# Mucool Hydrogen Absorber R & D


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Muons, Inc.

NORTHERN ILLINOIS UNIVERSITY

nicadd

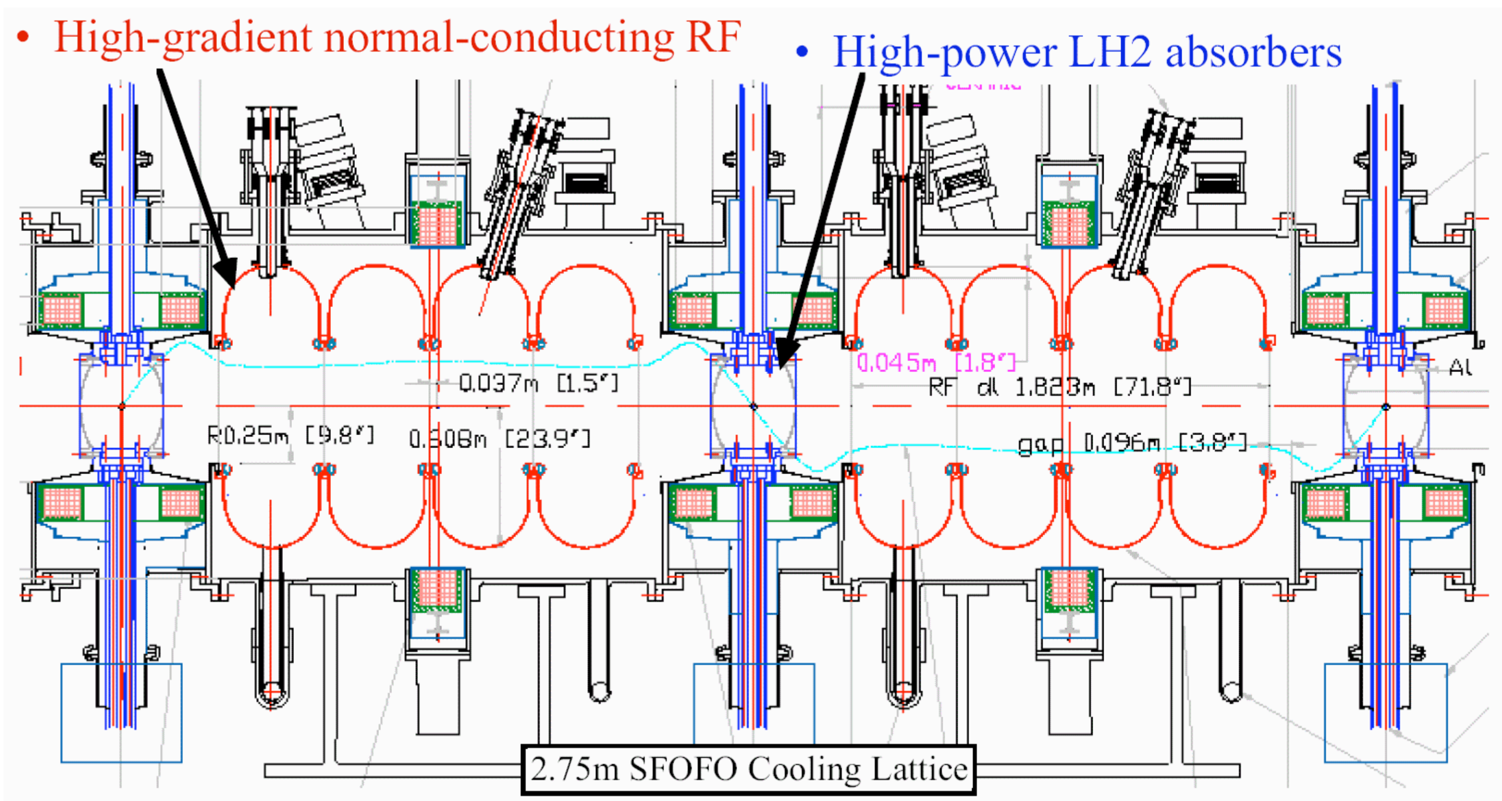

Cool 05

Galena, IL

Sept. 20, 2005

# MuCool: cooling channel R & D

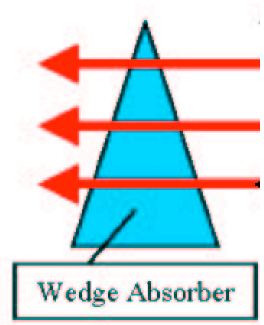
- **MuCool:** MC subset based at FNAL and charged with the development of muon ionization cooling channels
  - ⇒ **Goal: Cooling cell test in high-powered beam (MTA)**
- SFOFO Cooling Lattice – transverse cooling for ν factories

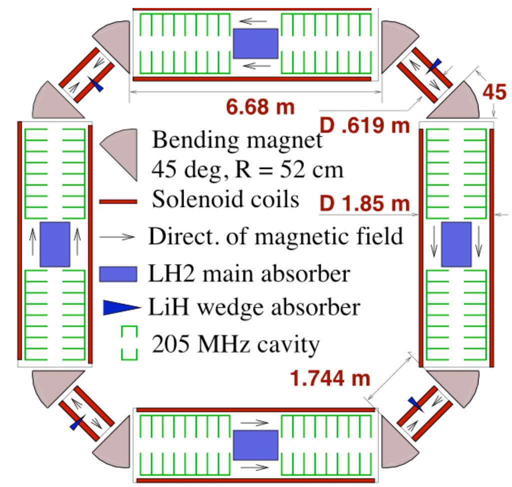


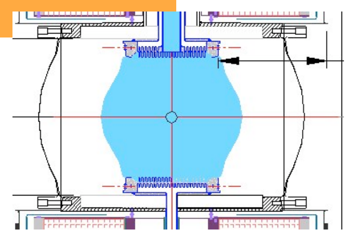
# The next generation ν,μ machines…

Cooling channels have a variety of configurations:

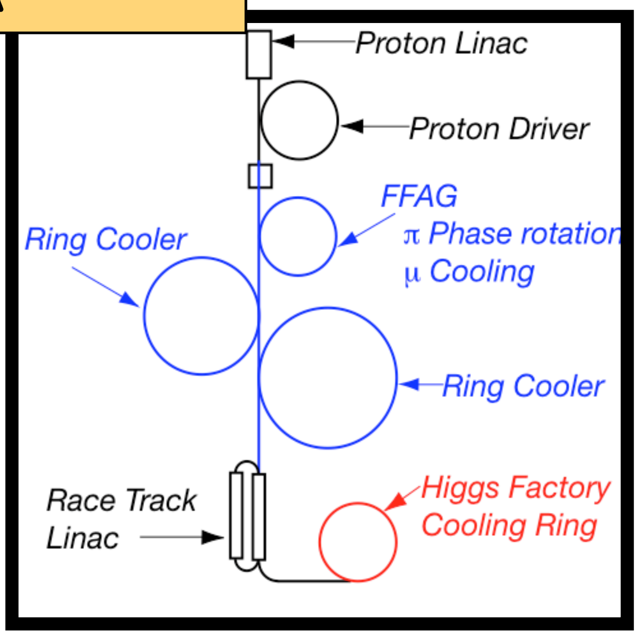
- Different geometries
- Different cooling cell designs
- Possible 6D cooling channels
- Different magnetic fields
- Gas, liquid and solid abs.

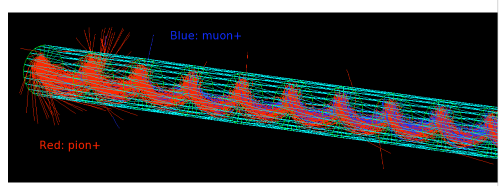


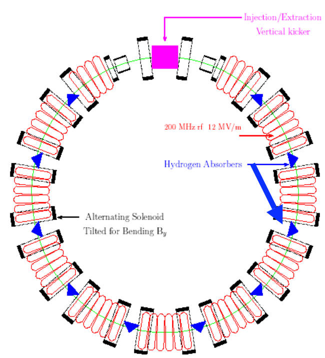



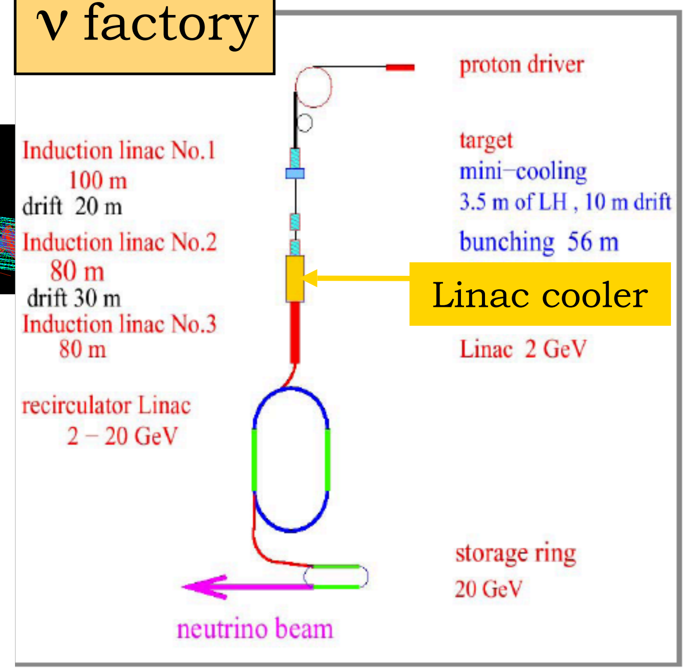
## μ collider




## ν factory



# Muon cooling and $H_2$ absorbers

- 2D Transverse Cooling

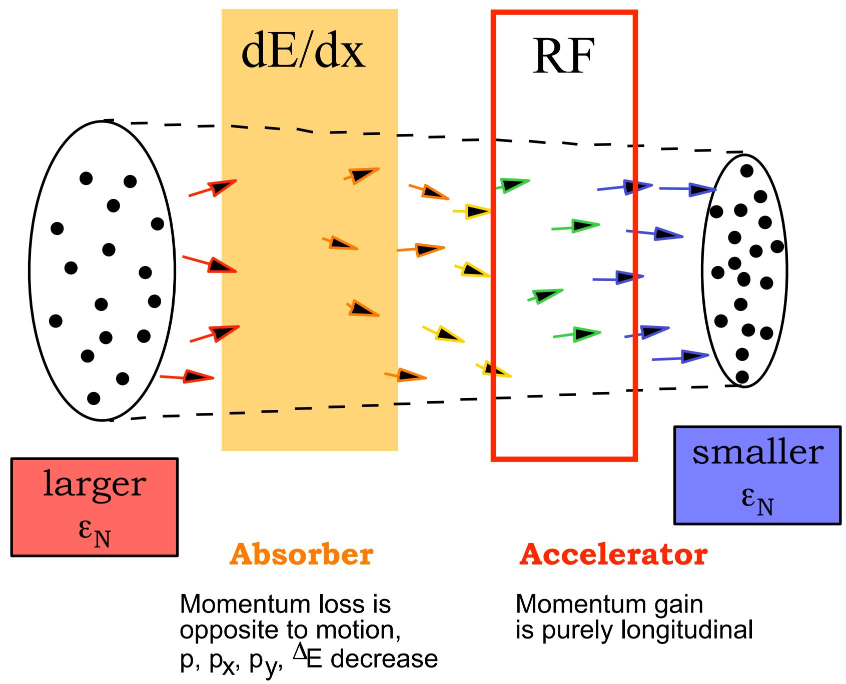
$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \text{GeV})^2}{2\beta^3 E_\mu m_\mu L_R}$$

