

Scientific and Education Activities on the GOLEM Tokamak in the Framework of the IAEA CRP

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on behalf of the tokamak GOLEM team

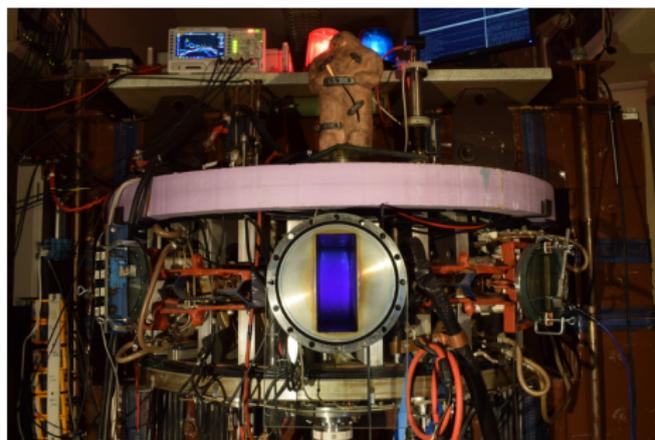
Prague, January 14, 2021

Table of Contents

- 1 Introduction
- 2 Work actually done (selected examples)
- 3 Training events
- 4 Plan for the next period

The GOLEM tokamak basic characteristics

The grandfather of all tokamaks (ITER newslines 06/18)



- Vessel major radius: $R_0 = 0.4$ m
- Vessel minor radius: $r_0 = 0.1$ m
- Maximum plasma current:
 $I_p^{\max} < 8$ kA
- Maximum toroidal magnetic field: $B_t^{\max} < 0.5$ T
- Typical electron density:
 $\langle n_e \rangle \in (0.2, 3) \cdot 10^{19} \text{ m}^{-3}$
- Maximum electron temperature:
 $T_e^{\max} < 80$ eV
- Maximum discharge duration:
 $\tau_p^{\max} < 25$ ms

Objectives in the Framework of the IAEA CRP

- 2.2.14.1. Main research activities proposed:
 - **Plasma edge studies** using advanced probe techniques.
 - Developing **diagnostics for runaway studies**.
- 2.2.14.3. Educational activities:
 - **on-site:** GOMTRAIC, a week of hands-on experiments at the GOLEM tokamak.
 - **remote:** Set of remote participation training courses

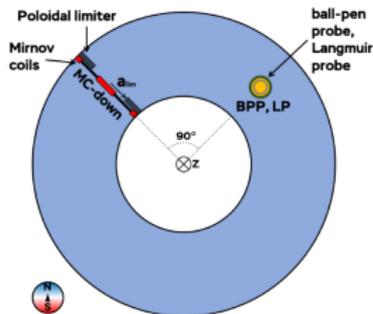
(Golem activities ratio: 20% Research, 80% Education)

Table of Contents

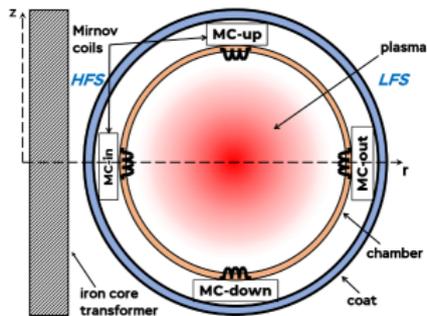
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Hydrogen and Helium Plasmas in the GOLEM Tokamak

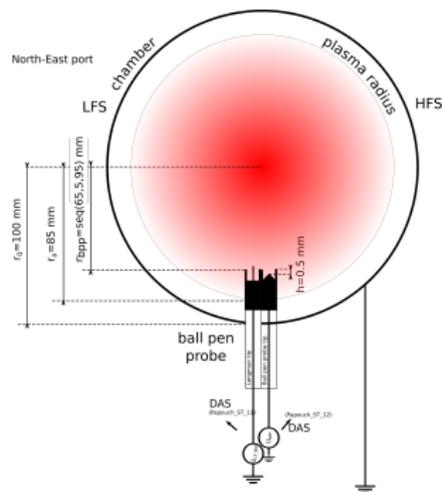
Result of the Training for the National Research Nuclear University "MEPhI", Moscow



