STATUS OF THE HZB CYCLOTRON

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Abstract

For more than 20 years eye tumours are treated in collaboration with the Charité – Universitätsmedizin Berlin. The close co-operation between Charité and HZB permits joint interdisciplinary research. Irradiations with either a sharp, well focused or a broad beam, either in vacuum or in air are possible. In addition, a ^{60}Co-source for γ-irradiations is available. Experiments now comprise dosimetry, detector comparisons, and ambulant mouse irradiations. Furthermore, radiation hardness tests on detectors, CCD-cameras and other electronics are performed.

In order to improve the beam diagnosis between the 2 MV injector Tandetron and the cyclotron a harp has been installed, leading to new beam line calculations for the injection line.

ACCELERATORS AND OPERATION

The k=130 cyclotron of HZB is served by two injectors: a 6 MV Van-de-Graaf and a 2 MV Tandetron (see Fig. 1 in [1]). The Tandetron is our usual injector for therapy, delivering an extremely stable beam. The Van-de-Graff injector is used as backup, for rare gas beams, and if a beam with a different time structure is required.

The standard beam is a 68 MeV quasi-DC broad proton beam. For experiments, time structures vary from quasi-DC to single pulses with a pulse width of less than 1 ns. The beam spot may be 50 mm in diameter with a homogenous distribution or may be focused to less than 1 mm.

Operation of the accelerator complex went smoothly. As the scheduled beam time is only little more than one week in two shift mode per month, major break-downs have an enormous effect on the relative down time, e.g. the high downtime in 2015 was due to faulty operation during run-up of the cyclotron. With exception of 2015, the relative down-time of the accelerator was below 5%. Furthermore, as can be seen in Fig. 1, most of the downtime occurs during the start-up phase of the accelerator complex. Since 2011 the Tandetron is our usual injector for therapy, improving the downtime. The main cause for down-time is the cyclotron. Here, the installation of the new low-level RF control [2] reduced the RF faults. 10% of the downtime is due to cuts in the electricity supply.

BEAM UTILIZATION

By far most of the beam time (85%) is delivered for therapy. The experimental use of the beam time is: accelerator development 8%, medical physics and dosimetry 5%, and radiation hardness tests about 2%.

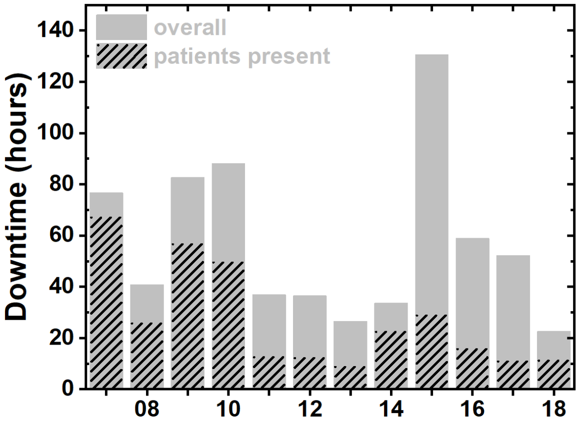

Figure 1: Downtime in hours for the past years. With exception of 2015, the relative downtime was below 5%.

Therapy of Ocular Melanomas

We now look back to more than 20 years of accelerator operation for proton therapy. Overall, more than 3500 patients have been treated. For the past ten years, nearly 220 patients have been irradiated each year in a routine workflow. Special cases were children, pregnant and breast-feeding patients.

In Tables 1 and 2 the clinical results of different radiation types used for the treatment of ocular melanomas of different centres as well as of Charité are shown. Compared to other radiation techniques, protons provide an excellent tumour control of 96% after 5 years as well as a very good eye retention rate.

Table 1: Tumour Control after 5 Years

Radiation	Others	Charité
^{106}Ru [3,4]	91%	ca. 92%
^{125}I [3]	91%	
Protons[3,5,6]	96%	ca. 96%
LINAC (SRT) [3,7]	94%	
Cyberknife (SRS) [8,9]	73%	

Table 2: Eye Retention Rate after 5 Years

Radiation	Others	Charité
^{106}Ru [10,4]	91%	ca. 92%
^{125}I [11]	91%	
Protons[5,12,6]	96%	ca. 96%
LINAC (SRT) [7]	94%	
Cyberknife (SRS) [8,9]	73%	

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Medical Physics

An observed side effect of radiation therapy is the radiation induced retinopathy one to two years after treatment. For a better understanding of the causes, ophthalmologists want to irradiate single mice eyes to observe the chemical and biological changes in eye tissue. The challenge lies in the small size of a mouse eye compared to the human eye. Thus, a very small irradiation field with sharp dose fall-offs to the sides as well as in depth is required. A Spread Out Bragg Peak with a maximum range of 7 mm and full modulation length is provided (Fig. 2). A second absorber of 2 mm thickness reduces the maximum proton range further down to 5 mm. Thus, the second eye is non-irradiated due to the sharp distal fall-off of less than 1 mm and can be used as a control. The irradiation is an ambulant procedure: The mice are transported from the animal husbandry of the Charité to HZB, have time for acclimatization, and are anesthetised. The mouse is positioned in front of the beam line with one eye placed at the isocenter. The position of the mouse during irradiation is monitored using the same camera as for clinical treatment. After irradiation the mice are transported back to the Charité. Up to now, about 60 mice have been irradiated with doses from 0 Cobalt Gray Equivalent (CGE) to 15 CGE.