Cooling
E- dE/dx

Heating
coulomb
scatt.: θ + $\theta_{rms}$

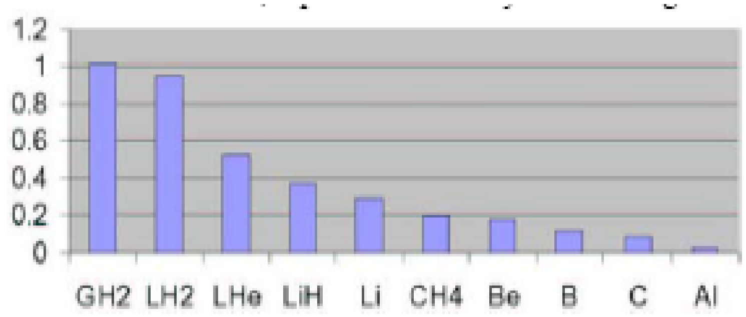
and

$$\epsilon_{N,\min} = \frac{\beta_\perp (14\ \text{MeV})^2}{2\beta m_\mu \frac{dE_\mu}{ds} L_R}$$




- Figure of merit: $M=L_R dE_\mu/ds$

$M^2$ (4D cooling) for different absorbers



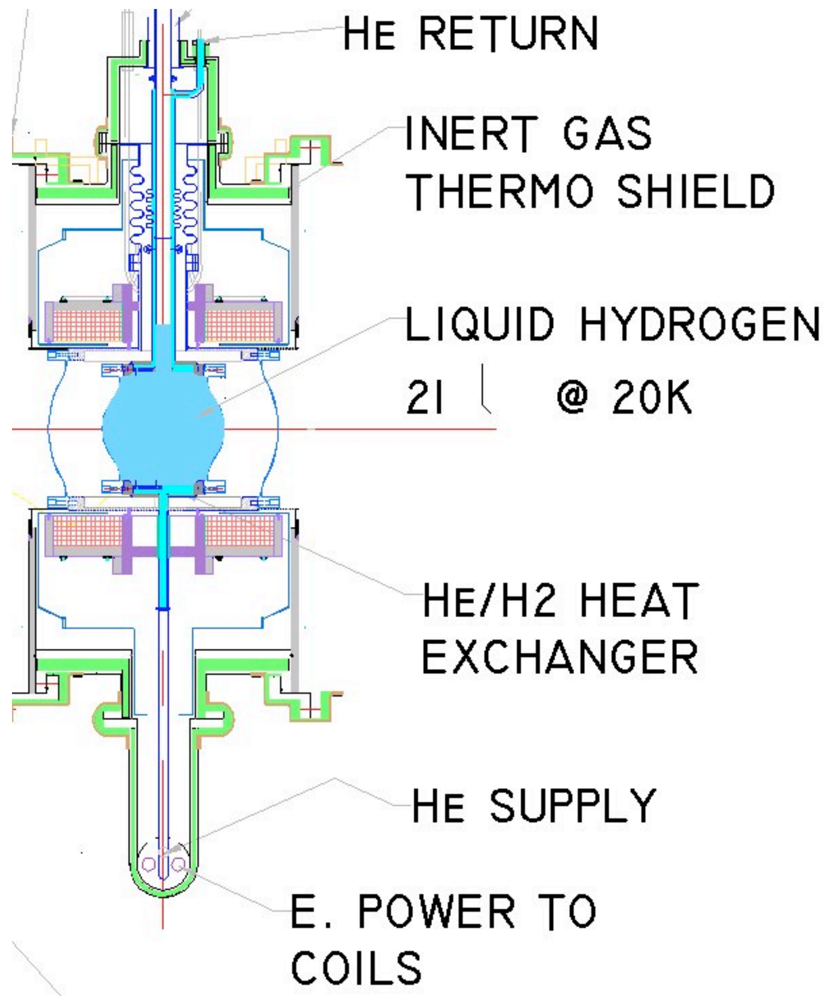

$H_2$ is clearly Best -
Neglecting Engineering Issues
Windows, Safety

# $LH_2$ Absorber Design Issues

- Design Criteria
  - ⇒ **High Power Handling**
    - Study II – few 100 W to 1 KW with "upgraded" (4MW) proton driver
    - 10 KW in ring cooler
      - – **Must remove heat**
  - ⇒ **Safety issues regarding use of $LH_2$ (or gaseous $H_2$)**

- $O_2$ and $H_2$ separation
- No ignition sources

⇒ **Window material must be low Z and** relatively thin **in order to maintain cooling performance**

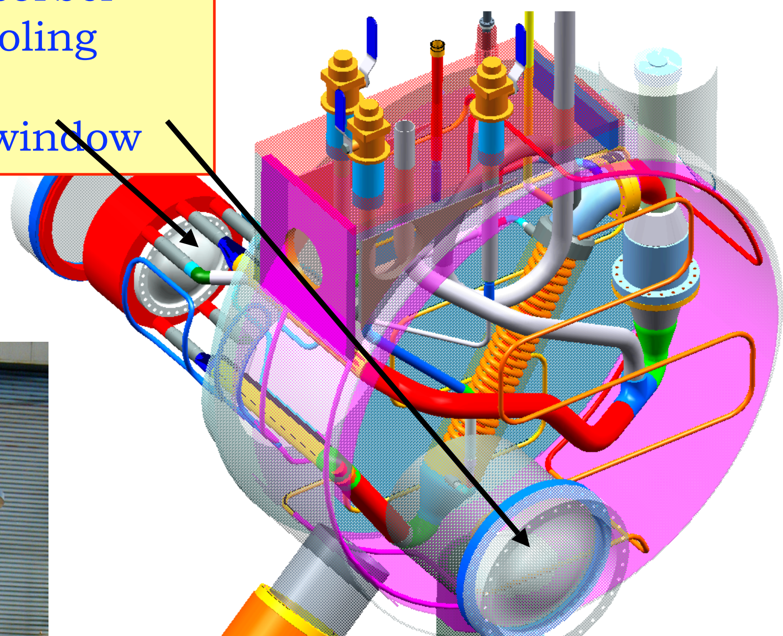


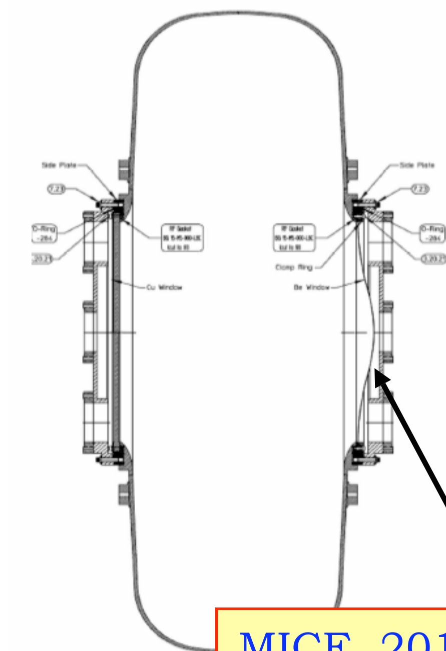

$H_2$ implies engineering complexity

# Thin windows in cooling channels

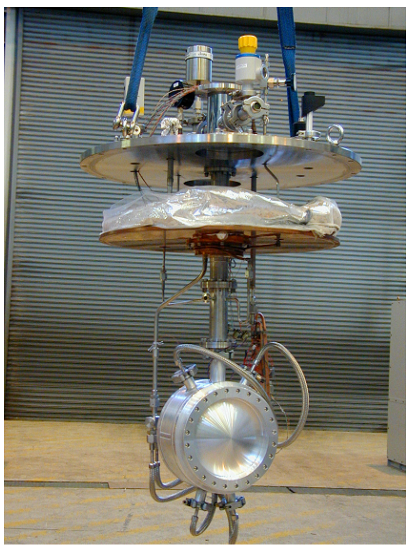
- Absorbers, Vacuum and RF windows

Forced-Flow Absorber with external cooling loop
And secondary window

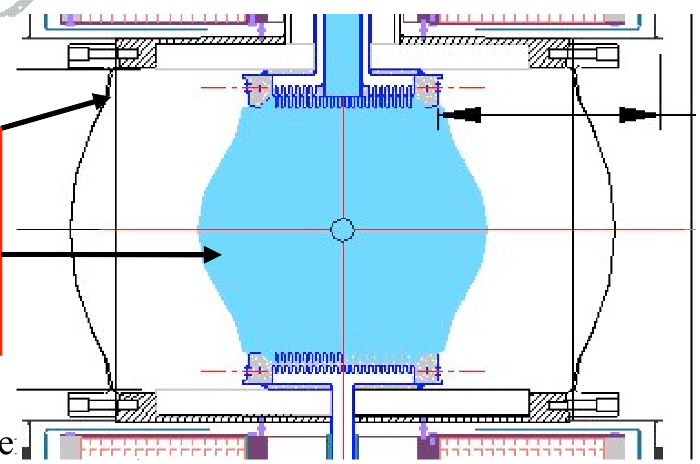




MICE 201 MHz RF (Be window)



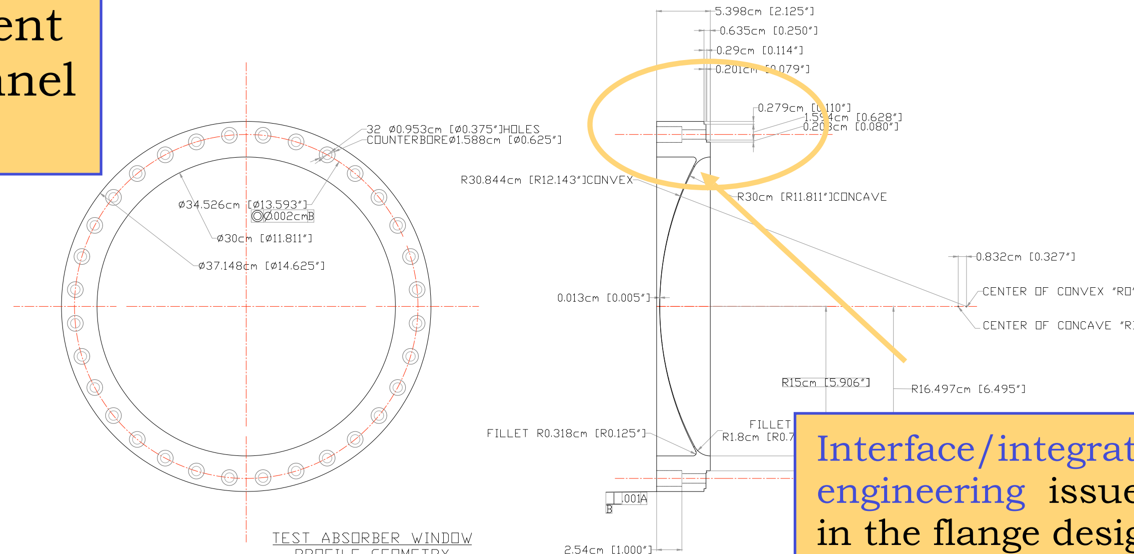
KEK Convection Absorber at MTA



MICE Convection Absorber in AFC module (and containment)

# Thin Windows Design

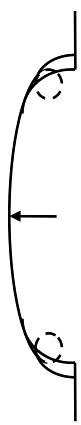
Window design independent of particular cooling channel configuration



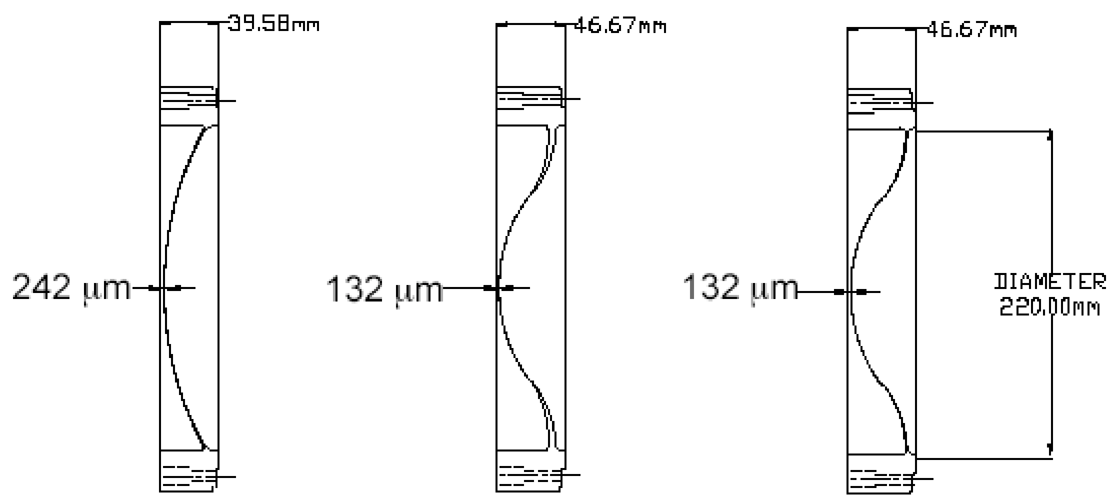

Cooling and safety issues are in the window profile

Interface/integration engineering issues are in the flange design

Originally..



