Tokamak GOLEM for fusion education - chapter 10

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The GOLEM tokamak is the oldest tokamak in the world. Currently, it is located at the FNSPE CTU in Prague and it serves mainly as an education device for students of tokamak physics. Remote control of the machine enables conducting experiments from all over the world using an internet connection. This contribution summarizes main research topics of study of the last year.

Calibration of the ball-pen probe and measurements of plasma parameters in H and He plasma. The principle of the ball-pen probe calibration lies in a simple equation: $\alpha = \frac{\Phi - U_{\mathrm{float}}}{T_{\mathrm{e}}}$, where Φ is the plasma potential, U_{float} is the floating potential, T_{e} is the electron temperature and α is a calculated calibration coefficient [1]. The combined probe head, installed on a movable manipulator in the radial direction in the tokamak, is composed of a Langmuir and a ball-pen probe. The electron temperature T_{e} and the floating potential U_{float} were calculated from IV characteristics of a biased Langmuir probe using the shot-to-shot method. The plasma potential was measured by the ball-pen probe. The data were then fitted using the equation $I = I_{\mathrm{sat}}(1 - \exp((U - U_{\mathrm{float}})/T_{\mathrm{e}}))$, where T_{e} and U_{float} are unknown. Then, Φ, U_{float} and T_{e} are used to calculate α.

To find out if there is any linear dependency of α on B_{t}, a statistical analysis was conducted as well. Firstly, dependency of α on B_{t} was fitted by a linear function. Then correlation coefficient and its level of significance was determined. Standard deviation and 95% confidence intervals were calculated as well to control the quality of the fit. The statistical analysis results showed that some linear dependence of α on B_{t} is probable. These measurements were conducted for both H and He plasmas, where for He plasma it was the first measurement of its kind. The final dependence of α on toroidal magnetic field B_{t} in the tokamak is shown in Figure 1.

To sum up the results, for H plasma the calibration coefficient $\alpha = (2.5 \pm 0.7)$ or, if a linear dependency is considered, $\alpha(B_{\mathrm{t}}) = 1.89B_{\mathrm{t}} + 1.85$. For He plasma $\alpha = (1.8 \pm 0.4)$ or $\alpha(B_{\mathrm{t}}) = 1.47B_{\mathrm{t}} + 1.49$. Knowledge of the calibration coefficient α may prove useful in measurements of the fast electron temperature using both Langmuir and ball-pen probe. The temperature is then equal to $T_{\mathrm{e}} = \frac{\Phi - U_{\mathrm{float}}}{\alpha}$.

Impact of swept edge plasma potential biasing on turbulence in tokamaks. Understanding of plasma turbulence is one of the keys to improving confinement in fusion

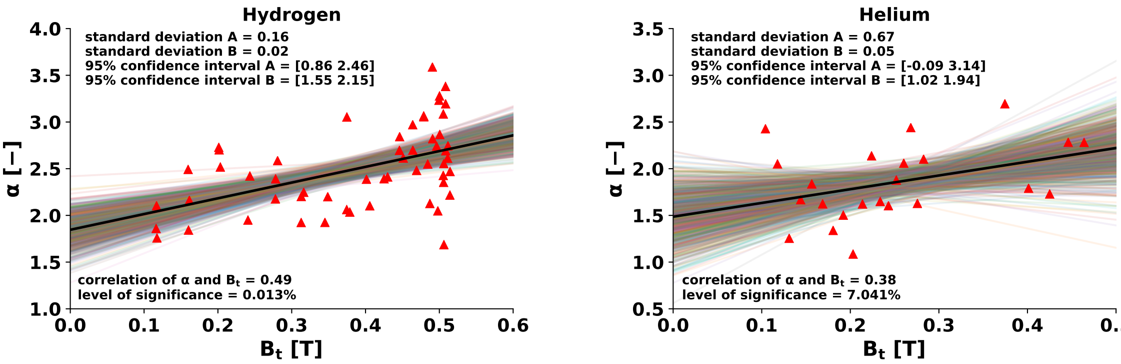

Figure 1: Dependence of the calibration coefficient α on toroidal magnetic field B_{t} in H (left) and He (right) plasma including statistical analysis.

