J. Plasma Phys. (2025), *vol.* 91, E121

doi:10.1017/S0022377825100469

The CHIMERAS project: design framework for the Collisionless HIgh-beta Magnetized Experiment Researching Astrophysical Systems

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(Received 15 November 2024; revision received 18 April 2025; accepted 24 April 2025)

From the near-Earth solar wind to the intracluster medium of galaxy clusters, collisionless, high-beta, magnetized plasmas pervade our universe. Energy and momentum transport from large-scale fields and flows to small-scale motions of plasma particles is ubiquitous in these systems, but a full picture of the underlying physical mechanisms remains elusive. The transfer is often mediated by a turbulent cascade of Alfvénic fluctuations as well as a variety of kinetic instabilities; these processes tend to be multi-scale and/or multi-dimensional, which makes them difficult to study using spacecraft missions and numerical simulations alone. Meanwhile, existing laboratory devices struggle to produce the collisionless, high ion beta ($\beta_i \gtrsim 1$), magnetized plasmas across the range of scales necessary to address these problems. As envisioned in recent community planning documents, it is therefore important to build a next generation laboratory facility to create a $\beta_i \gtrsim 1$, collisionless, magnetized plasma in the laboratory for the first time. A working group has been formed and is actively defining the necessary technical requirements to move the facility towards a construction-ready state. Recent progress includes the development of target parameters and diagnostic requirements as well as the identification of a need for source-target device geometry. As the working group is already leading to new synergies across the community, we anticipate a broad community of users funded by

a variety of federal agencies (including National Aeronautics and Space Administration, Department of Energy and National Science Foundation) to make copious use of the future facility.

Key words: astrophysical plasmas, space plasma physics, plasma devices, plasma instabilities, plasma nonlinear phenomena

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1. Motivation and summary of goals

1.1. *Scientific motivation for a new facility*

One of the major difficulties in studying space and astrophysical plasmas is characterizing energy and momentum transport across the broad range of scales of dynamical importance. For example, in galactic dynamics, there are roughly twelve orders of magnitude between the ion-scale fluctuations in the galactic disc and the much larger scales on which the energy transfer processes between the thermal plasma and cosmic rays operate (Brunetti & Jones 2014). Similar scale problems exist in our local heliosphere, where large-scale fluctuations driven by solar rotation are six orders of magnitude larger than small-scale fluctuations on electron gyration periods that terminate the turbulent cascade (Kiyani, Osman & Chapman 2015). Understanding the mesoscale processes that determine the energy partition between thermal plasma species and couple the small- and large-scale dynamics is critical for making progress on open questions in both space and astrophysical systems.

The processes that are most critical to understand, and currently most poorly understood, are those occurring in high-beta (thermal pressure is greater than or approximately equal to magnetic pressure), magnetized, weakly collisional plasmas (Kunz *et al*. 2019). These include, but are not limited to:

(i) Instabilities not only produce electromagnetic fluctuations but also constrain these same fluctuations by scattering particles and modifying the plasma's energy and momentum transport. These processes are important in a variety of astrophysical environments. In the solar wind, the role of pressure-anisotropy-driven instabilities in constraining the fluctuations present is well established (Bale *et al*. 2009). Outside of the heliosphere, instabilities play a large role in a number of astrophysical systems, including accretion discs at the heart of galaxies, galaxies themselves and the intracluster medium (Balbus & Hawley 1991; Quataert, Dorland & Hammett 2002; Quataert 2008; Kunz *et al*. 2014, 2022). Instabilities also play a large role in cosmic-ray energization near supernova remnants (Bell 2004), the coupling between the thermal plasma in the galactic disc and cosmic rays (Kulsrud & Pearce 1969), shock heating throughout the universe (Spitkovsky 2008; Caprioli & Spitkovsky 2013; Wilson *et al*. 2014, 2016) and potentially the generation of radio halos (Brunetti & Jones 2014). Relevant instabilities include firehose and mirror instabilities (Gary *et al*. 2001; Kasper, Lazarus & Gary 2002; Hellinger *et al*. 2006; Schekochihin *et al*. 2008; Rosin *et al*. 2011), heat-flux and gradient-driven instabilities (Komarov *et al*. 2016; Komarov *et al*. 2018; Riquelme, Quataert & Verscharen 2016, 2018; Verscharen 2016) and streaming instabilities (Bell 2004; Amato & Blasi 2009), among others.

https://doi.org/10.1017/S0022377825100469 Published online by Cambridge University Press