500 to 120 µm reduction




Modified torispherical
FNAL, Cummings

Tapered torispherical
Black, Cummings

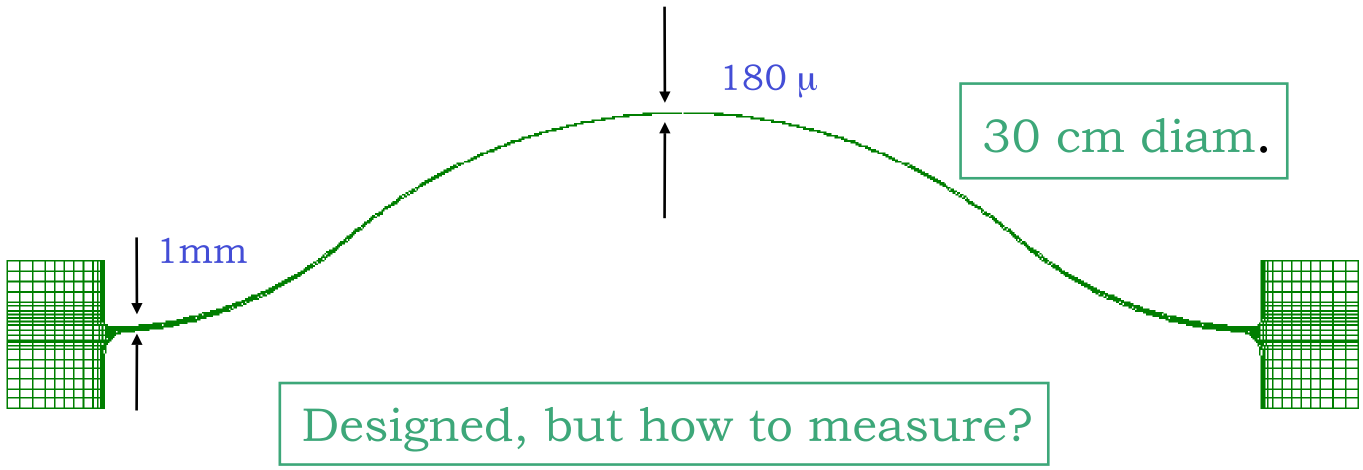
"Bellows"
Lau, Black

"Thinned Bellows"
Lau, Black, Ying

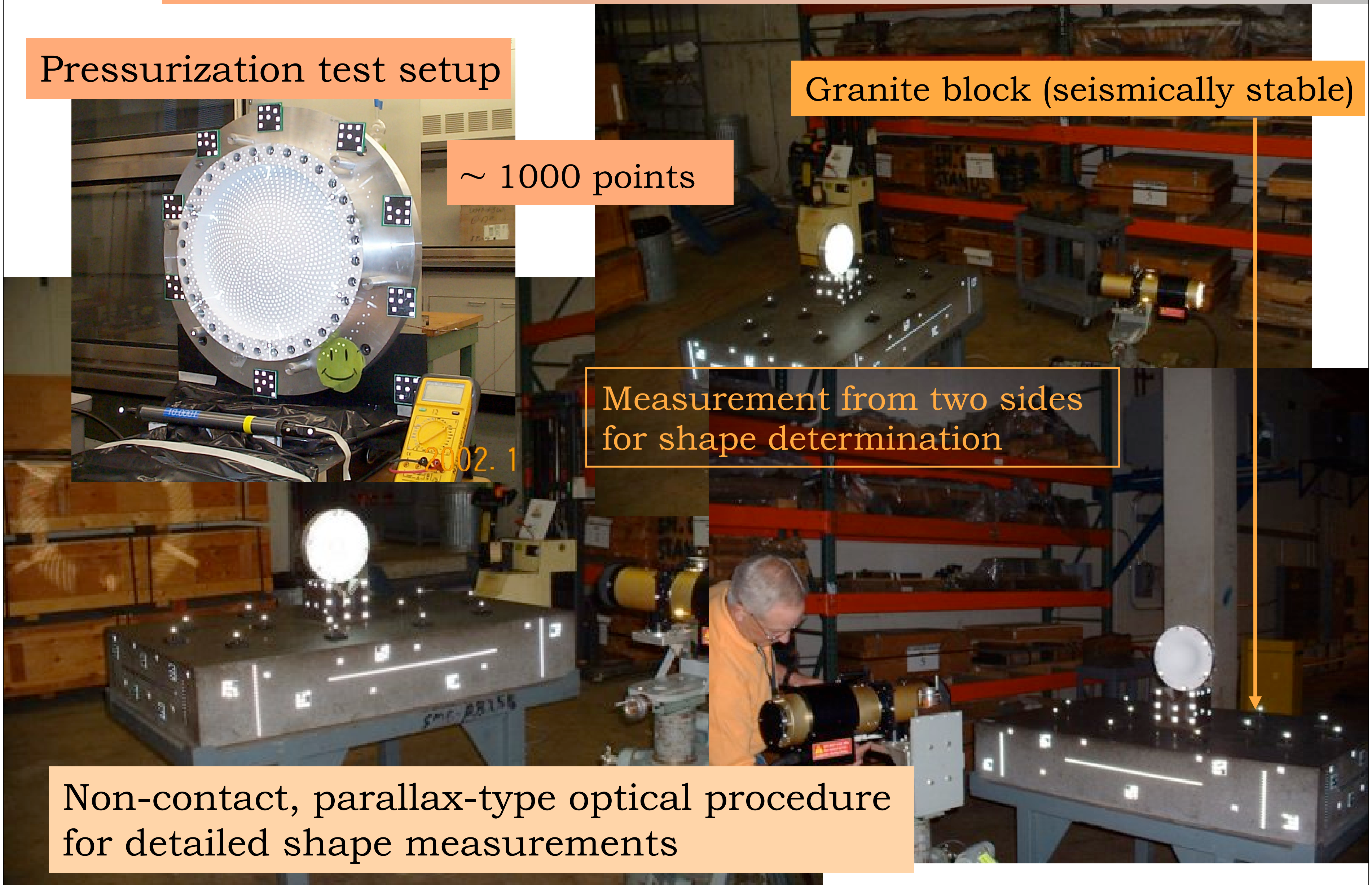
# FEA results on current bellows window design

The current window design has a double curvature to ensure that the thinnest part is membrane stress dominate (also used in the 200 MHz RF test cavity)

Here is the FEA (Finite Element Analysis) model on the Absorber window.



# Photogrammetic Test Setup (FNAL)




Pressurization test setup

~ 1000 points

Granite block (seismically stable)

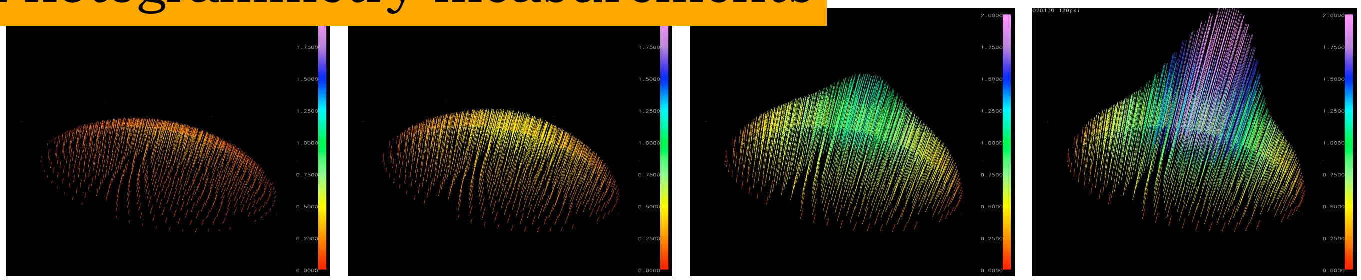
Measurement from two sides
for shape determination

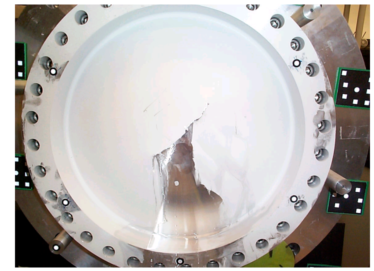
Non-contact, parallax-type optical procedure
for detailed shape measurements

# Torispherical window rupture tests

Muon Collaboration

Photogrammetry measurements



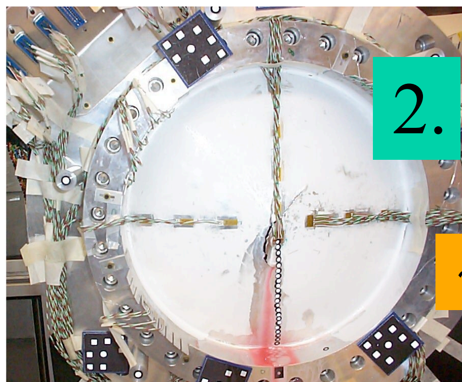


1.

130 μ window

Leaking appeared at 31 psi ..outright rupture at **44 psi!**

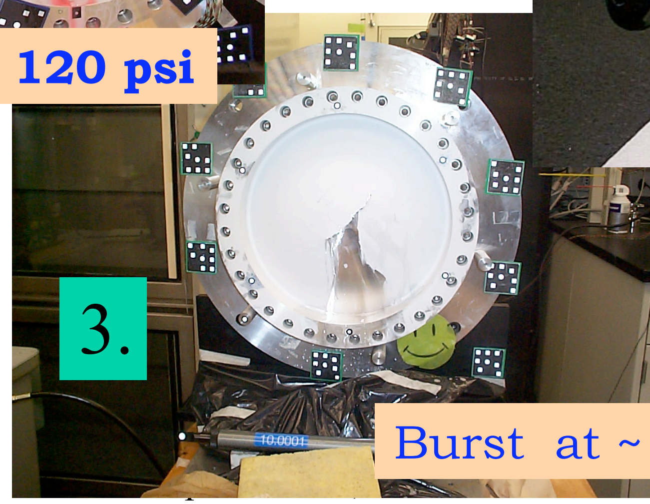
2.



Burst at ~ **120 psi**

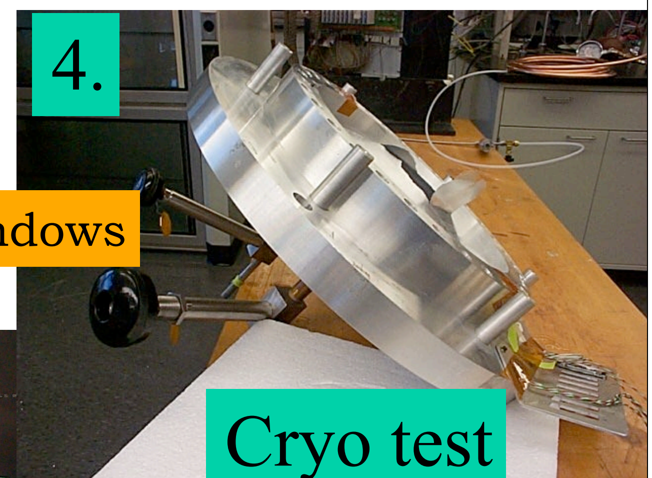
~350 m windows

3.



