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THE LIQUID HYDROGEN SYSTEM FOR THE MUCOOL TEST AREA

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Cryogenic Engineering Conference 2003

Headlines

- **Introduction to Muon Ionization Cooling R&D (MuCool)**
  - Organization & Mission
  - Principles and proposal
- **Cryogenics at MuCool Test Area**
  - MTA Presentation
  - Helium Cryogenic Facilities
  - MTA Cryo-System Flow Schematic
  - Hydrogen System Stability Issues
- **Forced-flow LH_2 Circuit**
  - Components and Requirements
  - LH_2 Absorber Cryostat
  - Heat Transfer Numerical Calculations
- **Conclusions**

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Introduction to Muon Ionization Cooling R&D (MuCool)

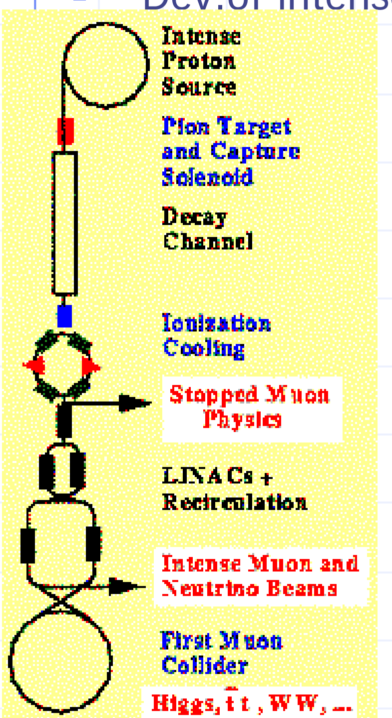
Muon Collaboration

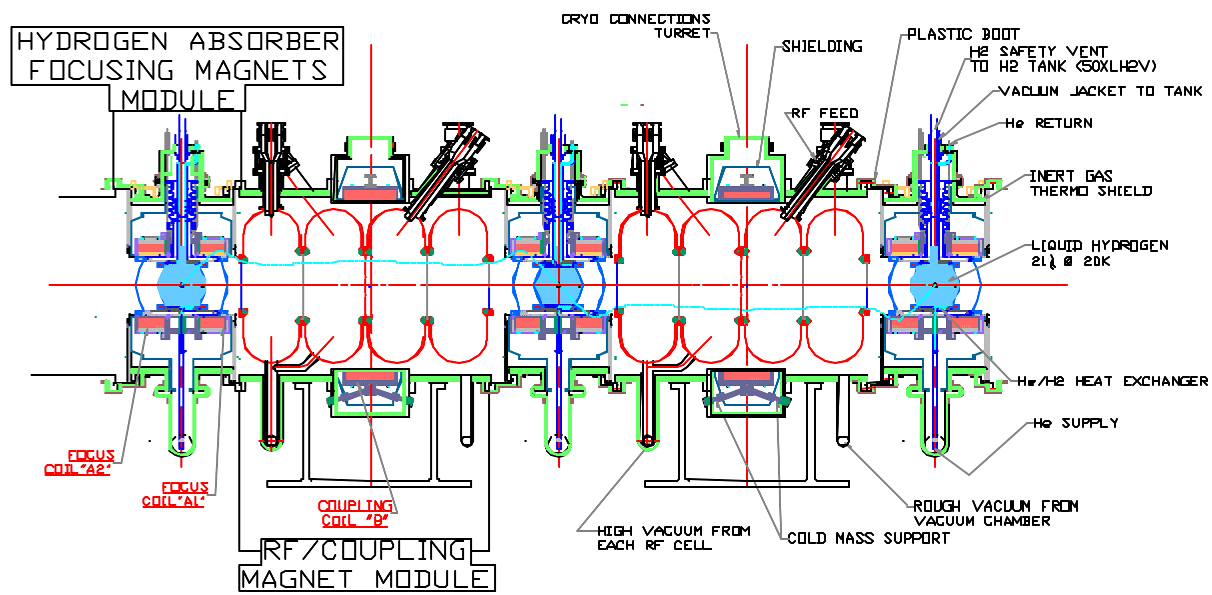
MuCool Collaboration: 18 institutions from US, Europe and Japan

- 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: $s_x = \sqrt{\dfrac{e_n b_x}{g}}$

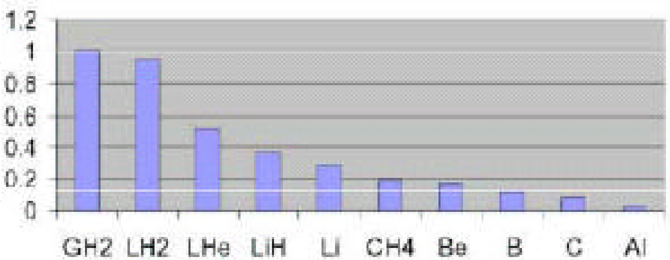
Energy Loss vs. Coulomb Scattering

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

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

$\dfrac{1}{L_R} a Z^2$ 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}	$dE/dx\vert_{min}$[b] $\left\{\frac{\text{MeV}}{\text{g/cm}^2}\right\}$	Radiation length[c] X_0 {g/cm²}	{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		—

Introduction to Muon Ionization Cooling R&D (MuCool) - Proposal

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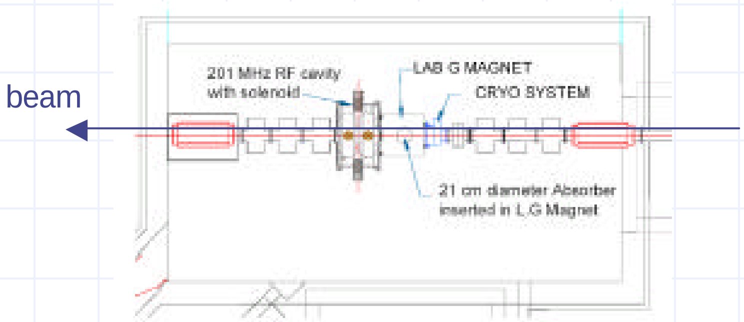
The beam is "cooled" by energy loss in the cooling channel; both transverse and longitudinal momentum is lost to collisions with atomic electrons but the longitudinal momentum is restored by the RF acceleration between the absorbers.



