J. Plasma Physics (2015), *vol.* 81, 345810202 © Cambridge University Press 2014
doi:10.1017/S0022377814001160

BABE – a brush cathode discharge for thermal fluctuation measurements

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(Received 1 August 2014; revised 29 September 2014; accepted 7 November 2014; first published online 8 December 2014)

For experimental tests of fluctuation theory in ideal plasmas and plasmas seeded with dust, the ideal environment would be that of stable quiescent plasma. In most laboratory plasmas the homogeneous state of the positive column is often unstable, rare exceptions are the so-called brush cathode discharges, proposed in the 60s, where a specially manufactured cathode allows stable operation in the abnormal glow regime and the only fluctuations present are those due the thermal motion of the particles. Such a device, the BAri Brush Electrode (BABE), has recently been built in a novel configuration that combines the advantages of the inverse design with those of the reflex geometry. The region between the two anodes is essentially field-free and extremely stable in wide range of plasma densities and collisionalities. Unprecedented low fluctuation levels of $\delta n/n \leqslant 10^{-5}$ in He and $\delta n/n \leqslant 5 \times 10^{-6}$ in Ar discharges have been achieved.

1. Plasma kinetic theory as a basis of diagnostic methods

Thermal fluctuations in plasmas are omnipresent and triggered by particle discreteness and the electromagnetic fields induced by it. Fluctuation theory describes fundamental plasma processes providing expressions for the evolution of the averaged and fluctuating distribution functions as well as the collision integral whose dependence on the dynamic permittivity manifests the collective nature of plasma interactions (Klimontovich 1967; Tsytovich 1995). The fluctuation framework also provides expressions for the spectral densities of fluctuating plasma quantities, e.g. electron and ion densities or electrostatic field, as function of the averaged distribution function (Sitenko 1967; Akhiezer et al. 1975). This particular outcome of fluctuation theory constitutes the basis of a number of independent diagnostics that can be implemented in diverse plasma environments.

While fluctuation theory is rigorous for collisionless fully ionized plasmas, there exist regimes where approximate methods have to be invoked. Measurements of the thermal fluctuations in laboratory plasmas offer the possibility to explore such regimes in a flexible and controllable environment. In such an environment, one might be able to address, for instance, the effects of neutrals and electron impact ionization, or the effects of Coulomb collisions and suprathermal particle sub-populations on the spectra of the fluctuations. Moreover, the fluctuation theory for dusty plasmas has been recently developed (Tsytovich and de Angelis 1999) and is of considerable

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https://doi.org/10.1017/S0022377814001160 Published online by Cambridge University Press

theoretical interest, due to the non-Hamiltonian dissipative nature of such systems. It has been demonstrated that the presence of dust can lead to drastic changes of the spectral densities of fluctuating quantities (Ratynskaia et al. 2007, 2010; Tolias et al. 2012) and while proof of concept measurements have been performed (Ratynskaia et al. 2007, 2010), highly controlled tests have not been feasible yet.

Thermal fluctuation measurements are rather challenging because of their low level and, as a consequence, the risk of being masked by perturbations due to instabilities present in the majority of the plasma configurations and discharges. Let us discuss the different possibilities to measure thermal fluctuations.

Plasma scattering of high frequency electromagnetic radiation; The EM scattering cross-section is proportional to the spectral density of the electron density fluctuations (Sheffield 1975). For wavelengths shorter than the Debye length, $\lambda \ll \lambda_D$, scattering is incoherent in character and the spectrum of the scattered signal reflects the electron distribution function. Such a diagnostic has been routinely employed for electron density and temperature measurements in low-temperature, ionospheric and fusion plasmas (Hutchinson 1987; Froula et al. 2011). For long wavelengths, $\lambda \gg \lambda_D$, collective effects come into play and the scattered signal can be used to extract rich information about not only the electrons but also the ions. Coherent scattering measurements are much more challenging, especially due to the lack of powerful coherent sources at relatively low frequencies. However, successful experiments have been conducted either with lasers in high density cold laboratory plasmas (Ramsden and Davies 1966; Kieft et al. 2004) or with gyrotrons in tokamaks (Bindslev et al. 1999, 2006).