Burst at ~ **120 psi**

4.

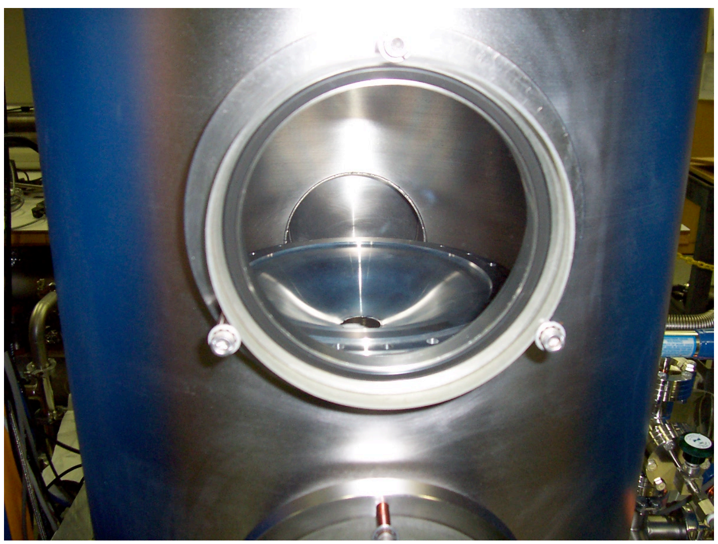


Cryo test

Burst at ~ **152 psi**

# Vapor deposition optical coating

1. System (FNAL, E. Hahn)
   a. Vacuum vessel
   b. Target filament
   c. Quartz crystal
   d. Oxygen system
2. Results
   a. Wrong oxide 1st round!
   b. Upgraded RF PS for non-conductor deposition



# Window R & D status

- Near future
  - ⇒ **New set of bellows windows to test – local manufacturer**

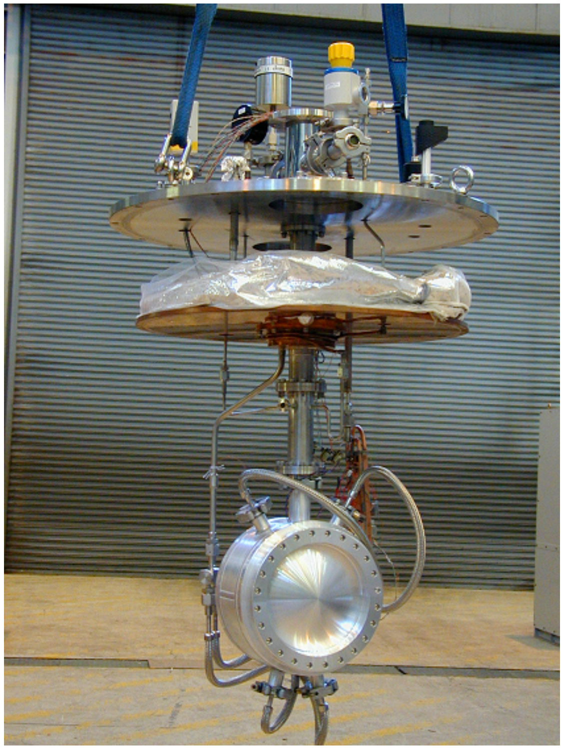
  - ⇒ **Vapor deposition for optical coating**
  - ⇒ **Develop certification procedures for operating windows**

- Have standardized design requirements for Mucool and MICE experiments

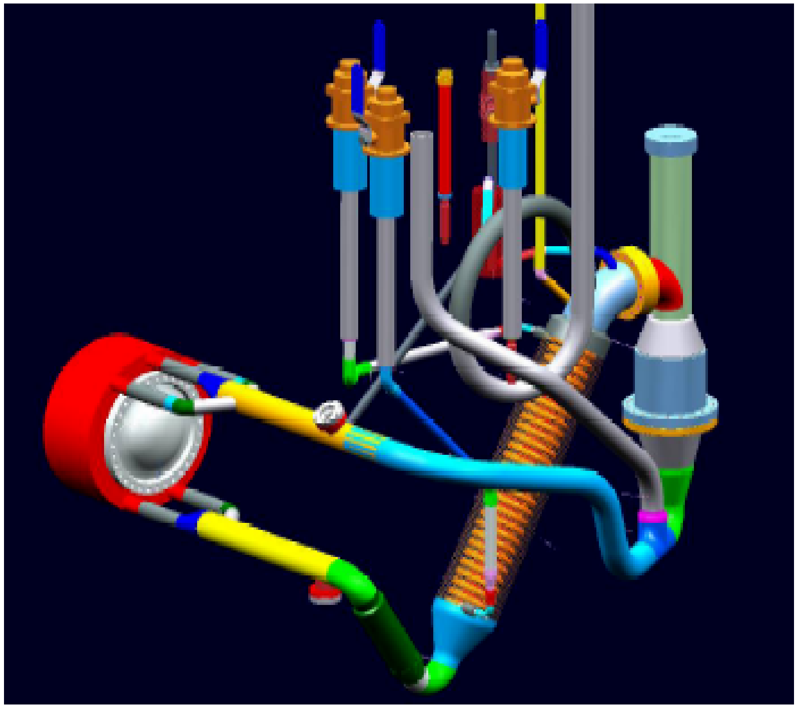
- Mucool window approach has passed MICE safety review

# Absorber R&D

- Two $LH_2$ absorber designs are being studied
  - ⇒ Handle the power load differently



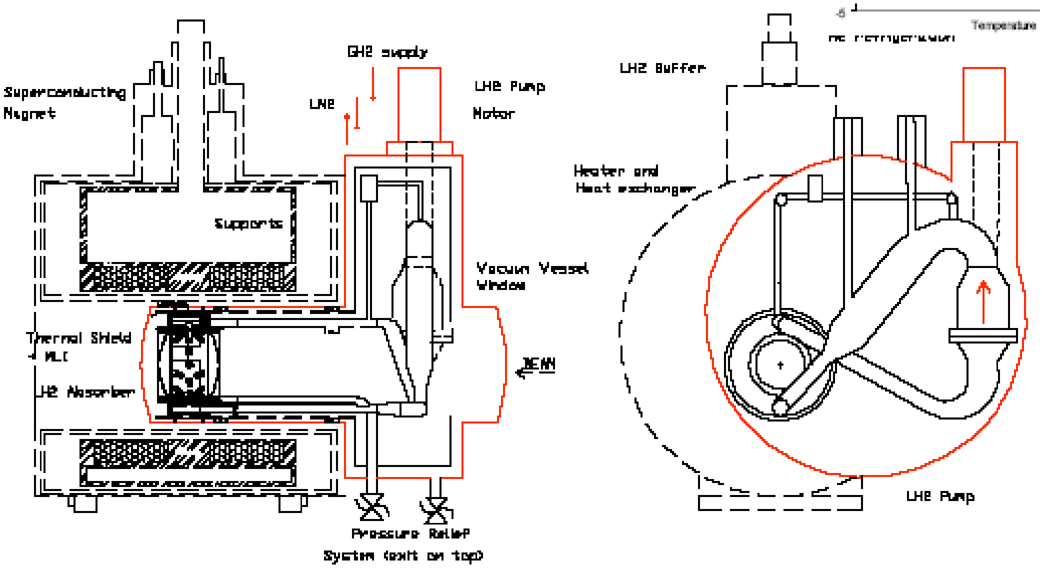
Convection-cooled. Has internal heat exchanger (GHe) and heater – KEK System

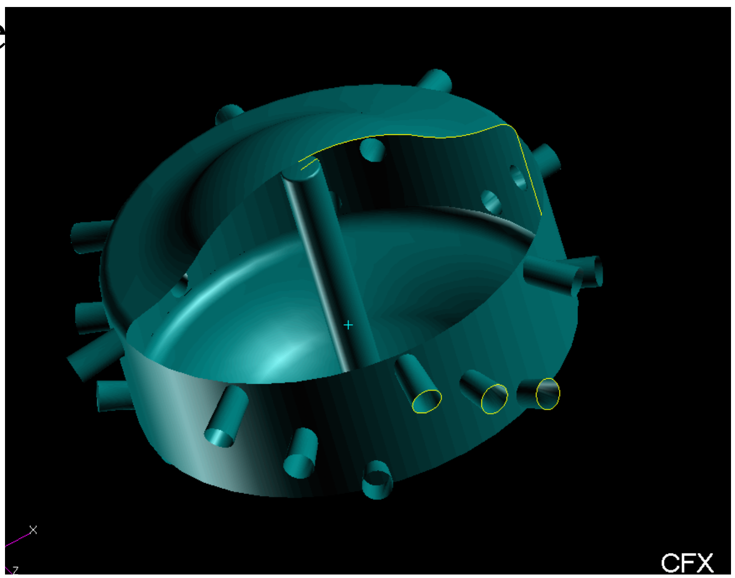


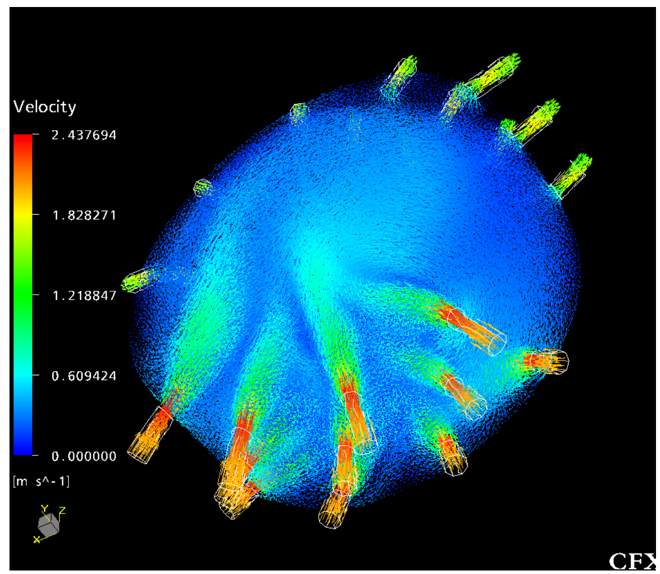
Forced-Flow with external cooling loop

# Forced-Flow Absorber

- Heat removed with external heat exchanger
  - ⇒**Nozzles in flow path establish turbulent flow**
  - ⇒**Simulation via 2D and 3D FEA**
- Prototype for MuCool te

