DESIGN OF DEDICATED PROTON SYNCHROTRON FOR PRAGUE RADIATION ONCOLOGY CENTRE

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Abstract

The dedicated proton synchrotron PRAMES (PRAgue MEdical Synchrotron) is a part of a PRAgue Radiation Oncology Centre. It has been developing exclusively for the third-order slow extraction of the proton beam. The maximum final energy should be at least 220 MeV to provide the cancer treatment depth of about 30 cm. The average current in the energy range should be about 10nA. The slow extraction of the accelerated particles is analysed. The general parameters of PRAMES and main systems are presented. Results of the lattice study, injection, acceleration and extraction are furnished in the report.

1 INTRODUCTION

Accelerator complex as a kernel of a comprehensive oncology hospital is presented. The hospital is planned to be built in Czech Republic and will be involved in the European net of the hadron therapy centres. The hospital should have at least three treatment rooms with a fixed horizontal beam and one - with a gantry. The output energy of the proton beam should vary from 60 till 220MeV [1]. The raster-scanning technique will be used to treat cancer. To realise this method, it is necessary to have the spill of the extracted proton beam long enough.

2 STRATEGY OF THE RING

The raster-scanning method of cancer treatment can be realised by using the slow extraction of the accelerated particles. The third-order resonance extraction should take place in this case. Resonant extraction is widely used in high-energy accelerators to deliver spills of long duration to experiments with secondary beams originating from external fixed targets. The spill time should be about 500 ms for medical application.

The third-order resonance is driven by a sextupole perturbation of the sextupole lenses installed in the dispersion-free drift spaces.

In the horizontal phase space, it defines a stable area and separatrices to move away the particles from the closed orbit. The first septum divides the part of the beam to be extracted from the circulating one. Its deflection is converted into a physical separation later on, where the second thicker septum deflects the beam further towards the extraction channel. The betatron phase advance between these septum should be less than $\pi/2$. Efficiency and low losses are important requirements for accelerators, so that the apparent septum thickness must be minimised.

It is necessary to minimise the angular dispersion of the separatrices corresponding to different energy spread. To solve this problem, superimposing of the separatrices for all momenta has been implemented in the LEAR machine at CERN [2] and now it is frequently used. Then the chromaticity correction should be realised in the focusing structure of the dedicated proton synchrotron. It can be done by two families of the sextupole lenses installed in the non-zero dispersion drift spaces of the ring.

There are several techniques to control of the third-order resonance extraction the long spill time. The amplitude-momentum selection technique is chosen to keep lattice parameters constant during extraction and to reduce the ripple sensitivity. The Steinbach diagram corresponding to this technique is shown in Fig.1.

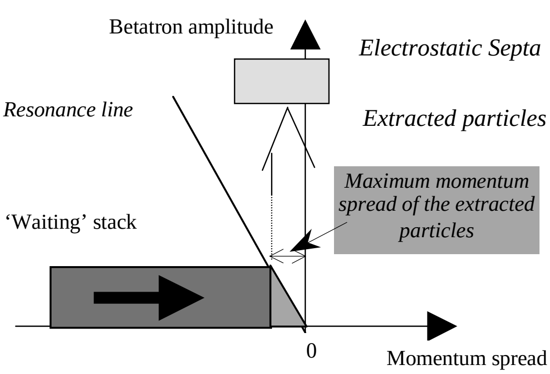

Figure 1: Steinbach diagram of the amplitude-momentum extraction technique.

In this case the 'waiting' stack should has a wide momentum spread with a small transverse emittance. An extra acceleration system is needed to realise this method and the spill cannot be switched on or off at the level of the resonance.

It is necessary to provide injection and acceleration of particles through a special timing to eliminate the structure of the beam. Special RF manipulations should be performed before extraction to get the unbunched (coasting) particle flow with possible homogeneity. These processes have been investigated for the dedicated proton synchrotron and results are discussed in the report [3].

3 FOCUSING STRUCTURE

To meet the requirements, the focusing structure of the dedicated proton synchrotron for cancer treatment has been developed. The general layout of the synchrotron including the injection beamline is shown in Fig.2. A double bend achromatic cell with rectangular dipole magnets is a basic cell of the lattice. The ring is composed from elements with separate functions.