Experimental set-up

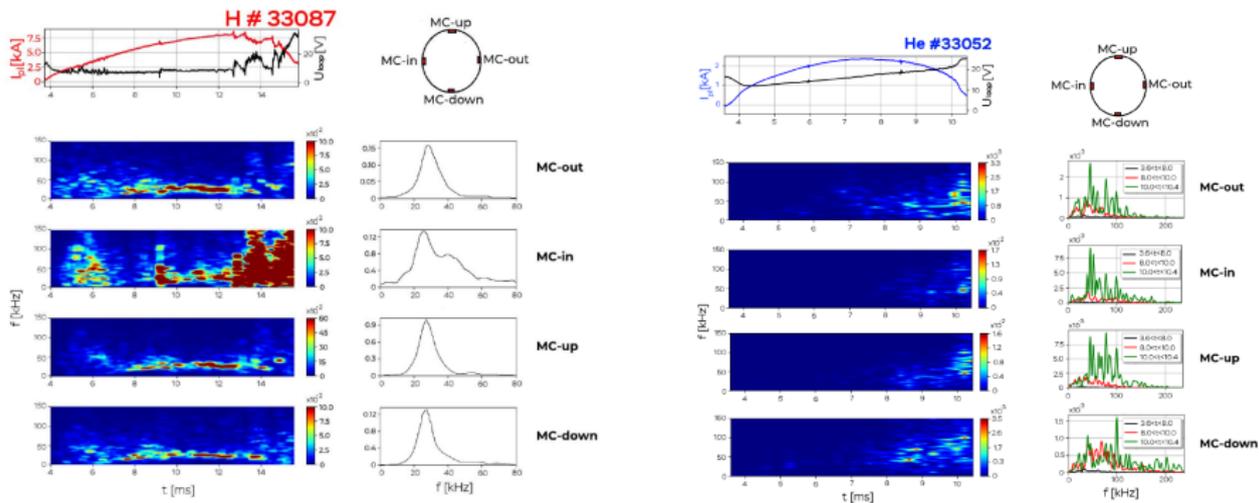


Mirnov coils to measure MHD activity



Ball-pen probe

H and He Plasmas in the GOLEM Tokamak: results

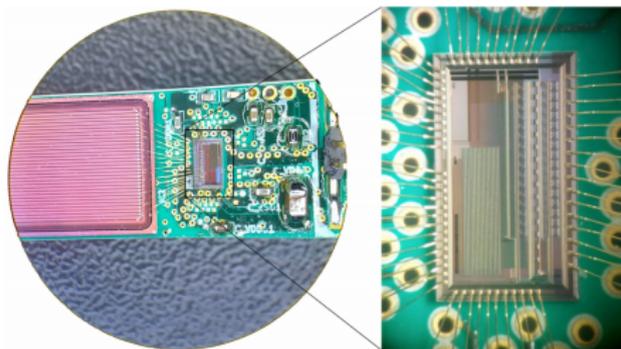


- Plasma scenarios in H and in He in the GOLEM are radically different.
- In hydrogen plasma magnetic instabilities usually occur near the maximum plasma current, that lead to the disruption.
- Helium plasma quietly extinguishes due to the exhaust of the magnetic flux in the primary winding of tokamak transformer.

Runaway electron diagnostics using silicon strip detector

In collaboration with the experimental particle group (diagnostics branch)

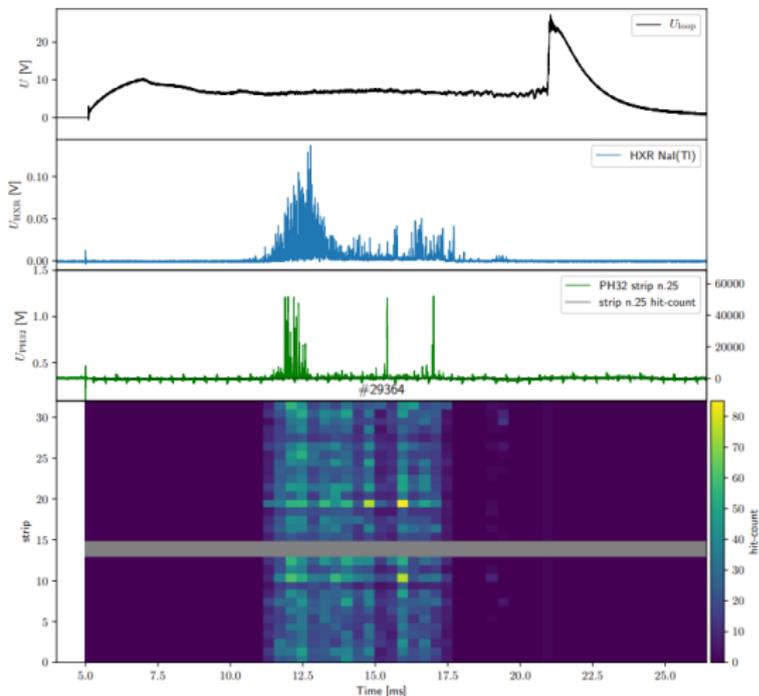
The silicon n^+ -in-p sensor consists of 32 AC coupled $250\text{ }\mu\text{m} \times 18\text{ mm} \times 525\text{ }\mu\text{m}$ strips.



