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Broadening of the parallel and perpendicular ion energy spectrum and correlation with turbulent potential fluctuations in a linear magnetized plasma

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Abstract

We previously reported electrostatic energy analyzer (GEA) measurements of the parallel energy distribution of ions incident on a floating target in PISCES-A [J. Cuthbertson, R. Lehmer, M. Jakubowski, S.C. Luckhardt, Bull. Am. Phys. Soc. 41 (1996) 1575]. The principal finding was that ion energy spectrum was *significantly* broader (6–8 eV) than the ion temperature expected from classical collision processes ($T_i \cong 2$–3 eV). In this paper, we present further gridded energy analyzer measurements, and Doppler broadening measurements of ion spectral lines. Moreover, we have varied plasma conditions such that the turbulent plasma potential fluctuation amplitudes covered the range 3 eV $< 2\delta\phi <$ 16 eV. Interestingly, during this variation, the width of the measured ion energy distributions varies over a corresponding range of 7 eV $< \Delta E_i <$ 28 eV; that is, the parallel ion temperature is comparable to our previous measurements of the parallel energy spread. These experiments are modeled using a 3D, time-dependent Fokker–Planck code [K. Kupfer, R.W. Harvey, O. Sauter, G. Staebler, M.J. Schaffer, Phys. Plasmas 3 (1996) 3644] for the ions, giving Coulomb collision effects parallel and perpendicular to B, and spatial variation parallel to the magnetic field. We suggest that the observed spectral broadening is consistent with rapid parallel and perpendicular fluctuations in the ion flow speed caused by turbulent plasma potential fluctuations and associated E × B velocity fluctuations. Direct ion heating by these potential fluctuations may also be of importance.

Keywords: Turbulence; Spectroscopy; Divertor simulator

1. Introduction

The energy spectrum of plasma ions striking a material surface, such as the target plates of a magnetic divertor, is of interest because it determines heat loads to the surface and plasma–surface interaction effects including implantation, sputtering, and various chemical reaction rates. The rates and other characteristics of these processes depend strongly, often non-linearly, on the energy of the impinging ion, and may have an energy threshold, as in the case of sputtering, below which the effect does not occur. Clearly, the high energy portion of the energy spectrum may be of importance in understanding these interactions. The experiments presented here suggest that the ion energy spectrum in the boundary plasma may undergo broadening that is related to the amplitude of turbulent potential fluctuations in the plasma. Normally modeling of the divertor region does not include such effects of turbulent fluctuations in the scrape off layer (SOL), however, if such fluctuations give rise to ion heating or otherwise create an energetic ion population, then predictions of the divertor performance

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Table 1
Visible spectroscopic Doppler broadening measurements on PISCES-B indicate relatively high ion temperature ($T_{i\perp}$) perpendicular to the magnetic field

Discharge gas	n_e (cm^{-3})	T_e (eV)	Carbon impurity		Main ion	
			λ (Å)	T_i (eV)	λ (Å)	T_i (eV)
Helium	1.0×10^{12}	30	6578	8 ± 1.5	4687	12.5 ± 1.5
Deuterium	0.7×10^{12}	40	6578	8 ± 1.5	–	–

will need reexamination. This ion energy spectral broadening would be expected to become more significant when the other contributions to the ion energy are small, for example, under conditions where the time averaged sheath potential is small or negligible.

2. Ion energy analyzer

In previous [1] and present experiments on PISCES-A we find that ion energy spectra measured by gridded energy analyzers (GEA) [3] are wider than expected from purely collisional processes [1]. In our experiments, the collisional mean free path for energy transfer between the hot electrons and the cold ion species is typically several times larger than the length of the plasma, thus the ion thermal width would be expected to be that of the ionization process itself, in the 2–3 eV range. The widths of the distributions observed in these experiments are substantially larger, ranging up to tens of eV, as discussed below.

We have also measured the perpendicular Doppler broadening of impurity and main ion spectral lines in a similar linear device, PISCES-B. High resolution visible spectroscopy yielded Doppler widths of various main ion and impurity ion spectral lines, as summarized in Table 1. In two experiments where helium working gas was used, the main helium ion Doppler width could measured. The carbon impurity Doppler widths were also measured in plasmas having both helium and deuterium main ion species. These measurements will not be described in detail here, but interestingly the Doppler width, which was measured perpendicular to the magnetic field, indicates an ion energy spread of typically 10–15 eV.

