The GOLEM tokamak bibliography

The tokamak GOLEM team

March 12, 2025

Official GOLEM Articles

Abbasi et al.: Artificial Neural Network-Based Tomography Reconstruction of Plasma Radiation Distribution at GOLEM Tokamak **Abbasi-2024-JOFE**

S. Abbasi et al. "Artificial Neural Network-Based Tomography Reconstruction of Plasma Radiation Distribution at GOLEM Tokamak". In: *Journal of Fusion Energy* 43.2 (2024), p. 64. ISSN: 1572-9591. DOI: 10.1007/s10894-024-00458-z. URL: https://doi.org/10.1007/s10894-024-00458-z.

Abstract: The paper presents an artificial neural network-based model for tomography reconstruction of visible plasma radiation distribution at the GOLEM tokamak. The model was trained using a dataset from emissivity phantoms and associated synthetic measurements from a poloidal cross-section of the GOLEM tokamak. The model validation was performed on the prediction of various unseen phantom samples with shapes similar to those in the training dataset. The backfit of line-integrated measurements indicates the considerable potential of the proposed model for reconstructing the position, size, shape and intensity of the radiation function of one cross section. Additionally, the neural network-based model offers a significantly shorter prediction time compared to traditional tomography methods, providing a substantial advantage.

Dimitrova et al.: Plasma properties in the vicinity of the last closed flux surface in hydrogen and helium fusion plasma discharges **Dimitrova-2024-PPCF**

M Dimitrova et al. "Plasma properties in the vicinity of the last closed flux surface in hydrogen and helium fusion plasma discharges". In: *Plasma Physics and Controlled Fusion* 66.7 (2024), p. 075022. DOI: 10.1088/1361-6587/ad5377. URL: https://dx.doi.org/10.1088/1361-6587/ad5377.

Abstract: The origin of the bi-Maxwellian electron energy distribution function (EEDF) observed in the scrape-off layer (SOL) of tokamak plasmas by means of Langmuir probes is still under discussion. It has been assumed that the ionization of hydrogen and deuterium neutrals by thermal electrons penetrating the SOL from the bulk plasma is the main reason for the appearance of a second Maxwellian. To validate this assumption, radial measurements of the electron temperatures and densities, or the plasma properties in helium plasmas in the GOLEM tokamak and the TJ-II stellarator were performed. The radial profiles of the low-temperature electron group densities follow the trend of the calculated radial profiles of the electron sources arising from the ionization of neutrals in both deuterium and helium plasmas in TJ-II. The difference in the radial location where the bi-Maxwellian EEDF appears can be explained by the difference in the rate coefficients for ionization of deuterium and helium. The results of probe measurements in GOLEM and the WEST tokamak divertor, at one radial location in the SOL, are compatible with the hypothesis concerning the ionization of neutral atoms and the type of the EEDF.

Abbasi et al.: Plasma diagnostics using fast cameras at the GOLEM tokamak **Abbasi-2023-FUSENGDES23**

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.

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

M. Pokorný, P. Mácha, and V. Svoboda. "Magnetic field simulations of the GOLEM tokamak via the NICE code". English. In: *Journal of the Abs Society* (2023). URL: https://www.journalasb.com/jasb2023vol4issue1/no3/.

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 **Cerovsky-2022-JINST**

J. Cerovsky et al. "Progress in HXR diagnostics at Golem and COMPASS tokamaks". In: *Journal of Instrumentation* 17.01 (Jan. 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 **Kulkov-2022-JINST**

S. Kulkov et al. "Detection of runaway electrons at the COMPASS tokamak using a Timepix3-based semiconductor detector". In: *Journal of Instrumentation* 17.02 (Feb. 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.

Sarancha et al.: Magnetic turbulence and long-range correlation studies in the Golem tokamak **Sarancha-2021-JPCS**

G Sarancha et al. "Magnetic turbulence and long-range correlation studies in the Golem tokamak". In: *Journal of Physics: Conference Series* 2055.1 (Oct. 2021), p. 012003. DOI: 10.1088/1742-6596/2055/1/012003. URL: https://doi.org/10.1088/1742-6596/2055/1/012003.

Abstract: 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.

Sarancha et al.: Hydrogen and helium discharges in the Golem tokamak **Sarancha-2021-VANT**

G.A. Sarancha et al. "Hydrogen and helium discharges in the Golem tokamak". In: *Problems Of Atomic Science And Technology, Ser. Thermonuclear Fusion* 4 (2021), pp. 92–110. DOI: 10.21517/0202-3822-2021-44-4-92-110. URL: https://doi.org/10.21517/0202-3822-2021-44-4-92-110.

Abstract: The helium plasma properties and confinement remain an important area of research in modern fusion devices. This work is dedicated to the helium plasma initiation and control in a small-scale tokamak Golem compared to hydrogen plasma. Helium and hydrogen plasmas are comprehensively compared and the optimum operational conditions for the start-up are found. Long-range correlations between lowfrequency (¡50 kHz) electrostatic and magnetic oscillations are found, as well as broadband (< 250 kHz) magnetic oscillations resolved in frequency and wave vector in helium plasma.

Siusko et al.: Breakdown phase in the Golem tokamak and its impact on plasma performance **Siusko-2021-UJP**

Y. Siusko et al. "Breakdown phase in the Golem tokamak and its impact on plasma performance". In: *Ukrainian Journal of Physics* 66.3 (2021), pp. 231–239. URL: https://ujp.bitp.kiev.ua/index.php/ujp/article/view/2020180.

Abstract: The effect of the breakdown phase on subsequent plasma parameters was investigated remotely in Golem tokamak. The dependence of breakdown voltage and the breakdown time versus the time delay between the trigger of the toroidal magnetic field B t and the trigger of toroidal electric field E t for different groups of the pressure magnitudes is built. The performed ex- periments have shown that for Golem tokamak the shorter is temporal delay - the better mean plasma parameters are obtained. In addition, the breakdown phase was discussed more detailed. In the discussion the analysis of the avalanche phase of the breakdown was made. The dominant mechanism of particle loses during avalanche phase, future steps, tasks were discussed and set.

Gryaznevich et al.: Contribution of joint experiments on small tokamaks in the framework of IAEA coordinated research projects to mainstream fusion research **Gryaznevich-2020-PST**

M. Gryaznevich et al. "Contribution of joint experiments on small tokamaks in the framework of IAEA coordinated research projects to mainstream fusion research". In: *Plasma Science and Technology* 22.5 (Mar. 2020), p. 055102. DOI: 10.1088/2058-6272/ab6d4d. URL: https://doi.org/10.1088%2F2058-6272%2Fab6d4d.

Abstract: Joint experiments (JEs) on small tokamaks have been regularly performed between 2005 and 2015 under the framework of the International Atomic Energy Agency (IAEA) coordinated research projects (CRPs). This paper describes the background and the rationale for these experiments, how they were organized and executed, main areas of research covered during these experiments, main results, contributions to mainstream fusion research, and discusses lessons learned and outcomes from these activities. We underline several of the most important scientific outputs and also specific outputs in the education of young scientists and scientists from developing countries and their importance.

Novotny et al.: Runaway electron diagnostics using silicon strip detector **Novotny-2020-JINST**

L. Novotny et al. "Runaway electron diagnostics using silicon strip detector". In: *Journal of Instrumentation* 15.07 (July 2020), p. C07015. DOI: 10.1088/1748-0221/15/07/c07015. URL: https://doi.org/10.1088%2F1748-0221%2F15%2F07%2Fc07015.

Abstract: We present a proof-of-principle measurement of runaway electrons in a small tokamak using a silicon strip detector. The detector was placed inside the diagnostic port of the tokamak vessel and detected the runaway electron signal directly. The measured signal was compared to the signal provided by other tokamak diagnostics, especially the hard X-ray scintillation detector, which detects secondary photons created by interaction of accelerated electrons with tokamak walls (indirect detection of runaway electrons). The preliminary results show that when not saturated, direct detection with a segmented silicon strip detector provides promising new diagnostic information including spatial and temporal distribution of the runaway electron beam, and the measurement results are in good agreement with hard X-ray measurements with a scintillation detector.

Dhyani et al.: Study of Runaway Electrons in Golem Tokamak **Dhyani-2019-JINST**

P. Dhyani et al. "Study of Runaway Electrons in Golem Tokamak". In: *Journal of Instrumentation* 14.09 (Sept. 2019), pp. C09029–C09029. DOI: 10.1088/1748-0221/14/09/c09029. URL: https://doi.org/10.1088%2F1748-0221%2F14%2F09%2Fc09029.

Abstract: High loop voltage and low-density plasma discharges at the Golem tokamak present favorable conditions for the study of the runaway electrons (RE). A probe is being designed and developed for the spectral measurement of the RE energy inside the last closed flux surface of Golem tokamak plasma. Design of the probe is based on simulation results of the FLUKA code that estimates the energy absorbed by the scintillating crystals and filters of various densities. In the simulations, graphite, stainless steel and molybdenum were tested to filter the supra-thermal electrons. Since having different light yield, YSO (Y2SiO5:Ce), NaI(Tl) and plastic (EJ-200) scintillating crystals were chosen for the simulations.

