THE SYNCHROTRON OF THE DEDICATED ION BEAM FACILITY FOR CANCER THERAPY, PROPOSED FOR THE CLINIC IN HEIDELBERG

A. Dolinskii, INR, Kiev, Ukraine
H. Eickhoff, B. Franczak, GSI, Darmstadt, Germany

Abstract

For the clinic in Heidelberg/Germany an accelerator facility is proposed for the treatment of cancer tumours with light ions using the 'intensity controlled rasterscan' method [1,2,3,4]. The layout of the synchrotron is presented, that is designed to accelerate carbon ions from an injection energy of 7 MeV/u up to a maximum extraction energy of 430 MeV/u, corresponding to a maximum magnetic rigidity of 6.5 Tm. In addition to carbon ions, the delivery of protons, helium- and oxygen ions are requested as well. Beside an overview of the compact synchrotron configuration ion optical properties and calculations of the main operation phases are described. A dynamical change of the ion optics is foreseen to meet the injection and extraction requirements. For beam extraction the 'transverse knock out' procedure [6] with variable flat top duration is proposed to maintain constant beam optics during extraction and to minimise the treatment time by multiple beam extraction within one synchrotron cycle.

1 INTRODUCTION

For treatments of deep-seated tumours in a light ion medical synchrotron a ^{12}C-beam should have a maximum range in water of 30 cm. This penetration depth correlates to a maximum beam energy of 430 MeV/u and a magnetic beam rigidity of 6.5 Tm. To fulfil the requirements of the intensity controlled rasterscan treatment a requested penetration range between 20 and 300 mm the ^{12}C -extraction energies must be selectable in the pulse-to-pulse mode between 50-430 Mev/u. The relatively large magnetic rigidity and the requirement for a fast change of the beam extraction energy demand for economical and technical reasons a synchrotron as the final acceleration stage.

A synchrotron has an advantage as an accelerator for cancer therapy because it can accelerate charge particle beams to various energies. Some of the essential design criteria of the synchrotron:

- the synchrotron should be kept compact in order to be installed in a public hospital.
- well proven operation modes should be foreseen to assure a high reliability.
- the number of magnet components is low in order to avoid failures at water and current connection.

Considering these conditions a light ion medical synchrotron has been designed and is presented in this paper.

2 SYNCHROTRON

2.1 Machine parameters and lattice

The synchrotron will provide the following main functions:

- injection and accumulation of the ions by means of the multiturn injection procedure;
- acceleration of the ions to the requested extraction energy ;
- slow beam extraction (with variable extraction times) .

Fig.1. shows an overview of the synchrotron with the major insertions. Table 1 summarises the main synchro-tron parameters.

The ring has a super-periodicity of 2 and consists of 6 periods of which 4 contain long straight sections and two short ones. Each period is formed by a 60 degrees bending magnet to keep the beam on a circular orbit and

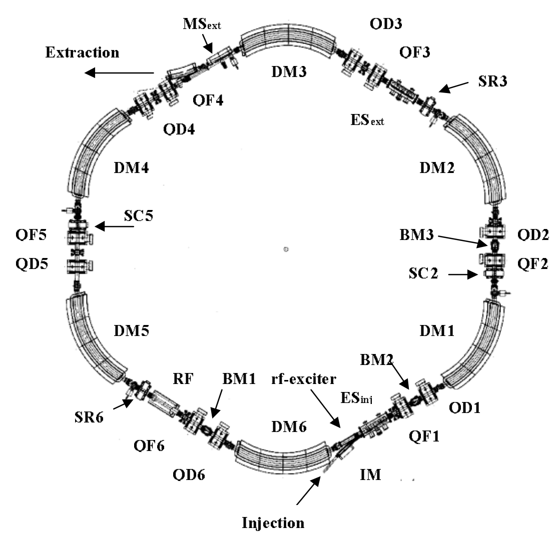

Figure 1: Layout of the Synchrotron.
DM – Dipole Magnet; QF/QD – Horizontal/Vertical focusing quadrupole magnet; SR/SC– Sextupole magnet; BM – Bump Magnet; RF- rf-cavity; ES- Electrostatic Septum, MS – Septum Magnet; IM – inflector magnet; rf_exciter – rf-exciter for knock-out extraction.

