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FORCED-FLOW LH_2 ABSORBER @ MuCool Test Area

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Headlines

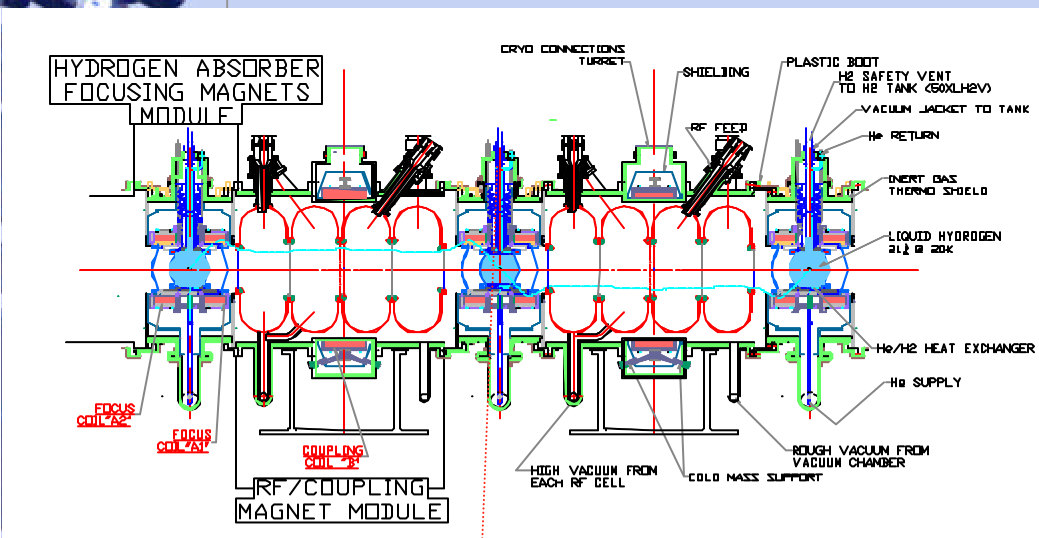
- MTA General Scope
- Cryo-System Characteristics
- SC Solenoid Magnet
- Forced-flow LH_2 Absorber Cryo-loop and Cryostat
- Instrumentation and Monitoring
- Process and Instrumentation Diagram
- Alternative solution – SAMPLE cryo-loop

- Hydrogen Safety
- Safety Documents
- Guiding Principles for Hydrogen Design
- Fermilab Cryogenic Safety Review
- Lessons Learned
- Concluding Comments

MuCool Test Area scope

- Design, prototype and bench test cooling-channel components :
  - LH_2 absorber: low-Z absorber
  - RF cavities: high accelerating gradient
  - SC solenoid magnet: high focusing magnet
- Support cooling demonstration for MICE
- Dev.of intense ionization beam - 400 MeV beam up to $2.4x10^{14}$ p/s

~570 W in 35-cm LH_2 absorber



LH_2 Absorber → Convection type

LH_2 Absorber → **Forced-flow type**

<u>**Cryogenics for ionization cooling…**</u>

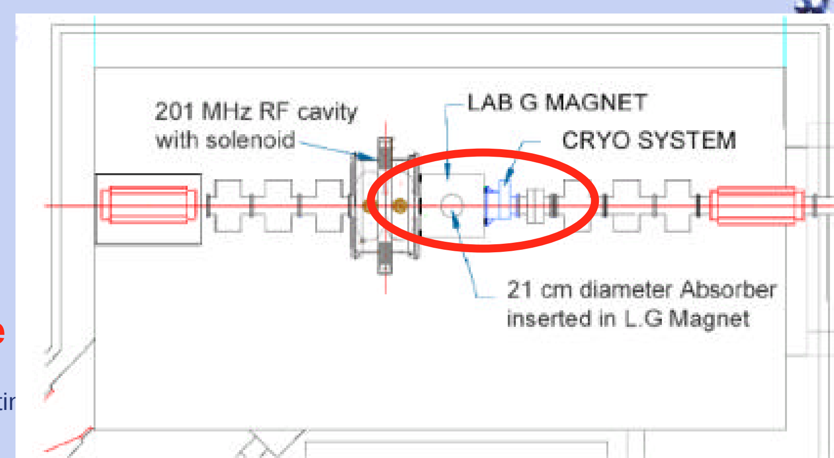
1) H_2 liquefaction

Use Helium as a coolant:

