Improving the Reliability of Particle Accelerator Magnets: Learning from our Failures

Cherrill M. Spencer (cherrill@slac.stanford.edu)
SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract—**There are many ways that a resistive particle accelerator electromagnet can fail, and most failure modes and their root causes are well known to more experienced magnet engineers. There are thousands of new electromagnets being fabricated every year and tens of thousands already operating in institutions worldwide. Yet some magnet engineers designing a new style magnet still do not make the design choices that will lead to fewer failing magnets, fabricators still make errors as they assemble magnets and magnets still operate, for e.g. with low conductivity water (LCW) that corrodes or erodes the coils' conductor. One reason for these continuing problems is the lack of readily available information on the most reliable materials, fabrication techniques, and operating parameters. In order to learn from the experiences of other institutions running accelerators regarding their magnets' failure modes and how they have dealt with them, a web-based survey was created with 64 detailed questions. The survey was completed by 28 designers and operators of accelerator magnets worldwide covering conventional magnets 5 to 55 years old, being used in all kinds of accelerators, in DC, ramping and pulsed modes. A detailed analysis of the survey's responses was carried out to find, for e.g., correlations between materials used and frequencies of related failure types. This paper describes the results of the survey analysis, leading to some more reliable design values, materials, fabrication techniques and operating conditions, especially the properties of the LCW, and thus provides advice on how to improve the reliability of accelerator electromagnets.**

***Index Terms*—accelerators, failures, reliability, resistive magnets,**

I. INTRODUCTION

WHETHER one is using electromagnets in a small particle accelerator to produce synchrotron radiation or in a very large accelerator to produce high energy particles for basic research experiments, or in a proton therapy medical device, their availability is paramount to the overall success of the machine. There are many ways that a resistive electromagnet, which is comprised of several different components, can fail, and most failure modes and their root causes are well known to more experienced magnet engineers. There are thousands of new electromagnets being fabricated for new accelerators every year and tens of thousands already operating in tens of institutions worldwide. Yet some magnet engineers designing a new style of magnet still do not make the design choices that will lead to fewer failing magnets, fabricators still make errors as they assemble magnets and magnets still operate, for e.g. with low conductivity water (LCW) that corrodes or erodes the coils' conductor. One reason for these continuing problems is the lack of readily available information on the most reliable materials and fabrication techniques, and on a set of operating parameters that will avoid some common failure modes.

In order to learn from the experiences of other institutions running accelerators regarding their magnets' failure modes and how they have dealt with them, a web-based survey was created with 64 detailed questions. There were 6 identifying questions, e.g. institution name, accelerator/beam line name, age of magnets; 12 questions about magnet design standards in effect when these magnets were designed; 15 questions about materials used and associated problems, e.g. epoxy resin and fillers, cracks in potted coils; 4 questions about types and frequencies of failures; 21 questions about their Low Conductivity Water system supplying the LCW cooling water and 6 questions about other failure types and their advice on ensuring reliable accelerator magnets.

II. WHICH ACCELERATORS COMPLETED THE ON-LINE SURVEY

An email invitation to complete the survey was sent to about 150 magnet engineers or accelerator operators or maintenance groups at particle accelerators all over the world; 28 people were kind enough to do the necessary research into their own magnets and complete the survey. Fig. 1 lists the 12 countries where the 21 institutions who completed the survey are situated. Some larger institutions completed multiple surveys for different sets of magnets made at various times, so in all 28 families of resistive magnets were surveyed.

Country where accelerators situated	**Number of accelerators**	**Number of institutions**
Australia	1	1
Canada	3	3
China	1	1
France	2	2
Germany	2	2
Japan	2	1
Russia	1	1
South Africa	1	1
Sweden	1	1
Switzerland	3	1
United Kingdom	1	1
USA	10	6
Totals 12 countries	**28 accelerators**	**21 institutions**

Fig. 1. List showing countries where accelerators are situated.

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Here is a list of the main uses of the 28 machines: High Energy Particle Physics Research: 10; Synchrotron Radiation Light Source: 7; Nuclear Physics Research: 6; Proton Therapy & Radioisotope Production: 4; Educational: 1. Although there is a wide range in accelerator use, the survey results show their magnets have much in common in their design, materials used, fabrication methods and maintenance practices.

