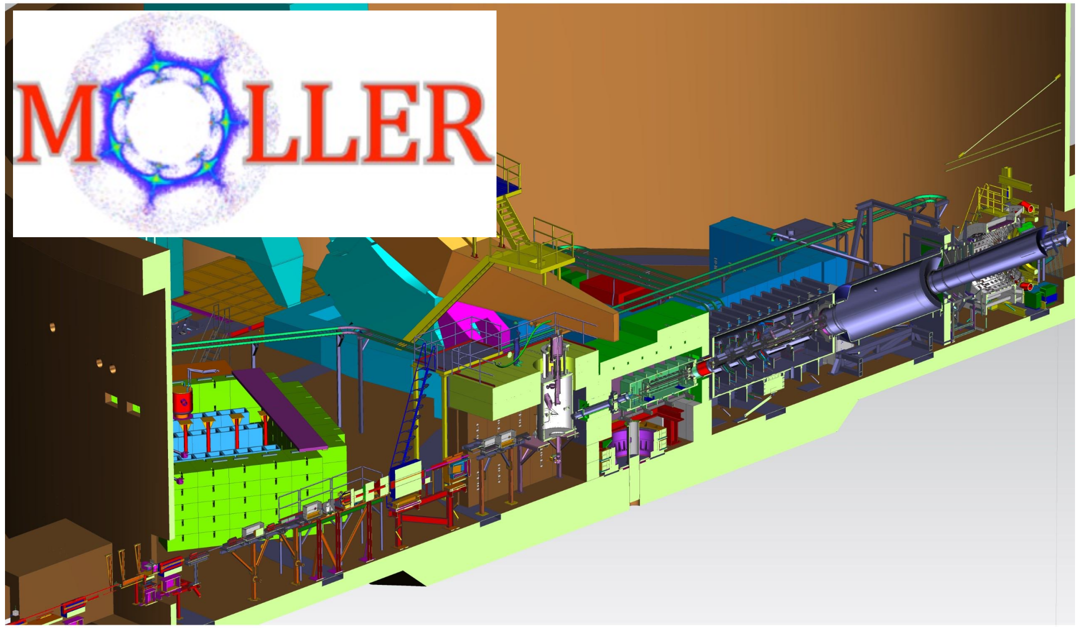
MOLLER Internal Final Design Review

Magnet Power Supply and I&C



Brian Eng
JLab
On behalf of Magnet Group, DSG, DC-Power

December 6th, 2022

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Outline

- Magnet Power Supplies (MPS)
  - Overview
  - Status/Milestones
  - Prototype
- FMEA and Magnet Interlocks
- Instrumentation and Controls (I&C)
  - Overview
  - Sensors
- Summary

MPS – Overview

- Each torus has its own separate power supply
  - All supplies are monopolar (Nominal)

Magnet	Current (A)	Voltage (V)	Power (kW)
Upstream	1075	77.5	84
Downstream - 1	2230	40	90
Downstream - 2	2440	42	103
Downstream - 3	3372*	57	185
Downstream - 4	3350	224	751

- Nominal values, capable of peak values at 120%
- Stability of 100 ppm over 24 hr and absolute accuracy of ±50 ppm
- 95% efficient at full load
- Full specifications see: PMAG0000-0100-A0014

MPS - Status

Key Milestones

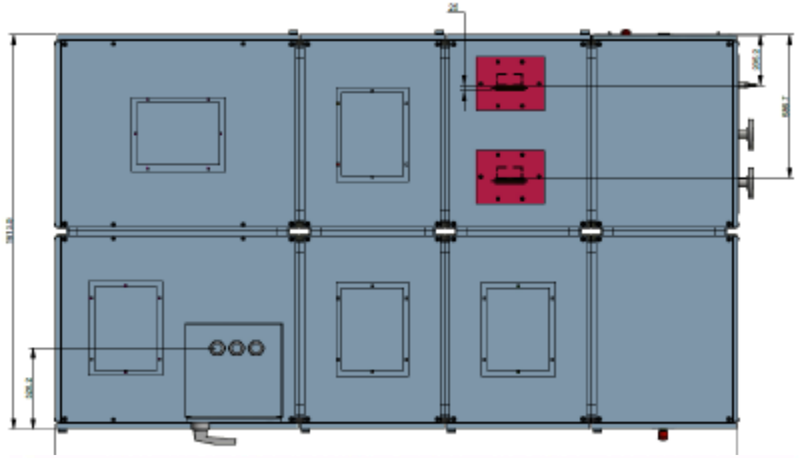
Activity	Start	End	
Power Supplies, Leads and Jumpers 60% Design Effort	08-Mar-21	30-Apr-21	**COMPLETE**
Power Supplies, Leads and Jumpers 90% Design Effort	10-Jan-22	07-Mar-22	**COMPLETE**
DS Toroid Power Supplies (DS3). On order with OCEM, Italy	Feb 2022	June 2023	**DS3 Prototype MPS on order**
US and DS (DS1, 2 & 4) Toroid Power Supplies, Leads and Jumpers	**At CD-3a**		
Instrumentation and Control (H/W and S/W) – Prototype and production	Sept 2021	Sept 2023	

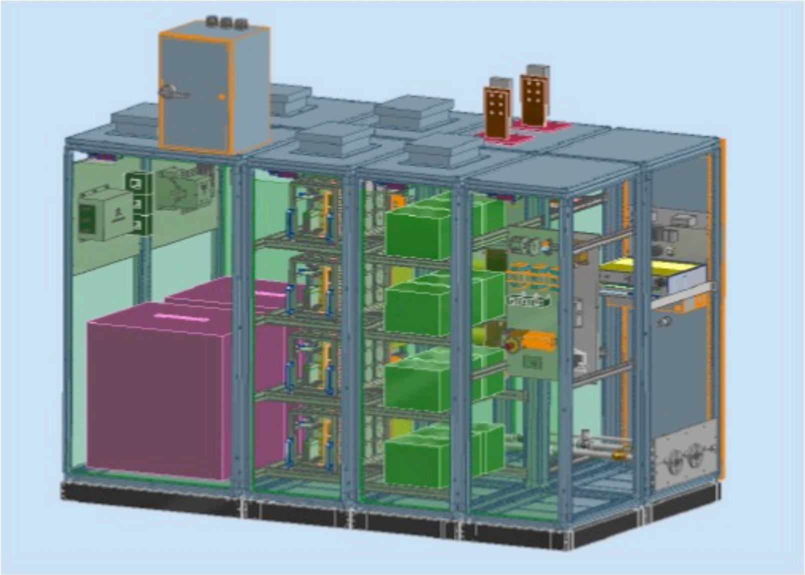
Status of activities

- Power Supplies Functional requirements - PMAG0000-0100-S0015 MOLLER (COMPLETE)
- Physics and Engineering Requirements for Magnet Power Supplies (COMPLETE)
- Magnet Power Supplies Specification Document both US & DS - PMAG0000-0100-A0014 (COMPLETE)
- Hall A – Location of PSUs and Lead Routing (COMPLETE) (Drawings to be approved)
- Water-Cooled Leads, Air-Cooled Jumpers - PMAG0000-0100-S0017 (COMPLETE) and Interfaces (IN PROGRESS)
- Control, Instrumentation – Drawings (IN PROGRESS), P&ID – COMPLETE
- Environment Safety and Health (IDENTIFIED AND INCORPORATED AS REQUIRED, based on FMEA)
- Magnet test lab set-up for the prototype coil - Low Power test (COMPLETED on SC3 and IN PROGRESS with tests for SC4)

MPS Prototype – DS3

- Schedule
  - Order placed on April 2022
  - Design review completed Aug 2022
    - Document UT-RT-0872
  - Critical components procured by vendor
    - DCCT in hand
    - FPGAs due end of Jan 2023
  - Factory acceptance testing March 2023
    - JLab staff on-site (Italy)
- Dimensions
  - 2810.4 mm (L) x 1613.5 mm (D) x 1900mm (H)
- Weight - 2500 kg





Note: DS3 chosen with highest current that can be used to charge all 4 magnets (US and DS1-2-3) and DS4 with limited power to due to wall power availability in the test lab! Full power available in Hall A.

