

March 2010

ANSTO/E-770

**AUSTRALIAN NUCLEAR SCIENCE & TECHNOLOGY ORGANISATION**  
**LUCAS HEIGHTS RESEARCH LABORATORIES**

**PRELIMINARY DETAILS OF A LIGHT ION FACILITY FOR HADRON THERAPY  
AND RESEARCH**

by

J. W. Boldeman, R. Banati, H. Buttner, D. Cohen & R. L. Garrett

**ABSTRACT**

*A proposal is being prepared for the construction of high-performance accelerator complex for radiation therapy and research. The accelerator will be capable of producing proton beams between 60 and 250 MeV and carbon beams with energies variable from 120 – 430 MeV/amu. This paper presents some of the background material supporting the proposal. Also included are some of the preliminary technical details of the accelerator complex and the transfer beam lines to the various treatment locations and experimental stations.*

ISSN 10307745  
ISBN 1921268093

## Contents

|   |    |
|---|----|
| 1. Introduction.....  | 3  |
| 2. Physics Principles in Hadron Therapy.....  | 4  |
| 2.1 Interaction Rate.....   | 5  |
| 2.2 Linear Energy Transfer.....   | 6  |
| 2.3 Lateral Deviation of Hadron Beams.....  | 7  |
| 2.4 Summary.....  | 8  |
| 2.5 Examples.....   | 8  |
| 3. Patient Numbers.....   | 10 |
| 4. Scientific Applications of a Hadron Therapy Facility.....                                  | 11 |
| 4.1 New Technologies.....   | 11 |
| 4.2 Radiobiological Research.....   | 12 |
| 4.3 Clinical Research.....  | 12 |
| 4.4 Basic Research.....   | 12 |
| 4.5 Atomic Physics.....   | 13 |
| 4.6 Detector Development.....   | 13 |
| 5. Procedures in the Construction of the Australian Hadron Research and Therapy Facility..... | 13 |
| 5.1 Specifications of the Australian Hadron Therapy Facility.....                             | 14 |
| 5.2 The Physics Design of the Australian Hadron Therapy Facility.....                         | 14 |
| 5.3 Details of the Accelerator Complex.....   | 15 |
| 5.3.1 Injection System.....   | 16 |
| 5.3.2 Synchrotron.....  | 17 |
| 6. Transfer and Transport Lines.....  | 21 |
| 6.1 Matching Section.....   | 21 |
| 6.2 Beam Size Module.....   | 23 |
| 6.3 Extension Module.....   | 25 |
| 6.4 Horizontal Beamline Facility.....   | 26 |
| 6.5 Vertical Facility.....  | 27 |
| 7. Treatment Facilities.....  | 28 |
| 7.1 Associated Facilities.....  | 29 |
| 7.2 Buildings.....  | 29 |
| 7.3 Construction Staff.....   | 29 |
| 8. Alternatives and Costs.....  | 30 |
| 9. Advisory Committees.....   | 31 |
| 10. Conclusion.....   | 31 |
| 11. Acknowledgements.....   | 31 |
| 12. References.....   | 31 |
| Appendix I PARTICLE THERAPY FACILITIES IN OPERATION (PTCoG).....                              | 33 |
| Appendix II Principal Diseases Treated with Protons at Loma Linda Medical Center.....         | 35 |
| Appendix III Number of Patients treated with Carbon Ion Therapy at NIRS, Japan.....           | 36 |
| Appendix IV Evaluation of Cancer Types in ECM expected to benefit from Hadron Therapy.....    | 37 |
| Appendix VI - Committees.....   | 39 |

# Preliminary Details of a Light Ion Facility for Hadron Therapy and Research

By J.W. Boldeman, R. Banati, H. Buttner, D. Cohen and R.F Garrett

## *Abstract*

*A proposal is being prepared for the construction of high-performance accelerator complex for radiation therapy and research. The accelerator will be capable of producing proton beams between 60 and 250 MeV and carbon beams with energies variable from 120 – 430 MeV/amu. This paper presents some of the background material supporting the proposal. Also included are some of the preliminary technical details of the accelerator complex and the transfer beam lines to the various treatment locations and experimental stations*

## **1. Introduction**

Australia has few landmark scientific research facilities in comparison with similar and even some smaller G20 countries. Current landmark facilities include the Australian Synchrotron, the research reactor, OPAL, and several radio telescopes. One landmark facility which is being introduced in many countries is a High Energy Light Ion Facility for Hadron Therapy and Research.

Cancer is a major burden on the Australian community - 1 in 3 men and 1 in 4 women in Australia will be directly affected by cancer during their lives. In 2005 for the very first time, the number of new cancer cases reported exceeded 100,000. The following year, it was estimated that there were 106,000 new cases of cancer diagnosed in Australia (60,600 males and 45,400 females). Cancer is the leading cause of death in Australia with over 36,000 people succumbing each year, in spite of a 30 percent improvement in survival over the last two decades. Cancers most commonly causing death are lung, prostate and colorectal in males and breast, lung and colorectal in women.

Although there are many kinds of cancer affecting different organs in the body, they all are caused by uncontrolled growth of abnormal cells. In a healthy individual, cells grow, divide, and die in a highly regulated fashion. During childhood, healthy cells grow and divide very rapidly until the individual becomes an adult. At this stage, cell growth slows until in most parts of the body, cells only divide to replace worn-out or dying cells and repair injuries. Cancer cells often travel to other parts of the body where they begin to grow and replace normal tissue. This process, called metastasis, occurs when cancer cells find their way into the bloodstream or lymphatic system of our body.

Cancer can be considered in two classes from the viewpoint of attempting to treat the patient

- Generalized cancer where the cancer has spread from the original infested area to other parts of the body
- Localised Tumours.

Based on European Union data, the proportion of generalised cancers, when detected, constitutes about 42% of all cases. Of these, the mortality rate is about 88%. The two treatment regimes are surgery and chemotherapy although radiotherapy has value for palliative care. The remaining 58% comprise localized tumours where a variety of treatment regimes including surgery, chemotherapy and radiation treatment result in prolonging patient life by more than 5 years in 57% of cases. However, the morbidity is still very high and

patient outcomes even with survival often leave the patient with some unpleasant physical consequences.

Improvements in radiotherapy over the last 20 years or so have contributed to increased survival but clearly there needs to be a major advance in treatment methods. Hadron Therapy (with protons, carbon ions) fills this gap and a large number of centres have been built in recent years or are under construction. Already more than 70,000 patients world-wide have been treated using this new method. **Appendix I** from reference 1 lists facilities currently in operation and their patient numbers to 2007. Also included in **Appendix I** is a list of new centres either under construction or in advanced planning.

The physical advantages that ion beams have over X-ray (photon) beams was first pointed out in 1946 by Robert Wilson (2) although this had little impact on the medical community at the time. The first application of charged-particle beams took place at Lawrence Berkeley in 1954 and, after a long period of low-level investment, major development of the technique began with the installation of dedicated hospital facilities at Loma Linda and Massachusetts General Hospital.

The first proposal to construct an Australian Proton Therapy facility was prepared in May, 2001 (3) as a discussion paper under the auspices of the Australian national Proton Facility Steering Committee. No specific facility was proposed and it was believed if support were achieved a commercial facility would be built at some unspecified location. Although the discussion paper solicited considerable interest no funding was obtained. The proponents continue to be active in promoting the technique.

A subsequent attempt to seek funding for a combined carbon-proton facility was launched at the 15<sup>th</sup> Pacific Basin Conference on Nuclear Power (4). This led to the establishment of a committee seeking private investment funds however because of the global financial crisis the private investment disappeared. This proposal differed from the original in that it was proposed that the facility be constructed using Australian resources. This philosophy has been retained in this third proposal.

Hadron Therapy facilities may be classified into three generations. The first generation comprises high energy nuclear physics facilities that have been adapted to provide beams for therapy. The second generation comprises specialist constructed facilities specifically for therapy purposes. These facilities are based entirely on the use of proton beams and are often sited in dedicated commercial operations. In recent years, research and treatment in Japan and in Germany have shown significant benefits for both proton and carbon beams. This has led to the construction in Europe and Japan of high performance facilities providing both proton and carbon beams. This new class may loosely be described as third generation facilities.

## **2. Physics Principles in Hadron Therapy**

Hadron Therapy is particularly suitable for the treatment of deep-seated tumours that are located near to critical organs and which respond poorly to conventional X-ray (photon) or electron radiotherapy. Because of the significantly reduced dose to healthy tissues during a typical treatment it is especially appropriate for tumours in children. In this expanding technology, beams of light nuclei (variously called in the literature light ions, hadrons but essentially either protons or carbon ions) are accelerated to very high energy and then used to target the specific tumour. Hadron Therapy is the modality of choice for the treatment of these

cancers because of the high level of control over the ion beam and because of the favourable ionisation distribution in the path length of that beam, in effect, the tumour killing capability of the ion beams. These qualities give hadron beams a fundamental edge over the best examples of conventional X-ray radiation treatment (5 - 9).

## 2.1 Interaction Rate

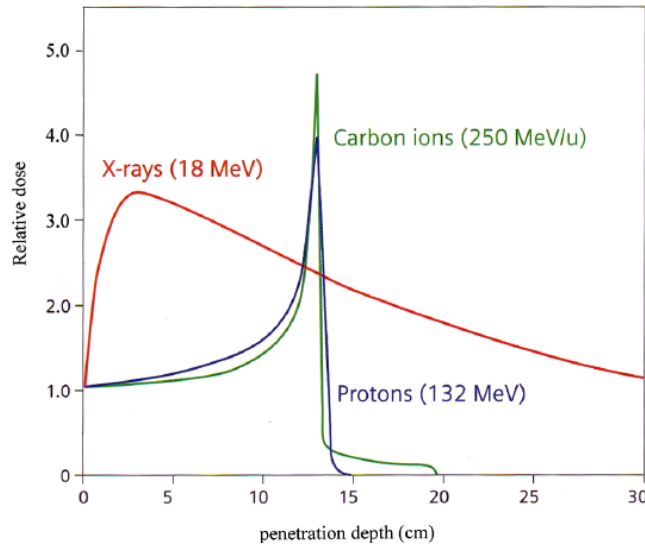
The value of hadron beams in radiation therapy can be readily understood by considering the underlying physics of the interaction of various types of particles with human tissue. The best technology currently available in Australia utilises X-rays (photons). Photons which is the generalized word to describe electromagnetic radiation i.e. X-rays, gamma rays, bremsstrahlung, interact with matter via three processes, Photoelectric effect, Compton scattering and Pair production. In principle each photon interacts only once with the components of the body and accordingly the intensity of the photon beam decreases as it enters the body. Therefore the dose deposited in the human body has an exponential term of the following form;

$$I = I_0 e^{-\mu x} \quad (1)$$

Thus, the maximum dose is delivered to the near surface of the body where there are healthy cells, there is no finite range to the dose distribution and the dose continues past the tumour being treated. Furthermore, because of the effective negligible mass of the photon, there is a large angular deviation of the photon beam as it passes through the body. On the contrary, hadrons e.g. protons and carbon ions have a different interaction process, principally coulomb interaction with target electrons in the irradiated body. The dose rate is given by the following expression

$$dE/dx = (e^4 Z_{\text{eff}}^2 Z^2 N / mv^2) * \text{other terms.} \quad (2)$$

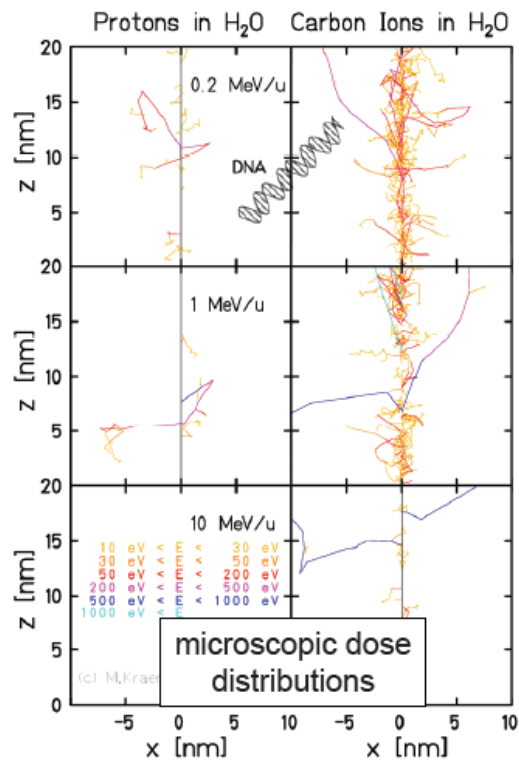
Simply, this means that a specific hadron ion gradually loses energy as it enters the body, slows down and finally stops altogether. At the end of its path it deposits a very large amount of energy as may be seen from the equation 2 above. This effect can readily be seen because of the term  $mv^2$  in the denominator which becomes asymptotically small as the energy or velocity of the particle decreases. This effect which is called the Bragg Peak has been known for more than 100 years and was first pointed out by the two Australian scientists, William Bragg and son. Furthermore, there is no radiation dose or energy loss after the ion has stopped. The key to the use of hadron beams is to adjust the energy of the hadrons so that they deposit their greatest energy in the tumour being targeted. The results of this difference in interaction are illustrated in Figure 1. The data for two ion beams, protons and carbon ions, and for traditional X-ray beams are shown. The dramatic increase in the radiation dose at the end of the carbon and proton pathways can be readily seen. Note that the doses in the figure are normalised to 1 at entry.



