<u>Doctoral thesis evaluation report</u>

Thesis title: Additional plasma heating of tokamak plasma by powerful beam of deuterium atoms on the COMPASS tokamak
Thesis author: Mgr. Klára Bogár, née Mitošinková
Referee: Dr. Athina Kappatou

The thesis provides a detailed description of the neutral beam heating on the COMPASS tokamak. Neutral beam heating is an indispensable heating system for almost all fusion devices around the world. COMPASS is one of the medium-sized tokamaks in Europe, providing extremely valuable experiments and results. This work characterizes the neutral beam injection (NBI) system on COMPASS with high level of detail and accuracy. This is critical for the interpretation of all NBI-heated experiments at COMPASS and its successor. Furthermore, the investigations of the consequences of the NBI heating on the plasma confinement and behavior add a piece to our understanding of the confinement of fusion plasmas and their MHD instabilities. As such, the thesis contains results that are not only new but also of key importance to the ongoing fusion research at IPP CAS.

The introductory chapter gives an overview of the thesis goals and sets the expectations clearly. It is followed by chapters providing the key background information on the additional plasma heating and current drive mechanisms, as well as the role and behavior of fast ions in a fusion plasma. The tokamak COMPASS and its NBI systems are introduced and descripted, and the experimental campaigns dedicated to the characterization of the neutral beam injection are then introduced. Chapter 6 contains the major part of the results on the impact of the NBI heating on plasma parameters. The power balance method is used to define the power delivered to the plasma. The induced changes on the plasma profiles are described, and the energy confinement time and the produced neutrons are assessed. The impact of NBI heating on the sawtooth instability and the ELMs are also discussed.

The thesis is well written and the results presented in a scientifically rigorous way. The goals of the work are clearly stated at the beginning and the results presented meet the expectations. The thesis provides a clear and detailed characterization of the NBI heating system on COMPASS, and a comprehensive analysis of its impact on the plasma has been performed and the remaining uncertainties sufficiently discussed. The work is well connected with other references and published articles.

The author demonstrates through this work and also through publications capability of executing high quality of scientific work, as well as awareness of the scientific results and developments in the fusion research field. The results presented build on the existing knowledge and provide the characterization and understanding of the neutral beam heating system at COMPASS, as well as its influence on the plasma and its behavior. The author is able to obtain and properly treat experimental data and measurements, and to develop methods and models for their interpretation. In large scale fusion experiments, the ability to collaborate and collect information and data from various sources, systems and people, is critical to the scientific progress. This also has clearly been the case in the course of this work.

As an external reviewer, I suggest some revisions and corrections, which refer to some spelling mistakes and minor details. These are summarized below, together with some detailed questions to the author.

The overall description of the work is comprehensive and shows focused and high-quality work, which is of high significance for any research applying NBI heating in COMPASS and its successor.

I congratulate the candidate for this work and I recommend this thesis to be awarded with a Ph.D. degree.

The referee

Dr. Athina Kappatou

Suggested revisions and questions to the author

Some concepts are introduced in the early chapters very briefly, and the author returns in later chapters to provide more details. To avoid creating unanswered questions due to the brevity in the first chapters, I would suggest to combine these sections. This is the case for example for the definition of the energy fractions in Chapter 2, the description of the passing and trapped particles in Chapter 1, the determination of the ion temperature and neutral background density in section 4.1.1 (expanded in Sec. 6.3.1).
Furthermore, since the additional plasma heating and current drive systems available are only described briefly in Chapter 2, which is justified as they are not used later in the thesis, it might make sense to combine this chapter with Chapter 1.

It would strengthen the thesis if a few sentences could be added in the introduction and conclusions chapters the placement of this work in the larger context of fusion research. The characterization of the NBI system is critical for the interpretation of all NBI-heated experiments at COMPASS, which is a device that has a prominent place among the medium-sized European tokamaks, as well as its successor device COMPASS Upgrade.

<u>Chapter 1 – Tokamaks</u>

- The sentence "some specific modes of the operation lead to the neoclassical transport" (end of p. 6) is too generic and could be clarified further.
- A short definition of turbulence is missing. The author can provide some more information and point to references (also for the classical and neoclassical transport).

<u>Chapter 2 – Additional plasma heating and current drive</u>

- Please provide references in sec. 2.1.1 on the control and suppression of magnetic islands, and on the use of ECRH to avoid impurity accumulation.
- Table 2.2: Impurities are quoted as X^+ and X^0 before and after charge exchange, respectively. It is more accurate to use a notation such as this: X^{+z0} and $X^{+(z0-1)}$, respectively, and similarly in the rest of the equations.

<u>Chapter 3 – Fast ions interaction with a bulk plasma</u>

- Figure 3.1: The figure does not represent the toroidal projection as mentioned in the caption. A more realistic picture of the orbits that also shows the movement of the particles also in the toroidal direction would be more appropriate (also Fig. 3.2 and 3.4).
- Section 3.5.2: Please define $P_{sep,norm}$ – is the radiated power taken into account?

