

© 2016 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

C. A. Romero-Talamás, E. M. Bates, W. J. Birmingham and W. F. Rivera, "DPLX: Experiment to Investigate Heating and Stability in Magnetized Rotating Dusty Plasmas," in IEEE Transactions on Plasma Science, vol. 44, no. 4, pp. 535-539, April 2016, doi: 10.1109/TPS.2016.2527625.

<https://doi.org/10.1109/TPS.2016.2527625>

Access to this work was provided by the University of Maryland, Baltimore County (UMBC) ScholarWorks@UMBC digital repository on the Maryland Shared Open Access (MD-SOAR) platform.

Please provide feedback

Please support the ScholarWorks@UMBC repository by emailing scholarworks-group@umbc.edu and telling us what having access to this work means to you and why it's important to you. Thank you.

DPLX: Experiment to Investigate Heating and Stability in Magnetized Rotating Dusty Plasmas

C. A. Romero-Talamás*, E. M. Bates*, W. J. Birmingham*, W. F. Rivera*

* Department of Mechanical Engineering, University of Maryland Baltimore County, Baltimore, MD 21250 USA

Corresponding author: C. A. Romero-Talamás

Abstract—An experimental setup is under construction at the Dusty Plasma Laboratory of the University of Maryland, Baltimore County (UMBC) to study viscous heating and stability in magnetized rotating dusty plasmas. Azimuthal rotation will be imposed on dust, electrons, and ions by having an axial magnetic field B in a vacuum chamber placed inside a 16 cm bore Bitter-type magnet, and a radial electric field E centered at the chamber axis. The resulting $E \times B$ rotation is expected to have sheared rotation, which leads to viscous heating from the radial velocity profile. However, heating may also lead to interchange modes that destabilize the rotation. The planned experiments are motivated by observations of parabolic ion and electron temperature profiles in hydrogen plasmas in a supersonic rotating magnetic mirror, where ohmic and viscous heating were the only mechanisms available for heating the plasma. The goal of the experimental setup is to magnetize and rotate dust with diameter $\sim 1 \mu m$ that can be individually captured by particle velocimetry cameras and software. The Bitter-type magnet is planned for a steady field of 10 T with a minimum duration of 10 s per experiment.

Index Terms—Dusty plasmas, plasma stability, plasma transport processes, magnetic confinement.

I. INTRODUCTION

For traditional plasmas, it is well known that magnetic fields modify heat and particle transfer in the direction of the magnetic field. In dusty plasmas, magnetic fields change how dust and electrons interact, and therefore have an impact on dust-dust interactions and charging. Experimental research in complex plasmas has largely concentrated in regimes that do not include magnetic fields, mainly because of engineering and cost constraints in making strong enough fields to magnetize dust grains. While there are many interesting dusty plasma cases that can be studied with relatively low fields ($< 1 T$), these cases only include magnetization of electrons and ions, but not of grains that are bigger than $\approx 0.5 \mu m$ in diameter. Grains smaller than this size are difficult to follow with conventional charge-coupled device (CCD) cameras, which are now a standard dusty plasma diagnostic. Indeed, experiments with strongly magnetized dust are considered the next frontier in dusty plasma research [1]. A handful of current and past experiments have made use of weak magnetic fields to effect electrons and ions, and indirectly dust. Experiments at the University of Iowa [2] and Kiel University [3] have reported using fields between 10–20 mT that have helped confine the background plasma. At fields ranging from 0.01–1 T, researchers from the Institute of Plasma Research (Baht, India), Kinki University (Japan), Tohoku University (Japan), Yokohama University (Japan), Max Planck Institute for Extraterrestrial

Physics (now under the Complex Plasmas Research group at the German Aerospace Center and Giessen University in Germany), University of Sydney (Australia), Institute of Physics (St. Petersburg, Russia), Christian-Albrechts University in Kiel (Germany), and Ernst-Moritz-Arndt-University in Greifswald (Germany), observed $E \times B$ drift (where E is the electric field, and B the magnetic field) attributed to magnetized ions dragging dust (and neutrals) in the $E \times B$ direction including rotation of strongly correlated and self-organized dusty plasmas [4]–[13]. Experiments with fields higher than 1 T are in operation at the Max Planck Institute [14], and recently at Kiel University [15] and Auburn University [16]. These high field experiments have been able to magnetize not just electrons and ions, but also dust in the 1–100 nm size range.

