**PROGRAMME OF COORDINATED RESEARCH ACTIVITIES**

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**Final Report for Contracts**

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| CRP code: F13019 | CRP title: Network of Small and Medium Size Magnetic Confinement Fusion Devices for Fusion Research |
| Contract Number: 22782 | Contract title: Scientific and education activities on the GOLEM tokamak in the framework of the IAEA CRP |
| Institute Name: Czech Technical University | |
| CSI:   Vojtěch SVOBODA | Alternate CSI: |
| Progress Report for year:    1-4    (year 1, 2, 3…) | Period covered:        (2018-06-20 – 2022-12-31) |

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| 1. Detailed programme of work, as planned at the beginning of the period, taking into account the recommendations given during Research Coordination Meetings (RCMs) and/or through communication with the Project Officer:   2.2.14.1. **Main research activities proposed**  The scientific activities focus on the field of plasma edge studies using advanced probe techniques and developing diagnostics for runaway studies.  2.2.14.3. **Education activities**  In the CRP context there are two planned education activities: GOMTRAIC, a week of hands-on experiments at the GOLEM tokamak, and a set of remote participation training courses. |
| 1. Results achieved in comparison with the planned programme of work.   Introduction  Tokamak Golem is primarily an educational facility and therefore its program is basically divided into two parts: i) a rich spectrum of various training courses and ii) a research program, which, however, is designed in such a way that the main actors are students who solve various tasks within of their bachelor's, diploma and doctoral theses under the guidance of experts in the respective fields. This device is also the oldest functioning tokamak in the world, and therefore research topics are chosen that are worthy of contributing in some way to the mainstream of scientific activities in the field of thermonuclear fusion. Historically, we are also trying to build on the topics addressed in the previous version of this tokamak at the Academy of Sciences of the Czech Republic under the name CASTOR. therefore, the main topics are: i) physics and diagnostics of the plasma edge and ii) physics and diagnostics of the so-called runaway electrons.  **Research activities**  \* plasma edge studies using advanced probe techniques  As part of so-called isotopic studies operational domains in hydrogen and helium plasmas on the GOLEM tokamak were investigated with focus on Self-induced transport barrier in the Helium plasma [Svo+19], [Saranch+21] and [Mac22b].  I:  Operational domains  =================  **Operational domain in hydrogen plasmas on the GOLEM tokamak [Svo+19],**  **Helium plasmas operation domain studies on the GOLEM tokamak [neni]**  **Hydrogen and Helium Plasmas in the GOLEM Tokamak [Saranch+21]**  **Self-induced transport barrier in the helium plasma on the tokamak GOLEM** [Mac22b]  Advanced electrostatic probes … using  ===================  Fast measurements of electron temperature on the GOLEM tokamak by means of Tunnel Probe [Macch]  **Electron temperature measurements using rail probe on the tokamak GOLEM** [Jirch] (in czech)  **Ion and electron temperature study in the edge plasma of the tokamak device**  [Darst].  Impact of swept edge plasma potential biasing on turbulence in tokamaks [Papch]  Magnetohydrodynamic studies:  =====================  **Magnetic turbulence and long-range correlation studies in the GOLEM tokamak** [Sar+21a]  **Magnetohydrodynamic Mode Identification for Golem Mirnov Coil Signals Using Singular Value Decomposition and Multichannel Variational Mode Decomposition Method for Analyzing Time–**  **Frequency**  [CJ22]  \* developing diagnostics for runaway studies.  **Diagnostics**  **========**  **Design and Development of Probe for the Measurements of Runaway Electrons Inside the GOLEM Tokamak Plasma Edge**  [Dhy19]  **Runaway electron diagnostics using silicon strip detector [Nov+20]**  **Runaway electron study at the COMPASS tokamak using the Timepix3-based silicon pixel detector with SPIDR 10 GBps readout.**[Kul21].  First Measurement of X-rays Generated by Runaway Electrons in Tokamaks Using a TimePix3 Device with 1 mm thick Silicon Sensor [Lin+18]  **Progress in HXR diagnostics at GOLEM and COMPASS tokamaks**  [Cer+22]  **Detection of runaway electrons at the COMPASS tokamak using a Timepix3-based semiconductor. Detector** [Kul+22]  **Physics**  **======**  **Study of Runaway Electrons in GOLEM Tokamak** [Dhy+19]  **The Runaway Electrons Production Dynamics Dependence on the Breakdown Phase of the Tokamak Plasma [Sius+21].