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Remote operation of the vertical plasma stabilization @ the GOLEM tokamak for the plasma physics education

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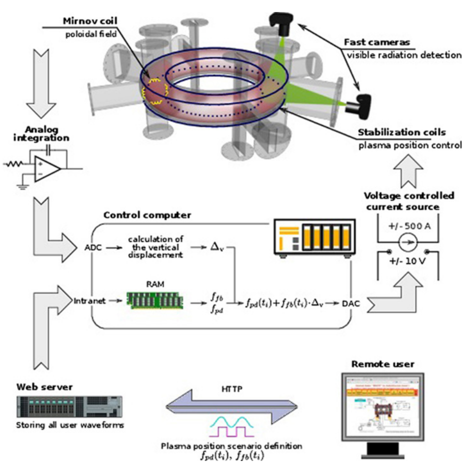
HIGHLIGHTS

- Understandable remote operation of a vertical plasma position control system in the tokamak GOLEM for educational purposes.
- Two combinable modes of real-time plasma position control: position based feedback and a pre-defined waveform.
- More than 20% plasma life prolongation with plasma position control in feedback mode.

GRAPHICAL ABSTRACT

* Understandable remote operation of a vertical plasma position control system in the tokamak GOLEM for educational purposes.* Two combinable modes of real-time plasma position control: position based feedback and a pre-defined waveform.* More than 20% plasma life prolongation with plasma position control in feedback mode.



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ABSTRACT

The GOLEM tokamak at the Czech Technical University has been established as an educational tokamak device for domestic and foreign students. Remote participation in the scope of several laboratory practices, plasma physics schools and workshops has been successfully performed from abroad. A new enhancement allowing understandable remote control of vertical plasma position in two modes (i) predefined and (ii) feedback control is presented. It allows to drive the current in the stabilization coils in any time-dependent scenario, which can include as a parameter the actual plasma position measured by magnetic diagnostics. Arbitrary movement of the plasma column in a vertical direction, stabilization of the plasma column in the center of the tokamak vessel as well as prolongation/shortening of plasma life according to the remotely defined request are demonstrated.

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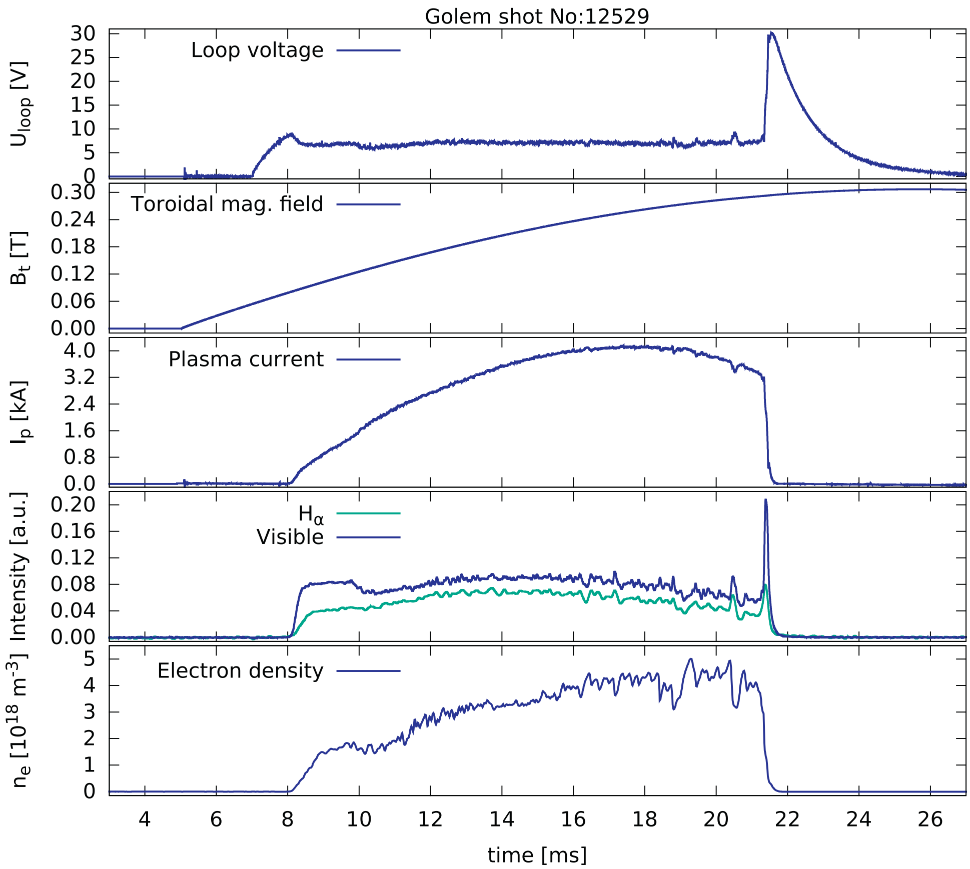