**Figure 1 Normalised Relative Dose rates for X-rays, protons and carbon ions.**

### 2.2 Linear Energy Transfer

Figure 2 shows the microscopic dose distributions for protons and carbon ions in water and DNA strand breakages for various energy ranges near the end of their tracks.

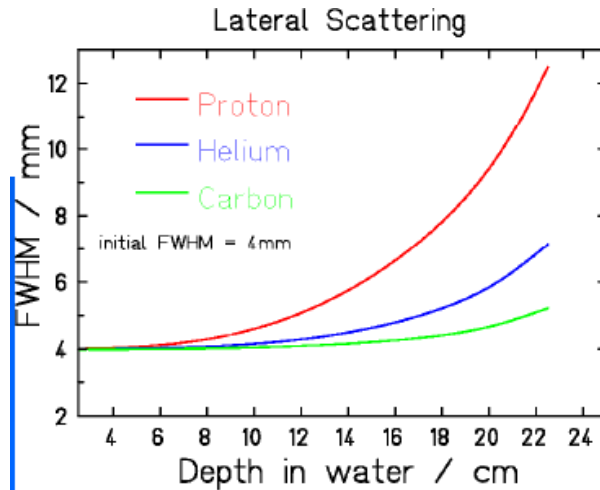


**Figure 2 Microscopic Dose Distributions for Protons and Carbon Ions (10)**

The dramatic increase in DNA double strand breakage observed with the carbon ions (right hand side of figure 2) shows that they are particularly useful in radiation resistant tumours. With single strand breakage, DNA has the ability to repair itself but with double strand breakage this is no longer possible.

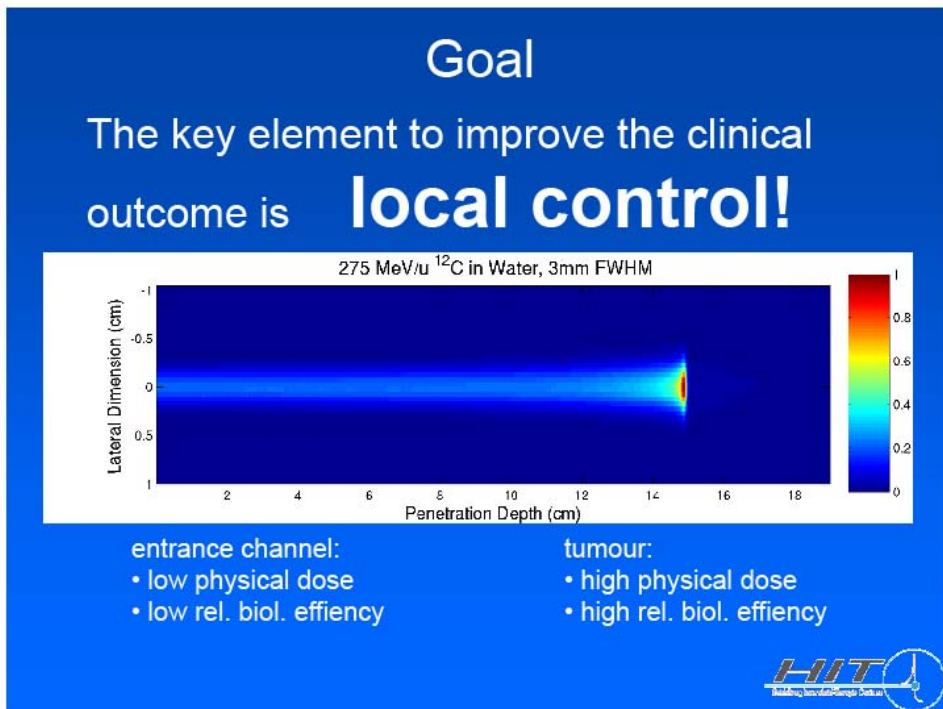
### 2.3 Lateral Deviation of Hadron Beams

A third important characteristic of the interaction of hadrons with human tissue is the lack of deviation of hadron beam from the original beam direction. Figure 4 from a presentation by Thomas Haberer (11 -12) shows the lateral scattering of three hadron beams as a function of depth in water. The lateral scattering is much less than that with photons and the degree of lateral scattering diminishes with atomic charge.



**Figure 3 Lateral Deviations of Proton, Helium and Carbon Beams in Water**

The value of all of these characteristics is revealed in Figure 4 taken from a presentation by Thomas Haberer (11). This shows the relative-dose distribution of a 4 mm wide 275 MeV/amu C beam in water.



**Figure 4 Relative Dose Distribution of a 275 MeV/u C<sup>12</sup> Beam in Water (11)**

## **2.4 Summary**

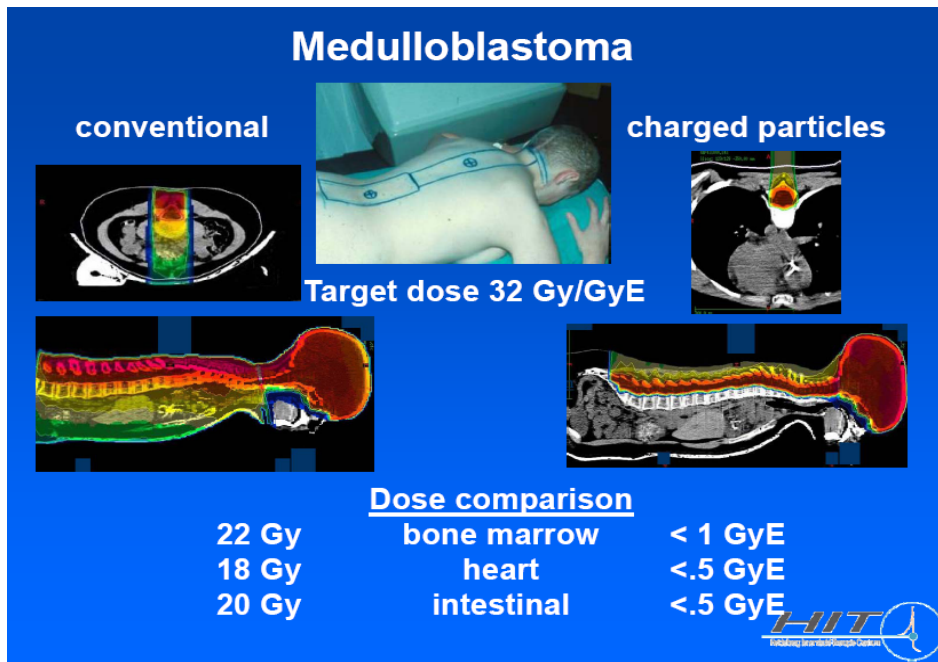
The advantage that hadron therapy has over conventional radiotherapy can be summarized as follows.

- In the treatment process, the dose to healthy cells is reduced by factors between 3 and 10. This is particularly important in the treatment of children who have many years of life before them.
- Because the hadron beams can be controlled by magnets and because of the small deviation of the hadron beam as it enters the human body it is possible to target tumours very close to critical organs.
- It is possible to kill tumours that are resistant to normal electromagnetic radiation.
- Hadron beams are more effective and the number of fractions (i.e. the number of times a patient needs to attend the facility) is reduced.
- Side effects such as nausea are reduced.
- With modern accelerator systems it is possible to use magnetically controlled pencil beams to radiate the detailed shape of the tumour. This is called raster scanning.

## **2.5 Examples**

There are many examples in the literature of comparisons of dose distributions for hadron beams with those using the latest technology with X-rays(photons). Two examples are shown below. Medulloblastoma is a highly malignant primary brain tumour that originates in the cerebellum or posterior fossa. It is particularly invasive and rapidly growing tumour that, unlike most brain tumours, spread through the cerebrospinal fluid and frequently metastasize to different locations in the brain and spine. Treatment begins with surgery followed by radiation therapy. Medulloblastoma is a cancer which affects young children. Forty percent of all cases are diagnosed in children under 5. Figure 5 (ref 11,12) shows a comparison of the dose distributions with charged particles (hadrons) and with intensity-modulated photons (conventional radiotherapy). The aim of both treatment methods is to give a dose of 32 gray to the spinal fluid. The dominant feature from this figure is the remarkable difference in the dose to bone marrow, heart and intestines with charged particle (hadron) beams relative to the dose with conventional X-rays. While the dose to the healthy bone marrow, heart and intestines is almost negligible with charged particle beams (<1 gray), the dose in conventional radiotherapy to these organs is alarmingly high and almost equal to the dose to the cancerous spinal fluid.

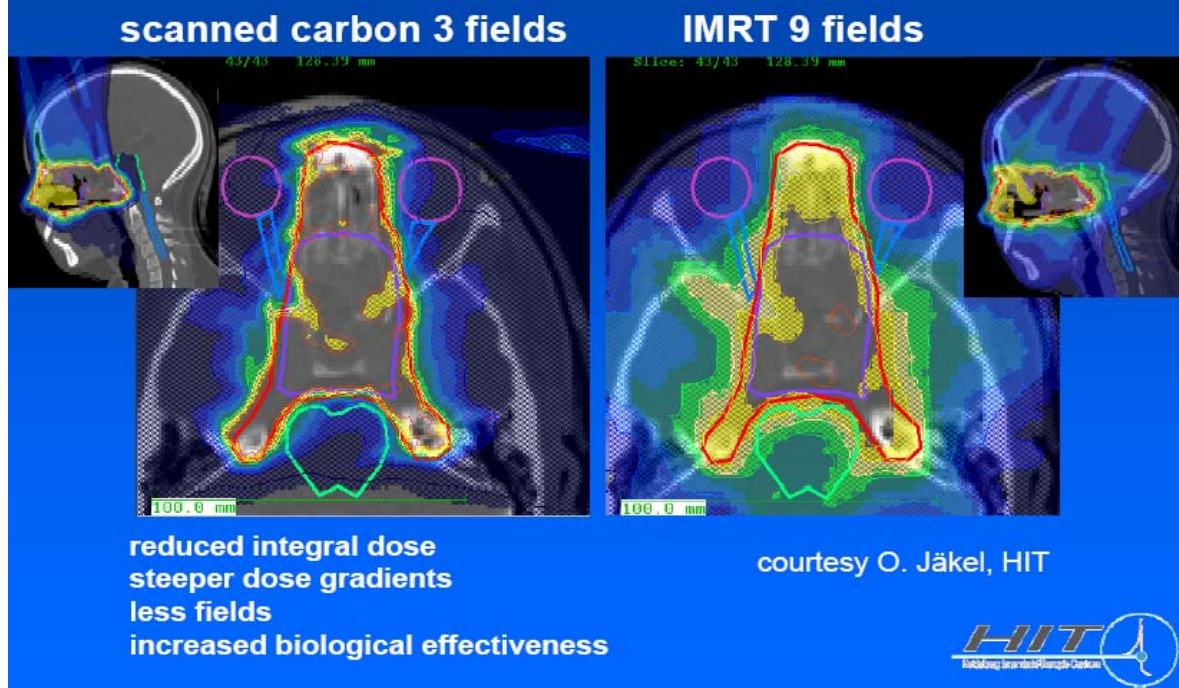




**Figure 5 A comparison of dose distributions for conventional and charged particle therapy of Medulloblastoma in young children**

Charged-particle beams are particularly suitable for cancers of the head and neck. Figure 6 (ref 11,12) presents a comparative dose distribution for charged particle beams, in this case carbon beams and conventional X-rays for a tumour circled in purple in the head below the brain and behind the eyes. With charged particles it is possible to avoid any dose to the spinal cord while with conventional radiography considerable damage would be done to the spinal cord. The spinal cord in Figure 6 is outlined in green and it is noted that with Intensity Modulated photons there is a considerable unwanted dose to the spinal cord.

