Project Notebook

Exploring Magnetic Fields in Inertial Fusion Plasmas

Code and other files on: https://github.com/silverOrca/Project

26/02/2026

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First I am beginning by reading some papers to gain an introductory understanding of the project and gradually develop insight into the different directions I could take it in, making a list of areas to research further.

Measurement of Magnetic Cavitation Driven by Heat Flow in a Plasma

https://doi.org/10.1103/PhysRevLett.131.015101

Example of the type of experiment I will be investigating computationally.

<u>Background:</u>

- Nernst effect: perpendicular temperature gradient and magnetic field generate a perpendicular electric field
- Showing how the Nernst effect causes advection of magnetic fields over small timescales (nanosecond)
- Use proton radiography (source that generates protons that are fired through a plasma and deflected by the magnetic field present and then detected over time to show how the magnetic field changes) to see that the magnetic field is being advected by heat flow (temperature gradients, Nernst advection) instead of only by general plasma flow (read later https://doi.org/10.1017/S0022377814000464)
- Magnetic field here is APPLIED but expelled by the plasma (this is the movement shown through the proton radiography, and is due to the temperature gradients), and is done so faster than the plasma expansion - movement from heat advection is faster than general plasma flow? (abstract says in advance of but check later)
- Expulses magnetic field from hottest regions of plasma to colder regions, meaning the magnetic field won't be confining the plasma properly, causing problems for fusion power and reducing yield.
- Says it is "Nernst-driven magnetic cavitation" - I imagine this means that the magnetic field becomes inhomogeneous and is absent from regions (cavities with no magnetic field)

- Nernst effect description: particles in the plasma subject to a temperature gradient perpendicular to the magnetic field are deflected. The particles in the region of higher temperature have larger gyroradii (higher energy) and a lower collision frequency (mean free path increases with temperature, collision frequency ∝ T^-3/2), meaning that the net momentum of particles is perpendicular to the temperature gradient and magnetic field, resulting in an electric field.
    - Perpendicular momentum because: particles gyrate perpendicular to B (around B lines), and on hotter side the gyroradius is larger and more uninterrupted (lower collisions), meaning they can drift more, whereas on cold side orbits are smaller and more localised, and because all drift in same direction but cold side drift less, there is an electric field?
    - $\mathbf{F}_\perp \propto -\nabla T_e \times \mathbf{B}$ [2]. S. I. Braginskii, J. Exp. Theor. Phys. 6, 358 (1958).
- The particles having this motion results in advection of the magnetic field:
- B is transported down temperature gradient by heat flow and down pressure gradients by plasma bulk flow which causes expulsion of the magnetic field
    - How is this resulting from the particle motion? MHD has that B is frozen into electron flow, so drifting electrons due to TexB will move B?
- Maxwellian distribution of heat flow is not so accurate (needs higher order moments in distribution)
- Would previously use MHD models but these don't explain the expulsion of the magnetic field without a change in density, and for steep temperature gradients MHD models which take into account Nernst effects still fail (nonlocal, when electron mean free path not small compared to length scale of temperature gradient - because of steeper gradient)
- Coupled magnetic field and heat flow, B restricts perpendicular heat flow

<u>Experiment:</u>

- Use laser-driven proton radiography to show that "the Nernst effect dominates changes to the magnetic field in underdense plasmas on nanosecond timescales" (p.2)
- Isolate the Nernst advection to show that the motion of the magnetic field is not coupled to the motion of the plasma
- Fired laser at a nitrogen target to produce a plasma
- The ratio between the cyclotron frequency and the collision frequency gives a Hall parameter describing conditions under which the magnetic field and heat flow are coupled strongly
- Get an equation from a previous paper describing the changes in the magnetic field, which incorporates hydrodynamic motion and Nernst advection in the advection term, a magnetic diffusion and resistivity gradient term, and a Biermann battery term, though here they ensure the latter two terms are negligible.
- They showed there was no self-generated magnetic field (Biermann battery term) by measuring whether there was a magnetic field present in the absence of an applied one
- Laser fired at gold foil to generate protons which fire through the nitrogen plasma

- Used interferometry to measure the density of the plasma / hydrodynamic advection
- Removed background B from results to reduce noise/blur using code
- Measure cavitation in plasma density after it becomes more ionised, but before this measure cavitation in magnetic field - decoupling of B from plasma flow, shows Nernst effect. First time measured here.
- Heat flow advection faster than hydrodynamic motion
- Can estimate Nernst velocity by measuring radius of peak of B at different times, which gives an estimate for the heat flow
- Did simulations of the magnetic field for each different model, MHD, extended MHD, and kinetic
- At edge of hot plasma B is stronger and the heat transport is limited by electron gyroradius (B) not the mean free path (T), and at later times leads to a magnetic transport barrier which acts to keep the heat transport local despite B cavity inside
- Investigate the above by using 3 different nitrogen gas pressures (density) and find that with decreasing density, the advection velocity decreases, as heat flow is slower, so slower magnetic advection and further restricted heat flow due to magnetic barrier