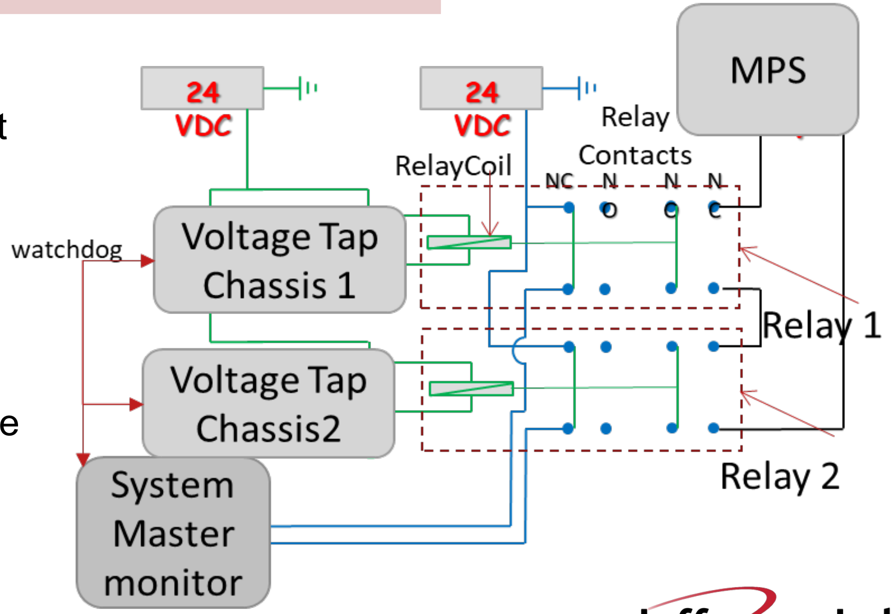
FMEA and Magnet Control Interlocks

FMEA - Magnet coils, Water leaks used to develop Interlocks

Parameter	Action	Severity Level
Voltage Tap High	Trip MPS	Primary
Temperature High	Trip MPS	Primary
Water Distribution Flow Low	Trip MPS	Primary
Water Pressure Low	Trip MPS	Primary
Vacuum High	Ramp Down MPS	Secondary
Chiller Failure	Ramp Down MPS	Secondary
Window Shutter	Ramp Down MPS	Secondary

I&C: Magnet Interlocks and Protection

- Primary protection is accomplished using hardwired multi-channel voltage tap readout
- A second multi-channel voltage tap readout runs through a PLC
- Each chassis reads the same VTs and performs the comparator function in parallel
- Voltages compared during three powering states
- All hardwire interlocks shared with system master digital input for monitoring and diagnostics
- Heartbeat messages are sent across nodes via Ethernet allowing automated response during communication outages
- Secondary protection is on outlet temperature, and flow of each coil



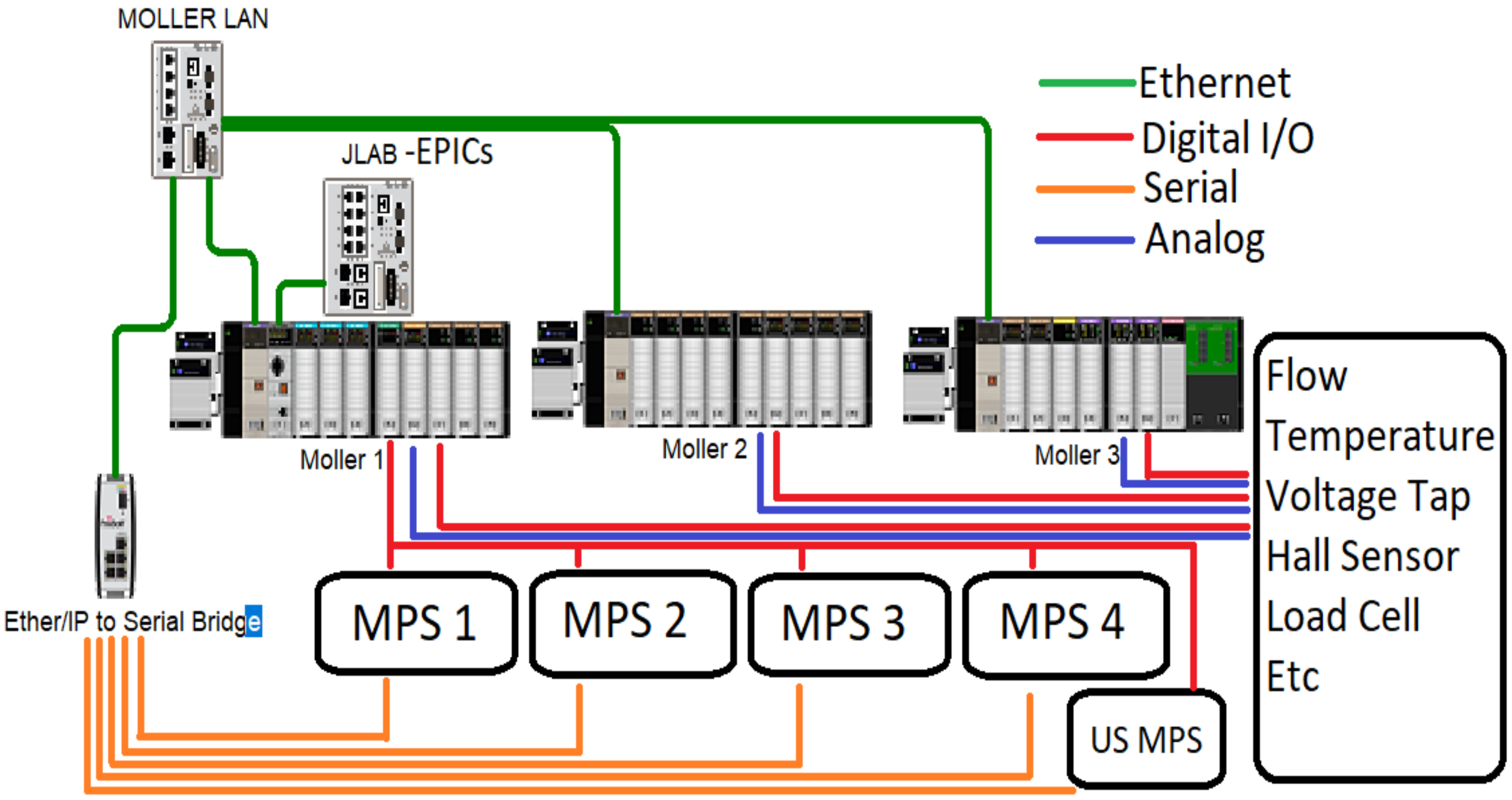
I&C – Overview

- **Philosophy**
  - Utilize similar hardware and software that was used in previous designs as much as possible, skilled labor available as well as being familiar to end users
  - Use COTS products whenever feasible (Only when technical specifications can't be met look to custom solutions)
  - Redundancy on common failure points - Power circuit, networking, sensors (VTs, temperatures, etc), when not feasible have spares available, e.g. PLC modules