At the University of Maryland, Baltimore County (UMBC) the Dusty Plasma Laboratory experiment (DPLX) was established to study strongly magnetized as well as unmagnetized dusty plasmas. Particular attention is given to experiments and theory involving viscous heating and shear flow in $E \times B$ rotating dusty plasmas, as this has relevance to heating and confinement of thermonuclear fusion plasmas and rotating magnetic mirrors, as well as astrophysical plasmas such as accretion disks.

II. MOTIVATION

A resistive magnet of the Bitter-type [17] is currently being designed to achieve fields of 10 T for at least 10 seconds per discharge, with the goal of magnetizing particles larger than $0.5 \mu m$ in diameter. Of particular interest in the DPLX, is the study of viscous heating and velocity shear that is expected in azimuthally rotating dusty plasmas. This type of heating is relevant to startup scenarios of tokamaks [18], as well as in alternative reactor concepts, such as supersonically rotating magnetic mirrors [19]. Magnetized dusty plasmas will be used in understanding, from an atomistic perspective, how $E \times B$ driven plasmas generate velocity shear profiles.

Ion and electron temperature profiles measured in hydrogen plasmas in the Maryland Centrifugal Experiment (MCX) [20], [21], as well as theoretical predictions based on magnetohydrodynamics models [19], show a peaked profile in temperature and velocity along the mirror radius. Figure 1 shows the measured T_e and T_i profiles. The only heating mechanisms for MCX and other similar experiments were ohmic and viscous heating. The density profile, however, was not directly known

in MCX; density was measured by integrating along a line of sight with an interferometer, and a density profile was inferred through numerical fittings of experimental diagnostics and magnetohydrodynamic (MHD) models [22], [23]. Shear flows have been measured in MCX plasmas [20], and viscous heating resulting from this shear together with Ohmic heat from the power source driving the $\mathbf{E} \times \mathbf{B}$ rotation, are responsible for the high temperature and $\beta > 20\%$, which is significantly higher than tokamaks ($\beta \equiv 2n\kappa T/\mu_o B^2$, i.e. the ratio of the thermal to magnetic pressures, is often considered an indirect measure of a concept's efficiency in magnetic field utilization for plasma confinement). No other other sources of heat were used to achieve ~ 100 eV temperatures in MCX [21]. In fact, it has been argued by Ellis *et al.* based on single-fluid MHD theory that no auxiliary heating would be required to achieve thermonuclear fusion in a rotating magnetic mirror [24]. To date, however, it has not been possible to separate Ohmic and viscous heating contributions in any rotating mirror experiment (to the best of the authors' knowledge), as it has been difficult to measure the balance of particle and energy input and losses, as well as density profiles radially and along the mirror's axis. A magnetized dusty plasma experiment with imposed $\mathbf{E} \times \mathbf{B}$ rotation would be expected to achieve heating and velocity profiles similar to those in hydrogen plasmas, such as those shown in Fig. 1, but at timescales and temperatures that are much easier to probe directly.

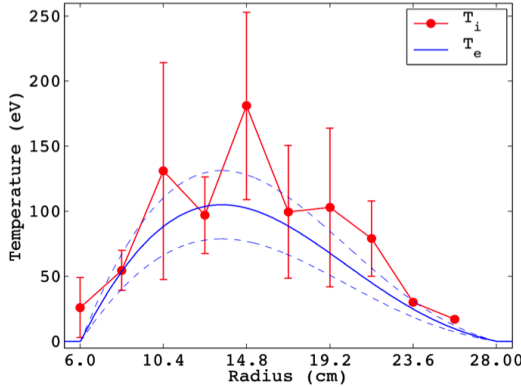


Fig. 1. T_i and T_e profiles for MCX. From Ref. [21].

