SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 13, No. 3, October 2016, 423-434

UDC: 621.384.6:007]:004.5 **DOI: 10.2298/SJEE1603423T**

Control System of ECR Ion Source Within FAMA

Ivan M. Trajić[1], Ljubiša Vukosavljević[1], Bora Novaković[1], Dragana Ćirić[1], Aleksandar Dobrosavljević[1], Dragan Munitlak[1]

Abstract: Recent upgrading of the Facility for Modification and Analysis of Materials with Ion Beams (FAMA), in the Laboratory of Physics of the Vinča Institute of Nuclear Sciences, included modernization of its electron cyclotron resonance (ECR) ion source. The ECR ion source was extensively used for production of multiply charged ions from gases and solid substances for more than 15 years, during which time its major subsystems were expended and therefore, it required complete reconstruction. As a part of this reconstruction we designed and put together a completely new control system of the ECR ion source. It is a distributed and fiber-optically linked control system based on the Group3 Control hardware and the control application written in the Wonderware's InTouch software. The control system should help and assist an operator in obtaining the appropriate operating parameters of the ECR ion source, maintaining and controlling operating parameters of the machine during its operation, as well as in monitoring weather the safety conditions are fulfilled during the operation of the machine. We tested the operation and performances of the new control system during the commissioning of the upgraded ECR ion source. Compared to the old one, the new system is more reliable, more user-friendly oriented, and it comprises several new useful control applications.

Keywords: Control system design, User interface, Ion source.

1 Introduction

The electron cyclotron resonance plasma source of multiply charged heavy ions (ECR ion source) [1 – 3] and its subsystems, represent machine M1 within the Facility for modification and analysis of materials with ion beams (FAMA) [4]. The plasma and the hot electrons are generated by the microwaves using the electron cyclotron resonance effect. The multiply charged ions are produced by the collisions of ions with hot electrons. The microwave frequency is 14.5 GHz. The axial confinement of plasma is obtained by two solenoid coils each with an iron yoke. The radial confinement of plasma is performed with the permanent

[1]Laboratory of Physics, Vinča Institute of Nuclear Sciences (www.vin.bg.ac.rs), University of Belgrade, P.O. Box 522, 11001 Belgrade, Serbia; E-mails: tivan@vinca.rs; vljubisa@vinca.rs; bora.novakovic@gmail.com; cdragana@vinca.rs; alexd@vinca.rs; munitlak@vinca.rs

hexapole magnet. The ECR ion source discharge chamber is held at high voltage of up to 25 kV enabling extraction of ion beams from the plasma.

The ECR ion source was designed and constructed by the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research, Dubna, Russia, in collaboration with the Laboratory of Physics of the Vinča Institute of Nuclear Sciences. The ion source was commissioned in May 1998 [2].

Several downsides have been noticed during the 15 years of the M1 machine operation [5]. In addition, the extensive use of the machine in such a long period of time expended its major systems and the machine required detailed reconstruction. The old control system was implemented on the industrial control system Honeywell Alcont 3000x, that became obsolete, which further led to lack of spare parts and technical support. As a part of upgrading and improvement of the ion source we decided to introduce a completely new control system of the machine M1 [6].

The main task of the control system (CS) is to help and assist the operator in the process of obtaining the appropriate operating parameters of the M1 machine and to extract the desired ion beam from the ion source; for example, ion species, charge state, beam intensity, and beam energy are some of the parameters that may be specified. The control system also monitors status of the machine parts and obtains alarm signals from the safety system. During its operation some parts of the M1 machine are at the voltage as high as 25 kV, soft X-ray emission is generated, and strong magnetic field is present at certain locations. Consequently, the machine has to be surrounded by the protective fence and it requires a remote control system.

2 Main Parts of Machine M1

The main systems of the M1 machine are the ECR ion source that is the core of the machine (ECR), vacuum system (VS), beam optic system (BOS), beam diagnostic system (BDS), gaseous substance inlet system (GSI), solid substance inlet system (SSI), safety system (SS), and control system (CS). We will briefly describe the main parts of each system that are integrated into the control system. The main parts of the M1 machine are shown in Fig. 1.

