

THE DESIGN OF DOSE PARAMETER ACQUISITION AND CONTROL SYSTEM FOR A PENCIL BEAM SCANNING SYSTEM IN HUST-PTF*

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Abstract

Pencil beam scanning (PBS) technology is a flexible and accurate dose delivery technology in proton therapy, which can deliver beams adapting to irregularly shaped tumors, while it requires precise diagnostic and real-time control of the beam dose and position. In this paper, a dose parameter acquisition and control system for the pencil beam scanning system based on the EPICS and LabVIEW is designed for HUST-PTF. The EPICS environment is built to realize the data exchange function between the front-end devices and control system. A channel access server (CAS) is designed to convert treatment parameters into the process variables (PVs) and expose them to the network for data sharing. Under current experimental conditions, the simulated beam current is generated according to the dose parameters in the treatment plan file. The current are processed by a digital electrometer and transmitted to the EPICS database in real time. Then the control system user interface based on LabVIEW is realized for displaying and parameter analysis.

INTRODUCTION

The pencil beam scanning nozzle is located at the end of the proton therapy machine in Huazhong University of Science and Technology Proton Therapy Facility (HUST-PTF). It is composed of scanning magnets, ionization chambers and other beam diagnostic equipment as well as related electronic devices and controllers. It is the last guarantee to accurately deliver the proton beam to the designated location of the tumor with accurate dose. This paper mainly focuses on the technology of controlling dose safety, and the dose parameter acquisition and control system has been designed by using software and hardware redundancy analysis.

Firstly, the dose monitoring system of the nozzle needs to obtain the treatment plan accurately from the Treatment Control System (TCS), extract the scan dose parameter, convert it into the actual machine parameters correctly, and confirm and display these data. Then, the control software needs to transmit data with the front-end devices efficiently. It sends the corresponding instrument parameters to the hardware devices in the nozzle accurately and gets feedback data, so as to control and monitor the beam dose accurately in real time. At the same time, fast interlocking protection can be carried out under exceptional conditions.

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As the main equipment for dose monitoring, two separate working ionization chambers are designed as redundant measures to ensure that the ionization chamber operates normally all the time. And the alarm threshold of the second ionization chamber is set to be 5% larger than that of the first device to ensure that when the first ionization chamber fails, the other device can still work normally, and the fault signal can be transmitted to the superior system.

In order to make the operation of the control system more intuitive and convenient, the graphical user interface (GUI) of the system is built with the LabVIEW development platform. The interface displays treatment plan parameters, actual treatment data, treatment progress, the working status of front-end devices and so on.

Finally, the treatment results are uploaded to the TCS when the treatment is finished. Also, if treatment is interrupted, the dose already applied must be uploaded in order to allow correct continuation after interruption. The corresponding framework of the control system is shown in Fig.1.

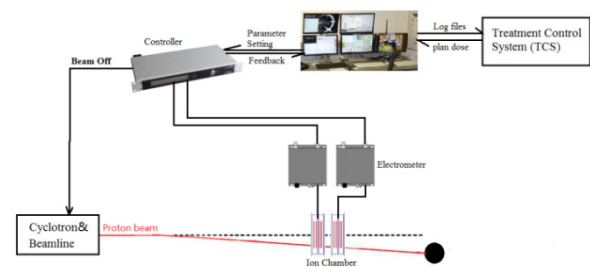


Figure 1: Control system framework.

LOGICAL DESIGN OF THE SYSTEM

Before the start of treatment, the first step is to accurately analyse the treatment plan file and obtain the ideal dose parameters. In order to ensure the safety of the transmission and correct interpretation of the treatment plan file, the DICOM standard data format is uniformly used for data interaction throughout the whole treatment process. The essence of the DICOM file is the binary file. Each data element contains four parts: Tag (Data element Identification)、VR (Value Representation)、VL (Value Length)、VF (Value Field)^[1]. By identifying the Tag of the dose parameter, the data element of planned dose parameter can be extracted out. Dose parameters are stored in VF part in hexadecimal from. Then we convert them to

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floating point numbers and display the results on the control software user interface.

Second, the conversion calculation from the treatment parameters to the instrument parameters should be designed. According to the working principle of the plate ionization chamber shown in Fig.2, when the proton beam passes through the ionization chamber, the gas molecules filled in the ionization chamber will be ionized, the positive charges and electrons will move toward the two plates under the traction of the high voltage of the plates. The amount of induced charge on the two plates will change with the beam current and time. The time-varying current signal will be obtained and amplified by an electrometer. Therefore, the dose parameter will be converted to a corresponding current value for quick comparison with the measured value from the electrometer.