<u>Useful follow up sources referenced:</u>

- Magnetic field expulsion reducing effectiveness in fusion: https://doi.org/10.1063/1.4890298, https://doi.org/10.1063/1.4935286
- Strong magnetic fields being applied in fusion to increase yield: https://doi.org/10.1063/1.3333505, https://doi.org/10.1063/1.3696032, https://doi.org/10.1063/1.4985150, https://doi.org/10.1103/PhysRevLett.129.195002
- Explains further on the motion of particles generating electric field and drifting: S. I. Braginskii, J. Exp. Theor. Phys. 6, 358 (1958).
- Showing the including Nernst advection is crucial for fast heating models: https://doi.org/10.1103/PhysRevLett.105.095001, https://doi.org/10.1088/0029-5515/53/7/073022, https://doi.org/10.1103/PhysRevLett.113.235001, https://doi.org/10.1103/PhysRevLett.114.215003, https://doi.org/10.1038/s41467-020-20387-7
- Laser-driven proton radiography: https://doi.org/10.13182/FST06-A1159
- Equation for change in B: https://doi.org/10.1063/1.5124144
- Supplemental material: Measurement of Magnetic Cavitation Driven by Heat Flow in a Plasma | Phys. Rev. Lett.
- Magnetic fields increase T and reduce instability growth: https://doi.org/10.1103/PhysRevLett.98.135001, https://doi.org/10.1103/PhysRevLett.107.035006, https://doi.org/10.1063/1.5085498

<u>Thoughts/summary</u>

- Not about self-generated B fields
- Not about magnetothermal instability
- Does show proton radiography used to measure magnetic fields and how they move due to the Nernst advection (need to understand Nernst for magnetothermal)

- In ICF B fields increase temperature and reduce instability growth, but means that for magnetised ICF needs stronger B fields as they are expelled from plasma
- Look into Hall parameter

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Magnetothermal instability in laser plasmas including hydrodynamic effects

https://doi.org/10.1063/1.4718639

Explaining the magnetothermal instability and how it is affected by factors such as density and temperature gradients and hydrodynamic effects:.

- “compresses magnetic field, concentrates the flow of heat, and enhances thermal energy spreading” (p.1)
- Destabilises plasma and is only driven by collisional transport phenomena, from Braginskii classical transport processes, when heat flows perpendicular to the magnetic field
- Coupling between Nernst effect and Righi-Leduc heat flow leads to unstable growth
- Effects which are not required include: density gradients, large anisotropies, hydrodynamic flow, but here they take into account gradients in n_e and T_e to account for effects from spontaneously generated magnetic fields, whereas previous works assumed an unmagnetised plasma
- Hydrodynamic motion doesn’t affect growth rate of the instability, but including density includes an extra term for self-generated B
- Magnetic fields generated from grad T_e x grad n_e (Biermann battery?) coupled with the Righi-Leduc heat flow drives a field generating thermal instability, and because they consider this here they see how this interacts with the magnetothermal instability. Find that it can either further drive unstable waves with the magnetothermal instability, or oppose them.
- Magnetothermal instabilities dominate CT regime and are only source of instability in HD regime
- Presence of instability means we should include Nernst effect and Righi-Leduc heat flow in models
- Assume that thermal pressure >> magnetic pressure
- For low K (cut off for real wave numbers) in CT regime, the perturbations mainly grow due to feedback between the Nernst effect and Righi-Leduc heat flow. For higher wavenumbers, the damping terms from thermal and resistive diffusion reduces the growth rate (goes to 0 when source and diffusion terms are equal). K real solutions are unstable.
- The source term for feedback between Nernst and Ettinghausen effects can’t drive instabilities on its own but reduces impact of diffusion

- The density gradient is what introduces the source term and modifies the velocity term V_b (which can enhance instability). The source term is the instability arising from field generating thermal instability, and drives instabilities when the temperature and density length scales are parallel (p.5)
- K increases with increasing instability (higher wave number is because of higher instability) and so K is key to understanding the effect of the two instabilities
- For HD regime real K solutions are also unstable, and similar results mean the two regimes growth rates are comparable
- In HD the field generating source can stabilise the magnetothermal instability because a variable in the equation can have a +ve or -ve sign, and +ve will drive instability whereas -ve will not.
- Can get contributions to overall cutoff wavenumber from characteristic wavenumbers of the magnetothermal instability in either regime
- Need steep temperature gradients for the magnetothermal instability
- For intermediate magnetisation, expect magnetothermal instability to dominate

Equations

- Important governing equations, minus magnetic tension: “the continuity equation (1), momentum equation (2), Faraday’s Law (3), and the thermal energy continuity equation (4)” (p.2)
- TABLE I. Dimensionless notation for effects arising from both collisional transport and the $\nabla T_e \times \nabla n_e$ mechanism.[33] Note that $\Lambda = \lambda_T/\delta$ is the ratio of the mean-free-path λ_T to the collisionless-skin-depth $\delta = c/\omega_{pe}$, where c is the speed of light *in vacuo* and $\omega_{pe} = (n_e e^2/\epsilon_0 m_e)^{1/2}$ is the plasma frequency.