The 28 sets of magnets had these age ranges: older than 50 years old: 1; between 30 and 50 years: 8; between 10 and 29years: 13; younger than 10 years: 6. There were 3 operating modes represented in the 28 sets of magnets, 19 sets ran in DC mode, 8 ramped up and down all the time and one was pulsed.

The 28 completed surveys were analyzed to see if there were any differences between how older magnets fail compared to the younger: the older than 30 year magnets have the same failure types and spread of failure rates as do the under 30 year old magnets. The DC magnets were observed to have the same failure types and spread of failure rates as the non-DC magnets. So the rest of the paper's observations apply to all 28 sets of magnets.

III. EXAMPLES OF SURVEY QUESTIONS

The survey had 12 questions related to magnet design standards in effect when the set of magnets was designed, e.g. "Does your institution have a written set of magnet design standards/rules?", three answers were possible: Yes {8 answered yes}, No {7} or Don't know what design standards were in effect back then {2}, one survey skipped this question. Other questions in this section probed for possible design standards, e.g. "In water cooled coils wound with hollow-core conductor do you have a rule regarding the maximum velocity the cooling water (LCW) can have (averaged over the whole water circuit)?" Three answers were possible: No, we do not have a rule about maximum LCW velocity {13}, Yes, we have a rule about maximum LCW velocity {13}, Don't know {2}. The 13 surveys who answered yes had to fill out the next question to report what their maximum allowed LCW velocity in a coil is, choosing the closest value from the list. The choices {number answering} were: 2 {4}, 3 {6}, 4 {2}, 5 {1} or more than 5 meters/second {0}. Other questions in the magnet design section asked about: rules about LCW temperature increases in coils and actual increases; rules regarding cooling channel's diameters and if they allow internal brazed joints in water-cooled coils. This data was used to see if there were correlations between design parameters and the kind of failures suffered by the magnets, as will be described below.

The survey had 15 questions about the materials used for various magnet components. Knowing that the amount of ionizing radiation experienced by the magnet components can affect the length of their useful life, the survey included definitions of 4 radiation levels. Assuming a 20 year lifetime for a magnet, running for 6570 hours per year, then low or no radiation → < 20 Gray/hour; medium radiation → between 20 and 200 Gray/hour; high radiation → between 200 and 500 Gray/hour and very high radiation → above 500 Gray/hour. In this section questions were asked about the type of LCW hose used and its properties (see Fig. 2 for one example), conductor insulating materials, coil winding methods, potting methods and epoxies, and laminated steel core assembly methods. Questions asked about cracks in potted coils and what they do to avoid them and about laminated core problems.

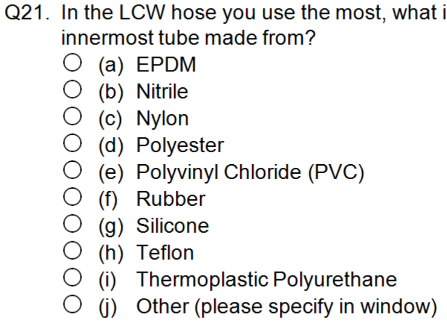
Q21. In the LCW hose you use the most, what is the innermost tube made from?
○ (a) EPDM
○ (b) Nitrile
○ (c) Nylon
○ (d) Polyester
○ (e) Polyvinyl Chloride (PVC)
○ (f) Rubber
○ (g) Silicone
○ (h) Teflon
○ (i) Thermoplastic Polyurethane
○ (j) Other (please specify in window)

Fig. 2. Survey question about material of innermost tube in the LCW hose their institution uses on the magnets they are answering the survey for.

The survey had 21 questions about the LCW system feeding the LCW to the survey-taker's magnets and failures associated with LCW. Questions enquired about the pH of the LCW and how it was controlled, the level of dissolved oxygen (DO) in the LCW, their equipment to remove DO and carbon dioxide from the LCW, filters to remove copper oxides, whether copper oxides accumulated sufficiently in the magnet cooling passages to block the flow of LCW, how often they flushed their magnets and what with, had their copper conductor suffered enough erosion to create a hole in the conductor and what precautions they took to minimize erosion. There were also questions about how and why their LCW hoses failed, how often and when they replaced hoses (before or after they leaked?), and what piping they used in high radiation areas.

