COMPUTER CONTROL OF A 3 MV VAN DE GRAAFF ACCELERATOR

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Abstract

The development of accurate computer control of a 3 MV Van de Graaff accelerator operation is described. The developed system comprises the accelerator turn-on and turn-off procedures during a normal run, which includes the setting of the terminal voltage, ion source light up, beam focusing and control of ion beam current and energy during operation. In addition, the computer monitors the vacuum and is able to make a detail register of the most important events during a normal run. The computer control system uses a LabVIEW application for interaction with the operator and an I/O board that interfaces the computer and the accelerator system. For everyday operating conditions the control implemented is able to turn-on and off the machine in about the same time as a specialized technician. In addition, today more users can make experiments in the accelerator without the help of a specialized operator, which in turns increases the number of hours during which the accelerator can be used.

Keywords: particle accelerator, control system, measurement systems, data acquisition, LabVIEW.

1. Introduction

In the Ion Beam Laboratory (LFI), from the Technological Nuclear Institute (ITN), a computer control system was developed for the existing 3 MV Van de Graaff particle accelerator. This work is part of an ongoing program of computer automation of suitable accelerators subsystems within the Laboratory.

The computer automation, control and monitoring of numerous features in particle accelerators is nowadays a common and important support tool, available in laboratories all around the world, with the purpose of helping the operator in setting and optimizing the machine parameters, constituting an alternative to permanent specialized staff supervising the accelerator operation.

The computer automation in accelerators can perform: 1. just a supervision of the machine status; 2. support the operator in setting the parameters or 3. take action on it autonomously, depending on a previously loaded program [1−8].

Most of the computer automation systems developed for particle accelerators use the National Instruments LabVIEW graphical programming language [6−8] since it is easy to use, and is geared toward instrument control and data acquisition.

The system was developed to automate the accelerator operation, in particular the procedures required to turn on and off the particle accelerator which include setting the terminal voltage, lighting up the ion source, focusing the beam and controlling the beam

current and energy during operation. In addition, the computer monitors the vacuum and is able to make a detail register of the most important events during a normal run.

In order to accomplish all the procedures correctly, it is necessary to control some parameters at any time. For that, the system developed uses a LabVIEW application for interaction with the operator and an I/O board that interfaces the computer and the accelerator system. The system is able to regulate some variables by itself, in order to manage the parameters that are essentials for the correct operation of the machine. To prevent any major problems, when the parameters cannot be adjusted for the programmed values, the system is able to shut-down the machine.

The Van de Graaff operation begins with the verification of pressure values inside the accelerator and beam lines. The operator proceeds to execute the start-up procedure that begins with the increase of the terminal voltage and ends with the generation of a stable ion beam. The accelerator is then operated in a steady-state mode for several hours or days, after which the ion beam is switched-off, the terminal voltage is decreased to zero and the accelerator is shut-down. During the steady-state period, it may be necessary to change parameters such as beam energy, beam current or ion species. Usually a specialized technician is needed, which increases operating costs.

The accelerator operation can be made easier by the use of a real time PC-based system to monitor and control key accelerator and beam parameters. This paper describes the automatic system developed to control the accelerator during a normal run.

Nowadays it is also possible to remotely control the particle accelerator using the freeware program RealVNC, which allows the user to control the accelerator from anywhere.

2. Van de Graaff accelerator

The Van de Graaff [9] particle accelerator used in this work, is an horizontal electrostatic machine, Model AN-2500, Type-A, manufactured by High Voltage Engineering Europe. The accelerator is housed inside an electrically insulated tank with a mixture of pressurized SF_6 and N_2.

Considering Fig. 1, the He^+ or H^+ ions are ionized in a radio-frequency (RF) ion source [10], located on a high voltage terminal, and accelerated, within a vacuum tube, towards ground by a large electrical gradient, distributed through a resistive divider. The ion beam is focused and steered in the acceleration tube and finally magnetically steers for one of the three available experimental lines.