- **Data Storage / Management**
  - PLC controller onboard SD Card to store critical events/data
  - Main data handling done by EPICS soft-IOC that uses Ethernet/IP driver to communicate with PLC over network (same setup successfully used at JLAB - Hall B and D)
  - Once in EPICS use Mya to archive/retrieve data (Accelerator developed and maintained, used site-wide as tool to interface with live/historical EPICS data)

I&C – Protection System Layout

- Primary Control provided by master processor with 1gbit Ethernet Interface
- Dual Ethernet Interface – (i) JLAB: IOC/EPICS and (ii) Private Local Network (PLN) for critical instruments
- Direct Interlock capability 5 or 24 VDC (e.g. voltage, temperature, field, flow, etc.)
- Each Chassis (dedicated to each magnet US and DS1-4) can independently safe out the system



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I&C – Sensor Types/Location/Channel Counts

I. **DS Torus Magnets: Drawings A09005-15-00-0101 / 102 / 103 / 104**
   - 52 RTDs (52 redundant sensor will be installed but not cabled to PLC)
   - 10 Klixons (thermal switches)
   - 56 voltage taps (56 redundant taps will be installed and cabled to VT chassis)
   - 3 vacuum gauges

II. **US Torus**
   - 7 each: Flow switches, Klixons
   - 1 DP sensor
   - 8 RTD's (redundant sensor will be installed but not cabled to PLC)
   - 2 voltage taps

III. **US Collimators**
   - 4 Each Limit switches, Flow switches, Pneumatic valves, Temperature Switches
   - 5 RTD's (+2 for Collar 0 – JLab Scope)
   - 1 each Flow meter, Liquid Level
   - 2 Pressure transmitters

IV. **Magnet Cooler (LCW Chiller): Drawing A09005-15-00-0106**
   - 8 pressure transducers
   - 9 RTDs
   - 4 control valves
   - 3 flow meters
   - 2 conductivity monitors, 2 pumps
   - 1 each: heater, UV lamp, liquid level

V. **Water Distribution: Drawing A09005-15-00-0111**
   - 7 RTDs
   - 5 each: flow meters, control valves
   - 6 pressure transducers

I&C – Risk Reduction

- PLC system is main component of the I&C, both in terms of cost and scope (anticipate delivery April 2023)
- Allen-Bradley (A-B) ControlLogix previously used for both Hall B & D magnets
- Investigating other vendors due to cost increases and potential lead time issues
  - A-B prices increased ~15% from quote in 2021 to 2022
  - Siemens PLCs used by Safety Group at JLAB
    - Siemens has higher channel count and costs less than comparable A-B unit
    - Prototype (Siemens) setup to be ordered (controller + one of each module)

Summary

- ✓ MPS – Order in place for the prototype MPS (DS3)
- ✓ The WCL and jumpers specification(s) are complete
- ✓ Instrumentation and control philosophy is defined
- ✓ P&IDs are in place and list of instrumentation is complete, wiring diagrams are in progress
- ✓ Magnet Protection/Interlocks fault logic has been generated
- ✓ Hardware and software development required for the system are identified and the work is in progress

Appendix

A. MPS – All 5 MPS Requirement
B. Final P&ID’s for TM4, Cooler, and Water Distribution
C. Magnet Power Supplies: Prototype testing
D. MOLLER – Mapping REQUIREMENTS
E. MOLLER – Electrical Safety

MPS – All 5 MPS Requirement

DETAILS	US Coil	SUB-COIL #1	SUB-COIL #2	SUB-COIL #3	SUB-COIL #4
NI (Nominal) – Physics (in Ampere-Turns)	5357.5	8914.8	12192.3	19391.3	33534
Normal Operating Current (A)	1071.5	2228.7	2438.5	3372.4	3353.4
Temperature (C) and B (T) for design	70/0.5	70/0.5	70/0.5	70/0.5	70/0.5
Voltage drop across 1 coil (V)	7.58	3.78	3.93	5.27	27.45
Voltage drop with all 7 coils in series (V)	53.03	26.48	27.52	36.89	192.14
Coil interconnect (splices + bus/leads) all (V)	9.87	10.59	8.81	9.84	18.98
1. Voltage drop across coils all (V)	62.90	37.07	36.33	46.73	211.12
1a. Power loss in Magnet (kW), VI	67.40	82.62	88.59	151.03	708.00
2. Voltage drop across – Air-Cooled Jumpers (both ends) + Water cooled leads 27 m long (V)+Jumpers vacuum end (CS1-2: 3kA and CS3-4: 4kA) +0.200V (all bolted connection)	2.09	2.09	2.09	2.00	2.00
2a. Power loss between magnet and MPS (kW): Air-Cooled Jumpers (both ends) + Water cooled leads 27 m long (V)+Jumpers vacuum end (CS1-2: 3kA and CS3-4: 4kA) +equivalent to 0.200V (all bolted connection)	6.5	6.5	6.5	8.3	8.3
Total Voltage drop (V_{Total}) across the magnet seen at Magnet Power Supply terminals (V), 1+2	65	40	39	49	213
Power requirement (kW) *(includes all 7 coils in electrical series), 1a+2a*	**74**	**89**	**95**	**160**	**716**

