

Technical Description
of the
Clinical Neutron Therapy System

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The Clinical Neutron Therapy System (CNTS) at the University of Washington is a computer controlled cyclotron and neutron therapy treatment facility. It provides proton beams which are used to produce fast neutrons for cancer treatments, and proton as well as other charged particle beams for medical radionuclide production and for experiments in medical physics and radiobiology. The facility has been in operation since 1984.

The major components of the CNTS system are a Scanditronix MC50 cyclotron, an isocentrically mounted neutron beam generator, a fixed horizontal beam neutron generator, an isotope production station, beam transport system, beam diagnostics, hard wired safety system, vacuum and cooling systems and computer control system. A more detailed description of the control system is found in [1].

The general layout of the facility is diagrammed in Fig. 1.

1 Fast Neutron Production

The Seattle CNTS facility treats cancer patients with fast neutrons. Fast neutrons are neutrons with energies greater than several million electron volt per particle (MeV). Fast neutrons are always produced by a nuclear reaction. At the Seattle facility, a 50.5 MeV proton beam impinges on beryllium. In the resulting reaction the beryllium atoms disintegrate into neutrons, which are electrically neutral, and other fragments, which carry electrical charge (they contain the protons from the beryllium nucleus). The charged fragments have only a short range and are stopped within the target assembly; the neutrons are very penetrating and leave the target. They are then collimated and are used for the irradiation of cancerous tissue.

2 Cyclotron

2.1 Introduction

The Seattle facility utilizes a cyclotron to produce the proton beam necessary for the production of the fast neutrons. A cyclotron is a cyclic particle accelerator capable of accelerating charged particles to high energies (or velocities). The Seattle machine was built by SCANDITRONIX AB of Uppsala, Sweden. It can accelerate protons to 51 MeV, corresponding to approximately 87 percent of the speed of light. It can also accelerate other charged particles such as deuterons, alpha particles (${}^4\text{He}^{++}$ ions) and ${}^3\text{He}^{++}$ ions.

(Insert floor plan diagram that shows both floors)

Figure 1: General layout of the facility

Beam intensity is measured in particles per second. Particles from an accelerator are charged; a flow of charged particles is most conveniently expressed as an electric current. For a typical therapy run the proton beam current extracted from the cyclotron and transported to the target in the therapy head is in the order of $60 \mu A$. At 50 MeV particle energy, this corresponds to a beam power of 3 kilowatt.

In a cyclotron the accelerated particles travel in circles (or more accurately in spirals) as opposed to linear accelerators where they travel along a straight line. Linear accelerators are widely used for conventional radiation therapy; in this application they accelerate electrons which are either used directly for therapy or are converted into X-rays. Linear accelerators can also be used for heavy particles like protons or ions. A 50 MeV proton accelerator would be quite long, measuring several tens of meters. A cyclotron, being a circular machine, is more compact. This is an advantage in a hospital based facility, where space is usually restricted. Other cyclic accelerators are betatrons, microtrons, synchrocyclotrons and synchrotrons. Each of these types of accelerators has its special characteristics which determine its range of applications.

A cyclotron can only accelerate heavy charged particles (and not electrons, which become highly relativistic even at moderate energies).

A cyclotron consists of two major systems: a *magnet* and a *radio frequency (RF) system*. The magnet has the task of keeping the particles on circular orbits and to keep them focussed during the acceleration.

The radiofrequency system produces alternating electric fields which are used to give a series of kicks to the particles, accelerating them to higher and higher energies.

In addition there are other important systems:

The *ion source* is a device which produces the particles before they are accelerated by the RF system. The Seattle cyclotron is equipped with an internal ion source, located at the center of the machine. In other cyclotrons the source may also be installed externally and the low energy particles from the source are injected into the accelerator by an injection system.

When the particles reach their final energy they have to be guided out of the cyclotron by the *extraction system*.

The area in which the particle beam circulates is kept evacuated by the *vacuum system*. This is necessary to prevent the particles from being scattered by air molecules, in which case the beam would be dispersed.

The *beam diagnostic system* consists of a set of probes and current pickup electrodes and is used to measure important beam parameters within the cyclotron. It helps the operator to produce the required beam quality without damaging the machine.

The *cooling system* circulates deionized water through all components which need cooling.

Fig. 2 shows a general overview of the MC50 cyclotron.

Following is a short description of these subsystems with emphasis on the Scanditronix MC50 cyclotron installed at the CNTS in Seattle.

2.2 Magnet System

In a cyclotron the particles are kept on circular orbits by a magnetic field. The radius of the orbit is determined by balancing the “centrifugal force” acting on the particle with the Lorentz force.¹ This leads to the basic “cyclotron formula”:

$$p/q = BR$$

where

- p = momentum of the particle (m kg / sec)
- q = charge of the particle (Coulomb)
- B = magnetic field acting on the particle (Tesla)
- R = radius of the particle orbit (m)

As the particles are accelerated they gain momentum and the radius of the orbit increases. The particles start near the center of the machine and spiral in increasing orbits until they reach the extraction radius from where they are guided out of the accelerator.

On each orbit they cross electric field gaps where they get accelerating kicks from the RF system. In a cyclotron the RF frequency is fixed. In order for the particles to arrive at the accelerating gaps in synchrony with the RF field, the orbiting time has to remain constant throughout the acceleration. The accelerated particle’s apparent mass increases with velocity (a relativistic effect). Therefore, to achieve this isochronous situation, the magnetic field has to increase as a function of radius in order to compensate for the relativistic effect.

