STUDY OF EFFECTS OF FAILURE OF BEAMLINE ELEMENTS & ITS COMPENSATION IN CW SUPERCONDUCTING LINAC*

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Abstract

Project-X is a proposed high intensity proton facility to be built at Fermilab in United States. The first stage consists of a superconducting linac (SC) operating in continuous wave (CW) mode to accelerate a H^- beam from 2.1 MeV to 3 GeV. Failure of any beamline element during operations induces a downstream mismatch of the beam which is especially severe when the failure occurs at low energy. A large mismatch causes emittance growth and ultimately results in beam losses. In a worst case scenario, the operability of the machine may be affected and long downtime may be needed to replace the failed element. To minimize possible downtime, the optics can be designed in a way that allows local retuning to make the machine operable. This paper presents studies performed to investigate retuning scenarios after failure of an accelerating cavity or a focusing magnet at critical locations in the Project-X CW superconducting linac.

INTRODUCTION

Project-X is a proposed multi-megawatt (MW) accelerator facility to be built at Fermilab [1, 2]. It would be a multiuser facility supporting a diversified experimental program at the intensity frontier. The proposed complex consists of two SC linacs. The first linac operates in CW mode to accelerate an average beam current of 1 mA from a kinetic energy of 2.1 MeV to 3 GeV and provides 3 MW beam of H^-. This 3 MW beam is distributed to several experiments at 3 GeV; a fraction of the beam is sent through a second stage SC pulsed linac for further acceleration from 3 to 8 GeV. A schematic of the baseline con-

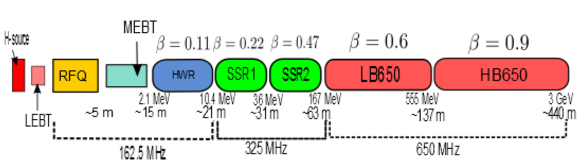

Figure 1: Acceleration scheme for 3 GeV CW linac.

figuration of the CW linac is shown in Fig. 1. It includes an ion source which provides 5 mA beam of H^- ions, followed by a Low Energy Beam Transport (LEBT) section used to transport and match the beam to the upstream end of an RFQ. The RFQ operates at room temperature at a frequency of 162.5 MHz and accelerates the beam to a kinetic energy of 2.1 MeV. The RFQ is followed by a Medium Energy Beam Transport (MEBT) section where the beam is chopped in order to produce the time structure necessary to serve different experiments simultaneously. The SC linac is segmented into five sections operating at three frequencies. The first section uses Half Wave Resonators (HWR) at 162.5 MHz to accelerate the beam from 2.1 MeV to $\sim$ 10 MeV. The next two sections use two families of Single Spoke Resonators (SSR) respectively labeled SSR1 and SSR2, to accelerate the beam up to a kinetic energy of 160 MeV. Two families of elliptical cavities operating at 650 MHz, designed for β_G = 0.61 and β_G = 0.90 respectively provide the final acceleration. Further details about the conceptual design of CW linac are presented elsewhere [3, 4].

GENERAL

Operation of the SC linac in CW mode is demanding on beamline elements, increasing the possibility of temporary or permanent failure of accelerating cavities and focusing magnets during the operation of linac. Failure of beamline elements such as cavities, solenoids and quadrupoles alters beam focusing, resulting in mismatch of the beam downstream of the failed element and causing beam losses. In some cases, losses become excessive and element replacement is necessary to re-establish nominal operation of the machine. Not only does this involve replacing a complete cryomodule (containing several cavities), it also involves warming up the enclosing cryomodule from operating temperature (usually 2K) to room temperature and subsequently cooling it down. Resuming nominal operations also involves going through a careful accelerator re-start procedure. The bottom line is that a single element failure can make the beam unavailable to the different experiments for a rather extended period of time. To prevent this from happening as much as possible, the linac optics needs to be robust enough to allow local compensation after a failure by retuning neighbouring elements. The numbers of cavities and focusing magnets present in each cryomodule needs to be sufficient to allow compensating for the loss of an RF cavity without exceeding the allowable field in any individual cavity. This paper presents studies performed to analyze beam dynamics after failure of a linac element and establish that the optics is flexible enough to support local compensation at critical locations.

FAILURE OF BEAMLINE ELEMENTS

The sensitivity of the linac performance to element failures depends on the location of the said element. Failure

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at low energy are more problematic as space charge effects are important in this regime. Beam optics is also sensitive at low energy which means a large mismatch propagating along the linac is likely to result in significant beam losses in the higher energy sections. Beam losses in excess of 1 W/meter may result in activation causing degradation of accelerator components, interruption in hand on maintenance and hazards from a personal health and environment safety point of view. Accordingly, we focus on the effects of failure of first RF cavity and solenoid in HWR section which is considered the most critical case due to the large transverse and longitudinal beam sizes at this location.

