The Henryk Niewodniczański
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

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Dr. Axel Jardin
The Henryk Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences (IFJ PAN)
Department of Radiation Transport Physics (NZ61)
ul. Radzikowskiego 152, 31-342 Krakow, Poland

Review of the doctoral dissertation of Mgr. Martin Imrisek "Study of instabilities in tokamak plasmas using radiation diagnostics"

The doctoral thesis of Mgr. Martin Imrisek "Study of instabilities in tokamak plasmas using radiation diagnostics" was carried out in the Department of Surface and Plasma Science of the Faculty of Mathematics and Physics of the Charles University in Prague, under the supervision of Prof. RNDr. Milan Tichy, DrSc, and of the two consultants Mgr. Vladimir Weinzettl, PhD and RNDr. Jan Mlynar, PhD. The general aim of the thesis is to investigate the impact of the so-called "sawtooth" MHD instability on the COMPASS plasma regimes and performance such as L-H, H-L transitions or correlation with ELMs. To do so, the soft X-ray (SXR) 2D tomography diagnostics is the main tool to reconstruct the core emissivity distribution and to characterize the sawtooth ramp-up phase, precursor phase, crash, and correlate them to plasma parameters. MHD equilibria of COMPASS, essential to evaluate plasma stability, are simulated with the FIESTA code, allowing as well the optimization of coils geometry for the COMPASS-Upgrade ongoing project. The provided documents consist of a 144-page manuscript and an appendix containing a list of two first-authored articles, 19 co-authored articles and other co-authored works and conference publications.

In Chapter 1, the author defines the goals of each chapter of the thesis, after a laconic but relevant introduction on global energy issues, the potential of fusion energy and tokamaks. Chapters 2 and 3 introduce the different concepts necessary to apprehend this PhD work. In Chapter 2, the MHD fluid equations and magnetic equilibrium in tokamaks are presented, as well as the conditions for MHD stability, a basic classification of instabilities (in particular sawteeth and ELMs) and main tokamak operational limits. The electromagnetic emission processes, namely bremsstrahlung, radiative recombination and line radiation are presented in Chapter 3, together with the associated diagnostic tool issues in tokamak plasmas. Fig 3.1(b) presents cooling factors calculated for several elements (1 < Z < 74). Please, clarify if they are total cooling factors or only “line radiation cooling factors” as stated in the legend. I would also expect a few words explaining why the L_W curve (Z=74) is interrupted for $T_e < 40\ eV$. The chapter concludes with the tokamak power balance and the possibility of using the detachment regime to limit plasma-wall heat flux. **Overall, the three introductory chapters are concise and well-written, with relevant references to the available literature.**

The three last chapters represent most of the manuscript volume and contain the most valuable scientific outputs of the PhD thesis. Each chapter is concluded by a summary of the main results, which is greatly appreciated to synthetize the scope and added value of the performed work.

Chapter 4 first focuses on simulating COMPASS MHD equilibrium with the FIESTA code. The comparison with EFIT++ shows a reasonable difference for different upper triangularities. In Fig. 4.2, the largest equilibrium difference is observed at the plasma edge ($z \simeq 0.3\ m$), while the largest difference of current is observed in the core ($R \simeq 0.55\ m$). I would therefore expect a comment explaining the possible origin of these discrepancies. The FIESTA code is then used to optimize the coils geometry for the COMPASS-U design, starting from plasma scenarios given by the METIS code. The solution obtained from FIESTA is a result of Tikhonov regularization expressed in Eq. (4.4), balancing the match with the expected signals (e.g. poloidal field) and the minimization of the norm of the solution (e.g. coil currents). There is however a lack of explanation related to the choice of the regularization parameter value for the presented FIESTA solutions. I would expect here a short clarification of this aspect. A vertical stability criterion of the plasma equilibrium is established in Eq. (4.7). It is stated that a stability criterion $f_s < 1.0$ would require very fast active feedback, and that $f_s > 1.5$ is preferable in practice for design purposes. A question related to this point is whether the value of 1.5 has been determined empirically, based on previous experience or relying on an existing model. An important aspect of this work is related to the optimization of the PF coils geometry for COMPASS-U. It has been demonstrated that placing the PF coils inside the TF coils is more advantageous than the original choice (outside the TF coils), allowing a better plasma control by the PF coils and a more homogeneous toroidal field, at the cost of enlarging the TF coils. Several results shown in this chapter are related to the publication [78], co-authored by Mgr. Martin Imrisek but not included in the appendix listing the author’s publications. The optimization of the divertor coils geometry revealed that PF1Lb connected to PF1La allows for a 3^o broader range of strike point angles while sparing a power source, which is a very positive outcome of this study. The same goes by pairing the CS coils, reducing further the number of power sources. The chapter concludes with simulations of various scenarios to test the robustness of the chosen PF coils geometry, spanning plasma current, toroidal field, triangularity, elongation and strike point sweeping, showing that the vertical stability criterion is respected and that MHD instabilities can be expected due to $q_{95} < 3$. **The presented study in Chapter 4 is essential for the proper preparation of COMPASS-U experiments and is a first demonstration of the relevance and quality of this work**.