¹Stated more rigorously, the radius is determined by equating the Lorentz force with the centripetal force required for a circular orbit.

(Insert cyclotron cutaway view drawing)

Figure 2: The SCANDITRONIX MC50 cyclotron and its major components.

The magnetic field is created by an electromagnet (Fig. 2). It consists of a 90 ton steel yoke with the main coil, which is powered by a current of up to 900 ampere. This creates an average magnetic field of up to 1.8 Tesla between the 1.40 m diameter pole pieces.

The necessary increase of the field with larger radii is accomplished by proper shaping of the steel of the magnet, together with a set of ten concentric *circular coils* (CC) or *gradient coils* (also called *gradient correction coils* or *circular trim coils*). The coils are numbered from 1 through 10 with coil #1 near the center of the cyclotron and #10 on the outside. Each coil consists physically of two separate coils, one installed on the upper pole piece, the other exactly underneath, installed on the lower pole (Fig. 3). The current in these pairs of coils can be adjusted individually to achieve the desired isochronous field shape.

The magnetic field is not uniform in all azimuthal directions. The field strength varies as the particles progress along their circular orbits. This magnetic field “flutter” alternately focuses and defocuses the accelerating beam, resulting in an overall focussing effect which prevents the beam from spreading and hitting components inside the cyclotron, thereby getting lost. This *azimuthally varying field* (AVF) was introduced by Thomas [2] and dramatically expanded the energy range of early machines. All modern cyclotrons are therefore AVF machines.

In practice, the azimuthal field shaping is done by steel shims, called *hills*, where the pole gap is reduced and the field strength increased, separated by *valleys*. The SCANDITRONIX MC50 has three spiral shaped hills and three valleys (Figs. 2, 3, 4).

Located in the three valleys are four sets of *harmonic coils* (HC), also called *harmonic correction coils* (HRM CORR), which are designated with letters A – D. Each set consists of three coils in the three valleys of the lower pole and three coils in the valleys of the upper pole piece. All the coils of one set are located at the same radius from the machine center. They are excited by DC currents in such a way that their total contribution to the field is zero. They can then be used to correct the particle paths to help keep the orbits centered within the machine. Otherwise small field deviations can add up over the repeated turns of the particles and the orbits can get uncentered with a resulting poor beam quality.

Harmonic coils D together with circular coil #9 are used to excite coherent radial oscillations of the beam just inside the extraction radius. These oscillations can be adjusted such as to produce increased separation between the last orbit and the particles on the extraction path thereby facilitating extraction.

(Insert drawing of cross-section of cyclotron)

1. Pole piece
2. Hill
3. Harmonic Coils
4. Circular Coils
5. Copper Liner (grounded)
6. Dees
7. Ion Source
8. Ion Source Cathodes
9. Ion Source Chimney
10. Ion Source Window
11. Circulating Beam

Figure 3: Schematic cut through the center of the SCANDITRONIX MC50 cyclotron

(Insert drawing of hills, valleys, and harmonic coils)

Figure 4: Arrangement of magnetic hills and the four sets of harmonic coils in the magnetic valleys

2.3 Radio Frequency (RF) System

The RF system has the task of accelerating the particles. The energy which the particles obtain is supplied through the RF amplifiers which feed the accelerating structures within the cyclotron.

In early cyclotrons there were two accelerating electrodes which were formed like the two halves of a closed pill box, cut in half (Fig. 5). Because of their shape they were called *dees* and the name has remained even though the shape of the accelerating structures of modern machines can look quite different. The SCANDITRONIX MC50 has two wedge shaped dees with a tip angle of 90 degrees (see Figs. 2 and 6).

The particles are accelerated by the electric field at the edge of the dees. The polarity of the field is alternated such that a particle encounters an accelerating field each time it crosses a dee boundary. Inside the dee (and in the 90 degree dee system also between the dees) there is an electric field free area where the particles just coast.

Each of the dees of the MC50 cyclotron is driven by its own driver/amplifier system. A frequency synthesizer produces the selected RF frequency and feeds it into the two RF modulator units. After appropriate amplification and taking into consideration interlocks which assure safe operating levels, the RF signals get to the two driver amplifiers, which in turn control the grids of the two power tetrodes located at the cyclotron. Inductive loops couple the power from the anodes of the tetrodes to the tuning cavities which together with the dees form quarter wavelenth antennas. The cavities are tuned to the RF frequency by a mechanical moving short using the *coarse tune* servo motor systems. The *fine tune* servo motor system moves a grounded plate facing the dee, thereby changing the capacity and keeping the system in tune. The fine tune system compensates for small deviations of the coarse tune system as well as for other variations like temperature changes.

The total power consumption of the RF system is about 80 kW.

2.4 Particle Acceleration

A cyclotron can be operated in several harmonic modes. In the first harmonic mode the frequency of the acceleration voltage equals the revolution frequency of the particles, in the second harmonic mode the RF frequency is twice the revolution frequency and so on. In the Seattle MC50 cyclotron protons are accelerated in the first harmonic mode to final energies of 29 to 51 MeV corresponding to an RF range of 20 to 26 MHz. In the first harmonic mode the dees are operated in “push-pull” mode, indicating that at any given moment one dee has the opposite electric polarity from the other. Fig. 6 (with the accompanying text

(Insert drawing of early dees)

Figure 5: Dee configuration of early cyclotrons

in Table 1) illustrates how a particle is accelerated in this mode.

