Cryogenics for the MuCool Test Area (MTA)

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COOL'05 – Galena, IL

Headlines

Scope

Helium Facility

Hydrogen Facility

Applications

1) Past: Convection LH_2 absorber

2) Present: SC Solenoid magnet

3) Future: Forced-flow LH_2 absorber, (Convection run 2)

Cryogenic Department

Cryogenic Cooling for Ionization Cooling

The MTA is a Fermilab test facility constructed to support new developments in the physics and engineering of muon beam cooling

MTA cryo-engineering requirements

- Design, prototype and bench test cooling-channel components
  - Provide helium and nitrogen refrigeration
  - Provide liquid hydrogen
  - Install equipment, instrumentation, DAQ & control in compliance with Fermilab safety policy (ES&H)

Previous US H_2 experiments : E158, SAMPLE, G0, Fermilab hydrogen experts

Important reference and guideline

FERMILAB: " Guidelines for the Design, Fabrication, Testing, Installation and Operation of LH_2 Targets – 20 May 1997" by Del Allspach et al. Fermilab RD_ESH_010– 20 May 1997

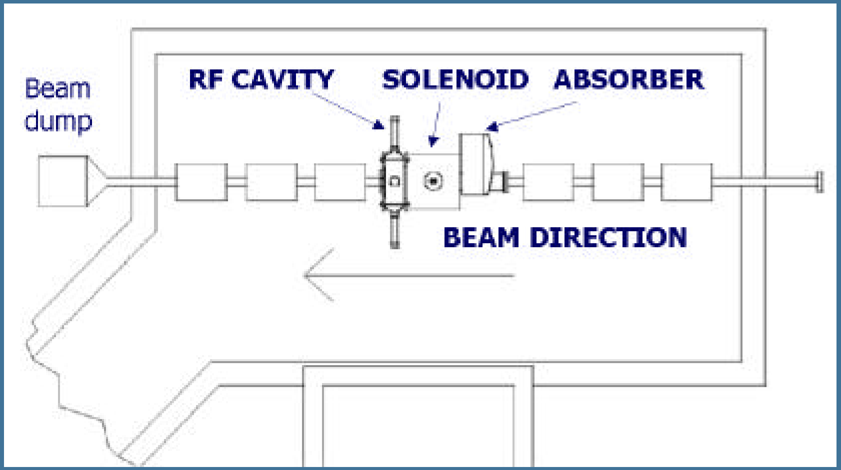
NASA: " SAFETY STANDARD FOR HYDROGEN AND HYDROGEN SYSTEMS: Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage, and Transportation"

Cryogenic Cooling for Ionization Cooling

Applications

- LH_2 Absorbers:
    - Convection scheme (<100W?) - MICE design
    - Forced-flow scheme (up to 300W) - MuCool design
- S.C. solenoid magnet for RF cavity test (long term: LH_2 absorber)
- Other applications using HP gaseous hydrogen : Muon Inc.

Proposed cooling channel test bench



Ionization & Cryogenic Materials

Material	Z	A	$\langle Z/A \rangle$	Nuclear[a] collision length λ_T {g/cm^2}	Nuclear[a] interaction length λ_I {g/cm^2}	$dE/dx\|_{min}$[b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length[c] X_0 {g/cm^2}	{cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n ($(n-1)\times10^6$ for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28[d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28[d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265[e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—

$$\frac{de_n}{ds} = -\frac{1}{b^2}\frac{dE_m}{ds}\frac{e_n}{E_m} + \frac{1}{b^3}\frac{b_\perp (0.014)^2}{2E_m m_m L_R}$$

$$\frac{dE}{dx} a \frac{Z}{A} \qquad \frac{1}{L_R} a Z^2$$

Ionization cooling

Bethe-Bloch multiple scattering

Cryogenic Properties of Various Gasses

M. Green: "Hydrogen Safety Issues compared to Safety Issues with Methane and Propane", CEC'05

Parameter	He	N_2	H_2	CH_4	C_3H_8
Triple point temperature T_t (K)	2.177^	63.15	13.81*	90.69	91.46
Heat of fusion @ T_t (J g^{-1})	-NA-	25.3	59.5*	58.41	79.97
Boiling temp. T_b @ 1 bar (K)	4.222	77.35	20.28*	111.67	230.46
Liquid density ρ_l @ T_b (kg m^{-3})	124.9	807	70.8*	422.4	585.3
Gas density ρ_g @ T_b (kg m^{-3})	16.89	4.622	1.339*	1.816	2.497
Gas to liquid volume ratio at T_b	7.395	175.6	52.87*	232.6	298.0
Gas V_{293} to Liquid V_b Ratio	699.4	645.6	792.9	591.4	379.0
Gas C_p @ T_b (J g^{-1} K^{-1})	9.144	1.341	12.24*	2.218	1.642
Heat of vaporization @ T_b (J g^{-1})	20.7	198.8	445*	510.8	424.8
Heat flux for ΔT=300-T_b (kWm^{-2})	~200	~27	~93	~47	-NA-
Broken vacuum heat flux (kWm^{-2})	~35	~1.6	~19	~0.31	-NA-
Critical temperature T_c (K)	5.195	126.2	32.98	190.6	368.8
Critical pressure P_c (MPa)	0.228	3.39	1.29	4.59	4.36

^ The lambda point temperature for helium. For helium liquid, gas, and solid can't coexist.
* This data is for para hydrogen. Ortho hydrogen changes to para hydrogen at < 100 K.

CEC 30 August 2005 Paper C1-J-03 2

Ionization & Cryogenic Materials

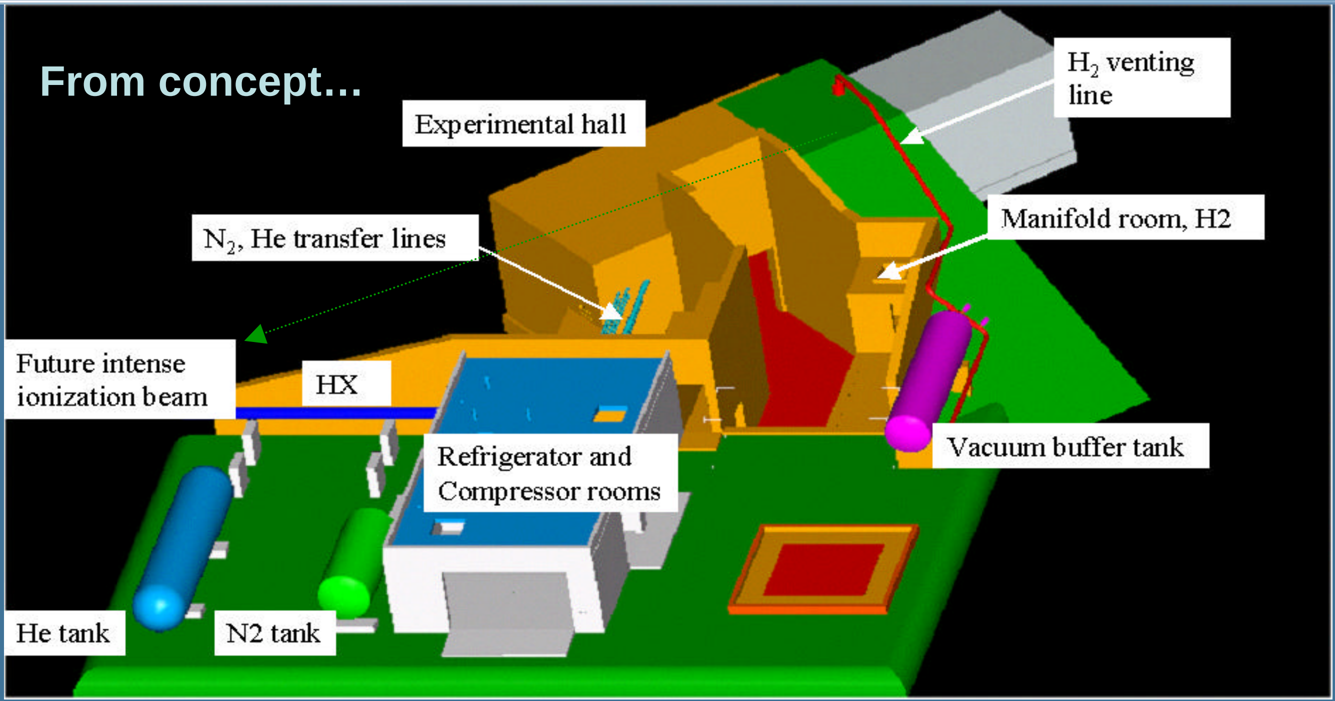
Source: NASA, Glenn Research Center Safety Manual

