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BEAM DYNAMICS SIMULATION IN SC LINAC FOR THE PROTON RADIOTHERAPY

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Abstract

Superconducting linear accelerators based on short independently phased SC cavities are widely used today in ADS and FRIB. Such accelerator can be useful as a proton therapy beam source [1]. The accelerator general layout to accelerate proton beam at the energy range 2-240 MeV will detail in this report. Obviously, in this linac will always violate the principle of synchronicity when the synchronous particle velocity is equal to the phase velocity of the accelerating wave and a slipping of particles relative to the accelerating wave. The beam dynamics simulation shows that linac should consist of four groups of identical cavities. Cavities should have phase velocities as β_g = 0.1, 0.18, 0.3 and 0.49 respectively. The choice of optimum parameters of accelerating cavities and focusing magnets will discussed and the beam dynamics simulation results will presented.

INTRODUCTION

Proton cancer therapy is developing based on normal conducting proton synchrotrons by Optivus, Hitachi and cyclotrons by Still River Systems, Varian, IBA [1, 2].

Traditional parameters of such facilities are the energy of the beam about 240 MeV with wide regulation, possibility of control of beam envelope from 3 to 6 mm, intensity of the beam at about 10^9 particles per second and energy homogeneity in the Bragg's peak.

The proton beam can be received also in linac, but main limitation is a low acceleration rate that involves to the high length of accelerator. Contemporary progress in SC linacs development, construction and operation experience let to propose their using for medical application. Such linacs have a very high rate of energy gain and can be compact thus, need low RF power feeding and large scale and power-intensive magnets are not necessary for it. But 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) can be the main advantage of SC linac.

A proton SC linac is usually based on the SC independently phased cavities. These structures can be used for proton acceleration in the middle energy region (ADS, SNS projects). It is desirable to have a constant geometry of the accelerating cavity in order to simplify manufacturing and to decrease the linac cost. [3]

Beam dynamics in such structure in polyharmonic field will be discussed in this paper with using BEAMDULAC-SCL code. [4] Also the energy variation in range 150-240 MeV with beam quality preservation will be proposed.

STRUCTURE LAYOUT

In this paper we limit the phase slipping factor 18% so the accelerator will be divided into four parts with geometric velocity of cavities β_g = 0.09, 0.18, 0.31 and 0.49 respectively, where the first two groups consist of the cavities has two accelerating gaps and the third and the fourth would consist of three gap cavities (see Fig. 1).

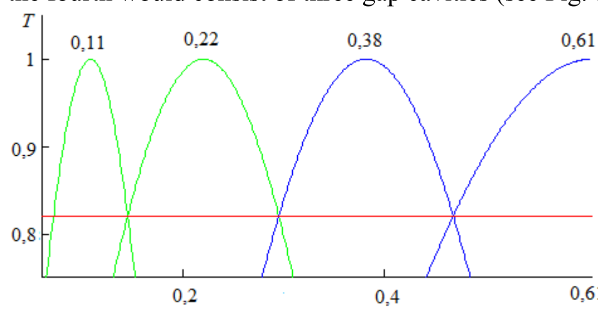

Figure 1: Slipping factor value depending on β.

Beam dynamics analysis results for the first part having the beam energy range from 2.4 to 10.4 MeV presents bellow. The electric field amplitude for each cavity is equal 3.21 MV/m, the length of each cavity 0.184 m, the particle phase into RF field -25° and frequency f = 176 MHz. Magnetic field which is need for beam transverse focusing is equal to 1.25 T. Transverse Floke parameter μ_r corresponds to envelope value X_m =5 mm is shown in Figure 2.

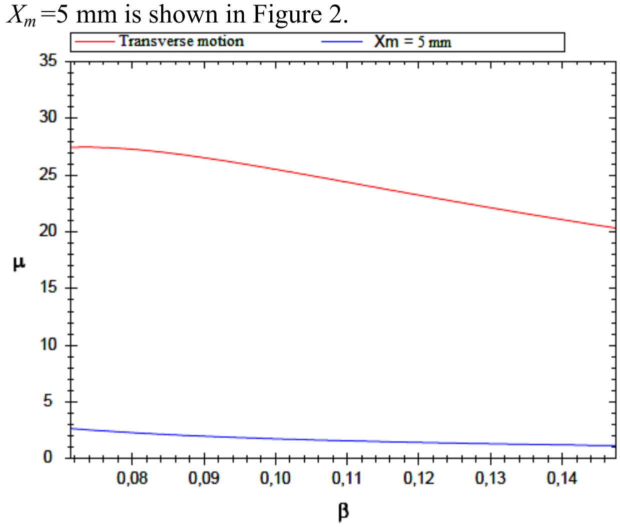

Figure 2: Transverse Floke parameter μ_r depending on β with envelope value X_m = 5 mm in the first part.

