Tokamak GOLEM for fusion education - chapter 15

J. Vinklarek[1], S. Abbasi[1], G. C. Amanekwe[1], J. Buryanec[1], J. Brotankova[1], J. Cerovsky[1,2], J. Chlum[1], O. Ficker[1,2], D. Kropackova[1], L. Lobko[1], S. Malec[1], P. Macha[1,2], M. Odlozilik[1], M. Pokorny[3], V. Svoboda[1] , M. Tunkl[1]

[1] *Faculty of Nuclear Sciences and Physical Engineering CTU in Prague, Czech Rep.*

[2] *Institute of Plasma Physics of the CAS, Prague, Czech Rep.*

[3] *Jana Nerudy Grammar School, Prague, Czech Rep.*

The GOLEM tokamak is the oldest operational tokamak in the world. Its main mission is the education of future thermonuclear fusion specialists. The GOLEM tokamak features full remote-control system [1] which extends its reach worldwide. GOLEM facilitates many student projects and theses, This contribution is devoted to current projects.

Spontaneous formation of a transport barrier within a helium plasma in a circular cross-section limiter configuration was successfully recreated and studied six years after the original experiment [2]. The formation of the transport barrier was implied primarily by a steep gradient in electron temperature (see Fig. 1) and an increasing radial electric field and shearing rate. The original experiment was enhanced by a measurement of the ion saturation current profile (see Fig. 1), which indicated plasma and impurity accumulation in the outer vicinity of the transport barrier. Preliminary analysis of fluctuations in SOL showed changes in turbulence properties, including both blob size and amplitude, and is to be improved by a new experiment with higher spatial resolution.

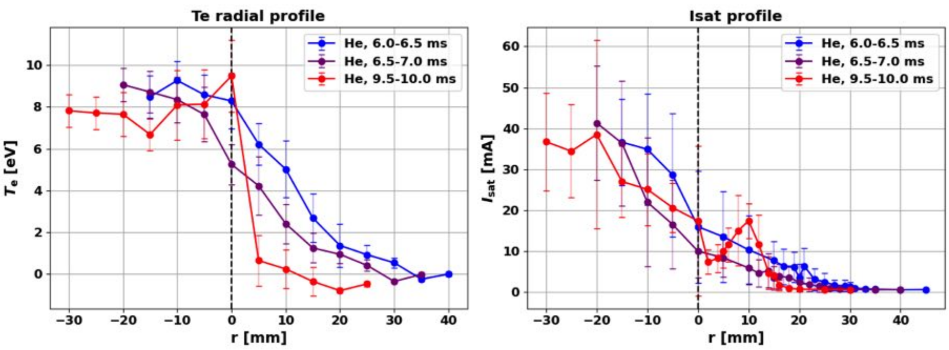

Figure 1: Left) Electron temperature profile. Right) Ion saturation current profile.

With the increasing possibilities of controlling the position of the plasma column and thus making more unique discharges, the current method of identifying the existence of plasma during discharge using characteristic drops in the loop voltage diagnostics is no longer sufficient.

Thus, a new **plasma detection method was successfully implemented using a photodiode signal** that is resistant to electromagnetic induction from stabilization coils and to various plasma behaviour.

An AdvaPIX Timepix3 detector with a 1 mm Si sensor has been installed on the Golem tokamak. The detector is included in the standard diagnostics for radiation detection. Thanks to improved data analysis and good temporal resolution of individual interactions, it is possible to monitor X-rays activity during the discharge. Now this resolution is set to 100 ns. It is shown in Fig. 2, where the deposited energy in the detector sensor during discharge #45502 and the total energy spectrum from the given discharge are shown. Currently, the AdvaPIX Timepix3 detector with a 2 mm thick CdTe sensor is being prepared for installation in standard diagnostics.

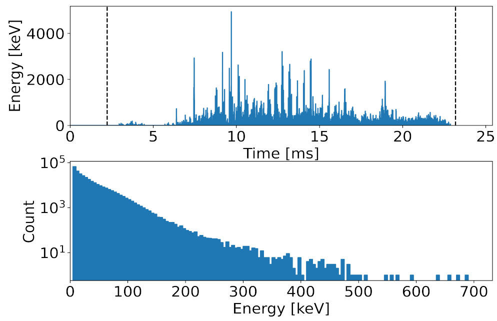

Figure 2: Energy deposited in the detector sensor during discharge #45502 (top). Total energy spectrum of discharge #45502 (bottom).

X-ray radiation from runaway electrons (RE) was simulated in Geant4.[3] Results shown in Fig.3 indicate that the distribution of radiation can be used to estimate the position of the RE limiter strike point. Furthermore, the simulation will be used to optimize the placement of the HXR probes around the tokamak and as input for the algorithm of deconvolution of the RE energy spectra.

Progress was made in **the automatization and energy calibration of scintillation detectors** for RE diagnostics. These detectors are used for the detection of produced bremsstrahlung radiation, which is dominantly caused by runaway electron impact on the molybdenum poloidal limiter. For proper analysis of acquired data detectors need to be periodically calibrated for which automatic methods were developed. A calibrated CeBr3 scintillation detector has been included in the basic GOLEM diagnostic. An illustrative spectrum of Bremsstrahlung radiation recorded during discharge #42243 is shown in in Fig. 4.

Visible tomography is currently integrated into the standard diagnostic. The final version uses Minimal Fisher Regularization for inversion and efforts are being made to optimize various elements of the process. The tomography is implemented using Jupyter Notebook, which also serves as an easily readable introduction to tomography at GOLEM. An artificial neural network-based model for tomography has been developed and is being optimized and investigated.

