FACULTY OF NUCLEAR SCIENCES
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Review of the PhD thesis entitled:
"**Relativistic Optics: The Frontier of Ultrashort X-ray Pulse Generation**"

by the reviewer **doc. Ing. Ondřej Klimo, PhD.**

Author: **RNDr. Marcel Lamač**
Supervisor: **Ing. Jaroslav Nejdl, Ph.D.**

Description of the thesis, the goals and their fulfillment

The submitted thesis consists of two main parts. The first part contains a comprehensive, or one could say an exhaustive, theoretical introduction to the topic of relativistic optics, including the emission of radiation from accelerated charged particles and the laser plasma interaction in two different regimes, when the plasma is transparent or opaque to laser radiation. This part is very well written, with a clear logical structure and a negligible number of mostly typographical errors. The text is more than 80 pages long, contains more than 280 numbered equations, and references more than 180 published scientific works. This part of the thesis is also valuable from a didactic point of view, as it summarizes all the most important theoretical aspects related to relativistic optics and, as such, could serve as a valuable source of information for future doctoral students. As stated in the introductory part of the thesis, it was also one of the goals of the thesis to produce a compendium of theory and literature relevant to the topic of the work, which was clearly and successfully fulfilled.

The second part of the thesis documents the author's contribution to scientific research and development. It contains four publications included in Appendix B (three of which are published and the fourth is under review to the best of my knowledge) and a commentary in Chapter 3 explaining the author's scientific achievement and contribution. In all cases, the author's contribution is clearly substantial because he is the first and corresponding author. The author developed theoretical models and numerically solved them, ran computational simulations using the well-established particle-in-cell method, analyzed the results, and prepared manuscripts for publication. This clearly indicates that the author is capable of independent scientific work at a very high level. Since three of the included publications have already been peer-reviewed and published in well-known or even excellent scientific journals with high impact on the scientific research, I do not need to comment on these results in detail. Nevertheless, I would like to explicitly state that the paper "Anomalous Relativistic Emission from Self-Modulated Plasma Mirrors" is an excellent work and its publication in Physical Review Letters journal is an outstanding achievement for a doctoral student.

The fourth manuscript, entitled "Bright coherent attosecond X-ray pulses from beam-driven relativistic mirrors", which was uploaded to Arxiv, has not yet been peer-reviewed to my knowledge. However, the idea contained in the manuscript is indeed interesting and novel. The demonstration of a relativistic

plasma mirror driven by a beam of positively charged particles whose stability is enhanced by self-restoration capability could have a significant impact on future research and applications in the field of X-ray sources and attosecond pulse generation. This manuscript is also very well written with no obvious errors. The methodology used in this work includes one-dimensional simulations and a theoretical model, which are in good agreement. It would be interesting if more realistic two-dimensional simulations could also be included, but this would probably be impossible for computational reasons.
The author included an impressive list of citations in the thesis. Citations are properly used where information has been taken from external sources and cannot be considered common knowledge. It is my opinion that the citation ethics were followed correctly. Furthermore, the common citation rules for scientific publications are followed, and citations refer to original sources. Nevertheless, I have to make a small critical remark here. The software used to generate the bibliographic section of the thesis produced several incomplete references (with missing page numbers) and made some capitalization errors. Unfortunately, this was not corrected by the author, which is not incomprehensible given the high number of references.

Topicality, results, and their impact on further scientific development

The topic of relativistic optics is related to the latest developments in laser technology, which lead to the generation of ultra-intense laser radiation. Relativistic optics and the generation of coherent X-rays and attosecond pulses are being investigated in many high-power laser laboratories worldwide. The two recently awarded Nobel Prizes are also related to this, making the topic very current and attractive for the scientific community. It is a great achievement of the author (and his supervisor and collaborators) that the results included in this thesis are of high significance in this very competitive environment.
As mentioned above, all four manuscripts/publications included in the thesis show novel and interesting results with a potentially significant impact on scientific research. In my opinion, the results published in the Physical Review Letters (PRL) journal and the results included in the yet-unpublished manuscript are of particular importance. The conversion efficiency to XUV emission in the relativistic instability-modulated emission (RIME) process demonstrated in the PRL paper could be considerably high under optimal conditions. This observation may thus result in the development of a new source of XUV radiation with very interesting properties. Similarly, the results contained in the yet unpublished manuscript may contribute to the development of a source of extremely short (a few attoseconds) and intense pulses of X-ray radiation comparable in peak brightness to XFEL radiation. Moreover, such a source can possibly be relatively compact and robust due to its self-restoration capability.

Questions to the author

1.) The possibility of approaching the Schwinger limit field is often being mentioned in connection with relativistic plasma mirrors. Several types of relativistic plasma mirrors are described in

your thesis. Could you compare these mirrors in terms of the possibility of approaching the Schwinger limit field and give your opinion on which of these possibilities seems the most promising?

2.) In your simulation of the Relativistic Instability-Modulated Emission (RIME) the laser pulse is of ultra-high intensity. In such a case, the so-called hole boring process can often be observed, in which the plasma (including ions) is pushed by the radiation pressure of the laser beam, which creates a hole in the density profile. Have you observed this process, and how would it affect the XUV emission due to RIME?

3.) The manuscript "Bright coherent attosecond X-ray pulses from beam-driven relativistic mirrors" contains the results of one-dimensional simulations. Have you also thought about doing more realistic two-dimensional simulations? Could you explain how challenging you expect these simulations to be?

Summary

In summary, I assess the thesis of RNDr. Marcel Lamač excellent or even outstanding. The contribution of the author and his ability for creative scientific work were clearly demonstrated in the thesis and the attached publications. It can be concluded that the work is at a high scientific level and that it meets the formal requirements for a doctoral dissertation. Should it be decided to apply for a PhD thesis award (e.g., to the Plasma Physics Division of the European Physical Society), I would support such a nomination with pleasure.

I recommend the thesis for the defense, and I recommend awarding the PhD degree to the author, RNDr. Marcel Lamač.

In Prague, September 6, 2024 doc. Ing. Ondřej Klimo, PhD.

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