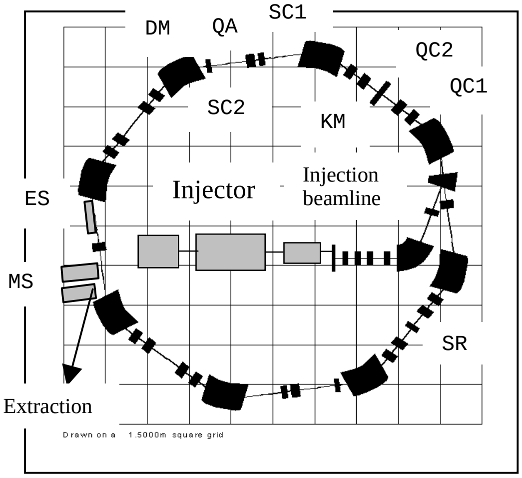

Figure 2: General layout of the accelerator complex.

The main dipole magnets (DM) are the 'curved' rectangular magnets with the 45-degree bending angle. The maximum magnetic field is chosen of 1.2 T to avoid the saturation effects of the pole edges and to escape high-order field components during the slow extraction. The main parameters of the ring dipole magnet are discussed in the report [4]. The ring circumference is equal to 41 m.

The main parameters of the lattice have been chosen to meet requirements of the slow extraction. The Twiss parameters of the lattice are presented in Fig.3. The betatron frequencies for the slow extraction are 3.333 and 1.630 in the horizontal and vertical planes, respectively.

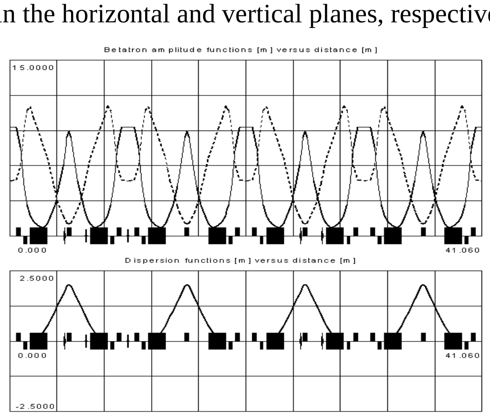

Figure 3: Twiss parameters of the focusing structure.

There are two families of the quadrupole lenses (QC1, QC2) installed in the zero-dispersion drift spaces to correct the 'working' point position. There are two families of the sextupole lenses (SC1, SC2) to correct the machine chromaticity. The strength of the sextupole lenses has been chosen to satisfy the Hardt condition. The natural chromaticities are -4.827 / -4.705 in the horizontal and vertical planes, respectively. The corrected horizontal chromaticity is equal to -2.650.

To perturb the third-order resonance, the lens (SR) is used. The strength of this sextupole lens is defined by the horizontal spiral step of the extracted particles. This step should be about 1 cm.

4 SLOW EXTRACTION

The electrostatic (ES) and magnetic (MS) septums are located in the non-zero dispersion drift space. The transverse normalised emittance is equal to 1 π·mm·mrad. In this case the horizontal beam size (2σ) of the injected beam at the azimuth of the electrostatic septum is 1.5 cm. Then the distance between the centre of the circulating beam and the edge of the electrostatic septum should be at least 2.5 cm. In this case the maximum size of the 'good field' region of the magnetic elements is equal to ±63mm (including ±10 mm of the allowed distortion of the closed orbit).

The vertical 'good-field' size is determined by the vertical beam size at the injection energy and equal to ±30mm.

The 'waiting stack' emittance is a function of the momentum spread of the extracted beam. As mentioned above, the momentum spread of the extracted particles has to be larger than the momentum spread of the accelerated particles. Moreover, before extraction it is necessary to get coasting beam (after special RF gymnastics). In this case one can control the slow extraction process changing the momentum spread. The main parameters of the betatron core for 'smooth' acceleration is under consideration at this moment.

The 'waiting stack' emittance as a function of the particle momentum spread is presented in Fig.4. The transverse rms emittance of the 220 MeV beam is equal to 1.3π·mm·mrad. Then the extracted particles will have the full momentum spread less than 0,07%. In the case of the 60 MeV beam (2.8 π·mm·mrad) the full momentum spread of the extracted particles will be less than 0,1%. The maximum allowed momentum spread of the extracting particles is equal to 0,6%. In this case the working point at the extraction does not cross dangerous resonance lines.

The electrostatic septum (ES) is used to get an initial particle deviation from the circulating one. The gap of the septa is equal 1.5 cm. The effective length is 80 cm. The maximum electrostatic field is equal to 100 kV/cm (for the 220 MeV beam).

The horizontal deviation angle of the reference particle at the entrance into the septa is equal to 23 mrad and 21 mrad for the particle with the momentum spread of 0.09. After the septa the angle is equal to 40 mrad for the reference particle.

