DESIGN FEATURES OF HIGH-INTENSITY MEDIUM-ENERGY SUPERCONDUCTING HEAVY-ION LINAC *

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Abstract

The proposed Rare Isotope Accelerator (RIA) requires the construction of a cw 1.4 GV superconducting (SC) linac that is capable of producing 400 kW beams of all ions from protons at 900 MeV to uranium at 400 MeV/u. The design of such a linac was outlined at the previous Linac conference. This linac will accelerate multiple-charge-states (multi-q) of the heaviest ion beams, for which the beam current is limited by ion-source performance. The linac consists of two different types of accelerating and focusing lattice: for uranium below ~85 MeV/u the focusing is provided by SC solenoids installed in cryostats with the SC resonators while in the high-beta section the focusing elements are located outside of the cryostats. A detailed design has been developed for the focusing-accelerating lattice of the linac. Beam dynamics studies have been performed with the goal of optimization of the linac structure in order to reduce a possible effective emittance growth of the multi-q uranium beam. A wide tuning range of the accelerating and focusing fields is required for acceleration of the variety of ions with different charge-to-mass ratios to the highest possible energy in single charge state mode. The focusing must be retuned for different ion masses to avoid resonance coupling between the transverse and longitudinal motions. Any visible impact of this coupling on the formation of beam halo must be avoided due to the high beam power.

1 DESIGN CRITERIA FOR FOCUSING LATTICES IN SC LINACS

In SC linacs focusing elements alternate with accelerating cavities. A medium energy ~ 1 GV SC linac consists of several types of superconducting cavities. For example, 99.5% of the RIA driver linac voltage is covered by seven different types of SC resonators [1]. In the design of the periodic focusing lattice of the SC linac several important issues should be taken into account. Standard criteria such as stability of the transverse motion and maximum possible acceptance certainly should be applied. In SC linacs, due to the high accelerating gradients available from SC cavities and the relatively long focusing periods, strong interactions between transverse and longitudinal motion may occur. Long focusing periods containing several cavities per period may decrease the cost of the accelerator. However, in some lattice designs, the transverse-longitudinal coupling can excite parametric resonance of transverse oscillations.

The condition for an n-th order parametric resonances of transverse motion is

$$\mu_t = \frac{n}{2}\mu_l \qquad (1)$$

where μ_t and μ_l are the phase advances of the transverse and longitudinal oscillations per focusing period. The analysis of parametric resonances is usually done in a smooth approximation of the equation of motions [2] written in the unitless variable $d\tau = \frac{\beta c}{S_f} dt$, where c is the speed of light, β is the particle relative velocity and S_f is the length of the focusing period. What follows is consistent with this theory. The accelerating field is represented as an equivalent travelling wave with positive stable equilibrium phase. For a given n, the resonance width is determined by

$$a_n \Delta_s < \mu_t^2 < b_n \Delta_s \ , \qquad (2)$$

where a_n and b_n are the boundaries of the stability region in the solution of Mathieu's equation, the defocusing factor Δ_S is given by the expression:

$$\Delta_s = \frac{\pi}{2}\frac{q}{A}\frac{1}{(\beta_s\gamma_s)^3}\frac{S_f^2}{\lambda}\frac{eE_m \sin\varphi_s}{m_u c^2} \ , \qquad (3)$$

where q is the ion charge state, A is the mass number, e is the elementary charge, m_u is the atomic mass unit, γ is the relativistic factor, λ is the wavelength of rf field and E_m is the amplitude of the equivalent travelling wave of the accelerating field. If we assume that the amplitude of the longitudinal phase oscillations Φ to be equal to the equilibrium phase angle $\Phi = \varphi_s$, then for $n=1$ and φ_s=30° one can obtain $a_1 \approx 0$, $b_1 \approx 1.79$ [3]. For $n=2$ these values are $a_2 \approx 3.93$, $b_2 \approx 4.31$. The subscript s denotes the equilibrium particle. The longitudinal phase advance per focusing period is approximated by $\mu_l = 2\sqrt{\Delta_s}$.

The focusing structure of the linac can be considered as a periodic structure of the linac containing a given type of SC resonator. Irregularities in the periodic structure due to the inter-cryostat drift spaces can be compensated by the absence of the first SRF cavity in the very first focusing period of the cryostats [4]. Table 1 shows the accelerating-focusing structure of the RIA driver linac. In the table, N_R is the number of SC resonators per focusing period and β_G is the geometrical beta of the cavity. The linac consists of two main parts: the low-frequency section containing drift tube SC cavities (DTL) and the 805 MHz section comprising elliptical cavities (ECL). The amplitude of the equivalent travelling wave of the accelerating field E_m varies significantly along the linac due to the many different types of SC resonators. The

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Table 1: Linac Structure

	f (MHz)	N_R	β_G	S_f *(m)*	**Type of focusing**
1	57.5	2	0.061	1.13	Solenoid
2	115	3	0.15	1.77	Solenoid
3	172.5	3	0.25	1.73	Solenoid
4	345	4	0.39	2.60	Solenoid
5	805	4	0.49	5.34	Doublet
6	805	4	0.61	5.84	Doublet
7	805	4	0.81	7.89	Doublet

