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Comparison Study of Electromagnet and Permanent Magnet Systems for an Accelerator Using Cost-Based Failure Modes and Effects Analysis*

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Abstract

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Abstract—**The next generation of particle accelerators will be one-of-a-kind facilities, and to meet their luminosity goals they must have guaranteed availability over their several decade lifetimes. The Next Linear Collider (NLC) is one viable option for a 1 TeV electron-positron linear collider, it has an 85% overall availability goal. We previously showed how a traditional Failure Modes and Effects Analysis (FMEA) of a SLAC electromagnet leads to reliability-enhancing design changes. Traditional FMEA identifies failure modes with high risk but does not consider the consequences in terms of cost, which could lead to unnecessarily expensive components. We have used a new methodology, "Life Cost-Based FMEA", which measures risk of failure in terms of cost, in order to evaluate and compare two different technologies that might be used for the 8653 NLC magnets: electromagnets or permanent magnets. The availabilities for the two different types of magnet systems have been estimated using empirical data from SLAC's accelerator failure database plus expert opinion on permanent magnet failure modes and industry standard failure data. Labor and material costs to repair magnet failures are predicted using a Monte Carlo simulation of all possible magnet failures over a 30-year lifetime. Our goal is to maximize up-time of the NLC through magnet design improvements and the optimal combination of electromagnets and permanent magnets, while reducing magnet system lifecycle costs.**

***Index Terms*— Accelerator, Cost, FMEA, Magnet, Reliability.**

I. Introduction

There is worldwide consensus that a high-energy, high-luminosity, electron-positron linear collider, operating concurrently with the Large Hadron Collider, is necessary to explore and understand physics at the TeV scale. The linear collider (LC) is envisioned as a fully international project, thus there will be only one LC to serve the world particle physics community and it must meet its luminosity goal through a guaranteed availability over a 30 year lifetime. Therefore, every LC component must be highly reliable and/or quickly repairable.

One viable manifestation of a 1TeV LC is the Next Linear Collider (NLC), based on normal conducting X-band cavities. In its 2003 configuration the NLC is roughly 32 km in length and uses about 70,000 components of which 8653 are magnets and another 6670 would be power supplies (PS), if all the magnets were electromagnets. It was thought there would be some advantages to replacing some of the electromagnets (em) with permanent magnets (pm), although every pm would need at least 20% of adjustability in its integrated strength to take part in a beam-based alignment procedure. For example, 3371 of the 8653 electromagnets could be replaced with adjustable permanent magnets and the number of power supplies would decrease to 3998, we call this a hybrid magnet system. We have developed a set of analysis procedures for engineers to use to compare an all-electromagnet LC with a hybrid magnet LC, from the reliability, availability and cost points of view.

Our new procedures allow engineers to decide how much money to spend on improving the availability of any LC component through design or other changes. The LC will not be built if it is "too expensive", we must find an appropriate balance between performance, reliability and cost. This paper uses the magnets and power supplies of the NLC to illustrate some useful modifications to the Failure Modes and Effects Analysis (FMEA) risk-identifying technique, which involve life cycle costs, from design to operation.

II. Problems With Traditional FMEA

A team of engineers following the traditional FMEA process consider all the possible failures modes of a system component, from design through operation, identify all their causes, and rank their severity, expected frequency and likelihood of detection. A multidisciplinary team at SLAC carried out a FMEA of a standard SLAC electromagnet [1] and identified 10 design changes that would improve its reliability. A prototype NLC quadrupole that incorporated most of these changes was fabricated in 2000 [2] and has been run for about 10,000 hours since without any failures. The degree of risk of each failure is represented by the product of these 3 ranked indices, called the Risk Priority Number (RPN). But inconsistent definitions result in questionable risk priorities, and the use of failure modes rather than cause and

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effect fault chains inhibits ones understanding of the true causes of failures [3]. Furthermore traditional FMEA ends with the calculation of RPNs, the team does not consider the consequences of the failures in terms of costs. They do not check that their design changes for avoiding failures cost less than the failures [4].

