Design and tuning of a fast beam energy selection control system for CYCIAE-230 cyclotron beamline

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Abstract

The preliminary beam test of the CYCIAE-230 cyclotron and its beam transportation system to the isocenter of the gantry was successfully conducted at the end of December 2023. During this, various beam transportation tests with different energies are carried out to verify the design of the energy selection system. The ESS consists of a pair of carbon wedge shape degraders, an apochromatic magnet system, and a related beam shape, the moment selecting slits. Once beam energy is selected, the rest of the beam transportation system is controlled to follow the ESS, including synchronization of the 51 beamline magnets in total. The CYCIAE230 superconducting cyclotron extracts a fixed energy beam of 242.25MeV. The double wedge degrader and the beamline system can modulate and transport the beam with energy from 242.35 MeV to 71.84 MeV. In an energy range from 232.12 MeV to 71.84 MeV, it was experimentally verified to be capable of switching down an energy layer (2mm water depth equivalent) within the order of magnitude of 50 milliseconds. Unlike other degrader designs, the CIAE degrader has a significant moment of Inertia, making it difficult to achieve fast control. A dedicated energy selection control system has been developed by CIAE, using the VxWorks real-time operating system and its multi-task scheduling to control the degrader and synchronize the related magnets quickly. The reported control system also includes an interpolation algorithm to automatically calculate the setpoints for different beam energy to facilitate the beamline's commissioning. A dedicated user interface is also included to facilitate the commissioning procedures. This paper will introduce the control system from both hardware and software and analyze the tuning results.

Overall of the CYCIAE-230 and its beamline

The CIAE cyclotron lab has committed significant efforts to develop a prototype for advanced research in proton therapy. The proton therapy beam transport line consists of the following components: a beam extraction section, an energy selection section, a telescope section, a room switching section (Bend section), and a rotating gantry section. as shown in Fig. 1.

The ESS of the CYCIAE-230 and its beamline primarily consist of a pair of carbon wedge shape degraders (Fig. 2), an apochromatic magnet system, a divergence slit, and a moment slit. The degrader design integrates a dual-wedge structure, enabling seamless and continuous adjustment of the beam energy.

