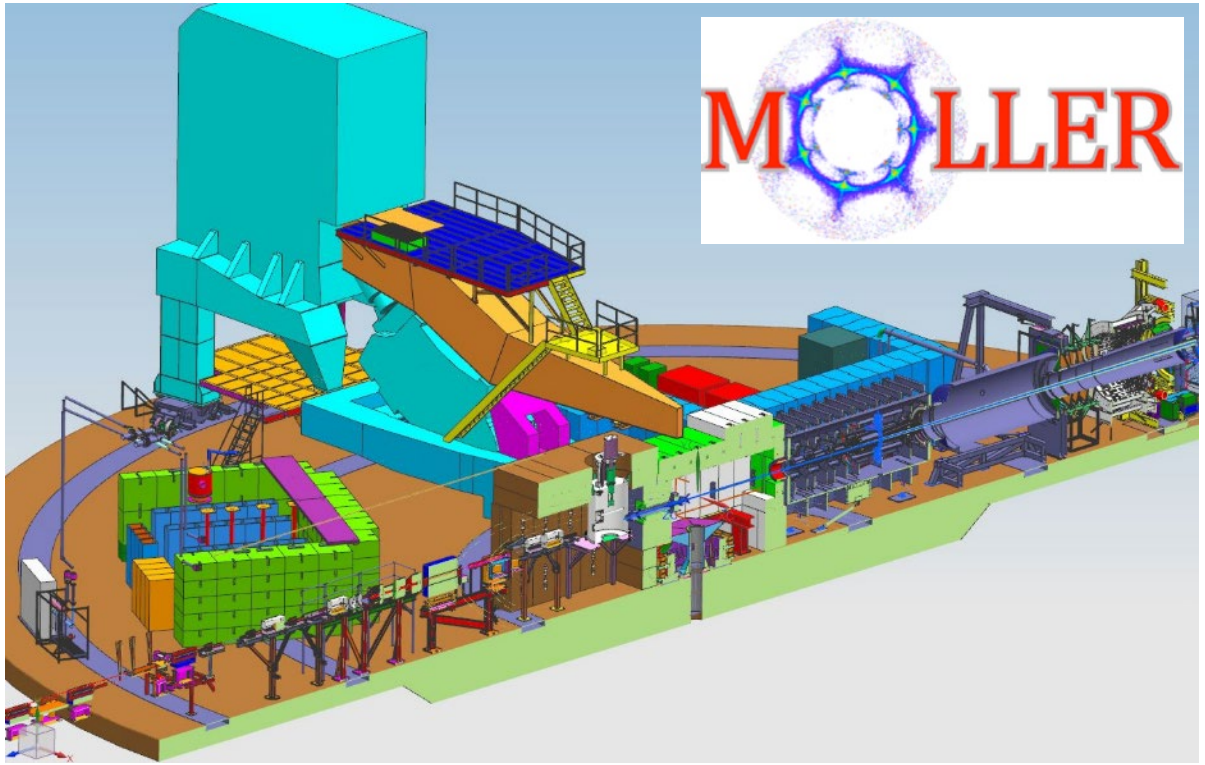
MOLLER Experimental Readiness Review #2

Moller Spectrometer – Mechanical and Cooling



Presenter – Eric Sun/Sandesh Gopinath

Moller – Spectrometer Team

July 28, 2025

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

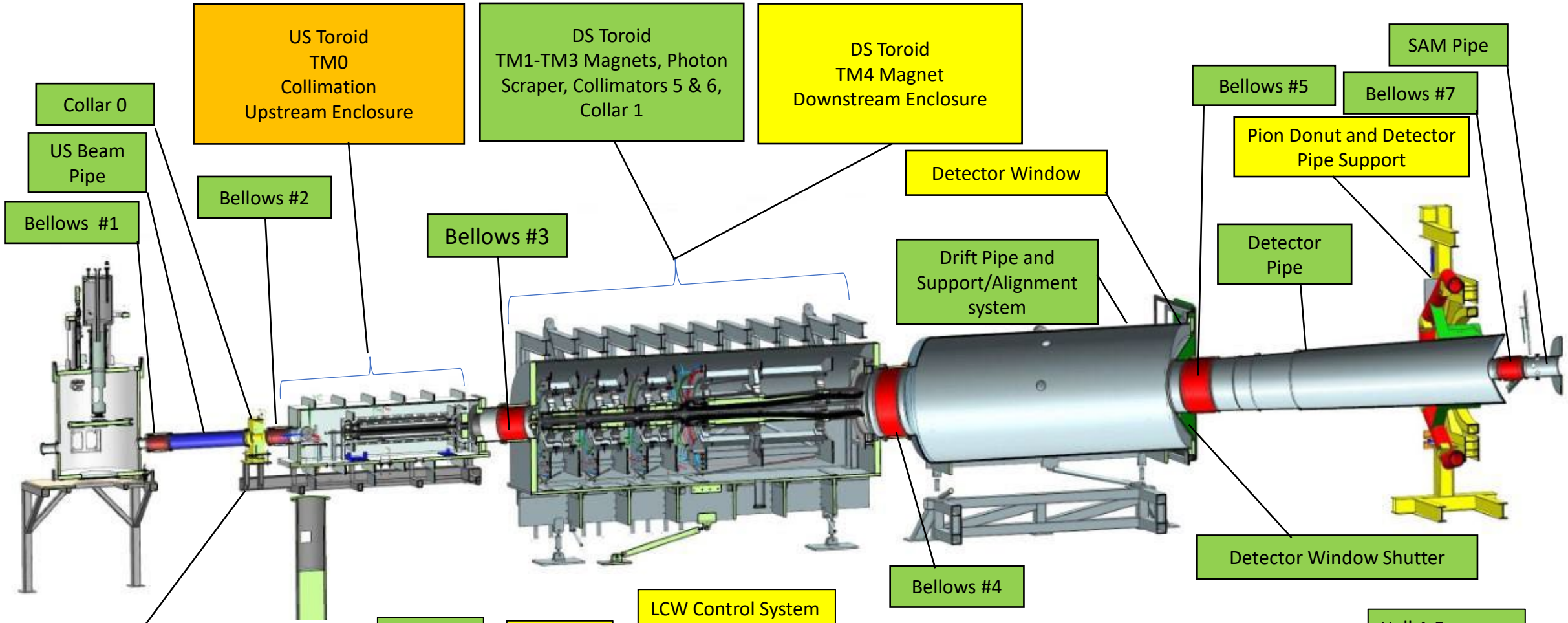
JSA

Charge Review

- Provide a summary of major magnet analyses done
- Provide summary of other MOLLER components (Bellows, Windows, etc.)
- Provide High-Level commissioning and Running plans
- Provide “What if” scenario if performance specifications are not met
- Mechanical and Cooling
  - pressure vessel system, piping, water cooled magnet
  - applicable codes & analysis
  - material test/code documentation (if any)
  - Magnet and LCW - cooling and controls
  - Considerations for loss of pressure or flow
  - Continuous monitoring instrumentation
  - LCW circuit: supply, return, cooling procedures (Collimators, magnet, MPS, etc.)
  - Pressure/Vacuum relief safety - sizing to handle a loss of vacuum and leak(water)
  - ODH analysis - worst credible release

Status

Spectrometer Overview - Moller Spectrometer Scope and Hardware Status



Status of Major Components

Major Components	Status	Applicable Codes	Pressure rating (PSIG)	Pressure or Vacuum Test	Helium leak test	Records available	Notes
TM0	Received coils and some components	B31.9	250				
TM1	Ready to power up	B31.9	250	390 psi (Jlab)	1.00E-08	Jlab signed PS-7	Witnssed by Marcus Anthony
TM2	Ready to power up	B31.9	250	390 psi (Jlab)	1.00E-08	Jlab signed PS-7	Witnssed by Marcus Anthony
TM3	Ready to power up	B31.9	250	390 psi (Jlab)	1.00E-08	Jlab signed PS-7	Witnssed by Probir Ghoshal
TM4	Ready to load coils	B31.9	250				
Bellows 1-5 and 7	Ready to install	ASME and EJMA	vacuum and 0.4 psig (1.03 atm)	Vacuum (vendors and JLab)	1.00E-08	JLab PMAG test reports and vendor test reports.	All bellows passed the leak tests.
Drift Pipe	Ready to install	ASME	vacuum and 0.4 psig (1.03 atm)	Vacuum (vendor)	1.00E-09	Vendor test report	Jlab witnessed the leak test in person.
SAM Pipe	Ready to install	ASME	vacuum and 0.4 psig (1.03 atm)	Vacuum (vendor)	1.00E-09	Vendor test report	Jlab witnessed the leak test through video.
US beam pipe	Ready to install	ASME	vacuum and 0.4 psig (1.03 atm)	Vacuum (vendor)	1.00E-09	Vendor test report	Jlab witnessed the leak test in person.
Detector Window	Ready to start Fab	JLab	vacuum and 0.4 psig (1.03 atm)				Tooling ready for real window ready, spare material available
US Enclosure	Finalizing design	ASME	vacuum and 0.4 psig (1.03 atm)				
DS Enclosure	Finalizing fabication	ASME	vacuum and 0.4 psig (1.03 atm)				
Collar 0	Ready for fiducialization	ASME	vacuum and 0.4 psig (1.03 atm)	Vacuum (vendor)	1.00E-09	Vendor test report	
Hi Pot test (TM1,2,3)	Completed (Passed)	IEEE/NEC	1.5 kV	7.5µA (5µA @1 kV) per Line to GND	<100µA	LogBook (entry)	Morgan and Probir

Beam Pipes and Bellows Received

Bellows 1 and 2

Bellows 3

Bellows 4

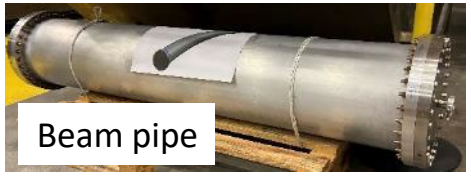
Bellows 5

Bellows 7

Detector Pipe with Neckdown window

Drift Pipe

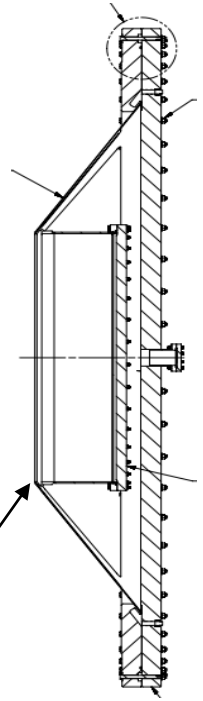
SAM Pipe



All meet specs, have been tested and are ready to install

Detector Window Status and Components

- Detector Window machining successfully completed using a vacuum chuck 2/5/2025
- Window assembly components received
- Window forming fixture fabricated

