PROJECT OF DEMONSTRATION CENTE R OF THE PROTON THERAPY AT DLNP JINR

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Abstract

JINR is one of the leading proton therapy research centers of the Russia. The modern technique of 3D conformal proton radiotherapy was first effectuated in Russia in this center, and now it is effectively used in regular treatment sessions. A special Medico-Technical Complex was created at JINR on the basis of the phasotron used for proton treatment. About 100 patients undergo a course of fractionated treatment here every year. During last 14 years were treated by proton beams more than 1000 patients.

A project of the demonstration center of the proton therapy is discussed on base of a superconducting 230 MeV synchrocyclotron. The superconducting synchrocyclotron is planned to install instead of phasotron in Medical Technical Complex of DLNP. The new transport channel is designed for beam delivery to the JINR medical cabin.

PROJECT OF DEMONSTRATION CENTER OF PROTON THERAPY

The pioneering proton therapy researches began at JINR in 1967 [1]. The phasotron with the proton energy of 660 MeV and current of 2 μA is used for medical applications [1-3]. More than 1000 patients were treated at JINR by the proton beams. During the last years around 100 patients per year got the proton treatment there.

The superconducting synchrocyclotron is planned to install instead of phasotron in Medical Technical Complex of DLNP. The new transport channel is designed for beam delivery to the JINR medical cabin. The equipment of the demonstration center of the proton therapy and realized here technologies will be lay in the base of the future Dubna hospital center of the proton therapy. The final stage of the project is creation of the Dubna hospital center of the proton therapy on basis of the superconducting synchrocylotron and the rotating gantry (Fig.1). The first stage of this project is related to the construction of the demonstration center of the proton therapy on base of a superconducting 230 MeV synchrocyclotron.

High magnetic field of 5T is used in the superconducting synchrocyclotron where the requirement of isochronism is unnecessary and weak focusing is obtained from the negative gradient of the rotationally symmetric magnetic field. The synchrocylotron has following peculiarities in comparison with the isochronous cyclotron: the RF frequency is periodically modulated and the beam is pulsed; the longitudinal dynamics becomes a major aspect of the beam physics with energy-phase oscillations bound by a separatrix; the beam is captured at injection only during a limited time window; the regenerative extraction is needed to recover the beam which has a very small turn separation at extraction; the extracted beam has a relatively low intensity of 20 nA; the central region is strongly reduced in size compared to an equivalent isochronous cyclotron.

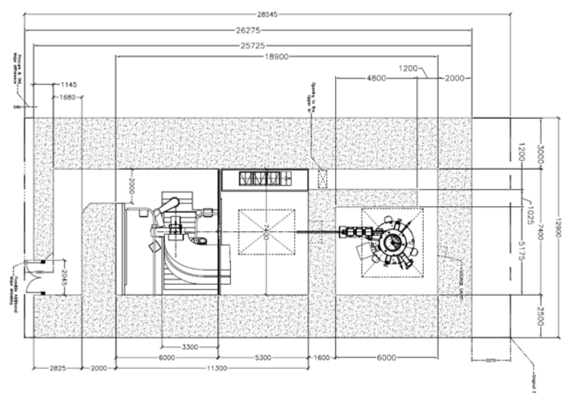

Figure 1: Scheme of Dubna hospital center of proton therapy.

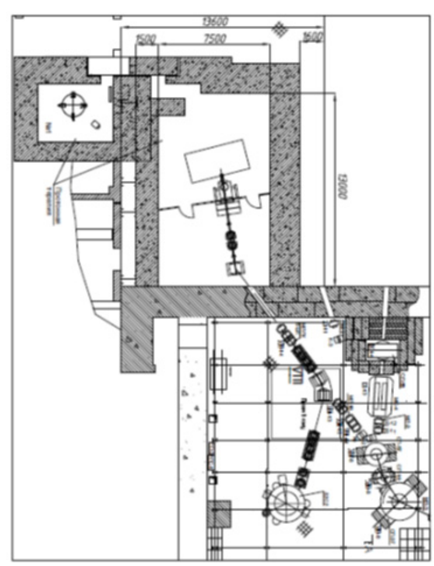

Figure 2: Scheme of synchrocyclotron with beam delivery channel and modernized medical cabin in demonstration center of proton therapy.

ISBN 978-3-95450-170-0

The synchrocyclotron S2C2 [4] (Table.1) has diameter of 2.3m. Main peculiarity of synchrocyclotron is connected with its superconducting magnets with magnetic field in hills and valleys of 5,64/5,24 T, correspondently. Four Sumitomo cryocoolers are used at realization of the superconducting regime.

