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## PROGRAMME OF COORDINATED RESEARCH ACTIVITIES

Webpage: [www.iaea.org/services/coordinated-research-activities](http://www.iaea.org/services/coordinated-research-activities)

### Final Report for Contracts

*Please send the Progress Report to [research.contracts@iaea.org](mailto:research.contracts@iaea.org)*

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)

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.

2 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**

I. physics and diagnostics of the plasma edge

A wide spectrum of advanced electrostatic probes (Tunnel , Rail, Ball pen, Mach, Double rake ) were tested in various tokamak regimes including swept edge plasma potential biasing, and used for fast measurements of ion and electron temperature. [Macch], [Jirch] ,[Darst] and [Papch]. Particular focus was applied to the isotopic studies of operational domains in hydrogen and helium plasmas and self-induced transport barrier in the Helium plasma, see [Svo+19], [Saranch+21] and [Mac22b].

Secondly studies dedicated to Magnetic turbulence and long-range correlation together with Magnetohydrodynamic Mode Identification Using Singular Value Decomposition and Multichannel Variational Mode Decomposition Method were performed with two sets of Mirnov coils surrounding poloidally plasma column at two different toroidal positions, see[Sar+21a], [CJ22].

II. physics and diagnostics of runaway electrons.

In the Diagnostics branch we focused on Design and Development of various Probes for the

Measurements of X-rays Generated by Runaway Electrons using silicon strip detector, Timepix3-based silicon pixel detector with SPIDR 10 GBps readout., TimePix3 Device with 1 mm thick Silicon Sensor and a set of scintillation probes with various crystals (NaI(Tl), YAP, CeBr and LYSO), see [Lin+18], [Dhy19], [Nov+20], [Kul21] and [Kul+22]. Based on these novel diagnostics we performed a set of sessions dedicated to general behaviour of **Runaway Electrons in GOLEM Tokamak** with focus on their **Production Dynamics Dependence on the Breakdown Phase of the Tokamak Plasma** [Dhy+19] and [Sius+21].

### III. Pioneering studies in connection with the application of the high temperature superconductors (HTS) magnets.

In the framework of the **IAEA coordinated research projects** experiments on the tokamak GOLEM were dedicated to many: 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. [GRY+20].

### **Educational activities**

#### I. GOLEM TRAINing Course (GOMTRAIC 2019)

.. 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 from ten countries) participated in the course to have hands-on experience of tokamak operation and perform experiments on the GOLEM tokamak.



GOMTRAIC students after successful presentations, the final day of the course

#### II. EPSs:

Each year, a summary of all student activities from bachelor to doctoral level on the Golem tokamak is summarized in a paper for the European Physical Society (EPS) conference on Plasma Physics:

- 2019: Tokamak GOLEM for fusion education - chapter 10 [Kul19]
- (Skipped due to covid)
- 2021: Tokamak GOLEM for fusion education - chapter 12[Mac21]
- 2022: Tokamak GOLEM for fusion education - chapter 13[Mac22a]

### III. 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. More info at [GSS19a, GSS19b]

### IV. Education and training of students

- \* Experiments related to CRP project triggered approx 10 bachelor and master thesis at the Czech Technical University
- \* Every year 3-5 hands-on/ on site tokamak GOLEM projects are produced for university students.
- \* Approx 6 projects for extremely skilled high school students was completed.
- \* More than 30 training courses of students has also been performed remotely, exploiting a unique feature of the GOLEM tokamak, which can be operated via Internet.

3

4 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):

[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. Istokskaja 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>.

[//ieeexplore.ieee.org/document/8876584](http://ieeexplore.ieee.org/document/8876584).

[Kul19] Mácha P. Istokskkaia V. Kropáčková D. Papoušek F. Adámek J. Čerovský 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>.

[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/10.1088/17480221/15/07/c07015>.

[Papch] Filip Papousek. “Impact of swept edge plasma potential biasing on turbulence in tokamaks” Bachelor project at the CTU Prague, 2020. url: <http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/20PapousekFilip.pdf>

[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*.

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.

5 Activities included in the programme of work which were planned, but were not implemented. Please state reason (i.e.: delays, issues encountered):

6 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):

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CSI Name and signature:

Date: 25.9.2022

Vojtěch Svoboda