Properties of gaseous (normal) hydrogen are as follows:

Reference temperature	68°F	527.7° R	293.1° K
Standard pressure (1 atm) psia	14.69 kPa	101.325 abs	
Density (at 527.7° R & 1 atm)	.00523 lb/ft^3	83.7 g/m^3	
Specific Volume (at 527.7° R & 1 atm)	191.4 ft^3/lb	0.0119 m^3/g	
Specific Heat	Cp= 3.425 Btu/lb-R Cv= 2.419 Btu/lb-R	Cp= 14.33 J/g-k Cv= 10.12 J/g-k	
Velocity of Sound	4246 ft/sec	1294 m/sec	
Heat of Combustion	Low = 51596 Btu/lb High = 61031Btu/lb	Low= 119.93 kJ/g High= 141.86 kJ/g	
Flammability limits Hydrogen-air mixture Hydrogen-oxygen mixture	Lower= 4.0 % volume Lower= 4.0 % volume	Upper= 75 % volume Upper= 95 % volume	
Explosive limits Hydrogen-air mixture Hydrogen-oxygen mixture	Lower= 18.3 % volume Lower= 15.0 % volume	Upper= 59 % volume Upper= 90 % volume	
Minimum spark ignition energy at 1 atm			
In air	1.9 x 10^{-8} Btu	0.02 mJ	
In Oxygen	6.6 x 10^{-9} Btu	0.007 mJ	

Parameter	H_2	CH_4	C_3H_8
Flammability limits in air (%)	4.0 - 74.2	5.0 – 15.0	2.1 – 9.4
Ignition temperature in air (K)	~855	~925	~770
Ignition energy @ STP (J/cc)	~0.74	~0.97	~0.76
Stoichiometric flame temperature in air (K)	~2580	~2340	~2390
Heat of combustion (kJ g $^{-1}$)	135.4	52.8	40.3
Liquid heat of combustion (MJ per liter)	9.59	22.29	23.56
Gas heat of combustion (MJ m $^{-3}$ @ STP)	12.09	37.70	93.48
Temp when gas is heavier than RT air (K)	~21	~162	~444

Cryogenic Systems for MTA Solenoid Magnet



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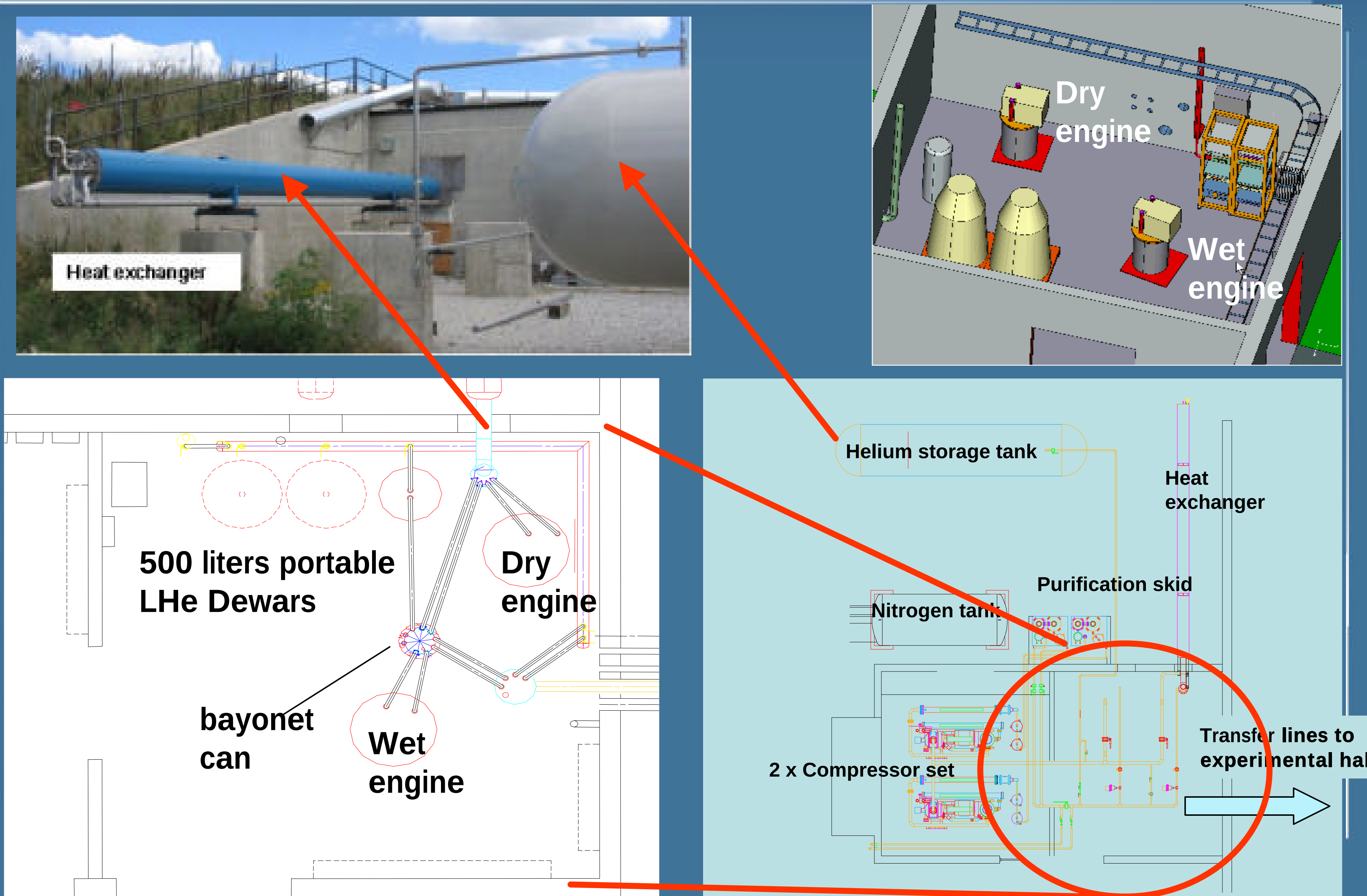
Tevatron-style Satellite Refrigerator



