Tokamak GOLEM for fusion education - chapter 17: magnetic islands, diamagnetic measurement, spectroscopy, transport barrier, ion temperature measurement

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Introduction. This contribution presents current student projects carried out at the GOLEM tokamak, operated at the Czech Technical University in Prague (CTU). It is the second of two contributions on this topic.

Neural-network-based magnetic island detection. The detection of magnetic islands in tokamak plasmas is typically performed manually, which limits the ability to systematically correlate these events with other phenomena, such as runaway electron generation and the formation of transport barriers. To address this, an automated detection algorithm based on a neural network is currently being developed and tested, utilizing the cross-correlation of Mirnov coil signals. To construct the training dataset, the signal from a single Mirnov coil is selected as a reference. The Pearson cross-correlation between this reference and the signals from all other Mirnov coils is computed using consecutive 0,3 ms time windows throughout the discharge. This procedure yields a 2D correlation matrix for each time step, where each row corresponds to a specific Mirnov coil and each column represents a discrete time lag, L. This is repeated with each coil as a reference. To preserve numerical fidelity, these 2D matrices are fed directly into the neural network. Each matrix is subsequently labeled based on whether phase-shifted harmonic signals—characteristic of a magnetic island—are observed across the full coil array. Presently, the objective is to establish a robust empirical threshold—specifically, determining the minimum spatial extent (number of coils) and temporal duration required to definitively confirm the presence of a magnetic island. This criterion is essential to distinguish genuine island structures from transient edge magnetohydrodynamic (MHD) events that exhibit similar signal footprints.

Spectroscopic study of transport barrier formation. This study investigates the possible formation of transport barriers in helium plasmas on the GOLEM tokamak using spectroscopic diagnostics. Despite recent modifications to the device, a steep electron temperature gradient (Figure 1) was observed in the outer plasma region, confirming that the transport barrier phenomenon persists under the updated configuration. The transition can be seen as the plasma changes colors from an orange to a violet hue.

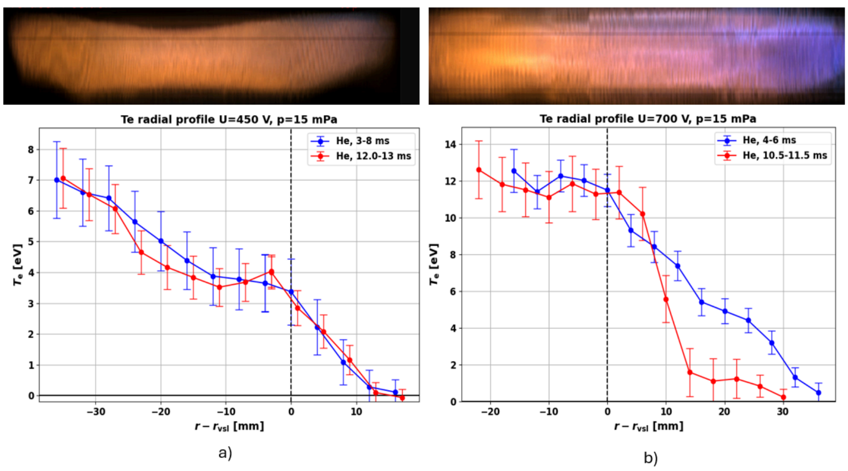


Figure 1: Comparison of T_e radial profiles at two different current drive voltages (different plasma currents). Upper fast-camera images show the temporal evolution of the plasma radiation (vertical view.)

Spectral analysis identified several low-Z impurities (Figure 2) potentially playing a dominant role on whether a transition is observed, through radiative energy losses. Three distinct discharge phases were identified from the temporal evolution of impurity line intensities: an initial impurity accumulation phase, followed by a plateau, or sharp decrease in accumulation for discharges undergoing a transition, and finally a decrease of the low-ionization states, potentially indicating a shift to higher ionization states or a thinner radiation shell.