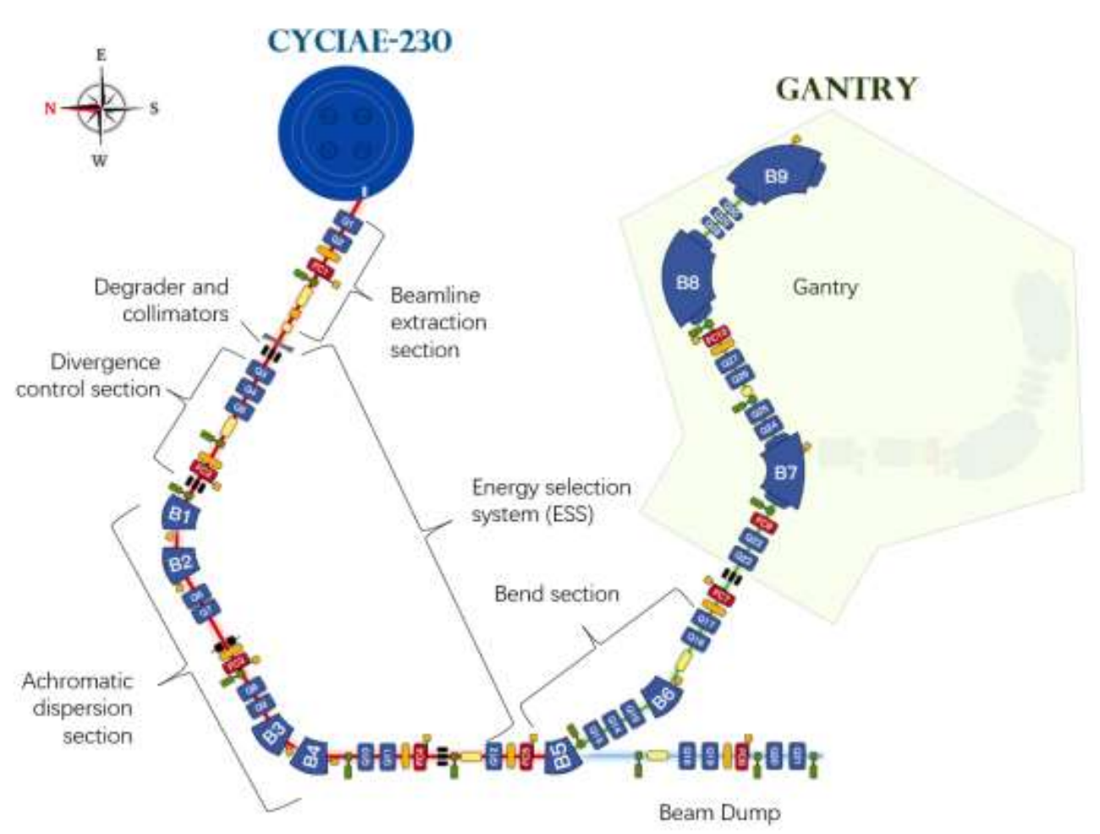


Fig. 1. Layout of the CYCIAE-230 and its beamline

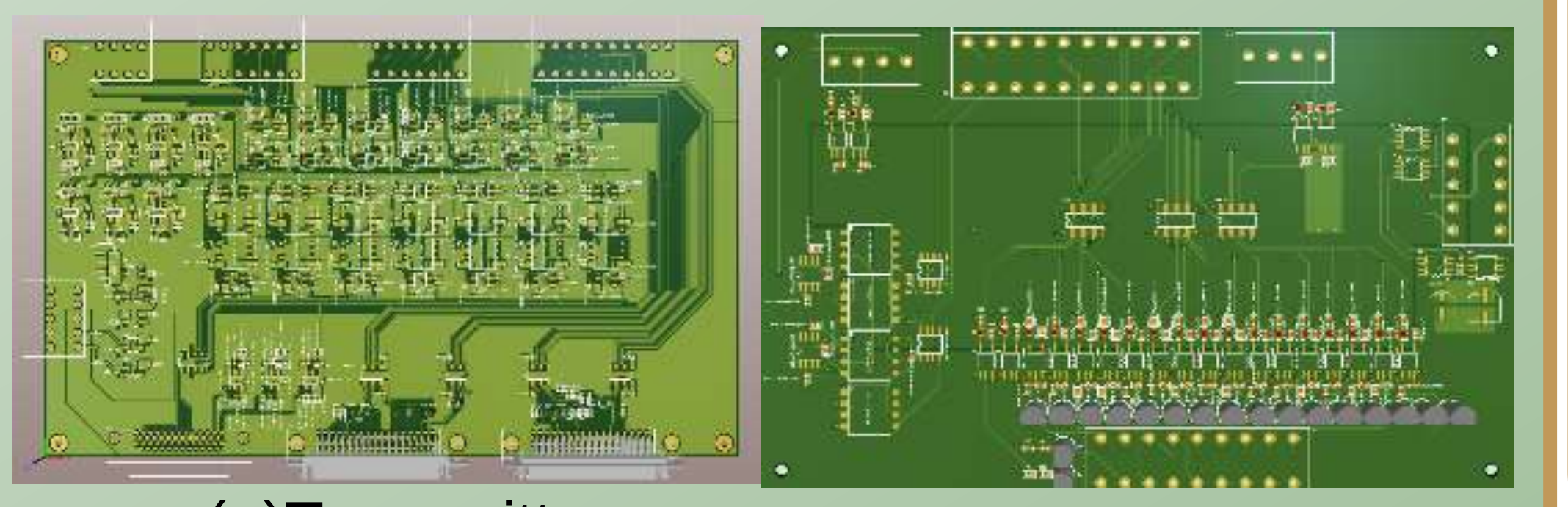
Fig. 2. The degrader of the CYCIAE-230

Hardware of the system

The hardware design of the control system uses a VME bus architecture, incorporating lower-level processors in motion control boards and system boards. These boards are interconnected through the VME bus via the chassis backplane, as illustrated in Fig. 4.

