LQXFA/B Cryo-assembly Test

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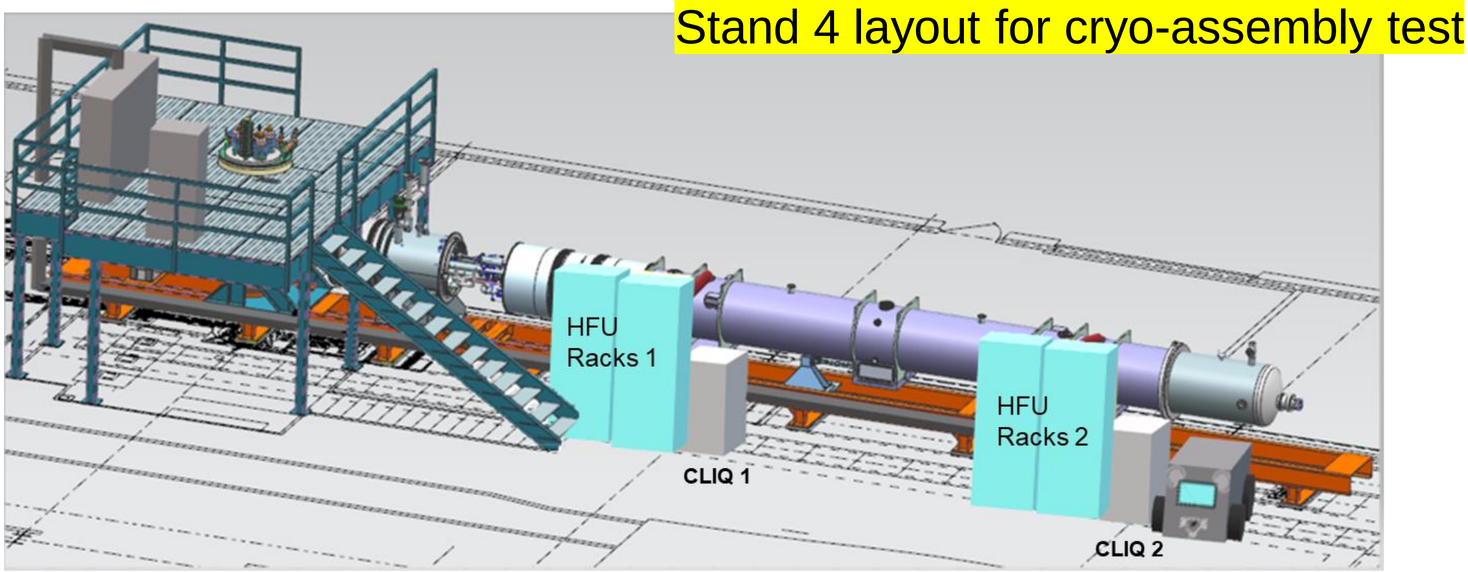
Horizontal Test Facility at Fermilab

- The only test facility in the USA capable to test the HL-LHC AUP Q1/Q3 cryo-assemblies
  - Previously used for testing the present LHC inner triplet quadrupoles at Fermilab in 2001-2006

- Project scope includes horizontal test of 12 cryo-assemblies - 2 pre-series, 8 series production and 2 re-works
  - First pre-series cryo-assembly test is expected to start in March 2022

