Magnet Reliability in the Fermilab Main Injector
and
Implications for the ILC

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Motivation

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- ILC Magnet Technical Systems
  - **Reference Design Effort and Report**
    - For reliable (>75%) operation, *High Availability* is a necessity and a concern for all systems
      - Availability group is reserving contingency of 10%
    - *Magnets* were allocated *unavailabililty* of 5%*0.15 =*0.0075*
    - >13000 Magnets in the 5 ILC areas, ~6800 Water Cooled
    - Magnet Availability Goal: MTBF ~$18 \cdot 10^6$ hours

      assuming: MTTR ~ 8 hrs
  - **Can this level of reliability be achieved w/o extraordinary cost??**
    - In the RDR text we said we thought this should be possible "by applying best modern engineering practices, ensuring adequate quality control of materials and procedures during fabrication, and use established guidelines for operation within reasonable environmental limits (water T, ΔT, flow)"

Motivation, continued

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- RDR Magnet Count, by ILC Area and Style
  - CONCEPTUAL DESIGNS [ILC-REPORT-2007-001]

TABLE 3.1-1
Numbers of Conventional (Normal Conducting, NC) and Superconducting Magnets and Magnet Styles in ILC Areas.

Magnet Type	Grand Totals		Sources			Damping Rings					2 RTMLs		2 Linacs		2 BDS	
				e-	e+		e- DR	e+ DR	e- Inj/Ext	e+ Inj/Ext						
	# of styles	total qty.	# of styles	total qty.	total qty.	# of styles	total qty.	total qty.	total qty.	total qty.	# of styles	total qty.	# of styles	total qty.	# of styles	total qty.
Dipole	22	1356	6	25	157	2	126	126	8	8	6	716	0	0	8	190
NC quad	37	4165	13	76	871	4	747	747	76	76	5	1368	0	0	15	204
SC quad	16	715	3	16	51	0	0	0	0	0	0	56	3	560	10	32
NC sextupole	7	1050	2	0	32	2	504	504	0	0	0	0	0	0	3	10
SC sextupole	4	12	0	0	0	0	0	0	0	0	0	0	0	0	4	12
NC solenoid	3	50	3	12	38	0	0	0	0	0	0	0	0	0	0	0
SC solenoid	4	16	1	2	2	0	0	0	0	0	1	8	0	0	2	4
NC corrector	9	4016	1	0	840	3	540	540	0	0	4	2032	0	0	1	64
SC corrector	14	1374	0	32	102	0	0	0	0	0	0	84	2	1120	12	36
Kickers/septa	11	227	0	0	19	5	46	46	0	0	1	52	0	0	5	64
SC wiggler	1	160	0	0	0	1	80	80	0	0	0	0	0	0	0	0
NC oct/muon spoiler	3	8	0	0	0	0	0	0	0	0	0	0	0	0	3	8
SC octupole	3	14	0	0	0	0	0	0	0	0	0	0	0	0	3	14
SC undulator	1	27	1	0	27	0	0	0	0	0	0	0	0	0	0	0
Overall Totals	135	13190	30	163	2139	17	2043	2043	84	84	17	4316	5	1680	66	638
Totals w/o Correctors	112	7800														
Total NC	92	10872														
Total SC	43	2318														

N= 13190 magnets/135 styles

NC= 10872 {6873 lcw, 3999 air}, SC= 2318

ILC Reference Design Report III-139

Magnet Systems

Motivation, continued

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- Availability Calculations (a simplified example)

  A = uptime fraction for one magnet

  MTBF = Mean Time Between Failures

  MTTR = Mean Time To Repair

  $\text{MTTR } (\sim 10\text{h}) \ll \text{MTBF } (\sim 10^6\text{h})$

  A= MTBF / (MTBF+MTTR)

  $1 - A \approx \text{MTTR / MTBF}$

  $\mathcal{a}$ = availability for system of N (=13000) magnets

  $= (A_1)(A_2)(A_3)\cdots(A_N) = A^N$ (assuming all equal)

  = (1 - 0.0075) *by decree*

  $\text{MTBF} = \text{MTTR}/(1 - .0075)^{1/N} \sim (8)/(5.8\ 10^{-7}) \sim 14\ 10^6\text{h}$

  if water cooled dominate, N ~7000 ⇒ $\text{MTBF} \sim 7.4\ 10^6\text{h}$

- Availability Group Assumptions? (details not in RDR)
  - 18 million hours implies ~17000 magnets (early ILC design)