To protect central processing units from radiation, particularly neutron damage, the controller is distanced from the cyclotron and beamline, using a custom EMC module (Fig. 5) to shield signals from electromagnetic interference and amplifie reliability in data transmission.

Fig. 4. VME crate



(a)Transmitter

(b)Receiver

Fig. 5. PCB for EMC boards

Topology of the ESS control

The control system can be divided into two parts: hardware and software(Fig. 3). The hardware consists of a VME bus controller and electromagnetic isolation modules. The software comprises VxWorks operating system-based embedded control codes and a personal computer program to provide a graphical user interface. This real-time control system adeptly operates the devices within the ESS, precisely adjusting them to the required settings for accurately controlling the beam energy ranging from 70 MeV to 240 MeV.

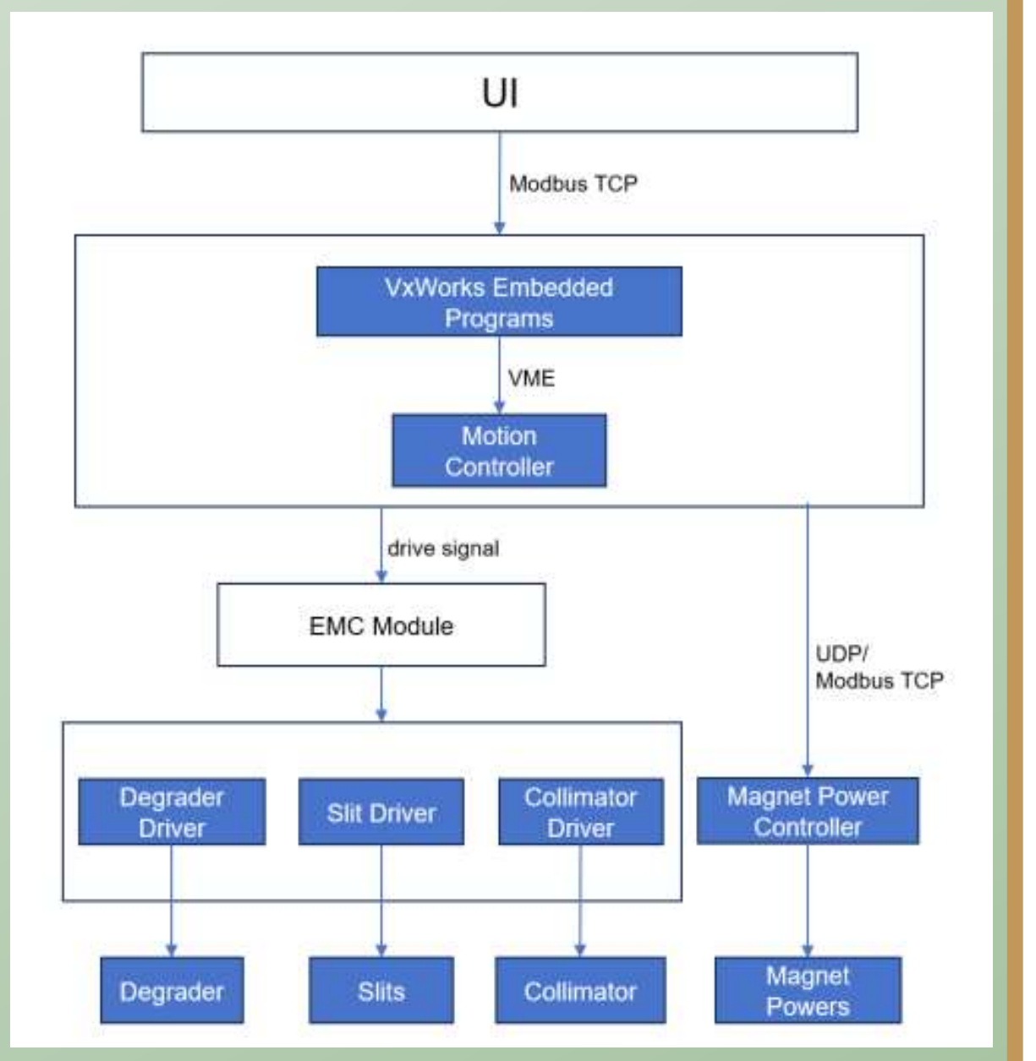


Fig. 3. Structure of the control system

Software design

The control system incorporates a VxWorks-based embedded, real-time multitasking operating system to manage its master/slave architecture. By scheduling tasks based on priority, which guarantees synchronization among all devices, enabling them to execute beam energy-dependent adjustments within a 50ms timeframe. The system uses a segmented PID control method (Fig. 6) for the magnet power supplies to optimize response times. Additionally, the control system is integrated with the Nozzle system, receives remote procedure calls via DDS to set the beam energy for the Nozzle system before further dispatching tasks to the devices. The control software incorporates a parameter-setting feature. The operator's task is simplified to merely entering the desired energy value, after which the system automatically adjusts all relevant parameters accordingly, as shown in Fig. 7.

