BEAM LOSS DUE TO MISALIGNMENTS, RF JITTER AND MISMATCH IN THE FERMILAB PROJECT-X 3 GEV CW LINAC *

J.-P. Carneiro†, V. Lebedev, S. Nagaitsev, J.-F. Ostiguy, A. Saini, B. Shteynas, N. Solyak
Fermi National Accelerator Laboratory, IL 60510, USA

Abstract

This paper presents an analysis of beam losses along the current design of the FNAL 3 GeV Superconducting CW linac. Simulations from the RFQ exit up to the end of the linac (∼440 meters) are performed using the beam dynamics codes `TRACK` and `TRACEWIN`. The impact of beam mismatch, element misalignments and RF jitter on the beam dynamics is discussed and corresponding beam loss patterns are presented. A correction scheme to compensate for misalignments is described.

INTRODUCTION

Simulations and measurements for operating facilities such as the Los Alamos Neutron Science Center (LANSCE) 800 MeV proton and H^- linac indicate that the beam losses in high power proton linac need to be minimized to about 1 W/m or less for energies above 100 MeV in order to allow "hands-on maintenance" on the accelerator [1]. For lower energies, higher losses may be tolerated since the activation is less effective. This requirement implies a meticulous monitoring of uncontrolled beam losses (arising from misalignments of accelerator components, RF jitter, beam mismatch or ionization of the H^- ions) during the design of the linac. This paper presents an estimate of the uncontrolled beam losses along the linac first without correctors and then with a correction scheme.

THE FNAL 3 GEV LINAC

A layout of the present configuration of the FNAL 3 GeV linac is presented in Figure 1 and described in detail in [2].

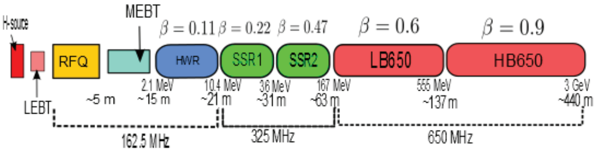

Figure 1: Layout of the FNAL 3 GeV CW SC Linac.

The linac is designed to deliver an average H^- beam current of 1 mA (from a chopped beam current of 5 mA) which at 3 GeV translates into an average beam power of 3 MW. The total length of the linac in its current version is approximately 440 meters. The injector consists of an H^- source followed by a Low Energy Beam Transport (LEBT) that matches the 30 KeV beam into a Radio-Frequency Quadrupole (RFQ) operating at 162.5 MHz. A Medium Energy Beam Transport (MEBT) chops the 2.1 MeV beam and provides the appropriate matching into the 162.5 MHz Half-Wave Resonators (HWR) section where the beam is accelerated to ∼10 MeV. Further acceleration to 167 MeV is achieved with two different types of Single Spoke Resonators (SSR1 and SSR2) operating at 325 MHz and final acceleration to 3 GeV is provided using two types of 5-cells elliptical cavities ($\beta = 0.6$ and $\beta = 0.9$) operating at 650 MHz. In the MEBT the focusing is done with quadrupole triplets. From the HWR cryomodule up to the SSR2 cryomudule focusing is done with 5 T superconducting solenoids located inside the cryomodules. The current version of the linac foresees as focusing elements in the 650 MHz section quadrupoles doublets located between the cryomodules. Not depicted in the layout of the FNAL 3 GeV CW SC Linac presented in Figure 1 is a ∼15 m drift space located at 1 GeV with the purpose to allow beam extraction for nuclear physics experiments.

SENSITIVITY TO ERRORS AND JITTERS

Static transverse misaligment errors of accelerator components (solenoids and quads) and dynamic RF jitter (field and amplitude) have been implemented into the beam dynamics code `TRACK` [3] in order to study the behaviour of the current lattice to such imperfections. A summary is presented in Table 1 with imperfections implemented from and including the MEBT up to and inluding the last $\beta = 0.9$ cryomodule. The transverse misalignements δ_{xy} are setup in the code such that the element ends are randomly misaligned (with a uniform distribution) horizontally and vertically by the same value which does not exceed the maximum input δ_{xy}. Concerning the dynamic RF errrors, `TRACK` generates Gaussian distributions truncated at 3σ.

