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**14 November 2018**

Dear Editor,

**Re: Revised manuscript JoVE58466**

Please find uploaded our revised manuscript JoVE58466 “***Optimization, test and diagnostics of miniaturized Hall thrusters***” by J. W. M. Lim, I. Levchenko, M. W. A. B. Rohaizat, S. Huang, L. Xu, Y. F. Sun, G. C. Portrivitu, J. S. Yee, R. Z. W. Sim, Y. M. Wang, S. Levchenko, K. Bazaka and S. Xu.

All the valuable comments and suggestions of the Reviewers and the Editor have been thoroughly taken into consideration and addressed in the revised manuscript.

We thank the Reviewers and the Editorial Office for their time, constructive criticism and valuable suggestions, and hope that the revised manuscript is now suitable for publication in **2D Materials**.

**Appended is a comprehensive list of revisions suggested by the Editor and Reviewers, and our responses/amendments in the manuscript.**

Yours sincerely,

Igor Levchenko

# Response to the comments and suggestions of the Editors and Reviewers with the detailed list of revisions made

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## Editorial and production comments:

**Comment:** 1. *Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues. The JoVE editor will not copy-edit your manuscript and any errors in the submitted revision may be present in the published version.*

**Response:** We thank the Editors for careful checking our manuscript. We have thoroughly proofread our work and believe it is fine now.

**Comment:** 2. *Please use American English throughout.*

**Response:** American English is now used throughout our manuscript.

**Comment:** 3. *Unfortunately, there are a few sections of the manuscript that show overlap with previously published work. Though there may be a limited number of ways to describe a technique, please use original language throughout the manuscript. Please see lines: the first 7 lines of the Abstract.*

**Response:** We have checked and rephrased the manuscript to make the text original.

**Comment:** 4. *Please remove the embedded figure(s) from the manuscript. All figures should be uploaded separately to your Editorial Manager account. Each figure must be accompanied by a title and a description after the Representative Results of the manuscript text.*

**Response:** We have removed the images and uploaded them as separate tiff files. A separate file with the descriptions is also uploaded.

**Comment:** Please submit the figures as a vector image file to ensure high resolution throughout production: (.svg, .eps, .ai). If submitting as a .tif or .psd, please ensure that the image is 1920 pixels x 1080 pixels or 300dpi.

**Response:** We have uploaded the images as separate tiff files with the resolutions not less than 300 and pixel sizes of about 3000.

**Comment:** *Please reduce the number of figures if possible. Some can be combined to be different panels of the same Figure number.*

**Response:** We have re-grouped and combined several images, thus the total number was reduced to 14.

**Comment:** *Please do not abbreviate journal references.*

**Response:** We have spelled out all references.

**Comment:** *Please define all abbreviations before use.*

**Response:** All abbreviations are now defined.

**Comment:** *Please revise the table of the essential supplies, reagents, and equipment. The table should include the name, company, and catalog number of all relevant materials in separate columns in an xls/xlsx file. Please sort the Materials Table alphabetically by the name of the material.*

**Response:** Revised Materials Table was uploaded.

**Comment:** *Please include a Summary that clearly describes the protocol and its applications in complete sentences between 10-50 words: “Here, we present a protocol to ...”*

**Response:** Summary was included to describe the protocol:

*Here, we present a protocol to test and optimize miniaturized space propulsion systems. Diversified sophisticatedly designed equipment, large vacuum chambers, powerful pumping platforms and various diagnostic complexes were used to perform precise, informative characterization of micro-propulsion thrusters under conditions close to those found in open space. Skilled personnel, adequate simulation and theoretical support are also of key importance to keep the micropropulsion design and technology progressing steadily. Development of novel materials is the second key factor that could ensure significant breakthroughs in improving performance characteristics of modern electric propulsion systems, including small satellites and CubeSats with the whole set of supply systems, peripheral instruments, tools and payload.*