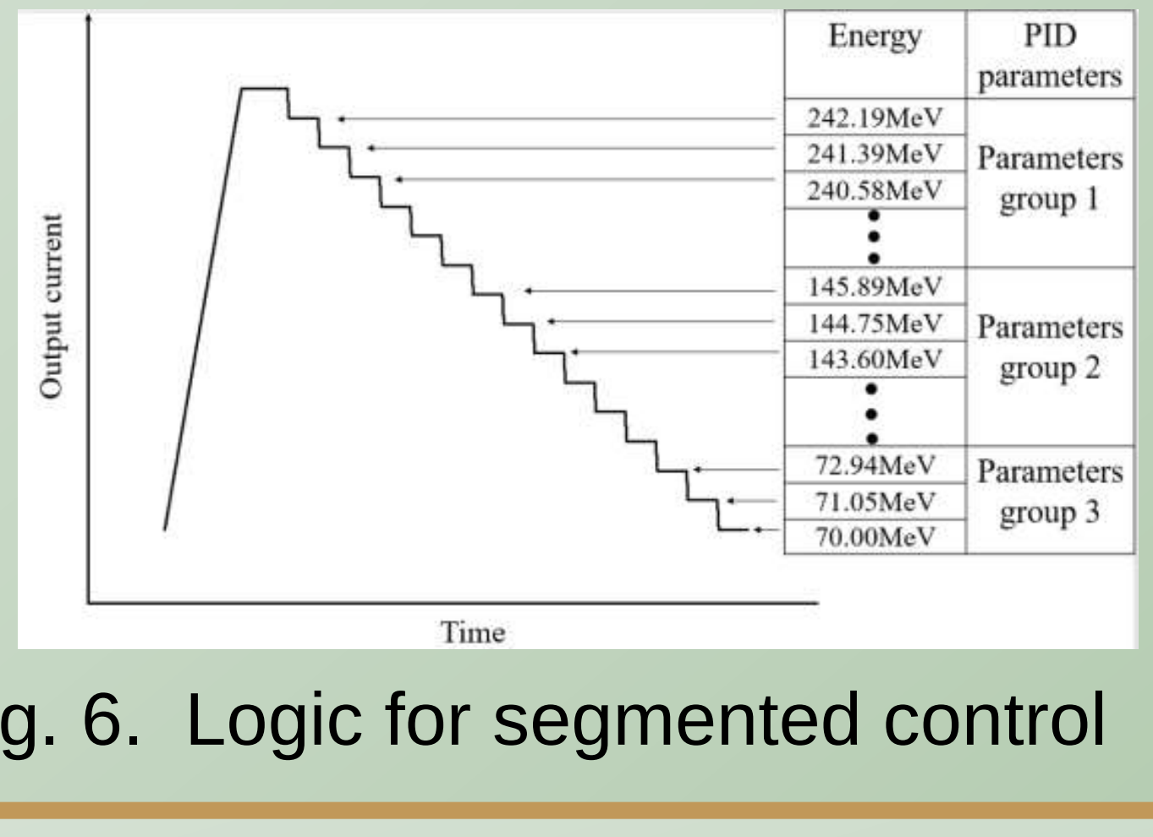


Fig. 6. Logic for segmented control

Fig. 7. Control system operator interface

Test results and future work

Equipment characteristics were selected for energy switching duration testing from 231.18 MeV to 230.36 MeV. The extracted data indicates that the single-layer energy switching time for the slowest beamline components, fell within 45 milliseconds, as shown in Fig. 8.

A three-dimensional water tank and an ionization chamber detector were used to measure the relative dose distribution of the beam as it traversed water along its forward direction. The depth at the 90% peak of the relative dose distribution curve (R90) was taken as the range of the beam in water for a particular beam energy. As Fig. 9 shown, the calculated energy regulation range facilitated by CYCIAE-230 and its associated beamline spans from 71.84 MeV to 242.35 MeV.

By developing a rapid control system, we have enabled quick switches between beam energy layers (2mm in water) and verified the range of beam energy provided by the beamline. In future research, the ESS will be tested in conjunction with the treatment terminal to verify the accuracy and repeatability of the beam energy selection.

