LA-UR-20-28574
Approved for public release; distribution is unlimited.

Title: Magnetic and kinetic effects in the hot-spot of inertial confinement fusion implosions

Author(s): Sadler, James David
Li, Hui
Flippo, Kirk Adler
Haines, Brian Michael
Walsh, Christopher A

Intended for: Asia Pacific Conference on Plasma Physics, 2020-10-26/2020-10-31 (Los Alamos (online), New Mexico, United States)

Issued: 2020-11-18 (rev.1)

Magnetic and kinetic effects in the hot-spot of inertial confinement fusion implosions

James Sadler
Hui Li
Kirk Flippo
Brian Haines
Los Alamos National Laboratory
james4sadler@lanl.gov

Chris Walsh
Lawrence Livermore National Laboratory

Los Alamos NATIONAL LABORATORY EST.1943

NNSA National Nuclear Security Administration

Managed by Triad National Security, LLC for the U.S. Department of Energy's NNSA

LA-UR-20-28574

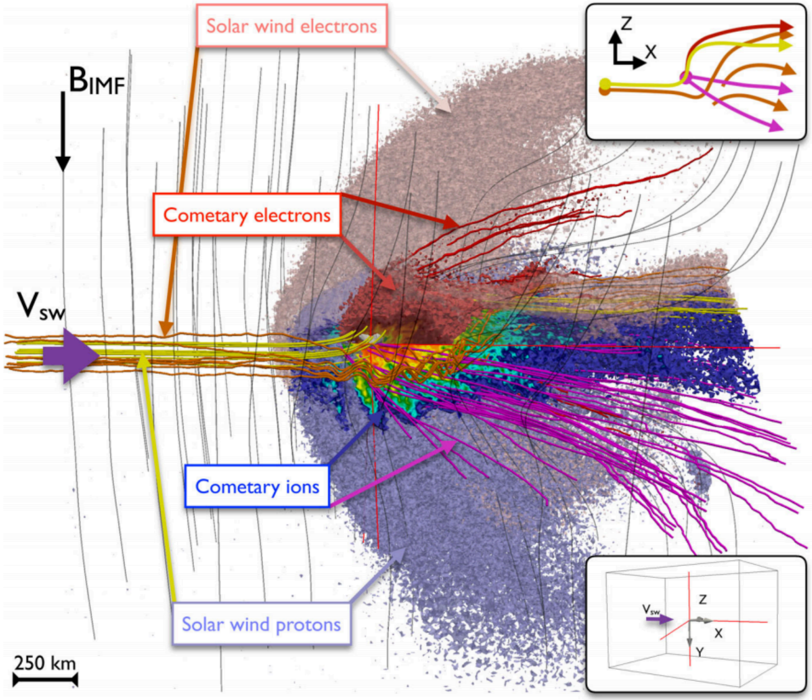
Magneto-hydrodynamics transport

- MHD – B field is advected with fluid flow
  - ICF capsule
  - Z pinch
  - Solar wind

$$m_e n_e \left(\frac{\partial \mathbf{u_e}}{\partial t} + \mathbf{u_e}.\nabla \mathbf{u_e} \right) = -\nabla.\mathbf{P_e} - e n_e \left(\mathbf{E} + \mathbf{u_e} \times \mathbf{B} \right)$$

$$\mathbf{E} = -\mathbf{u_e} \times \mathbf{B} - \frac{\nabla.\mathbf{P_e}}{n_e e} = -\mathbf{u} \times \mathbf{B} + \frac{\mathbf{J} \times \mathbf{B}}{n_e e} - \frac{\nabla.\mathbf{P_e}}{n_e e}$$

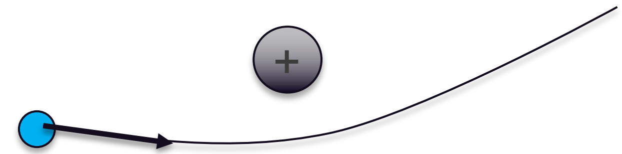
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} = \nabla \times (\mathbf{u} \times \mathbf{B}) = -\nabla.(\mathbf{u}\mathbf{B}) + \mathbf{B}.\nabla \mathbf{u}$$



Jan Deca et al., PRL 118 205101 (2017)

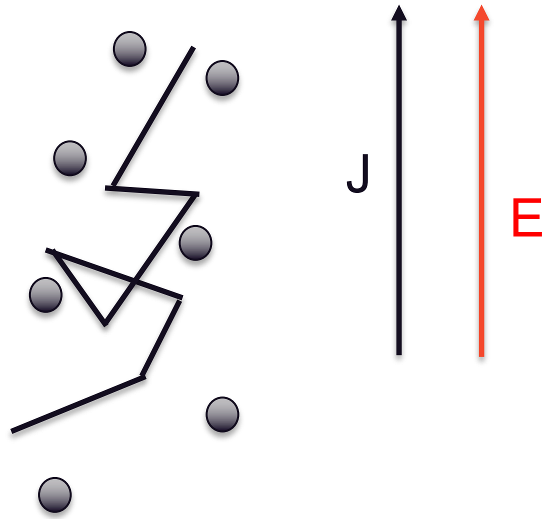
Plasma resistance

- Plasma is not a perfect conductor



- Electrons scattering timescale:
  - <1ns in laser plasmas

$$\tau = \frac{3.4\times 10^5}{\bar{Z}\ln(\Lambda)}\left(\frac{T_e}{\mathrm{eV}}\right)^{3/2}\left(\frac{n_e}{\mathrm{cm}^{-3}}\right)^{-1}\ \mathrm{s},$$



$$\frac{\partial \mathbf{v}}{\partial t} = -\frac{e}{m_e}\mathbf{E} - \frac{\mathbf{v}}{\tau}$$

$$\mathbf{E} = -\frac{m_e}{e\tau}\mathbf{v} = \frac{m_e}{n_e e^2 \tau}\mathbf{J}$$