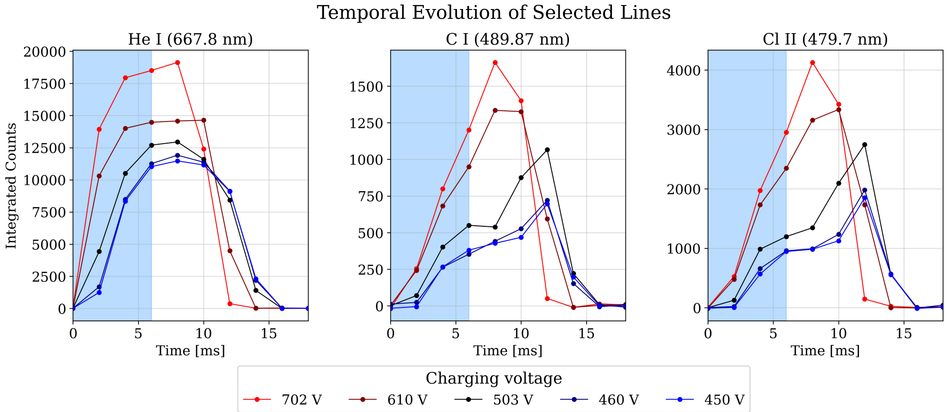


Figure 2: Temporal evolution of selected lines of main working gas and impurities, indicating the three discharge phases. Transition is not observed for voltages below 550 V.

A voltage threshold of approximately 550 V and a pressure limit below 50 mPa were identified as necessary conditions for the transition. Density scans have suggested that higher pressures suppress the transition through increased collisionality and electron cooling. These results highlight the importance of impurity control for achieving improved plasma confinement on GOLEM.

New fast spectroscopy diagnostic. A new diagnostic to monitor select spectral line emission intensity with high temporal resolution has been developed to investigate the potential role of impurities during spontaneous barrier formation. The experimental configuration incorporates beam splitters, long-pass dichroic mirrors, optical filters, and reverse-biased silicon photodiodes to isolate and monitor specific spectral lines, including H-alpha, He I, C II, N II, and O I. The spectral lines have been selected to cover the wide range of impurities present in the GOLEM tokamak, while ensuring that their intensity is sufficient to be reliably detected by the diagnostic. The selected load resistor for the photodiode circuit acts as an RC low-pass filter; therefore, a careful balance is required between maximizing the output voltage and achieving a higher frequency limit. For low-intensity lines, 1 MΩ resistors were used; otherwise, 100 kΩ. The measured signal intensities I_l were converted to incoming photon counts using the formula $N_l = \frac{I_l}{R(\lambda_l)\cdot T(\lambda_l)} \cdot \lambda_l$, which accounts for both the diode responsivity R and the transmittance T of the optical apparatus.