It is clear from the above measurements, the GEA data (Fig. 1) and the spectroscopic Doppler broadening data, that in the directions both parallel and perpendicular to the magnetic field, the ion energy spectral width is significantly broadened beyond the few eV level expected from ionization and collisional processes. We therefore must consider other processes to explain these observations.

Earlier we suggested that the energy spread could be related to turbulent plasma potential fluctuations [1]. PISCES-A plasmas typically exhibit potential fluctuations in the 10^2–10^5 Hz range, with peak-to-peak potential fluctuations of typically 10–30 V. Here we present a series of measurements, Fig. 2, correlating the RMS potential fluctuation amplitude and ion energy spectral width. The magnitude of the fluctuations was varied in these experiments by changing the plasma conditions, mainly the magnetic field, trim coil settings, and the pressure of the neutral working gas. The data in Fig. 2 show that the widths of the ion energy distributions are indeed correlated with the measured space potential fluctuation amplitudes. The width of the ion energy distribution is approximately linearly increasing with the potential fluctuation amplitude, obeying an approximate off-set linear relationship.

These results suggest that in the case of a turbulent plasma in contact with a surface, the energy distribution of ions incident on a surface may be broadened as a result of potential fluctuations in the near surface plasma. It is relevant that measurements of fluctuations in the plasma potential in the DIII-D divertor [4] are found, under some conditions, to have an amplitude a few times larger than the time-average potential drop to the surface.

3. FPET 3D Fokker–Planck code for plasma distribution functions

In order to gain insight into ion heating mechanisms in our experiments we consider a model problem. We

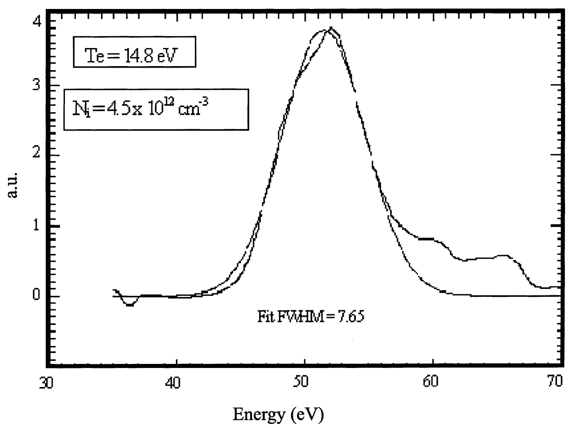

Fig. 1. Parallel kinetic energy distribution of ions exiting the end of the PISCES-A plasma column as measured by the GEA. The energy resolution of the GEA is 1 eV and Gaussian fits to the data have residual error of a few percent, typically.

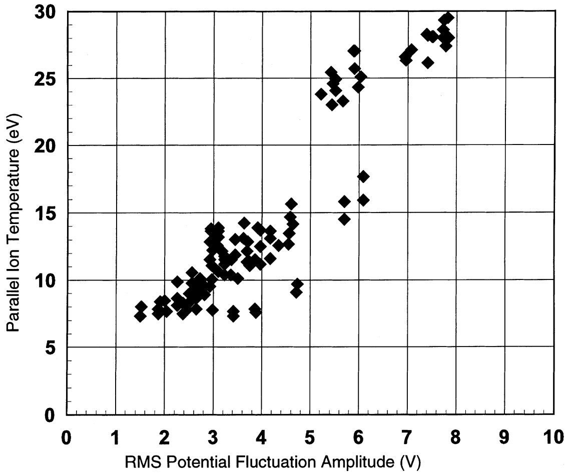

Fig. 2. The ion energy spectral width, ΔE_i, correlates with increases in plasma turbulent potential fluctuation amplitude. The range of fluctuation ampoitudes was obtained in PISCES-A by varying the plasma discharge conditions of filling pressure, magnetic field strength, and trim coil settings.

use the FPET Fokker–Planck code [2,5,6] with applied time-dependent parallel electric field, to directly model the effects on the fluctuations on the magnetized ions in PISCES-A. We consider a model problem where the potential fluctuations vary in the direction parallel to the magnetic field. The wave period is much greater than the wave-trapping time $(m_i/ekE_0)^{1/2} \gg 2$ μs, for a wave number k corresponding to three parallel wavelengths in PISCES (length $L_z = 100$ cm, and the fluctuating electric field E_0 is taken as 0.1 V/cm). The plasma density is in the range 10^{12}–10^{13} cm^{-3}. A 5 eV hydrogen ion will have a mean free path (mfp) for slowing and pitch angle scattering with ions in the range from 2.5 to 25 cm, which is shorter than the axial length of the experiment. The collision rate on electrons is $m_e/m_i^{1/2}$ slower. Thus, the hydrogen ions, and particularly the tail of the ion distribution, are in a semi-collisional regime in PISCES.

