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CRYOGENICS AT THE MUCOOL TEST AREA

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Headlines

- **MTA cryogenic requirements**
  - Tests under development
  - Description of cryogens and system warm gas
  - System characteristics
- **Cryogenic system installation**
  - Layouts
  - Helium and nitrogen systems
  - Hydrogen system safety requirements
- **Current test set-up: KEK convective LH_2 absorber test**
  - Cryo-system flow schematic
  - Components and requirements (see Shigeru Ishimoto's talk)
  - Status
- **Future test set-up: Forced-flow LH_2 absorber test (Conceptual Design)**
  - Cryo-system flow schematic
  - Components and requirements
  - Heat transfer numerical calculations (see Wing Lau's talk)

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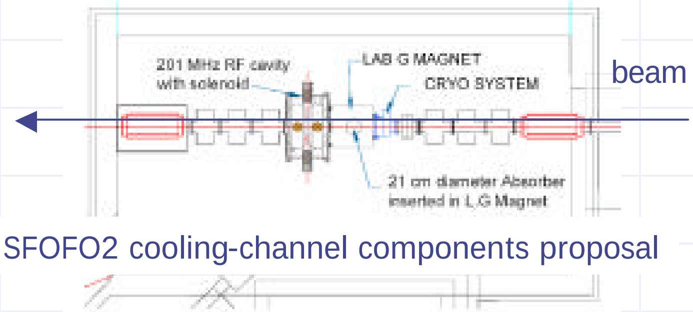
Tests under development

- Long term: MTA cryogenic systems are sized to accommodate SFOFO2 cooling-channel components (RF, LH_2 absorber, etc.):

➔ 25 liters of LH_2

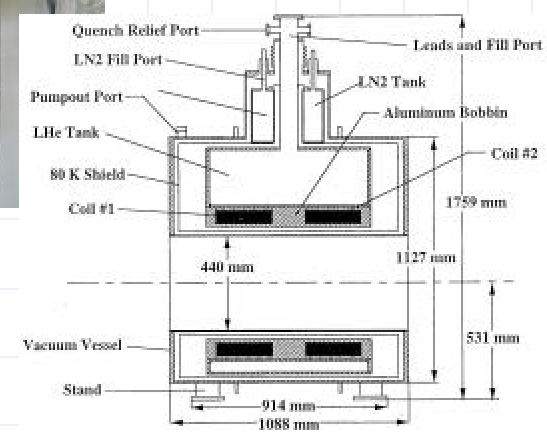


SFOFO2 cooling-channel components proposal

The beam is “cooled” by energy loss in the cooling channel; both transverse and longitudinal momentum is lost to collisions with atomic electrons but the longitudinal momentum is restored by the RF acceleration between the absorbers.

- Short term: KEK convective LH_2 absorber test:

➔ 6.2 liters of LH_2 (see Shigeru Ishimoto’s talk)



- FY04: RF test in the Lab G solenoid magnet:

Description of cryogens and system warm gas

- Configuration #1: Helium refrigeration plant (to be installed ~ Dec. 2004) :
  - 4 K mode - Lab G solenoid magnet supply
  - 14 K mode - Forced-flow He/LH_2 heat-exchanger supply: 500 W (static+dynamic)

- Configuration #2: Helium temporary Dewar set-up (KEK and RF/Lab G solenoid magnet) :
  - 4 K - Lab G solenoid magnet supply
  - 17 K - Convective LH_2 absorber: 100 W
  - Room temperature gas – KEK convective LH_2 absorber beam simulation

- Nitrogen :
  - LN_2 - Lab G solenoid magnet supply
  - Room temperature gas - Purged systems

- Hydrogen :
  - Gas H_2 subcool to 17 K, 0.12 MPa by He/LH_2 HX - Forced-flow LH_2 absorber
  - Gas H_2 cooled down to 17 K by He/LH_2 HX – KEK convective flow LH_2 absorber

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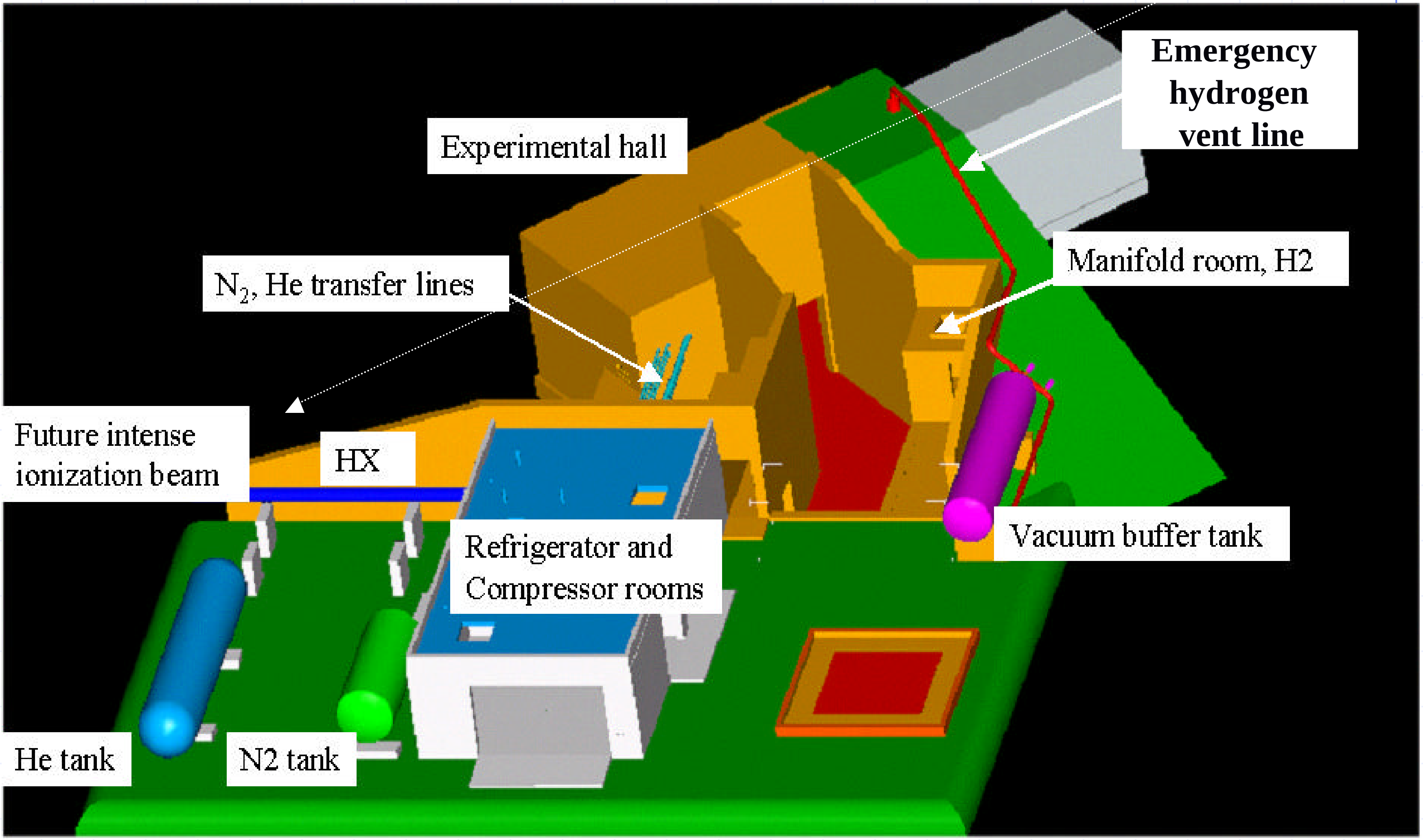
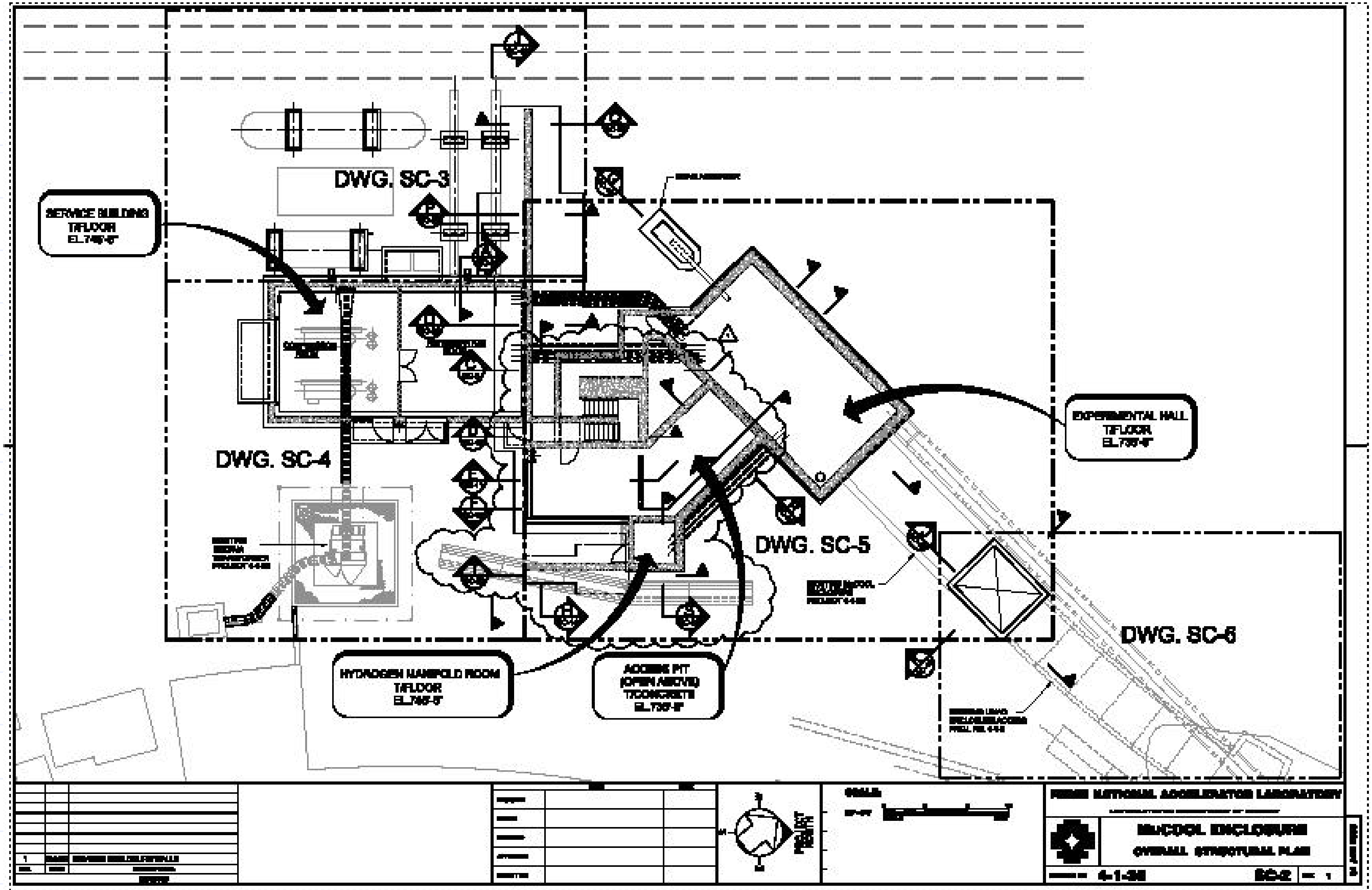
Cryogenic system 3-D drawing