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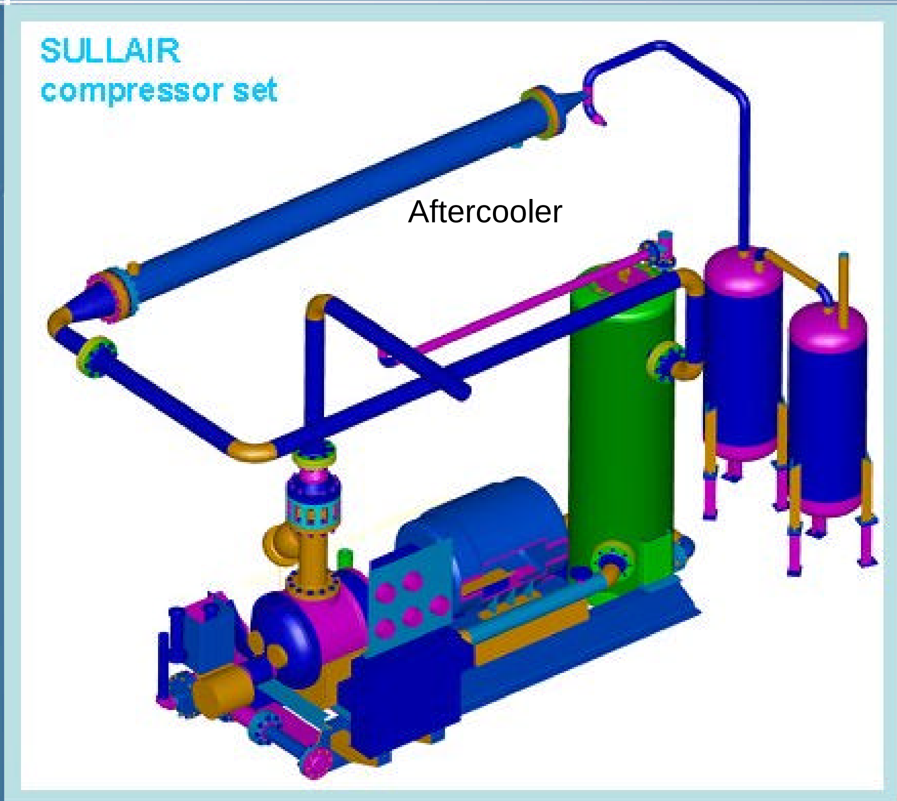
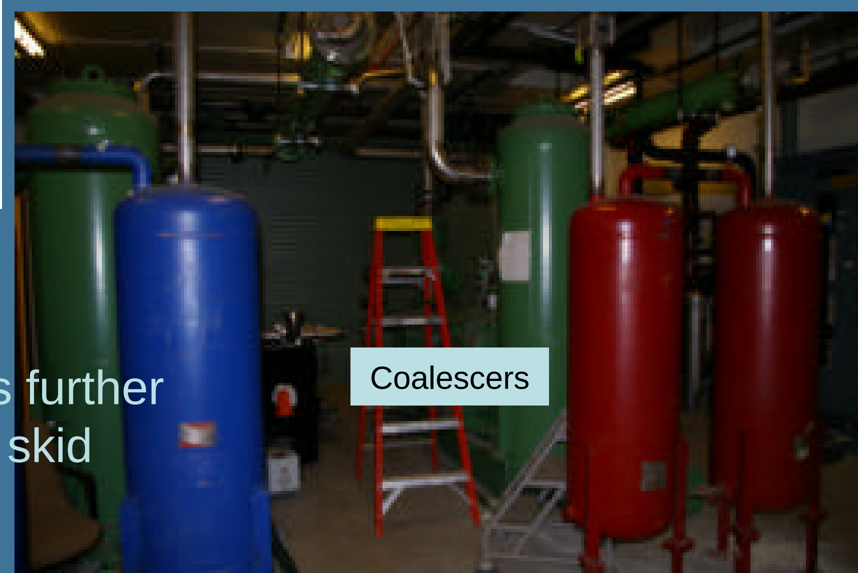
Installation of 300 KW Screw Compressors





Oil vapor contamination from helium gas is further removed through the outdoors purification skid

Refrigeration Modes

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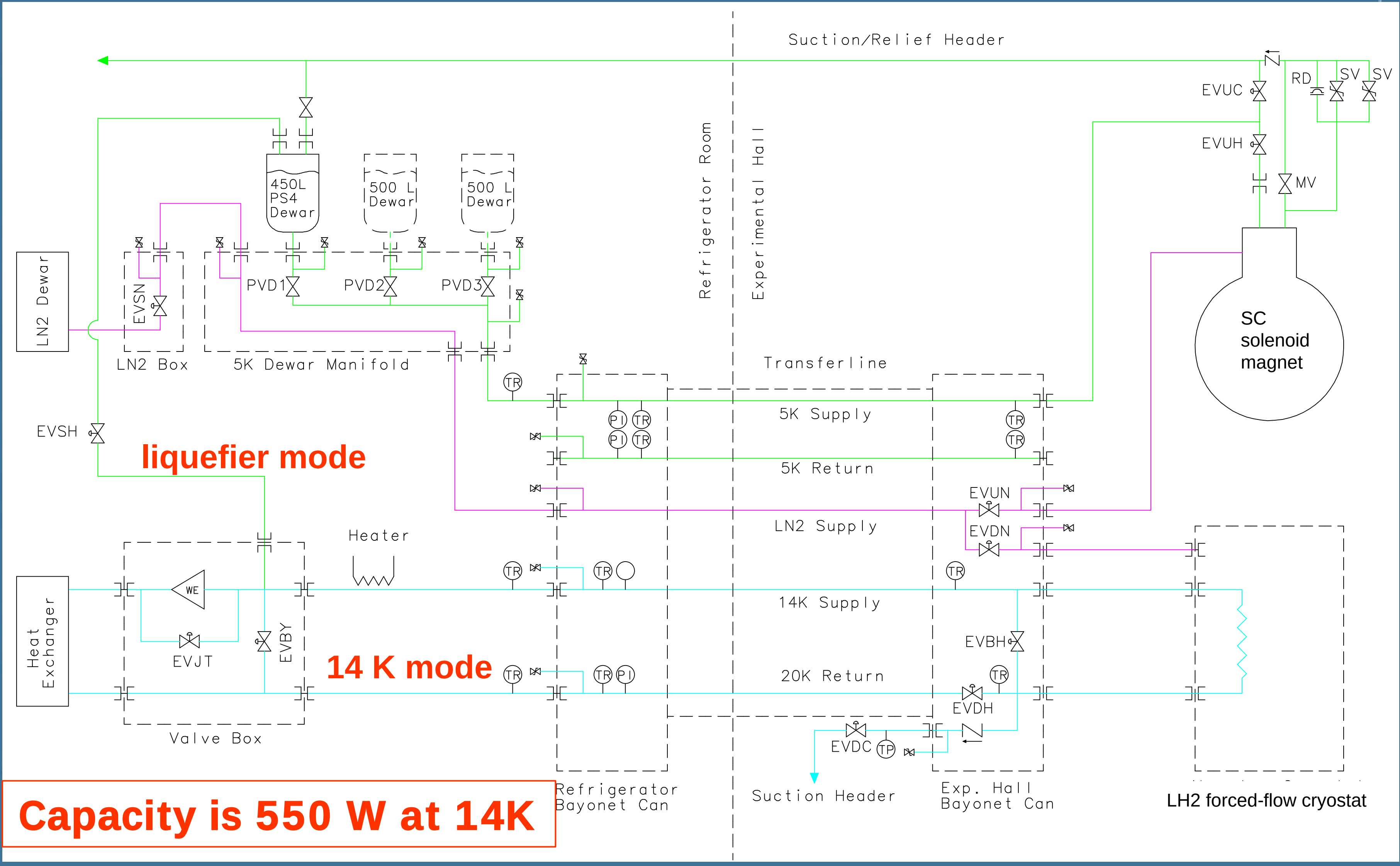

Capacity is 550 W at 14K

The MTA Process and Control System

Functions and Mandates:

- ✓ Monitor and control operations - Reliability
- ✓ Activate alarms for out-of-limits and hazardous conditions - Reliability
- ✓ Collect data for performance studies (complementary to users DAQ) - Accuracy

Safety equipment:

- Flammable gas detectors

-ODH detectors

- FIRUS system

- Building ventilation

- Flow switch

- Audio and visual alarms

- Crash buttons

- Annunciators

- Interlocks

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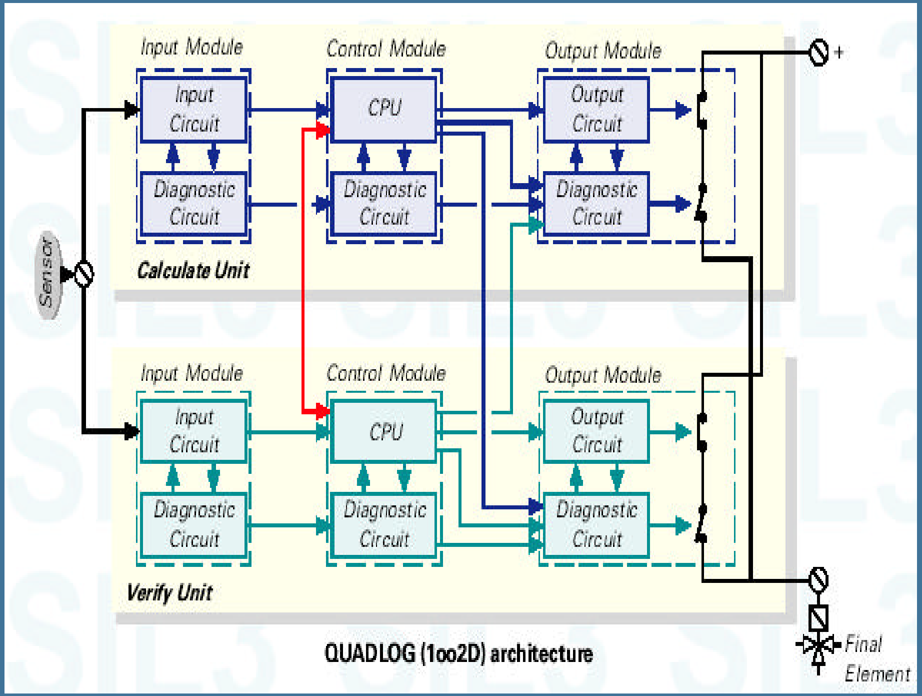
Siemens-Moore QUADLOG™

