

Multi-mode Remote Participation on the GOLEM Tokamak

V. Svoboda^a, B. Huang^{d,e}, J. Mlynář^{a,b}, G. I. Pokol^c, J. Stöckel^b, G. Vondrášek^a

^aFaculty of Nuclear Sciences and Physical Engineering CTU Prague, CZ-115 19, Czech Rep.

^bInstitute of Plasma Physics AS CR, CZ-182 21 Prague, Czech Republic.

^cInstitute of Nuclear Techniques, Budapest University of Technology and Economics, Association EURATOM-HAS, H-1111 Budapest, Hungary.

^dCulham Centre for Fusion Energy, OX14 3DB, Abingdon, Oxfordshire, UK.

^eDepartment of Physics, University of Durham, South Road, Durham DH1 3LE, United Kingdom.

Abstract

The GOLEM tokamak (formerly CASTOR) at Czech Technical University is demonstrated as an educational tokamak device for domestic and foreign students. Remote participation of several foreign universities (in Hungary, Belgium, Poland and Costa Rica) has been successfully performed. A unique feature of the GOLEM device is functionality which enables complete remote participation and control, solely through Internet access. Basic remote control is possible either in online mode via WWW/SSH interface or offline mode using batch processing code. Discharge parameters are set in each case to configure the tokamak for a plasma discharge. Using the X11 protocol it is possible to control in an advanced mode many technological aspects of the tokamak operation, including: i) vacuum pump initialization, ii) chamber baking, iii) charging of power supplies, iv) plasma discharge scenario, v) data acquisition system.

Keywords: Tokamak technology, remote participation, data acquisition system, education, nuclear fusion.

1. Introduction

Remote participation on fusion tokamaks has been demonstrated before on many devices such as DIII-D [1], the LHD [2], TJ-II [3] and JET [4]. With the increased usage of high speed networks, distributed computing and improvements in network based audio and video transmission have allowed remote participation to become widespread.

Various tools have been developed (such as VizAnalysis for JT-60 [5]) for communication and remote streaming however there is no apparent consistent set of tools for remote participation. Additionally there are different experimental data formats, such as MDSplus used at NSTX [6] and NetCDF used at MAST [7]. NSTX and MAST are two similar tokamaks each using different, but widely supported formats. The different data formats perform the similar function of storing fusion experiment data, but need different programs for their implementation. There have been efforts to interface these two different formats such as for the TRANSP code on JET [8].

The different tools for communication and data access provide challenges to remote participation, which may make collaboration less efficient. Fusion research is performed by some 25 institutions in the EU [4], and globally this number is larger. ITER will be an international project requiring extensive global collaboration, but there are many unknowns in how this remote participation will be put into practice. This paper discusses the usage of web browser based applications and SSH for remote participation on the GOLEM tokamak.

A tool based on web technology such as HTML can be most widely used, since all that is needed is a modern web browser. The application can then in theory be accessible to anyone with

an Internet connection, however in reality security restrictions would limit access. One such example is an MDSplus structural data view [9] which runs in an Internet browser. The GOLEM tokamak has expanded the capability of the Internet browser to enable full remote participation and operation.

2. The GOLEM tokamak

The GOLEM tokamak (formerly CASTOR) at Czech Technical University is demonstrated as an educational device for domestic and foreign students [10], [11]. The reinstalled tokamak ($R = 0.4$ m, $a = 0.085$ m) currently operates at a range of parameters ($B_t < 0.8$ T, $I_p < 10$ kA, pulse length < 15 ms) which corresponds to a very small fusion triple product. Despite this fact, small tokamaks can produce edge plasma with similar characteristics to large tokamaks and so have general validity [12]. Additionally the remote participation features could be applied to a tokamak of any size.

Plasma is generated using 4 basic electrical circuits. Each circuit is powered by charged capacitors connected to the coils through PC controlled thyristors. This enables the creation of the toroidal magnetic field B_t , toroidal electric field E_t in two distinct phases (breakdown and current drive) and a vertical magnetic field B_{ST} providing basic plasma stabilization in the horizontal direction.

The tokamak is equipped with a basic diagnostic system for measuring key plasma parameters, i) a single loop surrounding the transformer core measures the loop voltage U_{loop} , ii) a Rogowski coil surrounding the tokamak chamber measures the sum of the plasma and chamber current I_{p+ch} , iii) a small pick-up coil placed on the tokamak chamber detects the toroidal

magnetic field B_t , iv) a photocell which faces a glass port of the tokamak detects the plasma radiation from the emitted visible spectra. Additionally v) a 'fast' camera (1200 fps at a 336x96 resolution) is installed at a horizontal port to study the emission profile in the visible part of spectra, vi) a set of 4 small Mirnov coils surrounding the plasma column in a poloidal cross section allowing local magnetic field measurement and finally vii) a linear array of 20 AXUV detectors (bolometers) positioned at a vertical port detecting plasma radiation emission profile in ultraviolet and soft X-rays part of the spectra.

