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M. Regler, Th. Auberger,  
H. Schönauer and W. Mitaroff
Verein Austron

Editors:  
M. Regler and W. Mitaroff
Location (artist's view by G. Huber)
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\(^1\) Head of the Department of Therapeutic Radiology and Oncology of the Medical University of Innsbruck and President of the Austrian Society of Radio Oncology, Radiobiology and Medical Physics
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Preface 2011

Meinhard Regler (Verein Austron)

More than three years have passed since the preliminary first edition of these proceedings. Nonetheless the contributions have not suffered obsolescence. After the February 2007 decision of the Legislative Assembly of Lower Austria to support construction and operation of MedAUSTRON, the spirit of optimism was high in Austria. This Gantry Workshop was also an excellent opportunity for members of the Project Development Company (PEG MedAustron) to establish scientific contacts with the international hadron therapy community. Setting up from scratch a team of experts was not an easy task in a country that had no experience in accelerator construction. Anticipatory, however, a few PhD theses had already prepared the ground.

A pending question was the strategy w.r.t. a possible carbon beam gantry, and whether its immediate construction would risk to overstrain – technically and financially – the project MedAUSTRON. At present, there is no unambiguous medical evidence for the necessity of such a gantry.

Whereas at the time of planning this workshop I had dreamt of a carbon beam gantry (I had mentored the PhD thesis for a “Ferris Wheel Gantry” before), soon afterwards there was consent to postpone the decision of its construction, and to wait for the experiences gained elsewhere: the carbon beam gantry at Heidelberg, and recently a similar Japanese project.

This workshop was nevertheless a great success. Neither before nor afterwards had there been a meeting comparable to this one, which brought together leading experts from all over Europe, and which convinced the worldwide community with irrevocable certainty that MedAUSTRON had transpired from the planning to the realization stage.

In addition, this workshop was seminal for various other international activities, with the leadership of the scientific work now taken over by PEG MedAustron. The cooperation with CERN has been revitalized (after talks I had 2006 with CERN’s director-general R. Aymar), and a few EU funded projects have been established: “RegIonCo” (Regional Ion Therapy Cooperation), ENVISION (European Novel Imaging Systems for Ion Therapy), ULICE (Union of Light Ion Therapy Centers in Europe), and PARTNER (Particle Training Network for European Radiotherapy). Members of “Verein AUSTRON” are participating in all these projects, thus actively furthering ion therapy.
I am particularly pleased by the renewed cooperation with CNAO (formerly TERA). Already in 1995, after a meeting at the International Atomic Energy Agency in Vienna, U. Amaldi and I agreed to coordinate our efforts and to ask for support by CERN, which resulted in setting up the “Proton Ion Medical Machine Study” (PIMMS) working group led by Ph. Bryant.

Now the society “Verein AUSTRON” is about to close its doors, because it has ultimately achieved its goal: to promote the construction of a research facility of international significance in Austria. The groundbreaking ceremony will take place on the site in March 2011. The experts among the society’s members are now integrated in PEG MedAustron, or in the Construction and Operations Company (EBG MedAustron). In retrospect, this Gantry Workshop was the last scientific activity organized exclusively by members of the society.

My thanks are due to the society’s treasurer and webmaster W. Mitaroff who has taken care of the proceedings since 2008, maintains a version on the web, and managed the release of this revised edition. I’d also like to thank MR G. Burian who initiated and pushed the “Interreg IIIA Project”. Logoplan GmbH has kindly offered to sponsor the 2nd print run of 26 copies.

Vienna, in February 2011
Preface 2007

M. Regler (Verein Austron) and H. Schönauer
(Verein Austron and CERN)

MOTIVATION

After the decision of the Legislative Assembly of Lower Austria in February 2007 to resume the financial liability for the construction and operation of MedAUSTRON, a new era of considering the performance of MedAUSTRON was opened. During the search for private investors, which has failed, the ion gantry was only an option for possible tenders, although strongly requested by the Austrian radiooncologists.

The new situation allowed reconsidering an accelerator design developed by the accelerator experts of MedAUSTRON, which puts special emphasis on beam extraction with active energy variation, as is appropriate for an ion gantry.

During the PIMMS study an exocentric gantry had been studied by an Austrian PhD (Riesenrad Gantry), and experts from Fotec company carried out a study of an isocentric gantry. A similar isocentric gantry is under construction for the Heidelberg centre. However, nowhere in the world is an ion gantry operating so far.

It was therefore a natural concern of the “Verein AUSTRON” to call for a meeting, allowing a “tour d’horizon” to consider the different solutions discussed by scientists from research centers and by commercial companies.

ATTENDANCE / DETAILS

The meeting was scheduled from Friday noon, March 9, to Saturday evening, March 10. The fact that the meeting was held at the conference hotel (“Parkhotel Schönbrunn”) gave ample time for detailed personal discussions. 40 participants from Austria, Belgium, England, France, Germany, Hungary, Italy, Switzerland (including CERN), Slovakia, Sweden and the USA attended the meeting. Representatives came from all Hadron Therapy Centers in Europe (which use carbon ions) under construction (CNAO/Italy and Heidelberg Ion Therapy/GSI Darmstadt) or under serious consideration, as well as from Physics Research Centers and Medical Universities which support such developments. Six commercial companies which are prominent in this field also attended the meeting (ACCEL Instruments GmbH, Elimpex-Medizintechnik GmbH, IBA Particle Therapy, MT Mechatronics/Aerospace, SCHÄR Engineering AG and Siemens AG).
After the welcome message delivered by Peter Lukas, the president of the Austrian Society of Radiooncology, Thomas Auberger from the Medical University of Innsbruck held the opening talk, in which he put strong emphasis on the necessity of an ion gantry from the physician’s point of view, followed by a great variety of contributions from physicians, accelerator scientists and industry representatives. During his welcome address on Saturday morning Meinhard Regler underlined that the necessity of an Ion Gantry should be considered when designing the accelerator, as was the case for the PIMMS design.

CONTRIBUTIONS
A total of 22 contributions dealt with the different aspects of the ion gantry theme:

• The Rationale of an Ion Gantry.
  As there is a pending controversy about the necessity of a gantry, it appeared meaningful to have presentations providing answers hopefully contributing to a consensus.
  • The European scenario from the physician’s point of view
  • Treatment planning with and without a Gantry – the physicist’s point of view of the virtues of a Gantry
  • Can high-quality positioning systems for patients replace a rotating Gantry?
  • Comparative treatment planning for proton and photon therapy, in particular with regard to the influence of beam application techniques

• Status Reports:
  • Status of the Austrian – Hungarian Interreg IIIA Project “Med-Austron”
  • Status of MedAUSTRON
  • Status of HIT and the GSI Gantry
  • CNAO status and Gantry plans for the future
  • ETOILE status

• State of the Art:
  As only one ion gantry is currently under construction, it is of interest to learn about its problems and achievements; the same holds for the most advanced, atypical proton gantry:
  • Gantries for hadron therapy – an overview
  • Matching Gantry
  • The mechanics of the GSI Gantry
  • Proton Gantry – design considerations and state of the art
• Industry’s Concepts:
  • Mechatronic Systems for Gantry and Patient Positioning
  • Concept and performance of the RPTC Gantry Systems
  • The IBA Superconducting Gantry concept

• Innovative Concepts:
  From superconducting gantry studies over multi-room Riesenrad-like gantries to FFAG (fixed-field) structures, ideas are not lacking:
  • CEA study on superconducting Gantry magnets
  • Multi-room Gantry concepts, including the “Riesenrad Gantry”
  • Development of a centre for multiple simultaneous treatments for the Karolinska University Hospital in Stockholm
  • Non-scaling FFAG Gantry

• Summary and Conclusions:
  • As usual the speakers gave personal but comprehensive overviews of the present situation in the field.

WORKSHOP SUMMARY and CONCLUSIONS

In view of the motivation outlined above, a certain number of attendants was expected. The fact that far more people registered proved that it was the right time to review the state of the art. The latter was somewhat dormant due to stagnation of the larger projects in France and Austria and because the community is waiting for the results from HIT, where the world’s only ion gantry is being assembled. The anticipated cost of 10 to 15 M€ of any more conventional design appears prohibitive for local or private initiatives. In private discussions, the costs including the gantry building with appropriate shielding, patient preparation and safety access facilities were estimated to be of the order of 10% of the cost of the whole facility.

In the meantime, affordable proton gantries may be attractive even in an ion/proton therapy centre before a new generation of ion gantries is available. In this context it was important to have the most advanced proton technology presented.

On the other hand, the high costs encourage the search for new approaches. The exocentric, Riesenrad-like designs presented point in this direction, but they are finding little acceptance by radiologists because of their operational complications. Nevertheless one project at Karolinska Hospital is entirely based on two exocentric multi-room gantries.
The obviously appealing research on gantries with superconducting magnets is halted at the stage where prototypes would have to be built and tested, again due to the high costs. Such prototypes have to prove, among other things, that the required field variation speed can be achieved. Also, the effect of the stray fields can be established reliably only by means of measurements.

It was argued that synchrotrons are more favorable for a gantry but the arguments against SC cyclotrons are of a rather general nature: the required ion degraders may contaminate the beam with fragmentation products and create avoidable residual radioactivity.

Apart from the discussion of purely gantry topics it was felt that also the opportunity for the staff of the various European projects and industrial companies to talk to each other was extremely fruitful.

Vienna, in May 2007

PS: Some of the synopses have been updated.
Welcome

As President of the “VEREIN AUSTRON” I am very happy to realize that our Project “MED AUSTRON” is on its way to become reality within a few years. The Country Lower Austria is putting great effort into starting the construction of this main scientific Austrian project.

As a physicist and physician I am very excited of having the possibility in Austria to work on a challenging mission like this implementation of a new and promising radiooncologic form of treatment. In this context many questions of technical development arise. One of these important questions is the one for the necessity of a gantry in Ion therapy, which is expensive and complex.

To answer this question of necessity, costs and technical possibilities this workshop was organized, and I am personally very thankful to Meinhard Regler who at first succeeded to gather all experts in the field around this meeting in Vienna (which we all enjoyed very much), and secondly put immense work into the accruement of these Proceedings, which we are proud to present.

Peter H. Lukas, m.p.
President “Verein Austron”
SYNOPSES, Part 1:

The Rationale of an Ion Gantry
Opening talk:

Rationale of a Carbon Ion Gantry – the physician’s point of view

T. Aubeger, R.A. Sweeney, P. Lukas

Dept. of Therapeutic Radiology and Oncology, Innsbruck Medical University, and AUSTRON Society in the frame of INTERREG-III-Work Group on Ion Therapy

Abstract:

**Background and Objective:** There are controversies between physicists, economists and physicians whether gantries are really necessary in carbon ion therapy. The immense costs and unsolved technical problems on the one hand and the exclusion of a certain patient group which cannot sufficiently be treated and the potential loss of treatment quality on the other hand are arguments which have to be regarded. Our purpose was to evaluate the percentage of patients with benefit from a particle therapy, who can or cannot sufficiently be treated without a gantry and to show unsolved problems in fix beam treatment planning and therapy.

**Methods:** Based on comparisons of 5-10 treatment plans for various tumor entities and based on the distribution of indications for particle therapy in the Austrian epidemiological survey, we evaluated the number of patients, who could be treated with horizontal and/or vertical fix beam delivery systems and the patients

**Results:** In particle therapy more patients can be treated with horizontal and vertical beams than in photon therapy. By patients’ positioning on a 6-degree of freedom treatment couch oblique beam angles up to plus/minus 15 degree can be used. With regard to this enlargement of the sectors following percentage of patients can be treated: with horizontal beam: 27% with vertical +/- horizontal beam: 46% and exclusively with an ion gantry: 26%.

**Conclusion:** With acceptance of patients’ tilted position the number of patients needing a gantry can be reduced from 46 to 26%, but many problems in treatment planning and verifications have not been solved. From the medical point of view there are clear arguments for a gantry in particle therapy.

**Scientific Background**

There are clear arguments against full rotating gantries for particle therapy and especially for carbon ion therapy. Although gantries for proton therapy are space consuming and expensive, they are feasible in clinical routine and costs may be reduced with an increasing market. However, the construction of carbon ion gantries is much more complicated. A gantry weighing about 600 tons which shall rotate with a precision of <5mm is a great challenge for industries and raises costs substantially. A sum of about 15 million EURO per gantry may limit the realisation of facilities even they are planned as national carbon ion centres. Furthermore, technical problems including the mounting of verification systems for adaptive radiotherapy in the gantry are not completely solved.

Up to now only one prototype of a carbon ion gantry has been built worldwide. With exclusion of Heidelberg Ion Centre (HIT), all planned carbon ion centres in Europe will start without a carbon ion gantry.

During the last years there were several meetings of clinicians of the four project groups collaborating in the European scientific network ULICE, which included round tables discussing the necessity of carbon ion gantries. All discussions
resulted in a consensus that from the clinical point of view a gantry is necessary for proton therapy and for carbon ion therapy as well. Arguments included the increased need of high precision of patients’ positioning in adaptive radiotherapy (especially in raster scanning particle therapy) and the necessity of the very same conditions for an optimal comparison of particle therapy with all the new techniques of modern photon therapy (IMRT, SRT and SRS), in clinical studies. Even the representatives of HIMAC in Chiba/Japan, who have more than ten years experience in carbon ion therapy without any gantry recommended urgently to install a gantry from the beginning or at least in an early phase of operation.

Although, in particle therapy more tumor locations can be treated best by choosing horizontal and/or vertical beam angles than in photon therapy, in most cases the optimum beam angle cannot be defined in advance and for a certain percentage of tumors particle therapy without a gantry is actually not an advantage in comparison with modern photon therapy techniques. But no project group made any evaluation which beam angles are usually applied in carbon ion therapy with regard to the various tumor entities and how often these beam angles are needed. There is only one group from the NCC, Hospital East, Kashiwa [1], who investigated treatment plans for proton therapy of 161 patients suffering from head and neck cancer, lung cancer, hepatic cell cancer and prostate cancer (44.1%, 29.9%, 18.6% and 6.8%, respectively) and found following distribution of beam angles: out of 379 portals (2.4 portals per fraction per patient) 113 portals (30%) were delivered exclusively by horizontal beams (90/270 degree), 90 portals (24%) were delivered by vertical beams (0/180 degree) or combined by horizontal and vertical beams, and 176 portals (46%) needed beams of different oblique angles without any preference on a special direction.

**Material and Methods**

In a nationwide epidemiological survey on the potential demand for ion therapy in Austria [2;3;4] we came to the conclusion that 2079 cancer patients in Austria would benefit from particle therapy every year. This is a percentage of about 13 per cent of all new cancer patients who have to be treated by radiotherapy every year in Austria. This correlates very well with studies in other European countries [5;6]. As a back-up of this survey, treatment planning studies were performed at Innsbruck Medical University and Vienna University [7;8;9] with support of the AUSTRON Society. In these studies we compared treatment plans for ion therapy, IMRT and 3D-conformal radiotherapy for various tumor entities. For each tumor entity treatment plans of 5-10 different cases were performed and the most typical plan this entity was elected. Taking into account that for ion therapy less complicated planning techniques are feasible than for photon therapy we optimized treatment plans with regard to a minimum number of portals and a maximum simplicity of beam angles. When possible without any loss of dose conformity and saving of normal tissue, plans with horizontal and/or vertical portals were preferred. Because we have some experience in fix beam neutron therapy our department was involved in the development of oblique patients’ positioning systems [10]. It also collaborated with Medical Intelligence Company.
in the development of the HEXAPOD treatment couch, which can be rotated along the patient's axis up to plus/minus three degrees [11]. This system allows also greater tilt angles up to 15-20 degrees if there would be any demand for an increased rotation. Positioning with a tilt of 15 degrees is sufficiently reproducible and mostly tolerable for the patients. Therefore, in this plan comparison we defined treatment plans using exclusively horizontal or vertical beams and also treatment plans using beam angles of less than 15 degree from horizontal (90/270 degrees +/- 15 degrees) or vertical beam (0/180 degrees +/- 15 degrees) as plans which can be realised without a gantry. All other plans containing greater beam angles were defined as not feasible without an ion gantry. A further question was, whether a part of patients can be treated sufficiently using a treatment chair, which offers the option of an accurate fixation, as it is available in some centres for proton therapy and in the both carbon ion facilities in HIMAC/Chiba and GSI/Darmstadt. We estimated that all tumors of the brain, base of skull and head and neck without supraclavicular lymph node metastases should be suited for positioning in a chair. In addition treatment plan comparison was made with regard to the impact of patients' position on movement of organs and with regard to the difference of target volumes from beam angle to beam angle. (The results are shown elsewhere.)

Results

In many cases treatment planning for ion therapy is much easier than for conformal photon therapy and especially for IMRT. For proton therapy and even more for carbon ion therapy of many tumors the number of portals can be reduced remarkably in comparison with photon therapy. Therefore the mean of portals over all particle treatment plans was only 2.4. The higher RBE value of carbon ions and the active scanning technique increase the effect of the Bragg peak and amplify the decrease of the number of portals. For example figures 1 a+b show a comparison of treatment plans for 3D-conformal photon therapy (fig. 1a) and for proton therapy (fig.1b) in a patient suffering from an esophageal cancer. Since six portals and six different beam angels are used in the photon plan, the same dose conformity to the target volume can be reached with three portals in the proton plan. Because the oblique beam could also be delivered from 270 degree without any significant loss of quality, the treatment could be performed with a horizontal and vertical fix beam, too. The comparison of the two plans with regard to the dose distribution shows clearly the improvement of particle therapy with regard to the decrease of dose in the heart and in the lung. Whereas in the photon plan the major part of the heart is included in the 50% isodose and a small part in the 70% isodose, the dose maximum in the heart is 20% in the proton plan. In the photon plan a major part of the lung will be irradiated with a dose of between 20% and 30% of the proscribed dose. In the proton plan the lung volume getting more than 20% of the proscribed dose can be reduced to the half.
Figure 1a,b: Comparison of treatment plans for 3D-conformal radiotherapy (fig. 1a) and for ion therapy (fig. 1b) of an esophageal carcinoma. The photon plan consists of six portals including four oblique beam angles. The ion therapy plan consists of only three portals. The treatment plan for particle therapy shows a remarkable improvement regarding dose distribution to the heart and lung.