The silicon strip sensor connected to the PH32 readout chip



Runaway electron diagnostics using silicon strip detector



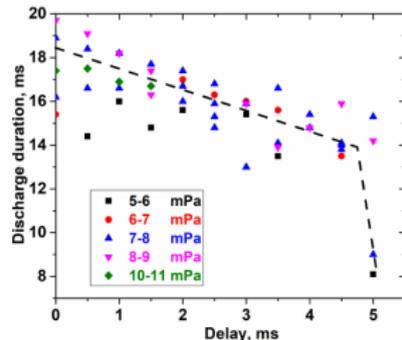
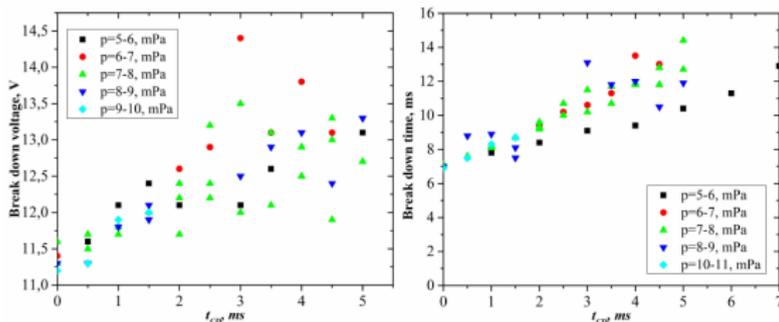
- Loop voltage of plasma discharge.
- HXR scintillation,
- Analog signal voltage in the 25th strip
- Number of hits in all strips.

#29364, the PH32 detector in the LGM collected a number of hits,

Breakdown Phase in The Golem Tokamak

As a result of Training course for the Kharkiv National University

Time delay t_{CD} of triggering Toroidal electric field E_t with respect to triggering Toroidal magnetic field B_t dependences:



- Increasing time delay is followed by an increase of the breakdown voltage and the breakdown time. This may cause an enhanced generation of supra-thermal (runaway) electrons, which is always unwanted effect in tokamaks.
- Increasing time delay leads to the reduction of the discharge duration. A rather dramatic reduction of the discharge duration for the lowest pressures at the time delay ≈ 5 ms is also observed.

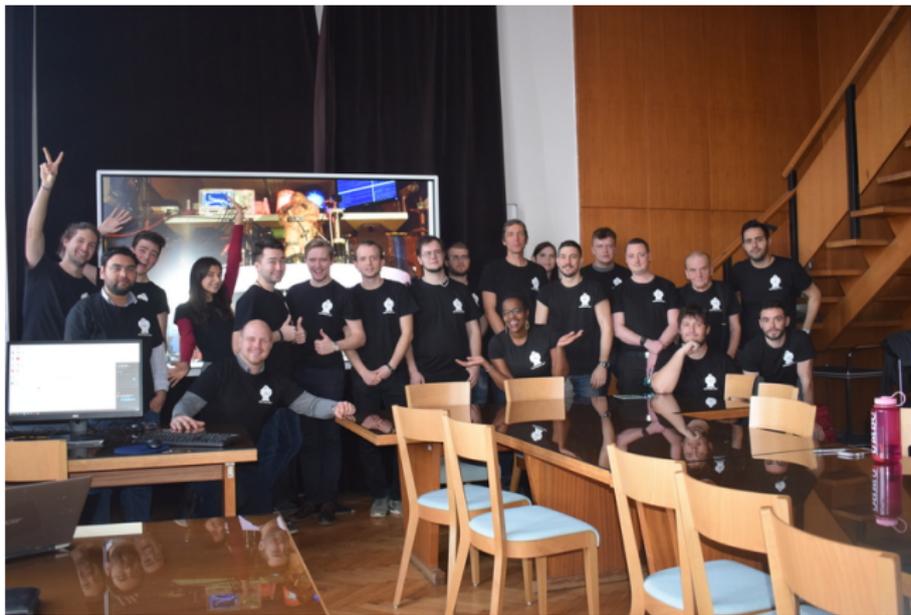
Table of Contents

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GOMTRAIC 2019: 5 -days mini-workshop (March, the 4th - 8th) at the GOLEM tokamak for ~ 15 foreign students.

