BRIEF COMMUNICATIONS

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Added discussion of ''Observations of fast anisotropic ion heating, ion cooling, and ion recycling in large-amplitude drift waves''

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A recent paper [S. J. Sanders, P. M. Bellan, and R. A. Stern, Phys. Plasmas **5**, 716, (1998)] identified neutral particle recycling as one important aspect of severe heating and cooling cycles observed in large-amplitude drift waves. An apparent inconsistency in the ionization mean free path of these neutrals, left as an open question in the original paper, is resolved in this comment. © *1999 American Institute of Physics.* [S1070-664X(99)00910-6]

In a recent paper, Sanders, Bellan, and Stern (SBS) reported observations of ions undergoing severe heating and cooling cycles driven by large-amplitude drift waves in the Caltech Encore tokamak.[1] One aspect of the cooling cycle involved cold neutrals returning from the plasma edge and re-ionizing. This ''recycling'' interpretation was strongly suggested by the periodic appearance and evolution of a narrow peak in the ion velocity distribution. However, a simple estimate for the ionization mean free path was found to be inconsistent with the measured spatial distribution of recycled particles, and this discrepancy was left as an open question in the manuscript. In the present comment, we explain and resolve the discrepancy. We show that a correct calculation of the ionization path length is fully consistent with the recycled particle interpretation.

SBS presented evidence that ions heat stochastically in the wave electric field before escaping confinement and reaching the vacuum chamber wall. When energetic ions impinge on the wall, they liberate adsorbed majority atoms, which then re-enter the plasma as cold neutrals. The neutrals ionize in the bulk plasma and can be probed by a laser-induced fluorescence (LIF) diagnostic tuned to an ion absorption resonance.[2] These cold ions manifest themselves as an anomalously narrow peak on the velocity distribution of the hot background plasma.

The cold ion spatial profile was measured and presented in SBS, and this profile served to quantify penetration of recycled neutrals into the plasma bulk (cf. Fig. 16 of SBS). Such ions were found only within a few cm of the plasma edge. Figure 16 showed that the cold ion density declined exponentially with distance from the wall; the *e*-folding length of this data represents the ionization mean free path l, and is found to be about 1.6 cm.

A simple theoretical estimate for l was given in SBS as $l = (n_e \sigma_{ei})^{-1}$, where n_e is the electron density and σ_{ei} is the cross-section for electron impact ionization. For the argon plasmas in Encore, $n_e \approx 10^{12}$ cm^{-3} and $\sigma_{ei} = 2 \times 10^{-17}$ cm^2,[3] yielding $l = 500$ m, clearly much larger than the observed path length. Thus it was stated that electron impact could not explain the observed re-ionization, and other mechanisms were hypothesized. However, one of us (R.F.B.) pointed out that the above expression for l cannot be used because of the finite width of the electron velocity distribution, $f(v_e)$. Instead, an expression containing the ionization rate coefficient for electron impact on neutrals must be used.[4] This expression can be obtained by considering the number dn_n of neutrals struck in time dt due to electrons with velocity in the range $[v_e, v_e + dv_e]$: $dn_n = n_n v_e \sigma_{ei}(v_e) dt f(v_e) dv_e$, where n_n is the neutral density. Integrating over v_e, writing $dn_n/dt = v_n dn/dx$, and solving for the neutral ionization length (*e*-folding length), one finds[5]

$$l = \frac{v_n}{\langle v_e \sigma_e \rangle n_e}. \tag{1}$$

Here v_n is the neutral velocity and $\langle v_e \sigma_e \rangle$ the ionization rate coefficient averaged over $f(v_e)$; the neutrals are cold and therefore treated as having a delta-function velocity distribution.

We evaluate l numerically as follows. At the time cold ions emerged in the Encore experiments, Langmuir probes indicated the electron temperature was about $T_e \approx 9$ eV (cf. time 220 μs in Figs. 4 and 13 of SBS). Thermally averaged rate coefficients are tabulated in standard references.[6] For argon with $T_e = 9$ eV, one finds $\langle v_e \sigma_e \rangle = 1.5 \times 10^{-8}$ cm^3/s. As for the neutral velocity, we use the thermal speed of a room-temperature argon atom, $v_n = 360$ m/s. With these values and $n_e = 10^{12}$ cm^{-3}, Eq. (1) yields $l \sim 2.4$ cm, in good agreement with the measured e-folding length of the cold ion spatial distribution.

The use of the room-temperature thermal velocity, above, is justified because recycling particles heat very slowly before ionization. After ionization, in contrast, particles undergo rapid stochastic heating in the drift wave fields, at the bulk heating rate $\dot{T}_{ion} \sim 0.1$ eV/μs (cf. p. 720 of SBS). It is mentioned in SBS that when the cold peak corresponding to recycled ions first appears in the ion velocity distribution, its temperature is about 0.4 eV (cf. Fig. 12). This value may be understood intuitively as follows. The LIF diagnostic measured the ion velocity distribution function at intervals of $\delta t = 10$ μs. Hence a room-temperature neutral, ionized just after one LIF sample, would appear as an ion of about $\dot{T} \cdot \delta t \sim 1$ eV at the following sample. In the case of many neutrals which begin escaping from the wall at time τ and ionize roughly uniformly throughout the ensuing 10 μs interval, one expects the resultant ions to reach an average energy of about 0.5 eV at time $\tau + 10$ μs, the time of the next LIF probe. Subsequently, the ions continue to heat even while reaching equilibrium with, and becoming indistinguishable from, the background plasma. These expectations agree well with observations presented in Fig. 14 of SBS: After first appearing as a 0.4-eV peak in the ion velocity distribution, the cold ion distribution widens and blends into the background plasma distribution on the time scale of ion–ion collisions.

In summary, the measured spatial distribution of cold ions discussed in SBS is well explained by electron impact ionization of neutrals near the plasma edge. The observed temperature evolution of these ions also indicates they originated as cold neutrals which returned to the central plasma, re-ionized, and began to heat stochastically along with the bulk ions. Thus the anomalous cold peaks observed in the ion velocity distributions of Encore edge plasmas are indeed the signature of neutral Ar atoms recycling from the chamber wall.

[1] S. J. Sanders, P. M. Bellan, and R. A. Stern, Phys. Plasmas **5**, 716 (1998).
[2] R. A. Stern and J. A. Johnson III, Phys. Rev. Lett. **34**, 1548 (1975).
[3] S. C. Brown, *Basic Data of Plasma Physics*, 2nd ed., rev., (MIT Press, Cambridge, MA, 1967), pp. 73, 143.
[4] R. C. Elton, in *Methods of Experimental Physics*, Vol. 9, part A, edited by H. R. Griem, R. H. Lovberg, and L. Marton (Academic, New York, 1970), Chap. 4.
[5] D. J. Rose and M. Clark, Jr., *Plasmas and Controlled Fusion* (MIT Press, Cambridge, 1961), Chap. 4.
[6] M. A. Lennon, K. L. Bell, H. B. Gilbody, J. H. Hughes, A. E. Kingston, M. J. Murray, and F. J. Smith, "Atomic and molecular data for fusion, Part II—Recommended cross-sections and rates for electron ionization of light atoms and ions: Fluorine to nickel," J. Phys. Chem. Ref. Data **17**, 1285 (1998).