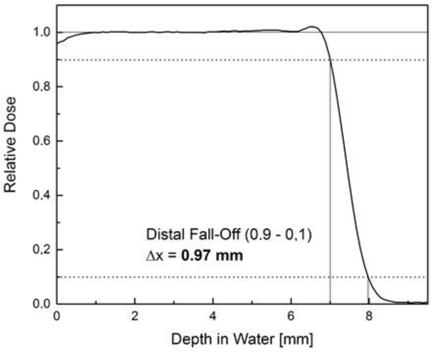

Figure 2: Spread Out Bragg Peak used for irradiations of mice eyes. The distal fall-off from 90% to 10% of the dose is less than 1 mm.

Dosimetry

Experiments on dosimetry comprised, among others:

- Determination of the radiation exposure to the foetus of a pregnant patient during eye tumour treatment with protons [13].
- Characterization of thin-film TLD, type LiF:Mg, Cu, P for the dosimetry with 68 MeV protons [14].

Radiation Hardness Tests

Radiation hardness tests can be performed using either γ-rays from a ^{60}Co source or protons from the cyclotron. At the ^{60}Co source, total ionising dose (TID) tests are performed using dose rate between 1 Gy/h to 100 Gy/h. The TID tests and proton irradiations can be performed on one site with short distances between the two irradiation rooms.

The proton beam size is adjusted to the size of the devices using different scattering systems or a wobbling system. The proton intensity varies between 10^4 p/cm² to 10^{13} p/cm². When irradiation times of more than 15 min are requested, the low proton intensities are challenging for precise measurements.

Radiation hardness tests are performed for industry, the German Aerospace Center (DLR), and research. Examples are e.g. commercial of the shelf electronics for space missions [15, 16] or solar cells [17].

Accelerator Development

For the installation of the 2 MV Tandetron, which replaces our RFQ, we had to accept constraints for the position of the Tandetron in beam direction: It had to fit to the existing beamline, and access to the cyclotron and emergency exits had to be maintained. Figure 3 shows the Ootran [18] calculations performed for the RFQ prior to its installation. The position of the Tandetron is marked with the yellow line. The beam profile monitor (BPM), a rotating wire scanner, had to be moved closer to the cyclotron. Thus, the BPM is not on a focal point, and tuning of the beam is ambiguous. Furthermore, the Tandetron is equipped at the end of the acceleration tube with an electrostatic quadrupole. This quadrupole is a triplet with only three power supplies and thus, asymmetric properties. Normal beam line calculation programmes cannot handle it.

A harp has been installed in the beamline to quantify the beam size. It consists of 25 wires in x and y, mounted on a standard movement unit [19]. The connection of the wires is done with flat cables and a printed circuit board (PCB). For the vacuum feed-through we used a second PCB board and epoxy (see Fig. 4). The leak rate of this connection is $1{\cdot}10^{-9}$ mbar/(l·s). Tests on a mass spectrometer revealed no out-gassing material which might be dangerous for the electrostatic quadrupole nearby. The read-out is done with the harp electronics from iThemba labs.

The beam profile measured with the usual BPM (Fig. 5, left) had shown two peaks in y. This was in the beginning explained as a slight misalignment of the beam. However, the measurements with the harp also revealed two peaks (Fig. 5, right). Further investigations showed that we have two beams: a proton beam and a beam of neutral hydrogen particles which is due to incomplete stripping in the Tandetron.

These measurements together with finite element calculations of the electrostatic quadrupole using SIMION [20] permitted to estimate the beam properties at the exit of the quadrupole. Thus, the beam line settings between the Tandetron and the cyclotron can be now be calculated.

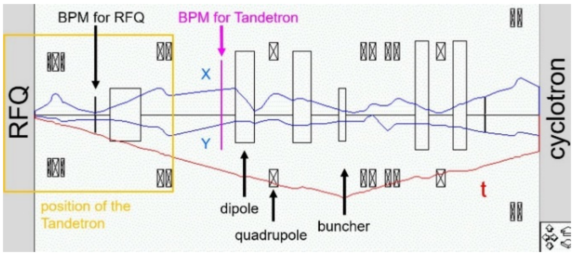

Figure 3: Ootran calculations for the beam line between RFQ and cyclotron.

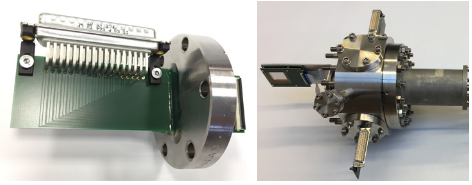

Figure 4: Vacuum feed through of the harp (left) and the connection to a standard movement unit with flat cables (right).

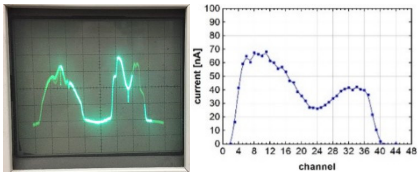

Figure 5: Beam profile after the Tandetron. Left: as measured with a BPM, showing the profile in x and y. Right: y profile measured with the harp.

CONCLUSION

Accelerator operation was reliable. With one exception, the relative down-time in the past years was less than 5%. Most of the down-time occurs during start-up of the accelerator. We will continue with our on-going improvements and developments in order to keep the down-time low.

In 2018, we celebrated the 20th anniversary of eye tumour therapy in Berlin, the only facility for proton therapy for ocular melanomas in Germany. End of June 2019, more than 3500 patients had been treated with protons in Berlin. The clinical data for protons show excellent tumour control and eye retention rate.

Experiments comprise accelerator research and development, radiation hardness testing for space applications, dosimetry, as well as radiobiological experiments.

The authors are indebted to iThemba labs for providing the electronic for the harp.

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