BEAM CONTROL FOR PROTON THERAPY

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Improvements to the NAC cyclotrons and beamlines were necessary before routine proton therapy could commence. Among these were a fast energy change procedure which could yield stable magnetic fields for 66 MeV and 200 MeV protons in less than one hour, systems to stabilise the position and angle of the beam on target and to stop the beam within a few milliseconds, as well as new beam alignment systems. One of the important characteristics of this treatment is the precision with which the dose can be controlled. This requires good long-term angular and positional stability of the proton beam. Thus a two-stage closed-loop control system was developed for steering the beam. The electronics associated with the detector of the second loop is also used to monitor the total dose received, providing total dose control. It also provides the operator controlling therapy with information about dose rates and beam profiles.

1 Introduction

During the first six years of operation, the NAC facilities were used for isotope production (66 MeV) on Mondays and Wednesday nights, and neutron therapy (66 Mev) on Tuesdays, Wednesdays and Thursdays. Nuclear physics research was done on Fridays, Saturdays and Sundays. In September 1993, proton therapy commenced and was included in this schedule on Mondays and Fridays, using an energy of 200 MeV. Inclusion of the latter in an already tight schedule made it important to minimise the time required for energy changes from 66 Mev to 200 Mev and *vice versa.*

Previously only two energy changes per week were needed when the beam was used either for physics research or neutron therapy and isotope production. With the beam required for proton therapy as well, up to four energy changes per week may be required. Energy changes previously took five to six hours: thus if this regime remained unchanged, a significant portion of the total operating time of the cyclotron would be used for changing energy. A more effective method of changing energy needed to be developed.

The patient treatment times for proton therapy can be as short as ten seconds compared with the two to three minutes which is typical of neutron therapy treatment. A faster means of stopping the beam for proton therapy had to be found to improve the accuracy of the delivered dose. The pulse selector located in the SSC has been modified for use as a fast electrostatic switch to provide precise control of dose for proton therapy.

One of the significant advantages that a proton beam offers to therapy is the precise positioning of the dose in three dimensions. The required lateral stability of the beam in the 10 m beam delivery system which contains no focal elements, is significantly better than that inherent in the beam extracted from the cyclotron. Thus a two-stage closed-loop beam control system has been developed to provide the required stability.

Beam position is detected by a quadrant ionisation chamber (Lawrence Berkeley National Laboratory)[1] and a locally designed multiwire ionisation chamber. A range monitor ionisation chamber provides information on the beam energy.

2 Energy changes

A new magnet field-setting procedure has been developed for the separated-sector cyclotron (SSC) and implemented on the cyclotron control system, in order to reduce the transition time between the isochronous fields for 66 MeV and 200 MeV proton beams by a factor of 3 (figure 1). This transition normally takes close to 3.5 hours (and 2 hours in the opposite direction) when the standard computer-controlled setting method is used, and this contributes considerably to the total time necessary to effect such an energy change.

With the new fast setting method the field transition from 66 to 200 MeV is completed in only 40 minutes (and 60 minutes in the reverse direction). Apart from eddy current compensation, the transitions are direct. When the field is increased, damping of induced eddy currents is achieved by a suitable overshoot of the main excitation instead of using the normal undershoot.

While the standard magnet field-setting procedure ensures

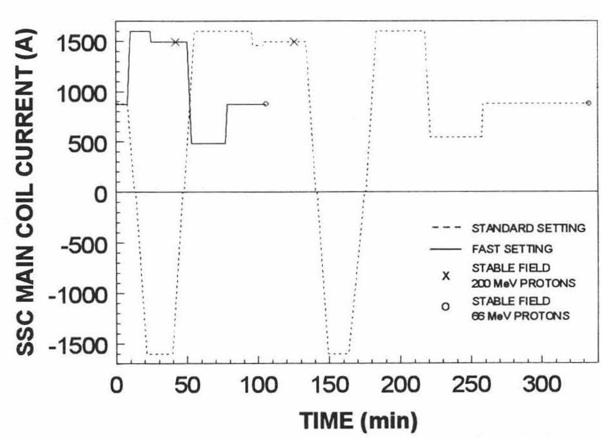

Figure 1. The new fast excitation setting of the sector magnets for isochronous field transitions from 66 to 200 MeV protons and back, compared with the equivalent standard setting method.

that the same sector-magnet field is generated with extremely high accuracy for a given choice of excitation currents (using 41 power supplies) irrespective of the magnetisation conditions at the beginning of the field change, the new method can provide similar results only for transitions from one specific magnetisation to another one. In order to compensate for remanence effects, the final excitation currents have to be adjusted for transitions from different initial fields to the desired field and must be determined experimentally in each case, together with optimum under- or overshoot values.