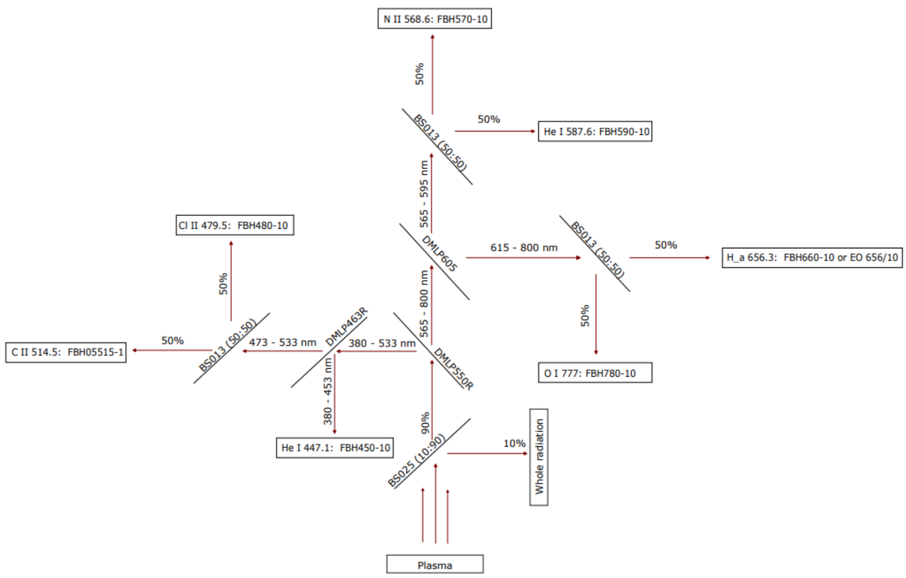


Figure 3: A schematic of the optical apparatus. The radiation from the plasma enters at the bottom, passes through a series of beam-splitters, dichroic mirrors, and spectral filters, and is detected by a photodiode.

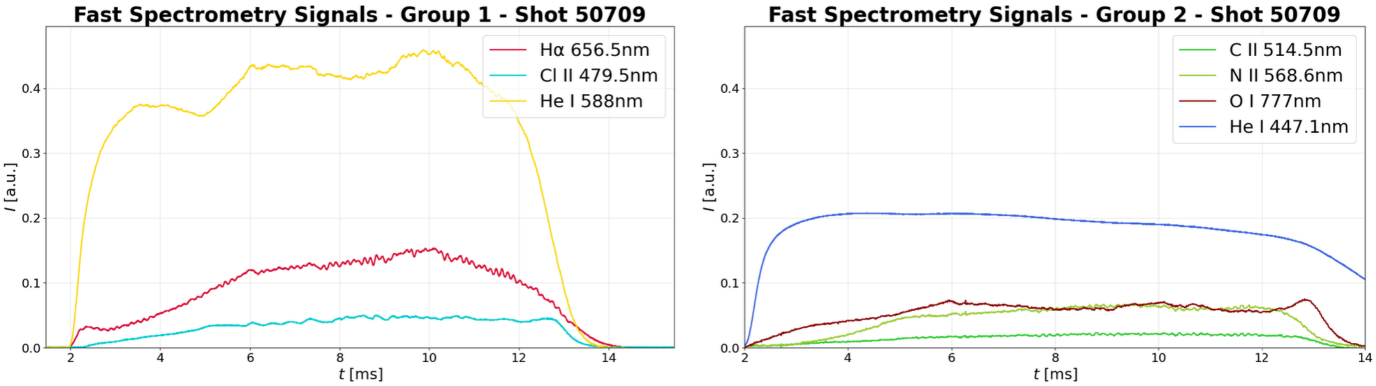


Figure 4: Spectral line intensities measured in a helium shot.

Initial testing demonstrated that the precisely monitored spectral lines represent only a small fraction of the total plasma radiation. Furthermore, discrepancies in signal magnitudes were observed when comparing the newly built fast spectrometer to the existing spectrometer. These deviations may stem from beam divergence, coaxial cable interference, or high-frequency dampening caused by the load resistor. Future iterations will focus on increasing detection sensitivity by active amplification of the current signal from the photodiodes using a transimpedance amplifier.

Electric probes. A dual electric probe-head consisting of two Langmuir and two ball-pen probes has been installed on GOLEM, see Figure 5. The design enables simultaneous I^+_{sat}, floating, and voltage-swept measurements. It is intended for transport barrier studies [1] and fast (up to 100 kHz) T_i studies [2]. The system is already measuring radial profiles of plasma properties, including radial drift velocity $v^{(r)}_{\mathrm{E\times B}}$, see Figure 6.

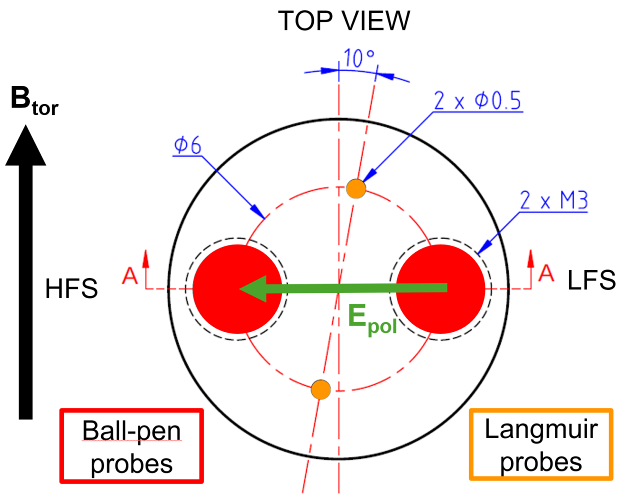


Figure 5: Dual probe-head scheme.

