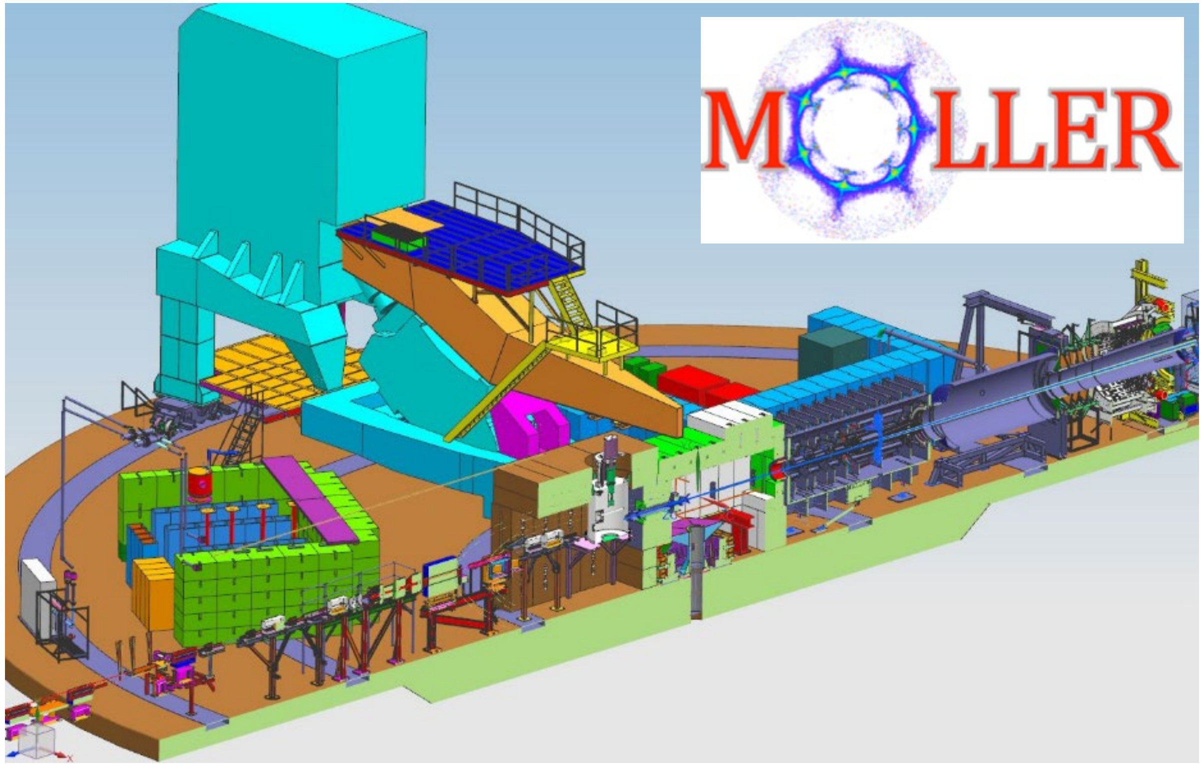
MOLLER Experimental Readiness Review #2

Magnet - Power & Protection, Operations and Documentation



Presenter - Probir Ghoshal

Moller – Spectrometer Team

DSG, Magnet Grp, Hall-A, Mech. Engineering Grp, Alignment Grp, DC Power, CAM

July 28, 2025

Overview and Key Considerations

- ❑ Summary and results of the major magnet analyses done – YES (*all EM and Fault scenarios and FMA competed and presented at 90% and CD2/3*)
- ❑ Summary and results of major components to be assembled in the test lab/hall – YES (Presented in the talk later)
- ❑ High-level commissioning and running plans (a list is prepared to complete prior to engineering run)
- ❑ "What if" scenario if performance specifications are not met (FMEA carried out and mitigation is in place to reduce the risk from High and Medium to Medium and Low moving forward)

Charge questions – Labeled for Electrical and control

Power and Magnet Protection (safety)

1. Primary and secondary magnet protection
2. Power leads/busbar ratings
3. Power supply –
   i. characteristics/design
   ii. performance and stability
4. Magnet interlock
   i. MPS interlocks (MPS, beam, vacuum, etc.)
   ii. Preventing shock to personnel
   iii. Preventing accidental grounding, arcing, etc.
5. Parameters monitored/expected thresholds/behavior logic
6. Failure Mode and Effect Analysis (FMEA)/"what if" analysis
   i. Spectrometer interface
   ii. Spectrometer - Instrumentation and controls

Magnet operation and documentation

7. Instrumentation and controls
   i. drawings and schematics
   ii. work rules/training requirements
   iii. operation manual/procedures
8. Identification of any special issue in the magnet system
   i. Magnet mapping
   ii. Training, LOTO considerations

Introduction

Overview of Power & Magnet Protection

Coil & Magnet –

a. LCW flow temperature limit completed at design conductors, coils, Conductor specifications were engineered to limit the temperature rise 35C and current density 20 A/mm^2

Eric/Sandesh - Talk

b. Magnet EM and impact on physics –
   i. Developed a program in the early stage to optimize the coil shapes and tolerances (independent of collaboration)
   ii. Added single loop return bus on all DS magnets to cancel out ant field influence of conductor self field
   iii. The conductors near the beam line is packed to the best of the manufacturing at the coil manufacturing stage
   iv. Magnet-Magnet interactions were analyzed at early stage of the project during structural design of the magnet system.

c. Importance of protecting magnets and power systems (What if analysis using FMEA tool) - *Design, manufacturing, system, functional, user, software to e*nsure safety and reliability in operations

d. Key Objectives - Preventing damage to equipment, ensuring personnel safety, operational efficiency (minimum interruption to physics)

Primary and Secondary Magnet Protection

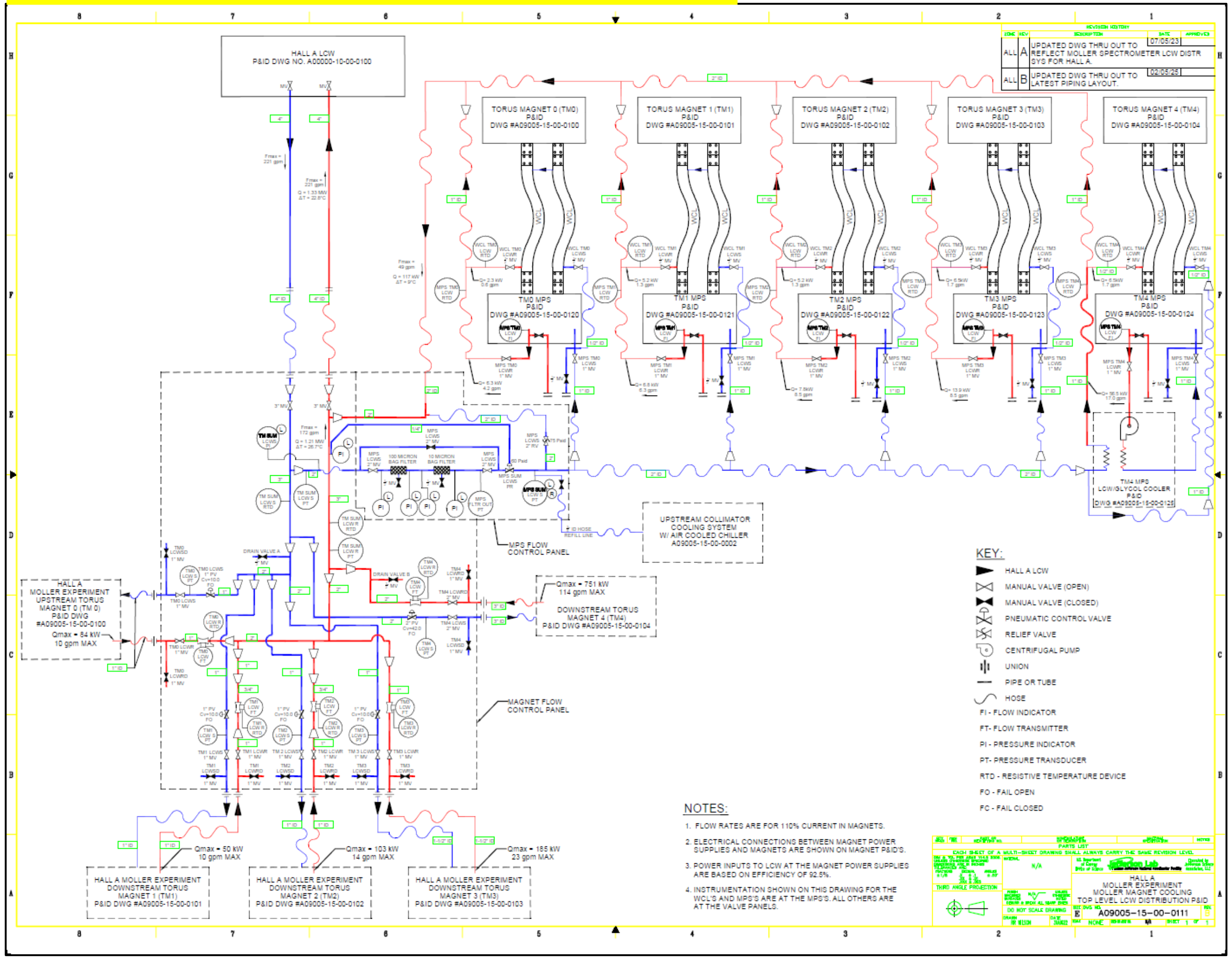
CHARGE #1

- **Primary Protection: First line of defense against faults**
  - First line against faults - Coils and Magnets are monitored via VT's
    - TM1 – TM3 are identical, TM4 has additional VTs due to double-pancake design
    - The chances of failure of the VT's are minimum (unless VT's are detached)

- **Secondary Protection: Backup systems to ensure reliability**
  - Coil and magnet temperature and flow
  - RTD's - every location inside the vacuum enclosure have redundant sensors and routed out of the vacuum enclosure, wired up to PLC rack. Only one RTD sensor monitored by PLC and can be switched over in case one fails (all will be wired up to the connector in the vacuum side)
  - RTD types – to be compliant in rad environment.
  - LCW (cooling) – return temperature and flow is for the magnet is always monitored