# Scanned Carbon vs. Intensity Modulated Photons



**Figure 6** A comparison of dose distributions from carbon and intensity modulated radiotherapy of a tumour

### 3. Patient Numbers

Typically, the number of cancer patients in Australia who require radiation therapy is over 40,000 per year. Presently, they are treated using various photon radiation facilities typically based on electron accelerators. While the treatment of almost all of these cases would benefit by the alternative use of protons or light ions, the proponents of Hadron Therapy facilities (e.g. 5) argue that approximately 15% of these would have a much better prognosis if ion therapy were used. In other words, approximately 6000 patients per year would have significantly better outcomes with ion therapy. Most of these would be treated with protons however a proportion of these cancers (typically 1200) are radiation resistant and carbon ions are necessary.

As examples of the application overseas of hadron facilities the patient numbers for proton beams at the Lima Londa Hospital in the US (**Appendix II**) and carbon beams at National Institute of Radiological Sciences, Chiba, Japan (**Appendix III**) are presented. Recently, an assessment has been made of the proportion of those cases where hadron therapy has a significant benefit to the patients. The numbers given in **Appendix IV** are based on European Union data. It is believed from all of the arguments presented above that there is a compelling case to install a Hadron Therapy facility in Australia.

## 4. Scientific Applications of a Hadron Therapy Facility

The second objective in the installation of a Hadron Therapy and Research facility follows from the many opportunities that such a facility would provide not only for ANSTO but also for the Australian research community in general.

### 4.1 New Technologies

The construction of the facility will in its own right introduce a great number of new technologies into Australia as has been seen with the construction of two pieces of scientific infrastructure, the OPAL research reactor and the Australian Synchrotron.

The OPAL research reactor is a world-class neutron source which is presently equipped with 9 high-performance beamlines providing a complete coverage of those areas of research where neutrons beams are the primary choice for the researcher. A full description of the capabilities is given in [www.ansto/Bragg](http://www.ansto/Bragg).

The Australian Synchrotron is a world-class synchrotron facility currently equipped with 12 beamlines that cover almost all aspects of research in material science, biology, crystallography etc. A full description is given in [www.australian-synchrotron/beamline](http://www.australian-synchrotron/beamline).

In addition to these major facilities there are a number of well developed tandem accelerators which focus on basic and applied science.

Despite this investment, Australia seriously lags well behind comparable overseas countries in its provision of major research facilities, although in astronomy, Australia is well placed and has a critical range of facilities such that in this specific area Australia is able to attract foreign investment. This is not the case in accelerator facilities.

It is important to point out the difference between the proposed facility and the Australian Synchrotron. In the proposed facility the accelerated particle is used directly in therapy and science. In the Australian Synchrotron, it is the secondary radiation from the electron beams that is used in the experimental systems. In operation the two facilities are quite different. The electron beams in the Australian Synchrotron are extremely relativistic whereas in the proposed facility the ions are only partly relativistic. The lifetimes of the electrons in the Australian Synchrotron are of the order of 20 hours whereas the ion beams are accelerated once and then used with, typically, a lifetime of 1 sec. The proposed facility is much more similar to the existing ion beam facilities currently operational on the ANSTO site. Therefore the two synchrotrons offer research opportunities in entirely different areas.

The construction of the proposed facility is scheduled to take four years. At the conclusion of this process Australia would have

- created an experienced accelerator community that now has the expertise to move to the next major initiative for Australia e.g. an Accelerator Driven System, energy recovery linac,
- introduced a high level expertise in ultra- high vacuum technology,
- established a new generation of extremely advanced control engineers would have been established,
- introduced an extended competence in magnet design,

- moved in a serious way into new and advanced detector design as a consequence of the requirements of the therapy facility
- established an understanding of radio- frequency systems
- extended the understanding of ion source design
- created an energetic and visionary group of people ready for the next challenge.

## **4.2 Radiobiological Research**

The proposed facility would revolutionise research in many areas particularly in the biological sciences because of its ability to produce a variety of very energetic particles previously unavailable in Australia. These include the following areas of research.

- The study of low-dose effects
- Radio Biological Effectiveness (late effects, genetic mutation, transformation) of high energy particles,
- Determination of radiosensitivity of different tumours and normal tissues and molecular correlates
- Detailed study of chromosome damage
- The importance of hypoxia
- interaction of ion therapy and chemotherapeutic agents
- integration of biologic data into biological modelling for treatment planning

Clinical dosimetry for heavy ions is not at the same level of accuracy as dosimetry for conventional photon facilities (no primary standardization laboratory) and all of the above areas of research are of high priority.

## **4.3 Clinical Research**

The proposed facility in its dual role of research and therapy will lead to substantial cross-disciplinary research between radiobiologists, clinicians and physicists. It should be understood that this facility introduces Australia into a new area of activity where currently there is no stand alone solution and there is an overwhelming demand for a multidisciplinary team. ANSTO through its relationships with the universities and medical institutions is in an excellent position to marry these different areas into a cohesive research team.

## **4.4 Basic Research**

In a number of areas of basic research the facility has the capability of extending Australian studies significantly. These areas include

- proton – neutron production cross-sections
- proton scattering cross-sections
- nuclear cross section measurements
- preliminary studies of ADS systems
- decay spectroscopy, gamma spectroscopy
- exotic beams and reactions.

## **4.5 Atomic Physics**

Atomic physics is an area where Australian scientists have an enviable reputation. The proposed facility will greatly extend their research opportunities and help them to maintain their current international reputation. Specific areas of operation include

- spectroscopy and atomic properties of relativistic ion systems,
- optical spectroscopy
- Atomic Collision Process,
- dielectric recombination measurements,
- heavy- ion ionisation processes,
- charge-state studies,
- coulomb fragmentation in heavy ion collisions,
- radiative electron capture studies.
- heavy-ion stopping in matter.

## **4.6 Detector Development**

The application of charged particle beams in therapy proposes extremely important questions for control and monitoring detector systems. Although therapy with hadron beams has been in progress for many years it would appear that the status of detector systems lags that in several other areas of research where Australia has previously developed a strong research presence.

## **5. Procedures in the Construction of the Australian Hadron Research and Therapy Facility**

Hadron Therapy Facilities by their very nature involve sophisticated physics, engineering and medical expertise. Presently, there are no commercial organizations accepting orders for combined proton carbon facilities. Therefore if Australia is to take advantage of this advance in the treatment of cancers it will be necessary to construct one with Australian expertise. This of course has the advantage that the technology involved in construction will now be resident in Australia.

To build the Australian Hadron Therapy Facility it is proposed to adopt the same principles of construction that have proved very successful in the past in Australia, particularly at the Australian Synchrotron. Thus, it is proposed that ANSTO and its partners will manage the project including the overall design of the facility. The project will be divided into a number of specific components and international suppliers will be contracted to supply these specific components. ANSTO will be responsible for the integration of all the components of a facility. ANSTO will also be responsible for commissioning the overall facility and its subsequent operation. Approximately 60% of the capital cost of the facility will be spent in Australia.

To minimize the risk, a close relationship has been established with a number of leading laboratories overseas. CERN is generally regarded as the world's leading research laboratory and has indicated that it is willing to advise on the project. Similarly, specialists from the Paul Scherrer Institute (Switzerland) have expressed an interest in helping. Preliminary steps have also been made to invite several other leading figures in accelerators and hadron therapy to

join the International Advisory Committee including specialists from Japan and the United States.

### **5.1 Specifications of the Australian Hadron Therapy Facility**

It is proposed that the facility be based on a versatile synchrotron accelerator capable of producing high-energy ion beams of both protons and carbon with the potential to utilise ion species between these two and additional light ions up to oxygen. The energy of the beams to be extracted from the facility will be variable. The requirements for both ion beams include

- Maximum penetration depth in the human body of approximately 32 cm
- Minimum penetration depth of 3.5 cm
- Sufficient current to provide 2 grays of radiation to a targeted tumour in about 2 – 3 minutes.

With these principal requirements the hadron beams must be variable in energy

- 120 - 430 MeV/u for C<sup>12</sup> beams and
- 60 - 250 MeV for protons.

Furthermore, a high degree of focus is required for the delivered beam plus a smooth deposition rate. The only accelerator facility capable of meeting all these requirements is a synchrotron.

### **5.2 The Physics Design of the Australian Hadron Therapy Facility**

To minimize the risk, reduce the construction time substantially and install a state of the art facility it is proposed to adopt an established synchrotron design. To this end, a small team of specialists conducted a feasibility study of alternate options and established strong relationships with key European laboratories.

As part of its promotion of the wide scale capability of modern accelerator systems and in response to requests from its member states, in particular the TERA Foundation (TERapia con Radiozioni Adroriche), (13), the CERN laboratory prepared a detailed design, PIMMS (Proton Iobn Medical machine), (14), of a high-performance hadron facility which is available to its member states. ENLIGHT, the European Network for Research in Light-Ion Hadron Therapy was also established to coordinate a pan-European effort with a common multidisciplinary platform for using light ions for radiation therapy.

This complete but generic design was adopted by the CNAO organization in Pavia (Italy), (Centre Nazionale di Adroterapia Oncologica), (15). While they utilized most of the PIMMS design they did make some small modifications as a result of the detailed engineering design. This facility has been constructed and is undergoing final commissioning at this time.

A second group, MedAustron (Austria) (16), has adopted the CNAO revisions to the PIMMS design. In collaboration with the Accelerator Division of CERN they have also made some additional refinements. The latest revisions to the PIMMS design result in a very high performance facility with high flexibility and complete diagnostic instrumentation, which has been described as the Rolls Royce of Hadron Therapy facilities. It is proposed that the Australian Hadron Research and Therapy Facility be based on the MedAustron improvements

of the original PIMMS design. Negotiations have begun with the relevant partners to secure agreement with this suggestion and, if possible, to purchase the engineering drawings for the synchrotron itself.

### 5.3 Details of the Accelerator Complex

A full design study will be produced following approval for construction. This will be based on engineering drawings from the European partners with some specific requirements for Australian conditions and the chosen site. However, a great deal of preliminary work has been done. The original PIMMS layout of the synchrotron and associated facilities is shown in Figure 7. This was a generic design incorporating a host of alternative features that potential constructors could consider.