The number of potential patients being treated sufficiently with horizontal and/or vertical portals and the number of patients needing a rotational gantry are shown in table 1. Summarizing the total number of patients suffering from all tumor entities which were evaluated in the Austrian epidemiological survey on the demand for ion cancer therapy we can estimate that out of 2079 cancer patients having potential benefit from ion therapy 571 patients (27 %) can be treated sufficiently by horizontal beams (+/- 15 degree of tilt) and 960 patients (46 %) can be treated by vertical +/- horizontal beams (+/- 15 degree of tilt). This means that 73 per cent of patients could be treated sufficiently without any gantry. Only in 548 patients (26 %) a rotational gantry would be necessary.

The question whether a part of patients can be treated sufficiently using a treatment chair depends extremely on fixation and mobility options of the chair and was not investigated for a special technical model. Table 2 shows a multiplication of the number of tumor entities which can be treated using a chair instead of a couch by the number of estimated patients who would benefit from ion therapy according to the Austrian survey.

As a result of this evaluation the number of patients treated sufficiently in a chair is very small and the expenses are not necessary when a centre has a rotational gantry available. Without an ion gantry it can be helpful only in tumors of brain, eye or head and neck. The cost-benefit analysis depends on the number of cases from these tumor entities. With regard to the patient numbers of our epidemiological survey we found only 117 cases out of 2079 (5.5 %) who could benefit from positioning in a chair.
Table 1: Estimated number of potential patients for ion therapy in Austria who could be treated by horizontal or vertical beams and of potential patients who only can be treated with a gantry.

<table>
<thead>
<tr>
<th>Tumor Entity</th>
<th>n</th>
<th>OGRO 2003</th>
<th>Beam</th>
<th></th>
<th>HZ</th>
<th>(%)</th>
<th></th>
<th>HZ+VT</th>
<th>(%)</th>
<th>Gantry</th>
<th>(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>brain tumors</td>
<td>128</td>
<td>96</td>
<td>75</td>
<td>32</td>
<td>25</td>
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<td></td>
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<tr>
<td>tumors of the base of the skull</td>
<td>20</td>
<td>12</td>
<td>60</td>
<td>4</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>eye melanomas</td>
<td>23</td>
<td>23</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>cancer of the head &amp; neck and thyroid gland</td>
<td>260</td>
<td>91</td>
<td>35</td>
<td>104</td>
<td>40</td>
<td>65</td>
<td>25</td>
<td></td>
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<tr>
<td>lung cancer</td>
<td>272</td>
<td>177</td>
<td>65</td>
<td>95</td>
<td>35</td>
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<td>mediastinal tumors</td>
<td>43</td>
<td>20</td>
<td>23</td>
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<td>colorectal cancer, liver and pancreatic cancer</td>
<td>397</td>
<td>278</td>
<td>70</td>
<td>119</td>
<td>35</td>
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<tr>
<td>cancer of cervix and corpus uteri and bladder cancer</td>
<td>99</td>
<td>69</td>
<td>70</td>
<td>30</td>
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<td>prostate cancer</td>
<td>470</td>
<td>445</td>
<td>95</td>
<td>25</td>
<td>5</td>
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<tr>
<td>bone &amp; soft tissue sarcomas, bone metastases</td>
<td>96</td>
<td>60</td>
<td>63</td>
<td>6</td>
<td>20</td>
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<td>M. Hodgkin + Non Hodgkin Lymphomas (15 pt.)</td>
<td>149</td>
<td>99</td>
<td>66</td>
<td>50</td>
<td>35</td>
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<td>breast cancer</td>
<td>48</td>
<td>28</td>
<td>58</td>
<td>20</td>
<td>42</td>
<td></td>
<td></td>
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<tr>
<td>pediatric tumors</td>
<td>74</td>
<td>74</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2079</td>
<td>571</td>
<td>27</td>
<td>960</td>
<td>46</td>
<td>548</td>
<td>26</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 2: Estimated number of potential patients for ion therapy in Austria, who could have a benefit from a treatment chair instead of a couch.

<table>
<thead>
<tr>
<th>Tumor Entity</th>
<th>n</th>
<th>OGRO 2003</th>
<th>Position</th>
<th></th>
<th>couch</th>
<th></th>
<th>chair</th>
<th></th>
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</thead>
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<tr>
<td>brain tumors</td>
<td>128</td>
<td>94</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>tumors of the base of the skull</td>
<td>20</td>
<td>10</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eye melanomas</td>
<td>23</td>
<td>23</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cancer of the head &amp; neck and thyroid gland</td>
<td>260</td>
<td>210</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>lung cancer</td>
<td>272</td>
<td>272</td>
<td>272</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mediastinal tumors</td>
<td>43</td>
<td>43</td>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>colorectal cancer, liver and pancreatic cancer</td>
<td>397</td>
<td>397</td>
<td>397</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cancer of cervix uteri and myometrium and bladder cancer</td>
<td>99</td>
<td>99</td>
<td>99</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>prostate cancer</td>
<td>470</td>
<td>470</td>
<td>470</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>bone &amp; soft tissue sarcomas, bone metastases</td>
<td>96</td>
<td>96</td>
<td>96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M. Hodgkin + Non Hodgkin Lymphomas (15 pt.)</td>
<td>149</td>
<td>149</td>
<td>149</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>breast cancer</td>
<td>48</td>
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<td>48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pediatric tumors</td>
<td>74</td>
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<td>74</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2079</td>
<td>1962</td>
<td>117</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Discussion

Beyond doubt, there are a certain number of tumor entities and locations which can be treated sufficiently with ions and there is a clear benefit with respect to the dose distribution even when a gantry is not available. However, there are various problems on treatment planning of target volumes in a centre which is equipped with only fix horizontal and/or vertical beams, especially, when an increase of treatment options shall be reached by rotated position of the patients. Three important aspects have to be noticed:

1. Besides treatment planning of high precision radiotherapy needs sophisticated imaging and image fusion of CT scans, MRI and PET, especially it needs same patient’s position during all planning and treatment procedures. For 3D treatment planning using oblique portals in a facility with fix horizontal and/or vertical beams the patient has to be brought in the same tilted position during all imaging and planning phases and later on during whole therapy. Different beam angles request different positions. This means, during one fraction of treatment the patient has to change his position several times and the verification of this position has to be done several times, too. Even more, for two different positions of the patient two separate treatment plans and in consequence two separate sets of verification portals are necessary.

2. The angle for oblique patient’s position has to be defined before treatment planning at the CT-scan. But the optimal beam angle is usually the result of isodose planning and it is difficult to estimate it in advance.

3. Organ movements between two differently rotated positions of the same patient may influence the complete dose distribution in the tumor and in the organs at risk. In a separate clinical experiment we compared CT scans showing organ movements of rotated patients in correlation with the rotation from five to five degrees. In consequence to the organ movements there was a significant change of dose distribution between the different beam angles with regard to the target volume and to the organs at risk. Up to now this paper is not accepted.

4. Until now we don’t have treatment planning systems to summarize dose plans from different treatment positions. Therefore tilting the patient in special positioning systems along his/her axis goes ahead with a loss of precision and with a remarkable increase of time consuming calculation and verification.

5. Everybody who intents to build an ion centre has to consider how much a carbon ion gantry will really cost in comparison with the loss of patients, who cannot be treated without a gantry. When we estimate a number of 1200 treated patients per year for one carbon ion cancer centre regarding the percentage of untreatable patients from our calculation there will be a loss of about 300 patients per year. Likely these are the patients, who would have the greatest benefit from ion therapy. Allowing only treatment plans with strictly horizontal and vertical beams about 550 patients could not be treated without a gantry.

6. Furthermore one has to compare costs of a gantry with the additional time for planning, positioning and treatment. When we expect that a gantry would
reduce time of patients’ positioning by at least five to seven minutes and when we assume an operation scenario of three patients per hour and two overlapping shifts of thirteen hours on 260 days per year, 3380 additional fractions can be delivered. When we estimate that one treatment includes about 20 fractions per patient, about 170 additional patients per year could be treated. Altogether, this additional throughput would compensate the expenses for an ion gantry over a time period of five years.

Therefore from the medical point of view fix beam facilities with a horizontal and a vertical beam delivery system are probably the best option for the first few years, but should be completed with at least one rotating gantry as soon as possible.

**Figure 2a-c:** Treatment plan simulating an irradiation with changing beam angles of +/- 15° from day to day(a+b) and summarized treatment plan (c). For virtual treatment planning the patient was not positioned in differently tilted positions.

**Conclusion**

From the medical point of view there are clear arguments for a gantry in particle therapy. In the sparse literature dealing with this problem about 46 per cent of cancer patients who would benefit from a particle therapy cannot be treated sufficiently with fixed horizontal and /or vertical beams. We can reduce the number of patients needing a gantry to 27 per cent, when we accept beam angles deviating up to 15 degree from horizontal and vertical beam. These small deviations can be reached by rotation of the patient on a 6-degree of freedom treatment couch. But the movement of the patient during a fraction or between fractions delivers various problems in therapy planning and verification, which have not completely been solved. Particularly patients who benefit most from particle therapy seem to be in the group which cannot be treated without a gantry. Also in patients who can be treated with a fix beam delivery system, very likely time saving would cover the expenses for a gantry within five years.

**Literature**

1. Nishio T, Ogino T., Annual Report of the Particle Therapy Division, Research Centre for Innovative Oncology, National Cancer Centre, Kashiwa, Japan, 2003


Treatment Planning with and without a Gantry: the physicist’s point of view

Oliver Jäkel

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Introduction

At the Heidelberg Ion Beam Therapy Center (HIT) the first heavy ion gantry worldwide has been installed. It has a diameter and length of approximately 13m and 25m, respectively. It weight is around 600tons with a moving mass of more than 400tons [1]. Although its diameter is comparable to proton gantries, its overall size and mass are exceeding the proton gantries by far (a typical proton gantry has a mass in the region of 120tons). This in turn causes significant costs for the surrounding building. The question to be addressed here, is, if such an installation is really needed, given the excellent dose distributions that can be achieved with carbon ion beams even by fixed beam-lines.

The paper is organized as follows: first some general aspects are outlined, which may be important, when comparing treatment plans prepared with or without a gantry. Then treatment plans for several anatomical sites of primary interest in carbon beam radiotherapy are being discussed. This includes a brief review of a planning study for skull base tumors as well as some cases of spinal and cervical chordoma, pancreatic carcinoma, prostate carcinoma and lung tumors. It should be noted, that all plans are calculated for a scanning beam and for indications of primary interest at the Heidelberg Ion facility.

General aspects

To answer that questions a number of treatment plans for various anatomical locations were prepared. The following aspects can be identified, which may be important in comparing treatment plans obtained by using a gantry with plans obtained using fixed beam lines:

• Quality of the treatment plans
• Range uncertainties due to: Organ movement, Patient setup, Metal implants
• Patient positioning: Prone/supine position, stability, comfort
• Other: Safety of the patient, QA, patient alignment, image guidance

The quality of the treatment plans is usually in the focus of planning studies and indeed gives important information on the expected dose distributions using
various techniques. The differences found in these comparisons, are however, often relatively small, so that a direct benefit from the dosimetric characteristics of a plan are not always obvious. One has to keep in mind, that these dose distributions are always connected to substantial uncertainties and is widely accepted among proton and ion therapy centers that treatment plans have to be assessed in terms of their robustness against various factors. Of special importance here are range uncertainties, since they are special for proton and ion beam therapy and may lead to severe over- or under-dosages in the target volume, which may both be critical for the patient. There are several reasons for range uncertainties, but all of them may be mitigated by using appropriate beam angles, rather than relying on fixed angles.

A separate issue (although some connections to the range uncertainties exist) is the positioning of the patient which is used. When a gantry is used, one generally has more flexibility in positioning the patient and can adapt more to the need of the patient. E.g. in the case of a para-spinal tumor, the patient would preferably be positioned in prone rather than supine position. This shortens the ion range and limits also uncertainties introduced by movement of the bowel. The prone position is, however not as stable as a supine position (especially for adipose patients) and may not even be tolerated by some patients, since it a may cause pain, as was reported for some of our patients being treated e.g. for pancreatic tumors. Even if tolerated, the prone position may simply be uncomfortable for the patient, which in turn may cause additional movement of the patient.

Some other aspects to be considered are the safety of the patient, which may be an issue for beam line concepts, where the patient may not be accessible at any time during the treatment (like in the Riesenrad design). Also aspects of quality assurance may be important, as these procedures may be more time consuming for some designs, which may lead to a reduced patient load and thus be relevant in terms of the overall facility performance. Also the questions of patient alignment and image guidance are an issue here. If e.g. a patient is treated in seated position (like e.g. in the Chiba facility), in order to gain flexibility in the treatment angles, then the additional problem of CT imaging in that position arises. Although a vertical CT scanner was realized in Chiba, it not a commercial and certified medical product and does not easily comply with the Medical Device Directive applicable in the EU. Other aspects may be laser and X-ray systems which are used for position verification and that have to be mounted in the treatment room close to the patient.

Skull base tumors

The case of skull base tumors was discussed in the literature already [2]. Skull base tumors were selected as they pose the toughest constraints on the positioning and conformity of the treatment. Three aspects were investigated in the paper: first the anatomical situation of 10 patients was analyzed by superimposing cylindrical projections of the tumor and organs at risk in order to
identify common treatment angles which may be of general use. Furthermore the
treatment angles of 50 patients that were treated with conventional RT were
visualized together with the selected angles for 9 treatment plans using an ion
beam gantry. The conclusions of this paper were the following: while for all
patients a reasonable treatment plan can be obtained even without a gantry, the
possible fine tuning of angles often gives some additional benefit on the dose
distribution. A clear benefit for the dose distribution was found in about 20% of
the patients with changes mainly in the medium dose range and less in the
maximum doses in organs at risk.

Para-spinal and cervical tumors
The main problem here is the direct vicinity of the tumor to the spinal cord, often
surrounding it partially or sometimes even completely. Since the tumor in most
cases is located anterior to the spinal cord, a vertical beam may be used with the
patient positioned in supine position. Given the restricted positioning accuracy
for spinal tumors, treatment plans composed of several posterior fields are more
favorable than a single anterior beam. A special problem for para-spinal tumors
is metal implants of titanium, which are commonly used to stabilize the vertebral
bodies and which are found in many patients. These implants may cause
significant range uncertainties. In order to avoid an irradiation through these
implants, a flexible beam delivery using a gantry is very valuable.

Pancreatic carcinoma
For these patients, a realistic treatment plan can in most cases only be achieved
with the patient in supine position. In order to avoid the bowel, spinal cord, liver
and kidney as the most important organs at risk and to avoid large uncertainties
due to organ movement, at least two inclined beams (preferably from posterior
direction) seem to be necessary. Fixed horizontal or vertical beams are therefore
ruled out and only inclined beam line might be useful, although they do not allow
an adaption to the individual situation of a patient.

Prostate carcinoma
For prostate cancer patients the treatment with two opposing horizontal fields of
protons or ions seems to be already a standard. A planning study on the
potential benefit of a gantry was published by our group and showed only very
minor benefits, when a gantry was used [3]. It was concluded that there is in
general no need for a gantry to treat patient with prostate carcinoma.

Lung cancer
There is a large variety of lung tumors in terms of location and size, so that it is
very difficult to make a general statement here. A general problem however, is
the large range uncertainty due to the lung tissue itself, but also due to the
intercostals regions and in general the breathing motion. In general a treatment
in supine position is preferred, in order to minimize the effects of breathing
motion. An example is given for a typical early stage tumor close to the thoracic
wall, which may be eligible for a carbon ion RT. A posterior beam helps
significantly to reduce the range uncertainty due to the little traversed lung tissue, while lateral beams would be connected with a much larger uncertainty.

**Summary and conclusions**

In summary the potential of a gantry for the various tumor sites is that for about 20% of patients with a skull base tumor, a significant benefit can be achieved by the use of a gantry. An important aspect is the possibility to fine tune the treatment angles. For para-spinal and cervical tumors a significant is expected for the majority of patients by the use of a gantry, due to the increase patient movement and the frequently encountered metal implants. Also for patients with pancreatic tumors (and similarly for all retroperitoneal tumors) a gantry seems to be a benefit for most patients due to the increased comfort in supine position and the reduced range uncertainties, while for prostate carcinoma (and maybe for some other pelvic tumor) patients no benefit is expected. Concerning lung tumors, there are certainly some tumors that are likely to benefit from the use of a gantry, although it is difficult to quantify these numbers.