Stockel et al.: Operational Domain in Hydrogen Plasmas on the Golem Tokamak **Stockel-2019-JOFE**

J. Stockel et al. "Operational Domain in Hydrogen Plasmas on the Golem Tokamak". In: *Journal of Fusion Energy* 38 (Mar. 2019), pp. 253–261. ISSN: 1572-9591. DOI: 10.1007/s10894-019-00215-7.

Abstract: A series of discharges in hydrogen were performed in two experimental sessions. The vessel was not conditioned before the first session, while inductive heating of the vessel and cleaning glow discharge were applied before the second session. Experimental results from both sessions are compared, and optimum operational conditions for the majority of key plasma parameters are determined. It is found that plasma performance with a properly conditioned vessel is significantly better, as expected. In particular, a noticeable increase of discharge duration, and of the electron temperature is observed.

Svihra et al.: Runaway electrons diagnostics using segmented semiconductor detectors **Svihra-2018-FUSENGDES**

Peter Svihra et al. "Runaway electrons diagnostics using segmented semiconductor detectors". In: *Fusion Engineering and Design* 146 (2019). SI:SOFT-30, pp. 316–319. ISSN: 0920-3796. DOI: https://doi.org/10.1016/j.fusengdes.2018.12.054. URL: https://www.sciencedirect.com/science/article/pii/S0920379618308196.

Abstract: A novel application of strip and pixel silicon radiation detectors for study and characterization of run-away electron events in tokamaks is presented. Main goal was to monitor runaway electrons both directly and indirectly. The strip detector was placed inside the tokamak vacuum chamber in order to monitor the run-away electrons directly. Whereas the pixel detector was placed outside the tokamak chamber behind a pin hole for monitoring the run-away electrons indirectly via radiation produce by interaction of the electrons with the plasma facing material. Results obtained using the silicon detectors are compared with already existing diagnostic methods consisting of scintillation devices detecting X-rays and photo-neutrons, providing the same results in the observable comparisons. Tests with the pixel detector proved that the pinhole camera is able to extract spatial information of interaction point (a place where the runaway electrons hit on the facing material) and the strip detectors indicate presence of additional signal from throughout the discharge. The performed experiments are innovative, illustrating possible development of new and easy to use diagnostic method.

Grover et al.: Remote operation of the Golem tokamak for Fusion Education **Grover-2016-FUSENGDES**

O. Grover et al. "Remote operation of the Golem tokamak for Fusion Education". In: *Fusion Engineering and Design* 112 (2016), pp. 1038–1044. ISSN: 0920-3796. DOI: 10.1016/j.fusengdes.2016.05.009.

Abstract: Abstract Practically oriented education in the field of thermonuclear fusion is highly requested. However, the high complexity of appropriate experiments makes it difficult to develop and maintain laboratories where students can take part in hands-on experiments in this field of study. One possible solution is to establish centres with specific high temperature plasma experiments where students can visit such a laboratory and perform their experiments in-situ. With the advancements of {IT} technologies it naturally follows to make a step forward and connect these with necessary plasma physics technologies and thus allow to access even sophisticated experiments remotely. Tokamak Golem is a small, modest device with its infrastructure linked to web technologies allowing students to set-up necessary discharge parameters, submit them into a queue and within minutes obtain the results in the form of a discharge homepage.

Svoboda et al.: Remote operation of the Golem tokamak with hydrogen and helium plasmas **Svoboda-2016-JPCS**

V. Svoboda et al. "Remote operation of the Golem tokamak with hydrogen and helium plasmas". In: *Journal of Physics: Conference Series* 768.1 (2016). DOI: 10.1088/1742-6596/768/1/012002. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84996848706&doi=10.1088%2f1742-6596%2f768%2f1%2f012002&partnerID=40&md5=e2758016f6bdd51be8c02e6f972a374e.

Abstract: The Golem tokamak was operated remotely via Internet connection during the 6th International Workshop and Summer School on Plasma Physics. Performances of hydrogen and helium discharges are compared in this paper. It is found, at similar vacuum conditions, that helium discharges are shorter but the breakdown of the working gas can be quite easily achieved at almost the same loop voltage. The plasma current in helium discharges is slightly lower than in the case of hydrogen. Turbulent fluctuations of the floating potential measured by means of an array of Langmuir probes reveal a noticeably different character in the two discharges.

Gryaznevich et al.: Contribution to fusion research from IAEA coordinated research projects and joint experiments **Gryaznevich-2015-NuclFus**

M. Gryaznevich et al. "Contribution to fusion research from IAEA coordinated research projects and joint experiments". In: *Nuclear Fusion* 55.10 (2015), p. 104019. DOI: 10.1088/0029-5515/55/10/104019.

Abstract: The paper presents objectives and activities of IAEA Coordinated Research Projects 'Conceptual development of steady-state compact fusion neutron sources' and 'Utilisation of a network of small magnetic confinement fusion devices for mainstream fusion research'. The background and main projects of the CRP on FNS are described in detail, as this is a new activity at IAEA. Recent activities of the second CRP, which continues activities of previous CRPs, are overviewed.

Markovic et al.: Development of 3D ferromagnetic model of tokamak core with strong toroidal asymmetry **Markovic-2015-FUSENGDES**

T. Markovic et al. "Development of 3D ferromagnetic model of tokamak core with strong toroidal asymmetry". In: *Fusion Engineering and Design* 96-97 (2015), pp. 302–305. ISSN: 0920-3796. DOI: 10.1016/j.fusengdes.2015.03.041. URL: http://www.sciencedirect.com/science/article/pii/S0920379615002100.

Abstract: Abstract Fully 3D model of strongly asymmetric tokamak core, based on boundary integral method approach (i.e. characterization of ferromagnet by its surface) is presented. The model is benchmarked on measurements on tokamak Golem, as well as compared to 2D axisymmetric core equivalent for this tokamak, presented in previous work. Linearized model well describes quantitative characteristics of {BR} field, generated by poloidal field coils located close to core central column, and distorted by ferromagnet. A discrepancy is seen between linearized form of model for {BR} field generated by coils under the transformer limbs and the measurements. Future work will thus include implementation of the non-linearity effects in order to further investigate this issue.

Svoboda et al.: Remote operation of the vertical plasma stabilization @ the Golem tokamak for the plasma physics education **Svoboda-2015-FUSENGDES**

V. Svoboda et al. "Remote operation of the vertical plasma stabilization @ the Golem tokamak for the plasma physics education". In: *Fusion Engineering and Design* 96-97 (2015), pp. 974–979. ISSN: 0920-3796. DOI: 10.1016/j.fusengdes.2015.06.044. URL: http://www.sciencedirect.com/science/article/pii/S0920379615300740.

Abstract: Abstract The Golem tokamak at the Czech Technical University has been established as an educational tokamak device for domestic and foreign students. Remote participation in the scope of several laboratory practices, plasma physics schools and workshops has been successfully performed from abroad. A new enhancement allowing understandable remote control of vertical plasma position in two modes (i) predefined and (ii) feedback control is presented. It allows to drive the current in the stabilization coils in any time-dependent scenario, which can include as a parameter the actual plasma position measured by magnetic diagnostics. Arbitrary movement of the plasma column in a vertical direction, stabilization of the plasma column in the center of the tokamak vessel as well as prolongation/shortening of plasma life according to the remotely defined request are demonstrated.

Gryaznevich et al.: Progress in application of high temperature superconductor in tokamak magnets **Gryaznevich-2013-FUSENGDES.pdf**

M. Gryaznevich et al. "Progress in application of high temperature superconductor in tokamak magnets". In: *Fusion Engineering and Design* 88.9-10 (2013), pp. 1593 –1596. ISSN: 0920-3796. DOI: 10.1016/j.fusengdes.2013.01.101. URL: http://www.sciencedirect.com/science/article/pii/S0920379613001117.

Abstract: It has long been known that high temperature superconductors (HTS) could have an important role to play in the future of tokamak fusion research. Here we report on first results of the use of HTS in a tokamak magnet and on the progress in design and construction of the first fully-HTS tokamak.

Markovic et al.: Evaluation of applicability of 2D iron core model for two-limb configuration of Golem tokamak **Markovic-2013-FUSENGDES**

T. Markovic et al. "Evaluation of applicability of 2D iron core model for two-limb configuration of Golem tokamak". In: *Fusion Engineering and Design* 88.6-8 (2013), pp. 835 –838. ISSN: 0920-3796. DOI: 10.1016/j.fusengdes.2013.02.142. URL: http://www.sciencedirect.com/science/article/pii/S0920379613002573.

Abstract: This paper presents evaluation of applicability of 2D iron core model for highly non-axisymmetric two limb configuration of Golem tokamak (former CASTOR). Presented results explain the long-term discrepancy between measured magnitudes of external poloidal field and those calculated by air-core approach on this tokamak. The model has been applied to two poloidal planes at different toroidal angles in the vacuum vessel region and has shown that close to central column of the transformer, it is possible to correct for 3D effects by variation of chosen dimensions of axisymmetric iron core model. Satisfactory agreement of the 2D model results with the measured distribution of {BR} field component was achieved.