Excitation adjustments for transitions between *fast-set* 66 and 200 MeV proton fields have been evaluated using beam phase measurements. These results confirm that remanence effects influence the field level as well as the isochronous radial field shape resulting from the trim-coils. We also found that a different compensation is necessary when the previous field is set by the standard method instead of the fast one. This problem is now avoided by first setting the 200 MeV proton field with the fast method from any arbitrary initial condition and then immediately following with the equivalent 66 MeV proton field, or *vice versa*. Although this double setting procedure takes considerably longer than a single one, it minimises the necessary field adjustments and is still shorter than the standard setting procedure for the 200 MeV proton field. Usually, no field adjustment is necessary at all with any of these setting procedures.

The time required to set the magnet field of the light-ion injector cyclotron SPC1 for any energy change has been reduced from 45 to 15 minutes. As a result of the change in the procedure used, new current settings for isochronous fields had to be determined using the newly-installed phase probe in SPC1 and a computer program for field isochronisation. The fringe field in SPC1 has also changed and new settings for the extraction elements had to be determined.

It has become clear that for proton therapy it will be important to deliver proton beams every week with the same characteristics – energy, energy spread, beam focus, etc. Much time was spent on standardising the machines settings for 200 MeV protons. The electrostatic injection channel[2] proved to be a great help in obtaining single-turn extraction as well as beams with a small emittance and low energy spread at extraction in the SSC. In order to enable proton therapy to be done at 200 MeV and to make provision for energy losses in air and in the window at the beam pipe, as well as for slight daily variations in the energy, we decided to deliver a proton beam with an energy of 202 MeV. The beam energy can be trimmed by putting thin plastic plates in the beam path to obtain the desired energy. Owing to small changes in the magnetic field as well as centring errors in the SSC, the beam energy delivered to the therapy vault varies between 201.5 and 202.5 MeV.

Every aspect of the energy change procedure has been considered and optimised to accomplish energy changes as fast as possible. The time required to make an energy change has in both cases been reduced to an hour and a half.

3 Monitoring of Beam Position

Beam position monitoring is performed by a DOS-based program running on a dedicated personal computer, for reasons of reliability. The program provides control and display functions, as well as an interface to the output from the quadrant and range monitor ionisation chambers[1]. The purpose of this system is to provide:

i. start/stop control, setting of operating parameters such as minimum and maximum counting rates, and setting of the beam's steering limits;
ii. safety interlock signals for low/high and off-centre beam conditions;
iii. display information such as a graphical representation of the quadrant and range monitor rates and an indication of the centred state of the beam - this information is also provided over the LAN network;
iv. control data, over the network, to other programs such as the position control system described in the next paragraph.

The program consists of two parts that run a synchronously: a hardware interface part and a user interface part.

At the hardware level, which is invisible to the user, the program interfaces to the ionisation chamber signals by means of a commercial counter card. For this purpose, interrupt handlers were written to handle the hardware interrupts generated by counters on the card. Counting totals and rates are collected for each one of the four quadrants and the 12 plates of the range monitor and are stored in a global data area for use by the interface part of the program. The initial hardware set-up and final cleanup procedures are handled at this level.

At the user level the program provides a graphical interface which provides all the capabilities listed previously. This section is event-driven so that it uses computer time only as a result of an intervention by the user. During the rest of the time it provides display and control information at fixed intervals driven by regular timing signals. The display is updated about 3 times per second and control information is sent over the network 6 times per second.

The user can select a display of either count totals or count rates. He also can set both low and high beam limits, as well as steering limits.

