DEVELOPMENT OF PROTON THERAPY AT THE SC LINAC WITH BEAMDULAC-SCL CODE

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Abstract

Proton cancer therapy complexes are conventionally developing based on synchrotrons and cyclotrons. High electrical power consumption and especial devices necessary to energy variation (as slow extraction systems and degraders) are the main problems of such complexes. At once SC linacs based on short independently phased cavities have a serious progress at present. Linear accelerator consumes less power comparably with cyclic and the energy variation can be easily realized by means of RF field amplitude and phase variation in a number of cavities. The accelerator's modular configuration which is now widely used in FRIB's or SNS's can be applied for therapy linac also. It is possible to choose the SC linac parameters and to do the proton and ion beams stability study with help of the BEAMDULAC-SCL code. This software also allows providing of the structure optimization and the beam dynamics control.

INTRODUCTION

Development of a simple in operation and cost-effective cancer treatment proton accelerator is very important now. Normal conducting cyclotrons and synchrotrons are conventionally uses for treatment. A number of comparatively compact SC synchrocyclotrons are under development. But 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 by 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 number of cancer therapy linacs projects as TOP [1], LIBO [2], TOP-IMPLART [3] are under R&D at present. The novel CYCLINAC concept combines compact low energy cyclotron and short linac is also discussed [4].

Contemporary SC linac technologies are used for development of spoliation neutron sources (SNS) and facilities for radioactive ion beams (FRIB). High-gradient quarter- and half-wave, elliptical and side-coupled cavities are used for beam acceleration and SC solenoids of quadrupoles for transverse focusing. The average rate of energy gain in SNS linac is about 4 MeV/m for example. It can be proposed that 200 MeV low intensity linac can be compact that 50 m.

The optimization of linac structure will done in this paper using BEAMDULAC-SCL code with was developed for heavy ion beam dynamics simulation in FRIB's. The possibility of permanent magnet using for transverse beam focusing will discussed, the limit gradient for different energy ranges will defined. The beam quality (beam envelope control in main) preservation is one of the main goals.

PERIOD LAYOUT

Let's we consider the linear accelerator, consisting of independently phased cavities and solenoids sequence first (fig. 1).

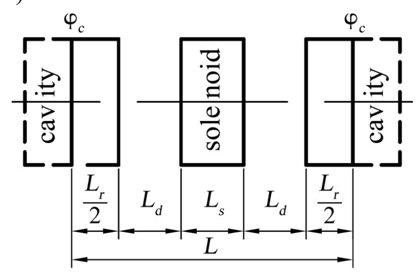

Figure 1: Layout of structure period.

For low-velocity ion beams the quarter- and half-wave resonators with few amounts of gaps are commonly used as accelerating structures. If SC resonators are used they should be the same, otherwise the cost of facility rapidly increase. This means that the phase velocity of the wave should be constant in each cavity. With a large number of resonators is economically advantageous to divide them into several groups, consists of identical resonators. Obviously, in this acceleration system will always violate the principle of synchronicity, when the synchronous particle velocity equal to the phase velocity of the accelerating wave at any time. I.e. in this case, appear a slipping of the particles relative to the accelerating wave. The slipping value must not exceed acceptable value, if not acceleration rate and rapidly reduced and beam longitudinal and transverse stability worse, and the transmission coefficient decreases. Therefore the number of identical resonators should be limited, and the number of groups consisting of identical geometry should be minimal.

Ions are accelerated and slipping relative to the RF field in dependence of the ratio between the particle velocity β and the phase velocity of the wave in cavity β_G.

The beam motion can be both longitudinally stable and accelerated in the whole system by control the driven phase of the accelerating structure and the distance between the cavities [5]. The beam focusing can be provided by solenoids or permanent magnet lenses (PML) which follow each of the cavity [6].

The conditions of longitudinal and transverse beam stability for the structure consisting from the periodic

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sequence of cavities and solenoids were studied early using transfer matrix calculation [7]. It is very important to know the bucket size since it relates to the longitudinal RF focusing in SC linac design. The smooth approximation can be used in order to investigate the nonlinear ion beam dynamics in such accelerating structures and to calculate the longitudinal and transverse acceptances [7].

