USE OF SMALL TOKAMAK GOLEM AS A TEST BED FOR APPLICATION OF HIGH TEMPERATURE SUPERCONDUCTORS IN FUSION DEVICES

V. SVOBODA*, J.STOCKEL***, M. GRYAZNEVICH**, G. VOROBLEV****, O. GROVER*

*Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, CR.
**Tokamak Energy, Tokamak Solutions, Oxford Instruments, GB (ST 25, ST 25 HTS)
***Institute of Plasma physics, Czech academy of Sciences, CR (COMPASS)
****Saint Peterburg University, RF.

Abstract

The tokamak GOLEM contribution to the IAEA Coordinated Research Activity have been performed in these tasks: i) Investigation of performance of HTS magnets during tokamak operations. ii) Providing experimental data for the development of new concept of advanced magnets in fusion devices, based on High Temperature Superconductors. iii) Studies of properties of HTS in tokamak environment: critical current dependence on magnetic field, temperature, stresses, etc. iv) MW driven pre-ionization - reduction in the loop voltage achieved for the plasma breakdown with respect to Electron Gun pre-ionization. v) Probe measurements performed in two different - tokamak and microwave – plasmas.

1. INTRODUCTION

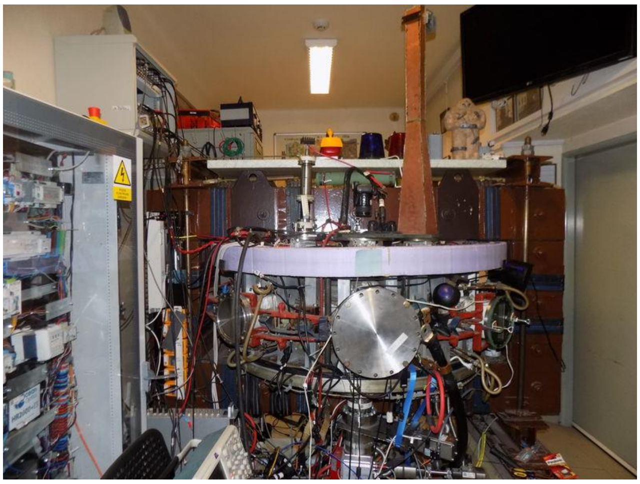

FIG. 1. Tokamak GOLEM equipped with cryostat and MW launcher

The GOLEM tokamak is operational at the Faculty of Nuclear Physics and Physical Engineering (FNPPE), Czech Technical University in Prague [1]. GOLEM is a small tokamak which was constructed at the end of 1950's at the Kurchatov Institute, Moscow as TM-1. The tokamak was moved to the Institute of Plasma Physics in Prague in 1977 and re-named CASTOR. After 30 years of operation, the tokamak was given to the FNPPE for education of students and renamed GOLEM.

The GOLEM tokamak has a circular cross section. The major/minor radii of the tokamak vessel are R_0 = 0.4 m, b= 0.1 m. The stainless steel vessel is equipped with a poloidal limiter (made of Molybdenum) of radius a = 0.085 m. The power supplies of individual windings are based on several condenser banks.

The tokamak is equipped by a set of simple diagnostics, which measure the loop voltage, plasma current, toroidal magnetic field, and visible emission. GOLEM is also equipped with interferometer, Mirnov coils, a visible spectrometer, an array of bolometers, a fast camera for time resolved pictures, etc.

Engineering and plasma parameters, which can be achieved on GOLEM are quite modest. The tokamak operates at maximum toroidal magnetic field of up to 0.5 T. The central electron temperature is less than 100 eV, the maximum line average density ~ 10^{19} /m^3, the maximum pulse length is around 18 ms. An unique feature of this experimental arrangement is the possibility of a complete remote handling operation via Internet access. From the client side the tokamak is operated through a HTTP or SSH connection, whereby a remote operator can set all the discharge parameters and submit them into a queue and then special software performs the queued discharges according to the submitted requests. Consequently all data in graphical/raw form are accessible on a special discharge web page. More than 2000 discharges were performed remotely across the borders of the Czech Republic as a part of a remote laboratory practice or a tokamak performance presentation for foreign students in various plasma schools, workshops, lectures and training courses.