Energy deposition by intense ionization beam in LH_2 absorber was estimated to 7-10 W/cm

Up to 300 W (nominal at 150 W) thermal power due to beam simulation to remove from LH_2 absorber

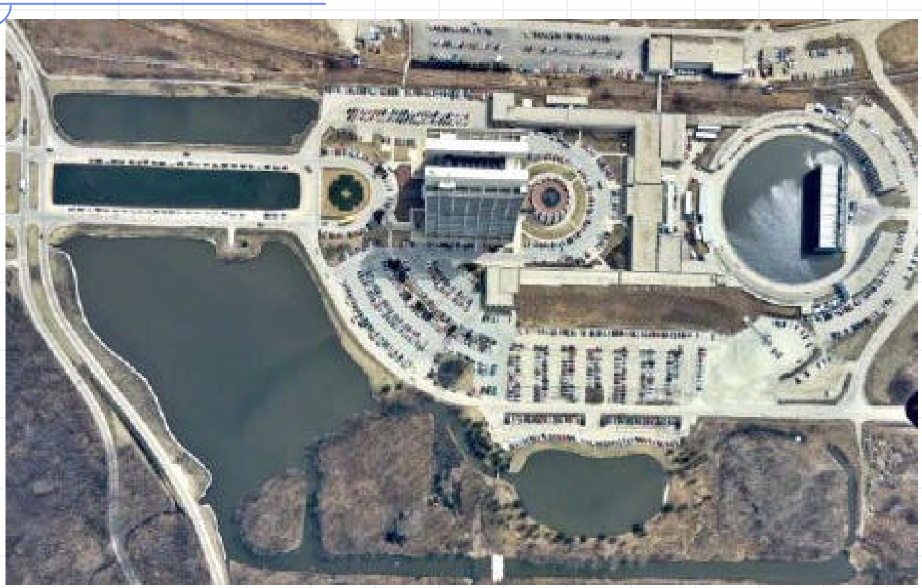
➔ Refrigeration: subcool hydrogen @ 17 K

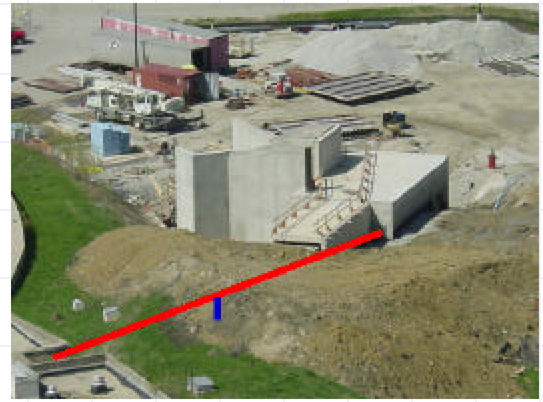
➔Two LH_2 absorbers heat transfer modes: convection and forced-flow types

Proposed system characteristics

Item	Value	Unit
Volume of the LH_2 loop	25	liter
Volume of the vacuum space	35,000	liter
Refrigeration capacity	500	W
Refrigeration max mass flow	27	g/s
Refrigeration operating temperature	14	K
Refrigeration operating pressure	0.2	MPa
LH_2 heat removal capacity	500	W
LH_2 operating temperature	17	K
LH_2 operating pressure	0.12	MPa
LH_2 density	74.28	kg/m3
H_2 boiling point 0.12 (0.21 MPa)	21 (24)	K
H_2 freezing point at 0.12 (0.21 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
20 degree C: liquid H2 volume ratio	790	-

