Flow Absorber Possibilities

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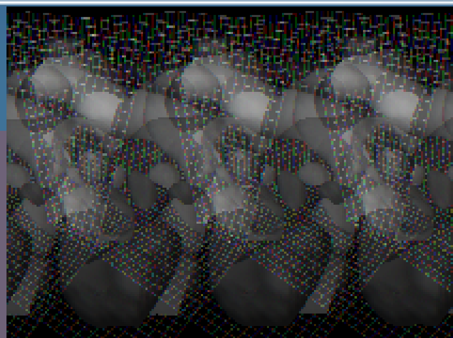
Neutrino Factory & Muon Collider Collaboration Meeting

@ IIT

03/12/06

Flow Absorber possibilities



D. B. Leinweber, hep-lat/0004025

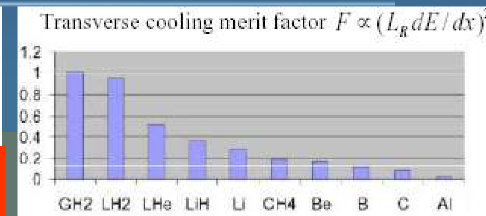
From simulations to experiments...

Headlines:

- Materials and fluids for Muon ionization cooling
- Disadvantages of the LH_2 choice
- Review of the basic LH_2 Absorbers designs
- Design philosophy for a hostile environment
- Implementing SAMPLE cryo-loop
- Cryo-system to support the LH_2 absorber tests at MTA
- Concluding comments

Materials and fluids for Muon ionization cooling

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 ($(n-1)\times10^6$ 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		—



Source: NASA, Glenn Research Center Safety Manual

$$\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2}\underbrace{\frac{dE_\mu}{ds}}_{\frac{dE}{dx} \propto \frac{Z}{A}}\frac{\varepsilon_n}{E_\mu} + \frac{1}{\beta^3}\underbrace{\frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu L_R}}_{\frac{1}{L_R} \propto Z^2}$$

Ionization cooling

Bethe-Bloch

multiple scattering

Item	Value	Unit
LH2 operating temperature	17	K
LH2 operating pressure	0.12	MPa
LH2 density	74.28	kg/m³
H2 boiling point at 0.12 MPa	21	K
H2 freezing point at 0.12 MPa	14	K
LH2 viscosity	3.05	10^{-6} Pa-s
LH2 specific heat	7696	J/kg-K
Heat of vaporization	445.6	kJ/kg
LH2 thermal conductibility	97	mW/m-K
Liquid H2 volume ratio at 20 degree C	790	-

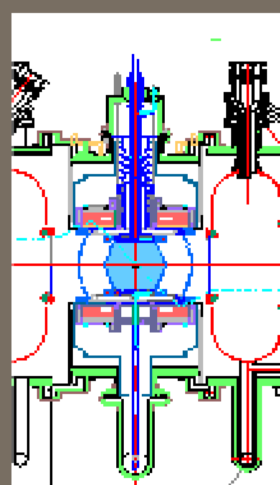


Table A5.1

Summary of Material Compatibility for Hydrogen Service

Material	Service GH2	Service LH2	Service SLH2	Remarks
Aluminum and its alloys	Yes	Yes	Yes	
Austenitic stainless steels with > 7% nickel (such as, 304, 304L, 308, 316, 321, 347)	Yes	Yes	Yes	Some make martensitic conversion if stressed above yield point at low temperature.
Carbon steels	Yes	No	No	Too brittle for cryogenic service.
Copper and its alloys (such as, brass, bronze, and copper-nickel)	Yes	Yes	Yes	
Gray, ductile, or cast iron	No	No	No	Not permitted for hydrogen service.
Low-alloy steels	Yes	No	No	Too brittle for cryogenic service.
Nickel and its alloys (such as, Inconel® and Monel®)	No	Yes	Yes	Susceptible to hydrogen embrittlement
Nickel steels (such as, 2.25, 3.5, 5, and 9 % Ni)	No	No	No	Ductility lost at LH2 and SLH2 temperatures.
Titanium and its alloys	Yes	Yes	Yes	
Asbestos impregnated with Teflon®	Yes	Yes	Yes	Avoid use because of carcinogenic hazard.
Chloroprene rubber (Neoprene®)	Yes	No	No	Too brittle for cryogenic service.
Dacron®	Yes	No	No	Too brittle for cryogenic service.
Fluorocarbon rubber (Viton®)	Yes	No	No	Too brittle for cryogenic service.
Mylar®	Yes	No	No	Too brittle for cryogenic service.
Nitrile (Buna-N®)	Yes	No	No	Too brittle for cryogenic service.
Polyamides (Nylon®)	Yes	No	No	Too brittle for cryogenic service.
Polychlorotrifluorethylene (Kel-F®)	Yes	Yes	Yes	
Polytetrafluorethylene (Teflon®)	Yes	Yes	Yes	

Disadvantages of the LH_2 choice

➔ Stringent safety requirements for mech. & elec. designs
(25 liters of LH_2 released into the air with a 10% yield = 4 kg of TNT)

➔ Need Cryogenic plant to supply LHe flow and subcooled LH_2 to 17 K

➔ None standard thin Aluminum windows to contain LH_2
- On-going effort to comply with safety requirements
- Supported by photogrammetry: Innovative none intrusive technique

Cryogenic Properties of Various Gasses

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

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

Gas H2: NASA, Glenn Research

Properties of gaseous (normal)