This acceleration potential is originated from a positive high-voltage power supply FAT-1 that deposits charges in a rotating insulating belt, with high dielectric strength, connecting the ground to the high-voltage terminal. The attached charge is carried mechanically against the potential gradient into this high-voltage metal terminal. The charge flows off the belt when it comes in contact with a metal brush and is deposited on the terminal, which acts as a Faraday cage (*i.e.* there is no electric field inside the terminal other than that from the charge on the belt). The terminal voltage is measured by a Generating Volt Meter, GVM, for slow varying voltage values, or by a Capacitive Pick-Up, CPU, for fast varying voltage values.

For small voltage changes or to limit the terminal voltage, a corona type device is used, consisting of a mechanical metal arm with short thin needles. For slow voltage changes this arm is moved back and forward into the terminal, for fast voltage changes this arm is polarized.

It is essential for the computer control implementation, to understand how the different currents flow in the accelerator, due to the distribution of the negative and positive charges, such as, the beam, column, charge and corona currents.

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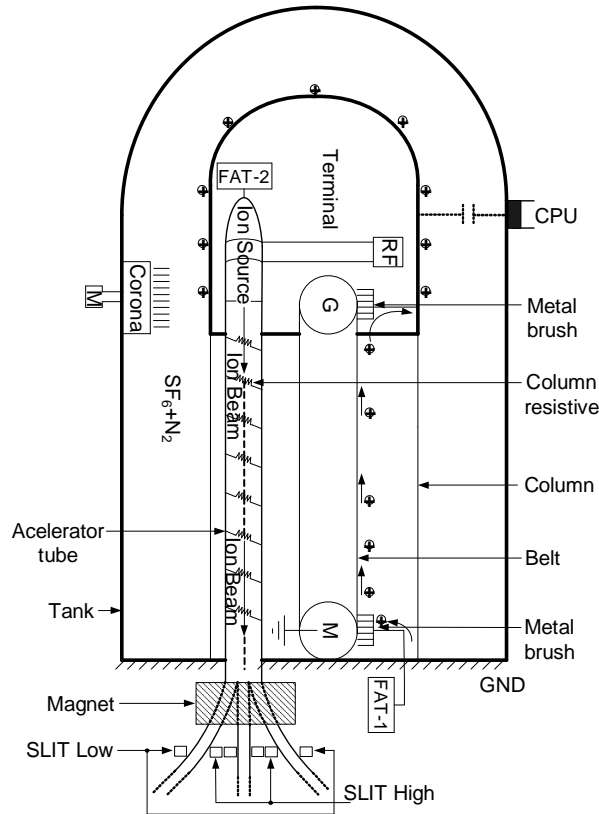*Metrol. Meas. Syst.,* Vol. XVII (2010), No. 3, pp. 415–426

Fig. 1. Schematic representation of the ITN Van de Graaff accelerator.

Fig. 2 shows a schematic equivalent electric circuit of the accelerator, where the column resistive divider and the corona control action are represented, respectively, by a 72.5 GΩ and a varying (0 to 100 GΩ) resistors from the terminal to ground. The ion source is represented by a current source and two series resistors, respectively 10 MΩ and 200 kΩ which are in series with the anode power supply and the FAT-2 power supply for protection.
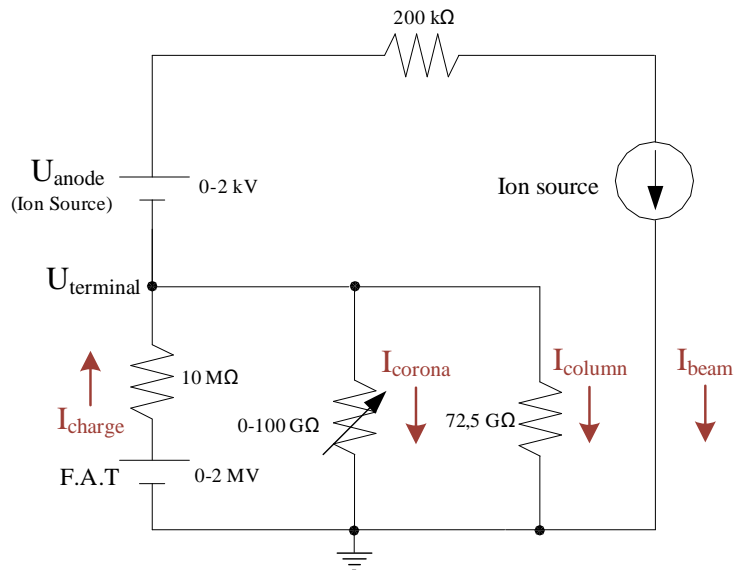
Fig. 2. Equivalent electric circuit of the "Van de Graaff" accelerator.