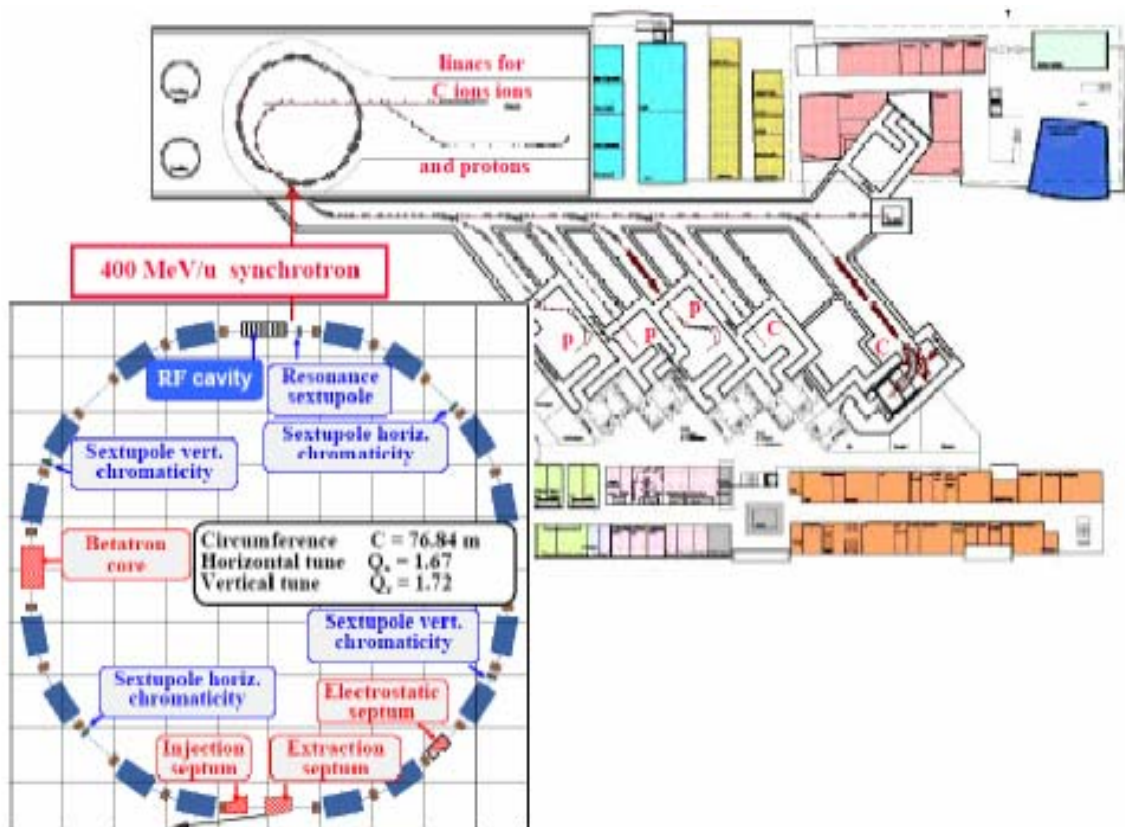


Figure 9. The general layout of the facility designed in the PIMMS [35]. The beam distribution line is long as it has the special feature that various functions are performed by different modules. The covered area is 15000 m<sup>2</sup>.

#### Figure 7 Generic Design of the PIMMS Facility

The principal elements of the PIMMS facility included

- Separate proton and carbon ion sources
- Two pre accelerators
- Transport line to the synchrotron
- Injection system into the synchrotron
- Booster synchrotron
- RF accelerator cavities
- Diagnostics

- Power supplies
- Vacuum system
- Cooling
- Extraction scheme using third order resonance extraction
- Beam transport system to the radiation areas
- Radiation areas
- Control system
- Safety
- Buildings.

As indicated previously, there have been some minor modifications of the original PIMMS design since it was first published in August 2000 and it is planned to incorporate these in an Australian facility.

For the purposes of the subsequent discussion, it is appropriate to consider the technical complex in three separate areas.

- Injection system
- Synchrotron
- Transport and radiation facilities.

### 5.3.1 Injection System

The injection system for the Heidelberg Ion Therapy (HIT) facility is shown in Figure 8 (11.12). It is noteworthy that in this facility the two pre-accelerators in the original PIMMS design have now been replaced by a single pre-accelerator. It should also be pointed out that the design on the HIT injection system was conducted by GSI Darmstadt and is not based on PIMMS. The equipment here is extremely specialised and it is proposed to proceed as CNAO and MedAustron have done in tender action for a complete system.

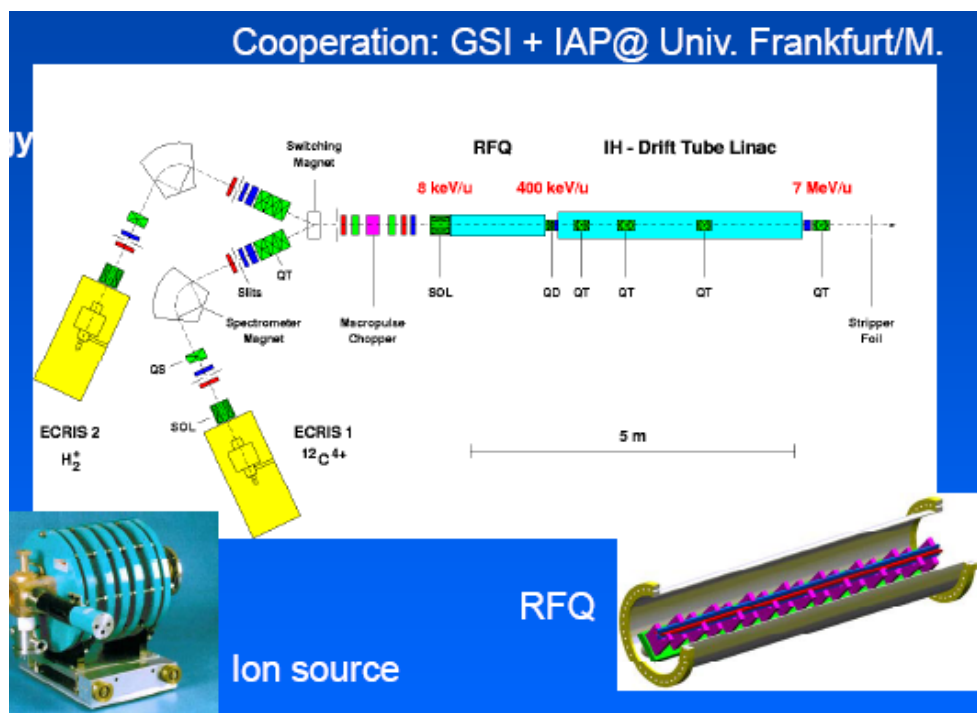


Figure 8 Injection System for the HIT facility - courtesy Thomas Haberer



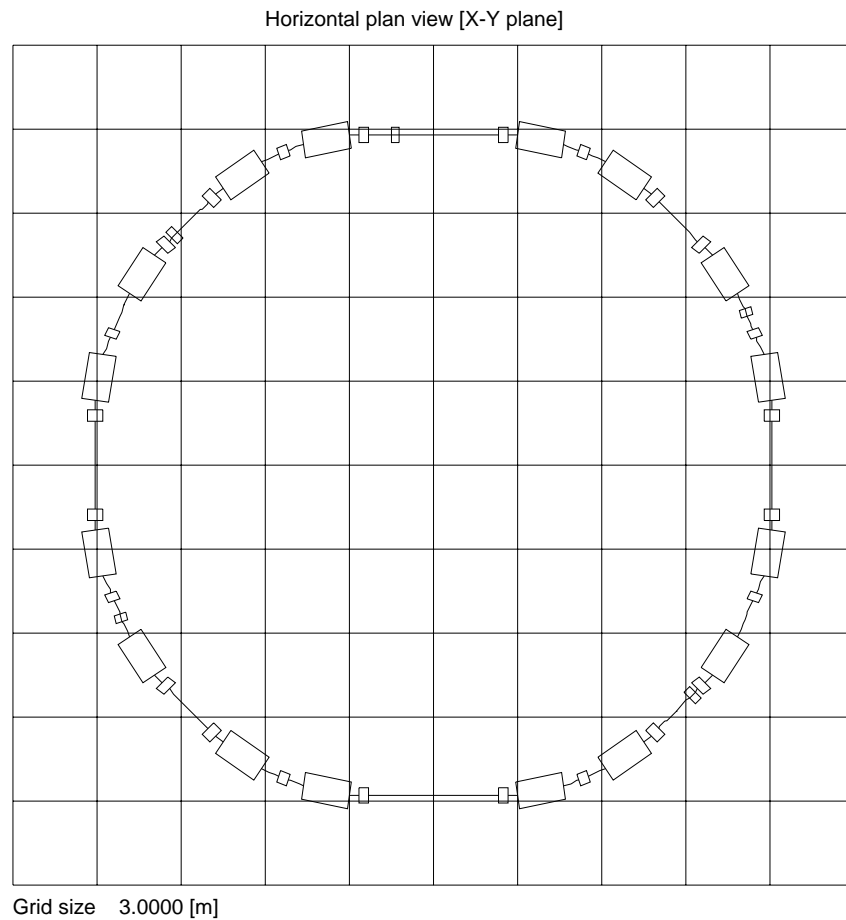
The actual location of the injection system with respect to the synchrotron is open to debate. CNAO have located the entire injection system within the perimeter of the synchrotron. This choice certainly saves on space and to some extent on concrete shielding. However the region inside the synchrotron becomes very crowded and no work can be pursued on the injection system independently from work on the synchrotron. On the other hand, MedAustron are planning to locate the injection system outside the perimeter of the synchrotron. The location of the injection system will be determined primarily by the amount of space available on the selected site.

The transfer line from the injection system to the synchrotron is relatively simple and could be included in the commercial injection system or constructed independently. This remains an open question at this time.

The details of the actual injection system and the fill structure will follow the practise at HIH, CNAO and MedAustron.

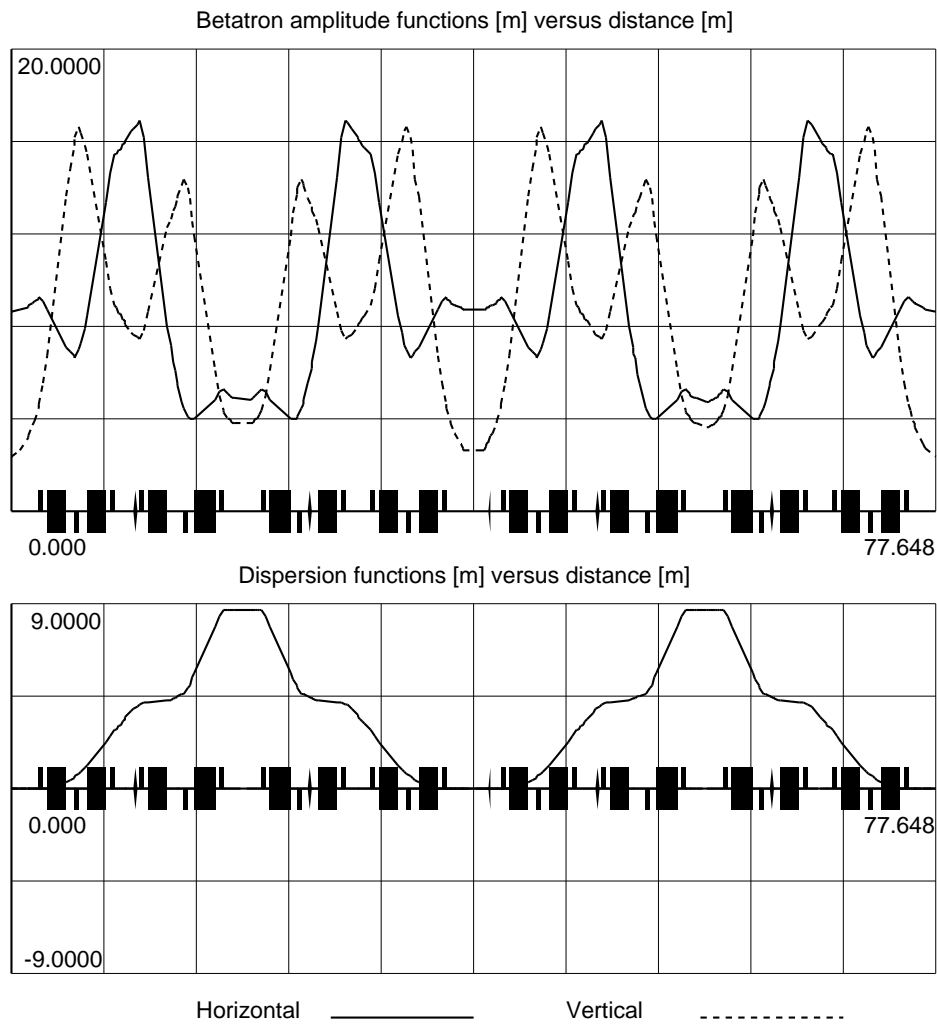
### **5.3.2 Synchrotron**

It is planned to construct the latest revised version of the PIMMS lattice.). The configuration of the accelerator component of the facility is shown in Figure 4, using the WinAgile Code (17), courtesy of M. Benedikt (CERN, MedAustron) (18) for the input file. The figure shows only the dipoles, quadrupoles and sextupoles of the latest revision. The input file provides complete data including diagnostics, correctors, RF, injection and extraction elements.