Reference temperature	527.7° R
Standard pressure (1 atm) psia	101.325 abs
Density (at 527.7° R & 1 atm)	83.7 g/m^3
Specific Volume (at 527.7° R & 1 atm)	0.0119 m^3/g
Specific Heat	Cp= 14.33 J/g-k Cv= 10.12 J/g-k
Velocity of Sound	1294 m/sec
Heat of Combustion	Low= 119.93 kJ/g High= 141.86 kJ/g
Flammability limits Hydrogen-air mixture Hydrogen-oxygen mixture	 Upper= 75 % volume Upper= 95 % volume
Explosive limits Hydrogen-air mixture Hydrogen-oxygen mixture	 Upper= 59 % volume Upper= 90 % volume
Minimum spark ignition energy at 1 atm	
In air	0.02 mJ
In Oxygen	0.007 mJ

Effort is on-going within two schemes

LH2: Convection scheme : Advantage of limit LH_2 inventory

for MICE: energy deposition ~100W

[IIT Internal Report-Cassel et al. 2001]

[NUFACT'01 – S. Ishimoto et al.]

[PAC'05 – MA.Cummings and S.Ishimoto]

(Cryocooler ~ 20 W)

LH2: forced-flow scheme : Advantage of maximum energy removed

for MuCool (energy deposition larger than 300 W)

[Adv. Cryo. Engr.,2004–C. Darve et al.]

[ICEC19, 2002 –C. Darve et al.]

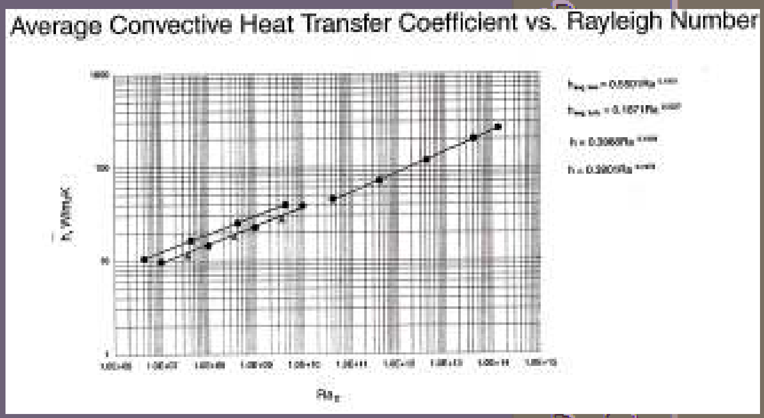
[Adv. Cryo. Engr.,2002 - Weisend II et al.]

[Research instruments & methods in physics research,1996-E.J. Beise et al.]

Review of the basic LH_2 Absorbers designs - Convection scheme

Numerical simulation (K.Cassel/IIT)

- Natural transverse convection
- Self regulating



Proposal:

➔Heat transfer area=0.2m^2

➔mdot=28 g/s

Design by S. Ishimoto [see MAC's talk]

Orders of magnitude:

{L=0.3m; R=20cm;Q=150 W}

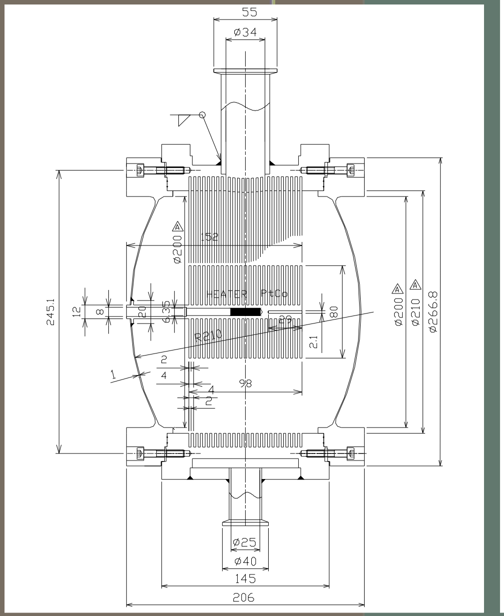
➔ Ra=7.25e13

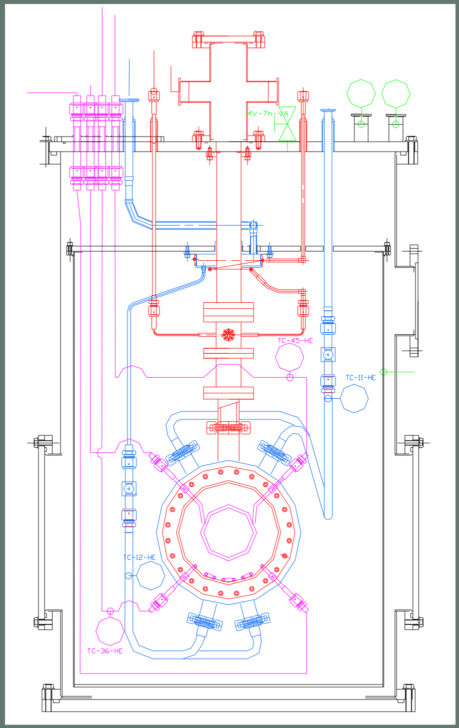
Convection heat transfer coefficients:

