LARGE SCALE SIMULATIONS OF THE FERMILAB 8-GEV H-MINUS LINAC: BEAM LOSS STUDIES FROM MACHINE ERRORS AND H- STRIPPING*

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Abstract

The latest parallel version of the beam dynamics code TRACK is capable of simulating a very large number of particles (1B or more). In the case of the Fermilab 8-GeV H-minus linac, it is possible to simulate the actual number of particles in the bunch. Taking advantage of this capability we are revisiting our original beam loss studies, but this time with larger statistics and including a new process of beam loss which is the stripping of H- ions. TRACK has recently been updated with the possibility of stripping H- by three different processes, namely black body radiation, residual gas interactions and Lorentz force stripping. Results of ideal end-to-end simulations (no errors) with the actual number of particles in a beam bunch (865M) as well as error simulations for different sets of errors with 10M and 100M particles per seed will be presented and discussed. These simulations were performed on Argonne's new computing facility "BG/P".

THE FERMILAB 8 GEV H-MINUS LINAC

The 8 GeV H-minus linac is part of an upgrade project for Fermilab to inject high-intensity proton beams into the Main Injector (MI) to use for a High Intensity Neutrino Source (HINS) [1]. The layout of the Linac and the HEBT leading to the MI is shown in Fig. 1.

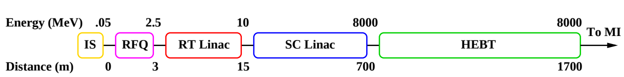

Figure 1: Simple layout of the FNAL 8 GeV linac.

The main parameters of the linac are given in Table 1. More details can be found in reference [2].

Table 1: Main Parameters of the Fermilab 8 GeV Linac

Parameter	Values
Output Energy	8 GeV
Output Frequency	1.3 GHz
Peak Current	45 mA
Average Current	25 mA
Pulse length	1 msec
Repetition Rate	10 Hz
Average Output Power	2 MW

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BEAM DYNAMICS SIMULATIONS WITH INCREASING STATISTICS

We have performed beam dynamics simulations for the ideal linac (no errors included) with increasing number of particles starting from 1 million (1M) to 865M which is the actual number of particles in a beam bunch at 45 mA. These simulations were performed on Argonne's new peta-scale computing facility "BG/P" [3] using the latest parallel version of TRACK [4]. Fig. 2 shows the beam total envelopes and emittances along the linac for 1M, 10M, 100M and 865M particles. It is important to mention that the corresponding rms envelopes and emittances (not shown) agree very well.

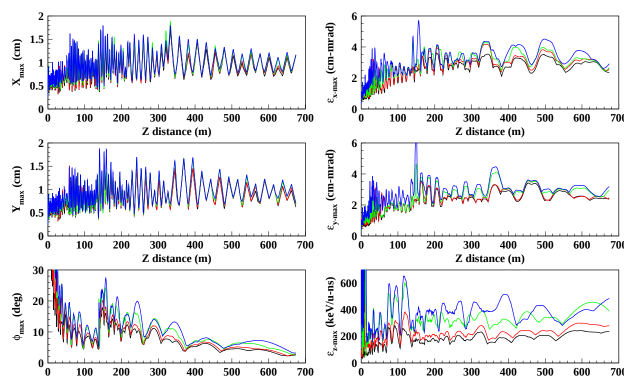

Figure 2: Beam envelopes (left) and total emittances (right) along the linac for 1M (black), 10M (red), 100M (green) and 865M (blue) particles.

We notice that the longitudinal quantities are generally more affected by the increasing statistics than the transverse ones. The emittances show a growth with increasing number of particles which reflects the formation of more tail as can be seen in Fig. 3 showing the phase space plots for increasing number of particles.

BEAM LOSS STUDIES

To Study beam loss, we perform beam dynamics simulations including all possible machine errors. From a given seed of a random number generator, we generate all the errors within their predefined distributions. The generated errors are then applied to the linac and the particles are tracked with this setup. This procedure is repeated for multiple seeds to simulate the linac with different setups. We typically use 100 seeds in our simulations. The whole 100 seed simulation is repeated for different error amplitudes to study the tolerances of a given design. The analysis of beam loss is a powerful tool to check the robustness of a given design. A design with excessive beam loss for the typical values of machine errors should be revised. Often multiple iterations are needed to reach a robust design.