(ii) Turbulence is a major channel of energy transfer in many space and astrophysical systems. Understanding the details of how turbulence transfers energy from scale to scale and the processes by which it ultimately transfers energy to the particles is critical for a number of open questions. The resulting energy and momentum transport affects everything from the state of the turbulent solar wind at Earth (Breech *et al*. 2009; Howes 2010) to the amount and type of radiation emitted from astrophysical objects such as accretion discs (The Event Horizon Telescope Collaboration *et al*. 2019*a*,*b*, 2021). Furthermore, turbulence affects the evolution of large-scale structures everywhere from our heliosphere (Tu & Marsch 1995; Verscharen, Klein & Maruca 2019; Richardson *et al*. 2022) to more distant galaxies and their surrounding circumgalactic media (Tumlinson, Peeples & Werk 2017; Ji *et al*. 2020; Lochhaas *et al*. 2023). Due to the very large-scale separation between the turbulent dissipation and the macroscopic evolution, widely used fluid models of these large-scale systems (Tóth *et al*. 2012; Thomas & Pfrommer 2022; Talbot *et al*. 2024) use effective heat conduction and viscosity terms to approximate the energy and momentum transport due to turbulent dissipation. The underlying turbulent dissipation model chosen can significantly affect the observed behavior of the system (e.g. Chael *et al*. 2018, 2019). The ambient, turbulent magnetic fluctuations in these systems can also affect the trajectory of cosmic rays, the most energetic particles in the universe, and can impact our understanding of where these fast, charged particles originate (Owen *et al*. 2023).

To enhance our understanding of energy and momentum transport in the aforementioned space and astrophysical systems, a plasma device capable of achieving collisionless conditions while being magnetized with high plasma beta is necessary. Basic plasma science experiments have had success in studying astrophysical phenomena where one or two of the conditions (collisionless, magnetized, and high beta) are met (Keiter *et al*. 2000; Brown & Schaffner 2014; Schaffner, Wan & Brown 2014; Dorfman & Carter 2016; Endrizzi *et al*. 2021; Peterson *et al*. 2021; Schroeder *et al*. 2021; Ji *et al*. 2023; Bose *et al*. 2024). However, existing experiments (e.g. Forest *et al*. 2015; Gekelman *et al*. 2016) struggle to achieve all three conditions simultaneously, leaving a key gap in our approach to solving the problems mentioned above. Recent community planning documents have therefore envisioned a next generation laboratory facility to tackle these problems (Carter *et al*., 2020; Milchberg & Scime, 2020; Baalrud *et al*., 2020; Dorfman *et al*., 2023; National Academies of Sciences, Engineering, and Medicine 2024). Unlike spacecraft, laboratory experiments can take multi-point measurements of a controlled, reproducible plasma (Howes 2018; Lichko *et al*. 2020, 2023). Such experiments can therefore complement and extend the utility of spacecraft in exploring the multi-scale and multi-dimensional physics that occurs in space and astrophysical systems. Thus, the proposed device will take advantage of these unique capabilities of laboratory experiments to enable novel plasma science experiments with broad relevance to space and astrophysical plasmas.

1.2. *Goals of the planning process*

To tackle this problem, the CHIMERAS (Collisionless HIgh-beta Magnetized Experiment Researching Astrophysical Systems) project working group has been formed under the auspices of MagNetUS, which is a network comprising several basic plasma science facilities and their collaborators. The working group consists of 30+ scientists from various parts of the community (space observation, numerical

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	Parameter	Regime	Reason
High beta	Ion plasma beta	$\beta_i \gtrsim 1$	Comparable magnetic and ion kinetic pressure
Collisionless	Collision frequency/Alfvén wave frequency	$\nu_{ei}/\omega < 1$	Minimize electron–ion collisions
Magnetized	Machine size in ion scales	$L_\perp \sim 50 \max(d_i, \rho_i)$ $L_\parallel \sim 100 \max(d_i, \rho_i)$	Study MHD Alfvén waves

TABLE 1. Machine requirements: key dimensionless parameter requirements that existing facilities struggle to satisfy which will open up a new physical regime for studies of energy and momentum transport via turbulence and instabilities.

simulations, theory, and laboratory experiments) and is actively defining the necessary technical requirements to design an experimental facility to address the science goals in § 1.1. Our planning process has two major aims:

(i) Design a device to create a $\beta_i = 8\pi n T_i / B^2 \gtrsim 1$, collisionless, magnetized plasma in the laboratory for the first time. This new regime will enable novel plasma science experiments with broad relevance to space and astrophysical plasmas. We will for the first time be able to study astrophysically relevant collisionless instabilities and magnetized plasma turbulence.