➔ Install compressor and refrigeration system

2) SC Solenoid magnet

Use LHe and LN_2



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Ionization Cooling and LH2

Muon Collaboration

Beam optic and emittance: $s_x = \sqrt{\frac{e_n b_x}{g}}$

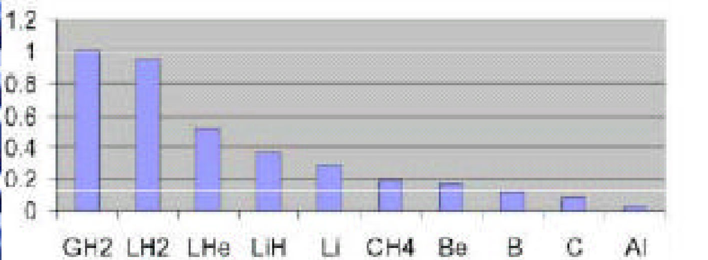
Energy Loss vs. Coulomb Scattering →

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

Ionization cooling: $\frac{dE}{dx} a \frac{Z}{A}$

Bethe-Bloch multiple scattering: $\frac{1}{L_R} a Z^2$

Transverse cooling merit factor $F \propto (L_R dE/dx)^2$



Choice of LH_2 and aluminum

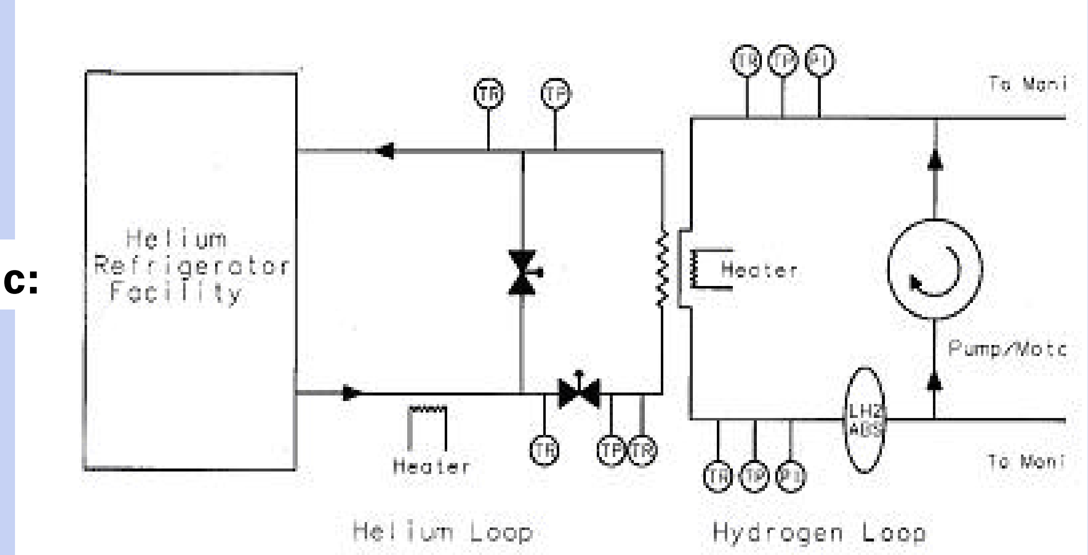
Material	Z	A	$\langle Z/A \rangle$	Nuclear[a] collision length λ_T {g/cm²}	Nuclear[a] interaction length λ_I {g/cm²}	$dE/dx\|_{min}$[b] $\left\{\frac{MeV}{g/cm^2}\right\}$	Radiation length[c] X_0 {g/cm²}	Radiation length[c] X_0 {cm}	Density {g/cm³} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive 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		—

Cryo-system characteristics

Item	Value	Unit
LH_2 operating temperature	17	K
LH_2 operating pressure	0.12	MPa
LH_2 density	74.28	kg/m^3
H_2 boiling point at 0.12 MPa	21	K
H_2 freezing point at 0.12 MPa	14	K
LH_2 viscosity	3.05	10^{-6} Pa-s
LH_2 specific heat	7696	J/kg-K
Heat of vaporization	445.6	kJ/kg
LH_2 thermal conductibility	97	mW/m-K
Liquid H_2 volume ratio at 20 degree C	790	-

Item	Value	Unit
Volume of the LH_2 loop	25	liter
Volume of the vacuum space	26,000	liter
Refrigeration capacity at 20 K	500	W
Refrigeration max mass flow	27	g/s
Refrigeration operating temperature	14	K
Refrigeration operating pressure	0.2	MPa

Simplified flow schematic:



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SC solenoid magnet

This magnet was built at Livermore and shipped to Fermilab for the study of 805 MHz RF cavities at Lab G.

References:

- M. Green, A test report for the Mucool superconducting solenoid, LBNL-45148 SCMAG-800