Using the second harmonic mode, deuterons can be accelerated to 14 – 24 MeV, ${}^3\text{He}^{++}$ ions to 21 – 35 MeV and ${}^4\text{He}^{++}$ ions to 28 – 48 MeV.

The description of particle acceleration given in Fig. 6 is correct for particles on the main orbit. Real beams always have spreads in angle and position of particles about the main orbit. The special shape of the magnetic field creates focussing forces which draw the particles towards the main orbit. As a result they oscillate around the main orbit both in radial and axial direction. There are also phase focussing forces which keep the particles together longitudinally (or in other words slow particles are accelerated more, such that they catch up, fast particles get accelerated less, with the end effect of keeping the particles together in bunches).

The final energy of the particles is determined by the extraction radius R and the RF frequency f . The velocity of the particles at extraction is $2\pi Rf$. This translates into kinetic particle energy using the relativistic formula

$$T = E_0(\gamma - 1)$$

with

$$\gamma = (1 - v^2/c^2)^{-\frac{1}{2}}$$

where E_0 is the particle rest mass (in energy units)

In order to accelerate a beam to this energy the RF frequency is determined. The magnetic field strength, the shape of the magnetic field and the dee voltage are then adjusted to give isochronous conditions and optimum extraction efficiency.

For a 50 MeV proton beam an RF frequency of 25.9 MHz is used, together with a dee voltage $U_{Peak} = 40kV$. This means the particles make about 440 turns during acceleration.

2.5 Ion Source

The Seattle cyclotron is equipped with an internal ion source located at the center of the machine (Figs. 2 and 3). The ion source delivers the charged particles which are accelerated.

Acceleration of a Particle in a Cyclotron

Acceleration of a particle in first harmonic mode in a cyclotron with 90 degree dees. This is the explanation for Fig. 6.

1. The positive particle enters dee #1 and is attracted by the negative potential of $-U_{Peak}/\sqrt{2}$. It increases its energy by $\Delta E = qU_{Peak}/\sqrt{2}$.
2. The particle coasts on a circular orbit (determined by the magnetic field) in the electrically field free region inside dee #1.
3. When the particle arrives at the edge of dee #1 the dee polarity has changed and the particle is accelerated again by the now positive potential $+U_{Peak}/\sqrt{2}$ between dee #1 and the grounded dummy dee.
4. The particle coasts in the field free region between the dees.
5. The particle arrives at dee #2 when the RF voltage of this dee is at $-U_{Peak}/\sqrt{2}$ and gets accelerated again.
6. The particle coasts inside dee #2.
7. The particle gets its 4th accelerating kick of this orbit when it leaves the now positive dee #2.
8. The particle coasts.
9. The cycle starts over again on the next orbit.

The overall energy gain per turn is $\Delta E = 2\sqrt{2}qU_{Peak}$. Note that in this mode of acceleration the phase between the dees is 180 degrees, they operate in push-pull mode. Similar diagrams can be drawn for the higher harmonic modes. In the even modes the dees are operated with 0 degree phase shift in push-push mode to achieve proper polarities for accelerating the circulating particles.

Table 1: Acceleration of a particle in a cyclotron

(Insert drawing showing dees and phases)

Figure 6: Acceleration of a particle in first harmonic mode in a cyclotron with 90 degree dees

The MC50 source is of the PIG type (short for Penning Ion Gauge) and operates in the following way:

Depending on the desired particle type the appropriate gas is delivered to the source via a needle valve (hydrogen for a proton beam, deuterium for deuterons, helium for alpha particles). The gas is then ionized in an electric arc similar to a fluorescent light. The arc discharge burns in a narrow vertical chimney. The discharge is started by applying a negative voltage (1000 to 1500 Volt) to two cathodes at the top and bottom of the chimney (see Fig. 3). Electrons are accelerated away from the cathodes towards the grounded wall of the ion source. Because of the magnetic field they cannot immediately reach the wall, instead they travel on spiral paths along the magnetic field lines up and down the chimney. They collide with gas molecules, ionizing them in the process. The ions are then extracted through the side of the chimney through a narrow slit or window (1×6 to 1×10 mm size) by the electric field from the dee tip, whenever the polarity of the dee is negative.

The cathodes in the Seattle source are of the “cold” style, meaning they are heated by the arc current flowing through them and by ion bombardment and not like in a “hot” cathode design where a heated filament is employed.

The power for the arc discharge is supplied by the *arc* power supply. This is a current stabilized supply and the operator can control the particle beam intensity by changing the arc current.

The geometry of the ion source and the surrounding central region of the cyclotron is very crucial for the proper operation of the machine. In order to have optimal conditions both for the first as well as for the higher harmonic modes, the SCANDITRONIX MC50 cyclotron is equipped with a dual ion source. There are two chimneys with the window of the $N = 1$ system facing dee #1 and the $N = 2$ system facing dee #2. All higher harmonic modes are run from the $N = 2$ chimney. The two chimneys have separate gas supply lines and the selection of the appropriate chimney is done via the gas inlet manifold.