(ii) Nurture the budding investigator network working on the device by involving researchers from different parts of the field (space observation, computer simulations, theory and laboratory experiments) and different career stages (including graduate students and postdocs) in the above discussions. This broad array of expertise will expose participants to subject areas and research techniques with which they may not be familiar.

A summary of the key dimensionless parameter requirements necessary to address our first aim is given in table 1. The high-beta condition is necessary because the space and astrophysical environments this machine aims to emulate are typically $\beta_i \gtrsim 1$, and the onset of several of the targeted instabilities is dependent on β_i. The collisionless condition comes from the two-fluid Alfvén wave dispersion relation (Mallet *et al.* 2023); to explore kinetic scales, we wish to minimize Alfvén wave damping in the regime where the waves are dispersive. Since the frequency of Alfvén waves in the device is expected to range from a fraction of the ion cyclotron frequency (f_{ci}) to slightly less than f_{ci}, we will sometimes write this criterion in terms of the ratio of the electron-ion collision frequency to the ion cyclotron angular frequency (ν_{ei}/ω_{ci}). The need to fit magnetohydrodynamic (MHD) Alfvén waves in the device gives rise to the magnetized condition; this leads to different conditions for machine length along the background magnetic field $L_\parallel$ and the machine diameter perpendicular to the field $L_\perp$. The relevant conditions are in terms of the ion gyroradius ρ_i and the ion skin depth d_i. We need to resolve perpendicular wavenumbers ($k_\perp$) that satisfy $k_\perp \rho_i \sim 1$ in order to capture the relevant anisotropy-driven instability physics. Meanwhile, we need to be able to launch Alfvén waves at perpendicular scales larger than both ρ_i and d_i in the turbulence experiments in order

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Set-up	n (cm^{-3})	T_e (eV)	T_i (eV)	B_0 (G)	f_0 (kHz)	f_{ci} (kHz)	d_i (cm)	ρ_i (cm)	ν_{ei} (rad s^{-1})	$\lambda_{\parallel 0}$ (cm)	$L_\perp$ (m)	$L_\parallel$ (m)
A	10^{13}	400	100	100	20	152	7.21	14.5	54.7	349	7.25	14.5
B	10^{13}	400	100	400	75	608	7.21	3.61	54.7	373	3.62	7.25

TABLE 2. Preliminary set of dimensional parameters in hydrogen plasma for both high-beta collisionless instabilities (A) and solar wind magnetized plasma turbulence (B): parameters are plasma density, electron temperature, ion temperature, background magnetic field, driven Alfvén wave frequency, ion cyclotron frequency, ion skin depth, ion gyroradius, electron–ion collision frequency, driven Alfvén parallel wavelength, chamber diameter and chamber length. Note that the ion cyclotron frequency and Alfvén wave frequency are both ordinary frequencies, while the electron–ion collision frequency is an angular frequency.

to avoid complications due to the presence of dispersive effects and Hall effects, respectively (Mallet *et al*. 2023). Since the smallest $k_\perp$ that can fit in the device will be $2\pi/L_\perp$, the factor of fifty is the minimum necessary to enable both the instability and the turbulence experiments, as it allows for $k_\perp\rho_i \gtrsim 0.13$ (or $k_\perp d_i \gtrsim 0.13$). The scale requirement in the parallel direction allows a low-frequency Alfvén wave ($\omega \ll \omega_{ci}$) to fit in the device; this may be seen by noting that the MHD Alfvén wave dispersion relation can be written as $k_\parallel d_i = \omega/\omega_{ci}$. The device will therefore be large enough to contain counter-propagating, low-frequency Alfvén waves for the turbulence experiments and large enough to resolve low-frequency Alfvén waves that result from the instabilities.

2. Accomplishments of the first workshops

The CHIMERAS project working group held the first design workshop 18–20 April 2024. During the workshop, the working group established a preliminary set of dimensionless parameters; developed a pre-prototype source/target geometry concept; determined measurement and diagnostic requirements; and emphasized the need for training and professional development opportunities for graduate students, post-doctoral scientists and early-career researchers. These parameters and requirements were further refined at the second workshop on 15–16 December 2024.