- Fermilab safety documents

- Peak field in the bore

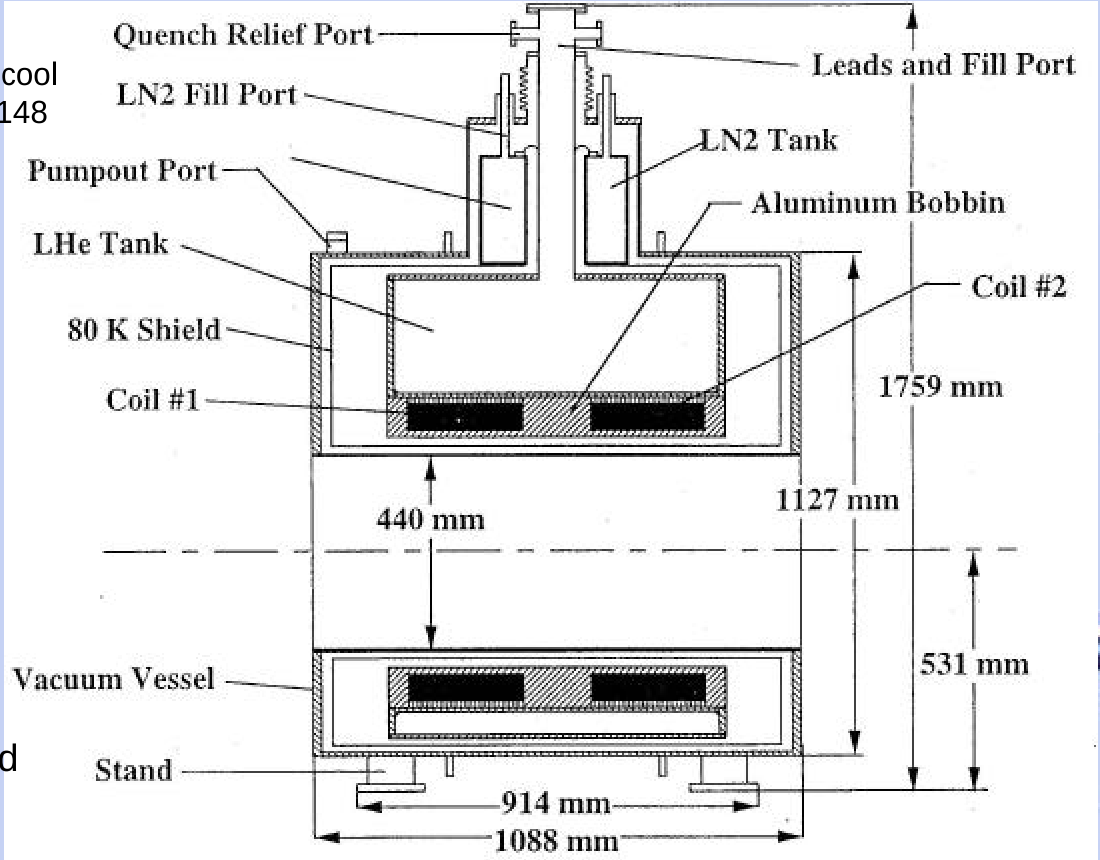
  Bmax = 5.04 T

- Peak field on the coil

  Bcoil = 5.85 T

- Operating current
  Iop = 230 A

- Energy stored in the solenoid
  E = 2.6 MJ

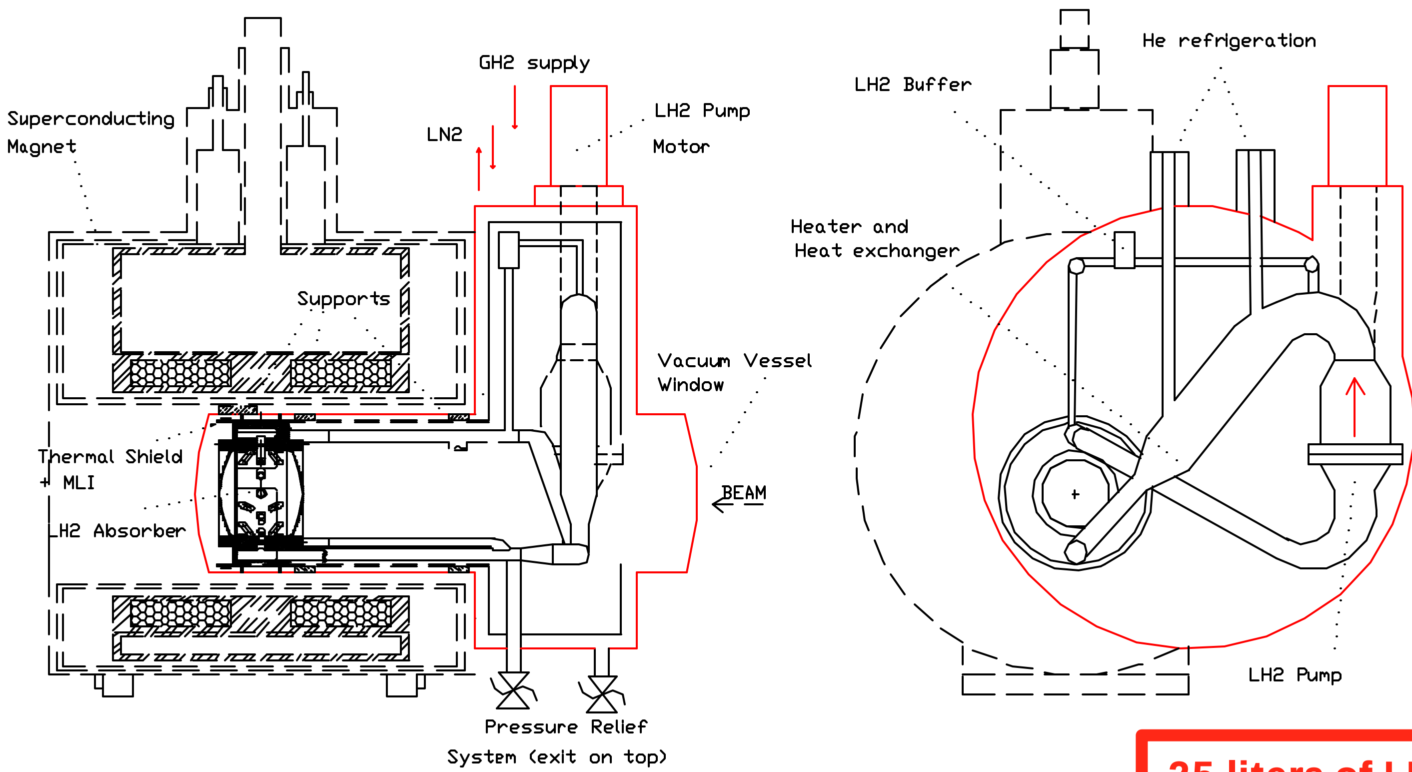


Forced-flow LH_2 Absorber Cryo-loop

LH_2 density fluctuation < +/- 2.5 % ➔ $\Delta T < 4$ K (goal set at 1 K)

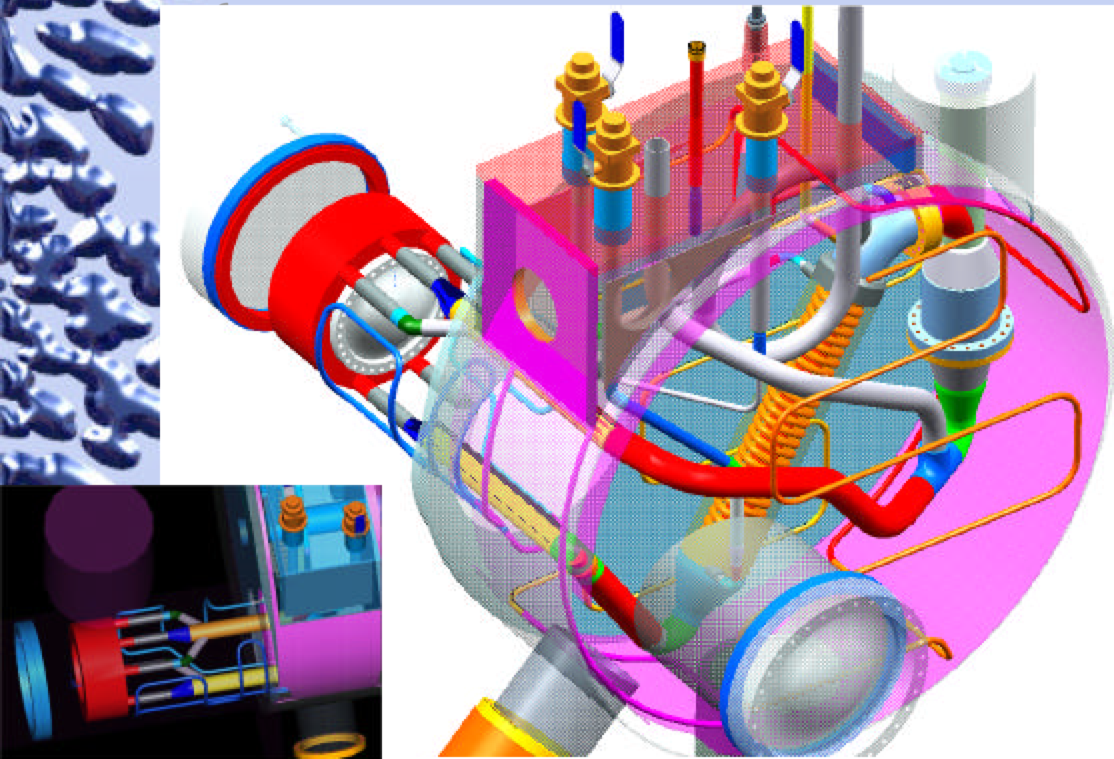
T_{LH2}= 17 K , P_{LH2}=1.2 atm (17.6 Psia, 0.12 MPa)