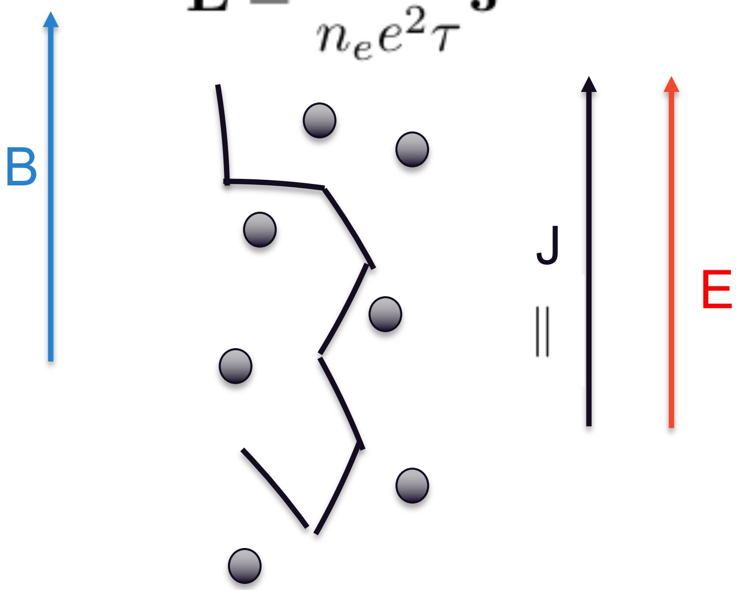
Spitzer Resistivity

Actually there should be an order 1 ‘transport coefficient’ here

Things are more complicated…
Strong B field affects the resistance - Braginskii MHD

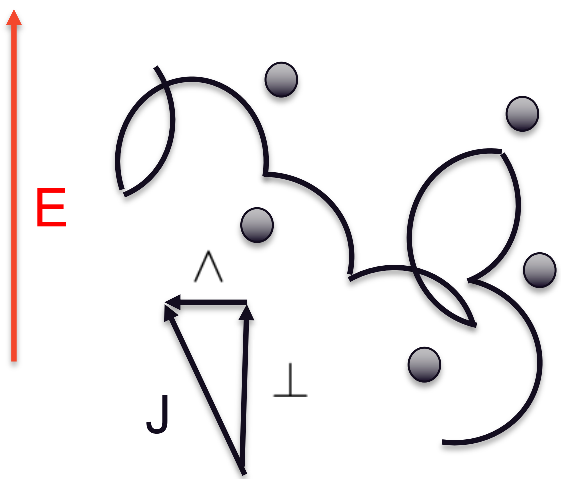
Resistance depends on direction of B

$$\mathbf{E} = \frac{m_e}{n_e e^2 \tau}\mathbf{J}$$



$$\chi = \frac{e|\mathbf{B}|\tau}{m_e} \simeq 1$$

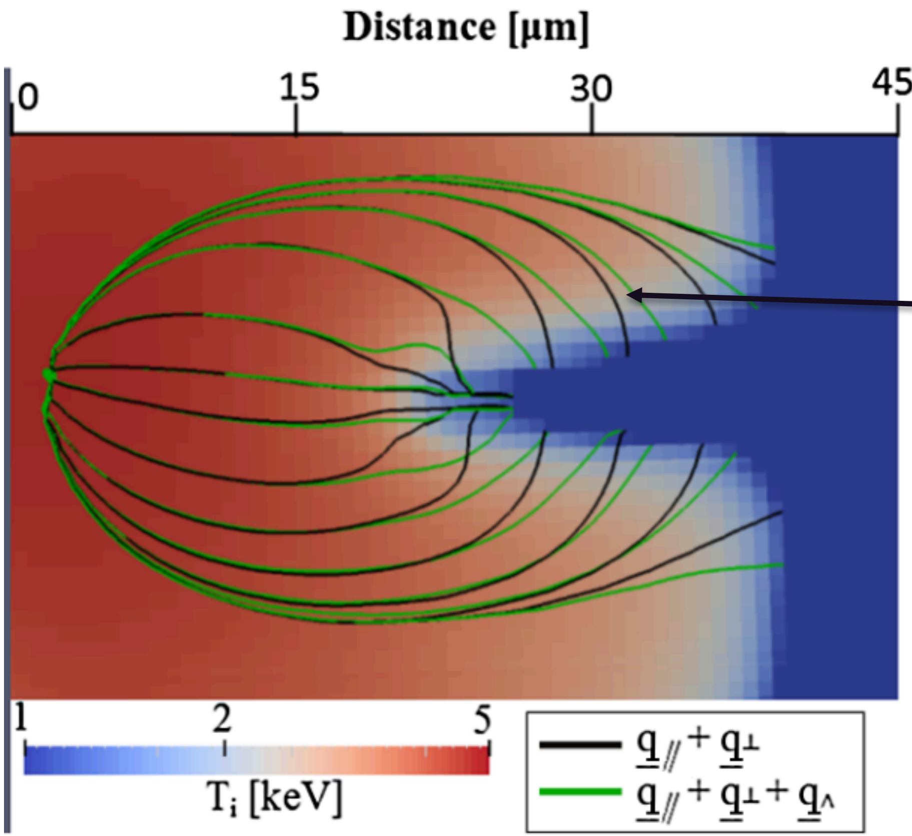
B $\otimes$



J is deflected away from direction of E

$$\underline{\alpha}.\mathbf{J} = \alpha_{||}(\mathbf{J}.\hat{\mathbf{b}})\hat{\mathbf{b}} + \hat{\mathbf{b}} \times (\alpha_{\perp}\mathbf{J} \times \hat{\mathbf{b}} - \alpha_{\wedge}\mathbf{J}),$$

