Research into Runaway electron physics basis on the small tokamak GOLEM
brief summary of the REs@tGOLEM current status
for the Grant proposal

February 5, 2023

1 Introduction

This document serves as a very rough (with the minimum necessary energy to create it) introductory overview of the activities in the area of physics and diagnostics of the Runaway electrons issues on the Golem tokamak through the relevant lists of publications for a given issue.

2 REs Physics

Comparison of COMPASS and GOLEM tokamaks is in the Master thesis [FickerMT15]. One paragraph in the article [StockelJOFE19] is dedicated to Runaway electrons.

References

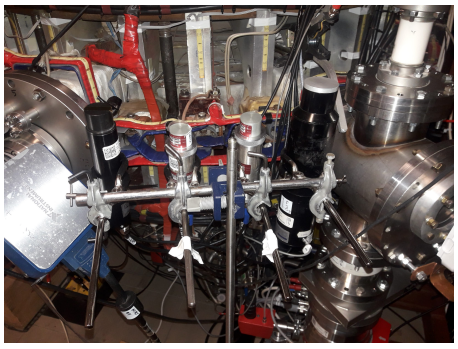
O. Ficker: Generation, losses and detection of runaway electrons in tokamaks **FickerMT15**

O. 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.

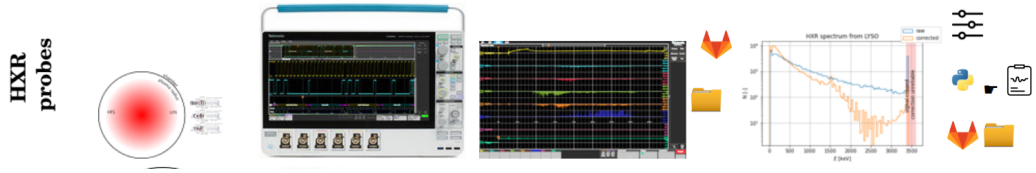
3 REs Diagnostics

3.1 Scintillation probes



The photo of the diagnostics.

A set of scintillation probes with various crystals is installed on the Golem tokamak i) NaI(Tl) 2"x2" N/A, ii) YAP(Ce) 1"x1" Hamamatsu R6094, iii) NaI(Tl) 2"x2" ET Enterprises 9266B, iv) CeBr3/YAP(Ce) 1"x1" Hamamatsu R3998-02, v) CeBr3/YAP(Ce) 1"x1" Hamamatsu R1234A and vi) LYSO.



The relevant diagnostic line from the discharge #39417.

Especially CeBr3 crystal were tested at the tGOLEM and then used at TCV and COMPASS tokamaks, see [CerovskyJINST22].

In vessel RE probe proposal in the [DhyaniJINST19] and [DhyaniEPS19] contributions.

References

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

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

Dhyani et al.: Study of Runaway Electrons in Golem Tokamak DhyaniJINST19

P. Dhyani, V. Svoboda, V. Istokskaia, J. Mlynar, 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.

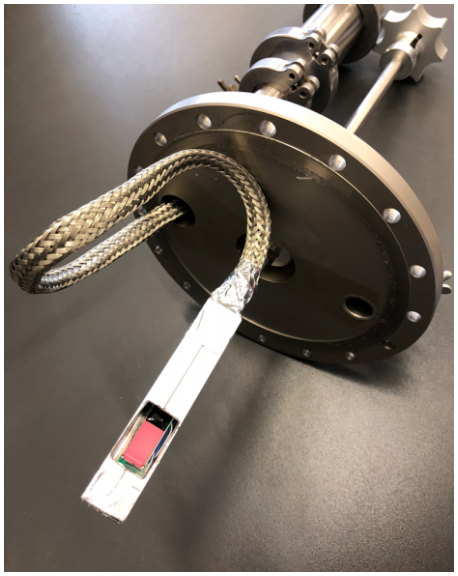
Dhyani et al.: Design and development of probe for the measurements of runaway electrons inside the Golem tokamak plasma edge DhyaniEPS19

P. Dhyani, V. Svoboda, V. Istokskaia, J. Mlynář, et al. "Design and development of probe for the measurements of runaway electrons inside the Golem tokamak plasma edge". In: vol. 43C. Europhysics conference abstracts. 2019, P1.1016. ISBN: 979-10-96389-11-7. URL: http://ocs.ciemat.es/EPS2019PAP/pdf/P1.1016.pdf.