**Comment:** *Please ensure that the Abstract is under 300 words.*

**Response:** The Abstract length is now under 300 words (277).

**Comment:** *Please place the superscripted numbered reference before the punctuation.*

**Response:** This was corrected, the superscripted numbered reference are now before the punctuation marks.

**Comment:** *Please do not number the paragraphs in the Introduction.*

**Response:** Numbering was removed in the Introduction of the revised manuscript.

**Comment:** *Please use complete sentences throughout the introduction and avoid lists.*

**Response:** Lists were removed in the Introduction of the revised manuscript. Complete sentences are used now.

**Comment:** *Please end each sentence and protocol step with a period.*

**Response:** Periods were added where appropriate, including protocol steps, in the revised manuscript.

**Comment:** *Please add more details to your protocol steps. Please ensure you answer the “how” question, i.e., how is the step performed? Alternatively, add references to published material specifying how to perform the protocol action.*

**Response:** The protocol was significantly re-developed and extended to address these comments.

**Comment:** *1.6: What weight is used?*

**Response:** The weight used was a precisely known and calibrated mass of copper loop. The mass of each copper loop depends on the intended sensitivity of the quadfilar stage being used. In this case, the mass of each copper loop was in the order of 100 mg for the extended calibration regime and 10 mg for the fine calibration regime. We have added this information in the revised version, page 4. See the representative results for more information on how the weights were used to find out the quadfilar thrust sensitivity.

**Comment:** *For all computational steps, please provide all user input commands: File | Save | etc.*

**Response:** These steps were added in the protocol. Mainly, they are the procedures of opening and closing files, i.e. quite apparent steps. Nevertheless, we have added this information, where appropriate.

**Comment:** Please provide all experimental and operational parameters throughout. We need specific values and numbers rather than a generalized protocol. What is the desired vacuum, etc.?

**Response:** All this information was added in the significantly extended protocol (i.e.,  $<10^{-5}$  Pa).

**Comment:** *We respect the confidentiality of some of the experimental design but please provide some more information so that others can replicate the protocol itself.*

**Response:** We have extended the protocol and added the information, and we believe the protocol is now quite reproducible.

We thank the Editorial for these very useful comments, and believe the manuscript is now at the level of the JoVE's high standards.

### Changes to be made by the Author(s) regarding the video:

1. Please ensure that the additional details above are reflected in the video as well.

2. Please increase the homogeneity between the written protocol text and the video narration. For example, the step 1 title is different in the video and the written protocol, protocol steps itself, etc.

3. Frame size/proportions issues

- 1:05-1:12 - Ideally, this image would fill the frame with no black or white borders. If that is impossible, the white background should be extended to fill the black borders on the left and right of frame.

- 7:40-7:48 - Rather than a slow zoom in on this image, we would recommend having it fill the frame and keeping it still. It will likely be of more use to the audience that way.

- 10:09-10:18 - This video needs to fill the frame. It would need to be reshot. Or, you could do what a lot of news shows do for vertical cell phone video: duplicate and enlarge the video, place the enlarged clip behind the original clip, and blur the enlarged clip. The process is described here: <https://www.youtube.com/watch?v=LdCLQ2DQ0NY>. This would make the square video seem more intentional and integrate it better with the rest of the video.

4. Editing issues

- 3:22, 3:41, 3:43, 4:06, 7:23, 7:52, 8:25, 8:46 - There is a blank frame in the middle of the edits at the listed times. This should be corrected.

- 3:19, 3:54 - The edits here are jump cuts ([https://en.wikipedia.org/wiki/Jump\\_cut](https://en.wikipedia.org/wiki/Jump_cut)), which tend to have a jarring effect on the viewer. They should be smoothed out with crossfades instead.

- 3:44-3:56 - This is a still shot of the apparatus that slowly zooms in. The image then jump cuts back to its original position at 3:54. The zooming motion also leads to the positioning of the on-screen text label to become misplaced. We would recommend using a still image of the apparatus that does not zoom in.

- 7:52-7:53 - This edit needs to be fixed. The video cuts to black with the text still on screen, then to a frame or two of Sun Yufei's interview, before moving on to the next clip.

5. Video quality issues

- 5:28-5:36 - This shot is overly shaky. Since no important action is happening in the shot, we would recommend using a still frame from this video clip in place of the live-action video clip itself.

6. Branding concerns

- 2:18 - There is a logo here for PSAC; logos, even for non-commercial entities, should be removed from the body of the Protocol.

7. Please show the beginning title card at the end as well.

Please upload a revised high-resolution video here: <https://www.jove.com/account/file-uploader?src=17832178>

We thank the JoVE's video team these suggestions, all of which were carefully implemented in the revised video, uploaded with the revised version of the manuscript.