**  As extraordinary  **Contribution of joint experiments on small tokamaks in the framework of IAEA coordinated research projects to mainstream fusion research** [GRY+20].  Experiments on GOLEM were dedicated to many pioneering studies in connection with the application of the high temperature superconductors (HTS) magnets: HTS DC and AC tests, HTS switch tests, plasma optimization with HTS coils and required modifications to the discharge scenario to reduce AC losses in HTS coils during current ramp-up, and also characterization of a quench in the HTS coil.  How does this support affect your outputs  List of publications related to the grant.  **Educational activities**  **GOleM TRAIning Course (GOMTRAIC 2019)**  GOleM TRAIning Course (GOMTRAIC2019) was held at the faculty of Nuclear Sciences and Physical Engineering in the Czech Technical University in Prague, Czech Republic during March 04-08, 2019. Sixteen students (from undergraduate to doctoral level and ten countries) participated in the course to have hands-on experience of tokamak operation and perform experiments on the GOLEM tokamak.  EPSs:  **2019: Tokamak GOLEM for fusion education - chapter 10 [Kul19]**  **2021: Tokamak GOLEM for fusion education - chapter 12[Mac21]**  **2022: Tokamak GOLEM for fusion education - chapter 13**[Mac22a]  **Online experimentation at the GOLEM tokamak**  The GOLEM tokamak offers students and other interested parties the opportunity to gain “hands-on” experience through online experimentation in the field of plasma physics and controlled thermonuclear fusion in tokamaks. A typical online experiment scenario is outlined. The new web application facilitating safe, easy and efficient online experimentation, including a live, real-time view of the experiment is described in detail. Simple access to the open and extensive database of experimental results is demonstrated. Finally, the wide range of possible experimental topics from past -and applicable to future- online experimentation sessions is reported. More info at [GSS19a, GSS19b]  **Education and training of students**  \* Experiments related to CRP project triggered approx 10 bachelor and master thesis at the Czech Technical University  \* Hands-on/ on site tokamak GOLEM projects  \* Approx 6 projects for extremely skilled high school students was completed.  \* More then 30 training courses of students has also been performed remotely, exploiting a unique feature of the GOLEM tokamak, which can be operated via Internet.  One figure that you think summarizes the advances made with the help of the IAEA grant. |
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| 1. Papers published and dissemination at national and international conferences on work performed under this Project (please enter a web-link or attach copies to this progress report):   I:  [Lin+18] V. Linhart et al. “First Measurement of X-rays Generated by Runaway Electrons in Tokamaks Using a TimePix3  Device with 1 mm thick Silicon Sensor”. In: 2018 IEEE Nuclear Science Symposium and Medical Imaging Conference  Proceedings (NSS/MIC). 2018, pp. 1–9. doi: 10.1109/NSSMIC.2018.8824534.  [Dhy+19] P. Dhyani et al. “Study of Runaway Electrons in GOLEM Tokamak”. In: Journal of Instrumentation 14.09 (2019),  pp. C09029–C09029. doi: 10.1088/1748-0221/14/09/c09029. url: https://doi.org/10.1088%2F1748-0221%2F14%  2F09%2Fc09029.  [Dhy19] Svoboda V. Istokskaia V. Mlynář J. Čeřovský J. Ficker O. Linhart V. Dhyani P. “Design and development of probe for the  measurements of runaway electrons inside the golem tokamak plasma edge”. In: vol. 2019-July. Europhysics conference  abstracts. 2019, P1.1016. isbn: 979-10-96389-11-7. url: http://ocs.ciemat.es/EPS2019PAP/pdf/P1.1016.pdf.  [GSS19a] O. Grover, V. Svoboda, and J. Stockel. “Online experimentation at the GOLEM tokamak”. In: 2019 5th Experiment International Conference (exp.at’19). 2019, pp. 220–225. doi: 10 . 1109 / EXPAT . 2019 . 8876482. url: https :  //ieeexplore.ieee.org/document/8876482.  [GSS19b] O. Grover, V. Svoboda, and J. Stockel. “Remote demonstration of the GOLEM tokamak”. In: 2019 5th Experiment International Conference (exp.at’19). 2019, pp. 239–240. doi: 10 . 1109 / EXPAT . 2019 . 8876584. url: https :  //ieeexplore.ieee.org/document/8876584.  [Kul19] Mácha P. Istokskkaia V. Kropáčková D. Papoušek F. Adámek J. Čeřovský J. Ficker O. Grover O. Jiráková K. Stöckel J.  Svoboda V. Kulkov S. “Tokamak GOLEM for fusion education - chapter 10”. In: vol. 2019-July. Europhysics conference  abstracts. 