2.1. *Preliminary set of dimensionless parameters*

Our preliminary set of parameters for both the instability (A) and turbulence (B) experiments are outlined in table 2 (dimensional) and table 3 (dimensionless). These parameters are optimized around the requirements in table 1 and assume that the experiments will be conducted in hydrogen plasma. The optimization process is illustrated in figure 1. The red and blue shadings indicate different levels of β_i and ν_{ei}/ω_{ci}, respectively; the regions with darker shading are better able to meet each of the first two requirements in table 1. In dimensional terms, the primary difference between the two experimental set-ups is the magnetic field strength, B_0; this difference is because the high-beta condition is not strictly necessary for the turbulence experiments (set-up B).

According to the requirements in table 1 and parameters in table 2, a large chamber with diameter $L_\perp \sim 50\max(d_i, \rho_i) = 7.25$ m and length $L_\parallel \sim 100\max(d_i, \rho_i) =$ 14.5 m will work for studying both turbulence as well as kinetic instabilities in

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Set-up	(v_{the}/v_A)	$k_{\parallel 0}d_i$	(ν_{ei}/ω_{ci})	β_e	β_i
A	172	0.13	0.057	16.1	4.03
B	43.0	0.12	0.014	1.01	0.25

TABLE 3. Preliminary set of dimensionless parameters in hydrogen plasma for both high-beta collisionless instabilities (A) and solar wind magnetized plasma turbulence (B): parameters are the ratio of electron thermal speed to Alfvén speed, parallel wavenumber corresponding to f_0 from table 2 times ion skin depth, the ratio of collisionality to ion cyclotron angular frequency ($\omega_{ci} = 2\pi f_{ci}$), electron beta and ion beta.

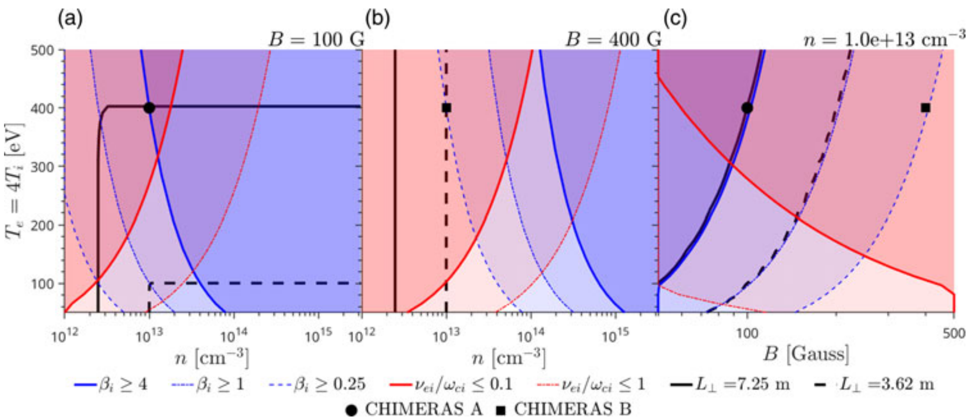

FIGURE 1. Location of set-ups A and B in parameter space. Blue shading indicates different levels of β_i while red shading indicates different levels of ν_{ei}/ω_{ci}. Black lines show the value of $L_\perp = 50\max(d_i, \rho_i)$ for set-ups A and B. (*a*) Location of set-up A in n-T parameter space. (*b*) Location of set-up B in n-T parameter space. (*c*) Location of both set-ups in B-T parameter space. Note that $L_\perp = 3.62$ m everywhere to the right of the $\beta_i = 1$ line in (*c*), not just on black dashed line.

a magnetized, collisionless, high ion beta plasma. Generating high-density plasma ($n > 10^{13}$ cm^{-3}) in a large chamber is challenging; thus, we use this as our upper limit on plasma density, which effectively sets the lower limit on the device size.[1] These limits were calculated assuming a hydrogen plasma. A helium plasma would allow for increased diagnostic flexibility (see § 3.1.2), but would increase the scale (in dimensional units) that corresponds to $k_\perp \rho_i = 1$ and thus necessitate a larger vessel size.

2.2. *Necessity of a source-target geometry*

To access new plasma parameter regimes in which the plasma is magnetized, collisionless, and high β_i, it was the conclusion of the workshop discussion that the configuration of the experiment would require a geometry in which a source plasma would fill a target chamber. This particular configuration arose from the key

[1]Since $\rho_i \propto \sqrt{\beta_i/n}$ and $d_i \propto 1/\sqrt{n}$, the required β_i and achievable plasma density n set the values of the ion scales.

