THE BEAM ENVELOPE CONTROL IN SC LINAC FOR THE PROTON RADIOTHERAPY

I.A. Ashanin, S.M. Polozov, A.V. Samoshin, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Moscow, Russia

Abstract

Proton cancer therapy is conventionally based on normal conducting synchrotrons and cyclotrons. The high electrical power consumption and especial devices necessary to energy variation are main problems of such facilities. Superconducting linacs based on short identical independently phased cavities have a seriously progress and it's development allow to propose their using for medical application. High accelerating gradient and small capacity losses nearly 10^{-4} W/m are main advantages in advance of normal conducting facilities, the energy variation can be realized by means of RF field amplitude and phase variation in a number of cavities. Besides linac structures are lack of unwieldy magnetic system, simplicity of input and output of particles and high current densities.

The parameters choose and the optimization for SC linac structure with energy up to 240 MeV and envelope control will discuss in this paper. The simulation was done using BEAMDULAC-SCL code [1]. The study of beam dynamics will direct to realize the energy variation in range 150-240 MeV with beam quality preservation.

INTRODUCTION

There are some conventional parameters of the facilities for the proton cancer therapy: the energy of the beam about 240 MeV with the possibility of the wide regulation, possibility of control of beam envelope up to 6 mm and intensity of the beam at about 10^9 particles per second.

The proton beam usually receives using proton synchrotrons or cyclotrons [2]. But it can be also received in a linac. The main limitation till recent times was a low acceleration rate that provides to the high length of accelerator. Nowadays progress in SC linacs development allows solving this problem. SC linacs have some significantly preferences. It's a very high rate of energy gain for the period of the structure that allows reducing of the facilities length and low requirement in RF power feeding. In addition power-intensive magnets are not necessary. And 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).

A proton linac based on SC independently phased cavities up to energy 240 MeV is an possible variant for medical application [3].

Beam focusing can be provided with help of SC solenoids following each cavity or with help of RF focusing [4]. Using a solenoid into focusing period will allow the separate control of the transverse and longitudinal beam dynamics.

Beam dynamics and beam envelope control in such structure will be discussed in this paper. The methods of energy variation in range 150-240 MeV will discuss.

STRUCTURE CHARACTERISTICS

With a large number of resonators it is advisable to divide them into several groups, consists of geometry identical resonators. Certainly, in this accelerating system will always violate the synchronism principle, when the synchronous particle velocity equal to the phase velocity of the accelerating wave during acceleration. A slipping of the particles relative to the accelerating wave is in evidence. The slipping value must not exceed acceptable value if not the acceleration rate will rapidly reduced and beam longitudinal stability worse. The number of resonators should be limited and the number of groups should be minimal [5].

So in this study the phase slipping factor was limited by 18%. Accordingly 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 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. Therefore 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). Values of length of solenoid were assigned 0.2 m and length of gap 0.1 m at the all accelerator length.

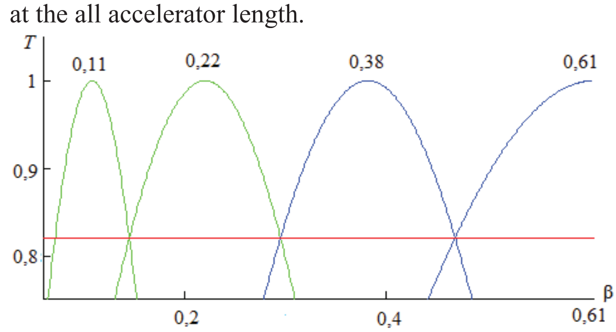

Figure 1: Slipping factor value depending on β.

TRANSVERSE MOTION STABILITY ANALYSIS AND BEAM ENVELOPE CONTROL

Transverse motion stability and beam dynamics analysis results for the first part having the beam energy range from 2.4 to 10.4 MeV will considered bellow. The accelerating field for each cavity is equal 3.21 MV/m, the

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cavity length 0.184 m, the particle phase into RF field -25°, frequency f = 176 MHz.

It is important to consider RF field's influence to transverse motion of a bunch in accelerating system. With knowing of the matrix period for longitudinal and transverse motions, it is simple to find Floke parameters μ_z and μ_r and stability conditions of longitudinal and transverse particle motion. It's necessary to change the value of a magnetic field with increase of the particle velocity. Value μ_r and border of area of stability of transverse motion depends on a choice of the amplitude value and a phase of RF field. It is easy to find the minimum value of magnetic field setting a value μ_r = 0. Minimal magnetic field needs for beam transverse motion stability with chosen parameters is equal 1.25 T (see Fig. 2.)