Taking into account the charge conservation theorem, the terminal voltage amplitude depends on the deposited charges by the belt (I_{charge}) and the number of charges that comes

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out the terminal to ground, which includes the column current (I_{column}), the ion beam current (I_{beam}) and the leakage current due to the action of the corona (I_{corona}), as shown in Fig. 2.

Considering the circuit in Fig. 2, when a voltage is applied to the terminal, $U_{terminal}$, two situations can take place. First, there is no ion beam, and then the FAT charge current is given by:

$$I_{charge} = I_{corona} + I_{column\ (lost\ charges)}. \tag{1}$$

Second, there is an ion beam, and then:

$$I_{charge} = I_{corona} + I_{column\ (lost\ charges)} + I_{beam}. \tag{2}$$

Knowledge of these currents gives also an indication on the general performance of the Van de Graaff accelerator.

3. Automation system

With the purpose of implementing the accelerator computer control, each of the accelerator processes was described using a flowchart. The actual implemented system comprises ten flowcharts to describe the control of the machine:
1. Accelerator switch-on.
2. Set the coarse terminal voltage.
3. Set the corona current and control range.
4. Change to GVM mode.
5. Set the precise terminal voltage.
6. Ion source gas selection.
7. Ion source turn-on.
8. Adjust ion source anode and gas.
9. Ion beam focusing.
10. Turn-off the accelerator. In this paper we discuss, in detail, the setting of the precise value of terminal voltage, the turn-on the ion source and the beam focusing.

In order to guarantee the success of the system, it was necessary to identify all the parameters that are necessary to be measured during all processes. The measures can be divided in two types: (i) high sampling rate, which are the ones that are measured during some specific parts of the process, like control range or terminal voltage; (ii) low sampling rate, parameters that are measured continuously, and in our case, translates in a measure that implies the safety of the system, the measure of vacuum.

The accuracy in measurements is extremely important because it will interfere in the correct use of the accelerator, and in the time dispended to obtain the beam focused. Being a low sampling rate, the measure of vacuum is present throughout the operation of the machine. Also, the system is programmed to shut down when the readings are not in the gamma of values pre-determined.

Additionally, the required electrical signals corresponding to the accelerator parameters were adapted for interfacing to a personal computer (PC), using two multifunction input/output boards (DAQ) from National Instruments, model PCI 6229. The number of required signals is the reason why two multifunction boards were used. In order to perform the total automation, we needed: 20 digital outputs (to control on/off actuators); 4 digital inputs (to read the status of the particle accelerator); 13 analog inputs (to read analog currents and voltages); and 4 analog outputs (to control some variable actuators).

Therefore the system consists of a PC, two multifunction input/output boards, and five electronic modules (*i.e.* electronic interface) for signal conditioning. These electronic modules

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that were developed correspond to: 1. mode selection (*i.e.* automatic or manual mode); 2. corona and belt drive motor adjustment; 3. ion source control; 4. readings (*i.e.* beam currents and vacuum values); 5. power source (*i.e.* electronic power supply).

The PC software runs under Microsoft Windows and is written in LabVIEW. The DAQ controls the electronic modules and the acquisition of digital and analogical signals.

