NEW BEAMLINES FOR PROTON THERAPY AT NAC

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Three shielded radiotherapy rooms exist at the National Accelerator Centre (NAC), one housing an isocentric neutron therapy unit and one which has been in use for several years for proton therapy. At NAC proton therapy has been limited almost exclusively to head and neck treatment because of the fixed horizontal beamline. Financial constraints have precluded the installation of an isocentric proton therapy unit. However, a new proton treatment station is now being installed in the third treatment room, with one horizontal beamline and one at 30° to the vertical. The rationale for these new non-orthogonal intersecting beamlines and the proposed layout of the treatment station are discussed. Progress with the construction of the new facility is described.

1 Introduction

The NAC separated-sector cyclotron (SSC) is used to supply particle beams for radiotherapy with both neutrons (via the p(66)/Be(40) reaction) and protons (at 200 MeV). The existing proton therapy station has been in operation since September 1993, and is equipped with a fixed horizontal beamline [1]. This station is currently used on four days per week, and almost exclusively for head-and-neck treatments.

The beam is scattered and collimated to form the 2-dimensional shape required for each of several different beam directions (treatment fields) for each patient. Patient-specific collimators must to be machined for each field, and a different range-shifter wheel has to be mounted for every treatment range required. This method is also not particularly well suited to the treatment of small lesions, since there is scattering of the protons from the collimator, with some energy-loss and a resulting reduction of the Bragg peak with respect to the plateau region. The setting-up time required for each patient in the treatment chair [2] is quite long, and limits the number of patients that can be treated on any one day. This is inefficient since the unused beam-time between patients is wasted, as the 200 MeV beam cannot easily be switched to other users – unlike the 66 MeV proton beam used for neutron therapy, which is switched to radioisotope production between patients, with a fast laminated switching magnet. The relatively high energy and low current of the proton therapy beam are unsuited to radioisotope production.

A second proton therapy station is now being planned for the remaining, unused, treatment vault. By switching the beam (relatively slowly) between the two proton treatment stations we can double the useful beam time and the total number of patients treated. We are proposing to use a spot-scanning system on the new station, which will obviate the need for the milling of patient-specific collimators. Spot-scanning in successive layers also permits us to build up a dose distribution in 3 dimensions which conforms much more accurately to the shape of the lesion being treated than is the case with the present scattering-plus-collimation technique.

An isocentric gantry would obviously be the system of choice, but this is ruled out by our limited finances, and it has been decided to utilise the quadrupole magnets and two of the dipole magnets from the beam-swinger [3] to provide two intersecting, non-orthogonal beams, as a compromise. One beamline will be a fixed, horizontal beamline, while the other will be fixed at 30° to the vertical. If the patient treatment couch can tilt by ±15°, then a larger area of entry points into the patient can in fact be reached [4] than with a vertical beam (figure 1). The use of the existing dipole magnets in an isocentric system was also considered, but such a system would not fit within the constraints of the existing vault. In addition, these magnets are heavy, with wide pole-pieces, and much lighter and more compact magnets would be required for an isocentric system.

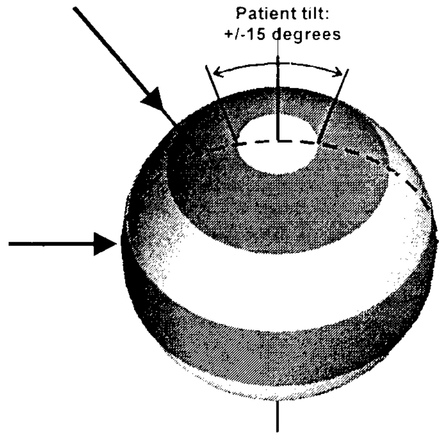

Figure 1: A representation of the surface area on a spherical object for beam entry points (dark grey shading) achievable with two beams – one a fixed horizontal beam and one fixed at 30 degrees to the vertical – combined with a 15-degree patient tilt. The actual area treatable is of course even larger, since the area scanned by the beam was here taken to be zero. For a vertical beam, only the (light grey) area indicated around the vertical axis would be available.