2019, P1.1068. isbn: 979-10-96389-11-7. url: http://ocs.ciemat.es/EPS2019PAP/pdf/P1.1068.pdf.  [Svo+19] Vojtech Svoboda et al. “Operational Domain in Hydrogen Plasmas on the GOLEM Tokamak”. In: Journal of Fusion  Energy (2019). issn: 1572-9591. doi: https://doi.org/10.1007/s10894-019-00215-7.   II:  [Nov+20]  L. Novotny et al. “Runaway electron diagnostics using silicon strip detector”. In: Journal of Instrumentation 15.07  (2020), pp. C07015–C07015. doi: 10.1088/1748-0221/15/07/c07015. url: https://doi.org/10.1088%2F17480221%2F15%2F07%2Fc07015.  III:  [Sius+21]  Siusko, Y., Svoboda, V., Stockel, J., Garkusha, I., Solyakov, D., Girka, I., . . . Shchibrya, A. . Breakdown phase in the golem tokamak and its impact on plasma performance. *Ukrainian Journal of Physics*, 66(3), 231-239 (2021). doi:10.15407/ujpe66.3.231  [Kul21] Kulkov, S., Marcisovsky, M., Svihra, P., Ficker, O., Cerovsky, J., Macusova, E., Weinzettl, V., Beuzekom, M., Fransen, M. , Bren, D. , Linhart, V., , Svoboda, V., Tunkl, M. “Runaway electron study at the COMPASS tokamak using the Timepix3-based silicon pixel detector with SPIDR 10 GBps readout”. In: vol. 2021-July. Europhysics conference abstracts. 2021, P3.1006. isbn: 979-10-96389-13-1. url: http://ocs.ciemat.es/EPS2021PAP/pdf/P3.1006.pdf.  [Mac21] Macha,P.,Hromasova, K., Kropackova,D., Lauerova, M., Socha, A., Malinak, J., Cipciar, D., Cecrdle, J., Svoboda, V., Stockel, J., Adamek, J., Papousek, F., Lobko, L. “Tokamak GOLEM for fusion education - chapter 12”. In: vol. 2021-July. Europhysics conference abstracts. 2021, P4.1028. isbn: 979-10-96389-13-1. url: http://ocs.ciemat. es/EPS2021PAP/pdf/P4.1028.pdf.  [Jirch] Jiri Malinak. “Electron temperature measurements using rail probe on the tokamak GOLEM.” Bachelor project at the CTU Prague, 2021. url: <http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/21MalinakJiri.pdf>  [Darst] Dario Cipciar. “Ion and electron temperature study in the edge plasma of the tokamak device”. Master thesis at the CTU Prague, 2021. url: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/21DarioCipciar.pdf  [Saranch+21]  George Sarancha, Alexey Drozd, Stanislav Ganin, Daniela Kropachkova, Ivan Kudashev, Vladimir Kulagin, Martina Lauerova, Alexander Melnikov, Nikita Sergeev, Oleg Krokhalev, Jan Stockel and Vojtech Svoboda. Hydrogen and Helium Plasmas in the GOLEM Tokamak. Prepared for publication in *Questions of Atomic Science and Technique.*  IV:  Articles:  [Cer+22] J. Cerovsky et al. “Progress in HXR diagnostics at GOLEM and COMPASS tokamaks”. In: *Journal of Instrumentation*. 17.01 (2022), p. C01033. doi: 10 . 1088 / 1748 - 0221 / 17 / 01 / c01033.  [Kul+22] S. Kulkov et al. “Detection of runaway electrons at the COMPASS tokamak using a Timepix3-based semiconductor. detector”. In: *Journal of Instrumentation* 17.02 (2022), P02030. doi: 10 . 1088 / 1748 - 0221 / 17 / 02 / p02030.  Conferences:  [Mac22a] Macha, P., M. Pokorny, D. Kropackova, M.Humpolec, J. Chlum, K. Wen, M. Tunkl, M. Lauerova, J. Brotankova, J.  Stockel, V. Svoboda, S. Kulkov, A. PodolnikJ. Caloud, S. Malec. “Tokamak GOLEM for fusion education – chapter 13”. In: vol. 2022-July. Europhysics conference abstracts. 2022.  [Mac22b] Macha,P., Svoboda, V., Stockel, J., Adamek, J., Seidl, J. “Self-induced transport barrier in the helium plasma on the tokamak GOLEM”. In: vol. 2022-July. Europhysics conference abstracts. 2022.  [Sar+21a] G Sarancha et al. “Magnetic turbulence and long-range correlation studies in the GOLEM tokamak” . In: Journal of Physics: Conference Series 2055.1 (2021), p. 012003. doi: 10.1088/1742- 6596/2055/1/012003.  Others:  [Jakch] Jakub Chlum. “Implementation of tomographic inversion on the GOLEM tokamak.” Bachelor project 2022. url:  <http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/22ChlumJakub.pdf>.  [CJ22] Jayakumar Chandrasekaran and Sangeetha Jayaraman. “Magnetohydrodynamic Mode Identification for Golem Mirnov Coil Signals Using Singular Value Decomposition and Multichannel Variational Mode Decomposition Method for Analyzing Time-Frequency”. English. In: JOURNAL OF FUSION ENERGY 41.2 (2022). issn: 0164-0313. doi: 10.1007/s10894-022-00329-5. |
| 1. Activities included in the programme of work which were planned, but were not implemented. Please state reason (i.e.: delays, issues encountered): |
| 1. Detailed programme of work for the coming year, taking into account the recommendations given during RCMs and/or through communication with the Project Officer (to be used as reference for the next Progress Report):   **-** |

CSI Name and signature: Date: 18.9.2022     

   Vojtěch Svoboda 