# GLOBAL INDUSTRIAL DEVELOPMENT OF ACCELERATORS FOR CHARGED PARTICLE THERAPY

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*Abstract*

This paper describes the current situation concerning industrial accelerators for medical hadron therapy facilities. Starting from high level requirements and considerations for a therapy facility more specific requirements for the accelerator will be deduced. The Varian ProBeam cyclotron is shown as an example of a medical accelerator and a statistical overview on other accelerators in us is given. The focus is strictly on industrially available equipment. As hadron facilities are extremely complex systems, in the confined space of this paper some simplifications are unavoidable.

## WHY HADRON THERAPY

The essential reason why hadron therapy is used is the special form of the depth dose curve for hadrons, which is very different from the exponential decrease of the curve for photons (see green curve in Fig. 1); The curve for hadrons has a pronounced peak, a low entrance dose and no dose after the peak (see red curve in Fig. 1).

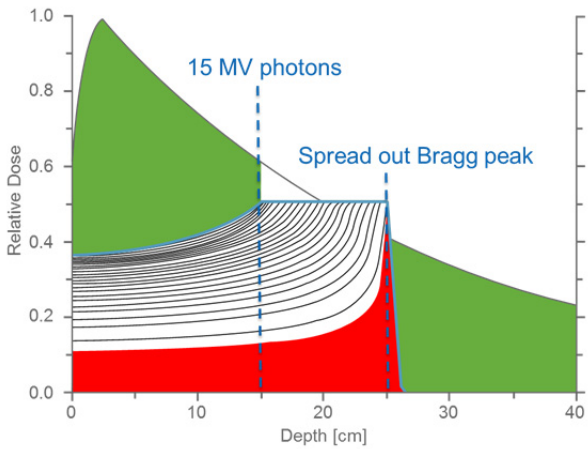


Figure 1: Depth dose curves.

This Bragg peak of a monoenergetic proton beam covers only a small area in depth. Therefore a homogeneous dose distribution in depth necessitates the weighted overlay of several energies, which creates the spread out Bragg peak (see gray curve in Fig. 1). This overlay of several energies creates an increase in the entrance dose but nonetheless the difference between a single field irradiation by 15MV photons versus Protons as marked by the remaining green areas is significant.

For the dose conformity in transversal direction to the beam path, two different techniques are used.

Scattering: this spreads the beam by adding scatter foils in the beam path to create a homogeneous transversal dose distribution which then is shaped by apertures.

Scanning: this spreads the beam dynamically by sweeping it in two orthogonal directions by magnets.

Figure 2 shows dose calculations [1] as an example for a convex shape tumor with a critical organ in the center which should be spared. The three columns show the results for scattering, scanning with homogeneous dose and scanning with Intensity Modulated Particle Therapy. In the first row this is shown for a single field applied from the direction of the white arrow and in the scond column for three fields. The tumor is the concave shape with an organ at risk in the center, which should be spared as much as possible. The dose is colour coded from highest in red to lowest in blue. Multiple fields show better conformity and sparing of organs at risk and the **I**ntensity **M**odulated **P**article **T**herpy case is cleary the best.

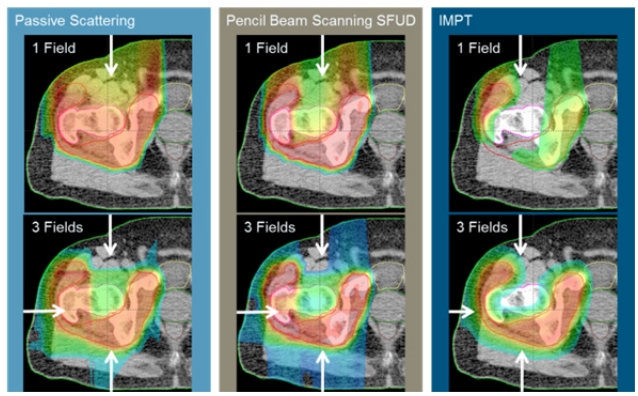


Figure 2: Dose conformity for different beam delivery systems.

Due to these benefits in dose conformity and sparing of organs at risk, proton therapy is used for a variety of cancer cases including head & neck, lung and pediatric.