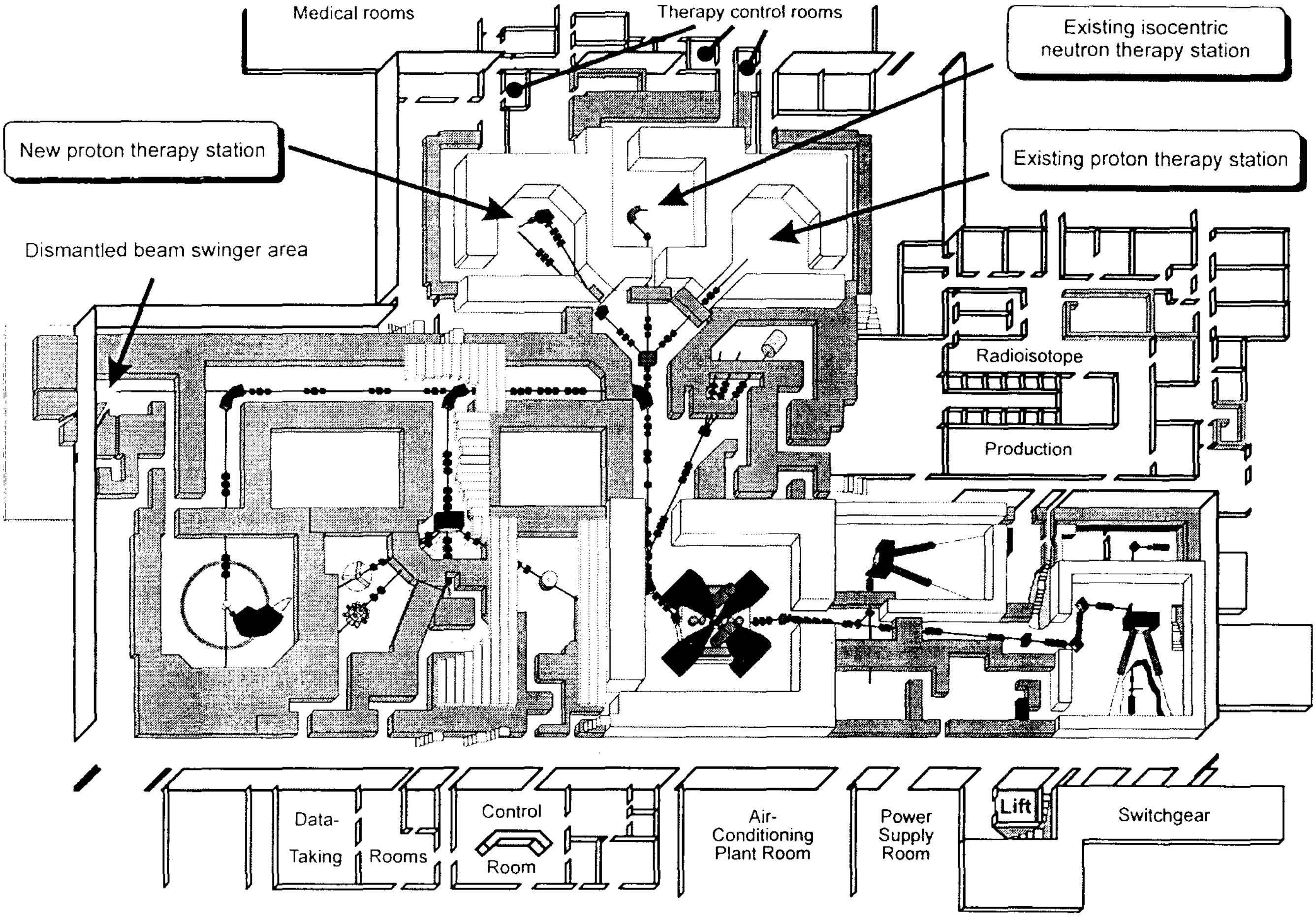

Figure 2: Layout of the NAC cyclotron hall and some of the ancillary areas. The radiotherapy treatment stations are indicated.