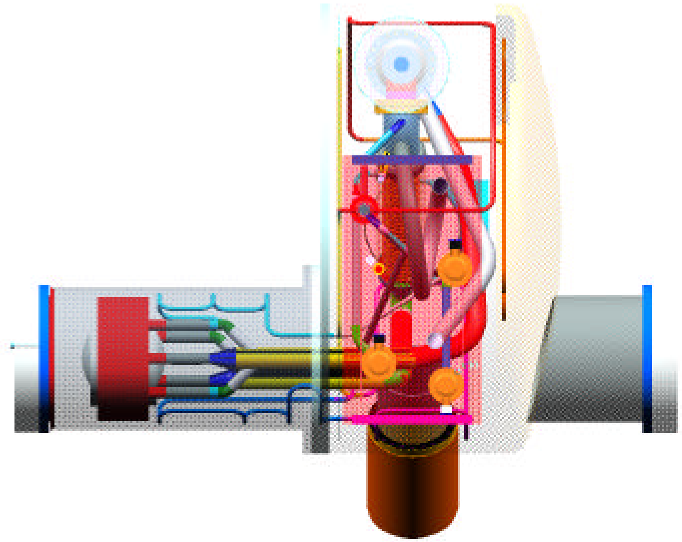
Forced-flow LH_2 Absorber Cryo-loop Conceptual Design (2002 proposal)

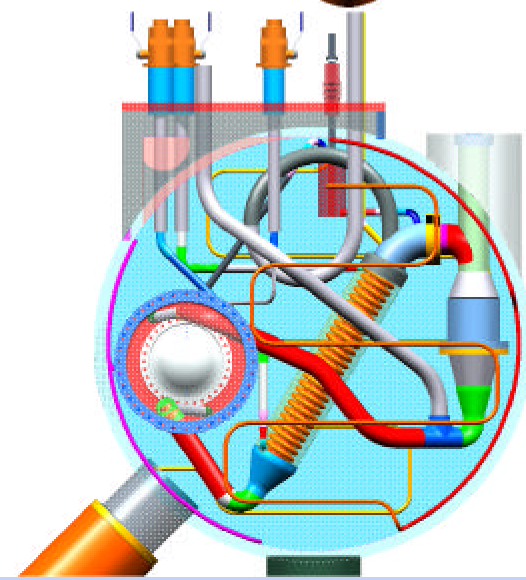


25 liters of LH2

MTA LH_2 Absorber Cryostat - 3D Model Conceptual Design – sept 2002



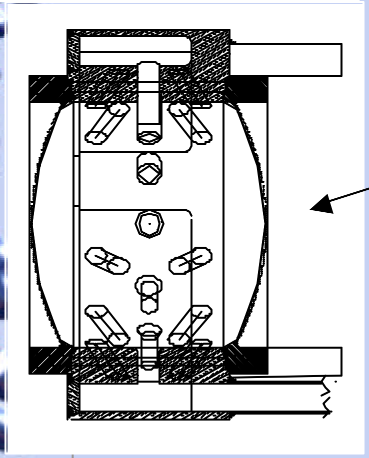




Total heat load estimation

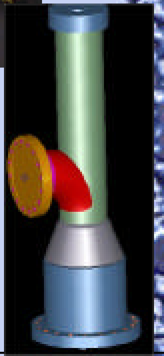
Heat load (W)	80 K	17 K
Mechanical Supports	67	6
Superinsulation	1.5	0.2
Cryostat windows	-	17
LH2 pump	-	50
Total	68.5	73.2

MTA LH_2 Absorber Cryostat – Components

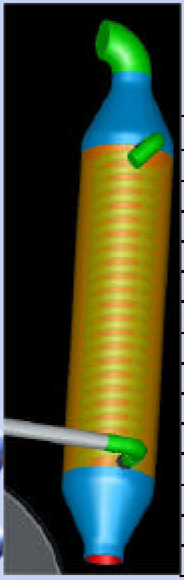


◈ Forced-flow LH_2 absorber

◈ LH_2 pump
(SAMPLE/ Caltech)



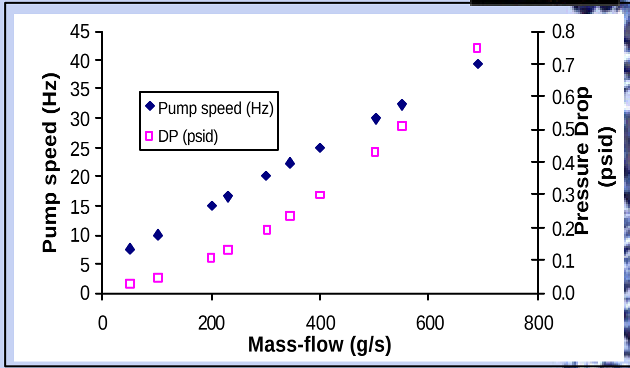
◈ He/ H_2 counterflow heat exchanger (500 W)



	LH_2	He	Unit
P	17.6	30.7	psia
$T_{average}$	17.5	15.8	K
m	63	21	g/s
r (P,T)	*74.28*	5.7	kg/m^3
Cp (P,T)	*8082*	5353	J/kg-K
h (P,T)	171.4	32.6	μpoise
l (P,T)	100	24	mW/m-K
Pr	1.382		
A_{flow}	14.55	1.56	cm^2
G	4.33	13	g/cm^2-s
D_e	0.336	0.378	cm
A_{hex}	11.25		cm^2/in
h	0.109	0.183	W/cm^2-
U	247		W/K

- Vacuum pump:

Diffusion pump
(small compression ratio, high thermal velocity and small cross section)
or
TMP (high pumping speed large H2 compression ratio)
purged with N_2 gas



Instrumentation and Monitoring

From Debbie Errede/ UIUC- absorber development and instrumentation (MTA absorber flow testing)

"The absorber will live in a hostile environment:

- The absorber will absorb 100-1000 Watts depending on beam intensity in cooling channel muon beam.
- The MTA will provide a 400 MeV proton beam of ~ 10^{13} protons/pulse @ 15 Hz to mimic the dE/dx deposition of a muon beam.
- The absorber sits inside a solenoid of 4 Tesla (~1.5 T at absorber in cooling channel design)
- The absorber is filled with liquid hydrogen thus operates at cryogenic temperature (14 –20K)

THUS the monitoring devices must be rad-hard, and able to operate in high magnetic fields and cryogenic temps."