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constraint in generating both large β_i and a magnetized plasma. Currently operating experiments which have $\beta_i > 1$ are too small to achieve the magnetized condition; when the plasma's own magnetic field is weak enough to achieve high beta, the ion gyroradius is often comparable to, or larger than, the system size (Bott *et al*. 2021; Endrizzi *et al*. 2021; Meinecke *et al*. 2022). Furthermore, any plasma created in a single chamber which has plasma pressure greater than magnetic pressure will rapidly expel the magnetic field; thus, the plasma will not remain magnetized.

Correspondingly, we must engineer a system in which an initially confined, magnetized, collisionless plasma source is allowed to expand into a secondary target chamber so that as the plasma expands, the plasma naturally enters the conditions desired due to its own dynamical evolution. To reduce the loss of plasma to the walls and improve confinement time, the walls of the target chamber can be lined with permanent magnets in either a line-cusp or a broken line-cusp configuration (Limpaecher & MacKenzie 1973; Gekelman & Stenzel 1975; Leung, Samec & Lamm 1975; Forest *et al*. 2015). Additionally, fusion-like temperatures can be realized in the source chamber through combinations of electron cyclotron resonant heating and neutral beam injection, which would push the plasma further into the collisionless regimes necessary to study the kinetic plasmas commonly observed in astrophysical systems.

This particular configuration has a number of added benefits for the physics goals we seek to address with this new facility. For example, the expansion of the plasma in this system is analogous to the expansion of the solar wind. This feature will allow the community to study how the effects of expansion on the distribution function may be limited by plasma instabilities and how the transport of momentum and heat in an expanding plasma may be modified by collisionless processes. Further, a source region can be constructed which provides a large degree of flexibility for the temperature of the plasma in the target chamber. This flexibility will allow for additional possible diagnostic options. For example, the proposed turbulence configuration can tolerate a range of β_i, so operating at lower temperature (lower β_i) is feasible. Although this choice will increase the collisionality, figure 1 shows there is significant flexibility in maintaining the collisionless condition. Decreasing the temperature by a factor of four will still keep the ratio of $\nu_{ei}/\omega_{ci} < 0.1$, thus minimizing the amount of collisional damping expected.

2.3. *Diagnostic/measurement requirements*

The key quantities to be measured are density (n), parallel ($\parallel$) and perpendicular ($\perp$) components of the electron (T_e) and ion temperature (T_i), as well as fluctuations in density (δn), magnetic field (δB) and bulk ion velocity (δv) associated with waves and instabilities.[2] The fluctuating quantities must be measured with sufficient spatial and temporal resolution to effectively study turbulence and instabilities. For the turbulence experiment, the parallel wavelength ($\lambda_\parallel$) of the excited Alfvén waves is expected to be comparable to or longer than the perpendicular wavelength ($\lambda_\perp$); thus the latter sets the limit for spatial resolution. For both the turbulence and ion-scale instability experiments, the key kinetic physics, e.g. the largest ion damping rates of turbulent fluctuations or the largest growth rates of unstable ion modes, is expected

[2]We have also indicated in table 4 when the distribution function (f) can be measured. In the indicated diagnostics, the parallel and perpendicular ion and electron temperatures, as well as the velocity fluctuations, are derived from this quantity.

to occur around $k_\perp \rho_i \sim 1$. Therefore, a spatial resolution smaller than $\sim\rho_i$ is desired for set-ups A and B. With this resolution and the desired vessel volume (table 1), we also have multiple decades of resolved scales for the turbulence studies (from $\sim$3.6 m driving scales down to $\lesssim$3.6 cm sub-ρ_i scales). The time resolution for the turbulence experiment is set by the requirement to measure oscillating quantities associated with an Alfvén wave (δB, δv, and at small scales δn). The frequency of the excited Alfvén waves is expected to range from a fraction of the ion cyclotron frequency (f_{ci}) to slightly less than f_{ci}. For the experiments on anisotropy driven ion instabilities, the bulk of the measurements are expected to be made at f_{ci} scales. Since f_{ci} is the highest frequency that needs to resolved, we require diagnostics that can sample data at rates at least $\sim$10 f_{ci}.

Typically, the aforementioned quantities are measured with good spatial and temporal resolution in basic plasma physics experiments using *in situ* probes. However, we will not be able to extensively use *in situ* probes, as the high heat and particle flux at the densities and temperatures in our proposed experiments (see tables 2 and 3) will significantly reduce the lifetime of the probes. An alternative solution is to adopt optical diagnostics developed by the fusion community as much as possible. These diagnostics do not require *in situ* components.