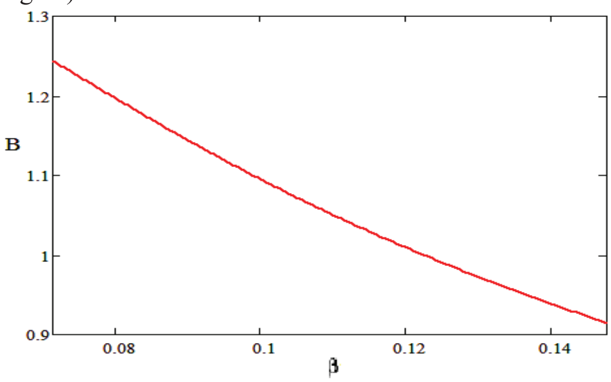

Figure 2: Magnetic field B depending on β.

Figure 3 shows that the phase advance of the longitudinal and transverse oscillations with the chosen accelerator parameters are not close to each other, which will not lead to a coupling resonance. Therefore beam motion will be stable.

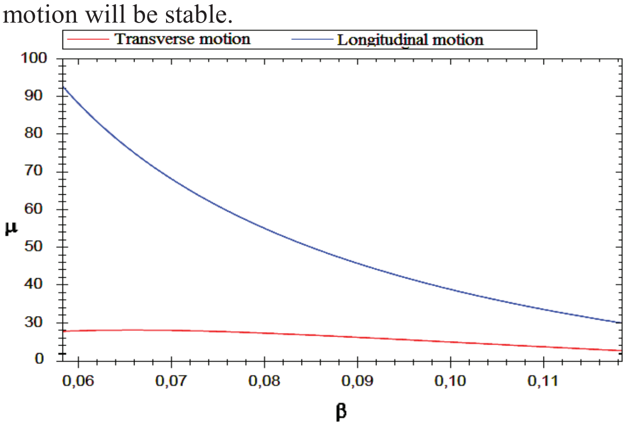

Figure 3: Longitudinal and transverse Floke parameters in the first part.

The final choice of necessary value of the magnetic field can be made when the maximum beam envelope size is set. If the beam envelope size will be high it is appear to strong couple between longitudinal and transverse motion that sharply worsens a quality of the bunch at the accelerator output. In our case this value X_m = 5 mm as one of the conventional parameters of the proton cancer therapy facilities and it will be set at all accelerator length.

The chosen value of the magnetic field 1.25 T makes it possible to limit the beam envelope value X_m by 5 mm. It's shown in the Fig. 4.

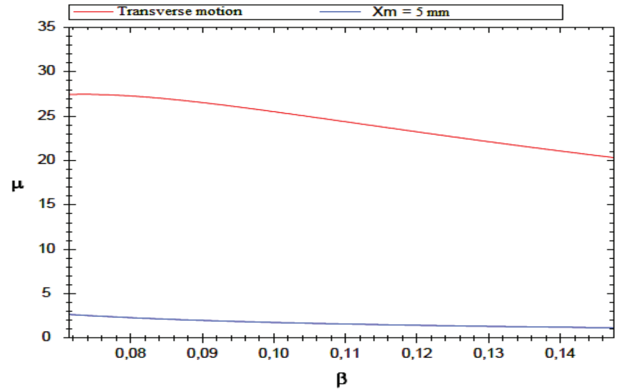

Figure 4: Transverse Floke parameter μ_r depending on β with envelope value X_m = 5 mm in the first part.

The cavities in the last group have the beam energy range from 123.2 to 240 MeV. The accelerating field 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 702 MHz.

Magnetic field which is need for beam stable motion is equal 3 T. This value is more than in the first section twice, but it is provide the beam stable motion in the bigger energy range.

As well as in the case described above Figures 5, 6 show that with the chosen accelerator parameters the beam motion is stable and it is possible to keep a set beam envelope value.

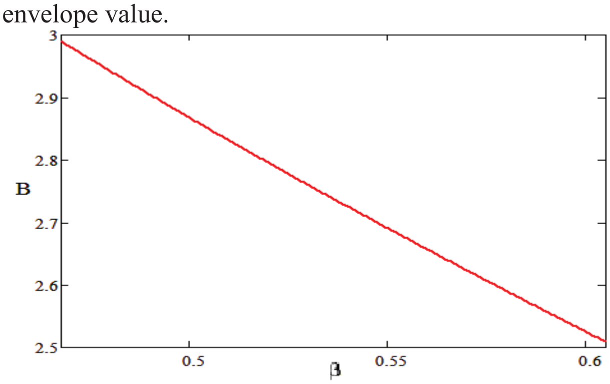

Figure 5: Magnetic field B depending on β.

