BEAM DYNAMICS OPTIMIZATION IN THE RARE ISOTOPE ACCELERATOR DRIVER LINAC*

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Abstract

A preliminary design of the superconducting linear accelerator of the Rare Isotope Accelerator (RIA) facility has been previously reported. The driver linac consists of about 400 superconducting independently-phased rf cavities, and is able to accelerate beams of any ion, including uranium, to energies of 400 MeV per nucleon and beam power of 400 kW. The linac has the novel capability of accelerating multiple-charge-state beams, which results in a significant increase in available beam current. Use of multiple-charge states imposes strict requirements on the steering procedure to avoid effective emittance growth. A program of detailed beam dynamics studies has been initiated to simplify the accelerator design, enhance its performance, and develop specifications for the engineering design of the accelerator systems. As part of the program, a correction algorithm has been developed that takes into consideration solenoid induced couplings. The correction method and initial results of corrections applied to the low- and medium-energy driver linac sections are presented.

TRANSVERSE EMITTANCE GROWTH

The effective transverse emittance of a multiple-charge-state beam oscillates along the linac due to the small mismatch in the focusing properties of each beam [1]. In the RIA driver linac the multi-charge beam emittance is well within the lattice aperture and the lattice is designed to preserve the beam quality. However, misalignments of SC resonators and focusing elements, passage through the strippers, and non-linear terms in the transport elements, can be sources of effective transverse emittance growth. In particular, misalignments of focusing components induce different deflections on beam particles of different energies or charge states, causing dilution of the transverse emittance. In addition, large trajectory excursions may lead to beam loss. In the RIA project, losses are to be limited to a factor of 10^{-4}. An effective trajectory-correction mechanism needs to reduce the emittance growth and limit the trajectory oscillations. We present a correction algorithm and initial results of its application to the low- and medium-β sections of the driver linac. Our algorithm is based on the dispersion-free correction technique developed by Raubenheimer and Ruth, whereby trajectory information from two or more different focusing configurations is used to correct lattice component misalignments [2]. Specifically, the trajectory for a given magnet setting is measured, and then the trajectory is measured again, for a different magnet setting. The difference trajectory is less dependent on beam position monitor (BPM) misalignments. The method consists of establishing a goal function that minimizes the trajectory. As shown in [2], the method is more effective in reducing the emittance than attempting to zero the trajectory at the BPMs in a "one-to-one" correction.

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CORRECTION ALGORITHM

Particle trajectories near the design trajectory can be described by transport matrices that map the particle initial phase-space coordinates at s_0 to its coordinates at a point s along the linac. A similar mapping can be defined for the centroid of a beam of non-zero emittance, which describes the beam central trajectory. To correct the trajectory one applies additional deflections induced by dipole correctors. In the low- and medium–β sections of the RIA driver linac focusing is provided by SC solenoids that rotate the beam and couple the horizontal and vertical beam motion. In this case, one needs to take the full transverse transport matrix into account. Considering only displacements of solenoids, the centroid horizontal coordinates at a position s can then be expressed as:

$$X(s) = x(s) + \sum R_{12}(s, s_j)\, \theta_H(s_j) + \sum R_{14}(s, s_j)\, \theta_V(s_j) \quad (1),$$

$$X'(s) = x'(s) + \sum R_{22}(s, s_j)\, \theta_H(s_j) + \sum R_{44}(s, s_j)\, \theta_V(s_j) \quad (2),$$

where X, X′ represent the corrected trajectory coordinates and x , x′ are the uncorrected measured coordinates:

$$x(s) = x(s_0)\, R_{11}(s_0,s) + x'(s_0)\, R_{12}(s_0,s) + y(s_0)\, R_{13}(s_0,s) + y'(s_0)\, R_{14}(s,s_0) + \sum d_k\, D(s_k,s)\,, \quad (3),$$

$$x'(s) = x_0(s_0)\, R_{21}(s_0,s) + x'(s_0)\, R_{22}(s_0,s) + y(s_0)\, R_{23}(s_0,s) + y'(s_0)\, R_{14}(s,s_0) + \sum d_k\, D'(s_k,s). \quad (4)$$

In (1) and (2), θ_H and θ_V are horizontal and vertical functions representing the distortions at s induced by dipole correctors at positions s_j. In both equations, ∑ represents a sum over j dipoles. The components of R represent the lattice transfer functions. In (3) and (4), $D(s_k,s)$ and $D'(s_k,s)$ relate the misalignments of a solenoid at s_k to the induced position and slope at s, and the sum is over N solenoids. Similar equations describe the vertical coordinates.