III. Lifetime Cost: a Measure of Risk.

Risk contains two basic elements (1) chance, measured by probability, and (2) consequence, measured by cost. A new methodology has been developed to overcome these shortcomings, it is called "Life Cost-based FMEA" [3], [4] It measures risk of failure in terms of cost. Cost is a universal language understood by engineers without ambiguity. Expected failure cost is defined as the product of the probability of a particular failure and the cost associated with that failure. Lifetime failure cost is the sum of all the expected costs for all failure scenarios at all stages of a system component's life: design, manufacture, installation, and operation. The probability of a failure can be characterized as the frequency of such failures in a system containing multiple components, e.g. in an accelerator with 6085 water-cooled magnets there will be 7 water leaks a year that cause a severe enough magnet failure to bring down the beam. The cost of each water leak includes labor costs to detect it, repair it and get beam running again, which are proportional to the times these tasks take, and the costs of parts that have to be replaced, e.g. a piece of Synflex water hose with fittings.

One performance parameter for a particle accelerator that a cost-based FMEA can help to improve is its “availability”, A, which is defined as the average ratio of the time a component or system is usable to the total amount of time it is needed. It is calculated as the ratio of the Mean Time Between Failures (MTBF) to the sum of MTBF and the Mean Time To Repair (MTTR). MTBF is the reciprocal of failure rate.

In order to be confident in expected failure costs there must be confidence in the failure rates and repair times being used. There are 2 main methods to estimate the MTBF and MTTR of accelerator components, either one uses historical operating data of such devices or one takes failure rates from published failure data tables for the various parts of the device and adds them together. Previously we have used the SLAC accelerator failure database (CATER) to make predictions about the availability of all the electromagnets (em) and their PS in the 2001 configuration of the NLC [5]. However we have no operating data on adjustable permanent magnets (at SLAC or any other accelerator) and had to use a mixture of the two methods, and study devices with similar parts.

IV. Estimate NLC Magnet Failure Occurrence Rates

Our premise is that the design of the NLC electromagnets and PS, their fabrication techniques, installation, maintenance schedules and repair procedures will be very similar to those used at SLAC over the past 27 years (8 years for PS), therefore they will have the same failure modes occurring at the same rates as SLAC failures. If the predicted availability of the NLC electromagnet system with these failure rates is less than the 0.95 required of it, then we study the failure rates and lifetime costs of the failures to determine which magnet system components should be redesigned for higher reliability. The same procedure was applied to the hybrid magnet system (it not being possible for all 8653 NLC magnets to be permanent, just injector and main linac magnets would be.)

A. Find MTBF & Availability of SLAC Electromagnets

We scoured the CATER database to find all magnet, switching PS and magnet mover failures in any beamline at SLAC which brought down the beam in the 5 year period 1997 to 2001. We categorized failures by magnet type: solid wire or water cooled and PS type: "small": <12A, <0.5KW and "large": >12A,>0.5kW. We carefully counted how many magnets, PS and movers were running in each beamline, and established how many hours each beamline was scheduled to run in that 5 years, thus we calculated number of magnet hours = no. magnets x no. running hours. Then we calculated the MTBF for any one magnet in that beamline = no. magnet hours / no. failures reported. Table 1 shows the data for water cooled magnets for selected beamlines. We chose not to include failures of the magnets in the SLC damping rings because they had known design flaws, imposed by severe space constraints, and we would not design NLC magnets with these same flaws. The MTBFs for different families of magnets, designed and built at various times the past 40 years cover a wide range; we used the average of 15 beamlines.

