NUMERICAL SIMULATION AND OPTIMIZATION OF THE VARIABLE ENERGY 60–1 000 MeV PROTON BEAMS AT THE PNPI SYNCHROCYCLOTRON FOR TESTING THE RADIATION RESISTANCE OF ELECTRONICS USED FOR NEEDS OF AVIATION AND SPACECRAFT

S.A. Artamonov, D.A. Amerkanov, E.M. Ivanov, G.I. Gorkin, G.A. Riabov, V.A. Tonkikh

1. Introduction

The synchrocyclotron (SC-1000) at PNPI accelerates protons to a fixed energy of 1 000 MeV with an intensity of the extracted beam of 1 μA. The accelerator has an extensive network of proton and π- and μ-meson beams, and a neutron beam [1]. However, to solve a number of problems of fundamental nuclear physics and a variety of applications, there is a need for beams of protons with lower energy. It is desirable to have proton beams of variable energy, which are concentrated in one system. The main method of producing such beams is to decelerate a primary beam by using the mechanism of ionization losses in the material, *i. e.* on the basis of using a degrader. At the time, this method was applied in the Joint Institute of Nuclear Research [2] to obtain a medical beam with 200 MeV from a primary beam of 680 MeV, and, for example, for formation of a beam with variable energy in the cyclotron medical centre, the United States [3].

At PNPI this method was also used previously in experiments to study the elastic *pp* scattering in the energy range 500–1 000 MeV [4] and in measuring the cross sections of a whole group of nuclei [5]. For these purposes, a beam with variable energy from 200 to 1 000 MeV with a relatively small intensity of 10^5–10^6 s^{-1} was developed and implemented [6]. However, many accelerators are used at present not only for solving scientific problems. More and more of their operating time is devoted to practical purposes.

The proton therapy at the SC-1000 with a beam energy of 1 000 MeV (the Gatchina method) gives very good results, but its application is limited to a fairly narrow range of diseases [7]. Therefore, in PNPI a possibility of forming a proton beam with the energy of 140–230 MeV for treatment of patients with oncological diseases of internal organs based on the effect of the Bragg peak was additionally investigated [8]. During the execution of works [4–6, 8], the simplest design of a degrader, which was a set of cylindrical copper disks 80 mm in diameter installed in the guide housing close to each other, was used. The degrader was located close to the output window of the accelerator; its length could be changed manually to produce the required energy.

Recently, a new applied problem has emerged. For successful operation of aviation and space technique in conditions of radiation, radiation-resistant electronics are required. A universal centre for testing electronic components (EC) for the needs of aviation and cosmonautics is being created at the accelerator SC-1000 PNPI jointly with the research Institute of Space Instrumentation. One of the main tools of such tests is the proton beam of variable energy. However, for multiple radiation tests of electronic components, it is necessary to have fast tunable beams with wider energy ranges than the previous ones – ~ 60, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1 000 MeV, and with a whole set of preassigned properties. In particular, for radiation tests, a higher beam current with a flux density of 10^8 $cm^{-2} \cdot s^{-1}$ and 10% homogeneity area of the beam of at least 25 mm in diameter is needed; it is necessary also to provide a possibility of temperature changes of the test object from +25 to +125 °C. For realization of all these conditions, it is necessary to build a degrader whose length can be changed remotely. Moreover, it is necessary to determine the material from which it is possible to produce the degrader and develop its automated construction. This will allow for each experiment the necessary value of the beam energy to be installed easily and safely, and to reduce significantly the dose load on the staff and unproductive consumption of the accelerator working time. The degrader is preferably positioned as close as possible to the focusing lens to increase the beam intensity at low energies. A complete computer control for the magnetic elements of the designed line should be fulfilled. A permanent test stand to work on the beams with the specified parameters should be built. Ultimately, the process of irradiation of electronic components should be maximally automated.