➔ Combines the beneficial features of a PLC (modularity, ladder logic and sequential programming, high-speed logic solving, and industrial strength) with high safety, high availability, and extensive diagnostics

➔ QUADLOG™ incorporates continuous PID control, analog I/O and a variety of operator interface options not typically available from a PLC

Integrated safety features for a fail-safe PLC

- **Fault tolerance**
- **Self-testing software**
- **Decreased start-up time and minimized downtime with online diagnostics and detailed error reporting**
- **Easier integration with other control systems via open communications**
- **Monitoring and automated response to pre-defined scenarios**



PLC Modules

SAM: Standard Analog Module
- Pressure Transducers
- Heater
- Electro-valve

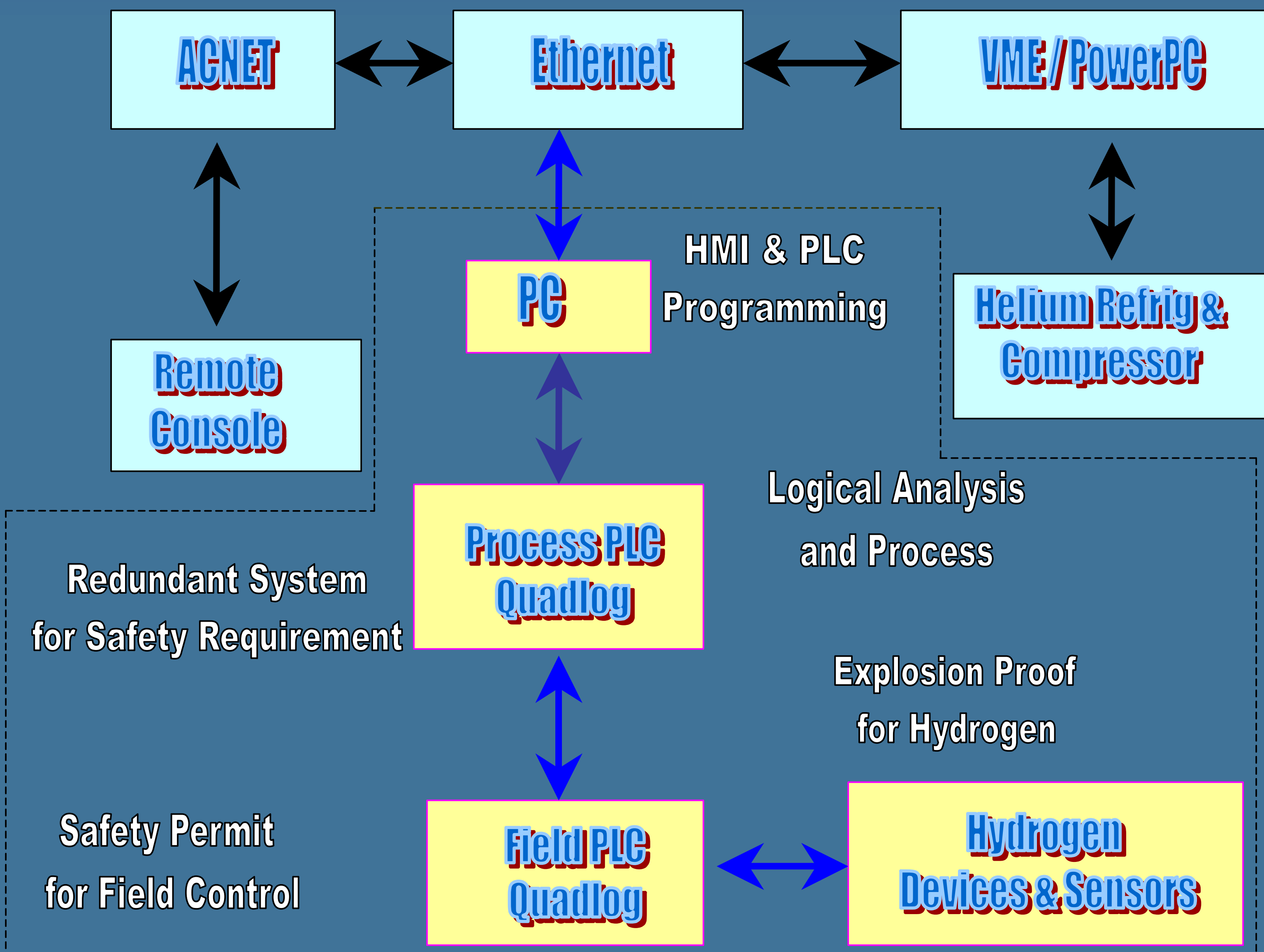
SDM: Standard Discrete Module
- EV, Pump, ODH, FIRUS
- LH_2 absorber liquid level too low
- H_2 presence in the absorber status
- Purge cabinet status
- Audio system status
- Emergency answer status (SD progress)
- FIRUS (ODH and H_2)
- Interlocks status

CDM: Critical Discrete Module
- Oxygen Deficiency Hazard (x4)
- Flammable gas detectors (x3)
- He cool-down start status
- System stop status
- System reset status

VIM: Voltage Input Module
- Level, Pressure, Flow, Temp. (Pt-co)

