

## HABILITATION THESIS REVIEWER'S REPORT

### Masaryk University

**Applicant**

Mgr. Jaroslav Hnilica, Ph.D.

**Habilitation thesis**

Diagnostics of High Power Impulse Magnetron Sputtering Discharge

**Reviewer**

doc. RNDr. Vítězslav Straňák, Ph.D.

**Reviewer's home unit, institution**

University of South Bohemia in České Budějovice, Faculty of Science

The habilitation thesis under consideration provides a comprehensive exploration of the applicant's professional activity, which is dedicated to advanced diagnostics in pulsed, high-power magnetron discharges, so-called High Power Impulse Magnetron Sputtering (HiPIMS) discharges. This thesis is comprised of eight scientific articles, that clearly demonstrate the profound impact the author has made on our understanding of the elementary processes in HiPIMS discharges. Structurally, the habilitation thesis is organized into two chapters, with (i) the first chapter dedicated to an examination of ionization zones, and (ii) the second chapter focusing on the fundamental analysis of the sputtering process and the determination of the absolute number of sputtered species.

The region of intense ionization zones in HiPIMS discharges, rotating in close proximity to the target, which are involved in the discharge self-organization, was first observed and described about ten years ago. The English assignment "*spokes*" was generally used for these ionization zones. It was experimentally proven that the HiPIMS discharge is not distributed homogeneously over the target surface. However, the regions with a high degree of ionization are formed and carried away by the  $E \times B$  drift at a speed of several kilometres per second and rotate above the racetrack area of the target (the racetrack being the area on the target with the highest erosion induced by the sputtering). This fact makes spoke diagnostics non-trivial because the investigation requires measurement with a high temporal resolution, which is demanding in terms of instrumentation, methodology, and demands for subsequent data processing. Furthermore, it is worth noting that only a handful of research groups worldwide, comprising approximately five groups with a few dozen experts, have committed themselves to the in-depth study of the spoke phenomenon within HiPIMS discharges. It is a great pleasure that I can state that Jaroslav Hnilica, who systematically studies spokes, belongs to this group. He has made a fundamental contribution to the existing knowledge in this field, evident through his authored publications. His essential works are primarily focused on probe and optical measurements describing the behaviour of spokes and show that spokes fundamentally influence the behaviour and parameters of the discharge. It is subsequently prescribed into technological applications in which HiPIMS discharges are applied. I greatly appreciate that Jaroslav Hnilica, was the pioneering researcher in the Czech Republic (to the best of my knowledge) to initiate a systematic exploration of this intricate field. His efforts have led to the creation of a research group, which has gradually expanded to include collaborators not only

from his domestic institution but also from other institutions in the Czech Republic as well as from foreign international research workplaces.

The second chapter of this habilitation thesis is devoted to determining the absolute number of sputtered species in the ground state in the discharge and combines fundamental and applied research. Acquiring knowledge about the number of sputtered particles in pulsed discharges, along with an understanding of their temporal and spatial distribution within the discharge, enables a comprehensive description of plasma-chemical processes. Simultaneously, it provides essential input data for mathematical simulations. Moreover, the flow of sputtered species onto the substrate plays a crucial role in the deposition and growth of thin films. Optimizing these parameters can lead to the deposition of an effective and well-defined coating, which is a critical factor in various technological applications. Therefore, the investigation of these parameters can be considered one of the most important and the most challenging tasks that Jaroslav Hnilica successfully faced.

As previously mentioned, the advanced diagnostics of HiPIMS discharges, a domain the applicant has been deeply engaged in, is comprehensively outlined through eight carefully selected articles, in which Jaroslav Hnilica plays a substantial role. Notably, the collaborative authorship across these publications is relatively small, demonstrating a wide-reaching international cooperation and a diverse composition of authors. From this, it becomes evident that the applicant's contribution is substantial. In three of these publications, the applicant is the first author and in the remaining five publications, his contribution is also essential. The details of applicant contributions can be found in the habilitation thesis on pages 5-6. The habilitation thesis presents a compact summary of advanced diagnostics of HiPIMS discharges, which has a range of about 40 pages. It is written in a cultivated form at a high technical, graphic, and formal level. The text is almost free of errors or typos. The attached articles are an integral part of the habilitation thesis. These were published in prestigious foreign scientific journals and went through a rigorous and challenging review process before their publication. Given these factors, I can leave the quality and results of these works out of this review. I can perhaps only comment that the presented habilitation thesis could serve as a successful teaching text; although I assume that the applicant himself probably did not have this ambition when writing.

I consider a broader spectrum of his professional activities and achieved results essential for the comprehensive evaluation of the applicant. In addition to the mentioned eight papers, which represent the core of the habilitation thesis, Jaroslav Hnilica has actively participated in numerous other research studies. In his bibliography, he indicates the co-authorship in an additional 30 articles, of which he is the first author in eight cases. I consider all these papers, published in respected scientific journals, to be of high quality and sufficiently demonstrate the erudition of Jaroslav Hnilica, his broad professional scope, and his substantial international collaboration. The aforementioned articles are mainly devoted to the exploration of pulsed magnetron discharges and the properties of thin films deposited by this technique. The articles thus focus not only on fundamental research but also on applied research, exploring the potential application of thin films with unique properties.

In conclusion, I can confirm that Mgr. Jaroslav Hnilica, Ph.D., is an erudite expert in the field of plasma physics and plasma deposition processes, with a particular focus on advanced diagnostics of pulsed magnetron discharges. He presented a high-quality habilitation thesis summarizing his significant contribution to advanced diagnostics. Throughout his scientific and pedagogical career, Jaroslav Hnilica has demonstrated creative potential and complex

thinking, which he showed in almost four dozen published works as a participating author. Therefore, I recommend the Scientific Council of the Faculty of Science at Masaryk University to accept the presented work as a habilitation thesis unequivocally and without any doubt. I am convinced that the work meets all the standard criteria established for habilitation work.

**Reviewer's questions for the habilitation thesis defence** (number of questions up to the reviewer)

I have the following questions about the thesis, on which the habilitation candidate could take a position during his presentation for the defense of the habilitation thesis:

1. In Chapter 1.4 *Spoke splitting and merging observed by a high-speed camera and strip probes*, you presented Figure 1.5, where you showed an experiment with embedded strip probes where part of the anode is cut out. What was the effect of the anode on the discharge?
2. The applicant mainly investigated titanium neutrals and ions using EBF and LIF techniques. Did you, or do you plan to study argon, which served as a working gas?
3. The results obtained using the LIF technique describing the transport of particles from the cathode to the substrate are essential for the scientific community. What other experiments are you planning?
4. What is the impact of the spokes on thin film deposition?
5. Could the applicant give a broader assessment of the current state of the so-called HiPIMS discharge and the extent of its knowledge? At first glance, it seems that the detailed description of the spokes has exhausted the fundamental investigation of HiPIMS discharges. Is this opinion correct?

**Conclusion**

The habilitation thesis entitled "Diagnostics of High Power Impulse Magnetron Sputtering Discharge" by Jaroslav Hnilica **fulfils – does not fulfil** requirements expected of a habilitation thesis in the field of Physics of Plasma.

Place: Dolní Vltavice

Date: October 28, 2023.