Electron heat flux is also deflected



$$\chi = \frac{e|\mathbf{B}|\tau}{m_e} \simeq 1$$

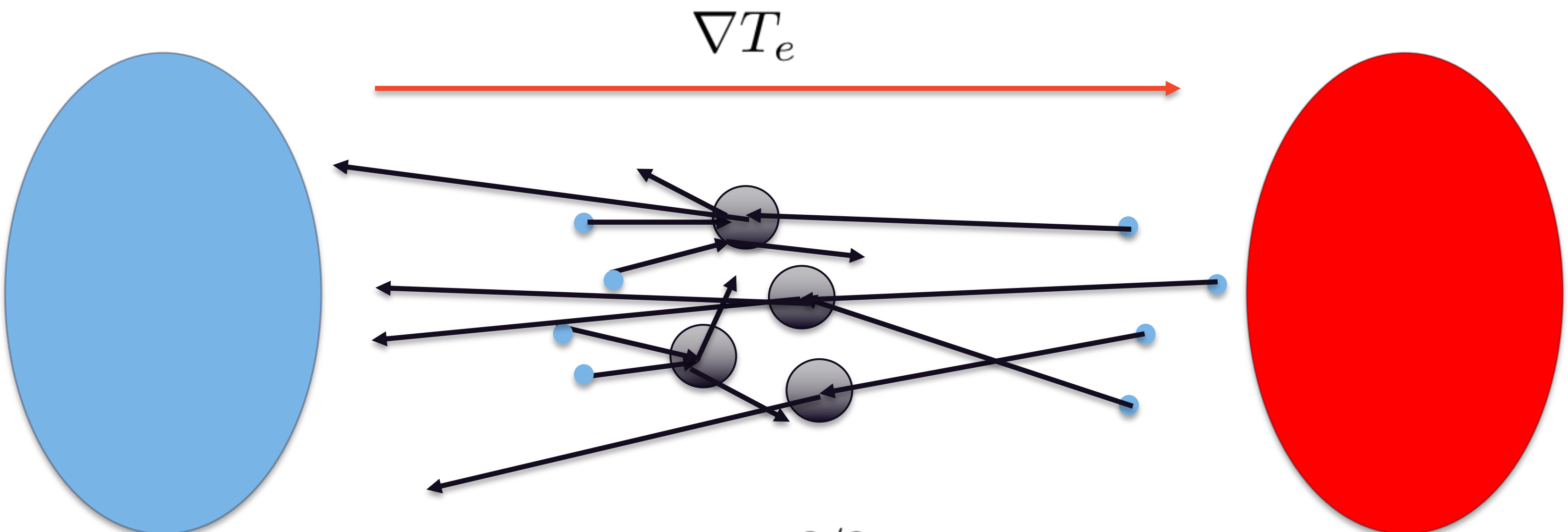
B field insulates and deflects the heat flow

So even weak B fields indirectly affect hydrodynamics

C. Walsh et al. Phys. Rev. Lett. 118, 155001 (2017)

The final jigsaw piece - Thermoelectric term

- Coulomb collisions lead to an additional thermoelectric E field term
- Faster electrons from hotter region are less collisional



$$\tau \propto T_e^{3/2}$$

Don't panic! It can be written in an (almost) simple form

Advection of B with a modified velocity

Resistive diffusion of B

Resistivity gradient term

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u_B} \times \mathbf{B}) + D\nabla^2\mathbf{B} - \nabla D \times (\nabla \times \mathbf{B})$$
$$- \frac{\nabla n_e \times \nabla T_e}{n_e e} + \frac{1}{e}\nabla \beta_{||}(\bar{Z}) \times \nabla T_e$$

Pressure term leads to Biermann source term

Thermoelectric gives a new Z-gradient source term

C. Walsh et al. Phys. Plasmas 27, 022103 (2020)

J. Sadler et al. Phys. Plasmas 27, 072707 (2020)

All of the difficult Braginskii terms just modify the B field advection velocity

Ideal advection

Resistance modifies Hall term

Also now a cross-Hall term

$$\mathbf{u}_{\mathrm{B}} = \mathbf{u} - (1+\delta_\perp)\frac{\mathbf{J}}{n_{\mathrm{e}}e} + \delta_\wedge \frac{\mathbf{J}\times\hat{\mathbf{b}}}{n_{\mathrm{e}}e} - \gamma_\perp \frac{\tau}{m_{\mathrm{e}}}\nabla T_{\mathrm{e}} + \gamma_\wedge \frac{\tau}{m_{\mathrm{e}}}\nabla T_{\mathrm{e}}\times\hat{\mathbf{b}},$$

B advected down Temperature gradients (Nernst Advection)

Also a cross-Nernst term along isotherms

Writing this simple new form requires defining new transport coefficients:

$$\delta_\perp(\chi,\bar{Z}) = \frac{\alpha_\wedge}{\chi}, \qquad \gamma_\perp(\chi,\bar{Z}) = \frac{\beta_\wedge}{\chi},$$

$$\delta_\wedge(\chi,\bar{Z}) = \frac{\alpha_\perp - \alpha_\parallel}{\chi}, \qquad \gamma_\wedge(\chi,\bar{Z}) = \frac{\beta_\parallel - \beta_\perp}{\chi}$$

Problem with the existing transport coefficients

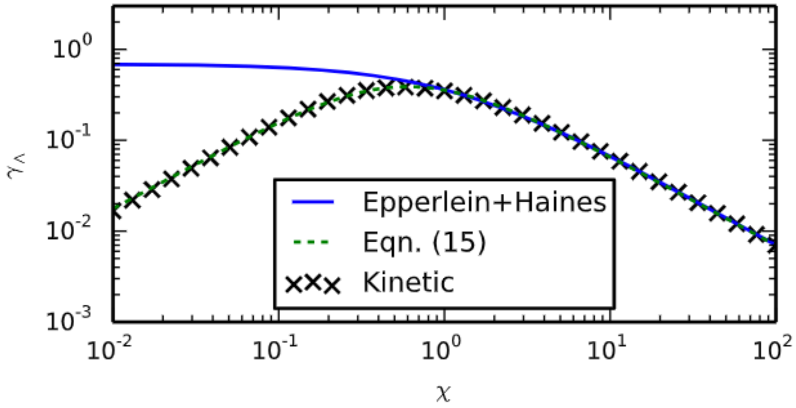
- Many ExMHD codes (Hydra, Gorgon etc.) use transport coefficients from Epperlein + Haines, Phys. Fluids 29, 1029 (1986)

$$\beta_1^c = \frac{(\beta_1'\chi + \beta_0')}{(\chi^3 + b_2'\chi^2 + b_1'\chi + b_0')^{8/9}}$$