Details of each failure in CATER gave the amount of time to detect, i.e. to realize which component’s failure had brought down the beam, and to repair it, adding all failures yielded the total time the beam was down, which we called the time to

TABLE I

Measuring Availability of Water cooled Magnets at SLAC, 1997-2001, Selected Beamlines

Dates Line Ran	Beam Line	Run Hours	No. of Magnets	Magnet Hours	No. of Failures	MTBF (hr)	TR (hr)	MTTR (hr)	Availability 1 Mag
	SLC	8828	1855	16,375,940					
5/1/97 - 6/8/98	HER	918	1016	932,688	16	1,023,496	95.5	5.97	0.999994168
	PEP II	6624	2155	14,274,720					
	BSY/FFTB	2196	198	434,808					
1/12/00 - 10/31/00	BSY/A-Line	630	520	327,600	3	4,758,240	9.9	3.30	0.999999306
	PEP II	7411	2155	15,970,705					
	BSY/FFTB(e+)	2795	198	553,410					
1/10/01 - 12/31/01	BSY/A-Line	820	520	426,400	5	3,194,141	37.9	7.58	0.999997627

repair, TR, and particulars on the failure, so we could place each one into a specific failure scenario, e.g. water leak from split hose leading to coil overheating, or turn to turn coil short due to damaged insulation. The mean time to repair, MTTR, for a certain category of failures is calculated by dividing their total repair time by the number of failures. The grand average repair time for SLAC water cooled magnets is 5.41 hours.

We found these numbers of failures during 1997-2001: 38 water cooled magnets, 2 solid wire magnets, 96 large PS, 70 small PS and 24 magnet movers. The TRs of 12 "water leak" failures ranged from 2 to 28 hours, these ranges must be accounted for when one calculates the predicted costs of failures for the NLC. To calculate the average SLAC water cooled magnet's MTBF we summed the magnet running hours from 15 beamline runs (=66,673,767 hrs) and divided that by the 38 failures to give 1,754,573 hours. Then the availability of one "average" SLAC water cooled magnet is 1,754,573/(1,754,573+5.41)=0.999996919. Similarly, the MTBFs & MTTRs for a solid wire magnet are 21,157,428 & 2.5 hours, for a small PS: 294,646 & 1.27 hours and a large PS: 106,700 & 1.98 hours. Note the wide range of MTBFs.

B. Estimate MTBF & Availability of Aadjustable PMs.

We have a model of an adjustable permanent magnet that uses pm bricks to drive flux through steel poletips and has rotating rods with pm cylinders just outside the core [6]. The field strength in the bore varies with the rods' angular position. The so-called tuners are rotated by an electro-mechanical linkage system driven by a stepper motor, which is controlled by standard electronics. The tuning rods will rotate to the minimum field position if certain parts of the stepper motor system fail.

In order to estimate the MTBF of such an adjustable pm, we looked at SLAC magnet mover failure data that caused the beam to be lost, because these movers had almost all the same components as the proposed tuner controller system, had been used in a similar radiation environment and with a similar duty cycle. In addition, we had to estimate the MTBFs for the additional pinion gear, 2 sun gear bearings and 16 shaft bearings that the tuner system has. The Weibull distribution is a useful way to analyze failures of components and quantify their reliability, its widespread use has led to tables of MTBFs for all kinds of items being developed and published. We took the typical MTBF of a shaft bearing with a 100% duty cycle and scaled it to a 0.3% duty cycle to model our tuning rods being rotated once a month to allow a beam-based alignment of the magnets to occur, this gave 16.6 million hours for one bearing. Combining 19 bearings' MTBFs and an empirical mover's MTBF of 347,687 hours, we calculate the MTBF for one adjustable pm to be 249,000 hours without any accounting for radiation damage to the pm bricks. The lack of definitive correlations between amount of radiation received and loss of remnant field, and the uncertainty in the levels of ambient radiation the NLC beamlines will produce, led us to make educated guesses of the number of annual radiation-caused pm failures, yielding an overall MTBF of 202,568 hours and a MTTR of 3.7 hours for an adjustable pm.

C. Predict Availabilities of Systems of NLC Magnets.

To calculate the A of a system of N equivalent components in series, one raises the A of one component to the Nth degree. In the 2003 NLC configuration, there will be 8653 magnets and we calculated the As of an all em system and a hybrid em and pm system using the above MTBFs and MTTRs. We predict the 8653 ems would be 0.9811 available, the 2512 small and 4168 large PS powering them would be 0.9155 available, leading to an unacceptably low overall A of 0.8982. The hybrid system would have 3371 pms, 5282 ems, 2512 small PS and 1486 large PS. We predict its overall A to be 0.8804+/-0.02 (our uncertainty in predicting radiation damage gives the 0.02 error), also much lower than the required 0.95.

