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CONTROL OF CYCLOTRON VERTICAL DEFLECTOR FOR PROTON THERAPY

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Abstract

China Institute of Atomic Energy (CIAE) has designed a superconducting cyclotron CYCIAE-230 to enhance the domestic development of proton therapy. A research program on the beamline and experimental stations for the proton therapy and the space science was launched by China National Nuclear Corporation (CNNC). The modern therapy methodology often requires rapid beam modulation on both the beam energy and the intensity. In this scenario, a vertical deflector is designed and installed in the cyclotron's central region. Applying a high-voltage electric field between the two plates can quickly adjust the intensity of the low-energy beam. Nevertheless, the voltage applied is nonlinear to the beam intensity. According to this requirement, a homemade controller for the vertical deflector is designed. Since the beam loss caused by the energy degrader is also nonlinear, this controller can compensate for the beam loss caused by energy modulation. To realize real-time control, the controller combines Field Programmable Gate Array (FPGA) and Digital Signal Process (DSP) as its control scheme design. Carried out by the DSP by interpolating the lookup table data, a feed-forward regulation is also designed to take care of the nonlinear compensation for the beam loss on the energy degrader. In the meantime, an ionized chamber provides feedback readings of the intensity just before the nozzle. A PID algorithm is also included by using FPGA, to archive the feedback control of the vertical deflector.

INTRODUCTION

Compact superconducting (SC) cyclotrons have the advantage of small size, cost effectiveness, high extraction efficiency and beam stability, which are very suitable for medical applications. A 230 MeV superconducting cyclotron is designed by China Institute of Atomic Energy (CIAE) to provide fix energy beam of 246 MeV with an intensity of about 300 nA for proton therapy [1, 2]. There are several items in the cyclotron that are related to the output beam current. For instance, the arc power of the internal ion source, the phase selecting system, the Dee voltage, and extracting high voltage (HV). Nonetheless, the arc power of the ion source and phase selecting system are not fast enough. The Dee voltage and extracting HV are too complicated to have fast modulation. Therefore, a fast beam modulation technique is urgently needed to speed up the beam intensity modulation in order to shorten the treatment time.

The upstream part of the beamline includes an energy degrader, which aims to adapt the beam energy to different treatment requirements, is adjusted by the Treatment Control System (TCS). The drawback of the energy degrader is that it modulates the current nonlinearly when changing beam energy. Due to the nonlinear nature of this energy change means, the beam transmission rate before and after the energy degrader will change drastically as the final energy changes.

Therefore, a vertical high voltage deflection system is installed in the central area of the cyclotron, which can modulate the beam in an independent manner and limit the loss of the beam at lower energy. Although this vertical high voltage deflection system is also nonlinear, the designed vertical deflector controller will solve this problem. It will compensate the beam lost on the degrader and the system. In the meantime, it will achieve fast switching of the beam within 100 μs and stable control of the beam to realize the new intensity modulated proton therapy (IMPT) and a new generation of time-driven intensity modulation continuous line scan technology to shorten patient treatment time. Last but not the least, it can provide redundant beam cut-offs for medical safety interlocks for proton therapy, safeguarding patient safety during the proton therapy.

OPERATING PRINCIPLES

This vertical high voltage deflection system comprises a pair of vertical deflector plates and a passive collimator. The plates are connected to a power supply outside of the cyclotron. It can actively provide initial power for low-energy beam. The vertical oscillation generated by the magnetic field will enhance the vertical off-axis motion, and the downstream collimator will eventually intercept these particles. The structure of the vertical deflector plate in the central area of the superconducting cyclotron and the principle of particles passing through the vertical deflector plate and collimator to regulate the beam intensity are shown in Figs. 1 and 2. The simulation assumes that the electric field in the vertical deflector plate is constant and acts in the 2nd to 4th turns of the particle trajectory to apply axial momentum to the particles. In contrast, the axial collimator acts in the 2nd to 5th turns, and the particles with

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larger axial bias are lost in the axial collimator to regulate the beam intensity.

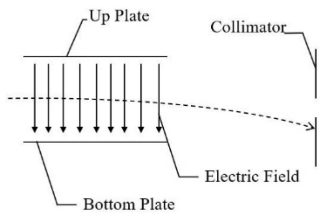

Figure 1: The deflector and collimator.

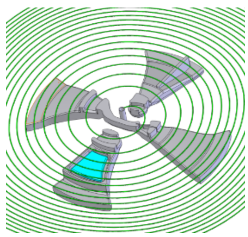
Figure 2: Vertical deflector beam modulation schematic.

