Tokamak GOLEM for fusion education - chapter 14

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The GOLEM tokamak is the oldest still operational experimental device in the high temperature tokamak plasma physics. Currently, its main mission is to be an educational device to train future thermonuclear fusion specialists. GOLEM is unique thanks to its remote-control system [1], which allows to carry out the discharge and instantly process experimental data remotely. This contribution is devoted to the current projects:

The distribution of REs in SOL was measured with two semiconductor strip detectors. Setup with two opposite-oriented sensors (see Fig. 1) was chosen so it is possible to observe trapped particles and RE backscattering from the limiter. During the discharge, REs are usually detected near the limiter edge or with a uniform distribution (Fig. 1, right side, 3.2 - 11.8 ms). At the end of the discharge, most of the energy is typically deposited on the LFS side of the limiter (12 ms).

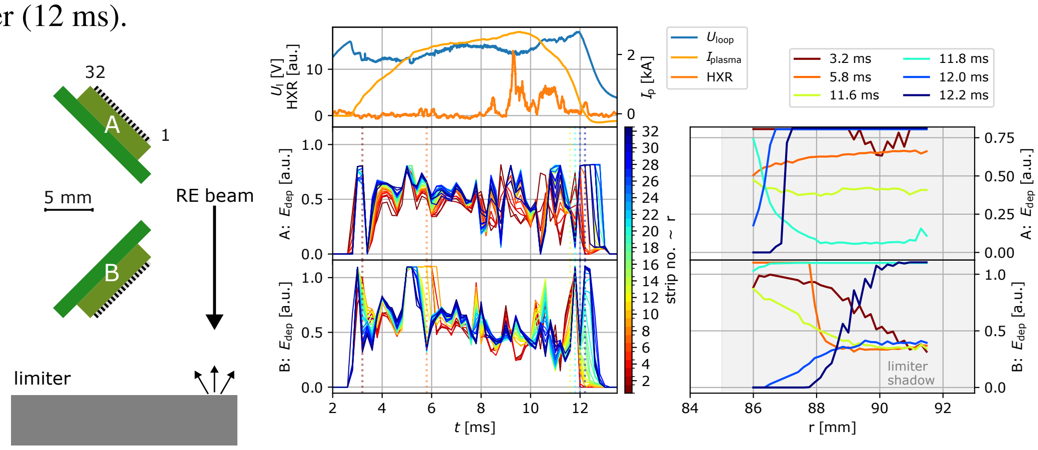

Figure 1: Left) Schematic of two detectors for measurement of RE distribution. Right) Deposited energy in the strip detectors on the left and resultant distribution RE on the right.

The 26.5 – 40 GHz ECE radiometer was placed radially on LFS at GOLEM. Due to low electron temperature and density in the GOLEM tokamak, the ECE radiometer cannot be used for electron temperature measurements. The radiometer is, however, sensitive to non-thermal high energy electrons and allows simulating radiation from plasma as a combination of single electron radiation. Matching this model to experimental signal via variation of electron energy distribution function gives possibility to estimate the distribution function.

According to HXR measurements, the distribution can be expressed as $f \sim e^{(-E/E_0)}$, and E_0 can be estimated from comparison of simulation and experiment. The Fig. 2 demonstrates matching of shape for experimental and simulated signal with $E_0 = 4\text{e}4$ eV before 9.2 ms of the discharge and $E_0 = 1.8\text{e}5$ eV afters. Comparison of obtained distribution functions with HXR distribution is also presented..

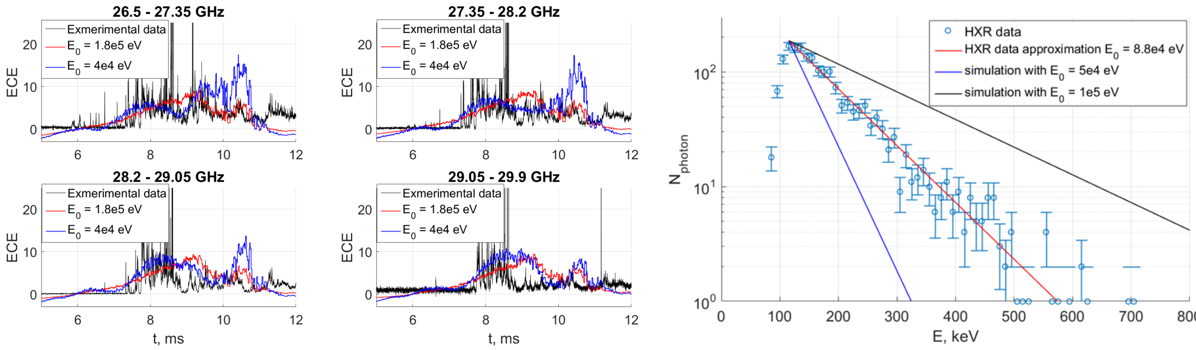

Figure 2: Left) Comparison of thin plasma model and experimental ECE signal. Right) Comparison of HXR energy distribution and electron energy distribution from ECE measurements.

