Report on Mr. TOMAS MARKOVIC's PhD Thesis titled

"Effect of magnetic field perturbations on tokamak plasma"

Thematical classification

The PhD thesis entitled "*Effect of magnetic field perturbations on tokamak plasma*" by Mr. Tomas Makovic is an interesting account of the physical understanding and exploration of three-dimensional (3D) non-axisymmetric magnetic perturbation effects on the 2D tokamak plasma MHD equilibrium and instabilities by applying a system of saddle-shaped magnetic perturbation coils (often referred as the resonant magnetic perturbation (RMP) coils in other experiments), modern diagnostics and idea linear MHD code on a small tokamak COMPASS, which is capable operating plasma in high confinement (H-mode) regime with the Neutral Beam Injection (NBI) heating. The COMPASS tokamak has unique equipment including a set of high-field-side (HFS) magnetic perturbation coils and excellent radial magnetic flux distribution measurements with a set of 104 saddle loops located just outside the vacuum vessel across its entire toroidal and poloidal range. All these features make this research work even more interesting.

For a long-pulse steady-state high performance operation of a fusion plasma, a reliable mechanism of active mitigation/suppression of transient divertor heat load induced by the periodic edge-localized-modes (ELM) is still needed. Through nearly 20 years of international collaborative research on many tokamak devices, RMP has been recognized as the most attractive ELM mitigation/suppression method and has been decided to install it on ITER. However, the physical mechanism is still not fully understood yet, which bring great challenge for the further optimization of magnetic perturbation configuration. Therefore, the influence of magnetic perturbations on the tokamak plasma stability and transport, as well as associated physics topics including rotating RMP shielding/screening and field penetration, have become an important subject to support physical understanding and exploration of RMP-ELM mitigation/suppression for the upcoming operation of ITER.

The thesis presented by Mr. Makovic dedicated to a systematic study of responses of both the core and the edge plasma to the external applied n = 1 and 2 non-axisymmetric magnetic perturbations on COMPASS. With support of the ideal MHD stability calculations, experimental studies of the field penetration threshold and RMP ELM mitigation have been carried out. Mr. Makovic pointed out where more work is required in this area and how this thesis will approach the problem. Thus, the work presented is shown to be currently relevant and well situated in the research field.

Content and contribution of the thesis

The key objective of this thesis was to assess the effects of low *n* (1, 2) magnetic perturbations on both the core and the edge plasma stability and transport on a small tokamak COMPASS. Towards this end, the following major results were made to achieve this objective:

- Parameter dependences of the penetration threshold for low *n* (1, 2) magnetic perturbations has been studied on COMPASS by taking into account the overall of plasma responses (mainly rotating screening currents), which are proportional but not equal to the vacuum calculation of external magnetic perturbations. The experimental results from COMPASS represent the small tokamak devices, and provide sufficient data points for the development of the empirical scaling of penetration threshold for low *n* magnetic perturbations.
- The field penetration threshold has been studied for the first time using the HFS RMP coils on COMPASS. The experimental results are consistent with the predictions of the empirical penetration threshold scaling. These unique experimental findings provide a new approach to optimally correct the error field induced by the assembly of HFS components.
- ELM mitigation by using a low *n* magnetic field has been successfully demonstrated on COMPASS, suggesting the possibility of applying this ELM control mechanism to small standard aspect ratio tokamaks. Furthermore, both, the experimental observations and simulations indicate that the vacuum approximation of the edge stochastization layer is not a sufficient criterion to describe the access to the ELM control.

It should be praised that Mr. Makovic did not only present the success achievements, but also reported limitations of the current study (such as the Type-III ELM H-mode of the target plasma on COMPASS), and possible way to improve further the description of the HFS-originating error field effect.

The thesis also contains a unique experimental study of the plasma confinement degradation thresholds under the error field originating from the inboard side of the torus. The outcome of Mr. Makovic' research work is important and valuable for accurate validation and interpretation of the plasma responses to the low *n* magnetic perturbations in support of further optimization of RMP ELM mitigation / suppression for the upcoming ITER operation.

