Comment on "Effects of magnetic field gradient on ion beam current in cylindrical Hall ion source" [J. Appl. Phys. 102, 123305 (2007)]

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It is argued that the key difference in the cylindrical Hall thruster (CHT) as compared to the end-Hall ion source cannot be exclusively attributed to the magnetic field topology [Tang *et al.*, J. Appl. Phys. **102**, 123305 (2007)]. With a similar mirror-type topology, the CHT configuration provides the electric field with nearly equipotential magnetic field surfaces and a better suppression of the electron cross-field transport, as compared to both the end-Hall ion source and the cylindrical Hall ion source of [Tang *et al.*, J. Appl. Phys. **102**, 123305 (2007)]. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2976361]

In a recent paper, Tang *et al.*[1] compare their Hall ion source with the different Hall thruster configurations, including end-Hall ion source[2] (EHS) and cylindrical Hall thruster (CHT).[3] Tang *et al.*[1] suggest that the major difference between these configurations is the use of "an enhanced radial component of a cusp-type magnetic field" in the CHT, as opposed to the mirror-type magnetic field in the EHS. This is incorrect because the CHT can operate with topologies of both cusp and mirror types.[4–7] The present correspondence is written to outline the differences in the operation of the CHT as compared to the EHS and the cylindrical ion source of Tang *et al.*[1]

The CHT (Ref. 4) features a combination of both EHS and conventional annular Hall thrusters of the so-called stationary plasma thruster (SPT) type.[8] Like the EHS, the CHT (Fig. 1) has a lower surface-to-volume ratio than SPT does and, thus, seems to be more promising for scaling down to low power space applications.[9] The principle of operation of the CHT, which was proposed in Ref. 4, is in many ways similar to that of a typical annular Hall thruster,[8] i.e., it is based on a closed $E \times B$ electron drift in a quasineutral plasma. The radial component of the magnetic field crossed with the azimuthal electron current produces the axial electric field ($E=-v_e \times B$), which accelerates ions and generates thrust. However, the CHT differs fundamentally from a conventional annular thruster in that the magnetized electrons in the cylindrical design provide charge neutralization of nonmagnetized ions not by not moving axially, but through being trapped axially in a hybrid magnetoelectrostatic trap.[7,10] Comprehensive studies of the CHT with cusp-type and mirror-type magnetic field configurations are reported elsewhere.[3,4,6,7,9–11] For the miniaturized low power CHT,[9] the optimal magnetic field configuration was shown to be an enhanced mirror type.[6,7]

A similar axial trap for the electrons should exist in the mirror-type magnetic configuration of the EHS and the cylindrical ion source of Tang *et al.*[1] According to Ref. 2 quoted by Tang *et al.*,[1] plasma measurements in the EHS suggest that the ions are electrostatically accelerated along the mirror with nonequipotential magnetic field surfaces toward the source exit, where the magnetic field is weaker. This is in contrast to the CHT, where the magnetic field lines form nearly equipotential surfaces. Indeed, plasma potential measurements in laboratory CHTs (Refs. 4 and 11) demonstrated that there is only an insignificant potential drop along the magnetic field surface closest to the thruster axis between the central ceramic piece and the channel exit.[4,11] This result has a simple physical explanation. For an isotropic electron velocity distribution function, the spatial distribution of electron density N_e along the magnetic mirror is independent of the magnetic field. Hence the Boltzman distribution for the Maxwellian electrons:[12,13] $N_e \sim \exp[e\phi(x)/T_e]$, where $\phi(x)$ is the plasma potential profile along the mirror axis and T_e is the electron temperature. The ion density distribution, which self-consistently affects $\phi(x)$, is independent of the local magnetic field in a Hall thruster as well, because ions are not magnetized. Thus, from the Poisson equation it follows that the variation of the ambipolar plasma potential along the magnetic mirror should be independent on B. Note that, in general, in a quasineutral plasma immersed in the mirror magnetic field, the momentum balance does not necessarily require the existence of the axial electric field [cf. Eq. (II) by

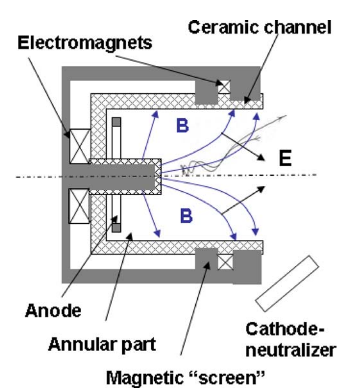

FIG. 1. (Color online) Schematic of a cylindrical Hall thruster. Superimposed magnetic field lines and electron trajectory in magneto-electrostatic trap are shown for illustrative purposes. A magnetic pole on the left side of the front electromagnet coils acts as the magnetic screen controlling the magnetic field profile in the cylindrical channel (Refs. 4 and 9)

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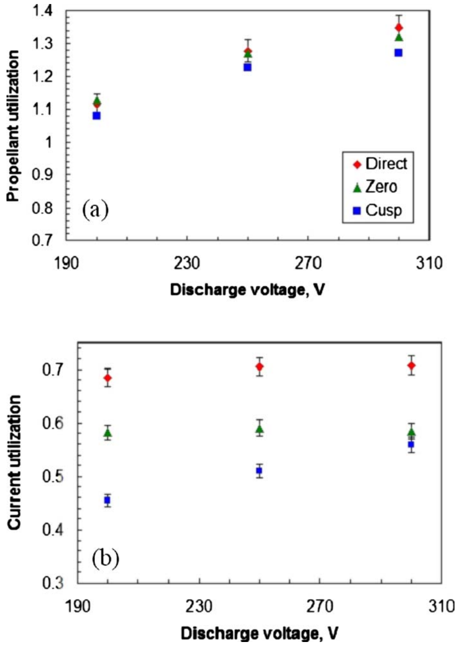