Motivation, continued

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- Main Injector may provide some useful data points
  - **Constructed, Operated with “modern approaches”**
    - RDR studied Magnet Availability of existing machines, esp. SLAC: wide MTBF range ~0.5 to 12 10^6 hr
    - Parts procured from industry; Design, Assembly at FNAL
  - **Hundreds of Magnets operated for 9 years**
    - Room Temperature Air and Water Cooled Styles
    - Both New and Refurbished magnets
  - **Magnet Technology Conference Publication**
    - Timely opportunity to document the FMI magnet performance
    - Attempt to draw some conclusions relevant to the ILC

FMI Magnet Reliability Study

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- MT20 Publication (5K07)
  - **Product of a team from various groups at FNAL**
    - Magnet Systems Department in TD
      - J. Blowers, D. Harding, O. Kiemschies (formerly Ops Dept in AD), MT, S. Rahimzadeh-Kalaleh (SIST),

        J. Tompkins (ILC Magnet Tech.Sys. area leader)
    - Main Injector Department in AD
      - D. Capista
      - Special thanks to people we interviewed
        - » {B. Mau, D. Augustine, R. Slazak B. Brown, D.Morris, others}
  - **FNAL Pre-print** FERMILAB-CONF-07-443-TD
    - reviewers suggested minor revisions; not yet implemented
    - *(deadline is Nov 9 – there is still time to make changes)*

Reliability Study, continued

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- Main Injector Magnets
  - **New Construction**
    - Incorporate lessons learned into design & fabrication
      - Analysis of failed MR quad magnet [N.Chester memo, 1990]
      - FMI Dipole Design Considerations [PAC, FNAL-Conf-91/127]
      - Prototype Dipole Construction, Meas [IEEE TransMag1992]
      - B2/B3 dipole reliability: thermal stresses [MTF-93-004,9]
      - **Magnet Cooling and Bus design:** [PAC, FNAL-Conf-95/145]
      - New C-Magnet design reviews
    - Concise Process Discussion: [FMI Tech. Design Handbook]
      - **This could be a separate seminar**
  - **Reworked Main Ring Magnets**
    - hipot, leak check – all passed (coil/impreg rework not required)
    - Replace ceramic insulators
    - Support and Vacuum tube changes

Reliability Study, continued

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- Main Injector Magnets
  [from FMI Tech. Design Handbook]
- Start of Operation:
  9/13/98
- Operating Efficiency:
  76.8%
- Study through 8/1/07

fdt = 77856 hours

(WQB: 10968 h)

Table 3.1-3.
Main Injector Magnet Count

		Ring	8 GeV	P150	A150	M R F0-F17	M R F17-SY	Abort	Total	Spares
IDA dipole 240"	N	108	-	-	-	-	-	-	108	5
IDB dipole 240"	N	108	-	-	-	-	-	-	108	5
IDC dipole 160"	N	64	-	-	-	-	-	-	64	4
IDD dipole 160"	N	64	-	-	-	-	-	-	64	4
BDM (240" B1/B2)	E	-	55	15	15	15	101	2	203	7
DDM (240" 2XB2)	E	-	-	-	-	-	1	-	1	1
EPB 5-1.5-120	E	-	4	-	-	-	-	-	4	1
ODM (240" B3)	E	-	2	-	-	8	2	-	12	2
IQC (100.13" MI)	N	32	-	-	-	-	-	-	32	3
IQD (116.26" MI)	N	48	-	-	-	-	-	-	48	4
BQB (84" MR)	E	127	-	7	7	5	26	2	174	7
BQA (52" MR)	E	-	37	-	-	-	4	1	42	4
SQA (17" P-Bar)	E	-	16	-	-	-	-	-	16	2
BQB, rolled	E	1	-	-	-	-	-	-	1	1
3Q120	N	-	-	7	7	-	-	-	14	2
3Q60	N	-	-	2	2	3	-	-	7	2
ISA (sextupoles)	N	108	-	-	-	-	-	-	108	5
MR trim quads	E	16	-	-	-	-	-	-	16	2
MR skew quads	E	16	-	-	-	-	-	-	16	2
CR skew quads	E	4	-	-	-	-	-	-	4	1
MR octupoles	E	62	-	-	-	-	-	-	62	4
HDC MR horz trim	E	-	27	7	7	4	14	2	61	4
IDH MI horz trim	N	104	-	-	-	-	-	-	104	5
VDC MR vert trim	E	-	26	14	14	4	14	2	74	5
IDV MI vert trim	N	104	-	-	-	-	-	-	104	5
Lambertson,A0	E	-	1	-	-	-	-	-	1	1
Lambertson,MI, 110"	N	-	-	5	5	-	-	3	13	2
C-magnet, MI, 131"	N	-	-	5	5	-	-	1	11	2
									0	
Totals:		966	168	62	62	39	162	13	1472	92

