ALTERNATING PHASE FOCUSING IN LOW-VELOCITY HEAVY-ION SUPERCONDUCTING LINAC*

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Abstract

The low-charge-state injector linac of the RIA post-accelerator (RIB) is based on ~ 60 independently phased SC resonators providing a total of ~70 MV accelerating potential. The low charge-state beams, however, require stronger transverse focusing, particularly at low velocities, than is used in existing SC ion linacs. For the charge-to-mass ratios considered here (q/A = 1/66) the proper focusing can be reached by using strong SC solenoid lenses with a field of up to 15 T. Both the number of the solenoids and field can be reduced applying Alternating Phase Focusing (APF). A method to set the rf field phases has been developed and studied both analytically [1] and with the help of the three-dimensional ray tracing code TRACK [2]. The paper discusses the results of these studies.

INTRODUCTION

The design goal for the RIB linac is to accelerate heavy ions up to 10 MeV/u and higher in the mass range from 6 to 240, starting with ions at charge state 1+ [3]. The initial section of the RIB linac is a low- charge-to-mass-ratio superconducting rf linac (SRF) which will accelerate any ion with q/A≥1/66 to at least ~1 MeV/u. The low-energy RIB linac will be based on 4-gap quarter wave SC cavities, which can provide typically ~1 MV of accelerating potential per cavity in the velocity range 0.011c<v<0.06c. The initial section of the linac consists of four classes of those cavities designed for different geometrical beta as listed in Table 1. The input beam is formed by upstream RFQs operating at room temperature. The initial normalized transverse emittance is $\varepsilon_T = 0.1\,\pi \cdot$ mm·mrad and the longitudinal emittance is $\varepsilon_L = 0.3\,\pi \cdot$ keV/u·nsec. The RIB linac described in this paper is designed using the 4-gap resonators designed for the RIA driver linac. These resonators, modified slightly to match the ATLAS operating frequency [3] are completely applicable for the RIB lianc.

REFERENCE DESIGN

As a reference design of the RIB linac we consider the focusing by high-field SC solenoids alternating with SC resonators. The main parameter which defines specifications to the focusing system is the defocusing factor which is significant due to the high accelerating field in the SC resonators and low velocity of ions.

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The phase advance per focusing period of the betatron oscillations μ is defined as

$$\mu^2 = \mu_0^2 + \alpha \sin\varphi\,, \qquad (1)$$

where $\alpha = \dfrac{\pi e q U L}{2 A m_e c^2 \lambda \beta^3 \gamma^3}$, μ_0 is the phase advance without any acceleration, α is the defocusing factor, φ is the particle phase with respect to the accelerating field crest in the resonator, eq and A are the charge and mass number of ion, L is the length of the focusing period, m_e is the atomic unit mass, c is the speed of light, λ is the wavelength of the rf field, β is the ion velocity in units of c. The formula (1) is valid for any particle phase with respect to the crest of the rf electric field in the cavity. There is a large phase slippage of the bunch in a SC resonator therefore it is convenient to introduce an effective phase φ_e which is measured with respect to the maximum energy gain phase angle in the resonator.

The transverse phase advance and average accelerating rate are inversely proportional to the length of the focusing period L. However the lowest possible value of L is limited by practically achievable focusing fields. Figure 1 shows transverse phase advance as a function of the solenoid field. The calculations have been performed for realistic field distributions both in the resonators and solenoids. The effective length of the solenoid is 280 mm,

Table 1: Resonators developed for the RIA driver linac.

Design beta of cavity	Frequency (MHz)	Maximum field (MV/m)	Voltage (MV)
0.017	57.5	20	0.82
0.024	57.5	20	1.07
0.031	57.5	20	1.25
0.061	57.5	20	1.35

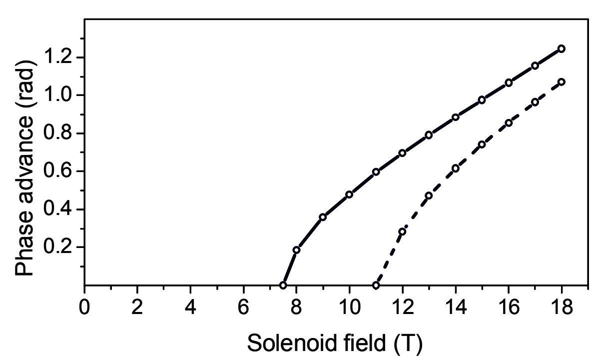

Figure 1: Transverse phase advance as a function of the solenoid field. The solid line corresponds to the bunch center and the dashed line - to the outermost particle phase.

