Final Project Report

# Dynamic Structure of Magnetized High Energy Density Plasmas

December 8, 2023

## 1 Overview

This report summarizes results of project DE-SC0022202 "Dynamic Structure of Magnetized High Energy Density Plasmas," which was originally funded for the period 08/01/2021 - 7/31/2022, but was no-cost extended to 7/31/2023. The primary objectives of the work, as stated in the original proposal, were "develop a theory to describe a novel state of magnetized high energy density plasmas, benchmark the theory using first-principles molecular dynamics simulations, and apply the results to develop a means to interpret x-ray scattering measurements in future experiments." These were the goals of the original project proposal, which was for a 3 year project. The project was ultimately funded for 1 year, and so the work completed focused on the goals described for only the first year of the proposed work. This included further developing a kinetic theory for strongly magnetized plasmas, applying it to compute fluid-scale (MHD) transport coefficients, and to test the predictions using molecular dynamics simulations.

The primary research objectives for the one-year project were accomplished. The work resulted in two publications in a well-respected peer-reviewed journal (Physics of Plasmas). One was selected as Editor's Pick and the other as a Featured Article. Several conference presentations were given disseminating the results of this research. The project supported the training of a graduate student who completed his PhD during the course of the project, and an undergraduate student research project. Highlights of the research results include:

1. **Barkas Effect:** This worked showed that the Coulomb collision frequency between electrons and ions has a strong dependence on the signs of the charges when a plasma is strongly magnetized. This is contrast to weakly magnetized plasmas, where the collision frequency does not depend on whether the interaction is repulsive or attractive. Calculations of the frictional drag on a test ion by a background of strongly magnetized electrons or positrons was computed and verified by comparing with molecular dynamics simulations. The results were used to compute the electrical resistivity, where it was found that strong magnetization in conjunction with oppositely-charged interactions significantly decreases the parallel resistivity and increases the perpendicular resistivity in comparison to theories that do not account for the strong magnetization effect on collisions.

2. **Temperature relaxation:** This work applied our kinetic theory for strongly magnetized plasmas to the macroscale transport process of temperature relaxation. Two main results were discovered: (1) strong magnetization causes the temperature relaxation rate to be anisotropic with respect to the magnetic field, and (2) strong magnetization causes and increase in the perpendicular relaxation rate, and an increase in the parallel relaxation rate for repulsive interactions, but a dramatic suppression in the parallel relaxation rate for attractive interactions.

The following section provides a list and abstract of each of the published works documenting these results. This is followed by a section describing the research highlights in more detail. The remainder of the report discusses presentations and professional development that resulted from this project.

## 2 Published Work

The results of this project led to the following peer-reviewed publications. Abstracts are included, which describe the main results of each paper.

1. L. Jose, D. J. Bernstein, and S. D. Baalrud, "Barkas Effect in Strongly Magnetized Plasmas," Physics of Plasmas **29**, 112103 (2022).

   * Selected as an Editor's Pick.

   Strongly magnetized plasmas, which are characterized by the particle gyrofrequency exceeding the plasma frequency, exhibit novel transport properties. For example, recent work showed that the friction force on a test charge moving through a strongly magnetized plasma not only consists of the typical stopping power component but also includes components perpendicular to the test charge's velocity. However, these studies only considered test charges that have the same sign as the charge of the plasma particles. Here, we extend these calculations to the case of charges with opposite sign (such as an ion interacting with strongly magnetized electrons). This is done with both a novel generalized Boltzmann kinetic theory and with molecular dynamics simulations. It is found that the friction force changes dramatically depending on the sign of the interacting charges. Likewise, the stopping power component for oppositely-charged particles decreases in magnitude compared with like-charged particles, and the perpendicular components increase in magnitude. Moreover, the difference between the two cases increases as the gyrofrequency becomes larger compared with the plasma frequency. The electrical resistivity is calculated from the friction force, where it is found that strong magnetization in conjunction with oppositely-charged interactions significantly decrease the parallel resistivity and increase the perpendicular resistivity.

