OUTPUT ENERGY VARIATION IN THE SC LINAC FOR THE PROTON RADIOTHERAPY

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Abstract

Current success of the superconducting linear accelerators based on independently phased SC cavities gives a seriously reason to consider such structure in proton radiotherapy. Superconductivity allow to solve at once some problems concerned with a low rate of energy gain, high length, higher capacity losses and higher cost of the proton linear accelerator subsequently. One of the traditional aims of such facilities is receiving of the beam energy about 240 MeV with possibility of fluently regulation in range from 150 to 240 MeV that responds to irradiate the tumors located at different depth. The possibility of beam energy variation by means of RF field phase in last resonators and number of the resonator turn-off becomes the major advantage of the proton SC linac.

The optimal choice of accelerator parameters and the beam dynamics simulation results with using BEAMDULAC-SCL code will presented [1]. Methods of the output energy variation with beam quality preservation in the proton SC linac will discussed.

INTRODUCTION

The very high procedure cost caused by accelerator and its engineering systems cost is main factor limiting proton therapy application and ideas to reduce the cost are very actual.

The proton beam basically receives in proton synchrotrons or cyclotrons [2]. The proton beam can be accelerated also in linac but main limitation is a low rate of the energy gain that involves increasing the accelerator length. Superconductivity allows essentially reduce the linac length, that is important by economic and technical aspects. Contemporary progress in SC linacs development allows proposing their using for medical application [3]. Such facilities satisfy to all standard demands for medical using. It's energy of the beam about 240 MeV with fluently regulation, possibility of control of beam envelope up to 6 mm, intensity of the beam not less than 10^9 p/s. Besides SC linacs have some significantly advantages. It's a very high rate of energy gain for the period of the structure that allows reducing the facilities length and low requirement in RF power feeding. Also the possibility of easily beam energy variation by means of a number of the resonator turn-off (deeply variation) or RF field phase in last resonators (slow variation).

Beam focusing can be provided with the help of SC solenoids following each cavity or with the help of RF focusing [4]. Using a solenoid into focusing period will allow to make optimal choice of main accelerator parameters and to provide the transverse and longitudinal beam motion stability.

Beam dynamics simulation directed to produce the fluently tuning of the beam energy in range 150-240 MeV with preserving beam quality will discuss. Such tuning of energy can be realized in the hardware way without use of padding filters by means of voltage change on cavities or of input phase variation in cavities.

GEOMETRIC CHARACHTERISTICS

It is advisable to divide accelerator into several groups, consists of cavities having identical geometry. A slipping of the particles relative to the accelerating wave presents in such SC structure. The slipping value must not exceed an acceptable value. The number of cavities should be limited and the number of groups should be minimal. The geometrical velocity β_g of the RF wave is constant for any group of cavities and the number of such groups in linac should be minimized to reduce the accelerator cost [5].

So in our case the phase slipping factor was limited by 18 %. The accelerator will be divided into four groups of cavities with geometric velocity of cavities β_g = 0.09, 0.18, 0.31 and 0.49 respectively. The first two groups consist of cavities with two accelerating gaps and the third and the fourth would consist of three gap cavities (see Fig. 1).

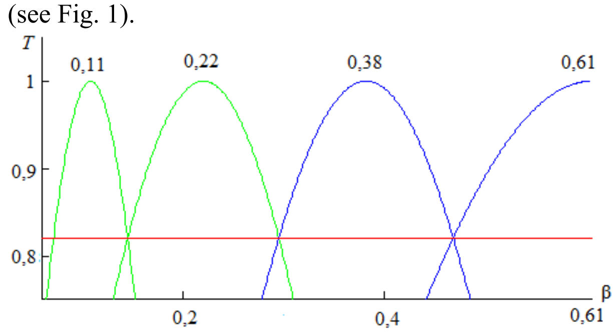

Figure 1: Slipping factor value depending on β.

BEAM DYNAMICS SIMULATION IN POLYHARMONIC FIELD

Beam dynamics simulation results for the last group having the beam energy range from 123.2 to 240 MeV will present below. The electric field amplitude for each cavity is equal 14.20 MV/m, the length of each cavity 0.386 m, the particle phase into RF field -25° and operating frequency f = 702 MHz, magnetic field B = 3 T.

Beam dynamics simulation results in polyharmonic field in the last part are shown in Figure 2.

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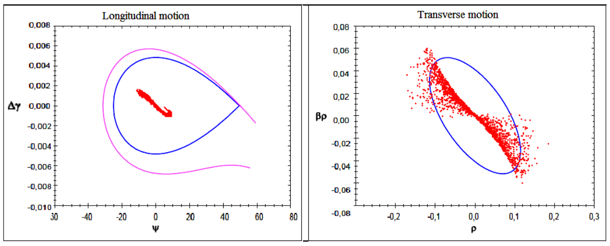

Figure 2: Longitudinal and transverse phase space in the fourth part.