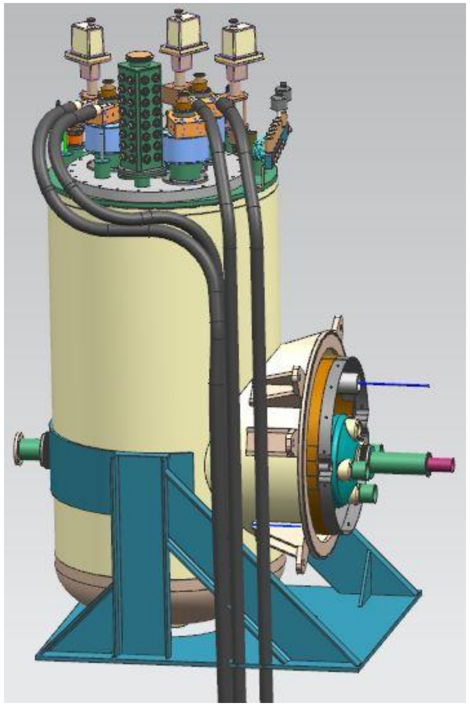


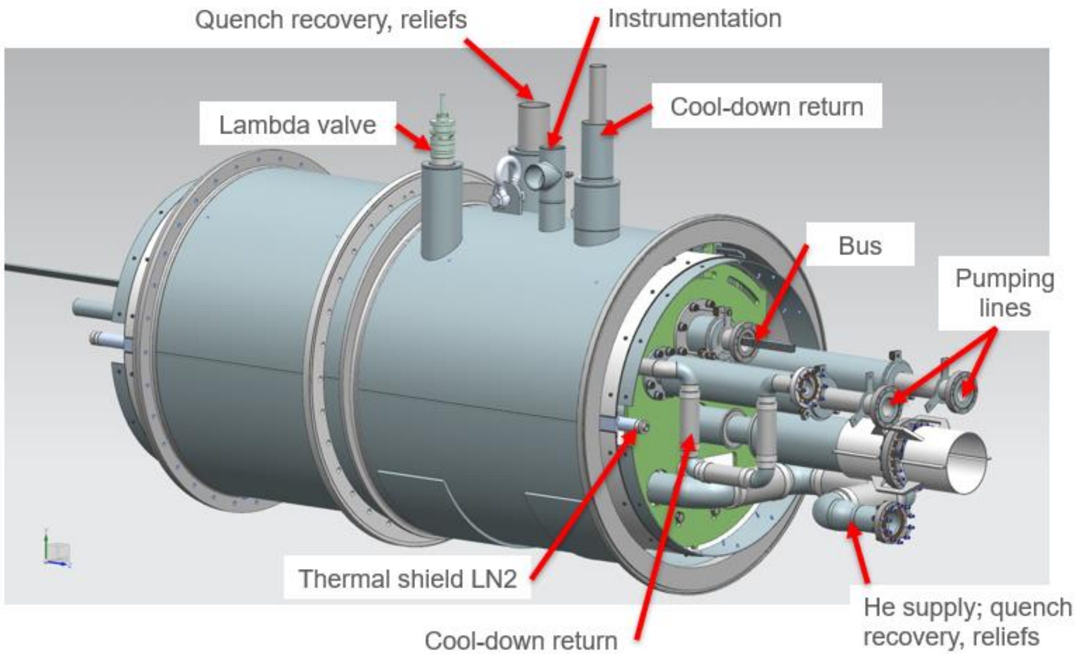
Horizontal Test Stand (Stand 4) Upgrades

- Major Stand 4 upgrades were completed and then successfully commissioned during the zero-magnet test in Oct-Dec 2020
  - Cryogenic Feed-Box/End-Box modifications
  - Design and fabrication of the Adapter Box between the Feed-box and the cryo-assembly
  - Cryo-assembly supports, lifting fixture
  - Interconnects, vacuum adapters
  - Controlled cool-down/warm-up system, new external cryogenic lines
  - Power bus refurbishment, new water-cooled flexible power leads
- Warm-finger (anti-cryostat) assembly with 100 mm inner diameter
- Process Controls upgrade at the horizontal test stand
- Quench Protection and Monitoring Systems
- Development and assembly of magnetic measurement systems

Major Cryo-mechanical Upgrades

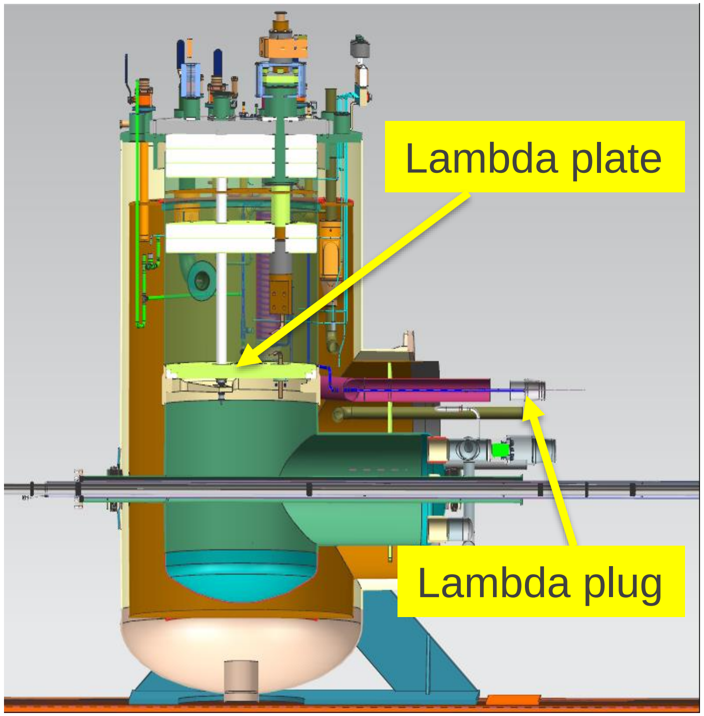
- Important addition to the stand - new Adapter Box designed and built as an interface between the existing cryogenic feed box and the new cryo-assemblies
  - Making use of old components, including the feed box, the feedbox insert (Top plate), vapor-cooled power flags





