The GOLEM tokamak bibliography

The tokamak GOLEM team

January 8, 2024

Official GOLEM Articles

Abbasi et al.: Plasma diagnostics using fast cameras at the GOLEM tokamak **AbbasiFUSENGDES23**

S. Abbasi et al. "Plasma diagnostics using fast cameras at the GOLEM tokamak". In: *Fusion Engineering and Design* 193 (2023), p. 113647. ISSN: 0920-3796. DOI: https://doi.org/10.1016/j.fusengdes.2023.113647. URL: https://www.sciencedirect.com/science/article/pii/S0920379623002302.

Abstract: Tomographic inversion of radiation determines spatial distribution of tokamak plasma radiation sources using line integrated plasma projections data. For measurements of the projections, fast visible radiation matrix cameras became broadly applied on tokamaks in recent past. These novel cameras opened new possibilities in high temperature plasma studies. The GOLEM tokamak of the Czech Technical University in Prague strives to implement up-to-date diagnostics with enhanced temporal and spatial resolution. Therefore, a novel diagnostic system of two crossed monochrome cameras Photron FASTCAM MINI UX50 was integrated into the GOLEM diagnostics. The proposed contribution will detail their novel port mounts (vertical and horizontal) at the GOLEM tokamak which have been designed so that additional optical measurements of the plasma core (e.g. plasma spectroscopy) is possible. As the main purpose of this study, we shall focus in particular on the frame rate potential which is high enough to make detection and observation of highly transient phenomena in the GOLEM plasmas possible. Progress in solving specific challenges of the ill-conditioned tomographic inversion via the algorithm optimization and testing for the GOLEM tokamak will be presented together with the first tomographic results.

Mácha et al.: Spontaneous formation of a transport barrier in helium plasma in a tokamak with circular configuration **Macha-2023-NuclFus**

Petr Mácha et al. "Spontaneous formation of a transport barrier in helium plasma in a tokamak with circular configuration". In: *Nuclear Fusion* (Aug. 2023). DOI: 10.1088/1741-4326/acf1af.

Abstract: We report on the first experimental observation of a spontaneously formed transport barrier in the tokamak with a circular configuration in helium plasmas. There was no external polarization of the plasma by electric field or other technique to form the barrier as it is typically used in tokamaks with circular plasma. In general, the transport barriers play an important role in plasma confinement especially in tokamaks with divertor configuration. In our experiments, we clearly observe distinct characteristics of a transport barrier, including a steep gradient of the electron temperature and an enhanced radial electric field along with the change in the plasma potential, floating potential, and electron temperature fluctuation. The electron temperature and the plasma potential are obtained by a combination of the ball-pen and Langmuir probe measurements with high temporal resolution on a shot-to-shot basis. This first experimental observation of the spontaneously formed transport barrier might bring new possibilities to obtain a fusion-relevant study of the edge plasma parameters and transport in helium plasmas even on small tokamaks.

Pokorny et al.: Magnetic field simulations of the GOLEM tokamak via the NICE code **Pokorny-2023-JABS**

M. Pokorny, P. Macha, and V. Svoboda. "Magnetic field simulations of the GOLEM tokamak via the NICE code". In: *Journal of the ASB Society* (2023), pp. 26–34. DOI: 10.51337/JASB20231206003.

Abstract: In this paper, the direct and inverse equilibrium computation mode of the NICE code is put into operation for the case of the GOLEM tokamak. This enables, for the first time, simulations of GOLEM's magnetic field. The computation mode put into operation simulates the magnetohydrodynamic equilibrium of a tokamak plasma based on a given plasma position or given currents in poloidal magnetic field coils. In order to set up NICE, a virtual model of GOLEM is introduced that includes axially symmetrical approximations of GOLEM's iron core and primary transformer coils. The results of NICE simulations are compared with experimental measurements, and it is shown that NICE simulations produce plasma equilibrium configurations typical for GOLEM. Nevertheless, a more detailed validation of GOLEM's virtual model and of the results of NICE simulations is to be performed in the future.