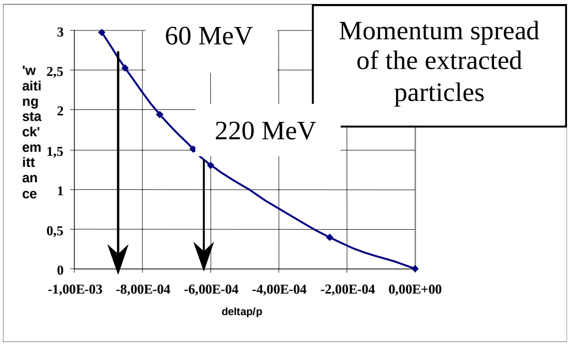

Figure 4: ‘Waiting stack’ emittance [π·mm·mrad] as a function of the momentum spread of the extracting particles.

The transverse phase-plane of the extracted particles before and after the electrostatic septum is presented in Fig.5.

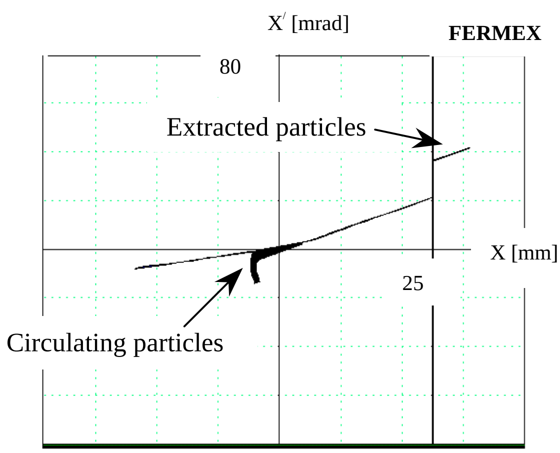

Figure 5: Transverse phase-plane of the extracted beam with the momentum spread (–0.001).

5 INJECTION BEAMLINE

The single-turn injection with the kinetic energy of 7 MeV is chosen to use a commercial linear accelerator as an injector. The beam intensity in the synchrotron has to be $6.25 \cdot 10^{10}$ particle per pulse in the case of the repetition rate of 1 Hz. The ring circumference is equal 41 m. To provide stable transverse motion in the ring at the injection energy the peak current of the circulating beam have to be less than 12 mA. It means that the phase length of the trapped proton beam should be ± 2.5 rad (h=1). The momentum spread of the trapped beam should be ± 0.3%.

The beamline consists of all the components from the end of the RFQ/DTL injector till the pulse kicker that brings the beam onto the central orbit of the synchrotron. The functions of the injection line are transport and matching of the beam from injector to synchrotron. After the RFQ/DTL linac it is necessary to use a debunching cavity to get the required momentum spread (±0.1%). The phase length of the injected beam should be ± 2.75 rad [4]. Detailed information about the injection beamline one can find in the report [5].

The injection line has been designed using the first order optics program with fitting (AGILE) and the envelope program TRACE2D to involve the space-charge effects. The beam envelope of the injected beam with the 50 mA beam current along the beamline is presented in Fig.6.

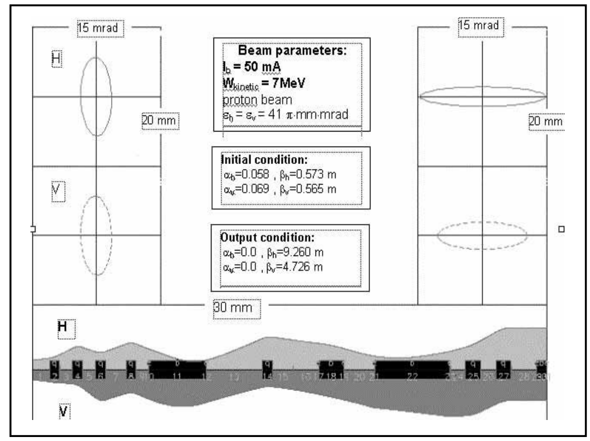

Figure 6: Beam envelope along the injection beamline.

The maximum quadrupole gradient of the lenses is equal to 3.6 T/m. The bending magnet should has a field index (n=0.845) and the dipole field of 0.42 T.

5 CONCLUSION

Main peculiarities of the Prague medical synchrotron for cancer therapy are discussed. The focusing structure has been improved to meet the requirements of the raster-scanning technique. The slow extraction mechanism is analysed. Main parameters of the extraction and injection beamline are determined.

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