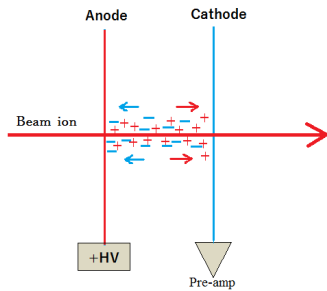


Figure 2: The principle of the ionization chamber.

The gain, which represents the number of electrons generated by a proton particle passing through the ionization chamber, can be obtained by Monte Carlo simulation. The relationship between the gain and the energy of the proton beam has been given in references [2]. When the time is known, the relationship between electrons and current can be obtained, in which case the dose can be associated with the current value.

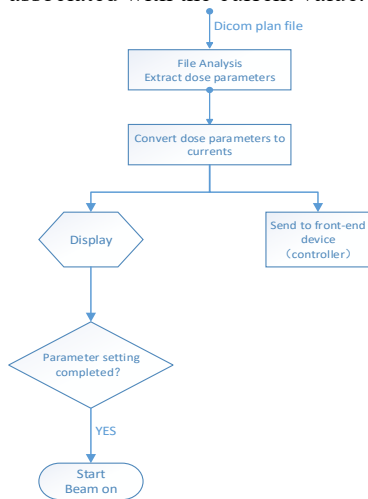


Figure 3: The workflow during the preparation.

After obtaining the correct instrument parameters, the parameters of each layer are sent to the front-end monitoring device for parameter setting, which needs to be implemented in the EPICS environment. After the setting is completed, the front-end device sends the confirmation

signal to the control software indicating that it is ready to turn on the beam for treatment. The corresponding logic block diagram is shown in Fig. 3.

During the treatment, the ionization chamber is always in operation, monitor the dose in real time and feedback the data to the controller. In the EPICS environment, the controller sends monitoring data to the control software for caching. The current waveform diagram and the running status of the front-end device are displayed by the user interface, and compared with the ideal plan parameters. Once a parameter is found to exceed the allowable safety tolerance scope, the controller outputs the beam off instruction immediately to turn off the beam and issues a warning in the user interface.

When the last point of the layer is illuminated, it is also necessary to immediately output the beam off instruction, turn off the beam, and display all monitoring data and treatment results by the control software, and save the record in txt format. The corresponding logic block diagram is shown in Fig. 4.

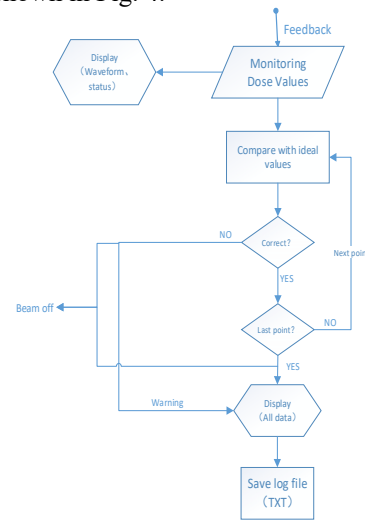


Figure 4: The workflow during the treatment.

SAFETY ANALYSIS

The normal operation of the system requires three important elements: monitoring equipment, logic blocks, and terminal response components. Fault analysis can be done from these three aspects. The possible causes of overdose error could be: (1) the failure of the dose monitoring device (ionization chamber). It fails to detect that the dose value has exceeded the safe range, or fails to feed back the detected dose value to the upper controller; (2) the logic block of the controller is not working properly. It fails to generate the beam-off signal in time, or sends an unplanned beam-on signal; (3) the terminal physical component is broken, and unable to respond immediately after receiving the correct signal, which causes the beam to fail to shut down in time, or to start the beam when no instructions are received from the superior controller.

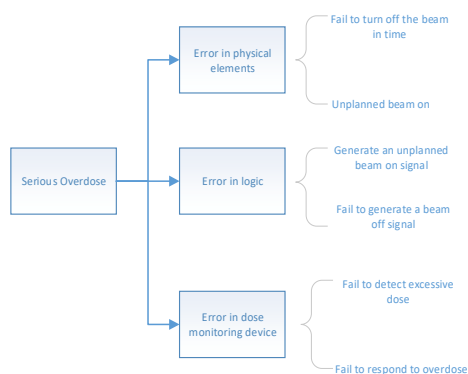


Figure 5: Fault tree.

