Tokamak GOLEM for fusion education - chapter 4

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Tokamak GOLEM is a small tokamak operating at the Faculty of Nuclear Sciences and Physical Engineering at the Czech Technical University in Prague. It has been serving for four years as an educational device for training students in fusion research. One of its essential features is the possibility of fully remote operation so it suits to international experiments with broad participation.This contribution concludes the main headlight topics of the last year.

Gomtraic

The GOlem reMote TRAIning Course (GOMTRAIC) is an education and training course meant for University students who want to get experience with operating of a fusion device. The Gomtraic 13 had a in-situ part, where the students could come for one week and get experience with the tokamak, take first measurements, and present first results.19 students participated from 8 different countries, exploiting remote operation possibility of the tokamak. Of those, 8 personally attended kick-off week in Prague. The course covered 6 different topics of tokamak physics and operation.

Plasma stabilization

The feed-back control of a plasma position system is being created on the GOLEM tokamak at the present. The plasma position is measured using 4 Mirnov coils placed at $b = 93$ mm from the minor axis of the tokamak, at poloidal angles of $\theta = 0, \pi/2, \pi, 3\pi/2$.

Vertical plasma position is controlled using horizontal magnetic field generated by four poloidal field coils. The vertical displacement of the plasma is processed in a computer by a program written in LabVIEW which integrates signals from Mirnov coils and calculates the vertical displacement with a frequency of 50 kHz. Output of this program is connected to the voltage source through a D/A converter. Voltage source drives current in the poloidal field coils system.

Comparison of two typical shots with feedback stabilization system and without is plotted in fig. 1. It is seen that stabilization affects the plasma position and prevents its upwards motion. The average prolongation of the plasma life was over 2 ms. However, there are pending issues with Mirnov coil signal integration, which are planned to be solved in the future. Meanwhile,

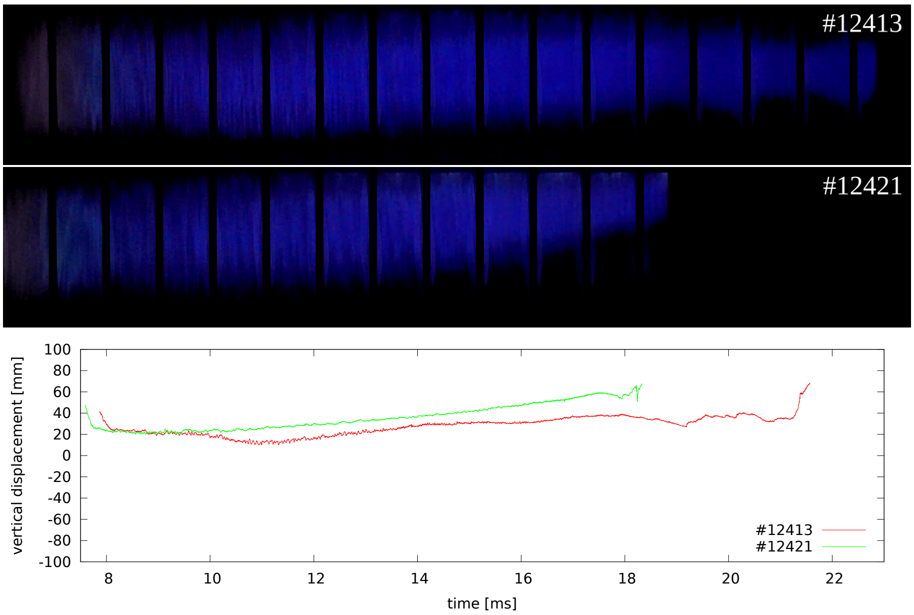

Figure 1: *Evolution of the vertical displacement of plasma using fast camera. The upper image (#12413) is with the feedback stabilization, middle (#12421) is without. Bottom: comparison of their vertical displacements measured by Mirnov coils.*

changes of plasma position are taken as more relevant, rather than absolute calculated position.