2. TESTING OF THE HIGH TEMPERATURE SUPERCONDUCTORS (HTS) IN THE TOKAMAK ENVIRONMENT

Two poloidal field coils made of the HTS were installed on the GOLEM tokamak. The HTS tape (50 m) was provided by the company "Tokamak Solutions, Culham, UK". For their installation on the GOLEM tokamak, two cryostats, made of polystyrene, were designed and manufactured at the Faculty of Nuclear Physics and Physical Engineering, Czech Technical University (CTU) in Prague. The HTS tapes are cooled by liquid nitrogen to temperature around 70 K with the cooling system developed at the CTU as well. Series of successful tests were performed in a broad international collaboration (Tokamak Solutions, CCFE, Fusion Association, Culham, all UK) and also with participation of the Institute of Plasma Physics, Academy of Sciences of the Czech Republic. The achieved results were published in the journal Fusion Engineering and Design [1].

2.1. Experimental setup

It has long been known that high temperature superconductors (HTS) could have an important role to play in the future of the tokamak fusion research [1, 2]. First results of the use of HTS in a tokamak magnet are presented. In the experiment, the two copper poloidal field coils of the small tokamak GOLEM in Prague [3] were replaced by two coils with 6 turns of the 2nd generation HTS (Re)BCO tape SCS12050-AP supplied by “SuperPower Inc.”, US. The coils were wound in-situ by hand to avoid the need to disassemble the tokamak. The dimensions of the tape are approximately 0.1x12mm, HTS thickness ~1um, with two 20um Cu stabilising layers on the 50um Hastelloy substrate and the maximum claimed current capacity at liquid nitrogen (77K) temperature of ~ 320 Amps. Two simple liquid nitrogen (LN) cryostats made by “Forma Machinery Ltd” in Latvia, were assembled and filled with LN to cool the HTS tape to below the critical temperature at which it becomes superconducting. Plasma pulses were then fired in a normal way with HTS coils providing the vertical field and the tokamak operated exactly as expected. There had been concerns that the plasma pulses might cause a “quench”, i.e. cause a sudden and potentially damaging transition from superconductor to normal conductor. However, many plasma pulses were achieved without any quenches. In addition, experiments without plasma have been performed to study properties of the HTS in a tokamak environment, i.e. critical current and its dependence on magnetic and electrical fields generated in a tokamak both in DC and AC operations, maximum current ramp-up speed, performance of the HTS tape after number of artificially induced quenches etc. Considerable experience has been gained during design and fabrication of the cryostat, coils, isolation and insulation, feeds and cryosystems. Fig. 2 shows the GOLEM tokamak with two HTS vertical field coils. The plasma is seen through the midplane port. The cryostat, feeds and coil designs have evolved and the final version of the cryostat has improved insulation, so the ice seen in Fig.2 on the coils has been avoided. The typical time of cooling to superconducting conditions has decreased from the initial value of 90 min to 15 min. The final design of feeds avoids the local overheating observed in earlier designs. It was also found that circulation of LN in the cryostat resulted in ~15% increase in the critical current.

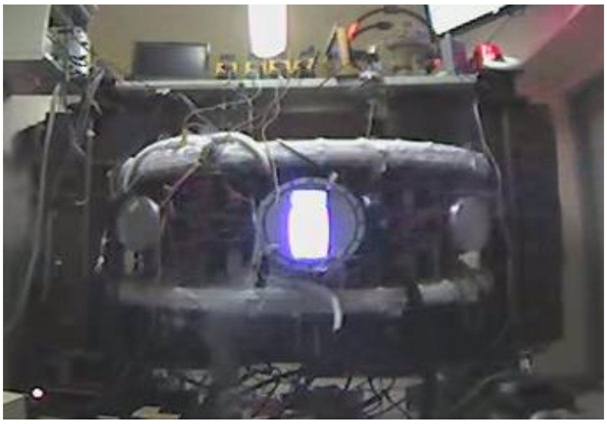

FIG.2. Plasma pulse in the GOLEM tokamak with HTS poloidal field coils.