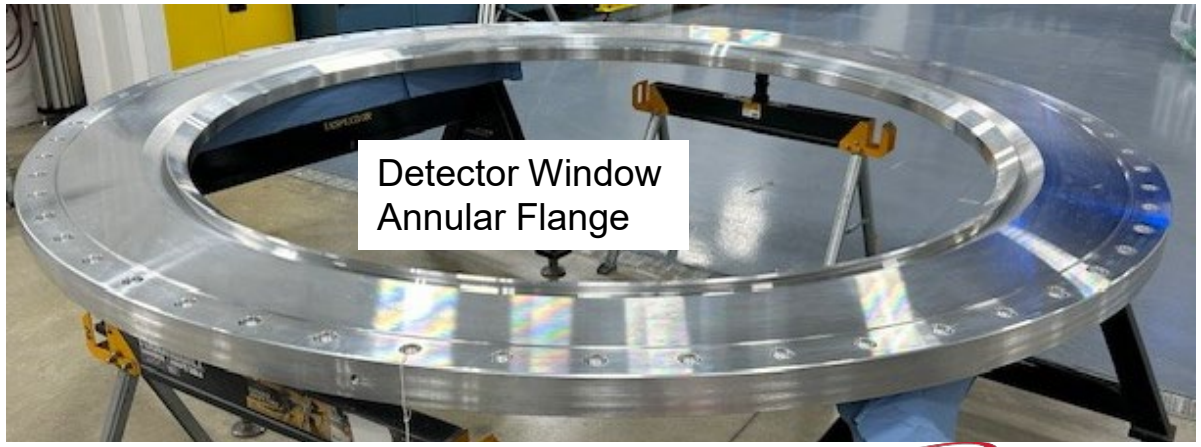


Detector Window Pneumatic Test Setup

Vacuum “chuck” Mechanism

Detector Window Pipe Nipple

Detector Window machining inhouse survey

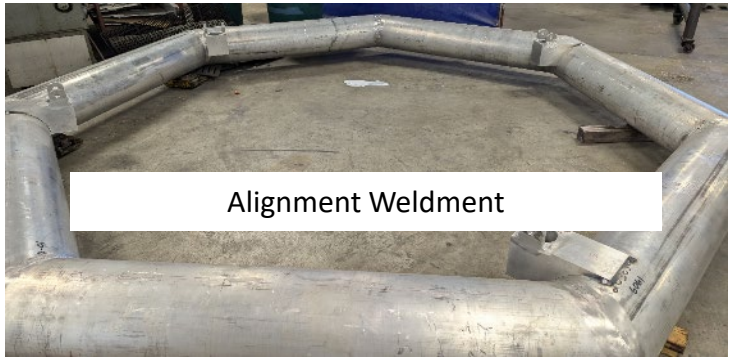


Detector Window Annular Flange

Pion Donut and Detector Pipe Support

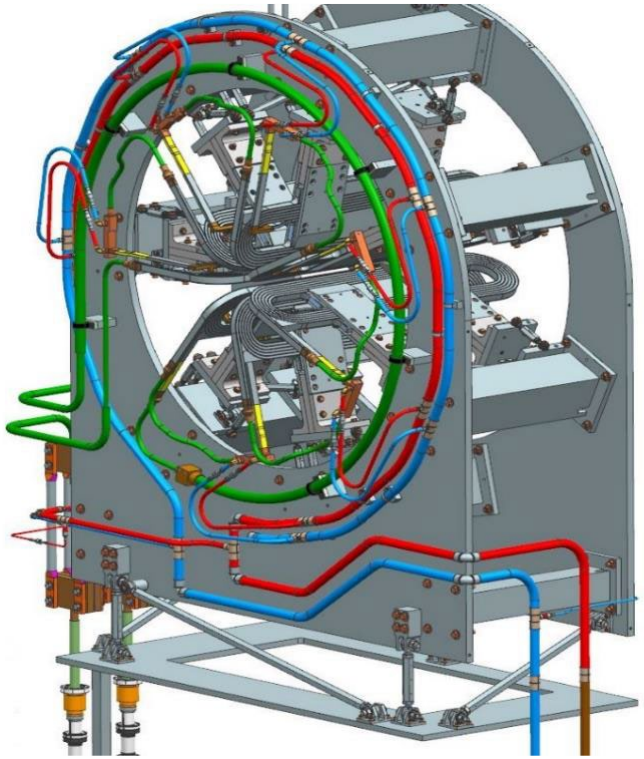

Frame Weldment

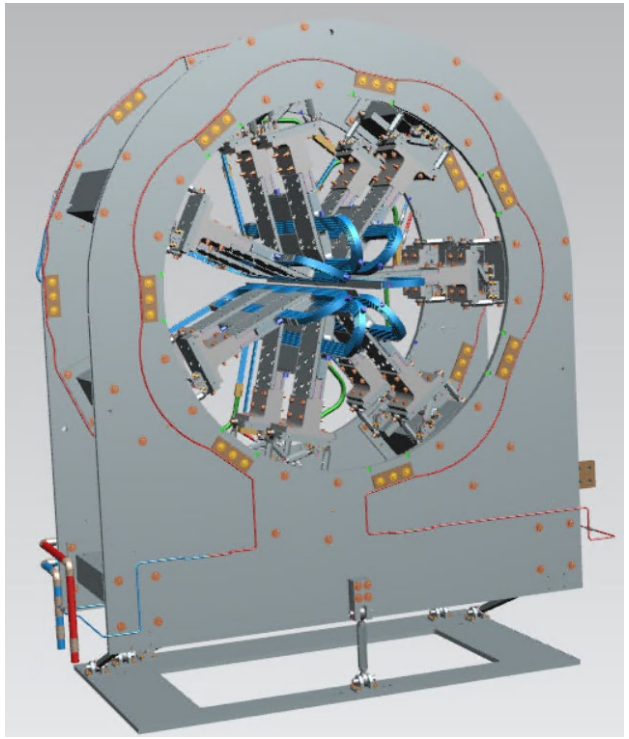

Pion Donut Canning


Alignment Weldment


Pion Donut Shipping Stand

Magnets

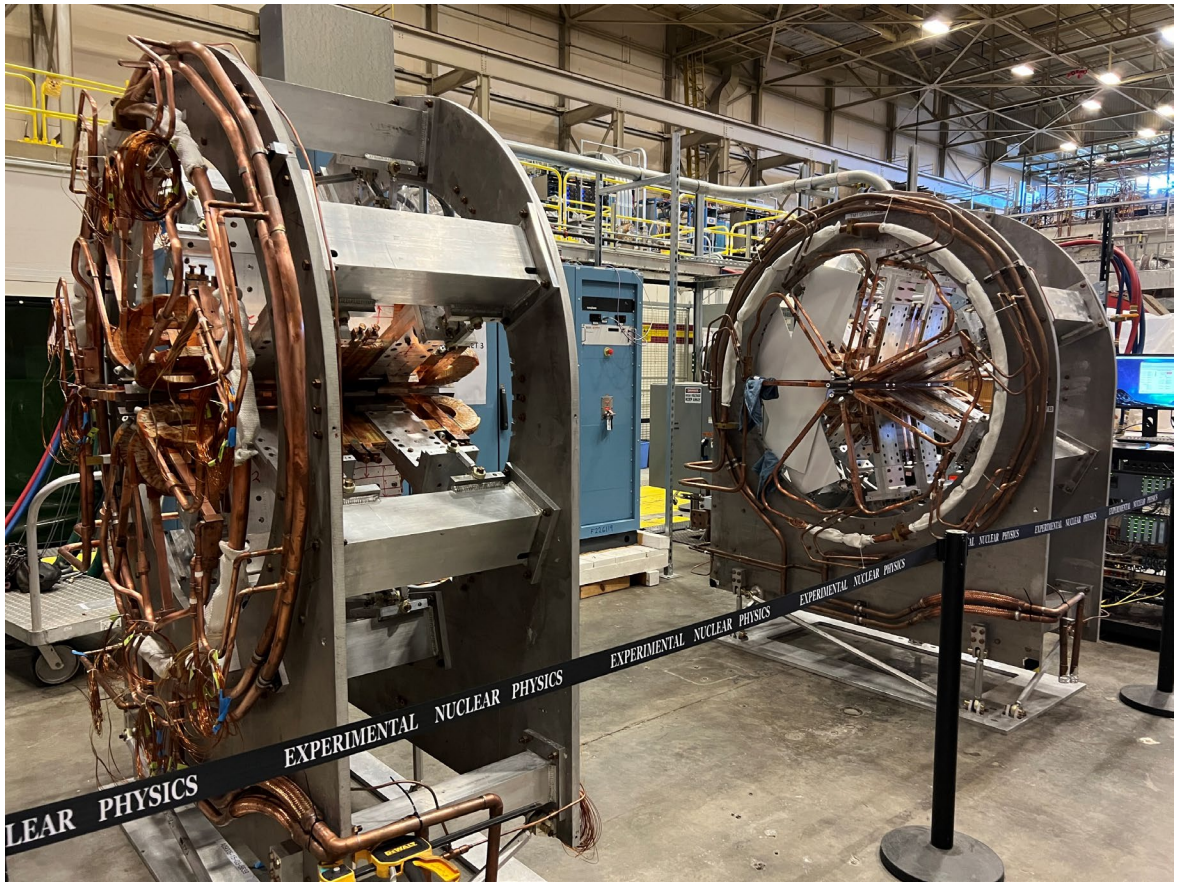




TM2 as designed

TM2 as fabricated

Magnets… and TM4 coils



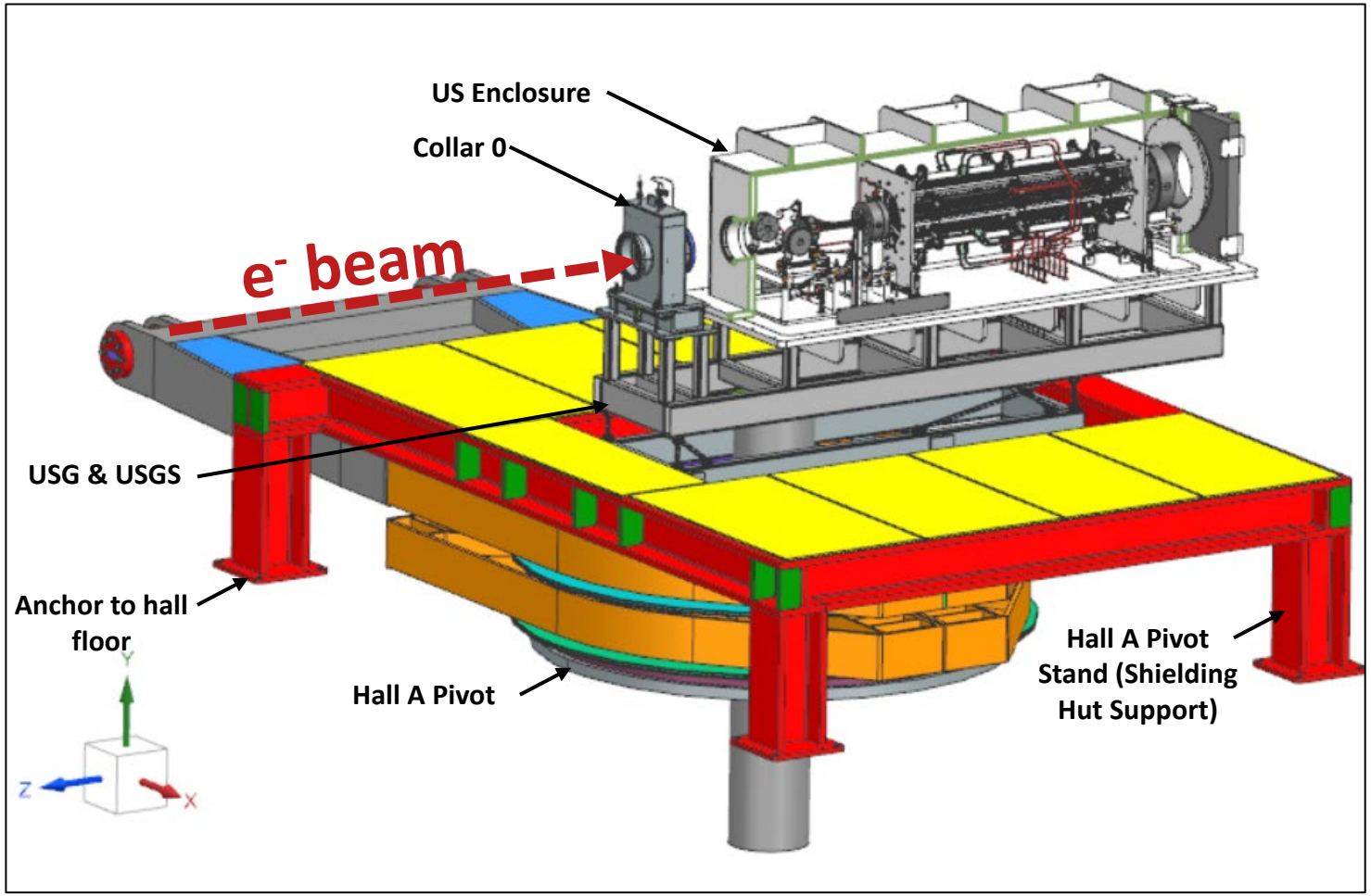
TM1 & TM3 fabricated and tested – Ready for mapping

4 x TM4 coils, SC4 coils in safely stored and being prepared to load into frame

Magnets …

- TM4 frame ready for assembly
- Belly plates were installed
- Two TM4 coils are ready to load into the frame

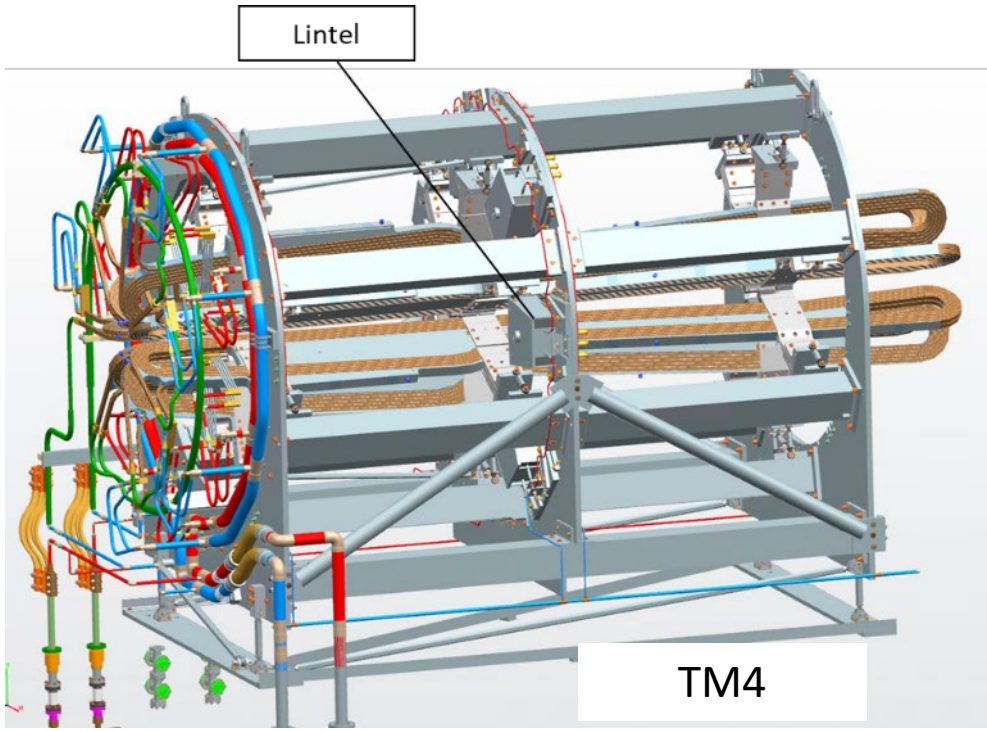
US Spectrometer

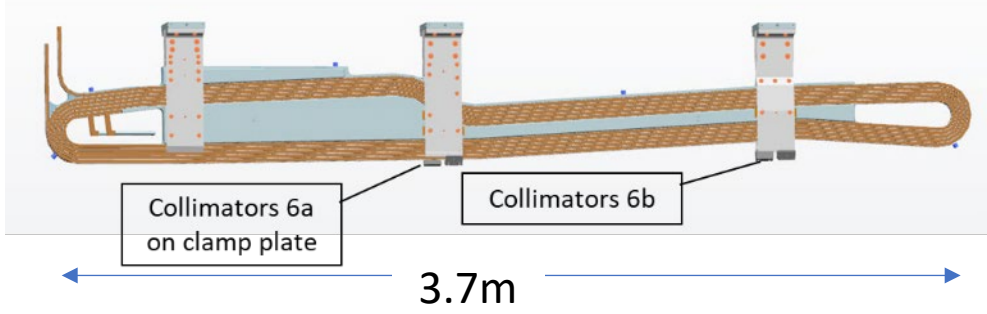


Component	Status
2 – Bounce Shield (2BS)	Received
Coils (TM0)	Received
Magnet Structure	Design complete, drawings in progress
Collimator 1-2	Design and drawings complete
Collimator 4	Received
Blocker & Sieve	Received
US Enclosure	Design in progress
US Girder (USG) & Girder support (USGS)	Design and drawings complete
Blocker & Sieve Actuator	Design in progress
Water-cooled feedthrough and Jumpers	Received

Magnet Details

- The four downstream magnets are air core copper magnets with low conductivity water (LCW) (*each magnet has 7 coils*)
  - Conductor location and NI specified by MOLLER collaboration
  - Each magnet has custom conductor optimized to meet the field, space and cooling requirements