The traditional criterion for magnetization has been to rely on the Larmor radius of the charged particle,

$$r_L = \frac{mv_{\perp}}{|q|B} \quad (1)$$

where m is the particle mass, q its charge, and v_{\perp} its velocity perpendicular to the magnetic field; as well as the collisionality of dust with neutrals [1],

$$r_c = \frac{\Omega_d}{\nu_{damp}} = \frac{qB/m}{\frac{4\pi\delta m_n N_n v_{tn} a^2}{3m}}, \quad (2)$$

where Ω_d is the dust cyclotron frequency and ν_{damp} is the collisional damping frequency (m_n is the neutral atom mass, N_n is the neutral particle density, v_{tn} is the neutral thermal

velocity, a is particle radius, and δ is a geometrical parameter of order 1 in the Epstein drag force [25], which is used here since we assume spherical dust moving slowly with respect to the rarified neutral gas). For a system of scale L , the criterion is satisfied if $r_L \ll L$ and $r_c > 1$, so long as there are no electric fields perpendicular to the magnetic field. For example, a 200 nm silica sphere will have a mass $m_d = 9.3 \times 10^{-18}$ kg; if $B = 5$ T, $P = 1$ Pa, $v_{\perp} = 2$ m/s, and $Z = 10^4$ for $q = Ze$ (where e is the elementary charge) then $r_L = 2.3$ mm and $r_c = 25$. Adding a radial electric field E_r , however, complicates this magnetization assumption. For example, if a relatively small radial field $E_r = 10$ V/m is added to a configuration in which \mathbf{B} is in the axial direction of a cylindrical system and oriented with gravity (i.e., the particle drifts only perpendicular to gravity) then the force balance is

$$m\ddot{\mathbf{x}} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}). \quad (3)$$

Figure 2 shows orbits for the present example, where the following initial conditions have been used to solve Eq. 3.

As the particle's diameter is increased, and thus also its mass, the orbits of a single particle become closer to the 15 cm circumference prescribed in the simulation; for the rightmost panel of the figure the apparent gyroradius is now ~ 2.5 cm. Of course, for a multiparticle system in a collisional regime,

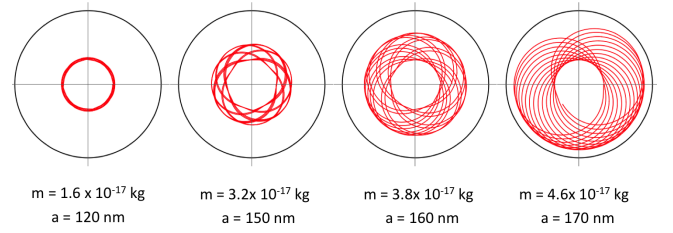


Fig. 2. Single particle simulation of $\mathbf{E} \times \mathbf{B}$ drift. The simulation circumference is 15 cm in diameter, and the particle mass and radius for solid glass spheres, m and a respectively, are indicated under each plot. Particle charge is assumed to be the same in all cases. The initial conditions for all cases are $x(0) = r_o = 0.025$ m, $y(0) = 0$, $\dot{x}(0) = 0$, $\dot{y}(0) = -v_{\perp} = -2$ m/s.

particles with a large gyroradius could leave the domain after just a few scattering collisions [26]. Several parameters can be adjusted to improve confinement. The magnetic field is the most critical one but it is the most difficult to produce experimentally at constant and high values. It is advantageous to keep the dust particles as large as possible so imaging diagnostics can be used to track them individually. At the same time, it is important to keep particles as light as possible so they can be confined in the experimental volume. A field amplitude $B = 10$ T and a cylindrical experimental volume of 15 cm diameter and approximately 10 cm in height are chosen as maximum design values. However, the magnet will have flexibility in field strength, duration, and gradient (along the magnet's axis). Assuming particles of density $\rho = 1500$ kg/m³ (e.g. melamine formaldehyde), it is possible to confine particles with 1 μ m diameter in a 10 T magnetic field, as shown in Fig. 3. Note that the parabolic profile in