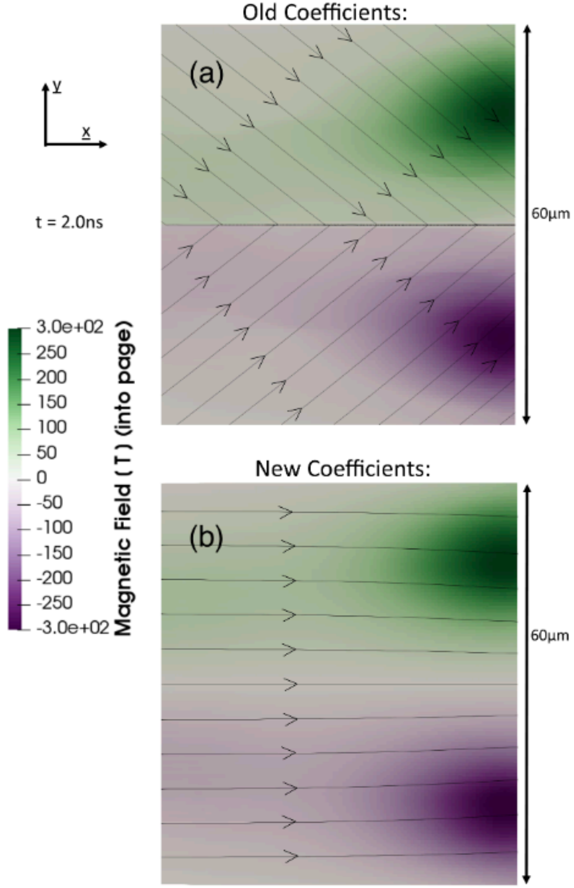
Cross-gradient Nernst coefficient

$$\gamma_\wedge(\chi, \bar{Z}) = \frac{\beta_\parallel - \beta_\perp}{\chi}$$

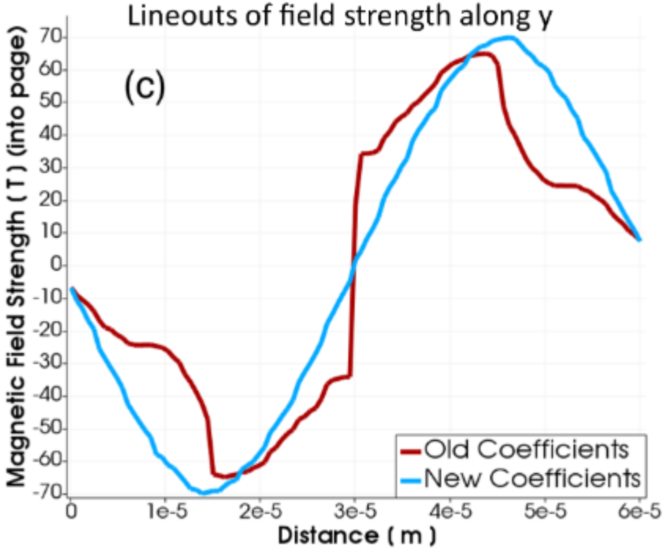
- We tried to calculate the new coefficients using their fits
  - It compares badly to full kinetic
  - So most ExMHD simulations have hugely over-estimated the cross-Nernst advection