Quasi-thermal noise spectroscopy-QTN; This technique refers to the measurement of the spectral density of electric field fluctuations as the voltage power spectrum in the terminals of passive dipole or monopole antennas. In space plasmas, QTN has been successfully implemented to infer the plasma parameters in environments such as the solar wind and cometary plasmas (Meyer-Vernet and Perche 1989; Meyer-Vernet et al. 1998). The technique has strong advantages over Langmuir probe measurements, as it is weakly sensitive to the spacecraft potential and photo-electron perturbations.

Fluctuation measurements with electrostatic probes; density fluctuations in laboratory and space plasmas via the ion / electron saturation current of a single biased electrostatic probe. Especially in the laboratory, such experiments are very sensitive to plasma perturbations and inhomogeneities or external EM noise sources owing to the low level of thermal noise.

Undoubtedly, scattering of radiation offers the most direct measurement of plasma fluctuations, being a non-invasive and wavelength-selective method. In fact, such measurements can be carried out in highly inhomogeneous or even turbulent plasmas, owing to the selection of a particular fluctuation wave-number k, which depends only on the scattering angle θ and the incident wave frequency ω_0, i.e. $k = 2(\omega_0/c)\sin(\theta/2)$. However, for tests of fundamental aspects of fluctuation theory, radiation scattering is technically demanding, as far as the source of nearly monochromatic incident radiation and the detector of scattered waves are concerned. Practically, coherent scattering is not even feasible in quiescent discharges, since for the relevant plasma parameters, owing to the low value of the Thomson cross-section, powerful microwave sources are required $\sim$1 MW. On the other hand, probes or antennas, apart from locally perturbing the plasma, by default measure signals that are integrated over the whole fluctuation wave-number range. This implies that these techniques require a stable operating plasma environment in order to detect low-level thermal fluctuations.

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2. Quiescent laboratory plasmas

A pertinent question that arises, concerns whether the level of thermal fluctuations can be quantified and how low it actually is. Fluctuation theory does not provide a conclusive answer since expressions for the fluctuating quantities are derived in terms of the natural fluctuations connected directly to the discrete nature of the system. For the latter only the properties of their correlator are known, hence only space-time correlations of fluctuating quantities and their Fourier transforms, known as spectral densities $S(\mathbf{k}, \omega)$, can be derived (Klimontovich 1967; Tsytovich 1995). Experiments, targeting conditions where the thermal motion of particles is not masked by perturbations due to instabilities, have reported fluctuation levels $\delta n/n$ ranging from $\sim 10^{-3}$ (McWilliams and Okubo 1987) down to $\sim 5 \times 10^{-5}$ (Geissler et al. 1972). Such low values are indicative of the necessity for extremely stable discharge conditions.

The Q-machine (Rynn and D'Angelo 1960) and the magnetic cusp (Schmidt 1966) are the most commonly known stable plasma configurations. Both configurations are run with a magnetic field, that is nonuniform for the cusp geometry. The Q-machine, typically producing fully ionized plasma, can be run in a mode where the drift instability is limited to the edge, while the central region exhibits $\delta n/n \sim 10^{-3}$, thus enabling measurements, for instance, cross-field diffusion of ions (McWilliams and Okubo 1987; Fasoli et al. 1992). The magnetic cusp can provide rather high plasma densities and mean free paths with neutrals such that the central region of the discharge can be considered collisionless and unmagnetized with a fluctuation level $\delta n/n \sim 10^{-2}$ (Ratynskaia et al. 2007, 2010). However, in these experiments, the intrinsic fluctuation level was still masked by the presence of noise due to the magnetic coil power supply. Nevertheless, such a level was sufficient to detect spectral modifications of the ion density fluctuations due to presence of dust, since the latter leads to a significant enhancement of the low frequency part of the spectrum.

Less known quiescent unmagnetized plasma discharges are the brush cathode (BC) and its variants (Allison and Chambers 1965; Persson 1965; Musal 1966). Such dc discharges achieve stable operation in the abnormal glow regime and have been shown to attain extremely low fluctuation levels $\sim 5 \times 10^{-5}$ (Geissler et al. 1972). As a result, successful measurements of plasma properties from the cross-spectrum of thermal density fluctuations have been carried out in the past. Our discharge belongs to this group, and before examining the peculiarities and uniqueness of our set-up, we first describe the characteristics and physics behind the BC concept.