The body of the ECR ion source has the injection stage coil (ISC) with the corresponding 1300 A DC power supply, extraction stage coil (ESC) connected to the identical power supply, microwave generator operating at 14.5 GHz (SHF), discharge chamber high voltage (25 kV) power supply (HV), extraction electrode positioning system (EE) with the step motor and its controller, and bias electrode connected to 300 V DC power supply (BV).

The vacuum system (VS) of the M1 machine has the five rotary vane pumps (RP1-RP5), four turbomolecular pumps with the controllers (TP1-TP4) that have different pumping speeds between 64 l/s and 700 l/s, two cryogenic vacuum pumps each having 800 l/s pumping speed (CP1 and CP2), thirteen vacuum gauges (VG) connected to the four vacuum gauge controllers, and eleven electro-pneumatic vacuum valves (VV).

Ion beam optic system consists of the solenoid lens (SL), magnetic quadrupole lens (QL), steering magnet (SM) and the analyzing magnet (AM). Each magnetic lens is connected to the corresponding DC power supply.

The beam diagnostic system consists of the two beam slits (S) with controllers, Faraday cup for precise beam current measurement (FC) installed on the electro-pneumatic actuator, Hall probe system (HP) for the measurement of the analyzing magnet field, and autonomous emittance measurement system (EM) which is not integrated into the main control system.

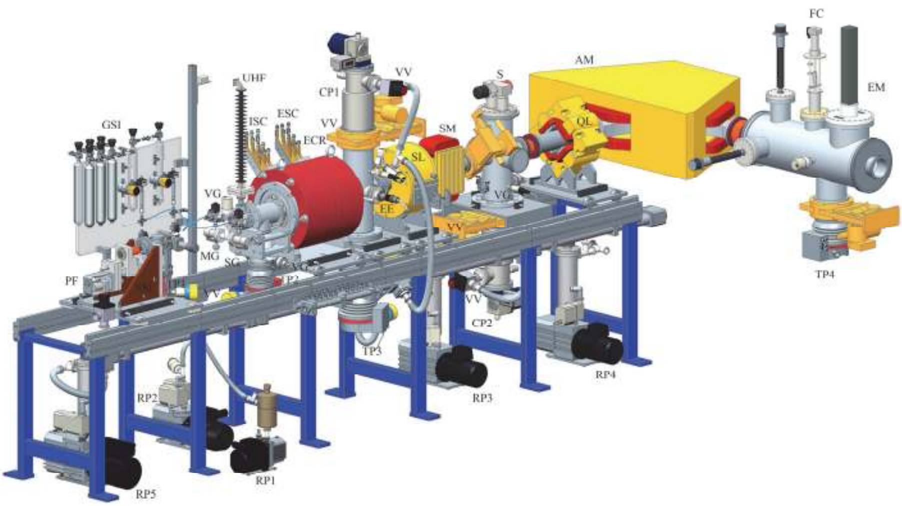


Fig. 1 – *A three-dimensional view of M1 machine. The abbreviations are defined in the text.*

The gaseous substance inlet system is based on the two precise gas dosing valves with appropriate controllers that are used for fine regulation of the main (MG) and the supporting gas (SG) flow into the plasma chamber. This system is used to obtain ion beams from different gases (e.g. nitrogen, oxygen, argon, krypton, xenon).

The solid substance inlet system is based on the miniature electric furnace (F) for heating and evaporation of solid substances. It can operate at up to

1700ºC. The furnace is inserted inside the plasma chamber by the furnace positioning device (PF) that uses the DC motor drive. This system is used to obtain ion beams from solid elements (e.g. lead, iron, hafnium, nickel).

The safety system operates independently from the control system. Its major goal is to protect people and expensive equipment from accidents during the operation of the M1 machine. Access to the machine is restricted by the protective fence due to the presence of high voltage and soft X-ray emission (safety switches installed on the door, grounding sticks used for discharging the static electricity etc.). Safety system also monitors the water flow and temperature of the cooling water for the magnet coils (ISC, ESC, SL and AM), discharge chamber and vacuum pumps. If the alarm is turned on it initiates immediate shut down procedure. At the same time, the corresponding information is transferred to the control system.