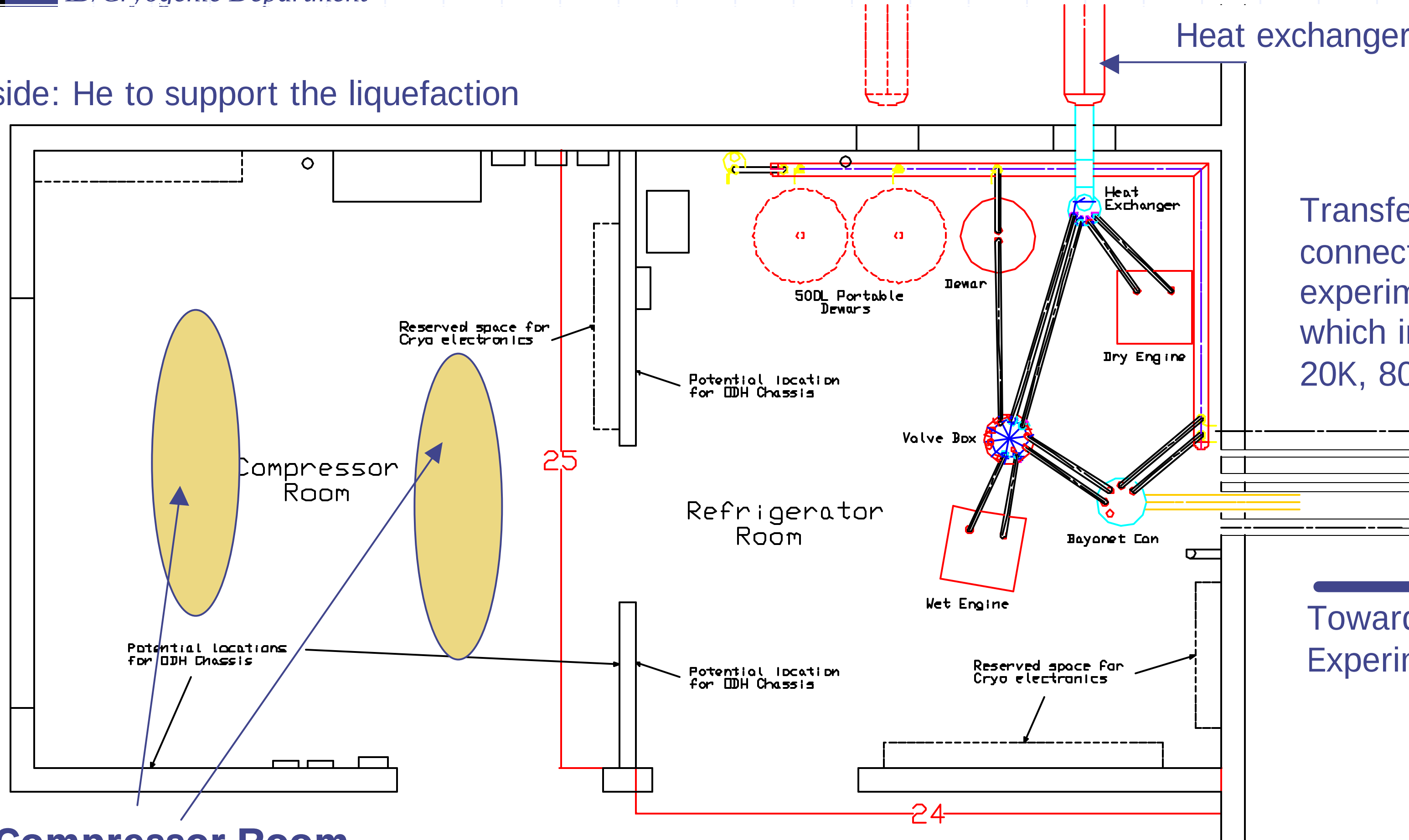


MTA layout


DWG. SC-3
DWG. SC-4
DWG. SC-5
DWG. SC-6
SERVICE BUILDING
EXPERIMENTAL HALL
HYDROGEN MANIFOLD ROOM
ACCESS PIT
(OPEN ABOVE)
MuCOOL ENCLOSURE
OVERALL STRUCTURAL PLAN

Refrigerator and compressor rooms

Outside: He to support the liquefaction



Heat exchanger

Transfer line connections to experimental hall which includes 5K, 20K, 80K circuits

Towards Experimental Hall

Compressor Room

- Two 400 HP 2-stage oil injected screw compressors

Refrigerator Room

- Tevatron satellite refrigerator to be operated on 5 K mode and 14 K mode (3” DE, 3” WE)
- Helium and nitrogen Dewar