3. The brush cathode concept

In the mid 60's, the concept of a BC was first introduced (Persson 1965), referring to a cold discharge with the cathode consisting of a set of metal wires with sharp points. The wires are closely packed, electrically and mechanically connected only on a common baseplate, essentially the shape of a thick brush. The discharge with such a cathode was operated in the abnormal glow region and shown to generate a high velocity electron beam. Persson explored a wide range of conditions and geometries, concluding that the discharge is in practice an extended negative glow sustained by a uniform electron beam with energies in the range 1–10 keV and lengths depending on the penetration depth of the beam into the gas. Electron densities in the range 10^{10}–10^{12} cm^{-3} and temperatures of 0.05–0.1 eV were found, i.e. a nearly field-free beam generated plasma, in which the plasma losses are dominated by volume recombination. As pointed out by Persson, such a plasma is a 'well-behaved'one,

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contrary to those requiring an electric field to be sustained and in which ambipolar diffusion is the dominant plasma loss mechanism, as in the positive column. A well-behaved plasma implies, among other things; (i) spatial uniformity over scales much larger than the characteristic plasma lengths – Debye lengths or mean free paths, (ii) enhanced stability such that 'the only acceptable fluctuations are those associated with the thermal motion'. The operating gas in this work was He.

However, the negative glow is not totally field-free. Aiming at creating a region with minimum electric field, the *reflex geometry* was proposed (Allison and Chambers 1965). In this configuration, two opposite BCs were facing each other with two annular anodes placed symmetrically from each cathode. In the central inter-anode region, the plasma is created by two counter-propagating beams with opposite residual negative glow fields that, in principle, should cancel each other. In addition, the use of a reduced inter-electrode distance, small compared to the reaching distance of the beams, aided in minimizing the non-uniformities due to the beam attenuation. Ar gas was used in this work.

One year later it was pointed out (Musal 1966) that the same negative glow plasma could be created by a flat cathode, the only difference with the BC being that – at a given cathode voltage – the discharge current and the charge density would be lower, due to the smaller cathode current. The real effect of the brush geometry was then to increase the effective cathode surface, i.e. to increase the current density over the discharge tube section. On the other hand, the brush geometry was of difficult construction and with several shortcomings such as a very large sputtering rate and the tendency of needle tip melting in case of accidental arcing. Musal proposed to replace the brush design with the *inverse brush cathode* (IBC) configuration, in which needles are substituted by holes. Operation with He showed that such a configuration is capable to provide similar performances (current density) to those of an equivalent traditional BC, and that the increase in current density with respect to a flat cathode was roughly a factor of two. Musal argued in his paper that the better performance of BC and IBC geometries was due to the larger surface parallel to the incident ions, since at grazing incidence the secondary electron yield per incident ion is larger. The author finally pointed out that the holes do not behave as hollow cathodes, since the pressure is too low and the mean free path is of the same order of magnitude as the diameter of the holes. Hollow cathode behavior would eventually start at much higher pressure and, in that case, only one hole would emit all the cathode current.

4. BABE – a reflex inverse brush cathode discharge

The BABE discharge, built in collaboration between Stockholm and Bari groups and currently located at CNR Bari, is an IBC in a reflex geometry. The arrangement is as shown in Fig. 1. The diameter of the cathodes is 54 mm. Ninety-five evenly-spaced holes of a 3 mm diameter and 25 mm depth have been drilled onto the cathode surface, the distance between the hole centres is 5 mm. The anodes are cylindrical aluminium surfaces of 54 mm diameter and 60 mm length. The distance between the cathode surface and the closer anode is 60 mm. The inter-anode central region is 110 mm long. Both cathodes are polarized with the same negative voltage, while the anodes are grounded, and are used as counter-electrodes for single probe measurements. The current power supply is a F.u.G. Elektronik GmbH mod. MCA 750–1500, with controlled current operation and a maximum of 1.5 KV negative voltage. The output voltage contains a nominal peak-to-peak ripple of $2 \times 10^{-4} + 50$ mV from the nominal voltage value, i.e. for example, at 1.5 KV the ripple amounts to 350 mV_{pp}. Within