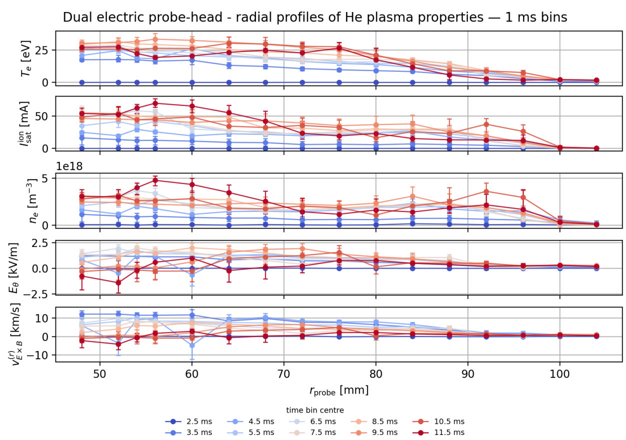
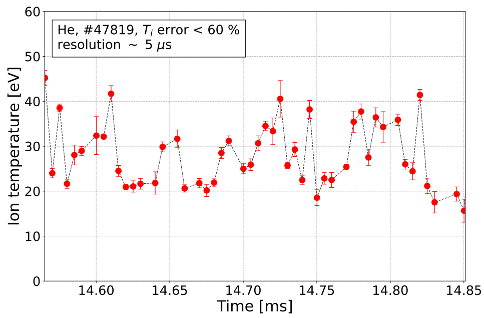


Figure 6: Radial profiles of He plasma properties #53189 – #53207.

Ultrafast ion temperature measurement. Ion temperature (T_{i}) was measured with an ultrafast temporal resolution of 5-10 μs in helium plasmas using a fast swept ball-pen probe [2], [3]. This temporal resolution falls below the typical timescales of turbulent structures (10 μs), enabling direct analysis of their dynamic evolution. Building upon previous campaigns, the data analysis is now performed using an improved, universal Python program designed for application across multiple fusion devices. This code has been successfully used to analyze data from the GOLEM, ASDEX Upgrade, and COMPASS tokamaks and is being tested on data from the Wendelstein 7-X stellarator. Time evolutions of T_{i} were obtained on the GOLEM tokamak across various discharges at different probe positions (see Figure 7). Statistical analysis of the ion temperature data reveals characteristic distributions with pronounced high-temperature tails, corresponding to positive skewness and high kurtosis [4]. The statistical properties of these unique ultra-fast T_{i} measurements on GOLEM are in reasonable agreement with a general parabolic relationship between skewness and kurtosis (K = aS^2 + b) bounded by a beta function in Figure 8. It shows and confirms that even ion temperature follows the nature of the scrape-off layer turbulence as it was previously observed on the COMPASS tokamak [3].