Table 1. Parameters of synchrocyclotron S2C2.

Irradiation	Active
Diameter, m	2,3
Weight, t	50
Magnet	Superconducting
Average field, center/extract., T	5,64/5.24
Voltage of dee-electrodes, kV	14
RF–frequency, MHz	90-61.5
Frequency of beam pulses, kHz	1
Average current, nA	20
Proton energy, MeV	230
Energy spread, 2σ, MeV	2,5
Horisontal/vertical emittance, π·mm·mrad	23.1/4.1

Figure 3: View of synchrocyclotron S2C2.

Many aspects were considered at optimization of the synchrocylotron magnetic system [4]: optimization of the pole-gap profile; definition of the pole radius and the 230 MeV extraction radius; optimization of coil current density and dimensions; dimensioning of the yoke to reasonably balance the outside stray fields; dimensioning and placement of all horizontal and vertical yoke penetrations; the optimization of the extraction system the shielding required for external systems such as the rotco and the cryo-coolers; the influence of the external iron systems on the accelerated beam; the influence of the fringe field on the external beam line; median plane errors introduced by the vertical asymmetry in the magnetic design and compensation of these errors; magnetic forces acting on the return yoke, the coils, the extraction system elements, external components.

Rf–frequency is changed from 90 MHz to 61.5 MHz, to compensate variation of the revolution period at acceleration caused by increase of the proton relativistic mass and reduction of the magnetic field. The RF resonator operates as a half-wave transmission line terminated on one side by the 180^0 dee and on the opposite side by the rotco. The 8-fold symmetry allows excellent mechanical stability and very good reproducibility of the RF pulse. It rotates at 7500 rpm giving 1 kHz repetition rate.

The central region is extremely compact with a first turn radius less than 2.5 mm and the first 100 turns within a radius of about 3 cm. Calculations show that particles with RF-phases in the range of [-60; +10]° are successfully accepted in synchrotron regime of stable acceleration. Pulse duration of particles captured in acceleration is equal to 7 us, the repetition frequency of beam pulses is 1 kHz, the duty factor corresponds to 0.7 %. Quantitative analysis of losses at injection and during a period of one synchrotron oscillation was carried out to estimate capture as a function of injection time relative to moment when the RF-frequency equals to the revolution frequency of the particles in the centre. Capture efficiency for the synchrocyclotron with driving magnetic field of ~5 Tesla was simulated [5]. Obtained results give capture efficiency of $8{\cdot}10^{-4}$.

Fast and precise pencil beam scanning requires a high dynamic range (a factor 100) in the charge per pulse and also good pulse repeatability. A cold-cathode PIG source is used because of its fast response, long cathode life-time and good pulse stability. The source is pulsed during 50 µsec, in synchrony with the RF.

Regenerative extraction based on $2Q_h = 2$ resonance is used. The regenerator creates a strong bump which locally increases the radial focusing and locks Q_h to 1. Extraction sets at this condition and a displacement of the beam towards the extraction channel steadily builds up. Correctors are used to compensate the undershoots of the regenerator and the extraction channel. A 3-bar corrector guides the beam through the fringe field. A permanent magnet quadrupole in the return yoke matches the cyclotron to the beam line.

In frame of JINR-IBA collaboration are planned to perform special research program oriented on formation of high average current of 100 nA as it was done for proton cyclotron C235-V3.

The simulation of the beam delivery was done from synchrocyclotron to the entrance in the treatment room. The beam is focused to the waist at the entrance of the energy degrader (Fig.4) with a small sizes of 1.95/1.3 mm in order to decrease a growth of the beam geometrical emittances after passing through the energy degrader.

After proton deceleration to energy of 180 MeV at passage through carbon degrader with thickness of 54 mm the beam energy spread corresponds to 4.5 MeV (3σ) and horizontal/vertical beam emittances increase up 36.9/19.3 π·mm·mrad.

ISBN 978-3-95450-170-0

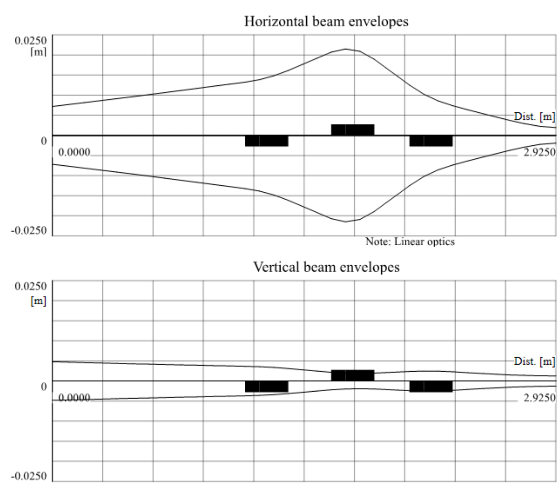

Figure 4: Beam transportation from cyclotron to degrader.