In conclusion it can be stated that for many patients an accurate and very conformal treatment can be delivered using fixed beams (even if restricted to horizontal beams). Depending on the tumor site there is, however, a certain percentage which would certainly benefit by the use of a gantry. These benefits are not always obvious (like the reduction of uncertainties in the delivered dose) and may be indirect, like the patient inducing less motion, when being in a more comfortable position. While the clinical benefit of ion beam therapy is still being evaluated against IMRT and IMPT in clinical studies, the quality of the treatment should not be biased by the beam delivery, which may lead to a suboptimal treatment at least for some patients. This, however, may change when more clinical experience was gained and maybe complicated cases can be sent to dedicated centers in the future.

**References**


“Can high quality patient positioning systems replace a rotating gantry?”

Reinhart A. Sweeney, MD, BSc,
Thomas Auberger MD
Department of Radiation Oncology, Innsbruck, Austria

Background

Highest quality positioning and fixation systems are mandatory for any precision radiation therapy with high doses applied to tumors abutting critical structures. Steep dose gradients need to be transferred from the planning to the treatment situation and any repositioning accuracy or intra treatment motion might cause not only treatment failure but also life threatening sequelae. Many different intra- and extracranial positioning systems have been developed which might be applicable in heavy ion therapy. Compared with photon therapy with its relatively cheap gantries, the main obstacle to similar degrees of treatment freedom is the prohibitively expensive gantry, which, to date, does not even exist.

This is less of a problem for cranial indications, where a seated patient can be rotated 360° in a special treatment chair, some of which can also tilt around isocentre to a certain degree. For extracranial indications, where it has been shown that multiple beam angles would be advantageous in at least one quarter of the expected indications (1), robotic treatment tables might be used to tilt a patient around her left right and cranio-caudal axes (Figure 1). This presentation discusses all current cranial and extracranial (re) positioning and fixation systems and focuses here on the anatomic consequence of tilting a patient instead of a gantry. Is organ shift an issue to be considered if patients are to be rotated instead of a gantry?
Materials and Methods

In preparation of the planning CT for extracranial stereotactic radiotherapy (ECSRT), two patients (Stage II / III Lung cancer) positioned in a stereotactic fixation system consisting of an individualized vacuum mattress and an optional vacuum pressure foil which sandwiches the patient into the vacuumcushion (BodyFix, Medical Intelligence)(2,3). Three spirals were acquired; one as usual, horizontally supine and two where the patient was rotated by 10 and 20° respectively, with and without the vacuum pressure foil (Figure 2). The rotated datasets were fused to the original one using the stereotactic frame as reference (Figure 3).
Figure 2: BodyFix (Medical Intelligence GesmbH) double vacuum fixation whereby the stereotactic frame (with patient) is rotated by 20°.

Figure 3: Reference Image (a) to which the tilted patient data set (b) was registered (mutual information based) using the stereotactic frame (arrows). A displacement of mediastinal structures (between lung which is contoured in blue) as well as surface skin (yellow) can be seen. Spinal canal (purple) in contrast is not displaced at this level. Also visible in (b) is the vacuum mattress surrounding the patient and the vacuum hose of the pressure foil system.

All relevant organs were contoured in the reference dataset only. By the fusion process, these structures, referenced only to stereotactic space, were transformed to the tilted dataset (thus disregarding the tilted anatomy).

The displacements were then easily measurable. The results are listed in Table 1.
## Displacement of tilted from reference position (mm)

<table>
<thead>
<tr>
<th></th>
<th>10°</th>
<th>20°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/o vacuum-foil</td>
<td>w/o vacuum-foil</td>
</tr>
<tr>
<td>lung tumor (GTV)</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>spine*</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>esophagus</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>mediastinum</td>
<td>12</td>
<td>15</td>
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<tr>
<td>Heart</td>
<td>15</td>
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</tr>
<tr>
<td>Liver</td>
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</tr>
<tr>
<td>abd. Aorta</td>
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<td>3</td>
</tr>
<tr>
<td>Kidneys</td>
<td>0-5</td>
<td>12</td>
</tr>
<tr>
<td>thoracic wall</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Abdominal wall*</td>
<td>&gt;15</td>
<td>±20</td>
</tr>
<tr>
<td>Bladder</td>
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</tr>
<tr>
<td>uterine corpus</td>
<td>n.I.</td>
<td>30</td>
</tr>
<tr>
<td>femoral heads</td>
<td>n.I.</td>
<td>15</td>
</tr>
</tbody>
</table>

* combination of lateral and anterior movement (falling out)

### Table 1: Displacements of organs from reference position (0°) at 10° and 20°, without and with (only at 20°) vacuum-pressure foil. w/o= without, n.I. = not imaged

Figure 4: Example further caudal: Note how the left kidney is displaced irrespective of vacuum foil and how the abdominal wall falls toward the patients left.
Discussion

From Table 1 it becomes very obvious that organs do move when a patient is rotated out of the horizontal to 10 and 20°. The limit of patient tolerance seems to be 20°, because, at this extent, the patients almost falls out of the vacuum mould. Probably a maximum of 15° would be a more reasonable maximum, even if a vacuum pressure foil is used.

Organ movements of 10-30 mm are largely unacceptable for precision high dose or high LET radiotherapy. Even a vacuum pressure foil, which serves to push patients into the vacuum mattress, doesn’t seem to suppress organ or even body surface position, the latter being very relevant for depth dose calculations. While no significances can be determined due to admittedly low data volume, we don’t believe there to be any major surprises should a greater number of patients be examined in this manner. Surely, organ displacements will be individual, depending mainly on body mass.

Conclusion

Tilting a patient up to 15° as alternative to a gantry is possible, but large safety margins will need to be applied if only one single planning CT is used. High precision treatments with organs at risk in close vicinity to the target volume would necessitate not only a separate planning CT dataset for each angle but also a verification (conebeam) CT prior to each treatment.
Bibliography


Gantry considerations for MedAustron

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This talk in the frame of the INTERREG Gantry Workshop 2007 presented the Gantry considerations of the MedAustron Design Study published in June 2004. The authors of the Design Study recommend two individual gantries, one for protons and one for carbon ions. Both have active scanning and an isocentric layout as suggested by the medical group.

The proton gantry should be preferably one of the commercially available solutions. As most appropriate the PROSCAN gantry was seen with the advantages of parallel scanning, a wide treatment room, easy access and the drawback of increased table rotations due to the reduced beam-line rotation.

For the recommended ion gantry a GSI-based beam-line was chosen with the advantages of parallel scanning, isocentricity and the known drawbacks of size and weight. With this beam-line an ion-optical sensitivity analysis regarding the beam position accuracy at the isocentre was carried out. Whose results led to a new mechanical support concept with almost individual elements. This new concept still needs further consideration and development in the future.
COMPARATIVE TREATMENT PLANNING PHOTONS VERSUS PROTONS:
IMPLICATIONS FOR GANTRIES

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In modern photon beam therapy, three-dimensional treatment planning with more than two fields has become the “gold standard” for the treatment of most diseases. Static field arrangements, delivered using isocentric linear accelerators with multileaf collimators for field shaping, are the most widely used treatment techniques. Advanced photon beam techniques enable to achieve a high degree of dose conformity in the high dose region, which is necessary especially if the planning target volume is located nearby an organ at risk, e.g. the spinal cord, or parotis, or the optic nerve. With a new generation of three-dimensional treatment planning systems with optimisation algorithms based on physical or biological objectives and inverse planning modules, a new degree of conformity could be achieved in photon beam therapy by varying photon fluence across the field. Intensity Modulated Radiotherapy (IMRT) is considered as one of the most advanced forms of radiotherapy with photons.

Within the context of precision radiotherapy with high energy photon beams, Stereotactic Radiotherapy (SRT) and image guided brachytherapy (IGBT) need to be considered as well. As for any precision radiotherapy technique, irrespective of beam quality, precise and reproducible positioning of the patient is a pre-requisite. To guarantee an optimal and safe treatment delivery
of highly conformal dose distribution, it is not only the treatment machine that needs to be precise, but also the fixation and positioning technique need to achieve as well the highest accuracy, if possible in the millimetre and sub-millimetre range. In that aspect IMRT has benefited from SRT experience. However, recently image guided radiotherapy has set new standards in photon beam therapy, in order to ensure a high degree of geometric precision at the patient level.

Due to the physical characteristics of high energy photon beam and new developments in photon beam delivery, i.e. intensity modulation, high degree of geometric flexibility of the treatment machine has become a basic feature of treatment units since decades. In other words, table and gantry are movable to allow irradiation from directions and even immobilisation and robotic tables enable fine-tuning of the patients position, including rotational degrees of freedom.

Proton beam therapy and ion beam therapy utilize the higher physical selectivity of these beam qualities and often enable delivering doses to complex target volumes with a higher degree of conformity than with megavoltage X-ray photons. In addition, ion beam therapy is superior to photons due to the reduced healthy tissue volume irradiated to low- and medium doses. Again, prerequisites for optimal dose distribution are precise immobilisation and image guidance for patient positioning.

Similar to the advances in photon beam therapy, in particular IMRT, proton and ion beam therapy has undergone a major improvement due to particle fluence variations. More specifically, passive scattering techniques are currently superseded by scanning techniques. At present, still most patients treated so far with proton beam therapy received treatments based on passive scattering techniques. The experience made with scanning systems for protons at the PSI Villingen and with Carbon ions at GSI Darmstadt, has pushed vendors of ion beam equipment and facilities, respectively, to make scanning commercially available.

At the Department of Radiotherapy, Medical University Vienna/AKH Wien, high precision radiotherapy techniques represent a key pillar in research activities. Within the framework of precision radiotherapy, several comparative treatment planning studies were performed in order to benchmark advanced photon techniques and brachytherapy with proton beam therapy [1-7].

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* There are numerous references for comparative treatment planning studies related to proton beam therapy. However, the present communication is based on own experience and treatment planning studies. Therefore, only own research work is listed.
The different planning studies included tumours with different sizes ranging from 1cm³ to 1 litre, and different locations: para-nasal sinus, prostate, cervical, and cervix cancer with paraaortic lymph node infiltration, paediatric cases, and uveal melanoma. Within these studies passive scattering techniques and scanning techniques were evaluated for protons, as well as single field proton therapy techniques with multiple field treatment plans from beam incident from fixed and variable directions.

In summary, even for particles with a high physical selectivity such as protons, a high degree of flexibility is needed to achieve optimal dose distributions. Especially for optimization algorithms as used together with scanning techniques, a rotational gantry enables avoidance of critical structures (OAR).

On the other hand, proton gantries have become a “standard” in most dedicated proton facilities, for passive scattering techniques as well as for new centers being equipped with active scanning solutions. Why should proton therapy go beyond current standards even if proton gantries are commercially and readily available? Marketing of protons versus high tech photons might be compromised if protons therapy is restricted to fixed and sub-optimal beam directions.

Although protons have a 10% higher relative biological effectiveness than high energy photon beams, they are still particles in the low LET range. For that reason it can be assumed that protons will be used with a similar fractionation scheme as photons. Image guided beam delivery is becoming more popular in modern radiotherapy. IGRT is almost a “must” in advanced photon beam therapy. It is well known that there are time variable effects, such as organ movement, tumor response, (small) daily positioning variations. Radiotherapy is a 4 dimensional problem with time scales range from seconds to days/weeks. IGRT approaches will be implemented in proton and ion beam facilities, because changes in anatomy and topography have a more profound consequence for charged particles than for photons. In particular, any organ or tumor movement in direction of beam incidence is more difficult to handle in particle therapy, than movements perpendicular to the incident beam. In other words, “depth” variations and density modifications along the direction of particle compromise the location of the Bragg Peak. Thus, flexibility in selecting appropriate beam directions with
minimal impact on the dose distribution, i.e. a rotating gantry, is highly desirable for image
guided and adaptive proton therapy.

One of the most critical arguments against proton gantries is the question whether protons are
“the” charged particle of choice in the long run. At this point one needs to distinguish between
low and high LET particles. High LET particles, such as Carbon ions, are different species and
are, and most probably will be used, in a different manner than low LET particles, i.e. for
different tumors with different treatments strategies. High LET radiation is a topic on its own
and will not be considered here in detail. When considering only low LET particles, Helium
ions might be an interesting alternative to protons. If an ion beam facility is able to accelerate
more than one ion species, e.g. with a synchrotron, than a proton gantry might be considered as
a “handicap” because it is not compatible with other ions. In an optimal scenario a proton
gantry would allow to delivery Helium ions but only with certain threshold energy. Helium ions
have an improved peak to plateau ratio and sharper lateral penumbras with increasing depth
compared to protons. Despite these advantages they are no more than an interesting research
topic. When a particle or proton facility is being established, there might be economic aspects
that cannot be neglected. A proton gantry, despite its costs, might be an adequate tool for
treating patients in an optimal way without putting too much stress to the staff for finding
compromises as might be the case with a limited number of fixed beam lines.

Proton beam therapy is a challenging field of radiotherapy, with numerous questions to be
answered in clinical research and physics research, respectively. In order to be able to delivery
proton beams in a competitive way compared to today’s high-tech photon beam treatments,
with many degrees of freedom for conformal avoidance, e.g. intensity modulation, image
guidance and inverse planning, a gantry is highly desirable. If protons are being used as a boost
option after larger volumes have been treated with advanced photon beam therapy, then a
proton gantry provides an additional degree of freedom to limit additional dose to already pre-
irradiated healthy tissue.

References:
comparison of advanced radiotherapy techniques for the treatment of abdominal


New opportunities for the border area around Wiener Neustadt are possible by the joining of Hungary and Slovakia with the European Union. This region has become the new threshold between East and West. As a result, cross-border cooperation has now become possible. This guarantees teamwork in economic and cultural fields.

In our specific project in the framework of the INTERREG IIIA Austria-Hungary programme "transnational research co-operation and location development MedAustron" cross-border activities in the field of ion radiotherapy will be initialised. This includes the following tasks:

* scientific and research co-operations dealing with medical and technical issues;

* information and communication including the preparation of brochures, the organisation of workshops etc.;

* development of new products, services and technologies in which the further development of a dedicated medical beam monitor, i.e. a CVD diamond detector, exhibits a major field of action;

* investigation of manpower potential and qualification requirements.

The following institutions are actively involved as partners in the project activities:

* Fotec, Research and Technology, Ltd., Austria;
* Verein AUSTRON, Austria;
* Regionalmanagement NÖ, Austria;
* Innovation Without Borders Public Association, Hungary;
* West Hungarian University, Sopron, Hungary;
* Slovak University of Technology, Slovak Republic.

The project is scheduled for two years and will be finished by the elaboration of a final report describing the activities and results which have been reached and performed during the project period. In addition it is intended to publish the scientific outcome in appropriate journals and conferences.
STATUS OF MEDAUSTRON

Dr. Marin Schirma, Dkfm. Theodor Krendelsberger

Before Mr. Krendelsberger gave his talk on the status of the realization process of the project MedAustron he conveyed information in a nutshell about the State of Lower Austria, the Industrial Quarter of Lower Austria and the Municipality of Wiener Neustadt, where the facility of MedAustron will be located.

Mr. Krendelsberger informed about the fact that the first tender of the project MedAustron (2006) looking for a private investor was cancelled because the bidding consortia were not prepared to take the market risks combined with this specific healthcare project.

Therefore the government of the State of Lower Austria decided to become the public investor of the project through a company set up for this purpose: EBG MedAustron Company Ltd. in Wiener Neustadt. According to the plans of the EBG Company MedAustron is designed to become a cancer treatment and research centre using an irradiation facility providing protons and carbon ion beams. In four for cancer treatment dedicated irradiation rooms 1200 patients will be treated per year. This number will probably increase during the following years of operation by an improvement of the treatment method. Two irradiation rooms are intended for the use of non-clinical research. In addition to the clinical parameters of the accelerator system a proton beam with energies up to 800 MeV will be available. Research programmes in the fields of radio-biology, medical radiation physics and experimental physics can be carried out at MedAustron in the near future.

The start of the construction of MedAustron will be in 2008. Trial operation is planned for 2012.

The financing of the facility has two main elements. The State of Lower Austria assumes a warranty of € 120 Mio. for MedAustron. The three public entities support the construction of the non-clinical research part of the facility with a financial aid of € 46,9 Mio.(Republic of Austria € 41,6 Mio., State of Lower Austria € 3,7 Mio., Municipality of Wiener Neustadt € 1,6 Mio.). The Municipality of Wiener Neustadt provides the real estate for the facility.
SYNOPSIS, Part 2a:

Gantries – State of the Art
Gantries for Hadron Therapy

Michael Benedikt, Philip John Bryant, CERN
Wien, 10.March 2007

1 Introduction
The treatment of tumours by hadrontherapy is greatly improved if the patient can be irradiated from several directions by means of a gantry, i.e. a section of beam line that can be rotated around the patient, see Figure 1. The gantry optics must be designed in such a way that the beam at the patient is independent of the rotation angle. Ideally, the full $2\pi$ should be available about the gantry axis and it should also be possible to rotate the patient, so as to access the full $4\pi$ solid angle. The requested field size is typically $20 \times 20\text{ cm}^{2}$ with a penetration up to 27 cm.

![Schematic view of a gantry with its fixed beam line and accelerator](image1.png)

Figure 1 Schematic view of a gantry with its fixed beam line and accelerator

Gantry designs can be divided into two broad geometric classifications:
- Iso-centric gantries, Figure 2 (a).
- Exo-centric gantries, Figure 2 (b).

![Iso-centric and exo-centric gantries geometries](image2.png)

Figure 2 Iso-centric and exo-centric gantries geometries
Furthermore, both of these designs can be adapted to two types of beam delivery:

- Voxel scanning, which is capable of complex 3D shaping of the irradiation dose, providing the tumour can be immobilised, see Figure 3 (a).

