DEVELOPMENT OF THE EQUIPMENT FOR THE PROTOTYPE OF A COMPLEX OF RADIOTHERAPY AT THE NUCLOTRON-M

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Abstract

The report deals with the construction of the carbon beam transport line for biomedical research at the Nuclotron accelerator complex, JINR, Dubna. We have studied the scheme and modes of magneto-optical elements of the channel. Used electronics described. We are discussed the compilation and realization of the plan of treating a tumor located at a depth up to 30 cm. Choice of beam scanning schemes and their optimization are shown.

INTRODUCTION

One direction in the development of the Joint Institute for Nuclear Research (JINR) accelerator complex is the design of a test bench for medicobiological research based on the JINR Nuclotron [1].

While designing the test bench, the general technique for manufacturing the hadronic therapy complex is tested.

In this work we present a calculation procedure for the optics of the charge particle transport channel of the hadronic therapy complex. This channel is intended for the transportation of the $^{12}C^{+6}$ carbon ions with an intensity of ~2 × 10^9 and an energy of 100–550 MeV/nucleon.

Figure 1 shows the circuit of the primary transport channel from the Nuclotron to experimental hall 205. An additional channel starts near the F3 focus of the primary channel.

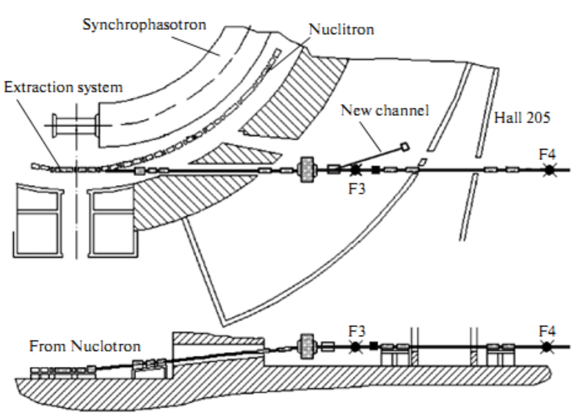

Figure 1: Layout of the primary transport channel from the Nuclotron. Top and side view. A branch of the designed channel before the F3 focus is shown.

PROBLEM STATEMENT

Mathematical Statement

To describe an envelope during beam transportation, one can use the matrix formalism:

$$X_{out} = M_N \cdot \ldots \cdot M_2 \cdot M_1 \cdot X_{in} , \quad (1)$$

where X_{out} and X_{in} are the column vectors ($X = (\beta, \alpha, \gamma)^T$) of the terminal and initial conditions (consisting of the parameters of Twiss matrix) describing the beam; M_1, … M_N are the transformation matrices of channel elements, i.e., drift gaps and quadrupole lenses. The thick lens approximation is used for the quadrupole elements. All transformation matrices are nonlinear with respect to the channel parameters, i.e., geometrical sizes of the elements and lens gradients.

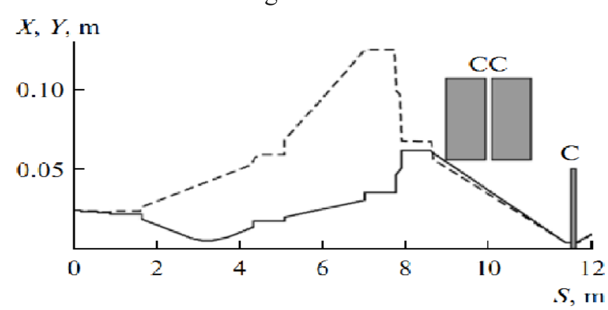

Figure 2: Position of the scanning system of magnets on a beam (CC). The scanning region in the beam focus (C).

The initial conditions for beam transport in the additional channel are taken as current values of the beam parameters from the Nuclotron primary channel. They should satisfy the conditions

$$M_{drift} \cdot X_{in} = X_{F3} , \quad (2)$$

where X_{in} is the initial conditions from Eq. (1), X_{F3} is the beam parameters in the F3 focus of the primary channel, and M_{drift} is the matrix of transformation from the additional channel branching point to the F3 focus.

The output transport values X_{out} should satisfy the focus conditions, i.e., the zero derivative of the beam envelope with respect to the transport coordinate:

$$\alpha_{x.out} = \alpha_{y.out} = 0 , \quad (3)$$

where $\alpha_{x.out}$ and $\alpha_{y.out}$ are the α components of the Twiss matrix in the focus of the additional channel.

