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PROGRAMME OF COORDINATED RESEARCH ACTIVITIES
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Annual Progress Report for Contracts

Please send the Progress Report to 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: 4 (year 1, 2, 3...)	Period covered: (2020-09-01 – 2021-08-31)

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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.

2. Results achieved in comparison with the planned programme of work.

* plasma edge studies using advanced probe techniques

Self-induced transport barrier in the helium plasma on the tokamak GOLEM

Transport barriers and transmissions into different regimes of plasma confinement are currently very discussed topics. The lattes research showed a connection between transport barriers and E × B shear flows, which are able to suppress turbulent structures by tearing them apart. This process leads to better particle and also temperature confinement. Therefore, there is a significant effort for transport barrier studies. Usually, transport barriers are induced by an external electric field, which is used for plasma biasing. This method is useful, however, spontaneously formed transport barriers can provide more information about the processes taking place in a tokamak plasma. In this paper, the self-induced transport barrier in the helium plasma on the tokamak GOLEM is observed and analyzed. More info in the article [Mac22b]

Magnetic turbulence and long-range correlation studies in the GOLEM tokamak

The small university-scale tokamak GOLEM equipped with the electric and magnetic probes becomes a test bench for studying the plasma turbulence and Zonal Flows, which are the essential processes affecting the plasma confinement. The broadband ($f_{BB} < 250$ kHz) magnetic turbulence was detected for the first time using the Mirnov probes. The two-dimensional (frequency–wavelength) Fourier power spectra $S(k, f)$ of the magnetic turbulence indicate the turbulence poloidal propagation. The long-range correlations (LRC) between the signals of magnetic and electric probes installed at different toroidal cross-sections were detected in the low-frequency range ($f_{LRC} < 60$ kHz), which is similar to the plasma potential LRC range observed in other devices. More info in the article [Sar+21a]

Magnetohydrodynamic Mode Identification for Golem Mirnov Coil Signals Using Singular Value Decomposition and Multichannel Variational Mode Decomposition Method for Analyzing Time–Frequency

In this paper, the method to study non-stationary signal characteristics in plasma tokamak using the

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combination of Multichannel Variational Mode Decomposition (MVMD) and Singular Value Decomposition (SVD) is investigated. We have applied this technique directly without any signal preprocessing techniques over the Mirnov coil signals to analyze the magnetic fluctuations produced by the rotating magnetic fields of the plasma in tokamaks. Extraction of Principal axes (PA) and Principal Components (PC) of multichannel Mirnov coil signals are through the singular value decomposition technique. The Multichannel variational mode decomposition technique is provided with a PC matrix to identify the dominant harmonics as K-modes. Finally, the Time–frequency analysis is carried out using Hilbert Transform (HT). The proposed technique handles multichannel Mirnov coil signals in parallel to frequency identification, and also to understand the poloidal structure during current perturbation. Artificially simulated data and Mirnov coil signals from Golem Tokamak aided in testing the proposed technique. In Golem data during the present rise phase, transition happens in the current perturbation from m = 4, poloidal structures to m = 3, and m = 2. The simulated data and Golem tokamak data generated the results of the proposed model. More info in the article [CJ22].

* developing diagnostics for runaway studies.

Progress in HXR diagnostics at GOLEM tokamak

Scintillation detectors are widely used for hard X-ray spectroscopy and allow us to investigate the dynamics of runaway electrons in tokamaks. This diagnostic tool proved to be able to provide information about the energy or the number of runaway electrons. Presently it has been used for runaway studies at the GOLEM and the COMPASS tokamaks. The set of scintillation detectors used at both tokamaks was significantly extended and improved. Besides NaI(Tl) (2 × 2 inch) scintillation detectors, YAP(Ce) and CeBr 3 were employed. The data acquisition system was accordingly improved and the data from scintillation detectors is collected with appropriate sampling rate (≈ 300 MHz) and sufficient bandwidth (≈ 100 MHz) to allow a pulse analysis. Up to five detectors can currently simultaneously monitor hard X-ray radiation at the GOLEM. The same scintillation detectors were also installed during the runaway electron campaign at the COMPASS tokamak. The aim of this contribution is to report progress in diagnostics of HXR radiation induced by runaway electrons at the GOLEM and the COMPASS tokamaks. The data collected during the 12th runaway electron campaign (2020) at COMPASS shows that count rates during typical low-density runaway electron discharges are in a range of hundreds of kHz and detected photon energies go up to 10 MeV (measured outside the tokamak hall). More info in the article [Cer+22]

Detection of runaway electrons at the COMPASS tokamak using a Timepix3-based semiconductor. Detector

Runaway electrons are considered dangerous for the integrity of tokamak vacuum vessels. To secure the success of the future tokamak-based machines, reliable diagnostics and mitigation strategies are necessary. The COMPASS tokamak supported the research of runaway electron physics via regular experimental campaigns. During the last two experimental campaigns dedicated to runaway electrons, a semiconductor detector with a Timepix3 readout chip, Si sensor, and the SPIDR readout system was tested. Time evolution signals, energy measurements, and sensor snapshots collected with the Timepix3-based detector are presented. More info in the article [Kul+22]

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* educational activities

Education and training of students

Experiments related to CRP project triggered bachelor and master thesis at the CTU:
Bachelor projects:

- Jakub Chlum: Implementation of tomographic inversion on the GOLEM tokamak. Defended 2022.

Master thesis:

- Marek Tunkl. XXYY. Defended 2022.
- Filip Papousek: Impact of swept edge plasma potential biasing on turbulence in tokamaks (Under construction)

Overal info about student's projects/contribution at the tokamak GOLEM in the article **Tokamak GOLEM for fusion education - chapter 13** [Mac22a].

Hands-on/ on site tokamak GOLEM projects

- For Students (bachelor level) of the FNSPE CTU in the frame of the Basic experimental laboratory. Back in hands-on mode after COVID pause. March 2022.
- Two projects for extremely skilled high school students: Elena Pumprlová (Effect of working gas pressure on the generation of runaway electrons in the GOLEM tokamak) and Matyas Pokorny (Probe measurements of edge plasma properties at the GOLEM tokamak using a motorised manipulator)

Training of students has also been performed remotely, exploiting a unique feature of the GOLEM tokamak, which can be operated remotely via Internet. Several on-site as well as remote courses were organized in the period 2021 – 2022, among these, major events were:

- Remote practice for Budapest University of Economics and technology, Hungary, November 2021.
- Remote practice for Torino University, Italy, December 2021.
- Remote practice for Eindhoven University, Netherlands, January 2021.
- Remote workshop for Fusion Master gathering on Cadarache, France, February 2022.
- Remote practice for Moscow University, Russia December 2020, March and April 2021.

3. 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):

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.

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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.

4. Activities included in the programme of work which were planned, but were not implemented. Please state reason (i.e.: delays, issues encountered):
   - Persistent problematic pandemic situation.

5. 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):

Main research activities proposed:
The scientific activities continues to focus on the field of plasma edge studies using advanced probe techniques and developing diagnostics for runaway studies.

Education activities proposed:
In the CRP context there are again two planned education activities based on first year experience: GOMTRAIC #2, a week of hands-on experiments at the GOLEM tokamak, and a set of remote participation training courses.

CSI Name and signature: Date: 18.9.2022

Vojtěch Svoboda