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REPLY TO COMMENT

Reply to Comment on 'Two-dimensional equilibrium of a low temperature magnetized plasma'

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In a recent paper [1] we discussed a two-dimensional plasma transport in a magnetic field. We assumed ambipolar diffusion both along and across magnetic field lines, where ion and electron flux densities are equal at every location at the boundary. The measured plasma density seemed to indicate too-fast a cross-field diffusion of the electrons to be explained by classical electron–ion collisions. In his comment (this issue) Simon suggests that the enhanced radial transport described in our paper should be explained by the 'short-circuit' effect, a mechanism he suggested many years ago [2, 3]. Ambipolar diffusion should not be expected, he claims. Rather, only the total current to the boundaries should vanish, as a result of electrons moving along the field lines while only ions diffuse outwards radially.

The possibility of different diffusion paths for ions and electrons enhancing plasma transport is important and may significantly affect the plasma behavior. Indeed, this possibility of enhanced nonambipolar diffusion through the 'short-circuit' effect is recognized in the recent literature (for example [4, 5]). Recently a way to control the plasma diffusion and to force either an ambipolar or nonambipolar diffusion has been suggested [6]. However, the 'short circuit' effect is expected to be dominant only if the cross-field diffusion induced by wall collisions is fast enough. In the Hall thruster the so-called wall conductivity (directly related to Simon's proposed mechanism) probably enhances electron cross-field transport, yet the electron transport is still largely impeded [7]. In fact, the operation of the Hall thruster relies on that impeding of the electron cross-field transport. Therefore, although the 'short-circuit' mechanism may play a major role, the conditions under which it is dominant are not obvious. As a result, cross-field transport generally and in radio frequency discharges in particular is an active subject of research even now, decades after Simon's related papers (for example [5, 8–10]).

In examining whether in the experiment described in our paper nonambipolar diffusion could enhance the transport one should note that the magnetic field lines in the experiment end at insulating boundaries. In his first paper [2] Simon noted that 'ambipolar diffusion may be restored if the end walls are separately insulated and allowed to float'. Later he concluded, as he cites in the comment from his Geneva paper [3], that surface collisions allow electrons to walk radially along the wall, allowing the 'short-circuit' effect to dominate even in the presence of insulating end walls. However, cross-field transport through collisions at such walls takes a finite time. Three regimes can be distinguished. In the first regime the end walls are too far apart and wall collisions are rare, so that cross-field diffusion is ambipolar, dominated by the slower electron diffusion. In the second regime the end walls are closer and the electron cross-field diffusion is enhanced by wall collisions. Cross-field diffusion ceases to be ambipolar but is still determined by the slower (though enhanced) electron cross-field diffusion. In the third regime the end walls are so close that the electron cross-field diffusion can exceed the ion cross-field diffusion. In that third regime cross field diffusion is determined by the now-slower ion cross-field diffusion. We will examine here the transition from the first regime to the second regime, namely, the transition from ambipolar diffusion to electron diffusion dominated by wall collisions (the enhanced electron cross-field diffusion might still be slower than the ion cross-field diffusion). We present here two different approaches for estimating the condition for this transition from ambipolar to nonambipolar cross-field diffusion.

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The first approach is to assume that there could be several subsequent wall collisions once an electron reaches the wall. For the cross-field diffusion to be enhanced by wall collisions, it is enough that the electron transit time along field lines, $L^2\nu_V/v_{te}^2$ be shorter than the electron transit time across field lines, $a^2\omega_c^2/(v_{te}^2\nu_V)$. Here L and a are the plasma sizes along and across field lines, v_{te} is the electron thermal velocity, and ω_c and ν_V the electron cyclotron and collision frequencies. The cross-field diffusion is nonambipolar, therefore, if $L/a < \omega_c/\nu_V$. According to this approach the 'short-circuit' effect should very often enhance cross-field diffusion.