L=700 mm and effective phase angle is φ_e=-20°. The solid line corresponds to the reference particle and the dashed line corresponds to the outermost particle in the longitudinal phase space with respect to the reference particle for the first period of the reference design. As is seen, a focusing field higher than 10 Tesla is required to provide stable motion of all particles in the bunch.

For the acceleration of heavy ions with q/A=1/66 from 75 keV/u to 1.0 MeV/u with effective phase angle -20°, the RIB linac requires a total of 63 resonators of four different types shown in Table 1. The constant average beam radius along the linac can be provided with average focusing field 14.7 T. The field varies along linac within ± 3% due to slightly different energy gain in the cavities. The full beam size does not exceed half of the aperture.

The cavities and solenoids will be distributed in seven cryostats with ~7 m length. The design of the cryostats is similar to those described in ref. [4]. There is a drift space between the cryostats [4] which the inter-cryostat distance 50 cm. Appropriate beam matching in both transverse and longitudinal phase space can be provided without any additional accelerating or focusing elements. However, careful tuning of the solenoids and resonator phases at each cryostat interface is required.

Beam dynamics simulations in the reference design of the RIB linac performed with the code TRACK [2] have shown that there is minor emittance growth along the structure as is seen from Fig. 2.

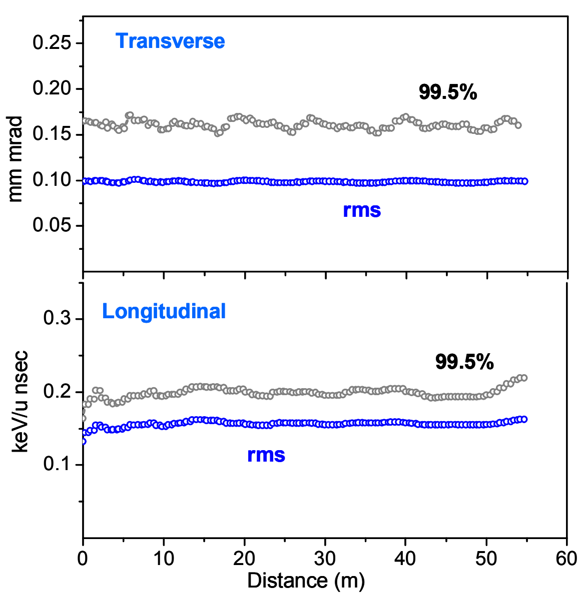

Figure 2: Emittance evolution along the baseline structure simulated by the TRACK code.

COMBINED FOCUSING STRUCTURE

The reference design completely meets the specifications for the RIB linac. However, it is achieved with a significant number of solenoids and the linac is long. As a result the real-estate accelerating gradient is ~30% of the gradient provided by the SC cavities. Also, very high-field SC solenoids are required. As was mentioned, above the required solenoid parameters are mostly defined by the high value of the defocusing factor α in the SC resonators. The strong defocusing can be converted to focusing by applying an alternating phase focusing (APF) [1]. As a result, the real-estate accelerating gradient can be increased. To create the APF, the effective phase must be alternated between positive and negative values. The analytical estimate has shown [1], that simultaneous stability of the transverse and longitudinal motion can be achieved despite significant phase slippage of up to 100^0 in an individual cavity. However to create a sufficient stability area, large values of the effective phases $|\varphi_e|$ in the cavities are required. The area of stability can be extended even for lower values of $|\varphi_e|$ by adding a focusing solenoid into the focusing period which will also allow separate control of transverse and longitudinal beam dynamics. The combined focusing structure (CFS) includes both SC solenoid and APF in every focusing period. Figure 3 shows phase advances in the CFS for two phase settings: 1) (φ_{e1}=-20^0, φ_{e2}=0^0) and 2) (φ_{e1}=-30^0, φ_{e2}=10^0). As is seen the phase advance in the CFS can be similar to those in the reference design. Unlike in the reference design, the focusing fields in solenoids are appreciably lower. The frequency of small longitudinal oscillations is similar to the reference design case but the real-estate accelerating gradient is higher because the focusing period consists of two or more resonators.

Figure 4 presents transverse beam envelopes along the first two cryomodules of the CFS simulated by the TRACK code. In the second cryomodule, the number of resonators per focusing period is increased up to three and four which is necessary to provide sufficient focusing while the parameter α drops as the ion energy increases. In the CFS shown in Figure 5, the average absolute value of the effective phase is equal to 20° as in the reference design while the required number of SC solenoids is significantly lower. In addition, the solenoid field is lower. The beam matching between the cryomodules is provided by appropriate adjustment of the effective phases in the outermost resonators and solenoid fields. As