Ten questions delved into how and with what frequency their magnets failed. My institution's experience with magnet failures over several decades led to a list of 9 common types of failures, and to detailed questions about power connection problems, insulation issues causing magnet failures, and their satisfaction with their coil epoxy lasting in high or very high radiation areas. Descriptions of their solutions to such problems were sought. Knowing that the root cause of many magnet failures is human error, one question asked about their lab's strategies for minimizing human errors at the design, fabrication and operation stages of magnets' lives. Another open-ended question asked for general remarks about how their institution ensures the good reliability and availability of their magnets. These open-ended questions generated lots of good advice which is summarized below.

IV. MACHINES RANK MAGNET FAILURES BY FREQUENCY

Survey takers had to find out how often their magnets had suffered, in the previous 4 or more years, any of the 9 main types of failures listed, and then to rank them for their frequency. They chose 1st rank for the failure type that happened the most in the previous 4 years, they chose 2nd rank for the failure type that happened the 2nd most often and so-on. They were asked to rank as low as they could and then to put 9th rank for all the remaining failure types their magnets had had at least once in the past 4 or more years. If their magnets had not had a type of failure then they did not rank that type. The resulting data is shown in the Fig. 3 below.

Rank your magnets by how frequently they suffer each failure type

Failure Type	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	Survey Count
Water leaks at braze joints	4	6	4	2	3	0	0	1	5	25
Water leaks from LCW hoses and their fittings	14	4	2	1	0	0	0	0	7	28
Water leaks from copper conductor	0	3	0	0	4	2	2	1	11	23
Insulation problems leading to shorted turns	0	2	3	2	1	3	3	3	5	22
Insulation problems leading to ground faults	1	2	1	4	3	3	1	1	7	23
Power connections: e.g. cable lug to terminal	3	6	3	1	0	3	1	1	5	23
Human error: e.g. LCW not flowing	3	4	5	2	2	1	0	1	4	22
Blocked water passages (e.g. from CuO)	2	2	5	2	0	2	2	0	8	23
Failures caused by poor design	0	0	1	2	0	2	0	1	13	19

Fig. 3. Nine common failure types ranked by frequency at 28 machines.

Looking at the "Survey Count" column in Fig. 3 one can see that 100% of the machines had magnets fail by water leaks in LCW hoses and their fittings; 89.3 % had water leaks at braze joints; 6 other failure types had occurred in 79-82% of the machines and the least common failures were those caused by poor magnet design.

From answers to other survey questions it was clear that most machines have less than 5 magnet failures per year, but each one can take many hours to repair, during which time the accelerator is not running, this represents a high overall cost. So we must pursue solutions to avoid/prevent the failures.

V. IMPLICATIONS OF THE TOP FOUR FAILURE TYPES

A. Order the "Popularity" of Failure Types

There is not room in a 4 page paper to describe all the data contained in the 64 questions answered by 28 accelerators, so I will focus on the 4 most popular failure types; these are defined by adding the number of machines ranking a type as 1st, 2nd & 3rd in frequency and finding the 4 highest totals.

B. Most Popular Failure Type: Water Leaks from Hoses

20 machines ranked failures of LCW hoses or fittings as 1st, 2nd or 3rd in frequency, but 7 machines ranked them as 9th compared to eight other failure types. What about their hose make? Were their fewer hose failures related to their hose make? There were 12 makes of hose listed in response to a materials question. I filtered the data to look at just these 7 machines and their hose makes, compared to the 14 who ranked hose failures first, I could not pick out a clear winner, all hose makes eventually fail. The non-conductive hoses that carry LCW are generally made from thermosetting plastics or thermoplastics or elastomers. All of which are organic molecules and their chemical bonds can be broken by ionizing or UV radiation. The hose materials degrade at various rates as ionizing radiation passes through them and they gradually lose their tensile strength, so at bends in particular the material will crack and the LCW will leak out. Another place this delamination occurs is near the crimped–on hose fittings.

There are hundreds of hose makes available to magnet designers and it seems that they chose hoses without considering radiation effects. Based on my survey data and published data of radiation resistance of various plastics, [1], I generated 2 lists of good and not-so good materials for LCW hoses. In general I recommend LCW hoses for magnets are constructed with 3 layers of material with a non-conductive reinforced outer layer and they meet the hydraulic hose standard of your country (e.g. SAE100R7 or DIN24951 pt 2).

GOOD MATERIALS FOR LCW HOSES (only 3!): Polyurethane; Nylon (as long as it the inner tube of 3 layers); Ethylene Propylene (EPDM) inside Kevlar.

