FAILURE MODES ANALYSIS FOR THE MSU RIA DRIVER LINAC*

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Abstract

Previous end-to-end beam dynamics simulation studies [1] using experimentally-based input beam parameters [2], including alignment and rf errors and variation in charge-stripping foil thickness have indicated that the Rare Isotope Accelerator (RIA) driver linac proposed by Michigan State University (MSU) has transverse and longitudinal acceptances more than adequate to accelerate light and heavy ions to final energies ≥ 400 MeV/u with beam powers of 100 to 400 kW. Further beam dynamics studies [3] were carried out using a new beam envelope code recently developed at MSU to optimize the setting of the rf phase and amplitude of the cavities throughout the linac. During linac operation, equipment loss due to, for example, cavity contamination, problems with cryogenic systems, or failure of rf or power supply systems, can lead to, at least, a temporary loss of some of cavities and focusing elements. To achieve high facility availability, each segment of the linac should be capable of adequate performance even with some failed elements. In order to prove the flexibility and robustness of the driver linac lattice design, beam dynamics studies were performed to evaluate the linac performance under various scenarios of failed cavities and focusing elements with proper correction schemes. The result of these beam dynamics studies is presented in this paper.

INTRODUCTION

The MSU RIA driver linac lattice has been established since 2002, and extensive beam dynamics studies performed have demonstrated that it provides good overall performance and satisfies all the RIA design requirements, even for the most challenging case of multi-charge state beam acceleration. Recently, a new longitudinal beam dynamics code developed at MSU has been used to automatically set up the Superconducting Radio Frequency (SRF) cavity phases and amplitudes to increase the linear acceptance and limit the longitudinal emittance growth along the RIA driver linac for multi-charge state beams. As a result, the longitudinal performance of the MSU RIA driver lattice was noticeably improved for the first linac segment. Figures 1 and 2 show the transverse and longitudinal beam emittances evolution for multi-charge state uranium ions along the RIA driver linac with and without alignment and rf jitter errors. Two-charge state uranium (28-29) is accelerated in the first linac segment (seg1), stripped to higher charge states (75±2) (c1), further accelerated in a second linac segment (seg2), stripped again to charge states (88±1) (c2), and finally accelerated to final energy in the last linac segment (seg3). The maximum transverse misalignments were ±1mm for the solenoids and ±2 mm for the quadrupoles and rf cavities. The dynamic rf errors in phase and amplitude for the accelerating cavities were ±0.5 deg. and ±0.5 % throughout the linac. Charge-stripping foil thickness variations of ±5% were assumed, and initial beam distributions from the RIA front-end that are based on experimental data, were used in the end-to-end beam simulations. The largest value of 100 seeds at each longitudinal position is shown (blue) in Figures 1 and 2.

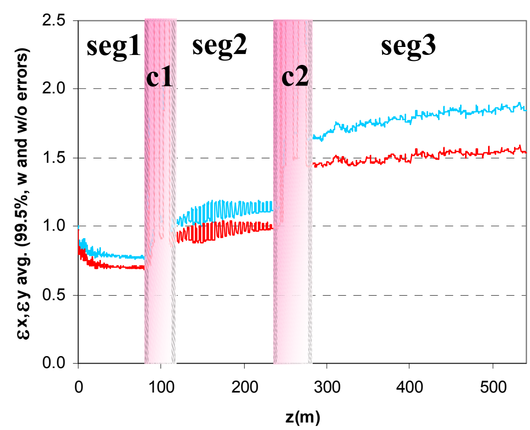

Figure 1: Transverse emittances of multi-charge state uranium beam w/o errors (red/dark) and with errors (blue/light) along the RIA driver linac.

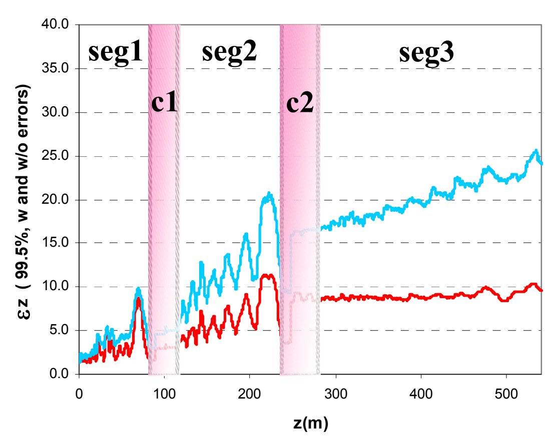

Figure 2: Longitudinal emittances of multi-charge state uranium beam w/o errors (red/dark) and with errors (blue/light) along the RIA driver linac.