Fig. 1. Evolution of a well executed GOLEM discharge. From top to bottom – the loop voltage U_{loop}, toroidal magnetic field B_t, plasma current I_p, the signal of photo-diode with H_α interference filter and electron density n_e.

1. Introduction

High quality education and training in the field of thermonuclear fusion are called for in the Roadmap towards a modern European Fusion Research Program as the demand for a new generation of high temperature plasma physicists and technologists strongly increases. Numerous specialized university curricula, training courses and plasma physics schools are organized in the frame of Fusion Education Network consortium Fusenet [3]. These educational activities suffer from not having appropriate “hands on” laboratory experiments, where the basics of high temperature plasma physics and technology can be demonstrated, trained and practice, since the relevant laboratory devices are extremely complex, sophisticated and expensive. Thus there is an obvious need to create shared and centralized experiments where students can participate both “on site” as well as remotely.

1.1. The tokamak GOLEM for fusion education

The GOLEM tokamak [2] (re-installed version of the CASTOR tokamak) at the Czech Technical University in Prague (major radius $R = 0.4$ m, plasma radius $a = 85$ mm) operates currently at a modest range of parameters, $B_t < 0.5$ T, $I_p < 8$ kA, pulse duration ~15 ms and with a limited set of diagnostics. A well executed discharge scenario (see Fig. 1) starts the toroidal magnetic field B_t at the time $t_{Bstart} = 5$ ms after the Data Acquisition System initiation $t_{DAS} = 0$ and the electric field (primary current field serving as a breakdown field as well) is triggered at $t_{CD} = 7$ ms and within this configuration breakdown into plasma occurs at $t_{PlBr} \sim 8.2$ ms.

After a complete reconstruction of its infrastructure the tokamak became an educational device making tokamak operation accessible to students worldwide via a web application, see [5]. The device has been used as an educational tool to numerous training courses, plasma physics workshops, demonstrations and remote laboratory experiments. More than 1000 remote discharges from foreign sites have already been successfully performed in the frame of FUSENET since the beginning of operation in 2009. The GOLEM tokamak offers its remote functionality to foreign universities and tutors of high temperature plasma physics and technology are welcome to contact authors to establish cooperation and explore its educational potential in the frame of various laboratory practices, training courses, plasma physics schools or lecture demonstrations.

1.2. Remote operation – basic level

The basic level of remote operation, see [5], gives remote participants a possibility to set up and submit basic tokamak technology parameters necessary to create plasma into a queue based system: power supplies for the toroidal magnetic field coil and the transformer primary coil, the pre-ionization tool and the injection system of the working gas via a web interface (see Fig. 2). After having checked the discharge set-up against safety and operational limits the control system processes the set-up and the results from basic diagnostics are presented instantly in a hypertext form of a shot homepage. Firing rate of one discharge per ~ minute is available, thus enabling systematic measurements, where participants can study the basic principles of tokamak technology, physics and operation, high temperature plasma diagnostics issues, breakdown studies, isotopic surveys, chamber conditioning examinations and can perform probe measurements, test various discharge scenarios, etc.