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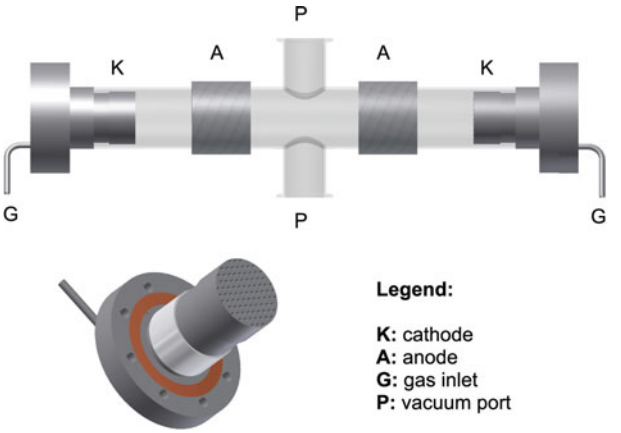


FIGURE 1. Sketch of the discharge apparatus and zoom-in of the cathode.

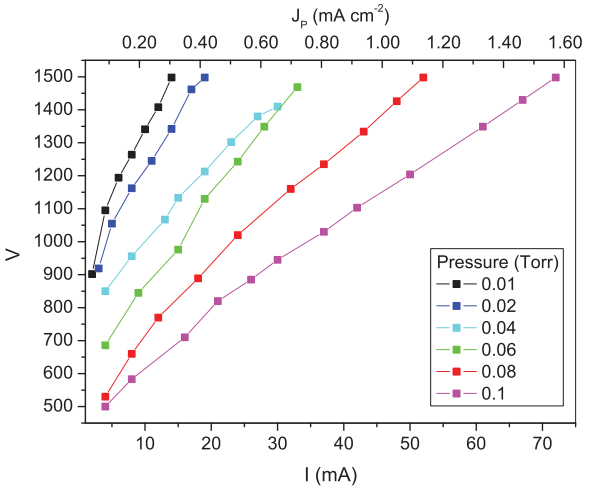


FIGURE 2. Discharge voltage versus current in Ar at pressures 0.01–0.1 Torr. J_P is the current density.

the limits of this supply voltage, the results of discharge voltage versus current measurements are reported in Figs 2 and 3 for Ar and He, respectively.

Figure 4 reveals the structure of the discharge at three conditions of He pressure and discharge currents. In all cases the region between cathodes and anodes is more luminous, corresponding to a higher electron density. Close to the cathode, the pink cathode glow is clearly visible, especially in the low pressure case, followed by the cathode dark space whose boundary with the negative glow is an 'exceedingly sharp and flat discontinuity' (Persson 1965). The central region shows a lower but quite uniform luminosity. This region is also produced by the electron beam, with low temperature bulk electrons incapable of further ionization.

The low electron temperature is an indication of the absence of an appreciable electric field: a temperature of 0.1 eV in He corresponds to a reduced electric field of about 0.06 Td, as calculated by the Boltzmann solver BOLSIG+ (Hagelaar and Pitchford 2005), this being an upper limit for a beam generated plasma. Then, for example, at 0.4 Torr the electric field must be less than ~0.008V/cm. Moreover, the

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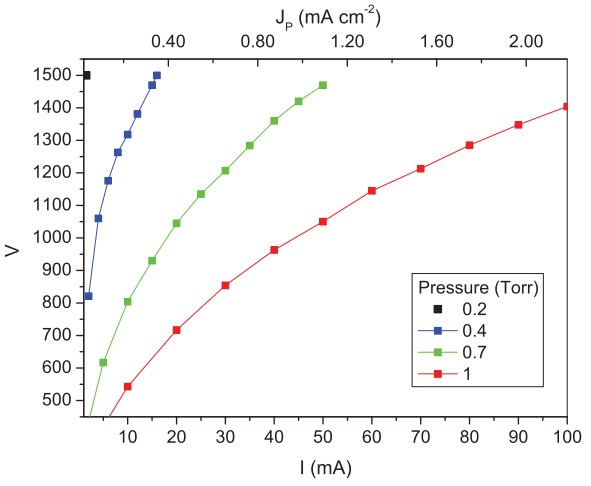


FIGURE 3. Discharge voltage versus current in He at pressures 0.2–1 Torr. J_P is the current density.