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RIA DRIVER LINAC LATTICE ELEMENT FAILURE ANALYSIS

SCL Segment I – Low β Section

Segment I of the Superconducting Linac (SCL) has 76 superconducting (SC) solenoid magnets and 122 SRF cavities positioned in 15 cryomodules. Due to the relatively low velocity and large transverse and longitudinal emittances of the ion beams from the RIA Front End, Segment I is more sensitive to the failure of focusing elements and accelerating cavities than any other segment in the RIA driver linac.

Focusing element failure

The scenario of a single SC solenoid magnet failure in a cryomodule in Segment I was investigated using LANA [4]. In each case, two solenoid magnets before and two after the failed solenoid were adjusted using DIMAD [5] to limit the local beam envelope distortion and to rematch the beam transverse Twiss parameters.

Figure 3 shows the transverse beam envelopes in Segment I for unperturbed lattice and two other cases with a single solenoid failure in Cryomodules No. 1 and No. 3 respectively. Failure of a single solenoid in Cryomodule No. 1 not only produces a large local beam envelope distortion, but also a significant transverse emittance growth. This is mainly due to the reduction of the local transverse phase advance, leading to a strong parametric resonance ($2\nu_T < \nu_L$) in the cryomodule affected. Similar results were obtained for the case of single solenoid failure in Cryomodule No. 2.

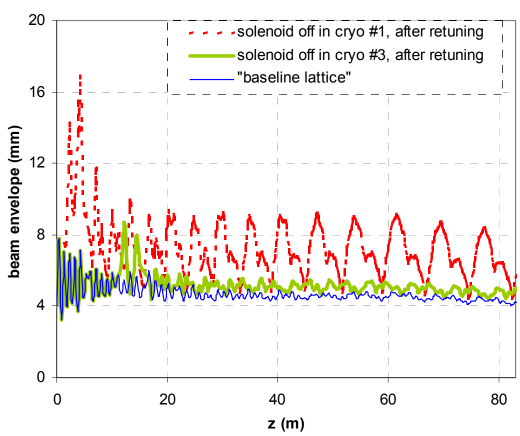

Figure 3: Beam envelopes of $U^{28,29+}$ beam for unperturbed lattice (blue) of Segment I, and for lattices with a single solenoid failure in Cryomodules No. 1 (red) and No. 3 (green).

For the case with a single solenoid failure in Cryomodule No. 3, only a small local beam envelope distortion was observed as shown in Figure 3. The beam envelope in the rest of segment matches well with unperturbed lattice indicating no significant transverse emittance growth. Any single solenoid failure in the rest of cryomodules in Segment I will have less of an impact due to the rapid beam acceleration. Consequently, a single solenoid failure in Crymodules No. 3 to No. 15 does not lead to significant RIA driver linac performance degradation or beam loss.

Accelerating structure failure

Three main issues arise with a cavity failure: loss of energy gain, longitudinal mismatch of the beam envelope, and control of the multi-charge state beam emittance. A new code using a specific tuning algorithm for the longitudinal beam dynamics [3] was used to obtain the proper correction scheme. Losing a cavity within the first two cryomodules of the first segment is a particularly sensitive case because any drift at this location represents a significant disturbance for the particle motion in the longitudinal phase space and because a cavity type transition occurs between the second and third cryomodules of the first segment. For any cavity failure in the first two cryomodules, it was found that an x% cavity loss had a 2x% effect because of the need to significantly retune neighboring cavities to both recover the energy as well as regain matched longitudinal condition.

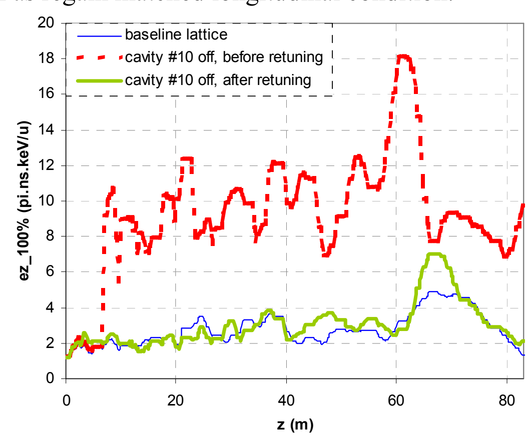

Figure 4: Longitudinal emittance along the first linac segment for $U^{28,29+}$ beam. The loss of a single cavity in the early part of the segment can lead to severe mismatch and phase space distortion if no cavity retuning is applied. After retuning, the performance of the segment is usually recovered.