3 Control System

All processes in the M1 machine including setting and maintaining of the operating parameters have response times typically in the range of milliseconds.

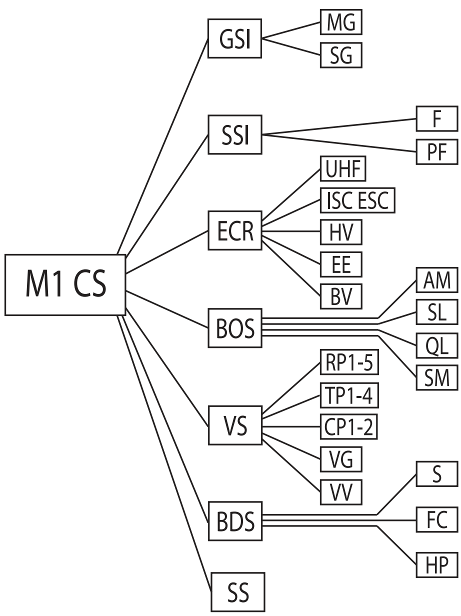


Fig. 2 – *Functional block scheme of M1 control system:*
GSI – gaseous substance inlet system, SSI – solid substance inlet system,
ECR – electron cyclotron resonance ion source body,
BOS – beam optic system, VS – vacuum system,
BDS – beam diagnostic system, SS – safety system.

On the other hand, the control system is facing demanding environment regarding electromagnetic interferences such as high voltage sparks in the ECR ion source, noise produced by electromagnetic valves, motors of the vacuum pumps, switches etc. During the operation of the ion source occasional sparks and instabilities in plasma produce large electromagnetic noise that can influence the surrounding electronic devices. The control system has to be resistant to all these interferences.

The functional block scheme of the control system is presented in Fig. 2. It shows the main parts of the M1 machine that are integrated into the new control system.

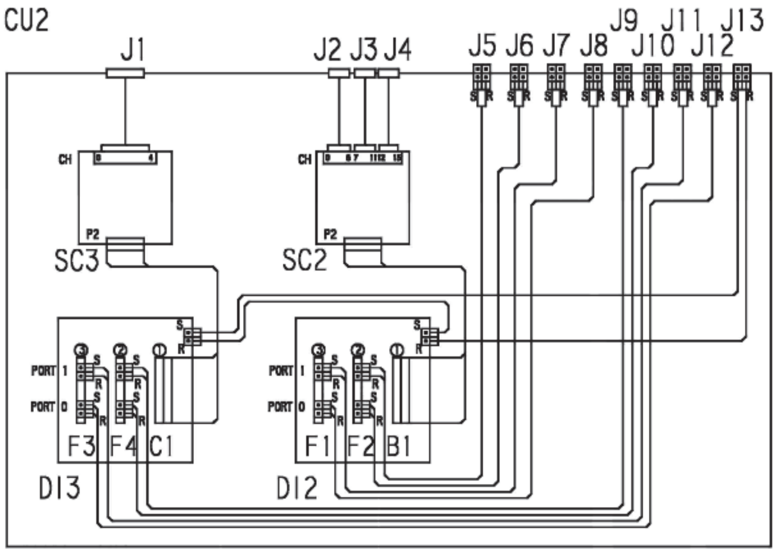
3.1 Hardware

The control system of the M1 machine (CS) is based on the Group3 Control hardware [7]. It is designed for scientific and industrial applications, and in particular for a particle accelerator control. It consists of the compact digital interface modules (DI) distributed throughout the machine to be controlled. Each module houses up to three I/O boards. The DI modules are interconnected in a fiber optic loop, providing noise free transmission of many analog and digital signals in a difficult environment such as the M1 machine. High voltage isolation and long distance transfer of signals are easy to implement using this low cost system.

The CS has four control units. The control units CU1, CU2, CU3 and HVCU (control unit on high voltage platform) are housed in four separate 19” subracks. Each control unit has one or two DI modules equipped with one, two or three boards (Fig. 3).