The electronic modules located between the accelerator control desk and the PC, as shown in Fig. 3, guarantee that all the command signals to and from the accelerator go through this electronic interface, enabling the Van de Graaff operation in manual or PC mode independently. All the electronic modules and the switch that allows the operator to choose the work mode are integrated in the accelerator control console.
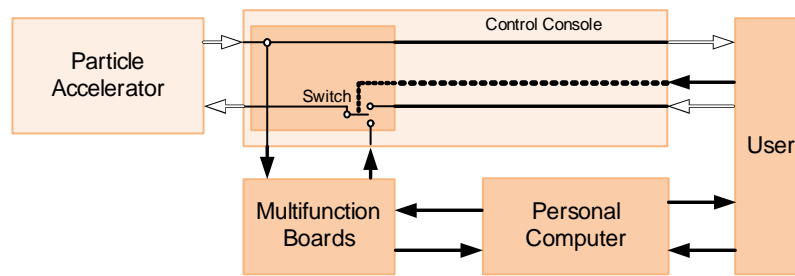

Fig. 3. Block diagram of the particle accelerator operation after the automatic control system was implemented. The white arrows represent pre-existing information flow. The black arrows represent added information flow.

4. Programming

We chose National Instruments LabVIEW to implement the control and monitoring application for the personal computer. It is a graphical programming language specially created for instrumentation and measurement, which is also used to control some particle accelerators around the world like the one in the Nuclear Structure Laboratory (University of Notre Dame) [6] or in the Idaho Accelerator Center [7].

Due to the complexity of the system, we chose to describe only three of the main flow diagrams that integrate the implemented system.

4.1. Precise terminal voltage flow diagram

The flowchart shown in Fig. 4 is used to set the desirable terminal voltage. This is done after the terminal voltage has been increased to a coarse value which is a pre-determined value that corresponds to [1200−1400] kV. The corona current is set between the operation range and the belt charge current going to the terminal equals, approximately, the currents leaving the terminal to ground.

In this particular procedure we use:
− 7 digital outputs – two for corona control, two for GVM control GVM, two for belt charge limit and one for automatic;
− 1 digital inputs − the led indicator of terminal voltage;
− 4 analog inputs − readings of belt charge limit, corona current, terminal voltage and vacuum;
− 1 analog output − belt charge limit.

Considering Fig. 4, first the pressure is verified inside the accelerator tube and beam lines. If the values are not in the range (maximum value is 2×10^{-3} Pa) an error message is sent and the accelerator is shut-down, in order to prevent major damages to the ion source. Otherwise

the corona current is adjusted between 15 and 35 µA, and the control range is adjusted between −100 and 100 µA by the belt charge limit.

The Control Range indicates the difference between the charge available and used. Extreme values should be avoided because they lead to a decrease in terminal voltage or possible sparks in the accelerator tube. In order to avoid these situations, the ideal value to obtain is zero.
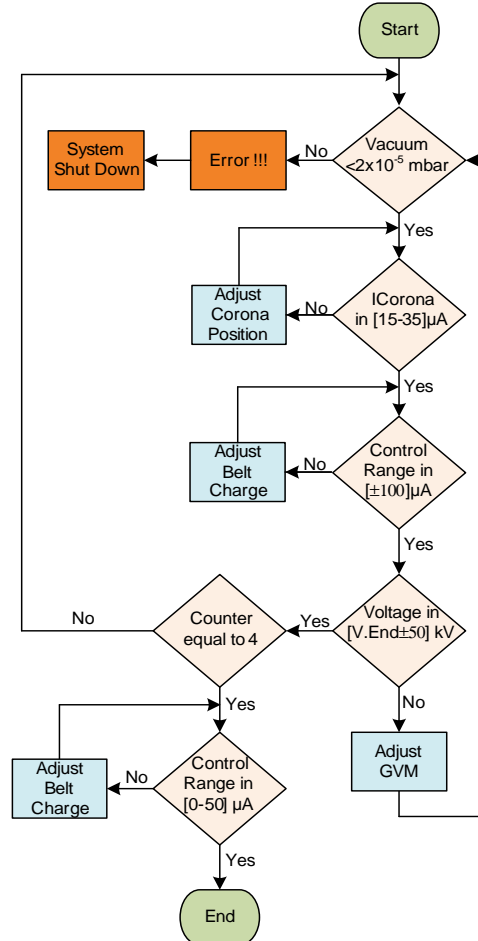

Fig. 4. Terminal voltage flow diagram.