Note- US coil total voltage drop and power is an estimate only

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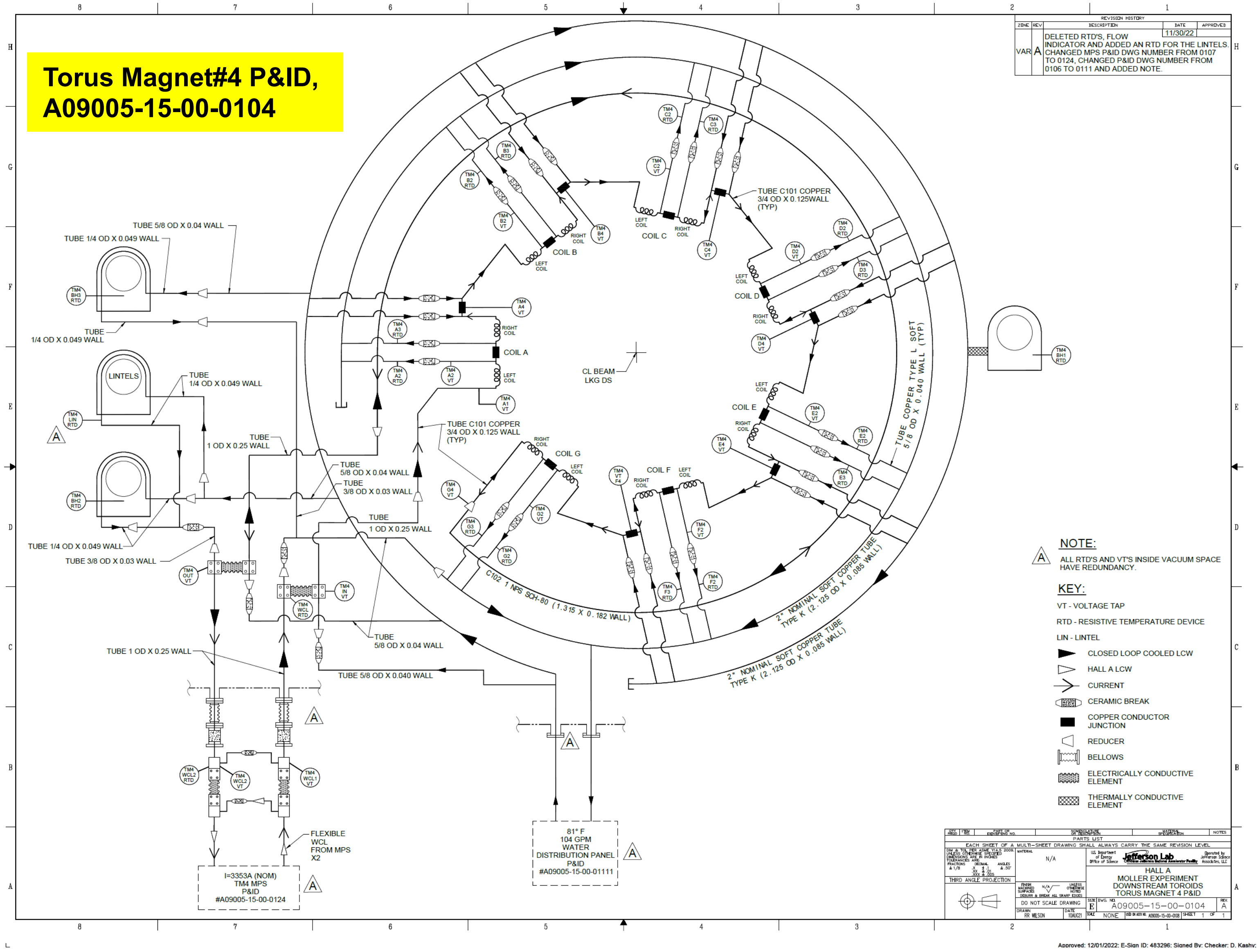
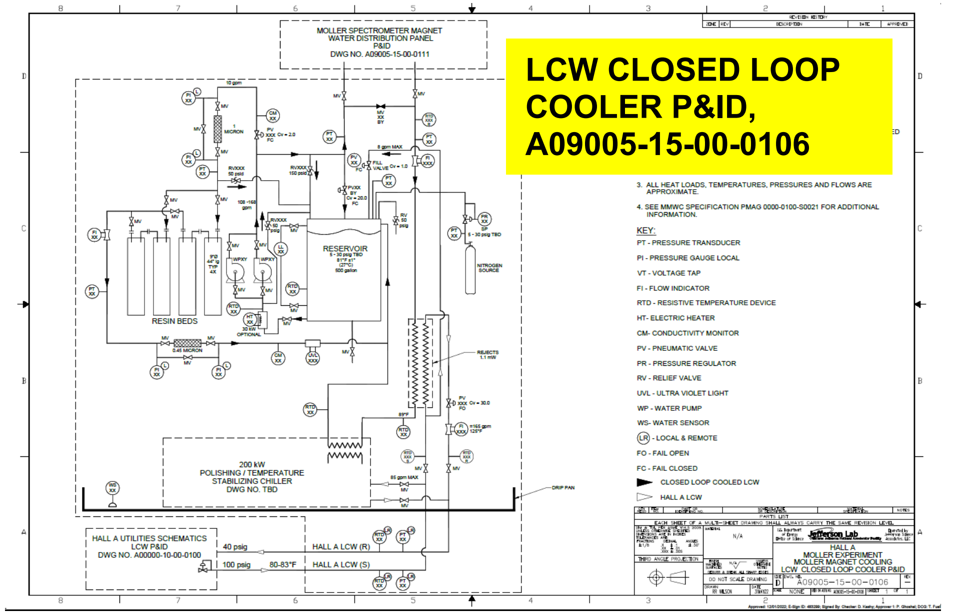
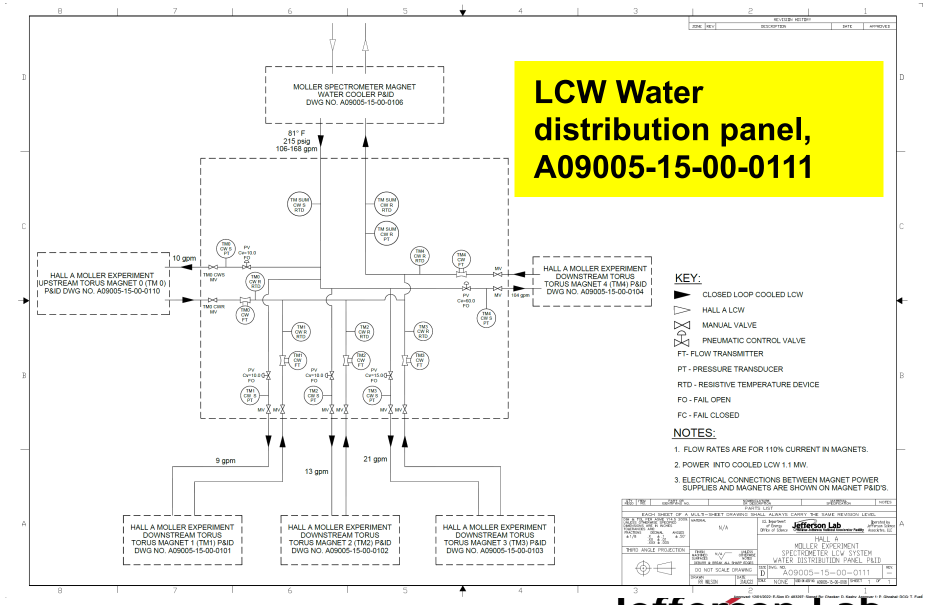
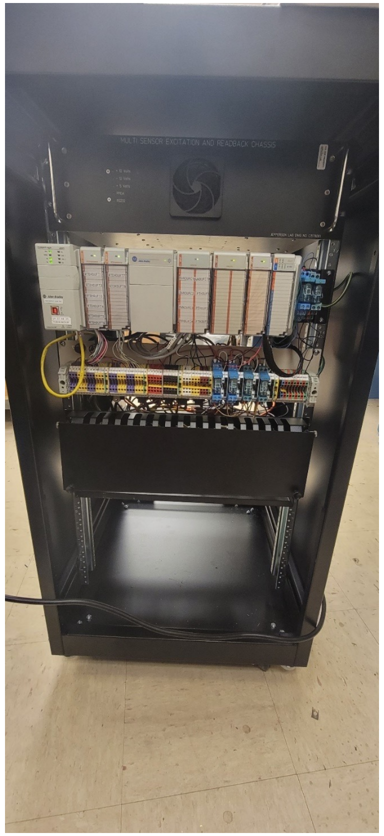
Typical P&IDs for TM4, Cooler, and Water Distribution