The results of self-consistent beam dynamics investigation in accelerating structures by means of BEAMDULAC-SCL code are discussed in this paper. The BEAMDULAC code is developing in MEPhI since 1999 for high current beam dynamics simulation in linear accelerators and transport channels.

SOLENOID FOCUSING

If we require that the slipping factor value does not exceed 20%, the accelerator should be divided into three parts with βg = 0.18, 0.3 and 0.5 respectively (see fig. 2).

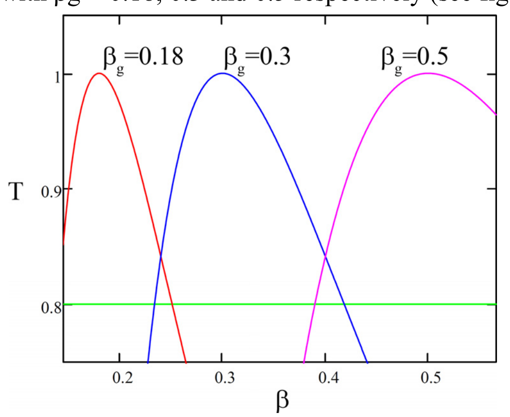

Figure 2: Slipping factor value.

Parameters of each part are given in Table 1. To reduce the paper size we present beam dynamics analysis results only for the last part having the beam energy range from 82 MeV to 200 MeV. The field strengthfor each cavity is equal 4 MV/m, the cavity length 2 m, the particle phase into RF field -20º, frequency f = 150 MHz. Figure 3 shows that with the chosen accelerator parameters the phase advance of the longitudinal and transverse oscillations are not close to each other, which will not lead to a coupling resonance, so beam motion will be stable. Note that the chosen value of the magnetic field makes it possible to keep the beam envelope lower than 3 mm.

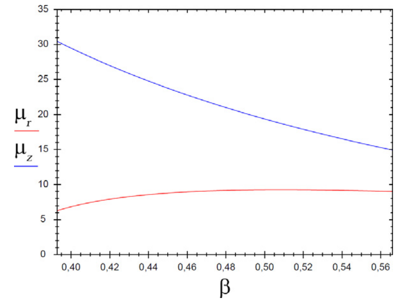

Figure 3: Longitudinal and transverse Floke parameters.

Figure 4 shows the separatrix size (maximum energy spread, red curve), the phase size (blue curve) and the separatrix area (green curve). We can see that the acceptance increases with the chosen parameters of the accelerator.

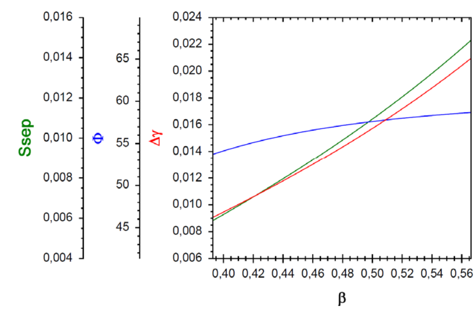

Figure 4: Separatrix dimension during acceleration.

Beam dynamics in the real field were carried out basing on the chosen parameters. The simulation results are shown in the Figure 5. The transmission efficiency is equal 92%.

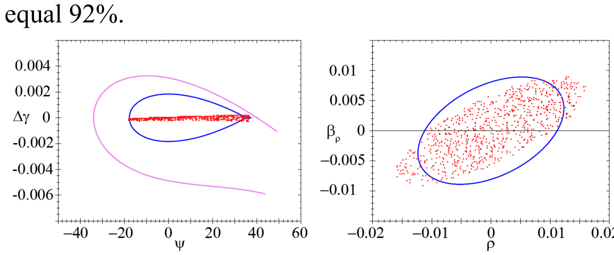

Figure 5: Longitudinal and transverse phase space.

With help of BEAMDULAC-SCL code, the number of periods of the accelerating structure can be defined, and therefore the total length of the accelerator. The total length of the accelerator, which consists of three sections, will be equal 46.72 m (see Table 1).