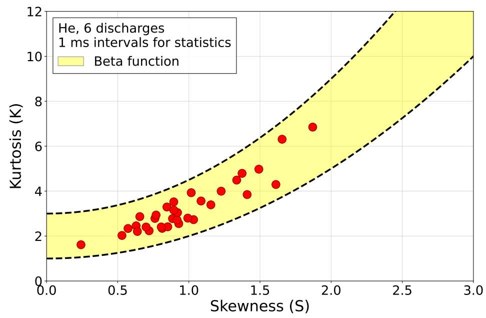


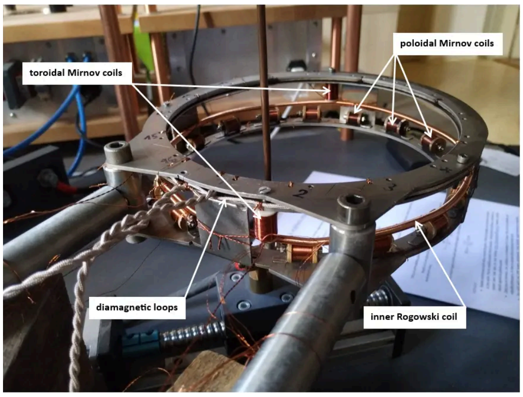
Figure 7: Measured time evolution of ion temperature.

Figure 8: Parabolic dependence of skewness and kurtosis.

Development of a new diamagnetic diagnostic. A diamagnetic diagnostic has been installed on the GOLEM tokamak to enable estimates of plasma stored energy and energy confinement time. The system consists of coaxial diamagnetic flux loops mounted inside the vacuum vessel, an in-vessel Rogowski coil for plasma current measurement, and a Python-based analysis framework for automated signal processing and integration with the GOLEM database.

The main challenge is the extraction of the small diamagnetic contribution from the dominant vacuum magnetic field. Several compensation schemes are therefore being investigated, including two coaxial diamagnetic loops operated in a differential configuration, a diamagnetic loop combined with a Mirnov coil measuring the local toroidal magnetic field, and a newly installed compensation coil. Their performance is currently being compared using dedicated vacuum and plasma discharges.

The present work is focused primarily on diagnostic validation and optimization of the vacuum-field compensation. The original in-vessel Rogowski coil exhibited construction-related issues affecting the measured plasma current signal and was subsequently damaged by an electrical short circuit. A new vacuum-compatible Rogowski coil was therefore designed and is currently being manufactured. Several improvements of the diagnostic hardware have already led to a substantial reduction of the signal noise. Nevertheless, the remaining noise still limits the quality of the vacuum-field compensation, and reliable estimates of plasma stored energy have not yet been obtained. Future work will focus on further noise reduction, optimization of the compensation procedure, and validation of the diagnostic using the new Rogowski coil.



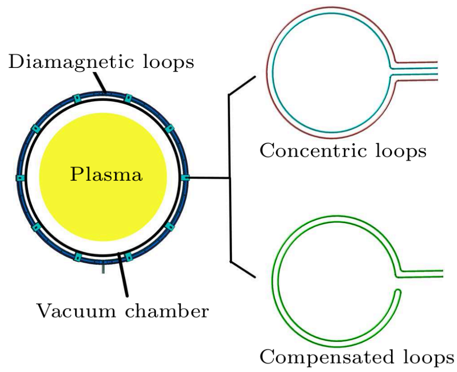


Figure 9: The assembled diamagnetic diagnostic.

Figure 10: A schematic of the diamagnetic diagnostic.

Acknowledgements This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS25/160/OHK4/3T/14.

Bibliography

[1] P. Macha and others, "Dual electric probe-head for transport barrier and fast ion temperature studies on GOLEM," *Nuclear Fusion*, vol. 63, no. 10, p. 104003, 2023, doi: 10.1088/1741-4326/acf1af.

[2] J. Adámek and others, "Fast ion temperature measurements with ball-pen probes on GOLEM," *Nuclear Fusion*, vol. 61, no. 3, p. 36023, 2021, doi: 10.1088/1741-4326/abd41d.

[3] D. Cipciar, J. Adamek, J. Horacek, J. Cavalier, and M. Hron, "Statistical properties of ion and electron temperature fluctuations in the edge of the COMPASS tokamak," *Plasma Physics and Controlled Fusion*, vol. 64, p. 55021, 2022, doi: 10.1088/1361-6587/ac5a0b.

[4] O. E. Garcia, "Stochastic Modeling of Intermittent Scrape-Off Layer Plasma Fluctuations," *Physical Review Letters*, vol. 108, p. 265001, 2012, doi: 10.1103/PhysRevLett.108.265001.