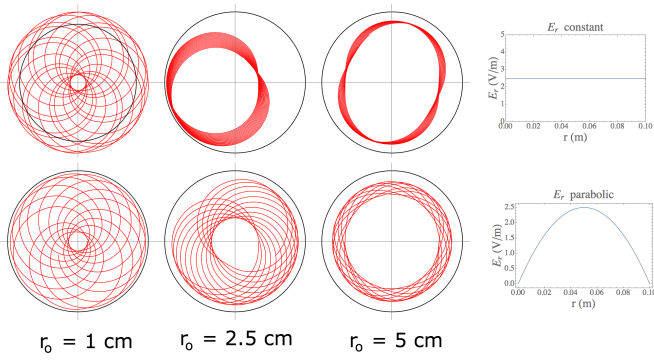


Fig. 3. Single particle simulation of $\mathbf{E} \times \mathbf{B}$ drift within a 15 cm diameter circumference with two different electric field profiles: top panels have flat profile at $|\mathbf{E}| = 2.5$ V/m and bottom panels have a parabolic profile peaked at $E_m a x = 2.5$ V/m. All cases assume a particle radius $a = 500$ nm, mass $m = 7.9 \times 10^{-16}$ kg, magnetic field $\mathbf{B} = 10$ T, and particle charge of $Ze = 10^4$. The label r_o refers to the starting radius inside the simulation circumference.

electric field yields better confinement than the constant case. Both are planned, as the parabolic profile is predicted by MHD simulations for hydrogen plasmas [27], but has never been confirmed experimentally given the difficulties in direct (i.e. insertable probe) measurements in high temperature and high density plasmas such as MCX. Particle tracking and direct probe measurements of the rotating dusty plasmas are also planned. Nevertheless, it is also recognized here that floating potential probes such as Langmuir probes [28], [29] are challenging in plasma flows with magnetic fields [30], [31], and thus diagnostics for dusty plasmas in high magnetic fields is under development at DPLX. Insertable probes are being developed taking existing theories into account, but the availability of a 10 T magnet that can vary in field strength and duration present an excellent opportunity to challenge such theories (e.g. Refs. [3], [32]) in experiments where dust is also magnetized (and not only electrons and ions), and develop corrections or new theories if need be.

III. VISCOSITY IN $\mathbf{E} \times \mathbf{B}$ ROTATING DUSTY PLASMAS

Exploiting the possibility to track individual particles given the relatively large particle size magnetizable in our planned experiments, we plan on following the methodology reported by Feng, Goree, *et al.*: they demonstrated experimental measurements of viscosity and shear flow in linear systems [33]. We will apply the methodology to azimuthally rotating dusty plasmas. Their method relies on using the Green-Kubo relations (see Ref. [34] and references therein), and starts with defining the off-diagonal stress tensor

$$P_{xy}(t) = \sum_{i=1}^N \left[m v_{ix} v_{iy} - \frac{1}{2} \sum_{j \neq i}^N \frac{x_{ij} y_{ij}}{r_{ij}} \frac{\partial \Phi(r_{ij})}{\partial r_{ij}} \right], \quad (4)$$

where i and j denote different particles, N is the total number of particles of mass m , $\mathbf{r}_i = (x_i, y_i)$ is the position of particle i , $x_{ij} = x_i - x_j$, $y_{ij} = y_i - y_j$, $r_{ij} = |\mathbf{r}_i - \mathbf{r}_j|$, and $\Phi(r_{ij})$

is the interparticle potential energy. Note that the position of particles vary over time, and hence the time dependence in Eq. 4. An autocorrelation function that is averaged over an equilibrium ensemble (where the averaging is denoted by triangular brackets) is then defined as

$$C_\eta(t) = \langle P_{xy}(t) P_{xy}(0) \rangle. \quad (5)$$

This is integrated to yield the viscosity η , which for a two-dimensional system is

$$\eta = \frac{1}{A k_B T} \int_0^\infty C_\eta(t) dt, \quad (6)$$

where A is the area of the system, k_B is the Boltzmann constant, and T is its temperature.

We recognize the experimental limitations in obtaining the necessary parameters in the above equations, and in particular the interparticle potential $\Phi(r_{ij})$ (these limitations are also discussed in the methodology of Feng, *et al.* in Ref. [33]). We plan to use the Yukawa potential models applied in theory and simulations to overcome these limitations (e.g. Refs. [35]–[38]). Another limitation identified by Feng *et al.* is the experiment duration for the integral in Eq. 6. In this case, measurements are necessarily made for a finite time given the difficulty in sustaining a high value magnetic field. However, our system is designed for nominal 10 second experiments in order to have about 20 events per day, but can also be configured for longer events (on the order of 2–3 minutes at 10 T and tens of minutes at lower fields) although with less events per day.