## REQUIREMENTS AND CONSTRAINTS

Hadron therapy treatments has slowly become available for more patient around the world. However, the total number of patients treated with hadrons (approx. 12,000

Table 1: Photons versus Protons

| | PHOTONS | PROTON |
|---|---|---|
| PRICE | 2 – 3.5 MUSD | 20 – 35 MUSD |
| FOOTPRINT | 100 m² | 200 – 400 m² |
| COST PER TREATMENT* | 400 Euro | 1000 Euro |
| PATIENTS PER YEAR | 2,500,000 | 12,000 |

patients per annum) is still nearly negligible compared to

the total number of patients that are treated with photons each year (approx. 2.5 million).

In order to better understand the obstacles for hadron therapy, let us look at some key data for photon and proton equipment (see table 1). To facilitate comparison, the proton numbers are based on a facility with a single treatment room. The costs per treatment are based upon estimations. [2]

These few numbers alone show huge differences. The price of the equipment for proton therapy is ten times as high as the price for photon therapy equipment. Furthermore building costs for a proton facility are much higher, due to the amount of shielding needed for high energy neutrons and the larger footprint of the equipment. For light ions the situation is even worse due to the significantly higher cost and footprint for the equipment.

For hadron therapy to catch up with photons and to be available for more patients, its cost, footprint, and maturity has to come close to the cost, footprint and maturity of photon facilities. In what follows I will try to deduce from the general requirements and considerations for a proton facility the requirements for a proton accelerator.

Figure 3 presents an overview of a complete proton facility. We have to be aware that this is much more than just the accelerator. The example shows the layout of a cyclotron based facility with three treatment rooms.

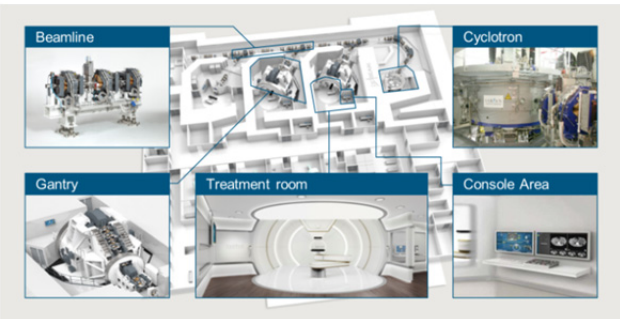


Figure 3: Layout of a ProBeam facility.

The facility consists of a degrader, an energy selection system, a beamline and a switchyard to single rooms, a gantry, and treatment rooms. The console area can be a placeholder to remind us of one of the biggest development efforts for a medical facility – the integrating software. The software is absolutely essential, since nothing would work without it, and it is a tremendous development effort, which easily is underestimated.

## *Financing*

Since financing is one of the biggest obstacles for hadron therapy projects, the means to improve the situation by specifying the requirements is worth some attention. I will focus on the private sector as the majority of future projects will be commissioned by it.

Financing for such projects is classical project financing based on expected revenue and return of investment plus interest in a defined time frame. The total amount due is typically split in 30 % equity and 70 % percent debt.

In order for the 70% loan part to be bankable, a solid business plan and low project risks are crucial.

As the financing amount goes up, all this gets more and more complicated. Costs for a multi treatment room center including building costs could easily go up to more than 100 MUSD. Lower total system costs will significantly help to finance the project.

Another important source of requirements is the return of investment for the customer as demonstrated by a business plan. We have performed a sensitivity analysis based on a generic business plan with realistic numbers. For a single treatment room facility with realistic costs and financing and an assumed total patient number after a ramp up of 500 patients per year, the saving of one minute per patient in the treatment room in average increases the earnings before tax per annum by nearly 1 million US$.

## *Beam Delivery*

One of the levers to influence the time per patient in the treatment room is the type of beam delivery.

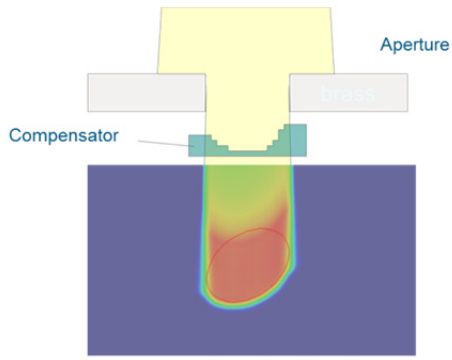


Figure 4: Scattering.

