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Availability and Failure Effects of NLC Main Linac Mechanical Movers

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Abstract

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1 Introduction

In order to achieve its alignment tolerances, the NLC main linac will require a large installation of remote controlled translation stages with multiple degrees of freedom. In particular, each of the 591 quads in each 250 GeV main linac will be mounted on a magnet mover with 3 degrees of freedom (x, y, roll); each of the 2304 RF structure girders in each linac will be mounted on a girder mover with 5 degrees of freedom (x, y, roll, pitch, yaw).

Simulation studies of main linac operation typically assume that all movers are operational at all times, in order to limit the complexity of the simulation. This is obviously not a realistic expectation for a system with so many components, especially when the number of sub-elements of each mover (stepper motors, rotary encoders, position transducers, cabling, control electronics, database, operator) are considered. The unavailability risk of the mover system is of particular concern for the NLC, since very few accelerators have ever been built with such a large fraction of its beamline hardware on remote-controlled translation stages.

In order to predict the availability of the movers, it is necessary to estimate a few quantities, specifically: how often will a mover break (mean time between failures, or MTBF); how long will it take to repair a mover (mean time to repair, or MTTR); what is the performance "hit" which accrues when movers are broken? To answer the first two questions we used historical failure data from the two large mover systems at SLAC, in the arcs of the Stanford Linear Collider (SLC) and in the Final Focus Test Beam (FFTB). For the final question, we can get some estimate from simulation studies of the NLC main linac in normal operation.

2 SLC and FFTB Movers

The SLC collided electrons and positrons head-on, but accelerated both bunches in a single linac. The co-moving bunches were brought into collision by a pair of collider arcs which bent the beam trajectories around by approximately 270 degrees in each case (from eastbound to northbound to southbound for electrons, from eastbound to southbound to northbound for positrons). Each arc contained approximately 450 combined function bend- quadrupole- sextupole magnets. Each arc magnet was mounted on a mover with a single degree of freedom (horizontal for horizontally-focusing magnets and vertical for vertically-focusing magnets) and a total range of motion of approximately 2 mm [1].

The FFTB contained a total of 32 magnet movers. Each mover was capable of x, y, and roll motion via utilization of 3 stepper motors; total range of travel in each degree of freedom was approximately 3 mm [2].

2.1 Assessing Mover Availability

The MTBF and MTTR of the magnet movers at SLAC were estimated by querying the online database of accelerator hardware and software failures (Computer Aided Trouble Entry and Reporting, or CATER) [3]. During the period from January 1 1997 to December 31 2001 there were a total of 23 reported mover failures during beam operations, all from the SLC arc movers. The failures were further categorized as follows:

- Human error (inadvertent hardware disconnections, blown fuses, etc): 2 cases
- Electronics (drivers, connectors, power supplies, etc): 17 cases
- Stepper Motors (including stepper motor wires): 0 cases
- Mechanical (links, cams, lack of lubrication): 2 cases
- Software: 0 cases
- Unknown: 2 cases.

All of the failures listed above occurred during accelerator operations. Other failures that occurred during pre-operations checkout are not included.

It is rather remarkable that there was not a single failure of a stepper motor. All of the stepper motors used in these movers were Superior Electric SLO-SYN motors, which advertise "continuous running life of 5 years can be expected." This would imply a MTBF of 44,000 hours, which is far smaller than implied by the zero failures in the SLAC movers; this is presumably a function of the reduced duty cycle of the SLAC movers compared to the 100% assumed in the Superior Electric advertisement.

When the total "live time" for the movers was computed, the resulting MTBF for magnet movers is 353,000 hours. The MTBF for all subsystems other than electronics is 1,353,250 hours. The MTTR was 1.4 hours. There were no failures in 5447 hours of FFTB operations, suggesting a MTBF for the more complicated FFTB movers in excess of 174,300 hours.