In fact, because several of the scientific questions CHIMERAS seeks to address require measurements of the particle distribution functions of electrons and ions, optical diagnostics will be a key component of the experimental measurement suite. Techniques such as laser-induced fluorescence (Boivin & Scime 2003; Gorbunov *et al*. 2017) and Thompson scattering (Ghazaryan *et al*. 2022; Kaur *et al*. 2024) have been routinely deployed in fusion and other laboratory plasmas, and recent demonstrations of these techniques to reconstruct three-dimensional distribution functions (Shi & Scime 2023; Gilbert, Steinberger & Scime 2024) are extremely promising. It has now been demonstrated that not only can these diagnostics provide spatially resolved measurements of the bulk non-ideal physics, such as the temperature anisotropy of electrons and ions,[3] but these diagnostics also offer resolved measurements of detailed non-Maxwellian features of the distribution function (Shi *et al*. 2022). Measurements of this fidelity allow for detailed phase-space analysis that may be used to identify the details of the energy transfer in collisionless plasmas. For example, measurements of ion temperature anisotropy in space plasmas have previously been related to ion cyclotron damping (Kasper *et al*. 2013) and stochastic heating (Chandran *et al*. 2013). Characterization of energy transfer using the field-particle correlation technique (Klein & Howes 2016; Howes, Klein & Li 2017; Schroeder *et al*. 2021) is a lower priority for CHIMERAS due to the challenges measuring fluctuating electric fields discussed in § 3.1.2.

Table 4 shows a list of possible diagnostics that may meet the goals of our experiments after suitable modifications. For some of the diagnostics, such modifications will require further research and development. This point will be discussed in § 3.1.2.

2.4. *Training and professional development*

The working group also understands the importance of training the next generation of plasma researchers on plasma source development, cutting-edge diagnostics,

[3]We note that because these measurements are spatially resolved and not line integrated, it need not be the case that the temperature anisotropy be defined with respect to a ‘guide’ field and could instead be with respect to a spatially resolved magnetic field perturbation.

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Parameter	Diagnostics	Remarks
n	Thomson Scattering (TS) Ghazaryan *et al.* (2022); Kaur *et al.* (2024) Multi-chord Interferometer (MCI) Juhn *et al.* (2021); Van Zeeland & Carlstrom (2004)	Best sampling frequency to be determined Line integrated measurement with high sampling frequency
f, $T_{e,\parallel}$, $T_{e,\perp}$	Thomson Scattering (TS) Shi & Scime (2023)	Best sampling frequency to be determined
$\delta n/n$	Beam Emission Spectroscopy (BES) McKee *et al.* (1999); Kriete *et al.* (2018); Bose *et al.* (2022)	Neutral beam is needed. In tokamaks, BES has been used to measure two-dimensional images of $\delta n/n$ showing turbulent structures. Spatial resolution may be limited to resolving ion scales.
$k_\perp$	Two-dimensional multichannel Charge Exchange Imaging (CXI) Major *et al.* (2022)	Neutral beam is needed. Carbon impurities may suffice. CXI has a better spatial resolution than BES. We will follow the developments of the fusion community.
$k_\perp$	Fast Camera Imaging (FCI) Thakur *et al.* (2014*a*,*b*)	Previously used to measure the mode structure in a cylindrical plasma. Spatial resolution expected to be better than CXI. Need to determine the minimum $\delta n/n$ that can be measured.
f, $T_{i,\parallel}$, $T_{i,\perp}$	Charge Exchange Recombination Spectroscopy (CHERS) Magee *et al.* (2011) Laser Induced Fluorescence (LIF) Boivin & Scime (2003); Gorbunov *et al.* (2017)	Carbon impurities may suffice May require helium plasmas with helium neutral beam
f, δv	Laser Induced Fluorescence (LIF) Boivin & Scime (2003)	May require helium plasmas with helium neutral beam
δB	Zeeman Quantum Beat Spectroscopy (ZQBS) Scime (2024); Gilbert *et al.* (2025)	Relatively new diagnostic for plasmas. Hydrogen plasmas may not work, and helium or impurities may be an alternative.