Time-consuming calculations for each required value of the beam energy were needed to implement such an ambitious program. With the software package GEANT4 [9], Monte Carlo (MC) simulations were performed of the passage of protons with an energy of 1 000 MeV with the desired properties, reflecting the experimental parameters of the beam through the degraders of copper and tungsten, and the lengths of the degraders for each energy ~ 60, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1 000 MeV were determined. For the specified set of energies, the parameters of the beams which passed through the copper degrader were calculated. The data were used as the input data for the MESON [10] and OPTIMUM [11] programs, which allowed us to trace the trajectory of each proton in the channel, optimize the beam parameters, and determine the optimal modes of all magnetic elements of the line. Thus, the main calculated parameters for each beam, such as intensity, energy heterogeneity, beam sizes, and the homogeneity of its spatial distribution have been obtained.

2. SC-1000 accelerator and the beam lines with variable energy

The intensity of the extracted proton beam with an energy of 1 000 MeV at the SC-1000 can be varied from 10^6 to $6 \cdot 10^{12}$ s^{-1}, and the beam diameter in the focus can be from 5 to 500 mm in the beam lines P2 (medical beam) and P3 (IRIS beam). The versatility of the synchrocyclotron of PNPI is due to the well-developed system of primary and secondary beams, which is shown in Fig. 1 in Ref. [12], where, in particular, the old layout of the equipment placement is presented: degrader, collimators, the parting magnet, two doublets of quadrupole lenses (ML1 and ML2), and the experimental set-up [4, 5] in the direction P3.

For radiation tests of electronic components, it is necessary to have beams of variable energy with the maximum intensity, especially for low values of energy. It is possible to increase the intensity of such beams without significant reworking of the existing line due to proximity of the degrader to the focusing lenses in the main hall of the accelerator. For this purpose, the degrader should be designed to fit into the gap of ~ 90 cm.

Therefore, it was decided to form a new beam of protons of variable energy ~ 60, 100, 200, 300, 400, 500, 600, 700, 800, 900 MeV on the current direction of P3 (1 000 MeV – on the current direction of P2). The alteration of the line is reduced mainly to designing and manufacturing of a new degrader with remote control, located at a new position of this line (see Fig. 1 in Ref. [12]). Three collimators 1, 2, and 3, limiting the size and divergence of the beam, two doublets of quadrupole lenses, and the SP-40 bending magnet remain the same. The total length of the line will be ~ 26 m.

3. Modeling with the GEANT4 software program

One of the most common and widely used codes for calculations of passage of particles through matter, based on the MC method, is the GEANT4 program [9]. In the present work, using this program we generated before the degrader a beam of protons (a few million trajectories) extracted from some vacuum volume of the accelerator line. It was assumed that the beam had a Gaussian form with the parameters $\sigma_x = \sigma_z = 0.64$ cm (x, z are the cross sizes) and the energy of 1 000 MeV (σ_E = 3.84 MeV), which correspond to the experimental results. Here σ is the standard deviation.

In the simulation of the passage of the beam through the degrader, the set of physical interactions (Physics List) describing the electromagnetic processes, Emstandard_opt3, was applied. The energy loss due to ionization, formation of δ electrons, multiple scattering, Compton scattering, bremsstrahlung, the photoelectric effect, the pair production, and e^+e^- annihilation were taken into account. All hadron interactions (elastic scattering, formation of mesons, decays of particles, excitation of nuclei and emission of photons, nuclear fission, neutron capture, and nuclei disintegration) were also linked up. The interactions described by the class G4InelasticProcess are of special interest in the field of hadronic interactions. Three models for inelastic interactions are provided in the package GEANT4. This is the algorithm GHEISHA, which was also implemented in the previous version of the GEANT3 [13], and the algorithms Bertini cascade and Binary cascade.

3.1. Determination of the material and length of the copper and tungsten alloy degraders

It was assumed in all calculations that the degrader is fabricated in the form of a cylinder 80 mm in diameter either of copper with the density ρ_m = 8.88 g/cm^3 or of the alloy of powders: tungsten (T) of 97.50, nickel (N) of 1.75, and iron (I) of 0.75% (TNI) with a density of ρ_w =18.6 g/cm^3.