- Spread-out beams with collimation, which is well suited to tumours that can move, e.g. lung. The most usual form of spread-out beam delivery is passive spreading, see Figure 3 (b), but it is also possible spread beams by wobbling and by non-linear lenses.

2 **Gantry design**

The geometric design of a gantry (dipole layout) is relatively straightforward, but the optical design for the beam matching is far more complicated. There are two basic aspects to consider:

- Obtaining the beam characteristics needed for the beam delivery.
- Matching the beam from a fixed system to a rotating system.

2.1 **Passive spreading gantries**

Passive beam delivery systems are placed after the last dipole of the gantry in what is known as the “nozzle”. To accommodate the drift space needed for the beam to diverge, passive spreading gantries have a conical geometry and a large diameter, see Figure 4. The Twiss functions and beam emittances at the entry to the double scatterer are not critical because the beam is strongly scattered. Furthermore, the positioning of the beam and the scattering elements is relatively insensitive, because the final accuracy
of the dose shape is given by a collimator just in front of the patient. Passive spreading systems are used with protons and almost always with cyclotrons. This makes it easy to obtain round beams and to match to the gantry by making a rotationally symmetric beam (see Section 3).

![Figure 4 Schematic view of a “conical” passive spreading gantry](image)

### 2.2 Parallel-beam voxel scanning gantries

Voxel scanning requires pencil beams of precise size, shape and intensity. This favours the use of synchrotrons and requires an optical system that can control all the Twiss functions precisely over large ranges. Parallel beam scanning is favoured because it reduces the surface dose concentration given to the patient. Obtaining a parallel beam requires a longer distance than the passively spread beam described earlier. To accommodate the optical system for parallel scanning, the scanning magnets are placed upstream of the last dipole and a cylindrical geometry is chosen for the gantry. The disadvantage of the “cylindrical” gantry is the large aperture needed in the final dipole, which increases size, weight and power consumption, see Figure 5.

![Figure 5 Schematic view of a “cylindrical” voxel scanning gantry](image)

An alternative to the “cylindrical” gantry is the “Riesenrad”, exo-centric gantry, see Figure 6. One important optical difference between these two gantries is that the dispersion can be corrected internally in the “cylindrical” gantry, while for the “Riesenrad” it is necessary to include the bend from the main extraction line in the matching to bring the dispersion to zero at the patient. Furthermore, the rotational
matching to the “Riesenrad” has the most rigorous requirements of all cases and is achieved using a “rotator” (see Section 3.3).

Figure 5 Schematic view of a “Riesenrad” voxel scanning gantry

3 Rotational gantry matching

The aims of the rotational matching are to make the shape and size of the beam spot at the patient totally independent of the gantry angle, to remove all correlation between momentum and position across the beam spot and, for the purposes of scanning, the optics inside the gantry must be independent of gantry angle. In some cases, it is necessary to consider the transverse beam distributions, i.e. to distinguish between beams from a resonant slow extraction in a synchrotron and a beam from a cyclotron. For scanning, it is necessary to design the optics of the line and the gantry as an integrated whole, e.g. beam size control may be in the line or in the gantry according to the method applied.

3.1 “Symmetric-beam” method with zero dispersion (exact)

The beam must be rotationally symmetric at the entry to the gantry with the same distribution (e.g. gaussian or KV). This requires equal emittances, equal Twiss functions between the planes and zero dispersion at the entry to the gantry. Furthermore, the gantry must be designed with a closed dispersion bump in the plane of bending.

3.2 “Round-beam” method with zero dispersion (partial)

The beam must have the same distribution (e.g. gaussian or KV) in both planes with the conditions of $E_x\beta_x = E_z\beta_z$ (equal sizes) and zero dispersion, at the entry to the
gantry. Furthermore, the gantry must be designed with phase advances of multiples of \(\pi\) in both planes (i.e. 1:1 or 1:n matrices) and a closed dispersion bump in the plane of bending.

### 3.3 “Rotator” method (exact and completely general)

This method will map all Twiss functions and the dispersion functions into the gantry coordinate system rigorously independent of the gantry angle and beam distribution. The gantry must be designed to give zero dispersion at the exit, but now the dispersion can be finite at the entry. This opens the way to a “Riesenrad” design.

The “rotator” method is essential for slow-extracted beams that have high emittance ratios. Figure 6 shows (top left) the Twiss functions in a rotator, (top right) the schematic layout of the incoming fixed beam line, the rotator and the gantry and (bottom) the multiplication of the transfer matrices to get the overall mapping into the gantry coordinate system.

![Figure 6 Synopsis of the “rotator” matching method](image)

\[
M_\alpha = \begin{pmatrix}
\cos^2 \alpha & 0 & \sin^2 \alpha \\
0 & \cos^2 \alpha & 0 \\
-\sin^2 \alpha & 0 & \cos^2 \alpha
\end{pmatrix}
\]

\[
M_{\mu_p} = \begin{pmatrix}
0 & 0 & 0 \\
1 & 0 & 0 \\
0 & 1 & 0
\end{pmatrix}
\]

\[
M_{\mu_q} = \begin{pmatrix}
0 & 0 & 0 \\
-\sin^2 \alpha & 0 & \cos^2 \alpha \\
0 & -\sin^2 \alpha & 0
\end{pmatrix}
\]

\[
M_{\nu} = \begin{pmatrix}
1 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

### 3.4 “Equal sigma” beam size method (partial)

This method equates the second moments (sigma) of the horizontal and vertical beam distributions. In the case of equal distributions, this is equivalent to equal beam shapes, but for a slow extracted beam, which has a quasi-rectangular distribution horizontally and Gaussian distribution vertically, the equivalence is not exact, e.g. the FWHH values will be different. This situation may, or may not, be acceptable after smoothing by scattering in the patient’s body.

The beam can be described by its sigma matrix.
The sigma matrix translates from the gantry entrance to the gantry exit as,
\[ \sigma_2 = M_{\text{Overall}} \sigma_0 M_{\text{Overall}} \]
where \( \sigma_0 \) is the matrix at the exit to the fix beam line, \( \sigma_1 \) would be the matrix after the rotation plane at the entrance to the gantry proper and, \( \sigma_2 \) is the matrix at the gantry exit, see Figure 7.

Figure 7 Layout for the “equal-sigma” matching method

The diagonal terms in the sigma matrix at the gantry exit give the beam widths,
\[ \alpha(2)_{1,1} = r_{1,1}^2 [\sigma(0)_{1,1} \cos^2 \alpha + \sigma(0)_{3,3} \sin^2 \alpha] + 2 r_{1,1} r_{1,2} \sigma(0)_{1,2} \cos^2 \alpha \]
\[ r_{1,2}^2 [\sigma(0)_{2,2} \cos^2 \alpha + \sigma(0)_{4,4} \sin^2 \alpha] + 2 r_{1,1} r_{1,2} \sigma(0)_{3,4} \sin^2 \alpha \]
where the coefficients of the transfer matrix \( M_{\text{Overall}} \) can be calculated from the rotation transfer matrix and the gantry transfer matrix.

\[
M_{\text{Overall}} = \begin{pmatrix}
 r_{1,1} & r_{1,2} & r_{1,3} & r_{1,4} \\
 r_{2,1} & r_{2,2} & r_{2,3} & r_{2,4} \\
 r_{3,1} & r_{3,2} & r_{3,3} & r_{3,4} \\
 r_{4,1} & r_{4,2} & r_{4,3} & r_{4,4}
\end{pmatrix}
\begin{pmatrix}
 \cos \alpha & 0 & \sin \alpha & 0 \\
 0 & \cos \alpha & 0 & \sin \alpha \\
 -\sin \alpha & 0 & \cos \alpha & 0 \\
 0 & -\sin \alpha & 0 & \cos \alpha
\end{pmatrix}
\]
Special solutions can now be found. For example if the gantry matrix is arranged to give \( r_{1,1} = 0 \) and the incoming beam is adjusted to give \( \sigma(0)_{2,2} = \sigma(0)_{4,4} \), then,

\[
\sigma(2)_{1,1} = \bar{n}_{1,2}^2 \sigma(0)_{2,2}
\]

A similar condition exists for the vertical plane.

**References**


The Scanning Ion Gantry at the
Heidelberg Ion Therapy Centre

Gantry Workshop, Vienna 2007

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Introduction

Ion beams have favourable physical and radiobiological properties compared to conventional radiotherapy modalities. So far only dose delivery via fixed-beam arrangements could be used to treat a total of more than 6,000 patients with particles heavier than protons. The clinical outcome can be essentially improved if multi-field irradiation techniques, i.e. the availability of scanning beam dose delivery combined with 360° access, would allow for optimal dose conformation.

Based on the key developments made in the frame of the experimental carbon ion therapy project hosted at the German heavy ion research lab, GSI, Darmstadt a dedicated, hospital-based combined proton-ion therapy facility, the Heidelberg Ion Therapy Centre (HIT), was designed and built [1]. Aiming at the treatment of more than 1,000 patients per year it is mandatory to carefully analyze the spectrum of indications with respect to the technical requirements. Superior dose distributions can be administered in about 20% - 30% of the patients if a gantry is available. In particular patients suffering from tumours in the trunk region (see fig. 1) will benefit from this added flexibility [2].

Fig. 1: Treatment plan for a pancreatic tumour to be treated in supine position using two scanned fields at ±20° in order to spare various organs at risk (bowel, liver, kidneys, spinal cord) and to minimize potential range uncertainties from organ movements (courtesy O. Jäkel).

Clinical Requirements

The clinical workflow can maximally be supported if the patients can be handled almost similar to a conventional photon treatment scenario, i.e. the supine patient is positioned by technicians that can
freely walk on a solid floor at the gantry nozzle. During the treatment the patient should not be moved to avoid misalignments and to allow for fast access to the patient in case of an emergency. The field size should not differ from the conditions in the horizontally fixed beam lines so that field patching will be a rare event. State of the art patient positioning and position verification systems need to be integrated in order to guarantee outstanding precision in the set-up procedure. Furthermore the digital x-ray systems must allow for fast imaging sequences as a relevant number of indications where organ movement can be expected will be treated at the HIT gantry. A high level of integration is required for an optimized clinical workflow.

Gantry Design

The crucial task in the design phase was to properly balance the need for compactness with the reliability requirement needed for 300 days of clinical use in a hospital environment. Furthermore the integration of the medical equipment (robotic patient positioner, digital x-ray systems, the moveable floor) at the gantry nozzle together with the inevitable anti-collision means was a challenging task. Based on treatment plan analysis and intensive discussions in a team of radio-oncologists, accelerator and medical physics experts about usability and safety issues neither combinations of fixed beam lines (inclined and/or vertical) nor eccentric designs were accepted. Solutions comprising reduced rotatability in the range from 180° to 270° were sorted out as the investment saving did not compensate for the hampered clinical workflow. For the resulting isocentric solution the cork-screw approach [3] was rejected in order to minimize the total bending power of the gantry beamline. Finally a single-plane, barrel-type configuration being relatively long was selected to be studied in detail (see fig. 2).

Fig. 2: A box girder construction (left, ACCEL/SEAG/GSI) rotated via two supporting wheels was designed in the frame of a first feasibility study and used to deduce the impact on the building interface. Aiming at a reduction in the overall weight while keeping the precision requirement of less than 0.5mm deformation at the ion-optical axis a truss-based supporting structure was developed (right, MT Mechatronics) and finally realized.

In 2002, when final decisions for the implementation had to be made, superconducting magnets where neither affordable nor could the required field quality of about 10^{-4} be guaranteed so that open questions concerning the rotatability and reliability of the cryogenic system needn't to be scrutinized at all. For beam optics reasons [4,5] the scanning system was placed behind the last quadrupole lens but upstream to the last bending magnet in order to reduce the radius of the beamline. Consequently a large aperture magnet of 22x22cm^2 having a weight of about 90 tons was
needed to transport the scanned projectiles into the isocentre. The scanning system was selected to be identical with the systems in the fixed beamlines at HIT and by means of edge focusing in the final 90° bending magnet a parallel scanning mode (SAD ≈ 50 m) could be realized.

Realization

Table 1 shows the main parameters of the scanning ion gantry being built at HIT. Preassembled parts of the supporting truss construction were shipped to HIT and mounted in the gantry room. About three month after the delivery of the first structure elements the initial rotation was carried out in April 2007. Laser-based precision adjustment of the individual beamline elements was used to achieve the deformation goals of some tenth of a millimetre depending on the individual ion optical element.

<table>
<thead>
<tr>
<th>Main Parameters of the HIT Gantry</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arrangement:</strong></td>
</tr>
<tr>
<td><strong>Scanning system:</strong></td>
</tr>
<tr>
<td><strong>Angle and speed of rotation:</strong></td>
</tr>
<tr>
<td><strong>Ion-optical functions:</strong></td>
</tr>
<tr>
<td><strong>Overall dimensions:</strong></td>
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<tr>
<td></td>
</tr>
<tr>
<td><strong>Main components:</strong></td>
</tr>
<tr>
<td><strong>Last dipole magnet:</strong></td>
</tr>
<tr>
<td><strong>Quadrupoles:</strong></td>
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<tr>
<td></td>
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<tr>
<td></td>
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<tr>
<td><strong>Acceptance (max.): horizontal:</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Parameters of the transported beams:</strong></td>
</tr>
<tr>
<td>Energy: 50 - 430 MeV/u</td>
</tr>
<tr>
<td>Magnetic rigidity: 1.03 - 6.6 Tm</td>
</tr>
<tr>
<td>Momentum spread: 0.2%</td>
</tr>
</tbody>
</table>

**Table 1:** The main parameters of the scanning ion gantry at HIT.
Having completed the mounting of the beamline components the medical equipment was installed. A cylindrical room comprising the clinical look and feel of a radiotherapy unit was prepared inside the 4.5m bearing at the 90° dipole magnet position (see fig. 3). Two flatpanel imagers were positioned under 60° at the beam exit and the corresponding x-ray tubes were mounted opposing under the moving floor. The robotic patient positioner shares its footing with the bearing.

**Fig. 3:** The patient environment inside the 4.5m bearing at the gantry nozzle. The drawing (courtesy MT Mechatronics) shows the gantry angle that will be used to position the patients. Here, the closed moveable floor allows for efficient patient handling. As soon as the gantry leaves this particular position the moveable floor flips to the cylindrical housing.

Recently the first proton and carbon ion beams were transported into the isocentre demonstrating the principle operation of the rotating beamline. Presently for commissioning purposes a dedicated beam diagnostics unit using a scintillating screen is mounted to the nozzle and records the beam intensity, position and width directly in the isocentre plane. In the upcoming months a fraction of the available beamtime will be used to establish the pencil beam libraries for all combinations of projectiles, energies, spot sizes and intensities.

**Summary and Conclusion**

Based on the clinical requirements an isocentric single plane, barrel-type scanning ion gantry with integrated beam scanning technology that allows for intensity-modulated multi-field irradiations was realized at the Heidelberg Ion Therapy Centre. Conventional magnet technology was combined with a supporting truss construction deduced from concepts proven in existing large radioastronomy telescopes will allow for more than 300 days of clinical use in a hospital environment. The requirements on the mechanical precision under rotation were demonstrated as well as the basic ion-optical functions of the moveable beamline. The worldwide first scanning ion gantry will be put into routine operation at HIT early in 2009.
References

2. Jakel O., this issue
Gantries for Particle Therapy

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Introduction

The Heavy Ion Cancer Therapy Facility HICAT at the University Hospital of Heidelberg is currently under construction. One unique feature of the treatment facility is the first heavy ion gantry in the world. The gantry will allow the patient treatment with different ion species up to 430 MeV/u and full geometrical flexibility. This functionality has to be maintained for up to 300 000 rotations over the envisaged life cycle of 15 years. The order for the design and delivery of the supporting structure as well as the integration of the main components was given to MT Mechatronics GmbH in July 2003.

MT Mechatronics Fields of Activities

MT Mechatronics GmbH is an international supplier of antennas, radio and optical telescopes, mechatronic systems and subsystems for medical apparatuses, car industry etc, and the related accessories and services.

MT’s know how is based on more than 40 years of continual international business with full range of in-house engineering capability for structural, mechanical and control systems, system simulation, own monitoring and control software, fabrication, erection, commissioning, and project management for small, large and long leading projects.

Gantries

MT Gantry systems are based on the telescope know-how and the experience with the delivery of about 50 Betatron facilities worldwide. The Gantry for the University Hospital in Heidelberg is the first Gantry for Heavy Ion Cancer Therapy in the world. It has been designed by MT Mechatronics and is currently under construction. High precision Gantries for Proton Cancer Therapy have been developed by MT in several studies as well.
Gantry for Heavy Ion Cancer Therapy Facility in Heidelberg

In July 2003 the order was placed to the company MT Mechatronics for the construction of the structure and the integration of the components. Since then intensive investigations have taken place to push the design towards construction feasibility. Main issues have been:

- the interfaces to the building
- the position and angular stability of the beam transport components under different gantry angles
- the compliance with medical legislation with respect to mechanical stability and safety
- the integration of the beam transport components into the supporting structure during the assembly process
- the control system safety
- the patient environment

Optimization of System Properties

The gantry is an integrated system consisting of structure, mechanics and control system. Overall system performance has been achieved by optimization of the subsystems considering the overall system behaviour.