  - TM4 coils are double pancake with two cooling circuits
  - Coils to be aligned to 0.5 mm at inner turn in phi and R
- Bulkheads, Collimators and Lintels are also cooled by LCW
- Coils are clamped with pinned brackets - to ensure a stable position
- Some clamps support collimators, which transport deposited heat to the coil LCW





Magnet operating parameters at 110% of nominal current						
TM#	Maximum Magnet Current (A)	Maximum Magnet Power (kW)	Conductor Current Density (A/mm^2)	Pressure drop (psid)	Max Water velocity (ft/sec)	Total Flow (gpm)
TM0	1178.7	71	21.6	100	11.16	9.59
TM1	2451.6	69	20.6	96.8	15.00	9.94
TM2	2682.3	79	17.2	99.6	14.95	14.21
TM3	3709.6	138	20.0	100.1	14.99	22.67
TM4	3688.7	718	18.5	99.9	13.86	113.8

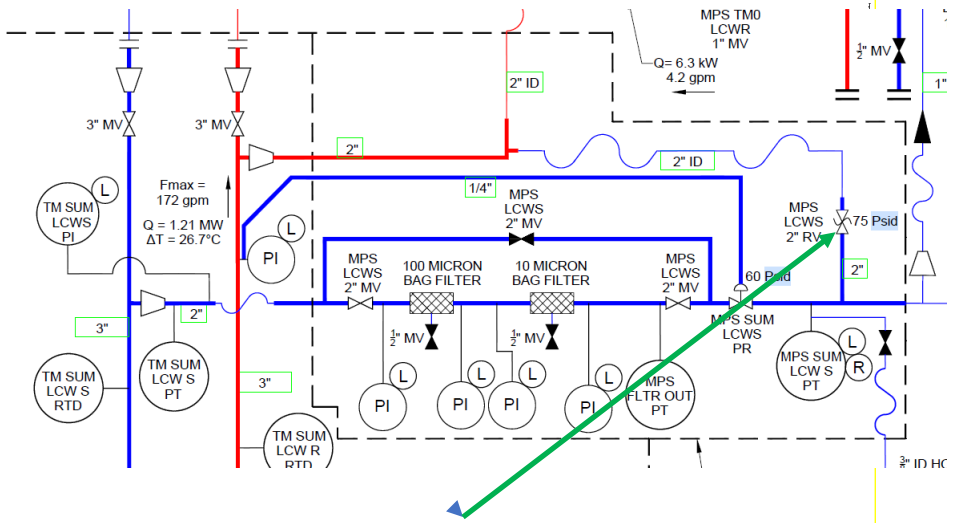
Reviews

- **Last successful and approved review**
  - IPR MAR 2025
  - CD 2-3 OCT 2023
  - FDR DEC 2022
- **No open recommendations for Spectrometer**

MOLLER Spectrometer Deliverables and Current Status - Summary

- **System requirement** - See SRD for details (PMAG0000-0100-S23 System Requirement Document)
- **Provide required magnetic field**
  - 5 Toroids magnet design complete
  - TM0 coils received
  - TM1, TM2 & TM3 assembly and hydrostatic testing complete
  - TM4 assembly in process – estimated completion AUG 2025
  - Magnet Power-up and mapping In process – AUG 2025
- **Vacuum environment for clean beam transport**
  - All beamline enclosures and components designed
  - Bellows, Beampipes, Drift pipe, Detector pipe, and SAM pipe leak testing and delivery complete.
  - DS Enclosure 90% fabrication complete
  - Vacuum pump-line design complete – PO placed, EDT Oct 2025
  - Vacuum blower setup received