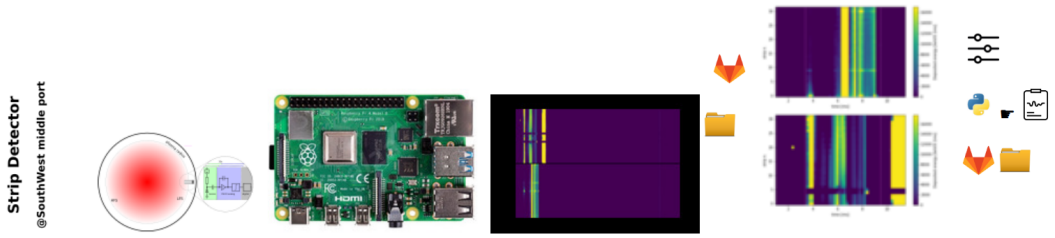
Abstract: FLUKA simulation results show that NaI(Tl) is a good candidate for the spectral measurement of the RE beam energy, since the amount of energy deposited by monoenergetic beam in the crystals is different as shown in figure 4. Further simulations will be carried out using GEANT4 and FLUKA codes, 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.

3.2 Strip detector

To measure the spatial and velocity distribution of Runaways.



The photo of the diagnostics.



The relevant diagnostic line from the discharge #39417.

This issue have been covered in these articles: [SvihraFUSENGDES18], [NovotnyJINST20] and [TunklMT22].

References

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.

Novotny et al.: Runaway electron diagnostics using silicon strip detector **NovotnyJINST20**

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

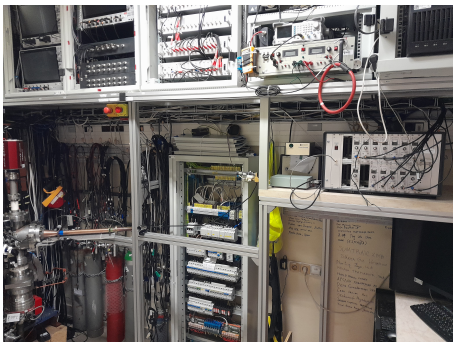
Abstract: We present a proof-of-principle measurement of runaway electrons in a small tokamak using a silicon strip detector. The detector was placed inside the diagnostic port of the tokamak vessel and detected the runaway electron signal directly. The measured signal was compared to the signal provided 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.

P. Svihra et al. "Runaway electrons diagnostics using segmented semiconductor detectors". In: *Fusion Engineering and Design* (2018). ISSN: 0920-3796. DOI: 10.1016/j.fusengdes.2018.12.054.

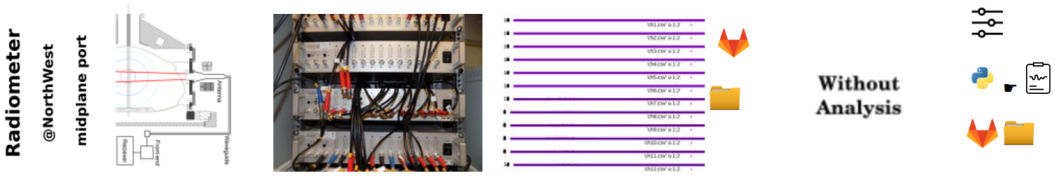
Abstract: A novel application of strip and pixel silicon radiation detectors for study and characterization of run-away electron events in tokamaks is presented. Main goal was to monitor runaway electrons both directly and indirectly. The strip detector was placed inside the tokamak vacuum chamber in 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.

3.3 ECE radiometer

A 16-channel heterodyne radiometer capable of directly measuring the emission of low-energy Runaway electrons via electron cyclotron emission.



The photo of the diagnostics.



The relevant diagnostic line from the discharge #39417.

Inspiration from the COMPASS tokamak installation and experimentation is in the [FarnikEPJ19] and [FarnikRSI19] publications.