RTM: Resistance Temperature Module
- Platinum and carbon temperature sensors

Modified Tevatron Cryogenic Control

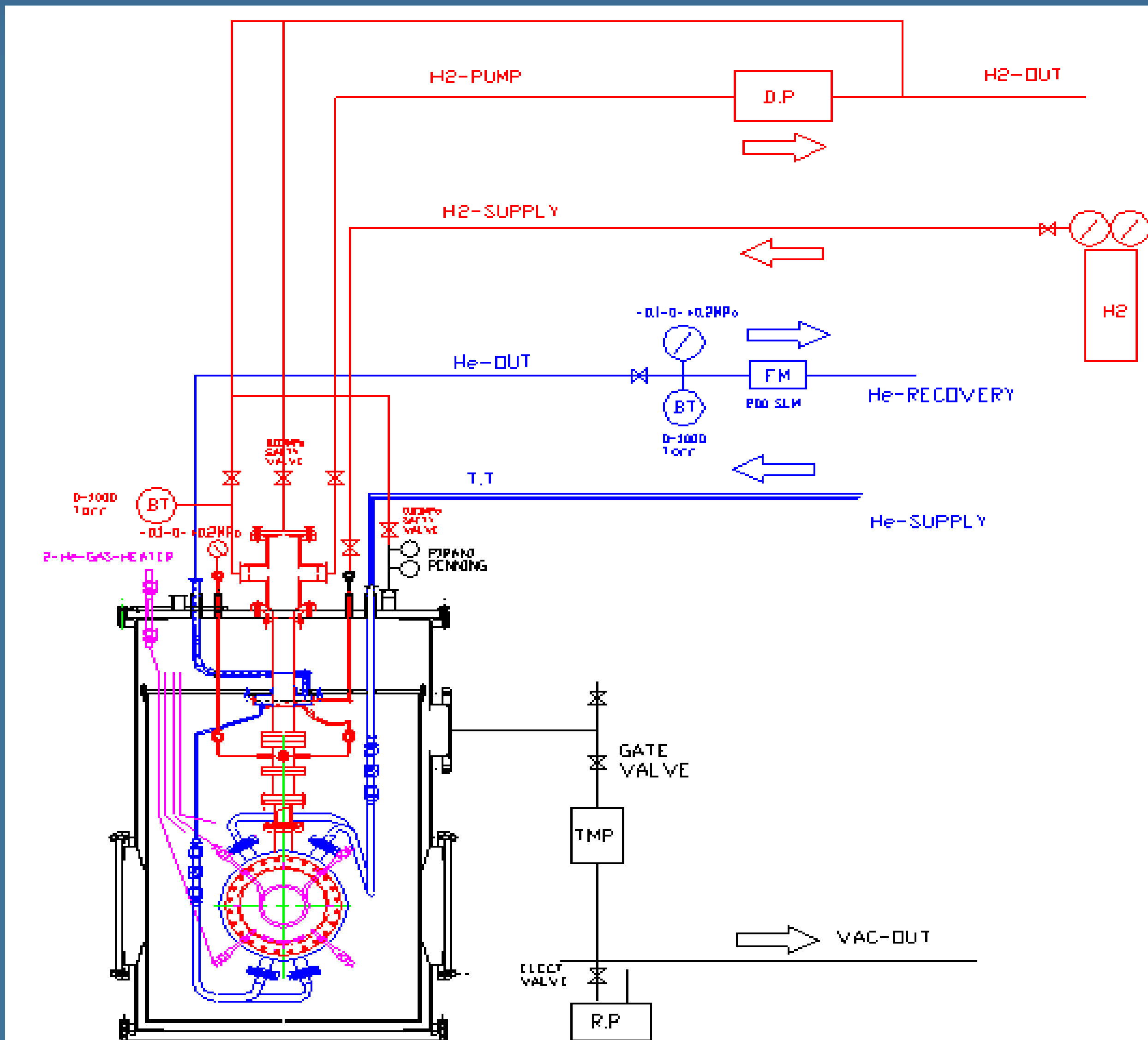


Mandates from Fermilab and Engineering Solutions

1) Need QUADLOG® Safety PLC for monitoring and automated response to pre-defined scenarios (hydrogen leak, vacuum rise, person entering interlocked room)
2) Establish a large set of procedural controls and written operating procedures
3) Meet NEC standards for Class I, Div 2, Group B, (Class I = hazard; Div 2 = hazard sometimes present;Group B = hydrogen)
4) Establish nitrogen purge box to meet NEC standards; contained ignition sources not meeting code
5) Build intrinsically safe barriers
6) All cabling using MC type or PLTC cable
7) Used H_2 gas detectors located in the experimental hall and in the gas manifold room for automated response
8) Use Excess flow valve on hydrogen gas fill line
9) Provide ‘secondary containment’ and use buffer tank on vacuum volume
10) Limit the MAWP of hydrogen vessel to 0.16 MPa

Note: Equipment @ Refrigerator: conventional Tevatron devices ➔ DirectLogic PLC

Application 1: KEK convection-type LH_2 Absorber Process and Instrumentation



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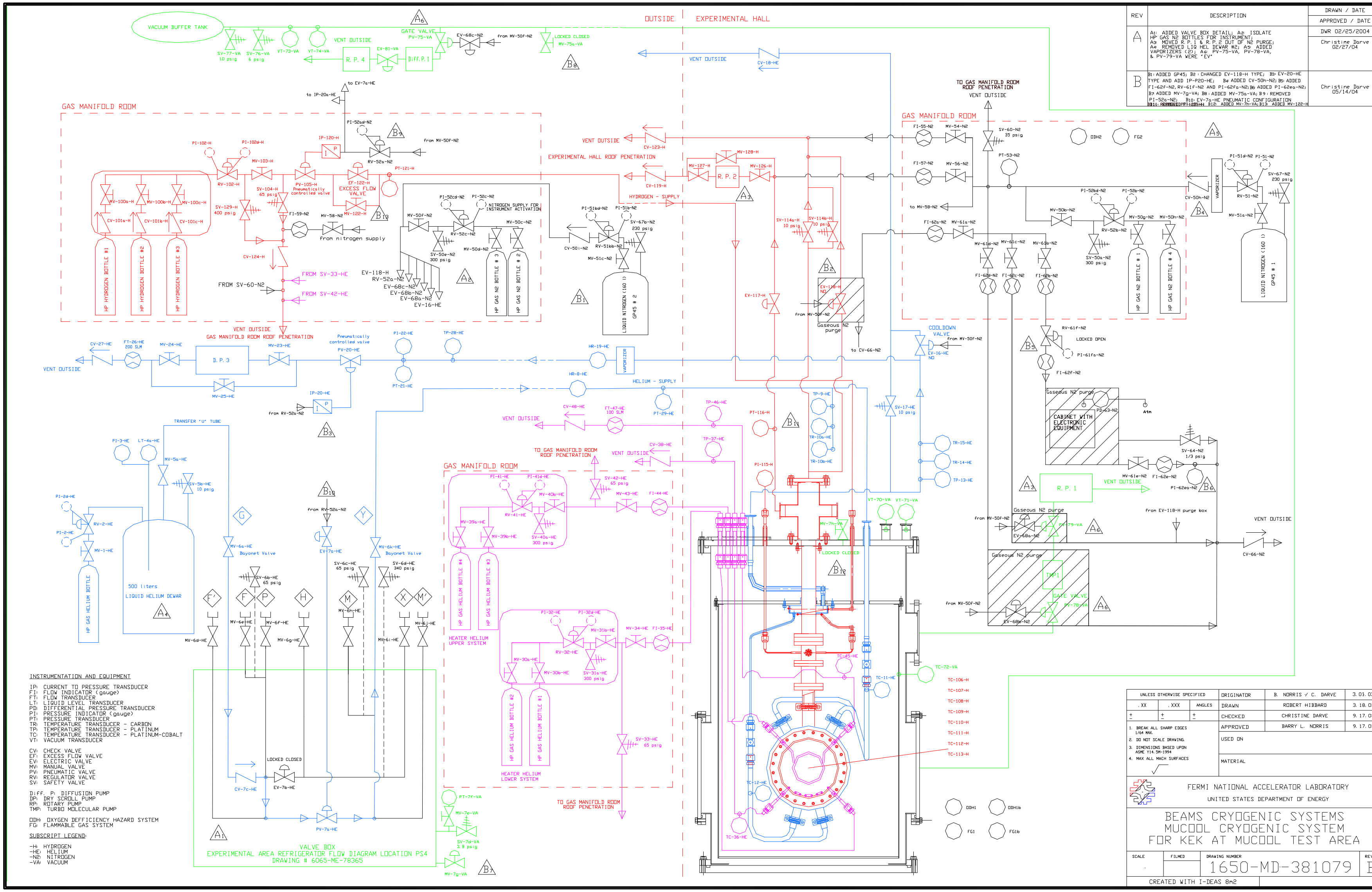
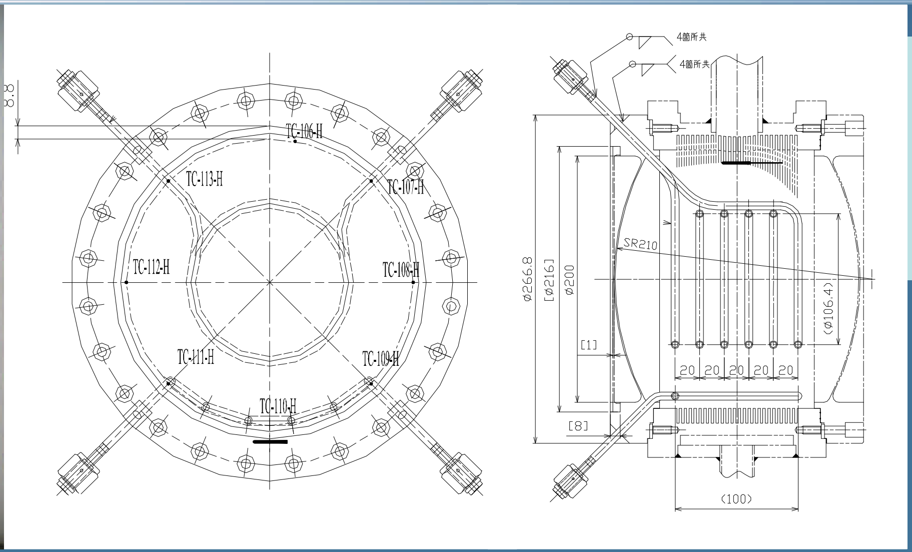
Application 1: KEK convection-type LH_2 Absorber Process and Instrumentation