FIG. 2. (Color online) The effect of the magnetic field configuration on the utilization efficiencies: (a) propellant utilization (the ratio of the total ion flux measured in the thruster plume to the gas flow rate in current units), and (b) current utilization, for the 2.6 cm diameter CHT thruster (Ref. 9). Measurements were conducted using a movable guarding ring ion flux probe 70 cm from the thruster exit, at the background pressure of 3 μtorr. The working gas is xenon.

Tang *et al.*[1]]. The axial electric field may appear in the near-axis region of the EHS or CHT configurations, but for a reason different than the mere presence of the magnetic mirror. Namely, the anisotropic electron distribution function,[14] ion focusing,[7,15] or enhanced plasma ionization can create a local elevation of the electrostatic potential near the mirror throat.

The electron cross-field transport in the CHT is suppressed much better[6,7,16] than in the EHS (Ref. 2) and, apparently, in the ion source described by Tang *et al.*[1] In fact, Fig. 2 demonstrates that for the enhanced magnetic mirror configuration (so-called direct configuration), the CHT can operate with a higher ionization efficiency and current utilization efficiency (the ratio of the total ion current measured in the thruster plume to the discharge current) than both of these ion sources (in Ref. 1, this ratio was 30%–60%). Assuming that the ways in which the electric field is produced in the EHS and CHT are similar, the observed differences in performance must be attributed to the differences[4,5,9] in the channel geometry and material, geometry and emission properties of the cathode, configuration and location of the anode, and gas injection. Similar to the ion source described by Tang *et al.*,[1] the CHTs can operate at high discharge voltages (demonstrated up to 600 V,[17] which was a limit of the power supply). However, CHT efficiency is higher, more than 30%–40% at 50–1000 W.[4,16]

Different variations on the CHT design[5] were proposed and tested, including those with and without the short annular part of the channel.[4,18] The magnetic circuit of the CHT includes a magnetic screen in order to form a favorable profile of the magnetic field, including the magnetic field distribution with a positive gradient.[4] For the larger and higher power CHTs, the cusp-type magnetic field was shown to be the favorable topology.[4] Moreover, the floating and biased segmented electrodes placed on the ceramic channel walls of the CHT can be used to control the plasma flow.[5,17] Another variation referenced by Tang *et al.*[1] is the ion source by Zhurin,[19] which appears very similar to the CHT configuration proposed earlier in Refs. 4 and 5, and studied elsewhere.[3,4,6,7,9–11,16–18]

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[1]D. Tang, J. Zhao, L. Wang, S. Pu, C. Cheng, and P. K. Chu, J. Appl. Phys. **102**, 123305 (2007).
[2]H. R. Kaufman, R. S. Robinson, and R. I. Seddon, J. Vac. Sci. Technol. A **5**, 2081 (1987).
[3]A. Smirnov, Y. Raitses, and N. J. Fisch, J. Appl. Phys. **94**, 852 (2003).
[4]Y. Raitses and N. J. Fisch, Phys. Plasmas **8**, 2579 (2001).
[5]Y. Raitses and N. J. Fisch, U.S. Patent No. 6,448,721 B2 (2002).
[6]A. Smirnov, Y. Raitses, and N. J. Fisch, IEEE Trans. Plasma Sci. **34**, 132 (2006).
[7]A. Smirnov, Y. Raitses, and N. J. Fisch, Phys. Plasmas **14**, 057106 (2007).
[8]A. I. Morozov and V. V. Savelyev, in *Review of Plasma Physics*, edited by B. B. Kadomtsev and V. D. Shafranov (Consultants Bureau, New York, 2000), Vol. 21, p. 203.
[9]A. Smirnov, Y. Raitses, and N. J. Fisch, J. Appl. Phys. **92**, 5673 (2002).
[10]A. Smirnov, Y. Raitses, and N. J. Fisch, Phys. Plasmas **11**, 4922 (2004).
[11]A. Smirnov, Y. Raitses, and N. J. Fisch, J. Appl. Phys. **95**, 2283 (2004).
[12]C. L. Longmire, *Elementary Plasma Physics* (Wiley, New York, 1967).
[13]V. P. Pastukhov, Nucl. Fusion **14**, 3 (1974).
[14]A. V. Turlapov and V. E. Semenov, Phys. Rev. E **57**, 5937 (1998).
[15]I. A. Kotelnikov and D. D. Ryutov, Sov. J. Plasma Phys. **11**, 655 (1985).
[16]Y. Raitses, A. Smirnov, and N. J. Fisch, Appl. Phys. Lett. **90**, 221502 (2007).
[17]Y. Raitses, A. Smirnov, and N. J. Fisch, Proceedings of the 37th AIAA Plasmadynamics and Lasers Conference, San Francisco, CA, 2006 (American Institute of Aeronautics and Astronautics, Reston, VA, 2006), AIAA Paper No. 2006-3245.
[18]A. Shirasaki and H. Tahara, J. Appl. Phys. **101**, 073307 (2007).
[19]V. V. Zhurin, U.S. Patent No. 2005/0237000 A1 (2005).