Tokamak GOLEM for fusion education - chapter 9

V. Istokskaia[1], M. Shkut[1], J. Cerovsky[1,2], M. Farnik[1,2], O.Grover[1,2], L. Hudec[1], P. Macha[1], J. Krbec[1,2], V. Svoboda[1], J. Stockel[1,2], J. Adamek[2]

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

[2] *Institute of Plasma Physics AS CR, Prague, Czech rep.*

The GOLEM tokamak, located at the FNSPE CTU in Prague, is the oldest tokamak in the world still in operation. 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.

Direct observation of the Anomalous Doppler instability by the Ball-Pen Probe. Low density discharges ($n_e \sim 10^{18} m^{-3}$) in the GOLEM tokamak usually exhibit an Anomalous Doppler Instability (ADI) [1], manifested by spikes of the loop voltage. This occurs when a sufficient amount of runaway electrons is generated. An example of a typical runaway discharge is shown in Fig.1. Three large positive spikes are observed in the loop voltage, accompanied by

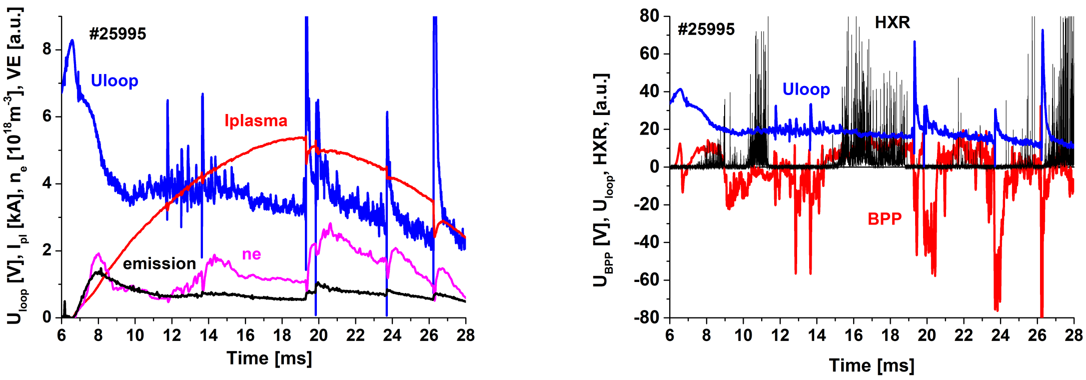

Figure 1: Left: Temporal evolution of a low density hydrogen discharge (#25995). Right: Temporal evolution of plasma potential at r = 70 mm and of the HXR emission. The loop voltage is plotted for reference.

a prompt increase of visible plasma emission followed by an increase of the line average density. This is a signature of an enhanced plasma wall interaction during ADI. The edge plasma is studied by the Ball-Pen Probe (BPP), which measures nearly exactly the plasma potential Φ [2]. The right panel compares the signal of the BPP with the signal of a HXR sensor. We observe strong HXR activity, which corresponds to the interaction of runaway electrons with the first wall. The HXR signal disappears before the ADI, which is interpreted as conversion of parallel velocity of runaways to the perpendicular one [1]. At the same time, significant negative peaks of the plasma potential are observed by the BPP located at r = 70 mm. However, this negative plasma potential occurs only at several as follows from its radial profile obtained radii of the plasma column during the ADI, on a shot-to-shot basis plotted in Fig.2.

The plasma potential Φ is elevated only inside the last closed magnetic surface (defined by the poloidal limiter with a = 85 mm). This implies a formation of a quite strong negative radial electric field $E_r = -d\Phi/dr \sim -5$ kV/m in a narrow region ($\Delta r \sim 5$ mm) at the plasma edge, which is not attached to the limiter. This should lead to a transient poloidal rotation due to the $E_r \times B_{tor}$ drift in this region.