During operation the program monitors these limits and generates a safety interlock signal when necessary. The exception, however, is for a few seconds after the beam is started, when the program won't trip on a steering limit in order to be give the beam some time to be centred.

The program can be run in either master or slave mode. In master mode only one instance can be run at a time, usually form the proton therapy control room. The master program handles the hardware as described above, provides a display, and broadcasts packets containing count and control data over the network. A simulation mode is provided for testing.

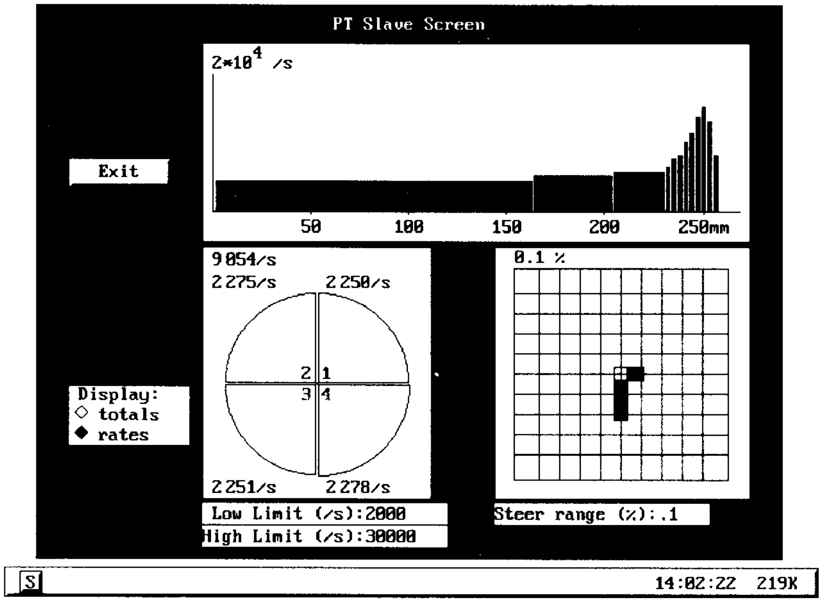

Figure 2. Slave screen display showing count rates for the range monitor ionisation chamber (top), the quadrant ionisation chamber (lower left), and the steering signals derived from quadrant count rates (lower right).

The program can be run in its slave mode on any number of personal computers at a time. In slave mode all hardware and control functions are disabled. The slave programs receive network packets and provide basically the same display as that which is seen on the master screen. An instance of the slave program is always run in the cyclotron control room during proton therapy sessions, in order to provide the operators with the information which they require to set up the beam. An example of the slave screen's display is given in figure 2.

The network packets are also received by other control programs, in particular the position control system described in the next paragraph. The steering signals are derived from the counting rates on the four quadrants. The horizontal signal is obtained from the difference between the sum of the two right chambers and the sum of the two left chambers. Similarly the vertical signal derives from the difference between the top and the bottom quadrants.

4 Position control

In applications at NAC other than proton therapy, beam targets have been placed at the focal points of the final quadrupole magnets. This has the advantage that any instability in the beam is intrinsically compensated by the quadrupoles. However, for proton therapy it was a requirement to focus the beam soon after the last quadrupole and thus some distance short of the isocentre in the therapy vault. Long–term beam stability was an immediate area of concern which could not be improved by improving the stability of the power supplies of the magnets in the beamline. This is aggravated by the distance of the last few magnets from the isocentre. The last pair of steering magnets is approximately 6 m from the isocentre while the last quadrupole triplet is just over 10 m away.

The required lateral positioning accuracy for the beam is better than 0.5 mm in both the X and Y directions. To achieve this accuracy with the given positioning of the magnets requires both an angular stability relative to the centreline of the beam path and lateral positional stability at the last measuring point. This can be achieved practically by selecting two points in the beamline some distance apart and actively steering the beam to keep it at the centreline at both points. It is implemented as shown in figure 3 and consists of two position control loops. The first loop has its detector at the first position reference point, located 5.92 metres from the isocentre. The signal derived from this is processed to produce an error signal. This is sent to a proportional and integral controller which controls the power supplies of a pair of steering magnets situated 2.86 metres upstream from the detector.