The length of the degrader for obtaining protons with necessary energy E_i was defined as the difference of the proton ranges, $L_D = R_0 - R_i$, where R_0 is the range of protons with the initial energy E_0 = 1 000 MeV and R_i the range of protons with the energy E_i.

Choosing a degrader made of copper, its degrader length L_{Dm} can be determined using this simple formula. In the case a degrader is made of an alloy of tungsten–nickel–iron powders, the length L_{Dw} of the TNI degrader can be determined also by the same formula.

Table 1 in Ref. [12] presents estimation results for a variant of the degrader made of the alloy of the TNI powders. It also shows for comparison the values of the mean ranges of protons of different energies obtained by the calculations using the well-known SRIM program [14]. It follows from Table 1 in Ref. [12] that the error in the calculation of the length of the degrader L_{Dw} according to the SRIM and GEANT4 for the entire range of energies reaches $\Delta L \approx 2\%$. The length of the degrader, calculated with SRIM, for all values of energies is larger than that determined using the code GEANT4. The experience of previous calculations [6] indicates that the difference of $\Delta L \approx 2\%$ can lead to significant inaccuracies in determination of the given values of energy.

An analysis of the calculation results shows that, taking into account modern possibilities in the manufacture of details by the powder metallurgy method, for each value of the energy, a degrader of the desired length from the TNI alloy can be formed on the basis of a combination of 13 base discs with the diameter of 80 mm. The disks should have the following thickness: 100, 100, 50, 50, 20, 20, 10, 5, 2, 2, 1, 0.5, and 0.3 mm. It was clarified in the process of developing the degrader that the production of the discs made of the TNI alloy with a specified density ρ_w = 18.6 g/cm^3 is possible in principle, but only with the use of a quite complex and expensive technology. It was therefore decided, together with the degrader from the TNI alloy, to consider the case where the traditional copper is selected as the material of the degrader. This required new calculations to find the design of the degrader and its collimator made of copper.

The final lengths of the degrader made of copper with the density ρ_m = 8.88 g/cm^3, obtained on the basis of calculations using the SRIM, GEANT3, and GEANT4 for different values of energies are presented in Ref. [12] in Table 2. The calculations showed that the technical implementation of the stacked degrader made of copper with ρ_m = 8.8 g/cm^3 is quite possible using 11 base disks 80 mm in diameter of the following thicknesses: 200, 150, 100, 50, 20, 20, 10, 5, 2, 2, and 1 mm.

3.2. Beams of variable energy after the copper degrader

In the calculations using the GEANT4 for protons which passed the degrader, the coordinates, the momentum, and the energy of each proton were registered at its output plane, and these parameters were recorded in a separate file for each required level of the beam energy for further multiple analyses. In additional files, information about primary protons (which did not experience inelastic interactions in the degrader) and secondary particles (products of inelastic interactions) was recorded.

The total energy distributions of the protons for different energy values at the exit of the degrader are presented in Ref. [12] in Fig. 2. Table 3 in Ref. [12] presents important results of the calculations for the entire range of energies: a_E – the mathematical expectation of the beam energy; σ_E – the standard deviation; P – the value of the momentum, and the value I/I_0 – the efficiency of the passage of the beam through the degrader in percentage of the intensity of the original beam. These results demonstrate that the magnitudes of the required energies are determined in the calculations reasonably well.

4. Modeling beams of variable energy in the P3 transportation path

One of the objectives of the present work is to calculate and optimize parameters of the beam of a variable energy for tests of radiation resistance of electronic components and to determine optimal operation modes of the magnetic elements of the beam line for all required values of energy. The degrader is a source of particles obtained using the GEANT4 software with a set of parameters that are, for further purposes, the input data for the programs MESON [10] and OPTIMUM [11].

4.1. Methods and algorithms for calculations of the transport channel

The optimized transport channel of the beam P3 consists of two doublets of lenses, a deflection magnet, and a collimator in the wall between the main and experimental halls. The focusing gradients of the magnetic fields in the lenses for obtaining a beam with the maximum intensity and minimum width of the momentum distribution on the target are varied in the optimization. The distance between the lenses in the doublets is not varied because the P3 channel is also used for other purposes.