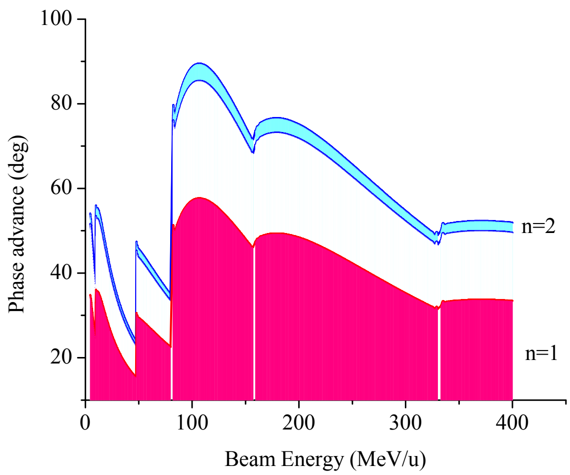

Figure 1:Unstable regions (shaded areas) of the transverse phase advance due to first and second order parametric resonances as a function of uranium beam energy.

typical range of the average field E_m in the RIA driver linac is 1.5-5.0 MV/m. The parameters E_m , S_f , q/A in (2and (3) are strong functions of the beam energy. Figure 1 shows the boundary values $\sqrt{a_n \Delta_s}$ and $\sqrt{b_n \Delta_s}$ *(n=1,2)* of the transverse phase advance μ_t along the linac calculated according the expression (2). If μ_t lies between these boundary values a parametric resonance can be excited.

In general, the phase advance per focusing period of transverse oscillations is optimised to provide the highest acceptance. For many periodic structures this condition occurs at $\mu_t \approx 65°$-80°. The increase of μ_t above this value is inexpedient due to the growth of the beam envelope modulation factor which results in less transverse acceptance. In addition, the focusing structure becomes more sensitive to errors and misalignments for large values of μ_t. As can be seen in Fig. 1 the highest tolerable value of μ_t occurs in the first section of the ECL. In the baseline design of the RIA driver linac this section contains four 6-cell, β_G=0.49 cavities per focusing period. However, as already mentioned in ref. [4] a focusing period containing three 6-cell cavities is preferable. In this case, the boundary values of the transverse phase advance in Fig. 1 drop to values similar to those in the second section of the ECL.

Similar analysis of the resonance boundaries for the phase advance has been carried out for lighter ions beginning from proton beams. In all cases the phase advance required to avoid parametric resonances are lower than for the uranium beam.

2 NUMERCAL SIMULATIONS

The above mentioned results were obtained from linear theory of particle motion. One can expect wider areas of unstable motion in numerical simulations. Extensive numerical simulations have been conducted in order to study the stability of transverse motion in the RIA driver linac for different focusing periods and transverse phase advances.

For these simulations we use the code TRACK which integrates particle motion in 3D electromagnetic fields [5]. The overall linac design is similar to the SC linac described in ref. [4]. The first simulation starts with a 9.2 MeV/u uranium beam with the longitudinal emittance 30 π keV/u-nsec taken intentionally to be 3 times larger than the expected emittance [4]. Note that even this large emittance is well below the longitudinal acceptance of this linac section. The transverse phase advances and required focusing fields have been calculated both by applying first-order matrix formalism and with the code TRACE [5]. In TRACE the transverse phase advance was obtained without the beam rotations in the solenoids. In TRACK, however, the realistic fields of the solenoids were included. As expected from the diagram in Fig. 1 the transverse motion is unstable for μ_t=30° in the beginning of 172.5 MHz section of the linac. In this case the resonance is strong and the energy of longitudinal oscillations transforms to transverse oscillations as is seen from the rms emittance behaviour in Fig. 2. The growth of the emittance containing 99.9 % of the particles along the

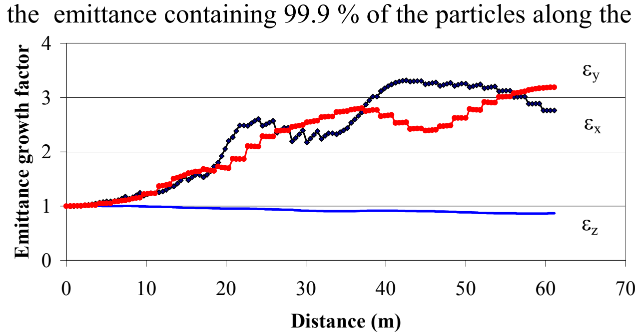

Figure 2: Rms emittance evolution along the 172.5 MHz section of the linac, μ_t=30°.

172.5 MHz section of the DTL for three values of the phase advance is shown in Fig. 3. For stronger focusing, μ_t=40° and 50°, the emittance growth is completely suppressed.