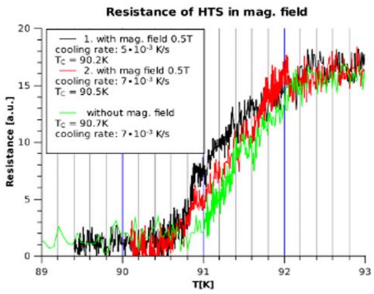

FIG.3. Dependence of the critical temperature for achievement of superconductivity in the HTS coil without and with 0.5T on GOLEM.

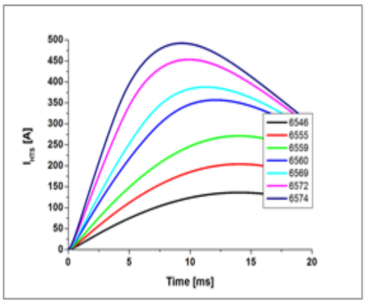

FIG.4. Evolution of the inductively induced current in the HTS coil in different pulses.

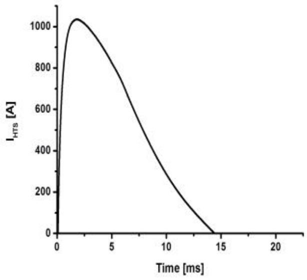

FIG.5. Evolution of the inductively induced current in record pulse 6975.

2.2. Basic HTS experiments in real tokamak operation:

Although it is known that the critical current in HTS strongly depends on magnetic field, for the GOLEM conditions, where magnetic fields at the coil position do not exceed 0.5 T, little effect has been observed for perpendicular field up to 0.5 T and superconductivity has been achieved at ~90.50 K, Fig.3. No quench has been observed at DC currents up to 250 A (the limit of the available power supply) during bench tests of the tape. The HTS was kept on the full current for tens of minutes with no observed changes in resistivity. In the AC tests, current up to 1 kA through the tape (6 kA-turns through the coil) has been achieved with no degradation of the HTS performance afterwards, although in such short pulse the current was probably distributed between the HTS and other components of the tape. Fig. 4 shows time evolution of the inductively induced current in the HTS coil demonstrating the current ramp-up speed of up to 90 kA/s, however, the highest rate of ~0.6 MA/s has been achieved in pulse #6975, Fig.5, where current through the tape has reached 1 kA.

In typical plasma pulses such a high level of current in equilibrium field coils is not needed and plasma operations have been performed with moderate I_{HTS} ~ 50-100 A current in the tape. This probably explains the absence of quenches during plasma pulses as the current was much below the critical value. However in some cases plasma disruptions occurred with corresponding induced electrical fields, and they also did not cause quenches. In future experiments, increases in both the plasma current and pulse duration are planned. To study quenches in DC operations, the current was increased and quenches have been observed at I_{HTS} ~ 150 A when operating together with other tokamak magnets but without plasma. When "up-to-destruction" tests have been performed, a quench caused an arc in the inter-turn isolation in one coil. There was no surprise that the location of the quench was under the limb of the iron transformer, where the highest leakage magnetic field has been measured. The damaged pieces of the tape have been cut out, the ends re-soldered and the coil has shown the same performance as before the accident, i.e. the local quench has not affected the performance of the rest of the coil. Over 25 quenches have been performed and a whole series of further experiments is now planned. The internal structure of the damage caused by the quench that caused arcing is under investigation.

2.3. Plasma position stabilization with HTS poloidal field coils:

As can be seen in Fig. 6, an appropriate radial magnetic field can prolong the plasma pulse by compensating the tendency of the plasma column to go upwards. With HTS coils in a superconductive state the coils target current can be reached with a much lower capacitor bank charging voltage than with the coils in a non-superconductive state. However, due to the low resistance the characteristic time constant of the circuit changed and the stabilization pulse was much shorter, making it ideal for fast feedback systems.

