

Plasma position control system for tokamak FT-2

© A.A. Bogdanov¹, Yu.V. Tuboltsev¹, Yu.V. Chichagov¹, N.A. Zhubr¹, M.Yu. Kantor¹,
L.A. Esipov¹, S.V. Shatalin¹, V.M. Zavadskiy¹, V.P. Lazutkov¹, S.V. Zavadskiy²

¹ Ioffe Institute, St. Petersburg, Russia

² St. Petersburg State University, St. Petersburg, Russia

E-mail: Alexander.A.Bogdanov@mail.ioffe.ru

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A new modular plasma control system on a modern hardware for tokamak FT-2 has been developed. The paper describes the system design, the principle of the plasma position control via thyristor keys, and the operating modes. In April 2025, the first tests of the tokamak FT-2 with the new control system were conducted in the mode of pre-recorded scenario of currents in the control windings. The tests proved the operability of the new system. Future development will be aimed at implementing of an automatic plasma confinement mode.

Keywords: tokamak, plasma, control system, FT-2.

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One promising trend in environmentally friendly power engineering is the development of a thermonuclear fusion reactor based on a tokamak with toroidal plasma confined by a strong magnetic field [1]. The position and motion of the plasma column in the tokamak cross section are determined by a complex of physical factors and are normally subjected to optimization and dynamic control in the process of a discharge [2]. Owing to a lack of proper corrective inputs adjusting the position of the column, the discharge in a tokamak often loses stability too fast or is not ignited at all. Current loops are used to control the position of the plasma column by vertical and horizontal magnetic fields in small tokamaks. The loop currents are specified according to a preset program or determined by an automatic control algorithm with feedback, which allow, among other things, for fast variation of the control input.

Experiments at the small FT-2 tokamak ($a = 8$ cm; $R = 55$ cm; discharge, up to 40 ms; magnetic field, up to 2.5 T) are carried out [3] in the ohmic mode, lower hybrid current drive and plasma heating, where the discharge parameters may change significantly within a few milliseconds.

Three poloidal current loops, which are denoted as R , H , and B , are used to control the plasma position. The R and H loops shift the column inward and outward, respectively, along the major radius, while the B loop shifts the column down. Controlled upward displacement of the plasma column is not needed, since it moves in this direction by itself without control inputs. The loops are connected to a capacitor bank via a set of 38 thyristor switches with ballast resistors that set the total loop current. The thyristor switch diagram is shown in Fig. 1.

Each switch is opened by a short pulse from a blocking oscillator, which is fed to the control electrodes of thyristors T_1 and T_2 . Thyristor T_2 connects the capacitor bank to a loop L . Capacitor C in the switch then charges through thyristor T_1 . To close the switch, a short pulse from

the blocking oscillator is fed to the control electrode of thyristor T_3 , which connects charged capacitor C in opposition to thyristor T_2 , switching it off.

Four types of thyristors are used in switches: TCh-25, TCh-80, TCh-125, and TB-400. They provide pulse switching currents ranging from 10 to 1000 A. The rise and decay times of the loop current are close to 0.5 ms and are set by resistances R_1 and R_2 and capacitance C .

A control system [4] based on a small-scale IC with discrete logic components, a general-purpose x86 computer, and controller of analog-to-digital converter on ISA bus has been used earlier to control the thyristor switches at the FT-2 tokamak. The system was found to have a certain performance capability, but also had a number of significant shortcomings. Specifically, the use of a large number of discrete components led to low reliability, and tasks could not be redistributed between the logic machine and the x86 processor to optimize control algorithms. In addition, the system eventually became difficult to maintain, since all the electronic components used had been discontinued and turned obsolete.

A plasma control device (PCD) in the form of an updated modular crate, which is fully integrated with the main data acquisition system and controlled via a local network (Fig. 2), has been designed in 2024–2025. It implements independent control of the operation of 96 thyristors and monitoring of their current state for opening and closing the switches at specific moments in time and allows one to record the position of the plasma column and certain other discharge parameters.