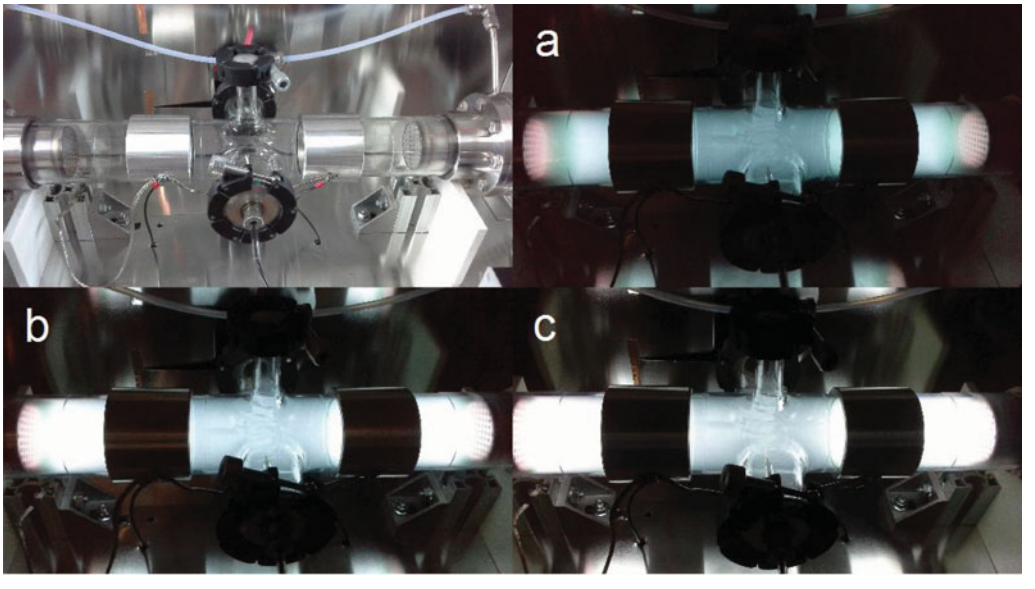


FIGURE 4. Images of the apparatus and the discharge in He at various pressures and discharge currents: (a) $p = 0.25$ Torr, $I_d = 5$ mA; (b) $p = 0.4$ Torr, $I_d = 10$ mA; (c) $p = 0.8$ Torr, $I_d = 40$ mA.

dust injection experiments confirm that the central region is essentially ambipolar field-free, see Sec. 6 for details.

5. Plasma parameters and fluctuation levels of BABE

Here we report on the plasma characteristics at the middle point of the central inter-anode region, of interest for fluctuation measurements.

The averaged plasma parameters have been deduced from Langmuir probe measurements. The measurement cycle has a 90 ms period at constant −70 V polarization for probe cleaning, followed by the 10 ms voltage ramp. The current

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is measured as the voltage drop across a 1 KΩ resistance. Voltage and current are measured by a two channel digitizing oscilloscope with a 14-bit resolution. The whole circuitry is battery operated. The measurement is made of 64 Ksamples and average over 1000 voltage cycles. We note that the circuit for the Langmuir probe characteristic is not the same as that used for the fluctuation measurements and hence averaging is needed in spite of the fact that plasma is extremely quiescent. Moreover, since the electron temperature is very low, high precision is required for identification of the plasma potential (the first derivative is calculated with a 0.01 V resolution). For the discharge conditions and with the cylindrical probe length of 3 mm and radius of 0.05 mm, the Druyvesteyn formula is applicable for the electron current (Demidov et al. 2002). The density estimates from the electron current at the plasma potential as well as from the ion current branch yield the same order of magnitude values.

For fluctuation measurements specially miniaturized probes with a radius of 9 μm and lengths below 1.5 mm, shielded by glass capillaries of 40 μm radii, have been used. The probe is polarized at -8 V, below the plasma potential, by a battery. The voltage drop across a 600 KΩ resistance is amplified by a state-of-the art low noise pre-amplifier, Stanford Research System model SR560 with 10^4 amplification factor and dc component suppression (ac coupling). The pre-amplifier output is measured by a computer controlled digitizing oscilloscope with 14-bit vertical resolution and 50 MHz bandwidth (TiePie Handyscope HS5). Both the pre-amplifier and the computer/oscilloscope are battery operated.

We point out that, for our plasma conditions, below the transparency region of Langmuir waves ($\omega_{pe} \sim 1$ GHz), the spectrum of plasma density fluctuations $S(\mathbf{k}, \omega)$ is nearly flat, i.e. has no particular features. The range below 100 kHz is of interest for our measurements, since in dust-free plasmas this is the relevant range for the cross-correlation measurements (Geissler et al. 1972), while in dusty plasmas the enhancement range is confined well below several kHz (Ratynskaia et al. 2007, 2010; Tolias et al. 2012) as discussed in Sec. 7.