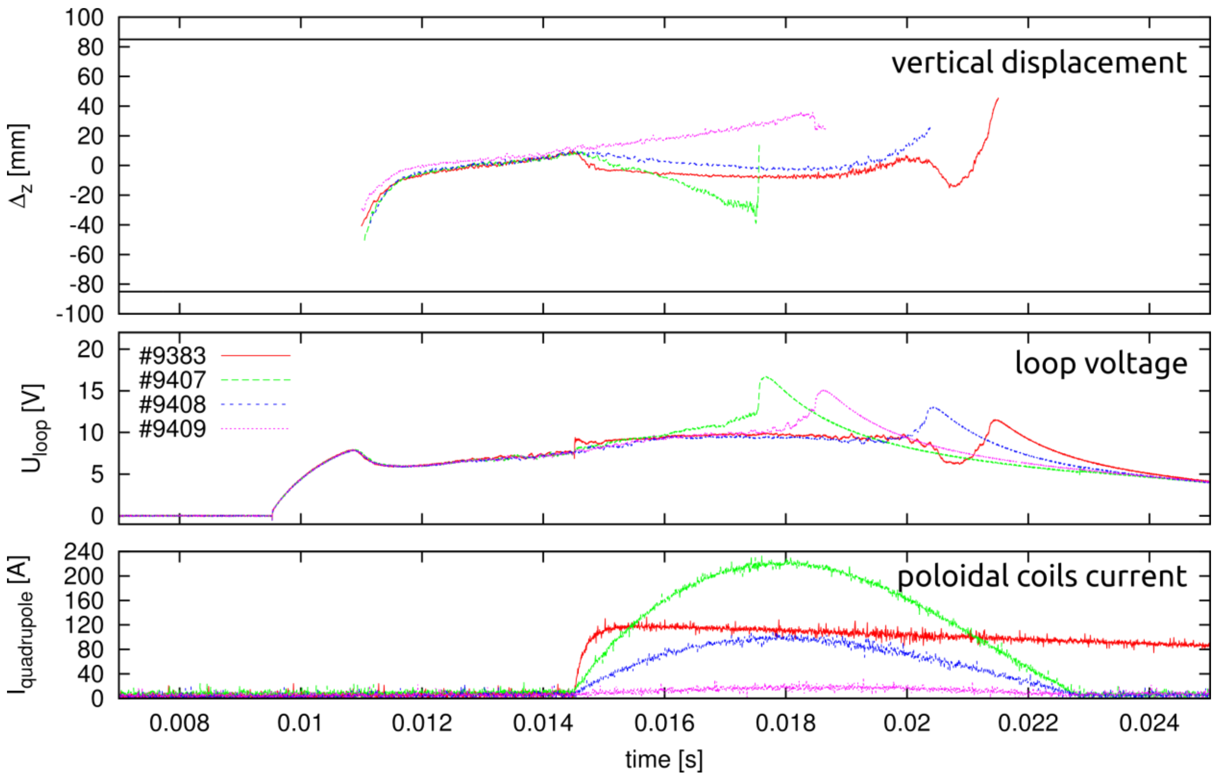

FIG. 6. Plasma displacement using the HTS coils. In discharges #9407 and #9408 the HTS coils were in a superconductive state and the capacitor bank charging voltage was only 70 V and 20 V whereas it was 400 V in discharge #9383 where the coils were in a non-superconductive state and the coil current was similar. Discharge #9409 is a reference discharge with no radial stabilizing field.

3. OPTIMIZATION OF THE PLASMA PERFORMANCE ON THE GOLEM TOKAMAK

Experiments with the HTS coils have shown that upgrading of several key elements of the GOLEM tokamak are required to improve tokamak performance. In particular, optimization of plasma breakdown and installation of feedback system for the plasma position control appeared to be necessary.

New systems for pre -ionization of the working gas have been installed and tested on the GOLEM tokamak. The microwave power source has been developed and manufactured in collaboration with experts from the St Petersburg State University, Russian Federation. This microwave source provides the electromagnetic wave at 2.45 GHz either DC or in pulse operation. The power is in the range of 1 kW. I has been demonstrated that the breakdown voltage is significantly reduced by 2-3 V with respect to the standard pre-ionization by means of the electron gun. Furthermore, pure microwave plasma was generated at low toroidal magnetic field, when the electron cyclotron resonance is present in the tokamak vessel.

Picture of the apparatus and the electrical scheme of power supplies are shown in Fig. 1 and Fig. 7.