Cryogenics at MuCool Test Area

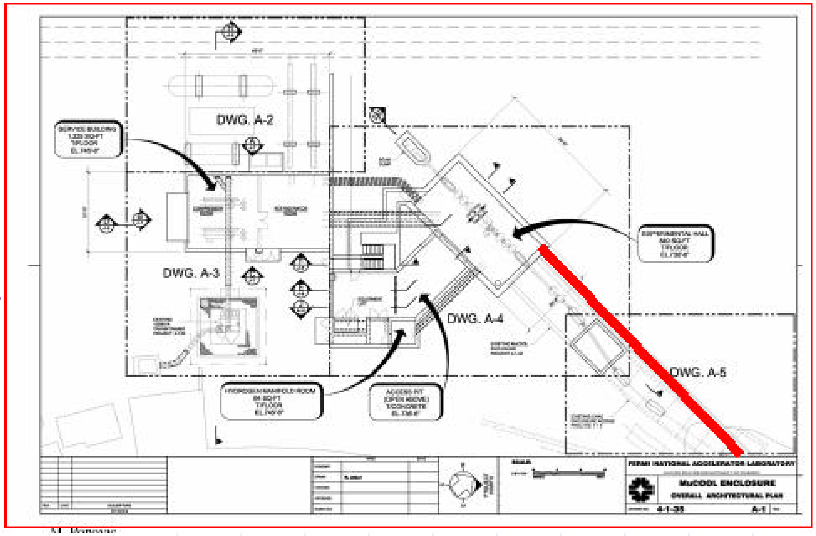


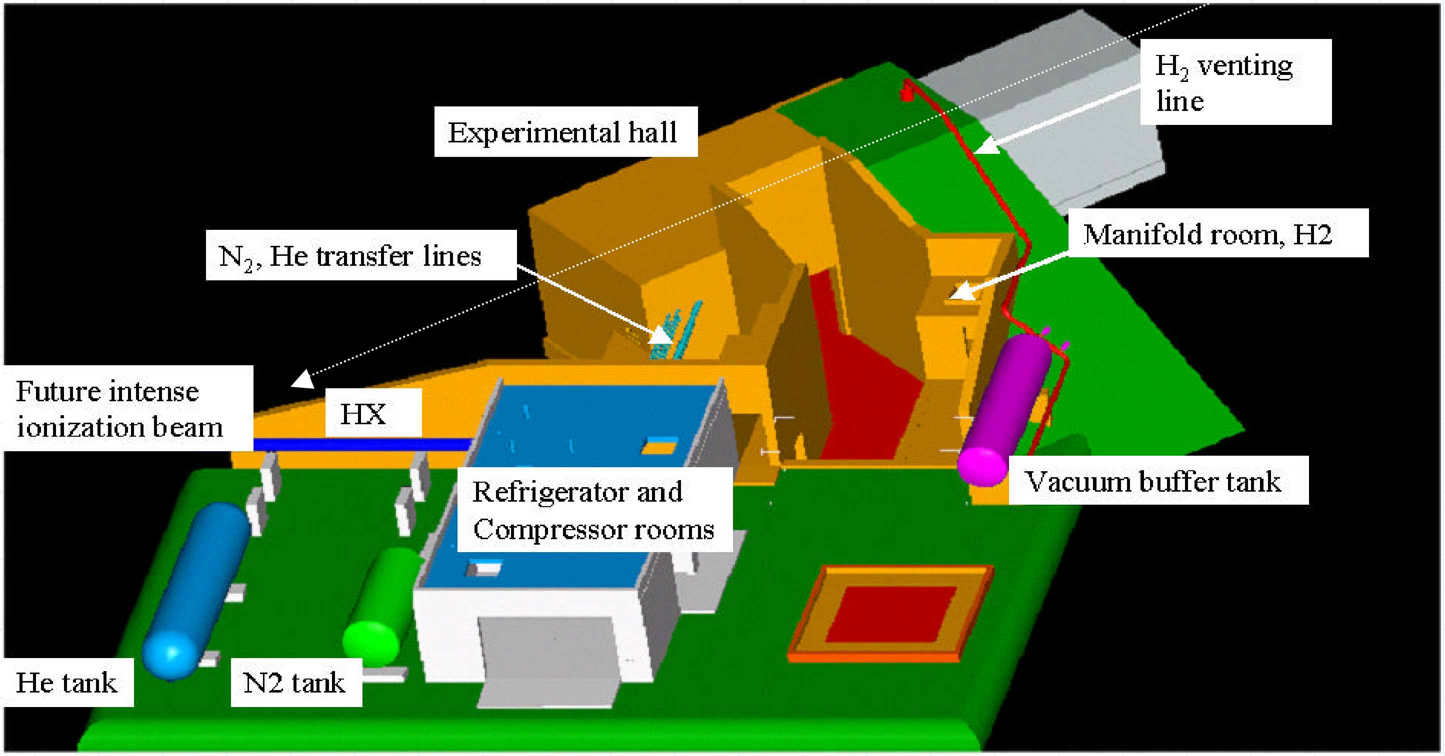


Cryogenics at MuCool Test Area

Construction of MTA building with beneficial occupancy on October 2003:

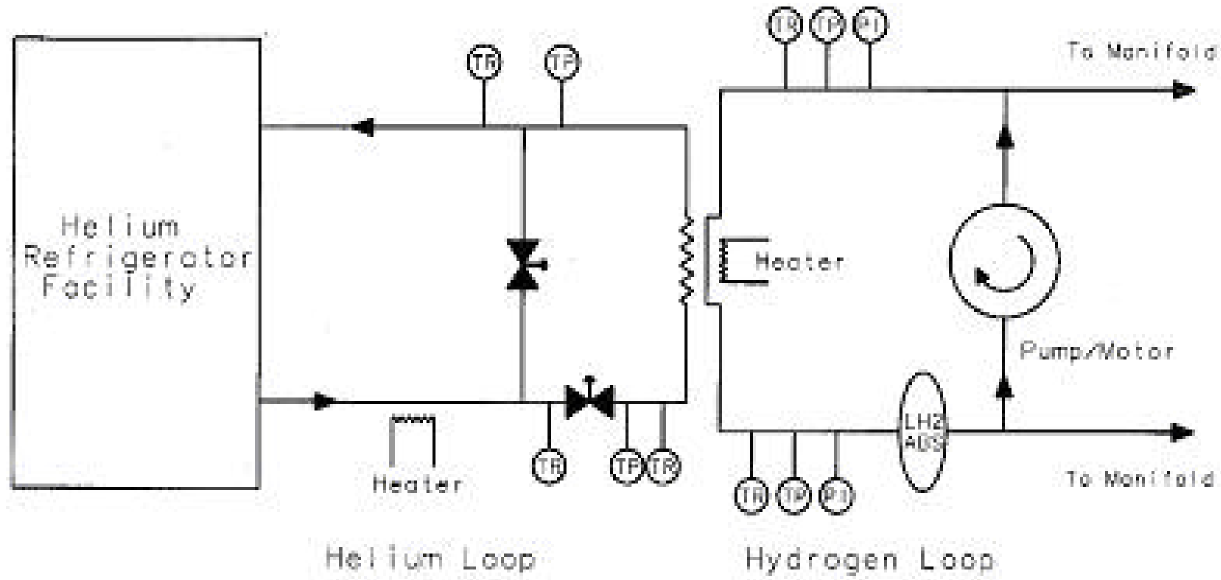
→ Test of convection type LH_2 absorber till March 2003
→ Test of forced-flow LH_2 absorber, RF cavities, etc.