Beam dynamics simulation results in polyharmonic field in the first part are shown in the Figure 3. The transmission coefficient is equal 100%. Parameters of all

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accelerator parts provides to high beam motion stability are presented in the Table 1.

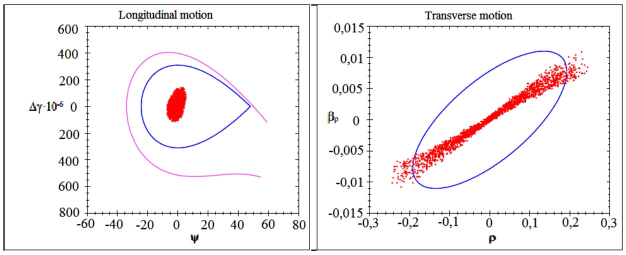

Figure 3: Longitudinal and transverse phase space in the first part

Table 1: Main accelerator parameters and beam dynamics simulation results

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*)
Geometric phase velocity, β_g	0.09	0.18	0.31	0.49
Frequency, *f*, MHz	176	176	352	704
Number of gaps, N_{gap}	2	2	3	3
Phase, φ, °	-25	-25	-25	-25
Length of resonator, L_{res}, m	0.184	0.374	0.487	0.386
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
Length of solenoid, L_{sol},m	0.2	0.2	0.2	0.2
Length of gap, L_{gap},m	0.1	0.1	0.1	0.1
Length of period, L_{per}, m	0.584	0.774	0.887	0.786
Number of periods, N_{per}	16	18	22	24
Length, *L*, m	9.344	13.932	19.514	18.864

Beam dynamics analysis results for the last part having the beam energy range from 123.2 to 240 MeV are the following: 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 which is need for beam stable motion is equal 3 T. Transverse Floke parameter μ_r corresponds envelope value X_m = 5 mm is shown in Figure 4.

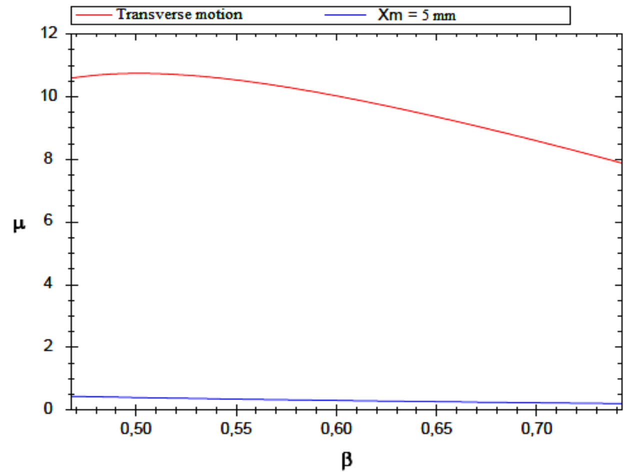

Figure 4: Transverse Floke parameter μ_r depending on β with envelope value X_m = 5 mm in the fourth part

Beam dynamics simulation results in polyharmonic field in the last part are shown in Figure 5. The transmission efficiency is equal 100%.

The simulation shows that the total length of the accelerator is equal 61.6 m.

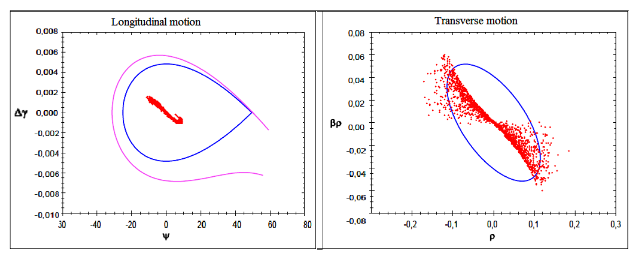

Figure 5: Longitudinal and transverse phase space in the fourth part.