2.6 Extraction System

One of the most difficult problems in a cyclotron for positive particles is the extraction of a useful beam out of the machine.

In the MC50 cyclotron the magnetic field is shaped (using circular coil #9) to produce what is called the “ $\nu = 1$ ” resonance at a beam radius of 57.0 cm. The expression “ $\nu = 1$ ” describes the case where the wavelength of the radial oscillations of the particles around the main orbit equals the circumference of the orbit. The oscillations then become coherent

with the orbiting frequency, resulting in an increase in oscillation amplitude.

This resonance increases the spacing between successive turns of the particles. A narrow copper *septum*, installed in the circulating beam, separates the particles in the last full orbit from the particles which are being guided out of the machine. In order to increase the orbit radius for the particles in the extraction path, an electric field is applied, followed by a region of reduced magnetic field strength.

The mean extraction radius of the MC50 cyclotron is 58.2 cm. This radius together with the RF frequency determines the energy of the particle beam.

The electric field for extraction is created by the negative (up to $-45kV$) *deflector* electrode installed behind the (grounded) septum (see Fig. 7). The septum shields the particles on the last orbit from the field, such that it acts only on the particles being extracted. The septum is rather fragile and can easily be burnt by excessive beam losses, which occur when the beam strikes the septum wall. A thermocouple is used to monitor its temperature, and the beam is turned off if the temperature gets too high.

Following the electrostatic deflector is the *electromagnetic channel* (EMC), consisting of a magnet coil which is powered such as to reduce the magnetic field from the main coil. In the MC50 cyclotron the current running through the main coil is combined with the current from the EMC power supply to feed the EMC coil with a total current of up to 1200 Ampere.

The mechanical position of the deflector/EMC assembly can be adjusted under remote control using three servo motor units (DFLENT, DFLEXIT, EMCEXIT).

After the EMC two passive mild steel *focussing channels* give the beam the desired focussing properties and an electromagnetic steering magnet (*internal steering magnet*, ISM) helps bring the beam onto the axis of the beamline emerging from the cyclotron.

With a well adjusted set of cyclotron parameters it is possible to extract between 60 and 85 percent of the internal beam and transport it down the beam line. This extraction efficiency varies with the type of particle and the particle energy.

2.7 Vacuum System

The area inside the cyclotron where the beam circulates is under vacuum to prevent the beam particles from being scattered by gas molecules. The vacuum is created by two pump groups, PG1 and PG2, located on opposite corners of the machine (Fig. 7).

(Insert cyclotron layout print)

Figure 7: MC50 cyclotron layout showing extraction elements, beam probes, RF and vacuum system

Apart from the control system, the vacuum system together with the associated part of the cooling system is the only part of the facility which is running continuously. It would take too long to obtain good vacuum if the system was shut down overnight.

Vacuum is not only maintained in the cyclotron itself but also in the beam lines. While the beam line pumps are smaller in size, the general arrangement of the pump groups is always the same (Fig. 8).

The vacuum pump groups are comprised of a combination of two pumps, a *mechanical pump* (MP) and an oil diffusion pump (DP). These two pumps complement each other. The mechanical pump cannot produce the high vacuum necessary for the operation of the accelerator, but can pump against atmospheric pressure on its exhaust side. The diffusion pump can pump the tank to 10^{-6} mbar but requires a backing pressure of less than 0.5 mbar.

The mechanical pump is used for the initial pump down of the system to the point where the diffusion pump can take over. This is the purpose of the bypass line. In this mode, the mechanical pump acts as a roughing pump. After the bypass line is closed, the mechanical pump acts as a backing pump for the oil diffusion pump.

Pump group PG2 is not equipped with a bypass line. The roughing of the cyclotron is entirely done by PG1 which has a large mechanical pump.

A water cooled baffle reduces backstreaming of oil vapors from the diffusion pump into the vacuum tank. Medium vacuum and high vacuum gauges monitor the performance of the system.

2.8 Beam Diagnostic System

In order to monitor the particle beam inside the cyclotron several beam diagnostic sensors are provided (Fig. 7).

The *main probe* is a motor driven rod which can be inserted into the machine and goes in to 17 cm radius. It intercepts the beam, which is stopped on the Tantalum probe tip. The main probe has a dual tip, the first part intercepts a portion of the circulating beam 1 mm wide, the second part stops the rest. The current striking each portion of the tip is measured by a *beam current amplifier* (BCA) and is displayed at the cyclotron control console.

The main probe can for instance be used to check the isochronism of the beam. A proper

(Insert diagram of vacuum pump group)

Figure 8: Schematic diagram of a vacuum pump group

beam has the same intensity independent of radius, indicating that no beam is lost during acceleration.

The *deflector probe* is similar to the main probe, but has a shorter range. It is used to measure the beam intensity of the last orbit and the intensity of the beam on the extraction path after it has passed the electrostatic deflector and the septum. This probe has a single Tantalum tip.

The beam probes cannot absorb the full beam power. For diagnostic purposes, the beam is run at lower currents to reduce the power.

At the entrance of the EMC, the Focussing Channels and the Internal Steering Magnet electrically isolated graphite pickups are installed. They intercept the outer fringes of the beam, which are not very useful anyway. These pickups are also connected to beam current amplifiers with readouts at the cyclotron control console. The currents are indications of the beam quality and can help to center the beam on the extraction path.

