STUDIES OF FAULT SCENARIOS IN SC CW PROJECT-X LINAC*

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Abstract

The success of the Project-X accelerator facility crucially depends on reliable operation of the 1 GeV superconducting (SC) continuous wave (CW) linac at stage-I. Operation at high intensity in CW mode puts stringent tolerances on beamline elements. Any fault affecting nominal operation of an accelerating or transverse focusing element will result in beam mismatch in the downstream sections. This in turn leads to emittance growth, and ultimately triggers beam losses. A robust lattice design allowing local retuning can make the machine operable even in the event of a fault, limiting the need for long unscheduled downtime. This paper presents studies performed to understand the consequences of failure of various elements. The outcomes of local retuning for different fault scenarios at critical locations in the linac are discussed.

INTRODUCTION

Project-X is a proposed multi-megawatt (MW) accelerator facility to be built at Fermilab[1]. It is envisioned as a multiuser facility that would support a diversified experimental program at the intensity frontier. In the current economic environment, funding profile limitations led to development of a staging strategy. The facility would be built in three stages. The first stage involves construction of 1 mA (average current), 1 GeV SC CW linac. The second stage would double the average current through stage I. Half of the beam would then be further accelerated in a 1-3 GeV SC CW linac. The final and third stage involves construction of 3-8 GeV SC pulsed linac. A detailed description of staging approach is presented elsewhere[2]. A schematic of the CW linac baseline configuration is shown in Fig. 1. It comprises a room temperature front end and a SC linac. The front-end includes an ion source, a low energy beam transport (LEBT) section, an RFQ and a medium energy beam transport (MEBT) section. The DC ion source delivers a nominal current of 5 mA at 30 keV. The beam is transported through the LEBT and matched to the RFQ. The RFQ operates at room temperature at a frequency of 162.5 MHz and accelerates the beam up to 2.1 MeV. The beam then enters the MEBT where it gets chopped to acquire the time structure required to drive different simultaneous experiments. Following the MEBT is a SC CW linac segmented into five sections. The first section is based on 162.5 MHz Half Wave Resonators (HWR) and accelerate the beam to $\sim$ 9 MeV. The next two sections use two types of 325 MHz Single Spoke Resonators (SSR) i.e. SSR1 and SSR2, to reach a kinetic energy of 156 MeV. The two final sections dubbed low beta (LB) and high beta are based on 5-cell, 650 MHz elliptical shaped cavities respectively designed for $\beta_G = 0.61$ and $\beta_G = 0.90$.

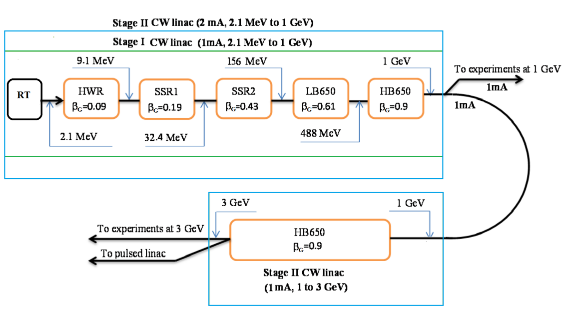

Figure 1: Acceleration scheme in Project-X CW linac.

GENERAL

Most of the complexity associated with a high intensity ion linac lays at low energy where dynamics is non-relativistic and space charge effects are significant. The success of Project-X accelerator complex is therefore decisively dependent on reliable operation of the 1 GeV CW linac at stage-I. Failure of any element such as cavity, solenoid or quadrupole alters the focusing period of the beam, resulting in mismatch in the downstream sections. This, in turn, causes emittance growth and drives halo formation and beam losses. In some cases, the losses may be prevent safe operation. Unscheduled downtime is necessary to replace a faulty element and return to nominal operating conditions. Minimizing such unscheduled downtime is especially important in a multi-user facility where several experiments are running simultaneously. With that in mind, fault scenarios need to be accounted for in the optics design. The design should robust enough to allow localized compensation of the perturbation caused by an RF cavity or magnet failure. This paper presents studies performed to analyze various fault scenarios at critical locations in 1 GeV SC CW linac at stage-I of Project-X. Failure mitigation using localized compensation is demonstrated.

LOCAL COMPENSATION METHOD

The local compensation method involves re-tuning of elements in the vicinity of a failed element to restore a smooth beam envelope along the linac. Specifically, the RF phase and field amplitude of cavities are varied to recover the nominal beam energy and the longitudinal profile while

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solenoids and quadrupoles are varied to restore the transverse dynamics. The constraints and assumptions applied during local compensation for Project-X SC CW linac are summarized below:

- Cavity accelerating fields: Fields are varied to recover nominal beam energy subject to the constraint that surface peak magnetic field in cavity should not exceed 70 mT.
- Cavity synchronous phases are varied in such a way that ratio of synchronous phase to longitudinal beam size is greater than 4. This assumption is made to achieve sufficient longitudinal acceptance.
- Field gradient in quadrupoles and axial magnetic field in solenoids are varied subject to the constraint that they cannot exceed design limits. These are 10 T/m and 6 T for quadrupoles and solenoids respectively.
- Minimum user disruption: The number of re-tuned elements is minimized in order to expedite the process of compensation.
- Local compensation cannot result in any losses (100% transmission).