SPARES = INT((SQRT(NUMBER))/2+.8) N = New Magnets E = Existing Magnets

Recycler NOT included

Chapter 3.1 5 Technical Design Handbook August, 1994

Reliability Study, continued

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TABLE I FMI MAGNET COUNT AND MAGNET HOURS

Style	Designation	Number	Magnet Hours
New Dipole	IDA, IDB, IDC, IDD	344	26782464
New Quadrupole	IQC, IQD, WQB, 3Qxx	108	7940232
New Lambertson	ILA	14	1089984
New C-magnet	ICA	11	856416
Rework Dipole	BDM, DDM, EPB, ODM	220	17128320
Rework Quad	IQB, BQA, BQB, SQA	233	18063672
New Trim, HOC	IDH, IDV, ISA	316	24602496
Rework Trim, HOC	Many Main Ring types	233	18140448

Water Cooled

Air Cooled

Reliability Study, continued

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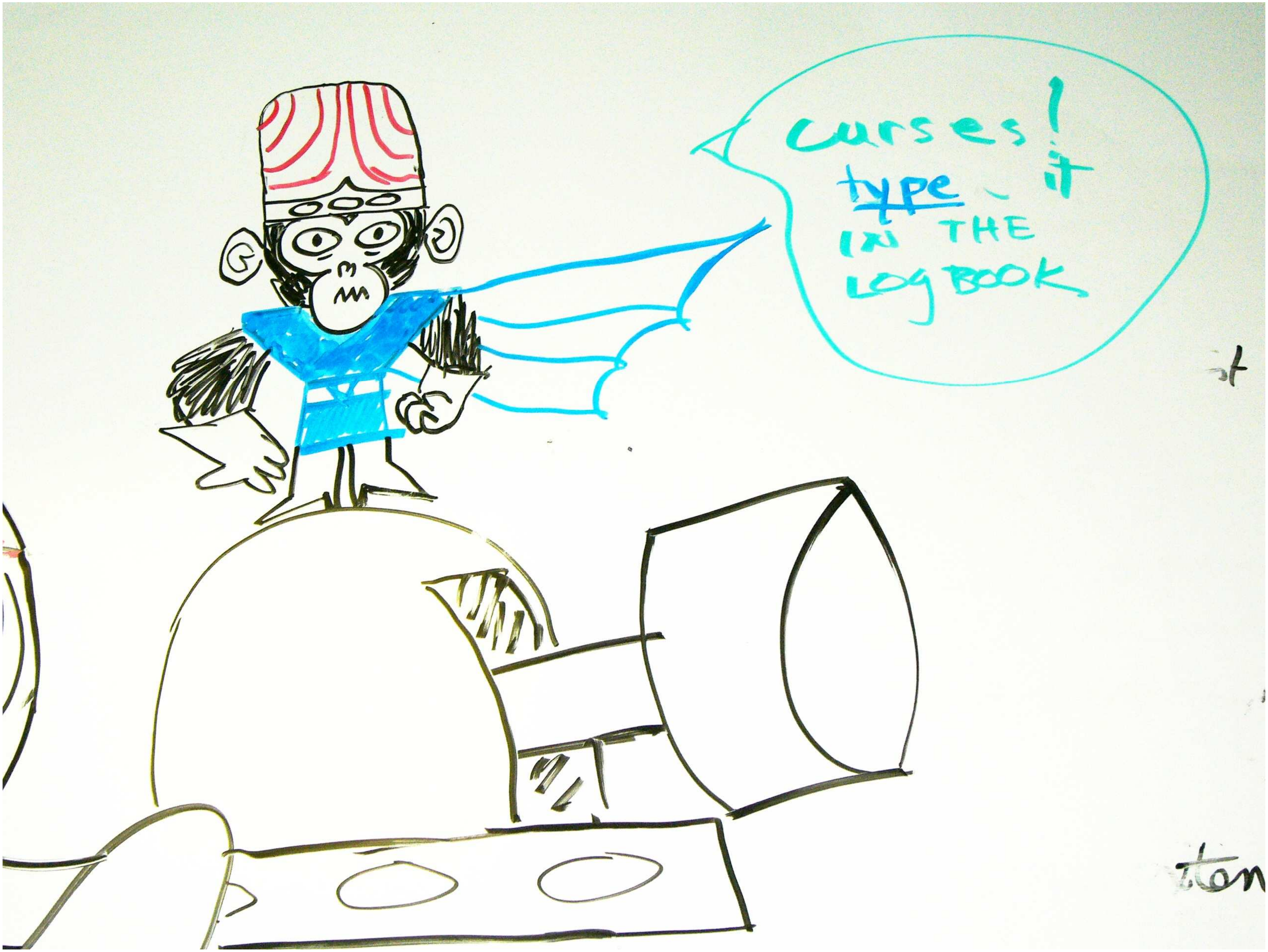
- Methods
  - **Research records on magnet “failures”**
    - Existing Failure Catalogs
      - AD lists of changed magnets (Augustine, Brown)
      - TD lists of suspicious magnets (Blowers)
    - Electronic Searches
      - MCR and elog
      - Machine elogs
      - TD “Onbase” Device Service Records
      - TD Accelerator Support web pages
    - Interview Key Personnel
      - AD, TD operations/MI/magnet experts
      - TD factory/repair technicians
  - **Worry: did we miss anything??** *(appeal to audience)*
    - How reliable are our records, memories, searches?