Scattering was used in the first facilities and still is the type used most often. The principle is shown in Figure 4. The beam is spread out by scattering and its outer contour is shaped by a specially shaped aperture. The depth contour is shaped by a specially shaped compensator. These components have to be machined for each different irradiation angle if multiple fields are applied. In addition medical personnel has to enter the treatment room for each field and to exchange the aperture and the compensator. All this necessitates a complete process chain of fabrication, storage and retrieval for the duration of the treatment (typical 30 fractions) and for the end disposal of the activated components after treatment.

Scanning uses two magnets to move the beam transversally (see Fig. 5) and to dynamically create the necessary dose distribution for one layer or energy. Then the energy is changed in accelerator or degrader and beamline and the next layer is applied in the same way. This has the benefit that no patient-specific apertures or compensators are needed and the time for entering the treatment room and the exchanging of components can be saved. This is today's standard for new facilities.




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As scanning is a dynamical process, the timing of the spot delivery and the time structure of the beam are crucial for the total duration of irradiation. Furthermore, faster line or contour scanning [3] are being developed, which are even more sensitive to current fluctuations than the currently used spot scanning..

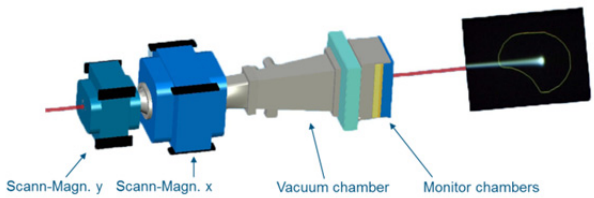


Figure 5: Scanning.

### *High Level Requirements and Considerations for a Proton Facility*

All the considerations mentioned and many others drive the high level requirements for a particle therapy facility. One central group of requirements, which can only be mentioned briefly, are medical device regulations and standards. They have severe consequences for the whole duration of the development process as well as for the manufacturing of the accelerator and of all system components.

The following table shows key system requirements that are relevant for accelerator requirements.

Table 2: System Requirements

| **Sys. requirement** | **adressed by** |
|---|---|
| *Investment:* | |
| Low cost of equipment | Accelerator cost |
| Low cost of transport | Acc. weight |
| Low cost of inst. & comm. | Automation |
| Low building cost / shielding / footprint | Energy variation & size |
| *Return of Invest:* | |
| High patient throughput | Scann. & dose rate |
| Operation 16h / 6d | automation & Robustness |
| Low cost of personnel | automation |
| Low cost of service | Autm. & rob. |
| Low cost of power | Superconductivity |
| Fast ramp up | Robustness |
| Number of patient referrals | IMPT & quality |

## SOME EXAMPLES AND ACCELERATORS IN USE

These general high level requirements and considerations for the total facility lead to the following high level requirements for the accelerator.

Table 3: Accelerator Requirements

| **Requirement** | **Value** |
|---|---|
| Low cost<br>Small footprint<br>Automated operation<br>Low service effort | <br><br>16h/6d<br>No long dwntime |
| Particle range in water<br>Energy at isocenter | 4,1 – 33 cm<br>70 -230 MeV |
| Typical current at isocenter | ~2nA or<br>~$3.2 \times 10^{10}$ p/s |
| Suff . production capacity<br>Medical device manufacturing | |
| Current time structure (Cycl.)<br>Duty factor (Synchr.) | Cw<br>Near to 1 |

The decision for a superconducting isochronous cyclotron for the Varian ProBeam product was made based on the following rationale:

- Lowest cost (evaluation against Synchrotron & Linac)
- Most compact due to superconductivity
- Continuous, high intensity beam (IMPT)
- Robust & Reproducible operation

This decision is also supported by a look into the statistics which shows a dominance of proton centers with cyclotrons.

The ideal accelerator for a medical facility is not necessarily the most advanced, cutting-edge accelerator technology, but in most cases the established, mature, robust, and cost-effective technology.