New location of the Lambda plug

- Separation between the 4.5 K and 1.9 K temperature levels moved from the Feed box to the Adapter box
  - A proven CERN lambda plug design was modified for the Horizontal test stand
- Shorter pump-down times and less liquid helium usage
- We can reproduce LHC tunnel conditions after quench
  - High Pressure up to 17 bar



- Lesson learned from testing old LHC magnets - due to limited maximum test pressure (~4.5 bar) some cryo-assembly components failed at CERN under higher pressure test

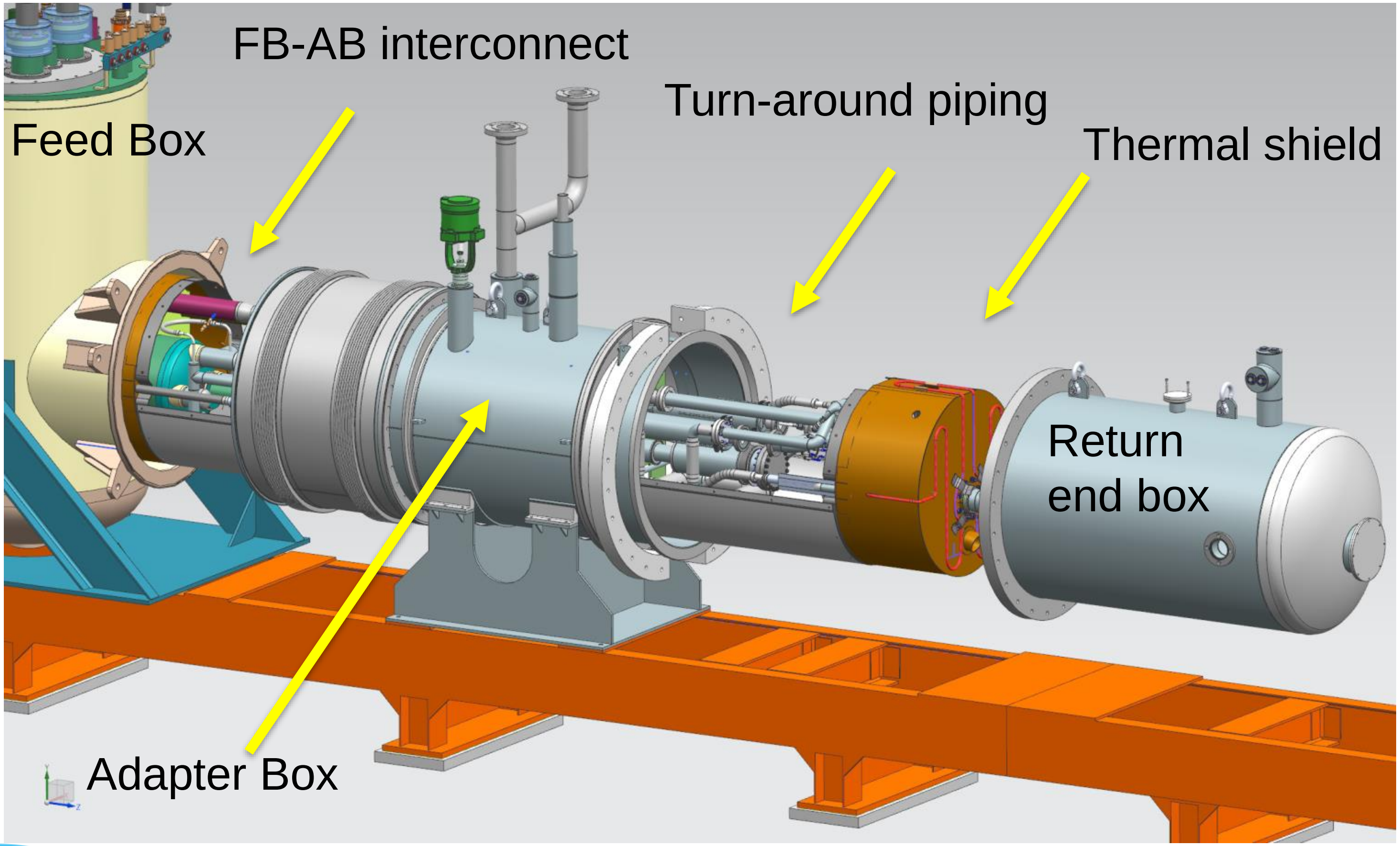
Controlled cooldown

- Maximum temperature difference between the ends of the cold mass must not exceed 50 K

- Controlled cooldown is accomplished in two stages: for temperatures above and below 80 K
  - For 300 K to 80 K cooldown, helium gas is cooled in a liquid nitrogen bath and then mixed with the 300 K helium
  - For further cooldown, 80 K helium gas is mixed with 4.5 K liquid helium