**Figure 9 Horizontal Configuration of the Synchrotron, courtesy M. Benedikt (CERN/MedAustron) – WinAgile Output**

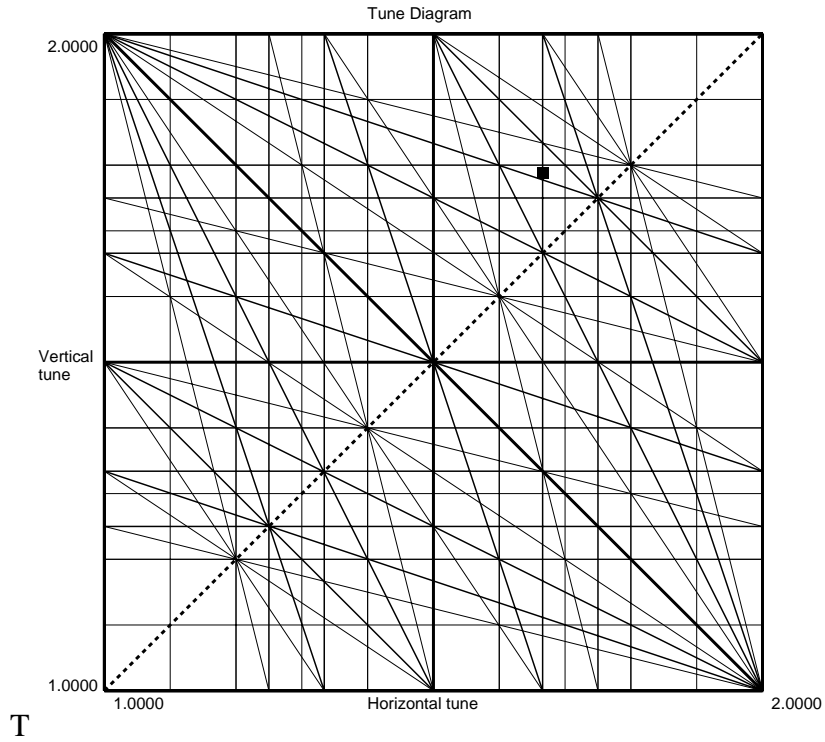
The calculated Betatron functions for this lattice with Carbon 6+ ions at 400 MeV/amu are shown in Figure 10.



**Figure 10 – Horizontal and Vertical Betatron Amplitude Functions plus Dispersion Functions – WinAgile Output.**

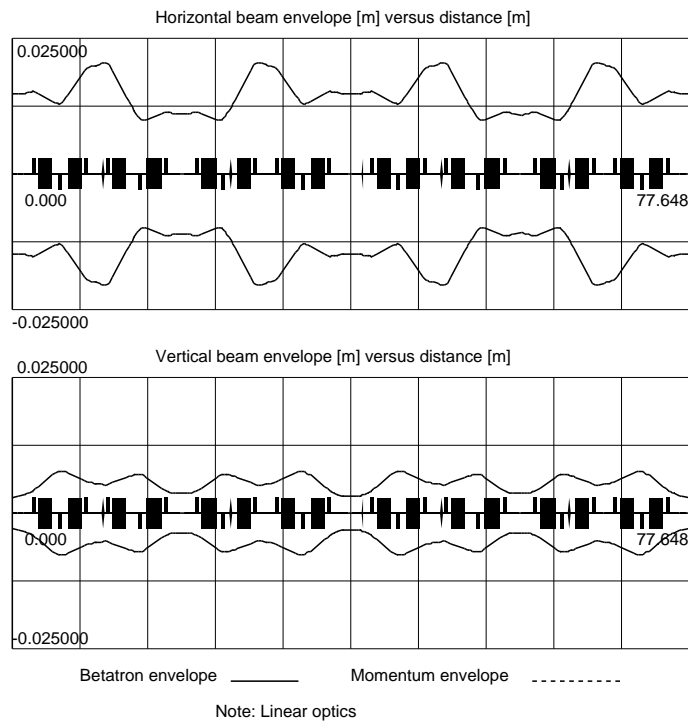
It will be noted that the circumference of the lattice is now 77.648 m.

It is planned to use third-order resonance extraction as is used at HIT, CNAO and most other synchrotron facilities. The horizontal tune diagram for slow third order resonance extraction is shown in Figure 11. This is the condition of the lattice for slow extraction. The details of the extraction system, RF etc are not discussed in detail here.



**Figure 11 Horizontal Tune Diagram showing the Horizontal Tune now shifted to the third order resonance at 1.6667.**

For the specified beam parameters, the  $2\sigma$  beam envelopes are shown in Figure 12 for a horizontal emittance of  $5 \pi$  mm mrad and a vertical emittance of  $0.73 \pi$  mm mrad.



**Figure 12 Beam Envelopes**

Table 1 lists some relativistic data for the Carbon beam at 400 MeV/amu.

**Table 1 Illustrative Kinetic Parameters for the Synchrotron**

|                   |                             |
|-------------------|-----------------------------|
| Particle          | 12 C 6+                     |
| Kinetic Energy    | 0.400 GeV/amu               |
| Average Momentum  | 0.952303 [GeV/c/u]          |
| Beta = v/c        | 0.714609                    |
| Gamma = m/m0      | 1.42954                     |
| Beta*gamma        | 1.02156                     |
| Magnetic Rigidity | 6.34641 Tm                  |
| Revolution Time   | 0.362444 10 <sup>-6</sup> s |

## 6. Transfer and Transport Lines

A comprehensive account of a potential configuration of the transport and transfer lines to the various treatment facilities has been given in the original PIMMS document (14). A more recent paper by M Benedikt (19) has expanded on some of the details. The principles expressed in these documents will be followed for the proposed Australian hadron Facility although there will be variations imposed by the site and the need to reduce the costs of the concrete.

In essence, the transfer and transport lines may be subdivided into a number of specific sub-units as discussed in PIMMS. The subsets include

- a matching section to match the extraction optics of the synchrotron to the continuing beamlines.
- a sub-unit in which the variation on the horizontal and vertical size of the transported beam to the various irradiation facilities can be changed. This one subunit will act for all beamlines.
- a second sub-unit to extend the beamline
- specific beamlines to take the beams to horizontal irradiation positions, vertical ones or beamlines in rotating gantrys.

In all of the subsequent discussion an effort has been made to reduce the number of independent components and to standardise on the dipole and quadrupole magnets as far as it is possible. For that reason all quadrupoles have the dimensions of the quadrupoles in the revised PIMMS synchrotron with effective field lengths of 360 mm. In addition the dipoles in the horizontal bending beam lines are identical with those in the synchrotron.

### 6.1 Matching Section

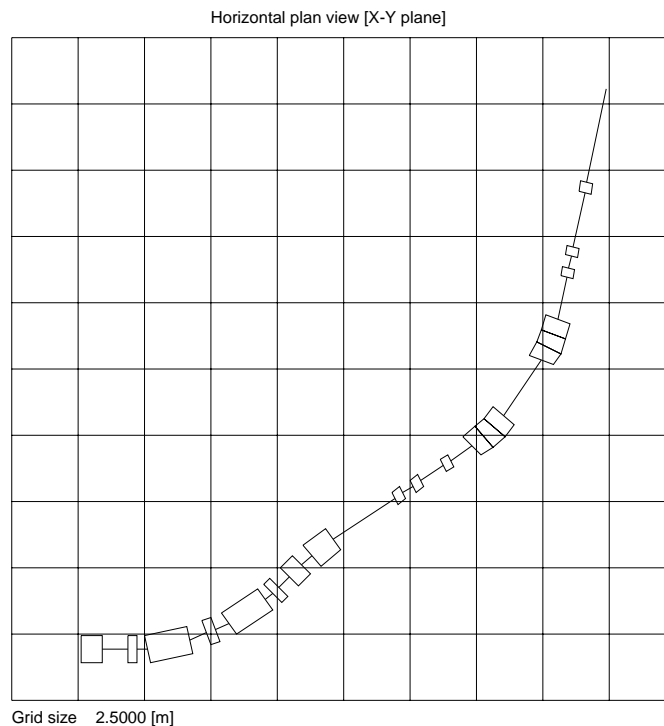
The matching section has been discussed in some detail in the original PIMMS paper. To provide an accurate assessment of the details of this section, the final components in the synchrotron lattice need to be modified in the computer input file essentially to account for the variations inherent in the extraction optics after tune horizontal tune has been moved to the third order resonance. This has been discussed in considerable detail in the original PIMMS design paper and the parameters presented there are adopted without discussion.

Essentially the matching section is required to provide optimum matching of the output optical parameters of the synchrotron beam (following third order resonance extraction) to a new set of convenient optical parameters that can serve as an optimum source for the following sequence of treatment and experimental facilities.

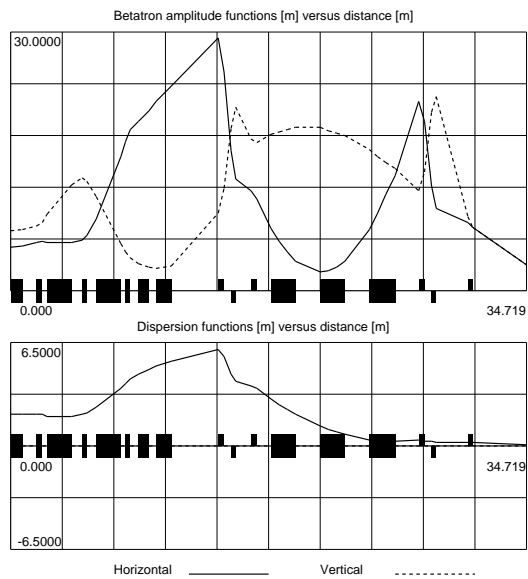
The geometry of the matching section is shown in Figure 13. The first 15 parameters in the input file for the WinAgile calculation are taken directly from the PIMMS Machine Study. Table 2 lists the required matching optical parameters for the entry and exit points.

**Table 2 Entry and Exit Optical Parameters**

| Parameter                        | Entry Point | Exit point |
|----------------------------------|-------------|------------|
| Horizontal Beta $\beta_x$        | 5.000 m     | 3.000 m    |
| Horizontal $\alpha_x$            |             | 0.00       |
| Vertical Beta $\beta_z$          | 7.000 m     | 3.000 m    |
| Vertical $\alpha_z$              |             | 0.00       |
| Horizontal Dispersion $\eta_x$   | 2.00 m      | 0.000 m    |
| Derivative Horizontal Dispersion | 0.00        | 0.000 m    |
| Vertical Dispersion $\eta_z$     | 0.00 m      | 0.000 m    |
| Derivative Vertical Dispersion   | 0.00 m      | 0.000 m    |



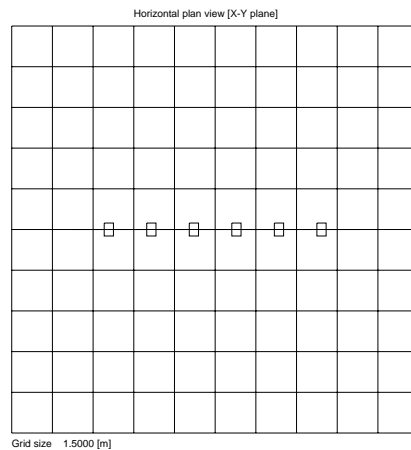
**Figure 13 Configuration of the Matching Section – WinAgile Output**



**Figure 14 Betatron Functions – Matching Section**

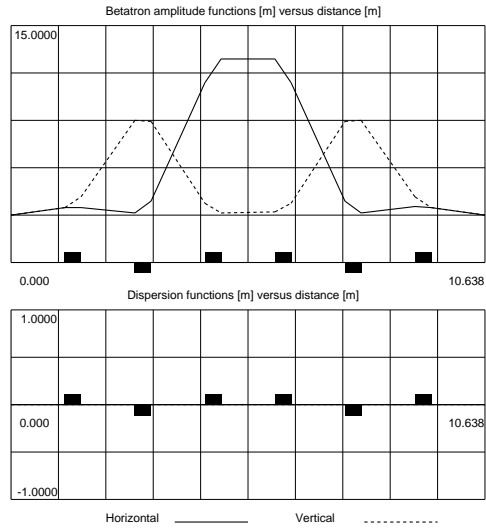
This configuration is by no means final and is under review. It may be possible to replace the final three dipoles by two that are identical to the dipoles in the synchrotron.