Failure of First Period in HWR Section

HWR is the first superconducting section in CW linac. The input beam energy is 2.1 MeV. The beam is non-relativistic and space charge effects are largest. As shown in Fig. 2 one period in HWR section consists of one solenoid and one cavity.

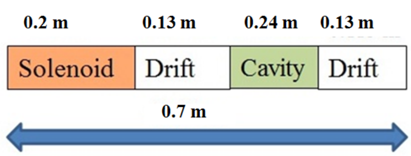

Figure 2: One period in HWR section.

Failure of a beamline element (cavity and solenoid) in first period of HWR section effectively introduce an extra drift space of 0.7 m which delays the first accelerating and focusing kick. As shown in Fig. 3, the beam size in the longitudinal plane grows along the linac due to the mismatch with subsequent sections. A similar behavior is observed in the transverse planes. The result is emittance growth and beam halo formation in the low energy sections which causes beam losses in the downstream high energy sections. A total of 15% of beam is lost along the linac after failure of the beamline elements in the first period of HWR section.

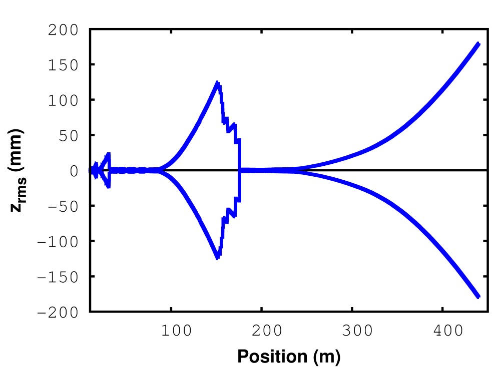

Figure 3: Beam trajectory in longitudinal plane after failure of first period in HWR section.

LOCAL COMPENSATION OF FAILED ELEMENTS

A local compensation scheme is applied to recover nominal performance of the linac. It involves tuning of neighboring elements in the vicinity of a failed element in order to achieve smooth beam propagation along the linac while preserving the final beam energy. Separate power sources for each cavity allows RF phases and amplitudes in cavities to be set independently. The phase and amplitudes are first varied to recover beam energy and to achieve smooth longitudinal envelope. The focusing strengths in focusing elements (solenoid and/or quads) are then changed to tune the transverse optics. The constraints and assumptions for local compensation are as follows:

- Accelerating field in cavity: accelerating fields are increased to recover the beam energy but the surface peak magnetic field in the cavity is not allowed to exceed 70 mT.
- Synchronous phases are varied in such a way that ratio of synchronous phase to longitudinal rms beam size remains greater than 3 to ensure sufficient acceptance margin.
- The number of retuned elements is minimized. This is necessary to expedite the process of compensation.
- 100 % beam transmission through the linac after local compensation.

Local Compensation of Failure of First Period in HWR

One bunching cavity and a quad triplet in the upstream normal conducting MEBT section and one solenoid and one cavity in each of the two downstream periods (after the failed solenoid and cavity in first period) are used to retune the lattice to obain smooth envelopes in longitudinal and transverse planes. Figure 4(a) shows beam longitudinal rms envelope before (green) and after compensation (magenta on secondary y-axis). Fig. 4(b) shows the beam transverse rms envelopes before and after compensation. It can be concluded from Fig. 4(a) and Fig. 4(b) that smooth envelopes in the longitudinal and transverse plane can be restored after applying local compensation scheme. As shown in Fig. 4(c) and Fig. 4(d), the beam emittances are also significantly improved after local compensation. However, relative to nominal operation at the end of linac, the emittances are respectively 33% and 23% higher.

There are two frequency transitions in the proposed baseline design of SC CW linac. A transition from 162.5 MHz to 325 MHz occurs at the end of HWR section. A transition from 325 MHz to 650 MHz occurs at the downstream end of the SSR2 section. If these transitions are not made properly, emittance growth and beam halo formation will take place which lead to beam losses in the downstream high energy sections. Proper matching is achieved