Dimensionless coefficient	Definition
Thermal diffusion	$D_T = \frac{c_B}{3}\kappa_\perp$
Resistive diffusion	$D_R = \frac{\alpha_\perp}{c_B \Lambda^2}$
Nernst advection	$A_N = \frac{c_B}{2\chi}\beta_\wedge$
Ettingshausen advection	$A_E = \frac{2\chi\psi_\wedge}{3 c_B \Lambda^2}$
Righi-Leduc heat-flow	$C_\kappa = \frac{c_B}{3}\chi\frac{\partial \kappa_\wedge}{\partial \chi}$
B -field generation by $\nabla T_e \times \nabla n_e$	$C_G = \frac{c_B}{2\chi}$

(p.3)

Experimental Relevance:

- Deforms thermal energy profiles, enhances spread of thermal energy, cools central region, meaning that might not be able to use fields to reduce non-local heat transport, though having magnetic fields still did reduce thermal flux
- Self-generated magnetic fields on the surface of plasma bubbles: measured B along bubbles surface and perpendicular to the field and temperature gradients there was “periodic modulation in the magnetic field structure” (p.9) which are the conditions for the MTI. Get growth rate and wavelength for MTI which could explain the field structure

- ICF and MIF: can get MTI growth rate for ICF computationally. One paper suggests MTI can affect nanosecond hohlraum heating. Better field gradient data for MIF; after implosion have parallel T_e and field gradients which is on border for MTI, and not enough data for during implosion.
- Kinetic effects: Small peak instability wavelengths compared to electron thermal Larmor radius means non-local transport and effects, which modifies the transport coefficients and "reduces the predictive power of our theory" (p.9), but can simulate using code and still get good results. Can have another kinetic effect from inverse bremsstrahlung (dominant heating in under-dense plasmas for certain laser intensities), which preferentially heats slower collisional electrons, flattening and broadening the distribution function and changing the transport coefficients

References:

- ICF: http://dx.doi.org/10.1063/1.1578638, http://dx.doi.org/10.1063/1.873499, http://dx.doi.org/10.1103/PhysRevLett.97.255001
- MIF: http://dx.doi.org/10.1007/s10894-007-9112-3, http://dx.doi.org/10.1103/PhysRevLett.103.215004, http://dx.doi.org/10.1063/1.3416557
- Suppression of heat transport: http://dx.doi.org/10.1103/PhysRevLett.98.135001
- Righi-Leduc heat flow: S. I. Braginskii, Rev. Plasma Phys. 1, 205 (1965).
- Nernst effect: http://dx.doi.org/10.1063/1.865100
- Density gradients resulting in the field generating thermal instability: http://dx.doi.org/10.1063/1.1694866, L. A. Bol'shov, Y. A. Dreizin, and A. M. Dykhne, JETP Lett. 19, 168 (1974)., J. H. Brownell, Comments on Plasma Phys. Controlled Fusion 4, 131 (1979)., http://dx.doi.org/10.1143/JPSJ.49.322, http://dx.doi.org/10.1143/JPSJ.50.668, http://dx.doi.org/10.1063/1.860099
- Hydrodynamic flow: T. J. M. Boyd and J. J. Sanderson, The Physics of Plasmas (Cambridge University Press, 2005)., 6R. P. Drake, High-Energy-Density Physics (Springer, 2006)., http://dx.doi.org/10.1088/0741-3335/51/3/035013
- Original theory of MTI: http://dx.doi.org/10.1103/PhysRevLett.105.175001
- Magnetic field generation and hot electron transport: http://dx.doi.org/10.1139/p86-160
- Defining K: http://dx.doi.org/10.1103/PhysRevLett.105.175001

Thoughts/summary:

- Look into Righi-Leduc effect
- Look into Hall parameter

I will read some documentation on PlasmaPy, the code we will be using for this project, so I can learn about the relevant physics and test out using the code myself.

Creating Synthetic Charged Particle Radiographs by Particle Tracing

https://docs.plasmapy.org/en/stable/notebooks/diagnostics/charged_particle_radiography_particle_tracing.html