## 6.2 Beam Size Module

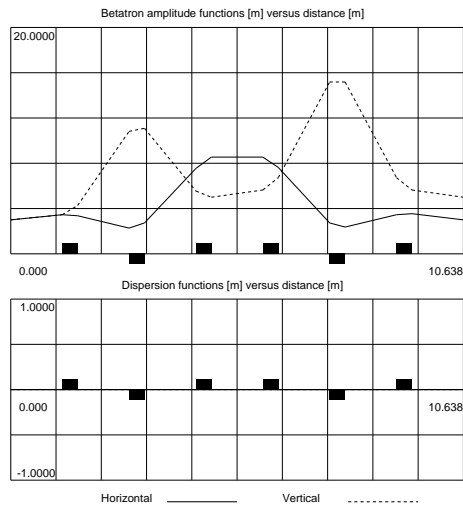


**Figure 15 Six Quadrupoles of the Beam Size Module**

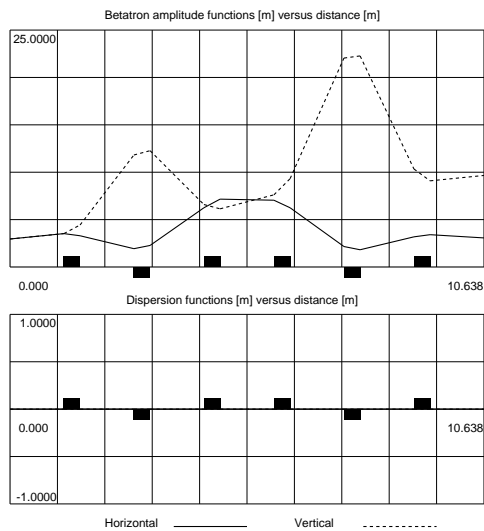
The beam size module comprises six standard quadrupoles. The objective here is to vary the vertical beta function from 3 m to at least 15 m to provide a variation in the vertical beam size at the treatment position. The horizontal beta function remains unchanged however variation in the horizontal beam size is achieved by phase variation. There is a detailed discussion in the original PIMMS design report. Figure 16 – 19 show the betafuncions for four different beam sizes.



**Figure 16 Twiss parameters (optical parameters) for  $\beta_z = 3$  m**

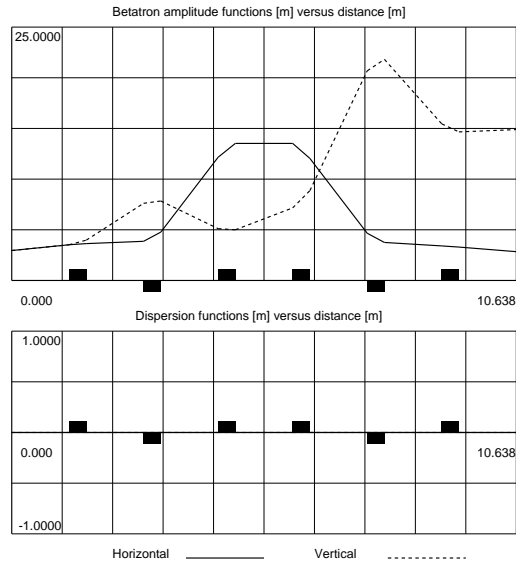


**Figure 17 Twiss Parameters for  $\beta_z = 5$  m**



**Figure 18 Twiss Parameters for  $\beta_z = 10$  m**

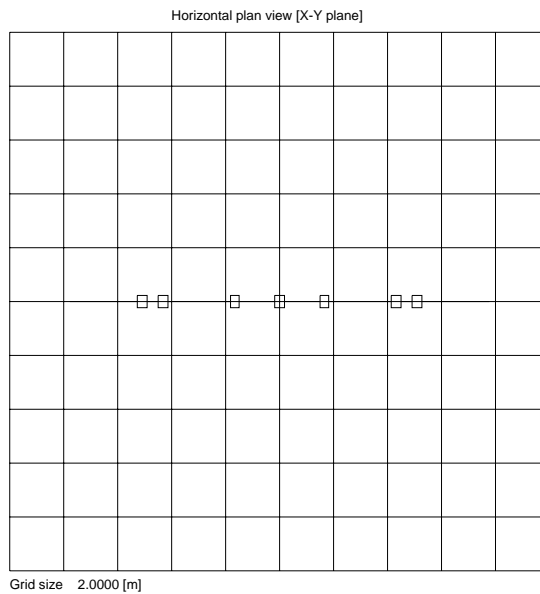




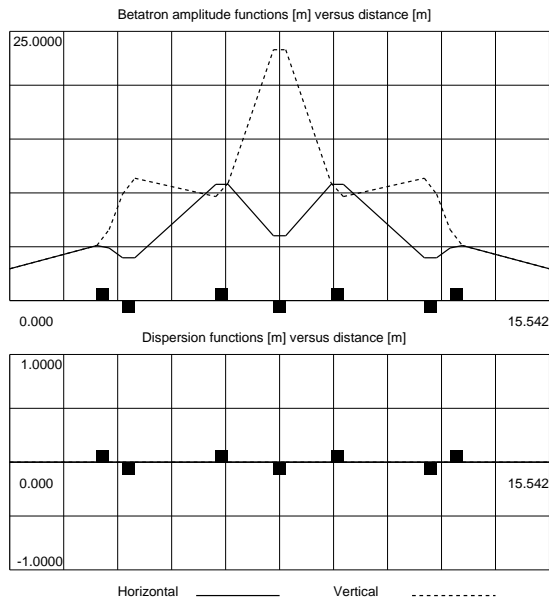
**Figure 19 Twiss parameters for  $\beta_z = 15$  m**

### 6.3 Extension Module

Following the philosophy of the PIMMS design, a symmetric module is required to transfer the beam from a specific location to the next delivery position. The seven quadrupoles to achieve this are shown in Figure 20 and the corresponding Twiss parameters for  $\beta_z = 3$  m are shown in Figure 21.



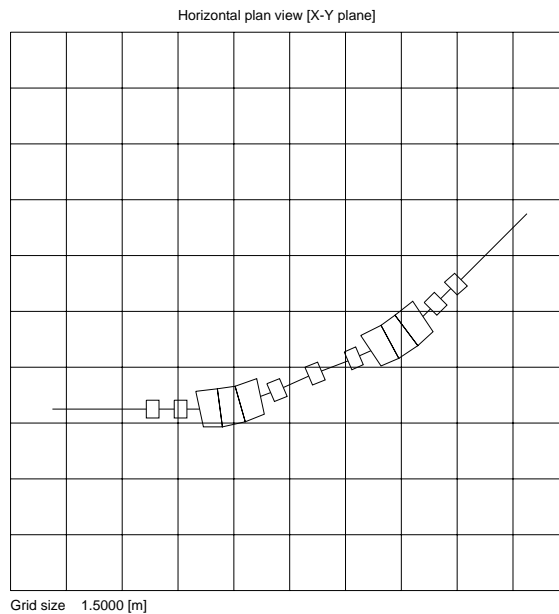
**Figure 20 Extension Module**



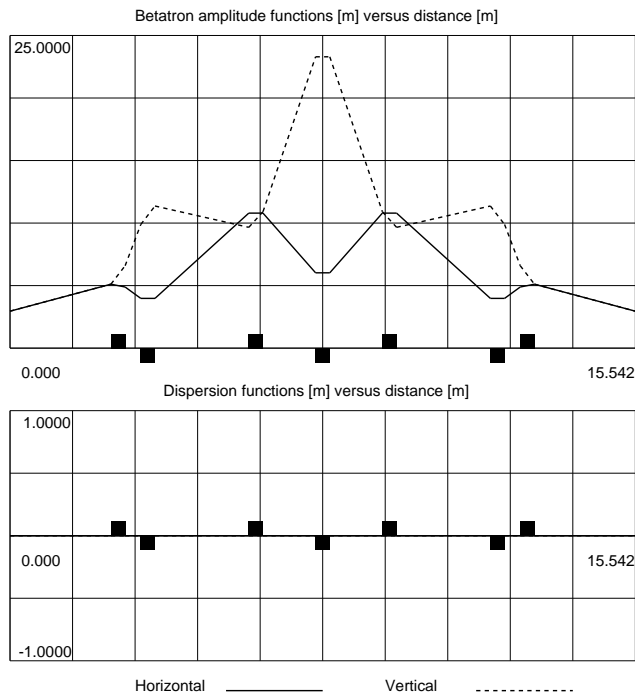
**Figure 21 Twiss Parameters for Extension Module**

### 6.4 Horizontal Beamline Facility

At this stage it is envisaged that the beam will be deflected through 0.78 radians (45 deg) to each of a number of horizontal radiation treatment positions. The module to achieve this is based on two standard dipole magnets and seven standard quadrupoles. The extension of the beam to the actual treatment location has not been finalised at this time and depends on the configuration etc of the shielding and related building. The configuration of the Horizontal Beamline Facility is shown in Figure 22 and corresponding Twiss parameters in Figure 23.



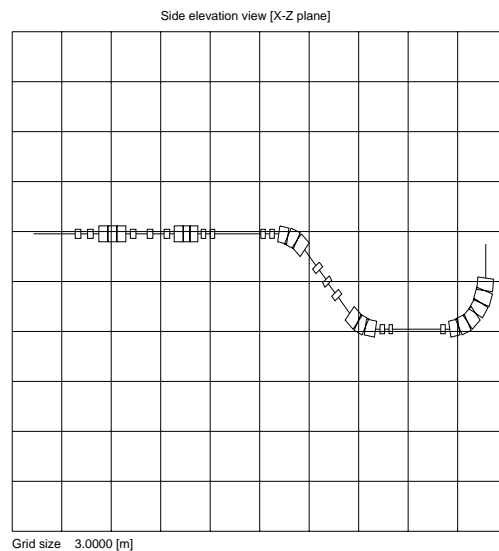
**Figure 22 Configuration of the Horizontal Beamline**



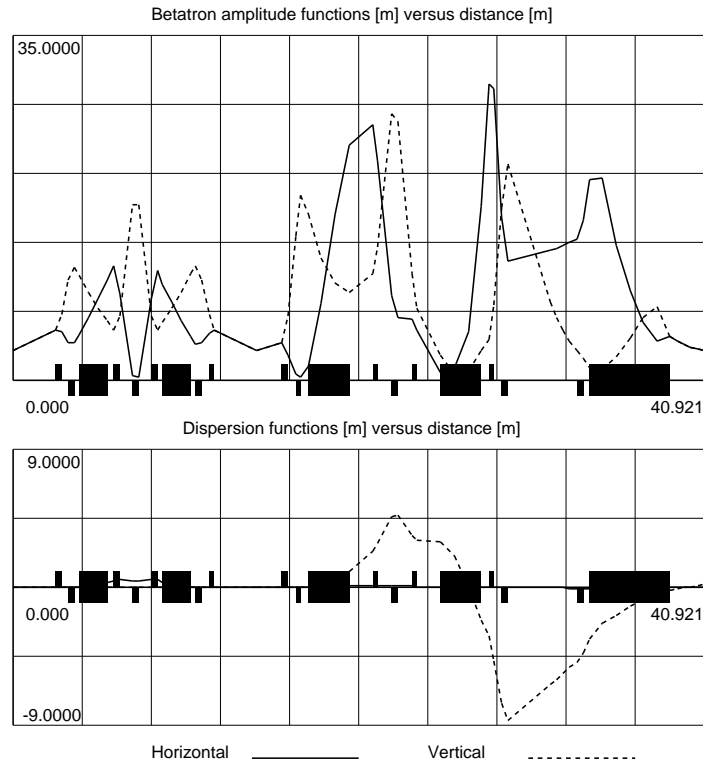
**Figure 23 Twiss Parameters for the Horizontal Beamline**

### 6.5 Vertical Facility

It is proposed at this time to have one treatment position with both horizontal and vertical beams. The design of the vertical beam requires very large dipole magnets. The configuration of the vertical beamline is shown in Figure 24 and the corresponding Twiss parameters in Figure 25.