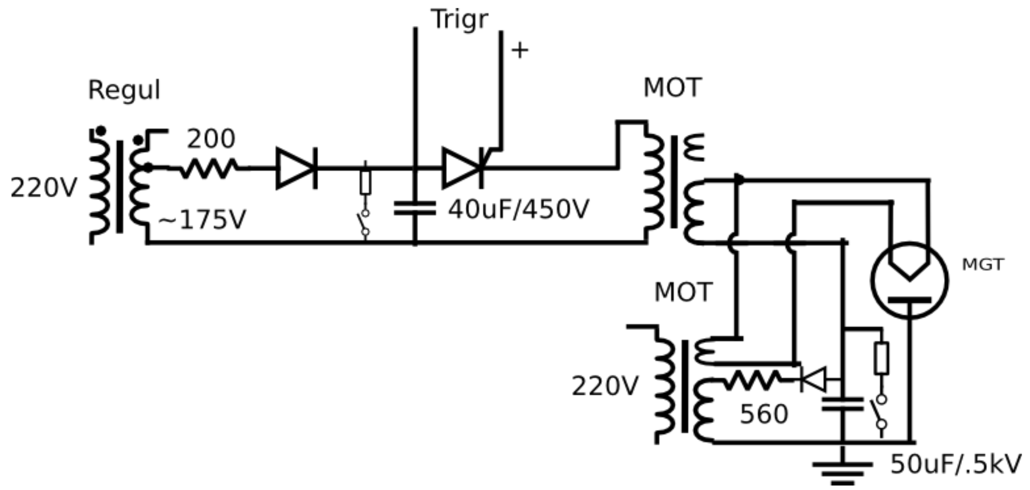

FIG. 7. The electrical scheme of the MW pre-ionization at the GOLEM tokamak

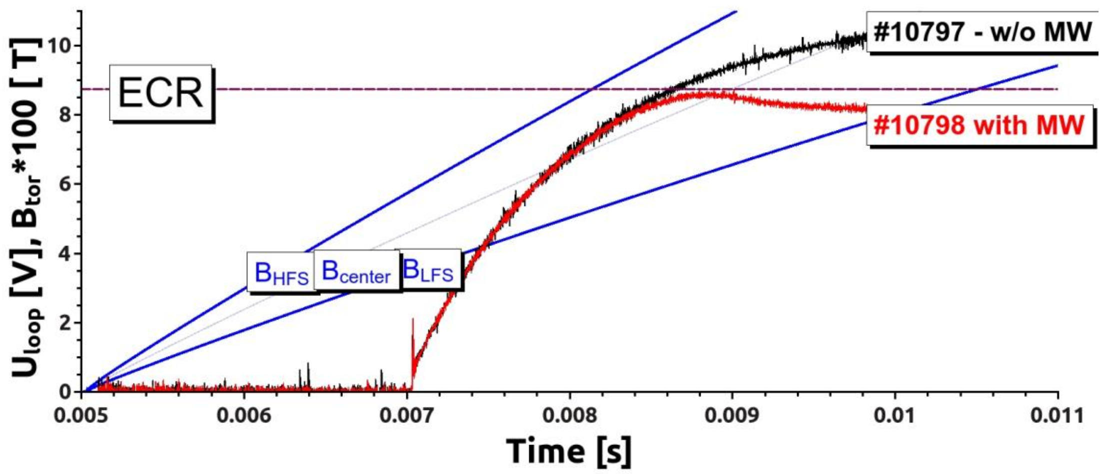

FIG. 8. Loop voltage characteristics of vacuum shot (black) and plasma discharge performed by means of microwave (red) - breakdown occurs when ECR layer is in the center of the vessel

Fig. 8 demonstrates that the microwave breakdown is effectively achieved with this apparatus. The RF power was injected in a short (<10 ms) pulse during the ramp-up of the toroidal magnetic field B_t and the breakdown occurs at B_t = 0.0875 T, which corresponds to localization of the Electron Cyclotron Resonance layer (for f = 2.45 GHz) inside the tokamak vessel. A series of discharges, where the breakdown was achieved either by electron gun or microwave pre-ionization was performed. Results are compared in Fig. 9. It has been proven that the MW pre-ionization is more efficient when the EC resonance layer is inside the tokamak vessel, while the electron gun pre-ionization acts better at low magnetic fields.