## Reviewers' comments:

### Reviewer #1:

**Comment:** *This manuscript mainly introduced how to build, test, and optimize a small Hall thruster (30mm) suitable for a small satellite of about 50 kg. It also shows the thruster operating in a large space environment simulator, and describes how thrust is measured and electric parameters, including plasma characteristics, are collected and processed to assess key thruster parameters. This work is meaningful, and I support this work, and believe it's worth of publishing after some amendments.*

**Response:** We thank the Reviewer for the encouraging assessment of our work. We have thoroughly implemented all the suggestions to enhance our work.

**Comment 1.** *In the abstract of this paper, the authors state that they will also address challenges and opportunities presented by new thruster materials. However, there is no research and experiment on new materials in this paper. It just summarizes previous research results and describes the current research status in the discussion part, I think it is necessary add a part about the thruster materials.*

**Response:** Thanks for this suggestion. This paper does not directly address the thruster materials issues, but is related to the equipment which could be used for the materials testing and technological plasma diagnostics, and on the other hand, it deals with the diagnostics of thruster behavior when some novel materials are applied. Due to the limited format of this work, we cannot include the material related protocol but we added a short sub-section stating the material issues in thrusters, and added some more relevant references, such as:

Levchenko, I., Keidar, M., Cantrell, J., Wu, Y.-L., Kuninaka, H., Bazaka K. & Xu, S. [Explore space using swarms of tiny satellites](#). *Nature* **562**, 185 (2018).

Levchenko, I., Bazaka, K., Ding, Y., Raitses, Y., Mazouffre, S., Henning, T., Klar, P. J. *et al.* [Space micropropulsion systems for Cubesats and small satellites: from proximate targets to furthestmost frontiers](#). *Applied Physics Reviews* **5**, 011104 (2018).

Levchenko, I., Bazaka, K., Belmonte, T., Keidar, M. & Xu, S. [Advanced Materials for Next Generation Spacecraft](#). *Advanced Materials* **30**, 1802201 (2018).

Bazaka, K., Baranov, O., Cvelbar, U., Podgornik, B., Wang, Y., Huang, S., Xu, L., Lim, J. W. M., Levchenko, I. & Xu, S. [Oxygen plasmas: a sharp chisel and handy trowel for nanofabrication](#). *Nanoscale* **10**, 17494-17511 (2018).

**Comment 2.** *In the representative results section, the Figure 7 and Figure 11 are not clear. To make this paper better understood, these two figures should be replaced.*

**Response:** Thank you, we have significantly enhanced, re-developed and re-grouped the illustrations.

**Comment 3.** *The author claims that they also demonstrate how the thruster is optimized to make it one of the most efficient small thrusters ever built. As a matter of fact, optimization requires a reference standard, and experimental data is required to indicate which aspects have been optimized, as well as the comparison of some important performances of the thruster before and after optimization. The thrust, specific impulse, power and efficiency should be added with figures or tables.*

**Response:** Thank you, we have added this information and have better shown the thruster parameters in the updated images.

**Comment 4.** *The author states that the new system can allow for up to 3 different thrusters to be mounted and tested simultaneously in the section 2.2. It is no doubt that it can reduce operational downtime and maximizing research output. However, how to make sure that these three different thrusters don't interact with each other?*

**Response:** Thanks for this insightful comment.

The thrusters can be mounted vertically in a single column and tested rapidly, one after another to avoid interactions between the different thruster systems. It has been verified that efficient evaluation of up to 3 different modules at a single instance is possible, thus significantly reducing the downtime during evacuation and purging processes required otherwise when testing systems individually. On the other hand, this system is a valuable opportunity for testing the thruster assemblies that should operate in a bunch, on the same satellite.

We have added a comment about this in the revised manuscript.

**Comment 5.** *I recommend adding the following recently publications about low power hall thruster (especially about permanent magnet and graphite channel wall):*

(1) Ding Yongjie, Li Hong, Sun Hezhi, Wei Liquiu, Jia Boyang, Su Hongbo, Peng Wuji, Li Peng, Yu Daren. A 200-W Permanent Magnet Hall Thruster Discharge with Graphite Channel Wall. *Physics Letter A*. 2018, 382, pp.3079-3082.