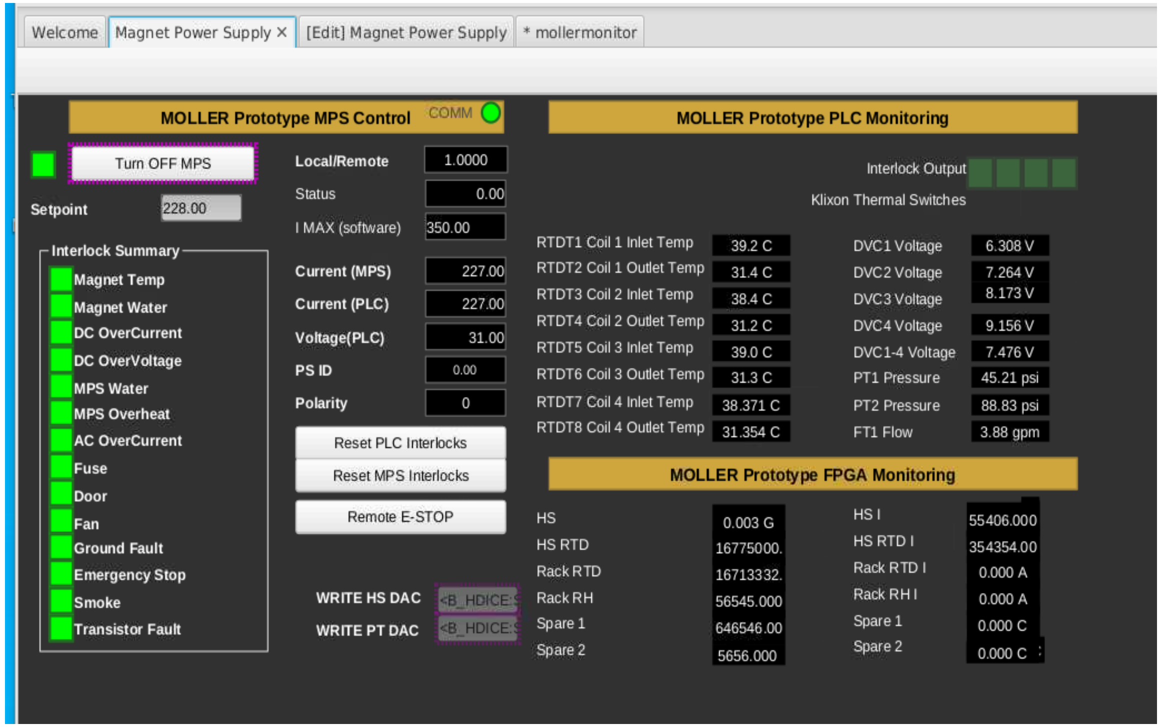


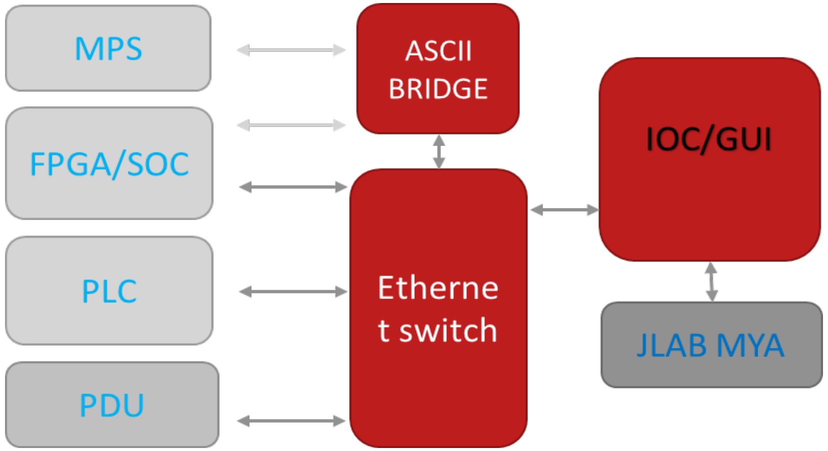


GUI set-up and readouts partially retired during Protoptype test in Mag Meas lab

MOLLER highbay Controls Rack:

- 64bit aarch64 SBC
- SOC FPGA ADC/DAC
- FPGA raw data through RS232
- scaled/corrected data through SOC 1Gb Ethernet (mqtt)
- PT1000’s, Vt’s, and flow measurement
- Front development testing design
- HDL development testing
- CompactLogix PLC
- Magnet Control & Monitoring
- MPS Control





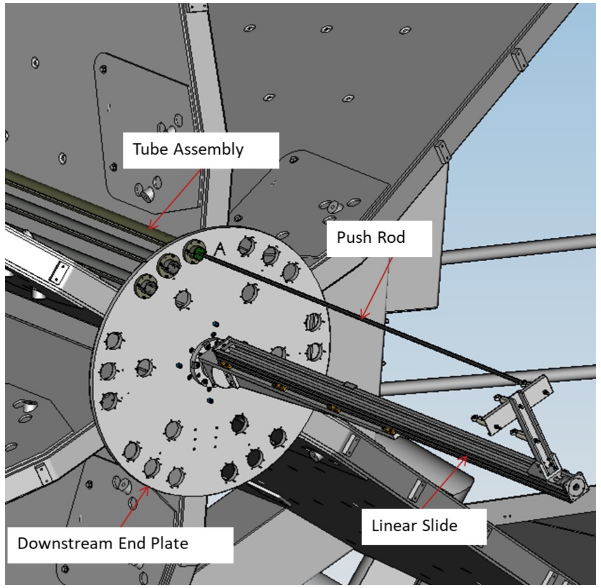
MOLLER – Mapping REQUIREMENTS

Mapping specification - definition wrt the accuracy and location requirements.

- Mapping design tool for mapping all sector plus the central bore.
- Uncertainty in variation of field from sector to sector (TDR)
- Modification(s) to OPERA model coil geometry to reproduce to measured field map

Complete Magnet – after assembly of magnet

- BMOD measurements (radially focusing component of field, BMOD) along Z in an open sector at r = 135 mm (TBR)
- Determination of magnetic center, measurement of any dipole moment in the bore
- Stray field measurements (location of 5 Gauss line)

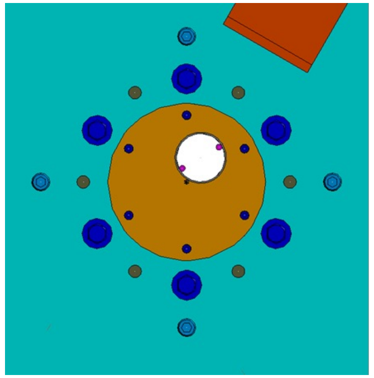


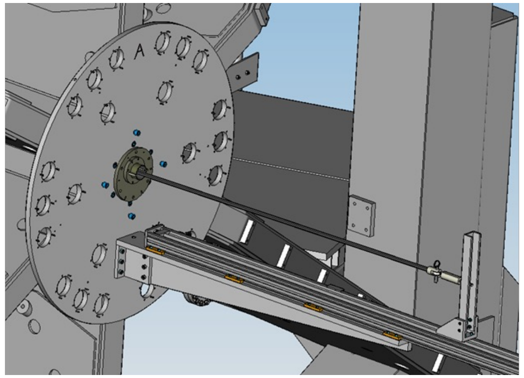
Mapping Tool used in HALL B Torus/Solenoid

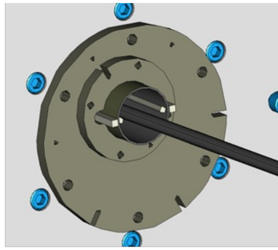
- Precisely machined upstream and downstream plates
- The plates will be surveyed prior to install to know hole locations
- Precise pins locate and orient the carbon fiber tubes
- Pins assure locating/repeatability of carbon fiber tubes to 0.05mm
- Linear slide/motor/controller accurate to 0.010mm

Mapping Tool Operation-Mapping the Bore

- The bore has a total of seven locations mapped in CLAS 12 Torus
- The center tube is offset from the collar center to take the 2.5cm radius measurement
- The assembly is rotated for each angle while maintaining the required local coordinate system orientation