2 Layout of Beamlines

The layout of the three radiotherapy vaults can be seen in figure 2. The central room is used with the isocentric neutron therapy system, while the right-hand room is equipped with the fixed horizontal beamline for proton therapy, and the left-hand room is available for the new proton therapy station.

The two dipole magnets from the old beam-swinger, which are being adapted, were specially designed with large pole faces, and are quite heavy. This is particularly true of the larger of the two magnets, which weighs approximately 23 tons. However, we can support this dipole inside the therapy vault with a strong, fixed, rigid steel framework.

We have determined that the non-laminated switching magnet serving the three therapy vaults can switch the 200 MeV proton beam from the left-hand vault to the right-hand vault (or vice versa) within 5 minutes, including the time needed for the magnetic field to stabilise sufficiently for accurate radiotherapy. With development of a better field-setting procedure, involving overshoots and undershoots, such as we now routinely use on the cyclotron magnets [5], we expect this time to be reduced even more. Given that patient set-up time is quite long, we expect that this switch-over can be done within an acceptable time between treatment of successive patients in the two rooms.

A schematic layout of the new station, showing the locations of magnets on the two intersecting lines is given in figure 3. For the upper beamline, the beam is directed upwards through 20 degrees by the first dipole (outside the treatment vault), and is then bent downwards through 80 degrees by the second dipole, so that the resultant beam is aimed downwards at 30 degrees to the vertical.

Calculations with TRANSPORT [6] show that an achromatic solution can be found for the upper beamline, which means that variations in the energy spread of the beam will not alter the final beam width at the intersection of the two beamlines. The calculated horizontal and vertical beam profiles for this beamline are shown in figure 4. The x and y plots refer to bend-plane and non-bend-plane beam envelopes, respectively. Particles with momentum which is different from the central momentum (the so-called "off-momentum" particles) cross over at the x-focus inside the fifth (y-focusing) quadrupole magnet, so that the overall transport is achromatic. The plots show a final beam spot of 1 cm size, defined in the usual way of TRANSPORT. The distribution of the beam within this spot will be taken into account in the treatment-planning program. Larger spot