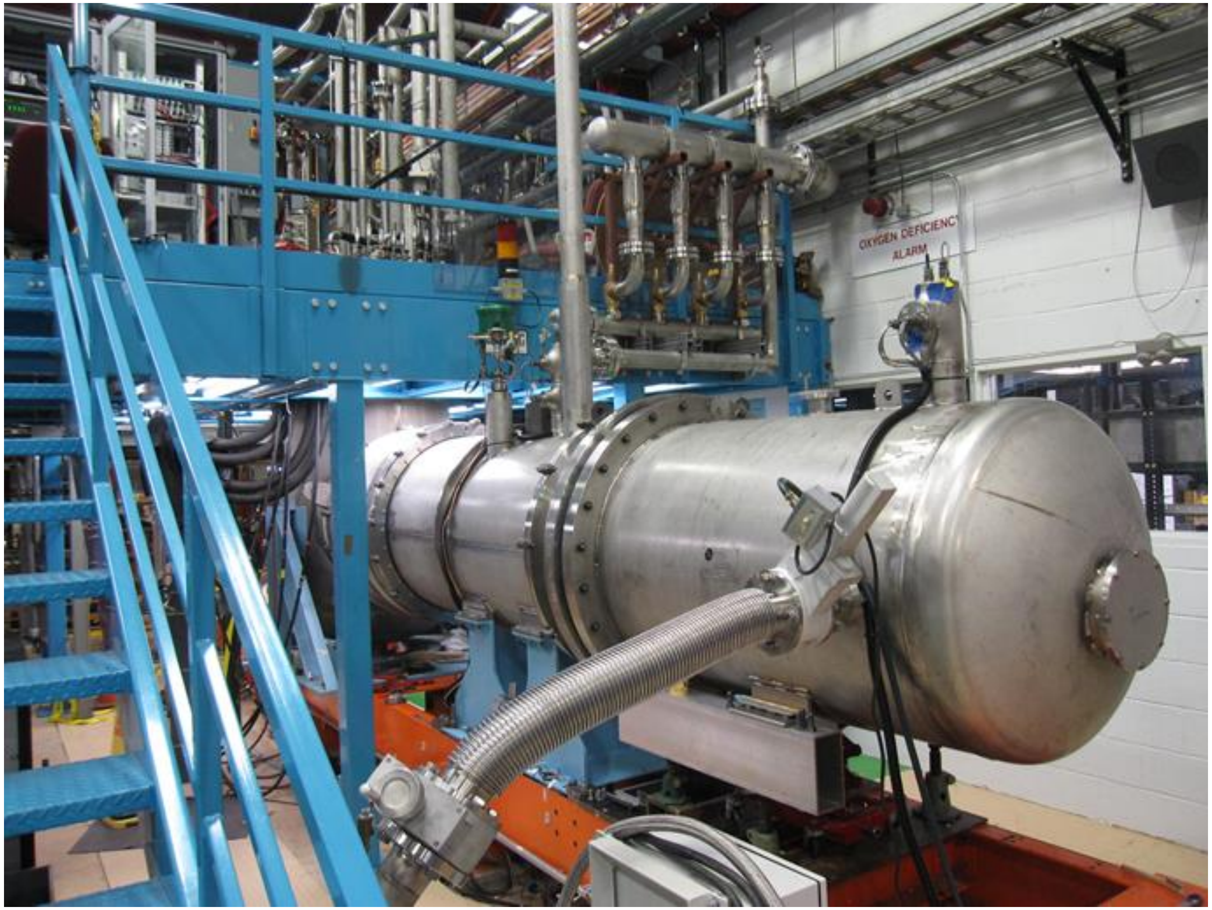
Zero-magnet test configuration

- Most upgrades have been installed at the Horizontal test stand and successfully verified during the zero-magnet (shorted bus) test in Oct-Dec 2020



Zero-Magnet Test

- Zero magnet test was a critical milestone for the Horizontal Test Stand Upgrade Project



Zero-magnet Test Results

- Functionality of the upgraded systems were successfully verified
  - New transfer lines, U-tubes
  - New adapter box, Feedbox to Adapter box Interconnects
  - Insulating vacuum
  - Cooldown and safe operation (including new lambda plug) at high pressure (17 bar)
  - High Voltage Withstand Levels passed at room and cryogenic temperatures (300 K, 4.5 K and 100 K)

- Controlled cooldown and warmup procedures verified

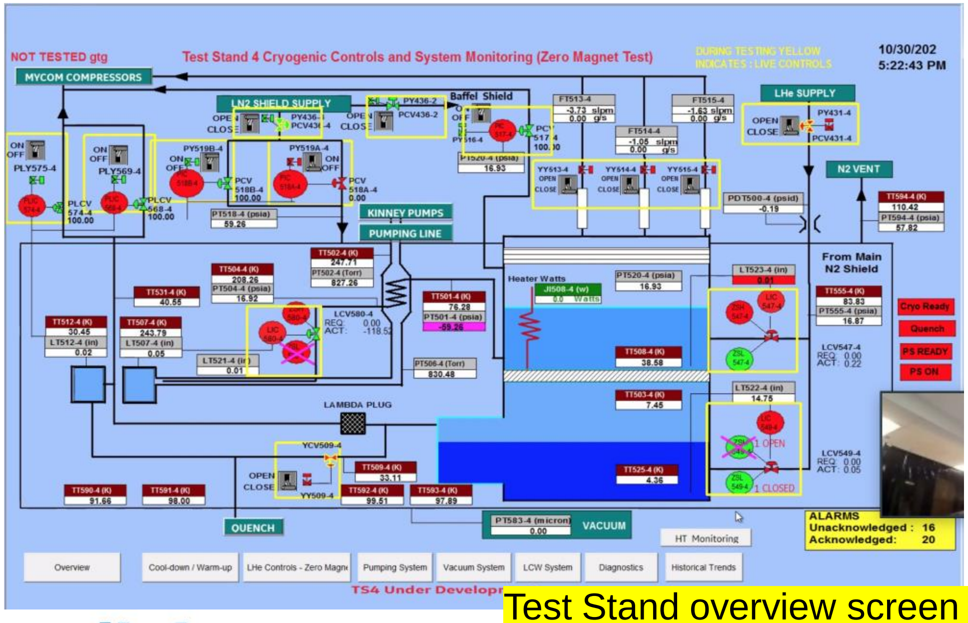
- Main vapor-cooled power leads verified up to 18.5 kA
  - The middle power lead achieved 17.6 kA which is sufficient for training individual magnets up to the ultimate current

- New Quench Protection and Monitoring Systems

Zero-magnet Test Results (2)

- New Process Controls system was successfully used during the zero-magnet test
  - Additional automation capabilities were added
  - Control loops for feed box liquid helium level, return end liquid helium level, feed box pressure control, and thermal shield pressure control were tuned