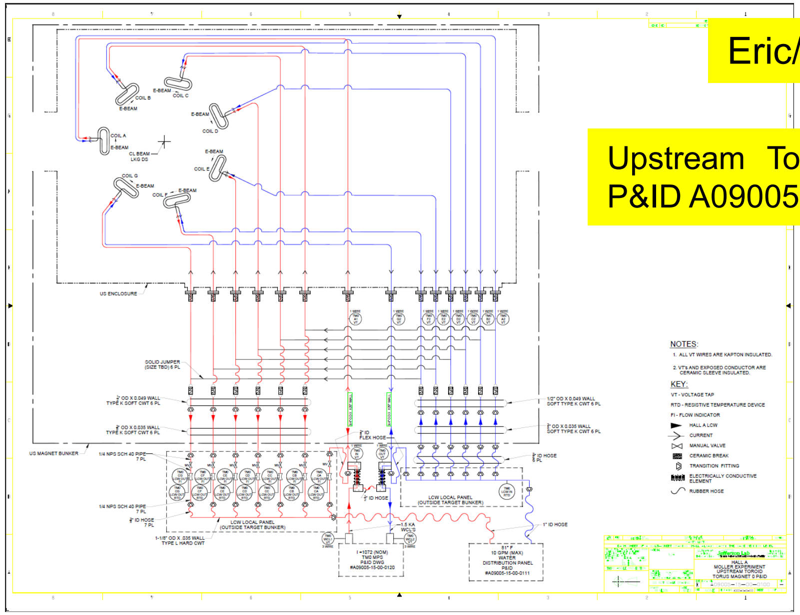
LCW Distribution – DS/US

MOLLER System P&ID for the LCW distribution in Hall - A09005-15-00-0111

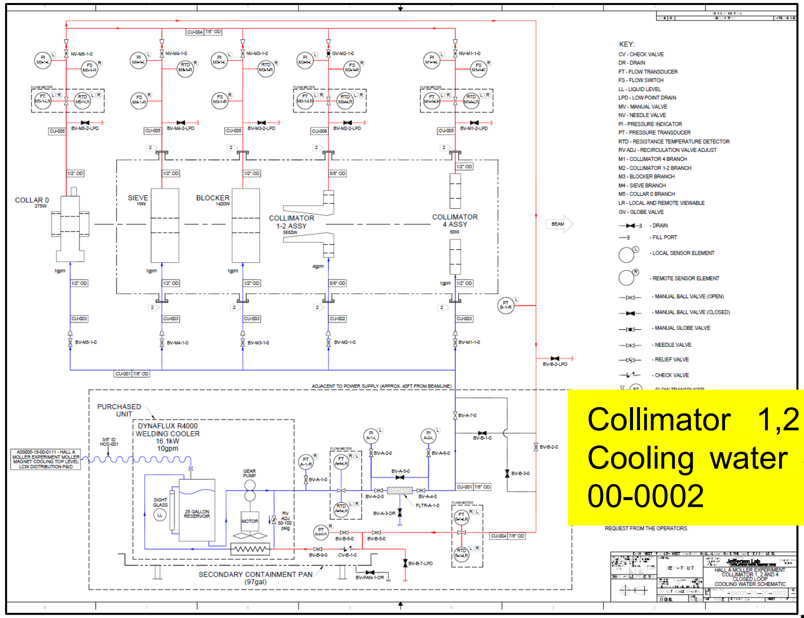


LCW Distribution

Eric/Sandesh - Talk



Upstream Toroid Magnet P&ID A09005-15-00-0100



Collimator 1,2 and 4 Closed loop Cooling water Schematic A09005-15-00-0002

Jefferson Lab

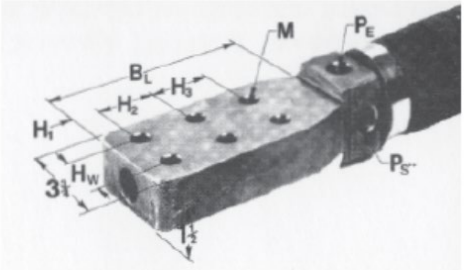
Power Leads/Busbar Ratings

CHARGE #2

- **Water cooled leads (WCL)** Specifications and ratings for various current capacities
  - 1500A (2), 3000A (4), 4000A (4)
- **Copper flexible jumper leads** – in air and in vacuum
  - 3000MCM, 22” (10) MPS end
  - 1500MCM, 15” (42) air and vacuum
  - 750MCM, 15” (32) air and vacuum

1. PMAG0000-0100-S0017 - Moller Spectrometer - Specification and RFQ US and DS Magnet WCL_Jumper leads
2. O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\6. Engineering Calculations-Analyses-Simulations\Electrical\Current Leads and Jumpers

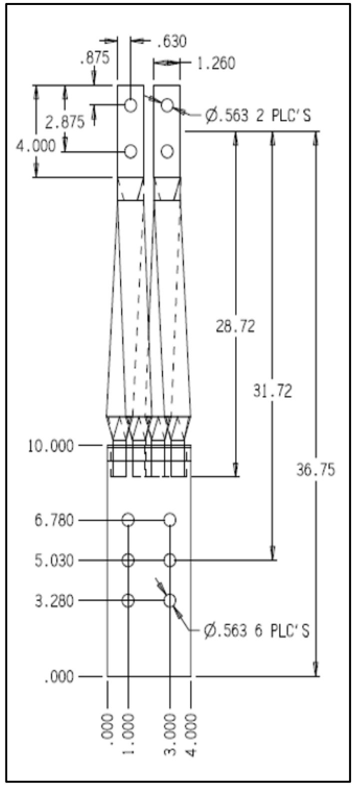
14

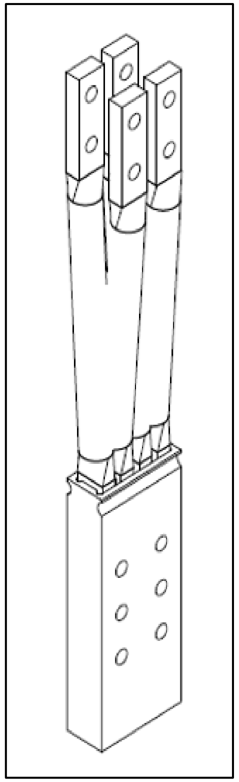


MCM SIZE	B_L	H_1	H_2	H_3	H_W	M	P_E	P_S**
1500	7	1-1/4	1-3/4	1-3/4	2	9/16	1/2	1/2
2000	7	1-1/4	1-3/4	1-3/4	2	9/16	1/2	1/2
2500	7	1-1/4	1-3/4	1-3/4	2-1/4	1-1/16	1/2	1/2

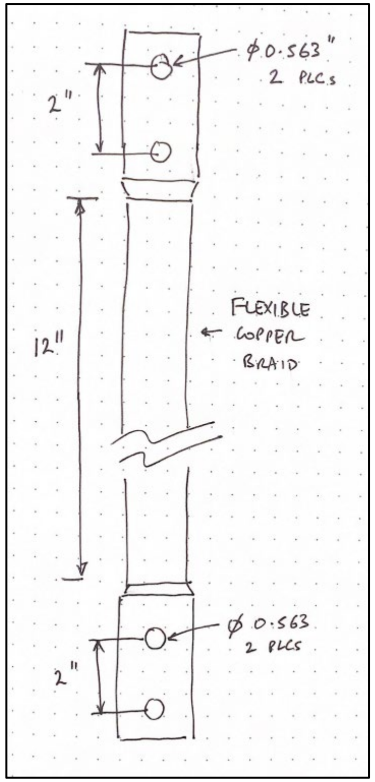
**Side port P_S only if specified, P_E standard.

Typical lead terminal at each end of water-cooled lead (WCL)



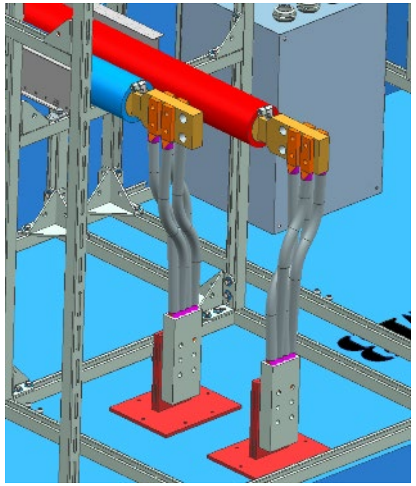


Typ Power supply bus bar end (Dimensions in inches)

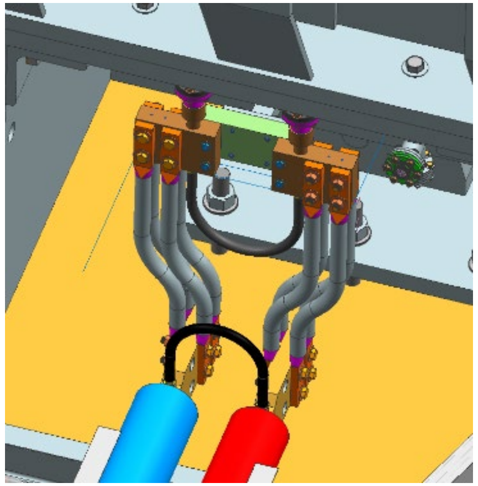


Typ. Flexible link jumper – Magnet current lead end

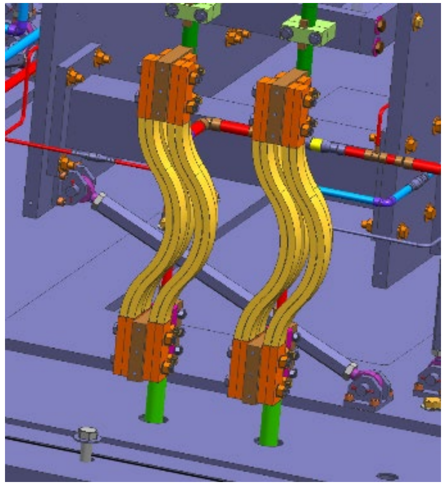
Spectrometer – Water Cooled Leads and Flexible Jumpers



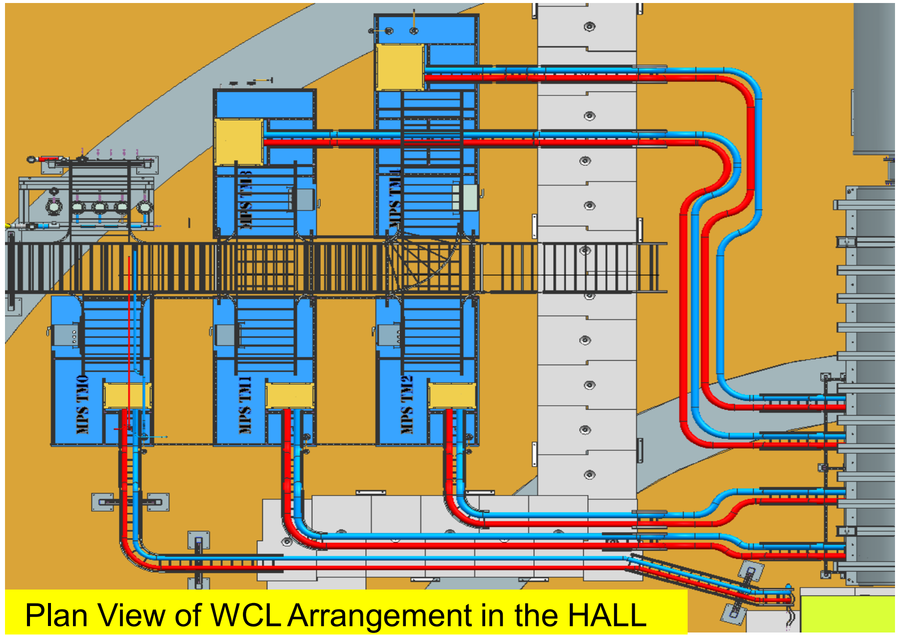
MPS TM0-4 Jumpers
(4x750 MCM)
3000 MCM total



WCL Connection at DS Enclosure
Air side Jumpers
(750 MCM each)
3000 MCM total

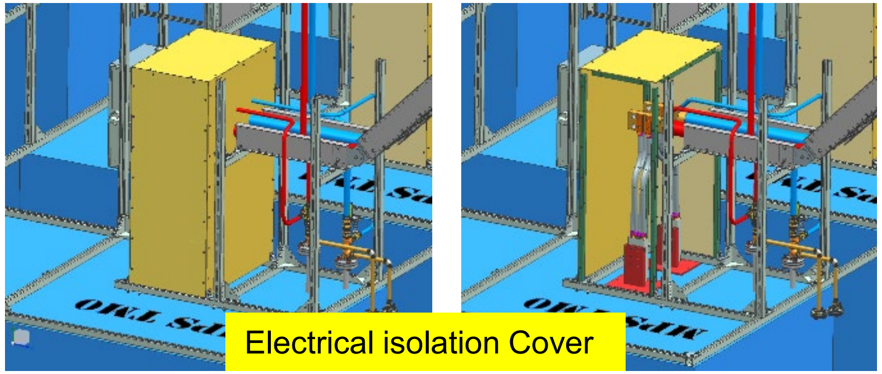


TM1-4 DS Enclosure Vacuum
Side Jumpers
(735 MCM each)
TM1&2 - #4x2 (2940MCM)
TM3&4 - #6x2 (4410MCM)