Chapter 4 – Tokamak COMPASS and its additional heating system

- I would suggest a more general title for this chapter: “The COMPASS tokamak” with two subsections on the diagnostics and NBI heating.
- Please add the reference to the EFIT code L. L. Lao et al, Nucl. Fusion **25**, 1421 (1985).
- Figure 4.9.: What is the origin of the H_α line in this situation? Please name the broad feature below the D_α and H_α lines.
- p. 35: What is meant by “fraction of heavy particles”?
- Comparison plots on the divergence and species mix of NBI1 would be useful to later understand the reduced power delivered by NBI1 (due to increased scraping, as shown later). Are NBI1 and NBI2 by design and construction exactly the same? Are the beam ducts similar?

Chapter 5 – Campaigns and simulations dedicated to the NBI characterization

- This chapter is a bit too short. It could very easily be merged in the chapter before as an additional subsection.
- I would suggest to explain here how the counter-injection is achieved (by reversing the current). This can also be noted in table 5.1 using negative values of I_p.
- In table 5.2, if I understand correctly, “flat-top” means “steady phase” (phase with plasma parameters as constant as possible) when either NBI is on or off. I would suggest to change the caption to something like: “An overview of the discharge type and phase utilised to investigate the different mechanisms. The analysis is presented in …”.
- Last part of p. 44: While references are provided, further information on the codes is missing. For completeness, some basic information on what type of codes these are and what they can do should be added here. This will allow the reader to better judge the comparisons between experiment and theory later.

Chapter 6 – Global plasma parameters during NBI heated discharges

- p. 47: “Therefore the peak value of the P_{NBI} after NBI is switched on corresponds to its real value. NBI-on name stands for this peak value position”: Does this mean that NBI is considered to be “on” when P_{NBI} has reached its maximum value?
- p. 60-beginning of p. 61: This section would benefit of a discussion on what the codes are and what the modelling includes (see also comment on p. 44). This could help elucidate the differences between the codes, and also against the experiment. For example, on p.78, could there be reasons for the differences of the simulation results that have to do with the codes themselves?
- Sec. 6.2: P_{AUX} (i.e. the power delivered to the plasma after part of it has been scraped in the duct) is used for the derivation of energy confinement. Is P_{in}=P_{AUX} or P_{in}=P_{net}, where P_{net} is the absorbed power?
- I wonder if a sketch of the neutral density and origin of the neutrals captured by the NPAs would help the reader understand better the difference between T_{CX} and T_i and the localization (or not) of the measurement. It should be clearly mentioned that to derive the ion temperature accurately, a more detailed forward modelling with codes like DOUBLE or FIDASIM has to be performed.
- E_{stop} is not clearly defined.
- I found section 6.3.3 a bit confusing. It is not clear to me how the fast ions could not be well distributed in the plasma.
- Section 6.4: The beam target neutron rate is mainly dependent on the electron temperature. Is a dependence on T_e identified in the analysed dataset?

Chapter 7 – Impact of NBI heating on MHD instabilities

- p. 90, last paragraph: Could the discussed effects be captured by modelling of the fast ion population and NPA signals?
- Fig. 7.14: if the ELMs in the cases with $P_{sep,norm}$>30kW/m^2 are type I ELMs, then all the H-modes analysed here have type-I ELMs, correct?
- How is $P_{sep,norm}$ calculated?

Language suggestions:

While the thesis is carefully written and the writing style is appropriate for a doctoral thesis, the author makes some English grammar and syntax mistakes, as is the case for all with English not as our mother language. In particular, articles ("a" vs "the") are often used incorrectly. For the final version of the thesis, it would be very useful to have an English speaker proof-read the document. Nevertheless, these do not at all hinder the reader from understanding the text, with the exception of a couple of sentences. I mention here a few of the mistakes that are repeated in the thesis, hoping this is helpful:

- Instead of "secured", I suggest "ensured", "guaranteed", "provided"
- "degrades" (not "degradates")
- "with respect to" and not "in respect to"
- Plural: "fast ion energy" and not "fast ions energy" (could be "fast ions' energy")
- "discharge phase" instead of "discharge stage"
- "all parameters" or "all the parameters", but not "the all parameters".
- Plasma density "growth" → "increase"
- p. 50: "unnoise" → without noise
- p. 57: realise → release
- I would suggest to avoid the use of first person singular in the thesis, as it is done for example in the last paragraph of Sec. 3.6., the last paragraph on p.34 and in Chapter 8.

Typos and other corrections:

- φ usually denotes toroidal quantities and θ poloidal quantities (end of p. 4, beg. of p. 5)
- Section 3.6: Fast ion D_α spectroscopy
- Eq. 4.8, last equation: correct the subscript c_{10}
- Eq. 4.9: "tg" is usually represented as "tan"
- Fig. 6.4: What is meant by "piles" in the y-axis label?
- Fig. 6.16: There no blue points (low power) in the right plot.
- p. 68: Conclusion (capital letter)
- Fig. 7.8: Are the numbers in the legend the times from the ELM crash?
- Please note the capitalization of words like "COMPASS", "ASDEX Upgrade" etc in the Bibliography.