The MESON program allows us to calculate the parameters of the primary and secondary particle beams by the MC method, which consists of modeling a large number of trajectories of particles passing the given magneto-optical system. The particles of the beam at the entrance to the magneto-optical system are defined in a separate file that contains information about the number of tracks for which the calculation is performed and the parameters characterizing the given particle: the coordinates and the vector components of the momentum, the module of the momentum, and the energy. The file is generated in a special way by the GEANT4 program. The trajectories in free gaps and in the magnetic lenses are calculated by usual formulas [15].

Along with a relatively simple task of the trajectory calculations in the given structure of the tract, the problem of optimizing its parameters should be solved [16]. The optimization problem combines two parts: 1) calculation of the parameters of the beam and 2) the algorithm for searching the optimum. Both of these tasks can be efficiently solved by the MC method.

4.2. Effect of the collimator after degrader on the beam parameters

To improve the beam parameters it was set in the calculations that the new collimator made of copper with the density ρ_m = 8.88 g/cm^3 would be located after the degrader. Based on the available practical possibilities for the placement, the collimator was chosen with a length of 132 mm. It was assumed in the calculations that the radius of the hole in the collimator could be varied from R = 1 cm to R = 5 cm. An analysis of the calculation results shows (see Fig. 3 in Ref. [12]) that the collimator strongly influences the amount of losses for all energy values in the considered range of variation of the radius of the hole.

4.3. Optimal alternation of the polarities of the lenses and the losses during the passage of the transport channel P3

It is commonly accepted that in the channels with a magnet deflecting the beam in the horizontal plane, the polarity of the first doublet HD–HF (horizontal defocusing–horizontal focusing) is chosen to get a small size of the beam after the magnet in the plane of its deflection. This representation was set in the initial calculations with the optimization of the parameters. However, further optimization calculations of the parameters of the channel revealed that the alternation of the polarities HF–HD for the two doublet lenses 20K50 gave for the specific geometry of the considered channel a higher intensity at the end of the path than the opposite polarities. Figure 2 in Ref. [17] presents a typical calculated change of the number of protons with the energy 60–900 MeV after the passage of the transport channel. The results of the optimization show that for all energies there is a significant decrease of the number of protons in the main hall of the accelerator, *i. e.* at the initial part of the tract. This is due to the fact that after the degrader and collimator the emittance of the beam is substantially larger than the acceptance of the channel. A similar situation is observed with the passage of the proton beam through the deflecting magnet SP-40 and the holes in the wall between the main and the experimental halls, which is a natural collimator with a hole diameter of 110 mm.

4.4. Optimization of the size of the beam for different energies

The optimal gradients of the magnetic fields in the lenses for all values of energies, achieving their maximum possible intensity with the minimum width of the momentum distribution at a target with a diameter of d = 5 cm, are presented in Fig. 5 of Ref. [12].

The optimal parameters of beams of different energies with the same diameter d = 5 cm of the target are presented in Table 1.

Table 1

Estimated parameters of beams of different energies at the end of the path for the same diameter of the target d = 5 cm*

E_i, MeV, desired	E_i, MeV, calculated	I, s^{-1}	$\Delta P/P$, %	σ_x, cm	σ_z, cm	Homogeneity 10%	
						x, mm	z, mm
60	62.1	$1.53 \cdot 10^{7}$	14.9	3.00	1.41	25.9	14.5
100	100.1	$4.60 \cdot 10^{7}$	12.2	3.63	1.37	35.2	14.7
200	197.9	$2.06 \cdot 10^{8}$	7.93	2.46	1.37	25.3	17.2
300	300.2	$5.87 \cdot 10^{8}$	4.70	2.48	1.44	24.0	19.0
400	399.1	$1.39 \cdot 10^{9}$	3.29	2.26	1.44	24.4	21.0
500	499.2	$3.13 \cdot 10^{9}$	2.49	2.27	1.38	23.3	21.5
600	601.0	$4.33 \cdot 10^{9}$	1.96	1.26	1.41	13.6	16.3
700	699.9	$7.23 \cdot 10^{9}$	1.51	0.86	1.51	12.0	27.0
800	800.2	$1.67 \cdot 10^{10}$	1.27	0.69	1.55	11.3	27.0
900	899.8	$5.10 \cdot 10^{10}$	0.98	0.57	1.48	11.7	19.7

