Opponent review of doctoral dissertation of
Ing. Jan Nikl
Modelling of non local energy transport in laser plasma

Study of an interaction of intense laser beams with solid targets is very desired in recent decades. Reasons for such research are the inertial confinement fusion as a clean and almost inexhaustible source of energy, highly energetic ion and electron sources for several applications, experimental astrophysics or study of warm dense matter. Next to the experimental and theoretical part of research, the numerical simulations are necessary to fully understand to all phenomena involved in plasma formation during the laser target interaction. Kinetic models formulated on the basic laws of physics, which describe all the processes implicitly, are very computationally demanding. Simplified model - magnetohydrodynamics (MHD) - is built through velocity moments of kinetic equation. However, this description lacks from presence of correct description of transport phenomena in the case of intense laser plasma interaction. Doctoral thesis of Ing. Jan Nikl is focused on development of numerical techniques describing this non-local energy transport in laser produced plasmas as well as other additional models for MHD Lagrangian method like the laser absorption, electron heat and radiation transport. Moreover, the thesis contains the author's contribution to the multi-dimensional numerical methods based on high-order finite elements and to the other approach based on cartesian tensor expansion of the kinetic Vlasov-Fokker-Planck-Maxwell (VFPM) model.

The dissertation is quite extensive - it contains 181 pages of text and supplements, divided into three main parts which consist of fourteen basic chapters and a number of subchapters. The author adhered to the usual structure of the dissertation. Theoretical background is overviewed in the first part. The first chapter deals with the kinetic theory, theory of collision operators is summarized and finally the velocity moments of the kinetic equation are derived to be used in the next chapters of the thesis. Moreover, the cartesian tensor expansion of the kinetic equation is shown for later use in one of the author's numerical models. The second chapter shows basic equations of MHD including the Lagrangian description and a special attention is paid to the construction of the equation of state in realistic cases of laser plasma interaction. Theoretical background of the heat transport is the content of the third chapter. Diffusion transport term is derived, its limits are discussed and simplified non-local transport models are proposed. Radiation transport as the other possibility of energy transport in plasmas and its numerical treatment is discussed in the fourth chapter. The fifth chapter is dedicated to the laser absorption. The ray-tracing model is described and its applicability to laser plasmas is discussed against the WKB solution of Helmholtz equation and the approach based on the stationary Maxwell's equations. The second part summarizes the author's contribution to development of numerical methods for description of laser interaction. The sixth chapter contains methodology of the finite element method used in the rest of the work. Author's new reduced VFPM code is presented in the seventh chapter. The method is tested on two example problems whose results are presented and discussed. The work was already published in Jounal of Computational Physics where one can find another example problems. Next chapters describe MHD model in the Lagrangian framework implemented into a multi-dimensional multi-physics code PETE2. Description of the numerical methods used in PETE2 is content of the eighth chapter accompanied by two example problems demonstrating abilities of the code. This work is also already published in an international journal and was presented in an international conference. The other part of author's research dealing with the so called Biermann battery causing a numerical instability is in preparation for publication, but a proposed solution to this issue is mentioned in the thesis. The next chapters summarize principles of implementation of closure models for diffusion transport (9), non-local transport (10) and laser absorption (11) and show their capability on several example problems. Last but not least, the final part is dedicated to presentation of simulation results under realistic conditions in 1D, 2D and 3D cases. The 1D simulation runs follow the case of aluminium target irradiated by the third harmonics of intense Nd:glass laser. The 1D case allows a more straightforward analysis of numerical results. Therefore, it was used to compare individual closure models for the radiation transport and for the electron heat transport developed in the previous parts of the thesis. In addition, the electron heat transport model is compared with the kinetic model at a later stage of system development. The 2D simulations was used for comparison of results of two laser absorption approaches and for the test of numerical solution of Biermann battery problem in the case of spontaneous magnetic fields. The last 3D case should demonstrate the capabilities of the code PETE2 for simulations of ablative processes. It is just a pity that the results of simulations in the final part of the work were not used for comparison with data taken from real experiments.

From the presented thesis it is clear that the author is very well versed in the issue. The elaboration of introductory chapters and an exceptional number of references to current literature prove that. Moreover, the author's contributions to the development of numerical methods describing the evolution of plasma during its interaction with intense laser beam (most of them have already been reviewed in peer-reviewed international journals) show that he is able to conduct independent research and to find a novel solution to a significant problem. I counted five original papers where the candidate is the first author, while in the next five he is a co-author, which testifies to the fact that the author's work is at a high level. Moreover, he is an author or co-author of eleven contributions to international conferences. The physical discussion of the obtained results based on the findings of recent literature is exhausting. From this point of view there is no need to ask further questions. However, I have a more common question on the developed VFPM code:

> My understanding is that the VFPM code requires a very small time step to run, making large-scale simulations on nanosecond scales impossible. What is the reason for developing this code? What are its advantages compared to classical Eulerian and Langrangian VFPM simulations? What types of simulations is this model intended for? Is it computationally demanding to add ion movement to the VFPM model?

The manuscript is well written, remarkable for its conciseness and clarity, and satisfy the highest standards. The chapters show a clear progression of the ideas being developed and are sufficiently detailed. The layout of each chapter is methodical and helps the reader to understand the main research problems and the efforts undertaken to address them. Formally, the submitted thesis has an excellent level. It is sufficiently equipped with visual documentation. Due to my knowledge of English I cannot adequately assess the language level, but the text is clear and understandable. The author did not avoid several typos, which, however, do not disturb the clarity of the text, and I will not even list them. A worse shortcoming is the erroneous references to equations in the first paragraph on page 42 (110 vs. 105) and at the beginning of chapter 7.2 (208-207 vs. 206-207). But these typos also do not diturb the clarity of the text. The list of references is extensive and their format is uniform. The only complaint I have is the missing references for the FEOS package, SHM and IEM in the text on page 39.

In the overall evaluation I recommend the submitted doctoral thesis of Ing. Jan Nikl to be accepted for defense and after a successful defense to grant him the scientific degree:

Ph.D.

Praha
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RNDr. Martin Mašek, Ph.D.