We need (2N+4) BPMs to solve for the misalignments and initial conditions. In the RIA driver, where space is limited due to beam dynamics considerations, BPMs must be placed between cryostats, and there are two or more solenoids per cryostat. Therefore the equations cannot be solved exactly and we seek least-square solutions for the trajectory equations.

The Optimization Function

We establish a goal function, Φ, whose minimum is found by sweeping the corrector strength parameter space. The function Φ is expressed as:

$$\Phi = \sum_j \left[\frac{(X_j + C_j)^2}{(\sigma_p + \sigma_b)^2} + \frac{(\Delta X_j + \Delta C_j)^2}{(2\sigma_p)^2} \right], \qquad (5)$$

where X_j, C_j denote measured and calculated deflections at position j, at nominal magnetic settings, and ΔX_j and ΔC_j are the measured and calculated deflections at non-nominal magnetic settings. Specifically, C_j and ΔC_j represent the sum terms in the right-hand sides of Eqs. (1) and (2), and depend on the lattice transfer functions. σ_p and σ_b are the BPM's rms precision and alignment errors, respectively. The minimization uses the measured trajectory and the difference trajectory with appropriate weights. We found that when BPM misalignments can be neglected the best optimization is obtained by excluding the difference trajectory in the algorithm.

LOW-ENERGY LINAC SECTION

A detailed layout of the low-energy section of driver linac can be found in [1]. This section precedes the first stripper and accelerates uranium atoms of charge states 28 and 29, from 190 keV/u to 10 MeV/u. Table I shows the initial and final values of some basic focusing-lattice parameters of the section.

Table 1: Some Basic Parameters of the Prestripper Lattice

Beam energy (MeV/u)	0.19 – 10.03
Frequency (MHz)	57.5 –115.
Number of cavities	85
Number of cryostats	10
Focusing period (cm)	54.9 – 177.3
Solenoid effective length (cm)	10 - 30
Focusing field (T)	7.0 – 10.2
rms misalignm. at sol. (mm)	0.09 – 0.17
rms misalignm. at cavities (mm)	0.17 – 0.17

A modification of the code TRACK was used in simulations of random error misalignments of the solenoids. The code calculates the response functions in Eqs. (1) and (2) at the BPMs in terms of delta-function kicks at the correctors, and looks for values of the corrector strengths that minimize Eq. (5).

In our simulations, we investigated two different corrector-placement options. In one option, we placed thin-element correctors inside the cryostats, after every two solenoids. In the RIA case, this option can only be realized if non-conventional correctors are used, given the lack of available free space in the cryostats. We have proposed the development of dipole coils superimposed on solenoids in a compact corrector element as a possible solution [3]. The simulations presented here use thin dipoles as a test of the effectiveness of the option. In the second scheme, the correctors were placed outside each cryostat. In both schemes, the BPMs were placed outside the cryostats.

Fig. 1 shows the horizontal and vertical emittance of the two-charged-state beam along the prestripper, before and after trajectory optimization. The uncorrected emittance growth results from simulations of 0.03-cm random uniform misalignment errors in solenoids and cavities. For this particular set of misalignments the uncorrected emittance grows fast with distance. There is no emittance growth after correction with thin-dipole placed after every set of two solenoids The oscillation of the "corrected" emittance is the natural oscillation of a multi-charged state beam in a solenoidal focusing channel.

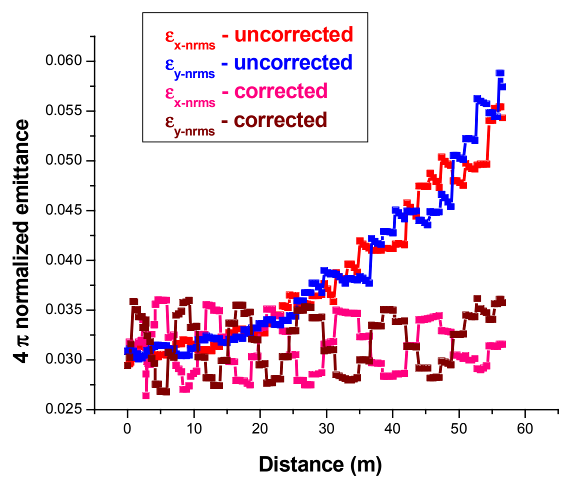

Figure 1: Emittance growth of a two-charged-state uranium beam in the low-energy linac section, resulting from ±0.03-cm random misalignments of cavities and solenoids.

In Fig. 2 we compare the horizontal position and slope coordinates at the BPMs before and after trajectory correction. The corrected values are plotted on the right side of the figure and are shown in a larger scale than the uncorrected values, for clarity. The corrector field distribution for the horizontal plane is shown in Fig.3. The required integrated-field strengths for the correction shown in Fig. 2 do not exceed a pre-estimated value.