NOT-SO-GOOD MATERIALS FOR LCW HOSES: Natural rubber; Synthetic rubber (e.g. Nitrile); Polyester (unfilled); Polypropylene; Polyamide (=Nylon) without any outer layers. Materials not listed here: have mixed success.

One noticeable difference regarding hoses in the survey: the labs who replace their hoses on a regular schedule or after inspection more often rank hose failures as 9th compared to those who wait until a failure to replace any hoses, so regular replacement of LCW hoses is recommended.

C. 2nd Most Popular Failure Type: Leaks at Braze Joints

14 machines ranked water leaks at braze joints as 1st, 2nd or 3rd, making them the 2nd most popular failure type. A leaking *internal* braze joint has more severe consequences than an external one: a turn to turn short requires the coil to be replaced/repaired. Is there a correlation between frequency of braze leaks and having a design standard that forbids internal conductor brazes? I did a filter on the question about design rules- either have a rule or don't, and looked at the frequency rankings of water leaks at braze joints, those machines with the rule had 3 1st and 2nd ranks, those without a rule had 7 1st and 2nd ranks, so I conclude that having a rule helps reduce the frequency of braze leaks. This example shows that having magnet design standards will improve magnet reliability.

D. Equal 3rd Most Popular Failure Type: Power Connections

A typical power connection problem mentioned by survey takers was a bolted connection between the magnet terminal and the lug on power cable becoming loose over time or it was not tightened enough when installed. Typical solutions mentioned were: use Belleville (=spring) washers under the bolts; inspect the power connections with an infra-red camera while running, after a maintenance period, before operations start; have techs tighten all connections as part of regular maintenance. Or, avoid use of bolted metal pieces by using connectors with louvered contacts and bayonet locking; these also help avoid incorrect power hook-ups.

E. Equal 3rd Most Popular Failure Type: Human Error

One survey question asked for strategies their institution uses to minimize human errors, here is a summary of the many strategies, not already listed, given in the responses.

1) Strategies at DESIGN stage of magnet's life:

Have written-down magnet design standards. Refer to past experience. Hold design reviews with "external" reviewers. Do computer modeling. Design in safety factors for field strength, temperature increase of LCW. Build a prototype magnet and measure it.

2) *Strategies at FABRICATION stage of magnet's life:*

Specify standard set of materials, and insist vendors use them: Cu, insulation tape, epoxy components. Monitor commercial vendor's operations closely. Hi-pot coils to steel core. Do hydrostatic pressure tests of coils. Measure LCW flow at its operating pressure. Design & use a traveler: step-by-step instructions for every fabrication task with spaces for test results & signatures. Train technicians to braze hollow-core conductor into the terminal block, to wind coils. Do full magnetic measurements of every magnet.

3) *Strategies at OPERATION stage of magnet's life:*

Put thermal switches on every LCW return conductor. Double check power connections before powering up. Check magnetic polarity with gauss meter at few amps. Put software limits on current allowed. Use flow switch alarms to indicate low LCW flow. Train technicians in installation tasks.

4) *Strategies AFTER A MAINTENANCE PERIOD:*

Go through a check list, inspect and verify mechanical items like "LCW turned back on". Use micro-switches on all water valves, read out by control system. Train technicians in maintenance tasks; give them time to do the job right.

F. 4th Most Popular Failure Type: Blocked LCW Passages

46% of the machines suffer blocked cooling water passages in their magnet coils at least once a year; 74% of the machines flush their magnets when their LCW flow decreases or their temperature goes over a set-point, thus preventing a complete magnet failure. Questions about the properties of their LCW system was where survey takers showed the most ignorance, to their detriment. If the LCW parameter values are not within certain ranges copper corrosion will occur and the resulting copper oxides can block the conductors' cooling passages. 25 knew what the resistivity of their LCW is (values ranged from 0.16 to 11 Megaohm-cm), but only15 knew the goal value of its pH. 17 did not know the dissolved oxygen (DO) level in their LCW and 14 labs did not have DO removal equipment.