Odstrcil et al.: Low cost alternative of high speed visible light camera for tokamak experiments **Odstrcil-2012-RSI**

T. Odstrcil et al. "Low cost alternative of high speed visible light camera for tokamak experiments". In: *Review of Scientific Instruments* 83.10, 10E505 (2012). DOI: 10.1063/1.4731003. URL: http://scitation.aip.org/content/aip/journal/rsi/83/10/10.1063/1.4731003.

Abstract: We present design, analysis, and performance evaluation of a new, low cost and high speed visible-light camera diagnostic system for tokamak experiments. The system is based on the camera Casio EX-F1, with the overall price of approximately a

thousand USD. The achieved temporal resolution is up to 40 kHz. This new diagnostic was successfully implemented and tested at the university tokamak GOLEM (R = 0.4 m, a = 0.085 m, BT ¡ 0.5 T, Ip ¡ 4 kA). One possible application of this new diagnostic at GOLEM is discussed in detail. This application is tomographic reconstruction for estimation of plasma position and emissivity.

Svoboda et al.: Multi-mode Remote Participation on the Golem Tokamak **Svoboda-2011-FUSENGDES**

V. Svoboda et al. "Multi-mode Remote Participation on the Golem Tokamak". In: *Fusion Engineering and Design* 86.6-8 (2011), pp. 1310–1314. ISSN: 0920-3796. DOI: {10.1016/j.fusengdes.2011.02.069}.

Abstract: The Golem tokamak (formerly CASTOR) at Czech Technical University is demonstrated as an educational tokamak device for domestic and foreign students. Remote participation of several foreign universities (in Hungary, Belgium, Poland and Costa Rica) has been successfully performed. A unique feature of the Golem device is functionality which enables complete remote participation and control, solely through Internet access. Basic remote control is possible either in online mode via WWW/SSH interface or offline mode using batch processing code. Discharge parameters are set in each case to configure the tokamak for a plasma discharge. Using the X11 protocol it is possible to control in an advanced mode many technological aspects of the tokamak operation, including: i) vacuum pump initialization, ii) chamber baking, iii) charging of power supplies, iv) plasma discharge scenario, v) data acquisition system.

Conference proceedings

Abbasi et al.: Plasma Tomography at GOLEM Tokamak using Neural Network model **Abbasi-2024-ECPP**

S. Abbasi et al. "Plasma Tomography at GOLEM Tokamak using Neural Network model". In: vol. 48A. Europhysics conference abstracts. 2024. ISBN: 111-22-33333-44-5. URL: https://lac913.epfl.ch/epsppd3/2024/html/PDF/P2-094.pdf.

Vinklarek et al.: Tokamak GOLEM for fusion education - chapter 15 **Vinklarek-2024-ECPP**

J. Vinklarek et al. "Tokamak GOLEM for fusion education - chapter 15". In: vol. 48A. Europhysics conference abstracts. 2024. ISBN: 111-22-33333-44-5. URL: https://lac913.epfl.ch/epsppd3/2024/html/PDF/P2-092.pdf.

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 **Chlum-2023-ECPP**

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 x 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.

Kulkov et al.: Runaway electron study at the COMPASS tokamak using the Timepix3-based silicon pixel detector with SPIDR 10 GBps readout **KulkovEPS21**

S. Kulkov et al. "Runaway electron study at the COMPASS tokamak using the Timepix3-based silicon pixel detector with SPIDR 10 GBps readout". In: vol. July. Europhysics conference abstracts. 2021, P3.1006. ISBN: 979-10-96389-13-1. URL: http://ocs.ciemat.es/EPS2021PAP/pdf/P3.1006.pdf.

Abstract: Runaway electrons (RE) that appear in tokamak plasmas are considered dangerous for the integrity of the future tokamak-based fusion reactors due to a large amount of energy they carry. Therefore, it is necessary to understand properties of such electrons in order to secure the success of future machines, e.g., ITER, which is one of the main topics of research at the COMPASS tokamak. Semiconductor detectors, which are widely applied in high-energy physics, may be a suitable addition to plasma diagnostics as they are not affected by magnetic fields and are well-equipped for soft X-ray spectra measurements. A hybrid pixel detection system based on the Timepix3 readout chip with a 200 um thick silicon sensor (in the further text - Timepix3) is a perfect example of such instrumentation.The Timepix3 sensor consists of 256 x 256 pixels with a pixel size of 55 x 55 um2 and, therefore, provides a high spatial resolution. Combined with the SPIDR readout system, Timepix3 is capable of simultaneous recording of Time-of-Arrival (ToA) and Time-over-Threshold (ToT) signals as well as pixel coordinates where the detection occurs with temporal resolution of 1.5625 ns. Additionally, from the number of pixels where a hit was detected, Timepix3 is able to determine either a photon, an electron or a heavier particle was detected. This work presents results acquired with the Timepix3 during the 11th RE-dedicated campaign conducted in 47th EPS Conference on Plasma Physics P3.1006 January, 2020 at the COMPASS tokamak.

Macha et al.: Tokamak Golem for fusion education - chapter 12 **Macha-2021-ECPP**

P. Macha et al. "Tokamak Golem for fusion education - chapter 12". In: vol. July. Europhysics conference abstracts. 2021, P4.1028. ISBN: 979-10-96389-13-1. URL: http://ocs.ciemat.es/EPS2021PAP/pdf/P4.1028.pdf.

Abstract: The GOLEM tokamak is the oldest tokamak in the world. Currently, it serves mainly as an education device for students of tokamak physics. Remote control of the machine enables conducting experiments from all over the world. This contribution summarizes its main research topics of the last year.

Malec et al.: Correlations in signals generated by runaway electrons in the GOLEM tokamak measured using the Timepix3 detection modules **MalecIEEE21**

S. Malec, V. Linhart, and V. Svoboda. "Correlations in signals generated by runaway electrons in the GOLEM tokamak measured using the Timepix3 detection modules". In: *2021 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*. 2021, pp. 1–6. DOI: 10.1109/NSS/MIC44867.2021.9875920.

Abstract: An application study of modern pixel semiconductor detectors for characterization of runaway electron events in a tokamak is presented. This study is based on comparative techniques utilizing spectroscopy and timing measurements of X-rays produced by the runaway electrons. The measurements were performed on the tokamak Golem using three Advapix detection modules. The first two modules were based on a Timepix3 R/O chip with a 1 mm thick silicon sensor. The last module was based also on the Timepix3 R/O chip but with a 2 mm thick CdTe sensor. The modules were placed at different positions around the tokamak chamber and were triggered by a common trigger signal. We have observed that energy spectra measured by the two identical modules in the same place are identical. The spectra measured in different places show variations which can be used for runaway electron characterization. The time evolution of the signals from the detection modules are well correlated. Comparison of

the time evolutions measured by the same two detection modules can be used for estimation of places where the runaway electrons interact with the tokamak matter.

Dhyani et al.: Design and development of probe for the measurements of runaway electrons inside the Golem tokamak plasma edge **DhyaniEPS19**

P. Dhyani et al. "Design and development of probe for the measurements of runaway electrons inside the Golem tokamak plasma edge". In: vol. July. Europhysics conference abstracts. 2019, P1.1016. ISBN: 979-10-96389-11-7. URL: http://ocs.ciemat.es/EPS2019PAP/pdf/P1.1016.pdf.

Abstract: FLUKA simulation results show that NaI(Tl) is a good candidate for the spectral measurement of the RE beam energy, since the amount of energy deposited by monoenergetic beam in the crystals is different as shown in figure 4. Further simulations will be carried out using GEANT4 and FLUKA codes, to interpret the signals obtained during the experiments. In GOLEM tokamak experiments, we measure HXR outside the machine that has S.S. (density 8.0 g/cm3) vacuum vessel of 0.2mm surrounded by a copper (density 8.96 g/cm3) donut shaped shield of thickness 10mm. Reported simulation results indicate that 2.5mm thin graphite (density 2.1 g/cm3) shield was able to absorb 1MeV beam effectively, indicating that the RE beam in the GOLEM tokamak has energy much higher than 1MeV, in general.

Grover et al.: Online experimentation at the Golem tokamak **GroverIEEE19-b**

O. Grover, V. Svoboda, and J. Stockel. "Online experimentation at the Golem tokamak". In: *2019 5th Experiment International Conference (exp.at'19)*. June 2019, pp. 220–225. DOI: 10.1109/EXPAT.2019.8876482. URL: https://ieeexplore.ieee.org/document/8876482.

Abstract: 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.

Kulkov et al.: Tokamak Golem for fusion education - chapter 10 **MachaEPS19**

S. Kulkov et al. "Tokamak Golem for fusion education - chapter 10". In: vol. July. Europhysics conference abstracts. 2019, P1.1068. ISBN: 979-10-96389-11-7. URL: http://ocs.ciemat.es/EPS2019PAP/pdf/P1.1068.pdf.