In order to produce a useful beam from the cyclotron the operator monitors probe currents and losses on the pickups. Additional information is available from diagnostic elements in the beamline outside the cyclotron. The operator adjusts coil currents, the deflector voltage, mechanical deflector positions and RF parameters to optimize the beam intensity and minimize losses in the machine. This activity is called *tuning* the cyclotron and the beam lines. A major function of the control system is to provide the operator with the means to tune the system from the *control desk* (CD), sometimes also called the cyclotron control console.

2.9 Cooling System

Cooling water is circulated through all the components which heat up during operation. This includes magnets heated by the current in the coils, the dees and other RF carrying structures, the ion source, where the arc burns and components such as the septum and the probe tips which are exposed to the particle beam. Most of the cooling system only needs to operate when the system is turned on, ready to produce beam. The cooling for the vacuum pumps has to be operational continuously. This part is supplied by a separate loop, the *24-hour loop*, which is running all the time (Fig. 9).

The cooling system also cools components along the beam line and in the therapy units. It also removes heat from air conditioning units in the Cyclotron Vault and in the Power Supply Room. The CNTS facility has its own dedicated cooling tower to handle the 500 kW cooling load. The capability of a cooling tower depends on outside weather conditions,

in particular on the wet-bulb temperature. In order to adapt to the limitations of the tower, the cooling system has its own (pneumatic) control system which keeps the temperature of the *primary cooling water*, circulating through the cyclotron and beamline equipment, at a constant temperature of 20 degree C in winter and at 25 degree in summer. This is accomplished by modulating the 3-way valve in the *secondary cooling water* system. The temperature of the 24-hour loop for the diffusion pumps is further reduced by a *chiller unit* such that its temperature is about 4 – 5 degrees cooler than the primary loop.

The primary cooling water is deionized for two reasons. It is necessary for water that is in contact with high-voltage components such as the deflector to be a good insulator. Also, the water must be free of elements such as sodium which would become radioactive. The secondary cooling water is not deionized, but contains glycol to inhibit freezing.

3 Beam Lines

After the beam leaves the cyclotron it is transported to various target stations, depending on its use. This is done by the beam line system (Fig. 10). It basically consists of a set of evacuated pipes, of about 60mm diameter, equipped with beam control and monitoring devices.

Following is a short description of the various components installed along the beam lines. Most components are repeated in several locations as similar functions are required along all beam lines.

3.1 Vacuum Pump Groups (PG) and Beam Line Valves (BLV)

The vacuum in the beam line system is maintained by six pump groups, separated by *beam line valves*. This ensures good vacuum (a few times 10^{-6} mbar) in all parts of the lines and facilitates maintenance, as the system can get shut down in sections. The *beam exit valve* (BEV) separates the cyclotron from the switching magnet pump group. For a schematic diagram of a group see Fig. 8.

3.2 Fast Valve (FV)

If an accident occurs in the isotope production line (break of an entry foil of a gas target) a fast valve sensor in this line triggers the fast valve near the exit of the cyclotron. This

(Insert diagram of cooling system)

Figure 9: Cooling system

(Insert beam line diagram)

Figure 10: Layout of the beam line system

valve closes within 25 milliseconds and protects the cyclotron from the fast pressure rise and potential debris.

3.3 Steering Magnets (STMG)

Steering magnets are used to make small corrections in the direction of the beam, in order to get it centered on the beam line axis. For instance the internal steering magnet (see under extraction system) together with the first steerer (X0) in the beam line is used to line up the beam on the axis of the first beamline section. Steerers are provided for corrections both in the horizontal plane (left/right or x-direction) and in the vertical plane (up/down or y-direction).

3.4 Quadrupole Lenses (Q)

Magnetic quadrupole lenses are used to focus the particle beam much like a light beam is focussed by optical lenses. Quadrupoles are used in sets of three called a *triplet* configuration. In the case of quadrupole #1 (Q1) and the gantry quadrupole (QG) all three parts of the lens (LENS 1, LENS 2, and LENS 3) can be controlled separately, in all other cases (Q2A, Q3A, Q2B and Q3B) lens 1 and 3 are electrically run in series and are controlled as one unit (LENS 13).

3.5 Stray Beam Detector (SBD)

Stray beam detectors are electrically insulated graphite donuts installed at strategic locations along the beamline. They have several functions. The beam tends to have “tails”, particles that travel close to the main portion of the beam but are too far out to be of use. They are intercepted by the stray beam detectors which have center hole diameters chosen to just let the useful beam pass. The beam arriving at the target stations is then free of unusable components. The beam losses on the stray beam detector can be measured and displayed at the control desk. This current is an indication of beam shape and beam position.

The monitoring of the currents from the stray beam detectors is again done in the beam current amplifier units. Apart from amplifying the signals to useful levels and transmitting them to the control desk, the BCA also contains current level monitors which trip if the current on a stray beam detector exceeds a set limit. The BCA then turns off the beam.

This protects the beam line equipment from being damaged by a poorly steered or focussed beam.

The stray beam detectors are part of the beam diagnostic system.

3.6 Beam Profile Monitor (BPM)

Beam Profile Monitors, sometimes also called Beam Scanners are used to obtain information on the beam shape. They consist of a rotating wire loop which moves through the beam. The beam particles knock out secondary electrons from the wire. This current signal is a measure of the beam intensity at that point. It is amplified and displayed at the control desk on an oscilloscope. The oscilloscope trace then shows the beam intensity as a function of the wire position and a well centered beam without tails appears as a Gaussian curve. The geometry of the wire loop is such that it crosses the beam at different times both in the horizontal (x) direction and in the vertical (y) direction providing information in both dimensions.