The corrosion of a metal is an electrochemical process by which the metal is oxidized. The metal atoms release electrons and become positive ions. If the copper is in water, here are 2 possible half-reactions:

$$4Cu + 2H_2O \rightarrow 2Cu_2O + 4H^+ + 4e^- \quad (1)$$

or

$$Cu \rightarrow Cu^{2+} + 2e^- \quad (2)$$

What happens to the cations, Cu^{2+}, depends on the environment the Cu is sitting in [2]. Here are 2 reduction half-reactions when there is dissolved oxygen in the water:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (3)$$

or

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad (4)$$

Half reaction (3) is typical in pH neutral (pH =7) or basic solutions (pH>7). When (3) is coupled with (1) then overall:

$$4Cu\ (solid) + O_2\ (gas) \rightarrow 2\ Cu_2O\ (solid) \quad (5)$$

Reaction (5) is favoured when there is a low concentration of DO in the water. When there is more DO the overall reaction will produce a different copper oxide:

$$2Cu\ (solid) + O_2\ (gas) \rightarrow 2\ CuO\ (solid) \quad (6)$$

If the pH is acidic (<7) then reaction (4) is favoured so the Cu^{2+} cannot find any e^- or negative ions and remain as dissolved copper ions; so the metal dissolves away = corrodes.

If either Cu_2O or CuO are produced they form as thin films on the Cu surface and prevent the water or O_2 from reaching it, this is called passivation, and the Cu does NOT corrode further [3]. The magnet engineer should work out what the concentrations of DO and pH values of their LCW need to be to avoid continuing corrosion of copper in the magnet coils. During the design or re-design of the LCW system, Fig. 4, based on experiments described in [4], should be consulted.

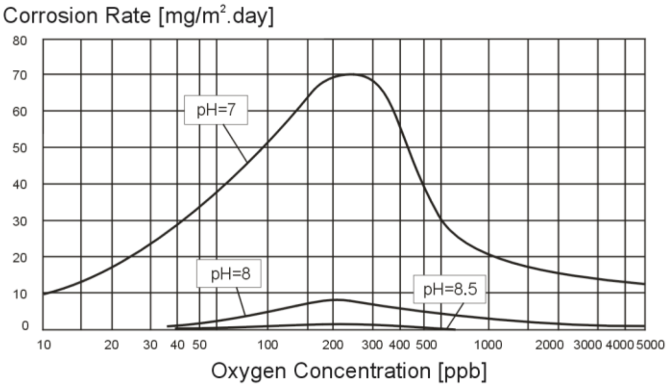

Fig. 4. Corrosion rate of copper in fast flowing de-ionized water as a function of dissolved O_2 concentration in the water, at 3 different pHs, [4].

To minimize the corrosion rate the LCW should run at pH>8 and *either* a very low DO content (<50ppb) *or* a very high DO content (>2000ppb). One wants to avoid a mid-range DO, 100-1000ppb, especially if the LCW's pH is around 7. The resistivity of LCW is related to its pH such that a pH of >8 may not satisfy the LCW resistivity requirements of the magnet system. It is also difficult to vary, control and measure the pH of LCW, but the advantages of fewer clogged magnets and not needing to flush magnets are worth the effort [5]-[10].

VI. Erosion and Insulation Failures

A survey question asked "Have your magnet coils or copper cooling pipes ever suffered enough erosion to create a hole in the conductor wall and so LCW leaks out?", 7 surveys answered yes and 3 observed erosion happening at tight or 90° bends in the conductor or pipe. Survey-takers generally knew that too high an LCW velocity in a coil was the root cause of erosion, exacerbated by tight bends. But half the labs did not have a velocity design standard; so many magnet designers had not calculated the velocity when they designed the coils. The safe range of velocities is >2 m/s (do not have too slow a flow, it will not cool the coil properly) and <4 m/s. Velocities above 5 m/s may disrupt the Cu_2O film, the Cu_2O particles will flow to hotter parts of the circuit where Cu_2O is less soluble and they may re-deposit. This process leads to gradual accumulations of particles that can stop the LCW flow; a smaller diameter channel will plug up sooner, [6], [11].

Insulation failures happened *less* often than one might have predicted: 42% of 24 machines report having no insulation failures in the previous 4 years. Vacuum impregnation was the most popular method of winding coils (19 out of 24) and was voted the method most likely to lead to reliable coils (more impervious to external water; outer dimensions more consistent; no air bubbles and so no path for water to leak in).

VII. CONCLUSIONS

No institution in the survey had failure-free magnets, but electromagnets can continue to function for decades. Engineering for reliability must be a priority [12]. Paying attention to the advice in this paper, especially about your LCW properties, will enhance your magnets' reliability.

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