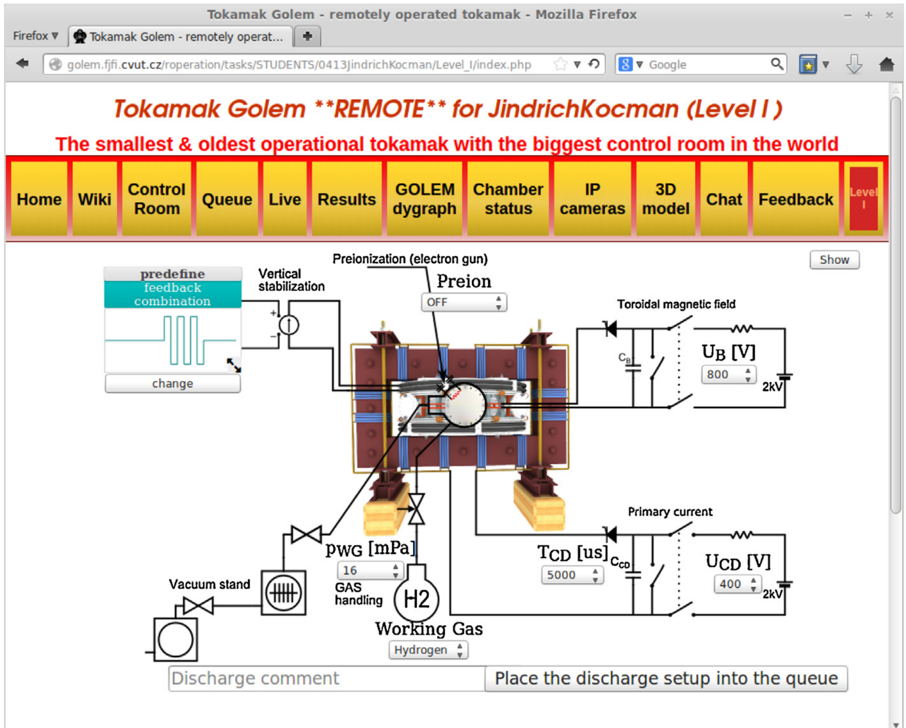

Fig. 2. The GOLEM tokamak remote control room layout. Basic engineering scheme of the tokamak combined with the web form enable setting up desired technology parameters to generate the plasma discharge. Left-top corner named “Vertical stabilization” represents the new level of the plasma scenario control.

1.3. Next step levels of remote operation

Since the tokamak GOLEM is mainly used for educational purposes it is extremely desirable to dive into the complexity of the tokamak control step by step, allowing participants to study the appropriate topics from the basic to the sophisticated levels. The current organization of the human–machine interface is organized as follows: (a) Level “system check”, with the purpose to test individual parts, where students can trigger toroidal magnetic field or toroidal electric field separately and observe their particular effect in the diagnostic system. (b) Level “basic tokamak plasma”, where the minimum technology required to control the tokamak is used to set-up the tokamak plasma: simultaneous trigger of the toroidal magnetic and electric field, while working gas and pre-ionization tool have been engaged in advance to the trigger. (c) Level “vessel conditioning”, where participants can study improved plasma performance regimes after vessel conditioning with the help of baking and glow discharge. (d) Level “E_t, B_t orientation”, where the influence of the mutual orientation of the toroidal magnetic as well as electric field on the plasma performance can be examined.

The presented article introduces a new level of remote operation, where students can set-up via web interface pre-defined or feedback plasma position control scenario that brings new horizons in the tokamak technology studies. The main challenge of such a goal is to link the standard plasma stabilization operation of the tokamak with the remote control room and thoroughly design a human(student)–machine interface.

The control of the plasma position on the old CASTOR tokamak was based on the analogue feedback system [6], which was not compatible with request of its remote control. Therefore, the new digital system have been designed on GOLEM with the strategy to be naturally implemented into the current basic remotely oriented control operation. As a first step the simple vertical direction control have been tested with the plan to clone it with necessary modifications to the horizontal version and finally link them both to the full operation stabilization system.

The paper is organized as follows: the first part introduces the simple methodical strategy to control the plasma position in two regimes: pre-defined and feedback. Then the experimental set-up of the HW arrangement linked to the net technology is described together with the SW solution and finally basic modes demonstrating its functionality are presented.

2. Remote control of the vertical plasma position

The new functionality has been implemented into the system allowing to perform remote plasma position studies. The left-top corner of the Fig. 2 (web oriented control room) represents the dialogue box where participants can set-up necessary parameters for vertical plasma management.