      (esp. wrt correctors: would we know? Run without?)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Reliability Study, continued

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- Methods
  - **Compare Lists/resolve discrepancies**
    - Understand details of each event
    - Eliminate “MI” failures not in the “study region”

    e.g. PS/Bus fault, not magnet;

    magnet in shared tunnel, not “MI” or beamline;
  - **Definition of “failure”: Magnet must be changed**
    - Hipot (short to ground) – 1000V for main bus; not *correctors*
    - Inductance (turn-to-turn short)
    - Overheating (loss of coolant accident)
    - Water Leaks
  - **Magnet Change may occur during a shutdown/ maintenance period (to prevent failure during operation)**
    - Would not count against “availability” in ILC (e.g.,LCW leak)

Reliability Study, continued

- Results
  - **Mean Time To Repair**
    - Careful study of elog to find cases where **magnet change** was the only activity preventing MI operation:
    - 7 cases <17.8 hours> from problem to startup
    - What's typically involved?
      - Diagnose problem (call in experts, assess problem)
      - Conduct Safe Access procedures (travel to site)
      - Field diagnosis, transport crews & equipment
      - Replace and align device
      - Conduct checkout and startup procedures
    - 8 hours is unlikely for replacement in ILC
      - » in Main Ring, it was said to be ~12 hours
    - may be faster to find/diagnose (~individually powered)
    - Long distances to sites; Stage magnets for installation?

Reliability Study, continued

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- Results
  - **Failure Rates (limits), by Style and Failure Mode**
    - MTBF = Nmagnets * Toperation / Nfailures
      - Note: we don't distinguish T "live" and T "down"
    - 90% CL Lower limits from Poisson Statistics

      Np=a (N large, p small, finite event probability a)

      $f(x) = e^{-a}a^{x}/x!$

      If Observe x=0, what is a for f(0)=0.1? a=2.3 (90%UL)

      numerical calc/lookup required for higher observed x:

      x={0,1, 2, 3, 4} $a_{90\%UL}$={2.3, 3.89, 5.32, 6.68, 7.99}

      $a_{95\%UL}$={3.0, 4.74, 6.30, 7.75, 9.15}

Reliability Study, continued

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- Results

Numbers

Of Failures

&

MTBF in

Hours

TABLE II MAGNET FAILURE STATISTICS

Style	Num Leaks	MTBF Leaks [hours]	Num Shorts (90%UL)	MTBF Shorts (90%LL) [hours]
New Dipole	0		0 (2.3)	(1.16 E+07)
New Quad.	1	7.94 E+06	4 (7.99)	1.99 E+06 (9.94 E+05)
New Lamb.	0		0 (2.3)	(4.74 E+05)
New C-magnet	0		0 (2.3)	(3.72 E+05)
Old Dipole	0		1 (3.89)	1.71 E+07 (4.40 E+06)
Old Quad.	3	6.02 E+06	9	2.01 E+06
New Trim,HOC	N/A		0 (2.3)	(1.07 E+07)
Old Trim, HOC	N/A		0 (2.3)	(7.89 E+06)