Helium Cryogenic Facilities

Flow schematic:



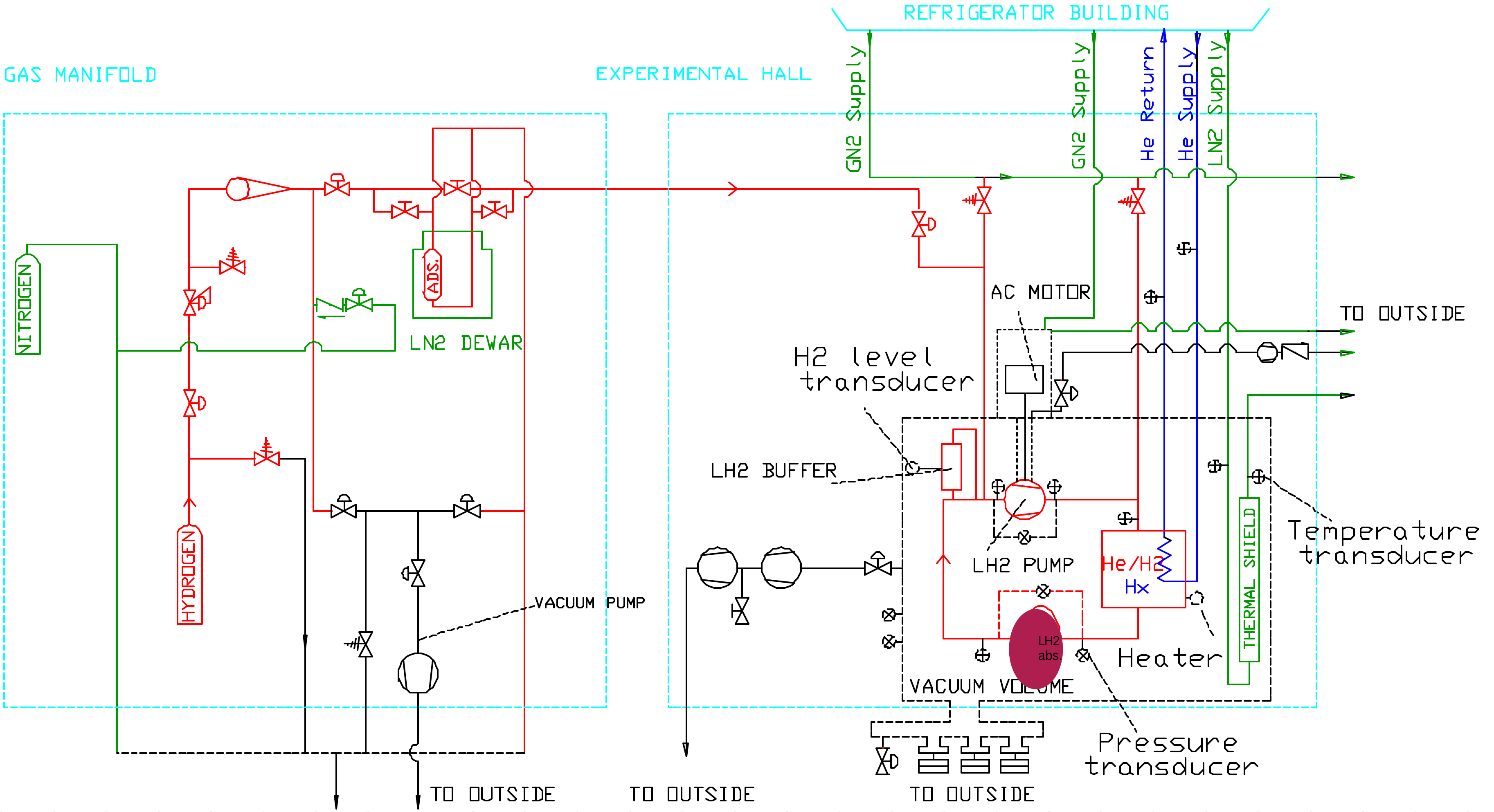
Compressor Room

- Two 400 HP 2-stage oil injected screw compressors

Refrigerator Room

- Tevatron satellite refrigerator used normally for <5 K operation (to be operated at 14 K output)
- Dual cylinder 30 K reciprocating expansion engine
- Transfer line connections to experimental hall which includes 5K, 20K, 80K circuits

MTA Cryo-system Flow Schematic



Hydrogen System Stability Issues

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

Class I Division II, Group B or intrinsically safe

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 (metal on metal, stone on stone)
- Impact sparks (sandblasting)
- 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 // 1.4 mbar)

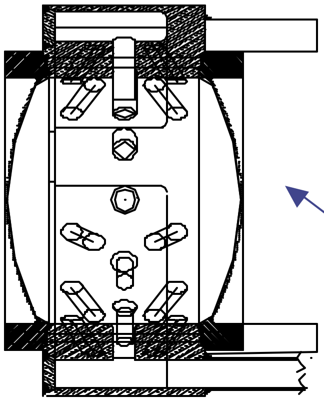
Hydrogen System Stability Issues

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

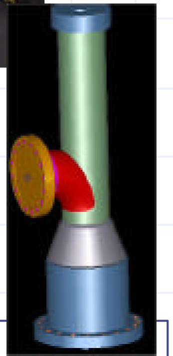
- ✓ Safety Review by Fermilab LH_2 experts.
- ✓ Hazard analysis (What-if, FMEA, etc.).
- ✓ Operating procedures, emergency procedures.
- ✓ Instrumentation and components testing.
- ✓ Training on use of LH_2 .

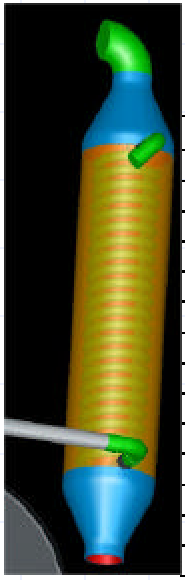
- ✓ Redundant safety system.
- ✓ 25 liters of LH_2 can be contained at SPT in the vacuum buffer tank: no secondary container.
- ✓ Material recommended: Aluminum, austenitic steel, copper, titanium, PTFE, Kel-F, etc.
- ✓ Radiation hardness: 0.11mS/hr (11mrem/hr).
- ✓ Purged venting line with N_2. , barrier, vent and exhaust system.
- ✓ Instrumentation choice: NEC, capacitance type, Output 4-20 mA signal to lower the risk of ignition.
- ✓ Safety PLC for process controls, warning, and interlock mechanisms (QUADlog).
- ✓ Weld and VCR fitting are preferred to flange or other fitting. Doubled-seal flange.