Parameters of all groups of cavities optimized by the same principle are presented in the Table 1.

Table 1: Main accelerator parameters and beam dynamics simulation results

Parameter	Value			
Energy range	1	2	3	4
Injection energy, W_{in}, MeV, (β_{in})	2.4 (0.07*c*)	10.4 (0.15*c*)	43.6 (0.29*c*)	123.2 (0.47*c*)
Output energy, W_{out}, MeV (β_{out})	10.4 (0.15*c*)	43.6 (0.29*c*)	123.2 (0.47*c*)	240 (0.61*c*)
Frequency, *f*, MHz	176	176	352	704
Geometric phase velocity, β_g	0.09	0.18	0.31	0.49
Length of resonator, L_{res}, m	0.184	0.374	0.487	0.386
Phase, φ, º	-25	-25	-25	-25
Electric field amplitude, *E*, MV/m	3.21	5.96	8.87	14.2
Magnetic field, *B*, T	1.25	1.7	2.3	3
Number of periods, N_{per}	16	18	22	24
Length, *L*, m	9.344	13.932	19.514	18.864

OUTPUT ENERGY VARIATION

Different values of energy allow irradiating tumors with various depths. So the energy range 150 – 240 MeV need to irradiate tumors deeper than 15 cm. Basic methods of energy variation are considered below.

The first method concluded in voltage variation on cavities (deeply variation). Some resonators may be turned off to realize this method.

Beam dynamics simulation results in polyharmonic field in the last part varying value of the electric field amplitude at preservation of other parameters, exactly B = 3 T, φ = -25º, f = 702 MHz, N_{per} = 24 are presented below. The electric field amplitude for each cavity is equal 9.84 MV/m, that according to output energy of 200 MeV (β_{out} = 0.57).

Beam dynamics simulation results with set parameters are shown in Figure 3. The transmission efficiency is equal 100%.

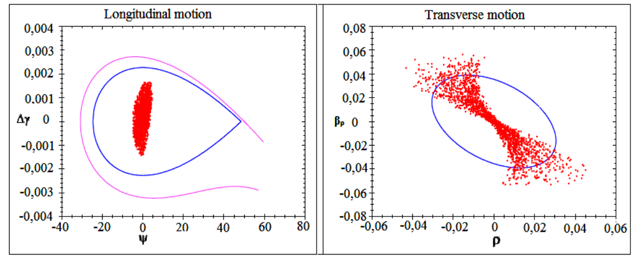

Figure 3: Longitudinal and transverse phase spaces in the fourth part with energy 200 MeV.

Beam dynamics simulation results in case when the electric field amplitude for each cavity is equal 3.34 MV/m, that according to output energy of 150 MeV (β_{out} = 0.51) are shown in Figure 4. The transmission efficiency is equal 100% but the bunch has higher phase space.

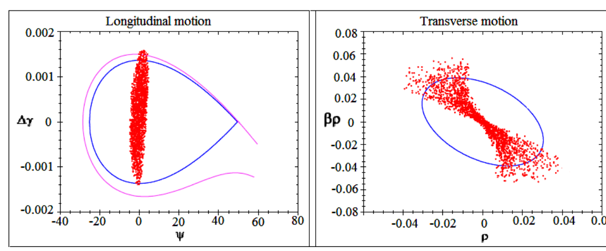

Figure 4: Longitudinal and transverse phase spaces in the fourth part with energy 150 MeV.

By the similar way the beam dynamics simulation was done with over energy values and varying of the corresponding electric field amplitude. Other parameters relating to this method of energy variation with accelerating field amplitude variation are presented in [6].

Note that the beam longitudinal phase volume decrease negligible and transverse emittance changes insignificantly and with the chosen accelerator parameters the beam motion is stable and it is possible to keep a beam quality.

The second way of output energy variation concluded in changing of RF field phase in a number of last resonators (slowly variation).

Beam dynamics simulation in polyharmonic field in the fourth part varying value of RF field phase in last 6 cavities at preservation of other parameters, exactly B = 3 T, E = 14.2 MV/m, f=702 MHz are discussed below.

The particle phase into RF field is equal -45º, than according to output energy of 200 MeV (β_{out} = 0.572). Beam dynamics simulation results in polyharmonic field with these parameters are presented in Figure 5. The transmission efficiency is equal 100%.

Other parameters relating to this method are presented in Table 2.