{Thein/out=14K/15 K;T_ LH_2 =18.5 K}

➔h_LHe=1580 W/m^{2}K

➔h_ LH_2 =210 W/m^{2}K

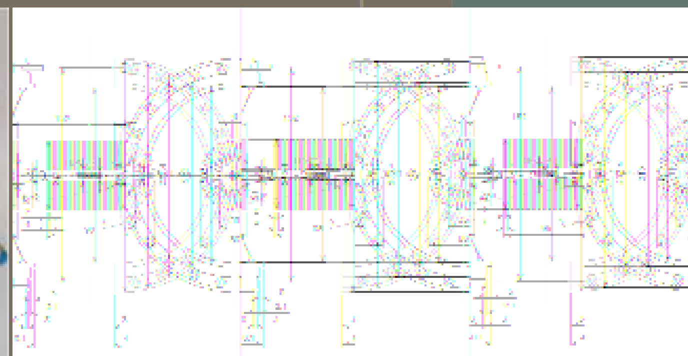




Review of the basic LH_2 Absorbers designs - Convection scheme

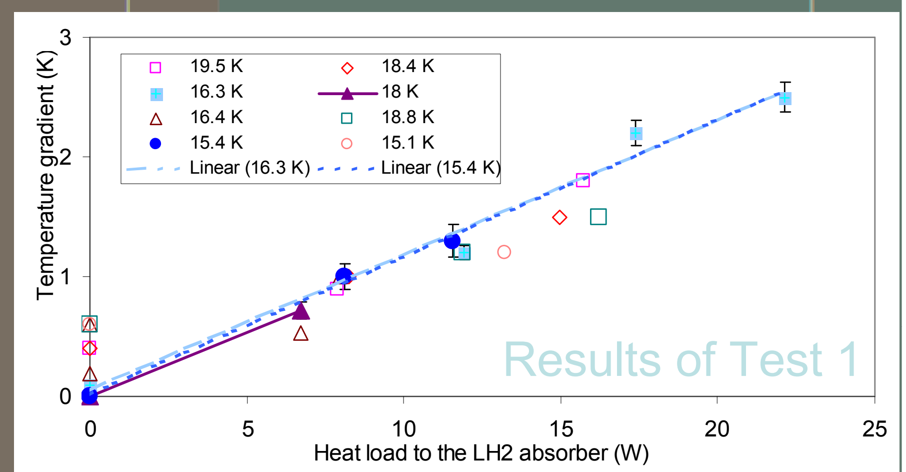
Experimental test (FNAL/KEK) 6.2-liter of LH_2

LNe test @ KEK; LH_2 tests @ KEK run 1 & 2



KEK Run1: some Lessons learned

- Safety review process and design requirements
- Operating procedures and flow sensitive
- Cryo-system and LH_2 absorber stabilities
- Instrumentation precision (TT, FT)
- Data interpretation: heater element influence
- Numerical simulations to valid test <-> prototype ?



[FNAL Internal report-11/05 “Reflections on Initial MTA Tests “, B.Norris, C.Darve, L.Pei]

Effort is on-going within two schemes

LH2: Convection scheme : Advantage of limit LH_2 inventory

for MICE: energy deposition ~100W

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[Research instruments & methods in physics research,1996-E.J. Beise et al.]

Review of the basic LH_2 Absorbers designs – Forced-flow scheme

External cooling loop for the LH_2 forced-flow absorber

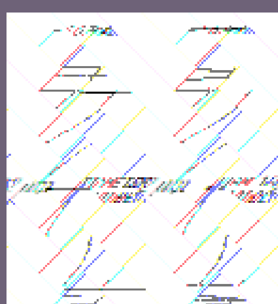
➔ Cryo-loop design with minimum of 25-liter

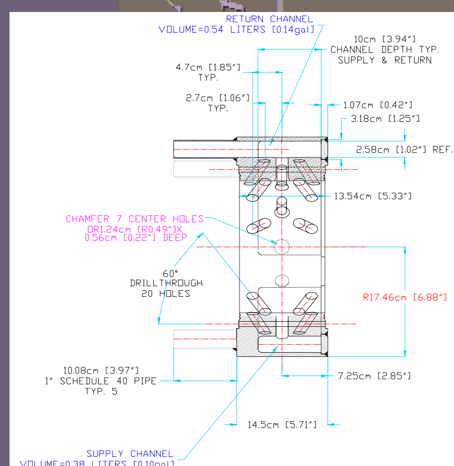
➔ Nozzle design and flow distribution to validate by a prototype test

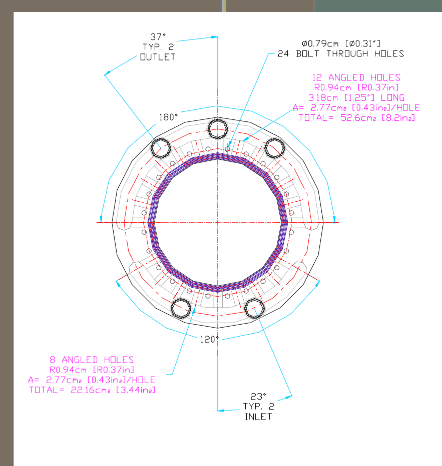
➔ Since 2001 few numerical simulations have permitted to optimize the windows geometry while complying with safety requirements - maximum allowable working stress in the aluminum (P_LH_2 =1.2 atm)