Reliability Study, continued

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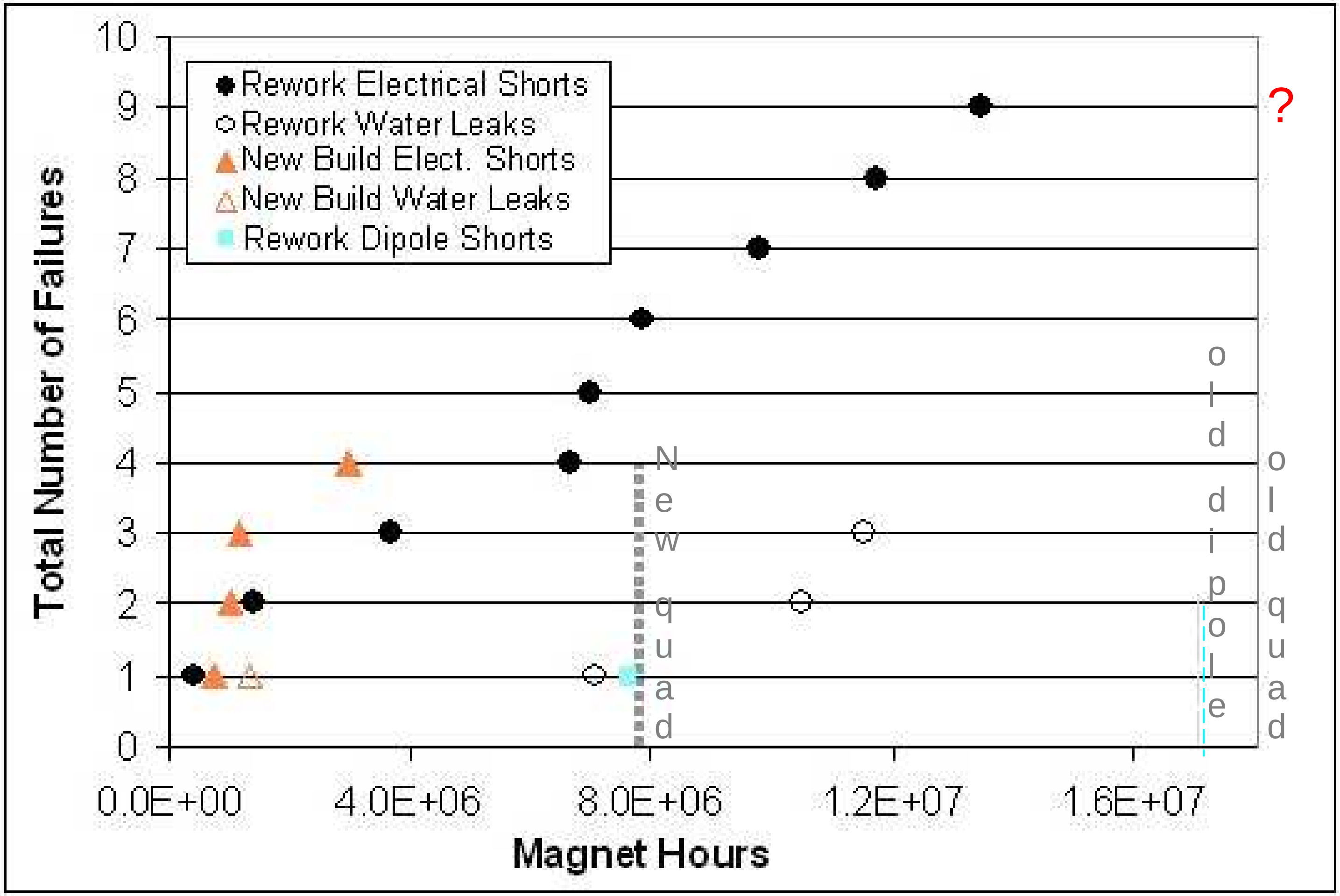
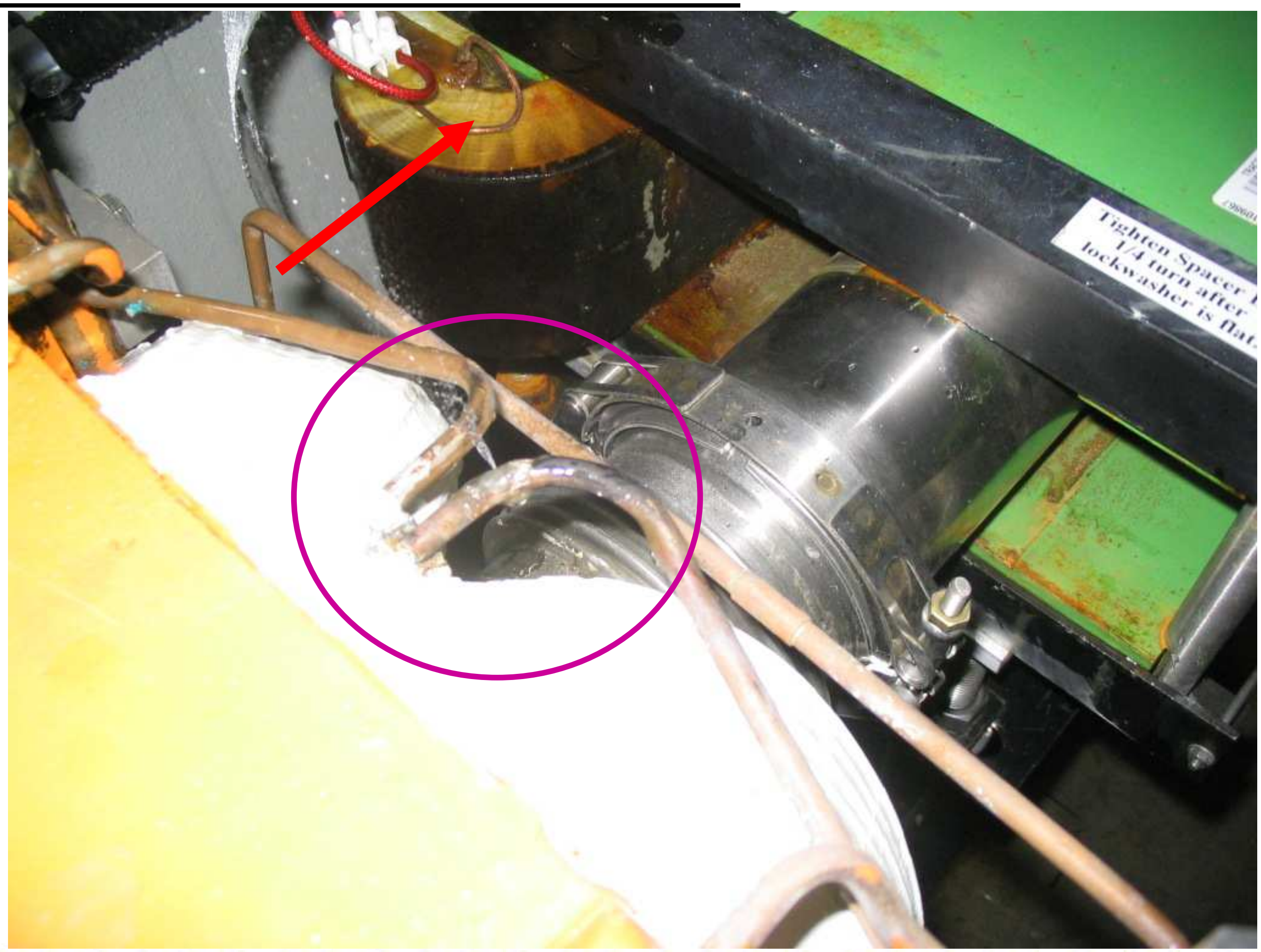
- FMI Quad and Dipole Failures vs Time