Table 1: The Accelerator Parameters with Solenoid Focusing

	W_{in}, MeV	W_{out}, MeV	β_g	L_{res}, m	E, MV/m	L_{sol}, m	B, T	N_{per}
1 range	10	28	0.18	0.72	4	0.2	1.5	6
2 range	28	82	0.3	1.2	4	0.2	1.5	10
3 range	82	200	0.5	2	4	0.2	1.5	10

APF AND SOLENOID FOCUSING

By using of an additional alternating phase focusing (APF) we can reduce the value of the magnetic field necessary for transverse focusing. In this case the period will consist of two cavities and one solenoid. If the entry phase of cavities are differs by the sign but are equal by value, the longitudinal stability region is small, therefore we choose $\varphi_1 = -25$ ° and $\varphi_2 = 20$ ° (in Figure 6 this value is represent as x). Note that the absolute value of negative phase must be greater than positive, otherwise the beam stability worse.

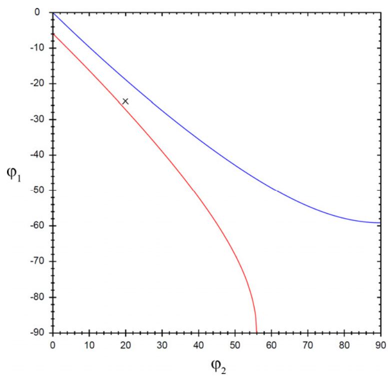

Figure 6: Stability diagram in terms of (φ_1,φ_2).

Chosen parameters of the accelerator are shown in Table 2. Other linac parameters are the same as in the previous case. Figure 7 shows that with the chosen parameters stability is keeping.

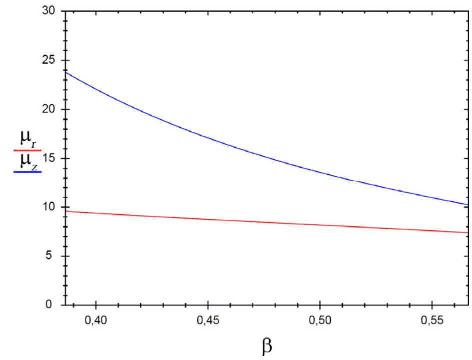

Figure 7: Longitudinal and transverse Floke parameters.

As in the previous case we consider the variation of separatrix size. In this case, the acceptance is much smaller than in the previous case (see Fig. 5 and Fig. 8), but also growing. Separatrix size can be increased by tuning the entry phase into neighboring cavities, but in this case we shift to higher phases area, which reduces the acceleration rate.

Table 2: The Accelerator Parameters with Solenoid Focusing

	W_{in}, MeV	W_{out}, MeV	β_g	L_{res}, m	E, MV/m	L_{sol}, m	B, T	N_{per}
1 range	10	27	0.18	0.72	4	0.2	0.6	3
2 range	27	79	0.3	1.2	4	0.2	0.7	5
3 range	79	200	0.5	2	4	0.2	0.8	5

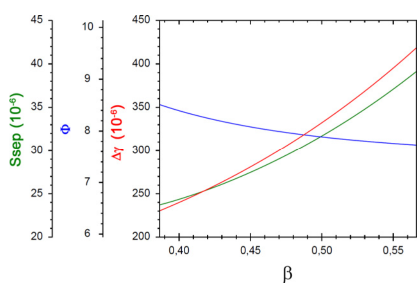

Figure 8: Separatrix size during acceleration.

The beam dynamics numerical simulation results in the real field are shown in Figure 9. The total length of the accelerator in this case is equal 42.82 m which is smaller than in previous case.

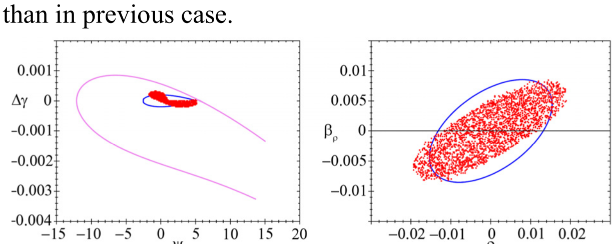

Figure 9: Longitudinal and transverse phase space.

CONCLUSION

A complex analysis of the proton beam dynamics stability was done with the help of especially designed BEAMDULAC-SCL code. The analysis shows that it is possible to develop a proton treatment linear accelerator with length less than 50 m and necessary for transverse focusing magnetic field will less than 1 T. Beam envelope control is possible this case. Optimal choosing linac parameters are shown in Tables 1 and 2.

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