In other words, we cannot design, build and repair the NLC magnets and PS just the same as we have SLAC magnets if they are to meet our NLC availability goals, nor would swapping in some pms help. We choose to do a "Life Cost-based FMEA" to identify those failure scenarios that would be most costly to the project if not prevented. These will be the types of failures we will tackle first as we develop strategies to increase MTBF and decrease MTTR and thus improve A.

D. Estimate Failure Occurrences and Frequencies

We assume the NLC will run 9 months (=6480 hours) out of every year for 30 years, during the other 3 months preventative maintenance will be done on all components. Subtracting their 0.9811 availability from 1 and multiplying the result by 6480 hours gives you the predicted downtime of the 6085 water cooled magnets per year, 120.5hours. Dividing this by the MTTR of 5.41 hours gives you the number of water cooled magnet failures per year in the NLC = 22.3. We call this the number of occurrences per year, or frequency. Using the information on the above-mentioned magnet, PS and mover failures we calculated the availabilities and hence the frequencies for many different types of magnet system failures, which enabled us to complete a long FMEA table of all possible failure scenarios, similarly for an adjustable pm. A selection of these scenarios are shown in Table II.

V. Predict Expected Failure Costs

Besides failures that occur during accelerator operations we accounted for other errors, e.g. for problems that might happen while a magnet was being installed, which would result in a later failure during operation. We gave educated estimates of the frequencies of such scenarios and how many hours of labor it would take to recover. Failures that both originated and were detected during operations were assumed to continue to re-occur for 30 years, all others re-occurred just once. The values quantifying these various parameters are in the columns under "input" in Table 2. The lifetime costs associated with each failure scenario, taking into account the frequencies, are calculated as explained in [5] and the *median* costs in US dollars are shown in the columns under "output" in Table II.

The "Recovery" time has a strong influence on the failure costs, it is the sum of the other 3 listed times. It is used through an "Opportunity" cost, which is the cost incurred when a failure inhibits the main function of a system and

TABLE II

LIFE COST-BASED FMEA TABLE FOR SOME WATER-COOLED MAGNET AND ADJUSTABLE PERMANENT MAGNET FAILURES

Type of Magnet	Failure Scenario	Ultimate Effect of Failure	Input									Output			
			Origin	Detection Phase	Re-occuring	Proby/Freqy	Detection Time	Fixing Time (hr)	Delay Time (hr)	Recovery (hr)	Quantity (hr)	Parts Cost ($)	Labor Cost ($)	Material Cost ($)	Opportunity Cost
Electromagnet	Water passage is blocked due to foreign object	Magnet overheats, is turned off	Oper	Oper	30	2	1	4		5	1	50	34,560	2700	3,750,000
	Damaged (crimped) coil	Shorted coil, magnet won't turn on	Inst	TR	1	1.8	0.5	2		0	1	1,250	1,280	5000	
	Water sprayed onto the coil	Shorted coil, magnet is turned off	Oper	Oper	30	0.8	2	8		10	1	50	30,720	1200	6,000,000
	LCW hose fails, water not cooling coil	Magnet overheats, is turned off	Oper	Oper	30	2.4	2	5.5		7.5	1	50	66,960	3600	13,500,000
	Water fitting or braze connection fails	LCW not reaching coil overheats etc	Oper	Oper	30	1	2	4.5		6.5	1	50	23,700	1500	4,875,000
	Loose Jumpers	Excessive heat lead to melting temp	Mfg	Test	1	4	0.5	2.5		0	1	100	1,560	400	
	Poor terminal connection design	Excessive heat lead to melting temp	Des	Test	1	0.011	1	8		0	40	100	494	44	
	Bad terminal Installation	Excessive heat lead to melting temp	Inst	TR	1	4	0.5	2.5		0	1	100	1,560	400	
	Poor thermal contact: thermal switch & cond	Magnet destroyed	Inst	Oper	1	1	0.5	4		4.5	1	11,000	600	11000	112,500
	Out of tolerance dimensions	Insulation Failure	Des	Proto	1	0.3	0.5	4		0	1	1,250	180	375	
Permanent	Electronics controlling stepper motor fail	Tuners in wrong position: beam lost	Oper	Oper	30	43	0.5	2		4.5	1	500	412,800	645,000	145,125,000
	Stepper Motor fails	Tuners in wrong position: beam lost	Oper	Oper	30	1.25	0.5	3		3.5	1	300	17,250	11,250	3,281,250
	Software controlling stepper motor fails	Tuners in wrong position: beam lost	Oper	Oper	30	2.5	1	1		3	1		16,500		5,625,000
	Tuner bearings get stuck	Tuners in wrong position: beam lost	Oper	Oper	30	24	1	3		4	1	100	360,000	72,000	72,000,000