Blocking oscillators are triggered by a logic voltage pulse with a duration of $4\mu\text{s}$, which may lead to false triggering due to interference under operating conditions. Therefore, a noise-immune circuit with a current loop and galvanic separation via an optocoupler was chosen as a means to transmit control pulses to blocking oscillators. A total of

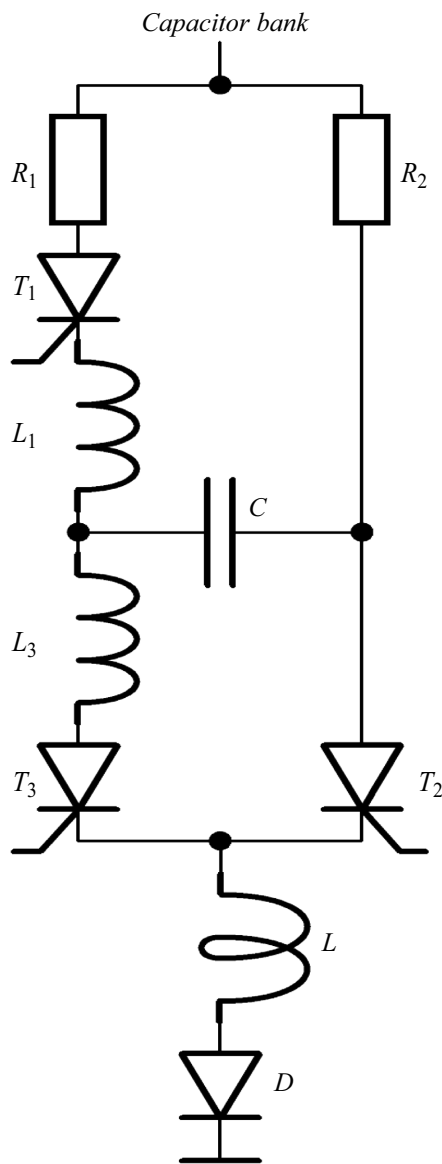


Figure 1. Thyristor switch diagram.

48 thyristor control boards (TCBs) were produced for this purpose. Each of them controls two blocking oscillators (i. e., two thyristors).

In turn, the PCD crate houses four thyristor control modules (TCMs), each of which features 32 control channels with current switches. Each control signal is transmitted from the TCMs to the TCBs via twisted pair over a distance up to 4 m. The cables chosen were standard F/UTP cat.6 cables with four twisted pairs and 8P8C connectors. Thus, four thyristors are controlled through one connector and one cable. A total of four TCMs can control a system of 128 thyristors. However only 96 of them are currently in use, providing a reserve for expanding the thyristor switch system. The maximum frequency of setting the state of all thyristors (without account for their own speed performance) is 230 kHz.

The current state of thyristor switches is monitored by picking up a signal from the anode of thyristor T_2 of a switch through a resistive voltage divider with the use of an acknowledgment module (AM). The AM has 40 channels, 38 of which are in use. Each channel features a comparator with controlled hysteresis for setting the lower and upper response thresholds. When the thyristor is closed, its anode voltage is approximately equal to the capacitor bank charge level and can reach 400 V. In the open state, the anode voltage of thyristor T_2 decreases significantly because of current through resistor R_2 separating the thyristor from the capacitor bank. To improve noise rejection, the hysteresis width for each channel is set in advance to 50 V. However, one can adjust the hysteresis magnitude in the course of operation (or when individual thyristors are replaced with thyristors of other types) individually for each channel using trim potentiometers in the comparator feedback circuit.

Thus, the comparator in the AM can determine the thyristor state. The lower trigger threshold is adjusted programmatically within the range of 0–110 V using a digital potentiometer. The hysteresis width (the position of the upper threshold relative to the lower one) for each channel is set by an individual compact manual potentiometer; by default, it is 50 V. To smooth out high-frequency noise, the bandwidth of the AM channels is limited by a low-pass filter at the level of approximately 3 kHz. The maximum polling frequency for the switches is 110 kHz.

All modules of the PCD crate are controlled via a data bus through a crossboard using a control module based on a DE10-Nano single-board computer. The central processing unit is a Cyclone V field-programmable gate array (FPGA) with an integrated 32-bit dual-core Cortex-A9 processor. The maximum clock frequency of this processor is 900 MHz, and the maximum achievable FPGA clock frequency is upward of 100 MHz, which ensures sufficient performance of control and measurement circuits. The use of such a component allows one to design the system without a rigidly fixed operating algorithm of both the logic machine and the control program and reassign their roles as needed.

The single-board computer runs on the OpenWrt operating system, which provides a wide range of programming tools and easy integration into a local measurement network.

The modules mentioned above provide an opportunity to perform experiments with a plasma discharge at the FT-2 tokamak in accordance with a pre-defined scenario of switches currents in control loops. In other words, the operator creates a table of currents in three loops (R , H , and B) and time delays that must be maintained before moving on to the next row of the table (i. e., to the next current values). When the synchronizer of the entire system is activated, trigger pulses are sent to the PCD and other FT-2 devices. The PCD processes the loops current scenario programmed into it and stores data on the state of thyristor switches in its memory.