If this is not possible, the GVM voltage reference is adjusted and all the previous steps are repeated. After the terminal voltage is achieved (± 50 kV), all the cycle is repeated four times, until the Control Range is between 1 and 50 µA, in order to turn-on the ion source.

4.2. Ion source flow diagram

The flow diagram shown in Fig. 5 is used to turn-on the ion source. This is done after the terminal voltage has been set to the precise value and the ion source gas has been selected.

Considering Fig. 5, first the ion source anode voltage is increased until it reaches 2 kV (*i.e.* maximum anode voltage). Then, the gas is introduced into the source, until the pressure reaches $4\times10{-3}$ Pa. Next, the gas pressure is slowly increased until the accelerator beam current reaches 0.2 µA, measured in a tantalum beam-stop; the ion source is turned-on.
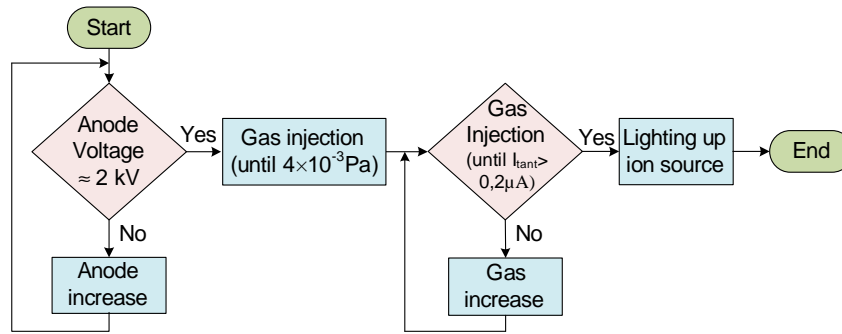
Fig. 5. Lightning up ion source flow diagram.

4.3. Beam focusing flow diagram

The flow diagram shown in Fig. 6 is used to focus the ion beam to a minimum spot. This is done after the ion source anode voltage and gas pressure have been decreased to normal operation values. Initially, at the start point, the focus is automatically fixed to zero. In order to know how to focus the beam, it was necessary to determine the correct value of voltage to apply to the plates of the focussing lenses. The beam is considered focused when the tantalum current is maximized.
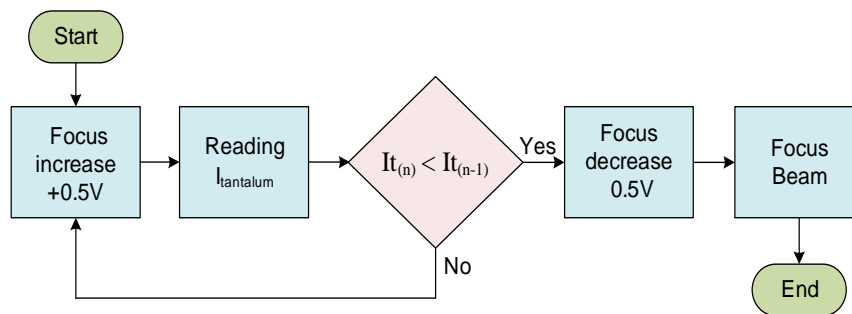
Fig. 6. Ion beam focus flow diagram.

Considering Fig. 6, the focusing is achieved by a successive iteration process voltage, controlling the focusing voltage, in order to maximize the tantalum current. We have implemented this by comparing the mean of the tantalum current taken over the last 10 measurements with the previous mean. When it decreases by 5% we consider that we have passed the maximum of tantalum current and decrease the focus voltage by 0.5 V. Finally, when the beam hits both the low energy and high energy slits the control mode can be changed to the SLIT mode, shown in Fig. 1.

To better comprehend the calculus of the values to achieve the focusing process, in Fig. 7 we show a chart with the beam stopper current as a function of the focus control voltage. Several passes were made by increasing the control voltage from 0 to 10 V and then decreasing it from 10 V to 0. It is clearly seen that two different trajectories are taken depending on whether the control voltage was increasing or decreasing. This behavior is due to the mechanical set up used to control the position of the cursor of the potentiometer inside the particle accelerator.