➔ minimize thickness => to reduce multiple scattering

➔ modify windows curve => to improve heat transfer

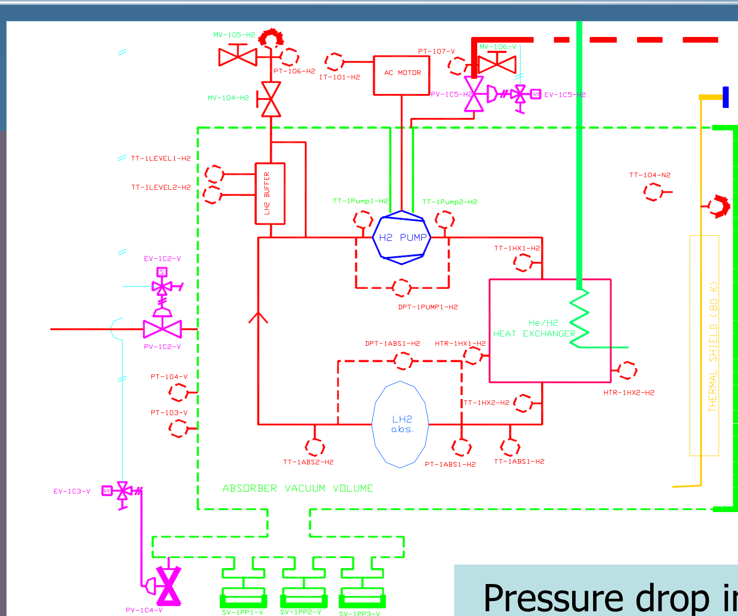


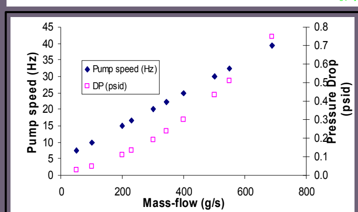




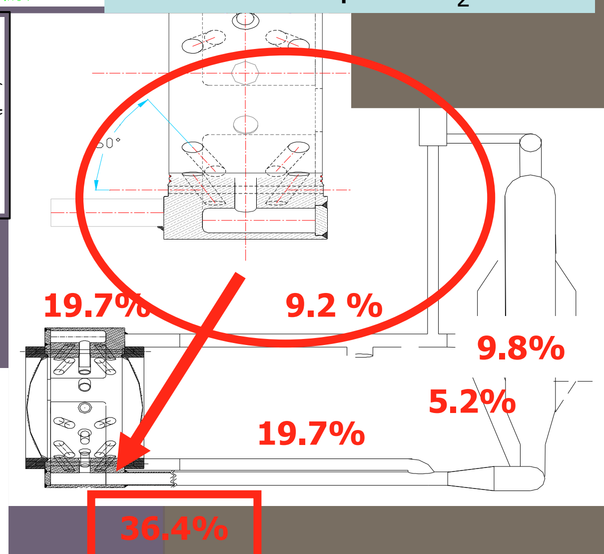
[Design by E. Black, W.Lau,S.Yang]

Review of the basic LH_2 Absorbers designs – Forced-flow scheme



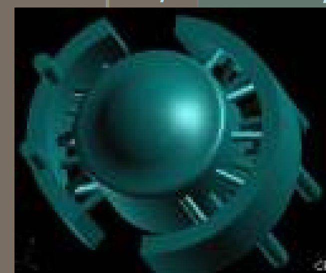


Pressure drop in LH_2 circuit



Need optimal flow mixing in absorber, but LH_2 pump:
ΔP = 0.365 psi @ m=450 g/s

- LH_2 absorber geometry
Several models and configurations:
→ w/ and w/o inner channel
→A: 11 inlet/15 outlet; B: 15/19



- Beam simulation
ϕ 10 mm, 300 W

- Heat → mdot →
Velocity at inner chamber

- LH_2 properties (17 K, 1.2 atm)

Using CFD

Field distributions

- **Velocity**
- **Temperature**

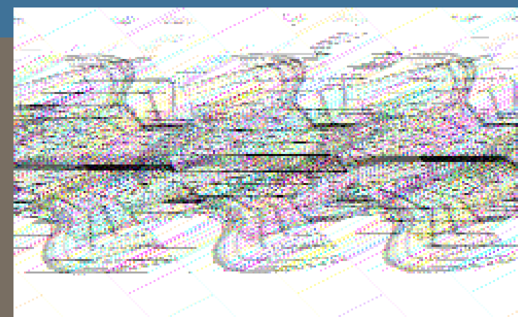
CFX solver (Ansys)

Fermi National Accelerator Laboratory
Cryogenic Department

Review of the basic LH_2 Absorbers designs – Forced-flow scheme

MuCool ~300W

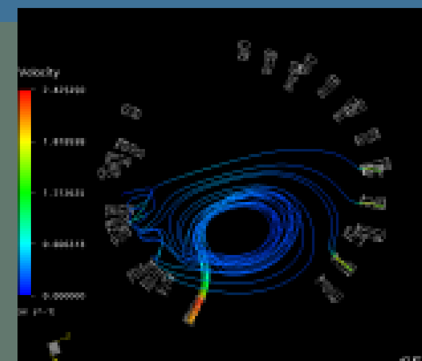
- Numerical simulation by Oxford Univ.:
  - Holding/Lau using Algor 2D (2002)