2.2 Extrapolation to NLC

Estimating the availability performance of the NLC magnet and girder movers from the SLAC magnet movers is not straightforward for several reasons. First, duty cycle: the NLC movers will probably move on the order of 1 second out of every hour. This is far larger than the duty cycle for SLAC movers, which could often go for weeks without being moved; on the other hand, it is far smaller than the 100% duty cycle used by Superior Electric in their 44,000 MTBF estimate, and the SLAC mover failures were dominated by electronics, for which it is not obvious that a higher duty cycle translates to a shorter MTBF. Second, the SLAC mover experience is dominated by 1-DOF arc movers, rather than 3-DOF magnet movers which are closer to the NLC magnet mover design; the further extrapolation to 5-DOF girder movers is even less clear (is it the equivalent of 2 magnet movers?). Third, there were no failures amongst the FFTB movers which are quite similar to the NLC quad movers, but on the other hand the statistics for this model are relatively small. Finally, the most failure-prone portion of the system – the electronics – is also the portion that is most likely to be different from the present design. In some ways the electronics will be more robust, given that we will engineer the new design to address vulnerabilities found in the old design. Other changes may actually reduce the availability, for example changing the quad movers from half-stepping to microstepping.

Still, a few order-of-magnitude conclusions are possible from the SLAC mover experience:

- Given that the MTBF for the existing SLC movers is 353,000 hours and that the MTBF for FFTB movers exceeds 170,000 hours, it is unlikely that the MTBF for the NLC movers will be under 100,000 hours despite the foreseen changes in design and electronics. Similarly, it is probably not realistic to expect the MTBF of NLC movers to be more than 1,000,000 hours, since this would be a factor of 3 improvement over the far simpler SLC movers. A resonable MTBF for an NLC mover is therefore between 100,000 and 1,000,000 hours.
- The MTBF for the movers is probably dominated by failures outside the accelerator housing, which are easier and faster to find and fix than failures inside the housing.
- The MTBF for the stepper motors at low duty cycle is much longer than the advertised 44,000 hours for full duty cycle.

Given all of the above, we can arrive at some approximate values which can be used to understand the luminosity performance of the mover availability. For the study of availability in the *Technology Options Report,* for example, a MTBF of 500,000 hours was assigned to each mover's "in-tunnel" components; any component which failed in the tunnel was left broken until the next access period for critical repairs. Similarly, a MTBF of 100,000 hours was assigned to each "out-of-tunnel" electronics unit, and a MTTR of 1 hour was assigned to this device. Each electronics unit controls 16 movers in this model [4]. Given that each NLC magnet mover has 3 stepper motors, it is reasonable to estimate that the MTBF for an NLC magnet mover would be about 1/3 as long as for an SLC arc mover which has 1 stepper motor. This would lead one to estimate an MTBF for "in-tunnel" subsystems of 450,000 hours and an MTBF for "out-of-tunnel" failures of 118,000 hours, which is rather close to the values used in the *Technology Options Report.* One might expect that the MTBFs for girder movers, using this logic, are only 3/5 as large as those for magnet movers. In this study we neglect this and use the 500,000/100,000 values for both systems.

3 Severity of Mover Failure

During normal operation of the linac, movers will be actuated to compensate for the effects of slow diffusive ("ATL") motion. In order to study the impact of this motion we repeatedly simulated ATL motion of the linac and simulated re-steering it in segments. For the simulation study, a total of 24 segments per linac were assumed, with a 60 second interval between steering one segment and steering the next. Thus, the time needed to move every element in the linac from an "old" position to a "new" one was 24 minutes. The steering operation was repeated 50 times for the entire linac. An "A" coefficient of 5×10^{-7} μm^2/m/second was used, corresponding to conditions at a reasonably quiet site with good geology.