MHD studies

The diagnostics means of B_θ perturbations (for detection of coherent MHD structures) have substantially improved in the course of the past year. Array of 16 Mirnov coils, installed inside of chamber on a removable mechanical manipulator, has been replaced with a new set with optimalized coil parameters [1]. Moreover, an additional set of 16 B_θ detection coils (along with mechanical manipulator of their own) of the same parameters was constructed, calibrated and installed into tokamak chamber. The latter took place within the scope of international collaboration with CICATA-IPN, Mexico. Use of detection coils of improved parameters enables clearer detection of magnetic islands present at low q regime of tokamak. Fig. 2 shows typical spectrogram of local B_θ fluctuations. Cross-correlation analysis of $14-15$ ms interval (see fig. 3) reveals typical signature of $m=3$ magnetic island rotation. Qualitatively, the results and data processing are of virtually same character as on larger devices, which turns GOLEM into a suitable student-training tokamak.

Avalanche phase at the plasma start-up on the GOLEM tokamak

Fig. 4 shows the temporal evolution of the loop voltage (unintegrated signal of poloidal flux detection loop placed on the top of the chamber) and the plasma current for #12229 in the time interval between emerging of the loop voltage and its drop.

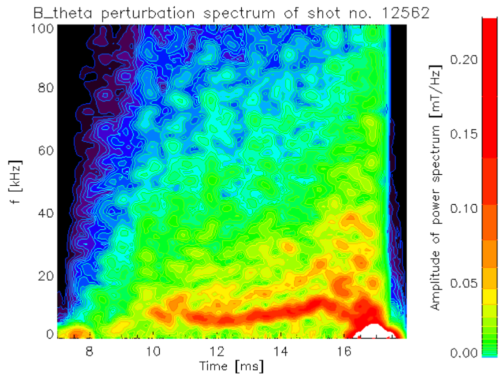

Figure 2: *Spectrogram of B_θ perturbations detected by an improved-parameter Mirnov coil located on $\theta = \pi/2$.*

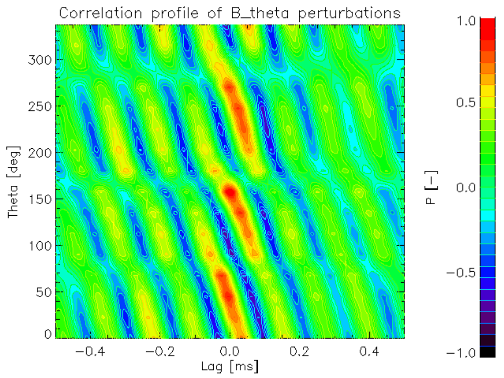

Figure 3: *Cross-correlation coefficients of B_θ perturbation signal on an array of 16 Mirnov coils. Reference coil chosen on $\theta = \pi/2$.*

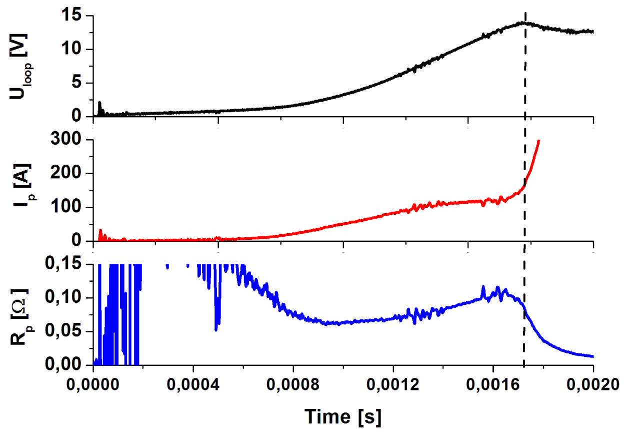

Figure 4: *Temporal evolution of the loop voltage, plasma current and the plasma resistance during the start up phase of the discharge #12229. The pressure of the working gas (H_2) is 29.3 mPa. The toroidal magnetic field is between 0.18-0.22 T.*