The energy spread (2.4%) is almost 4 times higher after passing the energy degrader than in the case of the extracted beam at the exit of the S2C2 accelerator. To decrease this energy spread and improve the energy distribution quality a momentum slit is placed in the beam line (Fig.5). The momentum slit is placed downstream the dipole magnets to such position where the horizontadispersion function is 1.6 m.

A collimator with a horizontal gap of 10 mm was chosen as a momentum slit. After passing the beam through this slit the energy spread is decreased from 2.4% to 1.6%. Beam transmission of the momentum slit corresponds to 42%.

The horizontal and vertical beam envelopes for the last part of the beam line from the exit of the momentum slit to the final focal point at the entrance to the treatment room are shown in the Fig.6. At the focal plane the horizontal/vertical beam sizes are equal to 9.6/9.7 mm. The horizontal/vertical beam emittance corresponds to 18.3/19 π·mm·mrad.

Two wobbling magnets will be installed to form the uniform dose distribution with transverse size of 15×15 cm in double scattering scheme. The efficiency of beam formation in double scattering scheme is about 30%. As result the average current on tumor target is about 2.4 nA at proton energy of 180 MeV.

At deceleration of proton beam in degrader to energy of 140 MeV it has the energy spread of 2.7 % (3σ) in focal plane, the horizontal/vertical beam size of 11/11.5 mm, horizontal and vertical beam emittances of 26.7/29.2 π·mm·mrad. The efficiency of momentum slit corresponds to 42% at slit gap of 15 mm.

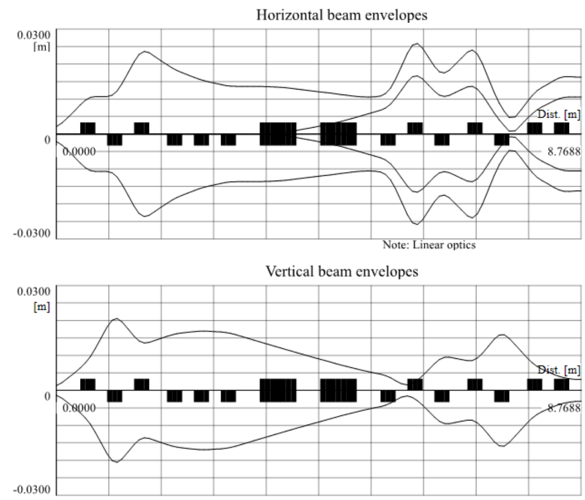

Figure 5: Beam transportation from degrader to momentum slit.

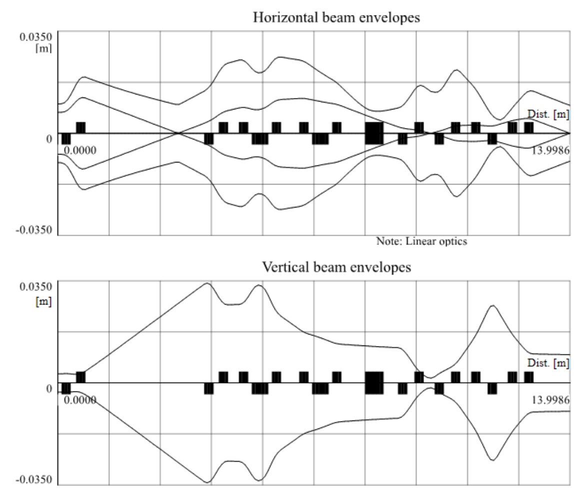

Figure 6: Beam delivery from momentum slit to entrance of treatment room.

REFERENCES

[1] O.V. Savchenko, J. Medical physics (2007), № 3-4.

[2] E.M. Syresin et al, Particle and Nuclei Letters, v.8, 635 (2011).

[3] S.A. Kostromin, E.M. Syresin Particle and Nuclei Letters, v.10, 1346 (2013).

[4] W. Kleeven et al, Proceedings of Cyclotrons 2013, Canada, MO4PB02.

[5] S.Kostromin et al, Proceedings of Cyclotrons 2013, Canada, WEPPT015.

ISBN 978-3-95450-170-0