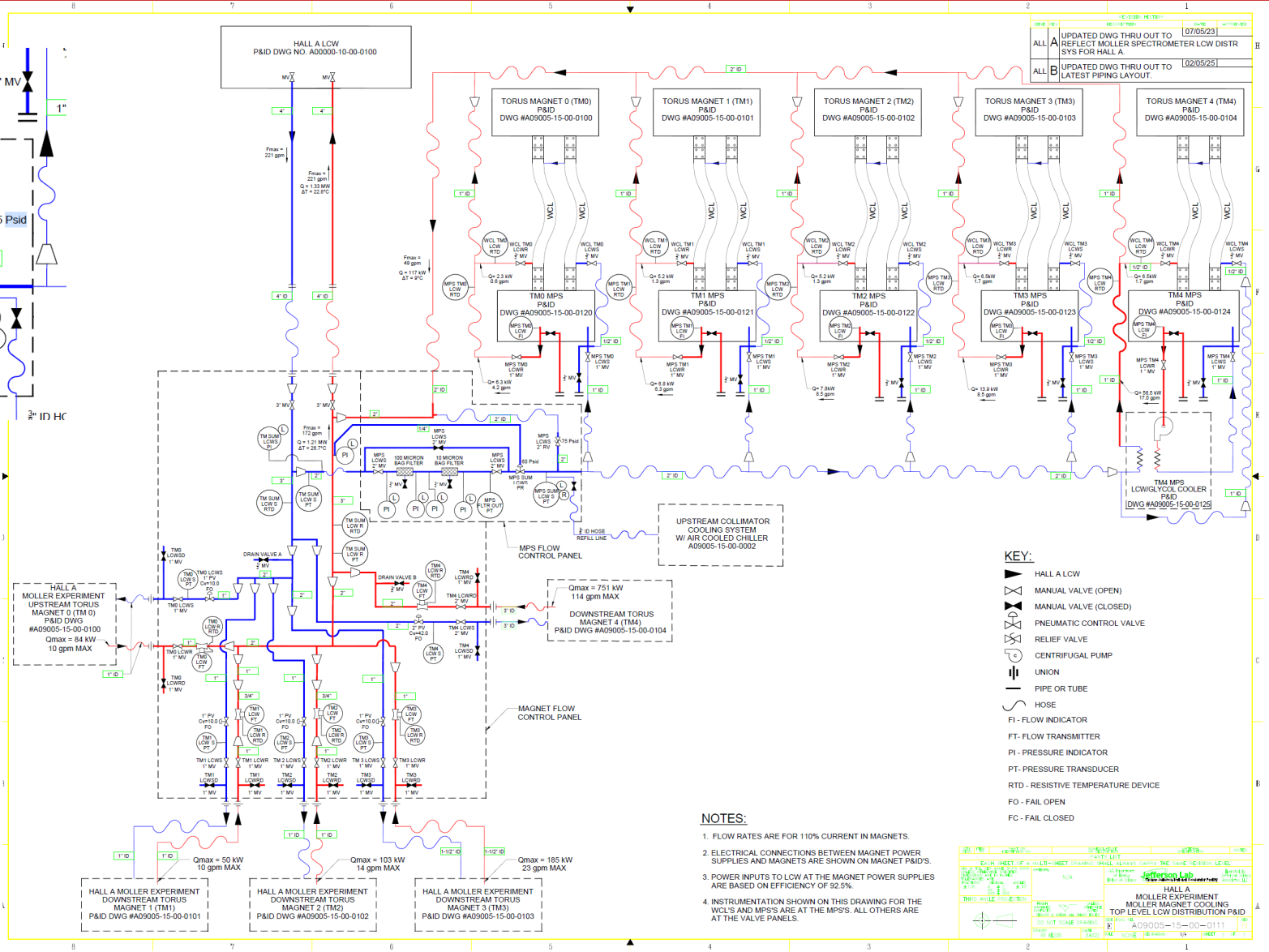
LCW System (Drawing A09005-15-00-0111-B)



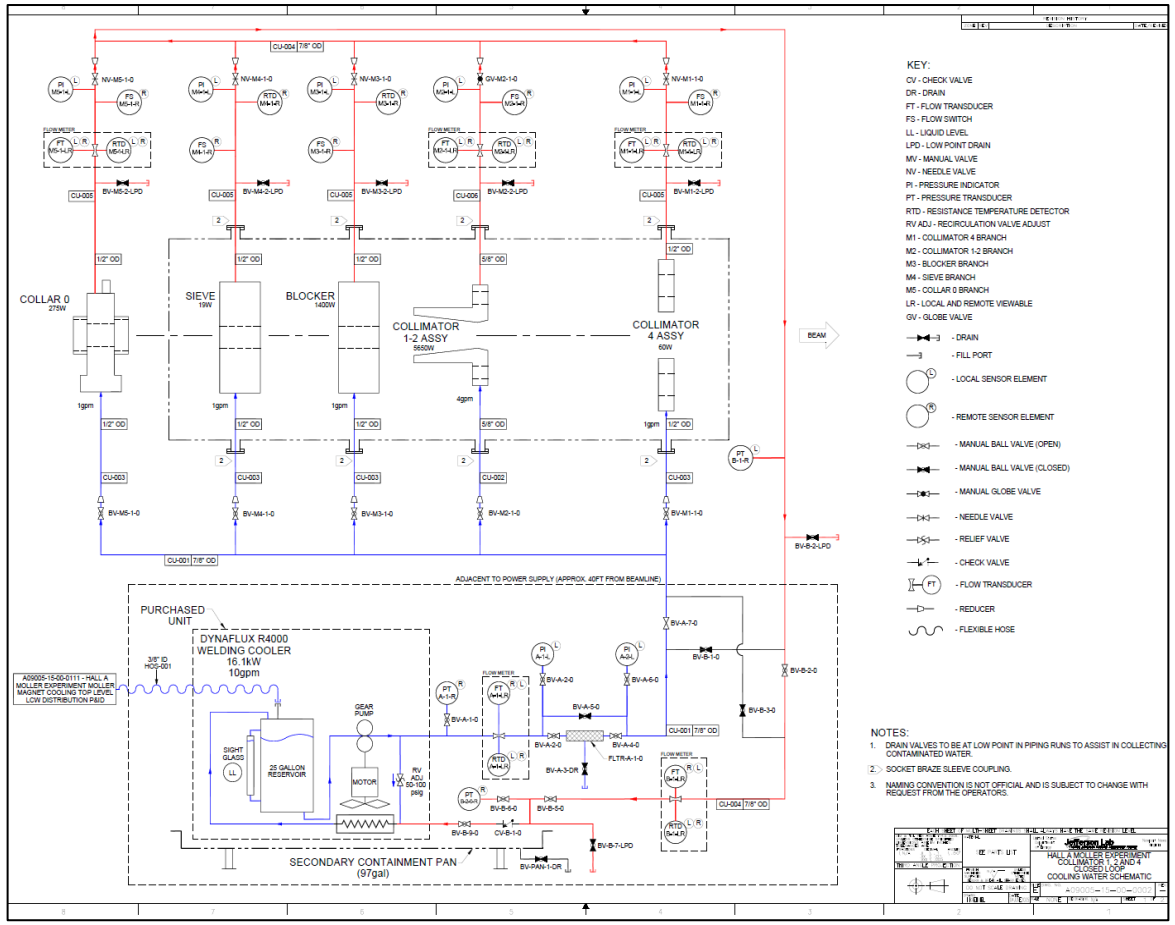
Set pressure of relief valve for MPS = 75 psid

Capacity needs

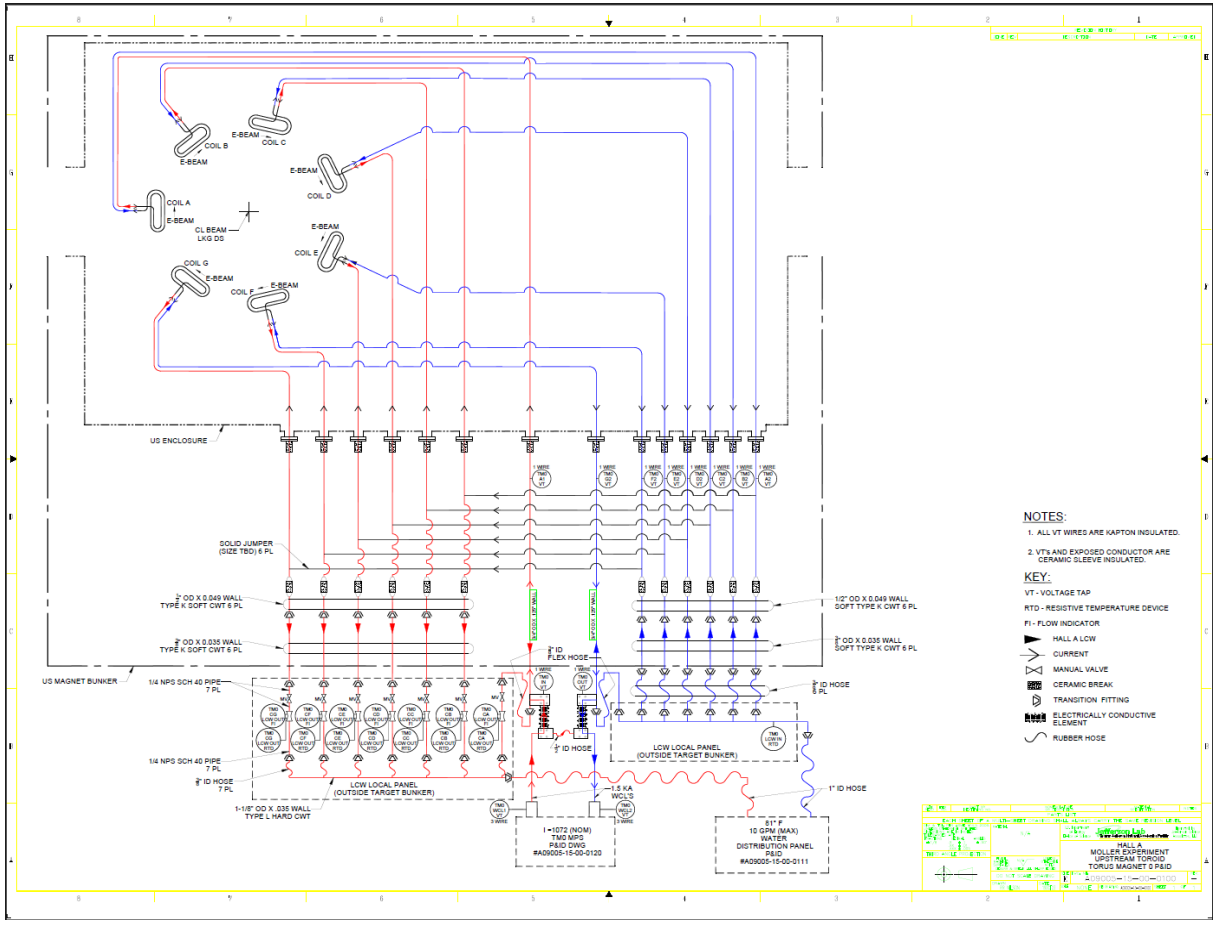
- Required 221 GPM and available 500 GPM in the hall
- System required pressure drop (100 psid) and supply pressure 235 psi in the hall