The dc and ac components of the ion saturation current I_i have been recorded for various discharge conditions and from the root-mean-square of the ac signal we have estimated the fluctuation level as $\delta I_i/I_i = \delta n/n$ implying that the contribution from electron temperature fluctuations, if any, is neglected (Ratynskaia et al. 2002, 2010). We point out that the ac signal in plasma is typically only 50–100% higher than the ac signal with the discharge off, i.e. than the pure electronic noise of the circuitry. This is sufficient for the estimation of the upper limit of the intrinsic plasma fluctuation level. With biasing and resistance as specified, the rms values are in the range 0.01–0.02 mV and DC values are in the range 0.2–1 V, resulting in ratios of $\delta n/n \sim 10^{-5}$ and below.

The results for He and Ar discharges are summarized in Table 1 reporting the values of the average plasma parameters as well as the fluctuation level. Such a combination of parameters is unique; extremely quiescent discharges with high plasma densities in absence of a magnetic field can be reached in low collisionality, i.e. low gas pressure, regimes.

6. Technical capabilities and future updates of the set-up

Further stability enhancement; The stability of the supply, to further reduce the voltage ripple amplitude, can be improved and the voltage of the supply can be increased by switching to a battery operated dc-dc converter. With actual technologies a lower ripple is achievable, $<$10 ppm of the output voltage. Higher voltage operation

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	Helium operating gas	
Discharge current	I_d (mA)	$2 \div 90$
Operating pressure	p (Pa)	$50 \div 130$
Plasma density	n (cm^{-3})	$10^9 \div 7 \times 10^{10}$
Electron temperature	T_e (eV)	$0.1 \div 0.15$
Fluctuation level	$\delta n/n$	$5 \times 10^{-5} \div \leqslant 10^{-5}$
	Argon operating gas	
Discharge current	I_d (mA)	$4 \div 30$
Operating pressure	p (Pa)	$2.5 \div 9$
Plasma density	n (cm^{-3})	$5 \times 10^8 \div 3 \times 10^{10}$
Electron temperature	T_e (eV)	$0.3 \div 0.4$
Fluctuation level	$\delta n/n$	$10^{-5} \div \leqslant 5 \times 10^{-6}$

TABLE 1. Currently available operating conditions and corresponding plasma parameters.

shall allow for higher densities at lower pressures, where the discharge is most stable and spatially homogeneous. At medium pressures with increased voltage, we anticipate to approach the highest value of plasma density reported for helium operation (Persson 1965), $10^{12}\,cm^{-3}$. Reduction of the central region size will also allow to increase electron density in the central region and to achieve a homogeneous discharge in a wider parameter range.

Multiple cathode pair operation; From the operation of the discharge in the present set-up, the feasibility of constructing more complex geometries with multiple reflex IBC pairs with a common central region is evident. This would not only increase the range of parameters, for example higher electron density at lower pressures, but would also provide a number of technical advantages, such as the enhancement of the total discharge current without loading single cathodes with larger power dissipation. In other words, independent reflex pairs would inject the electron beam into the central region while working at low power dissipation and low cathode sputtering rate, allowing for a better long term stability of the system with less or no cathode cooling requirements.

Measurement techniques; For fluctuation measurements both single point and cross-correlation measurements are feasible with two miniaturized identical probes as described above and two identical amplifiers/pre-amplifiers. For additional noise reduction, the insertion of low noise very high impedance – virtual ground – current pre-amplifiers located just outside the probe port is planned, as well as improved screening and grounding. Moreover, laser induced fluorescence (LIF) on Ar ions can also be applied (Diallo and Skiff 2005; Mattingly et al. 2013), though the feasibility of measuring at such low fluctuation amplitudes is to be addressed.

Injection of dust grains; Tests with introduction of calibrated dust populations, melamine formaldehyde monodisperse spherical dust of 2.7 or $1\,\mu m$ diameter and mass density $1.51\,g\ cm^{-3}$, have been carried out with the aid of an electro-mechanical injector with a fine mesh. Dust confinement proved to be problematic, since the inhibition of ambipolar diffusion in BC discharges leads to a very weak vertical electrostatic force unable to compensate for gravity, unlike typical DC discharges (Thoma et al. 2007; Khrapak et al. 2012). Thermophoresis (Rothermel

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et al. 2002), though technically cumbersome, appears the least perturbing method suitable for the set-up since electrostatic confinement schemes are inappropriate for the purpose of the experiments. Preliminary fluctuation measurements with continuous dust injection revealed an enhancement of the low frequency part of the ion density spectra as predicted by theory.