References

M. Farník et al.: Radiometry for the vertical electron cyclotron emission from the runaway electrons at the COMPASS tokamak **FarnikRSI19**

M. Farník et al. "Radiometry for the vertical electron cyclotron emission from the runaway electrons at the COMPASS tokamak". In: *Review of Scientific Instruments* 90.11 (2019), p. 113501. DOI: 10.1063/1.5099463. URL: https://doi.org/10.1063/1.5099463.

Abstract: Due to an increased interest in runaway electron (RE) phenomena in tokamak research, the need for diagnostics of runaway electron population in plasma has emerged. A novel diagnostic of the nonthermal electron cyclotron emission from runaway electrons can be utilized for this purpose. It was designed and installed at the COMPASS tokamak based on the available heterodyne radiometer. The vertical ECE (V-ECE) system uses a 16-channel heterodyne radiometer with a vertically placed E2-band horn antenna with a 76.5–90 GHz frequency range front-end. Simulations with the ray-tracing SPECE code have shown a measurement feasibility of the runaway electrons with energies up to 1 MeV. Due to a low optical depth of the plasma in COMPASS during RE discharges, reflected waves from the tokamak wall can be detected as well. First results show strong connection with other RE diagnostics at COMPASS. The V-ECE can obtain important information about RE population evolution and primary generation mechanism.

Michal Farník et al. "Runaway electron diagnostics for the COMPASS tokamak using EC emission". In: vol. 203. Jan. 2019, p. 03006. DOI: 10.1051/epjconf/201920303006.

Abstract: An electron cyclotron emission (ECE) diagnostic of suprathermal electrons was utilised for runaway electron (RE) experiments purposes in the COMPASS tokamak. Our vertical ECE (V-ECE) system consists of a 16-channel heterodyne radiometer and an E-band horn antenna with a 76.5-88 GHz frequency range front-end. Simulations used for the design of the diagnostic showed a possibility of detecting the emission of low-energy (50-140 keV) runaway electrons. We realized measurements with both extraordinary (X-) and ordinary (O-) mode linear polarizations. The amplitudes of the X-mode and O-mode signals are similar, which can be explained by depolarised reflected radiation. V-ECE measurements in low-density flattop discharges and in discharges with massive gas injections of high- Z elements show correlations with other RE diagnostics. Our results are in the agreement with the principles of the primary runaway generation mechanisms.

3.4 Timepix3

3.4.1 Advacam variant

The photo of the diagnostics.

The relevant diagnostic line from the discharge #39417.

See [LinhartIEEE18] and [MalecIEEE21] articles. This is the first use of this detector on the Golem tokamak, and the results are summarized in the Štepán Malec diploma thesis [MalecMT23]

3.4.2 Nikhef variant

This diagnostics was tested at the tGOLEM without publication. Results from the COMPASS installation are summarized in the [KulkovJINST22] paper.

References

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.

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

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

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

Š. 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.

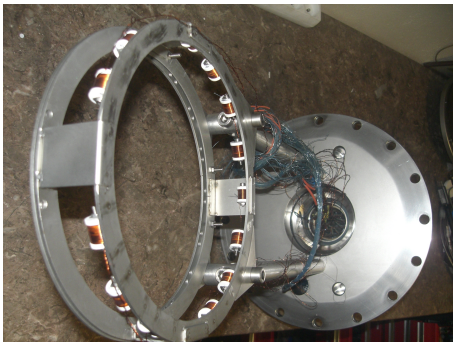
Linhart et al.: First Measurement of X-rays Generated by Runaway Electrons in Tokamaks Using a Timepix3 Device with 1 mm thick Silicon Sensor **LinhartIEEE18**

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.

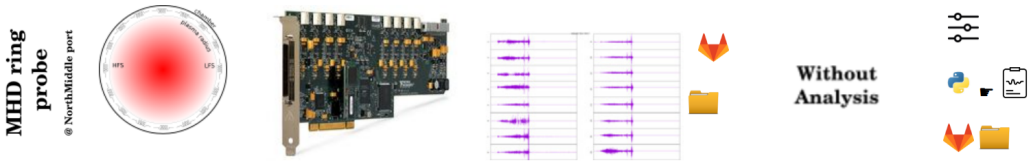
Abstract: An application study of modern pixel semiconductor detectors for characterization of runaway electron events in tokamaks is presented. Characterization techniques utilizing both spectroscopic measurements and monitoring of the intensity of secondary X-rays produced by the runaway electrons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

4 Other possible RE relevant diagnostics/issues

- Some Runaway Electron Modeling:
  - The simulation is being worked on radiation generation and transport in a simplified GOLEM tokamak model in the FLUKE systems (Jaroslav Čeřovský initiative for scintillation probes).
  - Geant4 simulation toolkit and the models are used to simulate a RE interaction in the tokamak and with the strip detector [TunklMT22].
- Magnetohydrodynamics, see [SaranchaJPCS21], [MarkovicMT12].