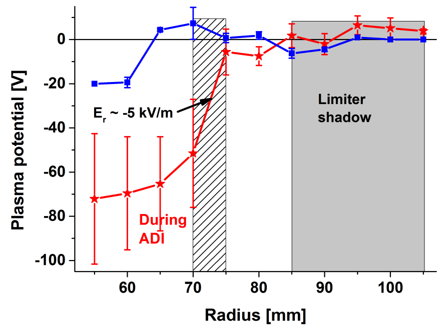

Figure 2: Radial profiles of the plasma potential during the appearance of the Anomalous Doppler Instability.

Runaway electron studies. Due to the low electron density (4-6$\cdot10^{18}$m^{-3}) and relatively high loop voltage (4-6 V), runaway electrons (RE) are recorded during almost every shot in the GOLEM tokamak. The detection is carried out mainly by a scintillator detector (NaTl), which records hard X-ray radiation (HXR) induced by the interaction of RE with the limiter.

According to the recent measurements, the influence of the condition of the first wall of the tokamak may have a considerable influence on RE generation. Using the so called "training" method, which means gradual running of discharges, the decreasing trend in the RE generation was observed during the experimental sessions. This behavior is attributed to the improving condition of the wall and cleaner plasma with smaller presence of impurities shot-by-shot. In

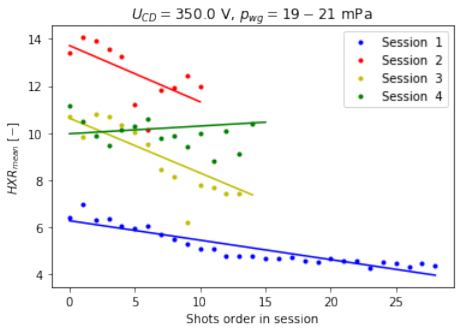

Figure 3: Evolution of the mean intensity during chosen sequence of discharges.

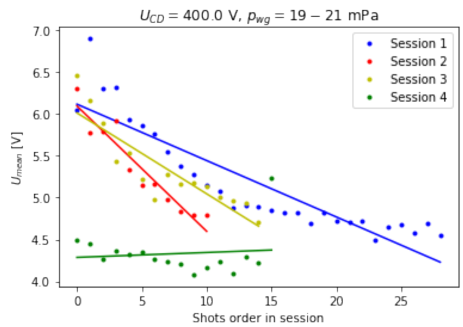

Figure 4: Evolution of the mean value of loop voltage during chosen sequence of discharges.

Fig. 3 the evolution of the mean intensity of the HXR radiation (HXR_{mean}) for chosen experimental sessions is displayed. It has a decreasing trend with the increasing number of discharges in the session. The evolution of the mean value of the loop voltage (U_{loop_mean}), which is shown in Fig. 4, is also decreasing during the experimental sessions, which implies an improvement of the plasma performance.

Additionally, the studies of RE include determination of the experimental value of the critical electric field in the GOLEM tokamak, which is defined as a minimum E-field required to generate any runaways. Theoretically, it can be approximated as $E_{crit} = 0.08 n_{20}$ [4], where n_{20} is the plasma electron density in units of 10^{20} m^{-3} (assuming that the only possible loss mechanism is collisional damping), but recent measurements demonstrated that this relation may be underestimated. It was discovered, that for GOLEM the theoretical prediction is 3 - 10 times below the experimentally measured critical E-field, meaning that other loss mechanisms than collisional damping controlling the dynamics of RE may be present.

Plasma radiation studies. The investigation of plasma radiation in the GOLEM tokamak can be used for the determination of important parameters such as the electron temperature or the density. By applying the coronal-radiative model, the electron temperature can be obtained by means of spectral intensity ratios gained from the equations for the emissivity of transitions. The photon emissivity coefficients were taken from the ADAS-OPEN database. The intensity ratios of helium spectral lines 668.00 nm, 706.76 nm and 728.33 nm and hydrogen spectral lines 433.99 nm, 486.06 nm and 656.19 nm, were used to estimate the electron temperature and density. Theoretical models of spectral line ratios of hydrogen and helium are shown in Fig. 5 and 6. These models were applied to measured experimental data and the results were compared with other methods commonly used at the tokamak GOLEM, e.g. the Spitzer formula, estimating the temperature from spectroscopy data. Fig. 5 shows that isolines of two different ratios of spectral lines for hydrogen are not perpendicular enough and measured data do not indicate reasonable results. The electron temperature calculated from helium spectral lines ratios is compared with results from another methods. This method based on the coronal-radiative model seems to be valid for helium, but improvement and calibration are needed to achieve a higher accuracy of measurement of spectral lines intensity.