Plan View of WCL Arrangement in the HALL

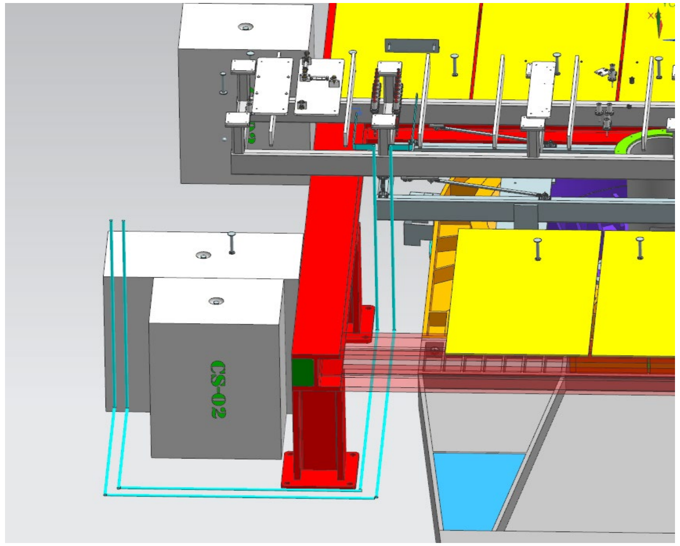
TM0 WCL 1000MCM
TM1&2 WCL 2500MCM
TM3&4 WCL 5000MCM

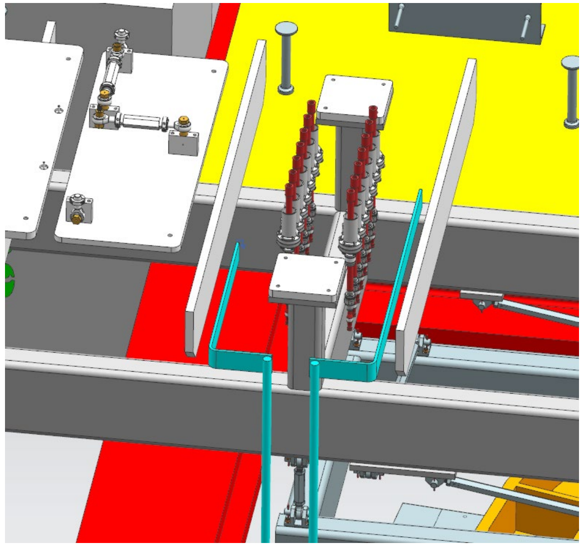


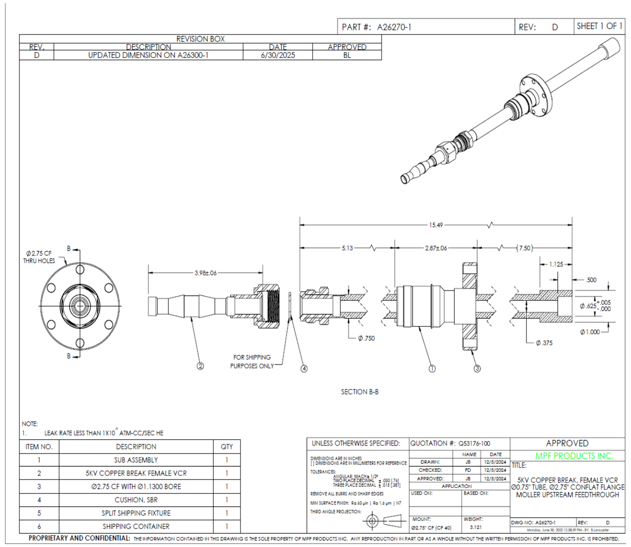
Electrical isolation Cover

Plan View: Arrangement in the hall, connection details, and electrical isolation.

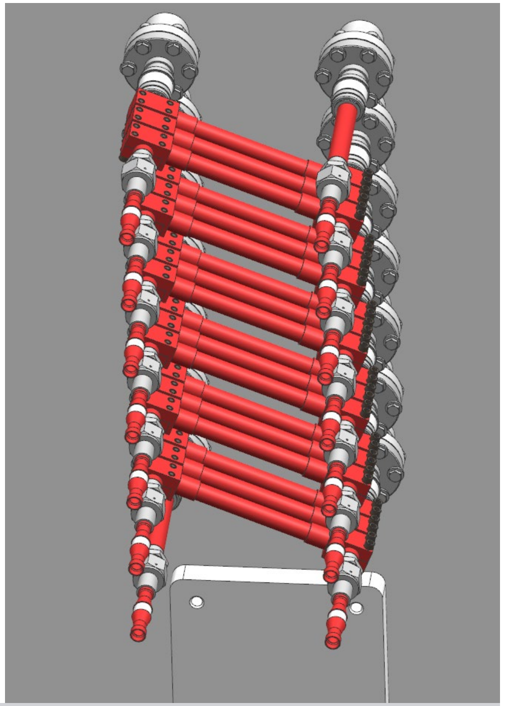
Spectrometer – US WCL and leads





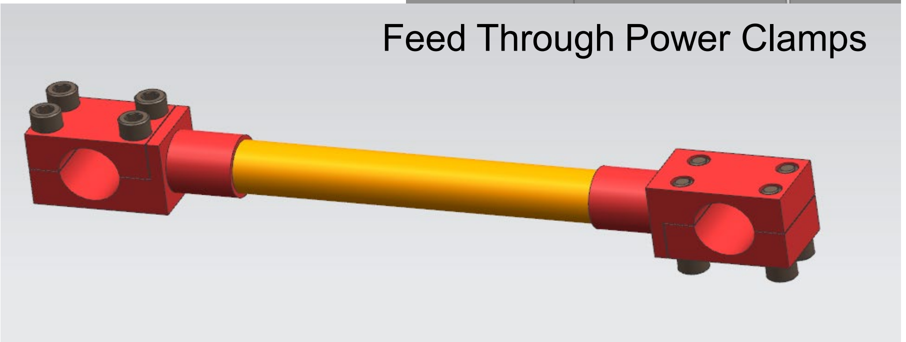


Electrical Power - Vacuum Feedthroughs



Power delivery (GND and electrical safety and engineering (in Progress)
- ¾" Nominal schedule 40 copper piping, Brazed/soldered joints
- Voltage drop of 1.11V, Water cooled

WCL (Non-Flexible)
- The sch 40 copper pipe will connect to these WCL
- Cooling water from the connections on the leads
- The MPS can support additional flow to cool the "Bus-tubes"



- Woven copper cable in orange
- Machined copper in red
- Carries 1200A, Current density is limited to 2A/mm^2

- The Bus tubes will terminate at a traditional copper bus bar.
- Clamps will join the bus bar to the vacuum feedthroughs
- Voltage drop along the bus is expected to be 42 mV

Power Leads/Busbar Ratings

- Flow Requirements:
  - Current capacity and thermal limits
  - proper sizing to prevent overheating
- Voltage Drop:
  - Calculations and considerations
  - Impact on system performance
- Design and Safety normal operation

MPS #	Power (kW)	Built/Assembly	Initial Test at OCEM	FAT (Remote)
TM0	84	Completed	Completed	02/17/2025
TM1	90	Completed	Completed	04/04/2025
TM2	103	Completed	Completed	02/21/2025
TM3	185	Completed	Completed	Completed
TM4	751	Completed	Completed	**07/24/2025**

FAT test recordings are available at –
O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\6. Engineering Calculations-Analyses-Simulations\Electrical\Magnet Power supply_Normal\Moller MPS OCEM Shared docs\FAT_TM2 and TM0-TM1_TM4 remotely

Electrical breakdown voltage and tracking voltage evaluated (insulation and test) –
O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\6. Engineering Calculations-Analyses-Simulations\Electrical\Breakdown and tracking Moller

Power Leads/Busbar Ratings

AC Power Requirement(s): Calculations and considerations (Impact on system performance)

P K Ghoshal 02/03/2023				Pwr Fact	0.85
Inpt: 3-phase, 480V	Input Voltage (V)	480			
	Worst 20% less Input	0.85	408		
Power Supply	New Nominal Oper Current (from NI)	Max_DC_Iout (A)	Max_DC_Vout (V)	Max_DC_Pout (W)	Max_input_Iphase (A)
US_T	1072	1290	93	119970	199.7
DS_T1	2229	2676	48	128448	213.8
DS_T2	2439	2928	51	149328	248.6
DS_T3	3373*	3882	65	252330	420.1
DS_T4	3352	4020	270	1085400	1807.0
Total					2889.2
Inp_VA					2041736
Txf_nominal_VA					2455.8

Power Supply Characteristics/Design

CHARGE #3

- **MPS (Magnet Power Supplies):**

  Overview and specifications
  - Importance of precision and reliability and handling
  - PMAG0000-0100-S0014 MOLLER MPS specification
- Performance and Stability:
  - Key metrics - Efficiency, ripple, noise
  - Added DCCT's to individual power modules

Ideally, using the operating current tap, the power supplies will provide 100 ppm stability (RMS over 24 hr) at the nominal operating current, but at a minimum must satisfy the stability values listed in Table 1 when operated with the nominal load values provided in Table 1.

Table 1: Nominal power supply operating characteristics.

Item	Power supply	Nominal Operating Current (DC Amps)	Output current stability better than (mA RMS 24 hours) at operating current	Normal Operating Voltage (DC volts, nominal)	L_{total} (milli-Henries)	R (ohms)
1	US torus	1075	500	77.5	0.631	0.059
2	DSTorus_1	2230	1000	40	0.153	0.015
3	DSTorus_2	2440	1000	42	0.246	0.013
4	DSTorus_3	3235	1500	57	0.348	0.013
5	DSTorus_4	3350	1500	224	3.051	0.056

Note: Load Characteristics Tolerance: Resistance 10% and Inductance 10%

Site acceptance test of TM3 with OCEM Installation team (3900A) @ JLab

TM3 Jan 2024

Handling procedure - Document UT-RT-0993/OCEM/Dated 05th June 2024
Test results from FAT - O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\6. Engineering Calculations-Analyses-Simulations\Electrical\Magnet Power supply_Normal\Moller MPS OCEM Shared docs\FAT_TM2 and TM0-TM1_TM4 remotely

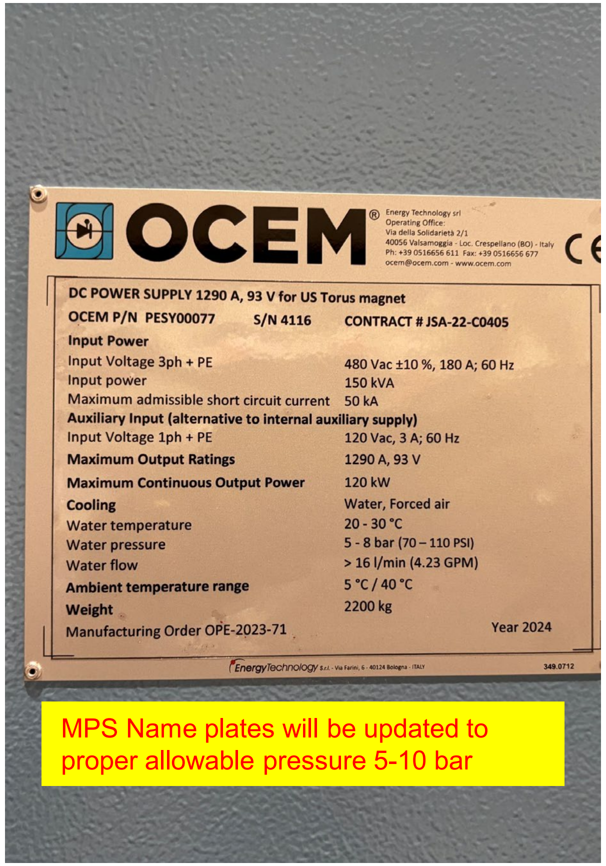
Power Leads/Busbar Ratings

MPS#	Power (kW)	Normal operating Voltage (V) and current (A)	FAT Voltage and current (limited load)	Error FAT (V & I) ppm
TM0	84	77.5/1075	93/1290	8.6/2.2 (10 ppm stability 8 hrs)
TM1	90	40/2230	48/2676	8.3/3.8 (7 ppm stability 8 hrs)
TM2	103	42/2440	51/2928	7.8/3.2 (12 ppm stability 8 hrs)
TM3	185	57/3235	70/2700 at OCEM (FAT)	10/2.4
			32/3900 at the LAB	<25 ppm Overall at JLAB
TM4	751	224/3350	77V/3000 A *(7/24/2025)*	Analysis in progress (over seems raw p-p 92 ppm)

FAT test recordings are available at –
O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\6. Engineering Calculations-Analyses-Simulations\Electrical\Magnet Power supply_Normal\Moller MPS OCEM Shared docs\FAT_TM2 and TM0-TM1_TM4 remotely