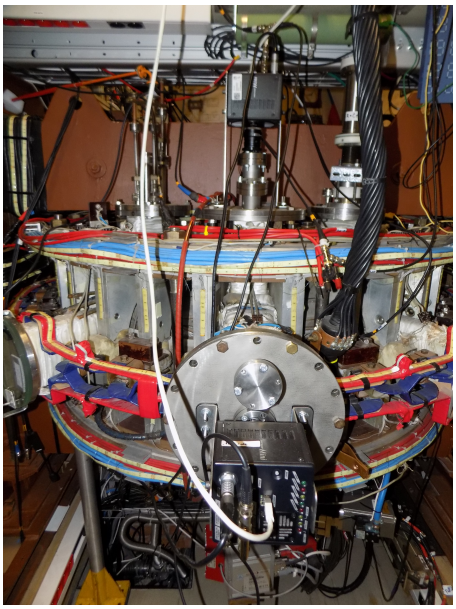


The photo of the diagnostics.



The relevant diagnostic line from the discharge #39417.

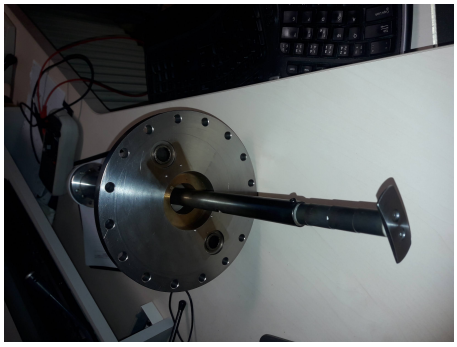
- Isotopic studies, see [SaranchaPAST21].
- Tomography.



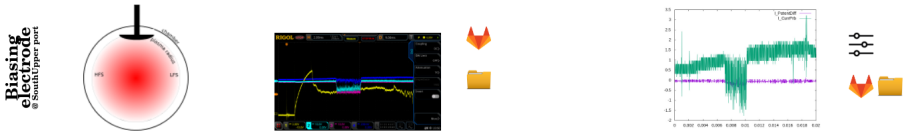
The photo of the diagnostics.

The relevant diagnostic line from the discharge #39417.

- Biasing electrode.



The photo of the diagnostics.



The relevant diagnostic line from the discharge #39417.

- Possible working gasses: Hydrogen, Helium, Argon, Deuterium.
- Foreseen diagnostics: i) Vertical and horizontal Bolometry, ii) A 32-channel high-resolution optical spectrometer capable of measuring ion temperature and plasma poloidal rotation rate.
- Preionization possible: i) cosmic rays, ii) electron gun/tungsten filament, iii) MW via magnetron 2.45 GHz
- Hypothetical diagnostics:
  - Cherenkov detector. This detector was used in the CASTOR era, see [VachaMT07]. Then an experimental campaign at the tokamak COMPASS is described in the [CerovskyMT18]. There are some indications that we could agree with colleagues from Poland and try to implement the diagnostics again on this tokamak.
  - Calorimeter, see installation at the COMPASS in the [CaloudMT20] .

References

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.

Sarancha et al.: Magnetic turbulence and long-range correlation studies in the Golem tokamak **SaranchaJPCS21**

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.

G.A. Sarancha et al.: Hydrogen and helium discharges in the Golem tokamak **SaranchaPAST21**

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.

J. Čaloud: Study of energy of runaway electrons in tokamaks **CaloudMT20**

J. Čaloud. "Study of energy of runaway electrons in tokamaks". Master Thesis. 2020. URL: %7Bhttp://golem.fjfi.cvut.cz/wiki/Experiments/RunAwayElectronStudies/Diagnostics/Calorimeter/library/DP_final_zp.pdf%7D.