Cryo-System instrumentation:

- ✓ **Goal:** 1) monitor and control operation 2) provide performance data 3) provide warming and/or alarm for out-of-limits conditions and 4) indicate a hazardous condition:
- ✓ **Type:** ~150 inst. : pressure transducer, temperature transducer (LS Cernox, Pt), LH2 level transducer (AMI), flow-meter, heater, excess flow valve, electro-pneumatic valves, certified safety relief valve, check valve
- ✓ ODH Detector, Flammable gas detectors
- ✓ **Selection:** NEC: Class I Division II Group B, range accuracy, response time

Physics: 36 cernox inside LH_2 absorber, more TBD

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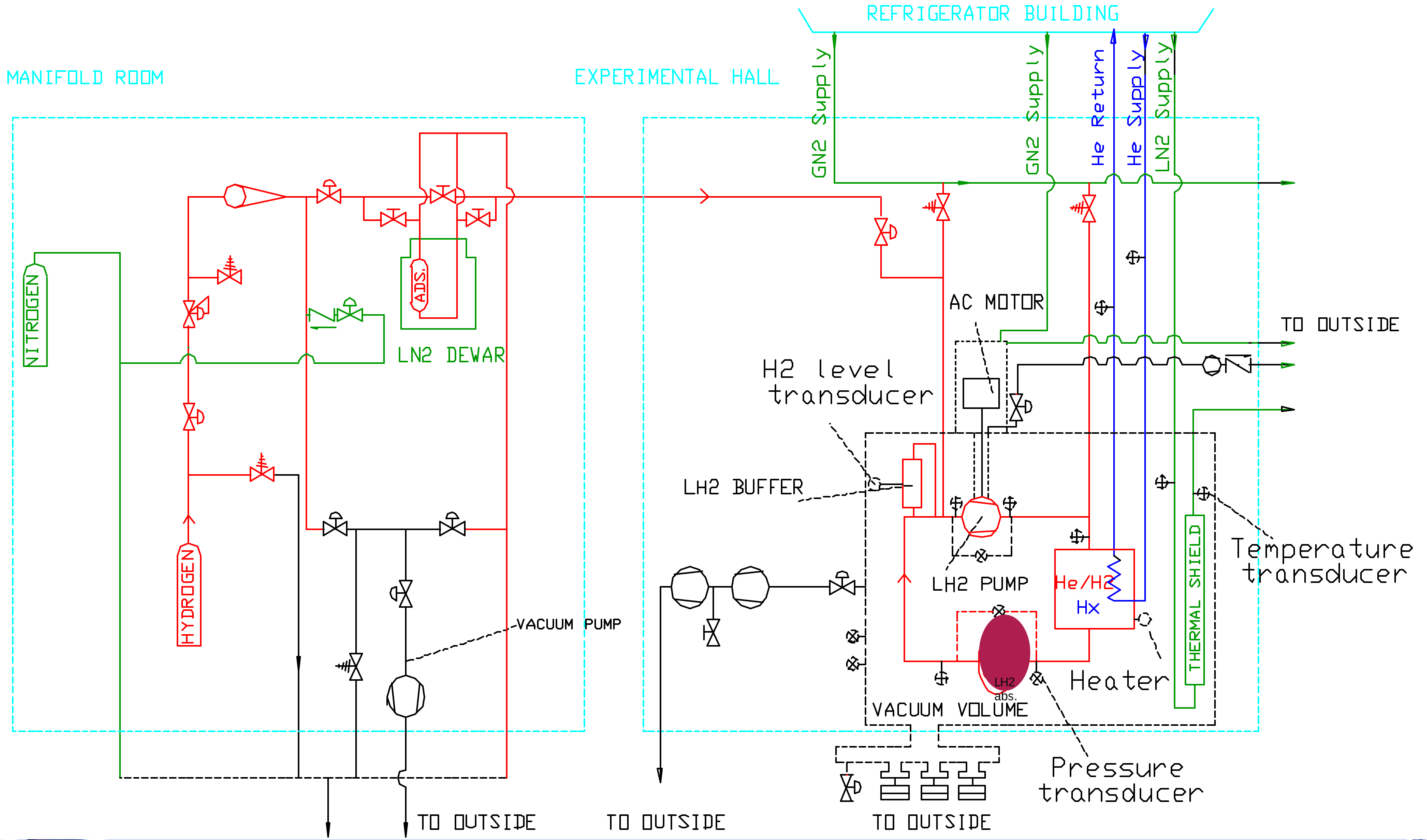
Process and Instrumentation Diagram

