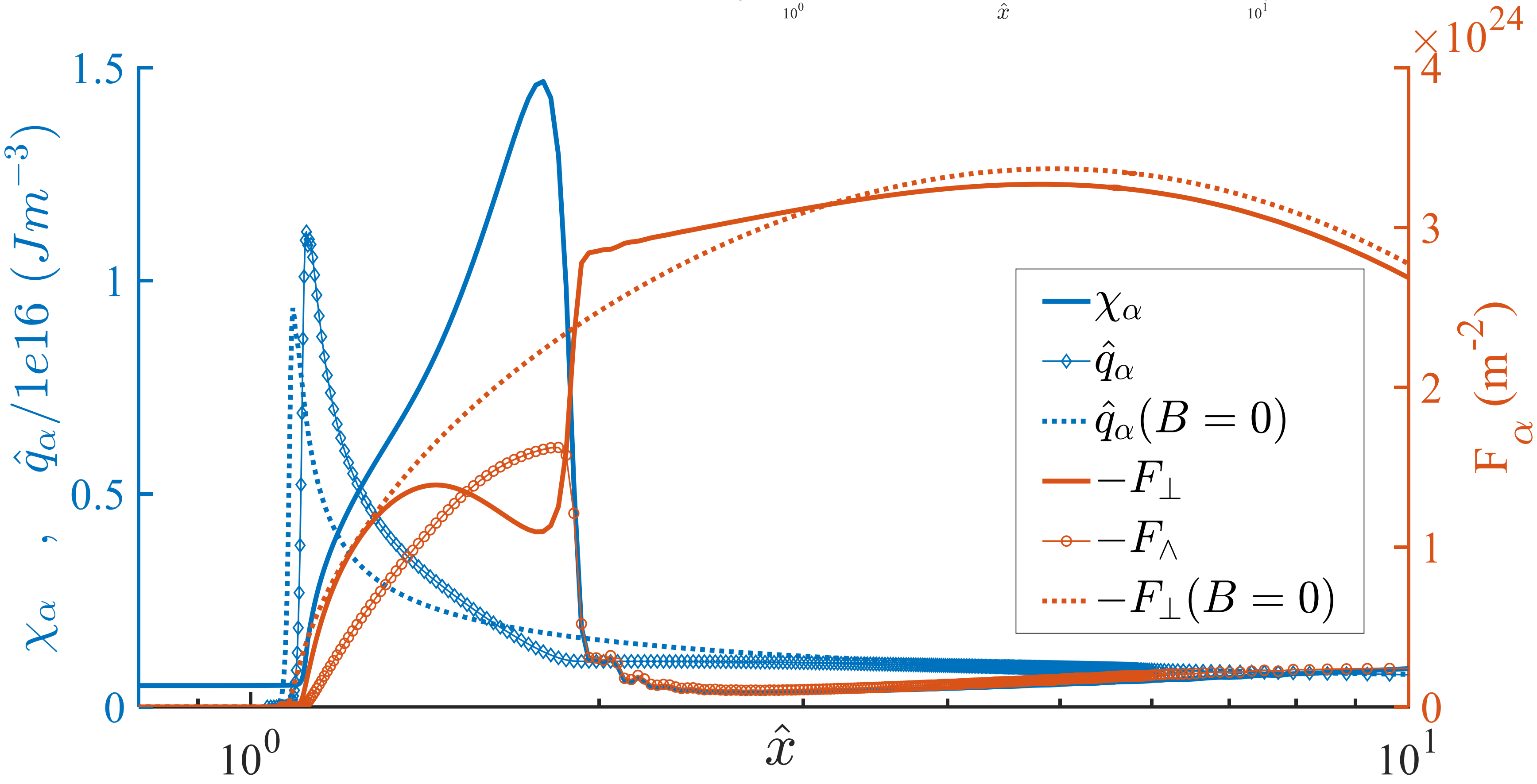
Initially uniform χ



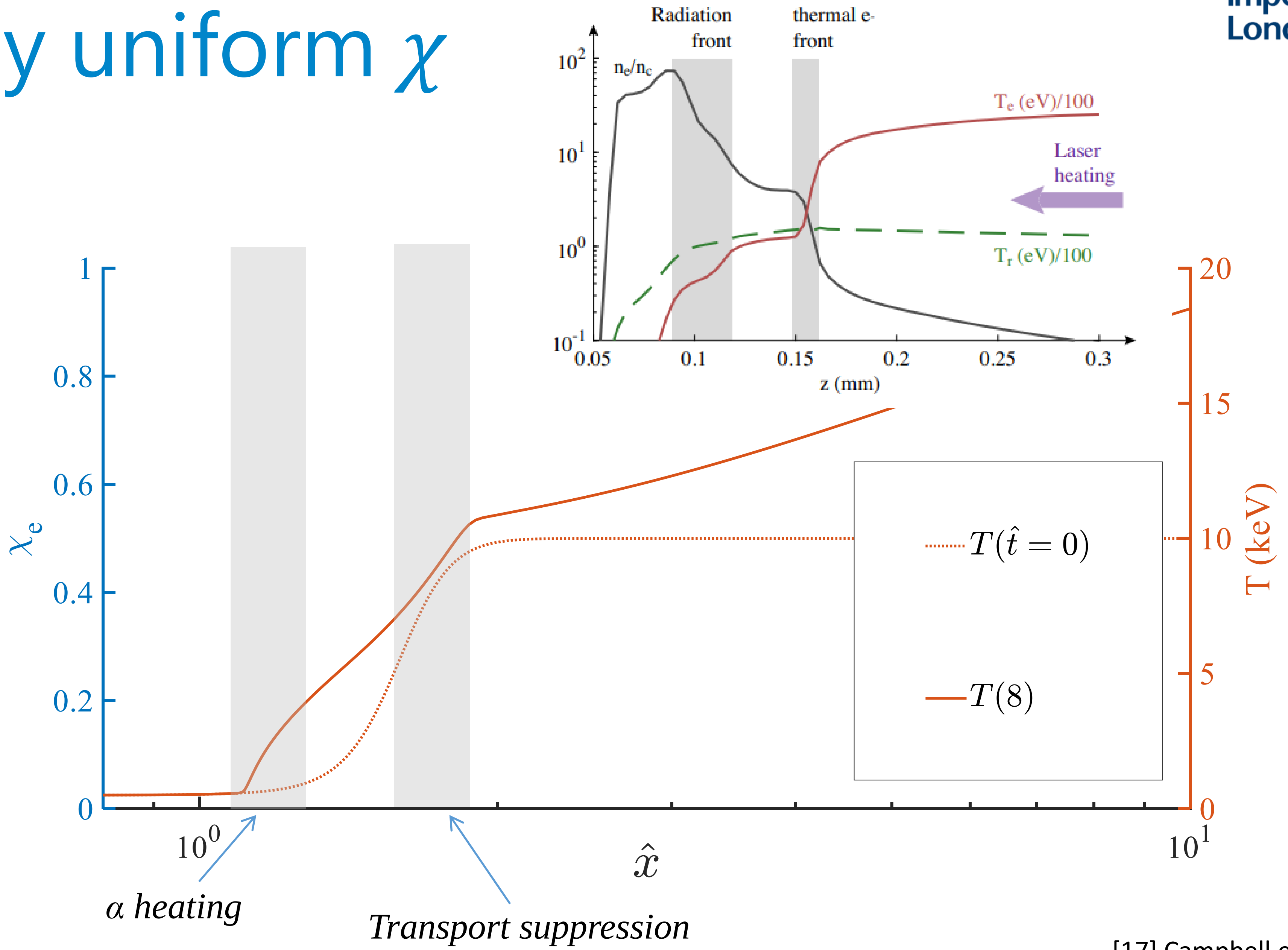


Initially uniform χ





Initially uniform χ



[17] Campbell et al, PRL **125**, 145001 (2020)