Abstract: The GOLEM tokamak is the oldest tokamak in the world. Currently, it is located at the FNSPE CTU in Prague and it serves mainly as an education device for students of tokamak physics. Remote control of the machine enables conducting experiments from all over the world using an internet connection. This contribution summarizes main research topics of study of the last year.

O. Grover and V. Svoboda and J. Stockel: Remote demonstration of the Golem tokamak **GroverIEEE19-a**

O. Grover and V. Svoboda and J. Stockel. "Remote demonstration of the Golem tokamak". In: *2019 5th Experiment International Conference (exp.at'19)*. June 2019, pp. 239–240. DOI: 10.1109/EXPAT.2019.8876584. URL: https://ieeexplore.ieee.org/document/8876584.

Abstract: The Golem tokamak serves as an educational device in the field of tokamak physics, technology, diagnostics and operation in the scope of the wider field of thermonuclear fusion. The typical scenario of a remote demonstration of the Golem tokamak is described. The new remote control and live status web interface in its mobile-ready form is presented.

Istokskaia et al.: Tokamak Golem for fusion education - Chapter 9 **IstokskaiaEPS18**

V. Istokskaia et al. "Tokamak Golem for fusion education - Chapter 9". In: vol. July. 2018, pp. 261–264. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Conferences/EPS/45th_Prague_2018/paper.pdf.

Abstract: The GOLEM tokamak, located at the FNSPE CTU in Prague, is the oldest tokamak in the world still operational. Its main mission is education and training of future fusion specialists in the Czech Republic. This contribution covers various student projects of the last year.

Linhart et al.: First Measurement of X-rays Generated by Runaway Electrons in Tokamaks Using a Timepix3 Device with 1 mm thick Silicon Sensor **LinhartIEEE18**

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)*. Nov. 2018, pp. 1–9. DOI: 10.1109/NSSMIC.2018.8824534.

Abstract: An application study of modern pixel semiconductor detectors for characterization of runaway electron events in tokamaks is presented. Characterization techniques utilizing both spectroscopic measurements and monitoring of the intensity of secondary X-rays produced by the runaway electrons were used. Energy spectra of X-rays and time evolutions of their intensity on two tokamaks

(Golem and Compass) were measured under different conditions and compared with results of standard runaway diagnostics. The energy spectra measured on both tokamaks have similar exponential shapes but with a significant variation in numbers of events per shot. The time evolutions of the X-ray intensity during several discharges on the tokamak Golem were measured using both the Timepix3 device and scintillation detectors (NaI:Tl and YAP:Ce). On a microsecond time scales, the signal time evolution measured by the TimePix3 device shows patterns in a form of unexpected or periodic-like increases of the intensity. We have also observed significant differences in number of events of the detected X-rays generated by the runaway electrons flying frontward and backward with respect to a limiter of the tokamak Golem. This fact declares that the runaway electrons have relativistic velocities. The experiments on the tokamak Compass provide similar results. Measurements in the immediate vicinity of tokamak Compass were impossible to perform because of a rapid change of the tokamak magnetic field. Measurements performed in the distance of at least 0.5 m from a diagnostic port of the tokamak Compass gave millions of correctly measured events per shot and an unknown number of events affected by pileups. The correctly measured events were used for construction of energy spectra and the time evolutions of the X-ray intensity.

Duban et al.: Tokamak Golem for fusion education - chapter 7 **EPSLeuven2016**

R. Duban et al. "Tokamak Golem for fusion education - chapter 7". In: *Europhysics Conference Abstracts. 43th EPS Conference on Plasma Physics*. Vol. 40A. europhysics conference abstracts. 2016. ISBN: 2-914771-99-1. URL: http://ocs.ciemat.es/EPS2016PAP/pdf/P5.009.pdf.

Abstract: As the oldest operational tokamak in the world, tokamak GOLEM at FNSPE CTU in Prague, Czech Republic serves primarily to educate students of the faculty in tokamak physics and related fields. This contribution covers various student projects of the last year.

Svoboda et al.: Tokamak Golem for fusion education - chapter 6 **Svoboda15:235954**

V. Svoboda et al. "Tokamak Golem for fusion education - chapter 6". In: *42nd European Physical Society Conference on Plasma Physics*. 2015. ISBN: 2-914771-98-3. URL: http://ocs.ciemat.es/EPS2015PAP/pdf/P2.164.pdf.

Abstract: GOLEM is the oldest operational tokamak in the world. It serves as an educational device at the Facuty of Nuclear Sciences and Physical Engineering at CTU in Prague. Several improvements of its diagnostic technology made during the last year as well as new experimental results are presented in this article.

Ficker et al.: Tokamak Golem for fusion education - chapter 5 **EPSBerlin2014**

O. Ficker et al. "Tokamak Golem for fusion education - chapter 5". In: *Europhysics Conference Abstracts. 41th EPS Conference on Plasma Physics*. Vol. 38F. 2014. ISBN: 2-914771-90-8. URL: http://ocs.ciemat.es/EPS2014PAP/pdf/P4.141.pdf.

Abstract: Tokamak Golem is one of the oldest tokamaks in the world, currently located at the Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague. It serves as an educational device and all experiments and development are done by students themselves under professional supervision. The contribution covers the major improvements made over the last year.

Hernandez-Arriaga et al.: Tokamak Golem for fusion education - chapter 4 **EPSHelsinky2013**

D. Hernandez-Arriaga et al. "Tokamak Golem for fusion education - chapter 4". In: *Europhysics Conference Abstracts. 40th EPS Conference on Plasma Physics*. Vol. 2013. ISBN: 978-1-63266-310-8. URL: http://ocs.ciemat.es/EPS2013PAP/pdf/P2.410.pdf.

Abstract: Tokamak GOLEM is a small tokamak operating at the Faculty of Nuclear Sciences and Physical Engineering at the Czech Technical University in Prague. It has been serving for four years as an educational device for training students in fusion research. One of its essential features is the possibility of fully remote operation so it suits to international experiments with broad participation.This contribution concludes the main headlight topics of the last year.

Ball et al.: First results from tests of high temperature superconductor magnets on tokamak **EPSStockholm2012HTS**

S. Ball et al. "First results from tests of high temperature superconductor magnets on tokamak". In: *Europhysics Conference Abstracts. 39th EPS Conference on Plasma Physics*. Vol. 36F. 2012. URL: http://ocs.ciemat.es/epsicpp2012pap/pdf/P2.052.pdf.

Abstract: The HTS coils have been routinely and successfully used at the GOLEM tokamak both for plasma generation and stabilization. Provided the LN cooling is sufcient and sustained, the HTS coils are reliable and can greatly reduce the necessary capacitor bank charging voltage,thus lowering the energy demands for plasma position control. The coil currents in fast ramp-up pulse operation exceeded those in the tape specication by almost 50 %.

Svoboda et al.: Recent results from Golem tokamak. 'Indeed, you can teach an old dog some new tricks. **EPSStockholm2012**

V. Svoboda et al. "Recent results from Golem tokamak. 'Indeed, you can teach an old dog some new tricks." In: *Europhysics Conference Abstracts. 39th EPS Conference on Plasma Physics*. Vol. 36F. 2012. URL: http://ocs.ciemat.es/epsicpp2012pap/pdf/P2.059.pdf.

Abstract: Hall sensors in a tokamak environment are being prepared on GOLEM. These sensors are one of the candidate solutions for measurement of stationary magnetic fields in fusion reactors. Energy distribution of HXR photons was measured at several discharge conditions on GOLEM using NaI(Ta) scintillator detector. Measured HXR photons spectrum ranges up to 1.5 MeV and peaks typically at 300 keV. We assume the measured energy spectrum of HXR photons correspond to the energy distribution of runaway electrons. Finally, the spatial and temporal characteristics of electrostatic turbulence in GOLEM edge plasmas were studied using the radial array of 16 Langmuir probes. Comparison of turbulence properties between standard hydrogen and helium discharges was done.

Bromova et al.: The Golem Tokamak for Fusion Education **EPSStrasbourg2011**

E. Bromova et al. "The Golem Tokamak for Fusion Education". In: *Europhysics Conference Abstracts. 38th EPS Conference on Plasma Physics*. Vol. 35G. 2011. ISBN: 2-914771-68-1. URL: http://ocs.ciemat.es/EPS2011PAP/pdf/P1.021.pdf.

Abstract: The Golem tokamak, (formerly CASTOR), became an educational device for domestic as well as for foreign students via remote participation/handling. It operates routinely for nearly two years at modest range of parameters and with a limited set of diagnostics. Wide range of tasks with varying levels of complexity covering tokamak physics, technology and operation can be studied by the future fusion specialists. Currently the diagnostics enrichment is strategic for the education usability of the device. Students participate in large extent on additional standard diagnostics methods development, including density measurement via microwave interferometry, plasma position (including tomography) studies using a set of Mirnov coils, two fast cameras and two linear arrays of bolometers. Moreover stabilization of the plasma position with an equilibrium magnetic field generated in the vertical magnetic field coils and plasma spectroscopy issues are under consideration.