Figure 1 shows the RMS change in quad mover setpoint in the linac as a function of time. From the ATL relation one may predict that the RMS change from the mover setpoints at $t = 0$ should grow as $t^{1/2}$. The curve in Figure 1 is close to this but a bit slower (a good fit is $t^{0.45}$); for our purposes a growth as $t^{1/2}$ is an acceptable approximation. After 20 hours, devices have typically converged on setpoints 0.8 μm from their initial ones. Since the algorithm for the RF girder movers causes them to "follow" the motion of the beam (which is controlled by the motion of the quads), it is expected that the RMS change in girder mover setpoint will follow the same law as the quad movers.

3.1 Emittance Consequences of Failed Movers

If some fraction of the magnet movers have failed, then the obvious consequence is that those magnets do not move to their new setpoints for some period of time. Assuming that the failed movers are detected, the simplest way to handle them is to remove them from the steering procedure entirely – let all the other movers in the beamline converge to their new setpoints and leave the magnet or structures on the broken mover fixed in position wherever they happened to be when their mover failed.

For incoherent beam-to-quadrupole offsets (ie, offsets with no component that resembles a betatron oscillation), the relation between emittance dilution and offset is given by:

$$\Delta\gamma\epsilon = \sum \mathcal{K}_j (\Delta y_j)^2, \tag{1}$$

where $\mathcal{K}$ is the relationship between offset and emittance for the jth quad, and Δy_j is the beam-to-quad offset for that quad. For the NLC main linac as an ensemble, this relationship can be approximated as:

$$\Delta\gamma\epsilon = N\mathcal{K}\sigma_y^2, \tag{2}$$

where N is the number of quads in the linac, σ_y is the RMS beam-to-quad offset, and $\mathcal{K}$ is an ensemble factor equal to approximately 0.931 m^{-1}. In the case of the NLC main linac, the emittance tuning algorithm is expected to converge on a dispersive emittance growth of 2.2 nm, corresponding to $\sigma_y = 2.0\ \mu\mathrm{m}$ [5].

If some number of magnets N_b lose the use of their movers, then the RMS offset of these movers will be the sum in quadrature of their post-tuning offset σ_y and the beam-to-quad offset from the mover not following the motions of the rest of the beamline. Let us denote this distance σ_b, thus:

$$\begin{aligned} \Delta\gamma\epsilon &= N\mathcal{K}\sigma_y^2 + N_b\mathcal{K}\sigma_b^2, \\ &= \Delta\gamma\epsilon_0 + N_b\mathcal{K}\sigma_b^2, \end{aligned} \tag{3}$$

where $\Delta\gamma\epsilon_0$ is the nominal emittance growth in the absence of broken magnet movers (the aforementioned 2.2 nm for growth from quadrupole offsets).

A similar law can be derived for RF girder failures, specifically:

$$\Delta\gamma\epsilon = 1.4\ \mathrm{nm} + N_b\mathcal{R}\sigma_b^2, \tag{4}$$

where $\mathcal{R} = 0.0675\ \mathrm{m}^{-1}$.

4 Net Impact of In-Tunnel Failures

Given an ensemble of 591 quadrupole movers, each of which has a MTBF of 500,000 hours, and assuming that all movers are operational at some time $t = 0$, we expect the number of broken movers N_b at a time $t > 0$ to be approximately given by $N_b = 1.18 \times 10^{-3}\ \mathrm{h}^{-1} t$. Figure 1 shows that if a magnet mover breaks and becomes stuck at a certain position, while all the other magnets and RF girders are continually realigned to compensate for the effects of ATL motion, the RMS offset of the quad on the broken mover from its optimal position grows with $\sqrt{t}$; a numerical fit to the curve in Figure 1 indicates that the relationship is approximately $\sigma^2 \approx 1.6 \times 10^{-15} (\mathrm{m}^2/\mathrm{h})\ t$. We can use this as an estimator for the quantity σ_b in Equation 3. In the continuum limit, the expected emittance dilution from failed quad movers at time t is given by the second term on the RHS of Equation 3, with N_b and σ_b replaced by the expressions $N_b = 1.18 \times 10^{-3}\ \mathrm{h}^{-1} t$, $\sigma_b^2 \approx 1.6 \times 10^{-15} (\mathrm{m}^2/\mathrm{h})\ t$:

$$\begin{aligned} \Delta\gamma\epsilon &= \frac{\mathcal{K}}{2}(1.18 \times 10^{-3}\ \mathrm{h}^{-1})(1.6 \times 10^{-15} \mathrm{m}^2/\mathrm{h}) t^2, \\ &= 8.79 \times 10^{-19}\ \frac{\mathrm{m}}{\mathrm{h}^2} t^2, \end{aligned} \tag{5}$$

where the additional factor of 1/2 takes into account the fact that the offset of a given magnet to the beam begins when that magnet's mover breaks, which is not necessarily at $t = 0$.

Figure 2 shows the expected emittance growth as a function of time over 1 calendar year if no broken magnet movers are repaired during that time. Note that the maximum value achieved is slightly under 0.07 nm, which is 0.35% of the 20 nm damping ring emittance. Thus the expected emittance growth from magnet mover failures is negligible, even if the movers are left in a failed state for a considerable length of time. It is interesting to note that a previous study indicated that failure of up to 5% of all linac movers would typically incur emittance growths of under 2 nm [6]. According to the figures established above, the mean time needed for 30 quad movers (5% of 591 movers) to fail is about 25,000 hours, and Equation 5 predicts an emittance growth of 0.5 nm, or 2.5%, after that time. This is quite compatible with the earlier estimate.

Applying a similar logic to the RF girder movers, we find that:

$$\Delta\gamma\epsilon = 2.49 \times 10^{-19}\ \frac{\mathrm{m}}{\mathrm{h}^2} t^2, \tag{6}$$

which is even less worrisome than the quad mover failure relation. Note that even if the girder mover MTBF is only 3/5 as long as the magnet mover MTBF (ie, 300,000 hours) the emittance growth from broken girder movers is still negligible.

5 Net Impact of Out-of-Tunnel Failures

In the case of RF girders, we can use the logic of the previous section to calculate the emittance dilution from a 16-channel mover controller failure. With a total of 144 RF girder controllers and a 100,000 hour lifetime, the number of failed controllers is 1.44×10^{-3} h^{-1} t, but the number of stuck RF girders is 16 times as large, or 2.30×10^{-2} h^{-1} t. This leads to an emittance growth versus time for failed RF girder controllers given by:

$$\Delta\gamma\epsilon = 1.24 \times 10^{-18}\ \frac{\mathrm{m}}{\mathrm{h}^2} t^2. \tag{7}$$

After 10,000 hours of operation the emittance growth from failed girder mover controllers could become comparable to the damping ring extraction emittance. Fortunately the MTTR for mover electronics is only 1 hour, and the mover electronics are accessible for repairs at all times. Thus there is no reason to expect that the NLC will go for 10,000 hours without any mover electronics repairs. Any reasonable frequency of repair – daily, weekly, or even monthly – will keep emittance growth from this source from ever being an issue for the linear collider.

A more difficult case to estimate is the emittance growth from a quad mover controller failure immobilizing 16 consecutive quads. The logic used for the girder-mover controller would suggest that

$$\Delta\gamma\epsilon = 4.40 \times 10^{-18}\ \frac{\mathrm{m}}{\mathrm{h}^2} t^2. \tag{8}$$

For the quadrupoles this logic breaks down because when several consecutive quad movers fail the beam develops betatron motion over the span of several quads – in essence, the underlying assumption of incoherent misalignments breaks down. Nonetheless, even if Equation 8 is wrong by many orders of magnitude, daily replacement of failed controllers will limit the emittance growth to unmeasurably small values.

