Tokamak GOLEM for fusion education - chapter 6

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GOLEM is the oldest operational tokamak in the world. It serves as an educational device at the Facuty of Nuclear Sciences and Physical Engineering at CTU in Prague. Several improvements of its diagnostic technology made during the last year as well as new experimental results are presented in this article.

Microwave interferometry

No reliable density measurement method was available on the GOLEM tokamak until 2015. This absence seriously limited many experiments performed on the device. A microwave interferometer that had been used on CASTOR tokamak was recently made operational. The refurbishment also included upgrade of its electronic circuitry. The interferometer is of Wharton's type, meaning that the diagnostic wave frequency (around 70 GHz) is periodically swept by a sawtooth signal during operation (about 25 MHz), which produces lower frequency beats after the wave interferes with a reference. From the phase shift between the beats and the sweeping signal the plasma density can be calculated. The dependence on amplitude attenuation is eliminated by this method.

An analog circuit was developed as an alternative to a traditional computer algorithm. This circuit has higher temporal resolution than the digital calculation at the cost of higher demands on data acquisition systems (DAS). However, it seems that the analog evaluation should produce satisfactory results for most of the conducted experiments. Figure 1 shows comparison of both evaluation methods during one of the shots.

The interferometer only gives information on line-integrated density along the path of the wave (vertical direction). Average density is then calculated by estimating the distance passed through the plasma (limiter diameter). No better estimate of the plasma density is calculated at present.

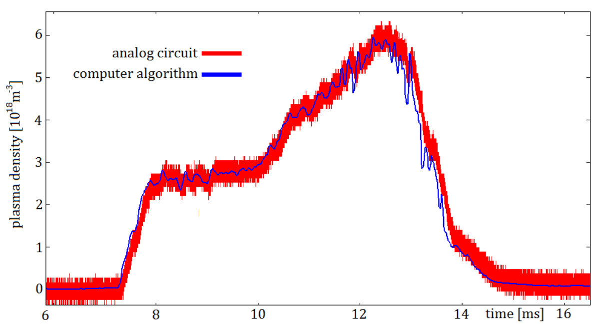

Figure 1: *Comparison of plasma density evolution as calculated by analog and digital means*

Plasma position control

The GOLEM tokamak is equipped with four Mirnov coils used for plasma position (both vertical and radial) measurements and a set of positional stabilization coils. An electronic system has been developed which connects the sensors and actuators to a closed loop. First, the sensor signal is preprocessed using an analog integrator and subsequent digital filtering (removal of parasitic signals from the toroidal field and the field of feedback coils). The plasma position is then calculated using either a simplified Grad-Shafranov model or an even more simplified straight conductor approximation; The results are fed into a nonlinear proportional controller. Finally, the actuator signal is estimated as a suitable combination of the controller output and a predefined waveform (can be configured through the virtual control room) [1].

Both the closed-loop feedback and the predefined waveforms have been shown to be able to stabilize the plasma position evolution. This also leads to longer plasma duration.

Runaway electrons

A new NaI(Tl) scintillation detector with a photomultiplier tube was installed for regular measurements. Although this detector is characterised by a relatively slow peak decay time, it can be useful in monitoring the runaway electrons (RE) losses via detection of the hard X-ray radiation released during their interaction with the wall. It seems that during standard operation (density $n_e = 3 - 8 \cdot 10^{18}$ m^{-3}), RE are created just during the plasma breakdown phase and/or during the plasma termination via some position instability (leads to creation of low density plasma in yet high electric field). The RE created during the breakdown drift to the low field side and are lost in few milliseconds, the loss of RE generated during partial plasma termination is usually faster and probably may occur on the high field side. Examples of both of these phenomena are shown in Fig. 2.

According to the analysis using the relation for primary RE generation rate (Kruskal-Bernstein), it is obvious that runaway electrons are created just during the breakdown (occurring at 12 ms) in the first shot presented in Fig. 2. In the second shot, the largest number of runaway electrons is created in the period of low plasma current and high loop voltage at the end of the discharge. The subsequent momentary recreation of plasma is probably caused by emission of secondary electrons from the wall after RE impact. The calculated RE densities seems to be reasonable regarding both plasma current and number of detected photons estimated from the HXR detector signal.

The tests of TimePix detector (hybrid silicon pixel detector) for direct fast electron measurements have continued. First measurements are planned for this year.

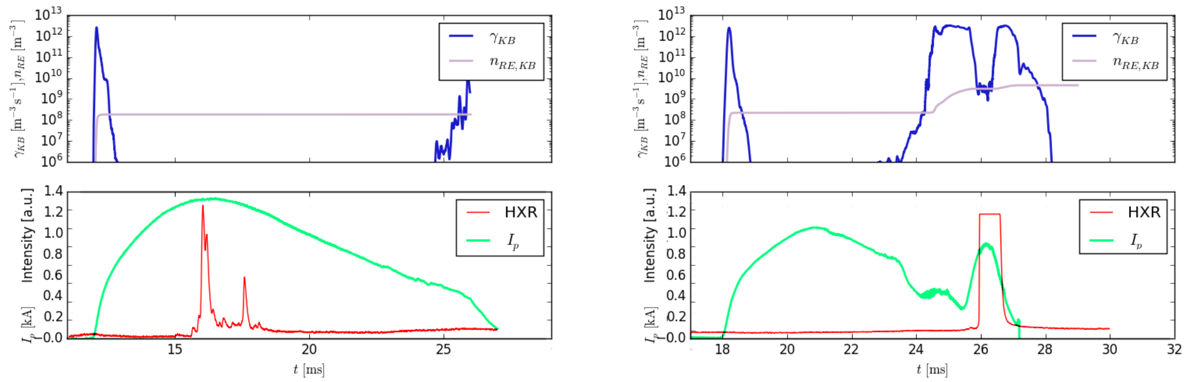

Figure 2: *Comparison of shots #18970 (left) and #18850, the latter one with a position instability; The figure shows the Kruskal-Bernstein rate (blue), an estimate of RE density (violet), plasma current (green) and the hard X-ray signal (red)*