prevents any creation of value; e.g. the beams are down and no luminosity is being accumulated. What to set this cost to per hour continues to be debated, we have calculated with 3 possible values: $10,000, $25,000 and $50,000 per hour. All of them far exceed what any technician earns in an hour so it is vital to minimize the recovery time to reduce costs. Taking the lifetime view of the all-em NLC, 6085 water-cooled ems would suffer just 2.4 failed LCW hoses a year that would turn off a magnet and bring down the beam. Does not sound so bad, but the lifetime cost to the project would be over $13.5M!

We use a Monte Carlo simulation with triangular distributions for some input parameters to estimate the possible range of failure costs [5]. We simulated the design, fabrication and installation stages plus 30 years of operations of an NLC em system and a hybrid system, 5000 times each, to find the distributions of lifecycle failure costs. Then we studied these costs to choose which devices had to be re-engineered to reach an availability of > 0.95.

VI. FAILURE COSTS COMPARISON RESULTS

The worst-case 30 year lifecycle failure cost for 6085 ems is $448M, and for 4168 large PS is $947.7M (using $50,000/hr opportunity costs), so we considered putting all these PS into a "standby redundancy" mode. Two equivalent PS would be connected to each magnet or magnet string, only one would be on until it failed, then the other PS would take over without any interruption and the failed PS would be repaired later during a maintenance period. Such a PS system has an MTBF of ~3.6 million hours as compared to 106,700 hours for a single PS. Using 4168 redundant large PS in the all-em case increases the overall availability to 0.9684 and drops the PS lifecycle failure cost from $947.7M to $29.3M. The potential savings and reaching A >0.95 justifies the several tens of millions of dollars it would cost to engineer and procure the standby redundant system.

It had been thought that replacing some of the ems and their not-so-reliable power supplies with permanent magnets would lead to a better overall availability, but, our cost-based FMEA showed that our first model of an adjustable pm suffered from too frequent failures in its strength adjusting system, see the lower 4 lines of Table II. Failures in the electronics controlling the stepper motor would cost over $146M. So we considered adding a "latch" to the stepper motor, which is always on and has to be overridden to allow the tuners to rotate to a new angular position. So, if the motor electronics failed, the tuners would be locked in their desired position and the magnet strength would not change. Thus the beam would not be lost, but an *adjustable* pm would become a *fixed* one. This solution works until the next beam-based alignment (BBA) procedure needs to be done and the magnets' strengths have to be decreased by 20%. We suppose the BBA is done once a month, by which time 8 pms will have "stuck" tuners, and the beams will have to be brought down before the BBA to allow these pms to be repaired. We assume the 8 can be repaired simultaneously by multiple crews. With "latched" adjustable pms and standby redundant PSs the mixed em/pm system availability would improve to 0.9321, which is still below the required 0.95. Its lifetime failure cost would be over $745M.

Comparing the availabilities and failure costs of 2 proposed NLC magnet systems, the all-electromagnet one is preferable.

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