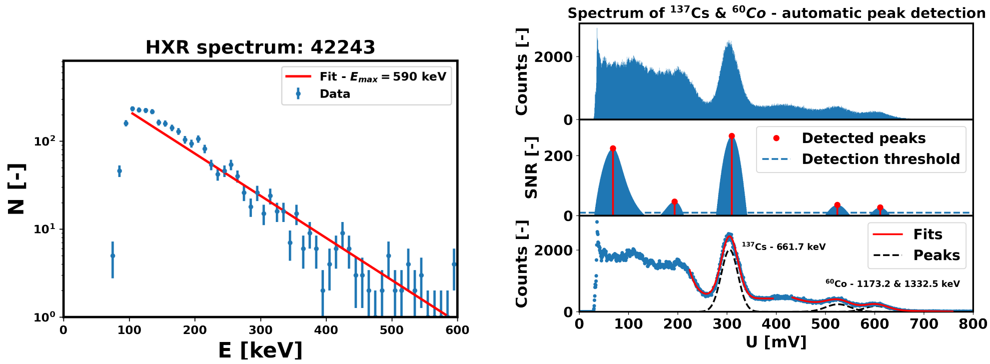

Figure 3: Left) Example of recorded bremsstrahlung spectrum by $CeBr_3$ scintillation detector. Right) Detector energy calibration.

One of the diagnostics routinely used at the GOLEM tokamak **dedicated to runaway electron investigation, is a pair of scintillation detectors** with $CeBr_3$ crystals ($1'' \times 1''$). These detectors are used for detection of produced bremsstrahlung radiation, which is dominantly caused by RE impact on the molybdenum poloidal limiter. For proper analysis of data, detectors need to be periodically calibrated. For this purpose, methods for automatic peak detection in the measured spectrum were explored and applied to calibration data (Fig. 3). An illustrative spectrum of bremsstrahlung radiation recorded during discharge #42243 is shown in In Fig. 3.

An educational video about the GOLEM tokamak vacuum system was created as the first in a newly emerging series serving as an introduction and an overview of the systems and diagnostics of the GOLEM tokamak [2]. The series is intended as an introduction to the tokamak technology for both students and a wider audience. The following episode is planned to provide a brief global summary of the essential components of the GOLEM tokamak, the necessary theory, working principle and their purpose.

Plasma current stabilization is being implemented on the GOLEM tokamak. Currently, we are unable to achieve a constant plasma current for a longer period of time, which is referred to as flat-top. The goal of this project is to control the plasma current using current amplifiers. To verify this technological solution, a table-top experiment was conducted, in which control of current through the chamber was simulated. The results can be seen in Fig. 4. Currently, the first tests of the current amplifier on the GOLEM tokamak are underway.

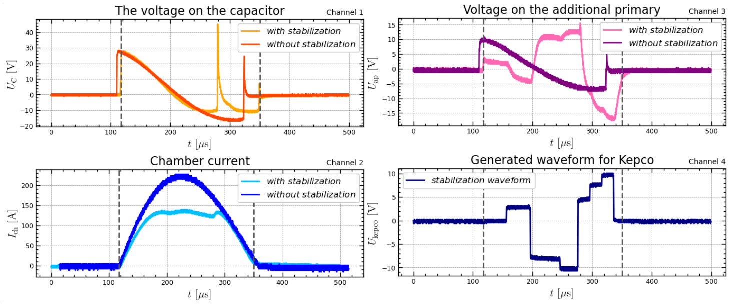

Figure 4: Table-top experiment data with and without the use of current amplifier stabilization.

A Compton Camera was created from a Timepix3 detector with a 2 mm thick sensor from CdTe. A schematic of the detector position is shown in Fig. 5. 50 discharges (#39048 to #39097) were analyzed. The reconstruction of Compton scattering and absorption was performed on an imaging plane 304 cm away from the detector. Here, the results are given only for the 100-150 keV interval in which the best resolution was achieved. A 2D deconvolution filter is applied to the image obtained by reconstructions. Fig. 5 shows the resulting deconvoluted image of reconstructions overlaid with a photograph taken from perspective of the detector.