FPET is a time-dependent Fokker–Planck code which is 2D-in-velocity, 1D-in-space along the applied magnetic field. Relevant literature for this model are given in Refs. [2,6]. More information on the numerical techniques, boundary condition implementation, and code results for PISCES-A simulations are given in Refs. [2,6–8]. The boundary conditions in the configuration space variable z for this study are that ions freely flow off the ends of the computational region, and the returning ion distribution is at much lower density and temperature than the central parameters. That is, we use absorbing boundary conditions.

The model we use to investigate mechanisms for ion heating relies upon the fact that the primary source of ions is the ionization of neutrals within the plasma. Neglecting the effect of heating by the electrons, we take the ion source to be a 5 eV Maxwellian; the choice of this initial temperature does not influence the heating process under examination. Our computational study consists of establishing a baseline target plasma due to a uniform source along the 100 cm length L of the computational zone, and then adding the electric field fluctuations. In the target plasma, the ions from the source flow freely under the influence of collisions to the absorbing boundaries, simulated end plates, of the computational region. The loss time from the computational region to the end plates is $\tau_{\mathrm{loss}} = L/v_{\mathrm{ti}} = 45$ μs, for $T_i = 5$ eV. To maintain a given central density n_{central} in the computation region, the source rate is found to be $n_{\mathrm{central}}/\tau_{\mathrm{loss}}$.

In our model, the applied fluctuation electric field interacts with the test particle ions from the ionization source. These ions become quickly trapped in the potential, interact collisionally, and move to the absorbing boundaries. We calculate the energy of the ions as they leave the computational region.

4. Results of ion distribution modeling

Results of a baseline simulation, without fluctuating electric field, are shown in Fig. 3. A steady state is established by a spatially uniform source of ions balanced by a loss rate n_i/τ_{loss} giving central density n_i, Fig. 3. Although the source ions initial energy is 5 eV, the steady state expansion of the ions to the end regions results in a 4 eV central temperature, and the temperature decreases further as the end plates are approached. The velocity distribution peak of the outgoing plasma is shifted by 0.7 of the ion thermal speed $(m_i/T_i)^{1/2}$, due to the free expansion. (An electron generated ambipolar potential would increase this somewhat.)

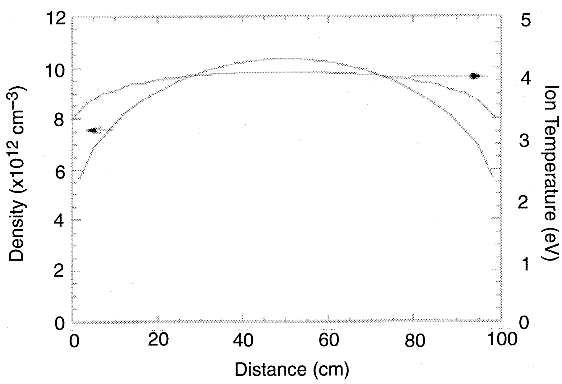

Fig. 3. Numerical modeling simulates formation of baseline ion density and temperature profiles. The ion source is uniformly distributed in space and has initial energy of 5 eV.

Next the effects of potential fluctuations are added. A standing wave electric potential at 10 kHz and parallel wavelength of 33 cm is applied to simulate the effects of the fluctuating potential observed in the PISCES plasma. The ions are strongly trapped, and fall into the potential wells created by the electric field. However, the heating of the distribution, as shown by examination of the random thermal energy, is only a small fraction of the applied potential. Note that both the density and thermal energy dependence on z fluctuate with the applied electric field. However, the dependence of the time average of these quantities is symmetric about $z \sim L/2$. Fig. 4 shows the fluctuating drift velocity of the ions, at each of the 200 time steps in the calculation. Fig. 5 shows the turbulent temperature obtained by time averaging the spread in energy in the fluctuations about the mean outwards flow at the ends of the computational region, for three simulations as a function of fluctuating potential.