Table 1: Summary of major synchrotron parameters

Circumference, C , m	64.986
Superperiodicity	2
Lattice type	DOUBLET
Long/Short section length, L,m	4.05/0.9
Injection	
Injection ion energy ,E , MeV/u	7
Magnet rigidity, BR , T·m	0.38-0.76
Injected emittance, ε , π mm·mrad	7
Horizontal acceptance, A , π mm·mrad	80
Vertical acceptance, A , π mm·mrad	25
Momentum spread at injection, Δp/p,%	±0.1
Tune Q /Q	1.72/1.74
Extraction	
Extraction energy, E , Mev/u	50-430
Magnet rigidity, BR , T·m	1.1-6.5
Extracted hor. emittance, ε π mm·mrad	1-5
Extracted ver. emittance, ε π mm·mrad	5
Tune Q /Q	1.672/1.72

a quadrupole doublet for beam focusing. The straight sections and the space between the quadrupole doublet are occupied with devices for beam injection and accumulation (inflector magnet IM, electrostatic septum ES_{inj}, three bumper-magnets BM1-3), acceleration (rf-cavity RF) and devices for beam extraction (electrostatic extraction septum ES_{ext}, magnetic septa MS_{ext}, sextupoles SR3, SR6, RF-exciter).

Additional orbit correction elements are foreseen (vertical correction magnets in each period and horizontal correction coils at each 60° bending magnet). As beam diagnostics devices a combined fast/slow beam transformer in period 4 is provided and hor./vert. capacitive pick-up monitors in each period to measure the beam position. A schottky pick-up probe will be installed for accurate diagnostic of the beam optics.

H-type dipole magnets are proposed with bending radius of 4.4 m and max. flux density of 1.53 T. A condition to the construction is to allow for ramping rates up to 1.5 T/s. A careful analysis was done of eddy current effects in the lamination and the metallic vacuum chambers. For stainless steel chambers with 3.0 mm wall thickness we got the time constant of $c \approx 2\cdot10^{-4}$ sec and a similar value from the conductor distortions within the useful aperture. Even for the lowest injection levels the field ramp can therefore be started with 1 T/s without generating relative errors larger than $2–5\cdot10^{-4}$.

The magnetic length of the 6 magnets in the ring must coincide within $1\cdot10^{-4}$ over the field interval between 0.088 T and 1.53 T.This corresponds to max. disturbance of amplitude of 8 mm in the closed orbit. The final tolerance is achieved by putting shims onto the steps of the end profiles and checking the result at medium fields.

The vacuum system of the synchrotron ring is designed to satisfy the following requirement: maintaining a pressure of less then 10^{-9} Torr to limit the losses due to electron capture processes at the residual gas to a value of less than 10%.

In the present synchrotron a proton or ion beam of 7 MeV/u is injected from a linac [3,4] to the synchrotron based on multiturn injection scheme. In order to meet the specific requests for multiturn-injection and slow beam extraction, especially for the slope of the dispersion function, a dynamical change of the ion optics between injection and start of extraction is foreseen.

At beam injection the synchrotron is tuned to the so-called 'injection mode', in which the dispersion function at the position of the injection septum is about 2 m and close to zero at the position of the rf-cavity.

The momentum acceptance for the injection mode is relatively large with Δp/p about ±0.4% for a hor. emittance of 80π mm·mrad. The lattice functions according to this setting over half of the ring are shown in Fig.2a. A slightly different setting of the ion optics is proposed for the beam extraction. The lattice functions of this so-called 'extraction mode' setting are shown in Fig.2b. At this mode the dispersion function at the electrostatic extraction septum is optimised to achieve

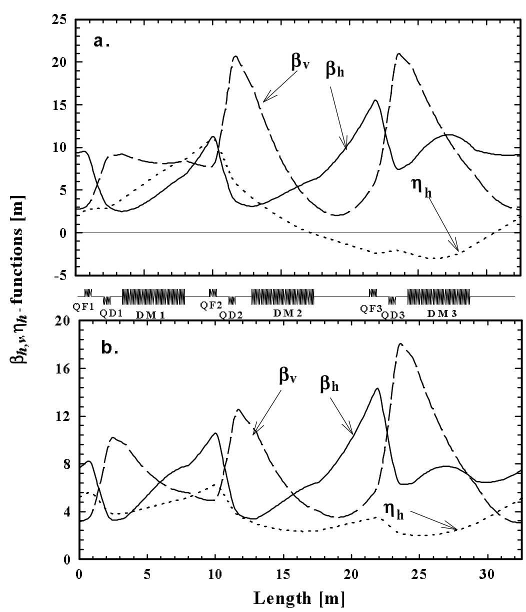

Figure 2: Twiss parameters of the Synchrotron at: a.- 'Injection mode', b.- 'Extraction mode'

the 'Hardt condition' [5] to attain momentum independent extraction conditions. This setting also mainly determines the requested apertures in the magnets, as for the suggested 1/3-order resonance extraction the particle amplitudes over the last three turns before the extraction takes place have to be taken into consideration.