3. Remote configuration of the GOLEM tokamak

Figure 1 shows the setup of the experiment. The outlined plasma generation arrangement and data acquisition system are both PC controlled and connected through a web server to the Internet.

Remote participants can set up to 10 parameters : 4 parameters for charging voltages U_B , U_{BD} , U_{CD} and U_{ST} for the capacitor banks, 3 parameters for time delay triggers (τ_{BD} , τ_{CD} and τ_{ST}), 1 parameter for the working gas H_2 pressure p_{H_2} and 2 parameters for requests for the preionization and working gas opening valve. The capacitor banks drive the toroidal magnetic field B_t , breakdown electric field E_{BD} , current drive electric field E_{CD} and the vertical stabilization magnetic field B_{ST} . The independent triggers start discharging capacitor banks at pre-programmed time delays, with respect to the start of the toroidal magnetic field B_t .

Measured data from the data acquisition system are collected and presented live online on dedicated web pages created for every discharge. Data are also accessible using wget software or standard routines in computer codes (such as routines available in Matlab, Mathematica, IDL, Labview, Octave, Gnuplot).

Synchronous conferencing (e.g. text based chat via skype, ICQ, etc.) between the remote participants and in-situ supervising technician should be settled to ensure initial training of the participants, basic check of the parameters prepared to be submitted to the system and consequently to help the participants with the interpretation of the acquired results.

As part of the communication system an Internet protocol camera is used which transmits live video and audio from the tokamak room.

4. Basic remote operation mode

Operation of the GOLEM tokamak by the remote participant can be performed by one of the following methods:

i) The remote participants log into the control system **accessing the WWW interface** using the HTTP protocol, see figure 2. Their choice of parameters (in a permitted limits) is submitted into a batch queue at the web server side and automatically executed in a succession via ssh protocol between the web server and tokamak control PC.

ii) Next the **command line method** based on SSH communication protocol (using the putty program on Windows OS) can be used to pass parameters in a permitted limits to the tokamak control PC and directly start capacitor charging process

followed immediately with plasma discharge triggering. A benefit of using the SSH protocol is that it is highly secure, ensuring that only the intended user is executing the commands.

This latter option is introduced in the examples below:

```
make shot Ub=500 Ubd=100 Tbd=3000 Ucd=300
Tcd=2000 Ust=0 Tst=0 pH2=20 PreIon=1
H2filling=1 COMMENT="Plasma test";
```

The parameters U_B , U_{BD} , U_{CD} and U_{ST} are the charging voltages U_B , U_{BD} , U_{CD} and U_{ST} , respectively of the corresponding capacitor banks. The parameters T_{bd} , T_{cd} and T_{st} are for the trigger sequence τ_{BD} , τ_{CD} and τ_{ST} determining the electric and magnetic field formation in [μs]. p_{H_2} defines the required working gas H_2 pressure p_{H_2} in the chamber in [mPa]. The other 2 boolean parameters are for preionization (PreIon) and working gas filling valve (H2filling).

An additional feature of the command line method is instruction looping, which allows the parametric scanning of the eight parameters. An example below shows a code to make a sequence of 7 discharges, where the capacitor bank for the toroidal magnetic field U_B is charged from 400 V to 1000 V in 100 V steps:

```
for Ub_index in 'seq 400 100 1000'; do make shot
Ub=$Ub_index Ubd=100 Tbd=3000 Ucd=300
Tcd=2000 Ust=0 Tst=0 pH2=20 PreIon=1
H2filling=1 COMMENT="Ub scan"; done
```

These command can also be used in creating a "makefile" with a set of a shot descriptions for offline processing.

5. Advanced remote operation mode

Advanced mode using the X11 protocol to run the GUI applications (virtual tokamak control panel) offers the possibility to control all of the technological aspects of tokamak operation, under appropriate supervision of an in-situ technician, who communicates with remote partners via internet conferencing tools and takes care about correct and safe operation of the device. The remote operator can be granted to control everything from "cold start", the standard diagnostic and acquisition session through to the device shutdown. The following technology systems can be operated: i) **Vacuum management**: provides independent control of all the vacuum valves, rotary and turbomolecular pumps. ii) **Gas fuelling management**: provides the arbitrary control of the working gas pressure. iii) **Chamber conditioning**: provides access to cleaning of the vessel using baking and glow discharge cleaning. iv) **Full control of tokamak parameters**: provides extended control of the electric and magnetic fields separately, allowing the investigation and behaviour of particular diagnostics under the defined operating conditions. v) **Data processing management modification**: for particular tokamak phenomenon studies.