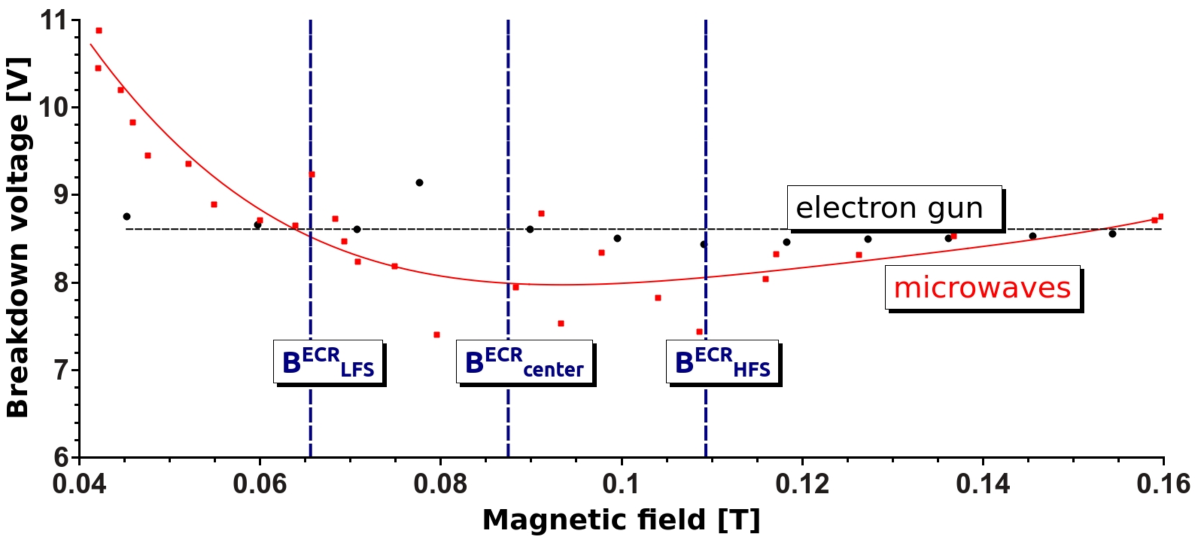

FIG. 9. Loop voltage at breakdown versus the toroidal magnetic field. Comparison of the microwave pre-ionization (red symbols) and the electron gun pre-ionization (black symbols) at the pressure of the working gas 10 mPa.

4. DEVELOPMENT AND TESTING OF NOVEL DIAGNOSTICS

To improve plasma diagnostic capabilities of GOLEM, several diagnostic tools are designed. In particular, The linear array of Langmuir probes for measurements of radial profiles and plasma fluctuations, The poloidal ring of 32 Mach probes to measure the poloidal distribution of flows in the edge plasma, 2 poloidal rings of 16 Mirnov coil probes to measure poloidal and toroidal magnetohydrodynamic activity in the edge plasma.

4.1. Probe measurements in the microwave plasma

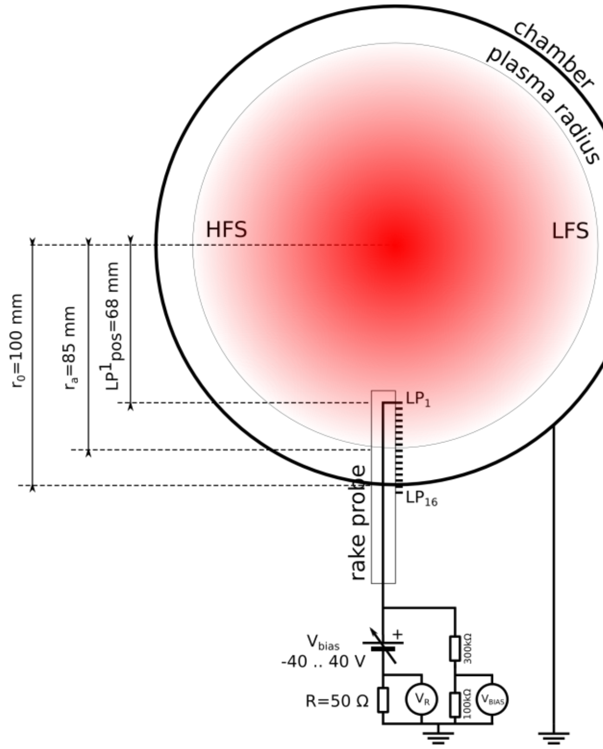

Fig. 10. Experimental setup

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 (see Fig. 10). 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. 11. 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 by Popov et. al.