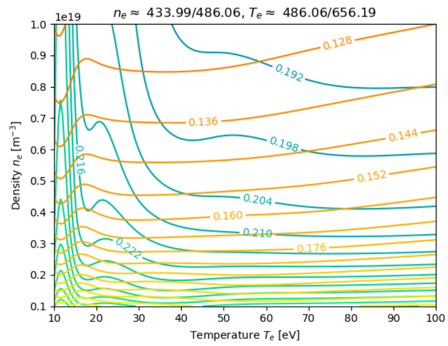

Figure 5: Model of line ratios of H.

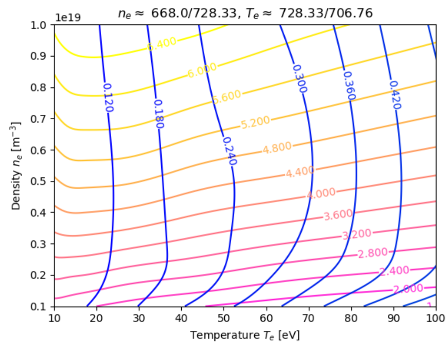

Figure 6: Model of line ratios of He.

Density dependence on other parameters of the plasma. No influence the of working gas pressure p_{ch} was observed in the GOLEM tokamak plasma. This led to the complex measurement of dependence of other plasma parameters on density, such as the chamber condition, chamber temperature T_{ch}, plasma current I_p, etc. Based on these measurements, a guide for achieving a specific electron density value during the discharge and for realization of shot-to-shot density scan was produced. Strong influence of the plasma current was found during this research.

The remote web control-room interface [5] of the GOLEM tokamak has been redesigned in order to provide a wizard-like walk-through and a more visually pleasing experience. The interface also requires the knowledge of an access token, further securing the operation of the device. The control page guides the user through the setup procedure (in order: working gas, pre-ionization, magnetic field and current drive capacitor charging). All steps, settings and their effect are clearly explained on the page. At each step the user selects a value of some numeric parameter and/or a given option with a checkbox. The "Set recommended value" button can be used to select a predefined setting. Then the user moves to the next step by clicking the "Next" button. The final "Submit" step is where the selected discharge configuration is submitted into the discharge request queue along with a comment describing the configuration (i.e. the scientific aim). The new interface also features a new Live real-time view page which shows a combination of the current values measured by the pressure gauges, voltage on the capacitor banks embedded in the engineering scheme together with a Live view of the reactor room and the the chamber through IP cameras and the discharge request queue.

Plasma current control. The GOLEM tokamak is currently not able to achieve a flat-top plasma current regime, due to its capacitor powered current drive circuit. However, a flat top regime can be achieved through the precise shaping of the resistance value by adding additional resistors to the circuit. A simple numerical code for vacuum discharge modeling has been developed, along with the physical tokamak table-top model. This model is based on the numerical solution of the transformer circuit differential equations, extended by equations for the magnetic flux to account for the iron-core saturation. Obtained results are in a good agreement with the experimental data. Additionally, an algorithm for the resistance shaping sequence design was implemented and tested.

Acknowledgement: This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS17/138/OHK4/2T/14.

References

[1] V.V. Parail, O.P. Pogutse, Nuclear Fusion, **18**, 3(1978)

[2] J. Adamek et al, Contributions to Plasma Physics, **54**, 3, p. 279, (2013)

[3] J. Adamek, et al., Rev. Sci. Instr. **87**, 043510 (2016)

[4] R.S. Granetz et. al., Physics of plasmas, **21**,7: 072506 (2014)

[5] V. Svoboda, et al., Fus. Eng. and Des.**68**, 1310-1314 (2011)