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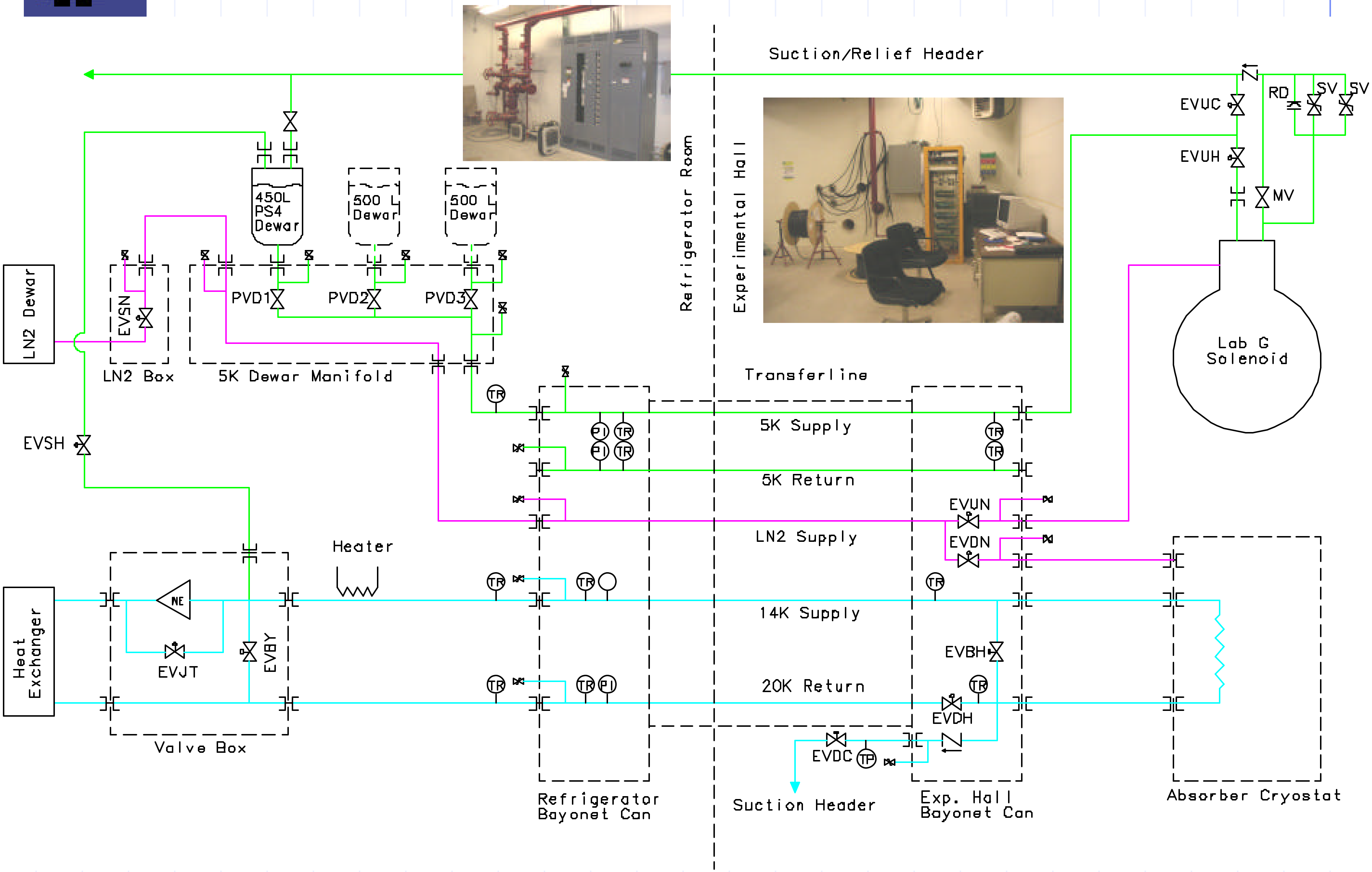
Proposed MTA Helium Flow Layout



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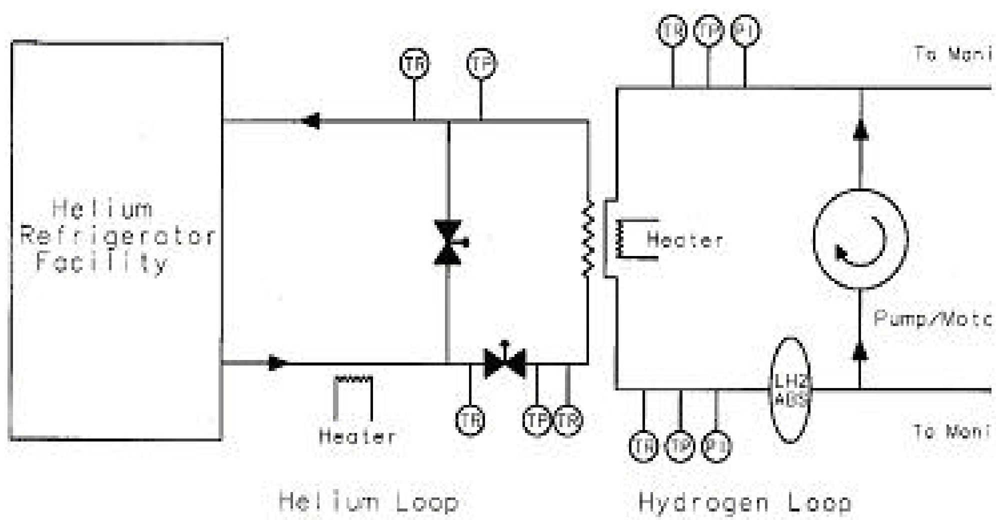
System characteristics and fluid properties

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:



Refrigeration test at Meson (Nov. 2003)

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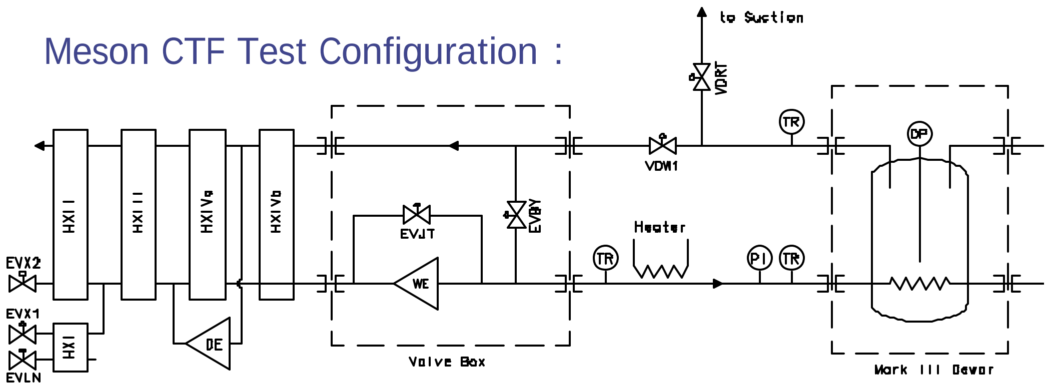
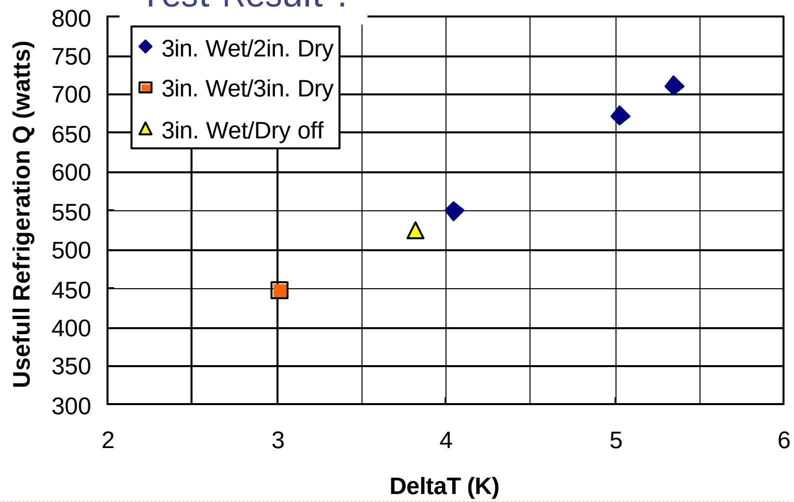
Meson CTF Test Configuration :



Test Result :



➢ **Tevatron Satellite in stand-alone mode: Measured liquefaction rate : 78 liter/hr**