Svoboda et al.: Tokamak Golem Remotely for Worldwide Fusion Education **Svoboda11:186333**

V. Svoboda and J. Stöckel. "Tokamak Golem Remotely for Worldwide Fusion Education". In: *Proceedings: SEFI - PTEE 2011*. Hochschule Mannheim - University Of Applied Sciences, 2011. ISBN: 978-3-931569-18-1. URL: http://sefi11.hs-mannheim.de/index.php?option=com_content\&view=article\&id=27\&Itemid=27.

Abstract: The GOLEM tokamak is a university-type experimental facility dedicated primarily for practical training of students who are familiar with basics of tokamak operation, data processing and evaluation of selected plasma parameters. Wide range of measurement tasks allows for preparation of different level student measurement programs. The Czech Technical University established in 2006 a new education curriculum "The physics and Technology of Thermonuclear Fusion". The GOLEM tokamak carries out its education mission in the frame of the fusion related practicum, bachelor and diploma thesis, and summer training schools. Furthermore, a number of excursions are regularly organized for various Czech high schools. As a result, some motivated high school students can participate in tokamak operation and solve selected elementary problems.

Svoboda et al.: Former Tokamak CASTOR becomes remotely controllable Golem at the Czech Technical University in Prague **EPSDublin2010**

V. Svoboda et al. "Former Tokamak CASTOR becomes remotely controllable Golem at the Czech Technical University in Prague ". In: *Europhysics Conference Abstracts. 37th EPS Conference on Plasma Physics*. Vol. 34A. 2010. ISBN: 2-914771-62-2. URL: http://ocs.ciemat.es/EPS2010PAP/pdf/P2.111.pdf.

Abstract: The CASTOR tokamak, which has been operated for 30 years at the IPP Prague was moved to the Czech Technical University in Prague and became an educational device for domestic as well as for foreign students, via remote participation/handling. The reinstalled tokamak (R = 0.4 m, a = 0.085 m), now baptized as GOLEM, operates currently at modest range of parameters, Bt ¡ 0.8 T, Ip ¡ 8 kA, discharge duration approx 13 ms, and with a limited set of diagnostics. This facility will be offered to the FUSENET (the 7th FWP European Fusion Education Network) as a (remote) practica experiment.

Master thesis

Godsfavour Chibueze Amanekwe: New Set of Inner Magnetic Coils at the GOLEM Tokamak **Bohous-2024-MastThes**

Godsfavour Chibueze Amanekwe. "New Set of Inner Magnetic Coils at the GOLEM Tokamak". Master Thesis. 2024. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/Godsfavour-2024-MastThes.pdf.

Abstract: Systems of magnetic diagnostics belong to the backbones of magnetic confinement fusion devices. The GOLEM tokamak has as a part of the control system a Rogowski coil for the plasma current measurement, and a small coil for the toroidal field measurement, both outside the vacuum chamber. A new system of magnetic coils was recently developed and installed inside the GOLEM vacuum vessel. The system consists of a Rogowski coil, two toroidal field coils placed on the high field side (HFS) and the low field side (LFS), and a diamagnetic coil. The inner Rogowski coil measures the plasma current being undisturbed by the current in the liner. The inner toroidal coils measure the toroidal field without the effect of the field penetrating through the liner. The most important contribution is provided by the diamagnetic coil used to establish the thermal plasma energy and the energy confinement time. First results from testing the new system are presented in this thesis. The coils were tested and calibrated, with the offsets and parasitic artefacts removed. They now measure with enhanced precision and have been embedded into the shot

web-page and database of the GOLEM tokamak together with the calculated thermal plasma energy and the energy confinement time.

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.

D. Cipciar: Ion and electron temperature study in the edge plasma of the tokamak device **CipciarMT21**

D. Cipciar. "Ion and electron temperature study in the edge plasma of the tokamak device". Master Thesis. 2021. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/21DarioCipciar.pdf.

Abstract: This thesis reports on a systematic ion and electron temperature measurements in the scrapeoff layer (SOL) of two tokamak devices. Results are obtained using a fast swept ball-pen probe with unprecedented temporal resolution (10 jits). Moreover, an improved analysis technique is presented which increases the amount of relevant data obtained in comparison to previously published research. The results with high temporal resolution indicate non-Gaussian ion temperature histograms with a peak at low temperatures and a high temperature tail associated with blobs. The blobs are originating in the vicinity of last closed flux surface and propagate perpendicularly to the magnetic field lines through the SOL plasma. The resulting fast measurements are used to simulate the I-V characteristic of a slow swept (3 ms) retarding field analyzer (RFA). The exponential part of the RFA-like I-V characteristic also determines the ion temperature, but with low temporal resolution (3 ms). The ratios of the ion to electron temperatures are studied for different plasma densities. We observed that the ratio depends on the line-average plasma density and it is close to 1-2 in the vicinity of LCFS and 3-4 in the main SOL. A study of the ion temperature fluctuations shows an agreement with a stochastic model for intermittent turbulence in SOL.

P. Macha: Edge plasma studies in tokamaks by the mean of advanced electric probes. **MachaMT20**

P. Macha. "Edge plasma studies in tokamaks by the mean of advanced electric probes." Master Thesis. 2020. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/20MachaPetr.pdf.

Abstract: This diploma thesis is dedicated to edge plasma studies in tokamaks by the means of advanced electric probes. After introduction of the theory and basic concepts of edge plasma physics, electric probes and numerical simulations, the analysis of probe data from COMPASS and Golem tokamaks is performed. Main focus is given to the fluctuations of plasma parameters and their respective profiles. A decrease of the level of relative fluctuations of plasma parameters in the velocity shear layer is observed and the impact of a quasicoherent mode on this decrease is discussed. The electron temperature is determined by the interpolation of measured tunnel probe current ratio in the scope of a wide parametric scan performed by numerical simulations, resulting in a high time resolution. This technique is cross-checked by a comparison with established electron temperature measurement methods. A good agreement between experiment and simulations on the electron side of the tunnel is observed.

B. Leitl: Tomografická rekonstrukce profilu vyzařování plazmatu na tokamaku Golem **LeitlMT**

B. Leitl. "Tomografická rekonstrukce profilu vyzařování plazmatu na tokamaku Golem". Master Thesis. 2019. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/19LeitlBorek.pdf.

Abstract: The thesis is dedicated to the integration of a new diagnostics of plasma radiation detection using AXUV detectors to the tokamak GOLEM diagnostic system. For two new AXUV20ELG detectors, transimpedance amplifers were constructed, the detectors calibrated and mounted on the tokamak GOLEM, the first on a small lateral equatorial port and the second upper TOP port, both on south-east toroidal position. Amplifed signals were digitized by an acquisition system and saved to the GOLEM

database. The tomographic method with Tikhonov regularization using minimization of a Fisher information from the tokamak COMPASS was adjusted for tokamak GOLEM parameters and used for a data processing.

J. Kocman: Řízení polohy plazmatického prstence na tokamaku Golem **KocmanMT**

J. Kocman. "Řízení polohy plazmatického prstence na tokamaku Golem". Master Thesis. 2015. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/15KocmanJindrich.pdf.

Abstract: Determination and control of the plasma position is one of the basic tasks in the tokamak operation. This thesis describes the current state of the plasma position control on the GOLEM tokamak with a focus on diagnostics for determination of the plasma position. The theoretical part contains formulae for vertical and horizontal displacement using poloidal magnetic field derived from Grad–Shafranov equation. The plasma position system is able to control the plasma in two perpendicular directions, the vertical and the horizontal. It provides two modes, the pre-defined and the feedback. The plasma position system has been implemented into the remote control room allowing to perform remote plasma position studies. Relative plasma-life prolongation of more than 50% was achieved with this system.

L. Matěna: Microwave interferometry on the tokamak Golem **MatenaMT**

L. Matěna. "Microwave interferometry on the tokamak Golem". Master Thesis. 2015. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/15MatenaLukas.pdf.

Abstract: After short introduction into nuclear fusion basics the thesis describes the interferometer used at CASTOR tokamak and basic phenomena necessary to understand its function. The interferometer uses frequency modulation of the diagnostic wave to eliminate dependence of the output signal on the amplitude of the diagnostic wave. Current status of single components of the device is than analysed. encountered issues are solved and the interferometer is installed at the Golem tokamak. Two ways of analysing the output signal are developed (digital and analog) and backup electronic circuitry is made should be old equipment from CASTOR times fail. Everything is eventually evaluated and the results of individual methods are compared.

Ondřej Ficker: Generation, losses and detection of runaway electrons in tokamaks **FickerMT15**

Ondřej Ficker. "Generation, losses and detection of runaway electrons in tokamaks". Master Thesis. 2015. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/15FickerOndrej.pdf.

Abstract: This thesis is focused on the so called runaway electrons that are generated in tokamaks under particular conditions. These energetic electrons are accelerated in the electric field of tokamak almost without collisions with thermal plasma particles and may cause large damage to the components inside the vacuum vessel. The brief derivation of runaway solution is given in the thesis and other properties of runaway electrons are summarised. The theoretical relations are subsequently applied to plasmas of COMPASS and Golem tokamaks. The analysis of data measured on COMPASS is focused namely on the investigation of the link between the processes of magnetic reconnection during the saw-tooth instability and bursts of runaway electrons. According to the COMPASS results, the energetic electrons are just ejected and not generated during these phenomena.