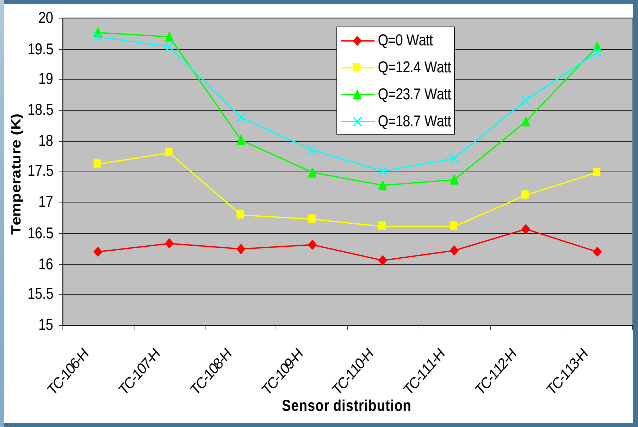
Cryogenic Departm

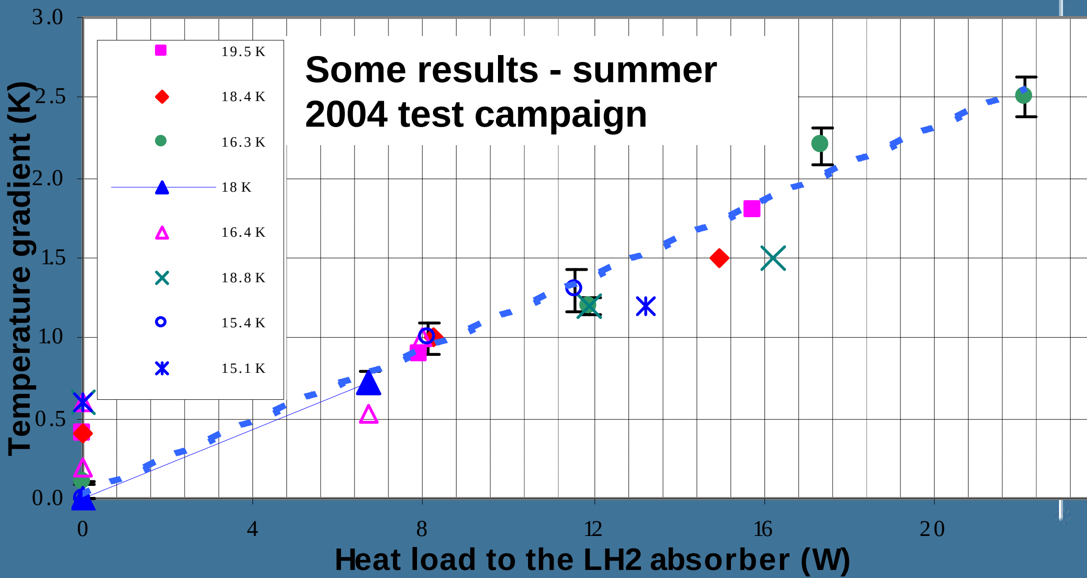
Application 1: KEK convection-type LH_2 Absorber Installation and Results



Platinum Cobalt temperature sensors
Element: platinum-cobalt diffused alloy
Temperature Range: 4K – 375K (R800-
Resistance at 0 C: 100 Ohm +/- 0.15 Oh
Permissible Range: +/- 0.5K
Repeatability: less than 10mK
Measurement Current: 2mA

6.2 liters of LH2





@ LH2 : T=16.3 K ; P=0.15 MPa

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Application 1: KEK convection-type LH_2 Absorber Installation and Results

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An upgrade would be needed to better quantify LH2 absorber performance with longer term tests under stable cooling conditions

• More heat deposed

➔Shorten transfer line to optimize helium usage/reduce heat load

• HTC improperly measured

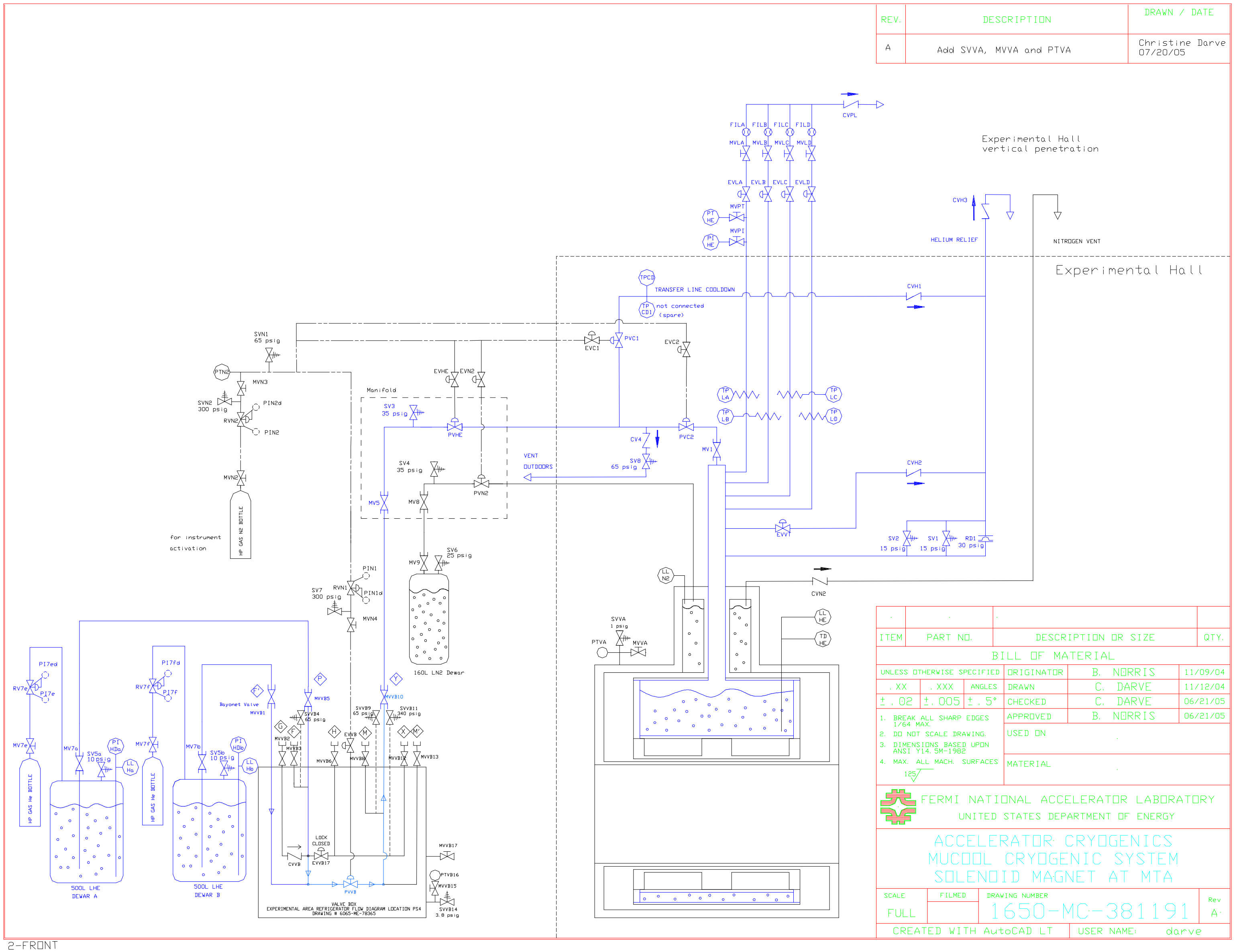
➔Immersed helium temperature sensors; remove warm helium heater and use electrical heater (KEK design: sheathed cartridge inserted in finned aluminum exchanger; temperature monitoring for auto-ignition concerns)

• Improve instrumentation

➔ Cernox thermometry, use liquid level probe for LH_2 bath

Ref: CEC'05 paper - A. Bross et. al, "An upgrade for the MuCool Test Area", submitted to Cryogenic Engineering Conference 2005, CEC'05