High rotation velocity in MCX was sought to avoid interchange modes (Rayleigh-Taylor-like instabilities in which magnetic flux ropes push out of the mirror, degrading particle and energy confinement). Supersonic velocities (with respect to ion sound speed) in MCX were achieved through a high $|E/B|$ ratio, which was programmed in the experiment by applying a high voltage between a center conductor and the grounded cylindrical vessel. This supersonic rotation was responsible for the high β values achieved in MCX. Dusty plasma β is a quantity that we will seek to measure in magnetized dusty plasmas, as well as the limits of stability in high rotation. The measurements required for Eqs. 4 and 6 will also be used in the calculation of β .

IV. MAGNET DESIGN AND CONSTRUCTION

The electromagnet under design at DPLX is of the type first pioneered by Francis Bitter [39]. The aim is to have an experimental volume of about 15 cm in diameter and a height of at least 5 cm in which the field is constant (to within a 10% of B_z at the edges of the vertical domain). The design and fabrication pose a significant engineering challenge, and careful optimization of parameters is required to minimize costs and maximize safety. We are developing analytical and computational tools that allow us to compare different magnet configurations for safety, performance, ease of use and fabrication, and cost. The design goals are to sustain

the magnetic field for at least 10 seconds, and be able to have at least 20 discharges per day. Calculations so far indicate that to achieve such a high field over the required experimental volume, a total ohmic power on the order of 6 MW is dissipated within the coils (assuming copper resistivity at room temperature). Besides the expected mechanical stresses caused by the large $\mathbf{J} \times \mathbf{B}$ forces within the coil (where \mathbf{J} is current density), the problem is mainly a thermal management one. The Bitter-type of coil uses conducting plates instead of wires, with the plates full of holes such that water at high velocity can remove the heat from the coil and avoid catastrophic failure. A set of analytic expressions developed by our group allow us to calculate the number and placement of holes for the magnet plates, while constraining the maximum temperature increase to a predetermined value [40]. The calculations take seconds [compared to hours for finite element analysis (FEA)], and have allowed us to compare different configurations such as split magnets, nested coils, or a single coil. Figure 4(a) shows a concept of the magnet plates and insulators, and dusty plasma chamber. Figure 4(b) shows the magnetic field inside and outside the Bitter plate assembly; our analytic calculations are checked with finite element analysis (FEA) software to verify magnetic field distribution, Ohmic power distribution, cooling water velocity and heat removal through the Bitter plates, and mechanical stresses on the magnet.

Industrial, deep-cycle batteries will be used to store enough electrical energy for 20 discharges, totaling about 1400 MJ (note that given the large inductance of the magnet, there is a ramp up time for every discharge, so the power required is more than that for 20×10 seconds). The electrical design to power the magnet represents a challenge because the currents produced by batteries is purely DC, and thus switching and safety technology (such as interlocks and emergency switches) need to be carefully chosen to maximize reliability and minimize costs. Interrupting DC currents is challenging because there are no zero crossing as in AC currents, bringing the possibility of arcing and degrading of conventional switches. The current magnitude required is in excess of 10 kA to drive the coils at maximum field. This will be accomplished by stacking batteries of 13.6 V each in series to reach a driving voltage based on the magnet resistance. Each stack will produce about 1 kA of current, and thus about 10 stacks in parallel are required. We are exploring different designs for normal operation switching as well as off-normal events (emergency interrupts, power outages, etc.).

Diagnostic access is only possible from the top of the magnet. Optical access is planned through fluorine doped tin oxide (FTO) glass, as well as periscopes that allow one or more cameras to be placed safely away from the high strength magnetic field. Probes are presently being tested in a 1 T prototype magnet that has been designed and built to test manufacturing methods and calculations. We expect to have the first tests of the 10 T magnet by the Fall of 2016. Experiments with the 10 T magnet will help advance our understanding of viscous plasma heating, help validate theory and numerical codes, and optimize \mathbf{E} and \mathbf{B} profiles in rotating