In Hall thrusters the so-called wall conductivity probably plays a major role by enhancing electron cross-field transport. However, even though the distance between the walls at the ends of the magnetic field lines is about 1 cm only, smaller than the spatial extent of the thruster across field lines, the cross-field mobility of the electrons is largely impeded by the magnetic field. Such a reduced cross-field mobility of the electrons is a feature that is crucial to the operation of the Hall thruster [7]. If the cross-field mobility of the electrons were as predicted by the approach described above, the electron mobility across field lines would not have been impeded at all. We therefore adopt a second, different approach for determining the enhancement of the cross-field mobility by the 'short-circuit' effect.

Wall collisions result in cross-field diffusion because the guiding center of an electron that collides with the wall can move radially one Larmor radius. Since electrons are reflected from the wall during such a collision, we suggest that the time period between two consecutive wall collisions be an electron transit time between the walls. As a result, ν_{sc}, the effective wall collision-frequency should equal the inverse of that electron transit time between the walls. The cross-field transport, determined by the electron transit time across field lines, is enhanced due to wall collisions, if $\nu_{sc} > \nu_V$, so that the cross-field transit time becomes $a^2\omega_c^2/(v_{te}^2\nu_{sc})$. In a low collisionality plasma, in which $p \equiv v_{te}/(\nu_V L) > 1$, the electrons flow freely along field lines and the transit time is L/v_{te}. The electron cross-field transport is then enhanced due to wall collisions as $\nu_{sc}/\nu_V = p(>1)$. If electron collisionality is not negligible, so that $p < 1$, the electrons diffuse to the wall along field lines and the electron transit time is then $L^2\nu_V/v_{te}^2$, as mentioned above. The ratio of frequencies of electron collisions with the walls and collisions in the plasma becomes $\nu_{sc}/\nu_V = p^2(<1)$, making wall collisions of a negligible effect so that cross-field diffusion is ambipolar. According to this analysis the 'short-circuit' effect is expected to be dominant, therefore, only when $p > 1$.

In the experiment described in our paper $v_{te} \approx 10^6\,\mathrm{m\,s^{-1}}$ and $L \approx 0.5\,\mathrm{m}$, while the classical electron–ion collision frequency is $\approx 10^7\,\mathrm{s^{-1}}$, so that $p \approx 0.2$. According to the second approach described here, which we adopt, the wall collision frequency is smaller than the classical electron–ion collision frequency by p and perhaps even by p^2. We do not expect the 'short-circuit' effect to be dominant under these conditions.

With regards to Bohm diffusion, we did not claim that this is a mechanism for enhanced transport, but only presented it as a demonstration of what enhancement of transport is required in order to explain the measurements.

In summary, the possible existence of a nonambipolar diffusion that could significantly enhance cross-field diffusion, the 'short-circuit' effect, should definitely be considered. The conditions under which this effect is dominant are not clear. According to our estimate, in the configuration studied in our paper the role of the 'short-circuit' effect is likely to be small.

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References

[1] Fruchtman A, Makrinich G and Ashkenazy J 2005 *Plasma Sources Sci. Technol.* **14** 152

[2] Simon A 1955 *Phys. Rev.* **98** 317

[3] Simon A 1958 *International Conference on the Peaceful Uses of Atomic Energy* vol 33, 2nd edn (United Nations: Geneva, Switzerland) p 343

[4] Lieberman M A and Lichtenberg A J 1994 *Principles of Plasma Discharges and Materials Processing* (New York: Wiley), pp 143–5

[5] Chen F F 1998 *Plasma Sources Sci. Technol.* **7** 458

[6] Baalrud S D, Hershkowitz N and Longmier B 2007 *Phys. Plasmas* **14** 042109

[7] Morozov A and Savelev V 2001 *Plasma Phys. Rep.* **27** 570

[8] Sudit I D and Chen F F 1996 *Plasma Sources Sci. Technol.* **5** 43

[9] Cho S and Lieberman M A 2003 *Phys. Plasmas* **10** 882

[10] Sternberg N, Godyak V and Hoffman D 2006 *Phys. Plasmas* **13** 063511