Muon Collaboration



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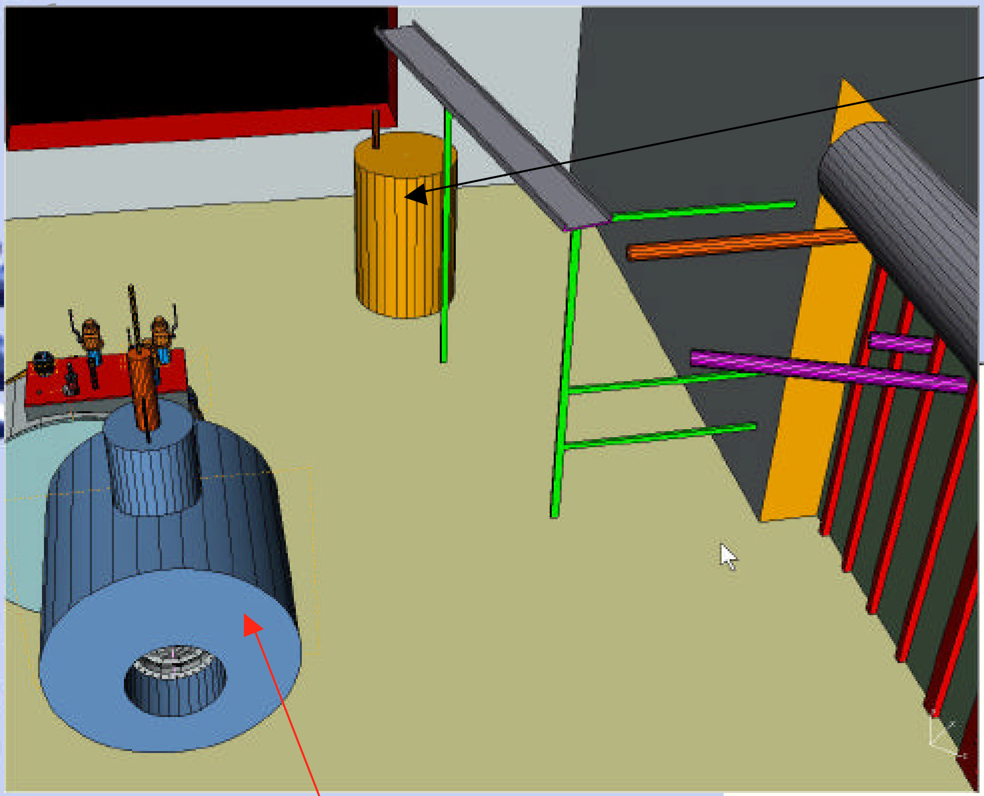
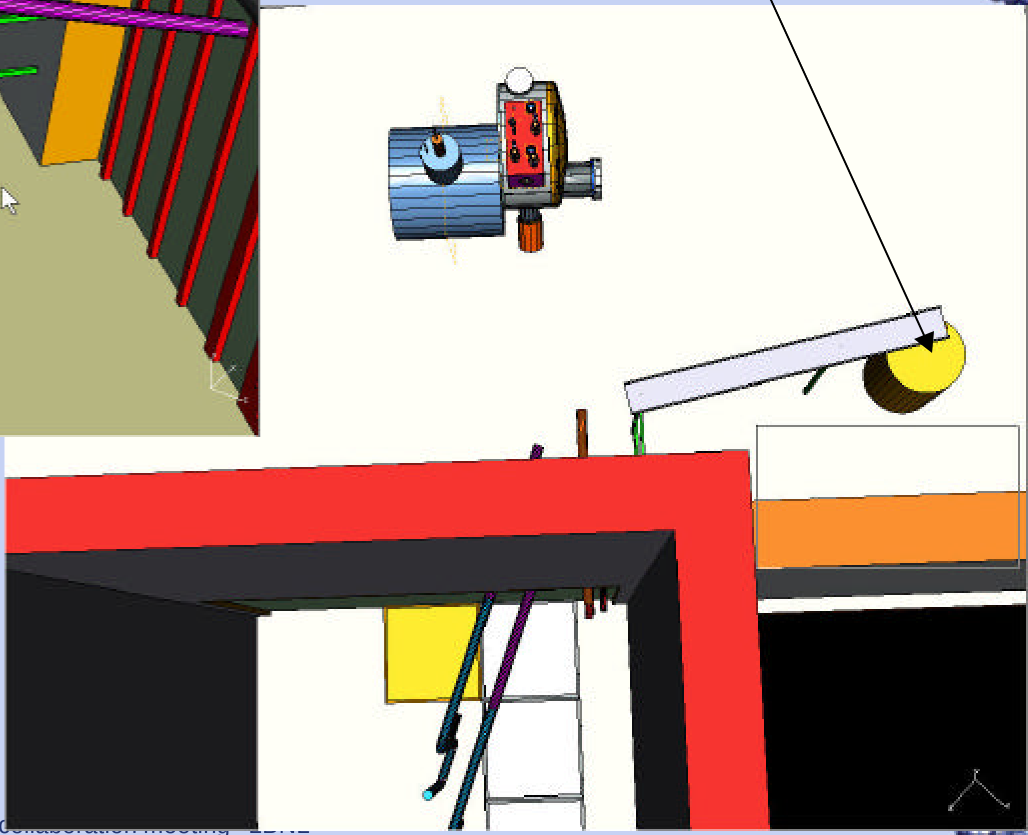
MTA Experimental Hall Layout