* Here ΔP is the full width of the momentum distribution of the beam at the half-maximum (FWHM).

The table results indicate that the requirement of 10% uniformity of beams with the dimension of ≥ 25 mm simultaneously for the two transverse coordinates x and z directions cannot be satisfied with the target of the diameter d = 5 cm for all values of energies. Therefore, more research is needed to obtain the necessary transverse beam sizes for the complete set of energies.

For this purpose, the optimization calculations were performed for different possible target diameters from d = 5 cm to d = 18 cm while maintaining the number of particles that reached the target. The information about the shape of the beam is given by the standard deviations σ_x and σ_z calculated by the specified method for each desired value of the energy.

Figure 6 of Ref. [12] shows how the optimized values of the standard deviations σ_x and σ_z depend on the diameter of the target for the energies of ~ 60, 100, 200, and 300 MeV. It is seen that for all these energies the standard deviation σ_x is a slowly varying function of d, while σ_z has a not predictable behaviour with increase of d.

The values of the gradients of the magnetic fields in the quadrupole lenses of the experimental hall for all values of the energies realizing their maximum possible intensity with the minimum width of the momentum distributions on the targets with the optimal diameters are presented in Fig. 8 of Ref. [12]. The calculation results for all energies are summed in Table 2.

Table 2

Estimated parameters of beams of different energies at the end of the path for the optimal diameters of the target

d_{opt}, cm	E_i, MeV, calculated	σ_x, cm	σ_z, cm	Homogeneity 10%	
				x, mm	z, mm
15	62.1	2.88	2.84	27.8	27.0
18	100.1	3.40	3.53	31.5	33.9
15	197.9	2.62	3.14	28.1	28.1
18	300.2	3.18	3.41	30.8	30.5
15	399.1	3.01	2.44	35.7	34.0
13	499.2	2.46	2.64	27.3	32.9
15	601.0	2.82	2.71	30.5	34.9
13	699.9	2.49	2.43	31.2	34.0
9	800.2	1.45	1.81	27.1	29.8
11	899.8	2.71	1.78	34.9	30.8

5. Conclusion

At the SC-1000 PNPI, together with the research Institute of Space Instrumentation, a universal centre for testing the electronic component base for aviation and space has been built.

For a successful implementation of this task, careful and time-consuming calculations for each required value of the beam energy were done. Simulations of the passage of protons with an energy of 1 000 MeV through copper and tungsten degraders were performed by the MC method using the GEANT4 software package [9]. As a result, the lengths of these degraders providing the required energies ~ 60, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1 000 MeV were determined. For the desired set of the energies, by selecting the copper degrader, the parameters of each beam which passed the degrader were calculated. The data were used as the input data for the MESON [10] and OPTIMUM [11] programs, which allowed us to trace the trajectory of each proton in the beam transport line, to choose the optimum size of the collimator of the degrader, to optimize the beam parameters in the channel, and to determine the optimal modes of all the magnetic elements of the tract. The main parameters of each beam, such as the intensity, the energy heterogeneity, the beam sizes, and the homogeneity of its spatial distribution were calculated. The calculations showed a possibility to form beams of protons in the energy range 1 000–62 MeV with the density of the intensity at the place of exposure from $1 \cdot 10^9$ to $6 \cdot 10^5$ $cm^{-2} \cdot s^{-1}$ with the 10% homogeneity area in intensity within a diameter of no less than 25 mm. A copper degrader with a remote change of its length and with a fully automated control system was designed and built. This system allows the necessary value of the beam energy to be installed easily and safely, and it allows one to significantly reduce the dose load on the staff and unproductive consumption of the accelerator working time in each experiment. The degrader was placed as close as possible to the focusing lens channel P3, which resulted in an increase of the beam intensity at low energies. A complete computer control of the magnetic elements of the line was implemented.