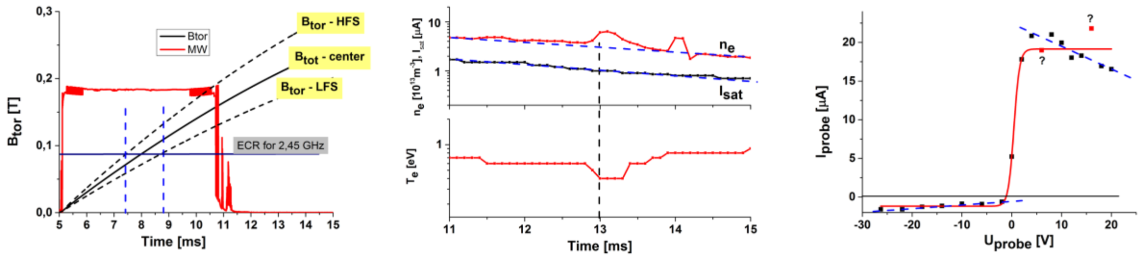

FIG. 11. Left - Temporal evolution of the toroidal magnetic field and the microwave power (the ECR resonance indicated); Center - Temporal evolution of selected plasma parameters after the MW power was switched off; Right - a selected IV characteristics (t = 12 ms, Bt = 0.188 T).

The resulting evolutions of the electron temperature and the ion saturation current are plotted in the central panel of Fig. 11. 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, 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**x**B** drift velocities are small.

5. EDUCATION AND TRAINING OF STUDENTS

The GOLEM tokamak 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 ~ 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. Several remote courses have been organized annually:

- French fusion master course together with Erasmus Mundus at CEA Cadarache, France
- GOMTRAIC – GOLEM Remote training course, education and training course oriented on basic understanding of experimental tokamak physics and control. It is meant for undergraduate and postgraduate students who want to get experience with operating of a fusion device. Prague, Czech Republic
- SUMTRAIC – Summer training course, Prague, Czech Republic
- EMTRAIC – Erasmus Mundus Training Course, Prague, Czech Republic
- SCIWEEK – Science week for high school students from Czech Republic. 4 groups of students making more then 100 on-site discharges performing spectroscopic studies, plasma position studies using fast camera, vertical plasma position studies using Mirnov coils and HXR studies at the tokamak GOLEM.
- Remote laboratory practice for students from Budapest University, Hungary.
- tokamak Golem have also contributed to the Prague Museum Night and Nights of Scientists – excursions for more then 100 visitors during the night.

Tokamak GOLEM have contributed to the programme of numerous lectures, demonstrations, workshops, plasma physics courses, etc. such as for: Ghent University 2009, TU Eindhoven 2011,2015,2016, Bochum University 2013, Garching 2013, Lemvig High School 2014, TU Kobehaven, TU Denmark 2015,2016, University of Belgrade 2015, BUTE Budapest 2010,2012-2014, Instituto Tecnologico Costa Rica 2010, University of Padova 2014, Workshops in Kiten 2014, Observatorium Valasske Mezirici 2014, Islamabad 2014, Global Tokamak Experiment 2010, Plasma physics course in Trieste, Italy, etc.

Experiments related to CRP project triggered bachelor and master thesis at the CTU:
Jakub Veverka – Bachelor thesis on plasma breakdown on the tokamak GOLEM
Jindrich Kocman – Master thesis plasma position control on the tokamak GOLEM

6. CONCLUSION

The HTS coils have been routinely and successfully used at the GOLEM tokamak both for plasma generation and stabilization. Provided the LN cooling was sufficient and sustained, the HTS coils are reliable and can greatly reduce the necessary capacitor bank charging voltage, thus lowering the energy demands for plasma position. The coil currents in fast ramp-up pulse operation exceeded those in the tape specification by almost 50 %. Other relevant results are presented in the Fusion Engineering and Design journal, see [1].

Regarding MW pre-ionization, it is more efficient when the EC resonance layer is inside the tokamak vessel, while the electron gun pre-ionization acts better at low magnetic fields.

Tokamak GOLEM contributed to a numerous educational events and activities with the help of its unique capability to be operated remotely. More than 2000 discharges were performed remotely across the borders of the Czech Republic as a part of a remote laboratory practice or a tokamak performance presentation for foreign students in various plasma schools, workshops, lectures and training courses.