2. L. Jose and S. D. Baalrud, "Theory of the Ion-Electron Temperature Relaxation Rate in Strongly Magnetized Plasmas," Physics of Plasmas **30** 052103 (2023).

   * Selected as a Featured Article.

   Recent works have shown that strongly magnetized plasmas characterized by having a gyrofrequency greater than the plasma frequency exhibit novel transport properties. One example is that the friction force on a test charge shifts, obtaining components perpendicular to its velocity in addition to the typical stopping power component antiparallel to its velocity. Here, we apply a recent generalization of the Boltzmann equation for strongly magnetized plasmas to calculate the ion-electron temperature relaxation rate. Strong magnetization is generally found to increase the temperature relaxation rate perpendicular to the magnetic field, and to cause the temperatures parallel and perpendicular to the magnetic field to not relax at equal rates. This, in turn, causes a temperature anisotropy to develop during the equilibration. Strong magnetization also breaks the symmetry of independence of the sign of the charges of the interacting particles on the collision rate, commonly known as the "Barkas effect". It is found that the combination of oppositely charged interaction and strong magnetization causes the ion-electron parallel temperature relaxation rate to be significantly suppressed, scaling inversely proportional to the magnetic field strength.

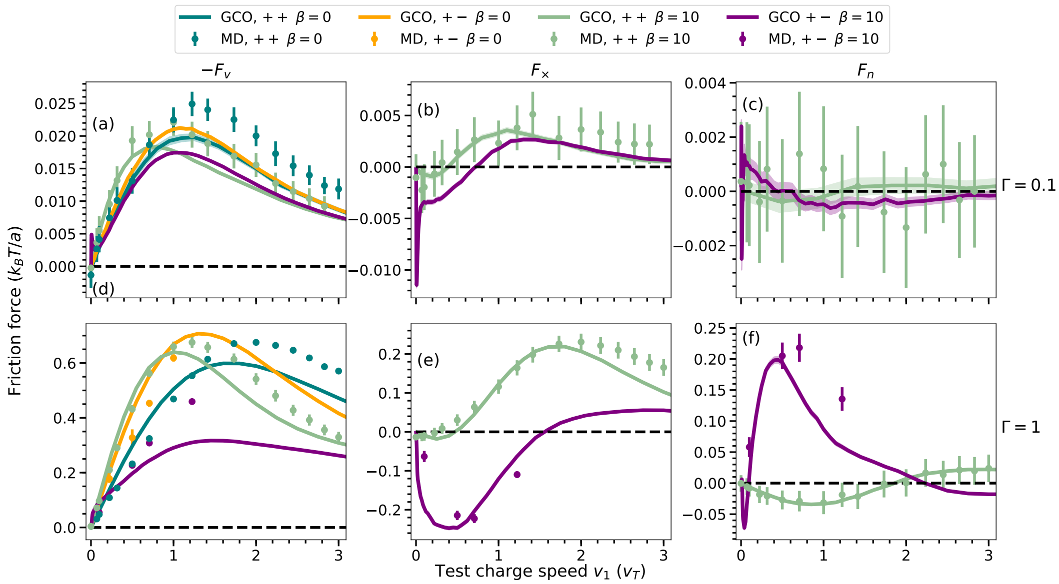


**Figure 1:** Comparison of generalized collision operator (GCO) and molecular dynamics (MD) results for the friction force on a test ion interacting with either positrons (++ case) or electrons (+- case). The friction force has 3 components in a strongly magnetized plasma: stopping power, aligned antiparallel to the ion velocity (left), transverse, perpendicular to the velocity in the plane formed by the velocity and magnetic field vectors (middle), and gyrofriction, in the direction of the Lorentz force (right). The top row shows results for a weakly coupled plasma ($\Gamma = 0.1$) and the bottom for a moderately coupled plasma ($\Gamma = 1$).