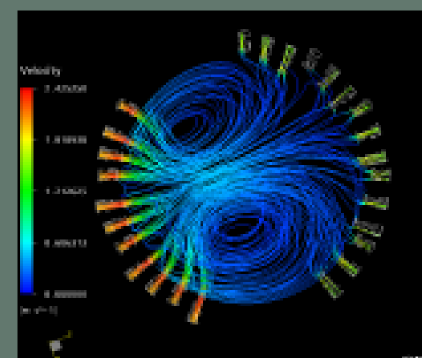


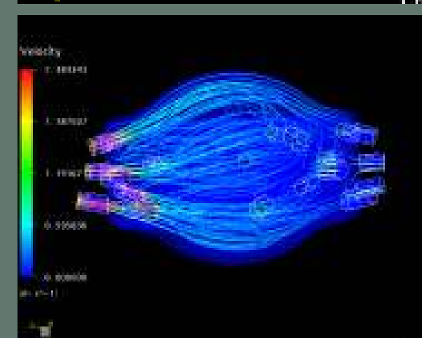
  - Yang/Lau using CFX 3D (2003)

Model	Inlet velocity	Initial Temp.	Heater	Reynolds Number	Temp. increase	Max. Pressure
8+12	2 m/s	17K	150W	4.2547E5	0.16K	279 Pa
11+15	0.5m/s	17K	150W	9.0158E4	1K	13.7 Pa
	2 m/s	17K	150W	3.49E5	0.38K	217 Pa

	config.\ velocity	0.5m/s	1m/s	2m/s	3.3m/s	4.4m/s
	11+15	8.6K	5K	0.96K	-	-
With Chamber	13+19	-	5.3K	2.47K	-	1.1K
	15+19	6.1K	3K	1.8K	0.86K	0.63K
Without Chamber	11+15	-	-	0.45K	-	-
	13+19	-	-	0.93K	-	-
	15+19	-	-	0.39K	-	-

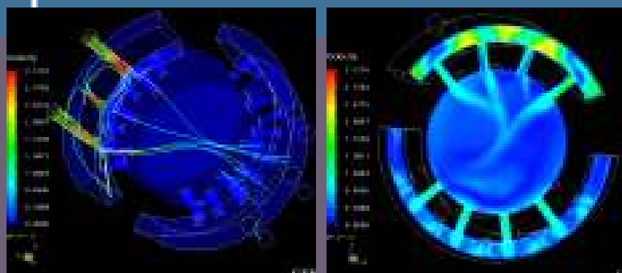




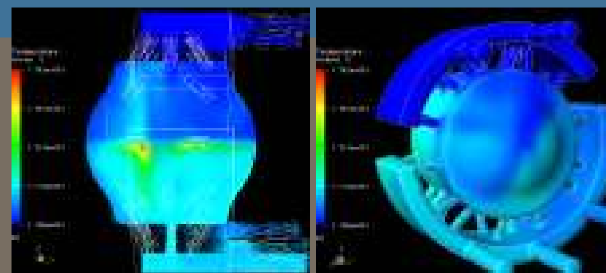


Review of the basic LH_2 Absorbers designs – Forced-flow scheme

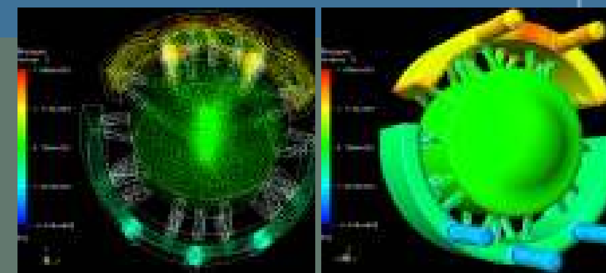
Velocity distribution:



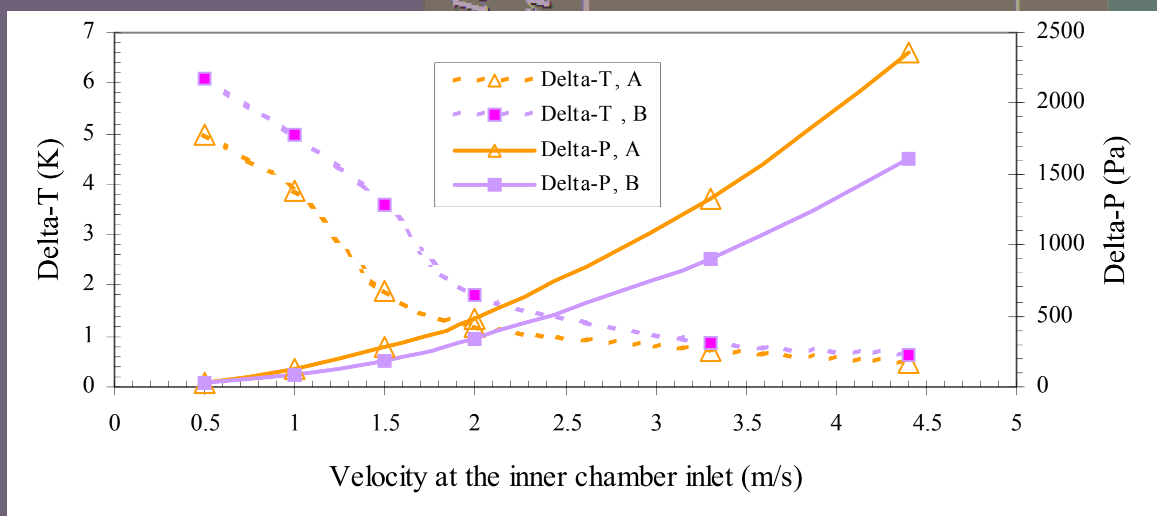
Temperature distribution:

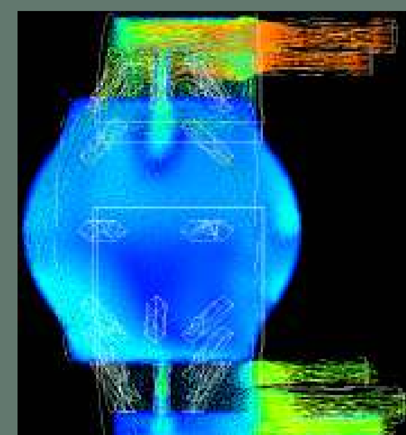


Pressure distribution:



These results are still waiting to be validated by experiment !!