Table 1 reports the error type of each element of the beamline, the error value and the total beam fraction lost at the end of the linac. For each set of errors, 400 randomly generated error runs were performed with `TRACK` on the Fermigrid [4] using $5 \cdot 10^4$ macroparticles per run. Two different Gaussian input distributions were tested during these runs: a first one cut at 6σ both transversely and longitudinally and a second one cut at 6σ transversely and 3σ longitudinally. For solenoid misalignments $\delta_{xy} > 200$ μm, beam losses surpassing 1 W/m are predicted by the code for both input distributions mainly in the vicinity of the frequency jump from 325 MHz to 650 MHz. The same

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† carneiro@fnal.gov

Table 1: Impact on the total beam fraction lost at the end of the linac of element misalignment errors and RF field jitter. From `TRACK`.

Elt	Error Type	Error Value	Fraction lost [%]	
			6σ long.	3σ long.
Sol.	δ_{xy}	100 μm	$2{\cdot}10^{-3}$	$5{\cdot}10^{-6}$
Sol.	δ_{xy}	200 μm	$3.2{\cdot}10^{-2}$	$2.9{\cdot}10^{-2}$
Sol.	δ_{xy}	300 μm	$8.9{\cdot}10^{-1}$	$8.8{\cdot}10^{-1}$
Sol.	δ_{xy}	400 μm	4.6	4.6
Sol.	δ_{xy}	500 μm	11.5	11.5
Quad.	δ_{xy}	100 μm	3.1	3.1
Quad.	δ_{xy}	200 μm	23.7	23.7
Quad.	δ_{xy}	300 μm	66.8	66.8
Quad.	δ_{xy}	400 μm	94.1	94.1
Quad.	δ_{xy}	500 μm	98.5	98.5
Cav.	$\delta_\phi + \delta_E$	$0.5° + 0.5\%$	$6.5{\cdot}10^{-3}$	$4.1{\cdot}10^{-3}$
Cav.	$\delta_\phi + \delta_E$	$1.0° + 1.0\%$	$9.7{\cdot}10^{-2}$	$9.5{\cdot}10^{-2}$
Cav.	$\delta_\phi + \delta_E$	$1.5° + 1.5\%$	3.2	3.2
Cav.	$\delta_\phi + \delta_E$	$2.0° + 2.0\%$	13.4	13.4
Cav.	$\delta_\phi + \delta_E$	$2.5° + 2.5\%$	29.4	29.4

observation is made with quadrupole misaligments $\delta_{xy} > 750\ \mu$m with losses evenly spread on the entire 650 MHz section. The study of the dynamic phase and amplitude jitter taken separately showed that no losses are predicted at $0.5°$ and 0.5% and losses below the 1 W/m limit are predicted for $1.0°$ and 1.0%. For jitters of $1.5°$ and 1.5% losses above the 1 W/m limit are observed mainly in the $\beta = 0.9$ cryomodules. These observation are valid for both input distributions.

Combined as reported in Table 1, losses higher than the 1 W/m limit and evenly spread along the $\beta = 0.9$ cryomodules are predicted by `TRACK` for RF jitters of $1.0° + 1.0\%$. The impact of the roll of the quads around the z axis, the dynamic field jitter of the quads and solenoids and the transverse misalignments δ_{xy} of the cavities was also studied with `TRACK` in the same configuration as previously mentioned (400 seeds). These three error types have a marginal impact on the beam dynamic for values respectively of 5 mrad, 1% and $\delta_{xy} = 1$ mm.