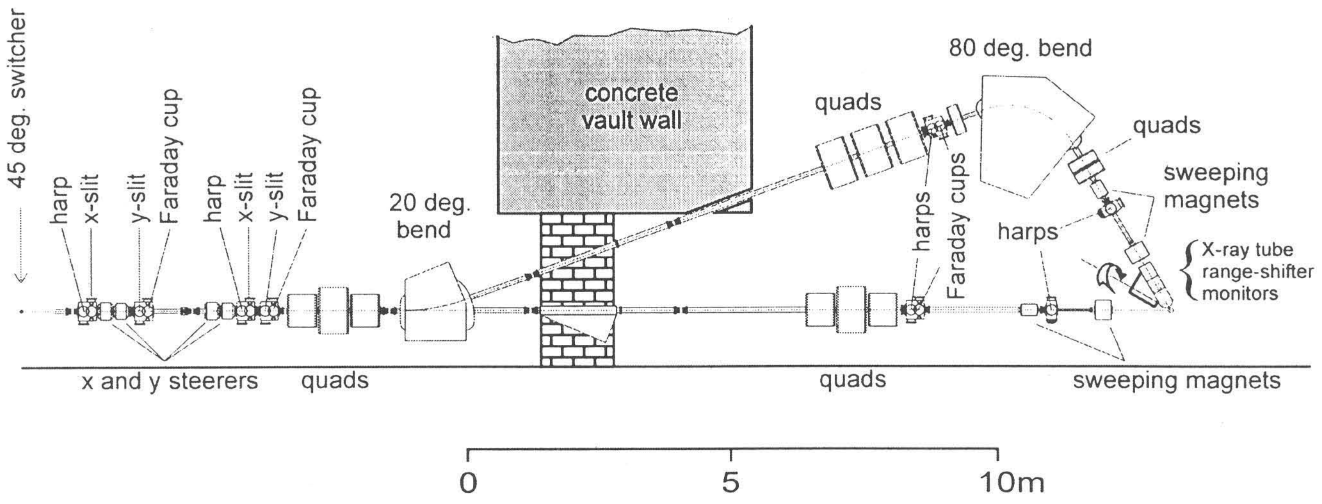

Figure 3: Schematic drawing of the new intersecting-beam proton therapy station.

sizes for treatment of large tumours can easily be formed by using the last pair of quadrupoles downstream from the 80° dipole.

The horizontal beamline will be equipped with a two-triplet telescope of quadrupoles, enabling the proton beam to be focused and held to a 1 cm diameter spot at the patient position (at the intersection of the two beams), or larger if desired.

3 Beam Scanning

Scanning of the beam spot through the irradiation volume can be achieved by magnets to sweep the beam in one (x) or two (x-y) directions, while discrete sheets of plastic material inserted into the beam as energy-degraders can be used to step the beam in the z-direction, i.e. in depth.

Since we require that the scanned beams are parallel to each other, a two-magnet scanning system is needed, with the first magnet providing the angular deflection required, and the second magnet making the direction of the displaced beam parallel to that of the original beam. Scanning the beam in both of the two orthogonal directions would require an impracticably large magnet for the second dipole, since the total scanned beam area required is 250 mm by 250 mm. Consequently, we have decided to follow the approach of the PSI system [6] and to obtain the second scan direction by moving the patient in small steps in a direction at right angles to the very rapid 1-dimensional magnetic scanning.

The 300-mm long laminated scanning magnets will be placed 1.7 m apart, which requires an 0.825-tesla dipole field in each magnet. Both magnets will have a 40 mm pole-gap, and about 500 A in each coil. Since we are constructing two (intersecting) beamlines, one set of scanning magnets will be required for each line. Power supplies could be common to both lines, and switched between the magnets as required. Close to the patient is the treatment "nozzle", a unit housing the degraders, diagnostic ion-chambers for dose-measurement, and possibly also the X-ray tube. To minimise costs, this will have to be rotated from one beamline to the other. A practical way of achieving this is to mount these devices in a single holder, which rotates around a strong supporting axis inclined at 30 degrees to the horizontal, indicated schematically in figure 3. The more expensive alternative would be to have duplicates, and to make them small enough not to clash with each other.

4 Vacuum System

To minimise scattering of the proton beam in air, the vacuum pipe should extend as far towards the patient as is practical. On the other hand, having the thin foil window – which might rupture – too close to the patient could be extremely dangerous. It appears to be best to place the exit foil window just before the second fast magnet. This also removes the need for a dangerously thin-walled vacuum chamber inside this fairly wide magnet, thus avoiding problems with eddy-currents which would restrict the achievable rise-time of the magnetic field.

5 Diagnostics

Beam diagnostic measurements for setting-up will be done using a standard NAC "harp" operating in the vacuum system immediately after the first fast switching magnet, and a gas-filled wire-chamber located immediately after the second fast magnet. These devices will be withdrawn during patient treatment. Ion-chambers in the "nozzle" close to the patient would give a rapid readout of the beam spot position and size at each successive scanning position.

At present it is proposed that the dose delivered at each scanning position be monitored in real time and used to stop the treatment at the end of each raster spot, as at PSI. A system which uses two independent monitoring computers would be required to control this.