Ex: 11+15 config _without channels _ inlet velocity at 2m/s, heater at 300W

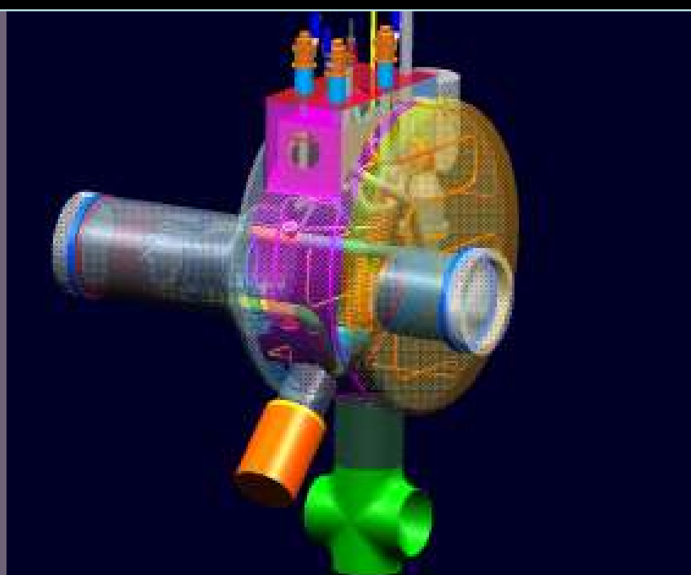
➔ Influence of flow symmetry and number of active nozzles

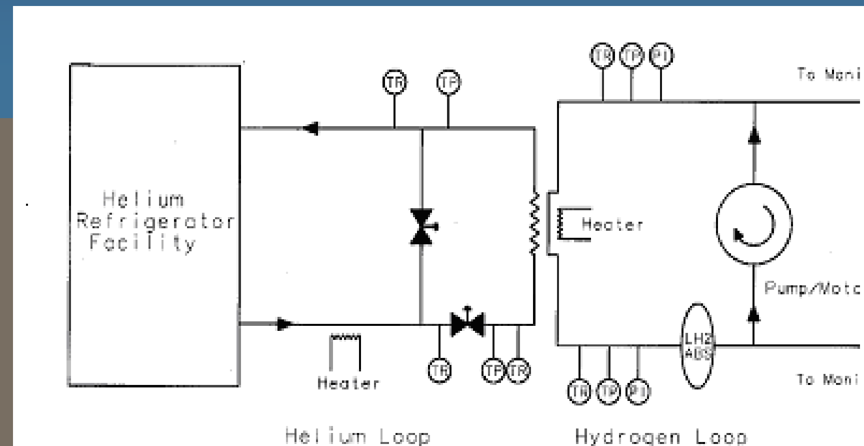
➔ Configuration with 15 inlet nozzles and 19 outlet nozzles; velocity 2 m/s at inner chamber inlet

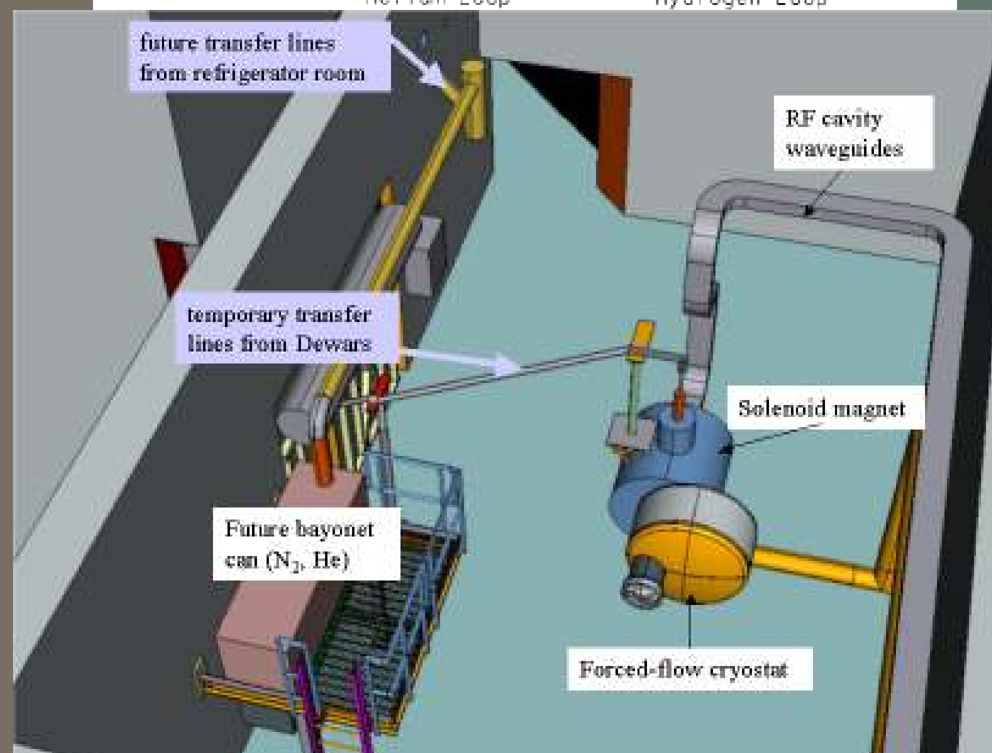
Review of the basic LH_2 Absorbers designs – Forced-flow scheme

25-liter of LH_2

27 g/s of helium @ 14 K, 1.2 atm







Engineering for LH_2 loop & cryostat (FNAL/cryo)

-Structural analysis

-Thermal analysis

- Hydraulic analysis (w/ Oxford Univ.)