The operator adjusts parameters to obtain the proper beam shape and position at various positions along the beam line while tuning the line. The beam profile monitors are part of the beam diagnostic system.

3.7 Faraday Cup (FC)

A Faraday cup is a beam stop which can be inserted into the beam line to intercept the beam. It is used to prevent the beam from continuing down a beam line if that portion of the line is not ready to accept it, and also to measure the intensity of the beam. For instance Faraday Cup 1 (FC1) can be inserted to monitor the beam from the cyclotron in order to tune it, while a patient is being prepared in one of the treatment rooms.

The Faraday cups are built to withstand the full beam power of up to 3.5 Kilowatts. For this purpose they are water cooled. The portion of the cup exposed to the beam is made out of graphite. Graphite can withstand the heat, and it also does not become unduly radioactive from the bombardment. The 50 MeV proton beam penetrates about 13 mm into the graphite. Over this distance the protons get slowed down, primarily by collisions with the electrons of the carbon atoms, until they are stopped. Electrons flow into the cup to balance the protons that are stopped there, giving rise to a current. The Faraday cups are electrically insulated from the rest of the equipment, and the current can be measured via a wire hooked up to a beam current amplifier unit.

The Faraday cups and the beam current amplifiers are part of the beam diagnostic system.

3.8 Switching Magnet (SWM, SWTMAGN)

The switching magnet is used to direct the beam to either the *isocentric treatment room* (line A), into the *zero degree line* (at present not installed) or into the *fixed beam treatment room* (line B).

3.9 Bending Magnet (BENDMAG)

The bending magnet (also called 48 degree magnet) can divert the beam from the fixed beam line into the *isotope line* (line C) where the production station for radionuclides is installed.

3.10 Nuclear Magnetic Resonance Unit (NMR)

As a result of hysteresis or changes in the thermal environment, it may be necessary to alter the current flowing to a magnet in order to establish or maintain the correct magnetic field which will optimize the beamline tune. This is especially important for the switching magnet and bending magnet, where the fields must undergo large and rapid changes in order to switch the beam into the intended beam line.

Utilizing the interaction between the magnetic field and the nuclear magnetic moment of protons in the sample of a probe, an NMR magnetometer is able to measure the magnetic field in the uniform field region of a magnet and regulate the output of the magnet's power supply to produce the desired field strength.

An NMR unit can be used to regulate the field in either the switching magnet or the C line bending magnet.

3.11 Isotope Production Station

The isotope production station at the end of the C line is remote controlled from the isotope laboratory adjacent to the cyclotron facility (not shown in Fig. 1).

3.12 Beam Plugs (BP)

The beam plugs are removable radiation shields mounted in the shielding walls between the cyclotron vault and the treatment rooms. They shield the treatment rooms from stray radiation from the vault. This allows beam operation in the vault while setting up a patient. The beam plug is a wedge of polyethylene and steel. It can be opened by pulling the wedge up along a sloped rail to let the beam pass underneath. It is not meant to stop the particle beam and is therefore not cooled. The particle beam must be stopped on a Faraday cup when the plug is closed.

3.13 Beam Line Elements in the Isocentric Gantry

The beam line extends through the arm of the isocentric gantry to the beryllium target in the head (Fig. 11). The bends in the particle path are achieved with the *gantry dipole* (GTYPDOL) which is made up of two parts, the 70 degree magnet and the 160 degree magnet. They are electrically run in series. A correction coil (GTYCORR) on the 70 degree magnet is used to balance the two magnets. A quadrupole triplet (*gantry quadrupole*, QG) focusses the beam and a steerer (XG/YG) is used to center the beam on target. In the XG/YG steerer a 100 Hz AC component (parameter names XWG/YWG) is added to the DC steering current. This causes the beam spot to describe a circle on the target thereby spreading the thermal load and insuring a uniform distribution of the proton beam. This portion of the magnet is called the *wobbler* or *spinner*.

A graphite stray beam detector in the gantry arm (SBD-G), a tantalum stray beam detector in front of the target (SBD-T) and a set of four copper quadrants (UP, DOWN, LEFT, RIGHT), which monitor the beam position at the target entrance, complete the beam line components of the gantry arm.

3.14 Beam Line Elements Connected to the Fixed Beam Treatment Unit

The final steering of the beam onto the fixed beam target is done by steering magnet XF/YF immediately after the fixed beam plug. This magnet has the same role as the gantry steering magnet XG/YG in the isocentric gantry and is also excited with a superposition of a DC current for steering and a 100 Hz AC current for wobbling.

(Insert isocentric gantry diagram)

Figure 11: Isocentric gantry including treatment head

4 Isocentric Treatment Unit

4.1 Introduction

The isocentric treatment unit (Figs. 11, 12) allows patient treatments with beams coming from different directions. The radiation source, in this case the beryllium target, is mounted on a gantry arm, which can be rotated around the patient. The arm carries the treatment head to which the collimation system is bolted. The arm, head and collimator weigh approximately 11 (metric) tons, the whole rotating assembly, including the counterweights, weighs about 39 tons. The point where the gantry axis and the collimator axis intersect is called the isocenter. This is typically where the tumor within the patient is positioned. The isocenter (as well as the cyclotron midplane and the beamlines) is located 120 cm above the floor. The “Isocenter Distance” or “Source to Axis Distance” (SAD) between isocenter and beryllium target is 150 cm.