**Figure 24 Vertical Beamline**



**Figure 25 Twiss parameters Vertical Beamline**

## 7. Treatment Facilities

As presented in Section 6, the various components of the transfer lines function as discrete modules. The philosophy is that these can be added together as desired. For example a specific configuration might be

- matching module
- beam size module which acts for all subsequent radiation positions
- a horizontal beamline
- with the dipoles magnets in the horizontal beamline switched off, an extension line would take the beam to the next treatment beamline.
- the next takeoff could be for a second horizontal beamline or a vertical beamline.

It is seen that the various designs are very flexible and can be fit together in a variety of configurations and the final configuration will be determined by the managers of the facility and the level of funding. At this time it is expected that well characterized ion beams would be supplied to

- one or two horizontal proton-carbon beamlines
- one combined horizontal and vertical beam carbon-proton radiation room
- one radiation chair in its own room
- one experimental station to develop new irradiation procedures and study new applications of high energy ion beams.

In addition to the treatment facilities, there would also be a need for supporting facilities associated with the site. In particular the new PETNET centre at Ansto would be particularly valuable in providing a supporting role.

## **7.1 Associated Facilities**

The facility will need a number of supporting facilities to ensure that the most efficient use is made of it. The facility itself will have in the treatment rooms, where carbon beams are to be utilized, a PET camera to monitor in real time the location of the radiation dose. This is possible because through the interaction with human tissue, the carbon 12 beams produce a small quantity of carbon 11 which is a well known PET isotope with a very short half life.

In addition, there will be a need for reception areas, treatment preparation areas and consultation rooms. There is also a need for some local accommodation and this is already available via the Lucas Heights Motel. Since ANSTO is a major user laboratory, a range of services is available for the large group of external users who are conducting experiments on the ANSTO facilities.

For the research activities proposed for the facility there is a need for a wide range of supporting scientific infrastructure. These include

- major computing and software support
- high technology engineering workshops
- radiation and dosimetry services
- electron microscopes
- a full range of laboratory services including glove boxes, fume hoods etc
- an animal laboratory including an animal pet camera
- ion beam analysis services on the ANTARES and STAR accelerators
- a deuteration facility
- the neutron beam facilities on the OPAL reactor.

## **7.2 Buildings**

The design of the building to house the Facility and its associated components has not been started. However preliminary drawings indicate that the space requirements for the accelerator system and the associated research and therapy rooms will require an area of approximately 6000 m<sup>2</sup>. In addition, buildings for the associated activities will require an area of approximately 5000 m<sup>2</sup>.

The actual location of the facility has not yet been determined. However there are a number of sites outside the security area of the present ANSTO laboratory that are under investigation. These areas are particularly attractive as there is a large rock shelf at Lucas Heights which would provide support for the heavy accelerator components and accordingly significantly reduce the costs.

## **7.3 Construction Staff**

The staff requirements to construct the facility have been evaluated based on previous experience in the installation of the tandem accelerator, ANTARES, and the construction of the Australian synchrotron. A total of 120 man years is needed. The actual breakdown of the prospective staff numbers is given in **Appendix V**. These numbers assume that a full sized

carbon proton facility is to be constructed. The numbers are clearly dependent on the size of the final facility.

## 8. Alternatives and Costs

The cost of a hadron therapy facility including all of the capabilities listed above was evaluated in early 2008 based on costs extrapolated from costs incurred in building the Australian Synchrotron and information from international suppliers. These costs have been inflated to 2010 dollars and a budgetary figure of \$180 M is believed to be more than adequate to produce a world class facility.

This proposal is for a very-high-performance state-of-the-art hadron therapy facility providing world class performance and allowing the options of incorporating new technologies as the science advances. Its construction would also introduce a great range of new technologies and capabilities into Australia and provide a platform on which to build further landmark facilities in the future. Some consideration is given below to lesser performance alternatives.

The alternatives include

- Commercial cyclotron facility – protons only
- Commercial synchrotron facility – protons only
- Nationally constructed synchrotron facility – protons only.

In evaluating the alternatives there is a number of over riding issues. The beamlines are to a large extent independent of the accelerator facility that drives them. So all of the options listed above would potentially be required for a commercially-based proton synchrotron and with some modification a cyclotron-based facility. Furthermore, the buildings which comprise a major component of the costs of a facility are not too different depending on the options. A combined carbon-proton synchrotron has a diameter of approximately 26 m versus a diameter of about 7 m for a proton synchrotron. Consequently, the footprint of a combined carbon-proton machine is about 20% larger.

A preliminary assessment of the pros and cons of the alternative options is given below.

Table 3 – Commercial Cyclotron – Protons only

| Pros                                   | Cons   |
|--|--|
| Low cost option<br>Possible lower risk | Slightly inferior performance relative to a synchrotron<br>No flexibility<br>Very limited research capability<br>Very limited technology transfer<br>Long term dependence on supplier organization<br>Therefore higher operational costs |

Table 4 – Commercial Synchrotron – Protons only

| Pros  | Cons   |
|---|--|
| Low cost option – several million more than cyclotron<br>Lower risk | More control of beam than with a cyclotron<br>Some flexibility but limited by the synchrotron<br>Limited research capability<br>Some technology transfer<br>Independence from the supplier |

Table 5 – Nationally Constructed Synchrotron – Protons only

| Pros  | Cons   |
|---|--|
| Potentially lowest cost of all<br>Greater flexibility<br>Good technology transfer<br>Improved research capability | Some risk<br>Less options than carbon-proton machine |

It is expected that construction of any of the facility will take approximately 4 years with two years required to ramp up the performance of the facility to full operational capacity. The annual cost of operating of the facility has been estimated at \$10 M/year.

## 9. Advisory Committees

In the planning and construction stage there will be a need to be a number of Advisory Committees. **Appendix VI.**

## 10. Conclusion

The risk involved in a national effort to install a hadron therapy facility has been substantially reduced because of the CERN study and the establishment of close relations with CERN and a number of other laboratories with considerable relevant experience. It is believed that Ansto and Australian science have the capabilities necessary to construct such a facility as other national groups have done. The construction of the Australian Synchrotron has been completed and incorporates many of the engineering features that are also needed for a hadron therapy facility. For the most part, specialist component manufacturers were contracted to provide items for which they were recognized as world leaders and activities on the synchrotron site were largely integration of the component parts.

## 11. Acknowledgements

The authors are particularly indebted to Thomas Haberer and Michael Benedikt who provided a great deal of extremely valuable data. We also acknowledge valuable information from Steve Myer, Hartmut Eichkoff, Lenny Rivkin and many other members of the staff at HIT, GSI, PSI and CERN.

## 12. References

1. Jean-Michel Lagniel, PAC-07, Albuquerque, New Mexico, MOZBC02, page 127.
2. R. R. Wilson (1946), Radiological Use of fast Neutrons, Radiology, 47, p 487.
3. Australian National Proton Facility, Discussion Paper, May 2001, Australian National Proton Facility Steering Committee.

4. J. W. Boldeman, An Entry Level Hadron Therapy Facility, 15<sup>th</sup> Pacific Basin Conference, Sydney 2006.
5. U. Amaldi (2001), Hadrontherapy in the world, Impact and Applications of Nuclear Physics, NUPECC.org/iai 2001/report/B32.pdf.
6. W. T. Chu, B. A. Ludewigt and T. R. Renner, Instrumentation for Treatment of Cancer using Proton and Light-Ion Beams, Rev. Sci. Instrum. 64(8), August 1993.
7. G. Kraft, Tumor Therapy with Heavy Charged Particles, Progress in Particle and Nuclear Physics 45 (2000), 473 – 544.
8. M. Regler, M. Benedikt and K. Poljanc, Medical Accelerators for Hadrontherapy with Proton and Carbon Ions, Hephy-Pub-757/02.
9. U. Amaldi, Conformal radiation therapy with hadron beams and the program of the TERA Foundation, Rays, (1998), Jul – Sept; 23 (3) pages 486 – 507.
10. M. Kramer, GSI, Darmstadt.
11. Thomas Harberer, Heidelberg Ion Therapy Center, Hadron Therapy Workshop, Erice 2009.
12. Thomas Haberer Heidelberg Ion Therapy Center, Particle Beam Production – A Synchrotron-Based System, PTCOG 2009.
13. U. Amaldi and M. Silari (editors), The TERA-project and the Centre for Oncological Hadrontherapy (second edition 1995).
14. Ph. Bryant et al., Proton-Ion Medical machine Study (PIMMS), Part 1, CERN-PS-1999-010, and Part II, 2000-007.
15. Sandro Rossi, CNAO Foundation, Radiotherapy Hadrons: new devices..
16. R. Potter, T. Auberger and M. Regler, Med-AUTRON – Ein Österreichisches Krebsforschung-und Behandlungszentrum zur Hadrontherapie in Europa, Machbarkeiststudie, 1998.
17. M. Benedikt: Optical Design of a Synchrotron with Optimisation of Slow Extraction for Dadron Therapy, Thesis, TU-Wien (1997).
18. Ph. Bryant, Agile program for synchrotron lattice design, <http://www.cern.ch/-bryant>



**Appendix I      PARTICLE THERAPY FACILITIES IN OPERATION (PTCoG)**

| Year | Proton(P)/<br>Carbon (ion) | Facility    | Location               | No of People |
|------|----------------------------|-------------|------------------------|--------------|
| 1961 | P                          | Harvard     | Boston, USA            | 9116         |
| 1969 | P                          | IITEP       | Moscow, Russia         | 3927         |
| 1975 | P                          |             | St Petersburg, Russia  | 1320         |
| 1979 | P                          |             | Chiba, Japan           | 145          |
| 1983 | P                          | PMRC1       | Tsukuba, Japan         | 700          |
| 1984 | P                          | PSI-1       | Villigen, Switzerland  | 4646         |
| 1989 | P                          |             | Dubna, Russia          | 318          |
| 1989 | P                          |             | Uppsala, Sweden        | 738          |
| 1989 | P                          |             | Clatterbridge, England | 1584         |
| 1990 | P                          |             | Loma Linda, CA         | 11414        |
| 1991 | P                          |             | Nice, France           | 3129         |
| 1991 | P                          |             | Orsay, France          | 3766         |
| 1993 | P                          |             | iThemba, South Africa  | 486          |
| 1993 | P                          | MPRI        | IN, USA                | 220          |
| 1994 | P                          | UCSF        | CA, USA                | 920          |
| 1994 | Ion                        | HIMAC       | Chiba, Japan           | 2867         |
| 1995 | P                          | TRIUMF      | Canada                 | 111          |
| 1996 | P                          | PSI-2       | Switzerland            | 262          |
| 1997 | Ion                        | GSI         | Germany                | 316          |
| 1998 | P                          | HMI         | Berlin, Germany        | 829          |
| 1998 | P                          | NCC         | Kashiwa, Japan         | 462          |
| 2001 | P + ion                    | HIBMC       | Hyogo, Japan           | 1099 + 131   |
| 2001 | P                          | PMRC2       | Tsukuba, Japan         | 930          |
| 2001 | P                          | NPTC        | Boston, USA            | 2080         |
| 2002 | P                          | INFN-LNS    | Catania, Italy         | 114          |
| 2002 | P                          |             | Wakasa, Japan          | 33           |
| 2003 | P                          |             | Shizuoka, Japan        | 410          |
| 2004 | P                          | WPTC        | Zibo, China            | 270          |
| 2006 | P                          | MD Anderson | Houston, USA           | 114          |
| 2006 | P                          | FPTI        | Jacksonville, FL, USA  | 15           |
| 2007 | P                          | RPTC        | Munich, Germany        |              |
| 2007 | P + ion                    | HIT         | Heidelberg, Germany    |              |