Beam dynamics in the first section of the ECL we also simulated. In these simulations, a longitudinal emittance is 60 π keV/u-nsec of the 81MeV/u uranium beam, two times larger than the expected emittance [4]. Figure 4 shows the growth of the vertical emittance containing 99.9% of the particles in the first section of the ECL for 3 different values of μ_t=70°, 80° and 90°. The particles motion is completely unstable for the phase advance less than 70°. The diagram in Fig. 1 does not indicate instability at μ_t=70°. In addition, the Smith-Gluckstern stability diagram shown in Fig. 5 also does not predict

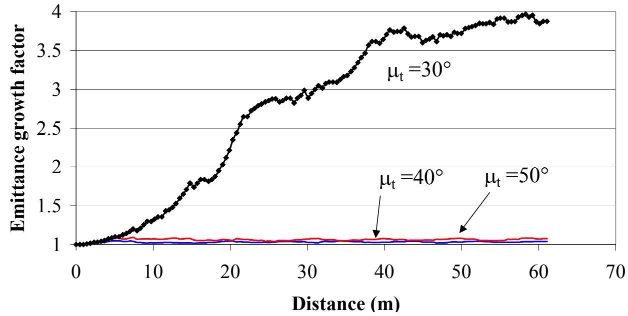

Figure 3: The 99.9% emittance growth along the 172.5 MHz section of the linac. The parameter is the transverse phase advance per period.

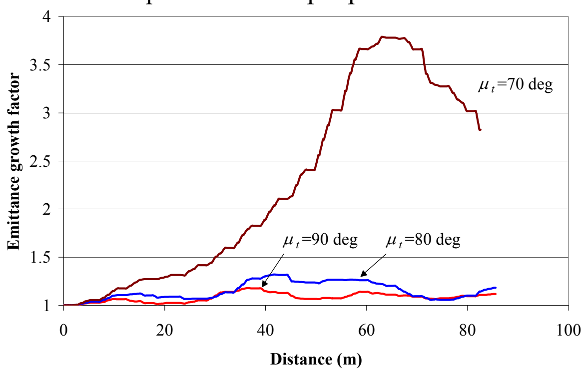

Figure 4: The 99.9% emittance-growth factor in the vertical plane along the first section of the ECL. The parameter is the transverse phase advance per period.

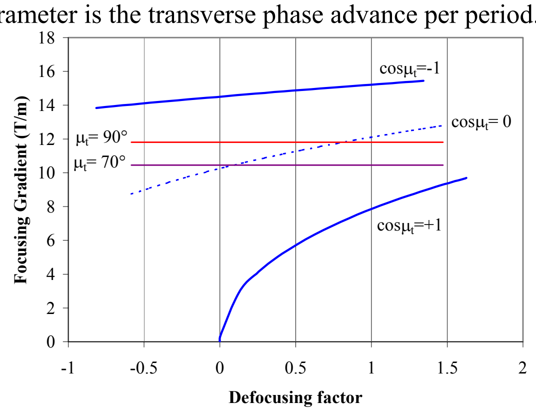

Figure 5. Smith-Gluckstern stability diagram calculated for uranium beam energy 120 MeV/u in the first section of the ECL. The two horizontal lines represent the working regime for maximum possible longitudinal oscillations within the separatrix $-\varphi_s < \varphi < 2\varphi_s$.

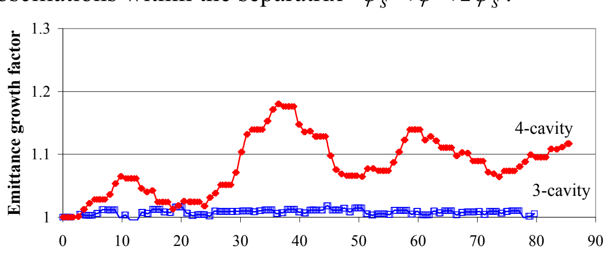

Figure 6: The 99.9% emittance-growth factor in the vertical plane along the first section of the ECL, μ_t=90°.

instability for μ_t=70°. We can conclude that the resonance obtained through numerical simulations is wider then it is given by expression (2). The minor emittance growth for the focusing channel with μ_t=80°-90° is associated with coupling of transverse and longitudinal oscillations near the parametric resonances [3,7]. Complete suppression of emittance growth in this energy range of the linac can be obtained in the focusing lattice with three SC elliptical cavities as seen in Fig. 6.

Similar analysis has been carried out for acceleration of lighter ions in the RIA driver linac. To avoid the conditions of the first and second order parametric resonances the phase advance should be higher than 50° in the DTL and higher than 80° in the ECL. These conditions are valid assuming maximum possible energy gain of non-uranium ions in the DTL.

3 SUMMARY

In the design of SC linacs parametric resonances in transverse motion must be identified and avoided. The transverse emittance growth of the beam is more pronounced for larger longitudinal emittances. The parametric resonance can result in the formation of beam halo in transverse phase space if appropriate measures are not applied.

In the RIA driver linac baseline design a transverse phase advance in the range 60°-80° is recommended for the DTL. A phase advance μ_t close to 90° is preferable in the ECL. The focusing period of the first section of the ECL must contain no more than 3 cavities. For all ions including uranium the above mentioned range of phase advances are suitable.

The results are valid for the selected lengths of the focusing periods of the RIA driver linac. Similar analysis techniques should be applied for different structures of the focusing period in SC linacs.

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