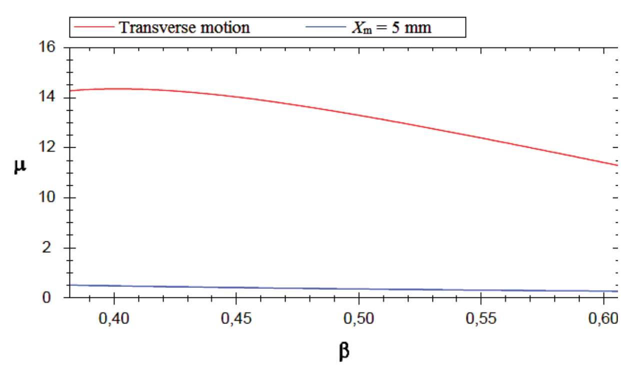

Figure 6: Transverse Floke parameter μ_r depending on β with envelope value X_m = 5 mm in the fourth part.

Parameters of all cavity's groups optimized by the same principle are presented in the Table 1. Note that as a result за beam dynamics simulation the current transmission coefficient is equal 100 % in every section due to the optimal choose of accelerator parameters [6].

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*)
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, º	-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
Number of periods, N_{per}	16	18	22	24
Length, *L*, m	9.344	13.932	19.514	18.864

OUTPUT ENERGY VARIATION

Two methods of energy variation are considered below. The first method concluded in variation of a number of the powered resonators (deeply variation). The second method concluded in changing of RF field phase in a number of last resonators (slowly variation).

Beam transverse motion stability analysis 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 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). Figures 7, 8 shows that with the chosen accelerator parameters the beam motion is stable and it is possible to keep a set beam envelope value.

By the similar way beam transverse motion stability analysis in the last 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 was done. Beam motion stability and beam envelope control was achieved.

The beam longitudinal phase volume decrease negligible and transverse emittance changes insignificantly and we can establish that the beam quality preservation with energy variation can be achieved with correct accelerating system tuning. Other results relating to these methods of energy variation was discussed in [6].

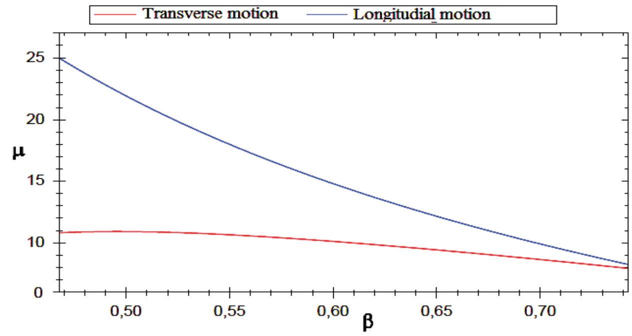

Figure 7: Longitudinal and transverse Floke parameters in case of deeply energy variation.

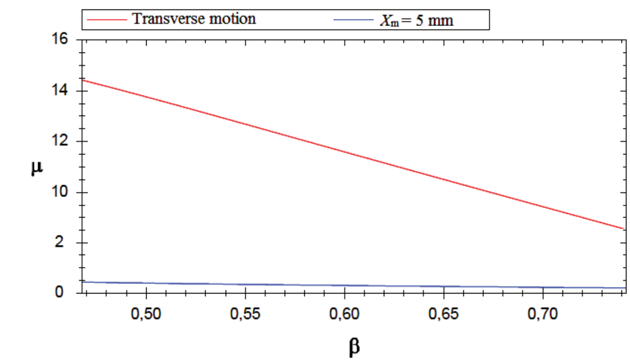

Figure 8: Transverse Floke parameter μ_r depending on β with envelope value X_m = 5 mm in case of deeply energy variation.

Transmission efficiency in these two cases still is equal 100% that completely satisfies set by us purposes.

CONCLUSION

Results of the optimization for SC linac structure with energy up to 240 MeV and envelope control are presented. Linac parameters were defined by numerical simulation. Two methods of the energy variation with beam quality preservation were proposed. Results of the beam envelope control and output energy variation was discussed.

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