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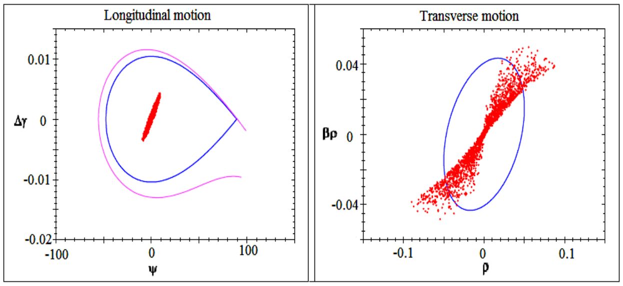

Figure 5: Longitudinal and transverse phase spaces in the fourth part with energy 200 MeV after phase variation.

Table 2: Beam output energy variation versus RF field phase in last 6 resonators

Phase into RF field, φ, °	Output phase velocity, β_{out}	Output energy, W_{out}, MeV
-25	0.605	240
-30	0.596	230
-35	0.588	220
-40	0.579	210
-45	0.572	200

The method to achieve more slowly variation is presented below. It's mean to varying of RF field phase in each cavity in each period in the last group in eligible range. It allows to receive the most exactly values of energy at irradiation of the tumors thus preserving of the beam quality.

Let's we consider the case with $N_{per} = 22$ and φ = -25 ° according to energy 222 MeV ($\beta_{out} = 0.592$), φ = -30 ° to $W_{out} = 218$ MeV ($\beta_{out} = 0.586$) and φ = -35 ° to $W_{out} = 214$ MeV ($\beta_{out} = 0.582$). RF-field phase values range was from -25 ° to -35 ° because at such parameters the most motion stability is provided.

Beam dynamics simulation results in polyharmonic field with φ = -35 ° and $W_{out} = 214$ MeV are presented in Figure 6. The transmission efficiency is equal 100%.

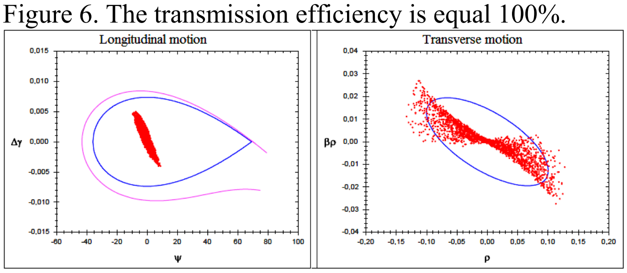

Figure 6: Longitudinal and transverse phase spaces in the fourth part with energy 214 MeV after phase variation.

Further it's possible to reduce the number of turned on resonators to 20 and receive values of energy 212, 208 and 200 MeV according to RF-field phase values φ=-25°, -30 ° and -35 ° respectively and to less values.

Beam dynamics simulation results in polyharmonic field with $N_{per} = 20$, φ = -35 ° and $W_{out} = 200$ MeV are presented in Figure 7. The transmission efficiency is equal 100%.

Other parameters relating to this method of energy variation are presented in Table 3. In all cases beam transmission efficiency is equal 100% and only when RF-field phase φ exceeds -45 ° this value decreases to 98-97%, beam motion insignificantly worsens and it can lead to cavities failure.

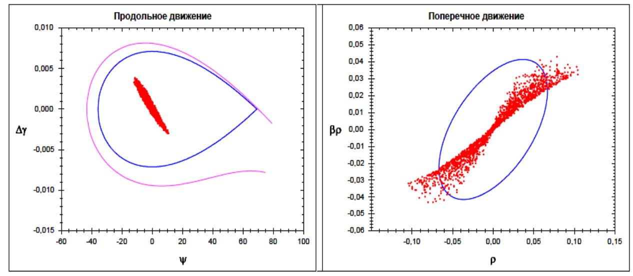

Figure 7: Longitudinal and transverse phase spaces in the fourth part with energy 200 MeV after phase variation.

Table 3: Beam output energy variation with RF field phase in different number of periods

N_{per}	RF-field phase, φ, °	Phase velocity, β_{out}	Output energy, W_{out}, MeV
	-25	0.580	212
20	-30	0.578	208
	-35	0.572	200
	-25	0.570	198
18	-30	0.568	194
	-35	0.562	190
	-25	0.560	188
16	-30	0.558	186
	-35	0.554	182
	-25	0.550	180
14	-30	0.547	177
	-35	0.544	173
	-25	0.540	170
12	-30	0.536	166
	-35	0.533	160

CONCLUSION

Choice of optimal parameters and it's optimization for SC linac structure with energy up to 240 MeV was done. Beam transverse and longitudinal motion stability study was made. Two base methods of the energy variation with beam quality preservation were proposed. The beam quality preservation with energy variation was achieved by correct accelerating system tuning.

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