The plasma resistance plotted in fig. 4 is calculated as $R = U_{loop}/I_p$. In cylindrical approximation, the plasma resistance is $R_p = \rho_{\varepsilon_0} 2\pi R_0/\pi a^2$, where $R_0 = 0.4$ m is the major radius, $a = 0.085$ m is the minor radius. In weakly ionized plasmas, the plasma resistivity is inversely proportional to plasma density n_e as $\rho_{\varepsilon_0} = 5.555 \cdot 10^3 \sqrt{E n_{H_2}/n_e}$ [Ωm,V/m, m^{-3}], where $E = U_{loop}/2\pi R_0$ is the toroidal electric field, n_{H_2} is the density of the working gas [2]. Consequently, the relation between the plasma resistivity and the plasma density on the GOLEM tokamak is

$$n_e = 6.31 \cdot 10^{15} \sqrt{U_{loop} p_{H_2}/R_p} \quad [\Omega, \mathrm{V}, \mathrm{Pa}, \mathrm{m}^{-3}]. \tag{1}$$

Furthermore, the drift velocity of electrons during the avalanche phase of the discharge can be estimated from the known plasma density and measured plasma current, as

$$v_d = \frac{I_p}{e\pi a^2 n_e} = 4.3 \cdot 10^4 \sqrt{R_0} \sqrt{\frac{U_{loop}}{p_{H_2}}} \quad [\mathrm{m/s}, \mathrm{m}, \mathrm{V/m}, \mathrm{Pa}]. \tag{2}$$

Plasma density and the drift velocity calculated from eqs. 1 and 2 are plotted in fig. 5. We see

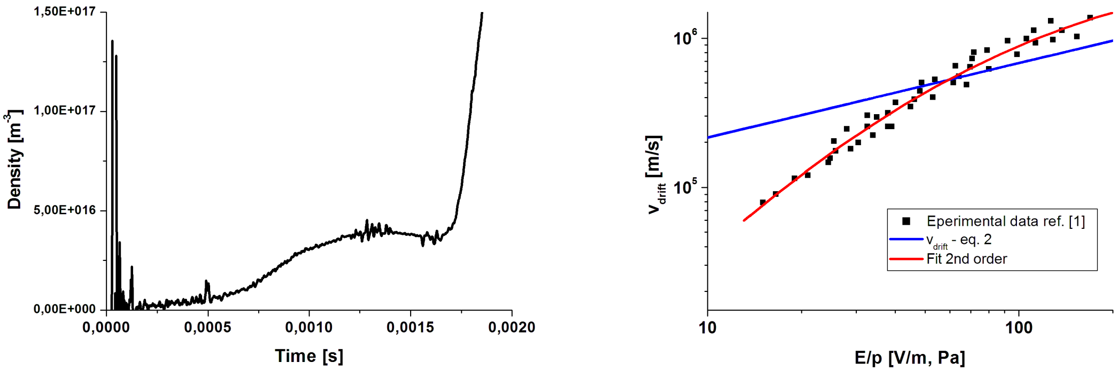

Figure 5: *Left: evolution of plasma density during the avalanche phase of #12229. Right: drift velocity versus the ratio V/p – blue line. Red line – fit to experimental data published in [3].*

that the plasma density at breakdown is in the range of $5 \cdot 10^{16}$ m^{-3}, which implies the degree of ionization is well below 1%. The electron velocity drift calculated from eq. 2 compared with experimental data measured without magnetic field and published in [3]. Reasonable agreement is achieved V/p > 50 V/m/Pa.

Dust studies

Experiments with a dust implantation into the plasma were performed on the GOLEM tokamak. The implanted particles were round 1 μm carbon dust placed on a rod. The probe was inserted to plasma at different positions, and the position of properties of radiating dust were measured using a fast camera EX-F1.

The results show that the dust velocity is strongly dumped, the initial velocity is > 50 m/s for plasma temperature around 10 eV, the dust propagates slower in denser plasmas, and that the radiation time is round < 5 ms.

Acknowledgement

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References

[1] T. Markovič, Master thesis, Dept. Of Phys., FNSPE CTU in Prague, 2013

[2] H. Prinzler et al, Czech J. Physics, B 34, 1984, p. 665

[3] V. A. Lisovski, Russian Physics Journal, No4, 1998, p. 394