Effect of the new fit functions in 2D Gorgon simulations

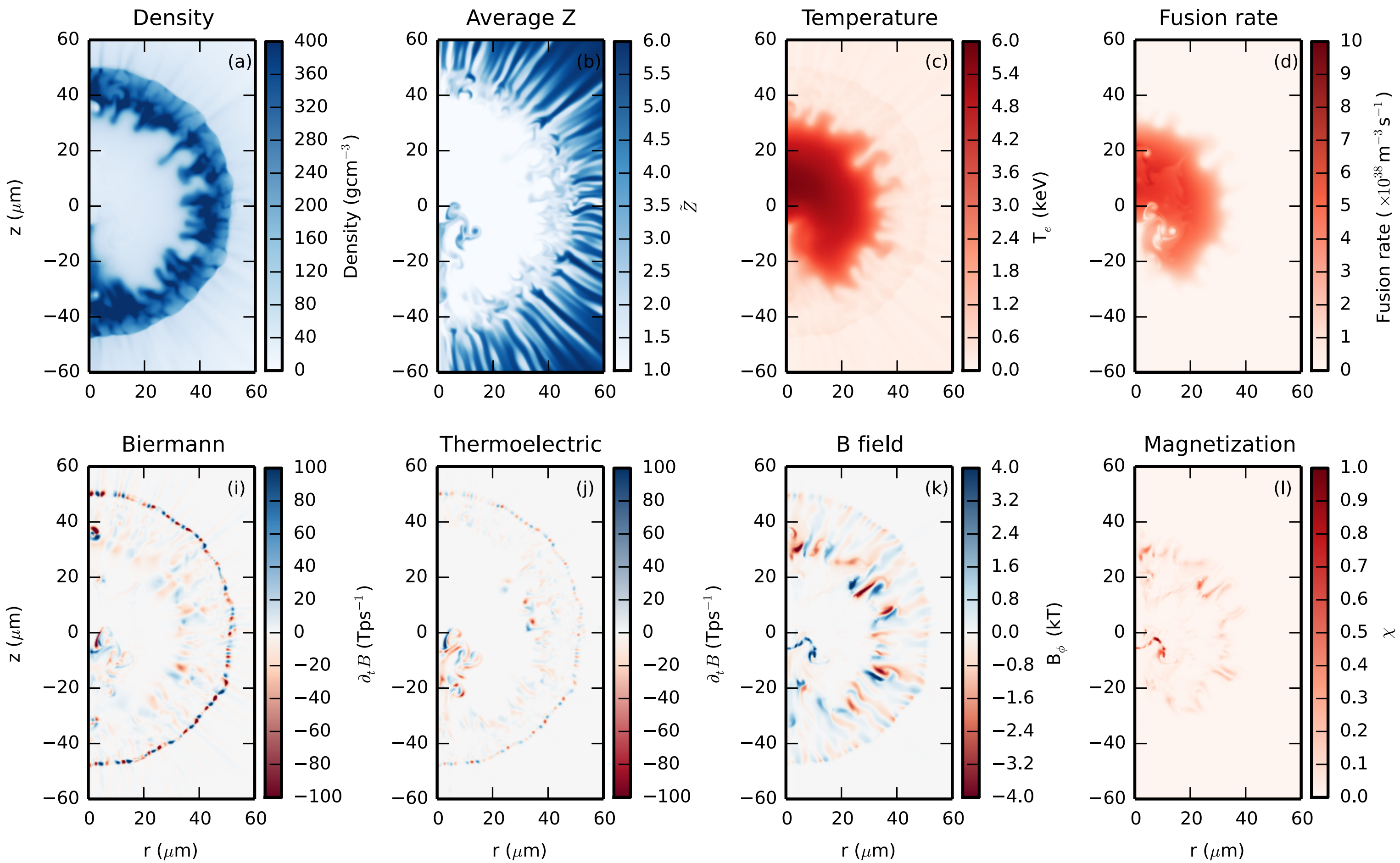


Using Epperlein + Haines coefficient fits, |B| was out by factor ~ 2 or more in some regions!!



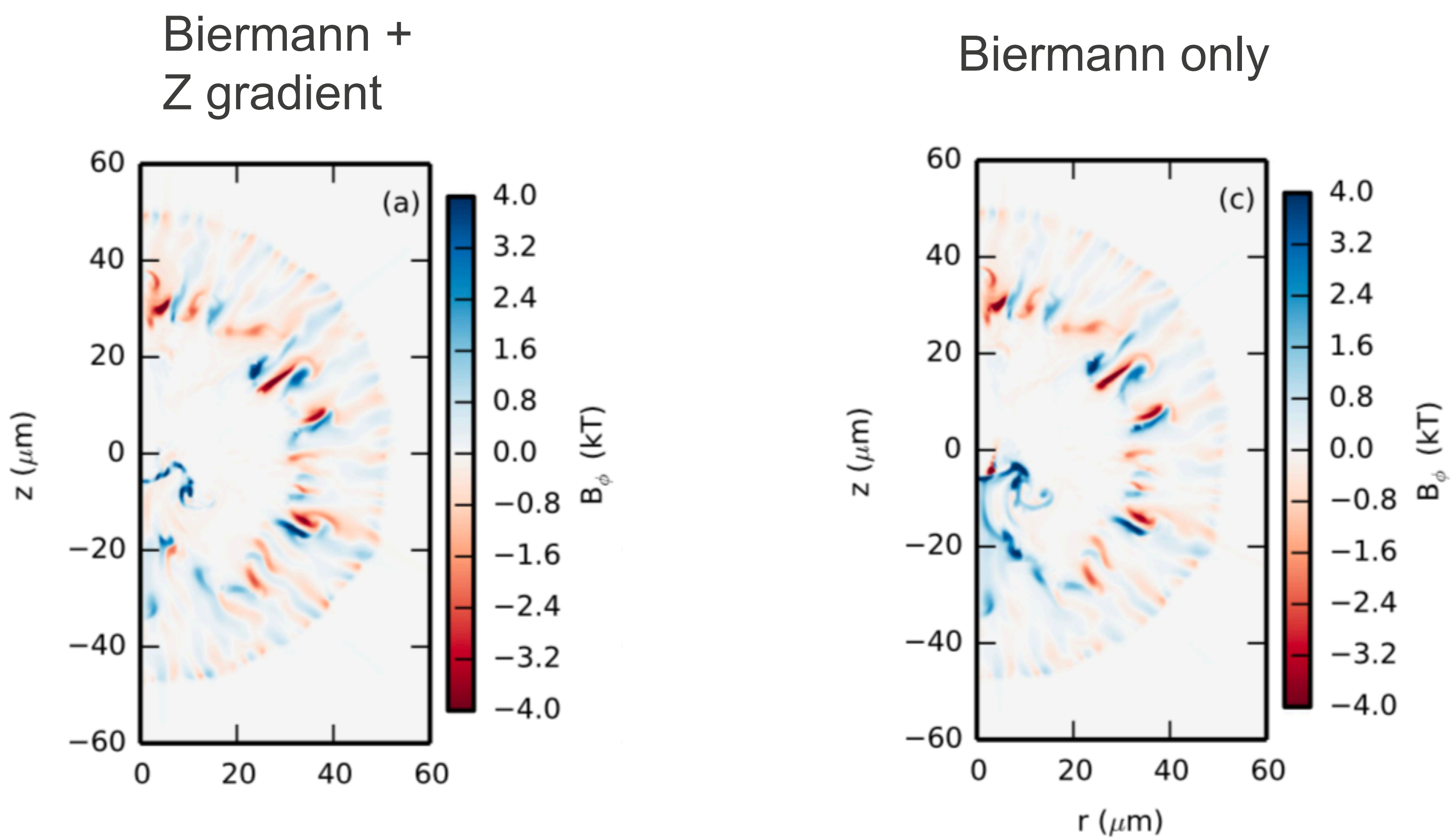
Their relative error for $\beta_\perp$ was low, but their functional form was wrong.

