ANALYSIS OF BEAM LOSS MECHANISM IN THE PROJECT-X LINAC*

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

Abstract

Minimization of the beam losses in a multi-MW H-minus linac such as ProjectX to a level below 1 W/m is a challenging task. The impact of different mechanism of beam stripping, including stripping in electric and magnetic fields, residual gas, blackbody radiation and intra-beam stripping, is analyzed. Other sources of beam losses are misalignements of beamline elements and errors in RF fields and phases. We present in this paper requirements for dynamic errors and correction schemes to keep beam losses under control.

INTRODUCTION

Beam losses in a high power linac need to be minimized in order to allow "hands-on maintenance" on the accelerator. This requirement implies an activation limit below 100 mrem/hr at 30 cm from the component surface, after extended operation of the machine (~100 days) and four hours of down time [1]. Simulations and measurements for operating facilities such as the Los Alamos Neutron Science Center (LANSCE) 800 MeV proton and H^- linac and Proton Accumulator Ring indicate this criterion corresponds to a beam power loss of about 1 W/m or less for energies above 100 MeV. For lower energies, higher losses may be tolerated since the activation is less effective.

Uncontrolled beam losses such as arising from misalignement of accelerator components, rf phase and amplitude jitter, beam halo or beam mismatch need to be carefully studied during the design of a high-power linac to ensure its robustness to the loss requirement of 1 W/m. Another potential source of beam loss in a H^- linac concerns the ionization of the H^- ions. In fact, as the H^- ions travel along the linac they are subject to blackbody radiation, electromagnetic fields (Lorentz stripping), collisions with the residual gas molecules and intrabeam forces (intrabeam stripping). Any one of these four effects may result in the stripping of the loosely bound electron (0.75 eV) of the H^- ion, which in turn produces activation through the loss of neutral hydrogen atoms.

This paper presents beam loss estimates along the 3 GeV CW Superconducting (SC) linac currently under developement at FNAL. The impact on the beam dynamics of accelerator component misalignements and rf phase and amplitude jitter is studied with the ANL code `TRACK` [2] and CEA code `TRACEWIN` [3]. An estimate of the losses from the four above-mentioned stripping mechanisms is presented.

* Work supported by the U.S. Department of Energy under Contracts DE-AC02-06CH11357 and DE-AC02-07CH11359.
† carneiro@fnal.gov

THE FNAL 3 GeV CW LINAC

A layout of the present configuration of the linac is shown in Figure 1 and detailed in [4]. The linac is designed to deliver an average current of 1 mA (chopped peak current of 10 mA) which at 3 GeV produces a beam power of 3 MW. The total length of the linac in its current version is ~ 445 meters.

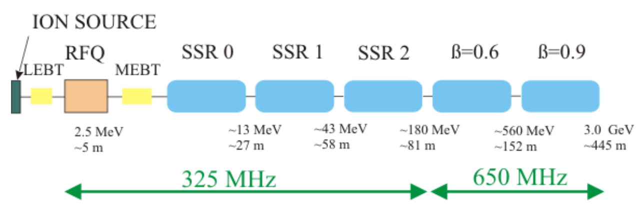

Figure 1: Layout of the FNAL 3 GeV CW SC Linac

The injector consists of an H^- ion source followed by a radio-frequency quadrupole (RFQ) and a Medium Energy Beam Transport (MEBT) that matches the 2.5 MeV beam into the SC linear accelerator. In order to efficiently accelerate the beam from 2.5 MeV to 180 MeV, three different types of Single Spoke Resonators (SSR 0, SSR 1 and SSR 2) operating at 325 MHz are foreseen, as depicted in Figure 1. Further acceleration to 3 GeV is achieved using two types of 5-cells elliptical cavities ($\beta = 0.6$ and $\beta = 0.9$) operating at 650 MHz. In the 325 MHz section, 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 quadrupole doublets located between the cryomodules.