- It was the first for many years successful cooldown at Stand 4



Test Stand overview screen – zero-magnet test

Quench Protection and Monitoring

- Full commissioning of the QPM system

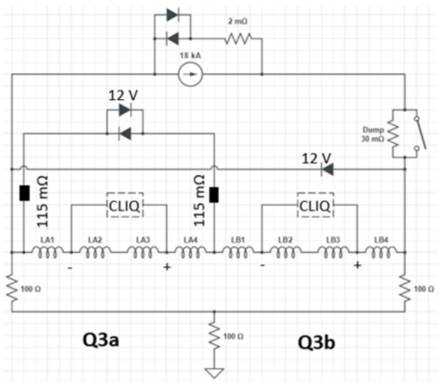
CERN HFU and CLIQ
In Zero-magnet test

- Real quench was successfully detected

Quench monitoring GUI

LQXFA quench simulations

- Peak voltage-to-ground calculated during a LQXFA quench at Stand 4
  - Simulations performed using the STEAM (CERN) framework, as well as LEDET and PSPICE software (V. Marinozzi with E. Ravaioli's help)
  - CLIQ failures simulated for various protection scheme



- Extra warm diodes are required to protect magnets in case of a single CLIQ failure
- No dump operation is recommended

1. No Dump, No CLIQ failures, 12 V bypass diodes on Q3a
2. No Dump, Q3a CLIQ failure, 12 V bypass diodes on Q3a

2b. No Dump, Q3a CLIQ failure, 12 V bypass diodes on Q3a (Q3a didode resistance is 200 mOhm instead than 115 mOhm)

3. No Dump, No CLIQ failure, no diodes on Q3a
4. No Dump, Q3a CLIQ failure, no diodes on Q3a
5. 30 mΩ Dump, No CLIQ failures, 12 V bypass diodes on Q3a
6. 30 mΩ Dump, Q3a CLIQ failure, 12 V bypass diodes on Q3a
7. 30 mΩ Dump, No CLIQ failure, no diodes on Q3a
8. 30 mΩ Dump, Q3a CLIQ failure, no diodes on Q3a
9. 2.5 mΩ Dump, No CLIQ failures, 12 V bypass diodes on Q3a