Application 2: Superconducting Solenoid Magnet Process and Instrumentation



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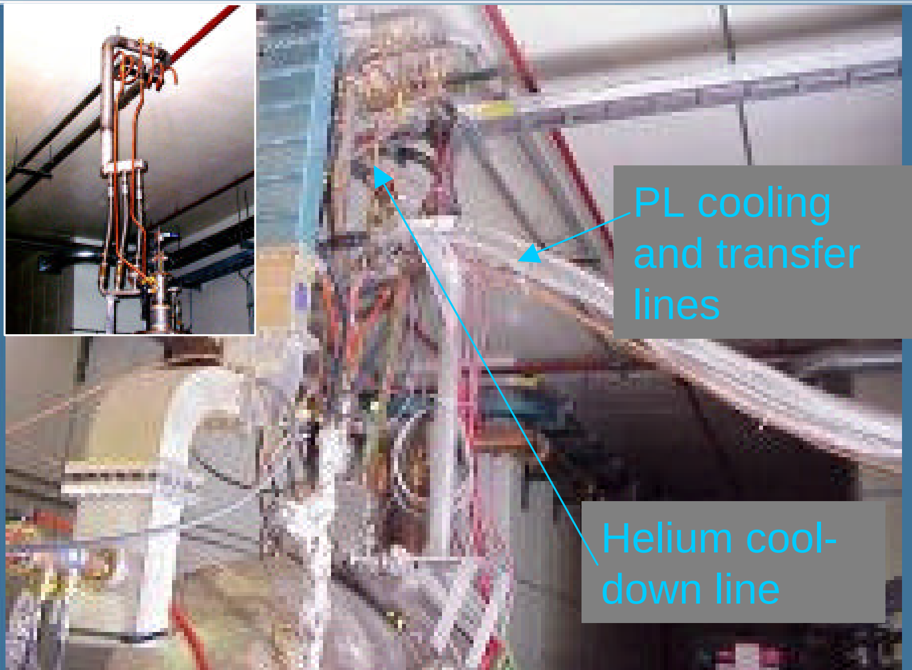
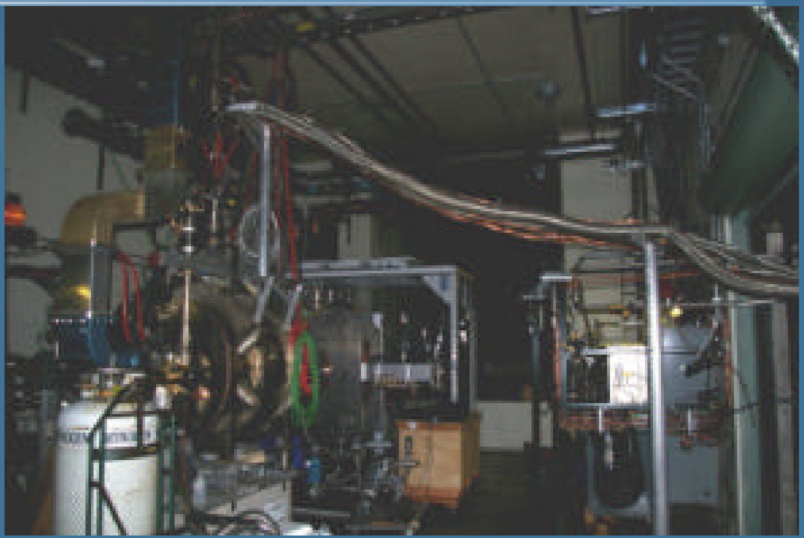
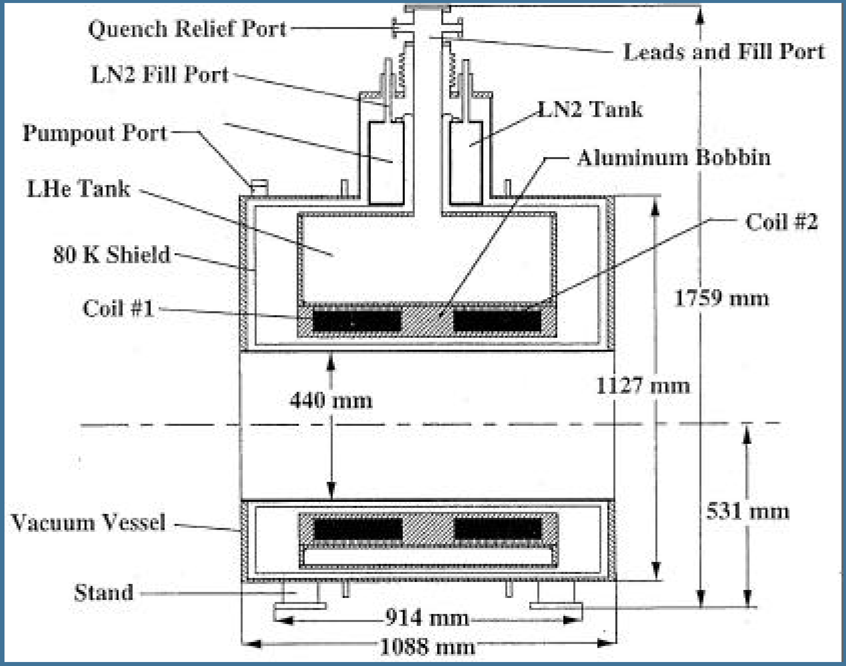
Application 2: Superconducting Solenoid Magnet Installation and commissioning







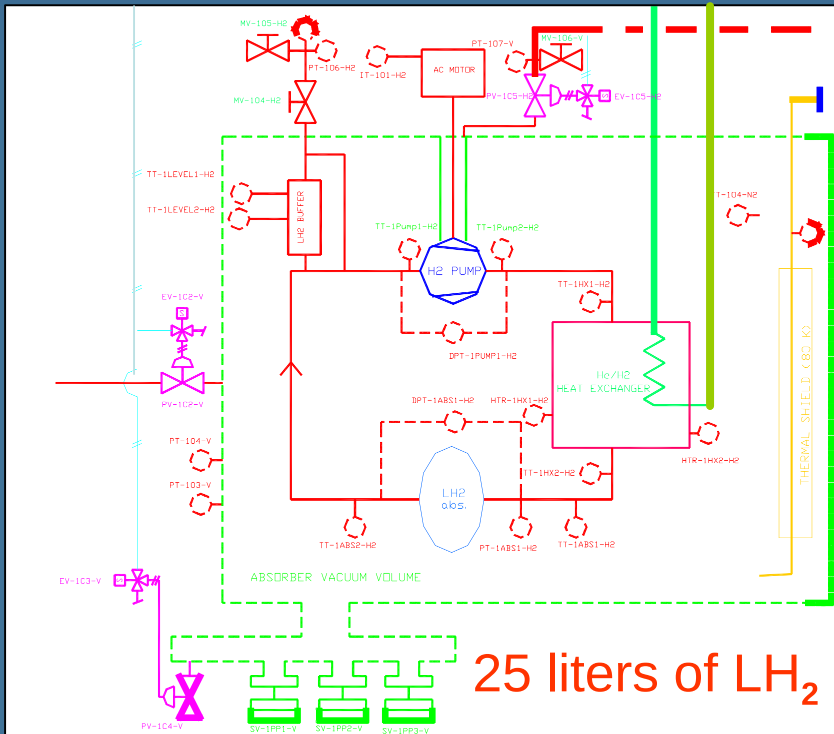
System was moved from another Fermilab area