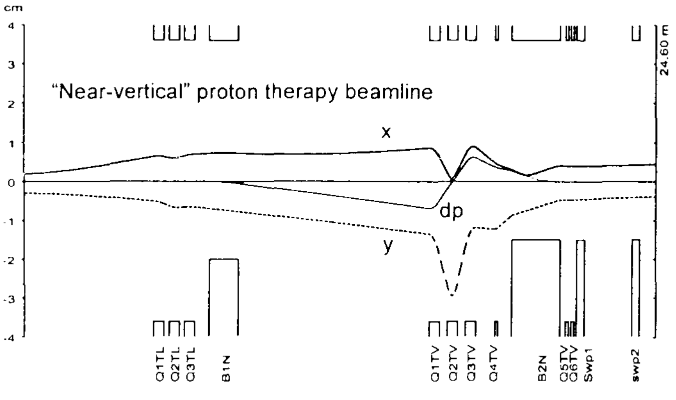

Figure 4: Beam profiles calculated with TRANSPORT for the beamline which will aim protons downwards at 30 degrees from the vertical. Dipoles are labelled B1N and B2N, while the two sweeper magnets are SWP1 and SWP2. The beam transport is achromatic from the switching magnet (far left) to the patient position (far right).

6 Modifications to Cyclotron and Beamlines

The requirements for beam quality, stability and repeatability are about an order of magnitude more stringent for spot-scanning than for scattering. As a consequence of the 9 energy changes per week which are now used at NAC [8], the magnetic field of the separated-sector cyclotron will not be stable enough for therapy using spot scanning, after an energy-change to 200 MeV, without some ongoing adjustment of the dee-voltage. Small but unacceptable changes in beam energy, direction and energy-spread would result. This problem will be tackled in the following way.

- We shall attempt to stabilise the SSC magnetic field by introducing NMR probes and an appropriate feedback system to the main power supplies of the sector magnets.
- A new, longer phase-probe will be installed in the extraction beamline, together with a more sensitive phase-measurement system.
- Automatic beam alignment will be introduced into the extraction beamline using existing "harps" and steering magnets.
- Energy measurement will be done on-line in the extraction beamline.
- Two pairs of horizontal and two pairs of vertical slits will be used in the new therapy beamline for emittance definition. (An alternative is a long copper collimator with various selectable apertures.)
- In order to improve the reaction time of the feedback system used to stabilise the beam position and angle in both existing and new therapy lines, we plan to install laminated steering magnets in both beamlines.

7 Fast Switch-Off

Between each spot in a spot-scan, the beam must be switched off to allow the scanning magnets to be stepped, and to reach stability at the new setting. The treatment time per spot can be of the order of 7 to 12 ms per spot, and the "off" time between spots should be significantly shorter. The existing pulse-selector inside the injection vacuum chamber of the SSC, which deflects the injected beam, is ideally suited to this task. It is presently used for switching the beam on and off during proton therapy, by means of a 1500 V DC voltage (in place of the RF plus DC combination which is used for pulse-selection). Electrically, the plates can be regarded as a simple 160-pF capacitor.

After switching off the beam in this way, the remaining particles circulating in the cyclotron continue to reach the patient position for a further 50 μs, i.e. only 0.6% of the 12 ms treatment time per spot, thus presenting no problem.

8 Present Status

The beam swinger has been dismantled, and the dipole magnets are being modified. This involves changing the entrance and exit edge-angles of the large 80-degree dipole, as well as the manufacture of new vacuum chambers. The field-measuring equipment used originally for the beam-swinger and the spectrometer magnets has been resuscitated and equipped with a new PC-based control system. A steel-girder support structure for the floor and beamlines has been installed in the vault and a floor has been fitted. Survey brackets have been positioned with respect to the beamline coordinate system. An industrial robot-arm has been purchased for control of the couch position.

While any target date must be regarded with caution, we aim to have this second proton therapy station commissioned during 1999 or early in the year 2000.

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