LCW System (US)



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



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

Analysis

Magnet - Analyses Complete

- **Coil and Magnet LCW flow/pressure drop analyses** were completed to design conductors, coils, and Magnet piping
  - Variables and limits were set in specification: Max velocity in conductors 15 ft/s, Magnet DP 100 psid, Max temperature rise 35 deg C [Ref: FDR design document]
- **Magnet structural analyses**
  - Coil and frame deflections for TM3 and TM4
    - Loads: Gravity, Thermal Coils and Frames, and EM [Ref: FDR documents]
    - Piping Stress: deflection due to gravity, thermal motion and alignment (1mm enforced deflection) (PMAG0000-0100-R0037)
    - Magnet piping design to ASME B31.9
    - Belly Plate/Epoxy Shear stress due to Thermal changes [Ref: Belly plate analysis documents]
- **Magnet EM analyses and effects on physics**
  - Magnet EM analyses complete
  - Field requirements developed [Ref: SRD documents]
  - Developed program (mustache plots) to allow us to study and optimize coil shapes independent of the collaboration

Vacuum Vessels and Piping

- **Vacuum vessels**
  - All calculations completed compliant to ASME and JLAB pressure safety requirements
    - All vessels are Category 1 Vacuum vessel and are designed using ASME BPVC VIII Division 1 as guidance
  - Movement under vacuum load studied
  - Critical vacuum deflections calculated using FEA
  - Anchoring design completed to handle vacuum and earthquake loads
  - Over-pressure (>0.4 psig) is prevented by a parallel pate device (*add to protect thin window from buckling*)
- **Detector window (Pressure and vacuum)**
  - Designed per Requirements for Components with Thin Windows, JLab E&SH Pressure and Vacuum Systems Safety Supplement
  - Prototype built (1/3 size) and hydrostatically tested to 65 psi with a design factor of 2.95
- **Pump-down cals**
  - Effective pumping speed calculated based on estimated outgassing rate (*add first pump down calculated to be 5 hrs but will depend on actual outgassing rate*)
- **Magnet piping with a design pressure of 250 psi**
  - Hall A LCW supply pressure is 235 psi
- **MPS piping** (MPS now re-rated at 10bar 145psig)
  - Set pressure of relief valve is 75 psid

Survey & Alignment

DS Magnet – Survey and Alignment

- Epoxy thickness on the belly of the coils was measured with an inductance probe. This information is tied into the global survey data set to allow accurate positioning of the inner conductor of each magnets coil
- Coil surfaces are surveyed prior to installing belly plates and tied into tooling ball mounts on the clamps.
- After belly plate and additional tooling ball mounts are installed, an additional survey will be done to tie in belly plates and new tooling balls.
- The Metrology team will use average epoxy thickness for each SC type per collaboration requirement offsets to determine beamline coordinates for each tooling ball mount and perform final coil alignment relative to the magnet frame centerline.

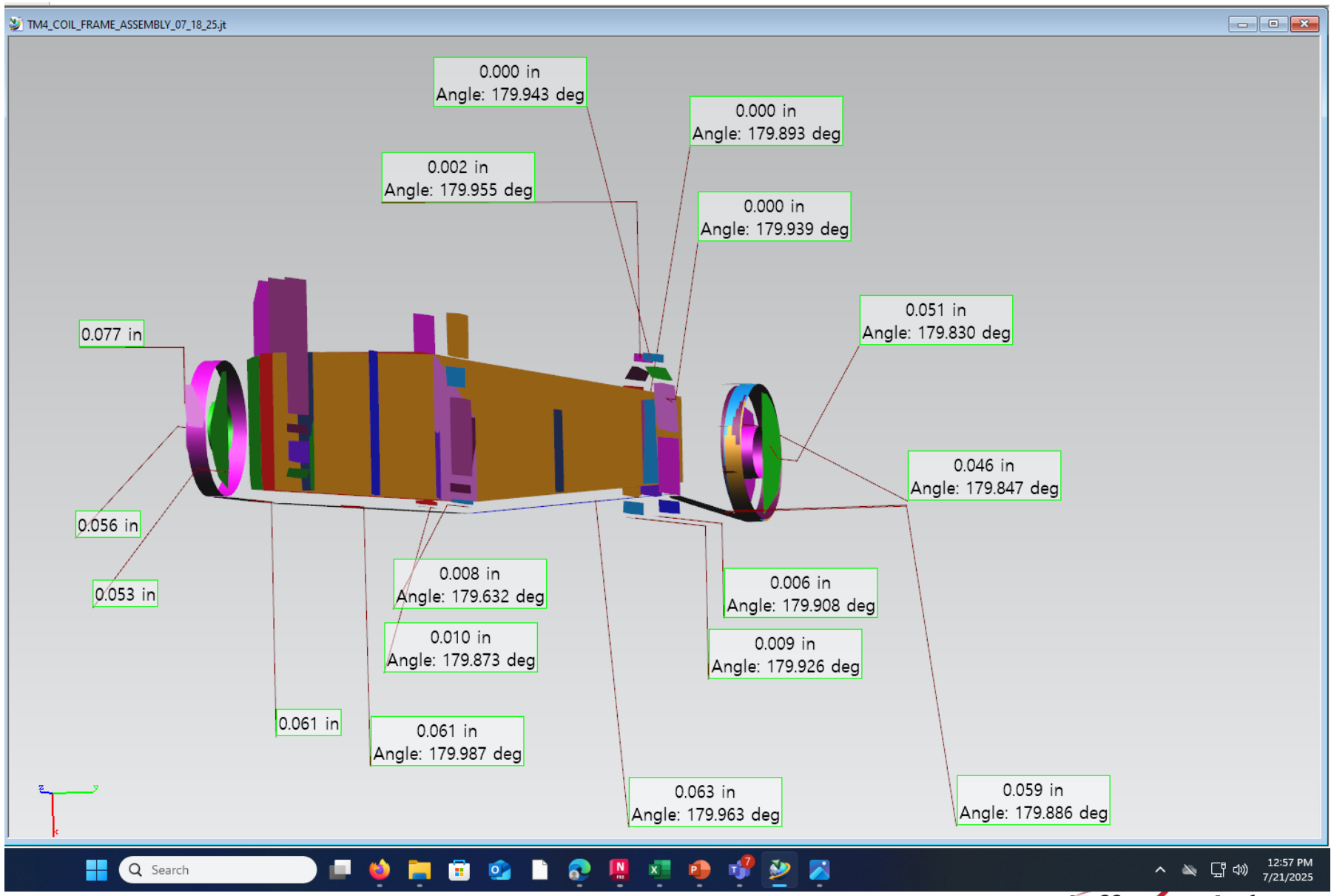
Inductance Probe measuring epoxy thickness

DS Magnet – Survey and Alignment

- All coils are surveyed before and after belly plate gluing (complete)
  - Belly side of inner turn for each type of SC is used to set Coil Location in R and Z Mid plane of coil epoxy sides is used to set Roll and Yaw
- All coil assemblies with collimators are surveyed before assembling the magnet
  - TM4 in progress
- TM1,2, 3 – Complete (before and after belly plates epoxied)
- Coil Fiducialization in the frame
  - TM 1,2, 3 Complete
  - Documented in MSD and reports from alignment grp (on going process)
- All DS coil frames fiducialized prior to loading TM1-3 Fiducials repeated to better than 100micron after loading all coils

Coils Survey results

- Mapped planes of the coil and clamp surfaces
- Dimensions on coil planes indicate epoxy thickness vs ideal CAD model
- Dimensions on clamps indicate distance as compared to 3D CAD
- Angled surfaces for collimators requested to be 0.1 degree of ideal



Quality Assurance

Workspace

- At the last review, analyses and drawings were the focus with a few pictures of prototype hardware.
- Today we are showing you fabricated hardware
- Hardware not currently needed is stored in off-campus facilities
- Last OPA we had a work area of 750 ft^2, now we have 3300 ft^2
- Spectrometer team includes
  - JLab support: Magnet Group, Technicians from Physics Division, Detector Support Group, Mechanical Engineering, Metrology, DC Power, Hall-A, ES&H
  - Contracted Engineering Services (US): Bartoszek Engineering, MIT-Bates
  - Contracts with many companies to provide hardware

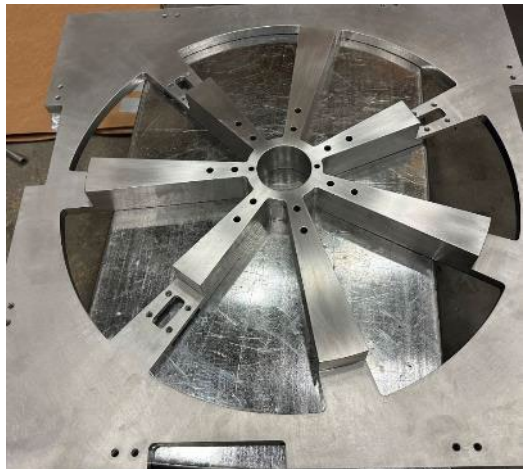

Workspace 02/2025


Workspace 08/2023


Hardware example = Collar 1

Receipt/QA, Specifications/Procedures & Storage

- **Receipt Inspections**
  - All received materials undergo a receipt inspection process, which includes completing an RIR (Receipt Inspection Report). Presently 109 reports have been completed.
  - Inspections based on specifications, statements of work, and drawings. Many include performance, material certs and strict magnetic permeability requirements.
  - A Non-Conformance Report (NCR) documents discrepancies between as received and the requirements
    - 9 NCRs have been completed, addressing issues such as small vacuum leaks, improper material surface finishes, and fabrication tolerances/dimensions
- **Specs and Procedures**
  - **50** approved specifications
  - **7** approved procedures and 4 in progress. Procedures are created for critical tasks.
- **Storage**
  - Off campus storage is done in two separate local rented warehouses; Thimble Shoals and Warwick
  - On campus storage is in the Test Lab and a large tent on the Accelerator Site, many of these items need further assembly and testing; others are too large for handling at off site locations



Reworked surface finish on Photon Scraper support

Jefferson Lab MOLLER

Nonconformance Report

Record No:	NCR-001	**Initiated By:**	Joe Lamont
Date Initiated:	2023/10/17	**Vendor Name:**	ASPEN AUTOMATION & MACH

1 Issue Description

Item(s) Identification	Photon Scraper Support
Requirement	SOW PMAG0000-0100-S0050 Rev. -, A09005-15-03-0201 Rev. -
Issue Description	Issue 1 - Missing QTY.6 of sub-item 2. (A09005-15-03-0201, ITEM 6) Item should be supplied by vendor when Issue 2 is returned to JLAB. Issue 2 - Surface finish is out of tolerance according to the requirements of A09005-15-03-0203 Note 2. (A09005-15-03-0201, ITEM 7) Item should be returned to vendor to be refinished. See Photos at bottom of form. Issue 3 - A09005-15-03-0201, ITEM 7 was not provided by the vendor. Item should be supplied by vendor when Issue 2 is returned to JLAB.