ERRORS AND CORRECTORS

The `TRACK` correction algorithm aims to steer the beam so that the transverse displacements measured by the BPM's are minimized. Figure 2 shows the `TRACK` simulations of the corrected / uncorrected horizontal beam centroid motion taking $\delta_{xy} = 1$ mm for solenoids and cavities, $\delta_{xy} = 0.5$ mm for quadrupoles, 0.5°+0.5% for dynamic RF jitter and quad roll of 5 mrad around the z-axis. In this correction scheme, 1 corrector and 1 monitor were used per solenoid and per quadrupole doublet. For the simulations presented in Figure 2, 100 runs were performed with `TRACK` with errors and correctors implemented from the HWR up to the end of the linac. No errors or correctors were implemented in the MEBT. The initial input distribution was the 6σ longitudinal and 3σ transverse previously mentioned and populated with 10^5 macroparticles. The resolution and the offset in position of the BPM's are respectively 30 μm and 1 mm. As presented in Figure 2, before correction the horizontal beam centroid grows along the linac to reach an amplitude of ±50 mm and losses much higher than 100 W/m are predicted by the code in several locations along the linac. After correction, the horizontal beam centroid motion keeps below 2 mm and no losses are observed.

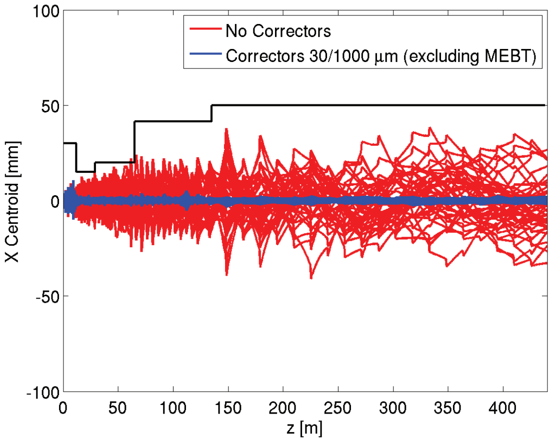
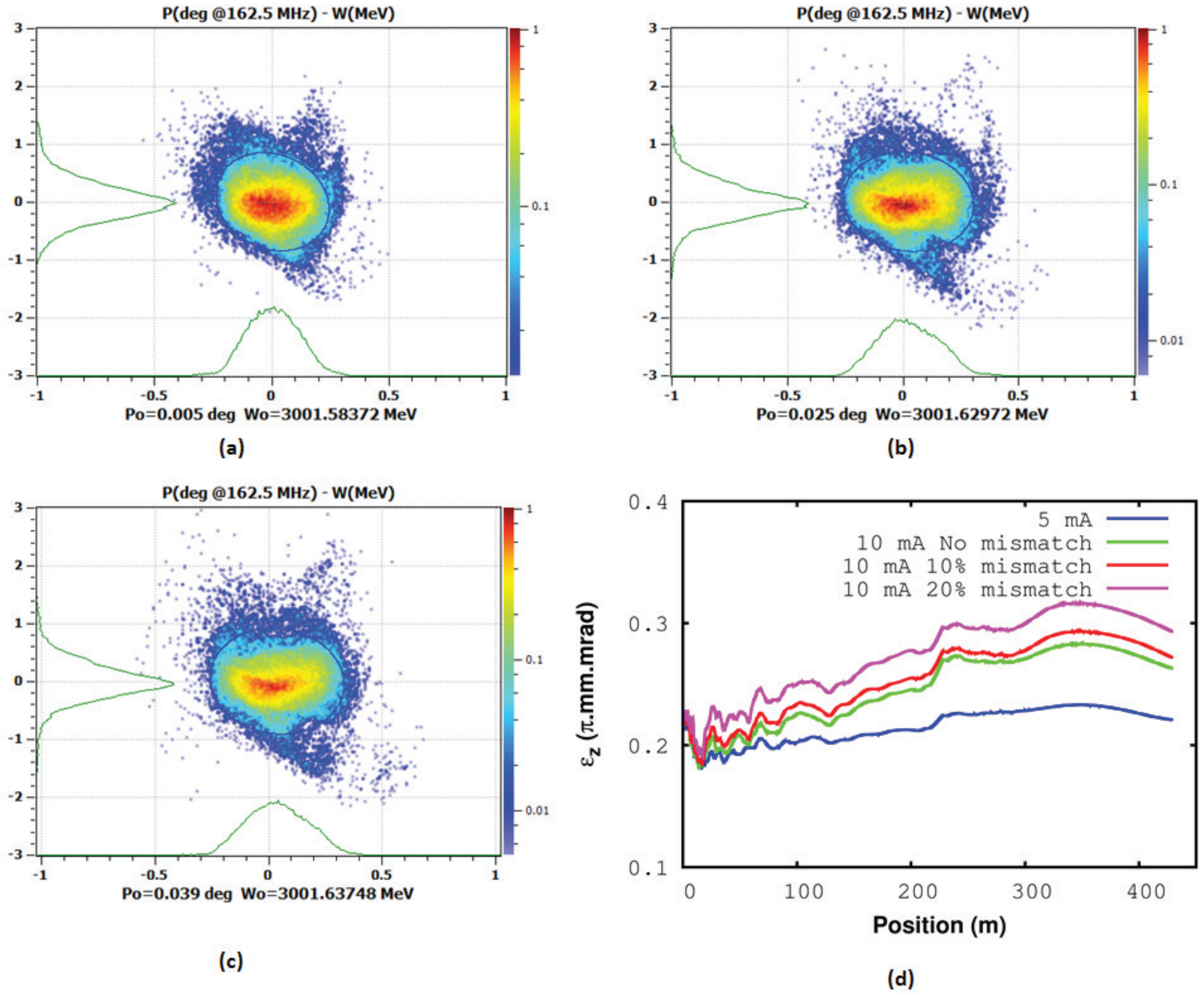