# 3 Highlights

## 3.1 Barkas Effect

The first task of the proposed work was to evaluate our previously developed kinetic theory of strongly magnetized plasmas for magnetohydrodynamic transport coefficients in a quasineutral plasma consisting of electrons and ions. This evaluation led to the discovery of a novel effect (Barkas effect): the Coulomb collision rate becomes dependent on whether the interacting species is an attractive or repulsive force. This is novel because in standard weakly magnetized plasmas the Coulomb collision rate is identical whether the interaction is attractive or repulsive. The work first computed the frictional drag on a test ion due to a background of either electrons or positrons, then used these results to compute the electrical conductivity tensor of MHD. Molecular dynamics simulations of the friction force were also computed and compared with the theoretical predictions as a means of validation of the theory (MD provides a first-principles computation of the Newton-Lorentz equations of motion). This comparison is shown in figure 1.

These computations showed that strong magnetization and the Barkas effect both contribute to significantly changing both the quantitative values of the collision rate, and the qualitative nature (asymmetry with respect to the magnetic field). This work also showed that these changes in the collision rate translate to significant changes in the electrical conductivity tensor. For conditions of $\Gamma = 1$ and $\beta = 10$, both the parallel and perpendicular conductivity coefficients are an order of magnitude greater than would be predicted if one did not account for the strong magnetization effect on the collision rate (see table 1 of reference 1 above).

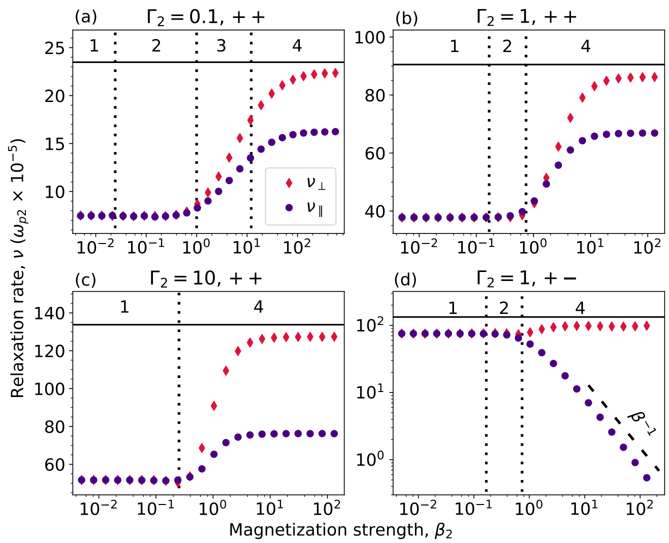


**Figure 2:** Predictions of the temperature relaxation rate in a ion-positron plasma (++ cases), or ion-electron plasma (+- cases). Red shows the relaxation rate perpendicular to the magnetic field, and blue shows the relaxation rate parallel to the magnetic field.

## 3.2 Electron-ion temperature relaxation

After studying the momentum-relaxation process of drag and electrical conduction, we studied an energy relaxation process: temperature equilibration. A summary of the main results is illustrated in figure 2. First considering repulsive interactions (ion-positron), the main results are that strong magnetization ($\beta > 1$) causes a significant increase in the relaxation rate, and that the relaxation rates differ in the parallel versus perpendicular directions. It is noteworthy that the increase in the relaxation rate is contrary to what early (overly simplified) kinetic theories predicted in the 1970's. These early models predicted that strong magnetization would cause a small decrease in the relaxation rate. Likely, this was a cause of a lack of further studies of strongly magnetized plasmas. Contrary to this, we find it increases the relaxation rate by a significant amount. Second, the asymmetry of the collision rate with respect to the magnetic field is a qualitative change compared to any previous kinetic theory prediction. It implies that even if the initial electron and ion distribution functions are symmetric, a temperature anisotropy can develop during the relaxation process. These results may be significant in a number of applications, including ICF in strong magnetic field scenarios if they reach the strong magnetization regime.