The following types of boards are used for the control system: the I/O board with eight analog inputs having 16 bit resolution, I/O board with 24 digital inputs or outputs, I/O board with two serial communication ports and I/O board with two analog outputs of 16 bit resolution. In total, the control system comprises 90 control channels: 7 analog inputs, 51 digital inputs, 2 analog outputs, 12 digital outputs, and 18 serial communication channels [6].

Field signals are connected to corresponding signal conditioner boards (SC), which accept signals (analog or digital), suppress transients from potentially electrically noisy environment and then transfer these filtered signals to I/O boards. Serial communication is performed via fiber optic cables. A fiber optic RS-232C adaptor (FTR) is used to provide bi-directional conversion between the standard RS-232C serial port and fiber optic cable and it is mounted as close as possible to the controlled equipment. These actions are taken to improve resistance of the control system to electromagnetic interference and noise.



a)

b)

Fig. 3 – *Electrical scheme and interior of CU2 – control unit 2, with DI – digital interface modules: F1-F4 – four serial communication boards, C1 – 8 channel analog board, B1 – 24 channel digital I/O board, SC2 and SC3 – signal conditioner boards, J – connector.*

A personal computer HP Compaq 500B is the control computer equipped with a Group3 loop controller (LC) which handles all communications with the DI modules through the fiber optic cables (Fig. 4).

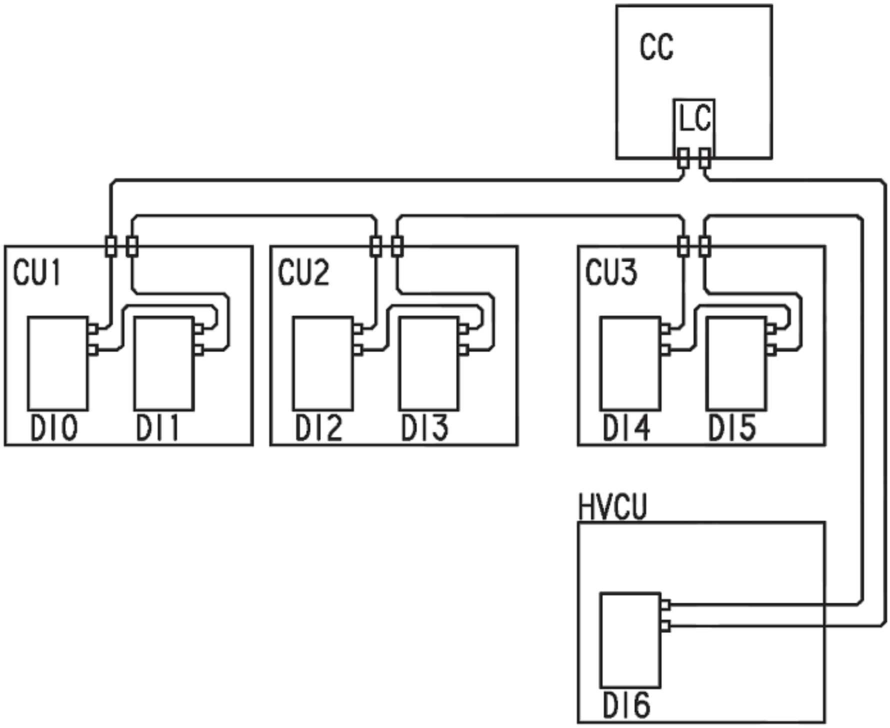


Fig. 4 – *Block scheme of control system: control units CU1, CU2, CU3, and HVCU (high voltage control unit) connected via fiber optic lines to CC (control computer): LC – loop controller, DI – digital interface module.*

3.2 Software

The control application of the new control system is written in the standard Human Machine Interface (HMI) software – Wonderware's InTouch [8]. Wonderware InTouch with Archestra Integrated Development Environment (Archestra IDE) is specially designed control software that enables fast and easy application development. Archestra IDE has powerful scripting and graphics editor that gives a programmer the possibility to design intuitive and user friendly custom controls with versatile functions.