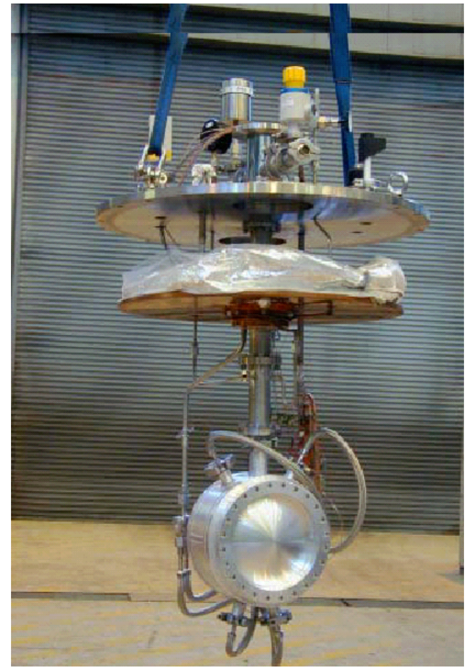


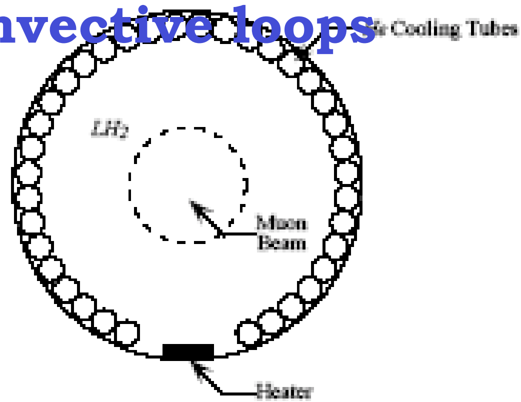



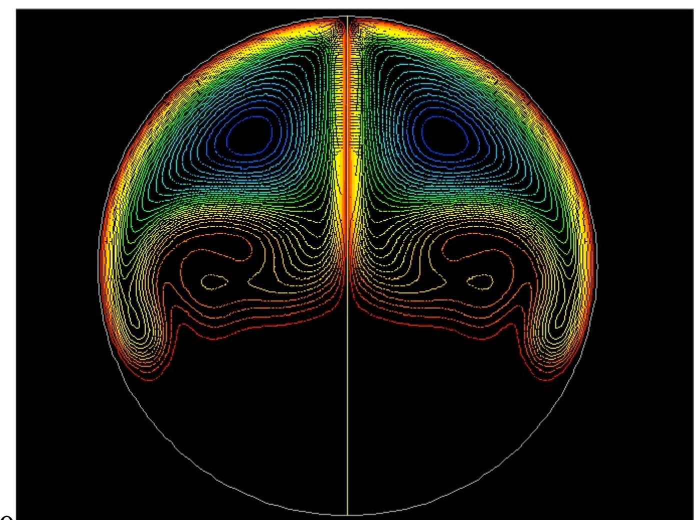



# Convection Absorber

- Convection is driven by beam power and internal heaters
- GHe heat exchanger removes heat from absorber walls
- Two-dimensional Computational Fluid Dynamics calcs:
  - ⇒ **Flow essentially transverse**
  - ⇒ **Max flow near beam**
  - ⇒ **Heaters required to setup convective loops**

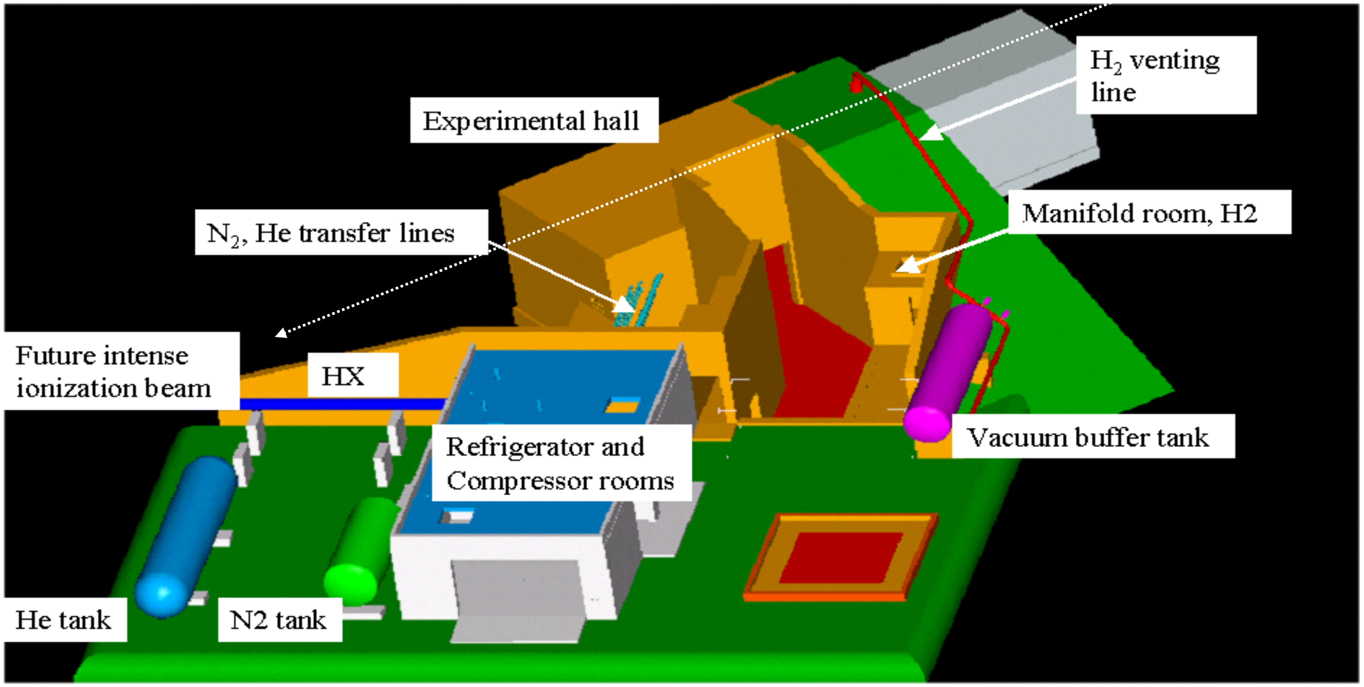




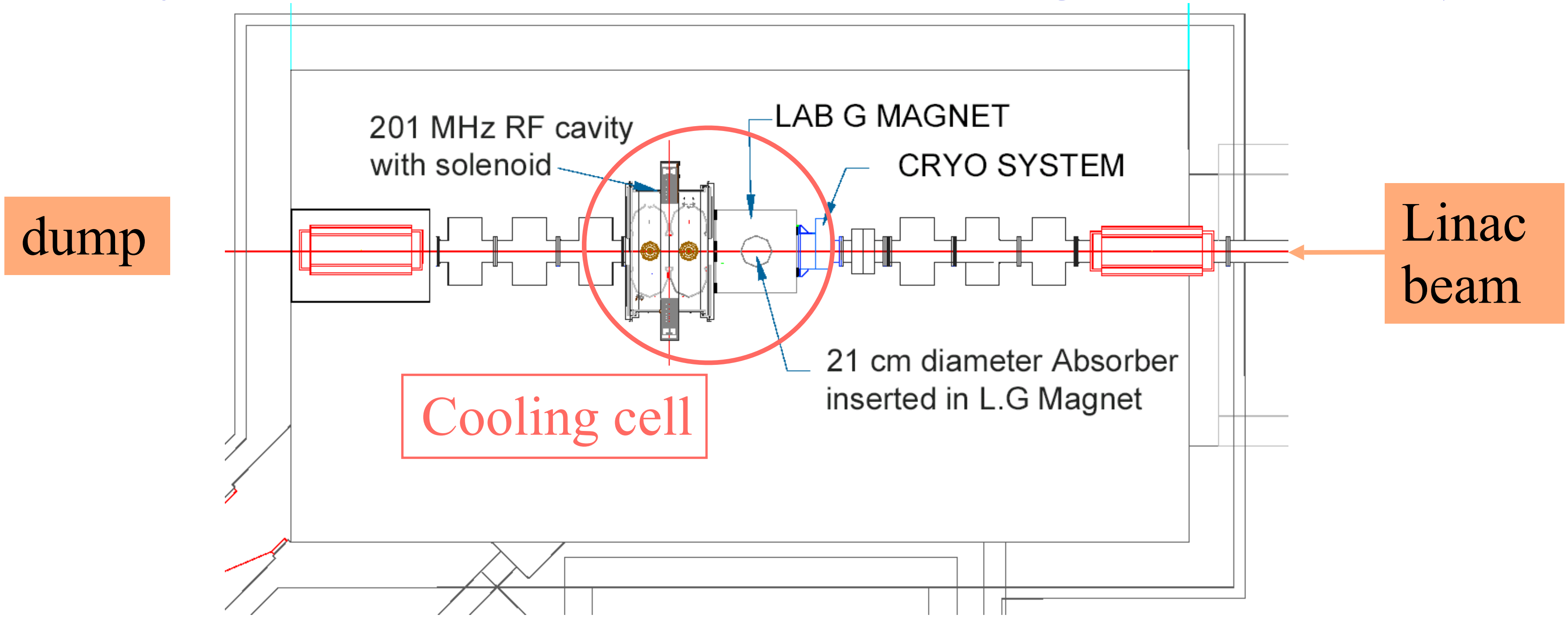
# Mucool Test Area

- The MTA is becoming our focus of Mucool activity
  - ⇒ $LH_2$ Absorber tests
  - ⇒ RF testing (805 and 201 MHz)
  - ⇒ Finish cryo infrastructure
  - ⇒ High pressure $H_2$ gas absorbers
  - ⇒ High intensity beam design



# MuCool Test Area

Facility to power test all components of cooling channel below)



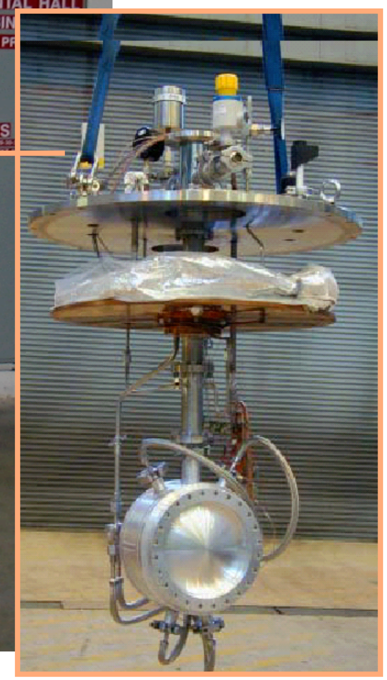

**Designed to accommodate full Linac Beam**

- $1.6 \times 10^{13}$ p/pulse @15 Hz
  - ➢ $2.4 \times 10^{14}$ p/s
  - ➢ 600 W into 35 cm $LH_2$ absorber @ 400 MeV