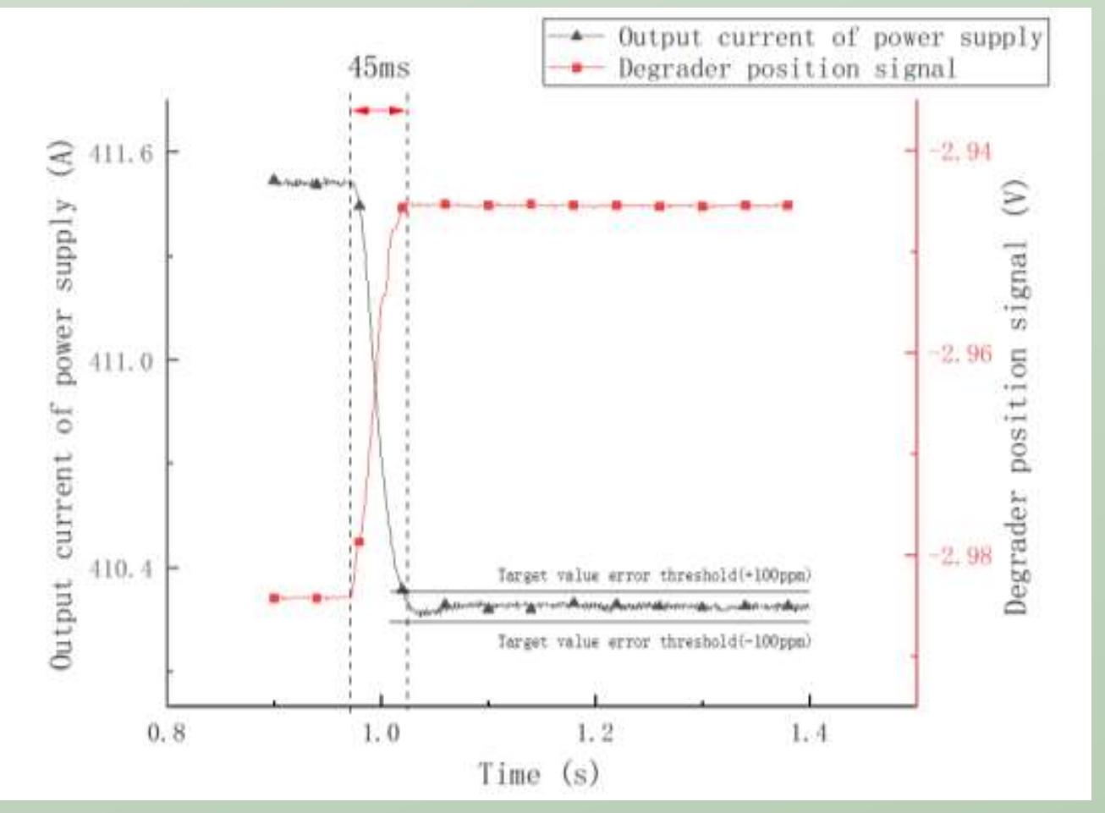


Fig. 8. Energy switching time test result

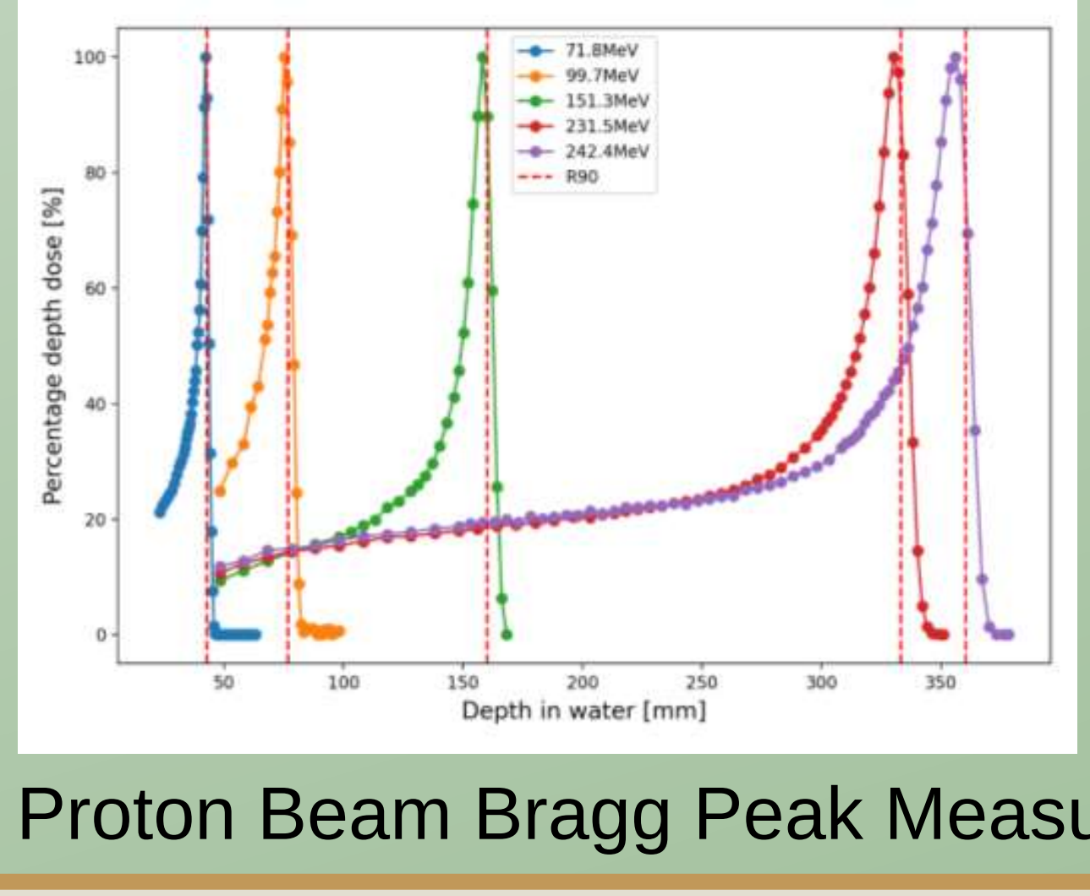


Fig. 9. Proton Beam Bragg Peak Measurements

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