The size of the beam envelope in the focus F_k of the additional channel is close to the possible minimum satisfying the geometrical limits of the setup. The envelope minimum is considered known and determined

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by the relative position of the scanning system and the scan region.

Thus, the problem is reduced to a determination of the parameters of transformation matrices from Eq. (1) belonging to the region of setup geometry and corresponding to the minimum envelope size in the additional channel focus (3) at specified parameters of the F3 focus of the primary channel.

Setup Restrictions

Additional restrictions of the transport problem arise in the use of specific optical elements and their mounting in the experimental hall. The following optical elements are used in the channel: dipole and deflecting magnets (SP-94) and a magnetic lens (ML-17).

The length of the transport channel is 12 m. The designed channel starts from a dipole magnet mounted in the primary transport channel at a distance of 5.25 m in front of the F3 focus (Fig. 1). Optical elements (quadrupole lenses) are located over the channel. There is a beam trap at the end of the channel, the test bench in F_k is right before the trap, and the beam scanning system is before the test bench. The scanning system consists of two similar deflecting magnets rotating at an angle of 90° around the axis relative each other.

One natural restriction of beam transportation is that the diameter of the vacuum pipeline is equal to 0.25 m, which passes through all the quadupole elements of the system. A magnet aperture of 0.3 × 0.13 m is a restriction at the final stage of the scanning system. The mutual position of the scan region and the system of scanning magnets is fixed.

The maximum current is limited for each quadrupole lens; this results in a limitation of the coefficient K <1.5 m^{-2} used for calculating the phase incursion on the lens at a preset energy range of 100–550 MeV/nucleon.

The beam cross section in the F3 focus of the primary transport channel is a circle 0.04 m in diameter [2], which makes it possible to define the initial conditions of beam propagation.

Horizontal and vertical emittances of the beam are assumed equal in the calculations [3, 4]; values of 25π mm mrad and 50π mm mrad were used [3].

The space region around the focus in the form of a cube with a side of 0.1 m is planned for the experiments. When scanning the region, the transport channel length changes. Correspondingly, the prolongation of the transport problem solution to the whole scan region should exist with fixed parameters of the channel geometry. That is, in addition to geometrical restrictions, conditions of the existence of a solution to the problem in the vicinity of scanning the final focus are imposed on the problem.

SOLUTION

Minimum Beam Size in Focus and Beam Emittance

The position of the scanning system relative to a target (Fig. 2) specifies the minimum beam size in focus restricted by the scanning system aperture. In view of the emittance formula $E = x'x$, the minimum beam size in focus can be estimated with good accuracy. Here, x' is the mean slope of the envelope at a segment before the focus and x is the envelope value in the focus.

For a preset aperture and the magnet arrangement, we have:

(i) a minimum focus diameter of 2.8 mm for an emittance of 25π mm mrad;

(ii) a minimum focus diameter of 5.6 mm for an emittance of 50π mm mrad.

Geometrical Restrictions to a Scan Region Normal to the Beam

The region of target scanning is restricted by an aperture of two successive magnets in a plane normal to the beam. The magnet aperture is 0.3 × 0.13 m for a specific channel; this agrees with the planned scan region of 0.1 × 0.1 m.

Results Obtained: Beam Envelope

Solutions have been found for emittances of 25π mm mrad and 50π mm mrad based on the above specified restrictions. The beam cross section in the focus F_k is close to the minimum for the given scanning system geometry:

(i) 3.0 × 3.0 mm for an emittance of 25π mm mrad;

(ii) 5.6 × 6.0 mm for an emittance of 50π mm mrad.

BEAM CONTROL

Beam Spreading and Additional Lens Focusing Suring Scanning along the Beam

Deviating along a beam from a focusing point, the beam spreads. The change in the beam size depends on the focus size for a fixed geometry of the scanning system. The change is as follows :

(i) 20% for a beam 3 mm in diameter (emittance of 25π mm mrad), i.e., 0.6 mm;

(ii) 6% for a beam 5.8 mm in diameter (emittance of 50π mm mrad), i.e., 0.35 mm along a beam over a scan region of ±0.05 m.

The beam spreading can be compensated by means of correcting the tuning of optical elements simultaneously with motion over the scan region. The maximum correction value is about 2%.