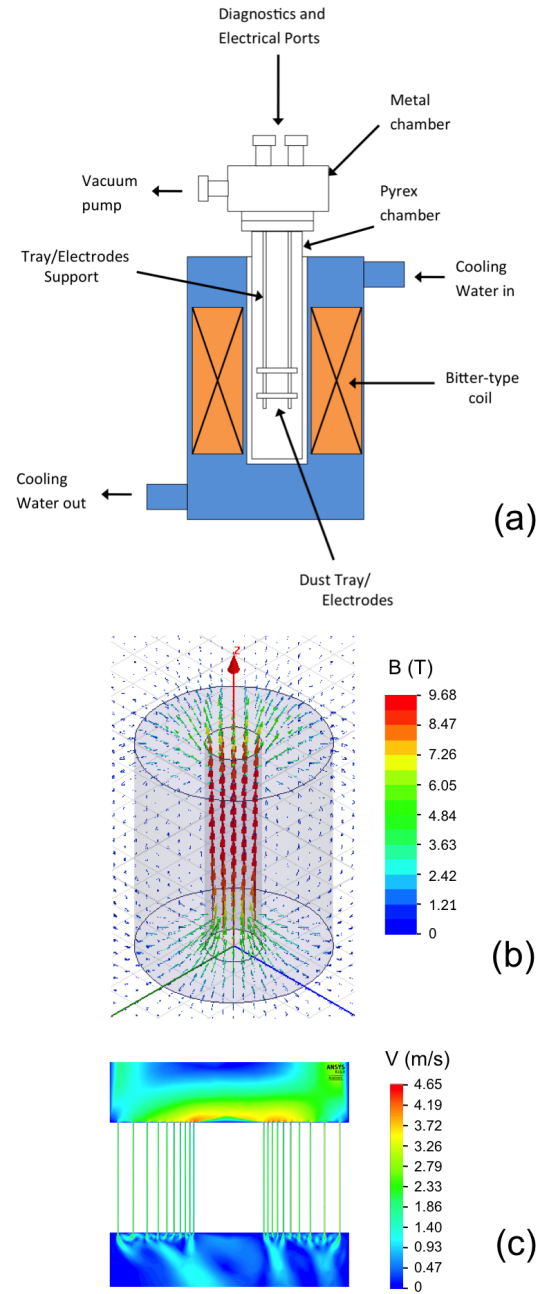


Fig. 4. (a) Concept of Bitter-type coil with drop-in dusty plasma glass chamber. (b) FEA verification of magnetic field. Maximum value occurs inside the bore at mid-point between top and bottom. (c) FEA verification of cooling water velocity field for the magnet plates inside the pressurized cooling tank. Average velocity is 2.6 m/s and approximately constant inside the cooling channels.

magnetic mirrors.

REFERENCES

- [1] E. Thomas Jr., R. L. Merlino, and M. Rosenberg. *Plasma Phys. Control. Fusion*, 54:124034, 2012.
- [2] C. Thompson, A. Barkan, N. D'Angelo, and R. L. Merlino. *Phys. Plasmas*, 4:2331, 1997.
- [3] T. Trottenberg, D. Block, and A. Piel. *Phys. Plasmas*, 13:042105, 2006.