	Wet Engine Flywheel Spee (rpm)	Wet Engine Inlet Temp. (K)	Wet Engine Outlet Temp. (K)	Wet Engine Outlet Press (psig)	Heater Outlet Temp. (K)	Calculated Flow thru Heater (g/s)	Heat Input (watts)	Dry Engine Flywheel Speed (rpm)	Dry Engine Inlet Temp. (K)
3" Wet Engine and	174.00	21.53	12.49	15.53	17.02	27.54	676.00	53.00	145.30
3" Dry Engine			*12.49*		*14.00*	*27.54*	*227.40*	*<--- Calculated Heat Input to Warmup to 14.0*	
			14.00		*17.02*	*27.54*	*448.50*	*<--- Calculated Heat Input from 14.0 K to 17.0*	
	176.80	23.76	13.58	16.01	18.05	25.27	608.80	23.71	181.30
3" Wet Engine and			*13.58*		*14.00*	*25.27*	*57.80*	*<--- Calculated Heat Input to Warmup to 14.0*	
2" Dry Engine			*14.00*		*18.05*	*25.27*	*551.00*	*<--- Calculated Heat Input from 14.0 K to 18.0*	
	176.80	24.54	14.00	16.00	19.02	24.91	673.30	33.00	172.50
	176.80	24.65	14.00	15.95	19.35	24.73	710.60	46.20	164.30
3" Wet Engine with	173.70	23.37	13.19	14.57	17.82	25.58	639.00	NA	NA
Dry Engine off and			*13.19*		*14.00*	*25.58*	*113.00*	*<--- Calculated Heat Input to Warmup to 14.0*	
5% EVLN Flow			*14.00*		*17.82*	*25.58*	*526.00*	*<--- Calculated Heat Input from 14.0 K to 17.8*	

Hydrogen System Safety Requirements

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 (art. 5032,etc.)
- Compressed Gas Associates

FERMILAB: " Guidelines for the Design, Fabrication, Testing, Installation and Operation of LH2 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"

Ignition sources (NASA Guidelines)

- Electrical sparks or static electricity (breaking electrical connections, nylon clothing, etc.)
- Friction sparks, Impact sparks (sandblasting)
- Hydrogen auto-ignition (hot points, etc.), Temperature 584 C

➔ Minimum spark energies for ignition of H_2 in air is 0.017 mJ at 1 atm, 300 K
Lower pressure for ignition is ~1 psia (min abs. 0.02 psia or 1.4 mbar)

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

Hydrogen System Safety Requirements

Elements of design to lower the risk of ignition and safe the cryo-system

- ✓ Safety reviews by Fermilab LH_2 experts.
- ✓ Hazard analysis (What-if, FMEA, etc.).
- ✓ Operating procedures, emergency procedures.
- ✓ Instrumentation and components testing.
- ✓ Training on use of LH_2 .

- ✓ 25 liters of LH_2 can be contained at SPT in the vacuum buffer tank: no secondary container.
- ✓ Safety PLC for process controls (QUADlog), interlock, and warning system.
- ✓ Redundant safety system.
- ✓ Purged H_2 vent lines and electronic cabinet with N_2.
- ✓ Conduit, Power Limit Tray Cable and MC cables.
- ✓ Instrumentation choice: C1 D2 GB, capacitance type, Output signal 4-20 mA
- ✓ Weld and VCR fitting are preferred to flange or other fitting.
- ✓ Material recommended: Aluminum, austenitic steel, copper, titanium, PTFE, Kel-F, etc.
- ✓ Radiation hardness: 0.11mS/hr (11mrem/hr).

Vacuum Buffer Tank implementation

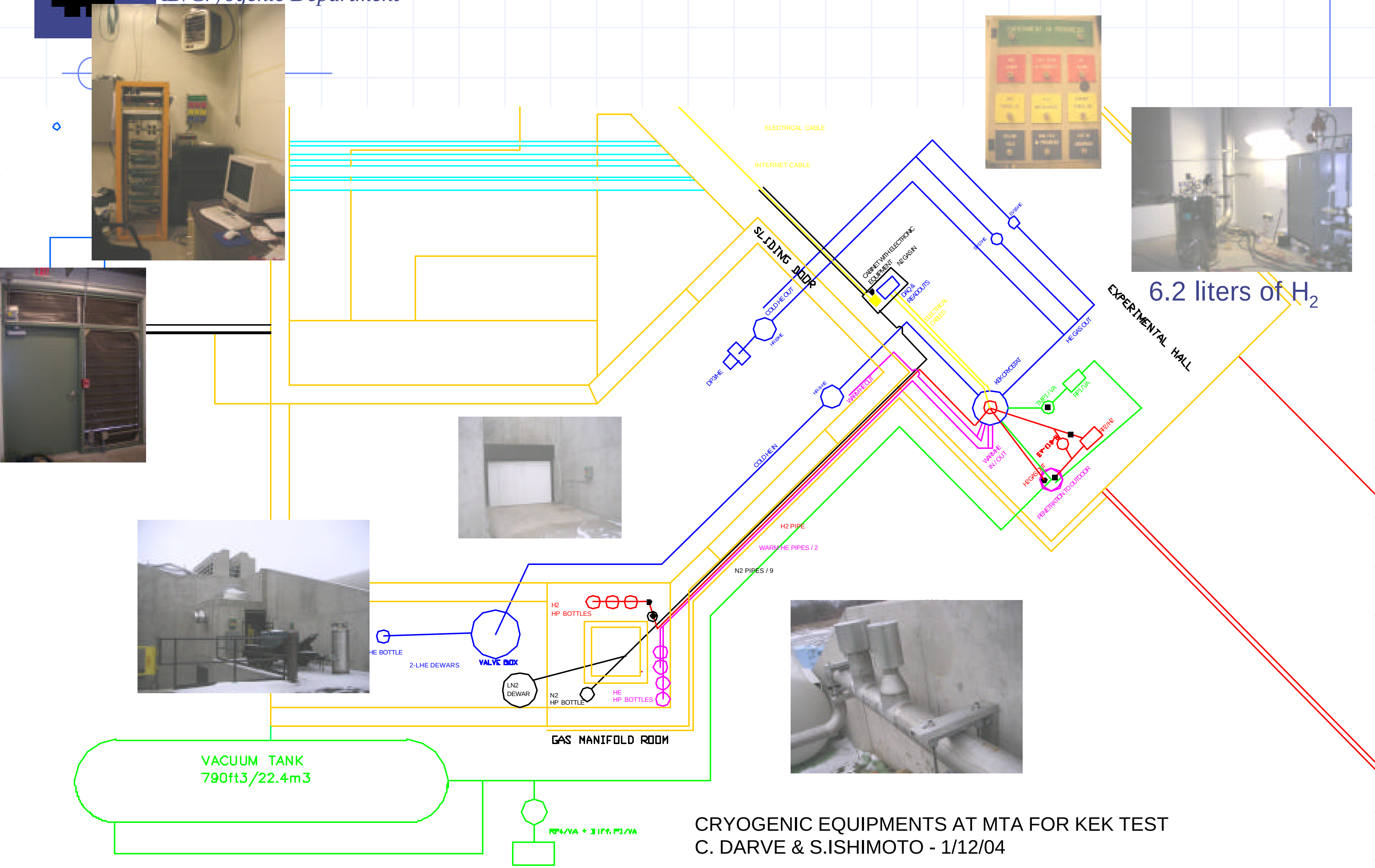
The total volume of the insulation vacuum in which the MTA LH_2 absorber is contained must be 790 times larger than the hydrogen cryo-loop capacity in order to withstand the saturated LH_2 expansion if a rupture of the system should occur.

H2 vent lines

Emergency hydrogen vent

A 22.4 m³ vacuum buffer tank is connected to the LH_2 absorber cryostat vacuum vessel to increase the vacuum volume and be in accordance with the safety requirements.