Power Supply Characteristics/Design

TM0 – MPS received (now in Physics storage)

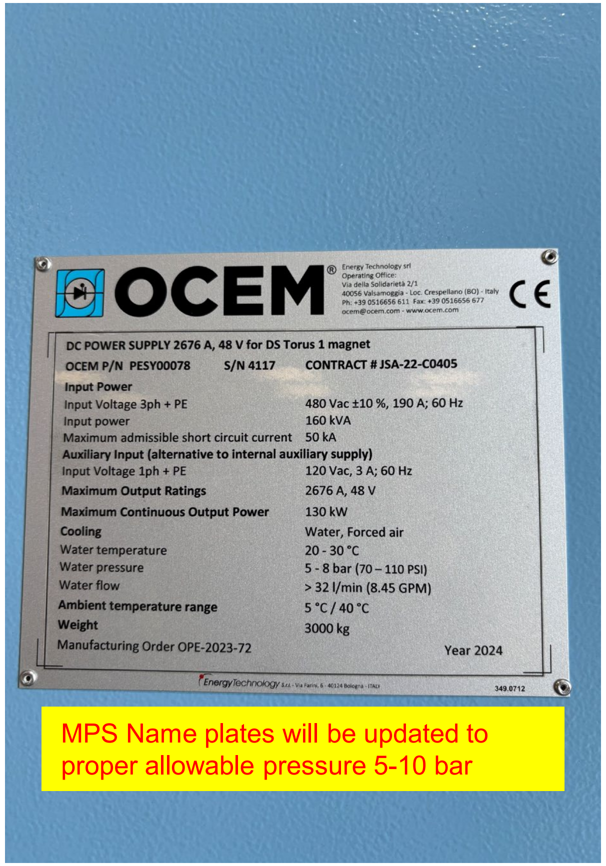


MPS Name plates will be updated to proper allowable pressure 5-10 bar

I/p – 150kVA, O/p – 120 kW, 1290 A, 93 V (Maximum), 4.23 gpm (16 lpm), air-cooled

Power Supply Characteristics/Design

TM1 – MPS received (now in Physics storage)

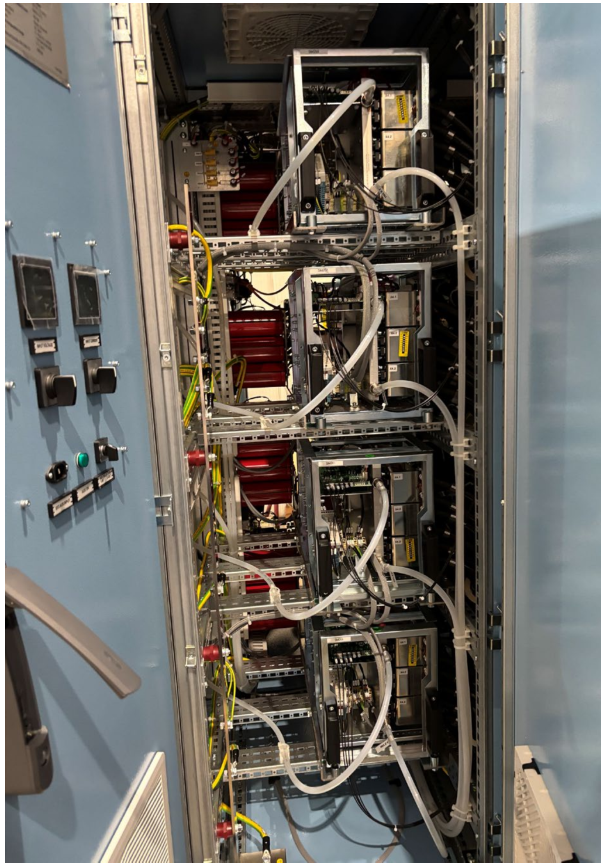


MPS Name plates will be updated to proper allowable pressure 5-10 bar

I/p – 160kVA, O/p – 130 kW, 2676 A, 48 V (Maximum), 8.45 gpm (32 lpm), Air-cooled

Power Supply Characteristics/Design

TM2 – MPS received (now in Physics storage)



MPS Name plates will be updated to proper allowable pressure 5-10 bar

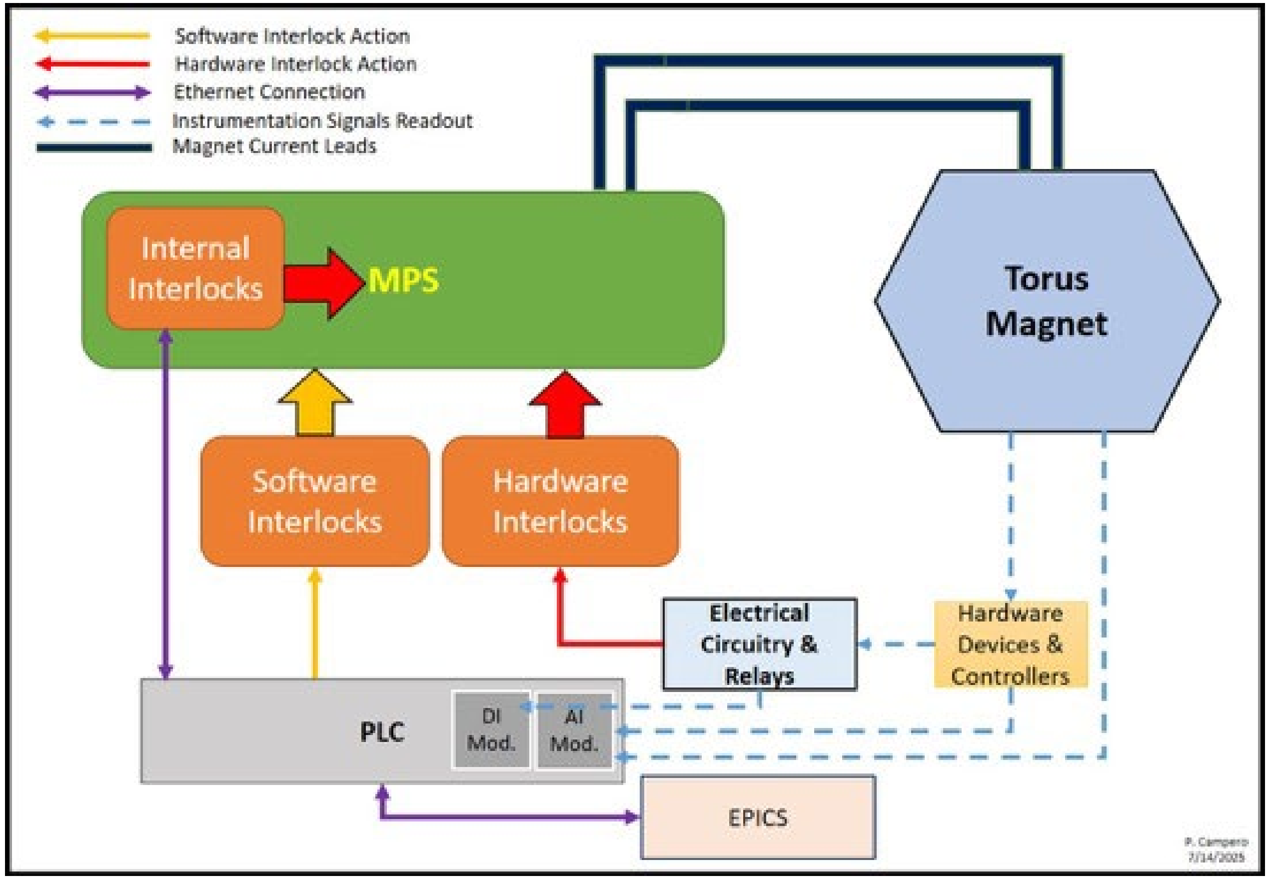
I/p – 180kVA, O/p – 150 kW, 2676 A, 51 V (Maximum), 8.45 gpm (32 lpm), Air-cooled

Magnet Interlock & Protection Systems

CHARGE #4

- Interlock Systems:
  - Types - process, electrical, software-based
  - Functions - Preventing unsafe operations, ensuring system safety
- Primary protection is accomplished via Voltage Tap (VT) with hardware voltage comparators between each magnet coil
  - Danfysik units used throughout JLab
- Second VT goes to PLC
  - Allows for additional comparisons to be performed and adjustable thresholds
- Secondary protection is the coil temperature and flow

Single magnet shown, same scheme used for TM0-TM4



MPS Personnel Safety

- Main concern is arc flash and shock hazards
- Default is to use Class 1 (≤ 60 VDC & ≤ 50 A) on I&C
  - Nearly all power is 24 VDC, some sensor signals are ± 10 VDC rest are 4-20 mA
  - The exception to this is the voltage taps for the overall MPS on TM0 and TM4 where the voltage is > 60 VDC
    - For consistency all MPS VTs have current limiting resistors installed inside the lead enclosure limiting current to < 5 mA on the tap wires
- MPS Protections
  - The MPS are incorporated with GND (notes for E&SH for JLAB) seen with Torus MPS#3 (prototype installed and commissioned in test lab)
  - Document # UT-NT-0766

OCEM POWER ELECTRONICS
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BOLOGNA ITALY
Edition 03/05/2022

Document UT-NT-0766

Page 1 di 9

GROUNDING IMPLEMENTATION
NOTES FOR JLAB DR-TORUS 3 PS

Author: Filippo Burini

Approver: Riccardo Morici

N. of attachments: /

O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\6. Engineering Calculations-Analyses-Simulations\Electrical\Magnet Power supply_Normal\Moller MPS OCEM\OCEM Comms\UT-NT-0766_Grounding implementation notes of JLAB DS-Torus3 PS.pdf

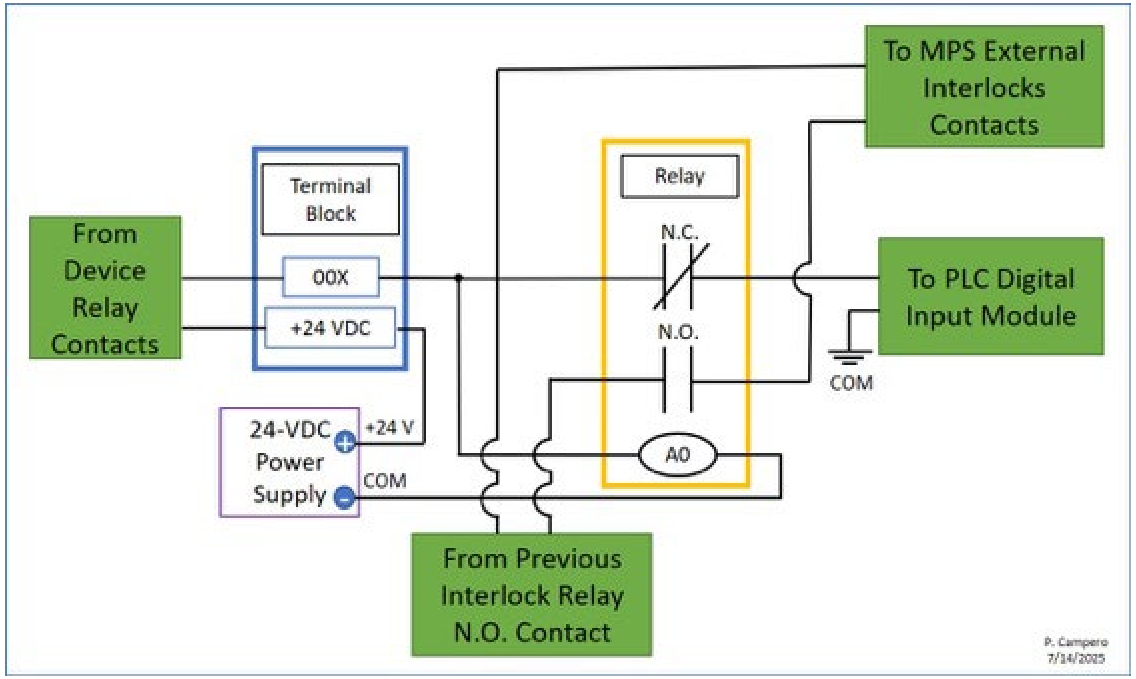
Parameters Monitored/Expected Thresholds/Interlock Logic