Failure Modes: Water Leaks



Failure Modes: Water Leaks

- *Are a great concern* – penetrate cracks in insulation and cause electrical failures (which stop machine)
- Monitored constantly during operation, and vigilence during tunnel accesses (but don't usually stop machine)
- Repairs (and level of) *made as needed* (judgement call)
- Generally occur at ***external braze joints*** and ***manifold connections***, but may be encapsulated in epoxy
- Careful design, technique, tests, minimum # internal joints in new construction: paid off !
- No Hose bursts have occurred (well beyond 5 year lifetime)
  - apparently no hose degradation from (p) radiation

ILC will have same design/fab/operations concerns *10

How to keep quality@low cost across many vendors?

Failure Modes: Overheating

- Failure to cool properly (design, operation) can result in
  - Thermal stresses (ΔT)/ insulation cracking
  - Epoxy and insulation degradation
  - Softening of braze joints, water leaks
  - Personnel hazards
  - FMI { Tin ~35 ^oC, ΔT_{max}~10 ^oC } are good guidelines
    - ILC considering ΔT_{max} of 25 ^oC for some magnets
- FMI temperature switches not interlocked to power supplies
  - one magnet burned by operating for hours without LCW
  - Recommendation for ILC is to interlock (flow ? and) temperature switches to PS
    - sensor reliability, costs, EDIA, issues

Failure Mode Discussion

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Failure Modes: Electrical Shorts

- FMI Main Dipole and Quadrupole Magnets must withstand 1000 V to ground Hipot test
  - High ramp rates and large inductance, many bussed magnets
    - Routinely done before/after access/maintenance to find and prevent problems during operation

