Muon Collaboration

Introduction

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MICE

Absorber Review Meeting
Fermilab
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Outline:

1. Collaboration
2. Brief review of ionization cooling
3. Choice of absorber medium
4. Power handling (linear *vs.* ring coolers)
5. Windows & containment
6. Summary

Absorber R&D Collaboration

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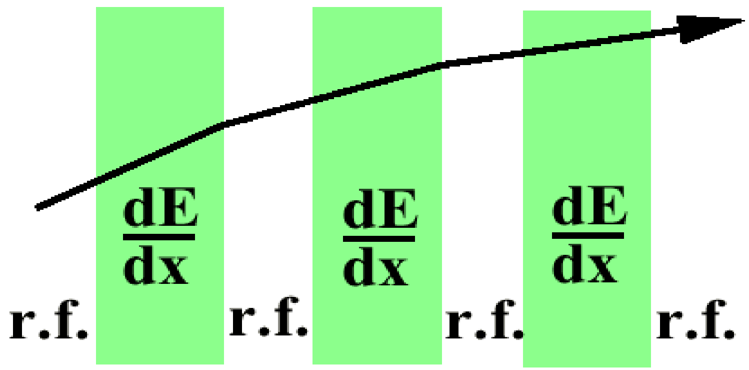
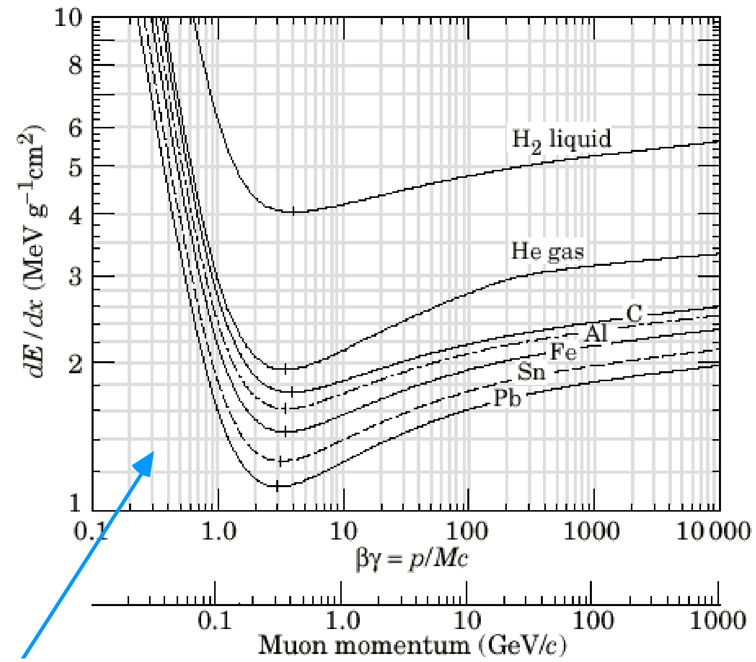
(Is this up-to-date?)

Ionization Cooling





- Absorbers:

$$\begin{cases} E \to E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta_{space}^{rms} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

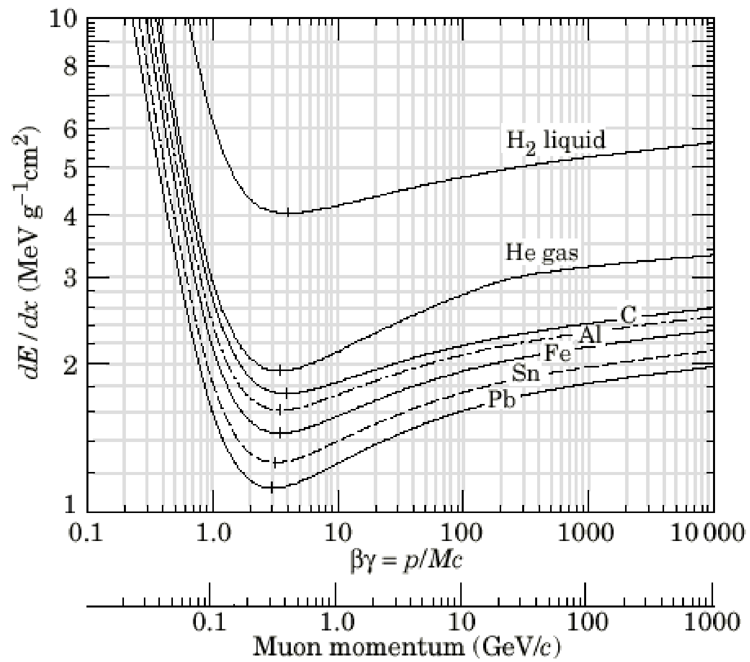
for thin absorber, $\theta_{space}^{rms} = \sqrt{2}\theta_0$, where $\theta_0 \approx \dfrac{0.014\,\mathrm{GeV}}{\beta cp}\sqrt{\dfrac{L}{L_R}}$ (Gaussian approx.)