**RF power from Linac (201 and 805 MHz test stands)**

# KEK test cryostat at MTA/ FNAL

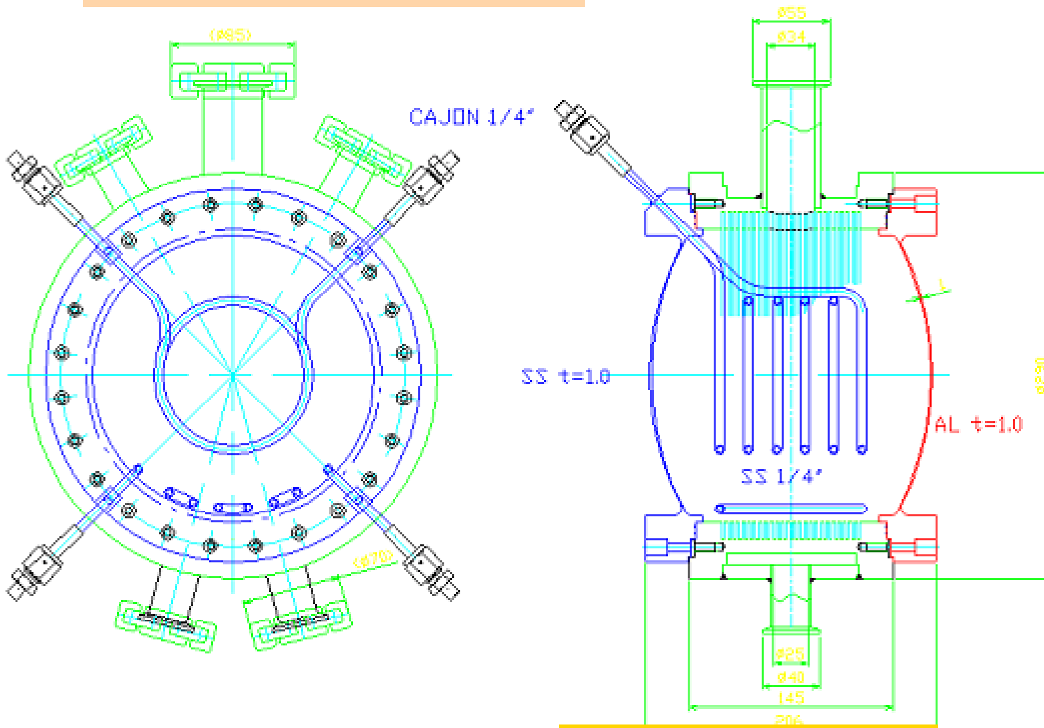

Pre-cryo plant:: cooling power from He dewars



# KEK absorber II

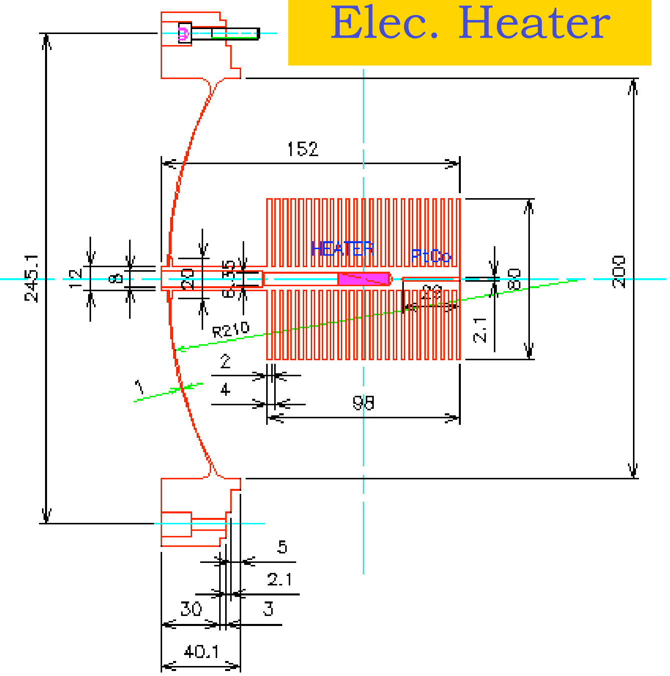
Muon Collaboration

2004 heater setup




2005 heater setup

Elec. Heater

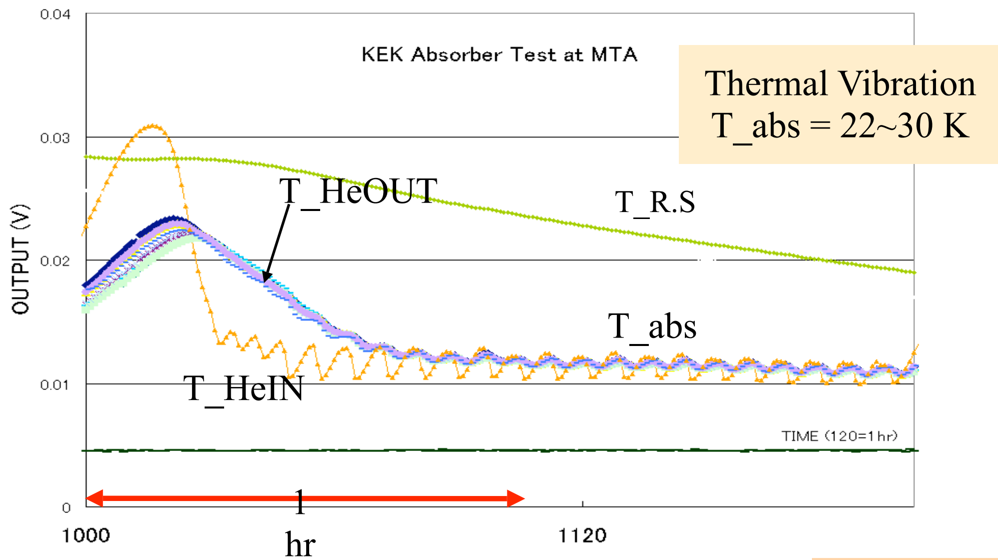


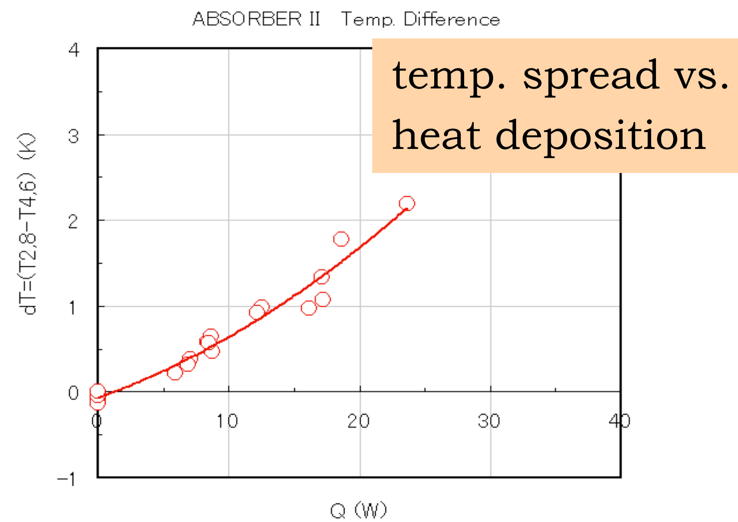

PtCo #1 - #8

G-He Heater

Better simulates beam heat deposition

# MTA KEK First Test Summary



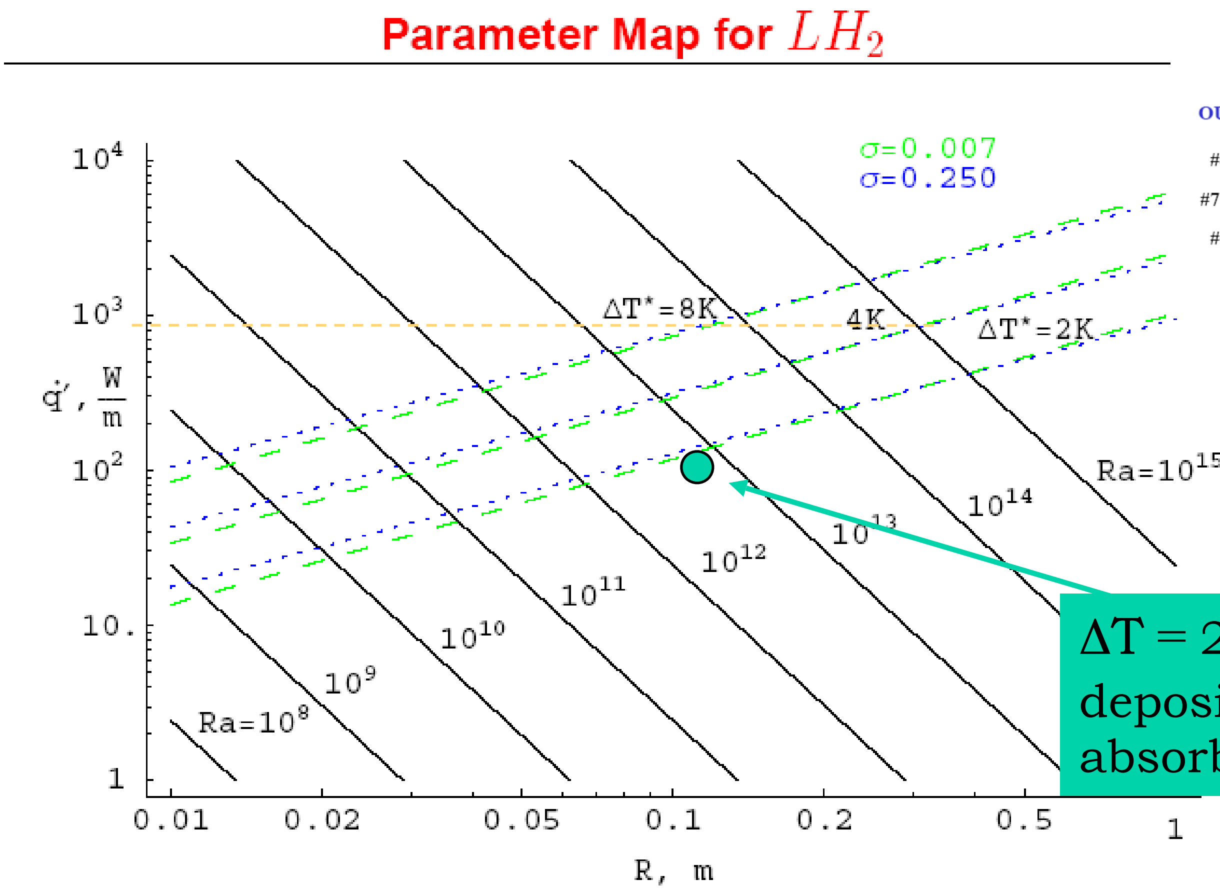



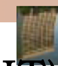

M. Cummings and S. Ishimoto, PAC2005, WPAE022

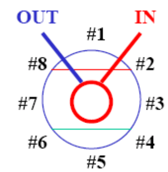
1. First run with an instrumented $LH_2$ absorber
2. Understood cooling control for heat deposition into relatively small $LH_2$ volume.
3. Successful fill, resolved **safety issues** for subsequent Mucool and MICE $LH_2$ and $GH_2$ absorber operations.

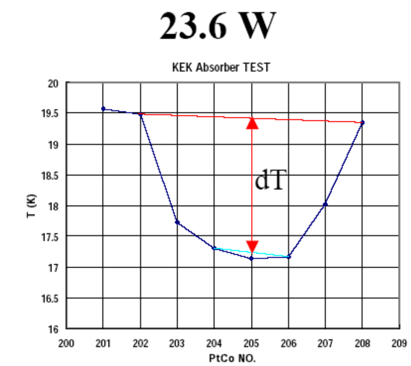
# Convection theory and data..

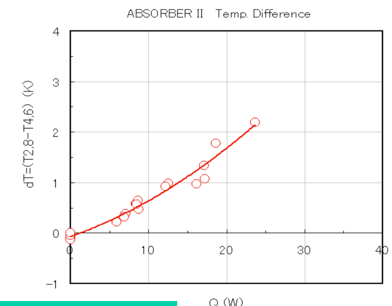
Comparison to CFD calcs (K. Cassel et al, 2004, IIT):





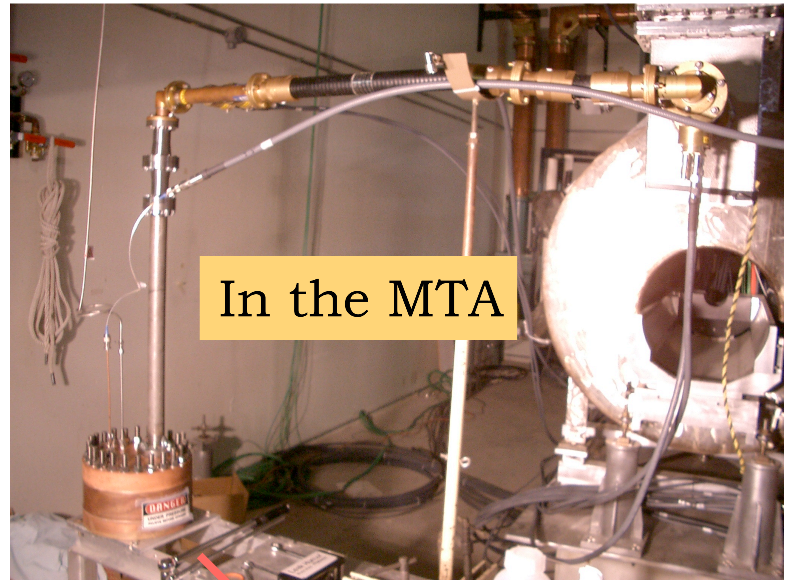



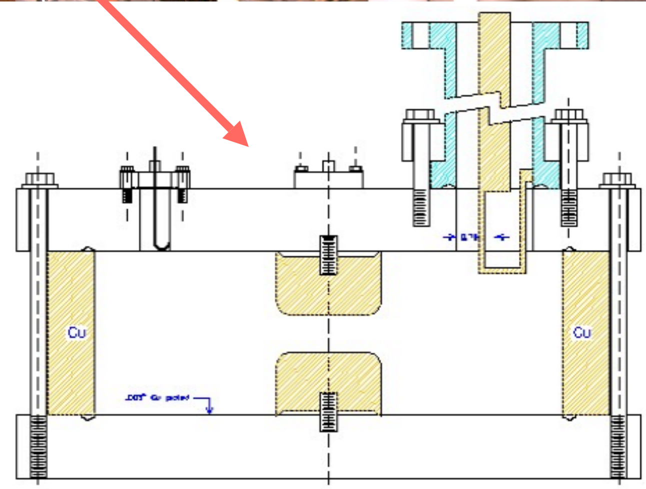

$\Delta T = 2K$ for 22W deposition in KEK absorber

Required heat absorption for cooling channel: ~800 W/m
That can be achieved but indicates the limitation of such absorbers technology.