B field post-processing of xRAGE hydro code - ICF



J. Sadler et al. Phys. Plasmas 27, 072707 (2020).

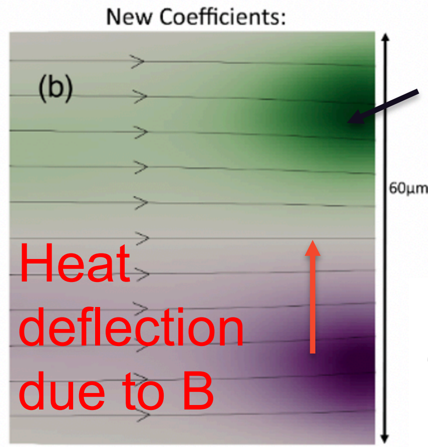
The new Z gradient source term makes a difference



New thermomagnetic instability

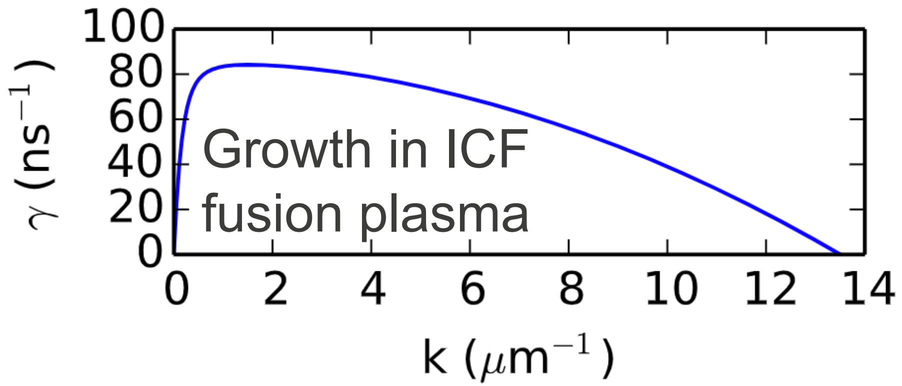
- By re-casting these equations, we also found a new ExMHD instability

- Opposing Z and T gradients create B field
  - This B field then deflects the heat flow, increasing the T perturbation



B field due to transverse T perturbation and Z gradient

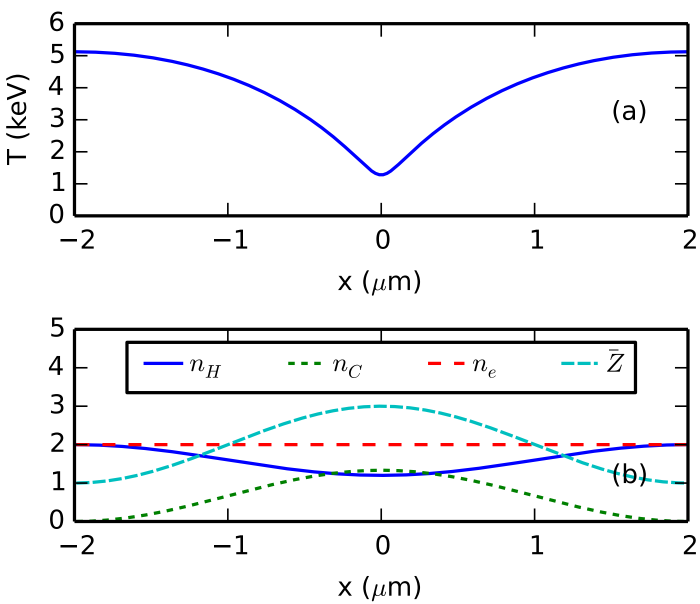
$$\frac{1}{e}\nabla\beta_{\|}(\bar{Z}) \times \nabla T_e$$

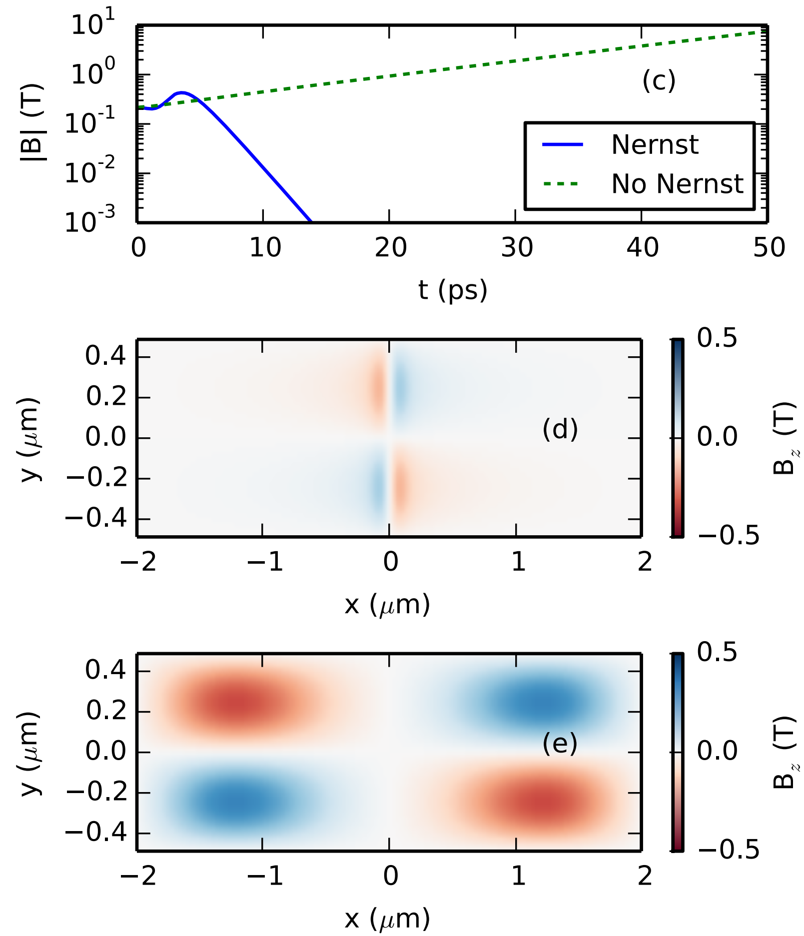


James Sadler et al., Phys. Plasmas (Submitted 2020)

