A STUDY OF FAILURE MODES IN THE ILC MAIN LINAC*

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Abstract

Failures in the ILC can lead to beam loss or even damage the machine. In the paper quadrupole failures and errors in the klystron phase are being investigated and the impact on the machine protection is being considered for the main linac.

INTRODUCTION

The main linac is the most expensive subsystem of the proposed International Linear Collider (ILC). Even a seldom failure scenario may be worth considering. On the other hand the large iris of its cavities provides for a higher operational safety margin compared to most other ILC subsystems. Several intricate failure scenarios are conceivable. Here we will investigate two examples where component failures cause a beam deflection large enough to hit the cavities.

METHOD

When the beam becomes unstable the details on how and where particles are lost depend on small differences in the linac alignment. We therefore consider a realistic model for an already commissioned, working linac with remaining alignment errors in the order of a few $100\ \mu m$ (Table 1). In this model an 1-to-1 steering algorithm is integrated to set the corrector dipoles in a way that all BPM readings go to zero. For the simulation we consider a linac of total arc length $10237.800\ m$ following the earth curvature. The initial beam energy is $15\ GeV$ and the (nominal) final beam energy $250.299\ GeV$. It consists of 302 quadrupoles with corrector dipoles and an equal number of klystrons. Each klystron feeds 24 cavities contained in 3 cryomodules. The gradient is $31.5 MV/m$ and the phase advance per FODO cell $\Theta_x/\Theta_y = 75^0/65^0$.

The simulation code is based on the Merlin library [1]. In addition results are confirmed with Placet [2].

	$\sigma_{x,y}$	σ_{rot-z}	$\sigma_{rot-x,y}$
Quadrupole	$300\ \mu$	$300\ \mu rad$	
BPM	$200\ \mu$		
Cavity	$300\ \mu$		$300\ \mu rad$
Cryomodule	$200\ \mu$		

Table 1: Assumed alignment errors for different linac components.

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RESULTS

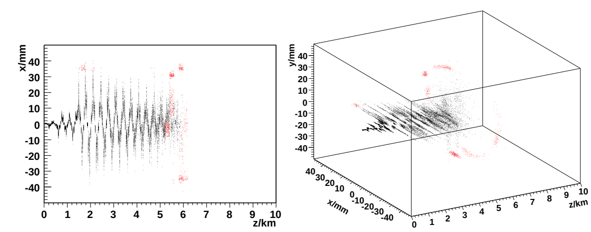


Figure 1: An example with 14 randomly failed quadrupoles along the beam line. Shown are the beam particles (black) at the position of the BPMs and the lost particles (red).

failing quads	% lost particles	failing quads	% lost particles
2	2 %	10	80 %
6	37 %	12	95 %
8	73 %	14	100 %

Table 2: Fraction of lost particles for different numbers of failing quadrupoles randomly distributed along the ILC main linac (preliminary).

Quadrupole Failures

If a quadrupole fails in our model the still active dipole field of the corrector will cause a kink in the nominal particle trajectory proportional to the compensated alignment error. A quadrupole failure does not only create a kink but it also modifies the β-function of the lattice. For the ILC main linac a typical quadrupole strength is $k \approx 0.06\ m^{-1}$. For an misalignment of $a = \sqrt{a^2_{Quad} + a^2_{BPM} + a^2_{Cryomodule}} \approx 400\ \mu m$ we get a typical value for the deflection of $\Delta\Theta = ka \approx 24\ \mu rad$. In a periodic FODO lattice the deviation would stay below $\Delta x < \Delta\Theta\, \beta_{max}/2 \approx 1.5\ mm$ ($\beta_{max} = 120\ m$) but since a quadrupole failure modifies the β-function the observed deviations are larger and the beam will already be lost at a smaller number of failing quadrupoles. For a first estimate we consider n failing quadrupoles in a row of length nL, where $L \approx 36\ m$ is the distance between 2 quadrupoles. The average deviation at the end of the row is: $\langle \Delta x^2 \rangle = \sum_{i=1}^{n} (n-i)^2 L^2 \langle \Delta\Theta^2 \rangle$. This expression exceeds the cavity aperture of r=35mm for 18 successive failing quads. A single quadrupole failure will not direct the beam outside the cavity aperture. This simple estimate has been verified by detailed simulations. Table 2 shows the results for the case where the failing quadrupoles are randomly distributed along the ILC main linac. An example case is shown in Figure. 1: The first quadrupole failures introduce strong betatron oscillations and destroy the quality of the beam but they are not able to drive the beam outside the acceptance. Only the collective effect of several failures can eventually accomplish this. It is obvious from Figure. 1 that when the beam is lost the β-function is so large that the beam is sufficiently diluted not to harm any of the linac components. The results in Table 2 are based on 100 different configurations randomly chosen according to Table 1. The detailed simulations show that on average only 8 failing quadrupoles are necessary for a beam loss.