CHARGE #5

- Monitored Parameters:
  - Current, voltage, temperature, flow, real-time monitoring
- Thresholds and ***Interlock Logic***:
  - Setting and adjusting thresholds
  - Behavior logic for automated responses to anomalies (PID's)
- Signals monitored have between one and three levels depending on the sensor
  - First: EPICS – optional, lowest threshold closest to operational value, used for early warning to shifters of potential problems, generally no action taken
  - Second: PLC – medium threshold, software comparison on PLC, ramp magnet to zero
  - Third: Hardware – highest threshold, hardware relay breaks interlock loop to MPS, ramp magnet to zero
- Example: VT with nominal setting of 5V – EPICS at 6V, PLC at 7V, Voltage Comparators at 8V

Hardware Interlock

Single channel of hardware interlock shown, additional hardware devices are connected in the same chain such that any device faulting will cause an interlock on the MPS



Magnet Safety and threshold (TM0-4)

Voltage Comparators (setting to start with during test and commissioning)

NOTE: Voltage drop might have an error of ~5% (Considered the worst case for design)
General - Coil A and G will have higher voltage drop compared to B-F

MPS	Magnet Power supply
PFL	Power Feedthrough

PMAG0000-0100-S0043 Specification for MOLLER Voltage comparator (DS1-4) now added US

Power Supply	New Nominal Oper Current (from NI)	110% Nominal	90% Nominal
US_T0	1072	1179	965
Power (kW)		74.8	50.0
V (acorss all coils)		63.4	51.9
V (across 1 coil)		9.06	7.41

Voltage comparators

	QD1		QD2		QD3		QD4		QD5		QD6		QD7	
Coils	A	B	B	C	C	D	D	E	E	F	F	G	G	A
mV	<10		<10		<10		<10		<10		<10		<10	

DAQ Chanels	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
Includes..	A	B	C	D	E	F	G	MPS-CoilA (IN)	MPS-CoilA (OUT)	MPS	PFL+Flex lead (IN)	PFL+Flex lead (OUT)
Voltage expected	9.06	9.06	9.06	9.06	9.06	9.06	9.06	2	2	68.42	0.5	0.5

Power Supply	New Nominal Oper Current (from NI)	110% Nominal	90% Nominal
DS_T1	2229	2452	2006
Power (kW)		69.4	46.5
V (acorss all coils)		28.3	23.2
V (across 1 coil)		4.05	3.31

Voltage comparators

	QD1		QD2		QD3		QD4		QD5		QD6		QD7	
Coils	A	B	B	C	C	D	D	E	E	F	F	G	G	A
mV	<10		<10		<10		<10		<10		<10		<10	

DAQ Chanels	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
Includes..	A	B	C	D	E	F	G	MPS-CoilA (IN)	MPS-CoilA (OUT)	MPS	PFL+Flex lead (IN)	PFL+Flex lead (OUT)
Voltage expected	4.05	4.05	4.05	4.05	4.05	4.05	4.05	2	2	33.32	0.5	0.5

Power Supply	New Nominal Oper Current (from NI)	110% Nominal	90% Nominal
DS_T2	2439	2683	2195
Power (kW)		78.9	52.7
V (acorss all coils)		29.4	24.0
V (across 1 coil)		4.20	3.43

Voltage comparators

	QD1		QD2		QD3		QD4		QD5		QD6		QD7	
Coils	A	B	B	C	C	D	D	E	E	F	F	G	G	A
mV	<10		<10		<10		<10		<10		<10		<10	

DAQ Chanels	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
Includes..	A	B	C	D	E	F	G	MPS-CoilA (IN)	MPS-CoilA (OUT)	MPS	PFL+Flex lead (IN)	PFL+Flex lead (OUT)
Voltage expected	4.20	4.20	4.20	4.20	4.20	4.20	4.20	2	2	34.40	0.5	0.5

Power Supply	New Nominal Oper Current (from NI)	110% Nominal	90% Nominal
DS_T3	3373	3710	3036
Power (kW)		165.2	110.7
V (acorss all coils)		44.5	36.5
V (across 1 coil)		6.36	5.21

Voltage comparators

	QD1		QD2		QD3		QD4		QD5		QD6		QD7	
Coils	A	B	B	C	C	D	D	E	E	F	F	G	G	A
mV	<10		<10		<10		<10		<10		<10		<10	

DAQ Chanels	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12
Includes..	A	B	C	D	E	F	G	MPS-CoilA (IN)	MPS-CoilA (OUT)	MPS	PFL+Flex lead (IN)	PFL+Flex lead (OUT)
Voltage expected	6.36	6.36	6.36	6.36	6.36	6.36	6.36	2	2	49.52	0.5	0.5

Power Supply	New Nominal Oper Current (from NI)	110% Nominal	90% Nominal
DS_T4	3353	3688	3018
Power (kW)		755.4	505.7
V (acorss all coils)		204.82	167.58
V (across 1 coil)		29.26	23.94
V (across per pancake)		14.63	11.97

Voltage comparators

	QD1		QD2		QD3		QD4		QD5		QD6		QD7	
Coils	A	B	B	C	C	D	D	E	E	F	F	G	G	A
mV	<10		<10		<10		<10		<10		<10		<10	

DAQ Chanels	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16	#17	#18	#19
Includes..	A		B		C		D		E		F		G		MPS-CoilA (IN)	MPS-CoilA (OUT)	MPS	PFL+Flex lead (IN)	PFL+Flex lead (OUT)
	AL	AR	BL	BR	CL	CR	DL	DR	EL	ER	FL	FR	GL	GR					
Voltage expected	14.63	14.63	14.63	14.63	14.63	14.63	14.63	14.63	14.63	14.63	14.63	14.63	14.63	14.63	2	2	209.82	0.5	0.5

Failure Mode and Effect Analysis (FMEA)

CHARGE #6

- FMEA Overview:
  - Purpose - Identifying and prioritizing potential failures
  - Process - Systematic, step-by-step approach

Normal Magnets (Copper water-cooled)
The identified categories of risk:
1. Magnet design – 45
2. Mechanical design – 43
3. Electrical design - 36
4. Instrumentation and controls – 21

The **common failure modes** in water cooled magnets are :
1. Water leaks - internal, joints/splices, hoses, and connectors, and
2. Electrical shorts - turn to turn and line to ground. Generally, turn to turn is less of a problem, due to the lower voltages involved
3. Overheating – usually caused by blockages in the water-cooling channels. The overheating could lead to degradation of the epoxy insulation, failure of brazed/soldered joints, smoke, and fire.

Spectrometer system FMEA is been developed and work will be in progress till the commissioning
O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\12. Quality Control Documents\FMEA\Magnets_coils (MOLLER SPECTROMETER - FMEA v2e.xlsx (overall system IN PROG)

NOTE: Coils cured at150 deg C, Trip point for exit water is XXC, and design water temp is 51C-58C depending on TM#

Failure Mode and Effect Analysis (FMEA)

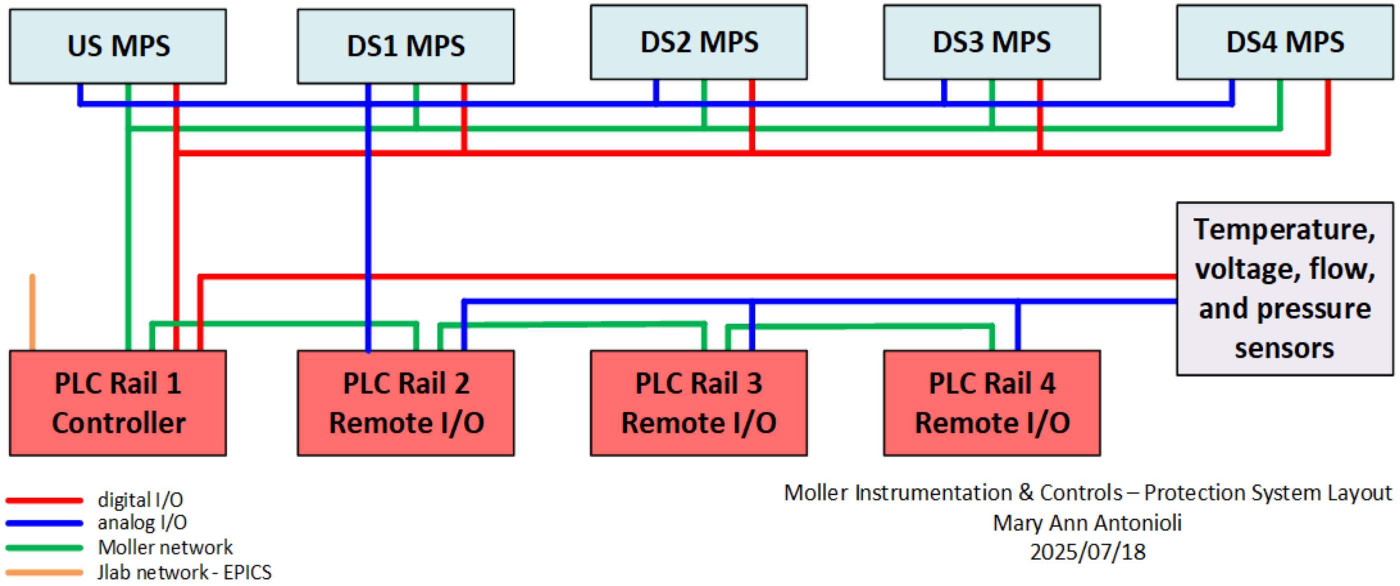
- "What If" Analysis:
  - Examples and scenarios
    - FMEA Target interface
    - FMEA with water leaks
    - FMEA with I&C (Proactive risk management) –
      - External hazard
      - Coils
      - Coil mass and insulation
      - MPS failures
      - Vacuum vessel and Gnd isolation
      - Control and sensor reading
      - LCW (magnet/WCL/MPS)
    - FMEA Collimators 5 & 6

O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\12. Quality Control Documents\FMEA

Instrumentation and Controls (I&C) Layout

CHARGE #7

- Isolated network between MPS/PLCs and JLab
- Controller has only connection to JLab network to pass tags to EPICS
- Additional PLC rails are for I/O expansion to fit within rack width

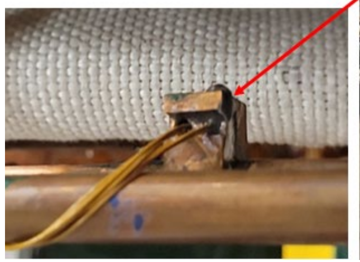


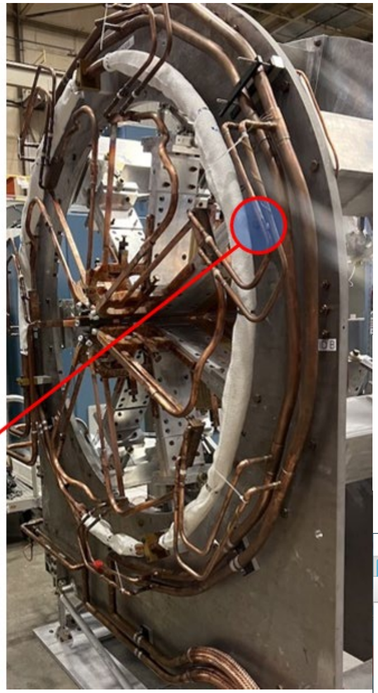
Parameters

- TM1 – TM3 are identical, TM4 has additional VTs due to double-pancake design *(TM0 – in progress)*
  - VTs: MPS, 2x WCLs, 2x Flexible Jumpers, 7x Coils (14x for TM4) - 2 wires for each
  - RTDs inside enclosure: 7x Coils, 2x Bulkhead (3x for TM4), 1x WCL Return
    - Redundant sensors for any inside vacuum enclosure, wired up to PLC rack but only single sensor monitored by PLC
    - Other RTDs outside vacuum enclosure
  - LCW: Return temperature and flow for magnet