This pre-programmed discharge control regime works well when the plasma column is stabilized by copper plates mounted near the walls of the tokamak vacuum vessel.

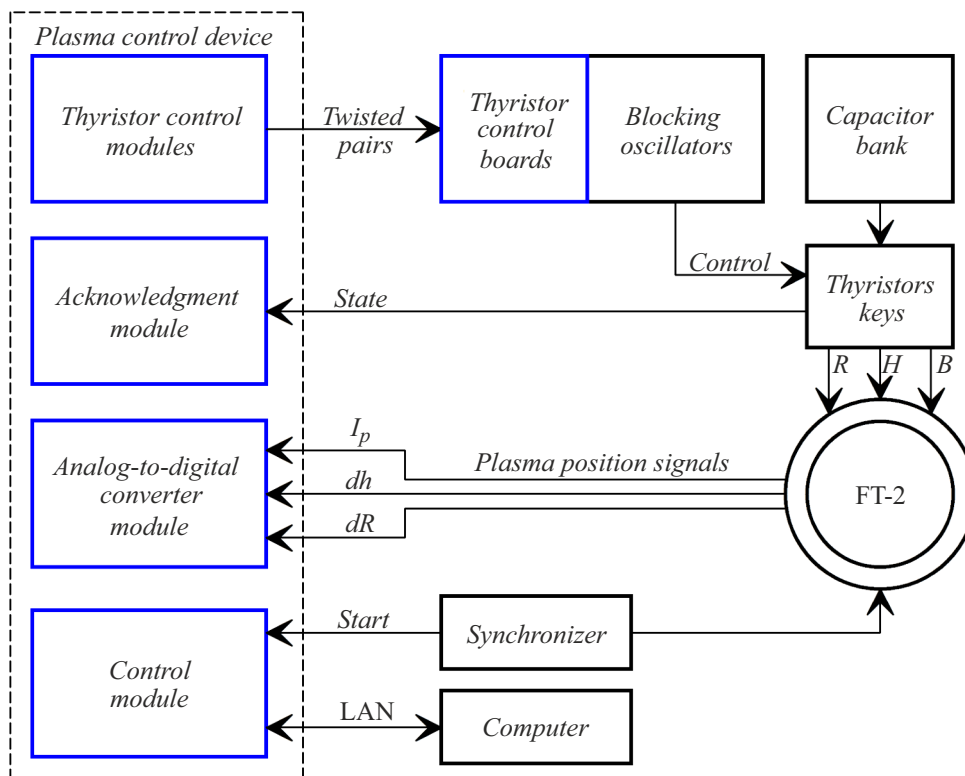


Figure 2. Structural diagram of the plasma control device and the FT-2 tokamak systems connected to it.

Such passive stabilization will be infeasible (or less efficient) in the upgraded FT-2 tokamak with a larger vessel. The tokamak discharge will then be controlled via feedback loops provided in the designed control system.

The plasma position will be controlled with a minimum cycle duration of 0.1 ms. The required positions of the plasma column are set in each cycle. The control system calculates the currents in control loops needed to compensate for deviations from the specified positions. Calculations are carried out according to the chosen algorithm using the dynamics of horizontal dR and vertical dh plasma column shift signals, which are measured by saddle loops in the tokamak, and plasma current I_p determined by a Rogowski coil. A four-channel analog-to-digital converter (ADC) module is used to record signals.

Each channel of the ADC module features a multiplexer, an adjustable offset and scaling circuit, a low-pass filter, and an analog-to-digital converter chip. The multiplexer allows one to connect a reference voltage to the channel for calibrating the measurement circuit without physical switching of connectors. The offset and scaling circuit provides an opportunity to adjust the input signal conversion function to the range of the analog-to-digital converter chip.

The ADC module allows for simultaneous digitizing of four analog 12 bit signals with a frequency up to 460 kHz. Each channel has a low-pass filter that provides suppression of high-frequency noise and limits the bandwidth to approx-

imately 250 kHz. The offset and scaling circuit allows for an input signal voltage range from ± 1.5 to $+5$ V.