TABLE 4. Promising diagnostics that can be used to measure key physical parameters. Important open questions in the 'remarks' column are elaborated on in § 3.1.2.

data analysis techniques and high-fidelity modeling that are crucial to the broader field of laboratory experiments for space and astrophysical plasmas. This unique facility will bring in scientists from different plasma communities, which will expose students and postdoctoral researchers to a broad range of interdisciplinary plasma

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topics. This synergy provides the perfect platform to serve as a training ground for young scientists. Moreover, this facility will also serve as a center for extensive plasma outreach and public engagement. The facility will bring together plasma scientists from all parts of the US, including several EPSCoR states, allowing us to implement outreach programs in diverse geographical locations and organize more targeted programs for primarily undergraduate institutes and minority serving institutes, in addition to pursuing research experiences for undergraduates and research experiences for teachers programs. Finally, leveraging current working group members' connections, we plan to work with other organizations such as the Coalition for Plasma Science and MagNetUS (a network of users of the magnetized plasma collaborative research facilities) and the education and outreach committees of the American Physical Society – Division of Plasma Physics, the Princeton Plasma Physics Laboratory, Oak Ridge National laboratory, along with federal agencies such as the National Science Foundation (NSF), Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) to organize summer schools and hands-on training workshops for graduate, undergraduate and high school students and teachers. This unique combination of a cutting-edge research and educational platform will simultaneously serve the missions of workforce development and public engagement.

3. Outstanding challenges and next steps

3.1. *Outstanding challenges*

Discussions at the workshops allowed the working group to more precisely define the outstanding challenges which must be answered before the construction of a device can begin. These questions fall into three categories: (i) plasma evolution and wave drive; (ii) diagnostic development and choice of gas species; and (iii) vessel size and shape.

3.1.1. Plasma evolution and wave drive

The source-target geometry provides a natural means of attaining conditions similar to the solar wind at 1 AU: $\beta_i \sim 1$, collisionless, and magnetized, but the precise hardware configuration needed to achieve the target parameters listed in tables 2 and 3 remains unresolved. While the magnetic field can be set by external coils, how the density and temperature evolve following ionization in the source chamber and plasma expansion into the target chamber is an open question. It is possible to extend the range of parameters by modifying the plasma once it is within the target chamber. This modification could take a number of forms, including neutral beam injection and radio-frequency heating. The expansion of the plasma can also be further tuned, and thus the excitement of anisotropy-driven instabilities further controlled, in the 'target' part of the source-target geometry by the addition of magnetic coils of variable strength near the interface between the source and target. Although the expansion itself may provide a source of turbulence due to the excited instabilities, controlled driving of the turbulence in the desired parameter regime (set-up B in tables 2 and 3) is desirable. While we may draw inspiration from existing antenna designs (Zhang *et al.* 2008; Gigliotti *et al.* 2009; Thuecks *et al.* 2009), substantial modifications will be necessary to account for the high heat and particle fluxes in CHIMERAS. Further research is necessary to better understand what hardware and driving configurations are best suited to our planned studies.

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3.1.2. Diagnostic development and choice of gas species

To measure all the necessary quantities identified in § 2.3 at the required spatial and temporal resolution, further research and diagnostic development will be required. Table 4 of § 2.3 gives a list of promising diagnostics that may meet the goals of our experiments after suitable modifications. Some of the questions that need to answered for implementation of the diagnostics are also given in table 4. In this section, we discuss open challenges that will need to be addressed to successfully measure the fluctuating quantities (δB, δn, δv) identified in § 2.3 as critical to the facility science goals. These challenges will require a significant amount of further research. The solutions will have important implications for the overall device design (see § 3.1.3) as some measurements may require helium plasma in lieu of the hydrogen set-up considered in tables 2 and 3.

Among the list of diagnostics in table 4, Zeeman Quantum Beat Spectroscopy (ZQBS), a method for measuring magnetic field fluctuations, may require the most significant amount of research for successful implementation in CHIMERAS (Scime 2024; Gilbert, Steinberger & Scime 2025). ZQBS will require ion or molecular species that can support Zeeman splitting in the presence of a magnetic field. In a pure hydrogen plasma, the ion species is a proton which will not exhibit the Zeeman effect. However, a diagnostic neutral beam may supply the necessary neutrals that may exhibit the Zeeman effect. Further research is needed to understand if quantum beats can be generated for Zeeman split lines of hydrogen atoms by a commercially available laser. If hydrogen is found to be unsuitable, then the next option would be to determine if impurities or helium plasma can suffice.