The control application has a form of control functions. The custom design with advanced functionality and animations is provided trough scripting which is written in the internal programming language of Archestra IDE. The applied design and graphics becomes an integral part of each control function.

The control program M1CS allows setting, changing and maintaining of the operating parameters of the M1 machine. The control panel on the control screen allows one to control the specific equipment or a part of the equipment. It includes the following control items: labels, statuses, commands and sliders. Control panel can appear in two versions: collapsed or expanded. Labels indicate the names of the control panel, statuses, commands and sliders. A status can be designated with a status light, a status bar or a number. The status light indicates the condition of the monitored variable by colour coding.

The status bar is used to display the value of an analog signal graphically and numerically. It displays the value of the signal as a number and at the same time as a colour stripe whose length is proportional to the approximate percentage of the maximum value of the measured signal. Command can be designated with a button or arrows. The button is used to switch the controlled equipment on and off, and to change the polarity of the controlled power supply. The arrows are used for fine and coarse adjustment of an analog value, usually voltage or current. These controls have three ways of operation slow, fast and very fast change of the signal. Slider is used for coarse adjusting of the voltage or current.

The control application includes three control screens appearing at the operator's monitor that are selectable by a tab selector at the top of the application window. Control screens are the following:

(1) The transport screen is used to set the parameters of the ECR ion source, produce ions inside the discharge chamber, extract the ion beam, transport the beam along the beam line and finally chose the desired ion charge state by adjusting the magnetic field within the analyzing magnet.

(2) The vacuum screen is used to control and monitor the status of the vacuum system equipment (pumps, valves) and observe the pressure at certain points of the vacuum system.

(3) The safety screen shows the status of the alarm signals obtained from the safety system.

(1) The transport screen is used to set the currents of the injection and extraction coils, to set the plasma electrode and the discharge chamber high voltage and the voltage of the bias electrode, to set the output power and monitor the reflected power of the microwave generator, and to control the main and supporting gas flow. It also enables control of the beam optic elements along the transport line by setting the currents in the solenoid and quadrupole

lenses, steering and analyzing magnets. The transport screen is also used to set the apertures of the beam slits before and after the analyzing magnet, perform measurements of the magnetic induction in the gap of the analyzing magnet and measurements of the ion beam current in the diagnostic box after the analyzing magnet.

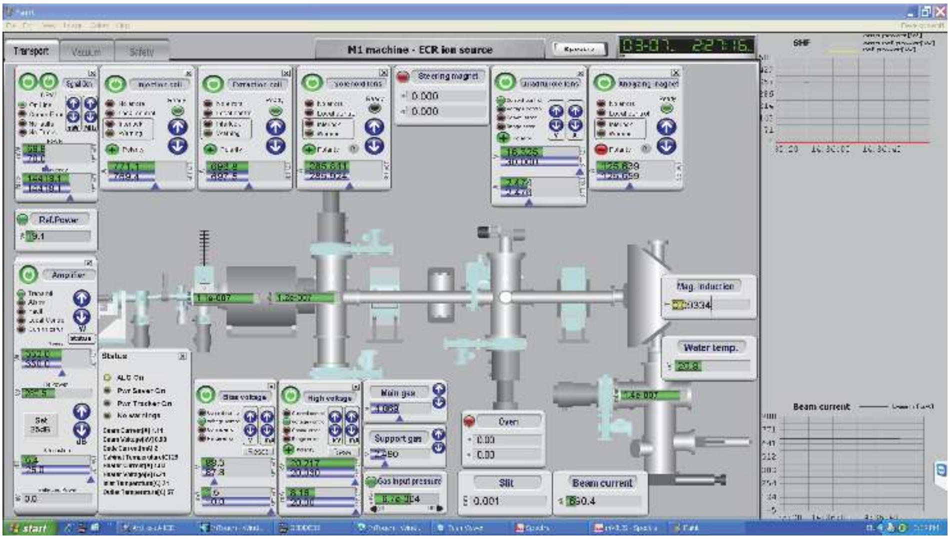


Fig. 5 – *Transport screen with expanded control panels during normal operation of machine M1.*

There are three additional applications integrated into the transport screen:

(a) Spectra application

(b) Extraction application

(c) Oven application

The magnetic induction within each of the ion-optical elements along the transport line is determined on the basis of the ion optics principles; namely the appropriate focusing is calculated according to the type and momentum-to-charge ratio of the ions that need to be focused.

