MULTIPLE-CHARGE-STATE BEAM STEERING IN HIGH-INTENSITY HEAVY-ION LINACS*

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Abstract

An algorithm suitable for correction to steering of multiple-charge-state beams in heavy-ion linacs operating at high currents has been developed [1]. It follows a four-dimensional minimization procedure that includes coupling of the transverse beam motions. A major requirement is that it obeys the restricted lattice design imposed by the acceleration of multiple-charge-state heavy-ion beams [2]. We study the algorithm efficiency in controlling the beam effective emittance growth in the presence of random misalignments of cavities and focusing elements. Limits on misalignments are determined by quantifying beam losses and effective steering requirements are selected by examining several correcting schemes within the real state constraints. The algorithm will be used to perform statistically significant simulations to study beam losses under realistic steering.

MULTI-Q-STATE BEAM DYNAMICS

For heavy-ion linacs an efficient way to achieve the high current intensities required by a high-power medium-energy machine is to accelerate simultaneously several charge states of stripped ions. Simultaneous acceleration of multiple-charge states overcomes the limitations of presently available ion sources and allows the use of a larger portion of the stripped beam. In addition, by using multiple strippers the linac length necessary to achieve the design energy can be reduced. Large transverse and longitudinal acceptances and minimization of drift spaces between cavities are effective means to preserve the beam quality. Other sources of emittance dilution, such as misalignments of transverse focusing elements and resonators can lead to beam losses and require correction. A steering algorithm designed for multiple-charge-state beams and obeying the lattice limitations and machine complexities of a high-intensity heavy-ion linac has been developed and preliminary results were published in [1]. Here, we present results obtained with a fully-developed version of the algorithm code implementation, applied to the linac driver of the proposed Rare Isotope Accelerator (RIA) project [2]. The RIA linac driver has a high degree of complexity due to the large number of components and the requirement that it accelerates beams of any ions, including uranium, to energies up to 400 MeV/nucleon and 400 kW of beam power.

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MINIMIZATION

An effective steering algorithm for multi-q ion beams should control emittance growth and reduce trajectory excursions to avoid beam losses. Most importantly, it should be tailored to the restricted choices of steering and diagnostics configurations, so as to be implement-able in a real machine. In the lower-energy sections of a SC heavy-ion linac designed to accelerate multi-q beams correctors need to be closely spaced, with more than one corrector placed in the same cryostat. Beam position monitors (BPMs) are placed between cryostats. Correction methods that zero out the beam position at a monitor by varying an upstream corrector tend to fail, because in general for such accelerators, the linear transport matrices between correctors and monitors form singular systems that require appropriate mathematical tools. A many-correctors-to-one-monitor system is best solved by least-square minimization.

Our algorithm is based on the determination of the beam response functions to known induced excitations to the beam trajectory and on the minimization of a goal function that depends on those transfer functions. We assume that the beam centroid can be mapped by functions relating the initial phase-space coordinates at a point s_0 to its coordinates at a point s along the accelerator. These *transfer functions* describe the lattice responses at s to the beam conditions at s_0. Given N misaligned elements, we need 2N+4 measurements of the beam position and angle at the BPMs to determine the misalignments and initial conditions exactly. Having more unknowns than equations, we find the corrector strengths by minimizing the function:

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

where $\mathbf{X_j}$, $\mathbf{C_j}$ are four-dimensional vectors and denote measured and calculated deflections at position j, respectively. σ_p and σ_b are the BPM's rms precision and alignment errors. Specifically, the vectors $\mathbf{C}$ depend on the lattice transfer functions, $\mathbf{R}$, and on the corrector strengths, $\boldsymbol{\theta}$:

$$\mathbf{C}(s) = \sum_k \mathbf{R}(s, s_k) \times \boldsymbol{\theta}(s_k).$$

The response functions include terms corresponding to coupling of the transverse planes and are calculated by inducing deflections of known magnitude at a corrector position and measuring the resulting changes in the beam coordinates at the BPMs. The corrector strengths that minimize the goal function Φ are subject to constraints imposed by realistic limits in corrector strengths.

Optional slope minimization can be implemented by scaling slope-related terms by appropriate weights to have comparable magnitude to the spatial-related terms. Physically, the beam slope could be measured by a beam-based alignment procedure, measuring the beam position at a monitor at a known distance from a focusing element, at nominal field setting, and measuring the position again, with the magnet at a different setting. The difference in the two measurements, together with the known distance, provides the slope measurement. Although for small misalignments position–only correction works well, we have found that correcting position and slope is more effective than correcting position only when misalignments are high.