According to the safety requirements of medical devices, the dose error should not exceed 5% of the planned value. For the fault analysis in Fig.5, we can take certain safety redundancy measures. First of all, to ensure the normal operation of the dose monitoring equipment, two sets of ionization chamber equipment are used for dose monitoring at the same time. The two sets of devices work independently by respective power supply, and the alarm threshold of second ionization chamber is set 5 % larger than the first set. The measurement results from two sets of devices are both fed back to the controller to ensure that when the first device fails, the other device can still work normally. When the difference between the dose values monitored by the two independent ionization chambers reaches $\pm 5\%$, the controller perform to turn off the beam and issue an alarm immediately.

During beam transmission, it is necessary to prevent the beam from being delayed due to the failure of the terminal physical elements, so multiple redundant devices are set up to control beam transfer. When the controller generates erroneous operating signals, such as overdose signals, the kicker magnet responds first and deflects beam out of axis rapidly. If it fails, there is an electrostatic deflector in cyclotron to control the beam. If it still doesn't work, then there is a High Frequency Generator in cyclotron, which can reduce the power to at least 20%. The "Proton Source Electronics Unit (PSEU)" can be the last measure to controls the ion source. When all terminal elements fail, it can turn off the proton source should be directly.

DATA TRANSMISSION

After obtaining the correct instrument parameters, an EPICS environment is built in the PC to achieve the data exchange function between the control software and the front-end equipment. An EPICS Channel Access Server (CAS) is configured as Input/Output Controller (IOC) in LabVIEW-based control software. Its function is to convert the treatment data into EPICS PV values, expose them to the network [3]. Then any clients in the network can access the data by inputting the PV name.

The electrometer used in this experiment is IC101 ion chamber controller produced by Pyramid, it is intended for the measurement of small charges or currents (from pA to μ A) generated by ionization chambers. Also, Pyramid

supplies an executable called IG2. In the database of IG2, the "channel" and the "wire" can be configured. Users can define any number of channels according to the function and interface of the device. These channels map one-to-one to EPICS PVs, and correspond to the "wire" (real physical channel of the device). The client can directly access any channels in the system according to the custom channel name, and all the channel names defined in the IG2 database will be recognized as PV by EPICS client program. So IG2 is used as an optional Channel Access Server in the system.

```

<channels>
  <channel name="r_IC101_3_current" wire="analog_in_current"/>
  <channel name="r_IC101_3_charge" wire="analog_in_accumulated_charge"/>
  <channel name="c_IC101_3_range" wire="analog_out_range"/>
  <channel name="c_IC101_3_init" wire="digital_out_initiate"/>
  <channel name="c_IC101_3_accum" wire="digital_out_accumulate_charge"/>
  <channel name="c_IC101_3_perio" wire="analog_out_integration_period"/>
  <channel name="c_IC101_3_resol" wire="int_out_resolution"/>
  <channel name="c_IC101_3_capacitor" wire="int_out_capacitor"/>
  <channel name="c_IC101_3_calibrate" wire="digital_out_calibrate"/>
  <channel name="c_IC101_3_bias" wire="int_out_external_bias"/>
  <channel name="c_IC101_3_biasmax" wire="int_out_external_bias_max"/>
</channels>
</board>
</hardware>
    
```

Figure 6: The example of IC101 channel configuration.

In this paper, the channels of IC101 are defined by IG2. Figure 6 shows the example of IC101 channel configuration, the channel "r_IC101_3_current" is connected to wire "analog_in_current". The wire correspond to the physical IC101 signal input channel which is used to collect measured current data. The channel named "c_IC101_3_initiate" is used to activate device motion. The client accesses the channel to convert the initiating instruction into the corresponding PV value, then the real physical channel outputs a pulse signal to activate the device. And there is an analog signal output channel to limit the measured current values. The channel is used to set the normal operating current range for IC101. When the measuring current exceeds the range, it stops working immediately to avoid damaging the equipment. According to the working principle of IC101, if we measure the charge accumulated on the capacitor in a defined period, we can know the average current during that time interval. It shows that both the capacitor size and the integration time have an impact on the measurement results. Therefore, IC101 measurement capacitance and integration time are set in IG2 database to make the measurement of current more accurate.