The structural optimization has been done by using the homology principle to achieve the best weight to stiffness ratio. Robust mechanics like roller bearings have been used and designed to assure minimum total error contribution and maximum reliability during Gantry lifetime. The control system consists of the servo system responsible for system performance and operation and the safety system responsible for system safety according to the rules of the medical law requirements.

Deflection and Rotation of Beamline Elements during Rotation of the Gantry

The 3D volume conformal rasterscan method requires reproducible beam positions for all gantry angles. Given the weight of the components to be integrated it was necessary to perform extensive FEM – calculations to optimise the supporting structure to the required stiffness without increasing too much the total weight of the system.

Finally a solution was reached which satisfies the individual requirements for position and angular stability of the relevant beam guidance components. The maximum peak to peak fluctuations of the beam guidance components under all gantry angles with respect to the optimum position are defined in a local beamline coordinate system, rotating with the Gantry, where
X = direction of the beam
Y = radial to the Gantry turning axis but perpendicular to the beam
Z = tangential to the Gantry turning axis

The maximum radial deflections that are allowed for the beamline elements are specified from 0.3 mm for steerers and 1 mm for the big dipoles. The position of the beamline elements will be measured at 12 rotating angles (30° steps). The predicted values are within specification.

In order to guarantee the reliability of the system, all these deviations have to be reproducible and therefore only elastic deformations are allowed. The security factors for the design were chosen in such a manner that more than the predicted three hundred thousand turns of the gantry over its envisaged life time can be done in an elastic manner. The design also assures the compliance to the medical law requirements with respect to mechanical stability.

**Actual Status in February 2007: Assembly in Heidelberg**

**Structure and Bearing**
The complete main structure including bearings and drive system is mounted. The turning axis is aligned with respect to the Gantry building. One side of the building is still open in order to have easy access for insertion of the beamline and beamline support structure.

**Beam entrance**
The beam entrance is supported by a third bearing that is currently being mounted and aligned to the Gantry axis. The bearing is mounted to the beamline support structure.

**90° Magnet**
The 90° magnet with an overall weight of 92 t is mounted in segments. The lower part of the magnet is currently resting on hydraulic jacks that are used to align the parts horizontally. In the next steps, the coils and the vacuum tube that are stored in front of the Gantry on the HEPT will be mounted.

**Gantries for Proton Therapy**

During various studies and design contracts, MT Mechatronics has developed the design for proton therapy Gantries. The gantry concepts are designed for 180° and 360° rotation angle and can be easily adapted to customer specification.
Summary

The Gantry designed for the University Hospital in Heidelberg shows that an isocentric Gantry for heavy ion therapy is feasible using conventional robust technology and standard magnets.

MT Mechatronics is prepared to supply gantries for heavy ion therapy or proton therapy. Isocentric Gantry designs for both treatment methods are existing. The design can be adjusted to new beamline technologies like superconducting magnets. Other Gantry designs like Ferris wheel gantry can be built according customer specification.
CNAO Status and Gantry plans for the future

M. Pullia –

CNAO Foundation

Abstract The Centro Nazionale di Adroterapia Oncologica (National Center for Oncological Hadrontherapy, CNAO) will be the first Italian center for deep hadrontherapy. It is presently under construction in Pavia. It will be based on an evolution of the PIMMS synchrotron capable to accelerate carbon ions up to 400 MeV/u kinetic energy and protons up to 250 MeV, energies which are necessary to treat deep seated tumors. Four treatment lines, in three treatment rooms, and a dedicated facility for clinical and radiobiological researches are foreseen in a first stage. Space for two additional rooms eventually equipped with gantries has been left aside the center and the synchrotron has been designed to work with these two additional lines, but they are intended as a future upgrade. The beam is injected into the synchrotron from the inside, to allow positioning all the injection chain inside the synchrotron ring itself, and also to better exploit the two non-dispersive regions in the synchrotron. The injection chain is made by a 8 keV/u Low Energy Beam Transfer line (LEBT), a RFQ accelerating the beam to 400 keV/u, a LINAC to reach the injection energy of 7 MeV/u and a Medium Energy Beam Transfer line (MEBT) to transport the beam to the synchrotron.

INTRODUCTION

The origin of the Italian hadrontherapy center dates back to 1991, when the first proposal was made [1]. In the same year the ATER experiment was launched by INFN.

In 1996 CERN, Med-Austron and TERA started the Proton Ion Medical Machine Study (PIMMS) [2] in collaboration with GSI and Onkologie-2000 joined later the study group. The study lasted approximately four years and resulted in a green-field conceptual design, with a particular attention to the theoretical aspects.

With the financial law of 2001, the Ministry of Health created a no-profit organization, named CNAO Foundation, to build and subsequently run the National Center for Hadrontherapy.

The realization started at the end of 2002, with the baseline design and the specifications of most of the parts of the machine, which was delivered in

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September 2003.

2004 has been the year of tendering and 2005 and 2006 have been the years of production.

In 2007 installation has begun and 2008 will be dedicated to commissioning.

**CNAO Buildings**

**General Layout**

The site, evidenced in Figure 1, is close to the internal highway of Pave and thus it is well connected by communication means. It is also located nearby the sites of three hospitals (San Matteo, Maugeri and Mondino) and the university campus and thus well placed to profit of clinical and research synergies that will be fundamental for the success of the CNAO initiatives. The buildings construction started in Autumn 2005 and it is going to be completed in fall 2007. The CNAO design is based on the following assumptions:

- the Centre will be devoted to the treatment of deep seated tumours (up to a depth of 27 cm of water equivalent) with light ion beams (proton, carbon ions and others) and to clinical and radiobiological research;
- the full-size CNAO will have 5 treatment rooms (3 rooms with fixed beams and 2 rooms in case with gantries) and one experimental room. For the first phase (CNAO - Phase 1) 3 treatment rooms will be equipped with 4 fixed beams, three horizontal and one vertical and an experimental room will be constructed (Figure 2).

Fig. 1. Location of the CNAO site (in green at the centre of the picture). Bottom right: area occupied by San Matteo hospital; top right: parking area; top left: part of the highway contouring the city of Pave.
At regime, on a double shift operation, five days per week and 220 days per year, the CNAO will deliver about 20 thousands sessions per year of hadrontherapy. The overall number of patients will obviously depend by the fractionation schemes adopted. The actual dimensioning of spaces and fluxes for patients, personnel and people are adequate for about 3000 patients per year. In addition, a room totally devoted for physical and radiobiological researches is under construction.

Fig. 2. Layout of the CNAO underground level - Phase 1.

The site of the CNAO allows the future expansion of the facility, both in the direction of the extracted beam channel and also to add a new research and clinical building close to the centre. The expansion in the direction of the extracted beam is potentially adequate to host two rooms for carbon ions, each approximately the same size of the present Heidelberg gantry, as illustrated in Figure 3. The choice of the CNAO foundation has been to postpone the construction of the expansion in order to validate the clinical necessity of the gantry for ions and also to wait for the technological improvements expected in this field. In the north side of the CNAO site space for a research building has been reserved. This facility will be added later on and will be conceived and organised in collaboration with the institutions that are already active on the research issues of the CNAO.
Accelerators

**General parameters**

The CNAO has been conceived to perform treatment of deep seated tumors with beams of ions with Z in the range 1 to 6 (eventually Oxygen, but with a reduced range). The beam shall be capable of delivering up to 2Gy in 2l in 2-3 min and to deposit the dose up to a depth of 27 g/cm². To reach this depth with carbon ions a total kinetic energy of 4800 MeV is needed. The requirement to accelerate many different ion species to a variable energy calls for the use of a synchrotron. The CNAO will start with protons and carbon ions, but the possibility to add other species is left open. The main requirements can be summarised in Table 1.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>$1 \leq Z \leq 6$</td>
</tr>
<tr>
<td>Range [g cm⁻²]</td>
<td>3 – 27</td>
</tr>
<tr>
<td>Energy range [MeV/u]</td>
<td>60 – 400</td>
</tr>
<tr>
<td>Beam FWHM [mm]</td>
<td>$4 \times 10^6$</td>
</tr>
<tr>
<td>Spill duration [s]</td>
<td>1 – 10</td>
</tr>
<tr>
<td>Max number of ions/spill</td>
<td>$4 \times 10^8$ for C, $10^{10}$ for p</td>
</tr>
<tr>
<td>Dose homogeneity</td>
<td>±2.5%</td>
</tr>
</tbody>
</table>

*a depending on the ion  
b in x and y independently
Fig. 3. Possible layout of the CNAO underground level - Phase 2.

Many different irradiation techniques are possible ranging from completely passive to totally active beam spreading. Despite the higher degree of difficulty, CNAO has opted for a totally active beam delivery because it is the one that allows the best conformation of the dose to the tumor shape.

**Synchrotron**

The CNAO synchrotron is made by two symmetric achromatic arcs joined by two dispersion free straight sections. The dispersion free sections host the injection/extraction region, the resonance driving sextupole and the RF cavity.

The total bending of 360° has been divided in 16 identical dipoles powered in series. The focusing action is provided by 24 quadrupoles grouped in three families and the chromaticities are controlled by four sextupoles grouped in two families. A fifth sextupole is used for resonance excitation.

Orbit correction is guaranteed by 20 steering magnets (11 H + 9 V). The total length of the ring is approximately 78 m. Multi turn injection is foreseen in order to relax the requirements on the source intensity. After injection at 7 MeV/u, the beam is scraped to the nominal emittance and then accelerated to the extraction energy in less than one second. The beam is then slowly extracted till when the iso-energy slice is completely irradiated and finally is destroyed on an internal dump during the standardization cycle of the magnets.
**High Energy Beam Transfer lines**

The four HEBT lines transport the extracted beam to the three treatment rooms. The layout of the whole accelerator complex is shown in figure 4. All the lines are equipped with a pair of scanning magnets which allow scanning over an area of 200 mm x 200 mm.

The extracted beam distribution is strongly asymmetric because of the slow extraction process. To cope with this beam, CNAO has adopted the “empty ellipse” approach [3] but has abandoned the modular structure in order to keep the layout as compact as possible.

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Fig. 4. Bird-view of the layout of the accelerators and beam lines of the CNAO.

**Gantries in Phase 2**

One of the major choices to make in choosing the gantry is the one between fixed and mobile iso-center. In the first case the iso-center is in a fixed position with respect to the building and the gantry rotates with all the magnets around that position. In the second case the gantry rotates around an axis near to its center of mass and the iso-center rotates around that axis as well.

Since the gantry type is not decided yet, it has been verified that both a fixed and a mobile iso-center gantry can be placed approximately in the same position. The optics in both cases foresees a phase-shifter-stepper module, a telescopic structure and a rotator to keep the beam distribution independent of the gantry angle. Figure 5 illustrates the two solutions and shows that the encumbrance of the two solutions is approximately the same.
Fig. 5. Possible gantry lines for CNAO: a) fixed iso-center, b) mobile iso-center, c) the two lines drawn together with the synchrotron.

Conclusions

The construction of CNAO in Pavia is progressing and even if in phase 1 there will be no gantry, everything is ready to expand the center with up to two gantries.

ACKNOWLEDGMENTS

The design of the accelerator system described in this document, is the result of the efforts of many people and of many institutions. The author would like to thank everybody for their precious help.

REFERENCES

SYNOPSIS, Part 3:

Industry’s Concepts
Mechatronic systems for particle therapy

H. Schär

Schär Engineering AG develops and supplies mechatronic components for the radio-oncology since 1983.

Today Schär Engineering AG is the technical leader in particle therapy for patient positioning systems and Gantries and others. Our customers are research institutes (for example the Paul Scherrer Institute) and also the European suppliers for proton therapy plants.

Schär Engineering AG supplies patient positioning systems for Gantries and fixbeam-rooms. Patient positioners for sitting and laying patients are being produced.

The redundant sensors in the patient positioners, the Gantries and Nozzles, together with the complete anticollision hardware and anticollision programmms, guarantee to fulfil the highest safety requirements.

Thanks to the weight sensors in the patient positioner, it is possible to calculate the weight and the point of gravity of each patient. This allows to move the patient from one position to the next within a precision better than 0,2 – 0,5 mm (different PPS) without a new patient position verification with imaging devices.

The rigidity of the Gantries allow to move magnets and collimators in space with a precision better than 0,3 – 0,5 mm.

Schär Engineering AG also develops and produces movable couches for patient positioners. These allow the preparing of the patient outside the treatment room, which reduces the stress on the patient and allows more patients being treated in the treatment room.

All these advantages make it possible to increase the precision of the therapy, to reduce the side effects of the therapy and to increase its efficiency.
The IBA gantry for Carbon beam therapy

Yves Jongen+, William Beeckman+, Mark Katz*

+ Ion Beam Applications sa, Belgium
* ITEP, Moscow, Russia

In radio therapy, we know that medical doctors prefer the freedom of beam incidence angle offered by isocentric gantries. However, in carbon beam therapy, the large magnetic rigidity of carbon beams of therapeutic ranges makes the design of isocentric gantries quite challenging.

Another solution, the ex-centric gantry was proposed by Anders Brahme and is offered by IBA, but this solution does present some practical limitations, and was generally found less attractive by prospective customers of IBA carbon beam therapy systems.

A true isocentric gantry is being built at the HICAT facility in Heidelberg. However, the HICAT gantry is often seen as too large, too heavy and too expensive to be the preferred solution for the future.

So the key question becomes: is it possible to build a carbon gantry that would be similar in size and cost to the (already large) gantries used today in proton therapy. We plan to demonstrate that the answer is yes, if the last magnet is a large gap, higher field superconducting dipole.

In the IBA carbon therapy gantry, the beam first undergoes a parallel displacement to 3.5 meters from the gantry rotation axis. This is achieved by two normal, resistive bending magnets having a field of 1.6 Tesla, and a bending radius of 4 meters. The two dipoles are separated by a triplet of quadrupoles. After this beam displacement, we find a second triplet of quadrupoles, and a pair of scanning magnets, used to scan the beam on the target at isocenter.

After the scanning magnets, the beam enters the last 90° superconducting dipole. This magnet has a gap of 20 cm, a maximum field of 3.2 T, resulting into a bending radius of 2 meters.

The last dipole is designed to achieve field ramps of 1 (to 2) Tesla/minute. At this speed, it is possible to change the energy of each layer at the energy degrader located at the cyclotron exit, without reaching excessive patient irradiation times. If we encounter problems with these relatively rapid rates of field change, adding a range shifter at the exit of the magnet like in the PSI gantry 1 would be a fallback position.

The optic of the new gantry was calculated by Mark Katz from ITEP. He found that it was possible to achieve achromatic optics providing a 3 mm spot at isocenter with quasi-parallel beam scanning at isocenter.

For the final, large gap superconducting dipole a first solution is presented. This solution uses Ni-Ti coils in a warm iron structure. The field has been calculated using the Vector Fields TOSCA simulation code, and seems to meet requirements. However, further optimization is necessary.
The plan is to cool the coil by conduction, using 4 three stage, 4°K, 1.5 W cryogenerators made by Sumitomo Heavy Industries. Two cryogenerators are located at each end of the magnet. The complete magnet has a mass of 28 Tons.

Finally, we propose a mechanical structure for the gantry. When a robotic patient positioner is used, a gantry rotation angle of 180° only (from 0° up to 180° down) is needed to reach any point in the patient body from any direction. This structure avoids the usual difficulties associated with gantry floors, and uses large, commercial roller bearings to support the rotating mass. We expect that the use of such bearing, in contrast to large rolling rings used in present gantry designs, will reduce the cost and mechanical wear of the gantry structure.

The resulting gantry is 9.2 m in diameter, 12.7 m long and 156 tons in mass. The cost is still being calculated, but should be quite lower than the cost of HICAT-like carbon gantries using resistive magnets.
Concept and Performance of the RPTC Gantry Systems

S. Schmidt, H. Göbel, J. Heese, U. Klein, D. Krischel, M. Schillo

Requirements on Positioning Systems for Particle Therapy

Today, high demands are imposed on particle therapy systems regarding the positioning precision for the beam (Gantry) and the precision of the treatment table. Typically, these are as follows:

Beam position: Deviations to be kept within 1-mm-radius sphere around isocenter
Contributions to the beam position precision arise from

- Mechanical Gantry deflections and
- beam optics (particularly for scanning systems)

The modern Pencil Beam Scanning technique clearly aims at sub-millimeter precision.

Patient position: Deviations to be kept within 1-mm-radius sphere around isocenter
Contributions to the patient position precision arise from

- Treatment table precision
- (X-ray) position verification precision (position of tubes and receptors, image quality, geometry calibration, image matching algorithm, users judgment)
- Patient immobilization
- Precision of planning CT and treatment planning

Reflecting these demands, it seems obvious that sub-millimeter precision should be achievable within this whole framework.

Besides these technical requirements, patient throughput is a major issue for all clinical facilities. However, this requirement competes with the technical demands, as it forces reduction of all treatment procedure durations to a minimum while keeping at the same time the maximum possible precision.

At the RPTC in Munich, a system was introduced aiming at maximum achievable precision while offering rapid and largely automated procedures for reducing the time a patient has to stay in the treatment room.

RPTC Positioning Systems

For the RPTC, ACCEL has delivered integrated positioning systems, consisting of high-precision isocentric gantries and treatment tables (mechanically designed and
manufactured by Schär Engineering). The gantries are equipped with X-ray based position verification systems (supplied to ACCEL by Brandis / MedCom). The beam is delivered via a raster scanning system.

During commissioning, all position precision requirements have been verified through various measurements. It was shown, that the Gantry isocentricity is better than 0.5 mm (radius). Special phantoms and tools exist that are used to adjust the proton beam with the same precision.