14. No Dump, Q3a CLIQ failure, no diodes on Q3a, magnet midpoint grounded

18. 30 mΩ Dump, Q3a CLIQ failure, no diodes on Q3a, magnet midpoint grounded

25. 15 mΩ Dump, No CLIQ failures, 12 V bypass diodes on Q3a

26. 15 mΩ Dump, Q3a CLIQ failure, 12 V bypass diodes on Q3a

35. 30 mΩ Dump, No CLIQ failures, 12 V bypass diodes on Q3a, 10 ms dump delay

36. 30 mΩ Dump, Q3a CLIQ failure, 12 V bypass diodes on Q3a, 10 ms dump delay

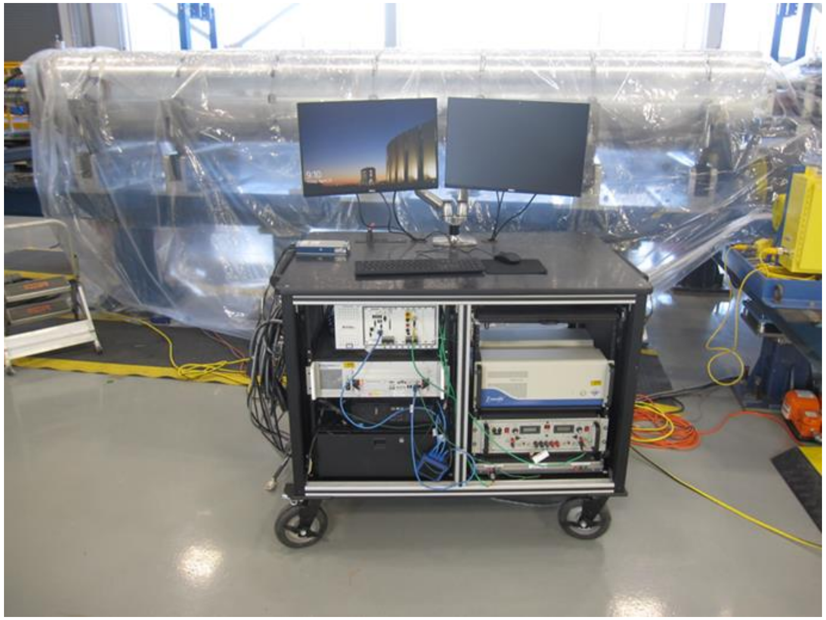
Vittorio Marinozzi

	CASE	Peak Q3a Magnet Voltage To-ground [V]	Peak Q3b Magnet Voltage To-ground [V]	Peak magnet midpoint voltage To-Ground [V]	Peak Q3a diodes current [A]	Peak current to-ground [A]	Hot Spot Temperature [K] (a/b)	Energy dissipated into dump resistor* [%]
No Dump	1	459	459	100	$26\cdot10^{-3}$	$0.6\cdot10^{-6}$	233/233	N/A
	2	434	481	300	1200	$0.25\cdot10^{-6}$	279/246	N/A
	2b	435	480	300	1100	$0.25\cdot10^{-6}$	279/246	N/A
	3	459	459	100	N/A	$0.6\cdot10^{-6}$	233/233	N/A
	4	1238	1227	1238	N/A	$0.25\cdot10^{-6}$	263/271	N/A
30 mΩ	5	764	462	462	500	$0.4\cdot10^{-6}$	215/229	6.94
	6	671	466	671	700	$0.3\cdot10^{-6}$	239/241	
