REVIEWER ASSESSMENT OF THE DISSERTATION submitted by
Ing. Ondřej Grover entitled
"Enhanced Plasma Confinement in Tokamaks with Focus on the Turbulence-Flow Interaction"

Reviewer: Prof. RNDr. Milan Tichý, DrSc.

Doctoral dissertation/written report submitted by Ing. Ondřej Grover contributes to the understanding of the processes in the plasma leading to the H-mode and associated phenomena such as limit cycle oscillations. The research was primarily performed in the COMPASS tokamak; however the collaboration with the ASDEX Upgrade and several other teams brought also important results. Studies of these oscillations led to the development and generalization of a first-principles-based model which systematically predicts the observed frequency of pressure relaxation limit cycle oscillations in the vicinity of the transition to H-mode in four tokamaks (JET, ASDEX Upgrade, COMPASS, Globus-M). That also contributed to the extension of different, but related model for the H-mode access developed for the ASDEX Upgrade tokamak to arbitrary ion plasma species. The contribution to the study of the alternative confinement regime I-mode (intermediate confinement) in the ASDEX Upgrade tokamak is also reported. Further important result of the dissertation is the characterization of the impact of the X-point configuration within the divertor region on the H-mode access in the COMPASS tokamak. That stimulated a search for a Type-I edge-localized-mode-free regime with both H-mode and I-mode features in the ASDEX Upgrade tokamak.

In chapter 1 the current state of knowledge of enhanced confinement in tokamaks is summarized. The survey of past work in this chapter shows that over the past decades a lot of progress has been made in predicting confinement and power requirements necessary for entering enhanced confinement regimes. Chapter 2 is devoted to the methods of experimental and theoretical analysis. This chapter describes the experimental and theoretical background used to study the phenomena described in chapter 1, which led to the results in chapter 3. In section 3.1 is reported the investigation of the transition to H-mode in the COMPASS tokamak including the study of the associated limit cycle oscillations. The subsequent development of an extended model for such limit cycle oscillations in many different tokamaks is described in section 3.2. The resulting generalization of a model for the separatrix operational space in ASDEX Upgrade to Helium and other ion species is covered by section 3.3. Finally, section 3.4 shows the author's attempts to investigate the intermediate confinement (I-mode) regime as an alternative to H-mode in the ASDEX Upgrade tokamak.

The goals of the thesis are briefly and aptly presented at the end of the Introduction: "*The primary goal of the thesis was to advance the understanding of the access to enhanced confinement regimes in tokamaks. More specifically the goal was to study the interaction between turbulence and flows in order to seek mechanisms leading to the transition to enhanced confinement.*" Since the work has been performed within a large working group and in the broad international collaboration the summary and declaration of direct contributions by the author are clearly presented on page 78 of the dissertation.

The work is written in the legible English. The format of the written report is good, the typographic errors are difficult to find. Figures are clearly set with intelligible captions. The author has chosen a style in which his own problem description alternates with the presentation of the copies of one publication and one manuscript. Even if the author has perhaps saved a few pages of his own text, this style did not contribute to easy legibility of the dissertation compared to the usually adopted style with the copies of the publications placed at the end of the author's own text. I have also missed the list of all co-authored publications in journals and in conferences.

The dissertation has a total of 92 pages, it contains many mostly color pictures. Most pictures are part of embedded copies of publications. The list of references in the dissertation includes 124 items, the oldest of which is from 1975 and the most recent from 2021. The dissertation contains one embedded publication in peer-reviewed journal Nuclear Fusion 58(2018)112010 (impact factor 3.706) and one manuscript entitled "Experimentally corroborated model of pressure relaxation limit cycle oscillations in the vicinity of the transition to high confinement in tokamaks", which was submitted to Physical Review Letters journal (impact factor 8.385). List of references includes another author's publication in Review of Scientific Instruments with impact factor 1.604 (2017); reference [56] and a co-authored publication [123], also in journal Nuclear Fusion. That might give impression that author's list of publication is not that long. However, a look at his publication list on the IPP website reveals in the period 2012-2021 Ondrej Grover's participation in 21 publications in respected refereed international journals and in 14 conference contributions; most of these have been later published in journals as well. Consequently, the author's publication activity I assess as excellent.

Formally, i.e. in terms of the structure of the information provided, the written report contains both a literature search and the current state of research, as well as a description of the methods used and measurement results and their analysis and evaluation of their contribution to the development of the discipline. In both of the – in the dissertation presented - publications, as well in that referenced under [56] Ondrej Grover is listed as the first author, which also emphasizes his significant contribution to the publications. The contribution of the author to the collaborative work [123] is documented on page 78. I especially appreciate that all the research presented in the dissertation has been performed in broad international collaboration.