An example of emittance-growth reduction obtained with the algorithm is given in Fig. 1, where the normalized emittances for a two-charge-state low-energy uranium beam (0.19 ≤ E≤12 MeV/u) are plotted before (U) and after position and slope minimization (C). As shown, the emittance growth due to misalignments is practically eliminated.

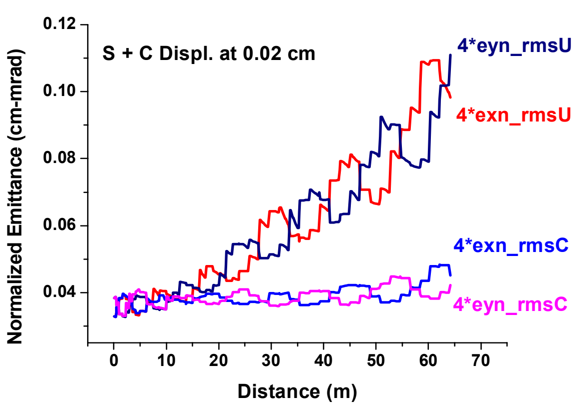

Figure 1: Two-charge-state emittance growth for random misalignments of solenoids and cavities, before and after the minimization procedure.

THE RIA LINAC DRIVER

Reference [2] gives a detailed description of the RIA driver linac. It consists of a room-temperature front-end and a three-section SC linac. The three sections are designated low-, medium-, and high-energy sections, and are separated by two stripper areas. The latter consist of a stripper foil or film, followed by a magnetic transport system. Two options have been proposed for the high-energy section: the baseline option uses elliptical cell cavities; the other option uses triple-spoke resonators [3].

The low-energy section precedes the first stripper and can accelerate uranium atoms of charge 28 and 29 from 190 keV/u to 12 MeV/u. There are 85 SC cavities distributed in ten cryo-modules. Focusing is provided by 40 SC solenoids, of lengths from 10 cm to 30 cm, and field strengths from 7 to 9 Tesla. In the machine, steering dipole coils will be superimposed on the solenoids. Preliminary results using the coils as steering elements have shown that no nonlinearity is introduced by the coil fields [4]. In the present simulations, correctors are represented by thin (delta-function) elements placed on the solenoids. The first cryostat contains eight periods of one cavity and one solenoid each. Three correctors ensure steering of the very low-energy beam. The next two cryostats have two correctors each, followed by one corrector per cryostat. One BPM is placed in each inter cryostat space.

The medium-energy section follows the first stripper; the uranium-beam energy increases from 12 to 85 MeV/u. Five charge-states are accelerated simultaneously, with the average charge equal to 74^+. There are 184 resonators and 45 30-cm long SC solenoids varying from 4.5 Tesla to ~7 Tesla, distributed in 21 cryostats. In this section, one corrector and one monitor per cryostat provide sufficient steering.

The baseline high-beta section, which comes after the second stripper, has been optimized to accelerate simultaneously five charge states of average charge 88^+. Transverse focusing is provided by 42 pairs of warm quadrupoles at ~0.4 Tesla pole-tip field. Elliptical cavities, of geometrical beta equal to 0.49, 0.69 and 0.81, totalling 172 cavities, are distributed in 43 periods. One corrector is placed every other period, and one monitor after each period.

We have applied the minimization method to random misalignments of magnet components and cavities to determine the correction effectiveness at increasing misalignment levels. Table 1 lists three alignment error levels for component end displacements. The values represent the maximum amplitude in a uniform random distribution.

Table 1: Misalignment for cavities and focusing elements, in cm. For solenoid displacements, the error depends on the solenoid length.

Element	Level 1	Level 2	Level 3
Cav	0.03	0.05	0.07
Sol	0.015 -0.03	0.015 –0.05	0.015 – 0.07
Quad	0.02	0.02	0.02

We simulated 50 different realizations of the driver linac with 40,000 macro particles each. All simulations refer to the baseline design. For an effective minimization, it is necessary to divide each the linac sector into sections. The corrected beam from an upstream section is input to a downstream section subject to errors, which is then corrected. We used a total of ten correction sections.

The results for Levels 1 and 2 are very similar: there are no beam losses, except at the stripper regions, where the losses are controlled [5]. For Level 3, there is total loss of particles, before correction, for three seeds. For the remaining seeds, partial losses of $3.4*10^{-3}$ occur after the second stripper region. For all levels, the algorithm reduces the uncorrected beam size by more than 50% per section.

We have compared the results obtained with the minimization procedure to those obtained by correcting the trajectory with a simple procedure that artificially zeroes the beam coordinates at determined "zero-elements". We denote the first as "beam-based" correction and the second, as "zero-element" correction [5]. In Fig. 2 the "beam-based"-corrected normalized horizontal emittance for 50 seeds is compared to the corresponding emittance obtained with "zero-element" correction, for Level-2 errors. The spikes at 80 and 180 m correspond to the stripper regions.