LH_2 Circuit – Components



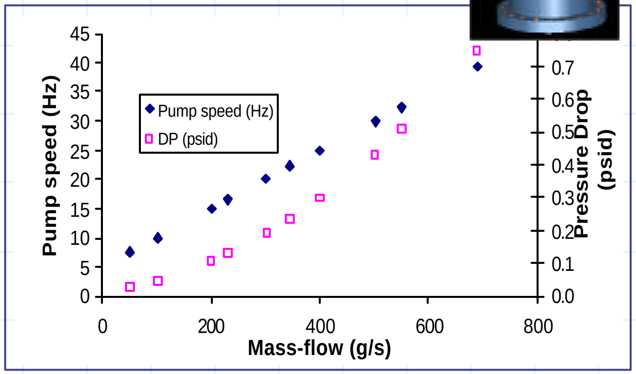
- LH_2 absorber
- LH_2 pump
- He/ H_2 counter flow heat exchanger (500 W)



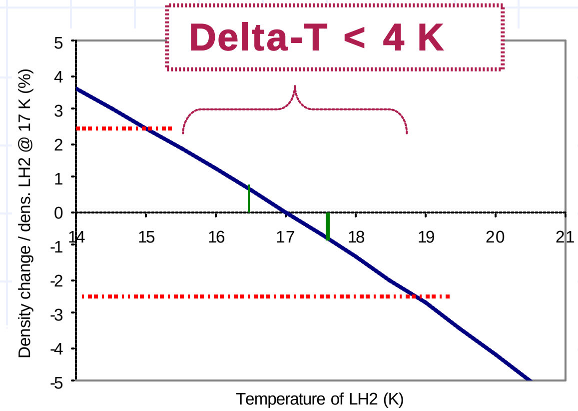


	LH_2	He	Unit
P	17.6	30.7	psia
$T_{average}$	17.5	15.8	K
m	63	21	g/s
r (P,T)	*74.28*	5.7	kg/m^3
Cp (P,T)	*8082*	5353	J/kg-K
h (P,T)	171.4	32.6	µpoise
l (P,T)	100	24	mW/m-K
Pr	1.382		
A_{flow}	14.55	1.56	cm^2
G	4.33	13	g/cm^2-s
D_e	0.336	0.378	cm
A_{hex}	11.25		cm^2/in
h	0.109	0.183	W/cm^2-
U	247		W/K

- ✓ 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.)

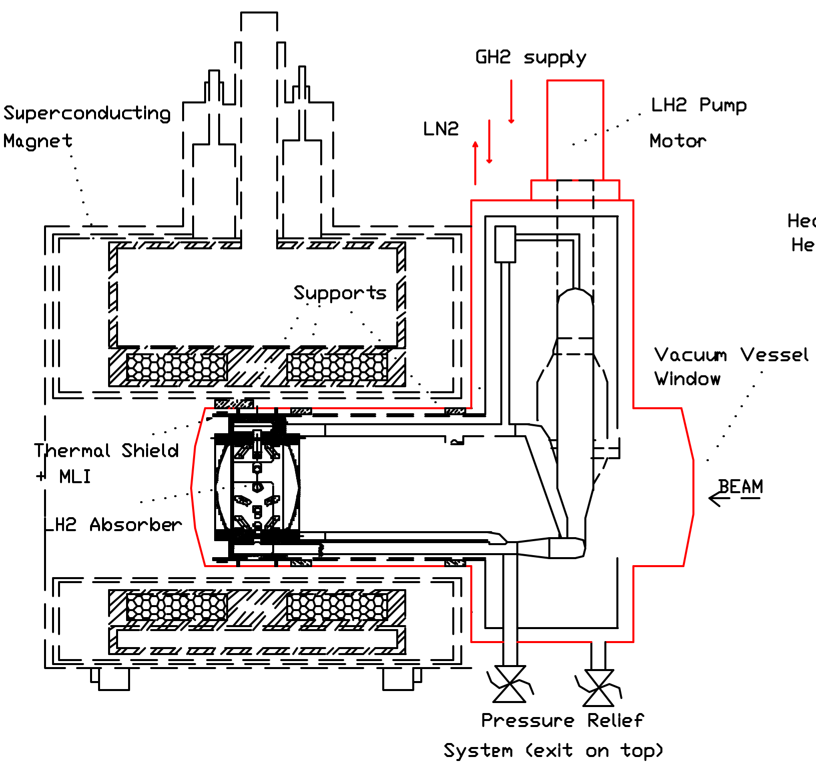


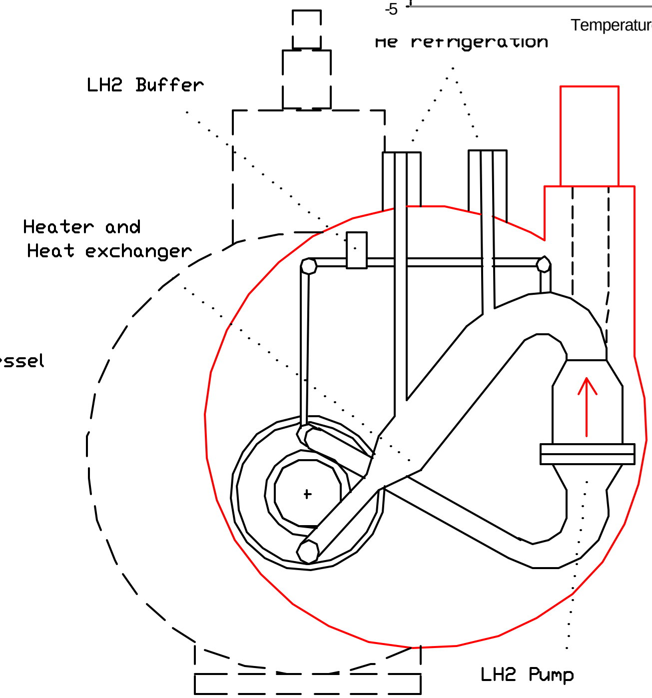
LH_2 Circuit - Requirements



LH_2 volume contained in LH_2 absorber

- ✓ Density fluctuation < +/- 2.5 %
- ✓ P=1.2 atm
- ✓ Subcool at 17 K to stay bellow boiling point
- ✓ 5 Tesla magnetic field