Additional comments and questions on the scientific results:

Below are some minor questions and comments that the author may need to clarify or discuss in order to further refine the thesis.

1) Page 30, figure 2.3, the location of pedestal is about Ψ_{norm} ~ 0.92-0.95, however, in figure 4.6, figure 4.12 and figure 4.22, the location of pedestal is far outside about Ψ_{norm} ~ 1.0. Why?
2) How accurate is the equilibrium calculation on COMPASS, especially the core plasma part. Are there any core MSE or POINT measurements that would improve the accuracy of the central q profile? How sensitive is the overlap field calculation depend to the position of the plasma axis? And to the q profile?
3) How the COMPASS Central Solenoid (CS) will influence the MHD equilibrium calculation? Especially during the ramp-up of the RMP coil current? Is the delay of field penetration after the RMP coil current reaches a plateau due to the CS effect? How would the CS affect the RMP ELM control experiment? Especially on the difference between LFS- and HFS-RMP ELM control experiments?
4) The error field penetration threshold scaling used in this thesis does not include plasma rotation dependence, and the plasma parameters, such as n_e, β_N, l_i… , used in the eq. 3.16 are not present local information at the rational flux surface. If the plasma is heated with different momentum input (by co-Ip and ctr- NBI injection), how much will the field penetration threshold vary?
5) The author highlighted the excellent radial magnetic flux distribution measurements with a set of 104 saddle loops located just outside the vacuum vessel across its entire toroidal and poloidal range on COMPASS. However, the thesis rarely discusses the analysis of changes in Br distribution with and without LFS or HFS-RMP based on this measurement.
6) Pedestal stability analysis is missing. It will help to understand why limited ELM mitigation is observed in COMPASS H-mode plasmas.

Quality of the writing

The thesis of Mr. Makovic, who is not a native English speaker, is written and generally good manner and easily understandable. There are minor typos, but they do not obstruct the understanding of the manuscript.

The form of the thesis is in a manner that befits a dissertation. The thesis firstly outlines the general situation in the field fusion research; the fundamental MHD equilibrium in magnetically confined fusion plasmas; and explains the specials that are interesting for the understanding of the work. The Chapter 2 introduces the COMPASS tokamak, where the experiments performed. Other than the general description of the device, the plasma operation domain and major corresponding diagnostics have been described. The major results from this thesis on the plasma responses to low *n* magnetic perturbations were discussed in the Chapter 3 and Chapter

4. The order of the Chapters is well arranged to guide the reader to understand the results step by step.

Minor comments on writing:

1) The Chapter 3, and 4 describe the major results from this thesis work. However, the background introduction in both these two Chapters is too lengthier, the author should focus on his own results, and shorten the well-known background, or move some of the descriptions to the Chapter 1, where the status of art was summarized.

2) There are minor typos. For example, Page 56, Figure 3.1 caption: "… eigenmodes o energy …". Page 77, Figure 3.19, "δB⁽x)" . The author may need double check the entire thesis.

Publications and awards

The work of Mr. Makovic has resulted mainly in two first author publications and several co-authorships to date. His contributions on measurements and modelling of plasma response field to RMP have been published in the Journal of *Nuclear Fusion* (4.215), while the development of 3D ferromagnetic model of tokamak core with strong toroidal asymmetry has been published in *Fusion Engineering and Design* (1.905). Both, *Nuclear Fusion* and *Fusion Engineering and Design* are well known in the field of fusion.

Summary and grading

In summary the PhD thesis is a very good work. Mr. Makovic has shown a clear logical progression of ideas and brought together various modelling and experimental results to a valid conclusion. His work contains physics understanding for plasma responses to external low n magnetic perturbations, which is important for RMP ELM mitigation/ suppression of the upcoming ITER operation. This is reflected in the impact of Mr. Makovic' PhD work by his scientific journal publications. Hereby, I would like to recommend that the thesis should be awarded a Ph.D. degree.

Prof Dr. Yunfeng Liang

Institut für Energie- und Klimaforschung - Plasmaphysik
Forschungszentrum Jülich GmbH
IEK-4 52425 Jülich, Germany

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