As illustrated in Fig. 3, the hardware of the vertical deflector system consists of three parts. The first part is a wide bandwidth, high-voltage power amplifier, a commercial product widely used in precise high voltage control applications. An analog 0-10 V voltage from the controller commands the power amplifier to provide a high voltage of 0-2 kV. The second one is a homemade controller, the vertical deflector controller, which is the most complicated device in the vertical deflector system; hence the operating principle will be discussed in detail and reported below. The last one is a 2 kV power supply that provides the amplifier power. The controller receives four signals from the outside, namely: arc power, potentiometer signal, SMA interface signal and beam set signal, which is an analog 0-10 V voltage.

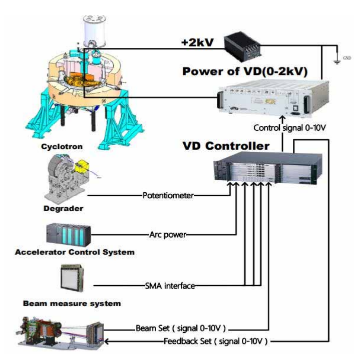

Figure 3: Vertical deflector system hardware.

HARDWARE

The vertical deflector controller board is based on the compact PCI architecture. Consisting of a pair of front and rear boards, this design allows for greater solution flexibility and versatility. The two front and single rear boards are connected by an FPGA Mezzanine Card (FMC) board. Since the design uses industry-standard interfaces, this complete digital board can also be reused in other designs. For example, beam diagnostics, etc. This makes the set of boards a digital development platform, providing greater efficiency in hardware and firmware development. In the application of rapid beam intensity control, look-up tables, PID algorithms and CPCI communication interfaces are implemented using digital resources such as DSP and FPGA on the motherboard.

According to the design requirements, the hardware architecture of the CPCI board is chosen to combine the FPGA of XC7A100T-2FGG484 under the ARTIX-7 series of Xilinx and the DSP of MC56F83789VLL, providing 4-channel ADC and 4-channel DAC; using Modbus TCP as the main serial communication interface; using RS232 as the test port for hardware function testing; 1GB DDR3 is used as the system memory; most of the FPGA's IOs are led out as backup IOs, with about 30 digital IOs; a clock input/output interface is provided for the system to accept sampling clocks from external sources or for cascading between multiple boards. The design block diagram of the whole set of boards is shown in Fig. 4.

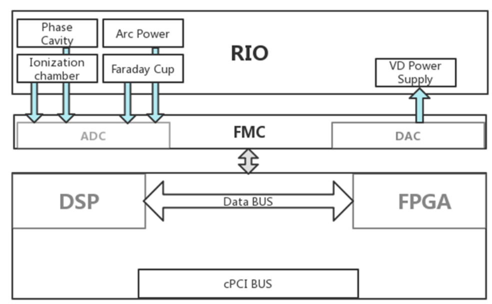

Figure 4: Block diagram of daughter-mother board circuit.

In Fig. 5, it shows a physical view of the motherboard. The motherboard mainly completes the implementation of the control algorithm and the CPCI communication with the upper computer, and the main chips are FPGA and DSP. The FPGA implements the PID control algorithm, ADC/DAC driver and CPCI communication, while the DSP implements the lookup table algorithm and Modbus TCP communication.

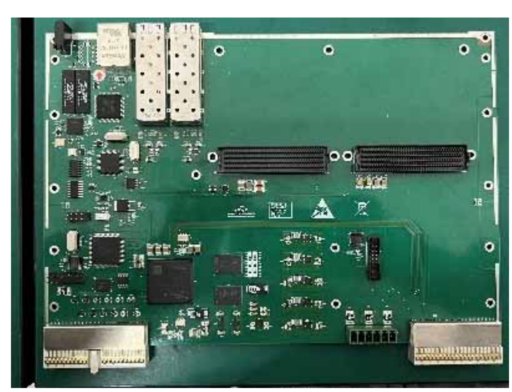
Figure 5: the vertical deflector controller mother board.

In Fig. 6, the daughter board is developed according to the operating principles of the vertical deflector system. According to functional requirements, the daughter board is equipped with 6-channel ADC and 1-channel DAC to the

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HV power supply. The daughter board's core function is to provide the necessary signal conditioning for the beam measurements and digitalization for the motherboard. The PID feedback of FPGA uses 3 ADC channels, and the look-up table of DSP uses three analog conversion channels.

As the main function board, the daughter board will input the signals obtained after photoelectric isolation into each function module, such as the detector module will convert the obtained power signal to the output voltage; the IV conversion module will convert the current signal to get the voltage signal, and the current signal has eight gear switching ranges; the ionization chamber module will convert the current signal to voltage signal; finally, the required four values of beam intensity, degrade beam transmission rate, Dee voltage beam transmission rate and vertical deflector voltage are obtained, so that four look-up tables can be established and processed by DSP to realize the look-up table algorithm.