# Gaseous Absorber – Muons Inc.

- Serendipitous exploitation of:
  - ⇒ **$19^{th}$ century science**
  - ⇒ **Muons unique cooling quality**
- Dense $GH_2$ suppresses high-voltage breakdown
  - ⇒ Small MFP inhibits avalanches (**Paschen's Law**)
- Gas acts as an energy absorber
  - ⇒ Needed for ionization cooling
- Only works for muons!
  - ⇒ No strong interaction scattering like protons
  - ⇒ More massive than electrons so no showers

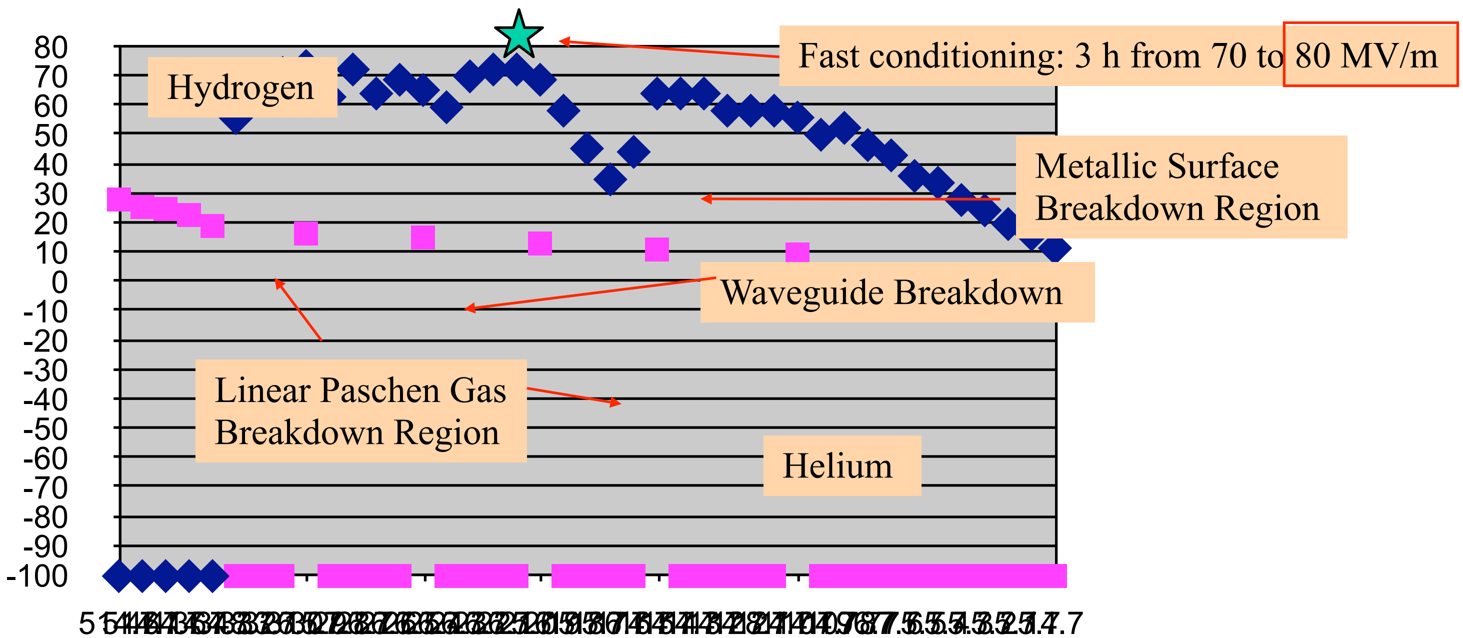



RF cell filled with $GH_2$

Rol Johnson, et al Muons, Inc.

# Lab G Results, Molybdenum Electrode

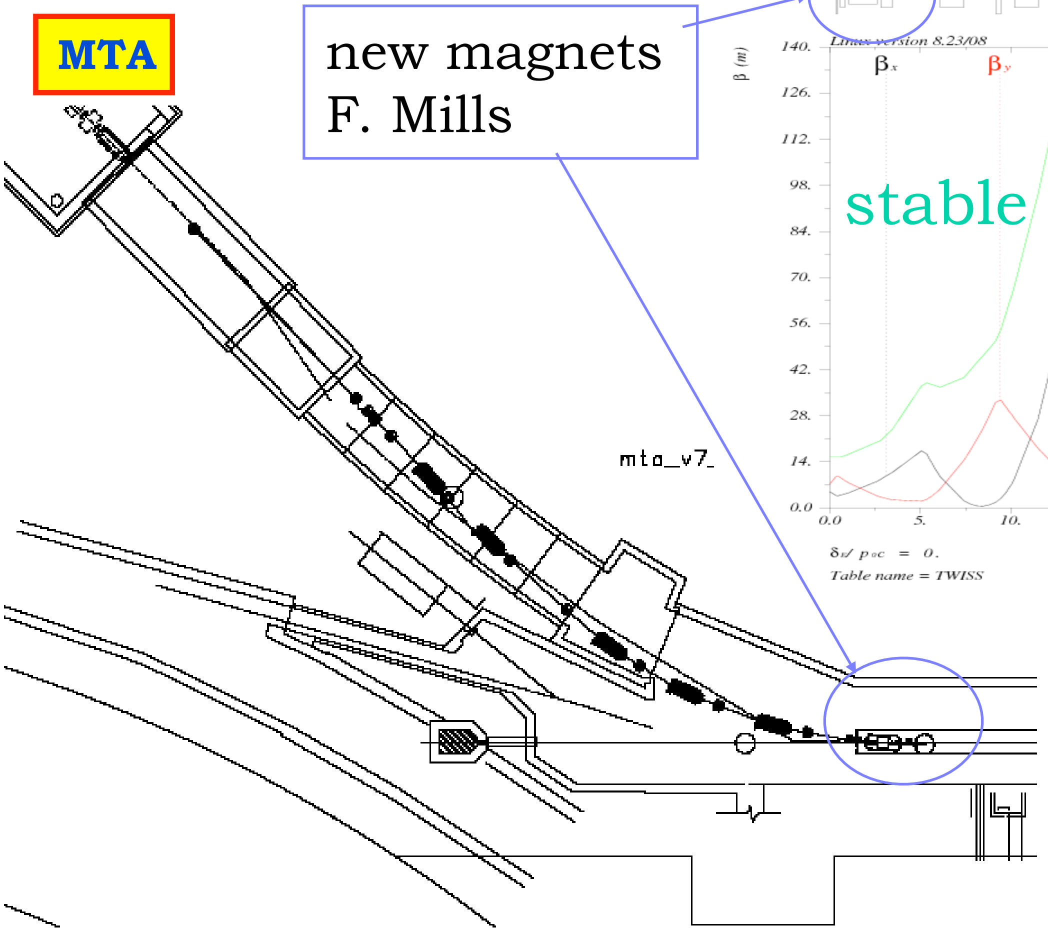


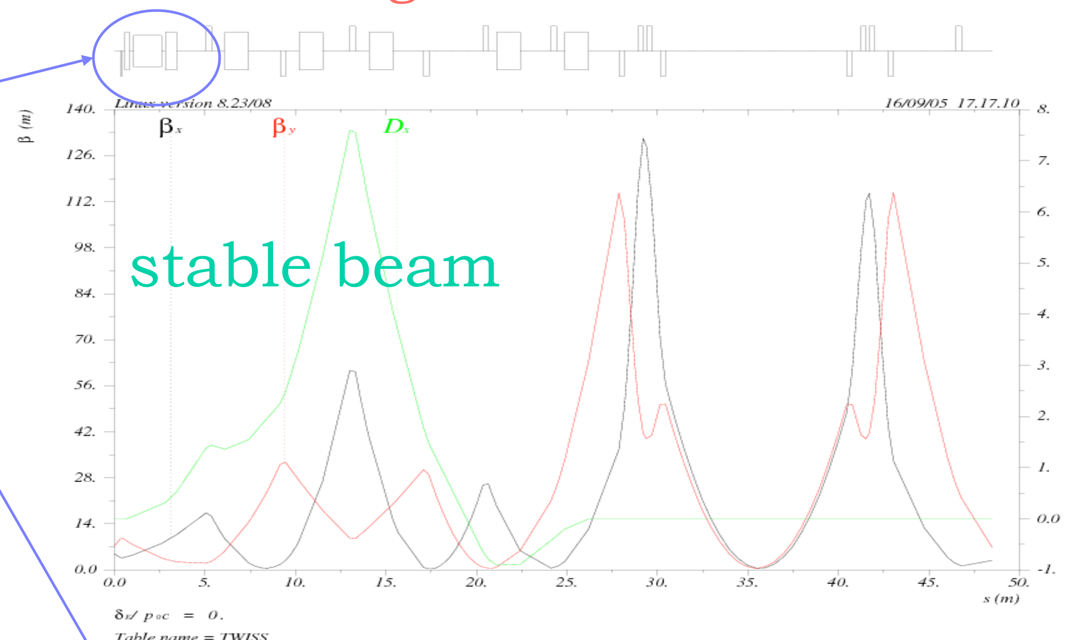

Tests of Gaseous RF cavity at FNAL MTA:

- ⇒ Completed room temp. tests with several different electrodes
- ⇒ Cryogenic test in Fall '05
- ⇒ Test inside solenoidal magnetic field (after 805 and 201 tests)
- ⇒ High-powered test in the MTA beam

# MTA High Intensity Beam

Beamline designed and costed by C. Johnstone for the MTA.
Part of the Linac Instrumentation Test Program




BEAM IN 2006

# MTA Absorber Task List

## Current program:

- $GH_2$ RF tests: cryo and magnet
- KEK $LH_2$ test (convection)
- FF $LH_2$ absorber construction and tests
- FF $LH_2$ and RF first cooling cell test
- $GH_2$ beam test
- Cooling cell beam tests

## Future projects:

- $LH_2$ HCC cryostat (Muons, Inc.)
- Lithium Hydride

# Concluding Comments

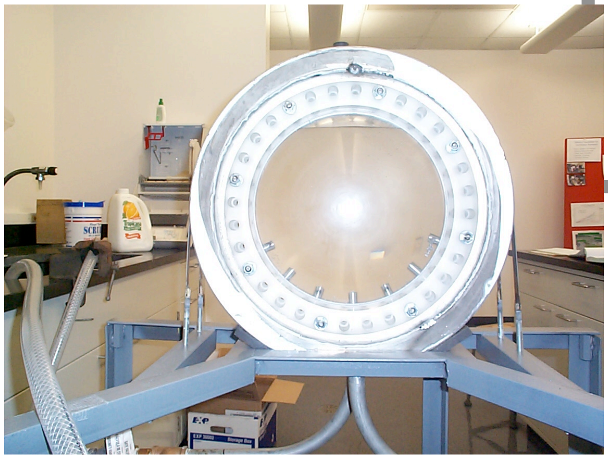
Mucool continues to have an innovative $H_2$ absorber program