2 Corrective Actions

Disposition (check one)			
Return to Vendor	Repair	Reject	Use as Is
x			

Customer Notification Required? (Yes / No)	No
Return to Vendor Form Number (If Applicable)	164679

No	Action Steps	Verification / Results
1	Remeasure surface finish	Surface finish is now within spec.
2	Verify missing purchased hardware	Hardware still missing. CAM decided to accept material and will purchase missing bolt separately.

3 Root Cause

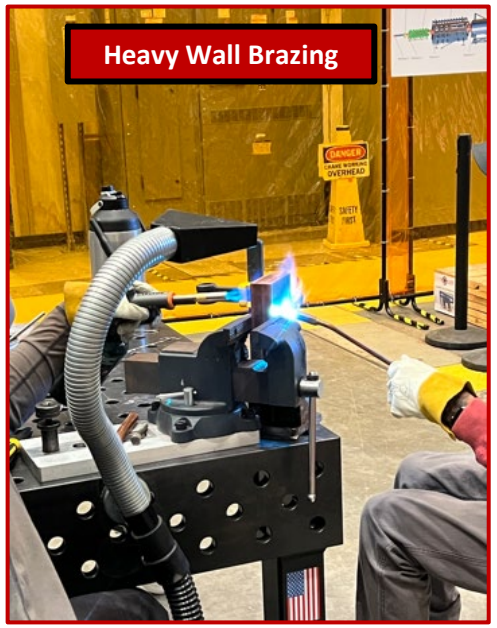
Vendor did not make part to drawing. Missed the step of higher tolerance surface finish.

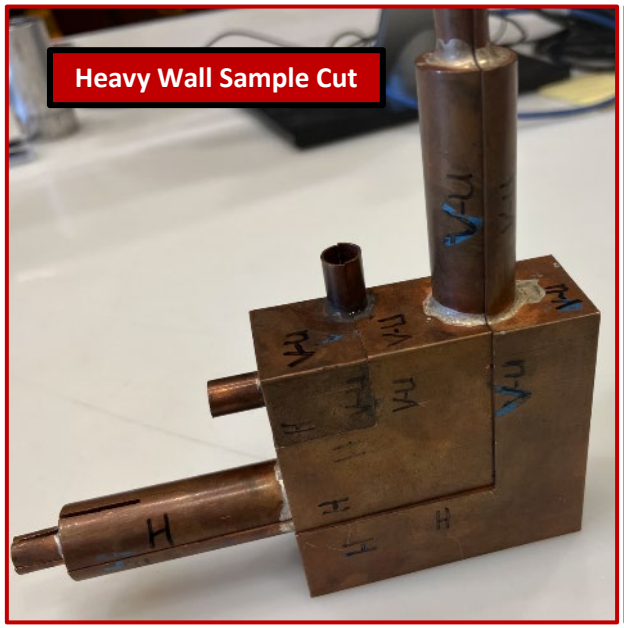
4 Preventative Actions

TR notifies procurement utilizing the "Return to Vendor Form". Procurement will then notify shipping and receiving and vendor. Procurement will settle cost and reparations with vendor.

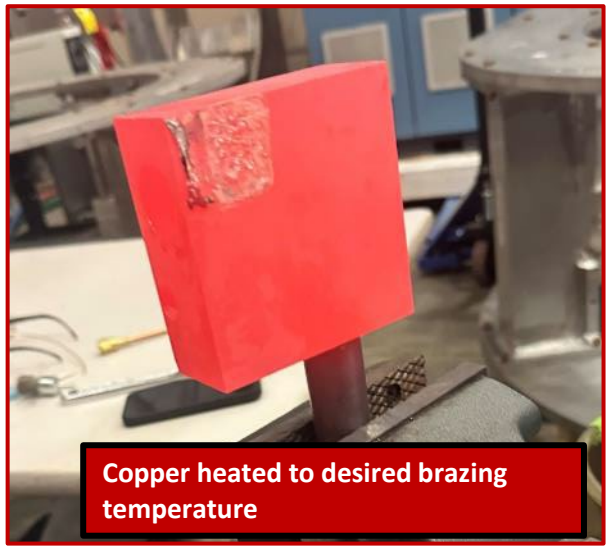
Personnel Qualification for Brazing and Soldering

- MOLLER process piping has been designed and built to ASME B31.9 rules
- Since the Electrical Bus carries up to 4 kA of current, we use heavy-wall custom blocks and adapters that require a strict brazing process to ensure high-quality joints
  - Cleaning
  - Joint clearance
  - Flux and braze rod material
  - Temperature control with fast heating
- Most of the brazing and soldering procedures and qualifications are complete
  - Completed processes and qualifications are; stainless to copper brazing, thin wall copper soldering and brazing
  - Heavy wall brazing procedure (shown here was the most difficult) we now have samples to be sent to testing company for qualification of WPS/PQR/WPQ


Heavy Wall Brazing


Heavy Wall Sample Cut


Cross Section


Copper heated to desired brazing temperature


Cu-SS Braze Samples

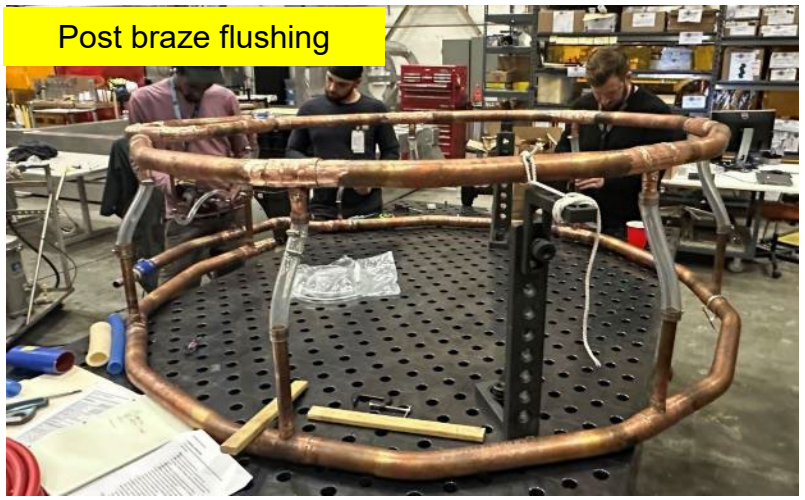
Water Piping Fabrication, Leak Testing

- All main water headers for the DS magnets are brazed and successfully leak tested.
- Leak testing is performed with either a cold trap or prior water-water flushing.
- Water connections to coils are soldered to avoid damage to the ceramic breaks or remelting the braze joints.
- Two Ceramic breaks have been successfully hydro-tested to 1500 psig
- Hi-Pot test up to 1.5 kV

TM1-3 Water Headers

TM4 header test fit with bulkhead

Water Header brazing



Post braze flushing

5kV ceramic break

Epoxy & Gluing

- EP33 is a rad hard epoxy system, with less than 10% strength loss after 200 MGy dose
- Vendor reported shear strength 2200-2400 psi on Al 6061
- Initial epoxy work on the belly plates gave low and inconsistent strength results
- The vendor had no data or experience bonding to either Al 7075 or W/Cu
- A detail test plan was developed, the results below show we achieve slightly lower strength for Al 7075 and higher values with W/Cu

Oven for Epoxy Tests

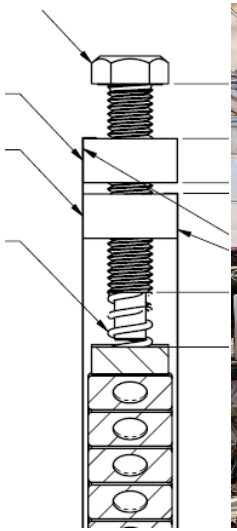
¾” diameter W/Cu and Al 7075 samples post torsional shear testing

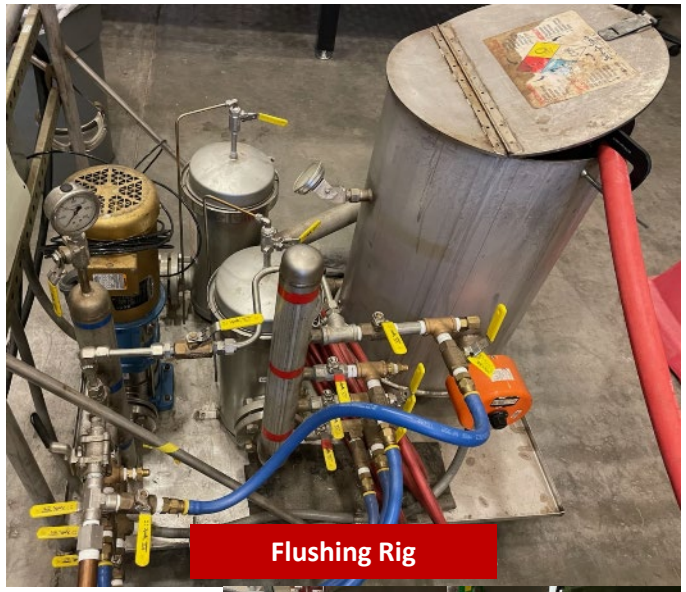
Epoxy Type	EP33	EP33
Metal Substrate	Al 7075	W/Cu 90/10
Preparation Date	1/29/2025	1/29/2025
Average Shear strength (psi)	2009	2884
Min Shear Strength (psi)	1688	2414
Max Shear Strength (psi)	2287	3372

Maximum shear stress on epoxy at W/Cu Belly Plates result during fast de-energization of coils causing the coil conductors to cool quickly due to LCW flow while the belly plate stays warm. Thus a shear stress of 350 psi is created