This hysteretic behavior has implications on the focusing procedure. To search the maximum current the control voltage in increased slowly from 0 (point 1 in Fig. 8). The maximum is said to be found when the tantalum current decreases by 5% from the maximum value it reached (point 2 in Fig. 8). By that time, the control voltage applied is higher than the

control voltage that leads to the maximum tantalum current. If the control voltage is then decreased to that value, we do not reach the previous maximum due to hysteresis.

The proper procedure is to set the control voltage to 0 again (point 3 in Fig. 8) and then set it to the desired value determined previously (point 4 in Fig. 8).
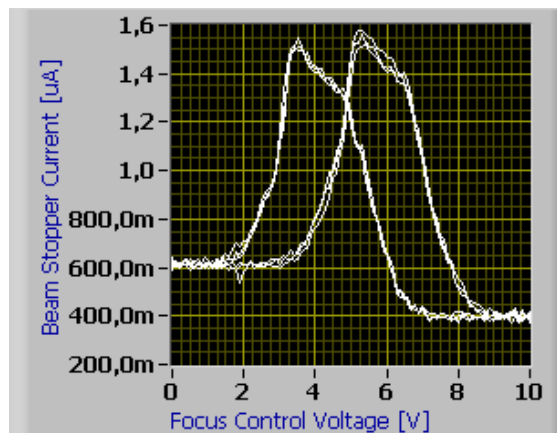

Fig. 7. Chart showing the relation between the tantalum beam stopper current and the focus control voltage for a terminal voltage of 1.315 MV and an ion source anode control voltage of 2.6 V. Multiple curves are represented. The curves which have a peak to the right were obtained with an increasing focus control voltage and the curves with the peak to the left were obtained with a decreasing focus control voltage.
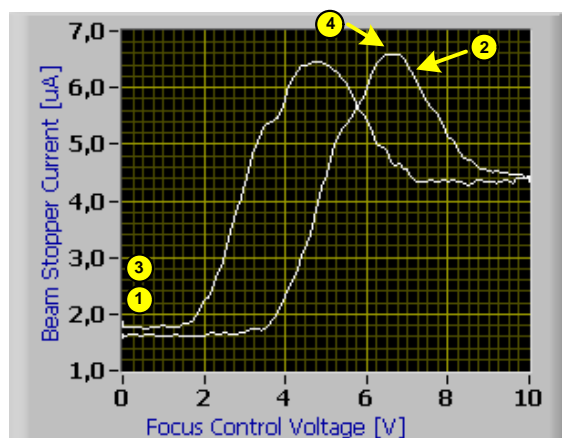

Fig. 8. Chart showing the relation between the tantalum beam stopper current and the focus control voltage for a terminal voltage of 1.951 MV and an ion source anode control voltage of 3.78 V. The curve which has a peak to the right was obtained with an increasing focus control voltage and the curve with the peak to the left was obtained with a decreasing focus control voltage.

5. Results

The layout of the user interface is shown in Fig. 9, where the operator has on-line information of the machine parameters. Here one can see the following features: 1. status of machine-executed steps; 2. actual machine state 3. actual parameters: a) belt charge, b) corona current, c) column current, d) slits current, e) tantalum current, f) vacuum pressure, g) control range, h) terminal voltage; 4. tantalum beam current versus the focus voltage, which indicates the ion beam focussing. It is important to refer that when the vacuum pressure is out of pre-determined values, the machine shut-down. In case of failure in any other parameter, instead of shut down the system turns to manual mode. In this case, the operator can revise all the

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steps acceding to the data recorded and check what is wrong in the base of the elements given by the system.

