FMEA on the Superconducting Torus for the Jefferson Lab 12GeV Accelerator Upgrade

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Abstract— As part of the Jefferson Lab 12GeV accelerator upgrade project, Hall B requires two conduction cooled superconducting magnets. One is a magnet system consisting of six superconducting trapezoidal racetrack-type coils assembled in a toroidal configuration and the second is an actively shielded solenoidal magnet system consisting of 5 coils. Both magnets are to be wound with Superconducting Super Collider-36 NbTi strand Rutherford cable soldered into a copper channel. This paper describes the various failure modes in torus magnet along with the failure modes that could be experienced by the torus and its interaction with the solenoid which is located in close proximity.

Index Terms—Torus, SSC-NbTi Rutherford cable, conduction cooled, superconducting magnet, magnet quench protection

I. INTRODUCTION

As part of the Jefferson Lab 12GeV accelerator upgrade [1] project, Hall B requires two conduction cooled superconducting magnets [2]. The torus magnet system is part of the Large Acceptance Spectrometer (CLAS12) experiment at the Jefferson Laboratory (JLAB), where the Continuous Electron Beam Accelerator Facility (CEBAF) is presently being upgraded to 12 GeV. A detailed Risk Assessment and Mitigation (RAM) process has been used to evaluate the overall magnet design and the robustness of its protection system. The magnet risk analysis includes electromagnetic (EM) analysis with eddy currents, Lorentz forces, thermal loading, and interaction with the superconducting solenoid which is located in close proximity to the torus.

The Torus magnet is comprised of 6 identical superconducting trapezoidal racetrack-type coils, electrically connected in series. Each coil is wound using outer dipole SSC NbTi cable soldered into a copper channel and potted within an aluminum coil case. The main parameters of the torus and solenoid magnets are listed in TABLE I. The torus magnet also includes the following as an integral part of the main system –

- a) A thermo syphon based 4.5 K heat exchanger system that “re-cools” a single stream of forced flow supercritical helium, (using 6 individual re-coolers), before and after it traverses through each coil. This supercritical helium stream provides indirect cooling to the superconducting magnet coil’s conductor edges through two spirals of copper tubing connected to copper cooling fins. Similar

arrangements cool bus-lines and part of the transport current leads.

- b) Conductor splices cooled via the exterior surface of the six re-coolers.
- c) Liquid Nitrogen cooled shields and supports that suspend the coils in space.
- d) Transport current leads from the magnet system to the cryo-tower which traverse the vacuum space.
- e) Instrumentation feed-through from the cryo-tower helium volume to the magnet insulating vacuum
- f) Magnet power supply and quench protection system (QPS)
- g) Magnet diagnostic system (MDS) associated with control and data acquisition system
- h) Electrical, compressed air and deionized water systems.

All components related to the magnet system (NbTi strands, cables, conductors, coils, potting, joints/splices, current leads, and insulation breaks) have been tested or are in the process of being tested at various test facilities both here in the USA and abroad

The MDS shall be used to monitor and display the status of the magnet, current leads (both vapor cooled and conduction cooled portions), and status during cool down, operation and warm up. A hardwired interlock safety system is being developed that will protect both magnet systems in the event of various fault scenarios. A reliable tried and tested quench detection and protection circuit is also part of the MDS. A rigorous Failure Modes and Effects Analysis (FMEA) have been carried out on the magnet and all system interfaces. This will lead to the establishment of a structured monitoring and controls procedure which will also be used during the commissioning phase for the magnets.

TABLE I: TORUS AND SOLENOID COIL KEY PARAMETERS

Parameter	Unit	Torus	Solenoid
Peak operating current	A	3770	2416
Operating Temperature	K	4.7	4.2
Coil peak field	T	3.58	6.56
Number of coils	[]	6	5
Total stored energy	MJ	14.2	17.2
Inductance	H	2	5.89

A detailed analysis has also been performed to investigate the electromagnetic interaction between the torus and the solenoid under various operational and failure modes and has also been included as part of the FMEA process [3].