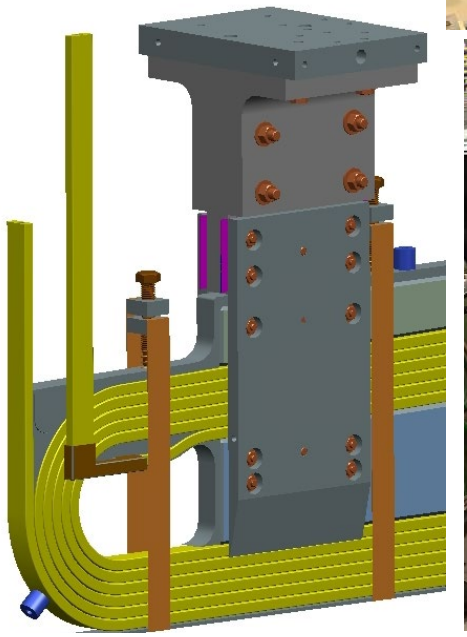
Coil Epoxy Steps

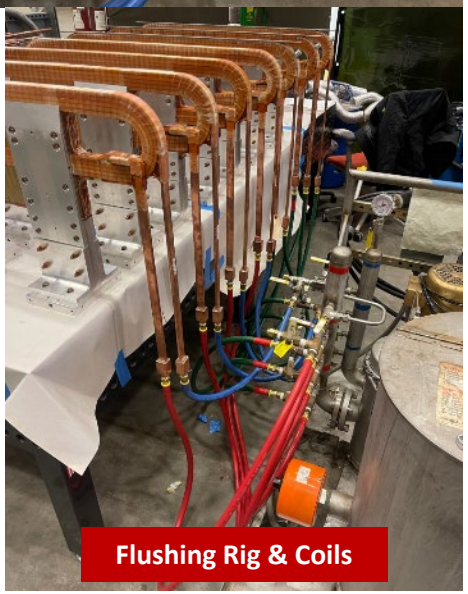
- Belly Plate and Tooling Ball Attachment Procedure
  - Parts cleaned then sand blasted on bonding surfaces
  - Strict pot-life limits being followed
  - Post curing epoxy strengthening at elevated temperatures being performed as recommended by epoxy vendor at 125 °F curing temperature (flushing rig)
  - Up to 7 coils can be heated simultaneously
  - Now with confidence in the EP33 epoxy, we have moved forward with epoxy work on belly plates and tooling balls
  - Risk Mitigation for Belly Plates now also includes spring loaded **Belly Plate Banding**





Flushing Rig



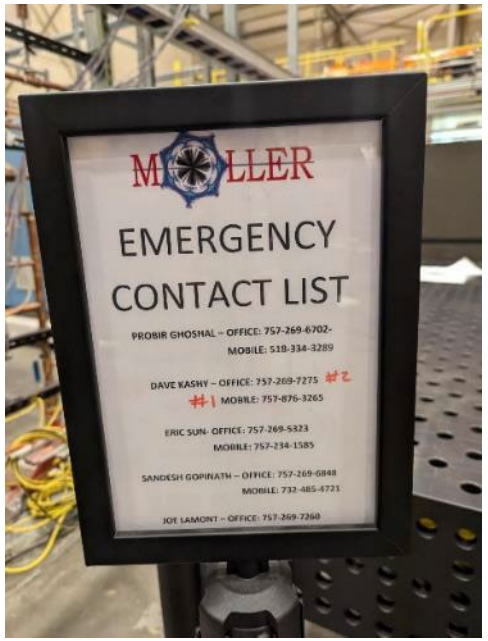


Flushing Rig & Coils

ES&H

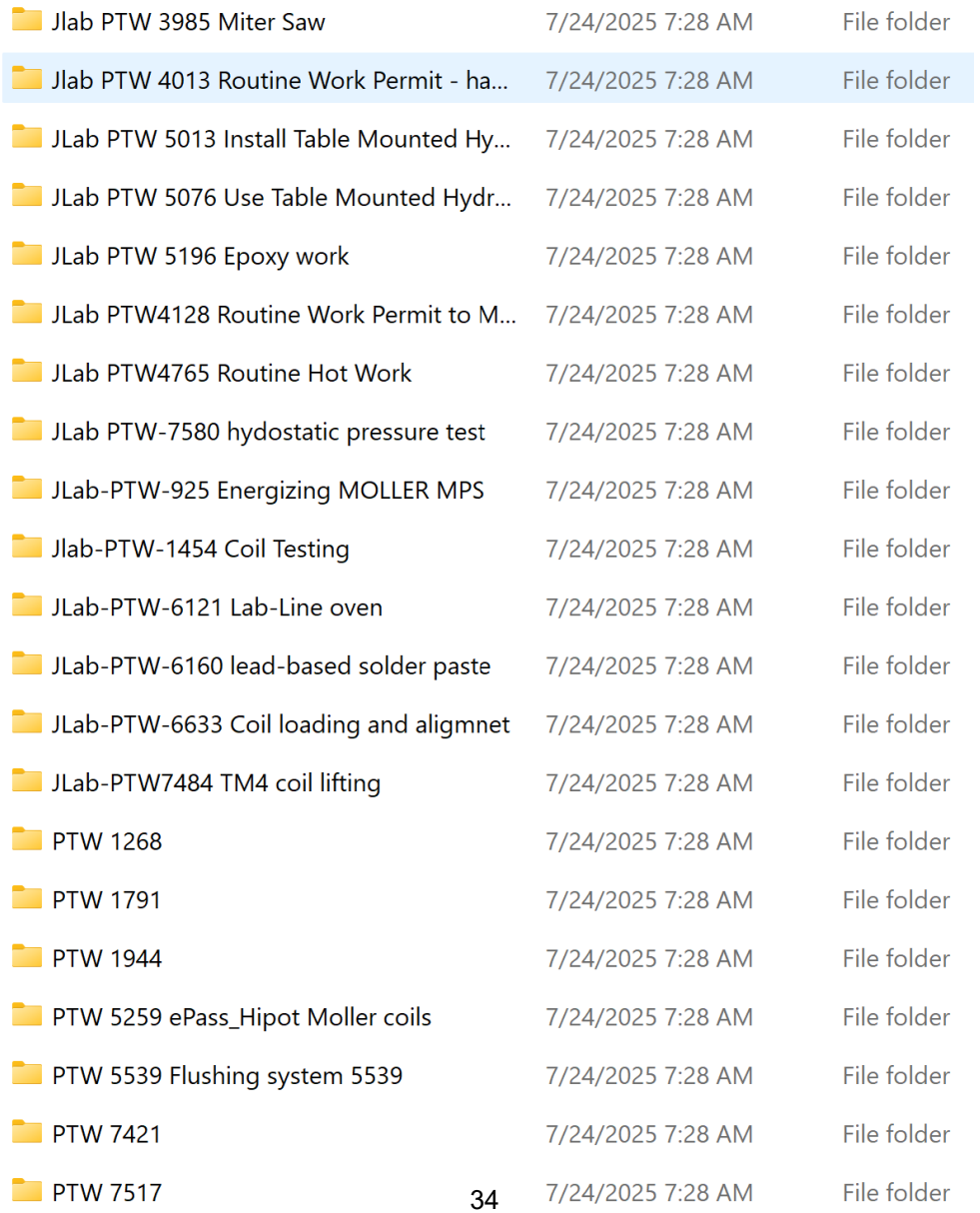
Spectrometer Overview - ES&H

- Daily whiteboard/toolbox meeting broad invitations:
  - Full MOLLER team
  - ES&H representatives
  - Division safety representatives
  - Others involved in MOLLER as needed
- Utilize the Management Safety Discussion Tool to document work.
- We work within the JLAB Integrated Safety Management (ISM) system
- Fully implement the Lab's ePAS policy.
  - HEPA and smoke vacuums are used where appropriate.
  - N95 masks are worn by respirator-qualified individuals when sanding composite materials.
  - Emergency Contact Lists are posted.
  - Work is performed by qualified personnel per JLab standards and, when appropriate our own procedures.
  - Trained engineers provide oversight and collaborate directly with technicians to ensure quality.
  - Trained individuals serve as fire watch staff.



ePAS

There is a total of 22 Current ePAS.



Jlab PTW 3985 Miter Saw	7/24/2025 7:28 AM	File folder
Jlab PTW 4013 Routine Work Permit - ha...	7/24/2025 7:28 AM	File folder
JLab PTW 5013 Install Table Mounted Hy...	7/24/2025 7:28 AM	File folder
JLab PTW 5076 Use Table Mounted Hydr...	7/24/2025 7:28 AM	File folder
JLab PTW 5196 Epoxy work	7/24/2025 7:28 AM	File folder
JLab PTW4128 Routine Work Permit to M...	7/24/2025 7:28 AM	File folder
JLab PTW4765 Routine Hot Work	7/24/2025 7:28 AM	File folder
JLab PTW-7580 hydostatic pressure test	7/24/2025 7:28 AM	File folder
JLab-PTW-925 Energizing MOLLER MPS	7/24/2025 7:28 AM	File folder
Jlab-PTW-1454 Coil Testing	7/24/2025 7:28 AM	File folder
JLab-PTW-6121 Lab-Line oven	7/24/2025 7:28 AM	File folder
JLab-PTW-6160 lead-based solder paste	7/24/2025 7:28 AM	File folder
JLab-PTW-6633 Coil loading and aligmnet	7/24/2025 7:28 AM	File folder
JLab-PTW7484 TM4 coil lifting	7/24/2025 7:28 AM	File folder
PTW 1268	7/24/2025 7:28 AM	File folder
PTW 1791	7/24/2025 7:28 AM	File folder
PTW 1944	7/24/2025 7:28 AM	File folder
PTW 5259 ePass_Hipot Moller coils	7/24/2025 7:28 AM	File folder
PTW 5539 Flushing system 5539	7/24/2025 7:28 AM	File folder
PTW 7421	7/24/2025 7:28 AM	File folder
PTW 7517	7/24/2025 7:28 AM	File folder

Rigging

- Lift plan created for TM4 coils
- Coil loading rigging was tested for TM1-3 coils
  - One ¼ ton come-along was used to lift and rotate the coils from horizontal to vertical
  - The original potting block, positioned at the coil nose, distributed the load