Sarancha et al.: Remote Plasma Physics Research and Teaching by Example of Turbulence Study at the University-Scale Tokamak GOLEM **Sarancha-2023-FST**

G. Sarancha et al. "Remote Plasma Physics Research and Teaching by Example of Turbulence Study at the University-Scale Tokamak GOLEM". In: *Fusion Science and Technology* 79.4 (2023), pp. 432–445. DOI: 10.1080/15361055.2022.2148842. eprint: https://doi.org/10.1080/15361055.2022.2148842. URL: https://doi.org/10.1080/15361055.2022.2148842.

Abstract: AbstractThe university-scale tokamak GOLEM provides a unique opportunity to perform remote thermonuclear experiments [V. Svoboda, J. Fusion Energy, Vol. 38, Part 2, p. 253 (2019)]. Undergraduate plasma physics students from three universities—Moscow Institute of Physics and Technology (National Research University), RUDN University, and National Research Nuclear University MEPhI—carried out joint remote experiments to train in tokamak operation and to study topics relevant for mainstream fusion research such as plasma start-up, comparison of hydrogen versus helium plasma characteristics, electrostatic and electromagnetic turbulence, long-range correlations, etc. New observations of the long-range correlations between low-frequency (¡50 kHz) quasi-coherent electrostatic and magnetic oscillations identified as m = 2 mode with several techniques were done, as well as of the broadband (¡250 kHz) magnetic oscillations resolved in frequency and wave vector in helium and hydrogen plasmas. The presence of broadband electrostatic and broadband magnetic turbulence has also been established at the plasma edge.

Cerovsky et al.: Progress in HXR diagnostics at Golem and COMPASS tokamaks **CerovskyJINST22**

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. URL: https://doi.org/10.1088/1748-0221/17/01/c01033.

Abstract: 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 x 2 inch) scintillation detectors, YAP(Ce) and CeBr3 were employed. The data acquisition system was accordingly improved and the data from scintillation detectors is collected with appropriate sampling rate (approx. 300 MHz) and sufficient bandwidth (approx. 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). Acquired data from experimental campaigns from both machines will be discussed.

Kulkov et al.: Detection of runaway electrons at the COMPASS tokamak using a Timepix3-based semiconductor detector **KulkovJINST22**

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. URL: https://doi.org/10.1088/1748-0221/17/02/p02030.

Abstract: 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.

Conference proceedings

Cerovsky et al.: Runaway electron studies via HXR spectroscopy at Golem, COMPASS and TCV **CerovskyECPD23**

J. Cerovsky et al. "Runaway electron studies via HXR spectroscopy at Golem, COMPASS and TCV". In: *European Conference on Plasma Diagnostics*. Rethymno, Apr. 2023. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Conferences/ECPD/5th_Rethymno_2023/poster.pdf.

Abstract: The research on runaway electrons in tokamaks continues to be important for safe and reliable operation of large fusion devices due to the potential risk of impact of so called runaway electron beams on plasma facing components which could cause a serious damage and lead to putting the machine out of operation. In order to investigate the properties of runaway electrons and provide useful information about their behavior under different experimental conditions (e.g. efficiency of various mitigation techniques or exploration of runaway electrons free regimes) many dedicated diagnostics has been utilized. One way of inferring features of runaway electrons is a measurement of their bremsstrahlung radiation which is generated by collisions with plasma ions or by their impact on the first wall when runaway electrons are deconfined and lost. Recently, diagnostic capabilities at GOLEM [1] were upgraded by installation of two scintillation detectors with CeBr3 crystals (1" x 1"), which were also successfully tested during the dedicated runaway electron campaigns at the COMPASS tokamak [2]. Moreover, both scintillation detectors were also installed at the TCV tokamak to extend for the first time the hard x-ray radiation diagnostics and provide an estimates of the maximal energy of runaway electrons. The aim of this contribution is to describe the diagnostic used and experimental conditions of the different devices. Additionally, illustrative examples of experiments from these three different devices are presented and acquired data by the diagnostic system for HXR spectroscopy is discussed and put into the context. The comparison with other relevant diagnostics is shown. At the GOLEM tokamak the spectroscopy system was used to observe the influence of the initial pressure of the working gas and maximal energy of HXR photons was estimated about 300 keV. On the other hand at the COMPASS tokamak