The most stark result from this study is the dramatic influence of the Barkas effect (bottom right panel) in the parallel collision rate. Here, the parallel collision rate is observed to dramatically decrease at a rate inversely proportional to the magnetic field strength. This opposite and dramatically different behavior causes a huge difference between the parallel and perpendicular relaxation rates, suggesting that a strong temperature anisotropy may develop during electron-ion energy equilibration. It also suggests that a temperature difference between electrons and ions can be very long-lived in a strongly magnetized quasineutral plasma, as the magnetization can strongly suppress the electron-ion energy equilibration. This is a qualitatively new and significant prediction. Some work to test it using MD was started by an undergraduate student (Ms. Julia Marshall) during the course of this project. With further funding in the future, we would like to finish this in order to test these novel predictions.

## 4 Contribution to career advancement of participants

This award supported the PI (Scott Baalrud), a graduate student (Dr. Louis Jose), and an undergraduate student (Ms. Julia Marshall). It has contributed significantly to career advancement. Dr. Jose graduated in April 2023. He is now a postdoc at the University of Michigan. Ms. Julia Marshall is now a senior in Nuclear Engineering and is applying to PhD programs to continue her education in plasma physics. The research supported by this project provided a major motivation for her to seek a career as a PhD plasma scientist.

## 5 Presentations

The following provides a list of presentations that communicated the results of the research supported under this grant:

1. L. Jose and S. D. Baalrud
   *Theory of the Ion-Electron Temperature Relaxation Rate in StronglyMagnetized Plasmas*
   65th American Physical Society Division of Plasma Physics, Denver, CO (October 2023).

2. L. Jose and S. D. Baalrud
   *Theory of the Ion-Electron Temperature Relaxation Rate in StronglyMagnetized Plasmas*
   Gaseous Electronics Conference, Ann Arbor, MI (October 2023).

3. S. D. Baalrud
   *dc electrical conductivity of strongly magnetized plasmas*
   Dense Z-Pinches, Ann Arbor, MI (July 2023).

4. S. D. Baalrud
   *Average Trajectory Method for Computing Magnetohydrodynamic Transport Coefficients*
   50th IEEE ICOPS, Santa Fe, NM (May 2023).

5. L. Jose and S. D. Baalrud
   *Theory of the Ion-Electron Temperature Relaxation Rate in Strongly Magnetized Plasmas*
   50th IEEE ICOPS, Santa Fe, NM (May 2023).

6. S. D. Baalrud and L. Jose
   *Dynamic Structure Function in a Strongly Magnetized High Energy Density Plasma*
   64th American Physical Society Division of Plasma Physics, Spokane, WA (October 2022).

7. J. Marshall, L. Jose, and S. D. Baalrud
   *Resolving extended space and time correlations in molecular dynamics simulations of strongly magnetized*
   64th American Physical Society Division of Plasma Physics, Spokane, WA (October 2022).

8. L. Jose, D. J. Bernstein, and S. D. Baalrud
   *Barkas Effect in Strongly Magnetized Plasmas*
   64th American Physical Society Division of Plasma Physics, Spokane, WA (October 2022).

9. S. D. Baalrud, L. Jose and T. Lafleur
   *Novel Transport Properties of Strongly Magnetized Plasmas*
   Gaseous Electronics Conference, Sendai, Japan (October 2022).

10. S. D. Baalrud
*Exploring Novel Properties of Strongly Magnetized Plasmas*
Journal of Plasma Physics Online Colloquium (August 2022).

11. L. Jose and S. D. Baalrud
*A Kinetic Model of Friction in Strongly Coupled Strongly Magnetized Plasmas*
49th IEEE ICOPS, Seattle, WA (May 2022).

12. S. D. Baalrud
*Kinetic theory of the force distribution function*
49th IEEE ICOPS, Seattle, WA (May 2022).