New thermomagnetic instability - Simulations

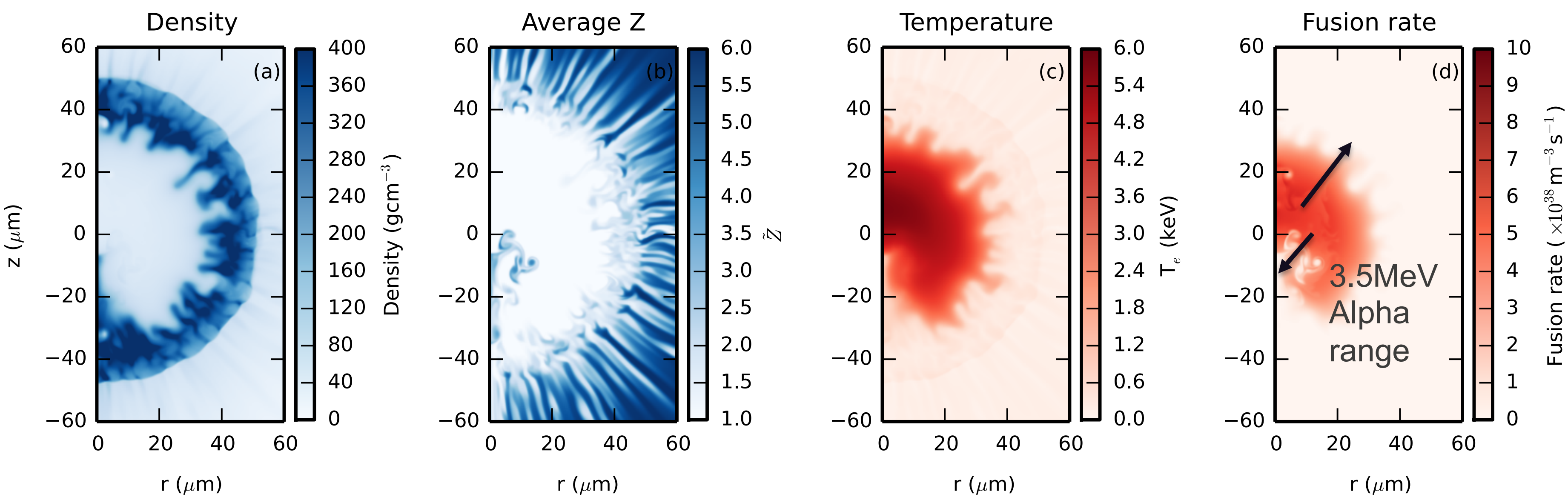
- We setup 2D ExMHD code with anti-parallel T, Z gradients
- In practice, the Nernst advection stabilizes it





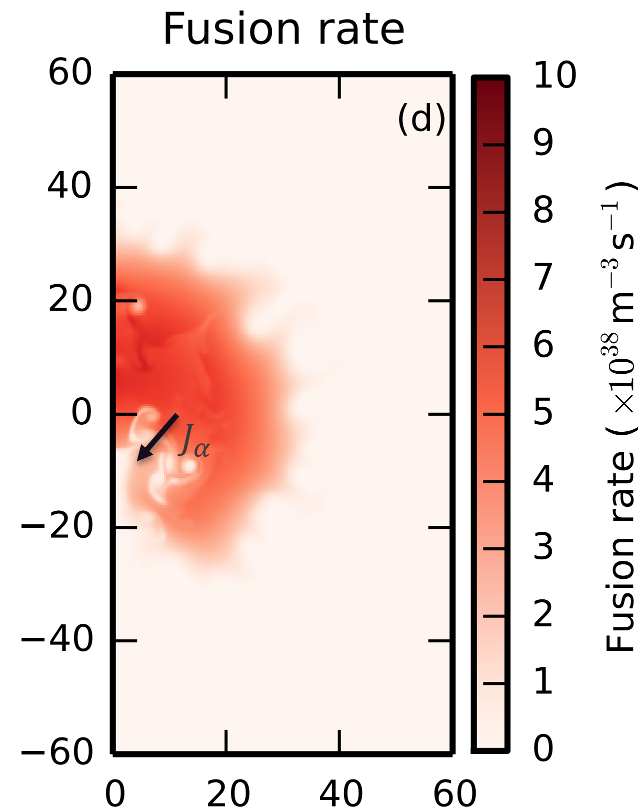
Fast alpha particles change the diffusion of contaminants

- Carbon jet enters the hot-spot due to fill tube + fluid instabilities
- Not much fusion within mix jet
- Large alpha flux into jet
- This changes the Ohm's law
- E field drives extra ion diffusion
- Carbon diffusion increases radiative loss, bad for yield



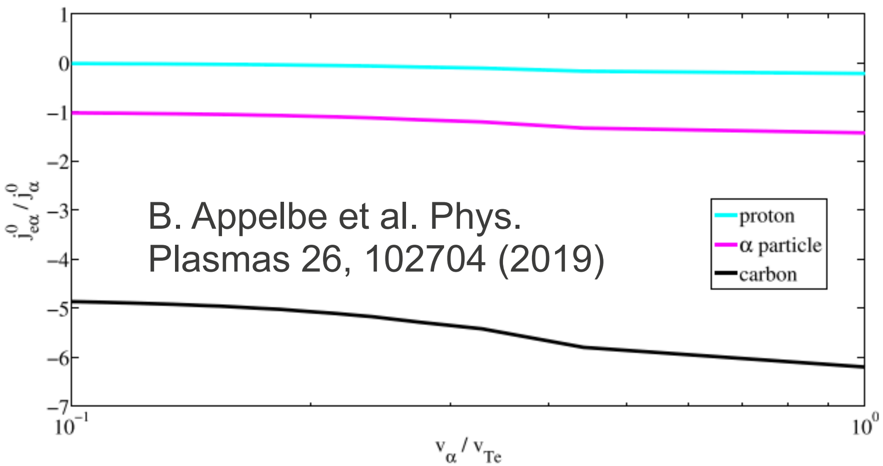
Alpha induced current

- Alphas stream into the mix region
- They dump energy. It is radiated away and wasted
- However, this alpha current also changes the plasma E field and ion diffusion
- What is this current?
  - Yield = 10^{16}, t_{burn}=100ps r_h = 30 microns
  - t_{alpha}= 10ps
  - ⇒ $n_{alpha} = Y^* t_{alpha} / t_{burn} / V = 10^{22}\ cm^{-3}$
  - $J_{alpha} = 2^*e^*n_{alpha}{}^*v_{alpha} = 10^{16} A/m^2$



