The GOLEM Tokamak for Fusion Education

E. Bromová[1], I. Ďuran[2], O. Grover[1], J. Kocman[1], T. Markovič[1], M. Odstrčil[1], T. Odstrčil[1],

O. Pluhař[3], J. Stöckel[2], V. Svoboda[1], A. Šindlery[1], G. Vondrášek[1], J. Zara[3].

[1]*Faculty of Nuclear Sciences and Physical Engineering CTU Prague, CZ-115 19, Czech Rep.*

[2]*Institute of Plasma Physics AS CR, CZ-182 21 Prague, Czech Republic.*

[3]*Faculty of Electrical Engineering CTU Prague, CZ-166 27, Czech Rep.*

Introduction

The GOLEM tokamak (formerly CASTOR) became an educational device for domestic as well as for foreign students via remote participation/handling. It operates routinely for nearly two years at modest range of parameters $B_t < 0.5$ T, $I_p < 8$ kA, pulse length < 15 ms, and with a limited set of diagnostics. Wide range of tasks with varying levels of complexity covering tokamak physics, technology and operation can be studied by the future fusion specialists. Find more info at http://golem.fjfi.cvut.cz .
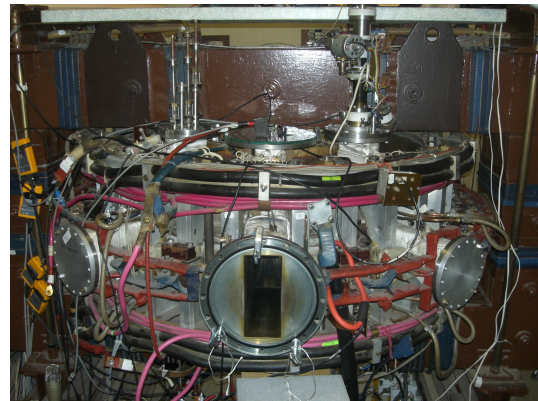

Figure 1: The GOLEM Tokamak

Currently the diagnostics enrichment is strategic for the education usability of the device. Students participate in large extent on additional standard diagnostics methods development, including density measurement via microwave interferometry, plasma position (including tomography) studies using a set of Mirnov coils, two fast cameras and two linear arrays of bolometers. Moreover stabilization of the plasma position with an equilibrium magnetic field generated in the vertical magnetic field coils and plasma spectroscopy issues are under consideration.

Recent Diagnostics Enrichment - Student's Contribution

Electron density measurement: the oldest and most widespread MW diagnostics is now implemented at the GOLEM tokamak. A generated MW interacts with the magnetized plasma which results in a change of the MW's phase. Interferometry evaluates the MW signal that has passed through plasma relative to the reference signal. See Fig. 2.

Determination and Control of the Plasma Displacement: for the determination of the plasma displacement the poloidal and the vertical magnetic field are used. The poloidal field is measured by the set of Mirnov coils and the vertical filed is measured by the former quadrupole
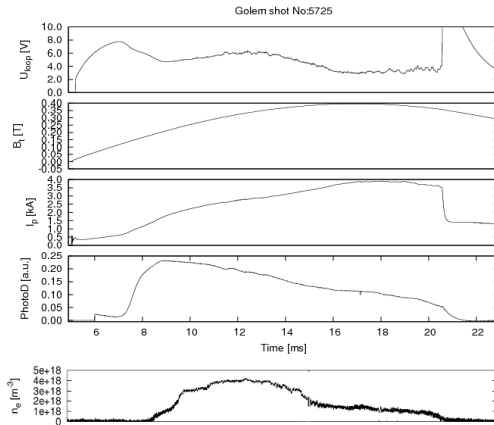
Figure 2: Evolution of a typical Golem discharge. The loop voltage, toroidal magnetic field, plasma current, signal of a photodiode, and newly the electron density measurement.

Figure 3: Horizontal and vertical plasma position, stabilization current and plasma current showing stabilization incidence on plasma behaviour.

system. See Fig. 3.