	7	1042	768	768	N/A	$0.5\cdot10^{-6}$	231/239	
	8	1744	1240	1240	N/A	$0.2\cdot10^{-6}$	237/250	
2.5 mΩ	9	480	460	120	0.1	$0.6\cdot10^{-6}$	231/232	
As 4	14	1044	1033	1044	N/A	$0.35\cdot10^{-6}$	263/271	
As 8	18	1512	1009	1500	N/A	$0.4\cdot10^{-6}$	237/250	
15 mΩ	25	612	463	230	270	$0.4\cdot10^{-6}$	224/232	3.58
	26	444	468	444	900	$0.35\cdot10^{-6}$	258/244	
30 mΩ 10 ms	35	515	459	459	440	$0.4\cdot10^{-6}$	223/233	6.37
	36	703	467	250	800	$0.3\cdot10^{-6}$	247/243	

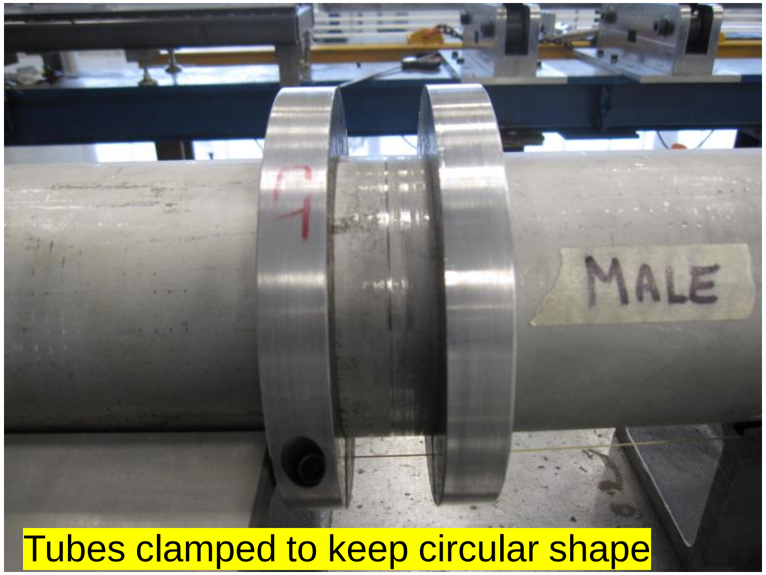
Magnetic measurement systems

- Rotating coil and Single Stretched Wire Systems will be used for alignment, field strength and harmonics measurements

- Two identical SSW systems are assembled and ready for operation
  - SSW1 successfully used in the first pre-series cold-mass measurements
  - SSW2 has been comprehensively tested and cross-checked

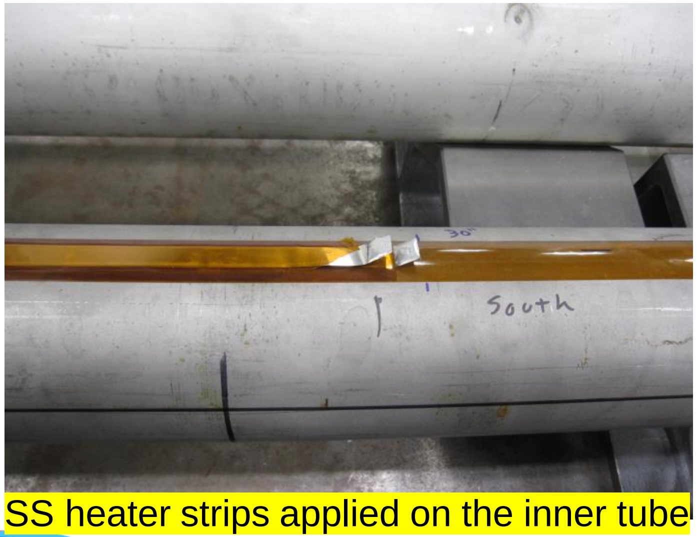


Warm finger assembly



Tubes clamped to keep circular shape

Leak check after welding



SS heater strips applied on the inner tube

MLI applied to the inner tube

Warm finger assembly (2)