II. FMEA PROCESS

Any failure that occurs when one or more intended functions no longer fulfils the requirements is used as the evaluation criterion [4]. The most critical system or component failures are those that have escaped the design

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reviews and in-house quality inspections and could be expected to be found within the experimental hall. The end results of failures that lead to unsafe conditions or significant

losses are rated high in severity. The FMEA process is used in identifying potential failure modes early on in the design phase.

TABLE II: EXTRACT FROM THE FMEA WORKSHEET FOR THE HALLB TORUS

FMEA	Mode	Effect		Cause w/Probability		Action		Ability to Detect and then Mitigate (mitigated rating)		Risk after Mitigation	Unmitigated	Instrument related Item	Part of MPS (X) or Control (C)	
Process step	Potential failure mode/component	Potential failure effects	SEV	Potential causes	Prob	Mitigation/Action/Control required	MIT	Current process controls	DET	RPN	Inaction Rating	UnMIT RPN		
External Hazards														
#	Fire in the Hall B Hall		10		3	Interface between VESDA and PLC Power Supply Control	30	VESDA System	2	60	2	60	Fire detection signal to fast dump	X
Coil and helium cold mass through service vessel														
#	Direct Turn-to-Turn Short during operations	For coils with less than 10% of the turns shorted out, coils are safe. Very small chance for Coil Burn-out	7	Bad insulation design or implementation	2	May run with slow charge and discharge of coils depending on resistance of the shorts. Take apart coil to remove short.	14	Detectable during initial ramp by Pick-up Coils and the fast data acquisition system connected.	3	42	9	126	Turn to Turn Short Detection	X
Power Supply Failures														
#	Dump resistor not rated for the full energy of a quench	Resistor overheats or melts, may cause loss of continuity and arc in resistor cabinet near the end of discharge	6		1		6	Order from qualified vendor	2	12	5	30	-	*
Control System														
#	Instrument wires are mis-wired at the instrument, connectors or in the wiring harnesses.		10		3		30	End to end check-out throughout assembly process	1	30	7	210	all instruments	X&C
A. Quench Detector(s) Failure Modes														
#	Quench Detector fails to detect legitimate quench	Full energy of magnet has potential to be dumped into coil portion that has quenched. Possible coil burn-out	7		3	PLC software quench detector is a back-up. It may be set to slightly higher thresholds.	21	Software quench detector detects quench even before Hardware Quench Detector and trips Fast Dump.	2	42	6	126	Quench detector	X
B. Other Hard Wire Interlocks														
#	Failure of Vapor Cooled Lead Voltage measurement – false low or null reading of voltage	Failure of fast dump system to work when it should. Possible lead burn-out	8		3	Archive voltages from Fast DAQ. Compare readings with earlier reading to determine if the false low value is realistic in continued operations.	24	Operator notified of dump	1	24	6	144	voltage controller	X
C. Fast Data Acquisition System (Pxi or FPGA)														
#	Failure of fast DAQ hardware, installed hardware, operators or algorithm to detect and respond to a turn-to-turn short.	Continued charging of magnet to full current with turn-to-turn short condition in play. Unexplained losses of helium during charging and discharging. Coil burn out possible	7		3	Institute self-check of system. Algorithm needs second party check before being qualified. Eyes-on-review of 1 vs. trim coil Plots plots needed throughout torus lifetime.	21	Self check of continuity and resistance of the pick-up coils by Fast DAQ before each charging of the magnet from 0 current detects problems with turn to turn short detection. Secondary review of data 1 vs. trim coil signal. Plots detects anomalies	1	21	5	105	fast Daq T-T-short detection	C