In conclusion, it should be emphasized that at the SC-1000 radiation tests of electronic components can be carried out not only in proton beams of variable energy 62–900 and 1 000 MeV, but in the neutron beam with a spectrum similar to the atmosphere neutron spectrum [18]. Thus, the synchrocyclotron PNPI is the only accelerator in Russia where extensive radiation tests of electronic components can be conducted in proton beams in the energy range of 60–900 and 1 000 MeV and in a neutron beam with energies 1–1 000 MeV.

References

1. N.K. Abrosimov, S.P. Dmitriev, V.A. Eliseev *et al.*, in *Proc. of the 7th All-Union Workshop on Charged Particle Accelerators, Dubna, 14–16 Oct., 1980*, **2**, 75–79 (1981).
2. V.P. Dzhelepov, V.I. Komarov, O.V. Savchenko, Med. Radiol. **4**, 54 (1969).
3. E.W. Cascio, J.M. Sisterson, J.B. Flanz, M.S. Wagner, in *Proc. of the IEEE Radiation Effects Data Workshop*, *21–25 July, 2003* (IEEE, Piscataway, NJ, 2003).
4. A.A. Vorobyev, A.S. Denisov, Yu.K. Zalite, G.A. Korolev *et al*., Preprint PhTI-430 (1972).
5. A.A. Kotov, L.A. Vaishnene, V.G. Vovchenko *et al.*, Phys. Rev. C **74**, 034605 (2006).
6. N.K. Abrosimov, E.M. Ivanov, Yu.T. Mironov *et al.*, VANT, Ser. Phyz. Rad. Vozdeistv. Radioelektron. Appar., No. 4, 43 (2003).
7. N.K. Abrossimon, Yu.A. Gavrikov, E.M. Ivanov *et al.*, J. Phys.: Conf. Ser. **41**, 424 (2006).
8. N.K. Abrosimov, E.M. Ivanov, G.A. Ryabov, M.G. Tverskoy, Preprint PNPI-2805 (2009).
9. GEANT4 a Simulation Toolkit, http://geant4.cern.ch/
10. N.K. Abrosimov, V.A. Volchenkov, G.A. Ryabov, in *Proc. of the 4th All-Union Workshop on Charged Particle Accelerators*, **1**, 258–261 (1975).
11. N.K. Abrosimov, V.A. Volchenkov, G.A. Ryabov, in *Proc. of the 6th All-Union Workshop on Charged Particle Accelerators*, **2**, 175–177 (1979).
12. S.A. Artamonov, E.M. Ivanov, N.A. Ivanov *et al.*, Phys. Part. Nucl. Lett., **14**, No. 1, 188 (2017), DOI 10.1134/S1547477117010046.
13. ROOT. Data Analysis Framework, http://root.cern.ch/installing-geant3
14. SRIM – the Stopping and Range of Ions in Matter, http://srim.org
15. G. Vol'nik, *Optics of Charged Particles*, Energoatomizdat, St. Petersburg, 1992.
16. D.M. Kuz'menkov, V.I. Chernetskii, *Algorithms and Programs of Random Search*, Zinatne, Riga, 1969, p. 145.
17. S.A. Artamonov, D.A. Amerkanov, E.M. Ivanov *et al.*, in *Proc. of XXV Russian Particle Accelerator Conf. (RuPAC 2016), St. Petersburg, 21–25 Nov., 2016*, pp. 105–107.
18. O.A. Sherbakov, A.S. Vorobyev, A.M. Gagarski *et al.*, in *Proc. of Int. Conf. on Radiation Effects on Components and Systems (RADECS-2015), Moscow, 14–18 Sept., 2015*, p. 40.