ACKNOWLEDGEMENT

This work was partially supported by the project RVO: 68407700 of the Czech Technical University in Prague. Additional support has been granted from IAEA technical contract CRP F1.30.14 on "Utilization of the Network of Small Magnetic Confinement Fusion Devices for Mainstream Fusion Research". The opinions expressed by authors do not necessarily represent the positions of the European Commission neither IAEA.

REFERENCES

[1] M. GRYAZNEVICH, V. SVOBODA, J. STOCKEL, A. SYKES, N. SYKES, D. KINGHAM, G. HAMMOND, P. APTE, T.N. TODD, S. BALL, S. CHAPPELL, Z. MELHEM, I. ĎURAN, K. KOVARIK, O. GROVER, T. MARKOVIC, M. ODSTRCIL, T. ODSTRCIL, A. SINDLERY, G. VONDRASEK, J. KOCMAN, M.K. LILLEY, P. DE GROUCHY, H.-T. KIM, *"Progress in application of high temperature superconductor in tokamak magnets",* Fusion Engineering and Design, **88** (2013) 1593-1596.

[2] MIKHAIL GRYAZNEVICH *et al.. Contribution to fusion research from IAEA coordinated research projects and joint experiments.* Nuclear Fusion, **55** (2015).

[3] V. SVOBODA, J. KOCMAN, O. GROVER, J. KRBEC, J. STÖCKEL. *Remote operation of the vertical plasma stabilization @ the GOLEM tokamak for the plasma physics education.* Fusion Engineering and Design. **96–97** (2015) 974–979.

Conference contributions:

O.Ficker, O.Grover, J.Kocman, J.Krbec, L.Matena, J.Stockel, V.Svoboda, G.Vondrasek. Tokamak GOLEM for fusion education - chapter 6. Poster presentation at the 42nd EPS Conference on Plasma Physics, Lisbon, Portugal. Vol. 39E ISBN 2-914771-98-3:P2.164,2015.

V Svoboda, A Dvornova, R Dejarnac, M Prochazka, S Zaprianov, R Akhmethanov, M Bogdanova, M Dimitrova, Zh Dimitrov, O Grover, L Hlavata, K Ivanov, K Kruglov, P Marinova, P Masherov, A Mogulkin, J Mlynar, J Stockel, A Volynets. Remote operation of the GOLEM tokamak with hydrogen and helium plasmas.

Proceedings of the 6th International Workshop & Summer School on Plasma Physics, Kitten. 2014. Accepted in the Journal of Physics: Conference Series.

O. Ficker, O. Grover , J. Kocman, J. Krbec, V. Loffelmann, T. Markovic , M. Matusu, J. Stockel, V. Svoboda, J. Veverka, G. Vondrasek. Tokamak GOLEM for fusion education - chapter 5. Poster presentation at the 41st EPS Conference on Plasma Physics, Berlin, Germany. Vol.38F:P4.141,2014.

Svoboda, V., Brotankova, J., Bromova, E., Grover, O., Kocman, J., Leitl, B., Markovic, T., Odstrcil, M., Odstrcil, T., Stockel, J., Ruzickova, T., Vondrasek, G., Vrba, O. Tokamak GOLEM for fusion education - chapter 4. Poster presentation at 40th EPS Conference on Plasma Physics, Espoo, Finland.

Ball, S., Ďuran, I., Grover, O., Gryaznevich, M., Kocman, J., Kovařík, K., Markovič, T., Odstrčil, M., Odstrčil, T., Růžičková, T., Stöckel, J., Svoboda, V., Vondrášek, G. First results from tests of high temperature superconductor magnets on tokamak. In Europhysics Conference Abstracts. 39th EPS Conference on Plasma Physics and 16th International Congress on Plasma Physics Stockholm

Svoboda, V., Duran, I., Grover, O., Gryaznevich, M., Kocman, J., Kovarik, K., Markovic, T., Odstrcil, M., Odstrcil, T., Stockel, J. Recent results from GOLEM tokamak. 'Indeed, you can teach an old dog some new tricks.' In Europhysics Conference Abstracts. 39th EPS Conference on Plasma Physics and 16th International Congress on Plasma Physics Stockholm