6. Operating the tokamak

The possibility to remotely control the tokamak GOLEM is, first of all, offered to the fusion oriented educational institutions, preferably involved in the FUSENET consortium (The

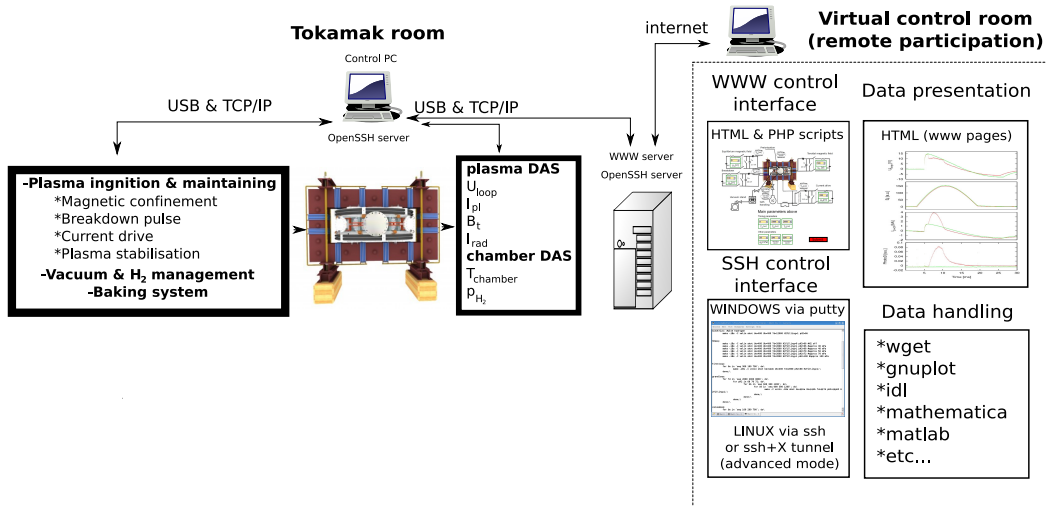


Figure 1: The tokamak GOLEM remote operation arrangement

European Fusion Education Network). No anonymous guest accounts are available.

Manuals and materials covering the fields of tokamak physics, technology and operation have been (and are currently being) created to provide the necessary basic training for GOLEM tokamak remote operators. These materials include instruction on a wide range of tasks with varying levels of complexity. Some of these are:

- Determination of the vacuum chamber parameters: chamber resistivity R_{ch} and inductance L_{ch} which can be deduced from “vacuum shots”.
- Basic plasma analysis from the data acquisition systems: loop voltage U_{loop} , magnetic field B_t , plasma current I_{pl} and determining the plasma discharge duration ΔT_{pl} .
- Evaluation of basic plasma parameters: central electron temperature T_e , edge safety factor q_e and plasma heating power P_{OH} .
- Various types of plasma breakdown studies can be performed: i) with or without the preionization jet, ii) effect of parallel or antiparallel orientation of the toroidal magnetic field B_t with respect to the toroidal electric field E_t , iii) the effect of a short (≈ 3 ms) breakdown E_{BD} pulse to the plasma formation, iv) time τ_{BD} and τ_{CD} delay optimization for plasma formation and v) effect of the working gas pressure p_{H_2} (Paschen’s law).
- Plasma position studies using a set of Mirnov coils, fast camera and a linear array of 20 AXUV bolometers .
- Stabilization of the plasma position with an equilibrium magnetic field B_{ST} generated in the vertical magnetic field coils.

Repetition rates on the GOLEM tokamak for a plasma discharge are quite high, with a shot taking place every 2-3 minutes. This enables scans of discharge parameters to be easily carried out in a couple of teaching hours.

The tokamak in this remote operation modes requires high level of safety treatment, therefore constant supervision of an

in-situ technician to ensure reliable and safety performance is essential. Operational sequence can be stopped immediately on a ‘push-button’ level at any time. In the case of possible abnormal behaviour of the device there also exist various levels of technological solutions assuring safe return to standard mode of operation.