[3], the data recorded in experiments focused on characterizing runaway electron beams properties and the efficiency of various mitigation techniques (e.g. graphite pellet injection). At TCV [4], the installed set of scintillation detectors proved to be useful as a source of complementary information to standard radiation diagnostics and helped to characterized generated runaway electrons beams. This contribution also briefly shows a progress in modeling the radiation transport using FLUKA [5], carried out in order to better interpret the obtained data.

Chlum et al.: Tokamak GOLEM for fusion education - chapter 14 **ChlumECPP23**

J. Chlum et al. "Tokamak GOLEM for fusion education - chapter 14". In: vol. July. Europhysics conference abstracts. 2023.

Ivanov et al.: Runaway electrons measurements by ECE on the GOLEM tokamak **IvanovECPP23**

V. Ivanov et al. "Runaway electrons measurements by ECE on the GOLEM tokamak". In: vol. July. Europhysics conference abstracts. 2023.

Macha et al.: Self-induced transport barrier in the helium plasma on the tokamak Golem **MachaEPS22-a**

P. Macha et al. "Self-induced transport barrier in the helium plasma on the tokamak Golem". In: vol. July. Europhysics conference abstracts. 2022. URL: https://indico.fusenet.eu/event/28/contributions/64/attachments/78/1153/EPS_2022_article.pdf.

Abstract: 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.

Macha et al.: Tokamak Golem for fusion education - chapter 13 **MachaEPS22-b**

P. Macha et al. "Tokamak Golem for fusion education - chapter 13". In: vol. July. Europhysics conference abstracts. 2022. URL: https://indico.fusenet.eu/event/28/contributions/164/attachments/178/1152/EPS_2022_golem_article.pdf.

Abstract: The contribution is devoted to the description of several students projects, related mainly to edge plasma diagnostics, investigation of selected issues of tokamak physics and plasma performance on the GOLEM tokamak, particularly: i) Plasma stabilization, ii) A research on runaway electrons (RE) physics, iii) Plasma edge studies with electrostatic probes and iv) Tomography.

Master thesis

S. Malec: Compton camera for detection of hard X-rays produced on the Golem tokamak **MalecMT23**

S. Malec. "Compton camera for detection of hard X-rays produced on the Golem tokamak". Master Thesis. 2023. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/23MalecStepan.pdf.

Abstract: This master's thesis deals with the creation of a Compton camera to detect hard X-rays on the Golem tokamak. First, simple simulations demonstrating the functionality of a single- and two-sensor Compton camera are introduced. The thesis further describes the correction of sub- mitted AdvaPix Timepix3 detectors to a phenomenon called timewalk and to cali- bration to determine the depth of interactions in sensors. The main result is that a single-sensor Compton camera with a CdTe 2 mm thick sensor shows the best results.

M. Tunkl: Development of a new runaway electron diagnostics method based on strip semiconductor detectors **TunklMT22**

M. Tunkl. "Development of a new runaway electron diagnostics method based on strip semiconductor detectors". Master Thesis. 2022. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/22TunklMarek.pdf.

Abstract: In this master's thesis, new diagnostics of runaway electrons on the GOLEM tokamak were developed. First, a simulation in the Geant4 toolkit was created to evaluate the effect of the backscattering of the runaway electrons from the limiter. Then, a silicon-based strip detector probe was designed and constructed with respect to the simulation result. Finally, the measured data were analyzed and compared to the relevant diagnostics and simulation results. Furthermore, a new scintillation detector was constructed from a silicon photomultiplier and a LYSO crystal. The signal from the silicon photomultiplier exhibited good characteristics. Even with multiple superimposed peaks, it was possible to reconstruct their original height and thus obtain the hard X-ray spectrum of the entire plasma discharge.