Klystron Failures

A change of the klystron phase will modify the acceleration. Eventually the deviation from the design beam energy becomes too large and the beam will become instable. Here we consider the case that the phase for all klystrons is changed by a common offset. The ILC main linac has a length of $l \approx 10\ km$ and the beam energy goes from $E_0 \approx 15\ GeV$ to $E_F \approx 250\ GeV$. We therefore can assume that, at position z, the beam energy is approximately $E(z) = E_0 + z/l(E_F - E_0)\cos\phi$, where ϕ is the common klystron phase offset. An energy change $E \rightarrow E(1+\delta)$ modifies the focal length of a quadrupole $f \rightarrow f(1+\delta)$ and the stability criterion for a periodic FODO lattice of cell length $2L$ requires that the betatron phase advance Θ_δ per FODO cells stays real:

$$|\cos\Theta_\delta| = |\frac{1}{2}Tr[M_{FODO}]| = |1 - \frac{L^2}{2f^2(1+\delta)^2}| < 1.$$

This becomes violated at $1 + \delta_{critical} = \sin\frac{\Theta_0}{2}$ where Θ_0 is the design phase advance of the lattice. In the approximation of a periodic FODO lattice along the length of the ILC main linac the stability criterion becomes violated at

$$\cos\phi = 1 + \delta_{critical}(1 + \frac{lE_0}{z(E_F - E_0)}). \qquad (1)$$

For the ILC the phase advance will be $\Theta_x/\Theta_y = 75^0/65^0$ corresponding to a stability limit for the energy shift of $\delta^x_{critical} = -0.39$ and $\delta^y_{critical} = -0.46$. The beam will therefore be lost predominantly in the horizontal plane at a klystron phase $\phi \geq 54^0$.

The above considerations have been confirmed by Merlin and Placet simulations. Table 3 shows the reduction of the final beam energy for different klystron phase shifts. At $\phi = 56^0$ half of the beam particles are lost (0 % at 54^0, 50 % at 56^0 100 % at 58^0). Figure 2 shows the distribution of lost particles along the linac. The particles are lost as expected predominately in the horizontal plane and as the phase shift increases earlier in z. At large phase shifts the different phase advance becomes less important and the distribution of lost particles becomes symmetrical in x and y.

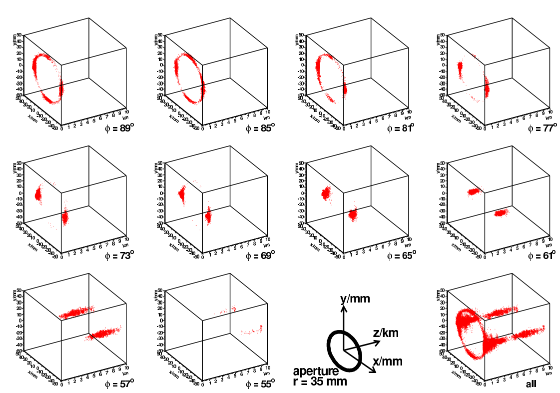
The beam is not lost within a single cavity but is spread over several modules.