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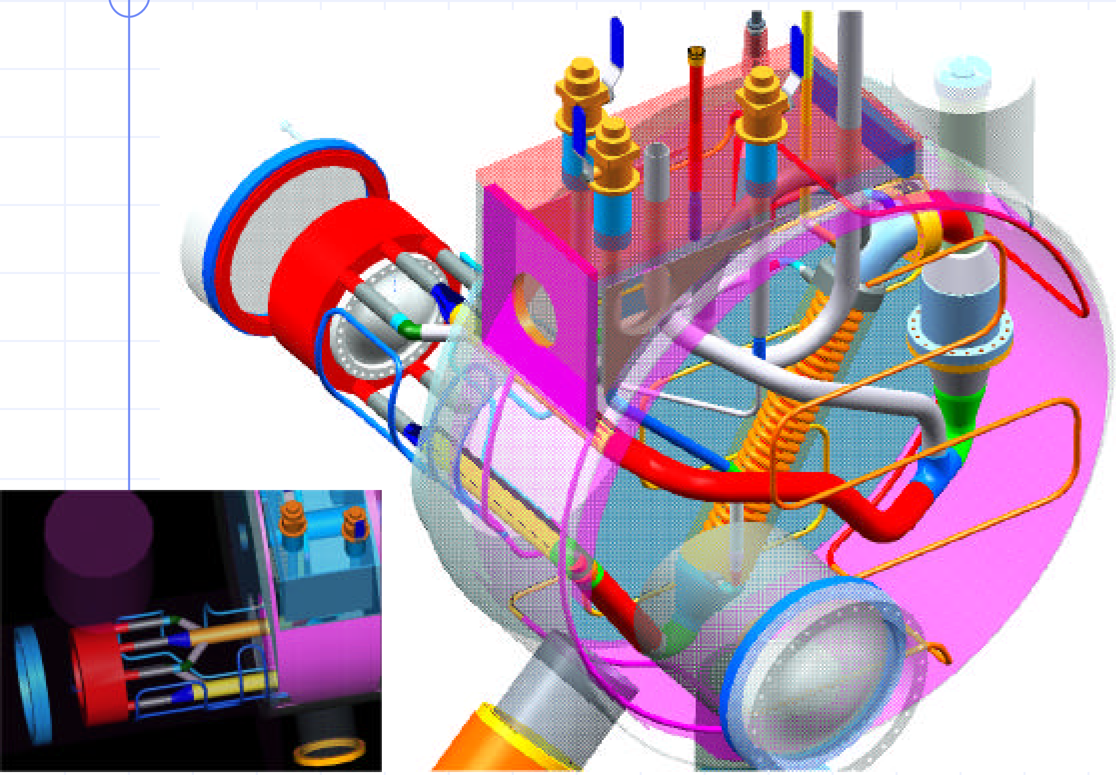
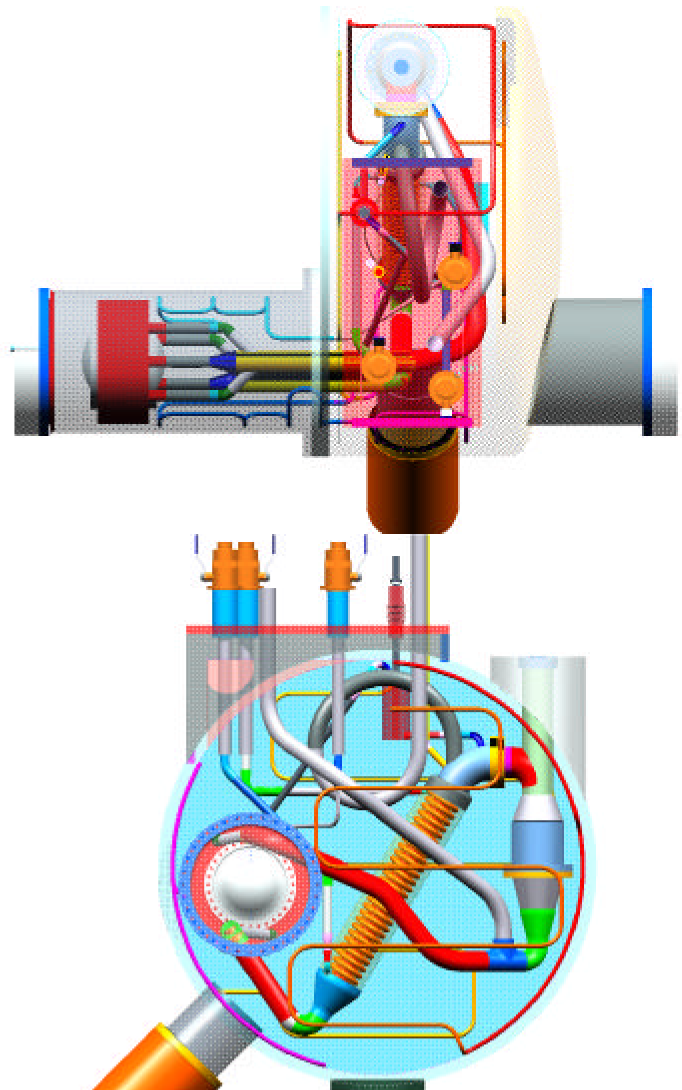
MTA LH_2 Absorber Cryostat – 3-D Model