Instrumentation and Monitoring

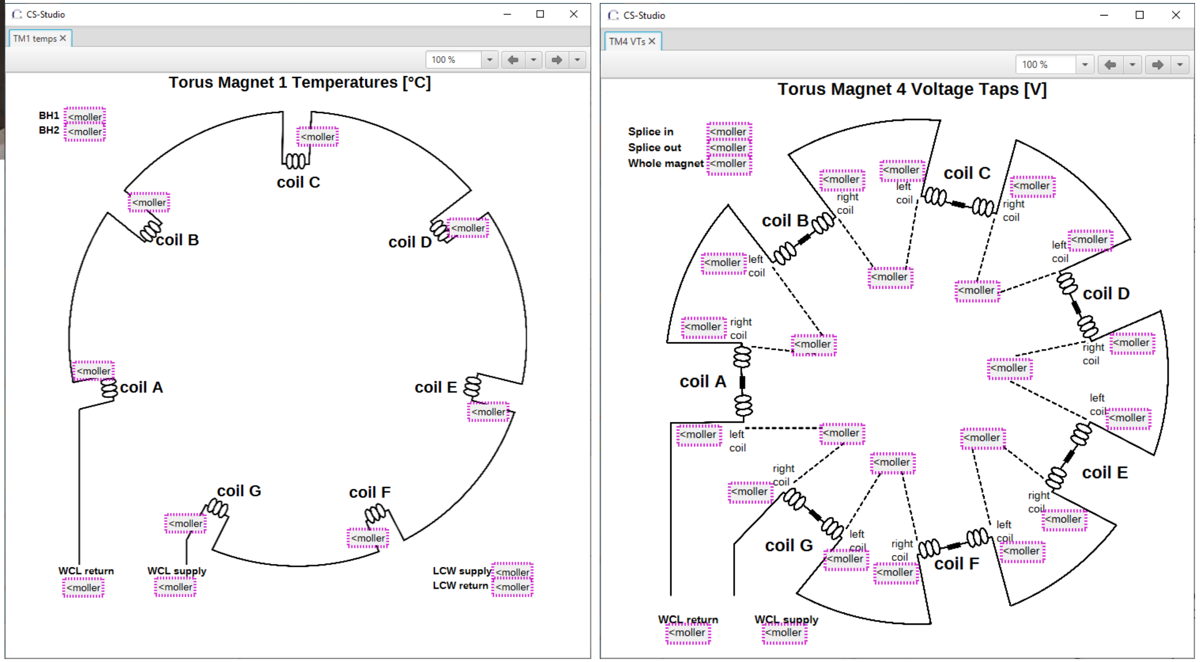
Kapton RTDs installed using DP33 epoxy - TM1-TM3 completed





- ➢ All sensors monitored by the PLC are also made available to EPICS
  - SoftIOC converts PLC tags to EPICS PVs
  - PVs used by the operational screens
  - Archiving of PVs via Mya (Accelerator developed and maintained)

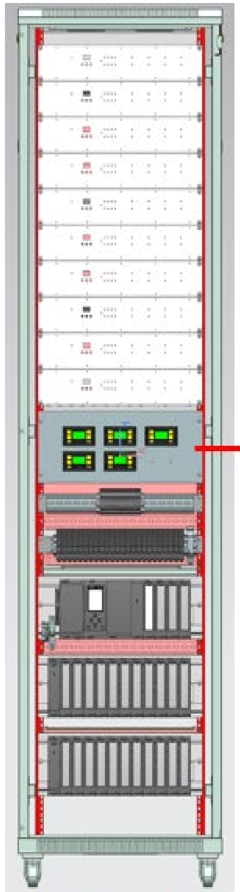
- ➢ EPICS Phoebus screens for RTDs and VTs completed
  - MPS in development, will be similar to Hall B
  - Magenta boxes are due to PVs not being live



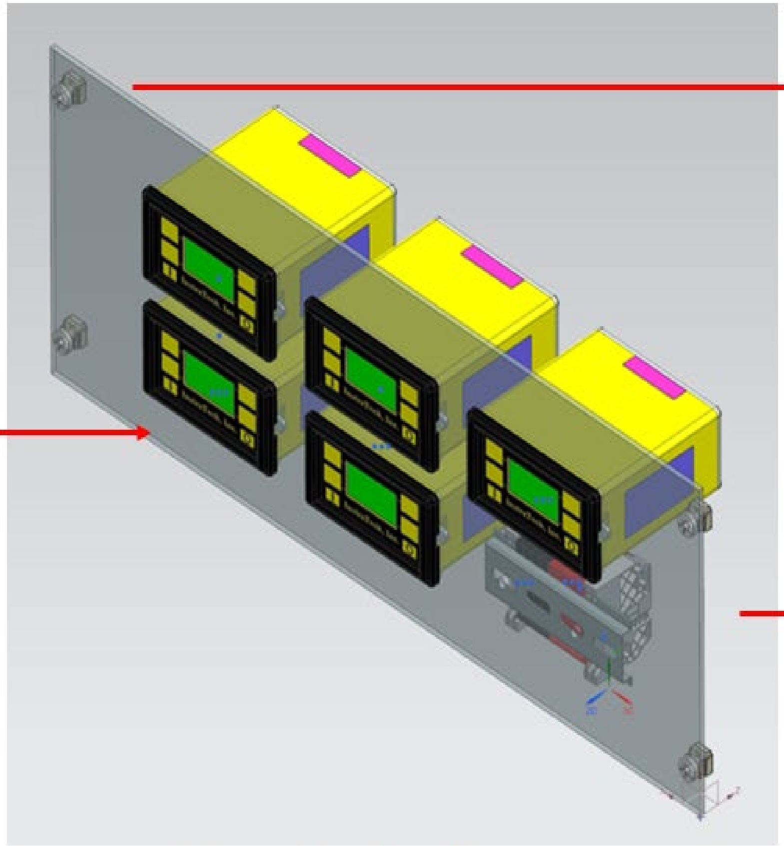
Magnet Operation & Documentation

- I&C is based on P&ID of various sub-systems: magnets, LCW panels, vacuum, etc
- Consists of either layout drawings or wiring diagrams
  - Layout drawings show location of components in relation to others, e.g. rack, PLCs, panels
  - Wiring diagrams show interconnection between components, e.g. voltage tap to isolation-amplifiers and voltage comparators
- Spreadsheet of drawings maintained for assessment (*in progress*)

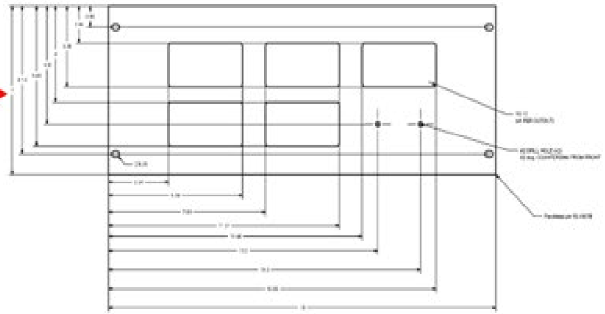
Documentation Examples



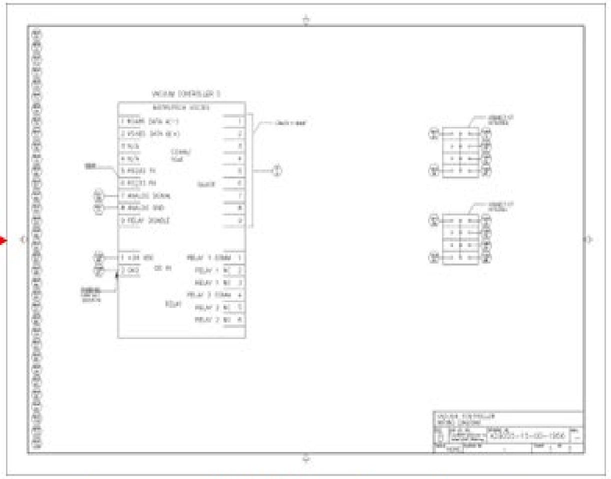
NX12 Rack Layout Front View



NX12 Vacuum Controller Panel Isometric View



Vacuum Controller Panel Fabrication Dimensions



Vacuum Controller Wiring Diagram Sheet 3

Magnet Operation & Documentation

List of Spectrometer system wiring, wiring, and documentation

Drawing	Sheets	Component	Drawing Type
500	1	torus magnet 0	voltage tap wiring diagram
501	1	torus magnet 1	voltage tap wiring diagram
502	1	torus magnet 2	voltage tap wiring diagram
503	1	torus magnet 3	voltage tap wiring diagram
504	1	torus magnet 4	voltage tap wiring diagram
3201	1	PLC 2 slot 1 network module	wiring diagram
600	2	torus magnet 0	ISO amp wiring diagram
601	2	torus magnet 1	ISO amp wiring diagram
602	2	torus magnet 2	ISO amp wiring diagram
603	2	torus magnet 3	ISO amp wiring diagram
604	3	torus magnet 4	ISO amp wiring diagram
3211	1	PLC 2, Slot 11	Vacuum Wiring Diagram
700	2	torus magnet 0	voltage comparator wiring diagram
701	2	torus magnet 1	voltage comparator wiring diagram
702	2	torus magnet 2	voltage comparator wiring diagram
703	2	torus magnet 3	voltage comparator wiring diagram
704	2	torus magnet 4	voltage comparator wiring diagram
3401	1	PLC 4 slot 1 network module	Wiring Diagram
1001	2	torus magnet 0	PLC 4 Slot 2 RTD temperature wiring diagram
1002	2	torus magnet 0	PLC 4 Slot 3 RTD temperature wiring diagram
1101	2	torus magnet 1	PLC 4 Slot 4 RTD temperature wiring diagram
1102	2	torus magnet 1	PLC 4 Slot 5 RTD temperature wiring diagram
1201	2	torus magnet 2	PLC 4 Slot 6 RTD temperature wiring diagram
1202	2	torus magnet 2	PLC 4 Slot 7 RTD temperature wiring diagram
1301	2	torus magnet 3	PLC 4 Slot 8 RTD temperature wiring diagram
1302	2	torus magnet 3	PLC 4 Slot 9 RTD temperature wiring diagram
1401	2	torus magnet 4	PLC 4 Slot 10 RTD temperature wiring diagram
1402	2	torus magnet 4	PLC 4 Slot 11 RTD temperature wiring diagram
1403	2	torus magnet 4	PLC 4 Slot 12 RTD temperature wiring diagram

1901	1	PLC controller 1	Layout
1902	1	PLC Remote I/O 2	Layout
1903	1	PLC Remote I/O 3	Layout
1904	1	PLC Remote I/O 4	Layout
1905		Rack Front	Layout
1906		Rack Rear	Layout
1950	1	24 VDC Power Distribution	Layout
1951	1	25 VDC Power Distribution	Wiring Diagram
1955	2	Vacuum Controller	Panel Layout
1956	3	Vacuum Controller	Wiring Diagram
1989		LCW mass flow controller	Wiring Diagram
1990	2	MPS	Power Supply Interlock Diagram
1991	1	PLC Watchdog Timer	Wiring Diagram
3101	1	PLC 1 Slot 1 CPU Module	Wiring Diagram
3102	2	PLC 1 Slot 2 DI Input Module	Wiring Diagram
3103	1	PLC 1 Slot 3 DO Input Module	Wiring Diagram
3301	1	PLC 3 slot 1 network module	Wiring Diagram
3302	1	PLC 3 slot 2	Wiring Diagram
3303	1	PLC 3 slot 3	Wiring Diagram
3304	1	PLC 3 slot 4	Wiring Diagram