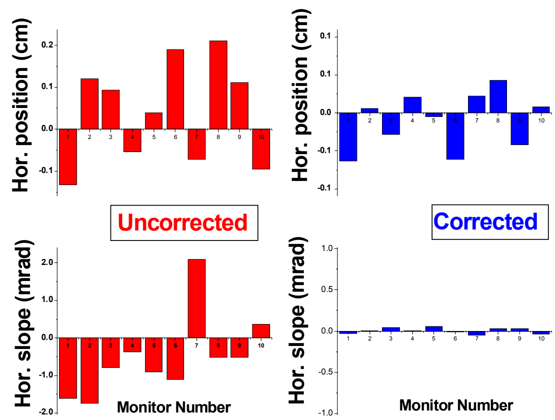

Figure 2: Comparison of the uncorrected (left) and corrected (right) BPM position (top) and slope (bottom). The corrected values are plotted at a larger scale, for clarity.

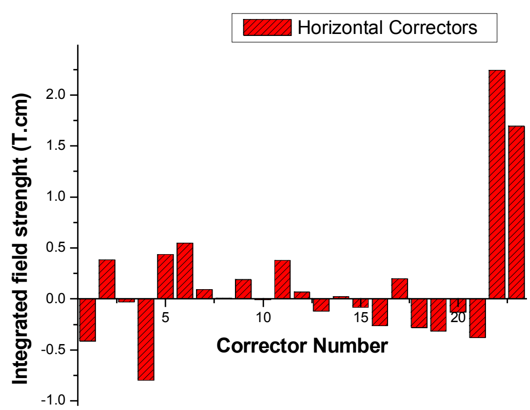

Figure 3: Required integrated–field strength for the correction shown in Fig.2.

MEDIUM- ENERGY LINAC SECTION

Table 2 contains some of the basic transverse focusing parameters for this section of the RIA driver, located between two strippers. It is designed to transport five-charge-states of uranium beam from 10 to 86 MeV/u.

Table 2: Some Basic Parameters of the Medium-Energy Linac Section

Beam energy (MeV/u)	10.03 – 86.24
Number of cryostats	26
Focusing period (cm)	173.4– 258.9
Solenoid effective length (cm)	30
Focusing field (T)	6.0 – 10.4
rms misalignm. at sol. (mm)	0.17
rms misalignm. at cavities (mm)	0.17

As shown in [1], in the absence of errors, there is no transverse emittance growth in the multi-charge beam. In the presence of errors, the growth can be very large. For the case of 0.03-cm random solenoid misalignments, the emittance dilutes by a factor of five. By optimization correction, the growth is reduced to a factor of 1.5, for this particular set of random misalignments, and with correctors placed outside the cryostats. The uncorrected and corrected emittances are depicted in Fig. 4, where we also plotted the nominal emittance values for comparison.

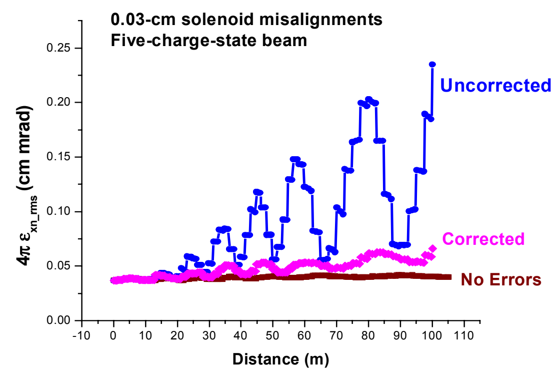

Figure 4: Transverse emittance without errors, and with solenoid misalignments, uncorrected, and after optimization.

SUMMARY

The optimization correction method effectively reduces the misalignment-induced emittance growth of a multi-charge-state beam. The method takes into account the coupling of horizontal and vertical motions in the solenoids and corrects for both position and angle errors.

The compactness of the lattice, required for optimal beam-dynamics, does not allow many choices for the placement of correctors. In a previous paper, we have proposed to develop combined-field solenoids that incorporate dipole steering coils. To confirm the effectiveness of using steering coils, we applied the optimization algorithm to a lattice containing fictitious thin-dipole correctors placed next to every other two solenoids. We found that the optimization restored the emittance to the nominal values and the corrected trajectory was much smoother that the ones resulting from the lattice with correctors placed outside the cryostats. This result reinforces the advantages of using the combined-solenoids-plus-steering-coils design option. Further studies in terms of a) optimal set of correctors, and b) sensitivity of the effective emittance growth to alignment errors will be undertaken.

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