ϕ	0^0	9^0	18^0	27^0	36^0
E_ϕ/GeV	251.5	248.6	240	225.9	206.4
45^0	54^0	63^0	72^0	81^0	90^0
182.3	154.0	(56.3)	(29.3)	(19.4)	(15.0)

Table 3: Final beam energy for different klystron phase offsets. Energy values in parentheses means that the beam is lost before the reduced final energy is reached.

Particle Densities

The final simulations are concerned with the question whether it is possible for a given misalignment configuration to lose the beam while the beam emittance is still small. Is it possible to create a large enough particle density to damage the accelerator cavities? To answer this questions the above simulations of klystron phase shifts had been repeated for 500 misalignment configurations randomly chosen according to Table 1. For each simulation 1000 particles are tracked. Then the particle density per cavity and mm^2 are calculated and for each misalignment configuration and for each klystron phase offset the maximum particle density is plotted as shown in Figure 3. Here a simplified model for the accelerator cavities is used where the aperture is represented by a single iris of radius $r = 35\ mm$ per cavity. The pattern of particle loss in Figure 3 follows equation (1) for $\delta = -0.46$. The plot shows that the maximum density stays below $10\ \%/mm^2/$cavity. This allows us to estimate the absolute particles density.



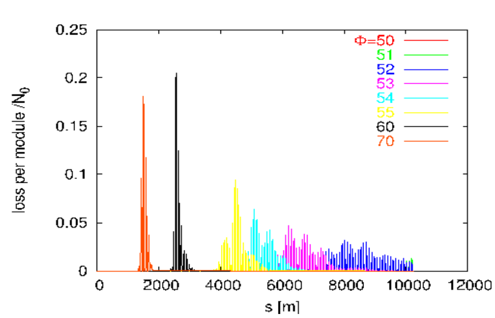


Figure 2: Spatial distribution of lost particle for different klystron phase shifts ϕ.

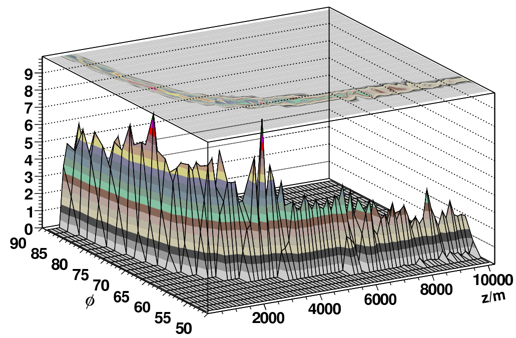


Figure 3: Maximum relative density of lost particles per cavity and mm^2 collected from 500 different configurations of misalignment.

For a SC module with 9 cells and a typical ILC bunch with $2 \cdot 10^2$ particles per bunch and 3000 bunches per train:

$$10\,\% \cdot 2 \cdot 10^{10} \cdot 3000/9 = 7 \cdot 10^{11} \text{ particles}$$

The typical particle density to generate a hole (copper) is $10^{13}/mm^2$. We are still more than an order of magnitude away from the critical value. Furthermore the above argument overestimates the particle density because two bunches will probably not hit exactly the same spot. Since the particles in different bunches are uncorrelated the the average density will be smaller. A reasonable control system that can abort the beam early will be able to reduce this value even further

CONCLUSIONS

- A single quadrupole failure will not direct the beam outside the cavity aperture. About 8 failing quadrupoles at random positions along the ILC main linac are necessary.
- A common klystron phase shift must become larger than 53^0 to lose more than 50% of the beam particles.
- A common feature in the studied examples is that the beam emittance is largely increased before the beam is lost.
- The particle densities observed in the cavities are less than $10^{13}/mm^2/\mathrm{cavity}$. There is no need for an abort system along the length of the linac.

REFERENCES

[1] http://www.desy.de/~merlin

[2] D. Schulte et al., CERN/PS 2001-028 AE and PAC2001