2.1. The overall arrangement of the remotely defined vertical plasma position stabilization

The overall strategy is described in Fig. 5. The remote user defines via a web interface the desired plasma position scenario via two time dependent discrete functions (i) pre-defined: $f_{pd}(t_i):(0,\ 40)\,\mathrm{ms} \rightarrow (-10,\ 10)$ and (ii) feedback-coefficient: $f_{fc}(t_i):(0,\ 40)\,\mathrm{ms} \rightarrow (-10,\ 10)$ where t_i denotes a discrete time series with a period of 0.1 ms (according to a feedback processing frequency $f_{FDB} = 10\,\mathrm{kHz}$). Actual horizontal plasma position $\Delta_v \in (-50, 50)\,\mathrm{mm}$ is monitored with a set of 4 Mirnov coils poloidally surrounding the plasma. These signals, after analogue integration, are digitized with the frequency f_{FDB}. Specialized Labview SW in real time mode links the scenario functions with the actual plasma position Δ_v and generates a plasma movement request $y(t_i) = f_{pd}(t_i) + f_{fc}(t_i)\Delta_v$ in the range of $(-10,\ 10)$ which converted into an analogue signal $(-10,\ 10)$ V and amplified to the vertical stabilization current $I_{VtSt}(t_i) \in (-500, 500)$ A maintains

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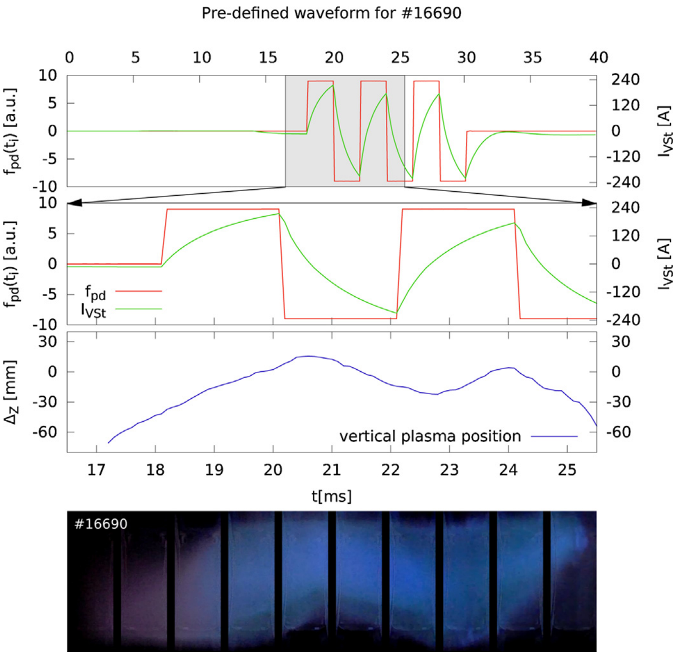

Fig. 3. Pre-defined plasma vertical movement mode test. Upper figure (together with zoomed detail) displays the pre-defined function for desired plasma shift, middle figure describes the signal from Mirnov coils reflecting the actual vertical plasma position and bottom figure displays a fast camera series of frames visualizing plasma movement in the vertical direction.

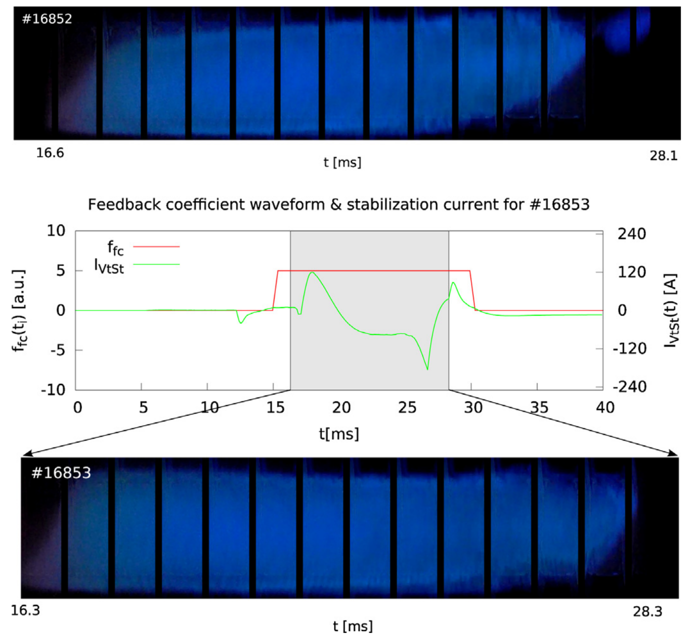

Fig. 4. Feedback plasma vertical movement mode test. From top to bottom: a fast camera frame series of a standard discharge without any means of stabilization, definition of feedback coefficient function $f_{fc}(t_i)$ together with resulting stabilization current and finally a frame series showing a stabilized evolution of the plasma column.

the desired magnetic force for vertical plasma movement. The resulted plasma shift is monitored with the fast cameras Casio FX1 [4] delivering a series of 1200 frames per 1 s.