ERRORS AND CORRECTORS

The impact on the current lattice of static transverse misalignement errors of accelerator components (solenoids, quads and cavities) and dynamic RF jitter (field and amplitude) have been studied on the FermiGrid with the code `TRACK`. A summary of the results is presented in Table 1. The transverse misalignents δ_{xy} are setup in the code such that the element ends are randomly misaligned (uniform distribution) horizontally and vertically by the same value which does not exceed the maximum input δ_{xy}. Concerning the dynamic RF errors, `TRACK` generates Gaussian distributions truncated at 3σ.

Reported in Table 1 are 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` using $5 \cdot 10^4$ macroparticles per run. For solenoid misalignments $\delta_{xy} > 300$ μm, beam losses surpassing 1 W/m are

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
Sol.	δ_{xy}	150 µm	$3.5{\cdot}10^{-5}$ %
Sol.	δ_{xy}	300 µm	0.4 %
Sol.	δ_{xy}	500 µm	9 %
Sol.	δ_{xy}	750 µm	38 %
Sol.	δ_{xy}	1000 µm	69 %
Quad.	δ_{xy}	150 µm	0 %
Quad.	δ_{xy}	300 µm	0 %
Quad.	δ_{xy}	500 µm	0 %
Quad.	δ_{xy}	750 µm	4 %
Quad.	δ_{xy}	1000 µm	22 %
Cav.	$\delta_\phi + \delta_E$	0.5° + 0.5%	0 %
Cav.	$\delta_\phi + \delta_E$	1.0° + 1.0%	$5{\cdot}10^{-6}$ %
Cav.	$\delta_\phi + \delta_E$	1.5° + 1.5%	0.04 %
Cav.	$\delta_\phi + \delta_E$	2.0° + 2.0%	0.9 %
Cav.	$\delta_\phi + \delta_E$	2.5° + 2.5%	3.6 %

predicted by the code mainly at the frequency transition. The same observation is made with quadrupole misalignments $\delta_{xy} > 750$ µm with losses evenly spread on the entire 650 MHz section of the linac. The study of the dynamic phase and amplitude field jitter taken separately showed that no losses are predicted respectively for $\delta_\phi = 1.5°$ and $\delta_E = 1.5\%$ and losses below the 1 W/m limit predicted for respectively $\delta_\phi = 2°$ and $\delta_E = 2\%$. Combined as reported in Table 1, TRACK predicts no losses at 1.0° + 1.0% and losses higher than 1 W/m for 1.5° + 1.5%. Figure 2 reports the maximum and average losses along the linac for this last configuration as predicted by TRACK and TRACEWIN. For TRACEWIN simulations, 100 runs were performed using $3{\cdot}10^4$ macroparticles per run. Noteworthy is the good agreement between the two codes which both predict high losses at the transition between the two set of 650 MHz cavities (~150 m).

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.

The TRACK correction algorithm aims to steer the beam so that the transverse displacements measured by the BPM's are minimized. Figure 3 shows TRACK simulations of the corrected / uncorrected horizontal beam centroid motion taking $\delta_{xy} = 1$ mm for all the elements of the beamline (solenoids, cavities, quadrupoles), RF field dynamic jitter of 1.0° + 1.0% and quad rolls of 5 mrad. In this correction scheme, 1 corrector and 1 monitor per solenoid and per quadrupole doublet were assumed. The resolution and the offset in position of the BPM's are respectively 30 µm and 1 mm. As presented in Figure 3, before correction the horizontal beam centroid growths along the linac to reach an