KEK convective LH_2 absorber test



6.2 liters of H_2

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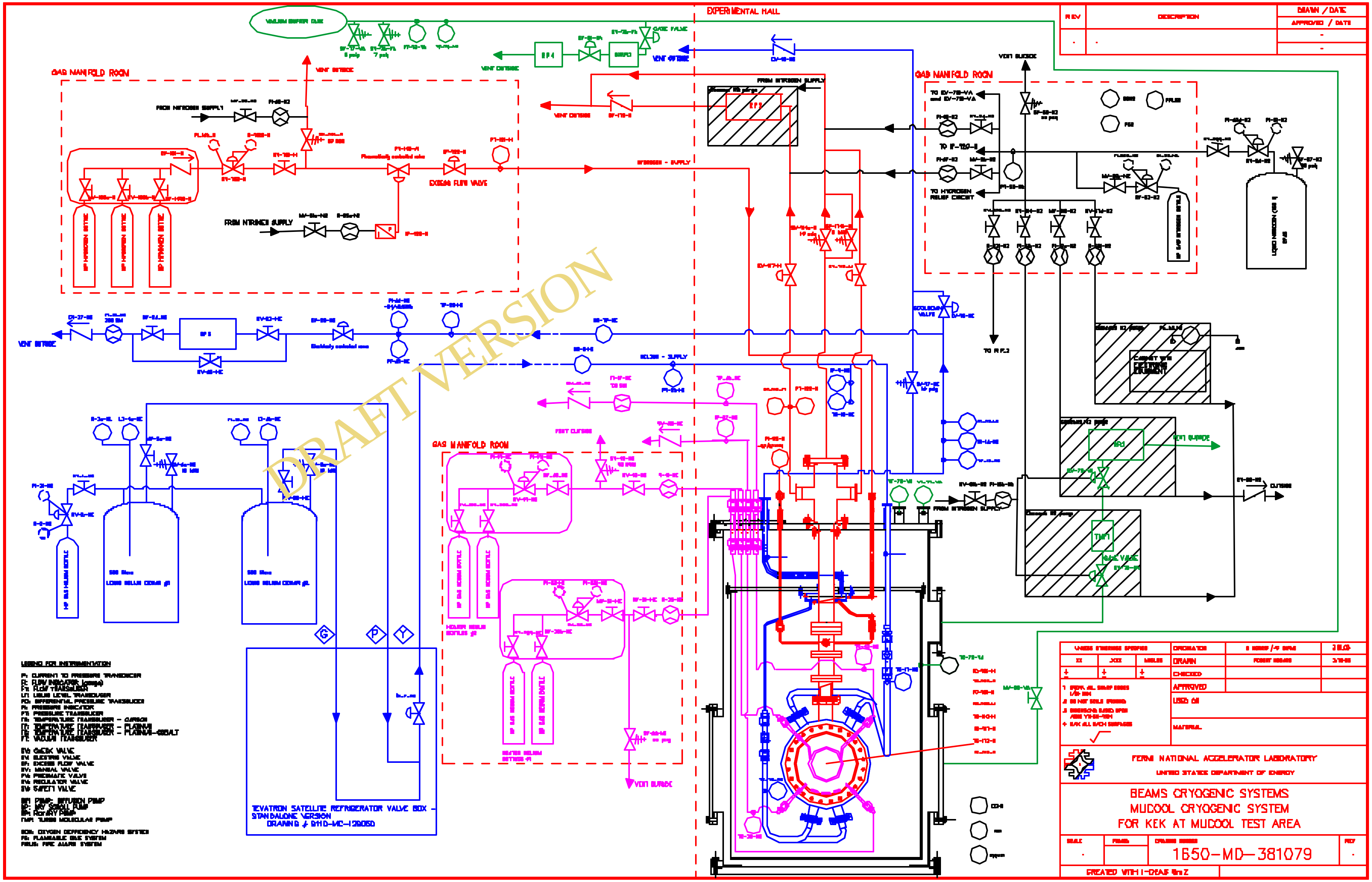
KEK convective LH_2 absorber test



KEK convective LH_2 Absorber test (Shigeru Ishimoto's talk)

KEK convective LH_2 absorber

KEK cryostat with H_2 to vacuum vent line

Instrumentation

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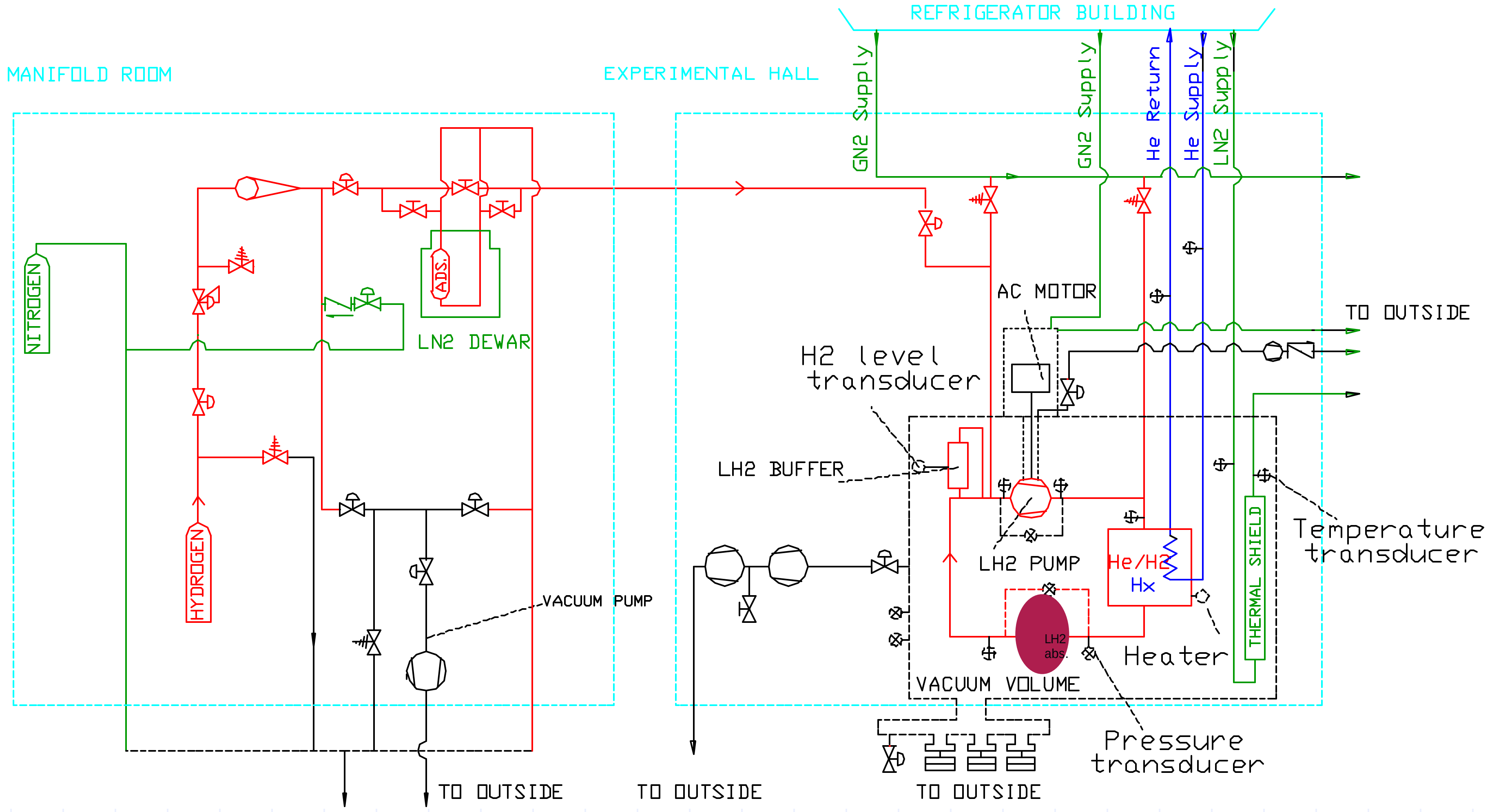
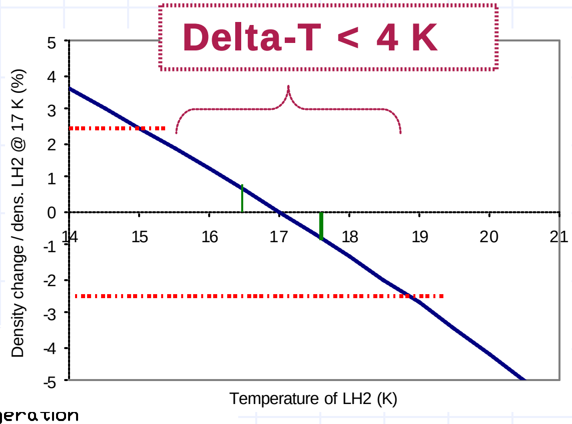
Forced-flow LH_2 Absorber test Flow Schematic