Muon Collaboration

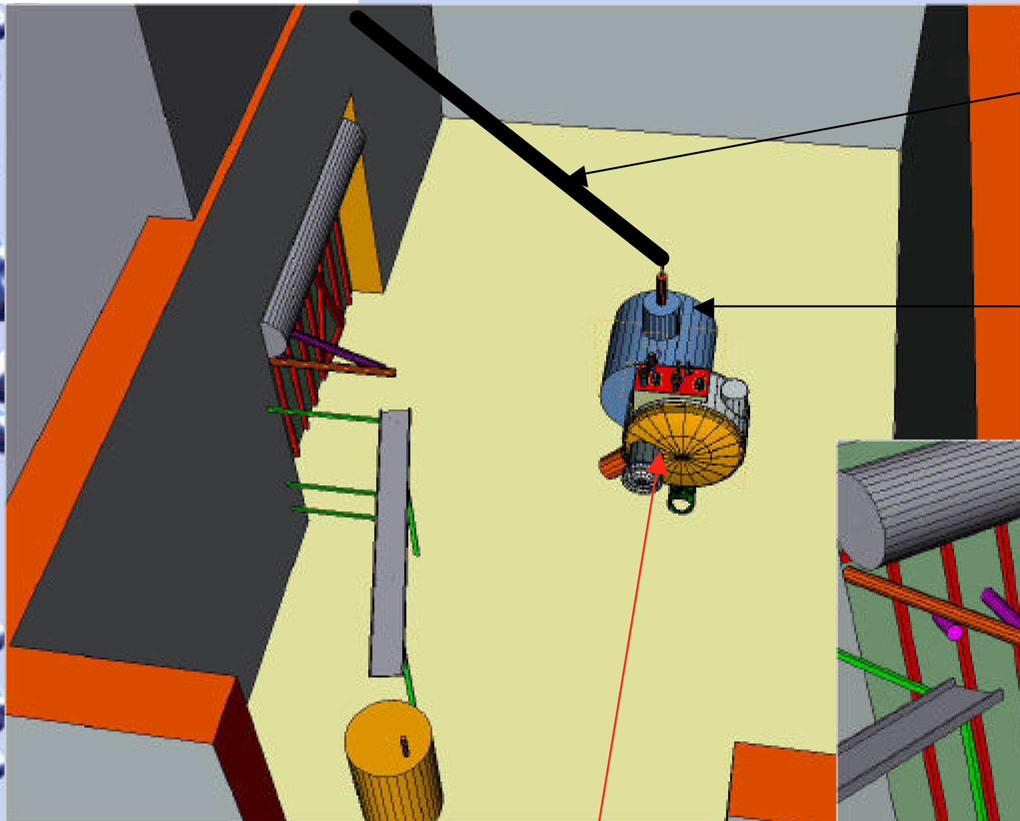


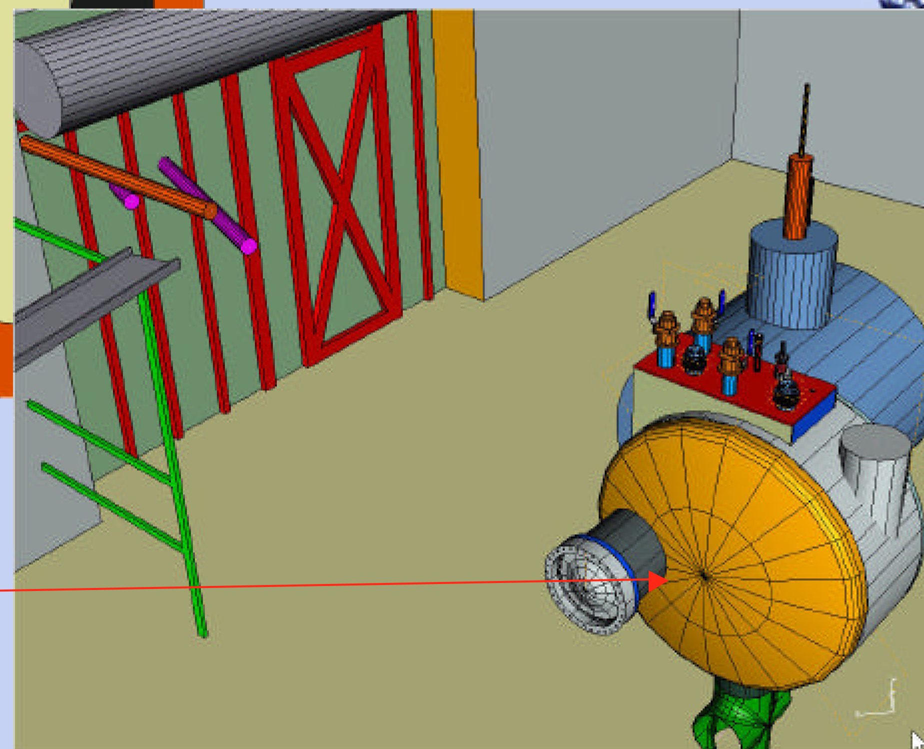
KEK cryo-system
(as currently installed)



SC solenoid magnet

MTA Experimental Hall Layout



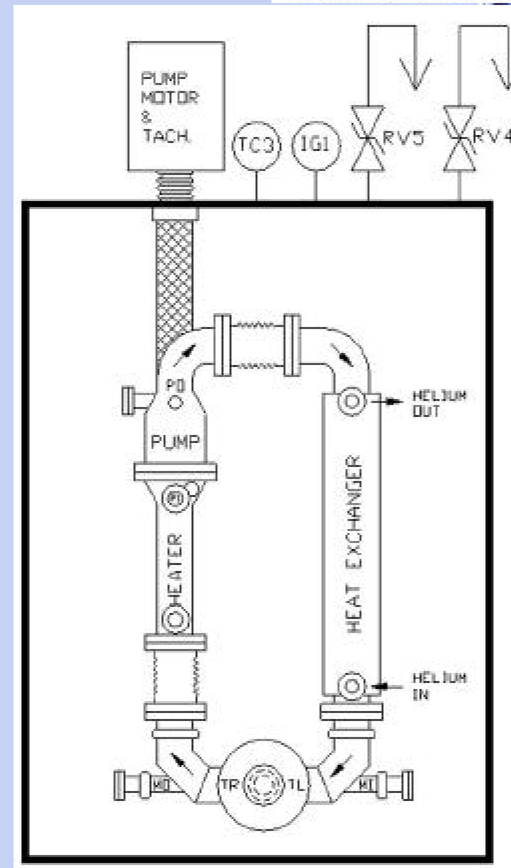


Transfer lines from cryo-plant

SC solenoid magnet

Forced-flow LH2 absorber cryostat

Alternative – SAMPLE cryo-loop



Characteristics:

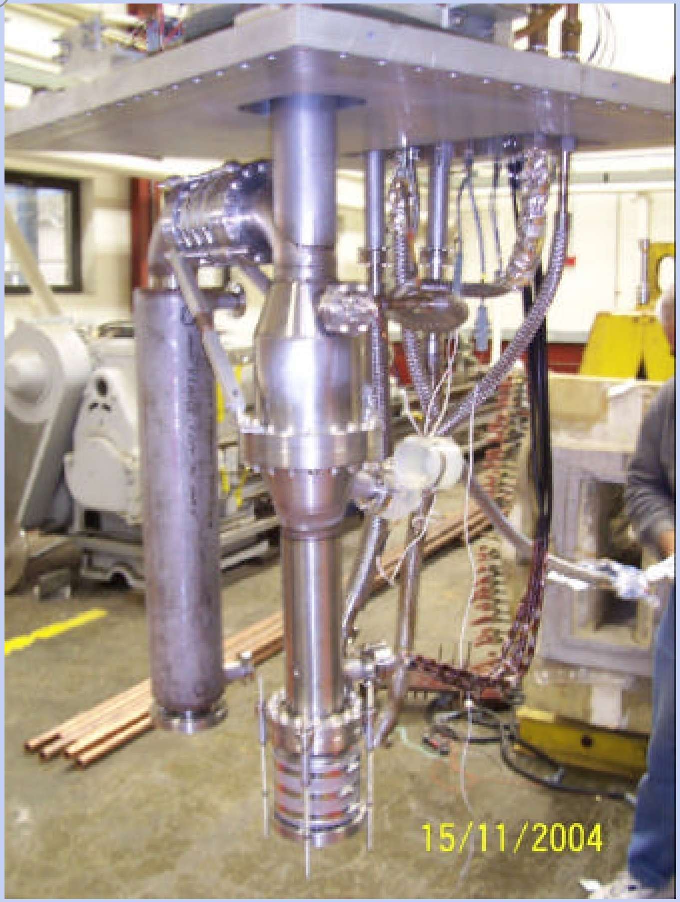
- Close loop using 25 liters of LH_2
- Heat exchanger: 1 kg/sec LH_2 flow
  - counterflow using copper hose and SS housing
  - dim : 85 cm, ϕ15 cm
- AC motor (10-60 Hz)
- Heater: 1 kW

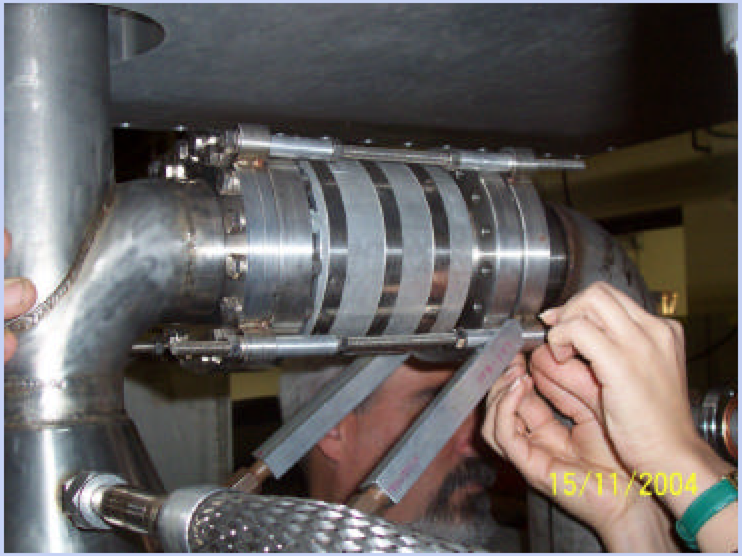
Reference: E.J. Beise et al., A high power liquid hydrogen target for parity violation experiments, Research instruments & methods in physics research (1996), 383-391