- Process and Instrumentation Diagram
- Venting considered
- Oxygen Deficiency Hazard

Cryo-system development

Design philosophy for a hostile environment

- Electrical components located in the experimental hall must be rated Class 1, Div. 2 Gp B or considered as intrinsically safe: e.g. He guard, N_2 purge, specific equipments, etc…
- Venting system designed to account for H_2 gas released from thermal expansion
- Building equipment: flammable gas, Oxygen Deficiency Hazard system, ventilation, audio and visual alarm
- Operating Procedures , interlock, Safety PLC, Personnel safety training

Additional instrumentation and materials requirements:

- Operate at cryogenic temperatures (physical properties)
- High magnetic field (absorber sits inside the 4 Tesla SC solenoid magnet)
- Radiation-hard (able to withstand more than 300 mS/hr)

Design guidelines:

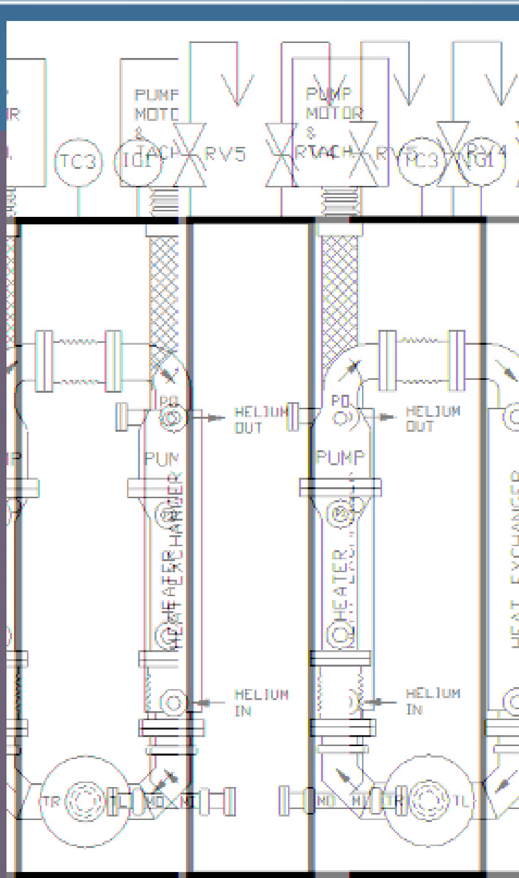
Safety codes: ASME, NEC, Fermilab ES&H Manual for pressure vessel and hydrogen target, e.g. " Guidelines for the Design, Fabrication, Testing, Installation and Operation of LH_2 Targets – 20 May 1997" by Del Allspach et al.