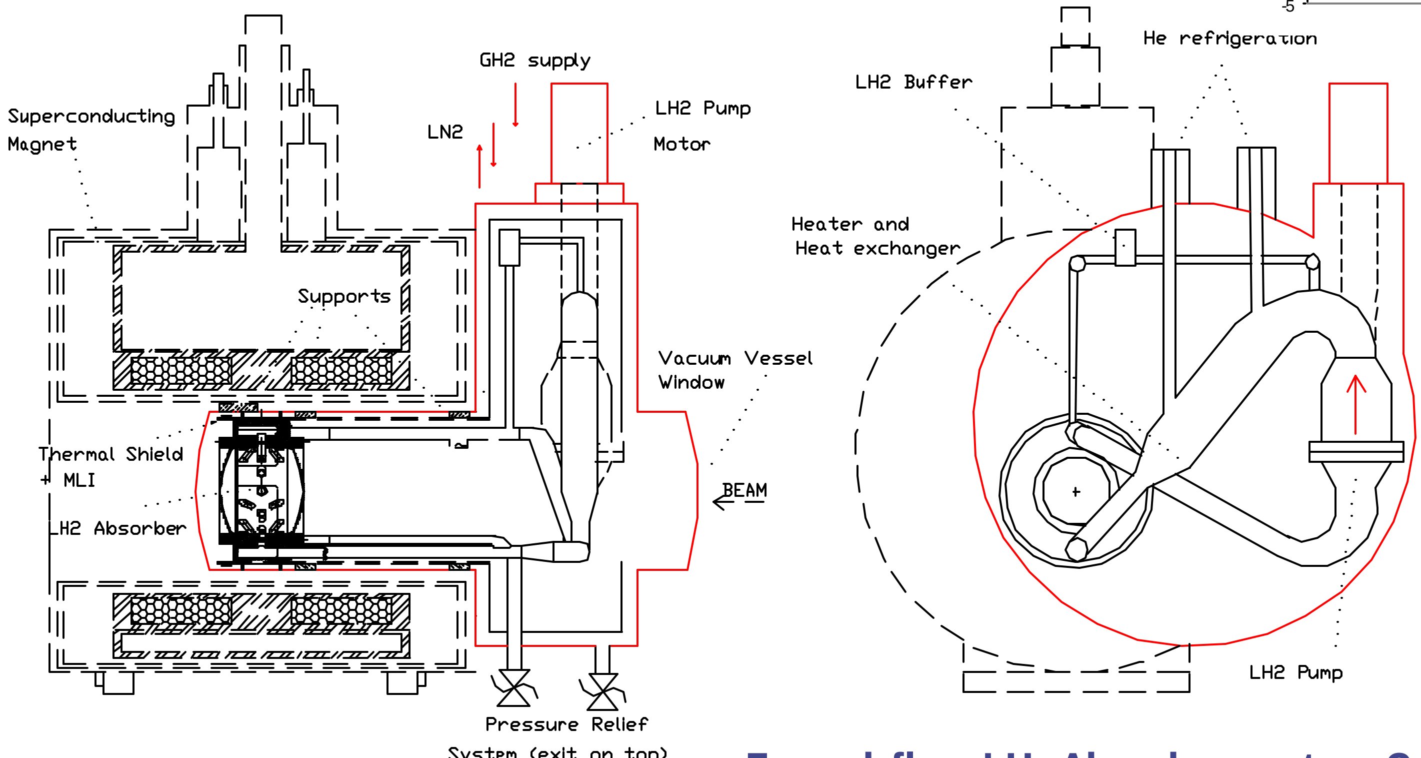


Forced-flow LH_2 Absorber Requirements



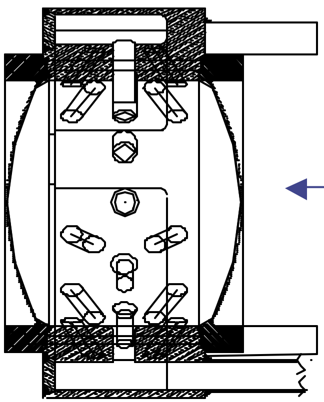
LH_2 volume contained in forced-flow LH_2 absorber

- ✓ Density fluctuation < +/- 2.5 %
- ✓ P=1.2 atm (17.6 Psia, 0.12 MPa)
- ✓ Sub-cool to 17 K to stay bellow boiling point
- ✓ Lag G solenoid magnet - 4 Tesla

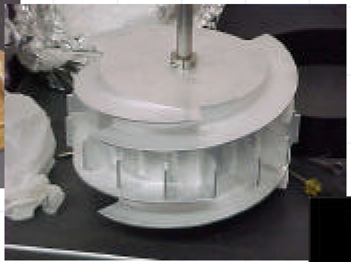


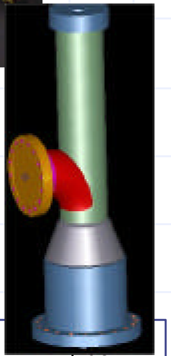
Forced-flow LH_2 Absorber system Conceptual Design

LH_2– Components

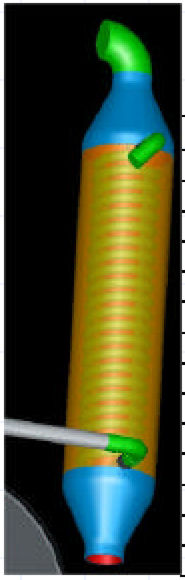


- Forced-flow LH_2 absorber (see Wing Lau's talk)
- LH_2 pump (SAMPLE/ Caltech)



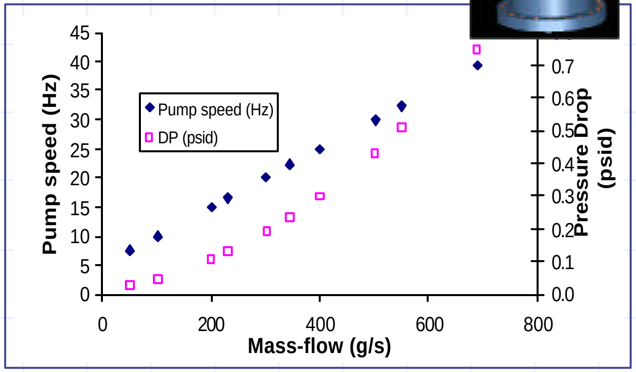


- He/ H_2 counter-current flow heat exchanger (500 W)



	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

- ✓ Transfer lines with cryo-system (H_2, He, N2)
- ✓ Instrumentation (PT, TT, LT, FT, IT, HR, etc.)
- ✓ Electro-pneumatic valves
- ✓ Piping (1", 2"IPS)
- ✓ LH_2 buffer (1 liter, LT, etc.)



