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 seven different types of SC resonators [1]. In the solution of Mathieu’s equation, the defocusing factor $A_s$ is given by the expression:

$$A_s = \frac{\pi}{2A} \frac{1}{\beta_{\gamma_s}} \frac{S^2}{\lambda} \frac{E_m \sin \varphi_s}{m_c c^2}, \tag{3}$$

where $q$ is the ion charge state, $A$ is the mass number, $e$ is the elementary charge, $m_i$ is the atomic mass unit, $\gamma$ is the relativistic factor, $\lambda$ 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 $\Phi$ is equal to the equilibrium phase angle $\Phi = \varphi_s$, then for $n=1$ and $\varphi_s = 30^\circ$ one can obtain $a_s \approx 0$, $b_s \approx 1.79$ [3]. For $n=2$ these values are $a_s \approx 3.93$, $b_s \approx 4.31$. The subscript $s$ denotes the equilibrium particle. The longitudinal phase advance per focusing period is approximated by $\mu_t = 2\sqrt{A_s} \sqrt{n} \beta_i$.

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, $N_s$ is the number of SC resonators per focusing period and $\beta_{\gamma_i}$ 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
Table 1: Linac Structure

<table>
<thead>
<tr>
<th>f (MHz)</th>
<th>n_s</th>
<th>( \beta_c )</th>
<th>S_1 (m)</th>
<th>Type of focusing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57.5</td>
<td>2</td>
<td>0.061</td>
<td>1.13</td>
</tr>
<tr>
<td>2</td>
<td>115</td>
<td>3</td>
<td>0.15</td>
<td>1.77</td>
</tr>
<tr>
<td>3</td>
<td>172.5</td>
<td>3</td>
<td>0.25</td>
<td>1.73</td>
</tr>
<tr>
<td>4</td>
<td>345</td>
<td>4</td>
<td>0.39</td>
<td>2.60</td>
</tr>
<tr>
<td>5</td>
<td>805</td>
<td>4</td>
<td>0.49</td>
<td>5.34</td>
</tr>
<tr>
<td>6</td>
<td>805</td>
<td>4</td>
<td>0.61</td>
<td>5.84</td>
</tr>
<tr>
<td>7</td>
<td>805</td>
<td>4</td>
<td>0.81</td>
<td>7.89</td>
</tr>
</tbody>
</table>

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

typical range of the average field \( E_n \) in the RIA driver linac is 1.5-5.0 MV/m. The parameters \( E_n, S_1, q/A \) in (2) and (3) are strong functions of the beam energy. Figure 1 shows the boundary values \( \sqrt{a_n \Delta \tau} \) and \( \sqrt{b_n \Delta \tau} \) of the transverse phase advance \( \mu \) along the linac calculated according the expression (2). If \( \mu \) 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 \( \mu=65^\circ-80^\circ \). The increase of \( \mu \) 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 \( \mu \). As can be seen in Fig. 1 the highest tolerable value of \( \mu \) occurs in the first section of the ECL. In the baseline design of the RIA driver linac this section contains four 6-cell, \( \beta_c=0.49 \) 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 NUMERICAL 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 \( \pi \) 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 \( \mu=30^\circ \) 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 172.5 MHz section of the DTL for three values of the phase advance is shown in Fig. 3. For stronger focusing, \( \mu=40^\circ \) 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 \( \pi \) 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 \( \mu=70^\circ, 80^\circ \) 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 $\mu_7=70^\circ$. In addition, the Smith-Gluckstern stability diagram shown in Fig. 5 also does not predict instability for $\mu_7=70^\circ$. 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 $\mu_7=80^\circ-90^\circ$ 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$^\circ$ in the DTL and higher than 80$^\circ$ 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$^\circ$-80$^\circ$ is recommended for the DTL. A phase advance $\mu_7$ close to 90$^\circ$ 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.

4 REFERENCES