6 Extrapolation to Less Optimal Geologic Conditions

The estimates of mover-failure severity in the previous sections assumed an ATL coefficient of 5×10^{-7} $\mu\mathrm{m}^2/\mathrm{m/s}$, comparable to what is observed at sites with favorable geology. At other sites the coefficient can be orders of magnitude larger. The emittance dilution in these cases scales linearly from what was shown above when using larger ATL coefficients. For example, the ground motion model for a site similar to KEK assumes about 20 times as much ground motion, or $A = 1 \times 10^{-5}$ μm^2/m/s [7]. In this case the emittance dilution from failed quad movers would reach 1.4 nm (7%) after one calendar year, but the nominal plan of repairing failed magnet movers within several weeks or a few months of their failure is still perfectly acceptable. As with the more optimal case, there would be no particular urgency to the mover repairs. Similarly, repairing failed girder movers at several week intervals and repairing failed controllers within one day of failure all appear to be reasonable even at a site with relatively large diffusive ground motion.

7 Estimation of Mover Availability in the *Technology Options Report*

In the *Technology Options Report,* failure of main linac mover systems was included in the estimate of integrated luminosity for the X-band linear collider ("US-Warm" option). The MTBF of the mover systems was as described above (500,000 hours for "inside" failures and 100,000 hours for "outside" failures). The MTTR was also included as described above (1 hour for "outside" failures; "inside" failures were left in a failed state until the accelerator was accessed for other, more critical repairs).

The *Technology Options Report* assumed that "outside" failures, which disabled 16 consecutive movers, did not have a luminosity impact on the machine. They also assumed that the luminosity was reduced by 1% for each "inside" failure, and that if the number of "inside" failures was sufficiently large the experts would "tune around" the broken units; such "tuning around" would take 30 minutes and would almost completely restore the luminosity (there would be a 0.1% persistent reduction until all movers were restored to operation).

The MTBF values in the *Technology Options Report* actually appear to be conservatively low compared to what SLC and FFTB experience would suggest. On the other hand, most of that experience is with the SLC arc mover, which is somewhat simpler in design than the NLC movers will be. The FFTB mover is quite similar to the NLC movers but operating statistics on this model are relatively poor. Finally, the NLC movers are expected to have a duty cycle which is much higher than either the SLC or FFTB units had, although still far from the 100% duty cycle used by Superior Electric in evaluating their SLO-SYN stepper motor MTBF. For all these reasons, some additional conservatism when extrapolating from SLAC movers to NLC models is warranted. The MTTR for "outside" failures is consistent with SLAC experience with magnet movers. The impact of "inside" failures is primarily set not by MTTR (assumed to be 2 hours in the *Technology Options Report*) but by the decision to continue to run with failed movers until some other, more serious failure is addressed by accessing the tunnel.

The assumption in the *Technology Options Report* that mover controller failures do not reduce the luminosity appears to be entirely justified by a more careful analysis of failed movers. The emittance increase due to the failed movers builds up very slowly over time, and in fact the characteristic time is orders of magnitude longer than the MTTR. The assumption of 1% luminosity reduction per failed mover for "inside" faults is, if anything, pessimistic; there appears to be no obstacle to ignoring small numbers of failed movers for extremely long periods.

8 Conclusions

The *Technology Options Report* included several assumptions about the impact of failed magnet or RF girder movers on the integrated luminosity of the X-band linear collider. These assumptions included mean time between failures (500,000 hours for "inside" failures and 100,000 hours for "outside" failures), mean time to repair (2 hours to do the work following a period of waiting for access for "inside" failures which could be several weeks, 1 hour for "outside" failures), and luminosity impact during the period between failure and repair (1% luminosity reduction per "inside" failure, no impact for "outside" failures). Based on the SLAC experience, the MTBFs in the report are somewhat conservative, but perhaps not insane given known differences between the SLAC mover systems and the systems planned for NLC, and the MTTRs are approximately correct. Simulation studies of accelerator alignment as a function of time suggest that the *Technology Options Report* is probably far too pessimistic in estimating the luminosity impact of failed movers. Although the luminosity will gradually degrade as more movers become stuck and as the rest of the beamline diffuses further and further away from the stuck elements, the time required for even a 1% luminosity reduction appears to be much larger than the anticipated period between repair opportunities. This is the case even assuming a relatively large diffusive ground motion component, such as what has been measured at KEK. We conclude that mover failures will cause negligible luminosity loss in the NLC.