Fig. 1 Failures with individual system identified in the process steps

FMEA is a tool used to eliminate or mitigate known potential failures, problems, and errors from systems under design. These risks are evaluated based on the Risk Priority Number (RPN) which is a product of 3 factors: probability of Occurrence (O), Severity (S), and Detection (D). At JLab [5], the analyses been organized around categories called failure modes, that is linked to the top level causes and effects of failures as shown in Fig. 1. We included in the FMEA the top level operational failures, where detection takes on a greater role, in order to mitigate and quantify. The RPN is used as a measure of overall risk and helps to identify the ranks - risk of the failure mode based on the 3 criteria [6-8]. The RPN columns in the work sheet identify risk areas with scores for both unmitigated and mitigated failures based on the ranking as shown in TABLE II. These RPN's indicate that some failure types could be perceived to be "worse" than others, but give no quantitative indication of their relative effects as a statistical measure for analysis. Larger RPNs indicate the need for corrective action or failure resolution.

Function

- Define potential Failure Mode (with cause of failure) and Severity of effect (S) - Severity is typically defined as the

seriousness of the potential "end effects," and is assessed independently of the causes.

- Define potential causes and evaluate Probability of Occurrence (O) - defined as how frequently the specific failure cause is projected to occur and results in the "failure mode".
- Define possible mitigation/action applied to current process and evaluate Detection difficulty (D) – Detection scores are generated on the basis of likelihood of detection – utilizing design reviews and testing procedures and experience in other halls, based on 2 parts – (i) before it becomes an issue and, (ii) detect issue before it has significant consequence.

Presently, the FMEA process is limited to failure mitigation from a technical perspective, driving designs that achieve the required performance specifications and safe operation of the magnet system. Independent cost base analyses have also been carried out to mitigate high risk items but is too wide a subject to be presented in this paper. TABLE III and TABLE IV summarize the probability criteria utilized as part of the FMEA process.

TABLE III: PROBABILITY OF OCCURRENCE AND DETECTION

PROBABILITY OF OCCURRENCE		
Ranking	Description	Criteria per year
1	Remote	P < 0.0007%
2	Low, very few failures	P 0.0007%
3	Low, few failures	P 0.0067%
4	Low, Occasional Failures	P 0.04%
5	Moderate, Sporadic Failures	P 0.2%
6	Higher, More Probable Failures	P 1%
7	High, Frequent Failures	P 2%
8	Higher, More Frequent Failures	P 5%
9	Very High, Failure Likely	P 10%
10	Very High, Failure Certain	P 20%
PROBABILITY OF DETECTION THAT PREVENTS OCCURRENCE		
Ranking	Description	Criteria
1	Highly detectable	P 100%
2	Very High	P 99.9%
3	High	P 99%
4	Moderately High	P 90%
5	Moderate	P 50%
6	Low	P 10%
7	Very low	P 1%
8	Remote	P .04%
9	Very remote	P 0.0067%
10	Non Detectable/ Or Data after Occurrence	0%

TABLE IV: LEVEL WITH RANKING OF SEVERITY

SEVERITY			
Ranking	Description	Criteria	ES&H Consequence Level
1	None	No Effect	
2	Very Minor	Apparatus is non-conformant, no dissatisfaction	
3	Minor	Apparatus is non-conformant, possible dissatisfaction	
4	Very Low	Apparatus is non-conformant, likely dissatisfaction	Extremely Low (EL)
5	Low	Apparatus's Primary function is unaffected, Secondary function is impaired or Primary function's usage is stopped and may be restarted readily	
6	Moderate	Apparatus's Primary function is unaffected, Secondary function fails	
7	High	Apparatus's Primary function is impaired or Primary function's usage is stopped and requires more than a shift to resolve	Low (L)
8	Very High	Apparatus's Primary function fails for extended period	
9	Hazardous	With Warning, Apparatus is unsafe for use but may be repaired with some effort	Medium (M)
10	Highly Hazardous or extensive repair required	Without Warning, Apparatus is unsafe for use and/or Primary Function fails and full disassembly required to repair	High (H)

With current process in control, *the unmitigated RPN with inaction rating* along with Mitigation/Action/Control mechanism with the ability of detection applied, new RPN after mitigation is evaluated as shown in TABLE II.