- Aim of the workshop:
 - Hands-on experience of tokamak operation and learn its basic principles.
 - Learn basic instrumentation of the tokamak operation and diagnostics.
 - Provide working experience with an integrated tokamak facility.
- Tasks for the workshop
 - (All) Hands-On measurements of plasma basic parameters.
 - (3 students) Study of runaway electrons in GOLEM tokamak.
 - (3 students) Plasma position control by vertical stabilization.
 - (3 students) Plasma Turbulence characterization with probes.
 - (3 students) Temperature measurement by ball-pen probe.
 - (3 students) Density measurements by microwave interferometer.
- Programme:
 - Mo: Introductory talks, the GOLEM tokamak visit.
 - Tue: Basic hands-on experience with tokamak operation
 - Wed: Tasks based experiments and data analysis
 - Thu: The COMPASS tokamak visit. Preparation of presentation by participants.
 - Fri: Presentations by participants.

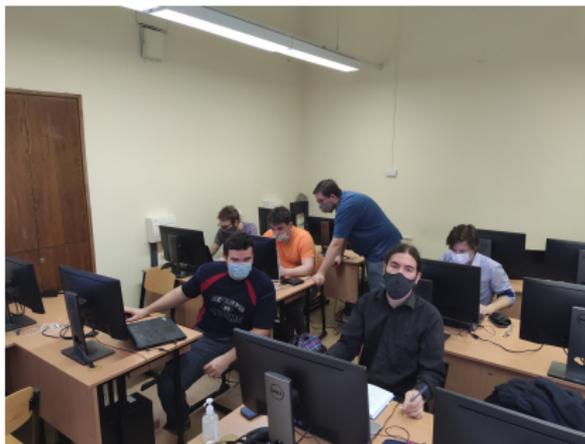
GOMTRAIC: Friday - final photo (after presentations)



Students:

- 2x Russia
- 3x Ukraine
- 2x Portugal
- 2x USA
- 1x Hungary
- 1x Slovenia
- 1x Italy
- 1x Belgium
- 2x Serbia
- 1x Iran

Remote training courses 10/2018-01/2021 inventory



C#19 version (Budapest BUTE University, November 2020)

i) 8th IWSSPP workshop, Kiten, Bulgaria, 12 June 2018, ii) Budapest University of Economics and technology, Hungary 19th, November 2018, iii) Padova University, Italy 23rd, November 2018, iii) Prince of Songkla University, Thailand, November 2018, iv) Eindhoven University, Netherlands 18th, December 2018, v) Torino University, Italy 20th, December 2018, vi) 5th ASEAN School on Plasma and Nuclear Fusion, 21-25 Jan 2019, Mahidol University, Thailand, vi) Fusion Master gathering in Cadarache, France 19th, February 2019, vii) Charkov University, Ukraine 13th, March 2019, viii) demo from ASDEX tokamak, Germany 25th, March 2019, ix) Moscow University, Russia 9th, April 2019, xi) Budapest University of Economics and technology, Hungary, offline, xii) Eindhoven University, Netherlands 14th, January 2020, xiii) Torino University, Italy 15th, January 2020, xiv) 6th ASEAN School on Plasma and Nuclear Fusion, 30th, January 2020, Thailand, xv) Moscow University, Russia 27th, May 2020. xvi) Budapest University of Economics and technology, Hungary 24th, November 2020, xvii) 9th IWSSPP workshop, Kiten, Bulgaria, 3rd December 2020, xviii) MIPT Moscow University 15th December 2020, xix) Torino University, Italy 17th, December 2020, xx) Eindhoven Technical University, Netherlands 5th, January 2021.

New level of remote training: ... with publication on the horizon.

- Workshop "Kiten 2018" : Operational Domain in Hydrogen Plasmas on the GOLEM Tokamak. Journal of Fusion Energy (2019) 38:253–261.
- Training course for the Kharkiv National University: Breakdown Phase in The Golem Tokamak and its Impact on Plasma Performance. Ready for publishing in Ukraine J. Phys.
- Training for the National Research Nuclear University "MEPhI", Moscow: Hydrogen and Helium Plasmas in the GOLEM Tokamak. Almost ready for publishing.