devices, as turbulent transport is responsible for the majority of energy and particle losses in tokamaks. Recent approach to the turbulence is via zonal flows and is referred to as the "drift wave–zonal flow turbulence paradigm". Since zonal flows are induced by the $\mathbf{E} \times \mathbf{B}$ drift, they can be generated by inducing an edge electric field with edge plasma biasing.

Following recent experiments conducted on the ISTTOK tokamak, where oscillatory zonal flows called GAMs were stimulated using AC edge plasma biasing, similar measurements using a double rake probe were performed on the GOLEM tokamak. As a consequence of experiments and simulations describing GAMs and their impact on turbulence, well-defined frequency of GAMs was derived as $f_{\mathrm{GAM}} = \frac{c_{\mathrm{s}}}{2\pi R}$, where c_{s} represents the sound wave velocity and R represents the major radius of the tokamak [2].

Assuming $T_{\mathrm{e}} = T_{\mathrm{i}}$, the sound wave velocity was estimated as $c_{\mathrm{s}} = \sqrt{\frac{\mathrm{k_B} T_{\mathrm{e}}}{m}}$, where $\mathrm{k_B}$ is the Boltzmann constant and m is the hydrogen ion mass. Around the radius $r = 70$ mm the electron temperature is $T_{\mathrm{e}} = 18$ eV, resulting in the expected GAM frequency $f_{\mathrm{GAM}} \approx 16$ kHz. Two KEPCOs model BOP 36–12M connected as master and slave were used as a power supply capable of providing a sinusoidal waveform with a frequency of up to 20 kHz and current and voltage up to 12 A and 72 V.

Series of shots with the double rake probe in U_{float} regime were performed to describe the plasma response to different biasing frequencies from 5 to 20 kHz and applied voltage from 0 to 64 V. Wavelet transform coherence of the probe signal and the corresponding applied bias voltage was used to determine whether or not the measured U_{float} was affected by biasing. In the coherence spectrum, it was apparent that the applied bias voltage is coherent with the fluctuations of U_{float}. It was supported by a slight growth of the mean of the signals, compared with a shot where no bias was applied (see Figure 2).

Development of a probe for runaway electrons energy measurement. Due to its high loop voltage and low electron density, the GOLEM tokamak present good experimental conditions for the study of the runaway electrons (RE). One of our research

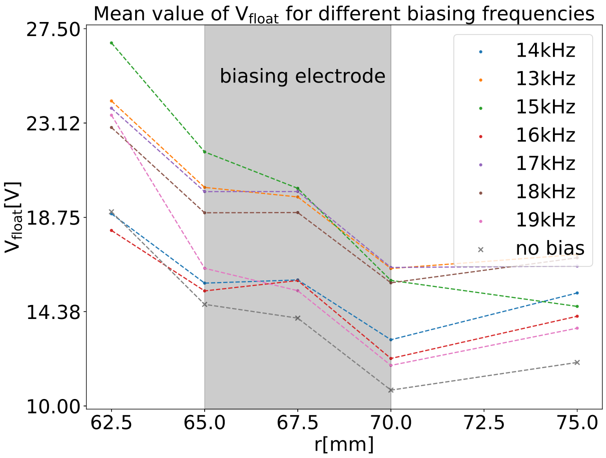

Figure 2: Radial profile of mean value of the floating potential U_{float} measured on the shot-to-shot basis where an AC biasing with different frequencies was applied.