Magnet Operation & Documentation

Work Rules/Training Requirements: Procedures and ePas

PMAG0000-0100-P0041 Procedure to make low voltage splice in radiation environment	In progress
PMAG0000-0100-P0042 Moller Torus (TM0-4) Operations Power Up Checklists	In progress
PMAG0000-0100-P0043 Moller Torus (TM0-4) Low Current Voltage Tap Check Procedure	In progress
PMAG0000-0100-P0044 Moller Torus (TM0-4) Power-Up and Power-Down Procedure	In progress
PMAG0000-0100-P0045 Moller Torus (TM0-4) Water-Cooled Leads Checkout Procedure	In progress
PMAG0000-0100-P0046 Moller Torus (TM0-4) Pre-Power-Up (TM0-4) Voltage comparators Tuning Procedure	In progress
PMAG0000-0100-P0047 Moller Torus (TM0-4) Pre-Power-Up Interlock Checkout Procedure	In progress
PMAG0000-0100-P0048 Moller Torus (TM0-4) Magnets Pre-Power-Up Power Supply Int Interlock Checklist	In progress
PMAG0000-0100-P0049 Moller Torus (TM0-4) Magnets Power Supply Maintenance Turn-on Checklist	In progress
PMAG0000-0100-P0050 Moller Torus (TM0-4) Vacuum Feedthrough Power leads Checkout Procedure	In progress
PMAG0000-0100-P0051 Moller Torus (TM0-4) Magnet Mapping Procedure	In progress

1. ePas in progress to work on MPS (TM3 prototype MPS) in Test lab with Multiple energy sources and associated Isolation Certificate (IC) that will go along with LOTO – ***Moller MPS PTW-7812 (in progress),*** include - replace LCW header, add DCCT to WCL, connect WCL and LCW to magnet.
2. All documentation with electrical and I&C (magnet test) is located - O:\Magnet_Design_Tools\Magnet Projects\MOLLER - Hall A\7. Reviews_Updates\ERR2 July 2025\Ref documents

Magnet Mapping

CHARGE #8

- Mapping Specification: Detailed documentation
  - PMAG0000-0100-S0057 MOLLER Magnet Field mapping requirements
  - Summary of magnetic field requirement

Magnet	Magnet length (mm) approx.	Field in gauss (max) @R=0 mm and R=24mm at any given Z location
TM0	2000	30/90
TM1	1004	30/70
TM2	1022	33/60
TM3	1000	37/50
TM4	4000	42/40 (@Z=2000 mm)

Short mapping procedure

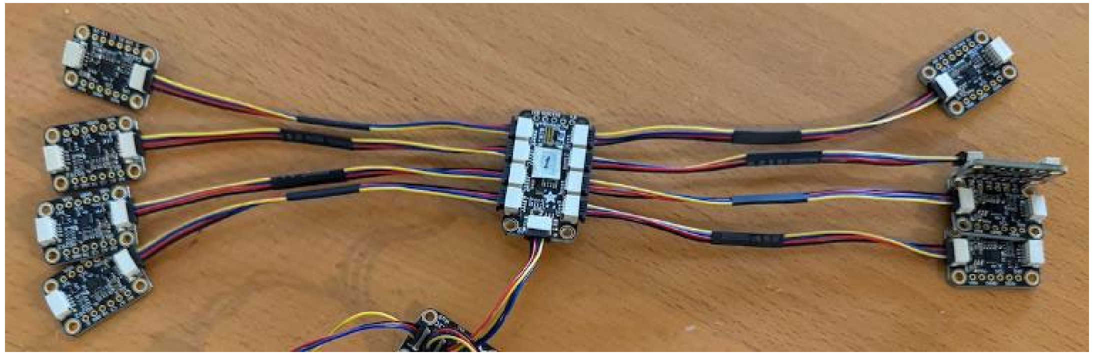
1. Ensure power supply is not powered/SAFE/De-energized
2. Insert the probe holder into the magnet
3. Survey the probe such that the probes inline with the through grooves are aligned to the coil A/X axis with the indexing feature surface perpendicular to it
4. Define a stay-out area based on the magnetic field and electrical safety requirements (ePas)
5. Perform measurements at half and full current as required (ePas)
6. De-energize power supply (ePas)
7. Rotate probe holder to orientation#2 - in the open sector
8. Repeat Step 5

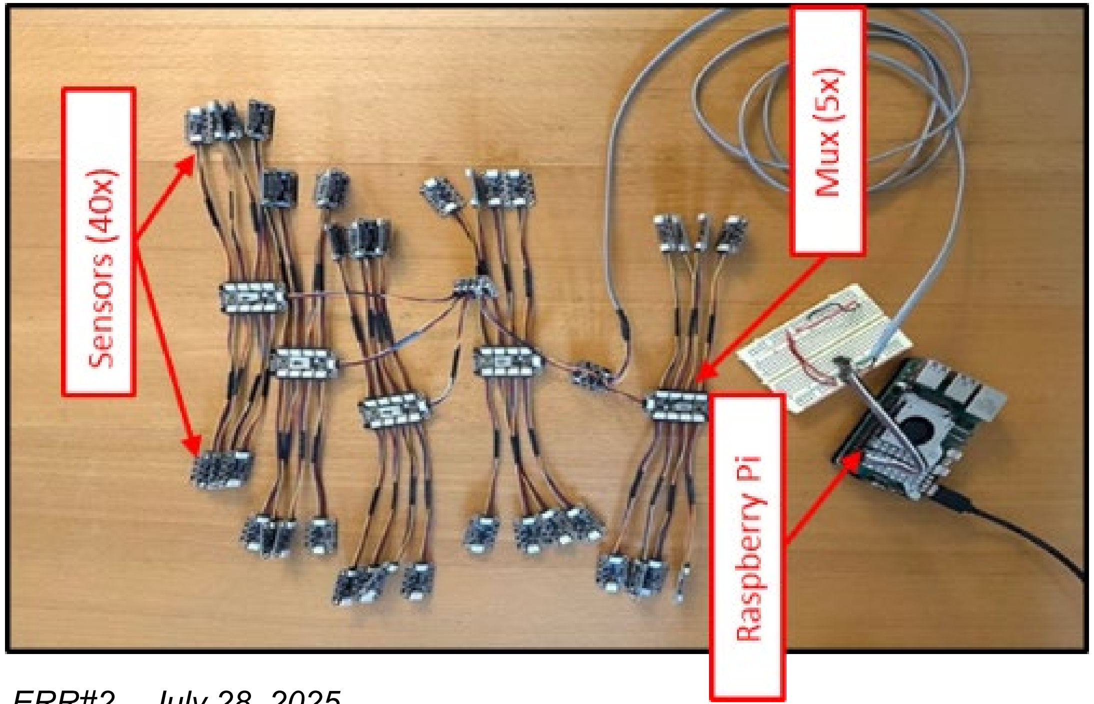
- Design Hardware: Key components and functions

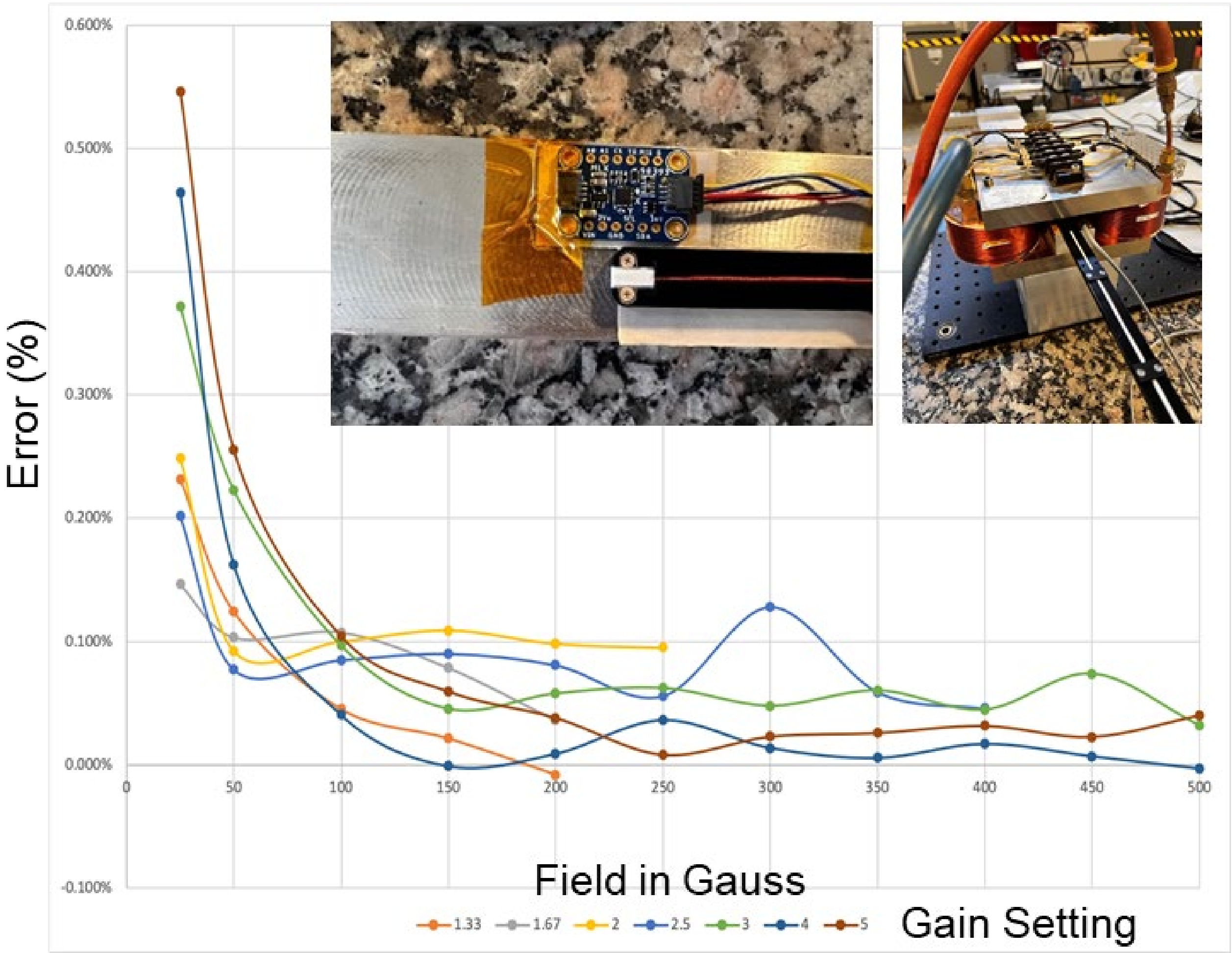
- ❑ Set up design and being built with multiple independent sensors
  - ➢ Lower cost, simpler operation, faster data acquisition
  - ➢ Melexis MLX90393 Magnet Field Sensor
    - Programmable dynamic range (5 – 50 mT)
    - I^2C digital communication‡
    - 16-bit optional temperature output
- ❑ Tested against calibrated reference sensor
  - ➢ Error with the measurement range <1%
  - ➢ Calibrated in a dipole magnet and Senis Reference Probe
- ❑ Sensors (for one measurement fixture) and DAQ in-hand (Total quantity for assembly is 40 3-axis sensors)

Magnet Mapping

Field Measurement (Electronics) – Assessment & Calibration



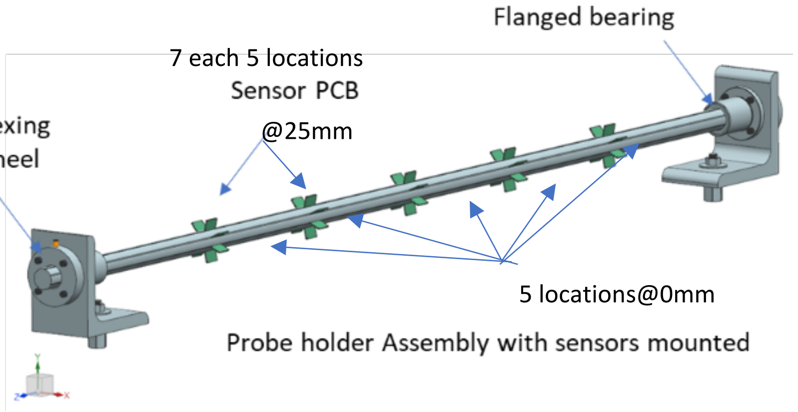




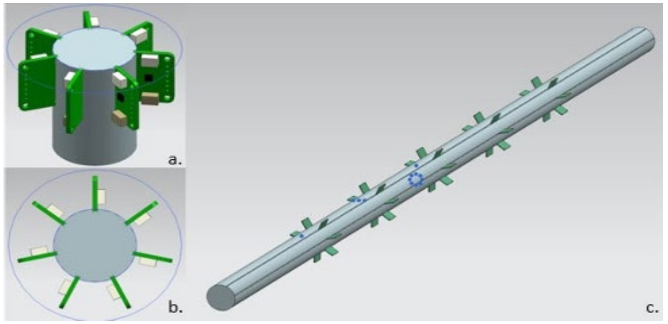
Magnet Mapping

Field Measurement (Mechanics)