The Spectra application is a useful tool for setting the operating parameters of the M1 machine. Measurement of the momentum-to-charge ratio distribution within the extracted ion beam is performed automatically in the diagnostic box after the analyzing magnet. The current of the analyzing magnet is varied in small steps in the specified range, while the currents of the solenoid and quadrupole lenses are adjusted according to the appropriate algorithm simultaneously.

The current of the analyzing magnet I_{AM} in amperes, is calculated as

$$I_{\mathrm{AM}} = \mathrm{c}_1 \sqrt{\frac{AU_{\mathrm{EX}}}{Q}} \approx \mathrm{c}_2 B_{\mathrm{AM}}\,, \tag{1}$$

where c_1, c_2 are constants, A is atomic mass of the ion species to be analyzed, expressed in amu, U_{EX} is extraction voltage of the ECR ion source in kV, Q is the ion charge state, and B_{AM} is magnetic induction of the analyzing magnet in mT.

The currents of the solenoid I_{SL} and quadrupole lenses I_{QL}, are calculated as

$$I_{\mathrm{SL}} = \mathrm{a}_1 + \mathrm{a}_2 I_{\mathrm{AM}}\,, \tag{2}$$

$$I_{\mathrm{QL}} = \mathrm{b}_1 + \mathrm{b}_2 I_{\mathrm{AM}}\,, \tag{3}$$

where a_1, a_2, b_1, b_2 are constants determined by the supplier of the transport lines and magnetic lenses.

The number of steps and the range of lens currents are set by the user. The maximal number of steps is 400. When the solenoid and quadrupole lenses are adjusted, e.g. the appropriate currents are applied throughout the lenses; the ion beam current is measured by the Faraday cup and recorded via a personal computer (Fig. 6).

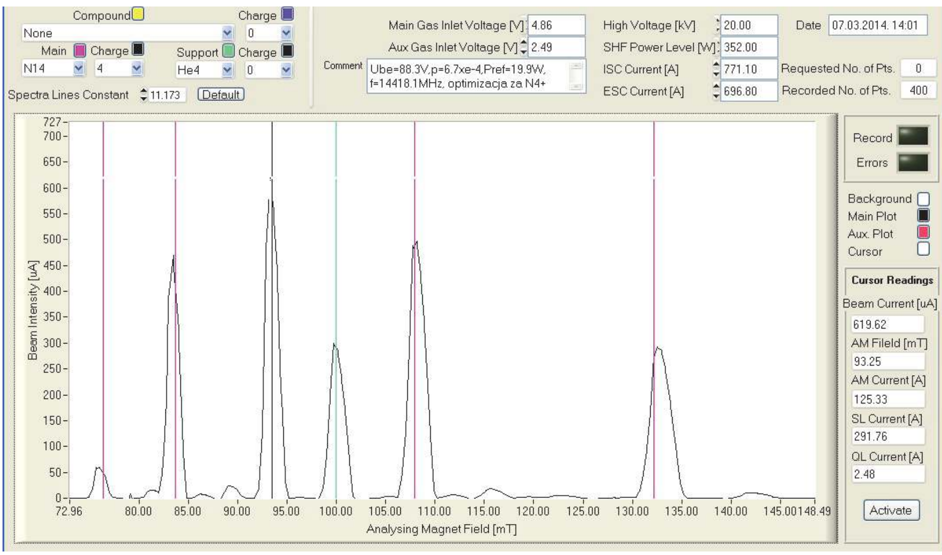


Fig. 6 – *Spectra application screen for nitrogen ion beam, with helium as supporting gas.*

At the same time, the magnetic induction inside the gap of the analyzing magnet is measured with a high precision Hall probe. Before the start of the measurements, user defines the main substance (ion beam type) and the supporting gas from the list, defines the number of steps and the range for the current of the analyzing magnet. After the spectra is recorded we can choose the optimal values for the currents of the analyzing magnet, solenoid and quadrupole lenses in order to obtain the required ion beam charge state.