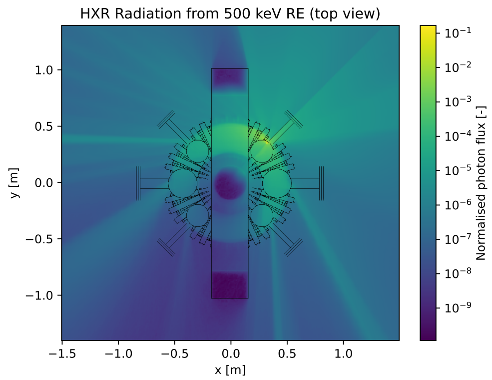

Figure 3: Distribution of HXR radiation generated from runaway electron interaction with the limiter simulated in Geant4.

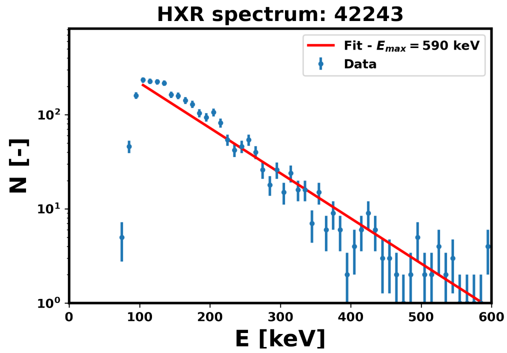

Figure 4: Example of recorded bremsstrahlung spectrum by $CeBr_3$ scintillation detector.

The tokamak assembly is now regularly recorded by fast monochromatic visible range cameras Photron FASTCAM Mini UX-50 from two angles. The aim is to detect small displacements of the coils during operation. **Motion amplification of fast camera observation** can provide useful information in this respect with low cost and low installation complexity. Neural network-based video motion magnification tools are an efficient option at this level of pixel resolution (max 1280x1024) and frame rate 2000 frames per second. For this project, specifically the software reported in [4] was used. External source of light automatically turning on at the start of the discharge sequence was introduced. Multiple moving objects in the field of view were recorded during the discharges. Most notably, the scintillation detectors placed on holders not connected to the tokamak were found to oscillate as their cover is subject to relatively strong magnetic forces. It appears that the observed toroidal filed coil consistently moved sideways by a couple of tens of microns as a shift of case edge in intensity was detected. The tool, however, requires more massive application to many discharges to prove to be able to deliver useful scientific results.

As part of the **plasma current stabilization project** on the GOLEM tokamak, it is necessary to determine the precise characteristics of the used circuits, such as the exact values of resistance, inductance, and capacitance. After studying the database with the measured values of these parameters, it was found that they were outside the estimated ranges, and it was necessary to remeasure these parameters. This was done by approximating the primary winding of the GOLEM tokamak with an RLC circuit, where it was necessary to replace the thyristor in the primary circuit with a traditional mechanical switch. This was done to measure the characteristic harmonic waveform of this circuit, from which the parameters of the circuit can subsequently be determined precisely using an analytical solution. However, more measurements need to be performed to verify the accuracy of these parameters before drawing specific conclusions.

The magnetic field measurements using the 3D MSL probe, previously utilized in studies such as [5], were conducted. During these measurements, a step-like signal was applied to the poloidal field coils, which are typically used for plasma position stabilization. In addition to the MSL probe, measurements from Mirnov Coils were also included. Both sets of measurements were subsequently compared to a simple magnetic model based on the Biot-Savart law, which does not account for effects from conducting structures like the vessel and copper shell, nor the effects of the ferromagnetic transformer core. From Fig.5, it is apparent that the model underestimates the measured data. Therefore, future comparisons against more sophisticated models incorporating the effect of eddy currents are envisaged.

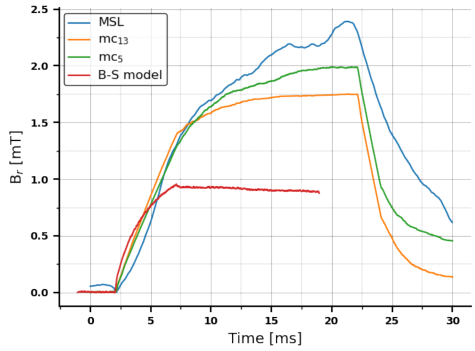

Figure 5: Radial components of the magnetic field , shot #44664

A **new system of magnetic coils** has recently been installed into the Golem tokamak and tested. The poloidal ring with Mirnov coils was furnished by an inner Rogowski coil, two inner toroidal field coils placed on the HFS and the LFS, and a diamagnetic coil. The inner Rogowski coil measures the plasma current being undisturbed by the current in the liner. Such the inner toroidal coils measure the toroidal field without the effect of the field penetrating through the liner. The most important contribution is given by the diamagnetic coil which enables to establish the energy confinement time derived from the thermal energy [6]. The output has been embedded into the GOLEM database.

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References

[1] V. Svoboda et al, Fusion Engineering and Design **68** (2011) 1310-1314

[2] P. Macha et al., Nucl. Fusion **63** (2023), 104003

[3] S. Agostinelli et al, Nuclear Instruments and Methods in Physics Research **506** (2003) 0168-9002

[4] T. Oh et al., arXiv (2018) 1804.02684

[5] K. Kovařík et al., Czechoslovak Journal of Physics, **56** (2006), B104–B110

[6] J. Brotankova et al., Czech. J. Phys. Suppl. **50** (2000)75-80 .