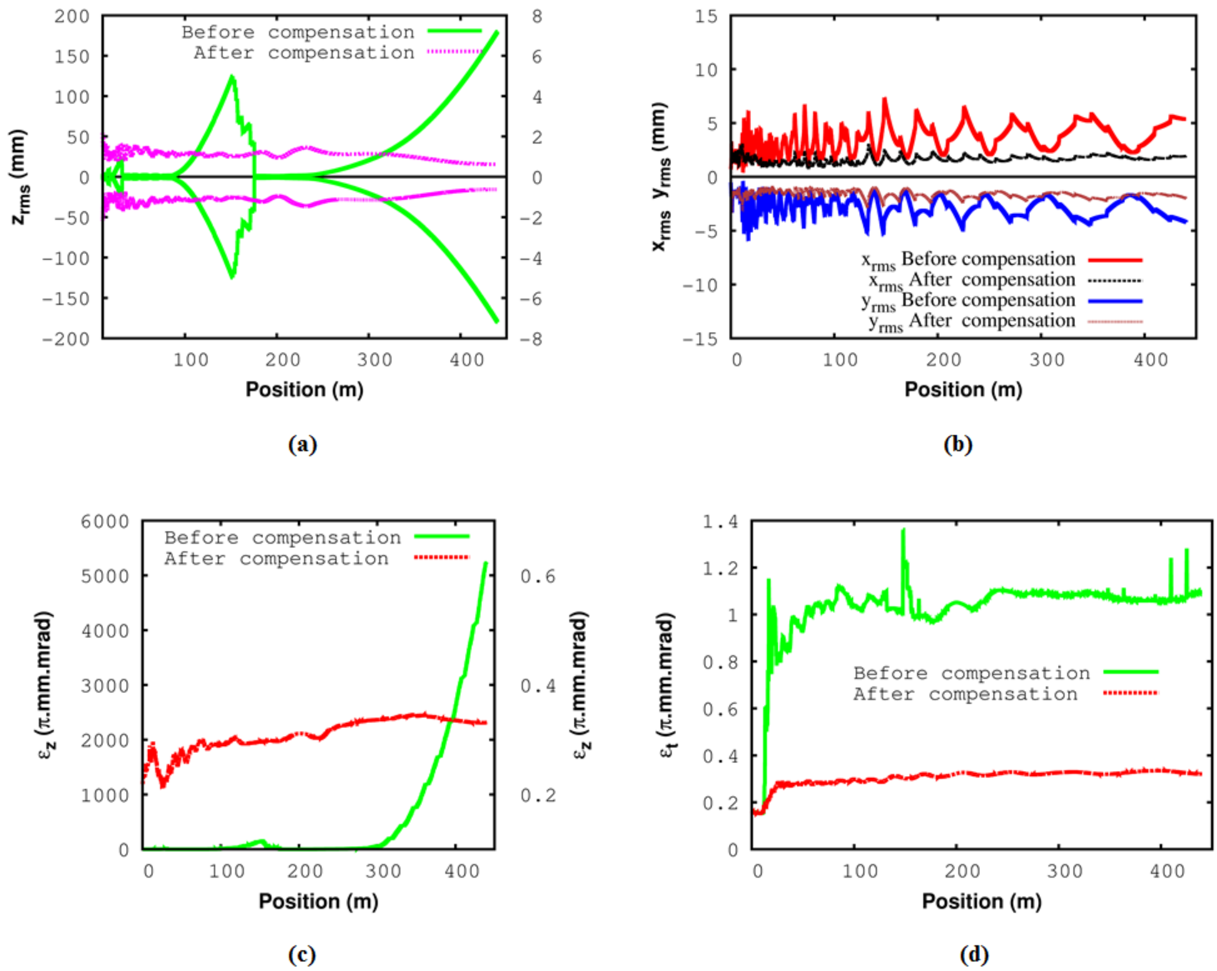

Figure 4: Beam parameters before and after applying local compensation: (a) longitudinal trajectory (b) transverse trajectory (c) longitudinal emittance and (d) transverse emittance.

by adjusting the gradients and phases of the outermost elements of each side of the transition. Thus, recovery from the failure of an RF cavity or focusing magnet at the end of HWR or SSR2 sections is important to avoid beam losses and hence replacement down time. Studies have been performed to understand the effects of failure of the last cavity in the HWR and SSR2 sections. Failure of the last cavity in the HWR section results in 3% beam losses which can be corrected by applying local compensation. No beam losses are observed after failure of a cavity at the frequency transition from 325 MHz to 650 Mhz. However, the failure results in emittance growth and degradation in final beam energy. Both problems can be addressed by local compensation.

CONCLUSION

Systematic studies have been performed to evaluate the robustness of lattice design of SC CW linac for the Project-X facility. It is demonstrated that lattice design is robust enough to allow operating the linac even with failed elements after applying local compensation. Failure of an element at low energy is most critical as it results in significant beam losses.

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