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

Heat Transfer Numerical Calculations

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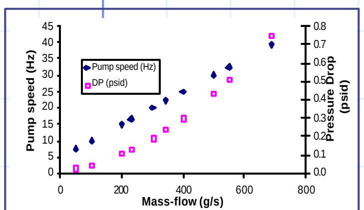
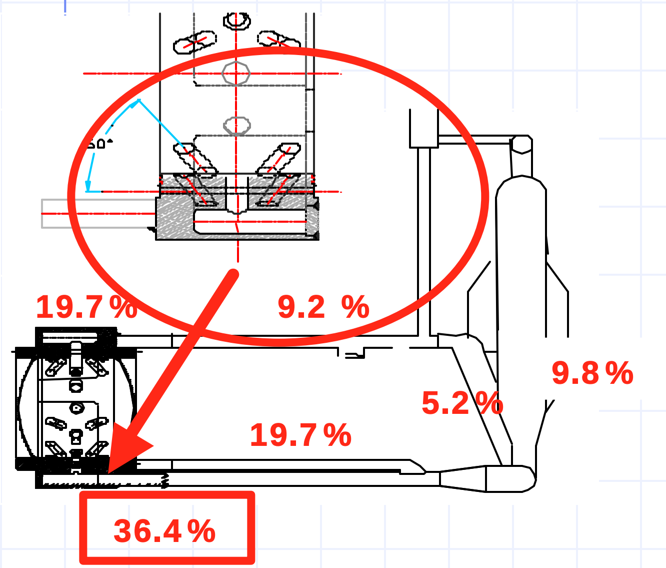
LH2 pump characteristics:
ΔP = 2,517 MPa (0.365 psi) @ m=450 g/s

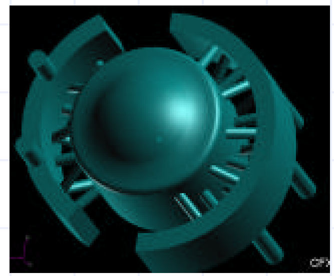


Pressure drop in LH_2 circuit



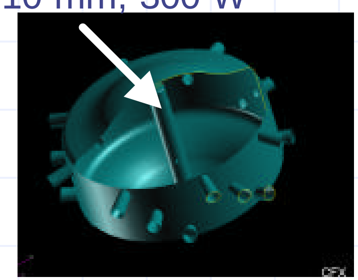
- LH_2 absorber geometry

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

➢ **Velocity distribution**

Heat transfer coeff.

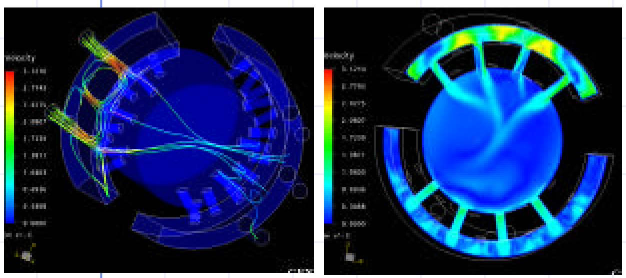
➢ **Temperature**

➢ **Pressure**

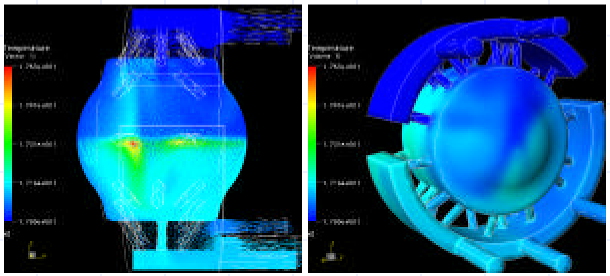
CFD

Heat Transfer Numerical Calculations

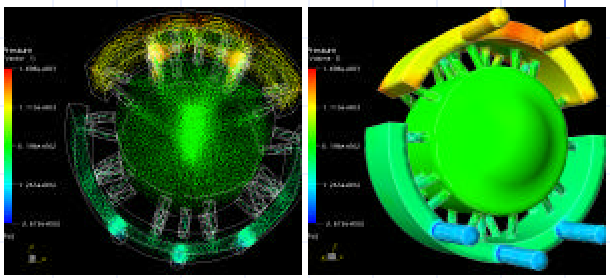
Velocity distribution:

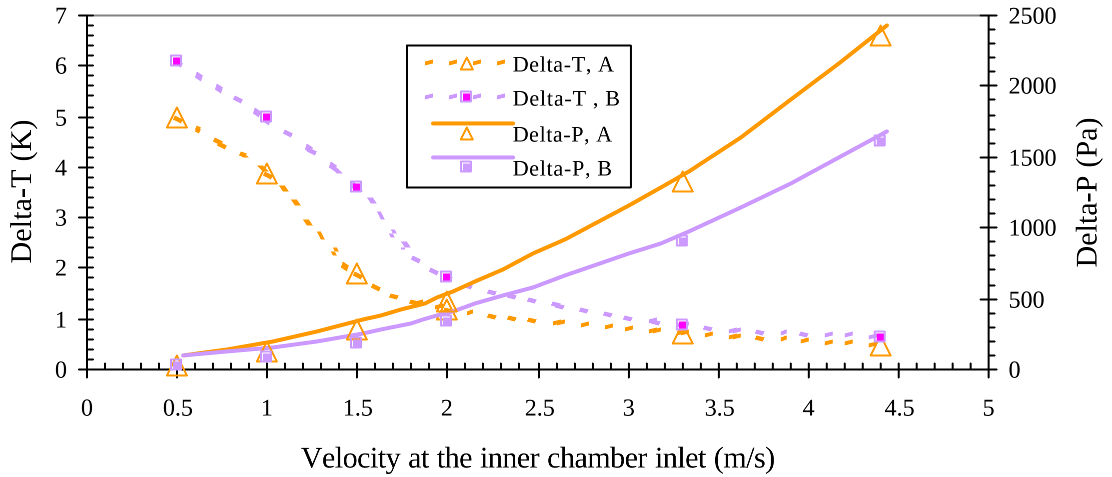


Temperature distribution:



Pressure distribution:





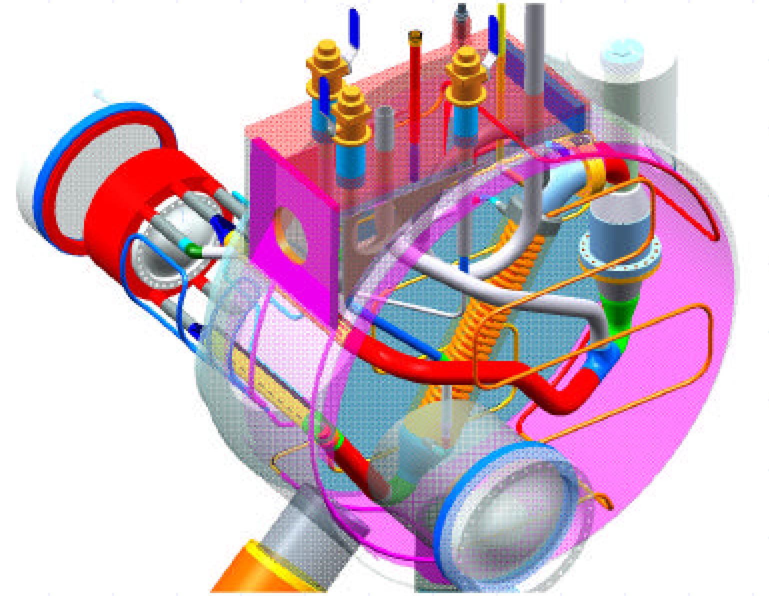
- ➔ Influence of flow symmetry and number of active nozzles
- ➔ Configuration with 15 inlet nozzles and 19 outlet nozzles; velocity 2 m/s at inner chamber inlet

Conclusions

- Challenge of LH_2 use to validate the feasibility of ionization cooling in LH_2 absorber (convection and forced-flow types)

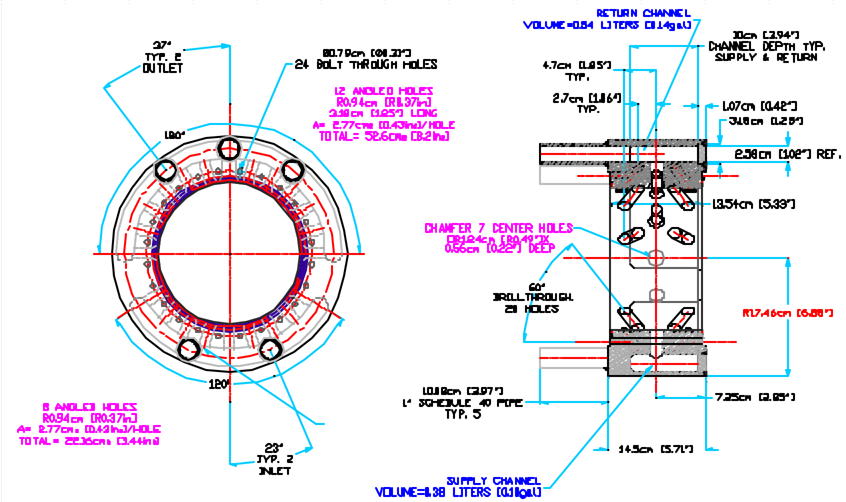
  - Development of the LH_2 system for the MuCool Test Area in compliance with safety codes. Implementation of a complete cryogenic refrigeration system.

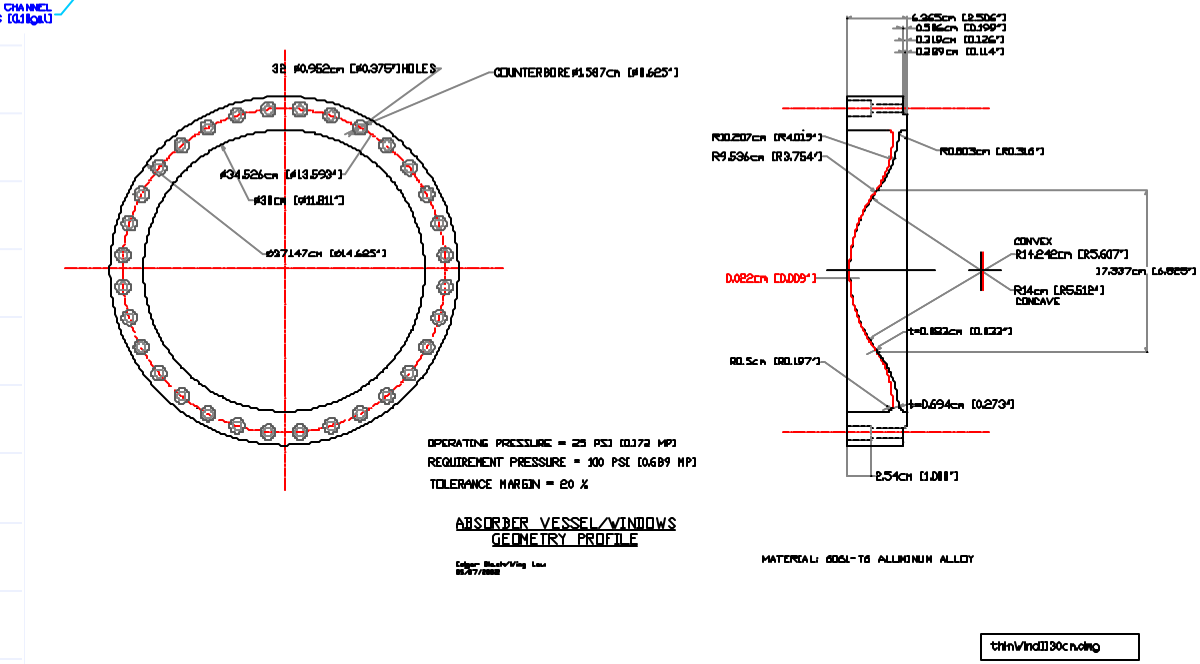
    - CFD results permit us to address the LH_2 force flow design and permit us to understand the interdependences between the LH_2 flow characteristics.



Additional slides

LH_2 Absorber Design





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