Effect of B field on burn propagation rate

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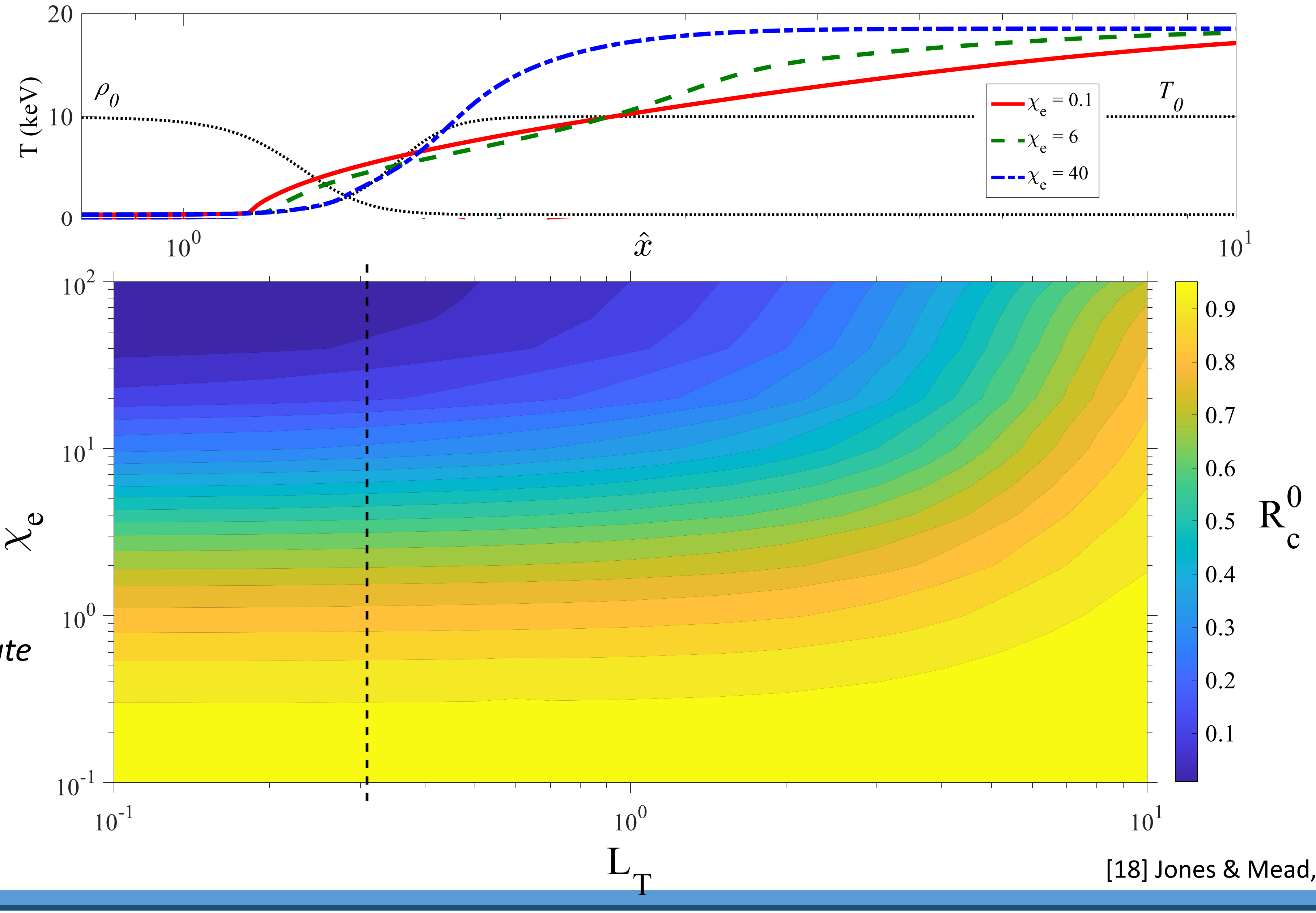

Larger χ_e reduces rate of burn propagation into cold fuel

[18] Jones & Mead, NF **26**, 127 (1986)

Contents

1. Overview of Burning Plasmas

2. The interaction of α particles with electrons
   - Appelbe et al, *Physics of Plasmas* **26**, 102704 (2019)

3. Magnetic field transport in propagating thermonuclear burn
   - Appelbe et al, *Physics of Plasmas* **28**, 032705 (2021)

4. Conclusions

Conclusions

- $\boldsymbol{\alpha}$ flux generates a collisionally-induced current in burning DT plasma
  - This current can generate and transport $\boldsymbol{B}$ field
  - Can perturbation of electrons have any other effects?
- Multiple processes contribute to $\boldsymbol{B}$ field transport at a propagating burn front
  - What transport effects occur in 2D/3D?
  - How does $\boldsymbol{B}$ field transport interact with instabilities?
- Magnetization grows rapidly at burn front, reducing energy transport
  - How significant is this effect in spherical/cylindrical geometry?