### *Which Accelerator Types are in Use?*

The following statistics is based on the data gathered by Particle Therapy Cooperative Group PTCOG [4]. This web page lists a total of 46 hadron therapy facilities in operation if corrected for facilities mentioned twice. Figure 6 shows the distribution of these facilities worldwide.

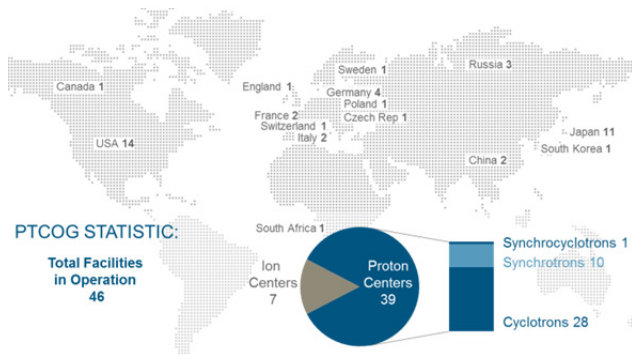


Figure 6: Statistic of facilities in use.

What is interesting is that Japan, with roughly on third of the population of the US, has nearly the same number of therapy facilities in operation. The country also operates the highest number of light ion facilities. This reflects the fact that particle therapy has been strongly supported by the Japanese government for a long time.

Figure 6 also shows the distribution of accelerator types used for proton and light ion centers. All seven centers treating light ions use a synchrotron. For protons the majority of them use a cyclotron.

### *Varian ProBeam Cyclotron*

The Varian ProBeam medical cyclotron is an isochronous superconducting cyclotron delivering protons at a maximum energy of 250MeV. It is based on a concept

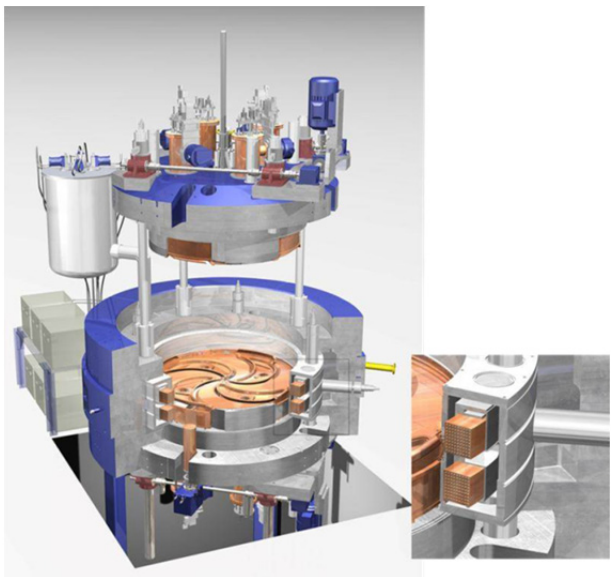

Figure 7: Varian ProBeam 250 MeV cyclotron.

Figure 8: Final assembly stand.

of the National Superconducting Cyclotron Lab in Michigan [5], and the detailed design was developed in collaboration with NSCL, PSI and other institutes. Figure 7 shows an artists view with a cut-out of the cryostat. It is a four sector machine with a pillbox design for easy opening. With its robust operation and high degree of automation it is well suited for a medical proton therapy facility. Optimization for manufacturing, transport and installation are also important aspects of the accelerator.

Manufacturing and all further steps up to final operations have to base on medical device compliant procedures and documentation.

Varian`s current series production capacity is sufficient for more than three cyclotrons per year and we will in future ramp up to more than double capacity. The fabrication site is organized into separated workstations where the various fabrication and assembly steps are performed sequentially - from winding the sc coils to final assembly and cold test (see Fig. 8). To avoid bottlenecks for some longer tasks, workstations are duplicated to allow work in parallel The fully assembled cyclotron is transported on an aircushion sled to one of the two test cells for final commissioning with beam.

The relatively low total weight of a superconducting cyclotron simplifies transport (see Fig, 8, which also shows the shipping of the cyclotron and the cyclotron being lifted into the vault by a temporary crane). The whole process of rigging for the cyclotron into the vault usually can be completed in a few days

### *Commercial Proton Therapy Accelerators: Overview*

Table 4 shows a summary of commercially available accelerators that are in use worldwide. Data for the last column in some cases was not available.