During the treatment the patient is lying on the treatment couch, very rarely sitting in a treatment chair. The couch (or chair) is attached to the *patient support assembly* (PSA), which is motorized and which allows the patient to be positioned with an accuracy of 1 to 2 mm.

The isocentric gantry is capable of rotating full 360 degrees. Because of the size of the gantry, a 3 m deep pit is necessary underneath the treatment couch, to allow irradiations from below. For access and safety reasons this pit is covered by a *moving floor*. It consists of two independently movable halves, driven by electric motors, which can be pulled out of the way automatically to let the gantry enter the pit (see Fig. 14).

4.2 Treatment Head

The treatment head is diagrammed in Fig. 11.

4.2.1 Target

The neutron beam is produced by bombarding the beryllium target with 50.5 MeV protons. The Seattle facility uses a “semi-thick” target, in which the protons are slowed down to half their initial energy in the cylindrical beryllium piece and then are stopped in a copper backing. This requires a beryllium thickness of 10.5 mm. The diameter of the beryllium cylinder is 12.7 mm, just slightly larger than the proton beam diameter of 10 mm, defined

(Insert isocentric treatment room illustration)

Figure 12: Isocentric treatment room showing gantry, patient support assembly and mobile pedestal

by the quadrant opening at the target entrance. The copper stop is 3 mm thick and has cooling water passing over its downstream surface.

All protons are stopped in the target assembly. The neutrons, created in nuclear reactions with the beryllium, leave the target primarily in the forward direction. In addition gamma rays are produced. They are also penetrating and are part of the therapy beam. Between 4 and 12 percent of the dose delivered to the patient is from gamma radiation.

The target assembly and other parts of the equipment exposed to the proton or neutron beam become radioactive. The gamma and beta radiation from this activity is present even after the beam has been turned off. This results in radiation exposure to personnel working with the equipment either for therapy or maintenance. The equipment and the building were designed to reduce this exposure and appropriate working procedures have been implemented.

4.2.2 X-ray Drawer

Immediately downstream of the target the so-called X-ray drawer is located. It consists of a massive steel block which can slide in a direction perpendicular to the beam axis.

The X-ray drawer can be moved to three positions: SAFE, TREAT and X-RAY. In the SAFE middle position a lead block is moved in front of the target to reduce the amount of gamma radiation coming from the target area when the beam is off. In the TREAT position the *primary collimator* is positioned in front of the target. In the X-RAY position an X-ray tube is positioned on the beam line axis.

The X-ray drawer is moved automatically into the TREAT position at the beginning of each treatment and back to SAFE at the end.

4.2.3 Primary Collimator

The primary collimator is a cone-shaped aperture immediately downstream of the target, which roughly collimates the neutrons emerging from the target in the forward direction. It reduces the intensity of the outer part of the beam which is not used for therapy.

4.2.4 Flattening Filter

Immediately after the primary collimator, and still installed on the X-ray drawer block, the *flattening filter* assembly is located. The flattening filter assembly consists of a set of steel absorbers, which absorb more of the center portion of the beam, thereby flattening the dose distribution across the treated area.

There are three possible filter conditions: no filter, small field filter and large field filter, which are chosen to give optimal conditions for a particular treatment.

4.2.5 X-Ray Tube

An X-ray tube can be positioned downstream of the Beryllium target on the beam line axis. It is used to approximately simulate the neutron beam geometry with X-rays for verification of the treatment setup. A film is exposed through the patient and the treatment field outline can be verified against anatomical landmarks.

The neutron beam cannot be used directly for this purpose because neutrograms do not give enough anatomical detail. There can be discrepancies between the neutron beam and the X-ray picture because the X-ray tube is not located exactly at the target position. This has to be taken into account when interpreting the X-ray film. In critical cases a neutrogram, showing the field outline can be superimposed on an X-ray image, showing the anatomy.

4.2.6 Ion Chamber

A transmission ion chamber follows the x-ray drawer. The neutrons (and gamma rays) pass through this chamber on their way to the patient. The chamber measures the intensity of the beam. It is connected to an electrometer system which integrates the signal. The whole system is called the *dosimetry system*. It is calibrated and is used to determine the dose delivered to the tumor and surrounding tissue. For safety reasons the dosimetry system is split into two completely independent systems with dual chambers, power supplies, electrometers and means to terminate the treatment.

The ion chamber is the last fixed unit in the head. All components downstream of the chamber rotate together with the collimator around the beam axis.

4.2.7 Wedge Filter System

A set of three wedge shaped tungsten blocks is mounted on the Wedge Turret. Inserted into the beam they absorb the neutrons unevenly, creating sloped dose distributions if this is desired. Only one wedge at a time is used and there is a NO WEDGE option. The wedges can be rotated and their orientation with respect to the treatment field can be at any of the four cardinal angles (or in other words the heel of the wedge can be towards the upper, lower, left or right edge of the treatment field).