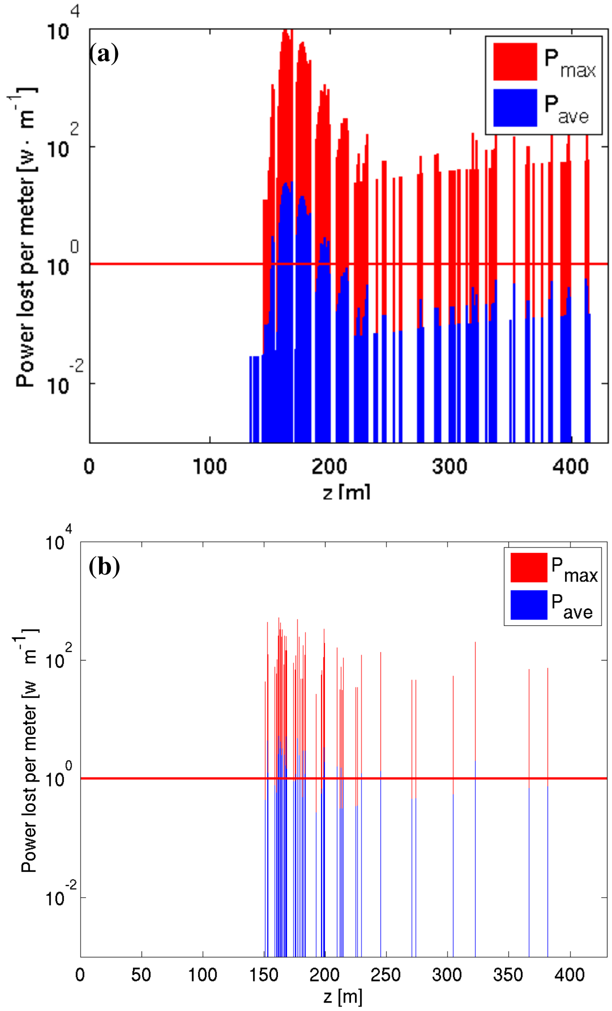

Figure 2: (a) TRACK and (b) TRACEWIN simulations of the maximum and average loss pattern along the linac operating at 3 MW for RF field dynamic errors of 1.5° + 1.5%. The red bar represents the 1 W/m limit.

amplitude ±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 3 mm and no losses due to element misalignments and RF field jitter are observed.

Based on this study and following a more conservative approach, the requirement for solenoids, quadrupoles and cavities misalignments is $\delta_{xy} = 500$ µm and $1.0° + 1.0\%$ for RF dynamic field jitter. The requirement on the resolution and on the offset in position of the BPM's are respectively 30 µm and 500 µm.

H^- STRIPPING LOSSES

Four mechanisms are currently known as capable of stripping the H^- ions during their transport along the linac leading to uncrontrolled beam loss. These mechanisms are: (i) the interaction of the H^- ions with the residual gas or (ii)

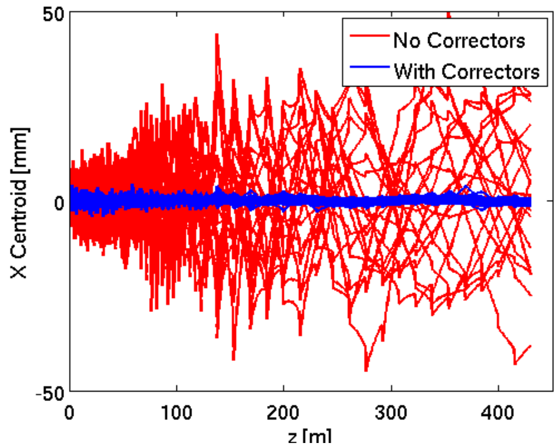

Figure 3: TRACK simulations of corrected / uncorrected horizontal beam centroid motion along the linac for the set of errors δ_{xy} = 1 mm (solenoids, cavities, quadrupoles), 1.0°+1.0% (dynamic RF field jitter) and quad roll of 5 mrad around the z-axis. 1 corrector and 1 monitor were used per solenoid and per quadrupole doublet.

with the electromagnetic fields, (iii) the blackbody radiation and (iv) the intrabeam stripping. This last mechanism has been described in [5] and it has been recently implemented in TRACK [6].