9 Acknowledgements

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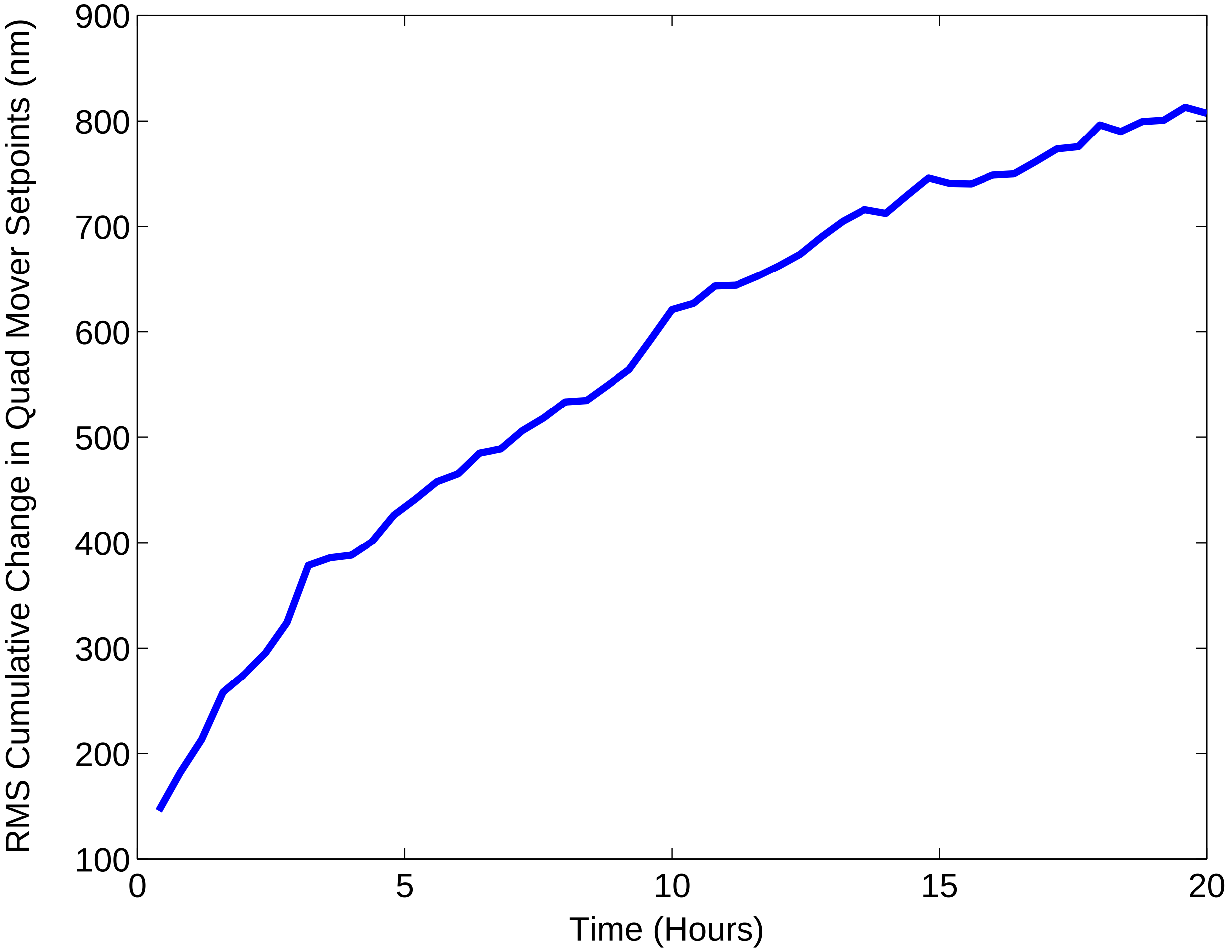

Figure 1: Time evolution of the RMS change in magnet mover setpoints as the linac is re-steered to take out the effects of ATL motion.