The function of IC101 is only to collect and feedback the monitoring data continuously. The device can not process the data. This function needs the upper controller to complete. In this experiment, the A560 Real-time controller produced by Pyramid is selected. It is intended to provide high-performance real-time processing of the data. The measured data fed back by the electrometer are compared with the ideal plan parameters in the controller. When the measured current or accumulated charge is different from the ideal plan parameters and the deviation exceeds the safety tolerable range, the beam should be shut down in time. In the simple connecting in Fig. 7, the IC101 connected to the A560 controller via fiber optics, and the A560 controller communicates with a GUI computer system via a Ethernet interface. The PVs of IC101 are

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exposed to the network by the IG2 (CAS). Other client GUI computers can then access the values.

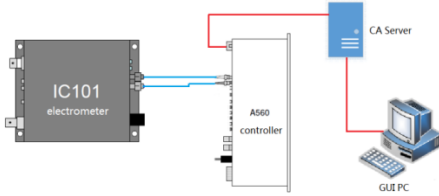


Figure 7: Example connecting for control system.

CONTROL SOFTWARE

A GUI software is designed, which can interact with EPICS to transmit and receive values of records. It is easy to realize with an extension tool named “CALab” which allow CA support in LABVIEW. Since the device and the PC are connected through the network cable, instead of serial communication the queue operation function group is used to implement the data caching in LabVIEW. The role of the queue function is data transfer, call up the treatment data in the CALab tool database and enqueue them for caching, then dequeue the cached elements into the spreadsheet when the treatment is stopped. The Obtain Queue function sets the maximum size of the queue. The default value is infinite, which avoids data overflow during the treatment process and causes some data loss.

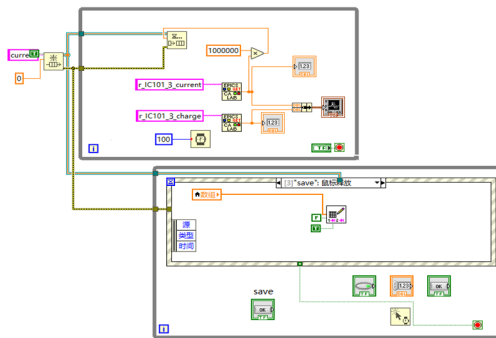


Figure 8: The example block diagram of control system.

Since the actual proton beam could not be obtained in the experimental stage, this experiment used a programmable digital source meter to generate a varying current to simulate the current signal which should be generated by the ionization chamber after receiving the proton beam to verify the function of the control software. Figure 9 shows the partial analog current waveform generated by the source meter according to the actual treatment plan parameters. The unit is A. The IC101 electrometer is connected to the current source meter through a coaxial-cable.

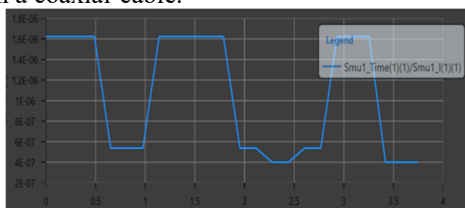


Figure 9: Analog current waveform.

In Fig.10, it shows that the control software user interface display the actual current waveform and the working status of the monitor devices. Compare the actual data saved in the log file with ideal values, due to external environmental interference and other reasons, there is a little error within the tolerable range. The actual current waveform is basically the same with the ideal current.

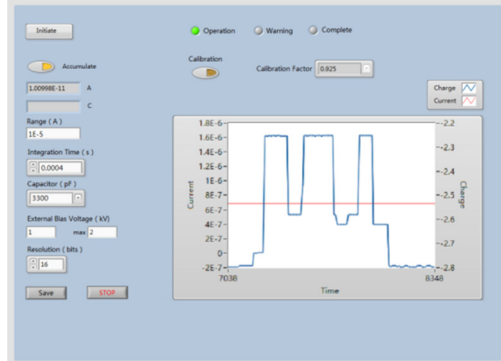


Figure 10: The design of the user interface.

CONCLUSION

In this paper, a preliminary design of the dose parameter acquisition and control system was carried out. Firstly, by interpreting the DICOM file of treatment plan, the planned dose parameters required for proton therapy are obtained, and then the acquisition and conversion of the planned treatment parameters are carried out through the design of the algorithm program. Next, the transmission of data between the control software and the end device is realized by setting up an EPICS environment in the PC. Finally, according to the dose safety requirements, corresponding redundancy measures are proposed. The working statuses of front-end devices are real-time displayed in the GUI. And the control software is designed in LabVIEW to display and save the actual treatment data, realize real-time monitoring and fast response of the signal to ensure safe and efficient operation of the treatment nozzle dose control system.

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