During his PhD study the author had to become familiar with many diagnostic systems, a.o. the Langmuir and the ball-pen probes, also with horizontally reciprocating probe head, Thomson scattering, lithium beam emission spectroscopy, microwave reflectometry. The published results of his successful international collaboration prove the author's ability to rather quickly become part of a foreign team and together with it to produce valuable results.

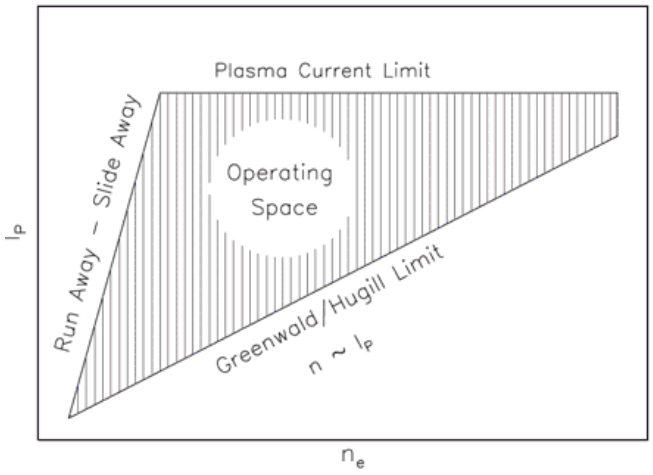
The key contribution of the Ondrej Grover's dissertation consists, in my opinion, in the extension of the theory presented in [23] for characterization the frequency of the limit cycle oscillations (LCO). The original theory led to the LCO frequency far beyond the experimental observations. The author included into consideration the induction term and the coupling to an Alfénic-like wave. The resulting expression (7) describing the LCO frequency well coincides within the predicted uncertainties with the experimental results from several tokamaks, JET, ASDEX Upgrade, COMPASS and Globus-M. In comparison to the previously proposed scalings, which were only empirical and used arbitrary proportionality constants limited to a single machine, the model presented by the author and the obtained formula (7) is based on first principles and correctly predicts the scaling with machine size as well as the up-down poloidal current asymmetry and the impact of the ion mass and charge.

Furthermore, the author attempted in section 3.2.1 to characterize so-called high-frequency oscillations (HFO) that were also observed in all the studied tokamaks. In preparation is a further publication for Nuclear Fusion journal describing the generalization of the separatrix L-H transition mode to arbitrary ion mass and charge, part 3.3.

The author took part in the team of ASDEX Upgrade tokamak as described in section 3.4. Here he was in charge for conceptualization of power ratio analysis of reflectometry measurements in the co-authored article [123], I-mode threshold database compilation and analysis, preparation and analysis of I-mode search in favorable ∇B drift experiments.

I have several questions and comments about the work, on which the author can take a position either during his presentation or during the subsequent discussion:

1) Only ohmic heating was used in experiments described in chapter 3.1. During the ohmic heating it is vital not to exceed the so-called Greenwald density limit, since otherwise plasma instabilities may arise. As it is written on page 67 “For all the discharges the Greenwald fraction was held constant at $n_e/n_{GW} \approx 0.5$ in order to prevent any expected confinement degradation with higher fraction values.” Could the author indicate in the figure from the original Greenwald work (Martin Greenwald 2002 Plasma Phys. Control. Fusion 44 R27) the range of discharge parameters used in his COMPASS experiments?



2) Please explain in more detail the correction of P_{LH} for density variation as described at the bottom of page 41.
3) To Fig. 3.4. E_r is determined from the measured plasma potential by differentiation with respect to distance. How many points correspond to the approximately 30cm radial distance? What smoothing method was used to calculate the E_r curves (since there is almost no noise on the E_r curves).
4) The search for an I-mode in favorable ∇B drift experiments, section 3.4.4, is described in a rather unclear manner. There are used the notions like “irregular I-phase”, “I-mode candidate”, “typical I-mode with an L-mode-like density”, “clear Type-I ELMy H-mode”. The author himself states in Conclusion that “… the H-mode-like density confinement suggests that this is not a typical I-mode. …” Could the author briefly explain the aim and the result of this investigation?

Dissertation by Ing. Ondrej Grover I rate as high quality. There is no doubt that during his postgraduate studies he did a great deal of work, a.o. in broad international collaboration and thus contributed to the development of knowledge in the field of study. The minor formal objections quoted above do not degrade the quality of the obtained results. In the opinion of the reviewer, all the goals of the dissertation stated above were met. Dissertation by Ing. Ondrej Grover "Enhanced Plasma Confinement in Tokamaks with Focus on the Turbulence-Flow Interaction" I therefore recommend for defense.

Prague, September, 27, 2021

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