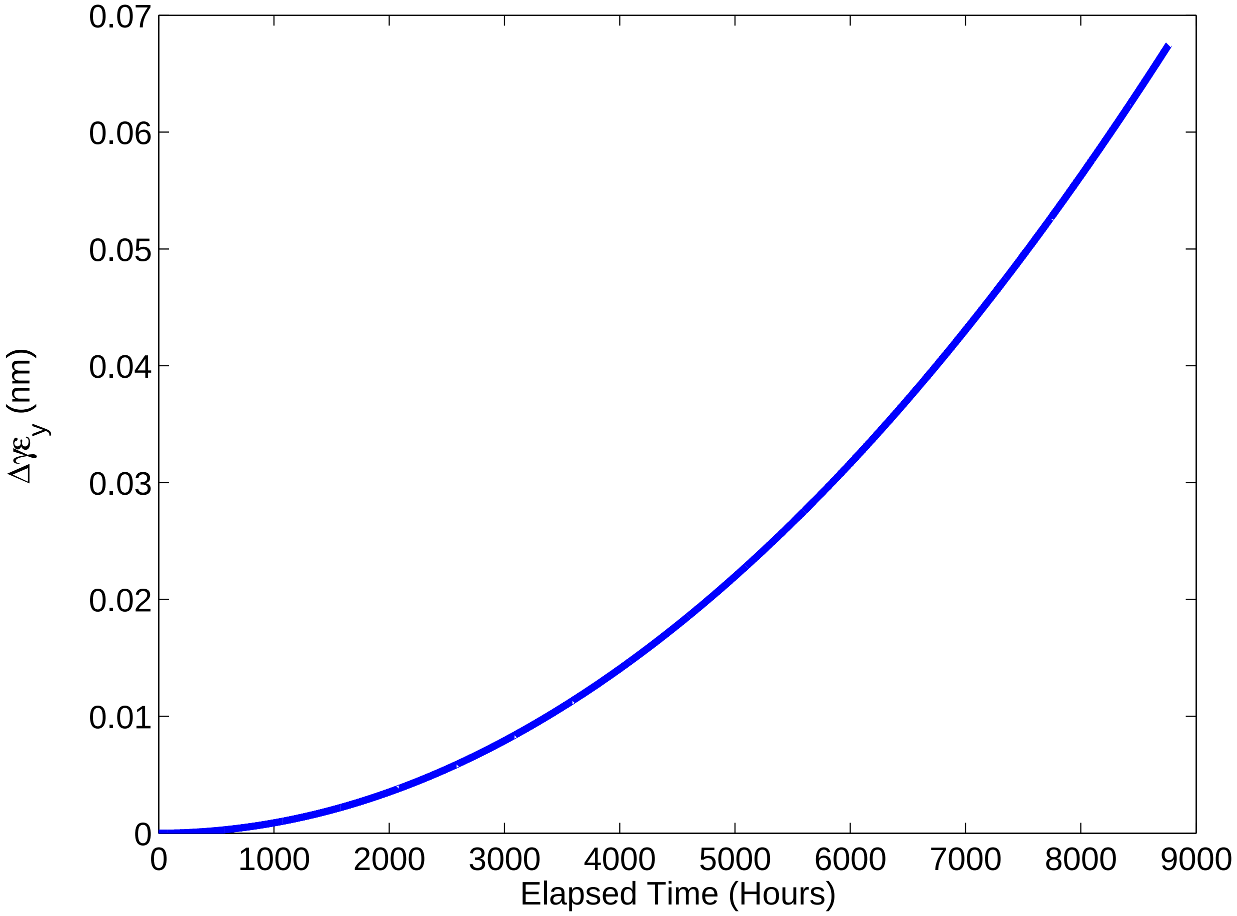

Figure 2: Expected emittance growth from failed quadrupole movers in the main linac, as a function of time in hours.