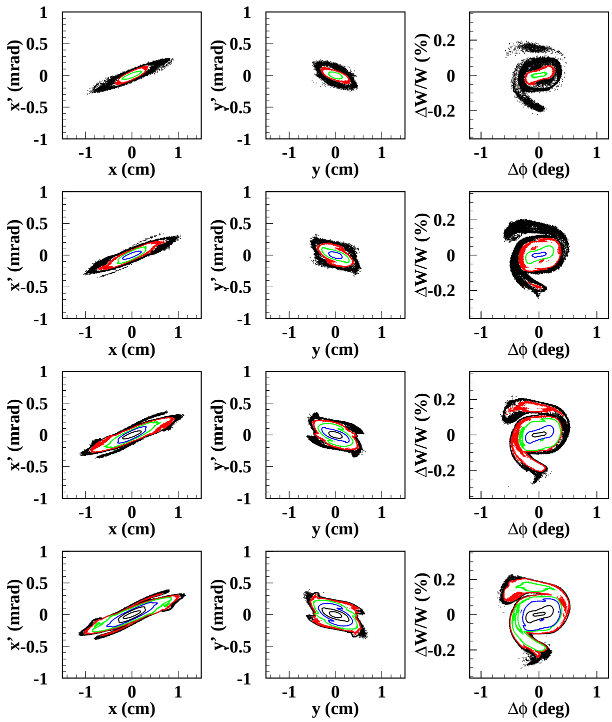

Figure 3: Phase space plots at the end of the linac with increasing number of particles from 1M (top) to 865M (bottom). The contours start from 1 particle (outer) and increasing in the power of 10.

Machine Errors and their Typical Values

Table 2 gives the list of machine errors included in the simulations and their typical values. The values are the maximum values for a uniform distribution and the rms values for a Gaussian distribution. A Gaussian error distribution is truncated at ± 3 times the rms value.

Table 2: Machine Errors and their Typical Values

Error	**Value**	**Distribution**
Cavity end displacement RT and SC spoke cavities SC Elliptical cavities	 0.5 mm 1.0 mm	 Uniform
Solenoid end displacement Short (18 cm) Long (32)	 0.15 mm 0.20 mm	 Uniform
Quad. end displacement	0.15 mm	Uniform
Quad. rotation error	5 mrad	Uniform
RF field amplitude jitter	0.5 %	Gaussian
RF field phase jitter	0.5 deg	Gaussian

It is important to note that in all the simulations reported in this paper we did not apply any corrections. In a real accelerator we should be able to correct all static errors but not the jitter (dynamic) errors. This should allow a better control on beam loss.

Previous Results Revisited

Due to a power normalization error, we have revisited our previous results [5] to have the right average output power of 2 MW at 1% duty cycle. The new results are shown in Fig. 4-(a) and Table 3. The main change is that the case with (1 %, 1 deg) was slightly below the 1 Watts/m limit, now it is slightly above. These simulations were performed using 100 seeds with 1M particles each and without corrections. Applying corrections to the (1 %, 1 deg) case should reduce the losses to be well below the 1 Watts/m limit.

Table 3: Beam Fraction Lost and Peak Power Loss for Different RF Jitter Errors

RF Errors	**Beam lost fraction**	**Peak power loss**
(0 %, 0 deg)	$1.6\ 10^{-5}$	0.2 Watts/m
(1 %, 1 deg)	$8.7\ 10^{-5}$	2 Watts/m
(2 %, 2 deg)	$2.9\ 10^{-2}$	800 Watts/m

Adding H-minus Stripping

TRACK has recently been updated to include H- stripping by three processes [6], namely black body radiation, residual gas interactions and Lorentz force stripping. Therefore, the beam pipe temperature and the quality of vacuum should be well controlled to limit H- beam loss by stripping. In these simulations, we assume the values given in Table 4.

Table 4: Temperature and Vacuum in Different Sections of the Linac

Section	**Temperature (K)**	**Vacuum (torr)**
RT Linac	300	10^{-7}
SC Linac	4	10^{-9}
HEBT	150	10^{-8}

Based on a previous study [6], the HEBT section should be cooled down to ~ 150 K to avoid excessive stripping by black body radiation which is the highest at 8 GeV. Fig. 4-(b) shows beam losses along the linac before and after adding H- stripping and Table 5 compares the beam fraction lost and peak power loss between the two cases. The results are for the linac only at (1%, 1 deg) RF errors.