In Fig. 10 is presented in detail the point 4 from the previous figure. This chart presented in the computer screen shows the tantalum current as a function of focus voltage. The vertical straight line indicates the final value of the focus voltage.
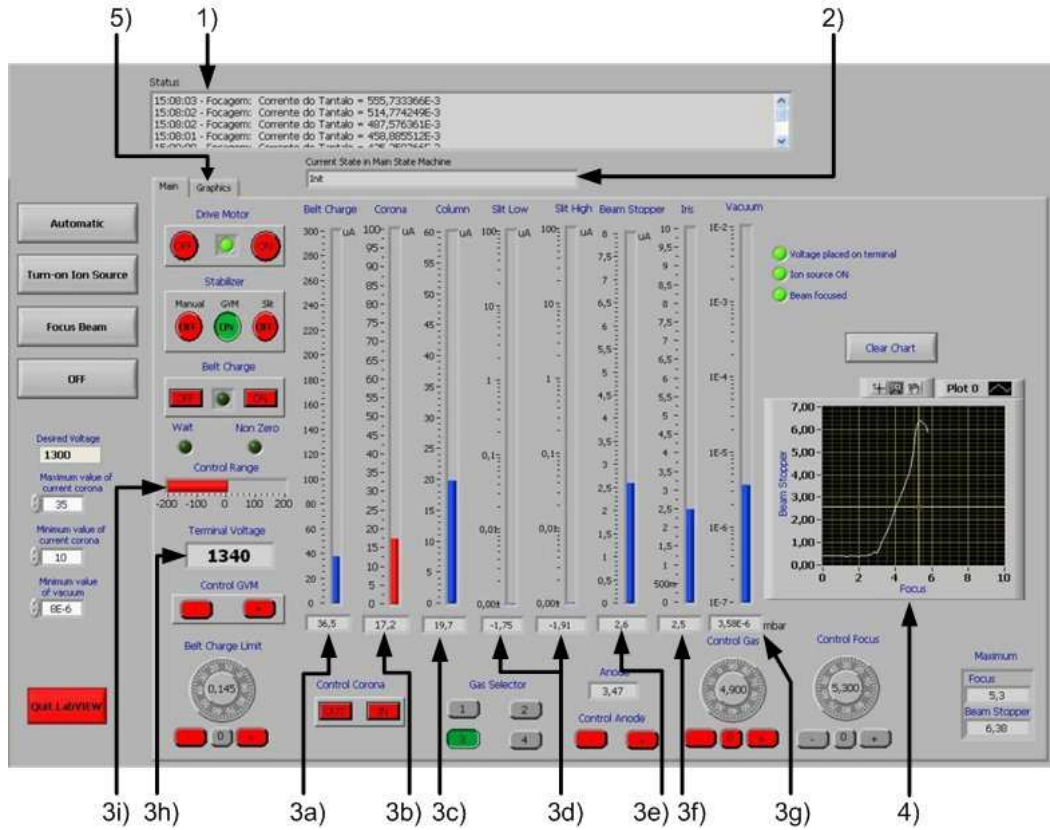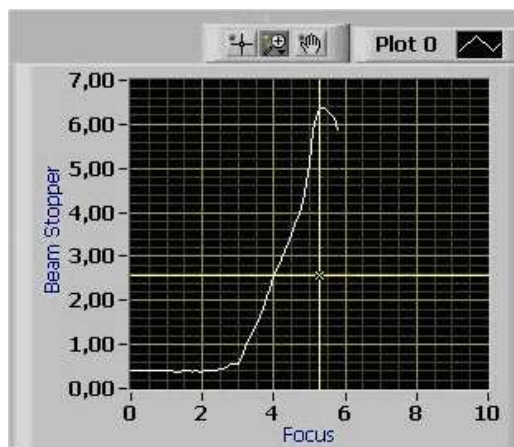

Fig. 9. Front panel.

Fig. 10. Chart presented in the user interface showing the tantalum current relative value (beam stopper) as a function of the focus voltage in volt.

Acceding to the additional parameters graphic (option 5 in the front panel), the user can consult additional parameters graphic. Although it refers to measures that are not used in all procedures, we have considered relevant for the user to be able to follow the behavior of the most important parameters during the operation of the machine. The extra available graphics

are: a) terminal voltage, b) corona current, c) belt charge limit, d) tantalum beam current, e) gas pressure, e) and f) column current.

