Tokamak GOLEM for fusion education chapter 5

O. Ficker[1], O. Grover[1], J. Kocman[1], J. Krbec[1,2], V. Loffelmann[1], T. Markovic[2,3], M. Matusu[1], J. Stockel[1,2], V. Svoboda[1], J. Veverka[1], G. Vondrasek[1]

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

[2] *Institute of Plasma Physics AS CR, v.v.i., Prague, Czech. Rep.*

[3] *Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Rep.*

Tokamak GOLEM is one of the oldest tokamaks in the world, currently located at the Faculty of Nuclear Sciences and Physical Engineering, CTU in Prague. It serves as an educational device and all experiments and development are done by students themselves under professional supervision. This contribution covers the major improvements made over the last year.

Runaway electrons

Golem tokamak offers a remarkable opportunity to study runaway electrons (RE), thanks to its very high loop voltage (5-10 V) during the discharge. The energetic photons released during the interaction of these fast particles with the vessel wall were detected by an anorganic scintilator detector (NaI(Tl)). It was confirmed in [1], that RE production (HXR emission) decreases with an increasing pressure of the working gas. Unfortunately, Golem is presently not equipped with independent plasma density diagnostics which would be more relevant. However, typical density can be estimated from the pressure of the working gas before the discharge. Furthermore, the Dreicer field ([2]) could be roughly estimated. For a typical temperature of 20 eV and density of $2 \cdot 10^{18} \mathrm{m}^{-3}$ Dreicer field is approximately 40 V/m. Therefore, a significant number of electrons may be accelerated up to 1 MeV.

One of the important parameters that can be used to study RE is the delay between the plasma breakdown and the beginning of the HXR signal. The correlation of the magnetic field and this delay for approximately 60 discharges is in figure 1. Data indicate that there are two types of discharges. In discharges with lower magnetic field, it seems that electrons are accelerated on timescales of several ms. As magnetic field fails to confime them, they most likely drift to the edge of plasma to hit the limiter in the early phase of discharge. Their energy and number depend on the loop voltage and density,

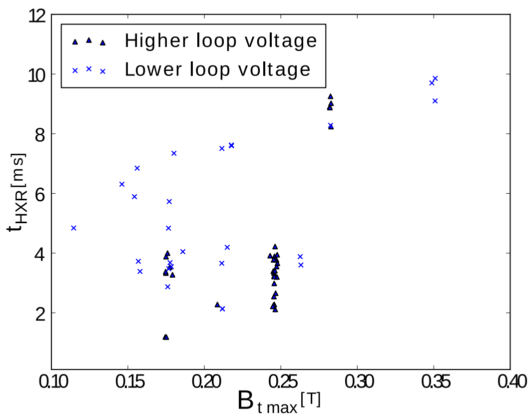

Figure 1: *Correlation of the magnetic field and the delay between breakdown and the beginning of HXR signal*

RE in discharges with a higher loop voltage generally hit the wall earlier. There is no significant change in the plasma current during the loss of electrons. The second type, with a stronger magnetic field, lose runaway electrons just before the end of the discharge, or not at all. In the case of loss, it seems that runaways are suddenly produced, because the plasma current reaches a narrow peak and then there is a strong emission of HXR. Although the loop voltage usually slightly rises during the discharge, the very short timescale of the growth of the plasma current before the HXR emission indicates that only already very fast electrons are further accelerated or there could be some local increase of electric field caused by an unspecified instability. This effect would deserve further investigation to support our hypothesis.

Microwave pre-ionization

The microwave generator operating at a frequency of 2.45 GHz and power P_{MW} 1.5 kW was used on GOLEM for pre-ionization of the working gas to reduce the loop voltage required for breakdown. Fig. 2 shows a selected set of results from experiments performed with the microwave pre-ionization

A series of discharges with the same amplitude of the toroidal magnetic field (150 mT) was performed. As it is evident from the top of Fig 2, the electron cyclotron resonance layer (BECR – 87.5 mT) occurs inside the vessel at t = 11 – 15 ms as marked by the shadowed region in Fig. 2. Than the time delay between energizing of the primary winding of the tokamak transformer and the trigger of B_t (t_{BP}) was increased on a shot to shot basis from 3 to 30 ms. It has to be emphasized that the breakdown cannot be achieved without MW. Evolutions of the loop voltage U_{loop} are plotted in the bottom of Fig.2. It can be seen that the maximum of the U_{loop}, which corresponds to the plasma breakdown, is noticeably reduced to 5 V, when the MW generator is switched on and simultaneously the ECR layer is inside the vessel, as expected. On the other hand, a successful breakdown is also achieved with significantly longer time delays, when the MW generator is already switched off at the breakdown voltage around 6 V. This implies that the ECR plasma is confined in the vessel much longer than the characteristic time of drift losses, which should be less than 1 ms. Better understanding of underlying physics would require more dedicated experiments.