Figure 4(a) shows the predicted beam losses from the four aforementioned stripping mechanisms as simulated with TRACK. These losses represent an average over 500 runs performed on the FermiGrid with 10^6 macroparticles per run. The warm sections of the linac (inter-cryomodule spacing) were set at 300 K in the code with a vacumm composition of 70% H_2, 10% H_2O, 10% 0_2 and 10% CO and a pressure of 10^{-7} torr. Concerning the cryomodules, a temperature of 2 K was used with 100% H_2 and 10^{-10} torr. It can be noticed from Figure 4(a) that in these conditions the stripping losses contribute to a general background below 0.1 W/m with some peaks reaching the 1 W/m limit. The main contributor to the background are the losses from the intrabeam stripping. The observed peak are the contribution from the residual gas in the inter-cryomodules spacing, as depicted in Figure 4(b) which concerns only stripping from this effect. Keeping the vacuum below 10^{-8} torr would reduce these peaks by one order of magnitude, i.e below 0.1 W/m. Stripping from blackbody or electromagnetic fields are not a concern for the current design.

CONCLUSION

With the proper correction scheme, the present lattice shows no losses for realistic element misalignements (solenoids, quadrupoles and cavities up to δ_{xy} = 1 mm) and RF field jitter (phase and amplitude up to 1.0° + 1.0%). 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 study the behaviour of this lattice with respect to beam mismatch coming for instance from the input distribution and/or the cavity field limitations .

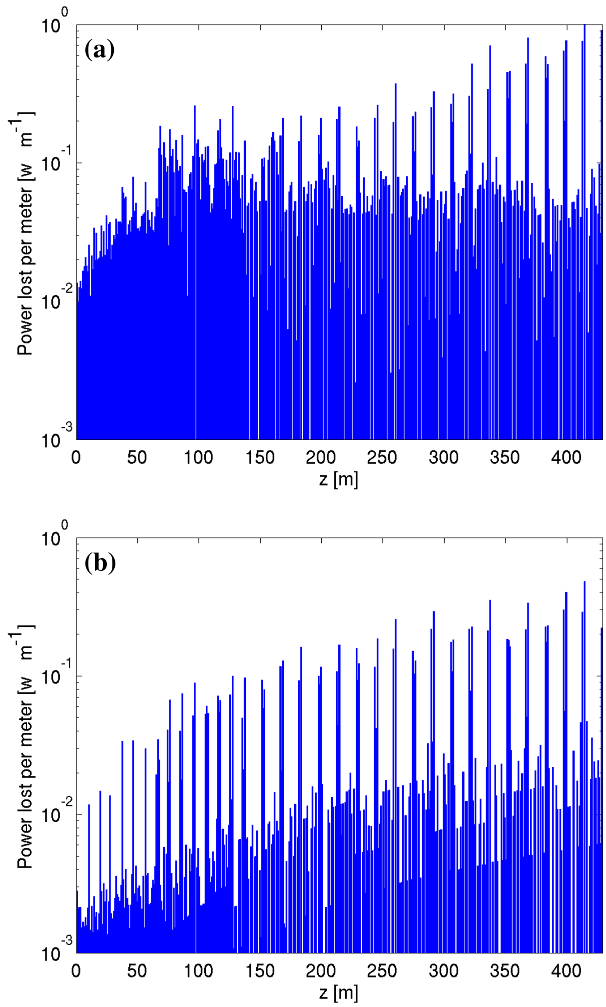

Figure 4: TRACK simulations of the beam power lost per meter from (a) intrabeam, blackbody, residual gas and lorentz stripping and (b) only residual gas along the FNAL linac operating at 3 MW.

ACKNOWLEDGMENT

The authors would like to thank B. Mustapha (ANL) and D. Uriot (CEA) for their support in using respectively the codes TRACK and TRACEWIN.

REFERENCES

[1] J. Alonso, FERMILAB-Conf-00/185, 2000.

[2] V. N. Aseev *et al.*, **TPAT028**, PAC05.

[3] TRACEWIN web site http://irfu.cea.fr/Sacm/logiciels/index3.php

[4] N. Solyak *et al.*, **MOP145**, these proceedings.

[5] V. Lebedev *et al.*, **THP080**, LINAC10.

[6] J.-P. Carneiro *et al.* **WEP091**, these proceedings.