FAULT SCENARIOS IN CW SC LINAC

Sensitivity of the linac performance to element failure is location dependent. Studies have been performed for different fault scenarios to understand their impact. The fault scenarios at the most critical locations are discussed in this section.

Failure of First SC Cavity in HWR Section

The HWR is the first SC section in the linac. It accelerates and focuses the beam coming out of the MEBT. One focusing period in the HWR section is composed of a solenoid and a HWR cavity. Failure of the first cavity in the HWR section is considered the most critical due to the large transverse and longitudinal beam size at this location. Since the beam is non-relativistic (2.1 MeV) failure of the first HWR cavity results in significant phase slippage that tends to grows in amplitude and ultimately causes beam losses in high energy section.

The local compensation method is applied to re-tune the beam optics. A bunching cavity and a triplet in the upstream MEBT, one solenoid in the same period of failed cavity and one solenoid and one HWR cavity in each of the three downstream HWR periods are used to recover a smooth beam profile. In addition, two HWR cavities (one in each of the two following periods) is used to recover the design energy at the end of the HWR section. Figure 2 and figure 3 show $1\sigma_{RMS}$ longitudinal beam size and normalized rms longitudinal emittance respectively. Abrupt changes in beam size and emittance characterize the beam losses which occur at the beginning of 650 MHz, LB section. It can be observed that there is no beam loss after

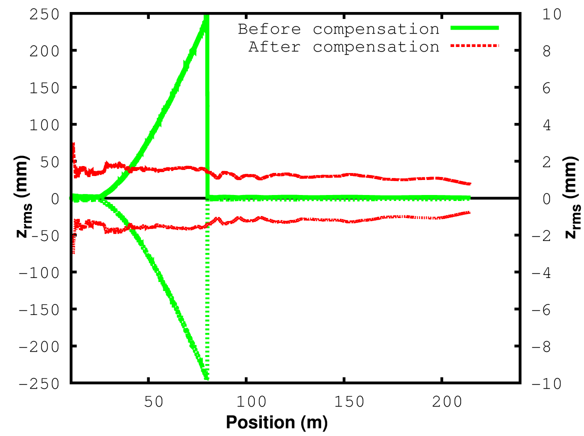

Figure 2: $1\sigma_{RMS}$ longitudinal beam size before (green) and after (red on secondary y-axis) local compensation of failure of first SC cavity in HWR section.

application of the local compensation method; the longitudinal emittance is also restored. Figure 4 shows the synchronous phase in the cavities and beam size for the retuned linac. Even with new setting of synchronous phases, the longitudinal acceptance is sufficient to accommodate a $6\sigma_{RMS}$ beam.

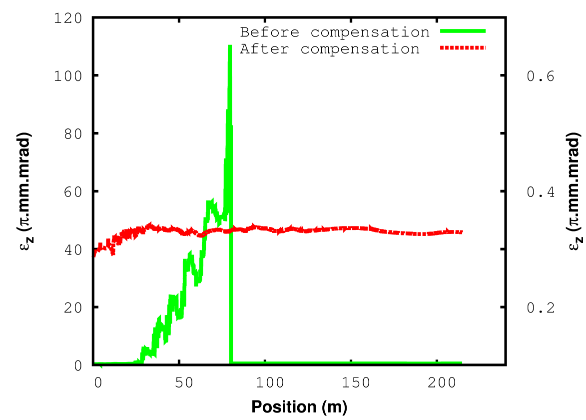

Figure 3: Normalized RMS longitudinal beam emittance before (green) and after (red on secondary y-axis) local compensation of failure of first SC cavity in HWR section.

Failure of First SC Quadrupole Doublet in LB Section

Solenoids are used to provide transverse focusing at low energy i.e. within the HWR, SSR1 and SSR2 sections. They are replaced with quadrupole doublets in the low beta (LB) and high beta (HB) sections. The nominal match between the SSR2 and LB section is very sensitive and involves outermost elements on both sides. Failure of the first SC quadrupole doublet is considered a critical event: it causes significant mismatch and envelope modulation in the downstream sections. Figure 5 shows $1\sigma_{RMS}$ transverse beam envelope before and after local compensation. It can be observed that failure of first SC quadrupole doublet in LB section results in significant distortion of trans-

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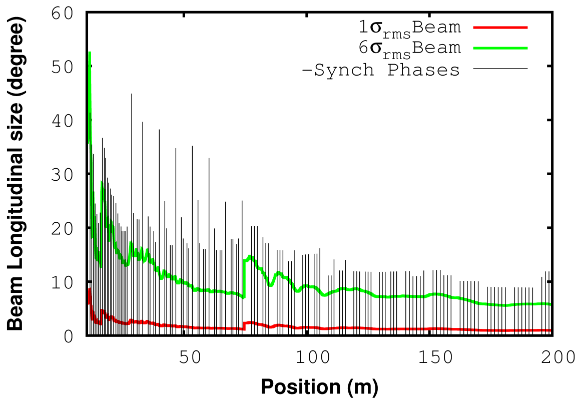

Figure 4: Longitudinal beam size in degree and synchronous phases after local compensation of failure of first SC cavity in HWR section.