T. Markovič: Measurements of magnetic fields on the tokamak Golem. **MarkovicMT12**

T. Markovič. "Measurements of magnetic fields on the tokamak Golem." Master Thesis. 2012. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/MasterThesis/12MarkovicTomas.pdf.

Abstract: In this thesis, a characterization of tokamak Golem magnetic fields and of methods of their measurement is provided. Specifically, calibration constants and methods of application of magnetic diagnostics on this device are summarized. This includes not only up-to date detectors of global discharge parameters, but also new detectors for local B_theta perturbation studies. Design, manufacture, calibration and tokamak implementation of the latter diagnostics (refered to as ring coils) is described in detail. Temperature-resistant state-of-art Hall probes provided by Poznan University of Technology are characterized as well, althought their tokamak implementation did not take place yet. Measurements of stray fields on tokamak Golem using ring coils suggest, that main cause of their presence is local saturation of ferromagnetic core, i.e. not currents in tokamak chamber. Measurement of plasma Btheta by ring coils was found to be less reliable as B_theta fluctuation measurement. The latter allows detection and characterization of plasma MHD structures – the magnetic islands. An investigation of tokamak Golem islands yields that they change their poloidal rotation frequency by following change in q, most likely due to tendencies to keep constant v_theta. For m = 3 islands, v_theta approx 0.7 km/s is observed, however for discharges with vertical stabilization horizontal field, island v_theta approx 2.0 km/s velocities are typical. Also, model of tokamak Golem magnetic field was developed. Model includes fields by windings of B_phi and external B_theta, by tokamak iron core and by tokamak chamber currents. A model of plasma B_theta perturbation field from MHD structures is presented as well.

Bachelor projects

Catalina Vásquez Leiva: Estudios de optimización de confinamiento magnético de plasmas en tokamak GOLEM **Catalina-2024-BachProj**

Catalina Vásquez Leiva. "Estudios de optimización de confinamiento magnético de plasmas en tokamak GOLEM". Bachelor project. 2024. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/FromAbroad/Catalina-2024-BachProj.pdf.

Abstract: En este informe se presenta el estudio realizado mediante la operación remota del tokamak GOLEM de la Universidad Técnica Checa de Praga. Se coordinaron tres sesiones experimentales para realizar descargas en el tokamak, pudiendo controlar distintos parámetros como la intensidad del campo magnético toroidal, la intensidad del campo eléctrico , el gas a utilizar (hidrógeno o helio) y su presión. El objetivo principal de la investigación fue estudiar cómo se comporta el tiempo de confinamiento con respecto a estos parámetros, en particular la intensidad del campo magnético. En adición a esto, se buscó identificar impurezas en el plasma mediante un análisis del espectro del plasma. La primera sesión de experimentos se destinó principalmente a estudiar la relación entre el tiempo de confinamiento y el campo magnético toroidal, utilizando gas de hidrógeno. En la segunda sesión se buscó corroborar los resultados anteriores y se utilizó espectroscopía para estudiar las impurezas. Finalmente, en la tercera sesión se corroboraron nuevamente resultados anteriores con respecto al tiempo de confinamiento y a espectroscopía utilizando además gas de helio. Se encontró que el tiempo de confinamiento tiende a aumentar cuando se incrementa el campo magnético, lo cual es consistente con estudios realizados con otros tokamaks. También se encontró que tanto la corriente de plasma como la temperatura tienden a disminuir cuando se incrementa el campo magnético, sin embargo la influencia de la presión del gas no fue estudiada en profundidad. Con respecto al análisis mediante espectroscopía, se lograron identificar impurezas como oxígeno, nitrógeno, carbono, hierro y molibdeno.

Derap Pena Mukti Sari: The Study of The Hydrogen Plasma Breakdown Phase in The GOLEM Tokamak Reactor **Sari-2024-BachProj**

Derap Pena Mukti Sari. "The Study of The Hydrogen Plasma Breakdown Phase in The GOLEM Tokamak Reactor". Bachelor project. 2024. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/FromAbroad/24DerapPenaMuktiSari-English.pdf.

Abstract: The breakdown phase of plasma in a tokamak is a crucial stage before achieving fusion conditions. This stage will influence the quality of electron production, plasma purity, plasma stability, and more. This study aims to determine the optimum parameters during the breakdown phase in the GOLEM tokamak by examining the effects of gas pressure and transformer core voltage on breakdown voltage, discharge duration, and maximum plasma current. The research is conducted remotely using a computer to access the website connected to the GOLEM tokamak. Eighty discharge data points from the GOLEM tokamak website database are plotted into graphs. The optimal gas pressure falls within the range of 7-15 mPa. In this pressure range, the discharge duration (Tdis) and maximum plasma current (Ip, max) reach relatively the highest values (11,59 - 13,56 ms; 2,6 - 3,82 kA). An increase in the transformer core voltage (UCD) results in an elevation of breakdown voltage (Ubreakdown), discharge duration (Tdis), and maximum plasma current (Ip, max).

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.

A. Kubincova: Advanced plasma vertical position reconstruction on the Golem tokamak. **KubincovaBP21**

A. Kubincova. "Advanced plasma vertical position reconstruction on the Golem tokamak." Bachelor project. 2021. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/21KubincovaAdela.pdf.

Abstract: During the tokamak discharge there are usually unwanted movements of the plasma ring. We measure these using diagnostics and filters which remove noise from the measured data. Kalman filter (KF) is such a filter. It can very effectively remove the noise and predict values of the observable based on a model. In this thesis we shall derive such model for vertical movement of plasma on the Golem tokamak. The model does not include the influence of control coils, however, we suggest a way to incorporate this effect. In the process we determined the time constant of the vessel and we measured for the first time the time constant of the shell to be 15.46 ms. This measurement agrees with the theoretical computation and it is higher than estimated. In the end we give recommendations for measurement of vertical position of plasma on the Golem tokamak using the KF.

J. Malinak: Electron temperature measurements using rail probe on the tokamak Golem. **MalinakBP21**

J. Malinak. "Electron temperature measurements using rail probe on the tokamak Golem." Bachelor project. 2021. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/21MalinakJiri.pdf.

Abstract: This bachelor thesis is devoted to the problem of measurement of edge plasma parameters with a new type of probe, the so-called rail probe. The advantage of this probe is that thanks to its design it can withstand extremely high heat fluxes and at the same time behaves as a proud Langmuir probe for a certain non-zero angle of incident field lines. The thesis summarises the fundamental physics of the Langmuir probe and sheath expansion. A manipulator was developed and constructed to allow tilting of the probe head, which includes a proud Langmuir probe and a ball-pen probe in addition to the rail probe. Comparative measurements of the electron temperature using all of these probes are presented and show conformity. The dependence of the obtained plasma parameters on the head tilt angle is also investigated. The measured data are compared with a 2D PIC simulation performed for a Golem tokamak. These 2D PIC simulations will be an essential part of the rail probe's development for the COMPASS Upgrade tokamak.

F. Papousek: Impact of swept edge plasma potential biasing on turbulence in tokamaks. **PapousekBP20**

F. Papousek. "Impact of swept edge plasma potential biasing on turbulence in tokamaks." Bachelor project. 2020. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/20PapousekFilip.pdf.

Abstract: In the tokamak plasma the edge plasma is the barrier between the hot confined plasma centre and the cold tokamak vessel. One of the fastest mechanisms of energy and particle loss from the confined plasma is turbulent transport. One of the concepts to understand turbulence and its self–organization are zonal flows, further referred to as ZFs. ZFs have two branches, near-zero frequency flows and geodesic acoustic modes further referred to as GAMs with higher frequency(typically tens of kHz on most tokamaks of modest size and regular aspect ratio). The symmetry and stability of ZFs cause the energy of turbulence to flow out and thus, ZFs cause saturation of drift–wave turbulence.

P. Macha: Měření parametrů plazmatu pomocí kombinované ball-pen a langmuirovy sondy na tokamaku Golem. **MachaBP18**

P. Macha. "Měření parametrů plazmatu pomocí kombinované ball-pen a langmuirovy sondy na tokamaku Golem." Bachelor project. 2018. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/18MachaPetr.pdf.

Abstract: The bachelor thesis is dedicated to the edge plasma parameters measurements and ball-pen probe calibration at the Golem tokamak. The first part introduces the theory of plasma and the physics of tokamaks, focusing on the Golem tokamak. The next part presents basic diagnostics of the Golem tokamak. The second part covers the physical principles of both Langmuir and ball-pen probes and the theory important for planned meassurements. Finally, the description of experimental set-ups probes at the Golem tokamak and experimental set-ups are given. The third part describes the experimental results obtained in hydrogen and helium plasmas. Based on the data, ball-pen probe calibration is determined and basic plasma parameters are evaluated. These results are finally presented and compared for both working gases. The thesis is concluded with the overal discussion and summary of all the achieved results.