Advantages:

1. Existing facility (safety, expertise)
2. Similar flow characteristics
3. Cost reduction
4. Design compatible with MTA proposal
5. Allow larger heat deposition

Alternative – SAMPLE cryo-loop





Hydrogen Safety

Risk:

- Hydrogen auto-ignition (hot points, etc.), Temperature 584 C
- Flammability limits for hydrogen are :

Air	U. 74.8%	Oxygen	U. 94.0%
	L. 4.1%		L. 4.1%

- Detonation limits in Air:18.3 - 59% hydrogen

(Lower pressure for ignition is ~1 psia; min abs. 0.02 psia or 1.4 mbar)

- Minimum spark energies for ignition of H_2 in air is 0.017 mJ at 1 atm, 300 K

Electrical sparks or static electricity (breaking electrical connections, nylon clothing, etc.)

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

Practical set of Guidelines:

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"

Fermilab Cryogenic Safety Reviews

The cryo-system was designed in accordance with :

- American Society of Mechanical Engineers (Boiler and Pressure Vessel Code, ...)
- National Electrical Code (art. 500, etc.)
- Fermilab Environment Safety & Health Code (Pressure vessel, vacuum vessel, piping, Oxygen Hazard Deficiency...)
- Compressed Gas Associates

+ especially : Fermilab ES&H – 5032 (Hydrogen targets)

= SAFETY + SAFETY + SAFETY

PROCESS:

Conceptual design (Audit: E158, G0, SAMPLE)

⇩

Internal (Cryo dept.) Engineering Review (24 sept. 2002)

⇩

Document generated for the forced flow cryo-system (no SAMPLE modification)
Report and calculations, Engineering notes, ODH analysis, FMEA, What-if-analysis,…

⇩ **Status-quo**

Safety Document Check list

As per Fermilab's policy, test / operation using liquid hydrogen needs approval from LH_2 safety panel

Generate a Safety Review Book containing all of the required documents of Chapter 5032TA, including the following:

1. Structural calculations on all parts of the target
2. Venting calculations for the target
3. Venting calculations for the vacuum space
4. Venting calculations for the secondary containment
5. Complete drawings of the target, vacuum system and secondary containment
6. Instrument and valve summary
7. Interlock list
8. Operating procedures
9. Emergency procedures
10. Operational call-in list
11. Material certification data on part
12. FMEA, what-if-analysis
13. Flow diagram
14. Testing results

Guiding principles for Hydrogen Design

Electrical equipments located in the Experimental Hall shall be Class I Division II Group B or intrinsically safe when hydrogen is present.

- Inert gas purge boxes around electrical equipment and connections which are not properly classified.
- Remove likely ignition sources and suspect unknown ignition sources
- Prevent hydrogen leaks to air (sys. design, component testing, operational procedure)
- Hydrogen systems should be kept at positive pressure
- Material choice: Austenitic SS, Aluminum alloys, copper, Ti, PTFE, Kel-F...

- ➢ 25 liters of LH_2 can be contained at SPT in the vacuum buffer tank
- ➢ Purge systems (operational procedures)
- ➢ Equipment automatic control to reduce hazards
- ➢ Fail-safe design
- ➢ Redundant safety features, H_2 excess flow valve, over range
- ➢ Safety PLC for process controls (QUADlog), interlock
- ➢ Alarm/Warning signal system (malfunction of critical equipments,to initiate emergency procedure)

Guiding principles for Hydrogen Design

- Preferred equipment: capacitance type, Output signal 4-20 mA
- Weld and VCR fitting are preferred to flange or other fitting
- Conduit, Power Limit Tray Cable and MC cables

- Detect accidental leaks (FG and ODH detectors)
- Fire and personnel protection
- Building ventilation requirement (fan and venting line)

The cost of the proposed design was estimated to ~ 60 k$

(2002 – w/o SAMPLE cryo-loop)

Lessons Learned

Learned from KEK test: design, fabrication and operate

(first test using LH_2 at MTA)

- Safety review process - Many months for cryo. dept. to design, fabricate, test, implement KEK equipment, and finally operate the first convection type LH2 absorber run…
- Use existing building detectors (FG, ODH), FIRUS system
- Using existing safety PLC (QUADlog)
- Same hydrogen venting and vacuum buffer tank
- Similar operational procedures
- Same persons (review committee, cryo. department (?))
- Use of existing SAMPLE cryo-loop brings the advantage (as long as its operation doesn't present greater risk than that assumed when facility was originally designed)
- E158 example : at least 18 months of safety system design before the first use of liquid hydrogen. E158 safely operated for 8 months.

Concluding Comments

➢ Development of MTA cryogenic system must be in compliance with Fermilab safety codes :

- Helium safety panel (Helium cryo-plant and SC solenoid magnet)
- Hydrogen safety panel (Forced-flow LH2 absorber cryo-system)

➢ MTA cryo-plant available :

- Forced-flow cryostat heat exchanger: 27 g/s of helium @ 14 K, 15 psig (2 bar)
- SC solenoid magnet: LHe (switch-over mode), LN2

<u>Open questions:</u>

- Operate LH_2 and SC solenoid magnet at MTA in accordance with LH_2 safety panel requirements
- Manpower
- Cost

Concluding Comments

To-do-list to operate the forced-flow LH_2 absorber cryo-system:

- Helium cryo-plant :
  - ✓ Installation and commissioning of the compressor room (Fermilab/Cryo dept. : piping contract in progress)
  - ✓ Design, installation and test of transfer lines (Fermilab/PPD : in progress)
  - ✓ Refrigeration system (Fermilab/Cryo. Dept.)
- Hydrogen system :
  - ✓ Redesign forced-flow cryostat to implement the SAMPLE cryo-loop
  - ✓ Complete numerical simulation to optimize the hydraulic system and LH_2 absorber body design (Oxford University)
  - ✓ Generate safety review documents
  - ✓ Engineering and hydrogen reviews
  - ➔ Final documentation acceptance
- Operate the system