      (most problems are related to power supplies and bus)

      surprisingly, failures are detected following OK operation
  - Hipot (short to ground) & inductance (turn-to-turn short =1) failures require a magnet change
    - Failures have mostly been of old and new quads;
      - one old dipole
    - **root cause is combination of compromised insulation + Water**

Failure Mode Discussion

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Failure Modes: Electrical Shorts- cont'd

- NO FAILURES of TRIMs, HOCs (air cooled)
  - can get wet too, perhaps less, but operate at lower {I x V}

    new and reworked styles have been very reliable (not LEP??)

    lower hipot requirements (in fact, it's not done)

    experience less thermal and Lorentz stress

    failures generally do not stop operation (but would be noticed)
  - Air-cooled styles should not be a problem in ILC
  - The challenge for ILC magnets is to build many reliable styles of water cooled magnets (from a global vendor pool)
  - Individual powering (mostly) and ~ DC operation
    - Hipot requirements may not be as severe (not known)
    - **Mechanical stresses from Lorentz force cycling reduced**

Reliability Study, continued

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- **New Quad Failures: Early Investigation**
  - Autopsies revealed cracks in epoxy at quad end
  - *Conclusion (theory?):* Design change (from MR IQB design) likely to have introduced a problem
    - G10 sheet insulation was added to improve insulation in "end plate" region (from MR quad failure study in 1990)
    - Coils were insulated and impregnated *with the Steel Core* into a monolithic unit (to avoid differential expansion)
    - Epoxy impregnation was incomplete around the G10 sheets, not able to see this
    - Non-uniform stresses led to epoxy cracking in the ends
  - Failure mode of FMI reworked quads ?
    - Autopsies not done (lower priority, resource limitations)

Reliability Study, continued

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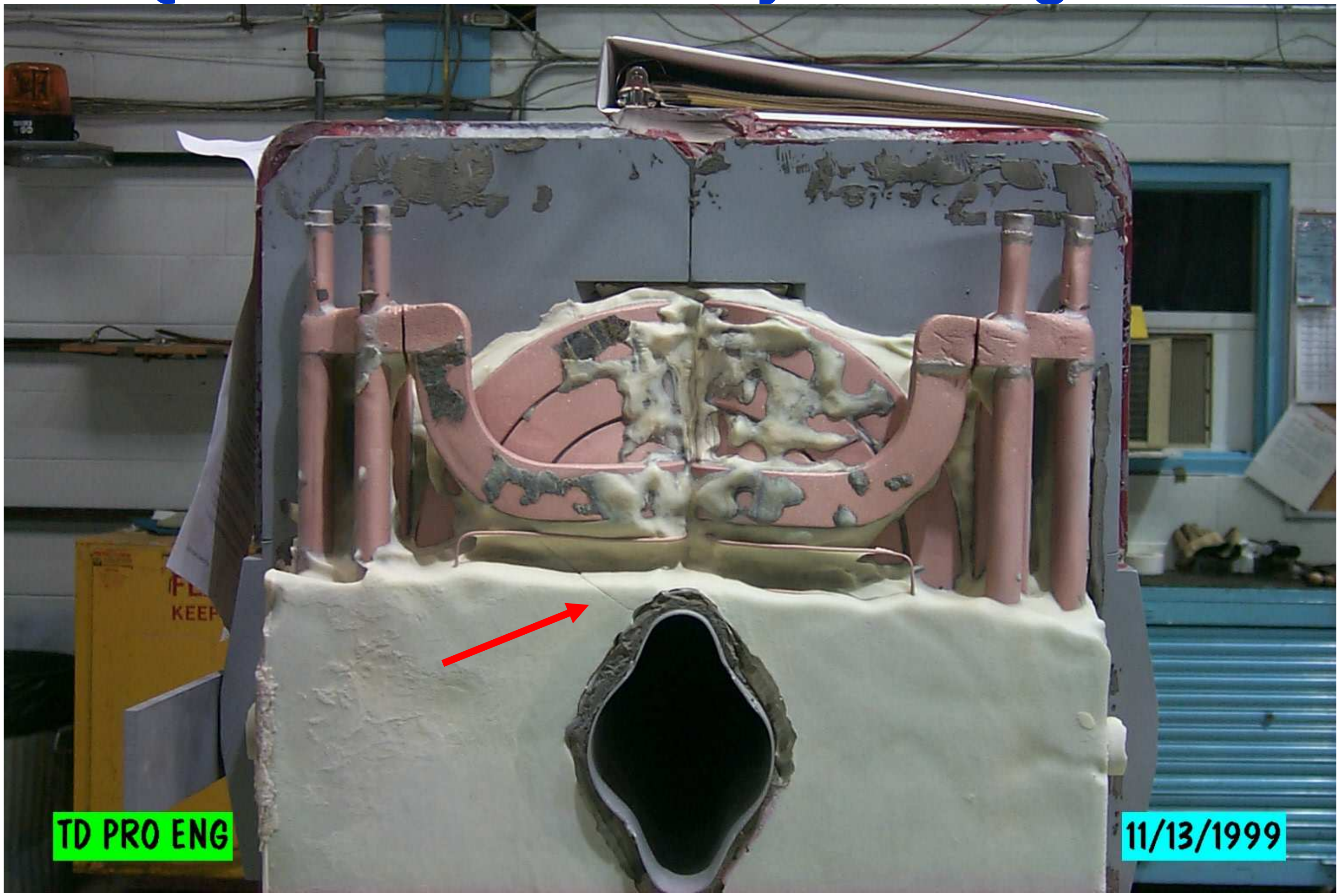
- **New Quad Failures: Early Investigation**