T. Okonechnikova: Prezentace tokamaku Golem pomocí technologie X3DOM **OkonechnikovaBP**

T. Okonechnikova. "Prezentace tokamaku Golem pomocí technologie X3DOM". Bachelor project. 2016. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/16OkonechnikovaTatiana.pdf.

Abstract: The bachelor thesis deals with 3D virtual world integration into the web page using X3DOM technology. Web interface implements important interactive functions to control the virtual world. It allows to work independently of the platform. The result of the project is a web application that introduces students of Physics and Technology of Thermonuclear Fusion with the tokamak Golem.

B. Leitl: Bolometrická měření na tokamaku Golem **LeitlBP**

B. Leitl. "Bolometrická měření na tokamaku Golem". Bachelor project. 2014. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/14LeitlBorek.pdf.

Abstract: The bachelor thesis is devoted to the description of properties of fast AXUV diodes and its practical application for the detection of plasma radiated power in UV and Soft-X-ray region at the tokamak Golem. Plasma position is fixed from fitting simple and double Gaussian curve to the measured data and the theory of symmetric Abel inversion is also analysed in the thesis, because it enables to display 2D profile of radiated power and its time resolution. Bolometric plasma diagnostics was put into operation on the tokamak Golem for test AXUV module and it is now possible to install two brand new detectors.

J. Veverka: Studium počáteční fáze výboje v tokamacích **VeverkaBP**

J. Veverka. "Studium počáteční fáze výboje v tokamacích". Bachelor project. 2014. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/14VeverkaJakub.pdf.

Abstract: The start-up phase of a discharge is the most important part of an experiment. It determines its success or failure. Effective generation if plasma in tokamak devices can be dependable on various parameters, e.g. working gas pressure, intensity of toroidal magnetic field or type of preionization. Optimization of the Avalanche ionization phase is therefore an important part of fusion research. This work summarises the principles of nuclear fusion reactions along with the history of development of controlled nuclear fusion. Afterwards, principles of a magnetic confinement of plasma in tokamak devices are described, together with the description of Golem tokamak, where the experiments were performed. In following parts, data that characterize the start-up phase of discharge are examined and presented, related to the type of preionization and values of discharge parameters (working gas pressure, intensity of electric and magnetic field). Short separate part is dedicated to interesting results using ECRH preionization (electron cyclotron resonance heating).

M. Matušů: Virtual model of tokamak Golem with real physical core **MatusuBP**

M. Matušů. "Virtual model of tokamak Golem with real physical core". Bachelor project. 2014. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/14MatusuMartin.pdf.

Abstract: Thermonuclear fusion is a potential energy source for next few centuries. In order to control this process on Earth, it is necessary to simulate conditions of Sun core. All matter is in plasma state in these conditions and therefore a thermonuclear reactor is needed to create a environment for the plasma. Requirements on such a reactor are stated in Lawson criterion. Tokamak device is except other types of thermonuclear reactor close to meet Lawson criterion. This device uses a strong closed magnetic field to confine plasma within reactor vessel. On the other hand, this set-up brings technical difficulties of the whole experiment. A lot of small tokamaks, which cannot meet fusion conditions, were build for a purpose of material and diagnostics testing. One of them is a Golem tokamak operating as an educational device at the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague. One of the most important functions of this tokamak is a discharge remote control via web interface. This specification set the main idea of a creation of a virtual model, which would give user more specific conception of the real tokamak. In order to make the model easy accessible, internet environment has been chosen again. Graphical elements of model were placed on the web with the use of a library WebGL. Such a model was extended by a physical core of simulations, reflecting back at the graphical model. The whole program is accessible on the Golem server at: http://golem.fjfi.cvut.cz/virtual/matusu/BachelorThMM/BMM.html.

R. Duban: Měření rychlosti toku plazmatu na tokamaku Golem pomocí pole Machových sond. **DubanBP**

R. Duban. "Měření rychlosti toku plazmatu na tokamaku Golem pomocí pole Machových sond." Bachelor project. 2014. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/14DubanRichard.pdf.

Abstract: Poloidal asymmetry of edge plasma flow speed is one of current topics of high-temperature plasma physics. This experiment on Golem tokamak allows us to measure flow speed distribution of edge plasma along the magnetic field lines with unique spatial resolution. This thesis describes basic concepts of plasmaphysics, thermonuclear fusion and basic principles of tokamak operation. Mean theme contains measurement of parameters of magnetized plasma with Langmuir and Mach probes. Experimental part of this thesis contains analysis of edge plasma flow speed having regard of its poloidal distribution.

J. Kocman: Zpětnovazební řízení polohy na tokamaku Golem. **KocmanBP**

J. Kocman. "Zpětnovazební řízení polohy na tokamaku Golem." Bachelor project. 2011. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/11KocmanJindrich.pdf.

Abstract: Determination and control of plasma column position play an important role in the operation of a tokamak. Stabilization of the plasma position in the Golem tokamak needs to be reinstalled after relocation to the FNSPE CTU. The theoretical part of this thesis contains formulae for vertical and horizontal displacement and the asymmetry factor (Shafranov parameter). This part also includes the derivation of the Grad-Shafranov equation and the resulting condition for the vertical magnetic field needed to stabilize the plasma position in the direction of the major radius. In the experimental part two methods for the determination of vertical position in the Golem tokamak are compared. The first one was derived in the theoretical part, the second one was used for the Golem tokamak in the past. Moreover, the horizontal displacement as a function of the external stabilizing vertical magnetic field was measured. The first results show an effect on the horizontal position. The final part of the thesis comprises a discussion about possible causes of a phenomenon which appears in discharges with long plasma life.

O. Pluhař: Interactive model of tokamak Golem. **PluharBP**

O. Pluhař. "Interactive model of tokamak Golem." Bachelor project. 2011. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/11PluharOndrej.pdf.

Abstract: Tokamak Golem is a useful piece of laboratory equipment on the grounds of Faculty of Nuclear Sciences and Physical Engineering of Czech Technical University in Prague. The main aim of this project is to create an interactive virtual world with tokamak Golem inside accessible online for public. This virtual world contains rich information of the tokamak from its visual appearance to basic functionality. Tokamak Golem has not been transferred into virtual environment before; therefore this project will be a great asset to students and professors in learning how the device works even before they go hands-on with the actual equipment. Virtual Reality Modeling Language (VRML) was used as a project requirement.

T. Markovič: Magnetic field configurations and their measurement on tokamak Golem. **MarkovicBP**

T. Markovič. "Magnetic field configurations and their measurement on tokamak Golem." Bachelor project. 2010. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/BachelorProjects/10MarkovicTomas.pdf.

Abstract: Basic overview of configurations of magnetic field in a tokamak, along with means of its measurement is provided. Since most common magnetic diagnostics sensors presently used are of inductive nature, pros and cons of two main concepts of analog integration are discussed. As galvanometric sensors such as Hall probes have been getting more attention lately as they do not require integration, characterization of these sensors is included. Along with description of magnetic field configurations on tokamak Golem, discussion concerning present state of its magnetic diagnostics with proposals of its modification is included as well. Extension of reliability range of Mirnov coils used for local magnetic field measurements is demonstrated on two different experiments. In the first experiment, modeling of poloidal magnetic field gives insight into permeability of chamber. The other experiment is aimed on first approximation of plasma column position with simple use of local magnetic field sensors. Additionally, a method of toroidal magnetic field cross-talk elimination in signal of poloidal magnetic field sensors is described.

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.

A. Socha: Poloha zóny vytváření turbulentních struktur v okrajovém plazmatu tokamaku Golem **sochaSOC**

A. Socha. "Poloha zóny vytváření turbulentních struktur v okrajovém plazmatu tokamaku Golem". High School Students' Professional Activities SOČ. 2021. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/21Socha_sikmostIsat.pdf.

Abstract: This work deals with the study of turbulent structures in the edge plasma of the Golem tokamak. The main goal of this work was to find the place of origin of turbulent structures. Plasma turbulence, and associated turbulent structures, are important for maintaining energy in the tokamak. The hypothesis is that in the marginal plasma there is a zone of turbulent structure formation, where the number of blobs and holes is the same, and which is firmly connected to the plasma edge - separatrix. It is this question that deals with the experimental part of this work, in which I wanted to confirm or refute this hypothesis. I searched for the zone of creating turbulent structures by measuring the radial slope profile. To check the measured data and at the same time to predict the measured values, I created a script in the Python programming language, thanks to which reconstructions of the plasma position in the poloidal section of the chamber, including the position of the probe, can be plotted. Unfortunately, the results of this work did not find a place of turbulent structures for technical reasons (limited length of the probe manipulator). On the other hand, the measured results indicate the presence of positive turbulent structures (blobs) on the outside of the separatrix, which is in line with the assumed theory.

M. Lauerová: Měření elektronové teploty na tokamaku Golem elektrickými sondami **lauerSOC**

M. Lauerová. "Měření elektronové teploty na tokamaku Golem elektrickými sondami". High School Students' Professional Activities SOČ. 2021. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/21Lauerova_ElTeplota.pdf.