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

LH_2 expertise from FNAL, SAMPLE, E158, G0…

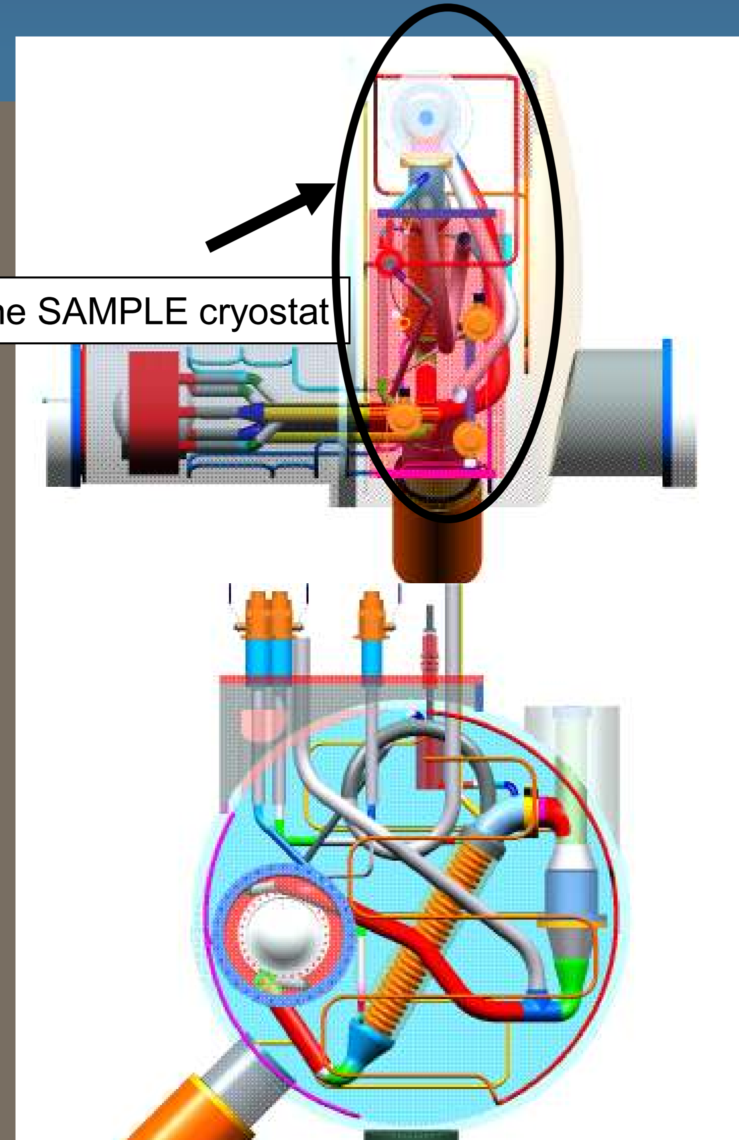
LHC experiences: Cernox use

Implementing SAMPLE cryo-loop



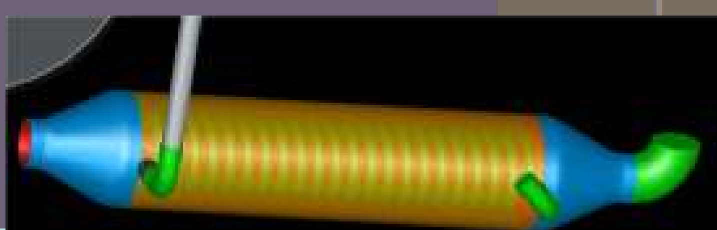
Same:

Modified to account for the SAMPLE cryostat



SAMPLE Heat exchanger:

- 1 kg/sec LH_2 flow
- Counterflow
- Cu hose and SS housing
- dim : 85 cm, ϕ15 cm



Implementing SAMPLE cryo-loop

Permit to save fabrication cost (heat exchanger, operational LH_2 pump and motor) to help get the forced-flow system online, but the current engineering design must reflect these modifications

Cryo-systems to support LH_2 absorber tests at MTA [see B.Norris's-talk]

➔ MTA facility equipped with Hydrogen test capacity
- MTA building: practicality of cryogenic cooling in hazardous environment
- Safety PLC (QUADlog), ODH, fan, vent, etc…

➔ First MTA helium distribution using helium and nitrogen Dewars to operate KEK convective-type LH_2 absorber test and the SC solenoid magnet

➔ Future Helium facility (compressor, refrigerator and transfer line) operating in switch-over mode [COOL'05]

- 4 K mode – to SC MTA solenoid magnet and other cryo-components.
- 14 K mode – to forced-flow, convective type LH_2 absorbers

Use Tevatron satellite components ➔ Expected liquefaction rate is 78 liter/hr

➔ Expander test has been performed to ensure the supply of 27 g/s of helium at 14 K, 15 psig (0.2 MPa) required for removing 300 W of heat deposition from the forced-flow absorber cryo-loop (Delta-T of 1 K)

[COOL'05 – "Cryogenics for the MuCool Test Area (MTA)" C.Darve, B.Norris, L.Pei]

What exist and what we need ?

What exist for future LH_2 absorber tests?

➔ Numerical models to simulate test results (convective and forced-flow schemes)

➢ More precise numerical model to account for experimental imperfections?

➢ Adequate instrumentation type, number and position to correlate data?

➔ Expertise from KEK run1 : value of designing safety into the system from scratch … Cryo-system design & fabrication, KEK cryostat analysis & test and finally operation

➔Towards a continuous supply of LHe [See B.Norris's talk]

- ✓ Installation of compressors
- ✓ Completion of the warm piping for the compressor room

What is needed for future LH_2 absorber tests?

➢ Towards a continuous supply of LHe

- ❖ Complete design, install and test transfer lines
- ❖ Complete design, install and test the refrigeration system
- ❖ System review documentation and finally commissioning…

How things might proceed – convective-type LH_2 test

Structural analysis, pressure tests, safety document preparation

⇩

Instrumentation and DAQ updated

⇩

Safety Review approval

Test the LH_2 convective type: KEK run 2
Using temporary infrastructure like during summer 2004 test

How things might proceed – Forced-flow LH_2 absorber test

Completed LH_2 cryo-loop design by integrating SAMPLE equipments

⇩

Safety Review approval

Satisfy the safety requirements for the thin window design: pressure and rupture tests, material certification, safety review document, etc…

⇩

Safety Review approval

⇩

Fabricate and assemble parts

Test the LH2 forced-flow absorber at MTA (in SC solenoid magnet)

⇧

Complete the helium cryo-plant:

⇧

Safety Review approval

⇧

<u>Compressors room</u>:

Complete the compressors refurbishing

as well as control&monitoring system

<u>Refrigerator room</u>:

Complete design and manufacture

(mechanical + electrical)

Concluding comments

On-going cryogenic efforts for the LH_2 absorbers
CFD models exist and need to be validated by experiment
- Forced-flow type: 3D by Oxford (2003)
- Convective-type: 2D by IIT (2001)

Safety review in-progress for the KEK convective-type run2

LH_2 cryo-loop conceptual design available since 2003
Design modification requested to implement SAMPLE heritage
Limited engineering resource available from FNAL/Cryo

➢ First LH_2 convective-type LH_2 absorber tested at MTA (summer 2004). Limited energy deposition. Lesson learned..

➢ Hydrogen facility was successfully designed, built and commissioned at Fermilab to support LH_2 convection absorber during summer 2004