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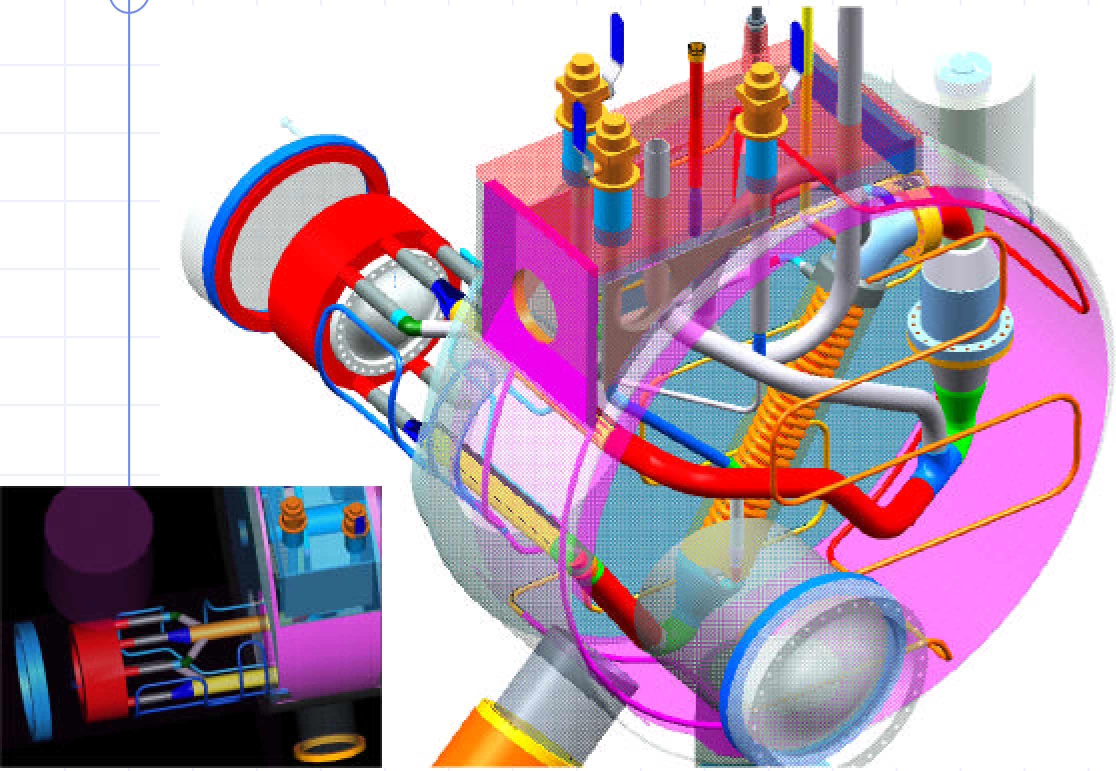
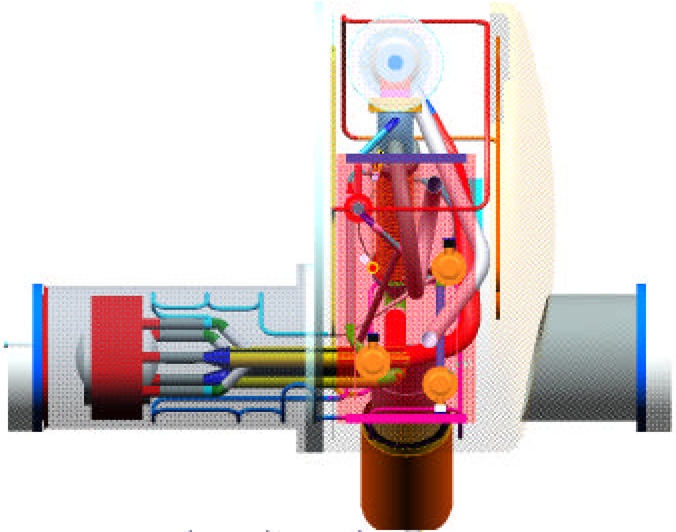
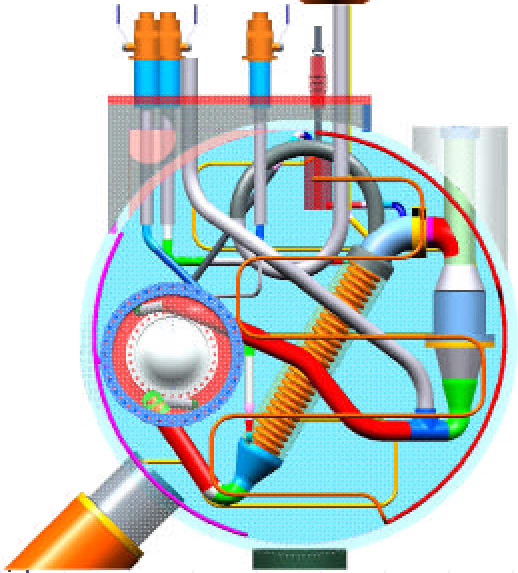
MTA LH_2 Absorber Cryostat – 3-D Model Conceptual Design







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

Conclusions

- The development of the cryogenic system for the MuCool Test Area is in compliance with safety codes.

- Helium refrigeration plant is sized according to the LH_2 forced-flow absorber test requirements and will make use of Tevatron satellite components.
- Expander test has been performed to ensure the supply of 27 g/s of helium at 14 K, 15 psig (0.2 MPa).
- Supply of 5 K helium to the Lab G solenoid magnet will be possible with a switchover mode of the refrigeration plant as the intense ionization beam will be off. Ten hours is needed to fill the solenoid magnet from 14 K to 5 K.
- Liquid helium Dewar will be used to ensure 1.58 g/s of helium supply to maintain the forced-flow LH_2 absorber at 14-20 K.
- Liquefaction rate is 78 liter/hr.

- A first configuration with helium and nitrogen Dewar will permit to operate KEK convective LH_2 absorber test and RF cavities test with the Lab G solenoid magnet.

- The Conceptual Design of the forced-flow LH_2 absorber design was presented.

Extra slides

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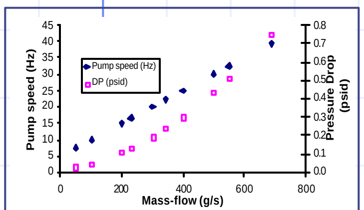
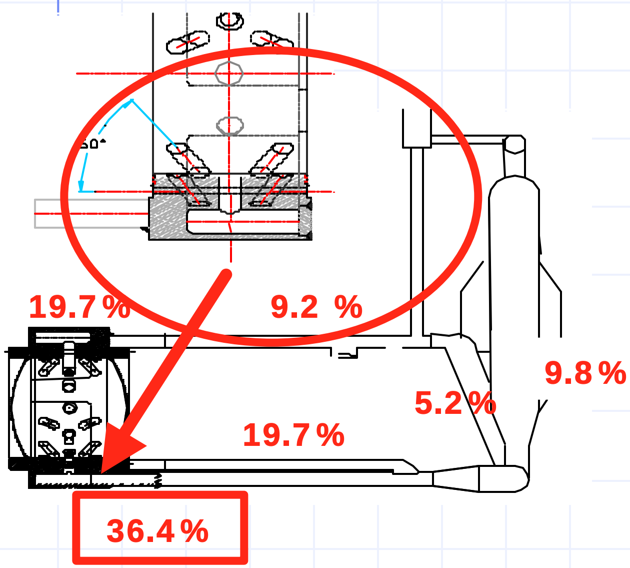
Forced-flow
Heat Transfer Numerical Calculations

LH2 pump characteristics:
ΔP = 2,517 MPa (0.365 psi) @ m=450 g/s

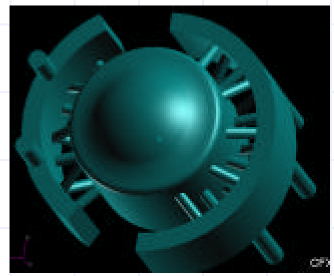


Pressure drop in LH_2 circuit



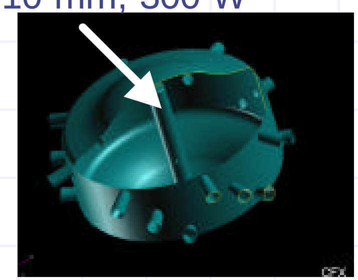
- LH_2 absorber geometry

Several models and configurations:
→ w/ and w/o inner channel
→A: 11 inlet/15 outlet; B: 15/19; etc



- Beam simulation

ϕ 10 mm, 300 W



- Velocity at inner chamber
- LH_2 properties (17 K, 1.2 atm)

CFD

CFD

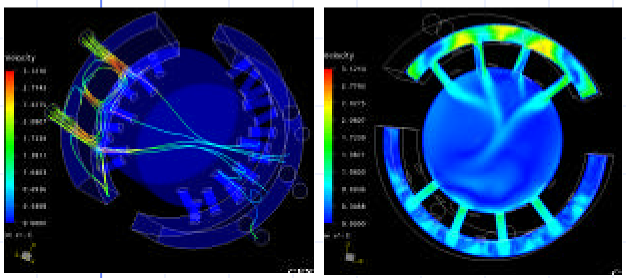
- ➢ **Velocity distribution**

Heat transfer coeff.