The detector is a multi-wire ion chamber with 47 wires stacked horizontally and another 47 stacked vertically, forming a cross-hatched pattern. It is so designed to give similar signals to the standard harp devices used in the rest of the beamlines. It is connected to the harp electronics which

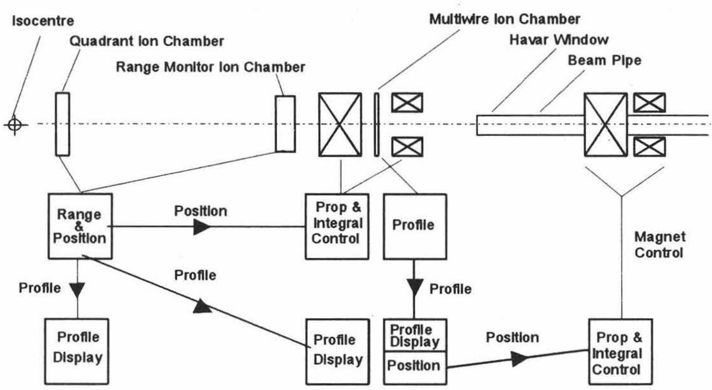

Figure 3. Schematic of the proton therapy beam control system.

provides a profile display and the position of the beam relative to the centre of the beam path. This positional value is then sent via a network to the computer that controls the magnet power supplies where a process implements proportional and integral control signals to the supplies that control the X and Y steering magnets.

As will be discussed later, the required response from this loop is slow, so it was decided not to implement differential control. Proportional control is used for large error excursions because it provides reasonably rapid response and is stable under large error signal conditions. For errors of less than 2.5 mm, integral control is used to reduce any errors to a minimum and to eliminate any offset errors between the reference and actual values of the power supplies. To avoid continual corrections from noise in the signal and any hunting arising from the integral control, a deadband of 0.2 mm is incorporated.

The detector of the second loop is the Berkeley quadrant ion chamber[1]. This is situated 0.34 m from the isocentre. As described above, the data from this chamber are processed by a computer to provide a display of the beam intensities in the four quadrants. The count rates from the quadrant ion chamber are sent via the network to another process in the same computer that provides the control for the first loop and controls a pair of steering magnets straddling the first detector. The former works in a similar manner to that of the first loop. Here the deadband is 0.04% and the threshold between proportional and integral control is 1.0%. Differential control was not attempted in this loop because of the presence of a significant amount of noise in the error signal. In order to reduce the effects of noise, the signal is sent at six times the required rate and a sliding average is calculated which provides a filtered error signal.

This loop samples at a rate of once a second which is sufficient to compensate for any drift and to maintain the beam within the required 0.5 mm tolerance on the target. The first loop samples a slower rate because the expected drift at the first detector would be low, as it is close to the focal point of the quadrupoles. A slower sampling rate was also chosen to minimise any interaction between the control loops

The error signals become large and meaningless when there is no beam between treatments. In order to avoid the steering components from being driven significantly off position and thus completely mis-aligning the beam at the start of each treatment, a threshold count rate which is below the normal range of treatment values is incorporated to cause the control action to cease when there is no beam.

4.1 Results

The second loop was first run on its own. The gain constants were adjusted to provide a slightly underdamped response, but the settling time of the system was found to be unacceptably long at approximately 8 seconds. After examin - ing the dynamic response of the various components of the system, it was found that the response time was determined by that of the steering magnet power supplies which had a response time of 7 seconds. With a relatively simple modification to the latter, it was possible to reduce its response time to 2 seconds. This produced a system settling time of 3 to 4 seconds which is considered acceptable.

The sampling rate of the second loop was found to be adequate in practice, while that of the first loop was increased from an initial 15 - second interval to 5 seconds, as the correction steps at the slow rate were rather large, causing the beam to go out of tolerance at the isocentre.

References

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2. J.L. Conradie et al; Development of the NAC Accelerator Facilities, *Proceedings of the 13th International Conference on Cyclotrons and their Applications (World Scientific, Singapore)* pp 95-98 (1992).