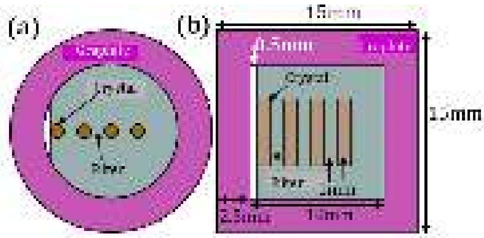

Figure 3: a) top view b) side view of the probe. The housing is shown in violet color, scintillating crystals are shown in brown and the absorbers (filters) in gray.

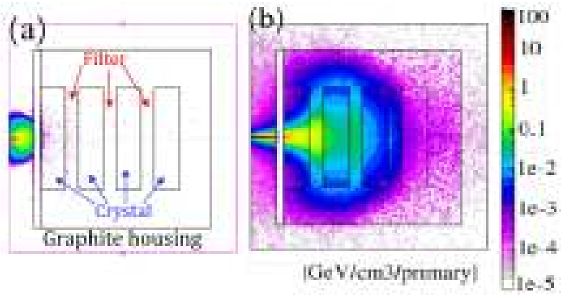

Figure 4: Energy deposited in the probe by a) 1 MeV electron beam, b) 10 MeV electron beam.

topics is the development of a probe for RE energy measurements inside the tokamak in the vicinity of the plasma edge, on the basis of the previous research [3]. The probe is based on scintillating materials alternating with heavy absorbers covered by a temperature resistant graphite housing. The probe scheme is shown in Figure 3.

Using the Monte Carlo code FLUKA [4], it is possible to model the probe geometry and to perform simulations of the interactions between the probe and the incident electron beam of different energies. Various materials of scintillators and absorbers were examined in the simulations using 1 MeV and 10 MeV monoenergetic electron beam. The RE energy deposition was scored in the probe for each design configuration.

An example of the energy deposition in NaI(Tl)+Stainless Steel design is shown in Figure 4. As can be seen, 1 MeV deposition is stopped already in the housing, which indicates that the GOLEM RE may have energies much higher than this value, since HXRs, generated in the RE interaction with the chamber, are generally observed outside the tokamak, being energetic enough to propagate through it. The optimization of materials and design is still ongoing.

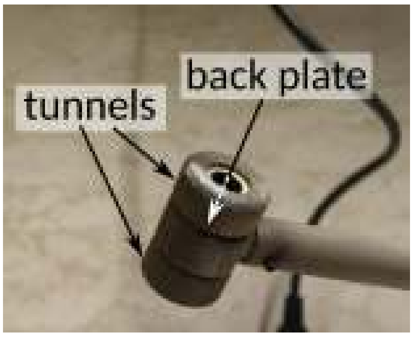

Figure 5: Double tunnel probe used in the GOLEM tokamak.

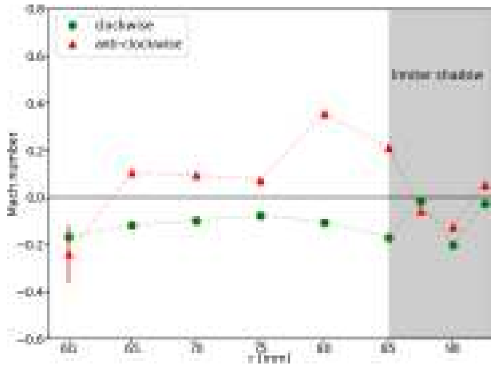

Figure 6: Mach number profile.

Double tunnel probe for measuring Mach number profile. A double tunnel probe installed at the lower tokamak port was used to gauge the effect of field reversal on the toroidal Mach number. The toroidal magnetic and electric field were oriented parallel to one another; the standard configuration is both fields clockwise and the field-reversed configuration is both fields anti-clockwise. The findings confirmed previous results from the TCV tokamak [5]: the plasma flows counter to the plasma current in the confined plasma, with the Mach number reaching values $M = 0.1$–0.4 (see Figures 5 and 6). The results were published in the form of a competitive high-school student research thesis (SOČ) which took the 11th place in the Physics category of the national round.

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