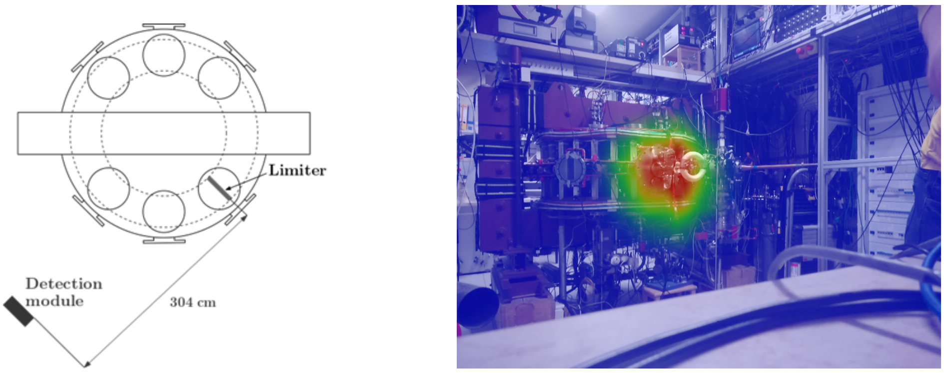

Figure 5: Left) Schematic representation of the detector position in the laboratory. Right) Overlay of a photograph from view of the detector and the deconvoluted image of the reconstructions.

Plasma position and magnetic field were simulated via NICE, a numerical code capable of plasma equilibrium reconstruction [3]. The regimes static inverse and static direct of NICE were implemented for GOLEM. A virtual model of GOLEM was introduced, in which the toroidally asymmetrical iron core and primary transformer coils were modelled by a central iron column, presented in [4], and a central solenoid. Optimal central solenoid parameters were determined via simulation comparison with experimentally measured currents in primary transformer coils. A graphical user interface was created for the use of NICE on GOLEM. Currently, NICE simulations produce equilibrium configurations typical for GOLEM (see Fig. 6), which has been confirmed by comparison with experimental measurements of plasma position.

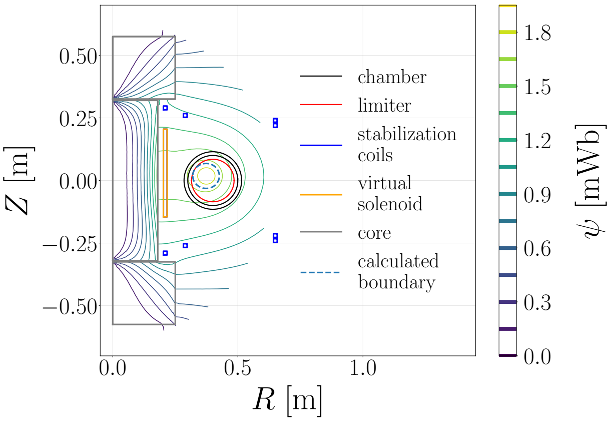

Figure 6: Example NICE simulation for typical GOLEM parameters.

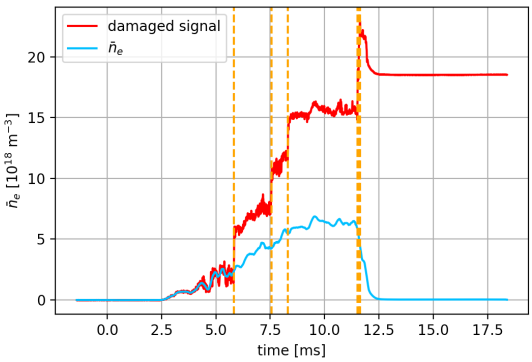

Figure 7: Comparison of the damaged (red) and the repaired (blue) n_e signal, shot #38400.

Interferometric diagnostics are routinely used in tokamaks to evaluate a line-averaged electron density n_e. Unfortunately, current diagnostics setup works properly only in the modest tokamak GOLEM regime. Especially with a rising plasma current, a short waveform of the probing beam can often be lost, causing a very high unphysical phase shift and a steep rise of n_e, as is shown in the Fig. 7, yellow dashed lines. This phenomenon is easily detected when the n_e does not drop to zero after the plasma disruption. As a temporary solution, a control code was written, which detects this defect and repairs the n_e (the blue line).

Visible tomography was implemented using minimum Fisher regularization using data from two fast cameras observing one poloidal cross-section of GOLEM. Two new, colour cameras have been installed and calibrated using a novel lens and geometry calibration method utilising 3D scanning. Visible tomography is currently being used in tandem with spectrometry data in studies of impurity injection and plasma-wall interactions.

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References

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