A typical extract from the FMEA worksheet for the torus is shown in TABLE II. The RPN scores as an extract of TABLE II is used to the following modes - magnet system diagnostics, safety interlocks, and quench detection & protection are discussed.

A suggested list of corrective actions and failure resolutions are classified.

1. Design solutions to eliminate the failure mode or reduce its likelihood, including: functional redundancies and error proofing the assembly, installation and usage.
2. Developing means of detecting causes of failure modes during manufacturing including: inspection, testing, and error proofing.
3. Providing diagnostics to easily identify the failure mode or cause during manufacture or operation.
4. Setting up monitoring and control mechanisms (e.g. interlocks) to prevent catastrophic failure during operation.

III. MAGNET SYSTEM DIAGNOSIS

The torus magnet diagnosis system shall utilize a PLC-based real-time/multiplexed industrial computer system for system control (PLC control) and a Field Programmable Gate Array (FPGA) based system for real time Data Acquisition (DAQ). A Laboratory Experimental Physics and Industrial Control System (EPICS) connection will be established via the local network which will enable experimental data to be acquired in real time and *may be* interrogated in real time. The server also communicates with other computers (e.g. End Station Refrigerator) by means of a fiber optic site network and the data will be processed on monitor computers during operation and experiments.

The inventory of data channels presently envisaged for the Hall B magnets (torus and solenoid) includes: channels for liquid helium (LHe) temperatures, 80 K shield temperatures, strain gauges, voltage taps, load cells, vacuum levels, and channels for the central interlock safety system which

includes: pressures, pressure drops, liquid levels, mass flows, vacuum levels, voltages, strains and displacements.

The torus magnet diagnostic monitor and control system will serve multiple roles:

- a. Monitoring all the technical diagnostic signals from magnets, magnet lead bus bar and vapor cooled current leads for operation and safety control
- b. Detecting magnet quench (signature), lead quench, splice quench, transport current lead section quench, and protective actions.

The torus and solenoid superconducting magnets are conduction cooled and as a result, the slow thermal response could be a potential mode of failure and requires detailed engineering in order to make the magnet subsystem robust and reliable. Both Hall B magnets possess low levels of Minimum Quench Energy (MQE) compared to bath cooled magnets and in order to mitigate this, sufficient operating margin in terms of temperature and short sample limit (SSL) has been applied to the design of these magnets

IV. SAFETY INTERLOCK

The interlock safety system as shown in Fig. 2, plays a vital role of magnet safety during commissioning and operation that links through magnet process control, PSU & alarm, QPS, vacuum system, cryogenic system. An interlock safety system and independent magnet protection system based on the threshold limits that are set will be active at all times - linked directly to serious failures.

Fig. 2 Layout for the system level input to magnet safety, protection and interlock

A. Faults

The key risks for the torus/solenoid identified in TABLE II are as follows:

- a. The defect in the design and/or degradation that does not satisfy the operating/physics requirements.
- b. Defects in the build and manufacture or degradation of insulation (thermal, vacuum).
- c. Helium mass flow not distributed uniformly over the cooling paths, or blockage occurs in cooling channel.
- d. Vacuum vessel cannot maintain required vacuum.
- e. Electrical insulation of magnet system deteriorates.
- f. Magnet power supply system loses control.
- g. A fault in the quench detection and protection system prevents the magnet from being protected normally.

Faults can be divided into 3 categories which may require different actions:

1. *Primary fault*: Serious fault. When a primary faults occurs, the control system fail/shuts, magnetic system starts fast-ramp-down protection, and the interlock safety system

notifies related systems to start primary fault/s protection applied to individual sections.