Figure 2: `TRACK` simulations of corrected / uncorrected horizontal beam centroid motion along the linac for the set of errors $\delta_{xy} = 1$ mm (solenoids and cavities), $\delta_{xy} = 0.5$ mm for quadrupoles, RF jitter of 0.5°+1.5% (dynamic RF jitter) and quad roll of 5 mrad around the z-axis. 1 corrector and 1 monitor are used per solenoid and per quadrupole doublet. No errors were implemented in the MEBT (only for the HWR up to the end of the linac).

Based on these observations and following a more conservative approach, the requirement for accelerator elements (solenoids, quads and cavities) is $\delta_{xy} = 0.5$ mm. This current lattice is more sensitive to dynamic RF jitters than the previous lattice presented in detail in [5] since this latest was not presenting losses for dynamic RF jitter of 1.0°+1.0%. As discussed in [2], it is believed that the matching at the frequency jumps for the current lattice needs some improvement to insure a smoother wavenumber evolution at these locations and this may lead to a more robust lattice in terms of longitudinal RF jitter.

SENSITIVITY TO BEAM CURRENT

Possible future operation at higher beam current requires a current independent lattice design. As a preliminary assessment, the baseline lattice was simulated using `TRACEWIN` with a 10 mA peak beam current. For this exercise the MEBT was excluded and the beam was matched to the input of the HWR section. Figures 3(a) and 3(b) compare the final longitudinal beam distributions at 5 mA and 10 mA respectively. No beam losses are observed in either case.



(a) (b) (c) (d)

Figure 3: Longitudinal beam distribution at the end of SC linac for (a) 5 mA, (b) 10 mA, (c) 10 mA with 20% mismatch in all planes and (d) longitudinal emittance along the linac for different cases. From `TRACEWIN` [6].

The effect of an input mismatch in all planes was investigated. At 20% mismatch, marginal beam losses are observed. Figure 3(c) shows the longitudinal beam distribution at the end of linac in this case. Figure 3(d) shows the longitudinal emittance along the linac for different current and mismatch scenarios. Although minor longitudinal tail development and emittance growth in longitudinal and transverse planes are observed, it is expected that 10 mA operation should be possible. Statistical studies of the effect of misalignments, RF jitter and amplitude errors will, of course, be required to validate this statement.

CONCLUSION

With the proper correction scheme, the present lattice shows no losses for realistic element misalignements (solenoids and cavities up to $\delta_{xy} = 1$ mm and quadrupoles up to $\delta_{xy} = 0.5$ mm) and RF field jitter (phase and amplitude up to $0.5° + 0.5\%$). Also with a vacumm at or below 10^{-8} torr at 300 K, stripping losses should remain below 0.1 W/m. The next step in our simulations is to continue the design of the Project-X 3 GeV CW linac ensuring a smooth wavenumber evolution along the accelerator which should then allow the lattice to handle sensitivity to RF jitter up to $1.0° + 1.0\%$ without losses.

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