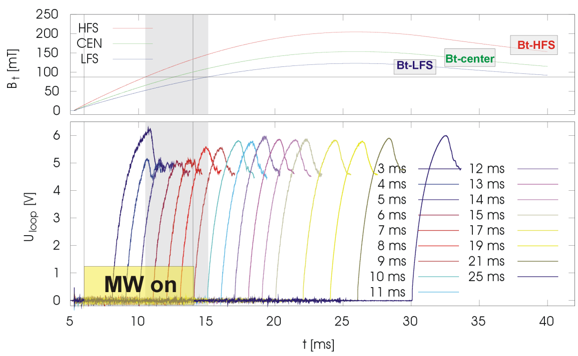

Figure 2: *Top: Temporal evolution of the toroidal magnetic field at the High and Low Field Sides of the GOLEM vessel. Bottom: Temporal evolution of the loop voltage at the start up phase in series of discharges (#13493 – #13518).*

Vertical position using fast camera

Vertical plasma position can be estimated by a pair of poloidally opposite Mirnov coils. Another possibility is to use the radiation profile measured by fast visible light cameras or bolometers which are in operation on GOLEM. Compatibility of these two methods was investigated. Fast cameras were used for measuring the radiation profile, because there is not enough data from bolometers in the database up to now. Only one of the two orthogonally looking cameras was used.

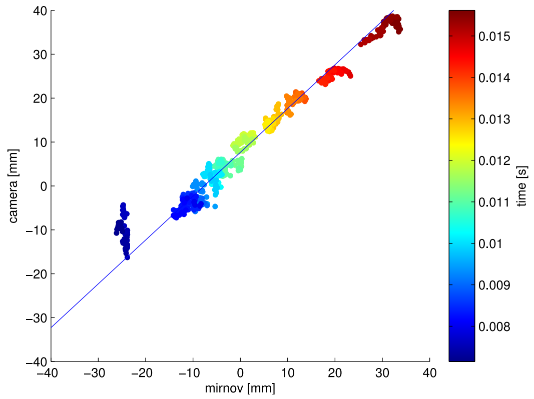

Figure 3: *Correlation of the vertical position from Mirnov coils and visible light camera for shot #12377*

The focal length of the camera is approximately ten times larger than the typical amplitude of plasma displacement. Plasma position was then estimated either by fitting a gaussian curve to the radiation profile or by calculating the center of mass of the thresholded profile. These two methods seem to produce similar results, the second one beeing faster. 20 shots between #11386 and #12384 were selected from which all required data is accessible. In most cases the plasma is steadily ascending during the shot, which was measured by both methods.

Both position estimates are strongly correlated, their mutual dependence seems to be linear even when the time dependece is nonlinear. However, the correlation is corrupted in several shots with vertical stabilisation. In these cases the radiation profile moves down, while the magnetic position estimate is still slowly ascending. Possible explanations is an inductive coupling between Mirnov coils and the feedback coils, which is not taken into account by the current algorithm.

Software reconstruction

The operating software of the device has undergone significant changes in order to make it more secure, extensible and accessible for students. The two main security improvements include task control which enforces task dependencies and ensures conflicting tasks will not damage the device (e.g. chamber cleaning and a discharge) and hardware resources control which prevents other processes from e.g. accidentally flipping a relay. The tasks are submitted to a queue and a dispatcher process runs the tasks according to the defined dependency rules (in parallel if possible), enabling users to submit e.g. a batch of discharge parameters with chamber cleaning tasks in between. The server-client model is used for user interaction which makes it possible to implement various user interfaces, from command-line scripts to web applications or stand-alone GUIs. The new operating software was written mainly in Python to make it easily readable for students and maintainable in the future. The Python source code is very intuitive and contains a large number of documentation strings and comments. The full source code is tracked using the Git version control system, documenting every change and provides an overview of development history. Students can easily clone the repository and propose their own changes which simplifies collaboration within the team. The Trac web application has been deployed to enable students to view the full source code of the operating software online and browse the history of changes and file issues.

Basic practica

Golem tokamak is a subject of several Bachelor's degree projects and Master's degree theses each year. Educational abilities of the tokamak were improved by the fact the tokamak experiments became a part of a study programme this year. Tokamak is now used in an experimental laboratory course in the basic physics curriculum. Students in second year of Bachelor's degree course engage in tokamak operation, probe measurements and analysis of measurements with basic tokamak diagnostics.

Virtual model

Virtual model of GOLEM tokamak with a real physical core is a bachelor thesis project, whose goals are to help with presentation of GOLEM and ease comprehension of basic tokamak physics by students. Graphical part is ensured by a 3D model loaded by a web page, making it easy accessible and an immediate way of presenting the tokamak. Thanks to the used programming languages (WebGL, THREE.js, etc.), which are supported by all main web browsers, there is also no need to download anything. The virtual model is extended by a few python scripts communicating with the web page on request. Those scripts are the second part of the thesis – the physical core: the simulation of physical conditions in the tokamak and their visualization in the 3D model.

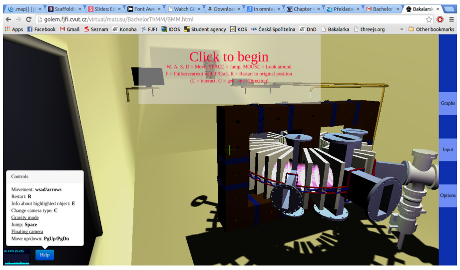

Figure 4: *Virtual model of the GOLEM tokamak accesed via a web browser*

References

[1] L. Kocmanova, Runaway electrons in the tokamak and their detection, Master Thesis at FNSPE, CTU , 2012

[2] H. Dreicer, Electron and ion runaway in a fully ionized gas, Physical Review, 1959