Abstract: The subject of this thesis is the study of the energy of runaway electrons on the COMPASS tokamak at Institute of Plasma Physics of the Czech Academy of Sciences. A calorimetric probe was designed and produced as part of this work to measure the energy and power of the runaway electron beam hitting the plasma facing components of the tokamak. Using the developed calorimeter, the energy was measured in more than 100 discharges in which the effectiveness of mitigation techniques of runaway electrons was studied. The unique feature of the system is the ability to measure the temperature evolution during the discharge. The analysis of the measured energies is complemented by the comparison with relevant diagnostics and systems.

J. Čeřovský: Studies of trajectories of relativistic electrons in the magnetic field of tokamak **CerovskyMT18**

J. Čeřovský. "Studies of trajectories of relativistic electrons in the magnetic field of tokamak". Master Thesis. 2018. URL: %7Bhttp://golem.fjfi.cvut.cz/wiki/Experiments/RunAwayElectronStudies/Library/COMPASS/DP_Jaroslav_Cerovsky.pdf%7D.

Abstract: This diploma thesis is dealing with so called runaway electrons, which are generated in the the tokamaks under particular conditions. These high energy electrons are accelerated in the electric field of tokamak and their impact onto the first wall of the experimental facility can cause serious damage. A brief summary of the fundamentals of runaway electron physics is given. The integration schemes dedicated for description of the dynamics of the relativistic particles in the magnetic field of the tokamak are presented. The given schemes were used to implement the program capable to calculate trajectories of the runaway electrons in the COM- PASS tokamak. The results of the particle simulations were compared with measurements from the Cherenkov detector, which detects energetic electrons escaping from plasma volume.

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 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 B by ring coils was found to be less reliable as B 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. For m = 3 islands, v 0.7 km/s is observed, however for discharges with vertical stabilization horizontal field, island v 2.0 km/s velocities are typical. Also, model of tokamak Golem magnetic field was developed. Model includes fields by windings of B and external B, by tokamak iron core and by tokamak chamber currents. A model of plasma B perturbation field from MHD structures is presented as well.

M. Vácha: Measurement of runaway electrons in the CASTOR tokamak **VachaMT07**

M. Vácha. "Measurement of runaway electrons in the CASTOR tokamak". Master Thesis. 2007. URL: http://golem.fjfi.cvut.cz/wiki/Experiments/RunAwayElectronStudies/Library/CASTOR_GOLEM/BPTX_2006_1_11320_NSZZ027_225362_0_46318.pdf.

Abstract: This thesis reports on results of the experimental measurements of fast electrons of energy higher than 50 keV on the CASTOR tokamak, which were performed using a new version of the Cherenkov detector. The measured radial distribution of the fast electron flux at different plasma densities and the dependences of the integrated Cherenkov

signal on plasma density, discharge current, and toroidal magnetic field are presented and discussed. Possible sources of the noise on the Cherenkov signals are analyzed.

5 Possible comparative studies with tokamak COMPASS results

See [FickerNF17], [CerovskyMT18], [FickerMT15], [VlainicPhD17].

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J. Čeřovský: Studies of trajectories of relativistic electrons in the magnetic field of tokamak **CerovskyMT18**

J. Čeřovský. "Studies of trajectories of relativistic electrons in the magnetic field of tokamak". Master Thesis. 2018. URL: %7Bhttp://golem.fjfi.cvut.cz/wiki/Experiments/RunAwayElectronStudies/Library/COMPASS/DP_Jaroslav_Cerovsky.pdf%7D.

Abstract: This diploma thesis is dealing with so called runaway electrons, which are generated in the the tokamaks under particular conditions. These high energy electrons are accelerated in the electric field of tokamak and their impact onto the first wall of the experimental facility can cause serious damage. A brief summary of the fundamentals of runaway electron physics is given. The integration schemes dedicated for description of the dynamics of the relativistic particles in the magnetic field of the tokamak are presented. The given schemes were used to implement the program capable to calculate trajectories of the runaway electrons in the COM- PASS tokamak. The results of the particle simulations were compared with measurements from the Cherenkov detector, which detects energetic electrons escaping from plasma volume.