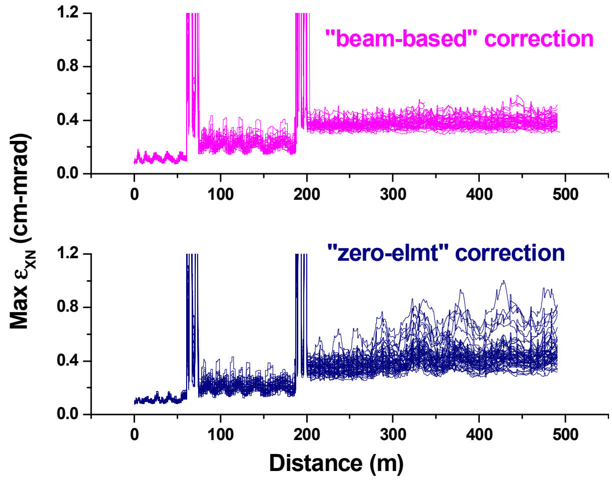

Figure 2: Corrected normalized emittance for Level-2 errors, shown for two correction methods.

In the high-energy section, the higher spread in the "zero-element" emittance is due to a smaller number of zero-elements than correctors used in the minimization method. Fig.3 shows the horizontal beam-centroid for Level-2 errors, with the beam-based-corrected centroid superimposed on the "zero-element"-corrected centroid.

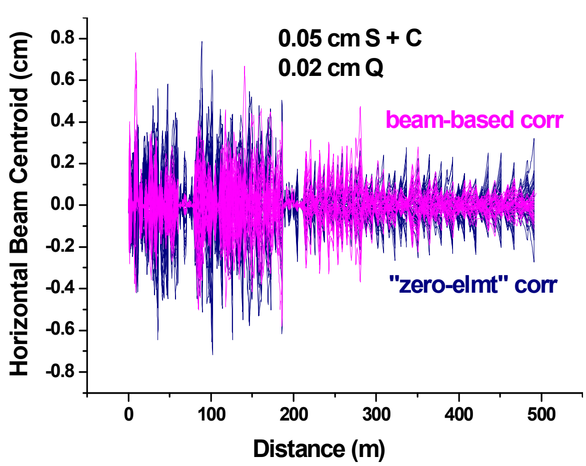

Figure 3: Beam-centroid oscillations along the driver linac, shown for 50 seeds.

As shown, the beam-based correction reproduces the latter remarkably well. After correction, the oscillations are reduced by 30% to 60%, relative to the uncorrected oscillations, in the lower-energy sections and by 75%, in the high-energy section.

The vertical and horizontal integrated-corrector-strength distributions are very similar in Levels 1 and 2, with all correctors staying within ±0.8 T.cm. Correction of higher errors, however, requires strengths as high as ±1.6 T.cm, as shown is Fig. 4. We estimate that the strength provided by a prototype solenoid-mounted dipole coil will be ~ 1 kGauss [4]. Assuming a 20-cm-length corrector, the maximum corrector strengths required are within the estimated limit.

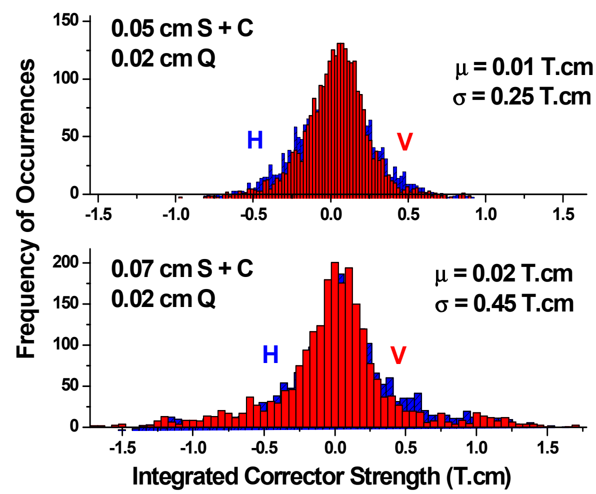

Figure 4: Vertical and horizontal integrated-corrector-strength distributions over 50 seeds, for two sets of errors. The vertical and horizontal distributions are statistically identical.

SUMMARY

A 4D minimization algorithm has been developed that can be used to characterize tolerances to transverse errors and losses. It can correct both position and angle, it accounts for solenoid-induced couplings, and it has been fully integrated in the code TRACK. The method produces identical results to those obtained by bringing the beam centroid to zero at specified locations. As a beam-based method, one of its essential features is that it can be implemented experimentally.

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