Probe measurements in microwave plasma

Pre-ionization of GOLEM discharges is performed by the microwave generator at f = 2.45 GHz. The resulting MW plasma is studied by means of the planar Langmuir probe located at the radius r/a = 0.8 (effective collecting area is 50 mm^2), and oriented perpendicularly to the magnetic field lines. Thanks to good reproducibility, the IV characteristics are measured on a shot to shot basis in 18 discharges (#18480 - #18497). The typical IV characteristic constructed at t = 12 ms is shown in the right panel in Fig. 3. It is seen that the saturation currents (I_{+sat} and I_{-sat}) are not constant. Increase of I_{+sat} is a consequence of the probe sheath expansion, however the decrease of I_{-sat} with the probe voltage is not yet understood. The fitting function was used to calculate plasma parameters by using the technique proposed in [4].

The resulting evolutions of the electron temperature and the ion saturation current are plotted in the central panel of Fig. 3. It is evident that plasma is confined in the vessel long time after switching-of the MW power at t = 10.8 ms. Since that time, the ion saturation current,

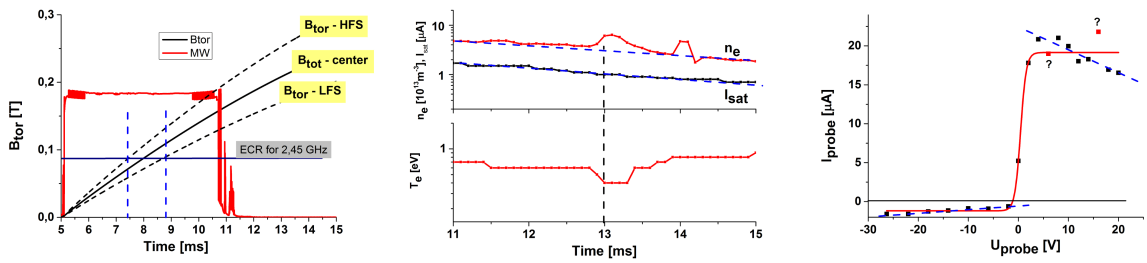

Figure 3: Left - *Temporal evolution of the toroidal magnetic field and the microwave power (the ECR resonance indicated);* Center - *Temporal evolution of selected plasma parameters after the MW power was switched off;* Right - *A selected IV characteristics ($t = 12$ ms, $B_{tor} = 0.188$ T)*

and electron density decay exponentially, with a time constant ~1.4 ms. Such a relatively long confinement of plasma is possible due to the low electron temperature, which remains constant at T_e = 0.6-0.8 eV. Consequently, the centrifugal and E×B drift velocities are small.

Visible light tomography

The tokamak is equipped with two visible light cameras observing the plasma from two perpendicular directions. With use of rolling shutter effect, a frame rate of 40 000 fps can be reached while reducing the resolution to single line of 336 pixels.

An algebraic algorithm has been utilized to reconstruct the 2D profile of visible light emissivity of the plasma. The algorithm is based on linear parametrization of the space of possible solutions followed by solving a system of linear equations for the parameters. Because of ill-posedness of this problem, it is solved approximately by Tikhonov regularization (with an assumption of smoothness). The calculation is being done for all three color channels recorded by the cameras (red, green, blue) separately. A correction of the sensor nonlinearity is applied before the calculation.

Figure 4 shows two examples of the reconstructions. The latter one shows a hollow emissivity profile typical for most discharges; This probably corresponds to radiation coming from colder regions of the plasma. Many smaller fast-evolving structures can be seen in the reconstruction; These are probably artifacts caused by reflections from the first wall.

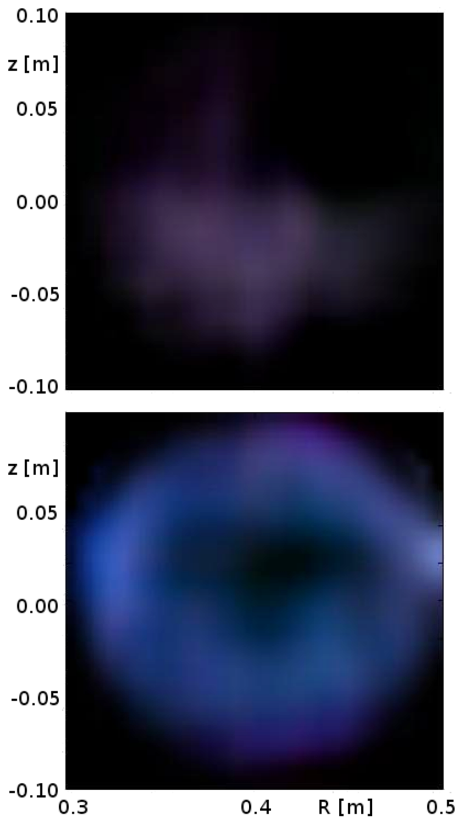

Figure 4: *Two tomographic reconstructions obtained during different phases of the same discharge*

References

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