The table precision has been proven via measurements with a laser tracker to be better than ± 0.32 mm. The use of the X-ray position verification system adds another source of uncertainty, which was verified to be uncritical via measurements with a dedicated phantom.

Both, the precision requirement for the beam axis and for the patient positioning systems have been verified. The measurements show that the beam axis and as well the table position can be kept within a sphere of 1 mm radius around the intended position, including all contributions to uncertainty.

The BodyFix and HeadFix systems from Medical Intelligence ensure that imprecisions resulting from the immobilization procedure do not contribute to longer patient set-up times.

**Integrated “Absolute Positioning” Concept**

In order to address the strong requirements on positioning precision as well as the demands on patient throughput, ACCEL has developed an integrated “absolute positioning” concept with the following key features:

1. A common framework is established linking the following systems together in a fixed positioning coordinate environment:
   - Planning CT
   - Treatment Planning System
   - X-ray Position Verification System
   - Treatment Table and Gantry

   The key element providing this linking functionality is the Treatment Control System. As a result, neither time-consuming pre-positioning with lasers is necessary nor the use of stereotactic frames.

2. Thanks to the high absolute positioning precision of the treatment table (not depending on patient weight or movement start point), only one X-ray verification is needed even with multiple fields.

3. A “one.button” automated table motion to the treatment position has been implemented in the motion control system, freeing the user from complicated maneuvers for getting the table into the right position.

   Via this concept, it is possible to conduct treatments within a minimum amount of time while keeping the high precision demands.
This has also been proven via simulated patient treatments that showed that a dose conformity within about a ±1% band can be achieved.

Hidden Problems

It must be pointed out that a few additional contributions to uncertainties need to be considered that have their origin outside of the particle therapy equipment:

• Imprecise CT table movements lead to unpredictable image distortion and therefore improper image matching during position verification.

• The long duration of a CT scan can potentially lead to image distortion due to organ / body motion.

• Patient weight loss between CT scan and treatment would lead to matching of differing images (DRR and active position verification image) generating imprecise results.

• If no fixed CT coordinate system is established, no direct coordinate transfer to the treatment system is possible resulting in longer patient set-up times.

• If multiple CTs with different properties are used for planning, there may be potential effects on positioning precision and coordinate linking.

Therefore, when aiming at increased precision for the particle therapy equipment, external systems need to be enhanced accordingly in order to provide an overall and homogeneous precision concept.

Summary

An integrated concept has been developed that fulfills precision and patient throughput requirements at the same time. The concept has been proven through various verification tests. While particle therapy equipment aims at submillimeter precision, external components add sources of uncertainty that may at least partially vitiate the technical achievements in particle therapy. This topic needs to be addressed.
SYNOPSIS, Part 2b:

Gantries – State of the Art (cont’d)
Proton gantries design considerations.  
The PSI Gantry 2 as an example.  

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PSI is still the only place in the world where proton therapy is applied using a dynamic beam scanning technique on a gantry. The present gantry, Gantry 1, has been used very successfully for patient treatments since 1996. This system is presently the only one in the world capable of delivering intensity modulated proton therapy (IMPT). Due to historical logistic reasons when it was built in 1991 as a parasitic device in a physics environment, the scanning of Gantry 1 is very accurate but rather slow; we can paint the dose on the target just one or a few times. This system is thus presently used for treating only well-immobilized lesions – i.e. tumors in the skull, spinal chord and low pelvis. Based on the past developments and successes of the proton therapy project, PSI decided in 2001 to expand the activities in this field by launching the project PROSCAN. The existing spot-scanning gantry (Gantry1) was connected in February 2007 to a new dedicated 250 MeV compact superconducting proton cyclotron (delivered by ACCEL GmbH). The operation with the new proton source is now very reliable and the treatments can be delivered routinely 5 days per week over the whole year without planned shut-downs (only one day each 2nd month). Two additional horizontal beam lines have been installed, one for eye treatments (Optis 2 – transfer of the OPTIS program from the injector 1 to PROSCAN – start of use planned for 2008) and one area dedicated to experiments (biology, dosimetry and other activities). In a fourth area we are realizing a second gantry, Gantry 2 (an improved version of the present gantry). Gantry 2 will be the new instrument for performing innovative developments at PSI in the context of PROSCAN, especially in connection with scanning applied to moving targets. The first beam through Gantry 2 is expected for spring 2008.

For Gantry 2 we have decided to use an isocentric layout, based again on beam scanning started upstream of the last 90° bending magnet, in order to keep the system as compact as possible. The radial dimensions of the gantry are important for saving space, especially in relation to our requirement to couple the beam from the horizontal beam line to the gantry at a small intermediate focus. We require this feature for providing an easy and fast way of checking the size and shape of the beam before injection into the rotating gantry. The vacuum of the gantry can be separated at this point from the vacuum of the cyclotron. With a small beam focus we can afford to
measure on-line the properties of the beam without spoiling the sharpness of the scanned beam. By virtue of the 1:1 imaging properties of the gantry beam optics we were even able to collimate dynamically the beam at the coupling point to the gantry to obtain an imaged collimation on the scanned beam. We can cross check through beam flux transmission ratios the proper matching of the selection of the beam energy in the two coupled achromatic beam line sections – one before the gantry and one after the coupling point. The system is designed for the transport of a large phase space (p x 3mm x 10 mrad) in X and Y to reduce unnecessary activation in the degrader. The beam will be scanned in two lateral directions with an infinite apparent beam source (double parallel magnetic scanning). The range of scanning of 12 cm by 20 cm is chosen as a compromise to keep power consumption low and scanning speed high. The scanning range will be extended by combining the fast beam motion of the sweeper magnets with the slow motion of the patient table (following the experience gained with Gantry 1). Through the double parallelism of scanning we can apply field patching techniques independently of treatment planning. The range of scanning is in this way essentially unlimited (on Gantry 1 we have already treated as a demonstration an 80 cm long cranio-spinal axis tumor in one single application). The patching of the fields will be applied with congruent linear fall-off in the overlapping region. The double parallelism of scanning is expected to bring other advantages, for example easier dosimetry and treatment planning. In connection with the simulation of scattering with the scanning beam we can for example avoid having to cut collimators with conical faces and avoid dose distortion errors from longitudinally shifted Bragg peaks in compensators.

On Gantry 2 we will considerably improve patient handling. We have decided to limit the rotation of the gantry to one side (from vertical beam from above -30° to vertical beam from below + 180°) and to compensate for this by rotating the patient table in the horizontal plane (instead of rotating the gantry). We can in this way achieve to have a flat fixed floor around the patient table at the isocenter and in part fixed walls and ceiling for mounting equipment in the vicinity of the patient table (connectors for anesthesia equipment, dosimetric devices etc), while keeping the freedom of choice of the incidence of the beam on the supine patient essentially unchanged. The treatment room looks very friendly and very open. Additional commercial equipment like a CT or CT-PET could be easily mounted within reach of the patient table.

For the patient positioning we will keep all options open. We can position the patient with a CT outside of the treatment room and then transport the patient ready for treatment with a new improved version of the patient transporter of Gantry 1 (a motorized guided version). We will have also the option to position the patient on the gantry prior to start (or during) the treatment with two fixed X-ray tubes with image amplifiers mounted at +,- 45° through the isocenter.

The most interesting feature of Gantry 2 is the possibility to take X-ray images in the beam-eye-view direction (BEV) in treatment position simultaneously to the proton beam (within uncertainties given by possible radiation damage of the imager due to
neutrons). The field of view of the BEV X-rays (of 16 cm x 26 cm) is not masked by collimators and compensators (a drawback with photons and scattering protons), nor by other equipment in the nozzle (a limiting factor with downstream scanning gantries). We thus have a kind of substitute of portal imaging for protons. This equipment should be used for QA in connection with respiration-gated irradiations or even for steering the beam to track tumor position (active tracking). We consider this feature very powerful especially in connection with the other technological developments for Gantry 2, which aim at the development of advanced beam scanning techniques, like treating moving targets using repainted scanning.

The development of new advanced beam scanning techniques has been started in a provisional test area of PROSCAN. To improve the speed of scanning we plan to use fast dynamic changes of the beam energy by changing the settings of the degrader and the beam line to the gantry. We could demonstrate in the horizontal test area changes of the beam energy in steps equivalent to 5 mm range within 100 ms (faster than with a synchrotron). The combination of the fast double magnetic scanning of the beam with fast energy changes is expected to provide a true volumetric repainting capability of 3d-conformally-shaped dose distributions. To considerably increase the basic speed of scanning we plan to use the modulation of the beam intensity at the ion source at a time scale of 100 microseconds. For this we have installed a vertical deflector plate in the first turn of the cyclotron COMET. The stability of the beam of COMET has been shown to be around 4 % sigma at 10 KHz. The control system of Gantry 2 will be capable of performing a discrete spot scanning similar to Gantry 1 from the very beginning in order to be able to treat on Gantry 2 immediately the same type of indications. Moving targets will be treated at a later stage by painting the beam continuously with modulation of the beam intensity. It should also be rather easy to simulate the scattering foil technique by painting repeatedly with constant intensity projected-BEV dose boxes (for optional use of collimators and compensators). The main goal is to treat on Gantry 2 moderately moving targets with repainting. Large target movements like for lung nodules will be treated in connection with gating or tracking. With the beam scanning technique of Gantry 2 we should be able to show the feasibility of beam scanning as a universal beam delivery technique (for treating also moving targets) and thus achieve the highest flexibility and efficiency of the beam delivery system with minimal equipment.
Actualized status of the French project: ETOILE

Jacques BALOSSO, director, for the ETOILE group*

The project to build the first French medical centre for carbon ion therapy (CIT) is at the end of 2007-08 winter developing its tendering process that should ultimately allow its opening to patients treatments in early 2013. It will be built in the town of Lyon, the third largest town of France (Fig 1). The spike event that initiated the project at Lyon University in 1997 was the honoris cosa doctorate of Ugo AMALDI, well-known physicist, enthusiastic promoter of charged particle therapy in Europe. Then Pr Jean Pierre GERARD, radiation oncologist of Lyon University, has obtained a quick consensus to consider a project supported by Lyon University. The rational was based on the experience of NIRS and GSI demonstrating the technical feasibility and the medical interest of a beam quality fundamentally different than photons regarding ballistic and RBE. In 2001 the region of Lyon-Rhône-Alpes, the wealthiest of France, decided to support the project and appointed three full time coordinators: a technical and a scientific ones and a general manager. Since then the project moved on regularly aiming at obtaining the French government authorisation end of 2004. Some political delay impeded the project authorization until February 2007. After this authorization, five hospitals from the Rhône-Alpes Region gather and founded a kind of consortium named Grouping for Health Activities “GCS” in French: the GCS-ETOILE.

The ETOILE project took his name in early 2002 for the contraction in French of “Site for Oncologic Treatment with Light Ions in European network”, “Etoile” meaning Star in French. ETOILE as a whole has actually two different aspects and could be considered as a dual project : i) a scientific project; ii) a medical project. The scientific aspect will continue to live and develop even when the clinical centre will operate.

The scientific project, instead of been the added value of the project, has been actually its first condition for existence and acceptance by the French health care system. In fact the French radiotherapy was tremendously behind in the late nineties, therefore, the hadrontherapy project looked too luxurious and the fear of huge financial diversion was rising. Actually radiotherapy needed a moving force in France and we decided to give that aim as the first one for ETOILE. This has been a great success and presently about one hundred researchers are working in close collaboration with the project. The main topics are: the development of highly fast and sensitive detectors for PET imaging, the modelization of organ deformation during breathing cycle, hadrons radiobiology and pharmacomodulation of the response to hadrontherapy of radioresistant cells, the study of carbon ions fragmentation for PET interpretation and hopefully its future use as a dosimetry tool, the fundamental and theoretical study of the RBE modelization starting from the local effect model of GSI group, innovative active beam control. This program has also integrated and participates to support a medical physics school that open in September 2004. The national reorganization of cancer care and cancer research in
France has recognized the value of this research program by fully integrating it in the national objectives of cancer research.

The medical project has a rather independent development and has been so far crucial to obtain the governmental authorization. Its objectives are to define as precisely as possible the indications for CIT, to predict the recruitment of the best indications and to demonstrate the feasibility and the medical interest of CIT. It will have to propose a recruitment politic making as clear as possible what will have to be considered as recognized indications and what will have to be studied thought clinical trial. To progress we have many times solicited the NIRS for early results and advices. We are deeply indebted to HIMAC team for its very friendly and helpful support in multiple occasions. From our studies we concluded that 5 to 12% of present radiotherapy indications could be taken in charge by hadrons in the future: 5% for CIT, the rest for protons. This accounts for a rough number of about 7500 cases of CIT indications per year in France. Taking into account the effect of a refine work up, the requirements of clinical trials and the reluctance of some old patients to move far from home, the present figure of ETOILE centre with a capacity of at least 1000 treatments per year seams consistent as a first offer. It supports also, in case of success, the project of a second French centre for the next decade. The indications summarized in figure 2 have been defined though a multi-step process: i) the thorough screening of any cancers situations by 7 specialized committees selecting about 70 potential indications; ii) the epidemiological study of the incidence of each of these potential indications has been extrapolated from a sample of 1% of the whole annual activity of radiation oncology in France; iii) a scientific survey of the cancer literature to define what could be considered as reference as a treatment and a clinical outcome for the main domains of indications; iv) immediately after the completion of each literature survey, a specific European review committee of experts was gathered for each localisation; the potential indications becoming through this process confirmed indications of CIT. The steps iii) and iv) have been completed so far for H & N tumours, adult sarcomas, gliomas, NSCLC, prostate, GIT tumours and paediatric sarcomas. Next ones will be endocrine and rare tumours and paediatric brain tumours later on in 2008. The step v) just starting, will be to define a common European politic for recruitment, health insurance commitment for care refund of confirmed indications and common definition of early multi-centre clinical trials. This very ambitious project has already involved the participation of about 80 MD. Another part of the medical project is a very detailed economical analysis relying on original medico-economic models to calculate the cost of the centre running according to different criteria and recruitment hypothesis. Through this study, the present figure, with the hypothesis of 1000 treatments per year of 13 sessions each in average, is a cost of about 21 000 € value of 2014 (at the time of full running of the centre). This represents an increase of less than 3% of the present global cost of radiation therapy in France and about 0.2 % of cancer induced hospital expenses in France. Thus it remains a “reasonable” cost fully comparable to other modern anti-cancer treatments not always as much curative as hadrontherapy. The construction process is another originality of ETOILE. A public-private partnership agreement (PPP, see figure 3) will be settled after a competitive dialogue along 2008-
2009 to select the consortium that will be in charge of the building and the operation of the ETOILE centre. Le public person, namely the GCS-ETOILE and its medical team will have the responsibility to provide the patients recruitment, to deal with the treatments and to pay the loan of the centre.

The reimbursement of the treatments will be the principal source of cash to pay this loan. Other resources could come from secondary activities including hosting of research teams. This way the building of ETOILE will help to promote an industrial solution aiming if possible at the highest similarity with the other European centres. This choice aims at reducing the cost and at participating to establish an industrial development and therefore an economically affordable dissemination of hadrontherapy. Our present estimation is that one centre for 10 millions inhabitants could be a realistic projection. In this project some technological researches are also carried out such as the development of a superconductive gantry.

The clinical Centre, at last, will be the fruit of this process to open beginning 2013. The rising activity to full running should take 2 to 3 years. The present figure is 1000 patients with in average 13 sessions each. However, the NIRS experience will certainly allow a larger number of treatments with fewer sessions than 13. The centre will be built in a university and medical area, surrounded by scientific institutes. It will have its own equipment for medical imaging (CT scan, MRI, PET), immobilizing devices making and of course treatment planning, but no inpatient facility relaying for that on the hospitals or hotels of the neighbourhoods. Anaesthesia possibilities for treating infants will be provided. Extensive out patient’s consultation facility will be provided as well as data management possibilities. No chemotherapy delivery will be provided, relying for that on the surrounding medical facilities and in particular the large anti cancer centre of Lyon, located 5 minutes walking. In particular for paediatric patients and for randomized adult clinical trials, proton beam delivery will be added to the CIT in the final project as well as the possibility to accelerate other lighter particles than carbon ions (helium, ...). The centre will be operated with a staff of about 84 persons including at the beginning 8 MD (accounting for 6 full time practitioners) with a special status maintaining their links with their originating institutions, and preserving thus the fragile balance of medical teams due to the deep lack of physicians in France. Hopefully, close cooperation with others European places as Catalonia or Switzerland, for instance, will create a fruitful stream of scientific and medical exchanges able to attract patients as well as radiation oncologists and alleviate this possible staff difficulty.

So, as it can be seen, this comprehensive hadrontherapy project has gained its credibility through its sound scientific and medical programs. The inspiration and the scientific support of pioneer project as those of EULIMA, NIRS, GSI, HIT and CNAO have been of great help, in particular for the medical aspects, which have been very sensitive in France. Therefore, ETOILE is continuing to look for tight scientific and medical cooperation with the European network of light ion centre (ULICE).
* Jacques BALOSSO, Marcel BAJARD, Marie-Hélène BARON, Marie-Claude BISTON, Jean-Pierre BOISSEL, Pauline BORDET, Annick BOURNE-BRANCHU, Olivier CHAPET, Patrick GAVIGNET, Chantal GINESTET, Jean-Michel LAGNIEL, Jean-Michel MOREAU, Pascal POMMIER, Joseph REMILLIEUX, Joël ROCHAT, Camille SAHLER, Marianne TERRY, Laurence VIAL, Guillaume WASMER.