7. First remote experiments and lessons learned

Remote participation over the Internet has been successfully performed with several foreign universities in Hungary, Belgium, Costa Rica and with a summer school in Kudowa, Poland. Real experimental sessions have been performed online as well as offline with the Budapest University of Technology and Economics. The Advanced operation mode was successfully tested with the Winter Plasma School in Marianska, Czech Republic.

Remote practices performed on GOLEM were overwhelmingly successful and popular among students. However, they have already taught some lessons and marked some directions for the development. The most important lesson was that for measurement experience, online measurements are very much preferred over offline measurements. The reason for this is quite clear: remote participants should really have the feeling of operating a device and take decisions based on their understanding of the previous results. In order to be able to schedule an online practice for students, reliable (and/or redundant) Internet connection has high priority. During the practices, it also became clear that in this rapidly changing phase of the GOLEM experiment supervision by a fusion scientist at the students’ site is clearly required to help with the interpretation. It was also concluded that programming help should be provided to students in processing raw data so that they can concentrate on online data processing and discussion of the results.

In a special event called the Global Tokamak Experiment [13], [14] using a web based system, over 4 hours 38 participants from 10 different countries carried out 83 plasma dis-

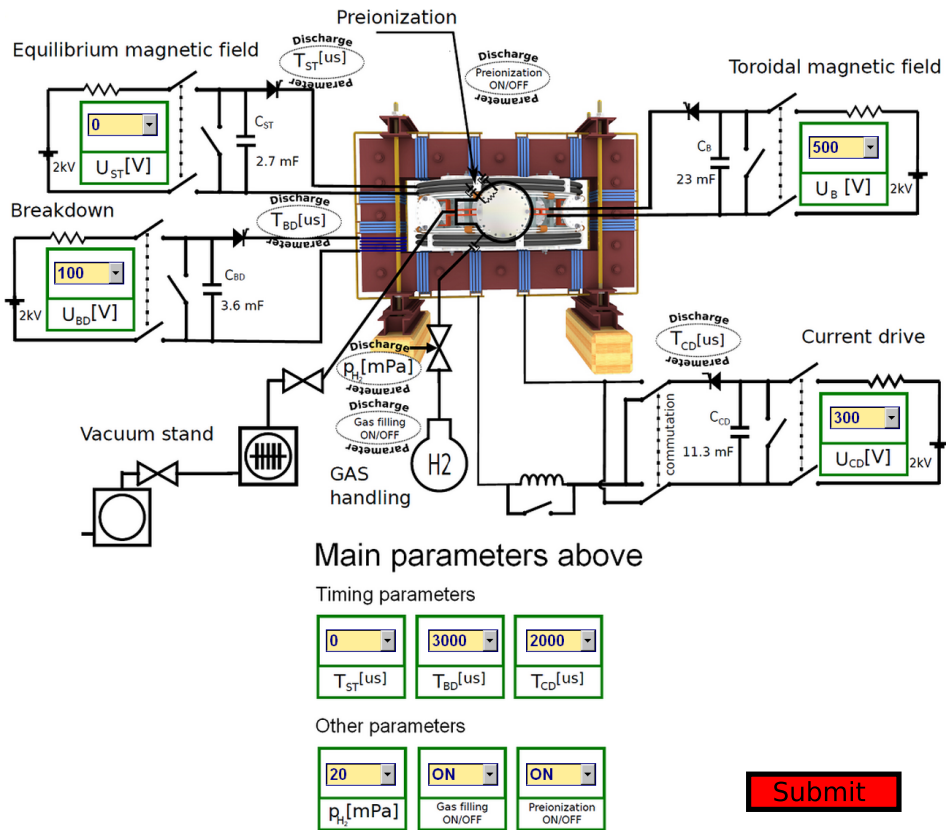


Figure 2: Tokamak GOLEM web based control room. Form fields indicating 8 numeral and 2 ON/OFF control elements to setup the required discharge parameters.

charges. Due to the global nature of this experiment a security feature using access keys (also referred to as tokens) were distributed to limit the usage of the tokamak. A login based system identified between participant, and experiment manager. Thus the machine was based in the Czech Republic, the experiment manager in the UK, and the participants in many other countries.

This demonstrated the ability to make a tokamak globally accessible and one way in which multiple participants can collaborate on a single tokamak, without the need for specialized software whilst maintaining security. Security also can be achieved using the standard HTTP/S proxy and firewall methods when using web based systems. Participants were presented with a live control panel which self refreshed, constantly informing people of the experiment status. The result of each plasma discharge was available on the system shortly after it took place.

Advanced mode with the help of X11 protocol showed satisfactory fast respond over the internet even with the connection speed slightly below the standard.