7. BABE as a test-bed of fluctuation theory

As aforementioned, the fluctuation framework is theoretically rigorous and experimentally verified in the case of collisionless fully ionized plasmas. BABE was constructed in order to perform experimental tests of fluctuation theory in other regimes, where fundamental postulates of the theory are violated and additional assumptions need to be employed.

Scanning the collisionality regime; In fluctuation theory, approximate methods are invoked to account for collisions with neutrals. Typically, a microscopic phase-space density version of the Bhatnagar–Gross–Krook (BGK) collision operator is employed (Bhatnagar et al. 1954), which essentially becomes an annihilation–creation operator (de Angelis et al. 2012). More elaborate approaches exist describing the atom sub-system through the classical model of atomic oscillators, i.e. pair of classical charged particles bound by a harmonic potential, however, despite their complexity they still cannot account for phenomena of quantum nature such as ionization and charge exchange collisions (Klimontovich et al. 1989). The BGK description is accurate in the strongly collisional regime, but not for intermediate collisionalities, where the contributions of collisional and Landau damping to the spreading of the spontaneous modes are comparable. The reflex IBC discharge is ideal for such studies, since it retains its quiescent characteristics in a wide range of pressures.

Dusty plasmas; In plasmas seeded with dust grains, the spectral densities of all fluctuating quantities are strongly enhanced. The modifications are most pronounced in the low frequency regime, i.e. well below the ion plasma frequency. They depend on the dust size and charge, number density, composition and can, thus, constitute the basis for an *in situ* dust diagnostic, particularly suitable for the detection of invisible sub-micron dust, both in laboratory and space plasmas (Ratynskaia et al. 2010). The physics behind the low frequency enhancement are rather straightforward in the dressed particle approach (Tolias et al. 2012); (I) The grains can sustain a large number of elementary charges, this high characteristic charge number is reflected in their plasma screening clouds and leads to enhanced fluctuations. (II) The grains are characterized by very low thermal velocities due to their large mass, this implies a slowly moving dynamic polarization cloud and translates to an elevated low frequency spectral component. (III) Dusty plasmas are inherently dissipative systems, since continuous absorption of plasma particles is necessary for grains to maintain an equilibrium charge, which, by the fluctuation-dissipation theorem, implies augmented fluctuations. In the cusp machine, successful proof of principle experiments were carried out with *in situ* produced dust (Ratynskaia et al. 2007, 2010). However, for the calibration and development of the diagnostic it is necessary to inject monodisperse pre-characterized dust populations. The existence of a field-free inter-anode region in the reflex IBC discharge, makes it ideal for dusty plasma fluctuation measurements, since the absence of the dominant ion drag and electrostatic forces, guarantees the formation of non-drifting stationary dust clouds.

Finite probe size effects; Probe measurements of the spectral density of ion density fluctuations are inherently invasive and therefore contain a form factor stemming

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from the finite size of the probe. Physically, the form factor expresses the fact that wavelengths smaller than the characteristic probe dimensions cannot be resolved, since the ion density at the probe location is essentially the uniform average of the ion density over the collecting volume of the probe (Williams and Chappell 1971). Mathematically, the form factor has a sinc-function behavior with oscillations either of sinusoidal -spherical probe- or Besselian -cylindrical probe- character and thus acts as a low-pass filter in wave-number space. It is worth mentioning that similar form factors arise in antenna measurements of the spectral density of electric field fluctuations (Meyer-Vernet 1979). They, again, stem from the finite size of the antenna and are related to the induced current density distribution on the antenna. Experiments with different probe geometries and dimensions are an invaluable tool, since they can provide independent measurements under the identical plasma and discharge conditions.

Acknowledgments

The authors express gratitude to Prof U. de Angelis for insightful discussions on theory of fluctuations. The financial support of the Swedish Research Council and the Lars Hierta Memorial Foundation is gratefully acknowledged. The authors would like to thank Dr I. Bykov and Mr. C. Corradi for skillful technical assistance.

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