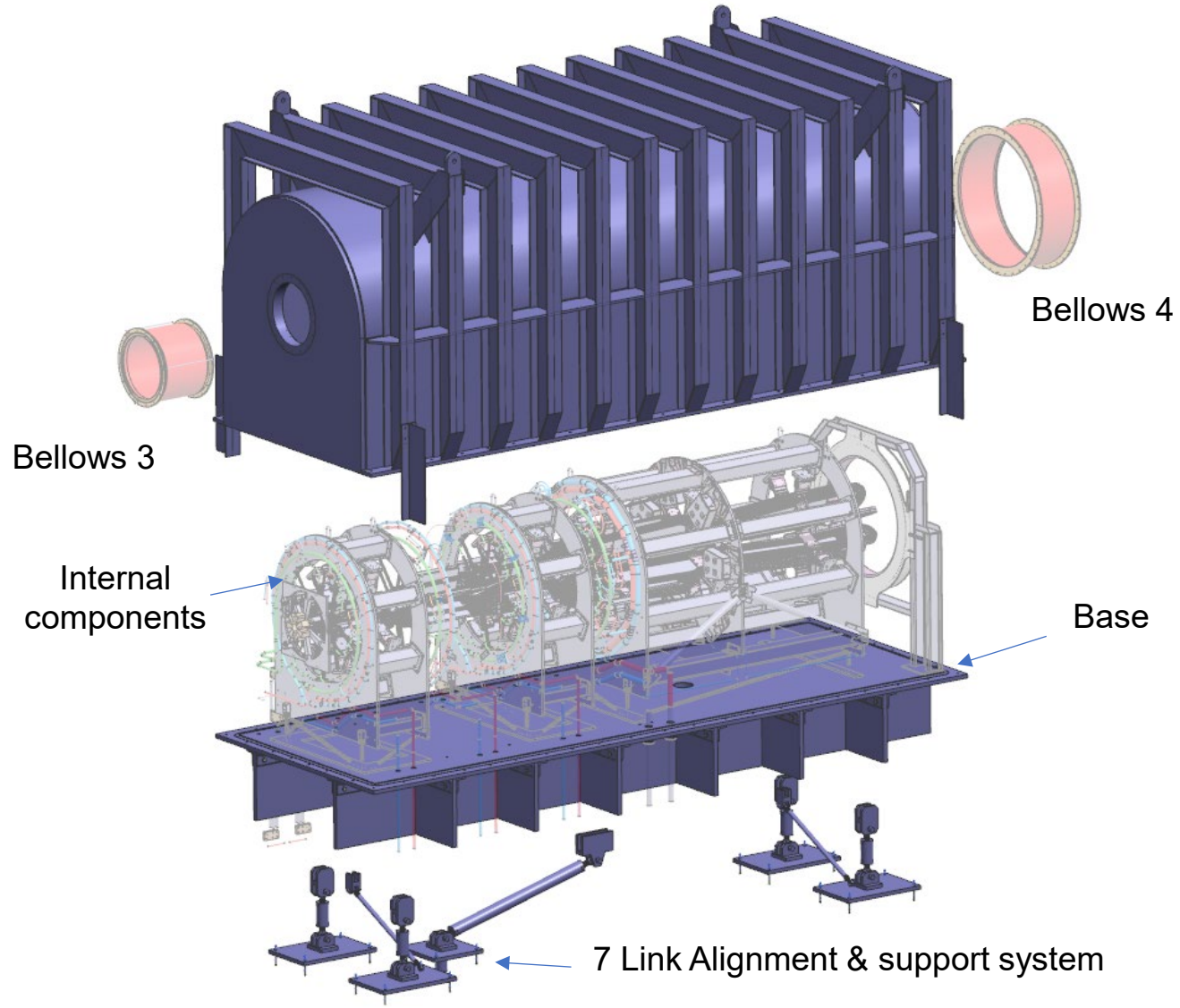
TM1 frame ready for loading

TM1 coil rigging test

Future

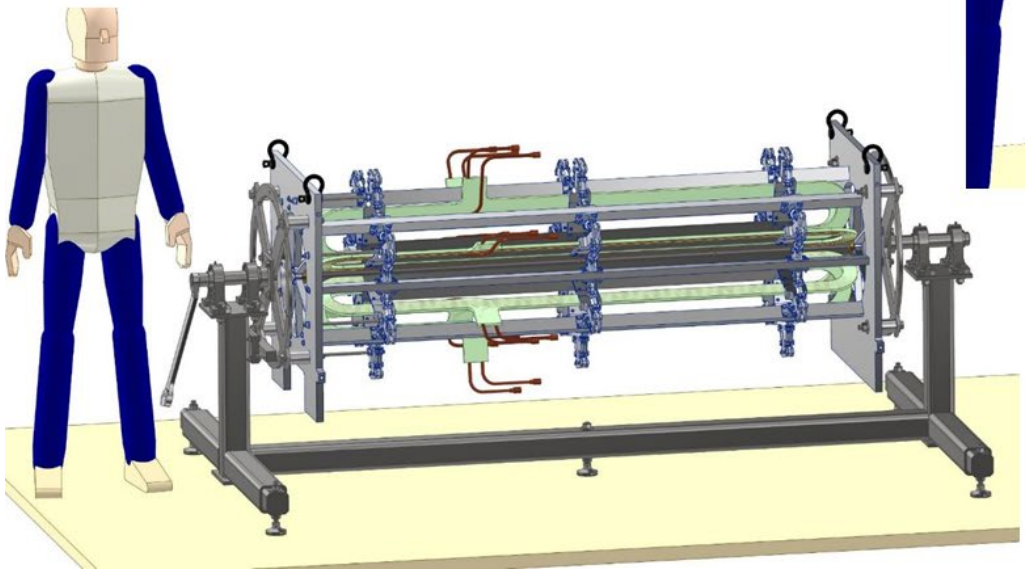
DS Spectrometer

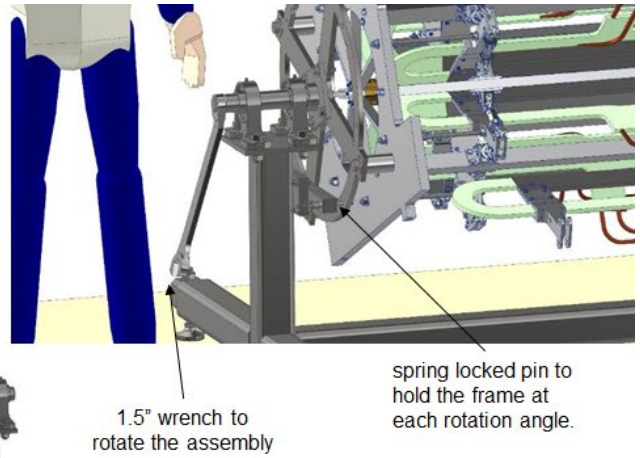
- Assemble TM4
- Power-up and magnet field mapping of DS Magnets
- Detector Window fabrication
- Receive and leak test DS Enclosure
- Load magnets onto DS Enclosure
- Braze water and electrical connections through DS Enclosure
- Complete grouting and anchor location drawings

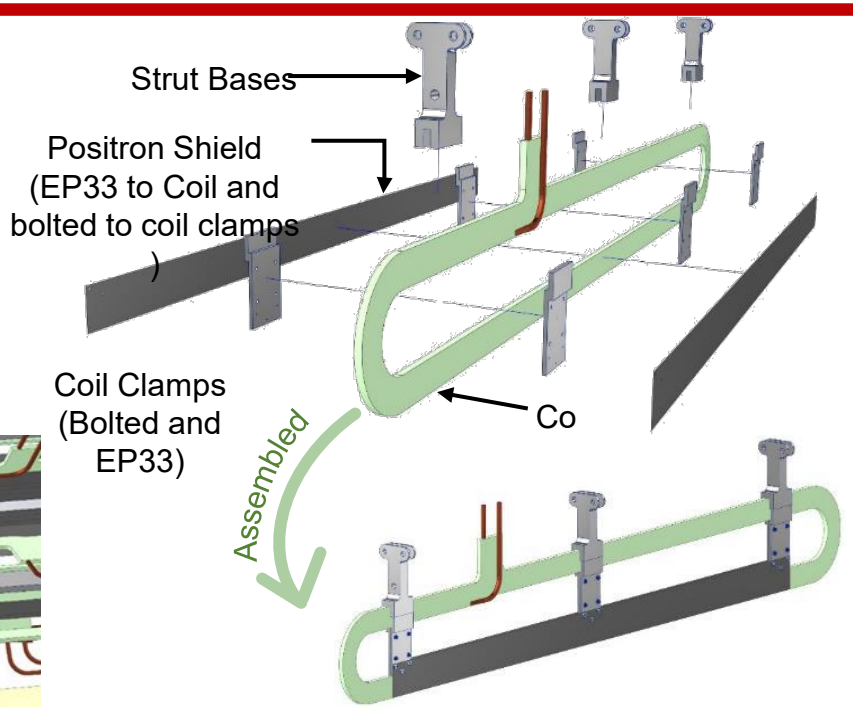


US Spectrometer

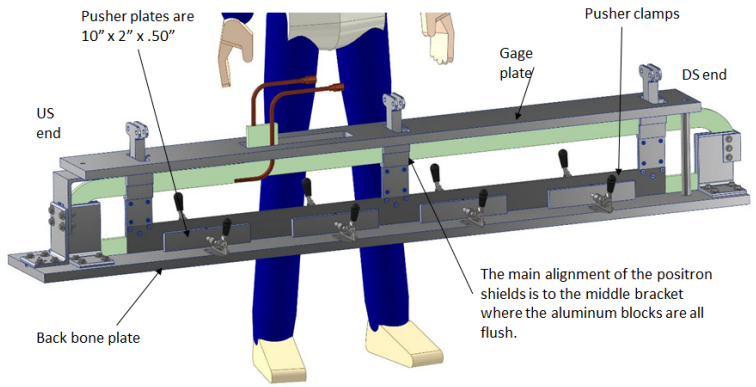
- Complete purchase orders placements
- Complete US Enclosure Design and procurement
- Create assembly procedure
- Create epoxy procedure







Assembled Coil Assembly



Survey and Alignment

- **Align TM4 coils**
- **Align Mapping equipment**
- **Survey DS enclosure**
- **Survey DS magnet on DS enclosure**
- **Survey US coil and magnet**
- **Survey US magnet, collimators on US enclosure**
- **Survey anchor location in the Hall**
- **Survey after final installation in the Hall**

What if…

Modes of failure.. and mitigations

- **Design**
  - Safety factor error (Components designed to code where applicable, calculations reviewed)
  - Errors in calculations (Calculations reviewed)
- **Fabrication**
  - Discrepancy in material quality (Material certificates required and magnetic permeability measurement)
  - Discrepancy in process (All welding, brazing, soldering documents are ASME-qualified. Components are examined, leak AND/OR pressure tested after fabrication. Procedure were developed.)
- **Assembly, Installation and handling**
  - Lift plans
  - Procedures and schematics
- **Measurement and monitoring**
  - Sensor failure (Redundant sensors to be installed, spare sensors available)
- **FMEA** completed for DS Spectrometer (See Probir's talk)

What If…

- **Considerations for loss of pressure or flow**
  - Pressure and flow head room available.
  - Magnet normal outlet temperature 51-58 degC depending on which TM#, additional head room up to 65 degC
- **Flow blockage**
  - Temperature and electrical interlocks in place
  - All MPSs will trip together
- **Low vacuum**
  - 0.01 Torr is the requirement, pumping designed to create 0.001 Torr.
  - Additional pumps procured
  - Additional pumping ports available to connect more pumps if required
- **EP33 failure**
  - EP33 samples were tested and procedures developed
  - Belly plate bands on DS coils implemented (secondary/redundant)
  - US coil – 2 Bound Shield will be thermally tested before installation

Summary

- **All Components were designed to applicable codes (ASME VIII Division 1, ASME B31.9, and JLab E&SH)**
- **All piping and vacuum components have material certificates.**
- **Receipt inspections were performed.**
- **All received components were tested according to applicable codes**
  - TM1, TM2, TM3 were hydrostatically tested to 390 psi per ASME B31.9
  - All vacuum components were tested under vacuum
- **Magnet piping were designed, examined and tested according to AMSE B31.9.**

THANK YOU FOR YOUR ATTENTION AND PARTICIPATING IN THIS ERR