Ficker et al.: Losses of runaway electrons in MHD-active plasmas of the COMPASS tokamak **FickerNF17**

O. Ficker et al. "Losses of runaway electrons in MHD-active plasmas of the COMPASS tokamak". In: *Nuclear Fusion* 57.7 (May 2017), p. 076002. DOI: 10.1088/1741-4326/aa6aba. URL: https://dx.doi.org/10.1088/1741-4326/aa6aba.

Abstract: The significant role of magnetic perturbations in mitigation and losses of runaway electrons (REs) was documented in dedicated experimental studies of RE at the COMPASS tokamak. REs in COMPASS are produced both in low density quiescent discharges and in disruptions triggered by massive gas injection (MGI). The role of the RE seed produced in the beginning of the discharge on the subsequent RE population proved significant. Modulation of the RE losses by MHD instabilities was observed at several characteristic frequencies, as well as by magnetic field oscillations related to power supplies. Magnetic islands seem to suppress the losses as the HXR signal is low and coherent with the island rotation frequency. Moreover, periods of increased losses of REs observed in the current quench (CQ) and early RE beam plateau phase of the MGI disruptions seem to be linked to the bursts of magnetic perturbation, and to the observation of filaments in the fast visible camera images.

Miloš Vlainić: Studies of Runaway Electrons in COMPASS Tokamak **VlainicPhD17**

Miloš Vlainić. "Studies of Runaway Electrons in COMPASS Tokamak". PhD Thesis. 2017. URL: http://golem.fjfi.cvut.cz/wiki/Experiments/RunAwayElectronStudies/Library/COMPASS/17VlanicPhD.pdf.

Abstract: Relativistic (up to tens of MeV) runaway electrons carrying about 10 MA are predicted to be generated after disruptions in ITER. Therefore, researching methods for mitigation of runaway electrons is one of the highest priorities for ITER's safety. As part of the EUROfusion consortium, a project on runaway electron studies was granted to the COMPASS tokamak due to, among others, its relatively low safety issues regarding potential runaway electron damage and flexibility of various plasma parameters (e.g. shaping, electron density, plasma current, etc.). Such features with a significant, but still safe, runaway electron population make COMPASS suitable for run- away electron model validation and scaling towards ITER. In this thesis, pioneering experimental work on runaway electrons performed in the COM- PASS tokamak is presented, accompanied with the implementation of the corresponding theoretical models.

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

O. 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.

6 The team

6.1 The core (proposal)

Honza Mlynář, Ondra Ficker a Eva Macúšová, Vojtěch Svoboda (chief engineer), Jana Brotánková, Daniel Mazur, Matěj Tomeš, David Břeň.

6.2 Possible contributors and their roles

- **Scintillation probes:** Jaroslav Čeřovský (PhD student), Jakub Vinklárek (Bachelor student). Expected Bachelor project 2023 "Characterization of scintillation detectors at GOLEM tokamak for Runaway electron studies").
- **Tomography:** Jan Mlynář, Sara Abbasi (Postdoc). Expected grant proposal at the Czech grant agency.
- **Strip Detector:** Marek Tunkl (PhD in the Joint program).
- **Timepix detectors:** Štěpán Malec (Master student, 2023 PhD planned), Sergei Kulkov (PhD student).
- **ECE radiometer:** Vladislav Ivanov (PhD in the Joint program), , Michal Farník (PhD student).
- **MHD activity:** Jana Brotánková?, Vladislav Ivanov (PhD in the Joint program).
- **The supervisory role/coordination of the REs experiments @tGOLEM:** Vojtěch Svoboda, Lukáš Lobko (PhD in the Joint program).
- **Optical spectrometry:** Matěj Tomeš (IPP Prague).
- **Bolometry:** Probably only if we invited Jakub Svoboda to help us somehow with it.
- **Physics periscope:** Ondřej Ficker, Jan Mlynář, Evka Macúšová (IPP Prague).
- **Numerical modeling** Jaroslav Čeřovský, Marek Tunkl.
- Other possible contributors: Roger Jasper? (Ghent University), Jan Čečrdle, nepojmenovaný doktorand ...?
- (... Missing Honza Stöckel.)

Notes

- Most here mentioned contributions are, besides the links, available here.

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The tokamak GOLEM team

February 5, 2023

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