Chapter 5 is devoted to the diagnostics and methods for tomographic reconstruction of SXR and AXUV emissions on COMPASS and JET tokamaks. First, the forward and inverse "ill-posed" problems relating a finite set of line-integrated measurements and the plasma emissivity field are defined. In this thesis, the Tikhonov regularization is used, with minimization of the Fisher information (MFR) and the Pearson's test for the optimization of the regularization parameter, which is a valid and robust approach broadly used in tokamaks. Since the matrix W representing $1/g$ in Eq. (5.9) depends on the solution g and requires an iterative process, I would expect a comment clarifying the choice of the initial step $g^{(0)}$ and whether a positivity constraint is used to prevent $g \leq 0$. In addition, in the case of anisotropic smoothing (wrt. magnetic field lines), please precise how the value of the coefficient of anisotropy is chosen. It is then shown how linear methods such as SVD, QR and GEV can help finding solution or moments of the distribution in a fast way, compatible with real-time applications, at the cost of a lower precision. If the rolling iteration was used in Chapter 6, e.g. to reconstruct the growth rate of the internal kink mode, I would expect here a comment about the additional uncertainty inherent to this method. The tomographic SXR and AXUV systems of COMPASS, including the geometrical étendue and calibration, are introduced in a clear way. The comparison of the SXR center of mass with the magnetic axis revealed a small systematic error of about 1-2 cm. In pages 61-64, linear methods are compared with MFR. The main results are summarized in Fig 5.13 and Table 5.3, showing an advantage for the GEV method, taking MFR or EFIT as a reference. The possibility of using such approach for real-time control of plasma position raises the question of impurity content: how the impurity concentration and poloidal distribution could impact the quality of plasma position monitoring by SXR, and what could be the strategies to mitigate this issue? In the next section, the AXUV diagnostic is used to study the radiation power loss, the radiation pattern during ELMs and during successful impurity seeding experiments at COMPASS. It would be advisable at this point to remind briefly the procedure used to estimate P_{rad} from AXUV measurements, and clarify what are the main sources of uncertainty. The correlation between the estimated power losses and the plasma density, temperature and plasma regime (L/H mode) are presented. Experimental scaling laws are derived based on the COMPASS shot database. The radiated energy during ELMs shows a linear dependence (Fig. 5.17) with the energy loss found by EFIT ($E_{rad} = 0.28\,\Delta W$). Very interestingly, in Fig 5.18 the propagation of ELM filaments could be observed with AXUV diodes, allowing a coherent estimate of their velocity of around 1.3 km/s. Finally, the developed tools are applied for the SXR diagnostic of the JET tokamak. SXR tomography can be quite challenging at JET due to sparse coverage, different toroidal locations, angles, and mostly different Beryllium filter thicknesses (100, 250, 350 μm). The system was used to observe the rotation amplitude of MHD modes, with limited results due to the constraints mentioned above. SXR reconstructions were also performed to analyze disruptions mitigated by gas injection, using each camera for independent tomographic reconstructions with high anisotropic smoothing along magnetic field lines (getting closer to an Abel inversion), and allowing to monitor the propagation of the Argon puff from the plasma edge to the core (Fig. 5.30), until plasma termination. **I read this chapter focused on plasma tomography with a great pleasure and I acknowledge the quality and novelty of the presented scientific results.**

In the sixth and last chapter, the sawtooth instability, which is present in the majority of COMPASS D-shaped scenarios and significantly affects the plasma behavior and performance, is characterized in details (sawtooth period, crash, inversion radius) thanks to the SXR tomographic tools previously developed. First, MHD theoretical background is presented via the energy principle, including the Porcelli model to introduce different criteria for the sawtooth instability - namely hot trapped ions, internal kink and resistive effects. Based on METIS simulations, Fig 6.10 shows that sawteeth at COMPASS are most probably associated with the resistive regime. The main plasma parameters investigated are the averaged electron density $\langle n_e \rangle$, central electron temperature $T_{e,0}$, poloidal beta β_p, NBI power P_{NBI}, resistive time τ_R and energy confinement time τ_E. Fig 6.11 and Table 6.2 present a summary of the correlations between the sawtooth period T_{saw} and the chosen plasma parameters, during plasma density scan experiments. It is shown that T_{saw} decreases with increasing T_e and τ_R, in contrast with JET experiments, indicating that current diffusion is not the driving mechanism. Besides, T_{saw} increases with n_e, β_p and τ_E, more consistently with the Porcelli criterion of resistive regime. However, increasing the sawtooth period also means less frequent sawtooth crashes, potentially increasing the confinement time. Fig. 6.12 shows that T_{saw} and the kink frequency increase with P_{NBI} in co-current, due to the change of toroidal velocity. I would here expect a comment explaining why Fig. 6.12(b) is restricted to the range 300 – 500 kW in comparison with Fig. 6.12(a). The results shown in Figs. 6.13 - 6.16 seem to indicate that the sawtooth period is actually more probably sensitive to τ_E *or* W than to P_{NBI}. In this case, what could explain the observed minimum of T_{saw} for NBI in counter-current regime? In Fig 6.18 related to the impact of confinement regime on T_{saw}, it seems that T_{saw} saturates for high values of the kinetic energy W. What could be the explanation for this observation? In the following section, the sawtooth inversion radius is determined as the region of lowest variation in the SXR reconstructed profile and usually represents around 45% of the minor radius at COMPASS. However, the dependency of the inversion radius to plasma parameters remains inconclusive. Finally, the effect of sawteeth on H-L, L-H transitions and