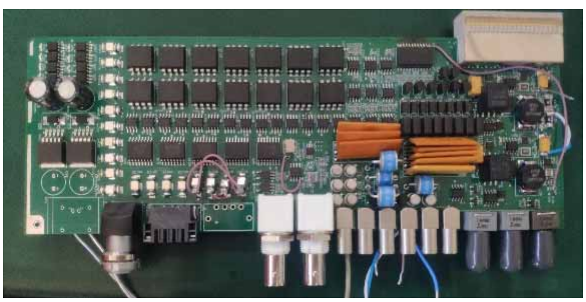

Figure 6: the vertical deflector controller daughter board.

In Fig. 7, The FMC board that connects the two boards is shown in the picture. The FMC board implements digital-to-analog and analog-to-digital conversion. ADC converts the current and voltage values of the daughter board to get the corresponding Dee voltage and other corresponding values, which are output to DSP to build a lookup table and calculated in DSP to get the corresponding values of arc power and other corresponding values to output to FPGA. This board is mainly for some fast digital-to-analog/analog-to-digital conversion calculations.

Figure 7: FMC board.

SOFTWARE

The software of the vertical deflector system involves embedded system development and host system interface development. Further, to meet the timing requirements of the dose delivery system, the algorithms of the vertical deflector system are implemented in dedicated hardware, e.g. the DSP and the FPGA. Related Single-Board Computer (SBC) runs the real-time operating system, VxWorks 6.9. The SBC is responsible for none time-critical tasks, such as communication with the Graphical User Interface (GUI). There is no operating system for the development of embedded software on DSP and FPGA.

In the DSP, a set of C codes is developed to achieve the feedforward control functions using a two-dimensional look-up table. As presented in Fig. 8, a higher voltage on the plates will yield a lower beam transfer ratio at certain beam energy. Under the same high voltage on the deflection plate, the lower the beam energy, the lower the beam transmission rate.

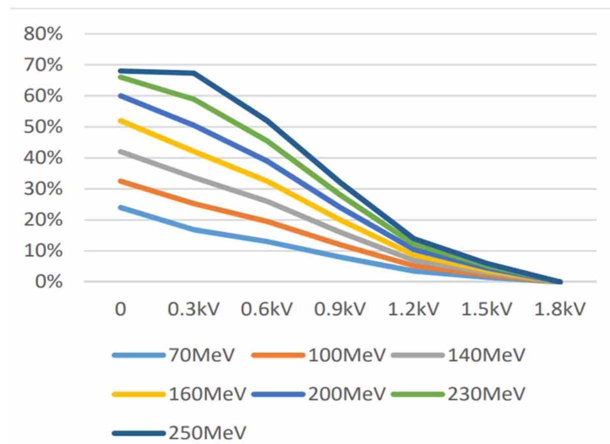

Figure 8: The corresponding relationship between vertical deflector voltage and beam current at the different energy.

The main system utilized for the software part is VxWorks. VxWorks operating system is an embedded real-time operating system (RTOS) designed and developed by WindRiver, Inc. in 1983 and is a key component of the embedded development environment. With good sustainability, high performance kernel and a user-friendly development environment, it occupies a place in the field of embedded real-time operating systems. It is widely used in communication, military, aviation, aerospace and other areas with high precision technology and high real-time requirements, such as satellite communication, military exercises, ballistic guidance, aircraft navigation, etc., with its good reliability and excellent real-time performance. The operation page of the VxWorks system is shown in Fig. 9.

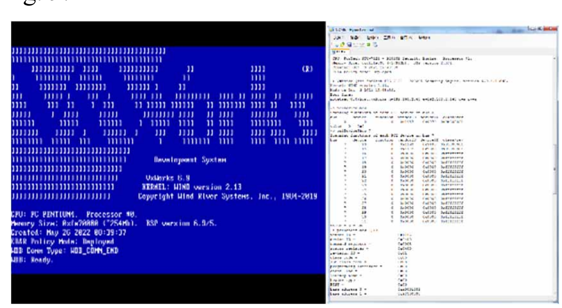

Figure 9: VxWorks system operation page diagram.

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CONCLUSION

The existing research work on the vertical deflector controller has more research results, and the technology is more mature, which has a more significant reference value for how to accurately and quickly control the beam intensity, and has greatly improved the system response speed and beam intensity adjustment accuracy.

The development of the vertical deflector controller is a key technology for the development of localized proton therapy devices, which will provide a technical guarantee for the localized proton therapy device to catch up with the latest generation of continuous line scan therapy technology and FLASH therapy.

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