(2) Lou Grimaud, Stéphane Mazouffre. Performance comparison between standard and magnetically shielded 200 W Hall thrusters with BN-SiO<sub>2</sub> and graphite channel walls. *Vacuum*, 2018,155,pp.514-523

(3) Ding Yongjie, Li Hong, Li Peng, Jia Boyang, Wei Liquiu, Su Hongbo, Sun Hezhi, Wang Lei, Yu Daren. Effect of Relative Position between Cathode and Magnetic Separatrix on the Discharge Characteristic of Hall Thrusters. *Vacuum*. 2018, 154,167-173.

(4) Stéphane Mazouffre, Lou Grimaud. Characteristics and Performances of a 100-W Hall Thruster for Microspacecraft. *IEEE Transactions on Plasma Science*. 46(2),pp.330-337.

(5) Ding Yongjie, Peng Wuji, Sun Hezhi, Wei Liquiu, Zeng Ming, Wang Fufeng, Yu Daren, Performance characteristics of No-Wall-Losses Hall thruster, *The European Physical Journal - Special Topics*, 2017, 226, 2945-2953

- (6) Ding Yongjie, Sun Hezhi, Li Peng, Wei Liqiu, Su Hongbo, Peng Wuji, Li Hong, Yu Daren, Application of Hollow Anode in Hall Thruster with Double-peak Magnetic Fields, *Journal of Physics D: Applied Physics*, 2017, 50(33), 335201.
- (7) Ryan W. Conversano, Dan M. Goebel, Richard R. Hofer and Ioannis G. Mikellides. Performance Analysis of a Low-Power Magnetically Shielded Hall Thruster: Experiments. *Propulsion and Power*, Vol. 33, No. 4 (2017), pp. 975-983.
- (8) Ryan W. Conversano, Dan M. Goebel, Ioannis G. Mikellides and Richard R. Hofer. Performance Analysis of a Low-Power Magnetically Shielded Hall Thruster: Computational Modeling. *Journal of Propulsion and Power*, Vol. 33, No. 4 (2017), pp. 992-1001.
- (9) Ding Yongjie, Sun Hezhi, Li Peng, Wei Liqiu, Xu Yu, Peng Wuji, Su Hongbo, Daren Yu, Influence of Hollow Anode Position on the Performance of a Hall-Effect Thruster with Double-peak Magnetic Field, *Vacuum*, 2017, 143, 251-261.
- (10) Ding Yongjie, Peng Wuji, Sun Hezhi, Xu Yu, Wei Liqiu, Li Hong, Zeng Ming, Wang Fufeng, Yu Daren, Effect of oblique channel on discharge characteristics of 200-W Hall thruster, *Physics of Plasmas*, 2017, 24(2): 023507.
- (11) Ding Yongjie, Peng Wuji, Sun Hezhi, Wei Liqiu, Zeng Ming, Wang Fufeng, Yu Daren, Visual evidence of suppressing the ion and electron energy loss on the wall in Hall thrusters, *Japanese Journal of Applied Physics*, 2017, 56(3): 038001.
- (12) Ding Yongjie, Peng Wuji, Wei Liqiu, Sun Guoshun, Li Hong, Yu Daren, Computer simulations of Hall thrusters without wall losses designed using two permanent magnetic rings, *Journal of Physics D: Applied Physics*, 2016, 49(46): 465001.

**Response:** All these references have been added in the revised manuscript, with the total number of references exceeding 80 now.

## Reviewer #2:

**Comment:** *There is no gross defect in this paper. But I get some advice for the author. Minor Concerns: The first one is about arranging your text and your figures. Figure 15 should be adjacent to the paragraph "Typical Hall-type thrusters are relatively simple".*

*Second, could you please focus on optimization of Hall thruster more rather than facility. If you can provide improvement of Hall thruster in figure 16 instead of your facility, it would be better.*

**Response:** Thank you for your suggestions.

In the revised version, we have significantly enhanced, re-developed and re-grouped the protocol, illustration and the general paper flow. Many additional information and references have been added. We believe the manuscript was now considerable enhanced, due to valuable criticism and suggestions of the Reviewers.

We thank again the JoVE's Editorial, video team and Reviewers, and believe the revised manuscript may be now accepted for publication.