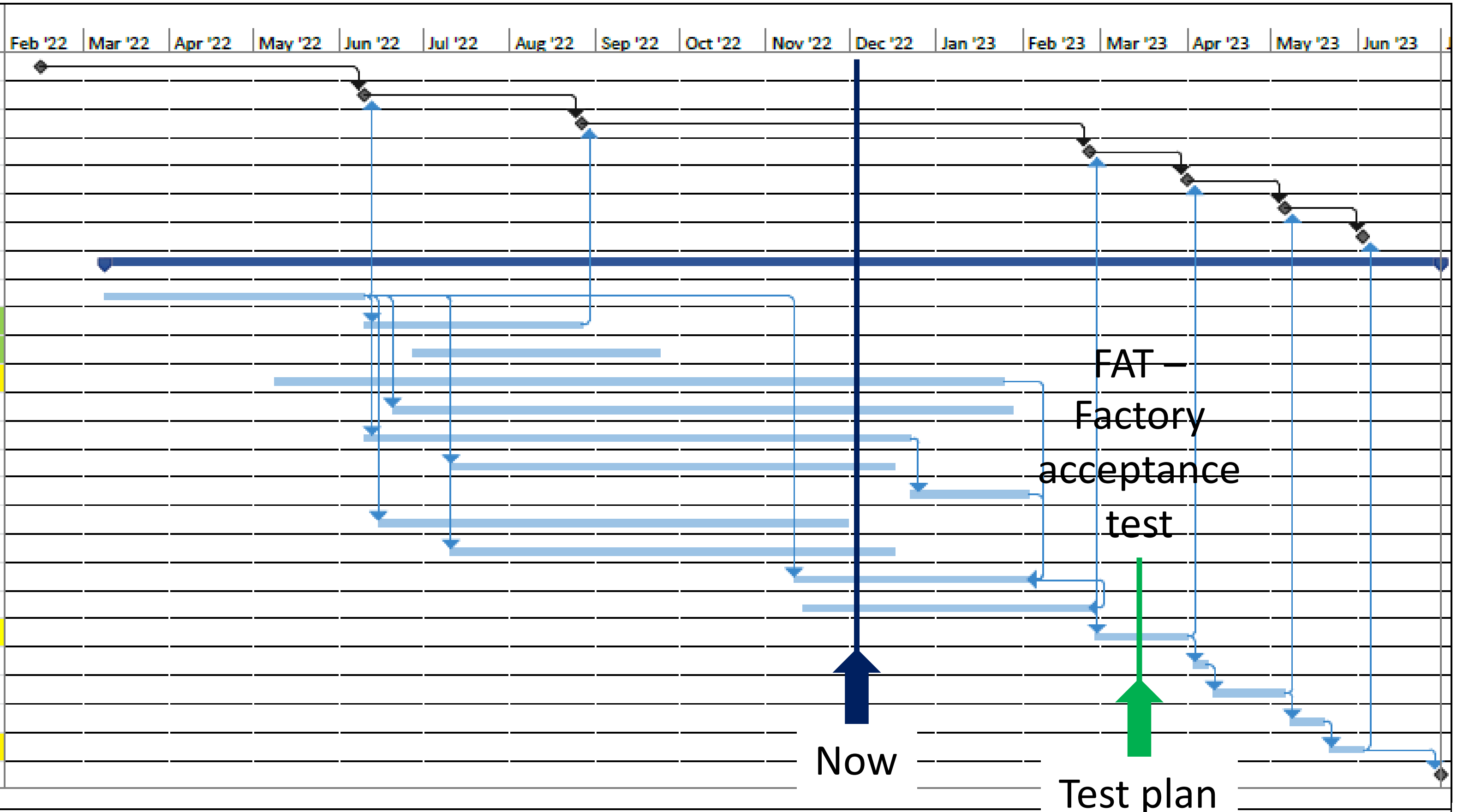
MOLLER – Electrical Safety

Component	Safety Analysis	Additional steps
All Magnet Power supply	6210 Electrical Safety Manual Electrical Safe Work Practice	1. NFPA 70E, 2015 - Standards for Electrical Safety in the Workplace 2. National Electric Code (NEC) Handbook 3. DOE–HDBK-1092, 2013 – Department of Energy Electrical Safety Handbook 4. ES&H Manual 6230 Electrical Safety Manual 5. JLAB-6220 AC Electrical Equipment Safe Work Program
Electrical and Instrumentation feedthroughs	6210 Electrical Safety Manual Electrical Safe Work Practice, Section 4. 6.	
Stored energy in the magnet	6210 Electrical Safety Manual Electrical Safe Work Practice, Section 4. 6.	
Hi-Pot test (leakage current test)	Hi-Pot test voltage 500V or 1.0kV/1.5kV (per ANSI/NETA ATA-2009), table 100.1 and apply temp comp factor based on table 100.14 or NFPA70 table 310.15(B)(2)(a)	Calculations

BACK UP

MPS Prototype – DS3 P6 Schedule

ID	Task Name	Start	Finish
1	Order Placement	14 Feb '22	14 Feb '22
2	Technical Design Report (TDR)	09 Jun '22	09 Jun '22
3	TDR Technical Design Review (Approval)	26 Aug '22	26 Aug '22
4	Completion of Manufacturing	24 Feb '23	24 Feb '23
5	FAT Factory Acceptance Tests	31 Mar '23	31 Mar '23
6	Delivery to JLAB	05 May '23	05 May '23
7	SAT Site Acceptance Tests	02 Jun '23	02 Jun '23
8	DS Torus - 3 (4000 A 60 V (240 kW))	09 Mar '22	30 Jun '23
9	Design	09 Mar '22	09 Jun '22
10	TDR approval	10 Jun '22	26 Aug '22
11	Detailled drawings & BoMs	27 Jun '22	23 Sep '22
12	Critical and LLT components procurement	09 May '22	24 Jan '23
13	FPGAs	20 Jun '22	27 Jan '23
14	PCBs	10 Jun '22	22 Dec '22
15	Ceramics capacitors	11 Jul '22	16 Dec '22
16	Control boards	23 Dec '22	02 Feb '23
17	IGBTs	15 Jun '22	29 Nov '22
18	Diodes	11 Jul '22	16 Dec '22
19	Procurement (SLT assembly items)	11 Nov '22	02 Feb '23
20	Production & Assembly	14 Nov '22	24 Feb '23
21	Preparation & FAT	27 Feb '23	31 Mar '23
22	Dismantling & Packing	03 Apr '23	07 Apr '23
23	Transportation	10 Apr '23	05 May '23
24	Installation	08 May '23	19 May '23
25	Preparation & SAT	22 May '23	02 Jun '23
26	Delivery of complete documentation	30 Jun '23	30 Jun '23