High Speed VIS Cameras: two cameras Casio EX-F1 have been installed in ports at one poloidal cross-section perpendicular to the plasma column. This configuration is suitable for VIS tomography. The camera can achieve frame rate up to 1200 fps, however the real time resolution is up to 40 kHz because of the "rolling shutter effect". See Fig. 4.

Visible Light Spectrometer: temporary gratings spectrometer based on the HS camera has been installed at the GOLEM tokamak. In the final configuration it will be capable of achieving time resolution of 0.1 ms and resolving power ($\Delta\lambda/\lambda$) of up to 300. See Fig. 5.

Array of Magnetic Field Sensors: an additional set of local magnetic field sensors is currently under construction. The array will consist of a brand new set of Mirnov coils for displacement, rotation and instability measurements and 4 experimental high-temperature Hall probes for measurement of all 3 components of local magnetic field.

Interactive Virtual Model

In order to present the GOLEM tokamak via Internet to distant users, an interactive 3D virtual model has been created. It consists of several parts assembled together - the tokamak itself, power supply infrastructure, rooms and access path. In addition to real environment, various virtual objects have been added to ease interaction/control and to provide extended information via textual legend and animations.
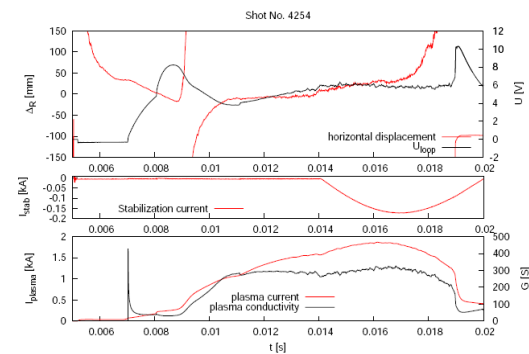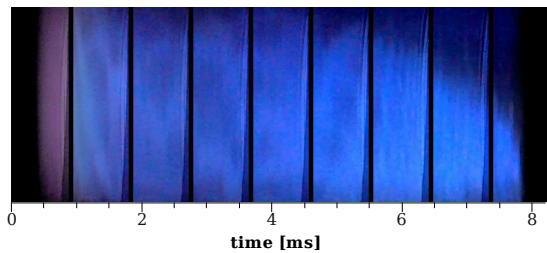
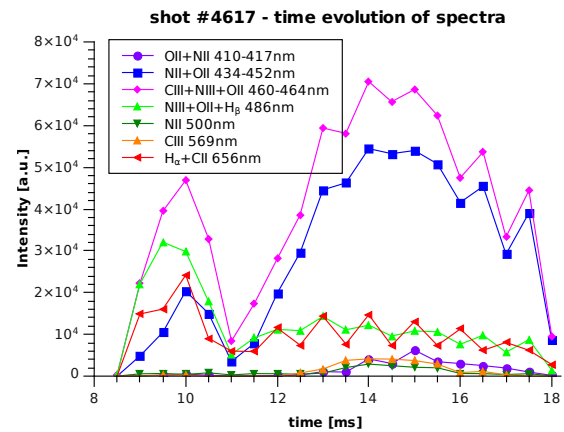Figure 4: Plasma column observed from the horizontal port during shot #3754, exposure time $50\,\mu$s.

Figure 5: Time evolution of the acquired spectra by the simple spectrometer with a time resolution of 0.5 ms.

The virtual model offers several ways to explore:

- To visit all rooms and corridors around the tokamak (Fig. 6 upper left). A user can freely walk through the environment (controlling own movements via mouse) or can be navigated along four pre-computed animated walkthroughs. This helps students to get familiar with the overall spatial layout and to imagine dimensions of the real equipment.

- To learn components of the TOKAMAK by clicking on various virtual parts. Selected part is then activated and presented to a visitor in various ways including simple animation, highlighting related components, showing short text annotation in free virtual space, opening web pages with detailed description, and possibly playing an audio clip. To make access to inner part easier, arbitrary components can be turned invisible via virtual control panel (Fig. 6 down left) called HUD (Head-Up Display).