Training courses - pandemic set-up

- Tokamak operator at the Golem tokamak
- Local student's tutors at their home/labs/offices.
- Students at their homes.
- + up to 3 czech PhD students (familiar with the GOLEM tokamak) ready to guide or assist with everything concerning tokamak GOLEM
- Students in a certain number of groups each having its own videoconference room and a tokamak controll room.



C#19 version (Torino Technical University, December 2020)

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Plans (adapted for remote regimes)

(step forward to the integral experiments)

- 2.2.14.1. Main research activities proposed:
 - Plasma edge studies using advanced probe techniques.
 - Measurement with double rake electrostatic probe to find the position of the velocity shear layer (VSL).
 - Operational domains of the GOLEM tokamak.
 - Physics of the plasma edge column with a focus on determining and comparing the position of the plasma edge by electrostatic, magnetic and radiation measurement methods.
 - Isotopic studies cont. with Sasha et al.
 - Ion temperature measurement.
 - Developing diagnostics for runaway studies.
 - Integral experiments focused on the behavior of runaway electrons, where a wide range of different types of HXR probes will be involved: scintillation, medipix, timepix, calorimetric and strip detectors.
- 2.2.14.3. Education activities:
 - GOMTRAIC 2021, a week of hands-on experiments at the GOLEM tokamak (maybe remote version).
 - Set of remote participation training courses (developing pandemic set-up)

Relevant References I

- Dhyani, P., Svoboda, V., Istoksaia, V., Mlynář, J., Cerovský, J., Ficker, O., Linhart, V. (2019). Design and development of probe for the measurements of runaway electrons inside the golem tokamak plasma edge. volume 2019-July of *Europhysics conference abstracts*, page P1.1016.
- Grover, O., Svoboda, V., and Stockel, J. (2019a). Online experimentation at the golem tokamak. In *2019 5th Experiment International Conference (exp.at'19)*, pages 220–225.
- Grover, O., Svoboda, V., and Stockel, J. (2019b). Remote demonstration of the golem tokamak. In *2019 5th Experiment International Conference (exp.at'19)*, pages 239–240.
- GRYAZNEVICH, M., STÖCKEL, J., OOST, G. V., BOSCO, E. D., SVOBODA, V., MELNIKOV, A., KAMENDJE, R., MALAQUIAS, A., MANK, G., MIKLASZEWSKI, R., and and (2020). Contribution of joint experiments on small tokamaks in the framework of IAEA coordinated research projects to mainstream fusion research. *Plasma Science and Technology*, 22(5):055102.
- Kulkov, S., Mácha, P., Istoksaia, V., Kropáčková, D., Papoušek, F., Adámek, J., Cerovský, J., Ficker, O., Grover, O., Jiráková, K., Stöckel, J., Svoboda, V. (2019). Tokamak golem for fusion education - chapter 10. volume 2019-July of *Europhysics conference abstracts*, page P1.1068.
- Linhart, V., Bren, D., Casolari, A., Čerovský, J., Farník, M., Ficker, O., Hetflejš, M., Hron, M., Jakůbek, J., Kulhánek, P., Macůšová, E., Marčíšovský, M., Mlynář, J., Švihra, P., Svoboda, V., Urban, J., Varju, J., and Vrba, V. (2018). 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)*, pages 1–9.
- Novotny, L., Cerovsky, J., Dhyani, P., Ficker, O., Havranek, M., Hejtmanek, M., Janoska, Z., Kafka, V., Kulkov, S., Marcisovska, M., Marcisovsky, M., Neue, G., Svihra, P., Svoboda, V., Tomasek, L., Tunkl, M., and Vrba, V. (2020). Runaway electron diagnostics using silicon strip detector. *Journal of Instrumentation*, 15(07):C07015–C07015.
- P. Dhyani and V. Svoboda and V. Istoksaia and J. Mlynar and J. Cerovsky and O. Ficker and V. Linhart (2019). Study of runaway electrons in GOLEM tokamak. *Journal of Instrumentation*, 14(09):C09029–C09029.
- Svoboda, V., Zhekova, M., Dimitrova, M., Marinova, P., Podolník, A., and Stockel, J. (2019). Operational domain in hydrogen plasmas on the golem tokamak. *Journal of Fusion Energy*.