- [4] S. Nunomura, N. Ohno, and S. Takamura. *Jpn. J. Appl. Phys.*, 36:877, 1997.
- [5] N. Sato, G. Uchida, T. Kaneko, S. Shimizu, and S. Izuka. *Phys. Plasmas*, 8:1786, 2001.
- [6] O. Ishihara, T. Kamimura, K. Hirose, and N. Sato. *Phys. Rev. E*, 66:046406, 2002.
- [7] P. Kaw, K. Nishikawa, and N. Sato. *Phys. Plasmas*, 9:387, 2002.
- [8] U. Konopka, D. Samsonov, A. V. Ivlev, J. Goree, V. Steinberg, , and G. E. Morfill. *Phys. Rev. E*, 61:1890, 2000.
- [9] F. M. H. Cheung, N. J. Prior, L. W. Mitchell, A. A. Samarian, and B. W. James. *IEEE Trans. Plasma Sci.*, 31:112, 2003.
- [10] V. Yu Karasev, E. S. Dzlueva, A. Yu. Ivanov, and A. I. Eikhvald. *Phys. Rev. E*, 74:0066403, 2006.
- [11] I. Pilch, T. Reichstein, and A. Piel. *Phys. Plasmas*, 15:103706, 2008.
- [12] M. Puttscher and A. Melzer. *Phys. Plasmas*, 21:123704, 2014.
- [13] M. Puttscher and A. Melzer. *Phys. Plasmas*, 22:073701, 2015.
- [14] P. Bandyopadhyay, D. Sharma, U. Konopka, and G. Morfill. *AIP Conf. Proc.*, 1582:281, 2014.
- [15] J. Carstensen, F. Greiner, and A. Piel. *Phys. Rev. Lett.*, 109:135001, 2012.
- [16] E. Thomas Jr., A. M. DuBois, B. Lynch, S. Adams, R. Fisher, D. Artis, S. LeBlanc, U. Konopka, R. L. Merlino, and M. Rosenberg. *J. Plasma Phys.*, 80:803, 2014.
- [17] M. D. Bird. *Supercond. Sci. Technol.*, 17:R19, 2004.
- [18] C. Alejaldre, F. De Marco, U. Finzi, S. Günter, J.G. Jacquinet, P.K. Kaw, Chairman, G.-S. Lee, C. Llewellyn Smith, I.C. Nascimento, C. Pan, M. Roberts, V.P. Smirnov and T. Tamano. *Nucl. Fusion*, 45:A1, 2005.
- [19] R. F. Ellis, A. Case, R. Elton, J. Ghosh, H. Griem, A. Hassam, R. Lundsford, S. Messer, and C. Teodorescu. *Phys. Plasmas*, 12:055704, 2005.
- [20] C. A. Romero-Talamás, R. C. Elton, W. C. Young, R. Reid, and R. F. Ellis. *Phys. Plasmas*, 19:072501, 2012.
- [21] R. R. Reid, C. A. Romero-Talamá??s, W. C. Young, R. F. Ellis, and A. B. Hassam. *Phys. Plasmas*, 21:063305, 2014.
- [22] C. Teodorescu, W. C. Young, G. W. S. Swan, R. F. Ellis, A. B. Hassam, and C. A. Romero-Talamas. *Phys. Rev. Lett.*, 105:085003, 2010.
- [23] W. C. Young, A. B. Hassam, C. A. Romero-Talamás, R. F. Ellis, and C. Teodorescu. *Phys. Plasmas*, 18:112505, 2011.
- [24] R. F. Ellis, A. B. Hassam, S. Messer, and B. R. Osborn. *Phys. Plasmas*, 8:2057, 2001.
- [25] P. S. Epstein. *Phys. Rev.*, 23:710, 1924.
- [26] C. A. Romero-Talamás, R. C. Elton, W. C. Young, R. Reid, R. F. Ellis, and A. B. Hassam. *J. Fusion Energy*, 29:543, 2010.
- [27] Yi-Min Huang and A. B. Hassam. *Phys. Rev. Lett.*, 87:235002, 2001.
- [28] L. Tonks and I. Langmuir. *Phys. Rev.*, 33:195, 1929.
- [29] R. L. Merlino. *Am. J. Phys.*, 75:1078, 2007.
- [30] I. H. Hutchinson. *Principles of Plasma Diagnostics*. Cambridge University Press, Cambridge, 1987. Chapter 2.
- [31] I. H. Hutchinson. *Phys. Rev. A*, 37:4358, 1988.
- [32] T. Trottenberg, B. Brede, D. Block, and A. Piel. *IEEE Trans. Plasma Sci.*, 32:742, 2004.
- [33] Y. Feng, J. Goree, and Bin Liu. *Phys. Rev. Lett.*, 109:185002, 2012.
- [34] Y. Feng, J. Goree, Bin Liu, and E. G. D. Cohen. *Phys. Rev. E*, 84:046412, 2011.
- [35] M. S. Murillo. *Phys. Rev. E*, 62:4115, 2000.
- [36] T. Saigo and S. Hamaguchi. *Phys. Plasmas*, 9:1210, 2002.
- [37] G. Salin and J. M. Caillol. *Phys. Plasmas*, 10:1220, 2003.
- [38] G. Faussurier. *Phys. Rev. E*, 69:066402, 2004.
- [39] F. Bitter. *Rev. Sci. Inst.*, 10:373, 1939.
- [40] W. J. Birmingham, E. M. Bates, and C. A. Romero-Talamás. *J. Thermal Sci. Eng. Appl.*, 2015. (Accepted for Publication).