8. Conclusions and future plans

GOLEM is a university based experimental facility dedicated primarily for the practical training of students who can get acquainted with the basics of tokamak operation, data processing

and evaluation of selected plasma parameters. A series of experiments can be compiled for students specialising in fusion plasma physics with more complex tasks, including advanced breakdown studies and plasma position control. Practical experimental sessions on the GOLEM tokamak could be appealing for universities as a cost effective alternative to building their own demonstration devices. Additionally remote tokamak experiments develop not only plasma physics and fusion skills, but also develop core competences such as communication, interpretation, process planning and team work. Using a web based system provides a high degree of accessibility and enables a large degree of collaboration.

A basic operation mode enables enough access for basic experiments focusing on plasma physics rather than technology. Control can be implemented through either a HTTP based graphical interface or command line through SSH protocol. More detailed studies of specific tokamak technology systems can be granted in advanced remote operation mode through X11 protocol. Remote operation is promoted by a local supervisor in both cases, however this supervisor is not required interfere with the remote controllers in case of normal operation.

Further upgrades to GOLEM are envisaged in the near future. Among those planned are an increase of B_t , I_p and plasma discharge duration. The possibility of basic plasma position stabilization is under investigation. Basic diagnostics will be

enriched with line integrated plasma density measurement using a microwave interferometer and expanded radiation (H_α and X-ray) measurement. Additionally planned is the investigation of plasma edge physics using probe measurements.

9. Acknowledgement

The financial support from MSM 6840770039 and A1581 is acknowledged. The authors express their appreciation of help from National Instruments and Pfeiffer Vacuum for their valuable contribution to the project.

References

- [1] B. B. McHarg, T. A. Casper, S. Davis, D. Greenwood, Tools for remote collaboration on the DIII-D national fusion facility, *Fusion Engineering and Design* 43 (1999) 343 – 355.
- [2] Y. Nagayama et al., Control, data acquisition, data analysis and remote participation in LHD, *Fusion Engineering and Design* 83 (2008) 170 – 175. Proceedings of the 6th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research.
- [3] J. Vega, E. Sanchez, A. Portas, A. Pereira, A. Mollinedo, J. A. Munoz, M. Ruiz, E. Barrera, S. Lopez, D. Machon, R. Castro, D. Lopez, Overview of the TJ-II remote participation system, *FUSION ENGINEERING AND DESIGN* 81 (2006) 2045–2050. 5th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research, Budapest, HUNGARY, JUL 12-15, 2005.
- [4] D. Schissel, J. Farthing, V. Schmidt, Advances in remote participation for fusion experiments, *Fusion Engineering and Design* 74 (2005) 803 – 808. Proceedings of the 23rd Symposium of Fusion Technology - SOFT 23.
- [5] T. Oshima et al., Development of environment for remote participation in fusion research on JT-60, *Fusion Engineering and Design* 71 (2004) 239 – 244. 4th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research.
- [6] W. Davis, P. Roney, T. Carroll, T. Gibney, D. Mastrovito, The use of MDSplus on NSTX at PPPL, *Fusion Engineering and Design* 60 (2002) 247 – 251.
- [7] G. McArdle, S. Shibaev, J. Storrs, N. Thomas-Davies, R. Stephen, The MAST data acquisition upgrade, *Fusion Engineering and Design* 85 (2010) 345 – 349. Proceedings of the 7th IAEA Technical Meeting on Control, Data Acquisition, and Remote Participation for Fusion Research.
- [8] J. Conboy, Interface to TRANSP NetCDF files for MDSplus servers, <http://users.jet.efda.org/expert/transp/Documentation/Reports/JDN/T107-2.pdf>, 2007.
- [9] G. Manduchi, C. Taliercio, J. Krom, Multiple-site remote data access for fusion experiments, *Fusion Engineering and Design* 60 (2002) 467 – 473.
- [10] FJFI CVUT, Tokamak GOLEM at the Czech Technical University in Prague, <http://golem.fjfi.cvut.cz>, 2007.
- [11] V. Svoboda et al., Former Tokamak CASTOR becomes remotely controllable GOLEM at the Czech Technical University in Prague, in: *Proc of the 37th EPS Conference on Plasma Physics*.
- [12] Van Oost, G et al., Joint experiments on small tokamaks: edge plasma studies on CASTOR, *NUCLEAR FUSION* 47 (2007) 378–386.
- [13] B. Huang, V. Nikolaeva, Global Tokamak Experiment, <http://tokamakglobal.com/>, 2010.
- [14] ITER news, Launch of the world's first global tokamak experiment, <http://www.iter.org/newsline/156/512>, 2010.