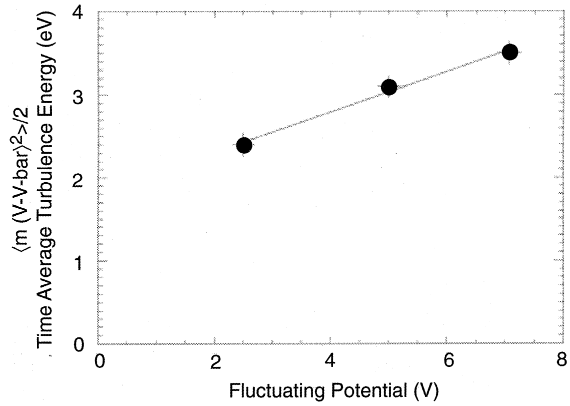

Fig. 5. Simulation of edge turbulent temperature obtained from time averaging the square of the fluctuation velocity about the mean, for three levels of fluctuating potential.

5. Discussion and conclusions

We discuss several possible mechanisms for ion heating in the following. Fluctuating ion flow velocities having an amplitude comparable or greater than the ion thermal speed may be present in these plasmas and could explain the spectroscopic Doppler broadening measurements. Alternatively, ion heating may be occuring by a mechanism that is not yet understood; relatively isotropic ion velocity distributions would tend to be generated by pitch angle scattering collisions.

It is evident in our model calculation, that there are large fluctuations of the drift velocity about the mean, at each spatial point. Such fluctuations could give rise to the turbulent broadening seen by analyzers which integrate over a time interval long compared to the fluctuation period, such as the gridded energy analyzer on PISCES. A similar interpretation is made of observed additional nonthermal spreading of line radiation from near the surface of the sun, which is assumed to be due to velocity Doppler broadening at scales smaller than the spatial resolution of the spectrographs [9].

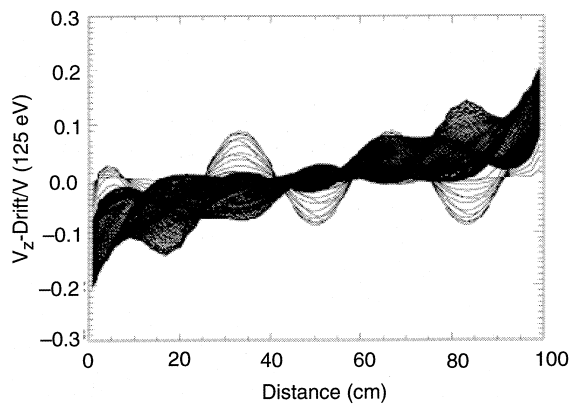

Fig. 4. Drift velocity versus axial (z) position, at each time step of the simulation. Large amplitude fluctuations in the drift velocity are evident.

The modeling above utilizes a spatially uniform ionization source. However, wave trapping effects can lead to a large oscillation in density, and hence ionization rate. If we make the ionization source proportional to the local density in our model, we find growing density fluctuations. Allowing the maximum density fluctuation to grow to 10^{14} cm^{-3} for the 5 eV potential case, the turbulence temperature is found to increase by 20%. As yet, it is not clear that this ionization instability can be responsible for the observed dependence of ion temperature on fluctuation amplitude.

Another contribution to the broadening of the perpendicular fluctuating velocity can come from potential fluctuation having a large perpendicular wave number, $k_\perp \rho_{ci} > 1$. Although not treated in the above model, we suggest that potential fluctuations of sufficient amplitude would generate substantial fluctuating particle flow velocities across the magnetic field. These fluctuating $E \times B$ drift velocities would then contribute to broadening the spectroscopic Doppler widths.

Further investigation is needed to distinguish between fluctuating flow speeds and thermal broadening, and further modeling is needed to determine if a broad spectrum of fluctuations can lead to heating of the plasma ions, and to investigate the effects of potential fluctuations having finite $k_\perp$.

These observations suggest that in the boundary and divertor plasma regions of fusion devices where large amplitude potential fluctuations are present, it is likely that broadening of the ion energy distribution can be expected. Such broadening may have implications for the performance of various plasma facing systems especially under gaseous divertor like configurations.

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