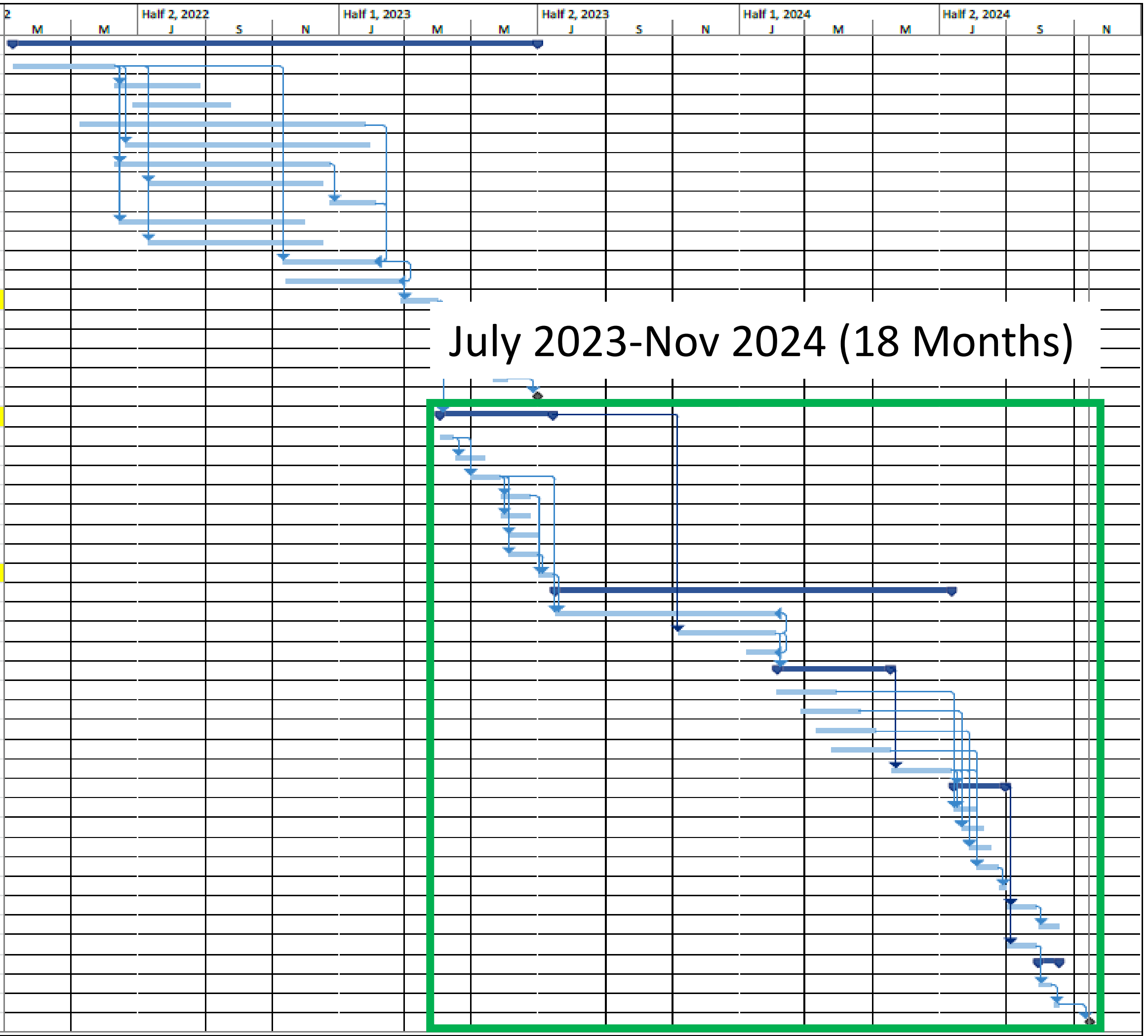
Project: JLAB - DS Torus 3
Date: 23 Sep '22

Task | Split | Milestone | Summary | Project Summary | External Tasks | External Milestone | Inactive Task | Inactive Milestone | Inactive Summary | Manual Task | Duration-only | Manual Summary Rollup | Manual Summary | Start-only | Finish-only | Deadline | Progress | Manual Progress

JLAB - DS Torus 3 - Main Project Schedule

MPS – Schedule for other 4 (US, DS1, 2, and 4)

ID	Task Name	Start	Finish
1	**DS Torus - 3 (4000 A 60 V (240 kW) (PROTOTYPE)**	**09 Mar '22**	**30 Jun '23**
2	Design	09 Mar '22	09 Jun '22
3	TDR approval	10 Jun '22	26 Aug '22
4	Detailled drawings & BoMs	27 Jun '22	23 Sep '22
5	Critical and LLT components procurement	09 May '22	24 Jan '23
6	FPGAs	20 Jun '22	27 Jan '23
7	PCBs	10 Jun '22	22 Dec '22
8	Ceramics capacitors	11 Jul '22	16 Dec '22
9	Control boards	23 Dec '22	02 Feb '23
10	IGBTs	15 Jun '22	29 Nov '22
11	Diodes	11 Jul '22	16 Dec '22
12	Procurement (SLT assembly items)	11 Nov '22	02 Feb '23
13	Production & Assembly	14 Nov '22	24 Feb '23
14	Preparation & FAT	27 Feb '23	31 Mar '23
15	Dismantling & Packing	03 Apr '23	07 Apr '23
16	Transportation	10 Apr '23	05 May '23
17	Installation	08 May '23	19 May '23
18	Preparation & SAT	22 May '23	02 Jun '23
19	Delivery of complete documentation	30 Jun '23	30 Jun '23
20	**Design (US Torus & DS Torus 1-2-4) - PURCHASE ORDER RECEIVED**	**03 Apr '23**	**14 Jul '23**
21	Dimensioning and Basic Simulations	03 Apr '23	14 Apr '23
22	Dimensioning and Simulations specific for each model	17 Apr '23	12 May '23
23	Electric design for the cabinets	01 May '23	26 May '23
24	Custom components specifications and preparation of FDR	29 May '23	23 Jun '23
25	Detailed Mechanical Design of the cabinets	29 May '23	23 Jun '23
26	Codification of components, BOM , Production Specifications	05 Jun '23	30 Jun '23
27	Control Integration and functional validation	05 Jun '23	30 Jun '23
28	TDR Approval	03 Jul '23	14 Jul '23
29	**Operations**	**17 Jul '23**	**12 Jul '24**
30	Procurement critical components	17 Jul '23	02 Feb '24
31	Procurement LLT items	06 Nov '23	02 Feb '24
32	Procurement SLT items	08 Jan '24	02 Feb '24
33	Assembly	05 Feb '24	17 May '24
34	US torus	05 Feb '24	29 Mar '24
35	DS Torus - 1	26 Feb '24	19 Apr '24
36	DS Torus - 2	11 Mar '24	03 May '24
37	DS Torus - 4	25 Mar '24	17 May '24
38	FAT Preparation (10 days per unit)	20 May '24	12 Jul '24
39	**FAT**	**15 Jul '24**	**30 Aug '24**
40	US torus	15 Jul '24	02 Aug '24
41	DS Torus - 1	22 Jul '24	09 Aug '24
42	DS Torus - 2	29 Jul '24	16 Aug '24
43	DS Torus - 4	05 Aug '24	23 Aug '24
44	Dismantling & Packing	26 Aug '24	30 Aug '24
45	FAT report (5 days per unit)	02 Sep '24	27 Sep '24
46	final documentation, operating manuals	30 Sep '24	18 Oct '24
47	**Transportation**	**02 Sep '24**	**27 Sep '24**
48	**On-site commissioning and Tests**	**30 Sep '24**	**18 Oct '24**
49	Installation	30 Sep '24	11 Oct '24
50	SAT	14 Oct '24	18 Oct '24
51	Delivery of complete documentation	15 Nov '24	15 Nov '24



Project: 21-R405082
Date: 23 Sep '22

Task		Project Summary		Inactive Milestone		Manual Summary Rollup	
Split		External Tasks		Inactive Summary		Manual Summary	
Milestone		External Milestone		Manual Task		Start-only	
Summary		Inactive Task		Duration-only		Finish-only	
Deadline							
Progress							
Manual Progress							