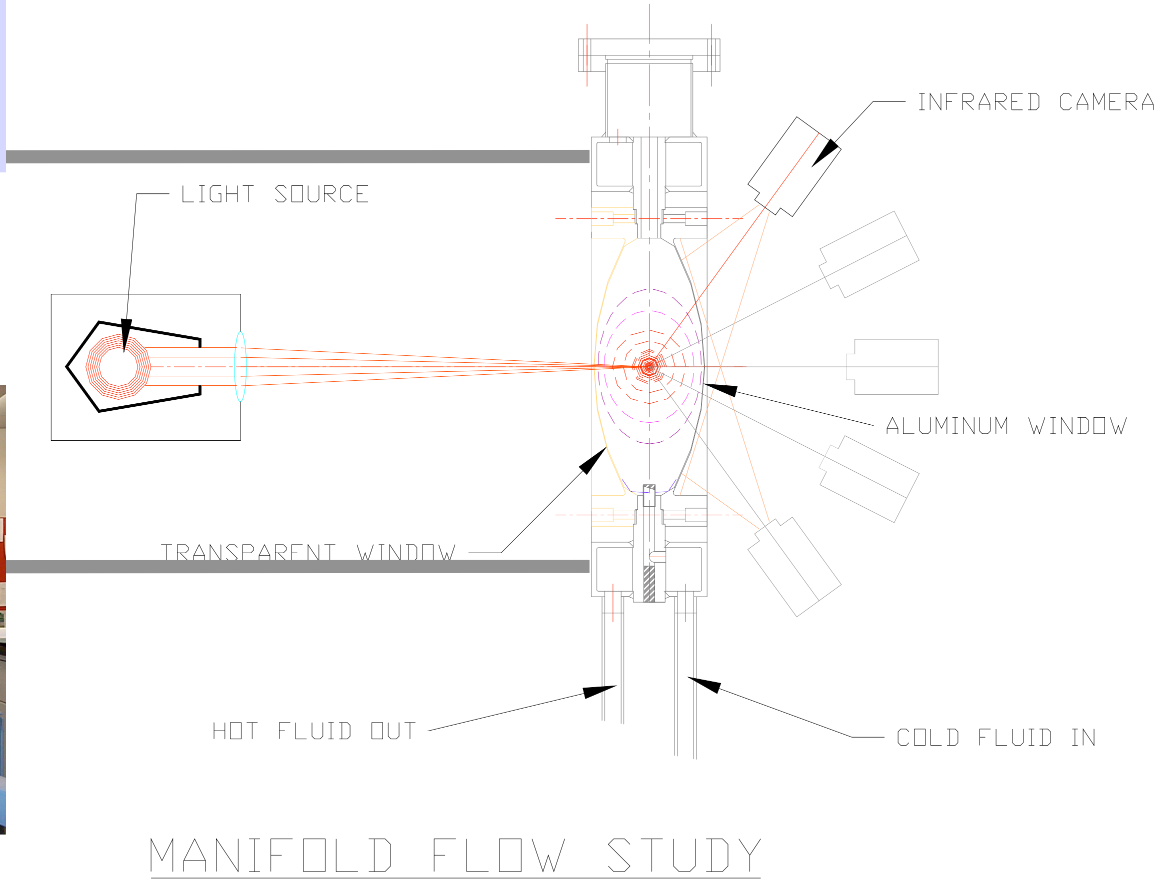
- Unusual collaboration of particle and accelerator physicists
- New technologies:
  - ⇒ **Thin window manufacture and measurements**
  - ⇒ **Convection $LH_2$ cooling**
  - ⇒ **Gaseous RF cavities**
  - ⇒ **Continuous absorber cooling channels (in design)**
- FNAL MTA is developing into a unique, world-wide target facility
- Mucool $LH_2$ and cooling R & D fully complementary to MICE and future 6D cooling demonstrations.

A different possible future for particle physics

# Infrared Flow Test

Testing 3-dimensional simulations with water flow test at FNAL Lab 6

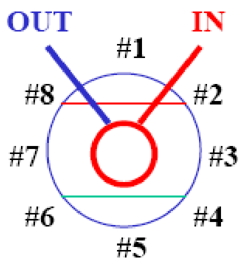




# Temperature uniformity…

Distribution of temp. probes

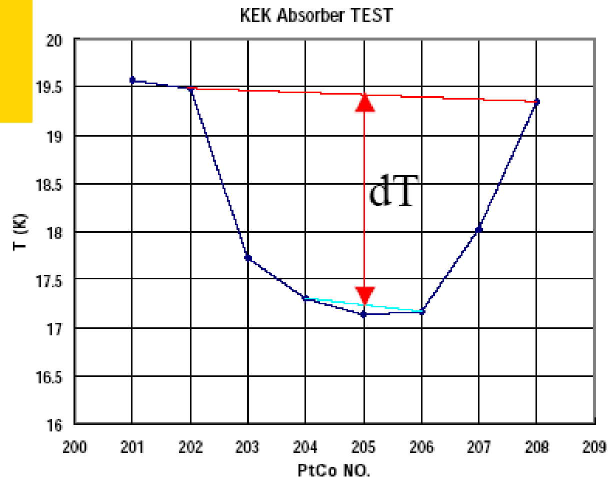
(central tubes introduce new artifice!)



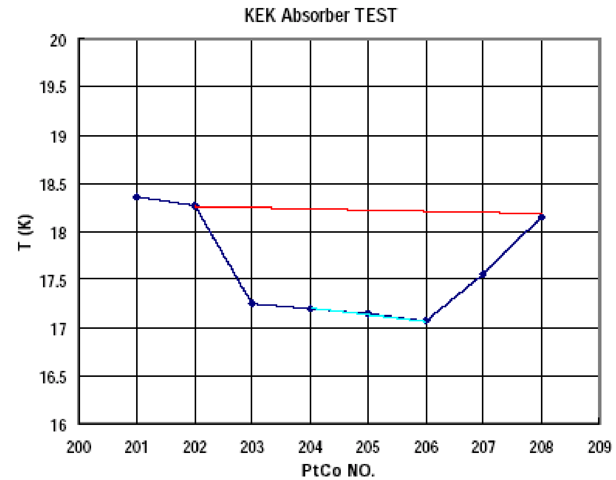

1) Large Heat makes dT large.

2) Asymmetry of #2-8, #4-6 comes from Warm-He IN/OUT

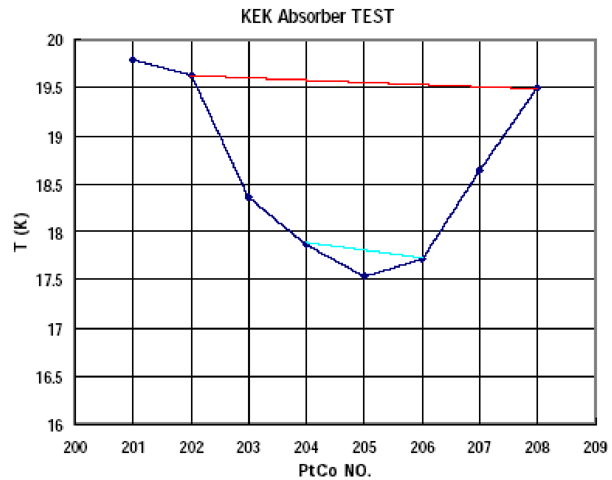
**23.6 W**



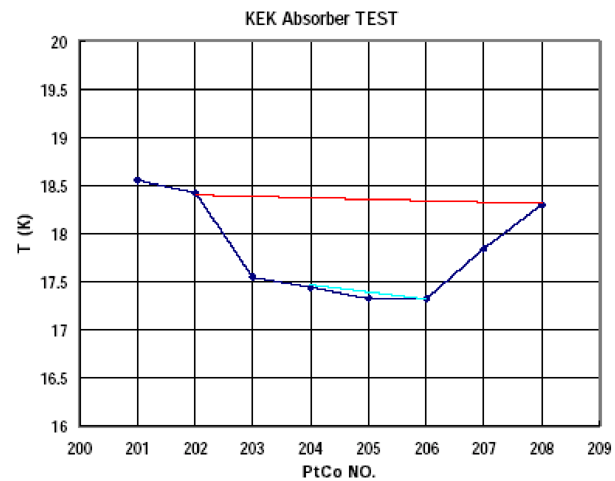

**17.2 W**



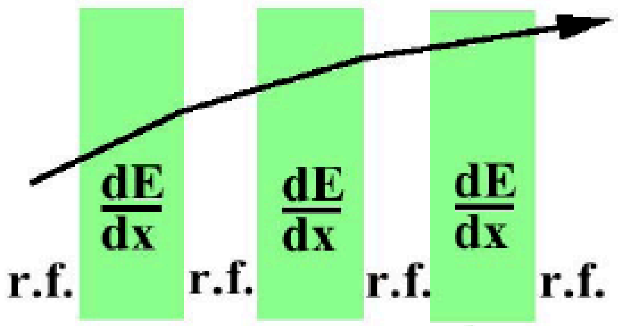

**18.7 W**

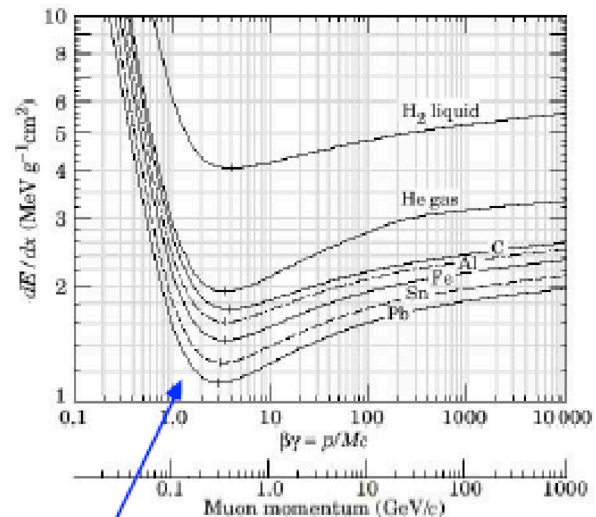



**12.6 W**



# Ionization cooling




→ Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

→ RF cavities between absorbers replace $\Delta E$

Net effect: reduction in $p_\perp$ w.r.t. $p_\parallel$, i.e., transverse cooling

**Muons decay:** must focus quickly – ionization cooling is the only option

**Note:** The **physics** is not in doubt

⇒ in principle, ionization cooling **has** to work!

… but in practice it is subtle and complicated so a test is important

# Safety

- For $H_2$, two principles driving system design :
  - ⇒ $O_2$ and $H_2$ separation
  - ⇒ No ignition sources
- At FNAL: guidelines for the $LH_2$ absorber system
  - ⇒ America Society of Mechanical Engineers (pressure and vacuum vessels, etc.)
  - ⇒ National Electrical Code <= (Class I Division II, or "instrinsically safe")
  - ⇒ Compressed Gas Associates
  - ⇒ Fermilab Environment Safety and Health Code

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 – electrical, friction, impact, auto-ignition
- ⇒ Minimum energy for ignition of $H_2$ is 0.017 mJ at 1 atm.
- ⇒ Combustion $H_2$ /air ratio from 4% to 75%

PRIMARY SAFETY MECHANISM IS CONTAINMENT: "EXCEPTIONS HANDLED BY VENTING $LH_2$ OUT OF THE AREA

# Safety Issues to be resolved

- Window certification
  - ⇒ Design certification different for vacuum/absorber windows
  - ⇒ Tentative real window certification: (could be the same as MICE)
    - Materials inspection
    - Measurement
    - Sub-elastic limit pressure tests

- Hydrogen zone (re) defined
  - ⇒ Problem for FNAL is that if all of the $LH_2$ were to vaporize into the MTA at STP, the highest possible concentration of $H_2$ is 7%.
  - ⇒ RAL sets the standard from ATEX (French **AT**mospheres **Ex**plosives) adopted by the EU in July 2003
    - Zone 0 – possible explosive concentration for extended periods
    - Zone 1 – possible explosive concentration for < 1000 hrs/year
    - Zone 2 – possible explosive contratcion for < 10 hrs/year

  - ⇒ Will be resolved in the context of a specific project (forced-flow absorber with RF, e.g.)