Features of Energy Absorption

The clearly pronounced feature of the energy absorption peak (Bragg peak) is used during target irradiation; therefore, the value of beam defocusing compensation increases when deviating from the central position during scanning.

The beam control function is chosen from the way target scanning and tolerance of the experiments is chosen.

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CONFIGURATION VARIANTS

The Number of Magnetic Lenses

To choose a specific configuration of the transport channel, variants of different numbers of focusing elements were considered.

We did not find solutions satisfying the initial and boundary conditions of the physical setup for the simplest configurations consisting of one or two quadrupole elements. The resulting envelops for configurations of three and four elements are shown below. These variants differ in size and focus shape; i.e., when increasing the number of lenses, an elliptical focus can be changed to a circular one.

The beam cross section in the focus F_k (emittance of 50π mm mrad) is as follows:

(i) 5.6 × 12.0 mm for a configuration of three lenses;

(ii) 5.6 × 6.0 mm for a configuration of four lenses.

A more complicated configuration of four lenses can be used when two lenses are mounted in the additional channel and two lenses are mounted in the primary one. In this case, the tuning of the lenses from the primary channel should be controlled for the beam transport.

Initial Conditions

To check the existence of a solution in other operating modes, other initial conditions of beam propagation in an additional channel were considered. The beam cross section in the F3 focus acts as a parameter determining these initial conditions.

In addition to a solution with a focus on the primary channel target of 0.04 × 0.04 m, we considered the solution for a focus of 0.1 × 0.12 m [4]. The beam envelopes are shown in Fig. 3 for both solutions.

The beam cross section in the focus on a target for configurations with initial conditions corresponding to different beam sizes in the F3 focus of the primary channel (the emittance is 50π mm mrad) is equal to

(i) 5.6 × 6.3 mm for the focus 0.1 × 0.12 m

(ii) 5.6 × 6.0 mm for the focus 0.04 × 0.04 m.

EQUIPMENT OF THE ADDITIONAL CHANNEL

We suggest the following equipment for the additional channel:

(i) magnetic lenses ML-17;

(ii) scanning and dipole magnets SP-94;

(iii) the pixel chamber and the wire chamber and read out electronics (see Fig.3).

CONCLUSIONS

The possibility in principle of designing an optical system for beam transport with different numbers of optical elements has been shown in the work. The correction values for the beam scanning function have been found.

The choice of parameters of the optical system is determined by the operating mode of the primary channel of the Nuclotron and the requirements of the medicobiological experiments that were conducted.

The choice of the temporal control functions of magnetic elements is determined by the planning problems of the experiment, i.e., the way the beam energy was controlled, the type of target scanning, etc.

The view of distribution of beam can see on fig.4 for on-line monitoring of the carbon beam (as one example).

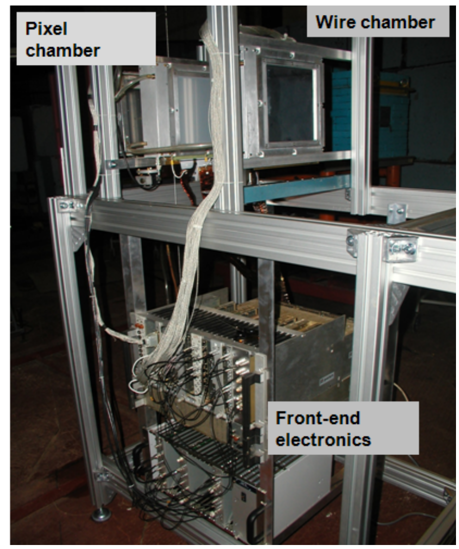

Figure 3: The pixel chamber and the wire chamber and read out electronics which were developed for on-line monitoring of the "intensive" extracted carbon beams.

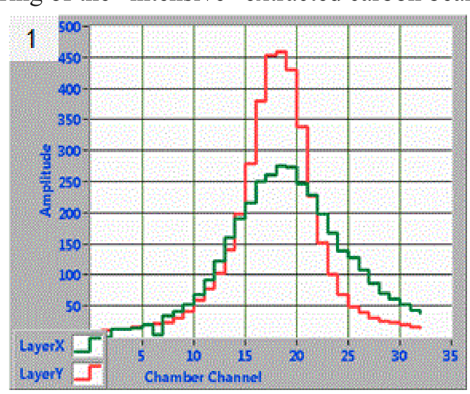

Figure 4: The view of distribution of beam is for on-line monitoring of the carbon beam.

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