2.2. The control function

The control function $y(t_i)$ is a superposition of two components: pre-defined $f_{pd}(t_i)$ and feedback $f_{fc}(t_i)$ functions and their time dependent pattern can be specified in three modes: (i) it can be selected from a list of pre-defined waveforms; (ii) the user can define the waveform in a similar way as adjusting a frequency generator (i.e. select type of the waveform /sawtooth, square, triangle, sine/, the start of the signal with respect to t_{DAS}, the length of the signal, its amplitude, phase and offset) and finally, (iii) the user can freely design an arbitrary waveform pattern with the help of a special web application.

2.3. SW

The software is divided into 3 layers. The first layer contains a graphical user interface and takes the form of a web page. The second layer is a server which stores all user waveforms and uploads them to the third layer: a control computer which is responsible for the current in the stabilization coils.

First layer – A web page with an extended web form for remote operation of the GOLEM tokamak. The type of stabilization to be used (predefined, feedback, combination) can be chosen by the user. Existing waveforms can be picked or new ones can be created. The created waveform is sent to the server and added to existing ones so any other user can then use it.

Second layer – A server which stores all waveforms. Provides information about existing waveforms for the first layer and receives the new ones. It also uploads the desired waveform to the control computer during the initialization procedure of a discharge.

Third layer – The control computer with the real-time operating system. The main loop with a frequency of f_{FDB} calculates the plasma position and combines it with the user's waveform. The result is sent to the current source which drives the current in the stabilization coils.

3. Functionality demonstration

Two possible remotely defined example situations have been tested: (i) pre-defined and (ii) feedback mode.

Fig. 3 depicts the ability to shift the plasma column upward and downward according to waveform definition $f_{pd} = \mathrm{sgn}(\sin[2\pi t/0.004])$ where $t \in (18, 30)$ ms. The toroidal magnetic field B_t is triggered at $t_{Bstart} = 5$ ms while the toroidal electric field is triggered at $t_{CD} = 14$ ms in the "flat top" part of B_t. Plasma breakdown occurs at $t_{PlBr} \sim 16.5$ ms. The desired plasma movement is initiated according to the pre-defined function at 18 ms, pushing the plasma ring upward. At 20 ms the stabilization current is commuted into opposite direction pushing the plasma column downward. From the fast camera photo series it is evident that the response to this request is (with some time delay, which can be assigned to electronic issues) adequate and it is possible to observe an upward and downward shift of the plasma column with the same frequency of 250 Hz as the pre-defined function.

Fig. 4 demonstrates the real-time feedback functionality of stabilizing the plasma column in the center of the tokamak vessel. Discharge #16852 was executed without any stabilization request, the discharge started at the bottom part of the vessel and tendency to move upward can be seen - the typical movement scenario for the GOLEM tokamak without stabilization. Thus the definition of the feedback coefficient f_{fc} function is to switch on the feedback stabilization before the start of the discharge with ∼1/2 strength to create a countering magnetic force through the stabilization current I_{VtSt} to preserve the plasma column in the center of the vessel. The result of such a stabilization can be seen from the fast camera observing discharge #16853 demonstrating good functionality of