**PARTICLE THERAPY FACILITIES COMMISSIONING, UNDER  
CONSTRUCTION – PLANNING STAGE**

| YEAR    | Proton(p)/<br>Carbon (ion) | Facility                         | LOCATION                                  |                    |
|---------|----------------------------|----------------------------------|---|--------------------|
| 2007/08 | P                          | PSI                              | Villigen, Switzerland<br>(OPTIS2/Gantry2) | Near<br>completion |
| 2007    | P                          | NCC                              | Seoul, Korea                              |                    |
| 2007    | P + ion                    | CNAO                             | Italy                                     | Near<br>completion |
| 2009    | P                          | UPenn                            | USA                                       |                    |
| 2009    | P                          | WPE                              | Essen, Germany                            |                    |
| 2009?   | P                          | iThemba Labs                     | South Africa                              |                    |
| 2009?   | P                          | RPTC                             | Koeln, Germany                            |                    |
| 2010?   | P                          | ICPO                             | Orsay, France                             |                    |
| 2010?   | P                          |                                  | Trento, Italy                             |                    |
| 2011?   | Ion                        | Gunma Univ                       | Japan                                     |                    |
| 2011    | P                          | Northern Illinois<br>PT Res Inst | Chicago, IL, USA                          |                    |
| 2011    | P + ion                    | PTC                              | Marburg, Germany                          |                    |
| 2011    | P + ion                    | ETOILE                           | Lyon, France                              |                    |
| 2011?   | P + ion                    | Med-AUSTRON                      | Austria                                   |                    |

More than 16 centres over 5 years: 11 in Europe, 5 in Germany - majority with ion beams .

## **Appendix II      Principal Diseases Treated with Protons at Loma Linda Medical Center**

### **Brain and Spinal Cord**

- Arteriovenous Malformations – treatment of defects of the circulatory system
- Isolated Brain Metastases – High radiation reduces symptoms
- Pituitary Adenomas – Fractionated radiation over radiosurgery

### **Base of Skull**

- Acoustic Neuromas – Benign tumours affecting hearing
- Chordomas and Chondrosarcomas – Tumours of the brain stem, spinal cord or central nervous system
- Meningiomas – Tumours treated in a few treatments

### **Eye**

- Uveal Melanomas – Malignant tumours treated with protons to minimize eye removal need

### **Head and Neck**

- Nasopharynx – Local carcinoma treatment via protons to reduce side effects
- Oropharynx Cancer (locally advanced) – Dose localization to minimize healthy tissue damage

### **Chest and Abdomen**

- Chordomas and Chondrosarcomas – Tumours of the brain stem, spinal cord or central nervous system
- Early Lung cancer – Local treatment to minimize lung injury

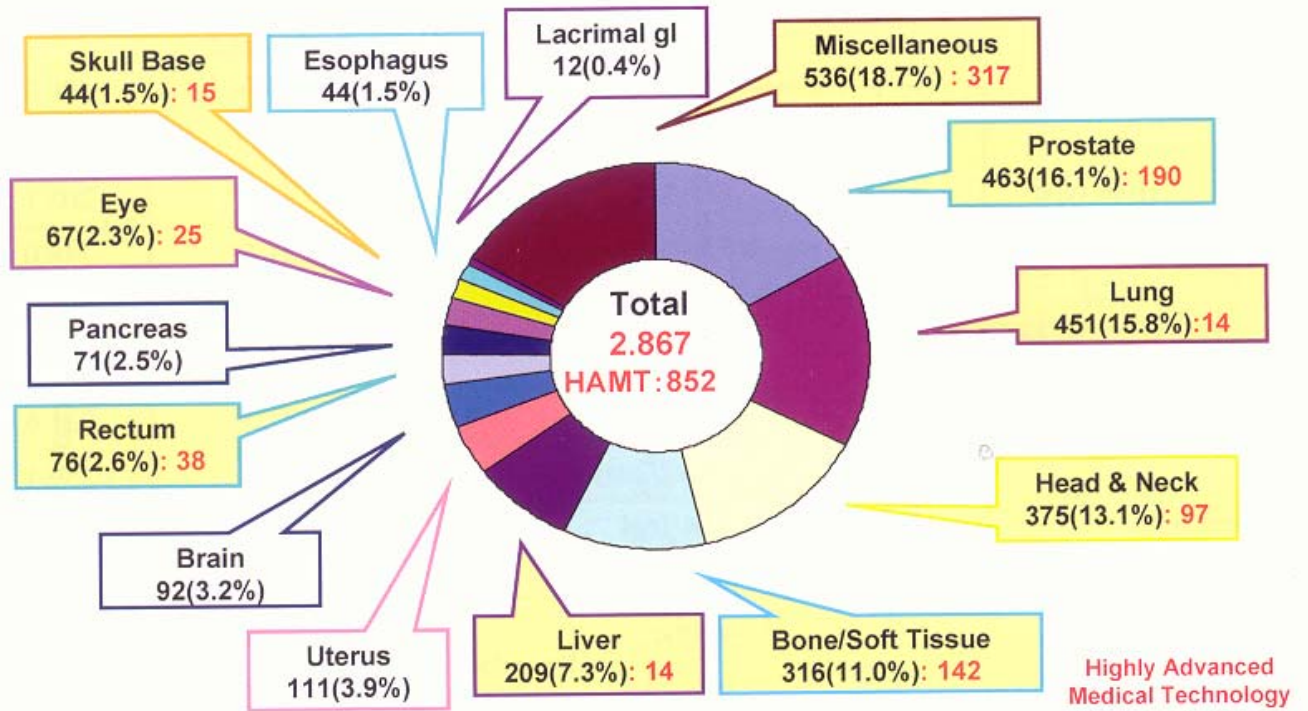
### **Pelvis**

- Prostate cancer – High dose, localized treatment for higher survival rate and minimum side effects

### **Tumours in Children**

- Brain tumours – Highly individualized localized treatment options via protons
- Orbital and Ocular Tumours – Proton treatment to prevent healthy lens and anterior chamber damage
- Sarcomas of the base of the skull and spine – a variety of condition now treated in children.

**Appendix III    Number of Patients treated with Carbon Ion Therapy at NIRS, Japan**



**Fig. 3.** Number of Patients registered in Carbon Ion Therapy at NIRS (Period: June 1994~August 2006).

J. Radiat. Res., Vol. 48, Suppl. A (2007); <http://jrr.jstage.jst.go.jp>

## Appendix IV Evaluation of Cancer Types in ECM expected to benefit from Hadron Therapy

Table 1. Cancer types, their incidences and the possible fraction to profit from IBT. The incidences are from various public sources, with emphasis on European numbers. The fraction sizes are rounded values from the consensus report of the ENLIGHT (European Network for Light Ion Hadron Therapy) working group. The list is sorted according to the expected numbers of patients for a population of 10 million.

| Indication                | Incidence (no./10 <sup>5</sup> people) | % for IBT | Annual cases |
|---------------------------|--|-----------|--------------|
| NSCLC                     | 54                                     | 20        | 1080         |
| Gastric cancer            | 16                                     | 45        | 720          |
| Prostate cancer           | 80*                                    | 25        | 575          |
| Liver cancer              | 10                                     | 50        | 500          |
| Head & neck cancer        | 13                                     | 25        | 325          |
| Non-Hodgkin lymphoma      | 14                                     | 20        | 280          |
| Rectal cancer             | 11.4                                   | 20        | 228          |
| Pancreatic cancer         | 9.8                                    | 20        | 196          |
| Bladder cancer            | 10.1                                   | 15        | 152          |
| Cervical cancer           | 6.7                                    | 20        | 134          |
| Uveal melanoma            | 0.6                                    | 100       | 60           |
| Brain tumors              | 2.3                                    | 25        | 58           |
| Bile duct cancer          | 2.7                                    | 20        | 54           |
| Soft tissue sarcoma       | 1                                      | 40        | 40           |
| Hodgkin lymphoma          | 2                                      | 20        | 40           |
| Anaplastic thyroid cancer | 0.7                                    | 45        | 32           |
| Salivary gland cancer     | 0.5                                    | 45        | 23           |
| Pediatric malignancies    | 0.6 (3.6/10 <sup>5</sup> children)     | 15        | 9            |
| Chordoma                  | < 0.1 (0.06)                           | 100       | 6            |
| Chondrosarcoma            | < 0.1 (0.03)                           | 100       | 3            |
| <b>Sum</b>                |  |           | <b>4515</b>  |

\*Related to 10<sup>5</sup> men.

**Appendix V**

**Construction Staff**

| Staff Member             | Cost/member | Number | Hadron  |           | Staff     | Construction | Costs        |
|--------------------------|-------------|--------|---------|-----------|-----------|--------------|--------------|
|                          |             |        | Year 1  | Year 2    | Year 3    | Year 4       |              |
| Project Director         | 300,000     | 1      | 150000  | 300000    | 300000    | 300000       |              |
| Deputy                   | 200000      | 1      | 200000  | 200000    | 200000    | 250000       |              |
| Project Engineer         | 250000      | 1      | 250000  | 250000    | 250000    | 250000       |              |
| <b>Accelerator Staff</b> |             |        |         |           |           |              |              |
| Accelerator Head         | 200,000     | 1      | 100000  | 200000    | 200000    | 200000       |              |
| Deputy                   | 150,000     | 1      | 75000   | 150000    | 150000    | 150000       |              |
| Accelerator Physicists   | 100,000     | 2      | 100000  | 200000    | 200000    | 200000       |              |
| Head Electrical Engineer | 150,000     | 1      | 75000   | 150000    | 150000    | 150000       |              |
| Electrical Engineers     | 100,000     | 2      | 100000  | 200000    | 200000    | 200000       |              |
| Head Mechanical Engineer | 150,000     | 1      | 75000   | 150000    | 150000    | 150000       |              |
| Mechanical Engineers     | 100,000     | 2      | 100000  | 200000    | 200000    | 200000       |              |
| Technicians              | 100,000     | 4      | 200000  | 400000    | 400000    | 400000       |              |
| Control Staff            | 120,000     | 6      | 360000  | 720000    | 720000    | 720000       |              |
| <b>Laboratory Staff</b>  |             |        |         |           |           |              |              |
| Head treatment           | 500,000     | 1      |         | 500000    | 500000    | 500000       |              |
| Deputy                   | 200,000     | 1      |         | 150000    | 150000    | 150000       |              |
| Software                 | 120,000     | 4      |         | 480000    | 480000    | 480000       |              |
| Technicians              | 100,000     | 3      |         | 400000    | 400000    | 400000       |              |
| Safety Officer           | 100,000     | 1      |         | 100,000   | 100,000   | 100,000      |              |
| <b>Administration</b>    |             |        |         |           |           |              |              |
| Business Manager         | 150000      | 1      | 75000   | 150000    | 150000    | 150000       |              |
| Business Assistants      | 80000       | 3      |         | 80000     | 160000    | 240000       |              |
| Receptionist             | 60000       | 1      |         |           | 60000     | 60000        |              |
| OAS                      | 80000       | 2      |         | 40000     | 80000     | 80000        |              |
| Contact Staff            | 100000      | 10     |         | 1,000,000 | 1,000,000 |              |              |
| Totals                   |             | 50     | 1860000 | 6020000   | 6200000   | 5330000      |              |
| Grand Total              |             |        |         |           |           |              | \$19,410,000 |

## **Appendix VI - Committees**

### **Council**

**Internationally recognised scientists from Major Research Institutions**

### **Physics and Engineering Advisory Committee**

**International specialists in Accelerators and Associated Facilities**

### **International Medical and Therapy Advisory Committee**

**International Specialists in Hadron Therapy and Associated Sciences**

### **National Advisory Committee**