The regime of system operation with digitizing of the plasma column position signals and feedback through a proportional-integral-derivative (PID) controller [5,6], which is implemented in software in the controller module FPGA, implies automatic maintenance of the plasma position in the FT-2 tokamak. The results of preliminary modeling reveal that the minimum permissible operating frequency of thyristor switches in the automatic regime is 2 kHz and that the implementation of this regime will require fine-tuning of the PID controller.

In April 2025, the control system of the FT-2 tokamak has been tested without plasma and in standard plasma discharge regimes. Figure 3 presents the results of testing the control system at the FT-2 tokamak without plasma. Line 2 (T_B) represents the control pulse for the thyristor switches of group B . Within this pulse, thyristors are switched to provide a set current in the vertical balance loop, which is reflected in saddle loop signal U_y (line 1). Similar signals for horizontal control of the plasma column position are represented by lines 4 (T_H) and 3 (U_r).

Figure 3 reveals significant smoothing of the response with regard to the U_r voltage front, which is attributed to a longer integration time of signals from the measuring loop. The response rate will be increased in future operation with feedback links.

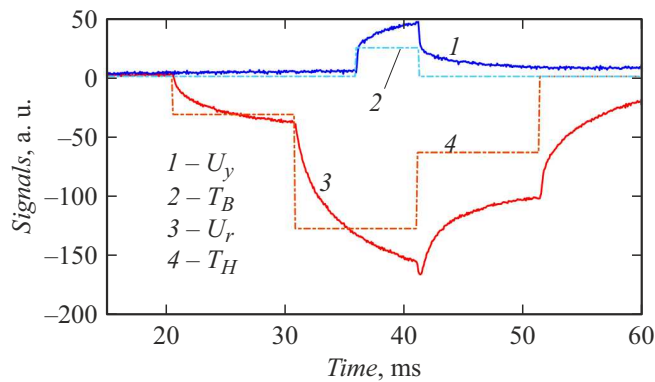


Figure 3. Example implementation of a given order of thyristor switches and response signals from saddle loops.

At present, the developed system is used to control the position of the plasma column in all discharge regimes. Figure 4 presents an example of operation of this system for discharge control with specified times of current switching-on and switching-off in the control loops.

The transfer of the plasma control system to a modern computer platform with state-of-the-art hardware components allowed us to increase the operation speed, implement condition monitoring, and expand the opportunities for further development of the FT-2 tokamak. The results of tests of the new plasma control system carried out in April 2025 revealed its operability and ease of use. The described system is already being used at the FT-2 tokamak in the regime of pre-programmed control of the plasma column position. Plans for further development of the setup involve the implementation of automatic maintenance of the plasma position via feedback loops.

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Conflict of interest

The authors declare that they have no conflict of interest.

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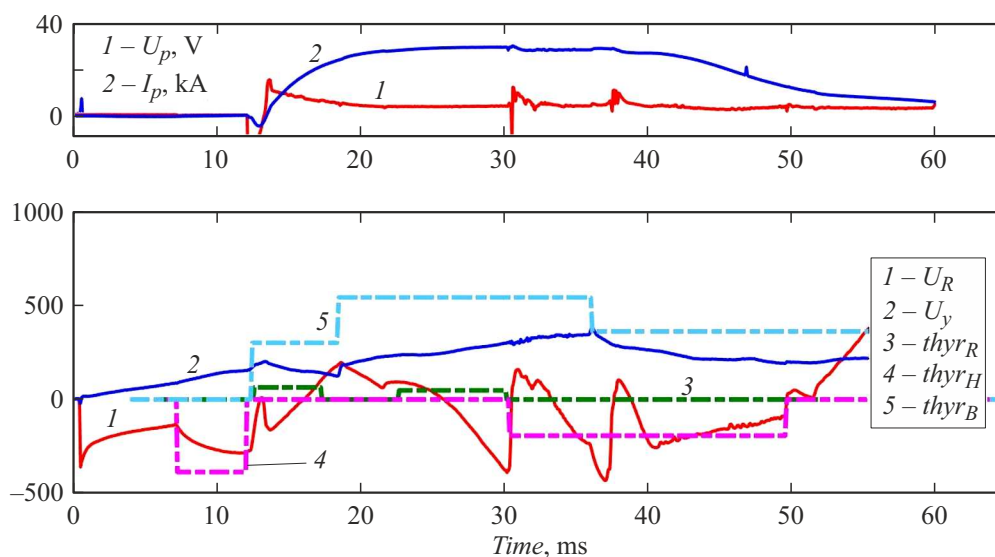


Figure 4. Example of pre-programmed control of the FT-2 plasma discharge.