**Figure 1**: Insertion of ETOILE building on the selected ground in Lyon (large blue volume)
Figure 2: Summarized indications of carbon ions therapy

**First intention indications**

- Locally advanced non metastatic *adenocarcinoma* of the **head and neck** (M0 including salivary glands and *adenoid cystic carcinomas* in general) and of the **thorax** (N0, M0)
- **Mucinous melanomas**
- Soft tissues *sarcomas* of medium and low grade, after incomplete or impossible surgery and without any threatening metastasis (including *chondrosarcoma* and *chordoma*)
- Small and medium size *non small cell lung carcinoma* (N0, M0) unsuitable for surgery.
- Local relapses M0 of *pelvic adenocarcinoma* previously irradiated by photons.

**Second intention indications**

- Prostate *adenocarcinoma*
- **Head and Neck** locally advanced *squamous cell carcinoma*
- High grade *glioma*
- The highly radioresistant or anatomically difficult *gastro-intestinal tumors* (hepatocarcinoma, some pancreatic tumors, pelvic tumors....)
Figure 3: The PPP process for ETOILE construction and operation

ETOILE construction flow-chart

The GCS-ETOILE is the stake holder

Juridical assistance for the contract writing

The industrials are candidates for the PPP and propose their offers through a competitive dialogue

The APP helps to produce the needed documents and to organize the tendering process

The contractor of the PPP will **build AND run** the Centre, the GCS-ETOILE will rent the facility
SYNOPSES, Part 4:

Innovative Concepts
CEA Saclay study on Superconducting Gantry Magnets

F. Kircher (CEA Saclay, France)

The paper gives the situation of a preliminary study which has been launched to look at the possibility to use superconducting magnets in a Heidelberg-like rotating gantry for 400 MeV carbon-ion beams. The expected advantages are a reduction of weight and cost, when taking all costs into account (capital, operation, building).

The main 90° bending dipole will use niobium-titanium superconductor and will produce a field in the range of 3.2 T. Because of the active beam scanning mode of operation, a large aperture (200 x 200 mm²) is required for this magnet, as well as a good field integral homogeneity (+/- 2.10⁻³). Care must also be taken to reduce the losses in the conductor and the structure when ramping down the field to move the Bragg peak. The use of cryogenerators and current leads made of high temperature superconductors will simplify the cryogenics aspect.

Previously expected for mid 2007, the full results of the study (technical feasibility, cost estimate, schedule for a prototype) are now foreseen for end 2007.
Development of a center for advanced tumour imaging and light ion, photon and electron therapy at Karolinska University Hospital.

Björn Andreassen, Johanna Kempe, Roger Svensson, Mark Katz and Anders Brahme

Abstract and Introduction: This presentation briefly covers the ongoing development of a therapy center with multiple simultaneous radiation modalities at Karolinska university hospital. The hearth of the facility will most likely be a superconducting cyclotron capable of delivering around 400 MeV/u carbon ions simultaneously to two separate excentric gantries who service four treatment rooms each. A number of different stable ions will be available ranging from hydrogen to oxygen but also PET emitting C\textsuperscript{11} ions and possibly B\textsuperscript{8} the lightest existing PET emitter. Several treatment rooms will also be equipped for narrow scanned high energy photon and electron beam treatments and a light ion research facility for physics and biology studies will be set up on two separate beamlines as shown in Fig1. The centre will include an advanced PET-CT and MRSI based diagnostic centre on the same floor and close to both the ion treatment facility and the high energy photon and electron facility. By docking the stereotactical treatment coach both to the treatment units and before and after the treatment to the diagnostic PET-CT units, iso dose delivery can be rapidly examined by imaging the radiation induced C\textsuperscript{11} and O\textsuperscript{15} activity produced during the treatment.

Light Ion Center: The Karolinska University hospital has a long tradition of cancer treatment by radiation therapy and has centers for tumour- and radiation- biology research. Radiumhemmet at Karolinska was established as early as 1940, after activities down town Stockholm during the first part of the century, and the human resources for ion therapy and the infrastructure for dealing with a large influx of patients is already in place. The proposed ion center will most likely be located in connection to the well established treatment facility with 8 electron accelerators taking full advantage of the strong research resources at Cancer Center Karolinska and the Clinical Infrastructure developed during a century of clinical research (Brahme et al 2003, Svensson et al 2005). The facility will also be close to the Cancer wing of the New Karolinska Hospital to be built between the Karolinska Institute and the Karolinska University Hospital. The layout of the light ion treatment area is illustrated in Fig 1 showing the superconducting cyclotron and the beamlines for ion transport including the beam splitter creating two high energy beamlines, one for each gantry, available for radiation therapy all the time. Before each gantry are placed separate beam decelerators bringing the energy down to the range required by the tumour depth of the patient being treated. Each excentric gantry provide radiation shielding for the internal beam transport so the personnel can work inside any of the four rooms as long as they are not being used for patient treatment. Since the treatment only takes a few minutes the major part of about 15 minutes can be used for accurate patient setup before the therapeutic beam is available. When the gantry is full scheduled for therapy up to 16 patients per hour can be treated with each gantry or 128 patients per 8 hour day. Of these in average 10 are finishing their treatments since in average 10-13 treatments are given in a curative protocol with light ion beams. Thus up
to about 2500 patients can be treated per year and gantry with 15 minutes interval between the treatments.

**Treatment Rooms:**

The treatment rooms around the two excentric gantries are shown in Fig 2. By dividing the full 360° rotation of the gantry into suitable sectors with useful beam directions and treatment options into four rooms each with about 60° segments the patient output can be increased considerably as the personnel can set up and bring out patients in the other three rooms while a patient is being treated in one of them. Figure 3, 4, 5 and 6 show how different patient setups and treatments, and although the entry angles in each room is limited to about ±60° by rotating the patient 180° on the coach the most common treatment are still easily and ergonomically possible by careful selection of the treatment room and beam directions. The patient will be docked to the rotary gantry on a stereotactic treatment and diagnostic coach as shown in the bottom right corner of Fig 8.

In Fig 3 and 5 a possible treatment plan for a lung tumour is shown with three or four fields allowing an almost equal degree of freedom as with an isocentric gantry or rotating the patient as used in CHIBA. In CHIBA this kind of treatment of lung cancer has been very successful particularly when performed in just four fractions during one week (Fig 3) and most recently in a single fraction of about 42 Gy delivered in a single session with four beams (shown in Fig 5). The local control of non small cell lung cancers of stage I using this kind of treatment is very high of the order of 95% five years after treatment, showing the high usefulness of carbon ions on severely hypoxic lung tumours. One minor complication for the proposed treatment in this room is that the patient sometimes need to be elevated quite high (position 3 and 4 in Fig 5). For this reason an automatic variable floor level will be used to reach the appropriate level. In Fig 4 a treatment plan and the patient positioning for a head and neck tumour is shown. The tumour in the case is a Bone and Soft tissue Sarcoma which is quite hypoxic and difficult to cure by either surgery or photon therapy or both combined. For these tumours carbon ions have become very successful too with around 85% local cure at five years at the same time as the boney structures are completely healed. This treatment room will probably also be used with a moveable floor to compensate for the change in elevation of the patient. Figure 6 shows a possible treatment plan for a prostate cancer (also adapted from CHIBA). By advantage the horizontal beam positions are not possible in this room but a strongly oblique anterior pair is as shown making a more flexible plan avoiding irradiation of the femor heads. For advanced prostate cancer (PSA>20) this type of carbon ion therapy has improved the treatment outcome from around 45% with photon IMRT and protons to almost 90% with carbon ions measured in terms of the probability of having biochemical relapse free control five years after the treatment. When a larger range of beam angels (more then ±60°) are needed for example with prostate cancer the treatment could be performed every second day in two different treatment rooms. With carbon ions this is already used in CHIBA and works well since the dose to normal tissue is very low so the normal tissue problems seen with for example 60°Co are not at all present.
In summary, figure 3-6 show clearly that carbon ions in an excentric gantry of the type proposed for the installation in Stockholm will allow practically all the very advantageous treatment methods developed at CHIBA for carbon ion therapy.

As a complement to the ion treatments the facility will as already mentioned also have two treatment units using high energy (~70MV) narrow scanned photon beams and two low energy units dedicated to dynamic IMRT with low energy photons using broad beam intensity modulation device. The high energy units are shown in Fig 1 and are positioned close to the PET-CT diagnostic center for rapid in vivo dose delivery verification through photonuclear reactions (Janek et al 2007).

**PET-CT Imaging:** Taking advantage of the fact that the delivered dose distribution using carbon ions and high energy photon beams can be registered by PET-CT imaging, the treatment facility will have an advanced diagnostic PET-CT center for tumour imaging and to verify the delivered dose distribution after any treatment fraction. This makes it possible to make adjustments to an ongoing treatment and thus improving the clinical outcome using the BIO-ART approach where the treatment is biologically optimized based on 3Dimensional in vivo predictive Assay using IMRT (Brahme 2003 and 2005) and QMRT (Intensity and radiation Quality Modulated Radiation Therapy).

**Excentric gantry:** The cyclotron will deliver ion beams to two excentric gantries shown in Fig 7 and 8. The gantry magnets are warm (not superconducting) with several quadruples and four bending magnets and two scanning magnets. The beam optics was developed in close collaboration with Mark Katz in 2005 for several versions of the gantry (one example shown in Fig 7). The Scanning magnets are placed before the last bending magnet which has a large aperture. The excentric gantry is far more compact (diameter ~6m), light and more highly cost effective then an isocentric gantry at the same time as all 360° of freedom are available when choosing beam angles by careful selection of treatment room. (Brahme 2003)

**Light Ions:** The main advantage of ion beams for radiotherapy is the increased ionization density or LET (linear energy transfer) and relative biological effectiveness (RBE) towards the end of the particle range. However, an increased LET and RBE in itself offers no therapeutic advantage unless there is a differential effect for example making the LET and RBE higher in the tumour than in the normal tissue. From this point of view Li ions would be a very good treatment option as these ions have a very strong ‘co-localisation’ of their high dose Bragg peak and high-LET therapeutic and apoptotic tumour lethal region (cf Fig 9 and Kempe et al 2007) at the same time as their low dose low LET region mainly reaches normal tissue where it induces DNA repair. The lithium ion is therefore an ideal particle when a high therapeutic dose is needed in a small tumour volume. With protons, of similar penetration depth as the lithium ions, the dose comprised of high LET particles in the Bragg peak region is very low whereas with carbon ions the high LET region extends both in to the plateau region and the fragmentation tail. For small to medium size tumours this can be a disadvantage as it not only increases the cell kill but also increases normal tissue damage.
Conclusion:
In conclusion the proposed center will allow a very high patient throughput at the same time as the therapeutic outcome is substantially better for advanced cancers than using photons and the cost per treatment is comparable or less than that for modern IMRT. Furthermore the excentric gantry combined with a superconducting cyclotron may allow the production of C\textsuperscript{11} and B\textsuperscript{8} that will provide more accurate dose delivery imaging than for example protons or carbon ions. The possibility to use lithium ions for smaller tumours open for truly biological optimized radiation therapy where the tumour is mainly eliminated by nature's own mechanism of apoptosis whereas normal tissues are stimulated to repair the low level of damage.

References:
J. Kempe I. Gudowska A. Brahme, Depth absorbed dose and LET distributions of therapeutic 1H, 4He, 7Li, and 12C beams Med Phys 2007 Jan;34(1):183-92
Multi-Room Gantry Concepts Based on the Riesenrad Gantry

H. Schönauer, CERN

Introduction

Since the PIMMS Study [Pimms] at CERN, a concept alternative to the conventional isocentric gantry is known (and subject to discussions and controversies). Dubbed the “Riesenrad” gantry, it places the heavy 90° bending magnet of a gantry on the axis of rotation. The major argument of its opponents is the (relative) inaccessibility of the patient cabin rotating around the central 90° bending dipole.

The Riesenrad Ion Gantry

In the frame of the PIMMS study, an elevator-based Riesenrad concept was thoroughly elaborated in a PhD thesis [Reimoser]. The large cabin facilitates both routine and emergency access and safety standards are as in conventional therapy. The calculated positioning precision remains in the sub-millimeter range (3σ < 1 mm).
A. Brahme’s Multiple-room Gantry Concept (International Patent filed 2005 [Brahme])

This concept replaces the moving patient cabin by a number of rigid treatment rooms, wherein the patient couch is displaced horizontally allowing in this way for a variety of angles of beam incidence. Beyond the bending magnet, shielding matter has to be rotated or displaced. An International Patent was granted in spite of an early publication by R. L. Martin, ACCTEK Associates.

Claim:

- The efficient use of two scanning and dosimetry systems in six different treatment rooms makes this solution extremely cost-effective, and there is ample time for patient care and setup with four rooms around each excentric gantry. Simulator treatment heads can be used in each room, while the real treatment takes place in another room and possibly with two simultaneous directions, either anterior or posterior oblique lateral beams in the two middle lower and upper treatment rooms, respectively.
Lateral View of the Brahme Multi-Room Gantry

The Exocentric Variant of the Multi-Room Gantry
Note that in one transverse plane scanning is performed upstream the main bending magnet
A Step Further: The Modular Exocentric Gantry

The preceding figures represent present the ‘state of the art’ of the multi-room concept. In fact, the “artist view” of A. Brahme’s concept is the actual proposal for the Hadron Therapy Facility at the Karolinska Institute.

The concept proposed here goes a few steps further:

- Profiting from the inherent necessary distances to the patient couches, the scanning magnets are placed downstream the main 90° dipole. Consequently, this magnet needs no more aperture than all other beam line elements.
- Consequently, one can imagine the 90° dipole composed of standard HEBT dipoles.
- In order to achieve zero dispersion at the isocentre, more bends are required for correct matching to the upstream zero dispersion transport line. Adding two opposite bends like in an isocentric gantry, the main 90° dipole is moved out of the centre. This further increases the SSD.
- The beam optics from the entrance to the gantry to the isocentre is a telescopic or even 1:1 mapping.

By virtue of these properties, an ion gantry can have less weight than a conventional isocentric proton gantry.
Combining Brahme and Modular Exocentric Gantry Concepts

Combining the rigid multi-room concept with the exocentric Riesenrad gantry we propose a rather compact hadron treatment facility. The treatment area is distributed on three vertical stories and spread out horizontally. The beam transport from the accelerator is limited to the required matching sections, which makes the concept particularly suitable for hospitals with limited footprint.

The Multi-Room Modular Exocentric Gantry:
A Step Back: the Frozen Gantry

If continuously variable beam incidence angles are dispensable, a set of fixed angles appears competitive:

It is in fact a standard 45° layout turned upright! Again, it could make sense where little ground surface is available or so expensive that tall buildings are common.

Conclusions:

Multi-Room gantry layouts require a minimum of ground plot area as compared with the typical horizontally spread-out treatment concepts and are certainly much less expensive. A multi-room gantry would be the layout of choice in a down-town hospital environment, if the local medical community accepts the modality of treatment rooms spread over a number of stories.
References:


[Brahme]: A. Brahme, Multiple Room Radiation Treatment System, PCT International Publication Number WO 2005/053794 A1, Publication 16.06.2006
Non-Scaling FFAG Gantries

D. Trbojevic

Brookhaven National Lab., USA

A novel idea about the proton/carbon gantry was presented, where the weight of the gantry can be reduced from 150 tons to 1500 kg! The major assumption and study is that the scanning system could be placed above the patient at ~3-4 meter distance. The scanning assumes an angle of 30 mrad. Detail study of carbon or proton ion penetration through the body shows no difference between the "straight" zero degrees ion entrance to the skin. This is mostly due to Coulomb scattering and spread through the body. to produce the same skin effect of the radiation requires just a different plan of the scan.

The iso-centric gantry is based on the non-scaling Fixed Field Alternating Gradient principle. The particles are transported through the gantry under extreme focusing through the alternating combined function magnets. In the case of a combination proton-carbon the superconducting magnets are required. The magnets required already exist on the market they are made by company in Florida. In addition the ion transport is possible for the whole therapy energy range. This simplifies dramatically the treatment.
MATCHING TO GANTRIES

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Abstract

Transport of ion beams in rotating ion-optical systems like a gantry requires special matching techniques that are described in the paper. Theoretical considerations have been demonstrated with the aid of WinAGILE simulations. Matching to gantries becomes important especially for slowly extracted beams with different emittances in horizontal and vertical plane that are delivered by pencil-beam scanning. Different matching methods are reviewed and compared.

1 INTRODUCTION

Beams extracted slowly from a medical synchrotron have different emittance diagrams in horizontal and vertical planes. In such a case, the beam parameters at the entrance to the rotating gantry become a function of the rotation angle and this angular dependence is, in general, transferred to the gantry isocentre unless special matching techniques are applied. Two basic matching strategies can be recognized:

• the input beam parameters are “rotated” together with the mechanical rotation of the gantry;
• the ion-optical setting of the gantry fulfills special ion-optical constraints to make some beam parameters at the gantry isocentre independent from the angle of gantry rotation.
2 THEORETICAL BACKGROUND

2.1 Matrix formalism

Beam-transport is usually described with the aid of the transfer matrix and the sigma-matrix. The transfer matrix \( \mathbf{M} \) describes the action of an ion-optical element on individual particle trajectories and is defined as:

\[
\mathbf{X}_{\text{out}} = \mathbf{M} \mathbf{X}_{\text{in}}
\]  

(1)

where \( \mathbf{X}_{\text{out}} \) and \( \mathbf{X}_{\text{in}} \) are vectors containing the particle co-ordinates at the exit and at the entrance of the ion-optical element, respectively.