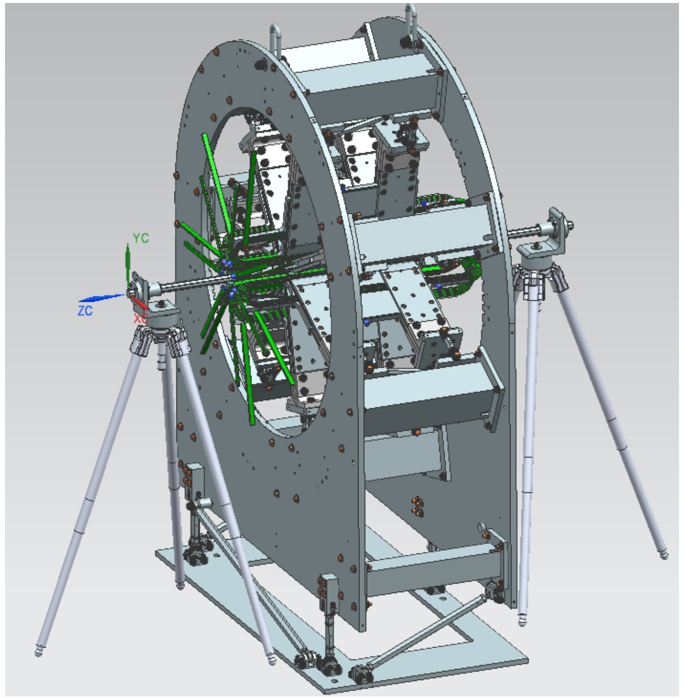
- ❑ Assembly allows field measurement at a radius of 25mm from the beamline and along the beamline
- ❑ Al 6061 Probe holder designed to accommodate sensors
  - ➢ 35 sensors for radial measurement
  - ➢ 5 sensors for field measurement along the beamline (between the r=25mm stations)

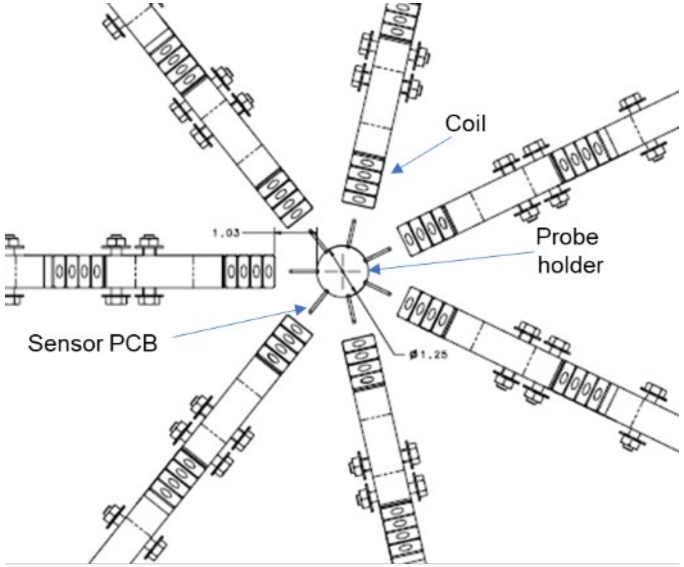


Probe holder Assembly with sensors mounted

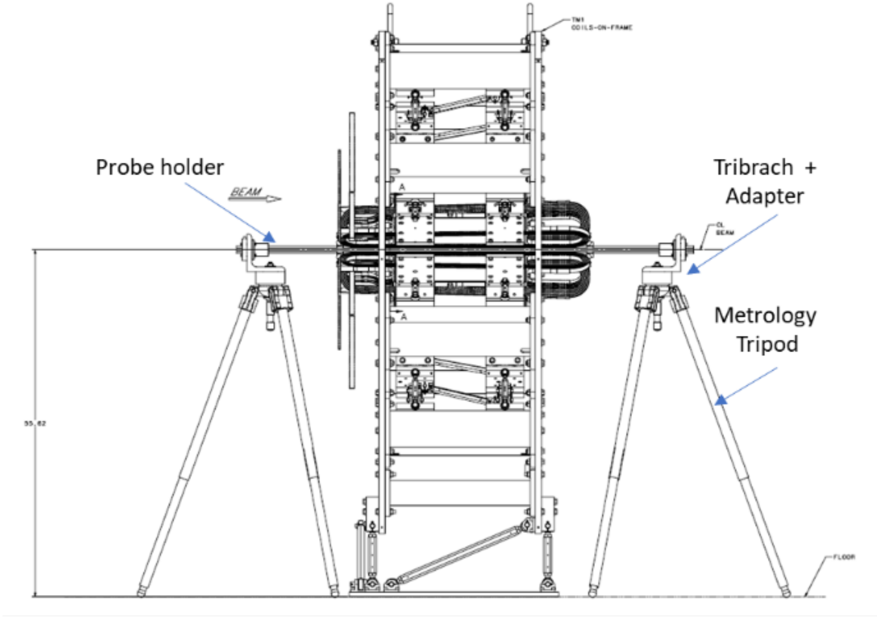


(a) Seven magnetometer PCBs (b) the distribution of the magnetometer PCBs around the Al rod, and (c) the entire instrument set up on the Al rod probe holder





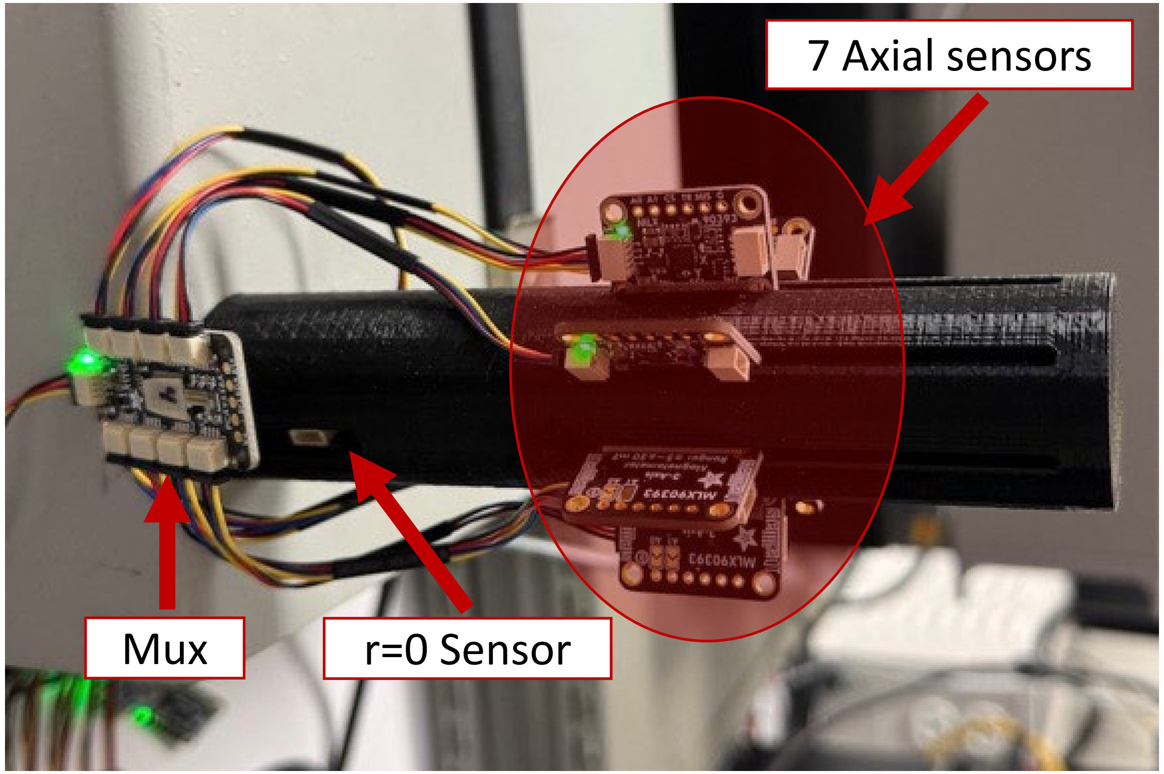
TM1 with Mapping Assembly – Along the beam line



TM1 with Mapping Assembly

Magnet Mapping

Field Measurement (data collection)



8 magnetometers & multiplexer installed on 3D printed section of assembly fixture

pi@ha-moller-map: ~/mapping

Sensor#	X (μT)	Y (μT)	Z (μT)	B_{calc} (μT)	Temp (^{O}C)
1	-17.100	-19.500	-59.532	64.936	24.912
2	6.000	-37.500	-108.900	115.332	25.907
3	28.200	-9.000	-16.456	33.868	23.341
4	-29.100	-27.900	-66.792	78.015	23.827
5	10.800	-69.600	-43.076	82.561	24.115
6	-42.600	-57.600	47.916	86.189	24.027
7	-13.800	-63.600	51.788	83.171	24.668
8	-12.300	-40.800	-70.180	82.105	24.646
9	44.400	7.200	-16.940	48.064	25.487
10	38.400	21.600	-45.496	63.333	25.885
11	6.300	19.200	-44.528	48.899	24.624
12	20.700	4.800	-51.788	55.978	23.938
13	32.100	-13.200	-35.816	49.874	23.031
14	-36.600	-25.200	44.528	62.907	25.088
15	-40.200	-18.000	74.052	86.161	24.447
16	-27.300	28.200	-42.108	57.564	25.310
17	1.800	25.800	-88.088	91.806	24.270
18	-17.100	8.400	-101.156	102.934	24.226
19	-40.500	26.400	-68.728	84.028	24.159
20	-84.600	2.700	-22.264	87.522	23.695
21	-71.100	14.400	33.396	79.862	25.686
22	-70.800	-2.100	-19.844	73.558	25.929
23	-69.000	-44.700	21.296	84.927	23.761
24	-53.700	-45.300	30.492	76.587	24.469
25	-83.700	-15.900	-144.716	167.932	22.699
26	-23.700	-96.300	-128.260	162.130	21.261
27	-133.800	-29.100	38.236	142.166	23.628
28	-153.900	-81.000	-61.468	184.457	22.566
29	-63.900	1.500	32.428	71.673	25.885
30	-29.400	-14.700	-44.044	54.957	23.385
31	-56.700	-5.700	34.848	66.796	24.027
32	-74.100	12.900	36.300	83.516	24.912
33	-54.000	-78.900	-55.176	110.388	22.168
34	-87.000	-70.800	3.388	112.219	23.673
35	-43.800	-22.500	36.300	61.175	24.004
36	9.000	-36.000	43.560	57.223	24.115
37	57.300	-49.800	44.528	88.012	25.376
38	42.600	-27.000	-31.944	59.701	24.336
39	23.700	-48.900	-81.796	98.201	22.434
40	-75.300	-73.200	85.184	135.221	24.558

Data display of X, Y, Z, B, and Temp of all sensors

Summary of Key Points

- Safety - the comprehensive magnet protection systems is envisaged (will be tried out on TM1, 2, 3 magnet in the Test lab)
  - MPS interlocks in place
  - GND and electrical safety wrt to MPS in built
  - Magnet – primary and secondary defined but will need to be revisited during commissioning
- Magnet and system FMEA is in place, with identified risks and mostly mitigated to low to medium risk
- Documentation – Started and needs to be followed up with all powering and ePas requirement(s)
- Training - prioritize safety and reliability
- Interface with electrical power and LCW in place and engineered to support the MOLLER experiment
- Magnet mapping is identified and shall be performed on all 5 toroid magnets in the spectrometer in the test lab high bay