What is the collisionally induced current?

- Fast alphas collide with electrons, driving a current
  - Brian Appelbe et al. did some nice Fokker-Planck kinetic simulations



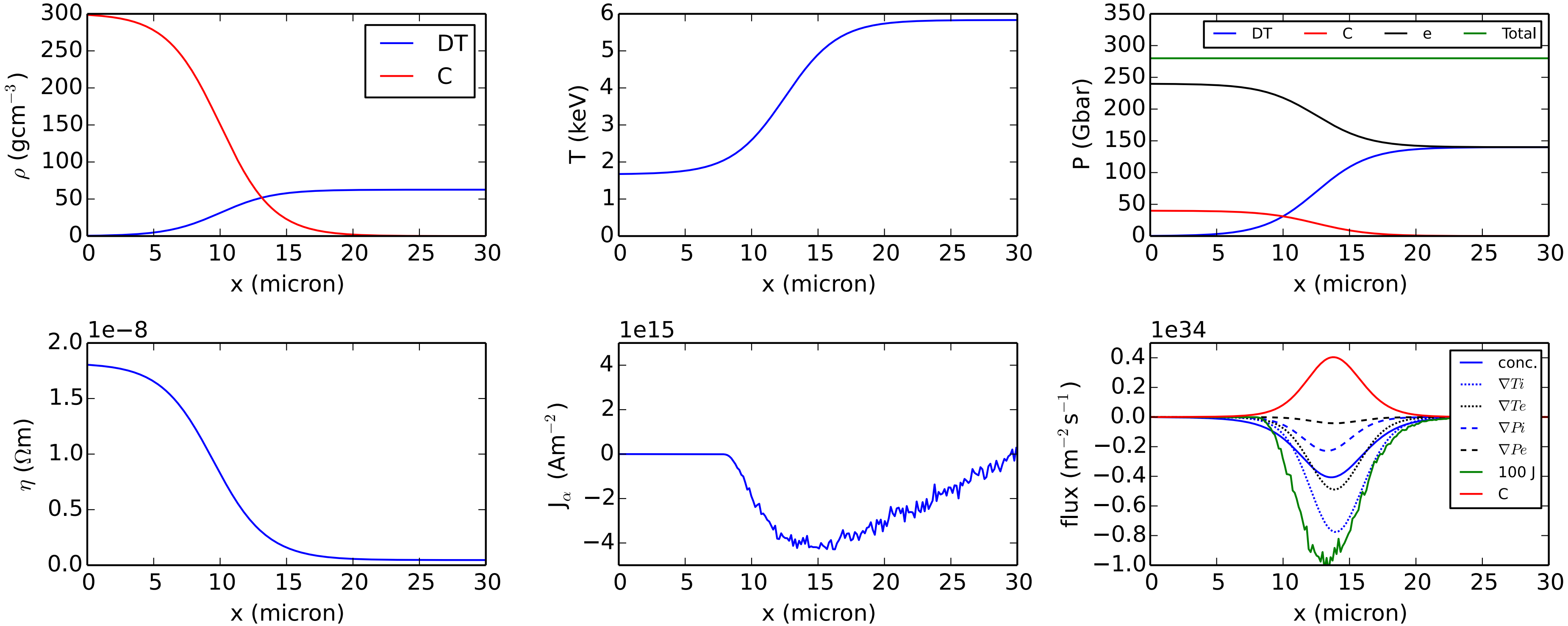
$$\mathbf{J} = \mathbf{J}_\alpha + \mathbf{J}_e$$
$$= \mathbf{J}_\alpha + \frac{\mathbf{E}}{\eta} + \mathbf{J}_{e\alpha} \quad = \frac{\mathbf{E}}{\eta} - \mathbf{J}_\alpha$$

$$\mathbf{E} = -\frac{\nabla . P_e}{n_e e} + \eta \mathbf{J}_\alpha - \frac{\beta_{||}}{e} \nabla T_e$$

- We said $J_{alpha} = 10^{16}$ A/m^2
- Using Spitzer resistivity from xRAGE simulation
  - E=10^6 V/m in H region
  - E=10^8 V/m in colder C region
  - Other terms are ~10^9 V/m

Monte-Carlo numerical calculations

- 1D setup similar to the carbon jet in xRAGE simulation
- Alpha particles with classical stopping power and fusion rate
- Using the HED plasma diffusion model of K. Molvig et al. Phys. Plasmas 21, 092709 (2014)



Conclusions

- The Epperlein + Haines transport coefficients have a subtle problem
  - Gives artificial discontinuities and dissipation
  - Our new fits fix these problems: **arXiv:2009.04562**
- B fields around the hot-spot reach 5kT
  - Z-gradient source term is important around mix jets
  - Heat flux is insulated/deflected
- There is a new MHD instability caused by Z gradients (e.g. mix jet)
  - In practice, Nernst advection stabilizes it
- Alpha particles stream into mix jets, increasing the E field
  - This increases the diffusion of mix. It looks like a small effect

Work funded by LANL LDRD-DR 20180040DR from groups T-2 and P-24 and the Center for Nonlinear Studies