ELMs is investigated in the last section. The L-H transition is experimentally identified by a significant drop in the Dα signal, as the plasma-wall interaction is strongly reduced. Fig 6.26 demonstrates statistically that the L-H transition is clearly correlated with the sawtooth crash, with a typical time delay < 1 ms corresponding to the first 20% of the sawtooth phase. A physical interpretation is given, i.e. that the edge plasma close to L-H transition is supplied by a sufficient heat pulse from the sawtooth crash to trigger the change of confinement mode. I would expect here a brief comment detailing what was the condition used (e.g. a threshold value) to identify precisely the time of L-H transition in the Dα signal. As it could be expected from the previous interpretation, it is also found and shown on Fig. 6.27 that the H-L transition is prevented in the first 20-30% of the sawtooth phase, due to the stabilizing effect of the sawtooth crash on the plasma edge transport barrier. With the same approach, it is demonstrated that the dithering oscillations are strongly modulated by the sawtooth cycle. Regarding ELMs, it seems that the transition from ELMy H-mode to ELM-free H-mode is correlated with the sawtooth crash that could be due to a sudden drop of the edge pressure gradient in the ELM stability diagram (thus crossing the peeling boundary condition), although the statistics remains weak for the available shot database. On Fig 6.31(b), the discharge #19137 seems to show that ELMs can be synchronized with the sawteeth crashes. However, one could raise some doubt while looking at Fig 6.31(a) showing sawtooth periods typically smaller than ELM periods for numerous discharges. Nevertheless, the author shows a clear correlation by plotting the delay between ELMs and sawtooth crashes, exhibiting a drop of ELM probability in the 1 ms just after the sawtooth crash, reinforcing the interpretation of the stabilizing effect of the sawtooth heat pulse on the plasma edge. **The sixth chapter focused on sawtooth oscillations in COMPASS contains very valuable results and conclusions supported by robust data analysis, that I believe are and will be highly valued by the fusion community**. As a last remark, I would expect a discussion about the extrapolation of the analysis performed in this thesis to the COMPASS-U project in terms of SXR tomography capabilities, expected sawtooth regimes and future experiments and data analysis.

In conclusion, I acknowledge the originality of the work presented in the thesis of Mgr. Martin Imrisek and the high quality of the obtained scientific achievements, in particular for COMPASS and COMPASS-U tokamaks. Obviously, the thesis is not without small flaws: few parts of the methodology and results are a bit concise and would benefit more detailed explanations, hence the number of my comments and questions, which also prove my interest for this work. Similarly, every terms in equations are not always defined, although the missing ones can easily be understood from the context or found in textbooks. Additionally, I have a few editorial remarks:

- the list of acronyms might be better positioned at the beginning of the manuscript,
- the articles “the”, “a” are sometimes omitted or reversed,

- Eq. (2.8): “= 0” is not strictly rigorous since “j” and “B” have a different physical unit,
- Sometimes, a color bar with physical unit is missing on 2D color plots (e.g. Fig. 2.2 or 5.16),
- Fig. 4.8: I believe that plots (a), (b) are reversed wrt. the legend and that “ΔI” → “I” for plot (b),
- Eq (5.3) → there seems to be a missing index “i” in “=Tg”,
- I think the abbreviation “circa” is more commonly used as “ca.” or “c.”, rather than “cca.”,
- Eq. (5.7): issue of homogeneity with P_i in W/m^2, if the chord brightness f_i itself is in W/m^2,
- Eq. (6.16): issue of homogeneity in the term $(1 - e^{-n_e})$? Is the term n_e normalized here?
- Fig 6.11: the legend mentions the loop voltage, but not all the parameters are actually plotted.

Nevertheless, these minor negative points do not affect the readability of the manuscript and the robustness of the excellent results presented in the thesis. Mgr. Martin Imrisek is the main author of two peer-reviewed articles related to his thesis and he is the co-author of numerous published articles and presentations at international conferences, demonstrating his capability of independent scientific work. I therefore recommend that the candidate be admitted to further stages of the doctoral defense.