The Oven application is used to set and maintain the temperature inside the oven, and to adjust the position of the oven inside the discharge chamber. This application is a part of the solid substance inlet system used to obtain ion beams from solid materials.

The Extraction application is used to set the optimal extraction electrode position relative to the plasma electrode at the exit of the discharge chamber.

(2) The vacuum screen is used to control and monitor the status of the vacuum system equipment. This includes 2 cryogenic pumps with corresponding compressors and controllers, 4 turbomolecular pumps with their controllers, 5 rotary vane pumps and 11 electro-pneumatic valves. Status of the equipment is defined by the colour coding on the screen: green - vacuum pump is ready, red – vacuum pump is not ready or is turned off, blinking red – error. In the case of vacuum valves, the green colour means the valve is open, while red means that the valve is closed. In addition, the pressure is measured at twelve points inside the vacuum system of the machine.

(3) The safety screen shows the safety status of the alarm signals obtained from the safety system of the machine. It helps the operator to find the cause of an emergency shut-down action.

4 Conclusion

The reconstruction and upgrading of the M1 machine was completed in 2013, while the commissioning was performed at the beginning of 2014. The results obtained during the commissioning demonstrated significant increase of ion beam currents as well as broadening of the available ion charge state range towards higher charge states. The operation of the ion source was stable and reproducible [5]. During the commissioning it was demonstrated that the new control system of the M1 machine was well designed, resistant to electromagnetic noise and interferences, reliable and comfortable to work with. In that sense, the new control system represents a powerful tool for the future experiments performed with the FAMA facility.

7 Acknowledgment

The authors acknowledge the support of this work provided by the Ministry of Education, Science and Technological Development of Serbia through the project Physics and Chemistry with Ion Beams, No. III 45006.

5 References

[1] A. Efremov, V. Kutner, S. Bogomolov, A. Lebedev, V. Loginov, N. Yazvitsky, A. Dobrosavljevic, I. Draganic, S. Djekic, T. Stalevski: Design Aspects and Status of Construction of the mVINIS Ion Source, Review of Scientific Instruments, Vol. 69, No. 2, Feb. 1998, pp. 679 – 681.

[2] A. Dobrosavljevic, I. Draganic, S. Djekic, T. Stalevski, A. Efremov, V. Kutner, N. Yazvitsky: Commissioning of the mVINIS Ion Source, 15th International Conference on Cyclotrons and their Applications, Caen, France, 14-19 June 1998, pp. 443 – 446.

[3] T. Stalevski, I. Vuleta, A. Dobrosavljevic, I. Draganic, D. Strbac, R. Balvanovic, S. Djekic: Safety and Control System of the mVinis Ion Source, 15th International Conference on Cyclotrons and their Applications, Caen, France, 14-19 June 1998, pp. 575 – 578.

[4] A. Dobrosavljevic, P. Belicev, V. Jocic, N. Neskovic, I. Trajic, V. Vujovic, Lj. Vukosavljevic: Facility for Modification and Analysis of Material with Ion Beams (FAMA), 19th International Conference on Cyclotrons and their Applications, Lanzhou, China, 06-10 Sept. 2010, pp. 107 – 109.

[5] V. Bekhterev, S. Bogomolov, A. Efremov, Yu. Kostyukhov, A. Lebedev, A. Dobrosavljevic, V. Vujovic, N. Neskovic, I. Trajic, Lj. Vukosavljevic, D. Ciric: Modernization of the mVINIS Ion Source, 21st International Workshop on ECR Ion Sources, Nizhny Novgorod, Russia, 24-28 Aug. 2014, pp. 68 – 70.

[6] Control System of the M1 Machine, User guide, Version 1.1, ELEX Belgrade, Belgrade, Serbia, 2014.

[7] Group3 Control Hardware.
Available at: http://www.group3technology.com/group3-distributed-control.

[8] Wonderware's InTouch.
Available at: https://www.wonderware.com/hmi-scada/intouch/technical-specifications.