To obtain satisfactory results in the event of a cavity loss, it was necessary to increase the gradient of nearby cavities. To avoid exceeding gradient design values, this may require an increase in the number of installed cavities [2]. Nevertheless, if the amplitude or the number of cavities is increased, the first segment can be retuned and the beam dynamics performance recovered. As an example, Fig. 4 shows the longitudinal beam emittance in the first linac segment for the sensitive case where the last cavity of the first cryomodule is off. Without retuning, the emittance growth is significant due to the strong mismatch created by the failed cavity. After rematching, the performance of the segment is recovered.

In the later part of the segment, it was found that a x% cavity loss had only a ~x% effect because the mismatch introduced by the failing cavity is reduced and

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because the energy recovery can be smoothly distributed among the remaining cavities in the lattice.

SCL Segment II – Medium β Section

The study of focusing element and cavity failure in Segment II is very similar to the analysis performed in the first segment. Segment II uses 208 superconducting Half-wave cavities for acceleration and 52 superconducting solenoids for transverse focusing in 26 cryomodules. Since there are only two solenoids in each cryomodule, proper rematching for a single solenoid failure requires some solenoids of neighboring cryomodules to be adjusted.

Single solenoid failure in the first six cryomodules in Segment II significantly reduces the transverse phase advance in the affected cryomodules, and leads to parametric resonance ($2\nu_T < \nu_L$) and substantial transverse emittance growth. Two possible schemes could be used to minimize this effect: increasing the number of transverse focusing solenoids per cryomodule or reducing the cavity amplitude to lower the longitudinal phase advance. Any single solenoid failure in the rest of cryomodules in Segment II will have a smaller impact on the beam dynamics. The beam simulation studies indicate that a single solenoid failure in crymodules No. 7 to No. 26 in Segment II does not lead to noticeable performance degradation

For the case of cavity failure, because the beam kinetic energy in Segment II is larger, the effect of the drift spaces on the longitudinal beam dynamics is weaker, which means that the mismatch induced by a failed cavity is relatively smaller than in the first segment. Also, because only one type of SC cavity is used in the segment, there is no transit time curve transition within the segment and it is easier to distribute the energy gain recovery on the remaining cavities. For those reasons it is concluded that an x% cavity loss has approximately a 1.5 x% effect for early cryomodules and x% effect for most of the segment.

The second segment could be tuned using the multi-charge state positioning scheme proposed by A. Facco et al. [6]. In this scheme, the centroids of the different ions of a multi-charge state beam must be positioned at the entrance of a segment such that the product $q/A\cos\phi$ is the same for all of them. This scheme, though interesting for its simplicity, has nevertheless a draw back when applied to the cases with failed cavities. Indeed, the stability of the positioning for the centroids of the single charge state beams in the longitudinal phase space requires the use of a constant average phase along the segment (except for the few cavities at the beginning and the end of the segments used for the positioning and the recombination of the bunch centroids). When a cavity fails, it introduces a mismatch that usually needs to be acted on, preferably by retuning the phase of the adjacent cavities. Doing so when using the multi charge state positioning scheme without further precaution breaks the relative positioning of the centroids (i.e the scheme advantages vanish). To improve the situation and keep using the scheme even when a substantial mismatch occurs along the segment (e.g. when two consecutives cavities fail in segment II), it is beneficial to retune the adjacent cavities to rematch the beam, but also to insure a good repositioning of the bunch centroids. In an ideal case, the beam is rematched within a few cavities and the centroids move along closed loops in the longitudinal phase space, leaving and coming back to their equilibrium position over the rematching cell.

SCL Segment III – High β Section

Segment III uses a total of 164 6-cell SRF elliptical cavities in 41 cryomodules with transverse focusing provided with room temperature quadrupole doublets in each inter-cryostat warm region. Unlike SC solenoid inside cryomodules, any of these quadrupole doublets are easily accessible and could be quickly repaired or replaced. In addition, Segment III is much less sensitive to cavity failure and longitudinal beam mismatch is much easier to correct due to high beam energy. A case where all four cavities failed in a single cryostat was studied. To longitudinally rematch the beam, a few cavities in the cryomodule following the failed cavities are used in a rebunching mode, and four cavities in the following cryomodules were detuned to create the drift space needed to provide a minus unit transformation over the rematching section. This scheme provides a straightforward correction procedure to rematch the beam effectively. Under this correction scheme the multi-charge state longitudinal emittance increase was ~30-40%. The degradation of the final beam energy can be easily compensated by increasing of the cavity voltage by 5% or by adjusting the synchronous phase in the segment.

SUMMARY AND CONCLUSIONS

Various scenarios of failed accelerating cavities and focusing elements in all three segments of the MSU RIA driver linac were investigated with beam simulations, and possible local and global correction schemes evaluated to avoid lattice performance degradation.

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