Former tokamak CASTOR becomes remotely controllable GOLEM at the Czech Technical University in Prague

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Introduction

The CASTOR tokamak, which has been operated for 30 years at the IPP Prague was moved to the Czech Technical University in Prague and became an educational device for domestic as well as for foreign students, via remote participation/handling. The reinstalled tokamak ($R = 0.4$ m, $a = 0.085$ m), now baptized as GOLEM, operates currently at modest range of parameters, $B_t < 0.8$ T, $I_p < 8$ kA, discharge duration ≈ 13 ms, and with a limited set of diagnostics. This facility will be offered to the FUSENET (the 7th FWP European Fusion Education Network) as a (remote) practica experiment.

Experimental setup

The engineering scheme of the GOLEM facility is shown in Fig. 1

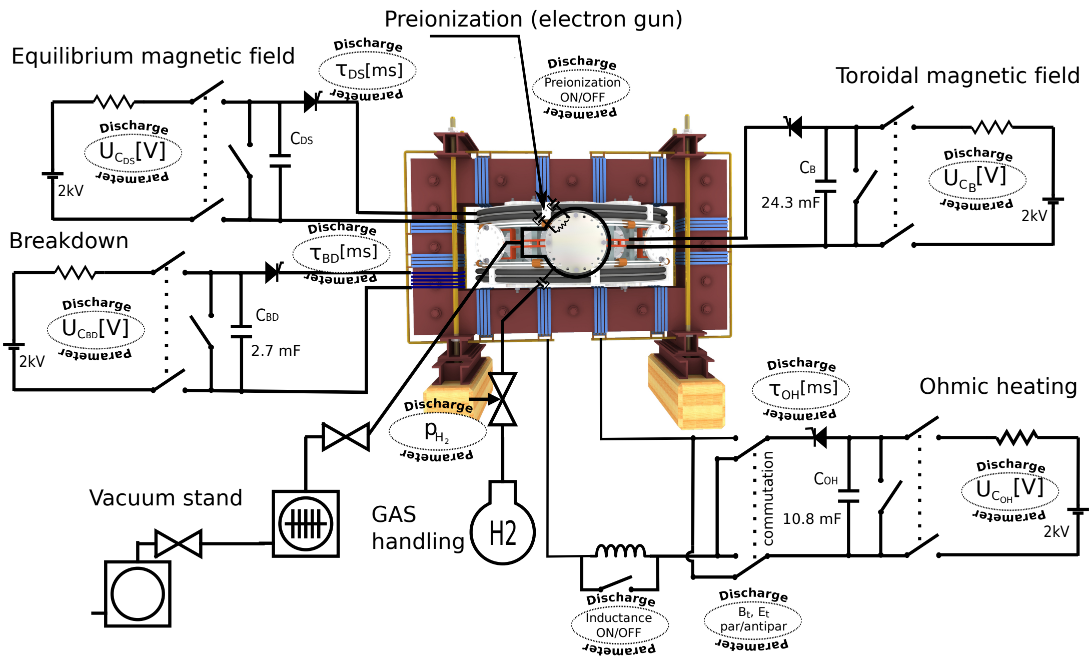

Figure 1: The Golem tokamak engineering scheme

The experiment is composed from the following principal parts:

- Circuit for generation of the toroidal magnetic field consisting of the capacitor bank ($C_B =$ 24.3 mF) charged up to $U_{C_B} = 2$ kV, which is triggered by PC controlled thyristor into a set of 28 magnetic field coils to generat the toroidal magnetic field up to $B_t \approx 0.8$ T.

- Circuit for generation of the toroidal electric field is composed of two capacitor banks. The first one is used for breakdown of the working gas $C_{BD} = 2.7mF$, $U_{C_{BD}} = 400$ V). The second bank is used for ohmic current drive and heating $C_{OH} = 10.8$ mF , $U_{C_{OH}} = 400$ V). Both banks are triggered by PC controlled thyristors into two primary windings of the transformer. The time delay with respect to a magnetic field (τ_{BD} and τ_{OH}) can be independently selected. The commutation switch can change the mutual orientation of the toroidal magnetic field and the plasma current. An inductance ($L = 5.9$ mH) can be included in the “OH“ circuit to modify the plasma current ramp-up.

- Circuit for generation of the equilibrium magnetic field, consisting of a set of capacitors charged up to $U_{C_B} = 1$ kV, which is triggered by PC controlled thyristor into a dynamic stabilization coil with time delayed pulse with respect to a magnetic field generation τ_{DS}

- Pre-ionization of the working gas is performed by an electron gun.

- Vacuum system, which allows reaching the background pressure ≈ 0.5 mPa.

- Gas handling system (again computer controlled) to control the pressure of the working gas (hydrogen) in the vessel in the range of $p_{H_2} \approx 10$ - 200 mPa.

- System for baking of the tokamak vessel and for the glow discharge cleaning.

Currently, the GOLEM tokamak is equipped by a limited set of basic plasma diagnostics for measurement of the loop voltage, the plasma current, the toroidal magnetic field, the plasma position with the set of Mirnov coils. Furthermore, the radial profile of the visible and soft X-ray radiation is measured by the array 20 bolometers.

A unique feature of this experimental arrangement is a possibility of a complete remote handling operation through the Internet access [1]. From the client side the tokamak is operated via putty or ssh connection with the help of a command line, where remote operator set all the discharge parameters and trigger charging process followed with the plasma discharge itself. Consequently all data in graphical/raw form are accessible via the special discharge web page.