Abstract: In this work I focus on the analysis of the tokamak edge plasma, a key area of interest on the path to commercial thermonuclear fusion. The study of the edge plasma is important because it dictates the interactions between the extremely hot plasma in the middle where all the fusion reactions occur and the vessel (it describes heat interactions and erosions of the vessel walls). I compare two methods of measuring the electron temperature using electric probes. My specific goal is to prove that the new and innovative combined method using a ball-pen probe and a Langmuir probe performs as well as the widely used swept Langmuir probe. I consider this analysis to be important because the combined probe method is much easier and less time consuming. Also, it measures with wider accruals, therefore it is possible to identify various turbulent structures.

P. Skála: Termojaderná fúze a experiment s vysokoteplotním plazmatem **skalaSOC**

P. Skála. "Termojaderná fúze a experiment s vysokoteplotním plazmatem". High School Students' Professional Activities SOČ. 2021. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/21Skala-sondy.pdf.

Abstract: Obecné fungování tokamaků. Diagnostika a princip získávání dat pomocí tokamaku Golem. Experimentální část: měření parametrů plazmatu pomocí sond BPP a DRP.

D. Kropáčková: Stabilizace plazmatu na tokamaku Golem **danySOC20**

D. Kropáčková. "Stabilizace plazmatu na tokamaku Golem". High School Students' Professional Activities SOČ. 2020. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/20Kropackova_Stabilizace.pdf.

Abstract: The aim of this work is plasma stabilization on GOLEM tokamak. In this thesis is also described the measurement of plasma position and measurement of vertical magnetic field.

M. Horák: Profil elektronové teploty v komoře tokamaku **horakSOC**

M. Horák. "Profil elektronové teploty v komoře tokamaku". High School Students' Professional Activities SOČ. 2020. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/20Horak_ElTeplota.pdf.

Abstract: Thesis focuses on the topic of the thermonuclear fusion and description of plasma development by defined global parameters. It explains the basic principles of tokamak's operation and clarifies problems for plasma maintaining. In addition, to this the thesis concentrates on measurement and development of electron temperature in tokamak chamber, depending on the distance of the probe from the centre of the chamber.

D. Kropáčková: Měření rotace plazmatu dvojitou tunelovou sondou na tokamaku Golem **danySOC19**

D. Kropáčková. "Měření rotace plazmatu dvojitou tunelovou sondou na tokamaku Golem". High School Students' Professional Activities SOČ. 2019. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/19Kropackova_RotacePLazmatu.pdf.

Abstract: The aim of this work is the measurement of the Mach number and the determination of the plasma rotation direction at tokamak GOLEM depending on the orientation of the magnetic and electric fields.

M. Grof: Poloidální rotace plazmatu na tokamaku Golem **grofSOC**

M. Grof. "Poloidální rotace plazmatu na tokamaku Golem". High School Students' Professional Activities SOČ. 2014. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/14Grof_RotacePlazmatu.pdf.

Abstract: Plazma je nedílnou součástí našeho vesmíru. Jeho pochopení nám pomůže lépe pochopit, jak vznikl náš vesmír, a umožní nám rozvoj nových technologií, zejména zdroj energie – termojaderná fúze, což je proces ve hvězdách. Tokamak GOLEM patří mezi nejstarší funkční tokamaky, ale neustále je na něm co zkoumat. Z pohledu magnetohydrodynamických studií lze zjistit mnoho důležitých informací o struktuře a pohybu plazmatu. Jednou z nich je rotace v poloidálním směru, kterou se zde zabývám.

M. Cvan: Termojaderná Fúze **cvanSOC**

M. Cvan. "Termojaderná Fúze". High School Students' Professional Activities SOČ. 2013. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/13Cvan_Fuze.pdf.

Abstract: The aim of my long-term thesis is to introduce high school students to the basic physical aspects of thermonuclear devices, particularly tokamaks. In the theoretical part, there is the basic knowledge necessary for getting this simpliest idea of tokamak operation. The practical part describes experiments that I made on the tokamak Golem in Prague.

O. Grover: Měření hustoty plazmatu interferometrickou metodou na Tokamaku Golem. **groverSOC**

O. Grover. "Měření hustoty plazmatu interferometrickou metodou na Tokamaku Golem." High School Students' Professional Activities SOČ. 2011. URL: http://golem.fjfi.cvut.cz/wiki/Presentations/Students/HighSchoolActivities/11Grover_HustotaPlazmatu.pdf.

Abstract: Měření hustoty plazmatu na základě šíření elektromagnetických vln v plazmatu. Využití modulace k umožnění zpracovaní dat.

Miscellaneous

The Golem Tokamak contributors: Magnetic confinement of high temperature plasma at the Golem tokamak **GMhandson**

The Golem Tokamak contributors. *Magnetic confinement of high temperature plasma at the Golem tokamak*. http://golem.fjfi.cvut.cz/wiki/Education/GMinstructions/extracts/GeneralHandsOn/docum.pdf. [Online; accessed 2-January-2020]. 2020.

Abstract: This assignment introduces students to the physics, technology, diagnostics and operation of the Golem tokamak. It comprises performing a tokamak experiment and exploring the basic scaling properties of magnetic plasma confinement.

Huang et al.: Global Tokamak Experiment **GTE2010**

B. Huang and V. Nikolaeva. *Global Tokamak Experiment*. http://tokamakglobal.com/. 2010.

ITER news: Launch of the world's first global tokamak experiment **iternews**

ITER news. *Launch of the world's first global tokamak experiment*. http://www.iter.org/newsline/156/512. 2010.

Jan Mlynář: Golem history **GolemHistory**

Jan Mlynář. *Golem history*. `http://golem.fjfi.cvut.cz/wiki/History/Articles/GolemHistoryHM.pdf`. [Online; accessed 2-January-2019]. 2010.

Abstract: Golem history since 1960.

Tokamak Golem contributors: Tokamak Golem at the Czech Technical University in Prague **Golem2007**

Tokamak Golem contributors. *Tokamak Golem at the Czech Technical University in Prague*. http://golem.fjfi.cvut.cz. 2007.

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 (Dec. 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.

Chandrasekar et al.: Data-driven disruption prediction in Golem Tokamak using ensemble classifiers **Chandrasekar20**

J. Chandrasekar, S. Madhawa, and J. Sangeetha. "Data-driven disruption prediction in Golem Tokamak using ensemble classifiers". In: *Journal of Intelligent & Fuzzy Systems* 39 (2020), pp. 8365–8376. DOI: 10.3233/JIFS-189155.

Abstract: A robust disruption prediction system is mandatory in a Tokamak control system as the disruption can cause malfunctioning of the plasma-facing components and impair irrecoverable structural damage to the vessel. To mitigate the disruption, in this article, a data-driven based disruption predictor is developed using an ensemble technique. The ensemble algorithm classifies disruptive and non-disruptive discharges in the Golem Tokamak system. Ensemble classifiers combine the predictive capacity of several weak learners to produce a single predictive model and are utilized both in supervised and unsupervised learning. The resulting final model reduces the bias, minimizes variance and is unlikely to over-fit when compared to the individual model from a single algorithm. In this paper, popular ensemble techniques such as Bagging, Boosting, Voting, and Stacking are employed on the time-series Tokamak dataset, which consists of 117 normal and 70 disruptive shots. Stacking ensemble with REPTree (Reduced Error Pruning Tree) as a base learner and Multi-response Linear Regression as meta learner produced better results in comparison to other ensembles. A comparison with the widely employed stand-alone machine learning algorithms and ensemble algorithms are illustrated. The results show the excellent performance of the Stacking model with an F1 score of 0.973. The developed predictive model would be capable of warning the human operator with feedback about the feature(s) causing the disruption.

Faridyousefi et al.: MHD Mode Identification from Mirnov Coils Signals in Tokamak Via Combination of Singular Value Decomposition and Hilbert–Huang Transform Analysis Methods **Faridyousefi20**

H. Faridyousefi, M. Salem, and M. Ghoranneviss. "MHD Mode Identification from Mirnov Coils Signals in Tokamak Via Combination of Singular Value Decomposition and Hilbert–Huang Transform Analysis Methods". In: *Journal of Fusion Energy* 39 (2020), pp. 1–9. DOI: 10.1007/s10894-020-00273-2.

Abstract: In this work, we investigate how to study the MHD activities in Tokamak plasma via the combination of singular value decomposition (SVD) and Hilbert–Huang transform (HHT) methods. We apply this approach to the Mirnov coil signal fluctuations analysis without any filtering technique. First, the principal axes (PAs) of a pick-up Mirnov signals are extracted by SVD analysis. Next, the harmonics of dominants PAs is obtained by empirical mode decomposition (EMD) analysis. Moreover, the time-frequency behavior of Mirnov signals are extracted by HHT. The proposed technique is employed to analyze Mirnov coils signals for mode type and frequency identification, especially in multimode MHD activities. We obtained Spatial–temporal structures of the Mirnov coils fluctuations in terms of correlation functions to better identification of mode number and frequencies of dominant MHD modes. We also present the results of this method applied to IR-T1 and Golem Tokamaks Mirnov coils signals. Consequently, satisfying results from SVD + HHT analysis method and spatial-temporal structures for IR-T1 and Golem Tokamaks Mirnov data observed.