Table 5: Beam and Power Loss Before and After Stripping

H- Stripping	**Beam lost fraction**	**Peak power loss**
No	$8.7\ 10^{-5}$	2 Watts/m
Yes	$4.6\ 10^{-4}$	10 Watts/m

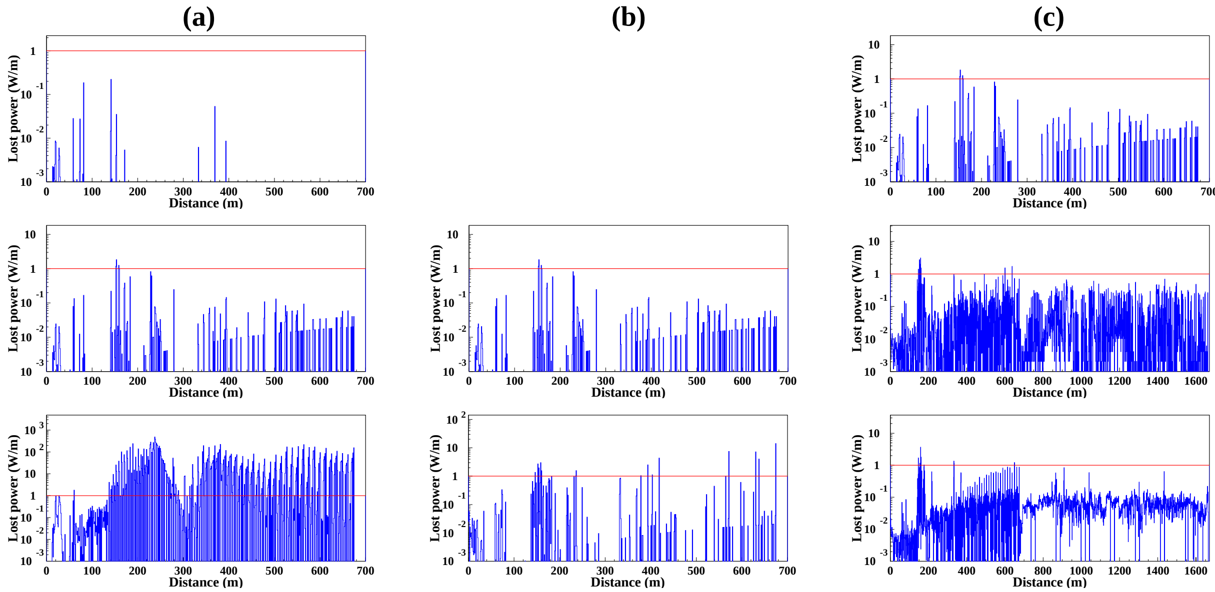

Figure 4: (a) Beam loss in Watts/m along the linac for RF jitter errors of (0 %, 0 deg) (top), (1 %, 1 deg) (middle) and (2 %, 2 deg) (bottom). (b) Beam loss in Watts/m along the linac before (top) and after (bottom) adding H-minus stripping. (c) Beam loss in Watts/m along the Linac and HEBT with increasing number of particles: 1M (top), 10M (middle) and after 100M (bottom).

Beam Loss with Increasing Statistics

Taking advantage of the new capability of TRACK we performed error simulations with increasing number of particles from 1M to 100M. Error simulations with the actual number of particles (865M) still a challenge because the simulation has to be repeated for 100 seeds. Fig. 4-(c) shows the beam loss for 1M, 10M and 100M particles. The simulations were performed for 1.7 km long Linac and HEBT including H- stripping and (1 %, 1 deg) RF jitter errors. The HEBT Section is about 1 km long transporting the 8 GeV H- beam from the exit of the linac for injection into the Main Injector. The HEBT comprises mainly quadrupoles and bending magnets as well as 4 buncher cavities.

From table 6, we notice a reduction in the fraction of beam lost and peak power loss with increasing number of particles per simulation to saturate at ~ 100 M. Tracking more particles reduces the discreteness of the simulation (charge per particle) which seems to lead to a reduction in beam losses.

Table 6: Beam and Power Loss with Increasing Statistics

Statistics	Beam lost fraction	Peak power loss
1M	5.0 10^{-4}	10 Watts/m
10M	3.7 10^{-4}	4 Watts/m
100M	3.4 10^{-4}	4 Watts/m

SUMMARY

Taking advantage of the new capability of the latest parallel version of TRACK to simulate very large number of particles, we have revisited our original beam loss studies in the Fermilab 8 GeV H-minus linac. In addition to higher statistics, we have included a new process of beam loss which is the stripping of H- ions by black body radiation, residual gas interactions and Lorentz force stripping. Results from end-to-end simulations with the actual number of particles in a beam bunch (865M) as well as error simulations with 10M and 100M particles per seed were presented and discussed. Tracking more particles reduces the discreteness of the simulation which allows a better description of beam halo and beam losses.

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