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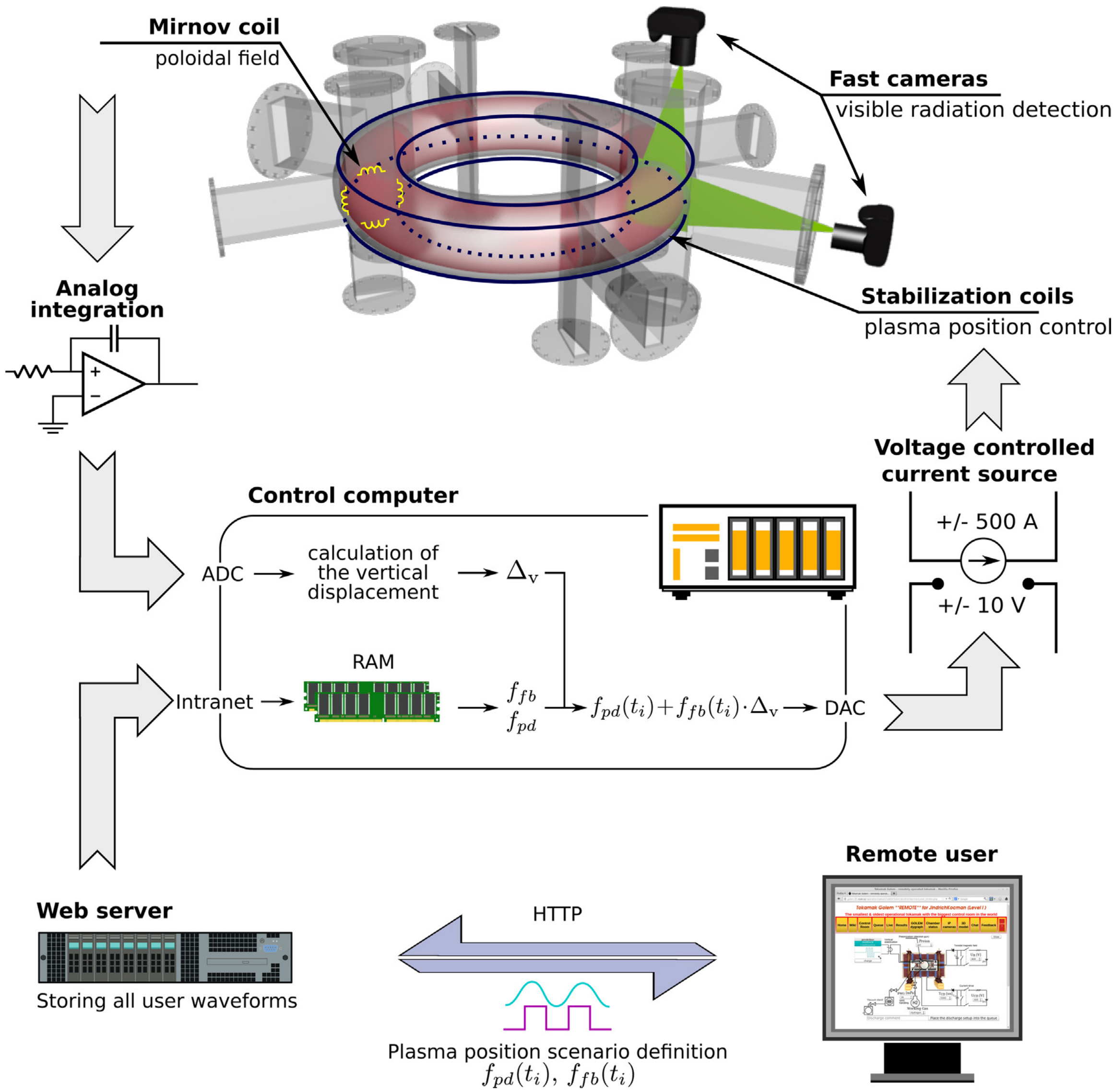

Fig. 5. The tokamak GOLEM remote vertical stabilization operation arrangement.

this feedback control system and relative plasma life prolongation from 11.9 ms to 13.5 ms.

4. Conclusions

Understandable plasma position control according to the remote user definition has been implemented in the GOLEM tokamak control system. It provides pre-defined and feedback modes as well as their combination of plasma vertical position control requests. The system now enables remote participants to study the effect of the horizontal magnetic field on the vertical plasma position using their own approach. Relative plasma-life duration prolongation of more than 20% can be reached with respect to the mode without any stabilization and moreover it is possible to set-up arbitrary, even not rational, plasma position scenarios, that can be used e.g. for testing the specific plasma physics and technology ideas.

Future outlook is as follows: (i) horizontal position control is planned to be implemented as a “clone” of the vertical position system, (ii) an increase of the stabilization current up to 1 kA for both plasma positioning systems is envisaged, (iii) feedback coefficient f_{fc} will express non-linear functionality of actual vertical position Δ_v, and iv) bolometers, electric probes [1] or other means of plasma position Δ_v detection are in the scope of possible inputs into the system.

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