- To visualize processes inside the tokamak. A user is properly scaled-down and teleported into the chamber having a possibility to see and "feel" animated magnetic field (Fig.6 down right). This unusual way of interior presentation makes a novel and unforgettable experience for students.

- To control selected processes of the real tokamak via web browser. This functionality is currently very limited due to security reasons and the final decision has not been done yet. The virtual model can be utilized in several ways - to simulate reactions to user's requests only (without any connection to real tokamak), to visualize real state and operation of the GOLEM tokamak (read-only mode), and to allow direct control of the GOLEM tokamak
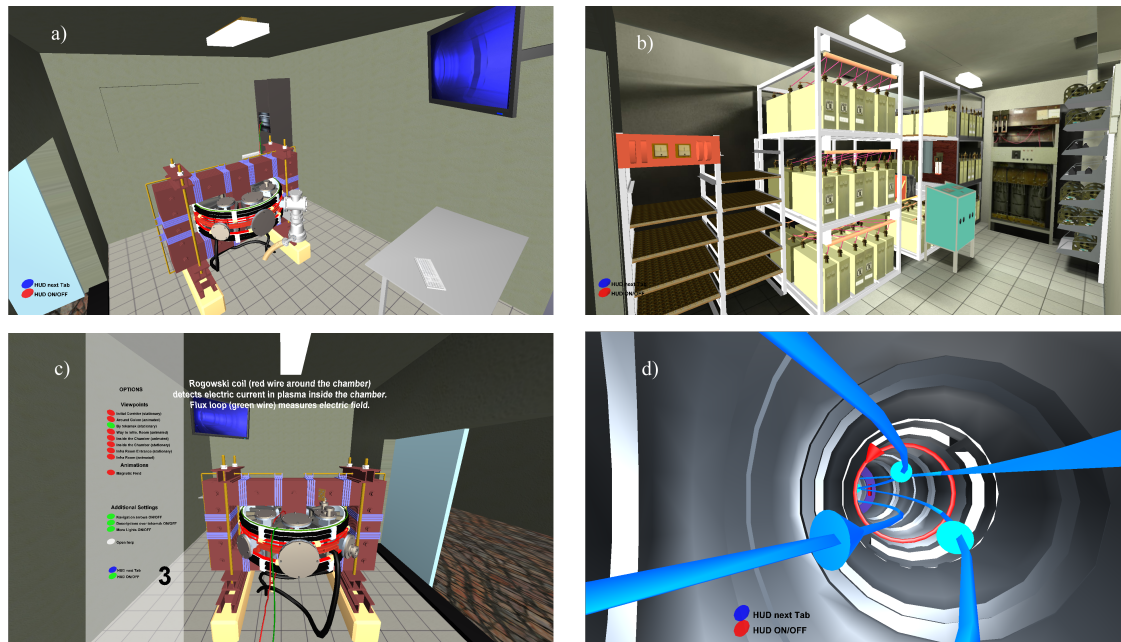
Figure 6: A general view of the virtual TOKAMAK model (a) and the power supply room (b). The Virtual HUD panel allows to control the visual, navigation, and simulation features (c) and visualization of the magnetic fields inside the chamber (d).

through interaction with its virtual model (read-write mode).

Summary

The proposed contribution summarizes the present status of GOLEM tokamak from engineering as well as plasma performance point of view and in particular, it presents the research and educational opportunities this new device offers to the fusion community.

Acknowledgement

References

[1] V. Svoboda, B. Huang, J. Mlynar, G.I. Pokol, J. Stockel, and G Vondrasek. Multi-mode Remote Participation on the GOLEM Tokamak. *Fusion Engineering and Design*, ():(Accepted for publication), 2011. ISSN .

[2] Zara, J. Virtual Reality Course - A Natural Enrichment of Computer Graphics Classes. *Computer Graphics Forum*, 25(1):(105–112), 2006. ISSN 0167-7055.