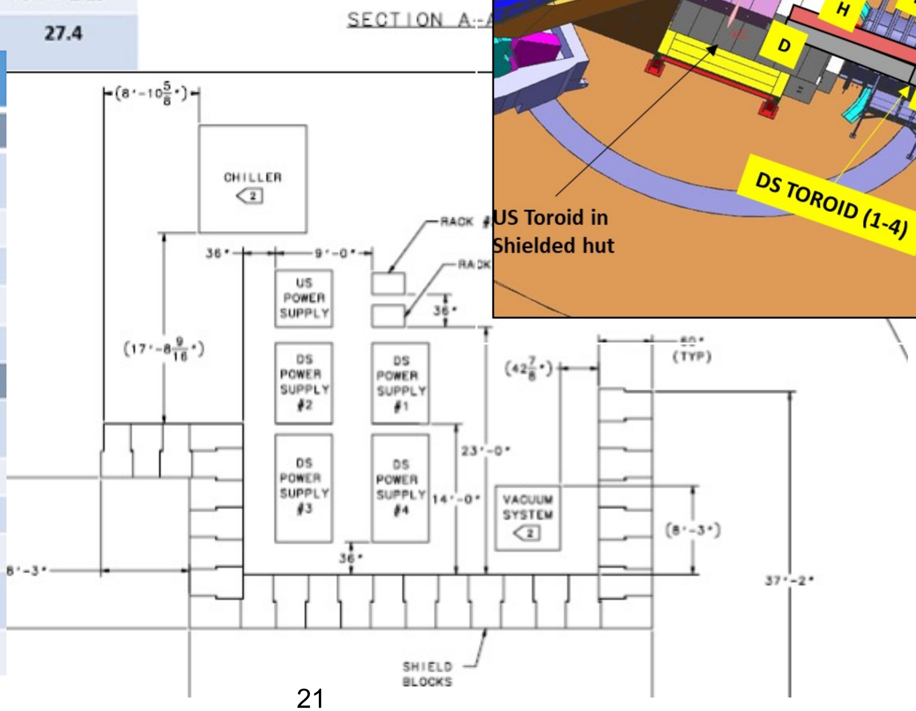
Page 1

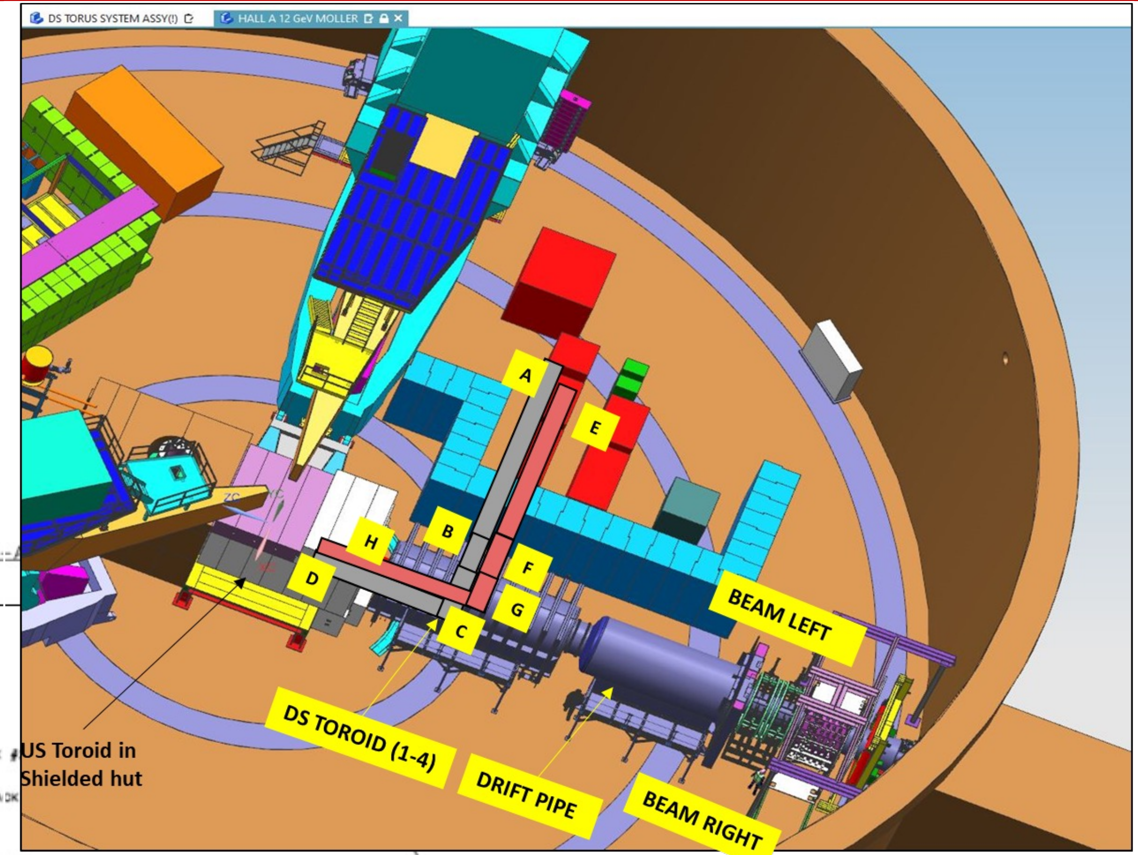
- Schedule Projected for other 4 (US, DS1, 2, and 4) from vendor.
- All critical items viz FPGA, DCCT will be on hand with OCEM
- The schedule will be evaluated after the prototype DS3 MPS installed and commissioned in the test lab.

Electrical connect between MPS and Magnet

ID	Route	Height above hall floor (m)	Length (m)
DS TOROID CURRENT LEAD ROUTING			
A	From top of magnet power supplies to exit at top of bunker (just below bunker roof), at outside wall of bunker	3.4	15.0
B	90° vertical drop to hall floor	3.4 to 0	3.4
C	From outside of bunker wall to underside of DS toroid	0	4.0
	TOTAL FOR DS TORUS (no margin)		**22.4**
DS TOROID INSTRUMENTATION LEAD ROUTING			
E	From top of instrumentation racks to exit at top of bunker (just below bunker roof), at outside wall of bunker	3.4	15.0
F	90° vertical drop to hall floor	3.4 to 0	3.4
G	From outside of bunker wall to underside of DS toroid	0	4.0
H	Along floor and up to feedthroughs on underside of DS toroid	0 to 1.29	3.7 + 1.29
	TOTAL FOR DS TORUS (no margin)		**27.4**

ID	Route	Height above hall floor (m)	Length (m)
US TOROID CURRENT LEAD ROUTING			
A	From top of magnet power supplies to exit at top of bunker (just below bunker roof), at outside wall of bunker	3.4	15.0
B	90° vertical drop to hall floor	3.4 to 0	3.4
C	From outside of bunker wall to underside of DS toroid	0	4.0
D	Along floor to underside of US toroid	0	5.6
	TOTAL FOR US TORUS (no margin)		**28.0**
US TOROID INSTRUMENTATION LEAD ROUTING			
E	From top of instrumentation racks to exit at top of bunker (just below bunker roof), at outside wall of bunker	3.4	15.0
F	90° vertical drop to hall floor	3.4 to 0	3.4
G	From outside of bunker wall to underside of DS toroid	0	4.0
H	Along floor and to center of DS toroid	0	3.7
I	From center of DS toroid, along floor and up to feedthroughs on US toroid	0 to 1.29	5.6 + 1.29
	TOTAL FOR US TORUS (no margin)		**32.99**





Cable tray for power
Cable tray for control (signals)

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