+ New PLC for LHe and LN_2 transfers

+ Modified cool-down procedure

+ Internet Rack Monitor (IRM) is used as a gateway from PLC to ACNET

Application 3: Forced-flow LH_2 absorber Process and Instrumentation Proposal

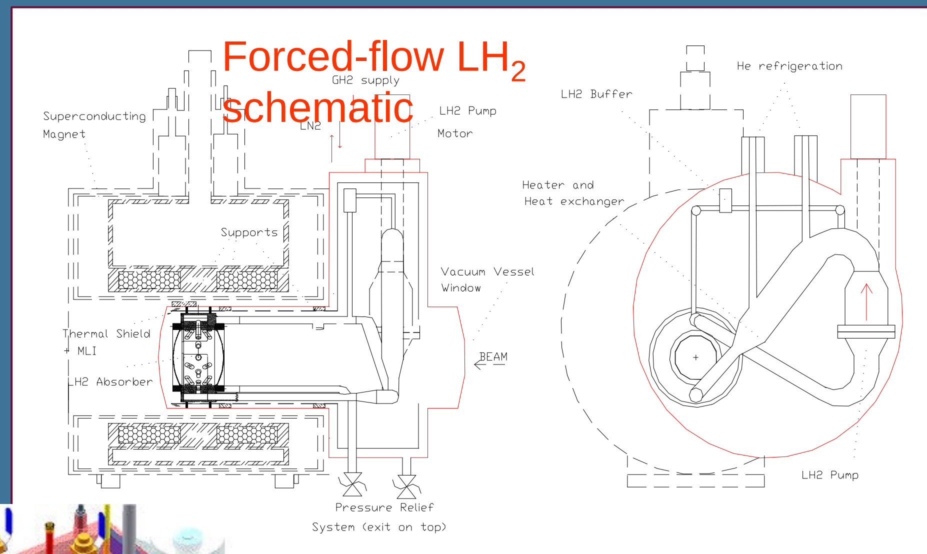


25 liters of LH_2

Total heat load estimation

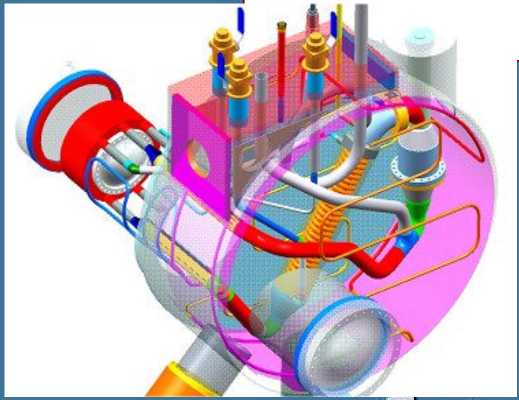
Heat load (W)	80 K	17 K
Mechanical Supports	67	6
Superinsulation	1.5	0.2
Cryostat windows	-	17
LH2 pump	-	50
Total	68.5	73.2

vs. 500 W for total refrigeration system



<u>**Safety issue:**</u>

25 liters of LH_2 released into the air and ignited with only a 10 % yield the energy equivalent to 4 kg of TNT



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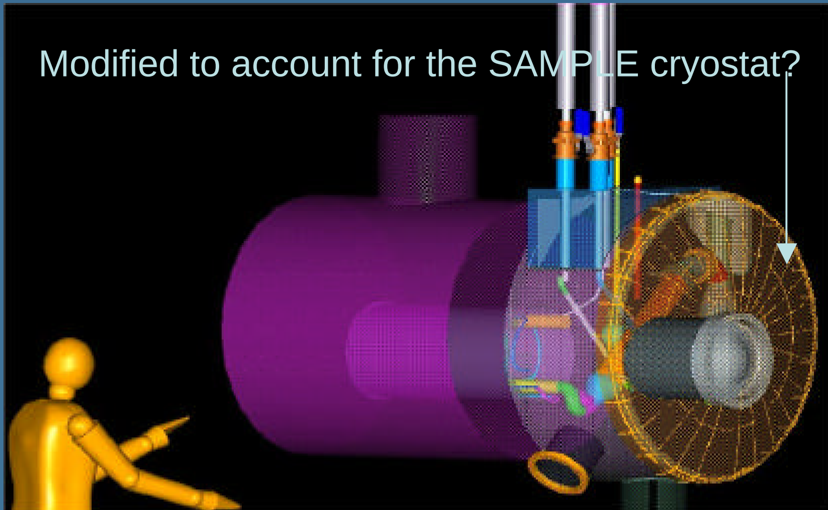
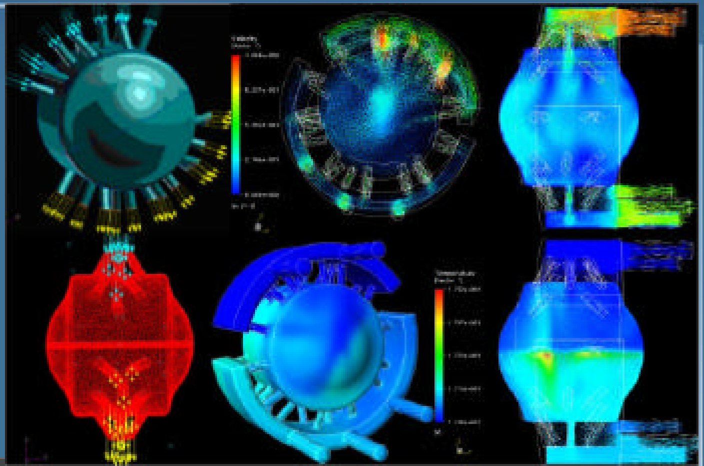
Application 3: Forced-flow LH_2 Absorber
3-D Conceptual Design





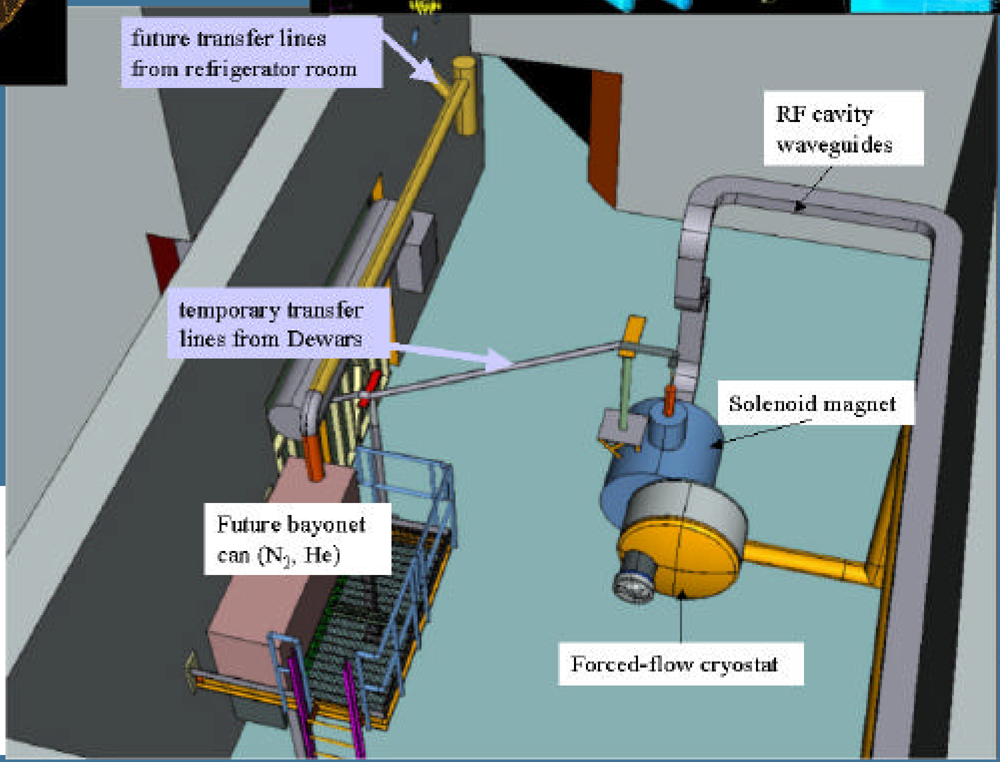
LH_2 loop and vacuum vessel

-Structural study

-Thermal study

- Hydraulic study (in collaboration with Oxford Univ.)

-Safety Review Documents



Reference papers:

C. Darve et al., "The Liquid Hydrogen System for the MuCool Test Area", CEC'03, 2003

C. Darve et al., "Cryogenic Design for a Liquid Hydrogen Absorber System", ICEC19, 2002

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Concluding comments

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On-going cryogenic efforts at MTA

- Hydrogen facility was successfully designed, built and commissioned at Fermilab
- Helium facility (compressor, refrigerator and transfer line) is under fabrication to complete the final infrastructure
- Temporary infrastructure has permitted to test the LH_2 convection absorber in summer 2004
- SC solenoid magnet cooling system is installed
- Forced-flow LH_2 absorber design must be completed

MTA "deliverables" shall prove the feasibility of ionization cooling but also the practicality of cryogenic cooling in hazardous environment

➔MTA = Fermilab facility fully equipped with cryogenic capacity (Hydrogen and Helium)