Reliability Study, continued

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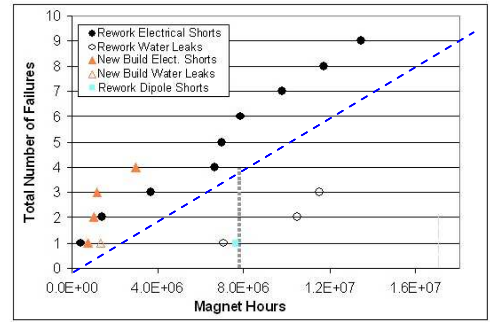
- **New Quad Failures: None “lately”**
  - Perhaps lucky (infant morality?)
    - not all quads may have suffered this problem
    - Compare rate of old Quads: avg the same!
    - too soon to tell… (need time: 2.3*MTBF)



- **New FMI Dipoles: No Failures**
  - Coils are insulated & impregnated independent of the Steel Core
    - One anchor, with features to limit Lorentz expansion
  - Recent WQB and IQC,D construction follows the new dipole design – no longer bonded to the Cores
    - **However, the old dipole design DID bond coils to core**
  - No WQB failures
    - only 7 x 1.5 years in operation

Reliability Study, continued

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- **ILC vs FMI Magnets summary**
  - ILC still largely conceptual designs
    - Iterating to reduce number, increase similarity of styles
      - Failure Modes & Effects Analyses need to be performed
        - » FMEA study of one FNAL quad style is planned
      - "Implications" are speculative – a lot of variables!
  - ILC mostly individually ~DC powered magnets
    - 1356 dipoles, 4165 quads, 1352 "other" water cooled
    - Reduced Lorentz stresses ?
    - Electrical failures of LCW-cooled may be less severe
    - Diagnosis of failure may be easier (lower MTTR)
      - Build in hipot / fault detection capability?
    - Lower voltage to ground requirement ?
    - Failure of air-cooled trims, HOCs may stop the machine
      - e.g., needed to center the beam in focusing elements

Reliability Study, continued

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- Conclusions
  - **It takes years to find out if you have a problem with reliability! (Even with large numbers of magnets)**
  - **"very good" air cooled FMI magnet reliability**
    - **No electrical failures in 42.7 million hours** >18.5 10^6 h (90%LL)
  - **"good" water cooled FMI magnet reliability**
    - Internal water leak rates are low
    - Electrical Failure Rates vary –
      - **New dipoles 26.8 million hours**: MTBF >11.6 10^6 h (90%LL)
      - **Old Dipoles: MTBF=17.1 million hours** > 4.4 10^6 h (90%LL)
      - Old and New Quads: MTBF = 2.0 10^6 h
        - » **Time will tell if new quads are really better**
        - » This may be a place for further study (FMEA)

Reliability Study, continued

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- Conclusions, continued
  - **Assess ILC MTTR estimates: 16 h (not 8 h) ?**
  - **Magnets Combined Need** a ~ .9925
    - 4165 Quads @ 2.0 10^6h gives a **~ .**967 (.984)
    - 1356 Dipoles @17 10^6h gives a **~ .**99879 (.9994)
    - What will superconducting magnet reliabilities be (Hera?)
      - how much of the availability budget they will eat
    - This will be challenging
  - **Other Caveats:**
    - Effects of different Radiation? protons, vs synchrotron
    - How to maintain the design/fabrication/QA expertise? (many experienced FMI-era engineers have retired)
    - How to maintain quality across the machine? ("magnet systems group" is an RDR entity)