OUTPUT ENERGY VARIATION

Proton beam of 60 - 80 MeV energy is necessary for radiation of the superficial tumors located at a depth up to 5 cm; at energy 240 MeV it is possible to irradiate tumors with localization depth to 26 cm. The main aim was to study of the possibility of the energy alignment with beam quality preservation. Two methods are considered below.

The first method concluded in variation of a number of the powered resonators (deeply variation). Some resonators can be turned off to provide this method. We also can to decrease the accelerating potential into a number of cavities (in one group of cavities as an example).

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

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Beam dynamics simulation results in polyharmonic field with these parameters are shown in Figure 6. The transmission efficiency is equal 100%.

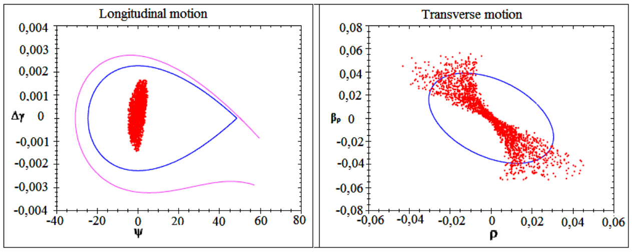

Figure 6: Longitudinal and transverse phase spaces in the fourth part with energy 200 MeV.

In case the electric field for each cavity in last part decreases to 3.34 MV/m the output energy 150 MeV (β_{out}=0.51) can be reached. Beam dynamics simulation results with these parameters are shown in Figure 7. The current transmission coefficient is equal 100%. The beam longitudinal phase volume decrease negligible and transverse emittance changes insufficiently and we can to appoint that the beam quality preservation with energy variation can be achieved with correct accelerating system tuning. Other parameters relating to this method of energy variation are presented in Table 2.

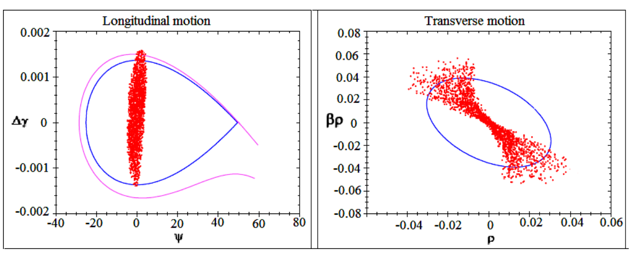

Figure 7: Longitudinal and transverse phase spaces in the fourth part with energy 150 MeV.

Table 2: Beam Output Energy Variation with Accelerating Field Amplitude Variation

Electric field amplitude, *E*, MV/m	**Output phase velocity, β_{out}**	**Output energy, W_{out}, MeV**
14.20	0.605	240
12.44	0.586	220
9.84	0.566	200
8.54	0.555	190
7.24	0.544	180
5.94	0.532	170
4.64	0.519	160
3.34	0.506	150

The other method of the output energy variation concluded in changing of RF field phase in a number of last resonators (slow 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 -45°, 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 8. The transmission efficiency is equal 100%. Other parameters relating to this method are presented in Table 3. It's necessary to variate RF field phase in more number of resonators for receiving a lower energy.

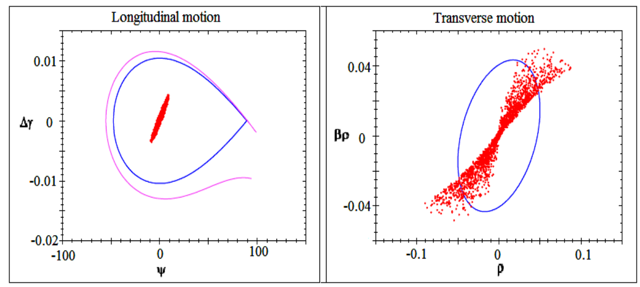

Figure 8: Longitudinal and transverse phase spaces in the fourth part with energy 200 MeV after phase varying.

Table 3: Beam output Energy Variation with 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

CONCLUSION

Results of beam dynamics simulation in SC proton linac for medical applications are presented. Linac parameters were defined by bumerical simulation. The linac should consist of four parts having geometric velocity of cavities and the total linac length will equal 61.6 m. Two methods of the energy variation with beam quality preservation was studied. Results of beam output energy variation was discussed.

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