2. *Secondary fault*: Dangerous fault (less severe than serious fault). When secondary faults happen, magnetic system starts slow-ramp-down protection.
3. *Subsystem fault*: shall include every subsystem self-faults. System control or monitor function could not be executed correctly when faults happen to any subsystem software and hardware devices.

Safety polling signals are envisaged under different fault categories and shall execute different signal detection mechanisms for different signals viz. that are closely related to system and personnel safety (primary fault, secondary fault and emergency button signals) e.g. applying different threshold levels of detection and execution process.

B. Design of Safety Interlock

The Hall B magnet safety interlock system will be a distributed system that will consist of, discharge process control, operating monitor, safety polling, sub-system and access control system.

Polling of each safety parameter (might be only one) is performed by every control sub-system. Control subsystems closely related to devices, like the vacuum, magnet diagnostic, cryogenic, will detect based on predefined safety parameters to determine whether device faults exist or not.

Each subsystem executes fault protection by analyzing a predefined parameter to judge the operating status of system. These systems shall send control signals to related devices as soon as they detect faults, then start any defined fault measures and immediately send fault signals to the safety polling system.

The safety polling system will decipher signals sent by subsystems and decide whether or not to notify operators and execute protections. This shall be the role of independent quench detection, fast dump that detects and decides the fast-ramp-down, slow-ramp-down and fast discharge fault signals.

V. QUENCH DETECTION AND PROTECTION

The quench detection and protection system is very important for any superconducting device. The functions of quench detection and protection system magnet system employed are the following: detect coil quench, detect splice and lead quench and send protective trigger signal, monitor coils (temperature), current lead and feeder transport current leads and performs safety actions. A simple method of detection that is traditionally used in superconducting magnets is planned with balanced bridge voltage, and when a voltage signal exceeds the threshold set at MPS, the discharging process shall be initiated.

The logic circuit for the quench detection system is shown in Fig. 3. When a quench occurs, the protection system is triggered and the discharging process is initiated. The protection is designed for fast discharge and controlled ramp down depending on the class of fault. In the case where the threshold set in the quench detector is reached, that will initiate a fast discharge through a total time that includes sensing time, breaker opening time, switching time and time to discharge. All other cases, before the threshold is reached, the control & interlock will initiate based on the decision process predefined. At the same time, the voltage signals are sent to

the data acquisition system and the central control system for analysis of cause of quench. All voltage signals are the primary and good means to detect a quench that is recorded in real time at >1 kHz.

Fig. 3 Magnet safety and protection layout

As an outcome of the FMEA process, typical of a few points/actions are mentioned -

1. Vacuum leak test at room temperature.
2. The superconducting magnet system 4.5 K, monitoring heat leak (*temperature sensors*), vacuum leak (*vacuum gauge*) and current leakage (*line to GND monitoring*).
3. Electrical insulation test at room temperature and low temperature: the insulation of the superconducting magnets system measured by dc voltage at room temperature and low temperature. The insulation of coils to be better than $10\text{ M}\Omega$ at 500 V and leakage current test $<10\text{ }\mu\text{A}$ at 100V over 1 minute [5].
4. Quench detection test: the quench detection system for any significant electromagnetic noise from surrounding.
5. Insulation damage - The Paschen discharge caused due to vacuum leak and/or local insulation damage is accounted for and appropriate threshold test voltage defined within the electrical and vacuum insulating environment.
6. Quench Protection and incorrect protection: Quench detection signals were sent incorrectly by detection system.

VI. CONCLUSIONS

The systematic approach is put together in order to identify the potential failures and risks to the overall magnet system that arises from design, manufacturing, instrumentation & control (I&C), power supply and, administrative procedures. This provides a quantitative overview of the operating regime of the magnet system with look up table for the said consequences that includes a brief description and mitigation actions that needs to be taken at every step. The risk assessment exercise helps to address the risk amount and level of redundancy required for every hazard introduced by operating superconducting magnets.

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