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For the Faculty Board at the Institute of Physics of Charles University

Please find below my referee report on the doctoral thesis "*Interaction of short-wavelength laser pulses with matter on various time scales*" by RNDr. Vojtěk Vozda.

Allow me start by stating that the thesis embodies an impressive amount of work and it has been a pleasure reading it and being transported into the world of laser-matter interaction across different lengths and time scales.

The thesis gives a good theoretical overview of time-scale phenomena spanning many decades, presents state-of-art X-ray facilities and a plethora of experimental techniques which the author has used to perform *ex situ* post-exposure analyses of samples after irradiated with extremely intense and short short-wavelength lasers. The strengths and novel scientific results of the thesis lie in beam fluence characterization of intense X-ray beams, which emerges as a backbone of the thesis. In this process, the author brilliantly manages to cover, and uncover, new processes in laser-matter interaction that happen on various times scales. These phenomena turn out to be relevant both for advancing our knowledge of the Warm Dense Matter regime, as well as for understanding material response that could have implications in nanotechnology.

The author's work is 11 scientific articles over a span of several years 2014-2020, of which four of them make the core of the thesis and are described in detail. These original papers have been written by the author (JALC 2018, Carbon 2020, OE 2020) or co-written (PRL 2020). The articles show a wide expertise at several X-ray facilities, FLASH and PALS, across several experimental campaigns. The papers also show good collaboration with other experimentalists, and with theoreticians and modelers. In such large collaborations, independence is not obvious and easily assessed, however the author gives a clear description of his own contribution to the articles discussed in the thesis. The publication record shows progression, starting with 2014 onwards as a co-author and collaborator, and ending in 2020 with several papers as main author, establishing the author's pathway towards independent scientific work.

The form of the submitted thesis is excellent and rises up in quality to the level of a review of the field, as "study material for students and scientists" alike, along the lines expressed by the author in his concluding remarks. Notably, Chapter 3 provides an extremely good overview of the time scale of interaction, from femtoseconds up to microseconds. Sub-femtosecond processes are mentioned briefly and with some references, and could make a good addition to this overview. The author writes witty footnotes, which are instructive and pedagogical, that show enthusiasm for the field and for scientific writing, a sense of humour and a joyful approach to popularization of science. References to imps, Feynman and extremely flat highways between Prague and Brno are as delightful as they are instructive. The thesis is well documented and has no less than 370 references of scientific literature.

The main motivation of the thesis, according to this referee, comes in Chapter 6 on “Beam characterization”, contains the originality of work and establishes the expertise of the author. Although not explicitly stated, the importance of beam characterization is often understated in literature and deserves the credit that this thesis brings. The author introduces his original work with NoReFry (submitted to OE 2020) and the usefulness to get fluence profiles, in particular for cases with nonlinearity on the accumulated dose. Knowledge of the beam is useful for any solid state or gas state experiments performed with X-ray free electron lasers where nonlinear effects arise, from High Energy Density Physics to Single Particle Imaging of biological particles. On a technical level, these are relevant to many experiments at the European XFEL, with their recent operation in the MHz regime.

The work on time resolved XUV measurements on aluminum foils (PRL 2020), brings also an original scientific output in terms of measuring changes of opacities using pump/probe XUV measurements, and constructing a forward model to explain the observations. Using the correct profile rather than integrated fluence is key in interpreting the phenomena, and showing strong absorption on time scales shorter than 100 fs. The author’s analysis is instrumental in obtaining the published results, however the author contribution to the original idea and the writing is less obvious and could be stated better.

Both the above works are relevant for understanding Warm Dense Matter regime, which can only be obtained on the surface of the Earth on extremely short time scales, but are relevant on planetary scales (example on Earth and Jupiter cores). This work also is of high interest for the field of Single Particle Imaging, which pursues delivering single proteins into a tightly focused X-ray beam with the goal of obtaining structure from single shots. SPI had an alternative approach to measuring the beam profiles, which has not been mentioned in the thesis. The SPI approach shown by Daurer *et al*. (IUCrJ 4, 2017, 251) uses diffraction and calculates the radial average of the beam profile from diffraction of spherical targets (latex or sucrose) and was employed at the CXI beamline at LCLS. Ho *et al*. (Nat. Comm. 11, 2020, 167) used a similar approach for characterisation of incidence fluence at the AMO beamline at LCLS. The findings agree well with a "non-Gaussian" profile presented in the thesis, and should be seen as a complementary approach.

The thesis does minutious studies of graphene on SiC substrate (Carbon 2020) with the stated aim to understand graphitization (not observed) or detachments due to X-rays exposure. The *ex situ* characterization includes a battery of diverse methods like Nomarski microscopy, atomic force microscopy to Raman and photoelectron spectroscopy. A side note, the XPS description in the thesis lacks depth; understandably this is not the expertise of the author, and the measurement results seem rather inconclusive. The author rightfully suggests other ways to proceed in the future. Overall, these studies are relevant for understanding the dynamics post-interaction, but also with possible applications in nanofabrication and nanoelectronics.

The next study on CdTe and Te inclusions with XUV irradiation (JALC 2018) is also extremely extensive and thorough (optical, AFM, Raman and photoluminescence), with prospective impact in semiconductors and photovoltaics. This work is outside the expertise of this referee, and while the description of the methods and results is quite meticulous, the impact in areas other than those mentioned above is less obvious to the referee.

Summary of main points
- New scientific results: **yes**, in several peer reviewed articles.
- Importance for the area: **yes**, central work for X-ray beam characterization at state-of-art facilities.
- Possible applications in other areas: **several**, impact in HEDP and SPI, possible applications in nano-manufacturing and photovoltaics.
- Form of the thesis: **excellent**
- Ability for creative scientific work: **yes**, shows progression in development

Sincerely,
Nicusor Timneanu,
Ph.D. in Physics, Docent in Biophysics