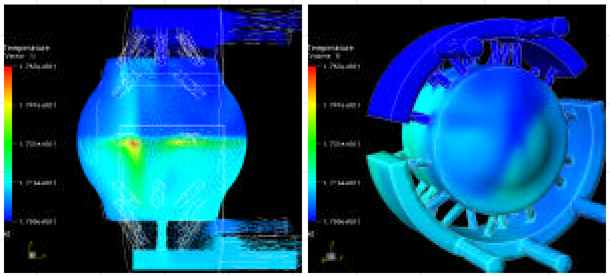
- ➢ **Temperature**
- ➢ **Pressure**

Forced-flow
Heat Transfer Numerical Calculations

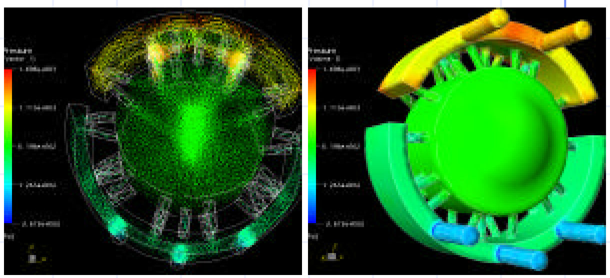
Velocity distribution:

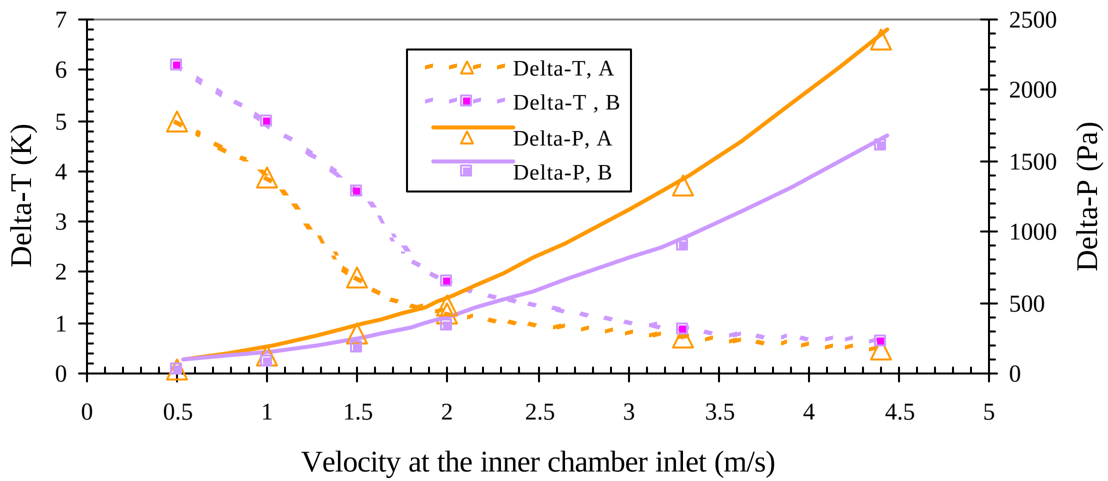


Temperature distribution:



Pressure distribution:





- ➔ Influence of flow symmetry and number of active nozzles
- ➔ Configuration with 15 inlet nozzles and 19 outlet nozzles; velocity 2 m/s at inner chamber inlet

The design of the MTA cryo-system permits us to create the Aborber Safety Review book-Ref ES&H:

5032.2: GUIDELINES FOR THE DESIGN, REVIEW AND APPROVAL OF LIQUID CRYOGENIC TARGETS

The Target Safety Review book shall contain 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

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Introduction to Muon Ionization Cooling R&D (MuCool)

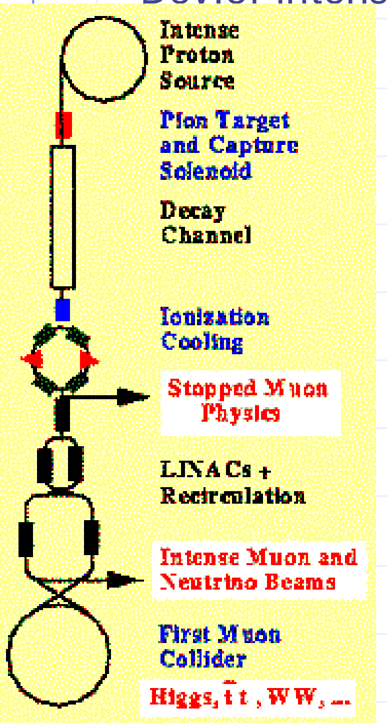
Muon Collaboration

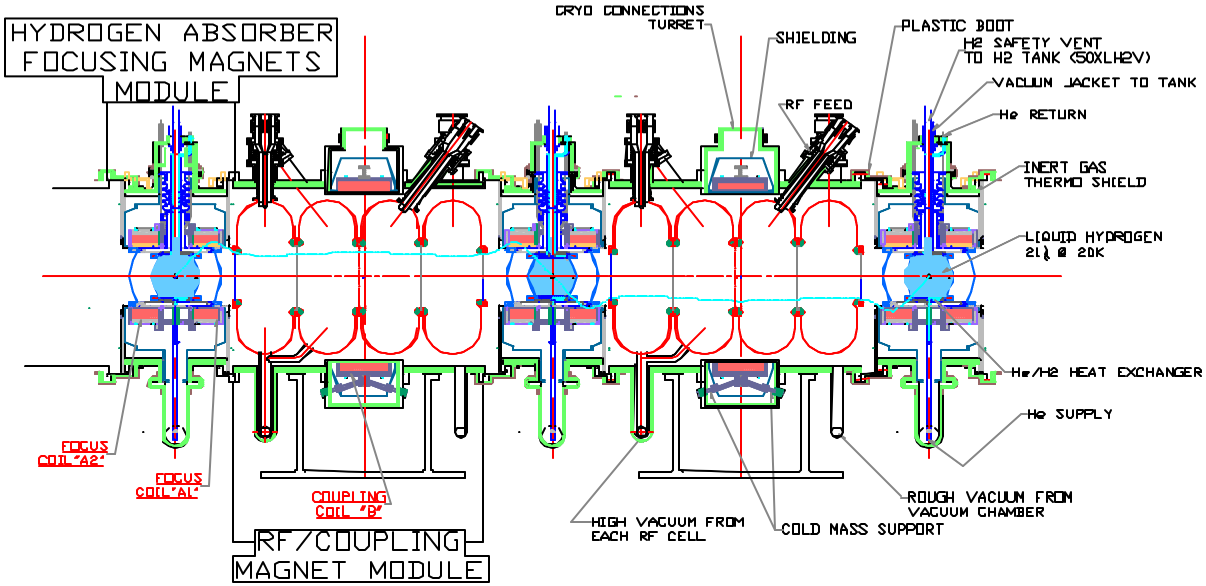
MuCool Collaboration: 18 institutions from US, Europe and Japan

- Muon Collider and Neutrino Factories ["Recent progress in neutrino factory and muon collider research within the Muon Collaboration", Physical review special topics- Accelerators and Beams, vol. 6, 081001 (2003)]

Mission

- Design, prototype and bench test all cooling-channel components (RF, LH_2 absorber,etc.)
- Support cooling demonstration in muon beam (MICE)
- Dev.of intense ionization beam (400 MeV beam up to 2.4×10^{14} p/s: 570 W in 35-cm LH_2 absorber)





Introduction to Muon Ionization Cooling R&D (MuCool)

Principles

Beam optic and emittance:

$$s_x = \sqrt{\frac{e_n b_x}{g}}$$

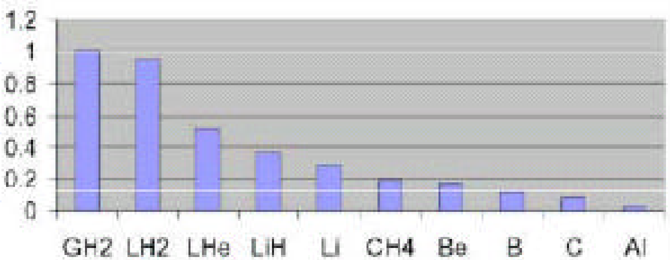
Energy Loss vs. Coulomb Scattering

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

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

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

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] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	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 ($(n-1)\times 10^6$ 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		—

Helium Cryogenic Facilities - Status

Cryogenics at MuCool Test Area