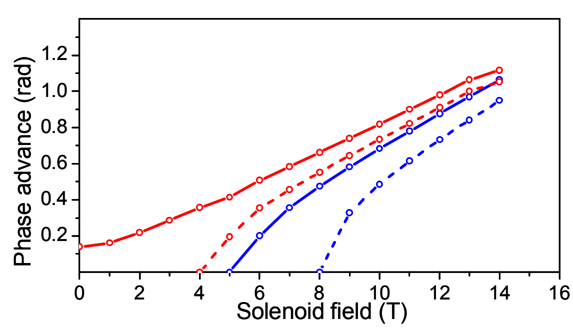

Figure 3: Transverse phase advance as a function of the solenoid field in the CFS. The blue lines correspond to the case (φ_1=-20^0, φ_2=0); the red lines are for the case (φ_1=-30^0, φ_2=-10^0). The solid line corresponds to the bunch center and the dashed line - to the outermost particle phase.

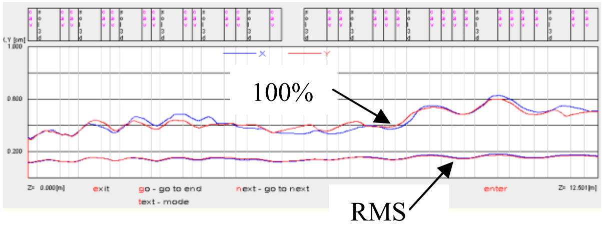

Figure 4: Transverse beam envelopes in first two cryomodules of the CFS.

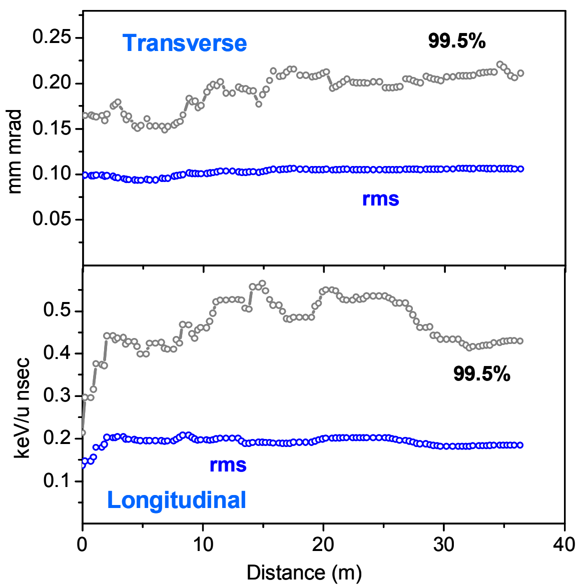

Figure 5: Emittances along the baseline structure simulated by TRACK code. Blue lines – rms, gray – for 99.5% simulated particles.

is seen from Fig. 3 the inter-cryostat transition does not disturb the beam envelope.

The disadvantage of the CFS is in strong coupling of the transverse and longitudinal degrees of ion motion. Figure 5 shows an evolution of transverse and longitudinal emittances in the CFS. As in the reference design there is no transverse emittance growth while the longitudinal rms emittance growth is 35% and emittance containing 99.5% of particles increases even more. The longitudinal emittance growth is a consequence of the electric field dependence from the radial coordinate in the low-velocity accelerating structures. This effect takes place in the first several resonators and can be minimized by lowering accelerating gradient or re-arranging the focusing period. Some additional studies are required to minimize the longitudinal emittance growth in the CFS.

COMPARISON OF TWO OPTIONS

The main parameters of two different lattices of the RIB linac, one based solely on high-field solenoid focusing and the other based on combined focusing by solenoids and APF are shown in Table 2. As is seen, the CFS allows reduction of the number of solenoids more than 50% and reduces the real-estate length of the linac. In addition the required solenoid fields are lower. A significant saving in the total cost of the accelerator is expected.

Table 2: Comparison of the main parameters of the reference and combined focusing structure.

Parameter	Reference design	Combined focusing
Average phase, deg	-20	-20
Number of resonators	63	73
Number of solenoids	69	27
Number of cryomodules	7	6
Average length of the cryomodule, m	7	5.5
Total length, m	54.7	36
Average real-estate accelerating gradient, MV/m	1.06	1.67
Solenoid field, T	15.0 – 13.5	14.0 – 12.0
Transverse phase advance	0.866 – 0.323	1.083 – 0.357
Longitudinal phase advance	1.00 – 0.245	0.549 – 0.256
Transverse rms emittance growth	< 1%	8%
Longitudinal rms emittance growth	22%	35%

CONCLUSION

Two options of the RIB linac section for acceleration of heavy ions with charge-to-mass ratio 1/66 have been studied: the reference design with periodic solenoid focusing and a combined focusing structure (CFS) with solenoids and APF. The CFS has obvious advantages compared to the reference design and can significantly reduce the cost of the RIB linac. However, additional studies to minimize longitudinal emittance growth in the CFS are necessary.

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