Several new developments indicate a trend towards superconducting cyclotrons which was started by the ProBeam superconducting cyclotron.

Table 4: Commercial Proton Therapy Accelerators

| **Company** | **Type** | **max. Energy** | **other Parameters** |
|---|---|---|---|
| | *Cyclotrons* | | |
| IBA Belgium | Proteus 235 n.c. isochr. | 230 MeV | $I_{max}$: 300nA cw<br>m: 220 t<br>d: 4.3m |
| Mevion US | S 250 s.c. synchr. | 250 MeV | m: 20 t<br>pulsed current<br>d: ~2m |
| Sumitomo Japan | n.c. isochr. | 230 MeV | $I_{max}$: 300nA cw<br>m: 220 t<br>d: 4.3m |
| Varian US | proBEAM s.c. isochr. | 250 MeV | $I_{max}$: 800nA cw<br>m: 90 t<br>d: 3m |
| | *Synchrotrons* | | |
| Hitachi Japan | PROBEAT slow-cycle | 250 MeV | $10^{11}$ p/pulse<br>rep.rate: 0.15-0.5 Hz<br>d: ~7m |
| ProTom US | Radiance 330 slow-cycle | 330 MeV | $10^{10}$ p/ pulse<br>d: 4.8m |
| Mitsubishi Japan | Slow-cycle | 250 MeV | |




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## OUTLOOK

### *Cyclotrons*

As can be seen by ongoing developments there is a trend towards higher field , more compact and lightweight superconducting cyclotrons. For the isochronous type there seems to be an upper limit, which is due to the necessary flutter. This type of cyclotron has immense benefits for fast scanning with its cw beam and higher currents. So it would be very desirable to find other ways of weight and/or cost reduction.

The alternative of using a synchrocyclotron has the benefit of an overall design that, compared to isochronous cyclotrons, is simple. But it has the significant disadvantage of the pulsed time structure of the extracted beam and limitations of the maximum average current. This limits the use of scanning especially for future developments of high dose rate line scanning to accelerate treatment.

It would be advantageous if in future the duty factor could be increased, e.g. by increasing the pulse rate or the duration of the extracted pulse at the end of the acceleration cycle.

### *Synchrotrons*

The compact design by Protom and the ongoing developments at Hitachi and Mitsubishi show a trend towards more compact and simplified synchrotron designs, which reduce foot print and cost. It is always difficult to decide on the injection energy. On the one hand, it limits due to space charge effects during injection the total number of protons that can be accelerated per cycle, and by that the total average dose rate that can be achieved for scanning. On the other hand, higher injection energy requires more complicated and costly pre-accelerators, typically a RFQ linac combination, which constitutes the major part of the costs of a synchrotron.

For future developments it would be highly advantageous if simple pre-accelerators with low cost for energies from 4 to 7 MeV existed – as would ideas to increase the duty factor of the extracted beam.

### *Other*

According to our analysis, Linac accelerators have always been too costly, and with the current available acceleration gradients were in the range of length above 20 m for 250 MeV protons. What can be done to reduce costs? Would the increase of acceleration gradients help? How could the pulse rate be increased without increasing costs? Answers to these questions could give the use of Linacs for hadron therapy a boost.

Laser acceleration is a relatively new development, with with broad support from many institution. It seems to have a lot of potential as a future hadron accelerator. But there are also still some areas where research needs to be carried out. How can the high pulse rates needed for scanning be achieved? Can a robust 16h 6 days a week operation be achieved? And what will be the cost of such a complete system, including the high power laser necessary to drive it? However, the last few years have shown that constant progress is being made in these areas, so viable design solutions might be developed in the near future.

## CONCLUSION

Particle therapy is about providing means to save lives. We need to bear in mind that what matters at the end is not technology but human beings. Thus the central guideline particle therapy development must be how to reach more people and save more lives. The most important criteria are :

- *Reduce cost of system*
- *Reduce footprint*
- *Simplify system*
- *Simplify operation*

## ACKNOWLEDGMENT

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