Bachelor projects

Jan Buryanec: Stabilizace proudu plazmatem na tokamaku Golem **Buryanec-2023-BachProj**

Jan Buryanec. "Stabilizace proudu plazmatem na tokamaku Golem". Bachelor project. 2023. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/23BuryanecJan.pdf.

Abstract: This thesis deals with the stabilization of plasma current on tokamak GOLEM. In the theoretical part, the nuclear fusion and the realization of a fusion reactor in the terrestrial environment is presented. Next, the technologies used on tokamak GOLEM are described and a research of present generation of plasma current and its possible improvements via the implementation of the KEPCO am- plifier on the transformer core are done. In the next part, the laboratory table-top experiment simulating the generation of a plasma current is constructed together with its numerical simulations. For simplification, the vacuum discharge was used. After the table-top experiment proved the simulations right, the calculations for one KEPCO are done and then, the sole implementation for tokamak GOLEM. In the end, the testing of a stabilization of current for a given implementation is made and then, the discussion of a number of KEPCO amplifiers and its effects is done.

M. Vanakova: Studium oscilací magnetického pole na tokamaku Golem **Vanakova-2023-BachProj**

M. Vanakova. "Studium oscilací magnetického pole na tokamaku Golem". Bachelor project. 2023. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/23VanakovaMarie.pdf.

Abstract: This bachelor's thesis deals with tokamak magnetic field configuration. It focuses on the poloidal magnetic field, which was studied on the GOLEM tokamak. It also presents the safety factor, a parameter defining tokamak magnetic field properties and characterising particular discharge. The poloidal magnetic field was measured by means of an array of sixteen Mirnov coils for several tokamak discharges with various plasma edge safety factor values. Measured data was analysed by statistical methods: Fast Fourier Transformation and Cross-correlation analysis. The presence of magnetic field instabilities (magnetic islands) was observed.

J. Chlum: Implementation of tomographic inversion on the Golem tokamak. **ChlumBP22**

J. Chlum. "Implementation of tomographic inversion on the Golem tokamak." Bachelor project. 2022. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/22ChlumJakub.pdf.

Abstract: The topic of this bachelor's thesis is visible light tomography of tokamak plasma and its implementation on the GOLEM tokamak. The thesis includes a theoretical summary of radiation processes in tokamak plasmas in the visible spectrum. The thesis then summarises the principles of the tomography inversion task and its solution with emphasis on the minimum Fisher Tikhonov regularization algorithm used here. The practical part of the thesis includes the calibration of two fast cameras for the their use both on the tokamak and separately. The calibration was tested by the tomographic inversion of a known emissivity profile. Finally, the tomography was tested on experimental data from the GOLEM tokamak. Its limitations and errors were discussed and options for futher development were suggested.

High School Students' Professional Activities

M. Pokorný: Měření a simulace polohy plazmatu na tokamaku GOLEM **pokorSOC23**

M. Pokorný. "Měření a simulace polohy plazmatu na tokamaku GOLEM". High School Students' Professional Activities SOČ. 2023. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/23PokornyPolohaPlazmatu.pdf.

Abstract: The first part of this work focuses on plasma position measurement, the second on its simulation. In the first part, we compare all available plasma position diagnostics at the GOLEM (CTU FNSPE) tokamak, i.e., Mirnov coils, a ball-pen probe, and a high-speed camera. Mirnov coils and high-speed camera data were mostly in accord; the plasma boundary is more clearly defined in the case of Mirnov coils, the camera registers visible plasma radiation in the order of 1 mm beyond the real plasma boundary. Ball-pen probe and camera data mostly weren't in accord; the ball-pen probe is effective only in the case of local plasma boundary measurement. On the basis of our comparison we recommend: Mirnov coils usage is appropriate when conducting a detailed plasma position analysis, ball-pen probe usage is appropriate for local measurements, and high-speed camera usage is appropriate for quick but imprecise measurements. In the second part of the work, we put into operation the static inverse and static direct regimes of the NICE code (B. Faugeras, 2020) for the GOLEM tokamak. For this intent, a virtual GOLEM model is created, which makes use of the toroidally symmetrical iron core model presented in (T. Markovič, 2013). It is shown, on the basis of measurement and NICE simulation comparison, that the value of magnetic induction running through the real and virtual iron cores differs by a factor of approximately 2. Regimes that have been put into operation are illustrated with concrete simulations, and it is shown that their results are in accordance with typical GOLEM plasma configurations. For quick and easy usage of these regimes, a graphical user interface is created.