The outcome of the research on ZQBS will determine how beam emission spectroscopy (BES) is to be implemented in CHIMERAS. BES measures $\delta n/n$ in a two-dimensional plane where $\delta n/n$ can be as low as 0.1 % (McKee *et al*. 1999). BES in fusion devices like DIII-D is used in deuterium plasmas with a deuterium neutral beam (McKee *et al*. 1999; Bose *et al*. 2022). If research on ZQBS suggests that helium ion species are necessary, then we will need to determine suitable helium lines and perform associated atomic physics calculation to support BES in a helium plasma.

To measure ion velocity, laser-induced fluorescence (LIF) has previously been used successfully in helium plasmas (Boivin & Scime 2003), and LIF may also work for measuring velocity fluctuations, e.g. (Palmer, Gekelman & Vincena 2005). However, if experiments are to be carried out in hydrogen plasmas, then we will need to explore the use of helium impurities to support LIF measurements.

Measurement of the wave electric field δE using spectroscopic techniques is expected to be difficult in CHIMERAS. Existing techniques used by the fusion community such as the motional Stark effect (Rice, Burrell & Lao 1997; Levinton 1999) and heavy-ion beam probes (Shah *et al*. 1999) have not reported results with the required spatial and temporal resolution outlined in § 2.3. We therefore plan to initially rely on the measurement of the quantities in table 4, with the development of a diagnostic for the measurement of fluctuating electric fields left to future work aimed at expanding the capabilities of the device.

3.1.3. Vessel size and shape

Any device must be sufficiently large to allow study of the full spatio-temporal evolution of the phenomena in question (see table 1), which means achieving a quasi-steady state. The minimum vessel size given in § 2.1 is based on rough estimates of the required spatial scales; however, a more precise quantitative analysis

https://doi.org/10.1017/S0022377825100469 Published online by Cambridge University Press

is necessary to move forward with plans for the device. Simulation studies will help us determine what specific device configurations – including size, geometry and species – are needed to achieve and diagnose our target physics. Such studies will allow a more precise determination of the expected cost of the experiment, which is strongly dependent on the size of the chamber. Per § 3.1.2, running experiments in helium makes additional diagnostic options possible. We will therefore also need to balance the utility of these diagnostic methods against device size considerations in order to determine the best experimental set-up for determining the dynamics of high β_i instabilities and magnetized plasma turbulence in previously unrealized experimental plasma regimes.

3.2. *Dissemination of workshop results and next steps*

The working group recognizes the need for community and government support if a device like the one we envision is to become a reality. Our first action toward building the necessary support is to disseminate workshop results to the broader astrophysics, solar physics, heliophysics and plasma physics communities. Members of the working group provided a progress report at the 2024 American Physical Society Division of Plasma Physics conference during the associated MagNetUS reception. As the project matures the working group will increase their presence at other conferences, including but not limited to meetings of the American Astronomical Society, American Geophysical Union (AGU) and Solar Heliospheric and Interplanetary Environment workshop.

The working group plans to host semi-annual workshops after the annual MagNetUS and AGU Fall meetings, respectively, to further develop the device concept and increase community engagement with and investment in the project. Our next steps are to further investigate the current state of the art in plasma diagnostic capabilities and plasma turbulent driver technology and to design a pre-prototype device capable of generating and maintaining a collisionless plasma. Potential research projects that support the design of a next-generation device and could be immediately proposed for funding will be discussed; such projects include but are not limited to diagnostic development efforts (such as those identified in § 3.1.2), development and testing of drivers for turbulence experiments and simulations to better establish the physics of the source and plasma expansion into the target chamber to test and refine the device design. We plan to seek federal and private funding to enable dedicated design and development work and accelerate the current pace of progress.

Acknowledgements

The CHIMERAS project working group is currently an underfunded effort; thus we especially appreciate everyone who has contributed to this white paper and/or the April 2024 workshop on a volunteer basis.

Editor Edward Thomas, Jr. thanks the referees for their advice in evaluating this article.

Funding

This work was supported in part by a workshop grant from the Heising-Simons Foundation #2024-5662. E. L. was supported in part by NRL base funding and the

2024–2025 Karle Fellowship. J.M.T. and S.B. were supported by NSF award AGS-2401110. J.J. was supported by the U.S. Department of Energy under Contract No. DE-AC02-09CH1146 via LDRD grants. Y.Z. was supported by the NASA Living With a Star Jack Eddy Postdoctoral Fellowship Program, administered by the Cooperative Programs for the Advancement of Earth System Science (CPAESS) under award #80NSSC22M0097.

Declaration of interests

The authors report no conflict of interest.

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