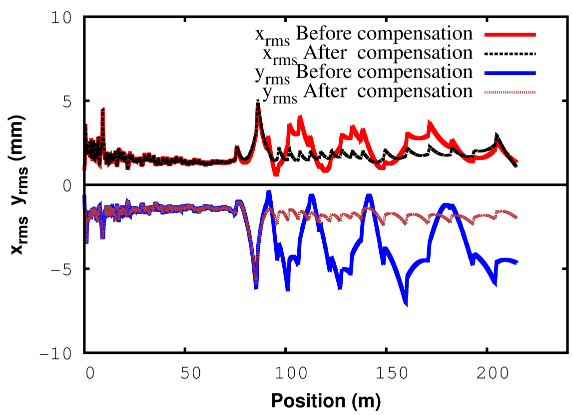

Figure 5: $1\sigma_{RMS}$ transverse beam envelopes before and after local compensation of failure of first SC quadrupole doublet in LB section.

verse beam profile, causing emittance growth in the downstream sections as shown in Figure 6. Again, application of the local compensation method results in a restored transverse beam profile and controlled emittance growth.

Failure of First Cavity in LB Section

Studies were performed to analyze the impact of a cavity failure at the frequency transition from 325 MHz to 650 MHz. It is found that failure of the first SC cavity in the LB section results in a 9 MeV beam energy reduction at 1 GeV linac output. However, no beam losses are observed. Fig. 7 shows that there are no abrupt changes in emittances. Emittance growth relative to baseline lattice [2] is less than 3% in longitudinal and horizontal plane and less than 7 % in vertical plane at the end of linac. We conclude that failure of cavity in the higher energy sections of the linac has minimal impact on performance.

CONCLUSION

Various fault scenarios were studied for the current Project-X baseline SC CW linac. Failures at critical locations, especially at low energy result in significant emittance growth and beam losses. Using local compensation, the optics design is flexible enough to allow recovery from failure of a RF single cavity or transverse focusing element. The output beam parameters and smooth beam profile in all planes are restored and 100% beam transmission is achieved.

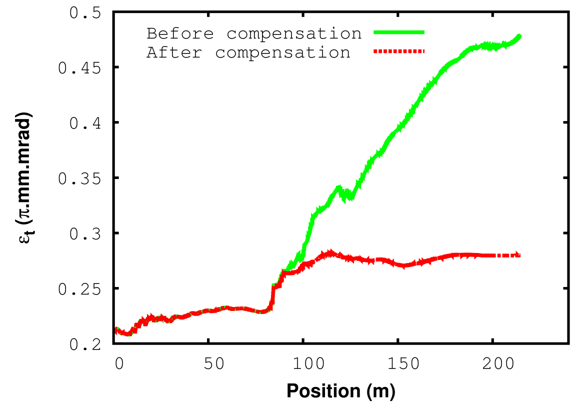

Figure 6: Normalized RMS transverse beam emittance before (green) and after (red) local compensation of failure of first quadrupole doublet in LB section.

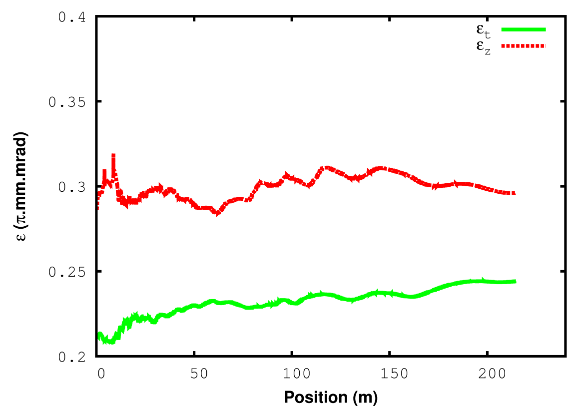

Figure 7: Normalized RMS longitudinal (red) and transverse (green) beam emittance in presence of failure of first SC cavity in LB section.

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[1] S. D. Holmes et al., Project-X Reference Design Report (June 2013), Project X-document 776-v7.

[2] N.Solyak et al., in Proceedings IPAC, Shanghai, May 2013, THPWO091, p. 3972 (2013).