During computer control mode, the accelerator measured signals (*i.e*. terminal voltage, beam current, corona current, vacuum, *etc*.) are, simultaneously, present on the accelerator control desk and on the personal computer, where more accelerator measured parameters are accessible than the ones available in the control desk. As a result, more help is available to the operator. As an example, if the corona device, seen in Fig. 1, is actuated, but the corona current stays constant, the system gives an error message, indicating that the device did not really change position due to some mechanical problem. Through the control desk, only an experienced operator can detect an abnormal situation like this. Additionally, if the PC mode is selected, the operator can choose between manual or automatic control.

When in manual control, in computer mode, the start-up procedure is similar to manual mode; the two principal differences is that the operator commands the machine trough the PC and it is given more information about what is happening and in an easy way due the simplicity of the front panel. All the steps can be followed in the PC.

In automatic control, in computer mode, the start-up is a more complicated process in terms of flowchart but is an easy way to start the accelerator and have a focused beam. The automatic control stops when the ion beam is focused.

The procedure of shut-down is straightforward: the system automatically decreases the ion beam current, turns all parameters to zero and shuts off the power.

When in computer mode, in case of a software "crash", is possible to initialize LabVIEW without restarting the PC. The computer program resumes the operation in the same procedure that was before, without the machine losing its stability.
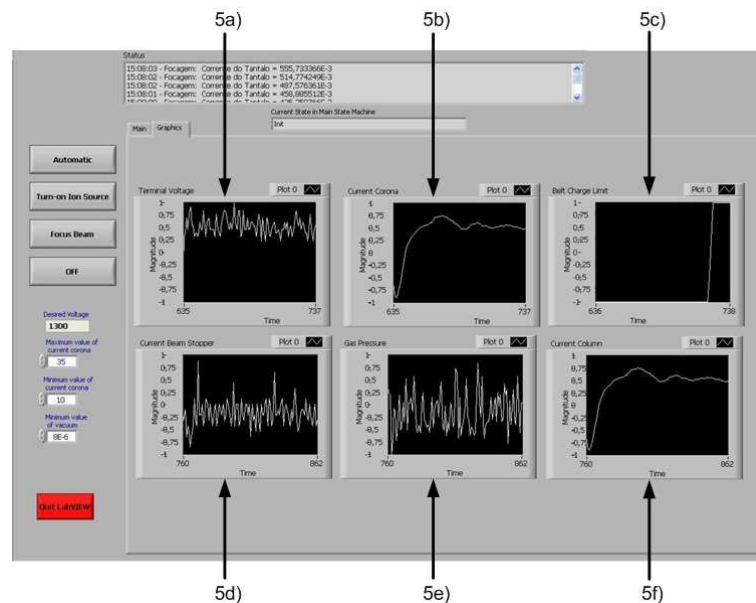

Fig. 11. Secondary panel.

6. Conclusions

We described the computer system developed to control, manually and automatically, the routine operation procedures of the 3 MV Van de Graaff particle accelerator installed at the Nuclear and Technological Institute, Sacavém, Portugal.

Two I/O boards were used to interface the accelerator signals and the computer, where LabVIEW tools support the software implementation of the accelerator operating procedures. A graphical interface is provided for the user.

This implemented system allows less qualified users to operate the particle accelerator. It also makes the operation easier by automatically performing the monotonous activities of setting up the particle beam and decreases the chance of incorrect operation that could lead to failure.

In the development the principal difficulties encountered were: 1. lack of information about the existing electric circuits; 2. the particle accelerator is in constant use making it difficult to test the automatic system; 3. the application has to take into account the diverse machine conditions that may occur during its lifetime. There is a basic example for this last difficulty encounter: the gas and anode control that is used not only to reduce the amount of gas used also to improve the source efficiency, preventing the abrasion of the ion source. Manually, this gas and anode control may represent an unexpected ion source turn off. Using the system developed this never happens because when it is about to happen, the system optimizes the parameters to counteract that situation.

Acknowledgments

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