As an example, a typical evolution of a discharge with an antiparallel orientation of the toroidal magnetic field and the plasma current is shown in Fig. 2.

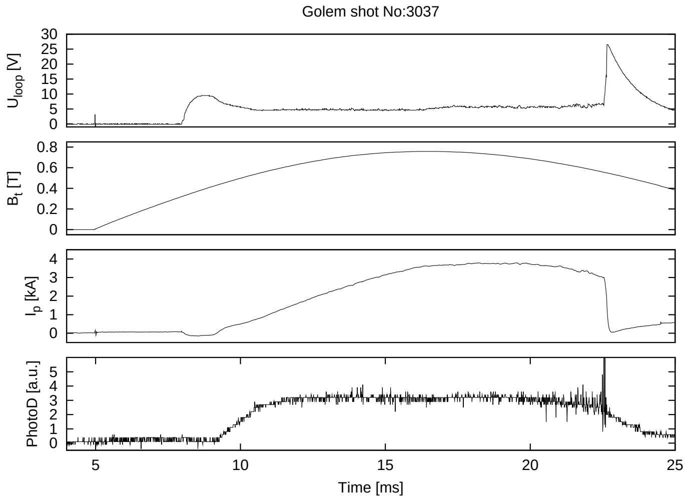

Figure 2: Evolution of a typical Golem discharge. From top to bottom - the loop voltage, toroidal magnetic field, plasma current, and the signal of a photodiode.

It is seen that that the breakdown occurs at the toroidal magnetic field $B_t \approx 0.4$ T. The loop voltage at the breakdown is ~ 10 V and it decreases to ≈ 5 V. The plasma current reaches the value $I_p \approx 4$ kA. The central electron temperature can be estimated from the plasma resistivity as $T_e \approx 80$ eV. The safety factor at the plasma edge is about $q(a) \approx 15$. The integral visible radiation is monitored by a photodiode (see the bottom panel in Fig. 2. It is interesting to note that this relatively long and stable discharge is achieved without any external vertical magnetic field.

Figure 3 shows results of our preliminary studies aimed to optimize the breakdown of the working gas. It is clearly seen that the loop voltage at the breakdown is significantly lower, when the direction of the plasma current is anti-parallel to the field lines of the toroidal magnetic field.

In the same figure, the theoretical curves for the minimum breakdown voltage are overplotted. These curves are calculated according the expression

$$U_{min}^{BD} = \frac{0.099\ p}{\ln(0.00375\ p\ L_{con})} \cdot 2\pi r \qquad \text{[V, mPa, m]} \qquad (1)$$

which is derived assuming that the ionization length L_{ion} is equal to the connection length L_{con}. The ionization length is $L_{ion} = 1/\alpha$, where α is the first Townsend coefficient in molecular hydrogen. The connection length strongly depends on the stray vertical magnetic field B_{vert}, $L_{con} \sim 1/B_{vert}$. It is seen that at the anti-parallel orientation the experimental point (red symbols) correspond to the connection length ~ 15 m., while for the parallel orientation the corresponding

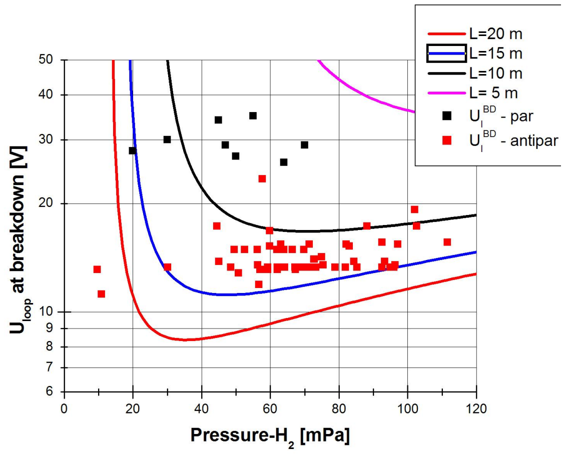

Figure 3: Loop voltage at the breakdown versus the pressure of the working gas.

connection length is ~ 7 m. One component of the vertical magnetic field is generated by the current in the vacuum vessel and its direction depends on the orientation of this current. We conclude that the vertical magnetic field from the vessel current "compensate" any other stray vertical magnetic fields for the anti-parallel orientation, while the vertical field is "amplified" for the parallel orientation. Therefore, the connection length and consequently the breakdown voltage depend on the plasma current orientation.

Conclusion

The GOLEM tokamak is now operational at the Faculty of Nuclear Sciences and Physical Engineering in Prague. It is a university-type of an experimental facility, which is exploited for practical training of students. Students are acquainted with basics of tokamak operation, data processing and evaluation of some plasma parameters. Repetition rate of plasma discharges is quite high (one shot in $\approx 2-3$ minutes), therefore scans of discharge parameters can be easily performed in a couple of teaching hours. The unique feature of the GOLEM tokamak is its capability to be handled remotely via standard Internet. Such remote operation has been already successfully performed with several foreign universities in Hungary, Belgium, Costa Rica and with a summer school in Poland. Further upgrade of GOLEM is envisaged in a near future. In particular, the number of data acquisition channels will significantly increase. This will allow to exploit more advanced plasma diagnostics, such as the microwave interferometer, various electric and magnetic probes, etc.

References

[1] Tokamak GOLEM at the Czech Technical University in Prague, http://golem.fjfi.cvut.cz, [online].