2.2 Injection

In order to achieve the requested dose rate of 2 Gy/min both for ion and proton beams with moderate requirements for the ion source and the linac the use of the multiturn-injection procedure in the horizontal phase plane is proposed with an accumulation factor of 10 compared to the pulse current delivered from the linac [3,4]. The injected beam is deflected from the middle energy beam transport system (MEBT) into the synchrotron by means of an inflector magnet (IM) and an electrostatic septum (ES_{inj}). The chopper in the MEBT line defines the injection time that has to be correlated with the excitation of the fast deflecting bumper magnets (BM1-BM3). The number of turns to be injected and the intensity gain depend on:

- the ratio of the available horizontal acceptance of the synchrotron (75-80π mm·mrad) and the horizontal emittance of the injected beam (7π mm·mrad);
- the momentum spread of the injected beam and as consequence on the dispersion function of the ring at the position of the ES.

To reduce the beam momentum spread to smaller than 0.2% and enhance the injection efficiency the installation of a debunching rf-cavity in the injection line is foreseen.

2.3 Acceleration

Beam acceleration is performed by means of a radio frequency (RF) accelerating cavity, that for increasing beam energies has to be synchronised with the variation of the current in the bending and quadrupole magnets. Before acceleration starts the ion beam is bunched on the second harmonics of the revolution frequency; this harmonics is maintained during the acceleration process. According to the ratio of the particle velocity between injection and extraction energy the frequency of the rf-accelerating system has to cover the range from 1 to 7 MHz. The rf voltage requirements are determined by the bunching and the acceleration process. For an initial momentum spread of ±0.14% for a p-beam the value of (Δp/p) after the bunching process is about ±0.39 %. This corresponds to an RF voltage of 910 V on injection level. The voltage V_{acc} needed for acceleration is determined by the time for the acceleration process, which is correlated to the maximum ramping speed of the main dipole magnets (dB/dt=1.5 T/sec), corresponding to an acceleration time of max. 0.88 seconds up to an extraction energy of 430 MeV/u. For this ramping rate an acceleration voltage of at least 420 V is requested.

2.4 Extraction

In order to provide sufficient time for tumour painting as well as for beam monitoring a slow beam extraction mode is necessary for the rasterscan beam delivery technique.

The rf knock-out extraction method [6] in combination with a variable extraction time from 1 to 10 seconds is proposed in order to use the beam spills as effectively as possible and to optimise the treatment time. In case of a variable extraction time, a multiple activation of beam extraction within the same cycle can be achieved. This feature is important to reduce the treatment time, as the time intervals needed for ramping the magnets can be minimised. The proposed RF knock-out extraction method allows an easy way for a fast activation and deactivation of the extraction within the same synchrotron cycle. This feature is also favourable in situations when a respiration-gated irradiation is performed.

The RF-knock-out method, which is routinely used at the HIMAC medical accelerator, has been also successfully tested at GSI [7]. The RF-knock out system is designed to extract a beam with a charge to masse ratio of 0.5-1 up to an energy of 430 MeV/u. The maximum voltage of 500 V_p (V_p = peak to peak voltage) with a frequency from 1 to 7 MHz can be applied to the horizontal kicker electrodes, having a length of 0.7 m and a gap of 0.15 m.

The particle amplitude is enhanced by means of a transverse rf-field at the RF-exciter, generated with a frequency that is synchronous to the betatron frequency of the particles; due to this excitation the particles are moved from the inner, stable region of the separatrix to the outer unstable part. By applying a residual voltage (about 1 kV) at the accelerating cavity on the extraction flattop during beam extraction it is possible to maintain good spill quality [8].

REFERENCES

[1] H.Eickhoff, et. al, ‘ The Proposed Dedicated Ion Beam Facility for Cancer Therapy at the Clinic in Hidelberg‘, these proceedings.

[2] P.Spiller, et. al., ’Gantry studies for the proposed Heavy Ion Cancer Therapy (HICAT) Facility’, these proceedings.

[3] A.Bechtoldet. et al., ’ Development of an RFG-injector for a therapy synchrotron’,these proceedings.

[4] B.Schlitt, U.Ratzinger, ‘Design of a carbon injector for a medical accelerator complex, EPAC’98, Stockholm, June, 1998, p.2377-2379

[5] W.Hardt, PS/DL/LEAR Note 81-6

[6] K. Hiramoto et.al. NIM, A322, (1992),p154.

[7] H.Eickhoff et al., GSI-Report, 99-1.

[8] P.Forck, et.al., ‘Measurements and Improvements of the Time Structure of a slowly extracted Beam from a Synchrotron’, these proceedings.