- Warm fingers assembly tested at Stand 4 with the upgraded probe drive system
  - Laser tracker used for precise location of the magnetic measurement probe

Probe drive cart and the shaft

WF with the measurement probe inside

Pre-series Cryo-assembly Test Preparation

- Upgrade of some components was completed after Zero-magnet test
- Quench recovery line assembly
- LCW (cooling water) system re-work at Stand 4 significantly improved cooling of the flexible power leads
- Quench Protection and Monitoring System for the production test
  - More DQD and AQD channels for the magnet test
  - Production Quench Monitoring System (Tier-III)
  - Upgraded current control and FO readout systems
  - Active Ground Fault System
- Reusable piping spools for cryo-assemblies
  - These components are required for Horizontal Test at Fermilab and will be removed before sending cryo-assembly to CERN

New Coldbox

- New liquefier will increase total LHe make rate to 600 ltr./hour and total liquid storage volume to 14,000 ltr.
  - Current cooling capacity: CTI-1500 liquefier with liquefaction rate up to 300 ltr./hour and 10,000 ltr. storage dewar
  - New liquefier is expected fully functional next spring

Other Off-project Improvements

- Various improvements have been made to improve overall reliability of the cryo-plant and power system at Fermilab's Magnet Test Facility
  - Full stream purification system helps to control contamination level
  - Four 30,000-Gal tanks were added to the existing six buffer tanks for storage of helium gas
  - Mycom Compressors added to the Warm Compressor System
- Combination of higher liquefaction and LHe storage capacities will significantly increase throughput in magnet and SRF cavity testing
  - Practically no downtime due to cryo-plant maintenance
- Existing 30 kA power system will be used for Q1/Q3 cryo-assemblies horizontal test
  - All water hoses and fittings were replaced recently
  - Dump switch charging circuits upgraded
  - Additional LOTO test points implemented

Cryo-assembly Test Plan & Documentation

- Documents of four different types will be under revision control
  - Test Plan
  - Test Procedures
  - Test parameters, conditions and results
  - Test checklist
- Every cryo-assembly will have a separately approved Test Plan
  - Describes most of the steps to be executed in detail
  - Essential parameters are explicitly written in the plan
- Test procedures describe various tests and equipment setup to be executed prior or during the test
  - More general documents without specifying test values
- Test parameters, conditions and results are consolidated in a single Excel spreadsheet
  - Describes all the test parameters required in Test Procedures, as well as detailed test conditions and results

Cryo-assembly Test Plan & Documentation (2)

- Test checklist
  - Guides the test step-by-step
  - Sign off is required for critical steps
  - Simplified Traveler
- Cryo-assembly Test plan is drafted
  - Full thermal cycle is planned for the pre-series cryo-assemblies and for the last two cryo-assemblies with magnets trained at Fermilab
- Magnetic measurement plan development still in progress
- Most of the test procedures were developed and successfully used during Zero-magnet test
  - Minor modifications are required for the cryo-assembly test
- Test reports will be generated for each cryo-assembly

Summary

- Functionality of the upgraded Horizontal Test Stand components were successfully verified during Zero-magnet test in Oct-Dec 2020
  - Quench recovery and 1.9 K cooldown of magnets will be verified only during the pre-series cryo-assembly test
- New Process controls system was successfully tested
  - Few more instrumentation will be added for the pre-series cryo-assembly test: the magnet and warm finger temperature sensors, quench line pressure and temperature sensors
- Quench Protection and Monitoring system for the production cryo-assembly is under integration tests
- Commissioning of SSW systems is complete, Rotating coil measurement system integration tests will be carried out in Oct-Nov
- Need to obtain Operation Readiness Clearance for the production cryo-assembly test
- Production test preparations are close to completion