E. Pumprlová: Vliv tlaku pracovního plynu na generaci ubíhajících elektronů v tokamaku Golem. **pumprSOC**

E. Pumprlová. "Vliv tlaku pracovního plynu na generaci ubíhajících elektronů v tokamaku Golem." High School Students' Pro-

fessional Activities SOČ. 2022. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/22PumprlovaRunaaways.pdf.

Abstract: This study investigates how working gas pressure affects the generation of runaway electrons in the tokamak Golem. The aim is to describe this relationship and the course of runaway electron generation in tokamak. The theoretical framework of this study inquiries into the topic of runaway electrons, the practical part tests a hypothesis: in low pressure plasma the number of runaway electrons is going to be greater than in plasma of higher pressure. The experimental part also includes the data analysis, which portrays the course of generation of runaway electrons. Scintillation detectors were used to collect the data, the analysis of values measured was conducted in the programming language Python. The experiment confirmed the hypothesis and the results opened new subjects to study more closely.

M. Pokorný: Sondová měření parametrů okrajového plazmatu na tokamaku Golem s pomocí motorizovaného manipulátoru **pokorSOC22**

M. Pokorný. "Sondová měření parametrů okrajového plazmatu na tokamaku Golem s pomocí motorizovaného manipulátoru". High School Students' Professional Activities SOČ. 2022. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/22PokornyProbes.pdf.

Abstract: This SOC thesis focuses on the measurement of edge plasma parameters using electrical probes at the Golem tokamak. In the theoretical part of the work, a basis for understanding plasma and its behavior is given and some general principles of thermonuclear fusion and tokamaks are presented. Finally, a theoretical basis for the measurement of edge plasma parameters by electrical probes is provided with an accent on the double tunnel probe. The practical part of the work first focuses on the process of putting into operation a new motorized probe manipulator and its application at the Golem tokamak. Moreover, the course and results of experimental measurements with the double tunnel probe are presented. Within two discharge series, we were able to measure axial profiles of ion saturated current thanks to the new motorized manipulator. Firstly, a calibration of the probe was done and axial profiles of ion saturated current were measured. Afterwards, measurements and calculations of parallel and perpendicular components of the Mach number of plasma rotation were performed. Furthermore, the time dependence of the parallel component of the Mach number in a parallel probe orientation to magnetic field lines was measured. Finally, two methods of calculation of the Mach number related to the axial profiles of ion saturated current were compared. The data received from ion saturated current axial profiles and Mach number measurements is in accordance with the results of multiple articles related to this topic.

Miscellaneous

Unofficial articles (without GOLEM cooperation/authors)

Chandrasekaran et al.: Magnetohydrodynamic Mode Identification for Golem Mirnov Coil Signals Using Singular Value Decomposition and Multichannel Variational Mode Decomposition Method for Analyzing Time-Frequency **ChandrasekarJFE22**

J. Chandrasekaran and S. Jayaraman. "Magnetohydrodynamic Mode Identification for Golem Mirnov Coil Signals Using Singular Value Decomposition and Multichannel Variational Mode Decomposition Method for Analyzing Time-Frequency". In: *Journal of fusion energy* 41.2 (2022). ISSN: 0164-0313. DOI: 10.1007/s10894-022-00329-5.

Abstract: In this paper, we have investigated the method to study non-stationary signal characteristics in plasma tokamak using the combination of Multichannel Variational Mode Decomposition (MVMD) and Singular Value Decomposition (SVD). 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. The article also compared this with other existing signal decomposition techniques.