4.2.8 Beam Defining Lamp

A light bulb is used to project an outline of the treatment field onto the skin of the patient. It is located at the same level in the treatment head as the wedges and is displaced sideways. A mirror brings the light source on the beam axis. The optics are arranged such that the apparent origin of the light coincides with the beryllium target.

4.2.9 Multileaf Collimator

The purpose of the collimation system is to absorb the neutrons not wanted for the irradiation of the tumor. Radiation to the surrounding healthy tissue is eliminated or reduced and complications from the treatment are minimized. The collimator opening is shaped to match the size and form of the *target area* within the patient. In the Seattle multileaf collimator this shaping is achieved by a set of 40 steel leaves which are individually motor driven (Fig. 13). The individual leaves are 650 mm long and have some polyethylene inserts as added neutron absorbers. The center leaves are narrower, corresponding to a width of 12.5 mm at the isocenter distance. The outer leaves have a width corresponding to 20 mm. The collimator can be set automatically via the *Leaf Collimator Controller* (LCC) or manually via switches mounted on the unit itself.

4.2.10 Glass Stop

The glass stop, also called the *gamma shutter*, is a 40 mm thick lead glass plate that protects people from residual gamma radiation from the collimator and head. During the treatment it is moved out of the way.

(Insert collimator diagram)

Figure 13: Multileaf collimator

4.2.11 Source to Surface Distance Projector (SSD)

An optical system projects a distance scale at the beam axis. The scale is visible on the skin of the patient and is used for proper positioning.

4.2.12 TV Cameras

Two closed circuit TV cameras are mounted on the outside of the collimator and are used by the radiation technologists to monitor the treatment area during the treatment from their console outside the treatment room.

4.3 Patient Support Assembly (PSA)

The treatment couch or Patient Support Assembly (Figs. 11, 12) has the task of precisely positioning the patient. It is normally equipped with a couch top, but a treatment chair can be fitted if needed.

The PSA is capable of all necessary motions:

- couch HEIGHT
- couch LATERAL translation
- couch LONGITUDINAL translation
- couch ROTATION (around a vertical axis through the isocenter)
- couch TOP rotation (around the support pillar).

The vertical support pillar is also called the *ram*. Apart from the top rotation all motions are motorized and can be controlled either from a local hand pendant or through the *Treatment Motion Controller* (TMC).

4.4 Moving Floor

The moving floor covers the 3 m deep pit underneath the gantry when the head is above floor level and it closes gaps around the gantry as far as possible during times when the head

is below the treatment couch. The floor is divided into two independent halves constructed of linked wooden slats with carpeting on top. As each half opens up the unused part of the floor is stored in a loop in the pit (Fig. 14). In order to allow the patient support assembly to rotate around its vertical axis through the isocenter, the floor is supported on one side of the pit by two rails which can be retracted to let the PSA support ram pass through.

4.5 Auxiliary Treatment Room Equipment

The *mobile pedestal* (Fig. 12) is a small local control console which can be rolled around in the treatment room and which is used to locally control the equipment. It has two hand pendants attached to it, one to control the motions of the gantry and PSA, the other for the moving floor.

A large electronic wall display in the treatment room shows the current numerical value (e.g., in cm or degrees) of the gantry and collimator rotations and the PSA motions.

A patient alignment laser system projects a set of lines which intersect at the isocenter and are used for precise positioning.

A room TV camera is used to observe the patient during therapy.

A patient intercom allows the patient to talk to the technologists at the therapy console during the treatment.

5 Fixed Beam Treatment Unit

The fixed beam treatment unit does not have a rotating gantry. Instead the head is fitted to the end of a horizontal beam line. The fixed beam head assembly is an exact duplicate of the isocentric unit, providing the same rotational capabilities for wedges and the attached collimator. There is no leaf collimator installed on the fixed beam unit. The collimator consists of a main shielding assembly into which interchangeable cones for different square field sizes can be inserted. As this arrangement is clearly not as versatile as the isocentric gantry with the leaf collimator, the fixed beam unit is only used for experimental physics and radiobiology setups.

(Insert moving floor diagram)

Figure 14: Moving floor

6 Shielding Doors

There are two concrete shielding doors which control access to the rooms where radiation is present: the vault door and the treatment room door (Fig. 1). They are hydraulically driven and run on railroad tracks. No people are inside a room with the beam turned on, with the exception of the patient during therapy. The beam can only be turned on in a room if the door is closed. There is only one therapy door for both treatment rooms because the beam is sent to only one room at a time. A system with doors was chosen over a system with access mazes because of the limited space available.

7 Control room

The control room (Fig. 1) contains the cyclotron control console (also called the control desk, CD) and two therapy control consoles (also called treatment control desks, TCDA and TCDB), one for each treatment room. Both treatment rooms are reached by passing through the control room.

8 Power supply room

A room on the (second) floor above the control room (Fig. 1) contains all the power supplies. In addition, this room also contains all the control computers, including the main control computer, the Programmable Logic Controller (PLC) that controls the vacuum and cooling systems and some other devices, the relay rack containing the hardwired safety interlock system (HSIS), the auxiliary control computers provided by Scanditronix including the Leaf Collimator Controller (LCC), Treatment Motion Controller (TMC) and Dose Monitor Controller (DMC), and the control electronics for the Elven equipment. The power supply room also contains the Scanditronix I/O cabinets that contain the input/output cards that interface signals to the main control computer. In addition the floor controller system and the main power switchboards are located in this room.

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