The sigma-matrix of the beam \( \mathbf{\sigma} \) is defined by the equation of an ellipsoid describing the phase-space volume of the beam:

\[
\mathbf{X}^T \mathbf{\sigma}^{-1} \mathbf{X} = 1
\]  

(2)

The action of an ion-optical element on the sigma-matrix is given:

\[
\mathbf{\sigma}_{\text{out}} = \mathbf{M} \mathbf{\sigma}_{\text{in}} \mathbf{M}^T
\]  

(3)

where \( \mathbf{\sigma}_{\text{in}} \) and \( \mathbf{\sigma}_{\text{out}} \) are the sigma-matrices of the beam at the entrance and at the exit of the ion-optical element, respectively.

It can be shown that the transfer matrix of co-ordinate system rotation, \( \mathbf{M}(\beta) \), is:

\[
\mathbf{M}(\beta) = \\
\begin{pmatrix}
\cos \beta & 0 & \sin \beta & 0 & 0 \\
0 & \cos \beta & 0 & \sin \beta & 0 \\
-\sin \beta & 0 & \cos \beta & 0 & 0 \\
0 & -\sin \beta & 0 & \cos \beta & 0 \\
0 & 0 & 0 & 0 & 1
\end{pmatrix}
\]  

(4)
where $\beta$ is the angle of gantry rotation. Obviously, rotation of the co-ordinate system causes coupling between the horizontal and vertical transverse planes.

### 3 MATCHING METHODS

#### 3.1 Rotator

The rotator concept is based on inserting a dedicated matching section called “rotator” in-between the fixed beam-line and the gantry. Let the transfer matrix of the rotator $M_{rot}$ be:

$$
M_{rot} = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & -1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}.
$$

(5)

If the gantry is rotated by an angle $\beta$ with respect to the fixed beam-line, the rotator must be rotated by the angle $\frac{\beta}{2}$. This means, that the angle $\frac{\beta}{2}$ appears between the exit of the fixed beam-line and the entrance to the rotator and another angle $\frac{\beta}{2}$ appears between the exit of the rotator and the entrance to the gantry. The overall transfer matrix from the exit of the fixed beam-line to the entrance to the gantry $M_{over}$ will be:

$$
M_{over} = M_{\left(\frac{\beta}{2}\right)}M_{rot}M_{\left(\frac{\beta}{2}\right)}.
$$

(6)

Performing the matrix multiplication yields $M_{over} = M_{rot}$, which is the unit matrix in the horizontal plane and the “minus-unit” matrix in the vertical plane. This means, that in the horizontal plane, particles will enter the gantry exactly with the same co-ordinates (expressed in the rotated co-ordinate system) as they left the fixed part (the fixed co-ordinate system). In the vertical plane, their co-ordinates will be reversed. Assuming a beam containing always both $[Z_0 \ Z'_0]$ as well as $[-Z_0 \ -Z'_0]$ particles, this effect does not play any role. The $[Z_0 \ Z'_0]$ and $[-Z_0 \ -Z'_0]$ particles just
exchange their positions in the emittance diagram. The beam parameters in the rotated co-ordinate system are therefore identical to the beam parameters in the fixed co-ordinate system in both planes. In other words, they are rotated together with the co-ordinate system rotation.

3.2 Equal-sigmas matching

Without using the rotator, the beam parameters at the entrance to the rotating ion-optical system become a function of the rotation angle. This angular dependence is, in general, transferred to the gantry isocentre. Angular independence of some beam-parameters can be achieved by applying a special set of ion-optical constraints upon the gantry that have been derived in [1]. Fig. 1 illustrates the rotation independence of the beam-spot for 4 mm beam-size at the isocentre. The beam envelopes are shown for rotation angles from 0° to 90° in 10° steps. In one extreme position (0°), the horizontal plane of the gantry transports the beam with the minimum emittance (minimum input beam-diameter) while the vertical plane of the gantry transports the beam with the maximum emittance (maximum input beam-diameter). In the second extreme position (90°), the situation is inversed. Other beam-envelopes showed correspond to the rotation angles from 10° to 80°. The output beam-diameter is independent from the angle of gantry rotation.
Fig. 1 Demonstration of rotation-independent beam transport in a rotating gantry.

4 DISCUSSION AND CONCLUSIONS

4.1 Protons versus heavy-ions

Heavy-ions require different beam-delivery techniques compared to protons. Proton therapy beams are usually formed by passive beam-delivery systems (scattering and collimation) whereas heavy-ions should preferably be delivered by pencil-beam scanning. That is why, the problem of non-symmetric beam-transport is less relevant for protons even if they are produced by a synchrotron. It is also not relevant for cyclotrons because the extraction techniques used in cyclotrons are different from those used in synchrotrons. The proton gantries are therefore designed and operated successfully assuming the symmetric ion-optical properties of the beam. It is the
combination of the resonant slow-extraction with the pencil-beam scanning and the rotating gantry, which requires the special matching.

4. 2 Rotator versus non-rotator concept

There are essential differences between the rotator and the non-rotator concepts. As far as the principle is concerned, the rotator removes the angular dependence of the beam parameters at the entrance to the gantry. This is achieved by an extra matching section with a special transfer matrix that maps particle co-ordinates from the fixed co-ordinate system into the rotated co-ordinate system. This is equally true for particles displaced due to the dispersion of the incoming beam-line. That is why, the rotator is able to match even non-achromatic rotating systems like the Riesenrad gantry [2]. The rotator concept is a universal approach that can be applied to any rotating ion-optical system and provides full rotation independence of all beam parameters. A disadvantage is an extra space needed for the rotator (10 – 15 m of the beam-line) and mechanical rotation of two beam-transport sub-systems, the rotator and the gantry. The first may cause problems to fit the limited space available at a hospital, the latest may contribute to the beam-position inaccuracy due to the mechanical misalignments of the rotated beam-transport elements.

The non-rotator concept removes the angular dependence of some beam parameters at the exit of the rotating system still tolerating the angular dependence of the input beam parameters. It can be applied to achromatic systems only that are, in addition, able to fit a special set of ion-optical constraints. The angular dependence can only be achieved for selected output beam parameters. A disadvantage of the non-rotator concept is therefore obviously the restricted applicability. An advantage is, that matching is in fact done by the gantry beam-transport system itself without any additional space needed for a matching section.

There are two different sets of ion-optical constraints based on either parallel-to-point or point-to-point imaging. The only successful design so far has been achieved for parallel-to-point imaging [1]. Special imaging conditions may be exploited for making
the beam-transport less sensitive to mechanical misalignments, which may simplify the design of the mechanical supporting structure. For example, the parallel-to-point gantry will entirely be insensitive to shifting the whole structure with respect to the incoming beam-line supposing that the gantry aperture is designed with a reasonable safety margin.

REFERENCES


Summary

E. Griesmayer

The workshop was divided into four scientific sessions. The first session considered the rationale of an ion gantry and included reports on project activities around MedAustron. In the second session state of the art developments of ion and proton gantries were discussed. In the third session presentations were given by industry about the latest industrial concepts concerning ion gantries for particle therapy. Finally, in the fourth session innovative concepts for novel techniques for ion gantries were discussed. In total there were 22 presentations.

Thomas Auberger opened the First Session “The Rationale on an ion Gantry” presenting the European scenario from the MD’s point of view. He cross referenced the statistical data from NIRS with requirements in Austria and concluded that for proton therapy a gantry is essential, and that tilting the patient is connected with problems in treatment planning. Cheaper and smaller carbon ion gantries shall be developed.

Oliver Jäkel presented a comparison of treatment planning with and without a gantry from the medical physicist’s point of view.

Reinhart Sweeney discussed a high-quality patients positioning systems that can replace a rotating gantry. He showed impressive examples of high-precision fixation systems, positioning systems and some practical examples of what happens when patients are turned.

Rolf Seemann presented his latest developments concerning the mechanical concept and a sensitivity study on an ion gantry with conventional magnets and a dedicated expansion bearing technique. This was worked out during the MedAustron design study.

Karin Dieckmann compared treatment planning for proton and photon therapy, regarding influences of beam application techniques. She summarized that multiple field techniques are often better than single field techniques. A gantry makes treatment planning more flexible and allows patient positioning without moving the patient during treatment.
Thomas Schreiner presented the status of the Austrian – Hungarian Interreg IIIA project “MedAustron”, a transnational research co-operation and location development MedAustron which aims for the initialisation of cross-border activities in the field of MedAustron.

Theo Krendelsberger reported on the status of MedAustron. He pointed out that MedAustron shall be a “centre of excellence” in cancer treatment and cancer research, it shall provide a world-class irradiation facility for radiation biology, radiation physics and physics in two separate experimental rooms. Further on MedAustron shall be a nucleus for collaborative research activities in Central Europe and it shall be accessible for international research groups on the basis of cooperation contracts.

The Second Session “Gantries – State of the Art” was opened by Michael Benedikt who presented an overview on gantries for hadron therapy (prepared co-operation with Phil J. Bryant). He summarised the principles of passive spreading and beam scattering, he compared divergent-beam voxel-scanning gantries, parallel-beam scanning gantries and the principle of transverse scanning, before he talked about exo-centric gantries, the Riesenrad gantry and novel gantry designs including beam matching.

Thomas Haberer showed the latest status of HIT and the GSI gantry. It was impressive to see the photographs demonstrating the enormous progress of the German project, in particular the ion gantry.

Eberhard Sust from MT Mechatronics reported on the status of the GSI gantry. He demonstrated that industry is willed and able to face the challenge of a big innovation in medical technology.

Marco Pullia showed us the status of CNAO and the gantry plans for the future. He presented pictures from the site, the synchrotron vault and impressively much of concrete. Plans for the future expansions for two ion gantries and a dedicated idea for a gantry with mobile isocenter completed the talk.

Emilio Pedroni gave a remarkable clear presentation on design considerations and state of the art proton gantries. He discussed scanning and scattering in gantries first, giving scanning the clear preference. He then explained advantages, limitations and achievements of pencil beam scanning including clinical results from PSI. He pointed out the sensitivity of scanning to organ motion. Repainting would be a way out as he demonstrated on the example of the PSI gantry 2.
Jacques Balosso presented the status of the ETOILE project. It was a good surprise to hear that a governmental approval for the amount of 1.25 M€ per year was given to start the construction process in Lyon on 12th of February 2007. ETOILE hopes to start the construction in 2009 and the first treatments by the end of 2012.

In the Third Session “Industries Concepts” Hugo Schär presented mechatronic systems for gantry and patient positioning. Treatment chairs, the RPTC gantry including a patient transporter, patient positioner, diagnostics and safety, a movable couch, a 6-D patient positioning system and the PSI gantry highlighted the high-precision mechatronic systems of his company.

Yves Jongen from IBA introduced his innovative superconducting gantry concept. The superconducting magnet technology allows for a magnetic field of 3.2 T and a remarkable reduction of the dipole weight to some 28 tons. The proposed gantry has 9.2 m diameter, is 12.7 m long and has a rotating mass of 156 tons.

Stefan Schmidt from ACCEL Instruments presented the concept and performance of the RPTC gantry systems and explained the advantages of the customer-tailored solution.

Francois Kircher from CEA opened the Fourth Session “Innovative Concepts”. He presented a CEA study on superconducting gantry magnets including a magnetic field strength of the gantry dipole magnet of 3.22 T. The design has to respect a fringe field at the patients head of less than 5 Gauss. A fancy mechanical alignment of the coils reduces the weight for the magnet to 17 tons. A final design and a costs estimate should be available by the end of 2007.

Björn Andreassen talked about the development of a centre with multiple simultaneous treatments for the Karolinska University Hospital in Stockholm. In this proposal a superconducting cyclotron provides protons. Two excentric gantries are foreseen, four treatment rooms per gantry. The capacity reaches up to about 5000 patients per year. Each room allows several treatment directions over ±60 degrees. All angles between 0-360 degrees are available by rotation of the patient on the couch 180 degrees and careful selection of treatment room.

Horst Schönauer talked about multi-room gantry concepts, including the “Riesenrad Gantry”. He explained the operating mode of the Riesenrad Gantry concept, Brahme’s multiple-room gantry concept and the “frozen gantry” as a contrast. He summarized the pros and cons of gantries taking latest projects and technical developments into account.
Dejan Trbojevic explained the principles and advantages of non-scaling FFAG gantries in a dedicated presentation. He summarized that gantries made of non-scaling FFAG using superconducting combined function dipoles provide two main advantages: first of all orbit offsets for the required energy range are very small allowing use of small magnets and secondly the estimated total weight is 1.5 tons with respect to 135 tons.

Marius Pavlovic closed the scientific part of the gantry meeting with his explanations on matching to gantries. In a few slides he introduced the maths of the rotator and equal sigma principles. He showed plots about the influence of dispersion effects on the target and he pointed out that the problem of matching to rotating gantries was solved respecting that there are even several possibilities available depending on the choice of parameters of the incoming beam and the type of the gantry.
Workshop Programme

Date: 9 - 10 March 2007
Location: Austria-Trend “PARKHOTEL SCHÖNBRUNN”, Wien
          Hietzinger Hauptstraße 10–20, A-1130 Vienna, Austria, EU
Organizers: M. Regler, Th. Auburger, H. Schönauer, W. Mitaroff

Friday, 9 March 2007

12:00 Registration
13:00 Coffee
13:30 P. Lukas, UK Innsbruck, President of the “Verein Austron”: Welcome

Session 1a: The Rationale of an Ion Gantry (Chair: P. Lukas / M. Regler)

13:40 Th. Auburger, UK Innsbruck and MedAUSTRON:
Opening talk: Rationale for a Carbon Ion Gantry – the physician’s point of view

14:10 O. Jäkel, UK Heidelberg and HIT:
Treatment planning with and without a Gantry – the physicist’s point of view of the virtues of a Gantry

14:40 A. Sweeney, UK Innsbruck:
Can high-quality patients positioning systems replace a rotating Gantry?

15:10 Coffee

Session 1b: The Rationale of an Ion Gantry, cont’d (Chair: Th. Auburger / O. Jäkel)

15:40 R. Seemann, fotec:
Gantry considerations for MedAUSTRON

16:00 K. Dieckmann, UK Vienna:
Comparative treatment planning for proton and photon therapy, regarding influences of beam application techniques

16:30 Th. Schreiner, P. Csizmar, Th. Auburger, E. Griesmayer:
Status of the Austrian – Hungarian Interreg IIIA Project “Med-Austron”

16:50 Th. Krendelsberger, PEG:
Status of MedAUSTRON

17:20 Discussion

19:00 Workshop Dinner: at the venue
**Saturday, 10 March 2007**

9:00 M. Regler, Verein AUSTRON: Welcome

**Session 2a: Gantries – State of the Art** (Chair: M. Bajard / M. Regler)

9:10 M. Benedikt and Ph. Bryant, CERN: Gantries for hadron therapy – an overview (presented by M. Benedikt)

9:45 Th. Haberer, HIT: Status of HIT and the GSI Gantry

10:20 E. Sust, MT Mechatronics: GSI Gantry

10:35 M. Pullia, CNAO: CNAO status and Gantry plans for the future

10:55 **Coffee**

**Session 3: Industry’s concepts** (Chair: T. Haberer / M. Pullia)

11:15 H. Schär, SCHÄR Engineering: Mechatronic Systems for Gantry and Patient Positioning

11:40 Y. Jongen, IBA: A superconducting Gantry concept

12:05 Stefan Schmidt, ACCEL Instruments: Concept and performance of the RPTC Gantry Systems

12:25 **Lunch**

**Session 2b: Gantries – State of the Art, cont’d** (Chair: H. Schönauer / M. Pavlovic)

13:55 E. Pedroni, PSI: Proton Gantries – design considerations and state of the art

14:45 J. Balosso and M. Bajard, CHU Grenoble / UCB Lyon / ETOILE: ETOILE status (presented by J. Balosso)

**Session 4: Innovative concepts** (Chair: E. Pedroni / M. Benedikt)

15:15 F. Kircher, CEA: CEA study on superconducting Gantry magnets

15:40 **Coffee**

16:05 B. Andreassen, Karolinska Institute: Development of a centre with multiple simultaneous treatments for the Karolinska University Hospital in Stockholm

16:20 H. Schönauer, CERN and MedAUSTRON: Multi-room Gantry concepts, including the “Riesenrad Gantry”

16:40 **Short break**
16:55  D. Trbojevic, BNL:
Non-scaling FFAG Gantries

17:10  M. Pavlovic, TU Bratislava:
Matching to Gantries

17:30  E. Griesmayer, fotec:
Summary

18:00  Th. Auberger, UK Innsbruck and MedAUSTRON:
Final remarks

19:00  “Heuriger” (offered by PEG):
at Zahel in 1230 Wien, Mauer Hauptplatz 9
## List of Participants

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<th>Family Name</th>
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<td>Auböger</td>
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<td>Marcel</td>
<td>Bajard</td>
<td>Univ. Claude Bernard / ETOILE, FR</td>
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<td>Jacques</td>
<td>Balosso</td>
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<td>Eric</td>
<td>Baron</td>
<td>GANIL-ASCLEpios, FR</td>
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<td>Marcel</td>
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<td>National Oncol. Inst. Bratislava, SK</td>
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