- RF cavities between absorbers replace ΔE
- Net effect: reduction in $p_\perp$ spread w.r.t. $p_\parallel$, i.e., transverse cooling
- But energy spread increases due to energy-loss straggling $\to$ beam losses

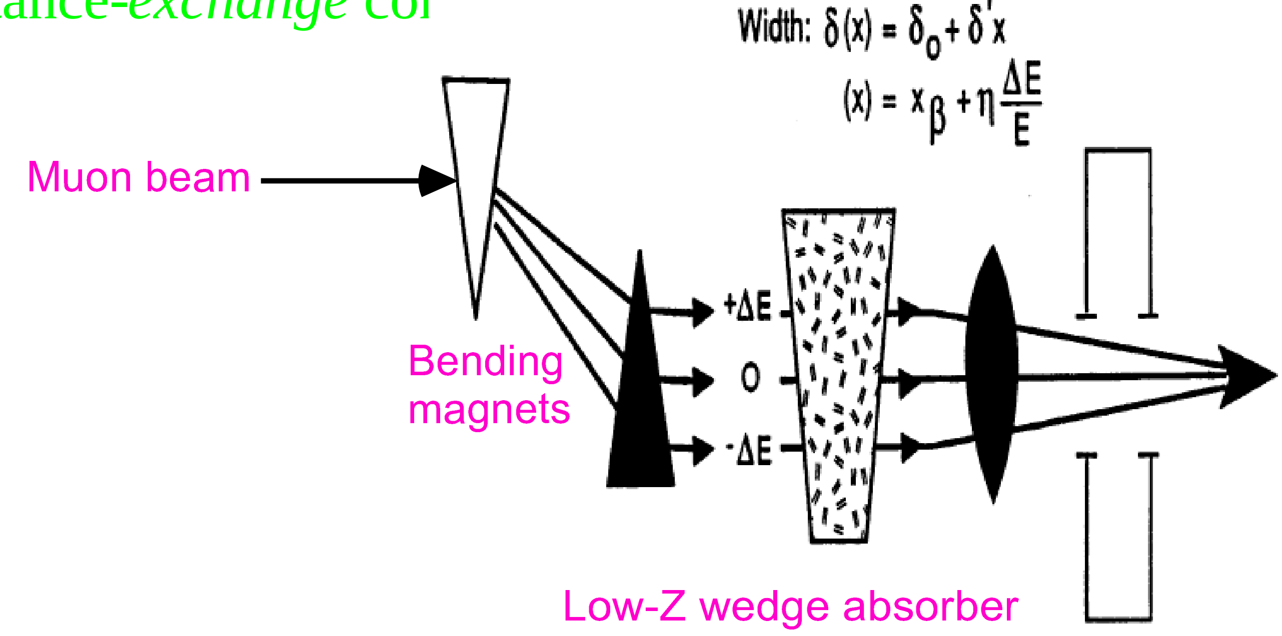
Longitudinal Ionization Cooling?

- At or below ionization minimum, dE/dx slope zero or negative ⇒ no negative feedback
- Above ionization minimum, dE/dx slope positive
  - but too small to be useful, and
  - straggling (random fluctuations in ionization rate) significant

⇒ ∃ no good regime for longitudinal ionization cooling



→ Emittance-*exchange* cor



Comparing potential absorber media:

- 2D transverse-cooling rate: $$\frac{d\varepsilon_{x,N}}{dz} \approx -\frac{1}{\beta^2}\frac{\varepsilon_{x,N}}{E}\left|\frac{dE}{dz}\right| + \beta_\perp \frac{(0.014\text{ GeV})^2}{2\beta^3 E m_\mu L_R}$$

Mat'l	**ρ**	***dE/dx***	***dE/dx* /cm**	**L_R**	**merit**
	(g/cm^3)	(MeV/g·cm^2)	(MeV/cm)	(cm)	$(L_R\, dE/dx)^2$
LH_2	0.0708	4.05	0.29	866	1
LHe	0.125	1.94	0.24	755	0.51
LiH	0.82	1.94	1.59	106	0.44
Li	0.53	1.64	0.88	155	0.28
CH_4	0.42	2.42	1.03	46.5	0.19
Be	1.848	2.95	2.95	65	0.17

– "merit" ∝ 4D transverse-cooling rate

⇒ In the scattering-limited cooling regime, as equilibrium between cooling and heating is approached, hydrogen is best by factor ≈2

Absorber Power Handling

- Neutrino Factory Feasibility Study II absorbers:

Absorber	Length (cm)	Radius (cm)	Window thickness (μm)	Number needed	FS-II power (kW)	"Rev.-FS-II" power (kW)	
Minicool?	175	30	?	2	≈5.5	≈22	(Not LH2)
SFOFO 1	35	18	360	16	≈0.27	≈2	
SFOFO 2	21	11	220	36	≈0.1	≈0.9	

– power dissipation w/ 4-MW Proton Driver & both μ charges at once

– First, estimate rate of bulk temperature rise if no flow:

$$c_p = 1.1 \times 10^4 \text{ J/kg}\cdot\text{K}$$

$$\Delta T / \text{s} = \frac{\langle P \rangle}{c_p V \rho} = \frac{\langle P \rangle / L}{c_p A \rho}$$

$$= \frac{2 \text{ kW} / 0.35 \text{ m}}{1.1 \times 10^4 \text{ J/kg} \cdot \text{K} \times \pi (0.16\text{m})^2 \times 70.8 \text{ kg/m}^3}$$

$$\approx 0.1 \text{ K/s}$$

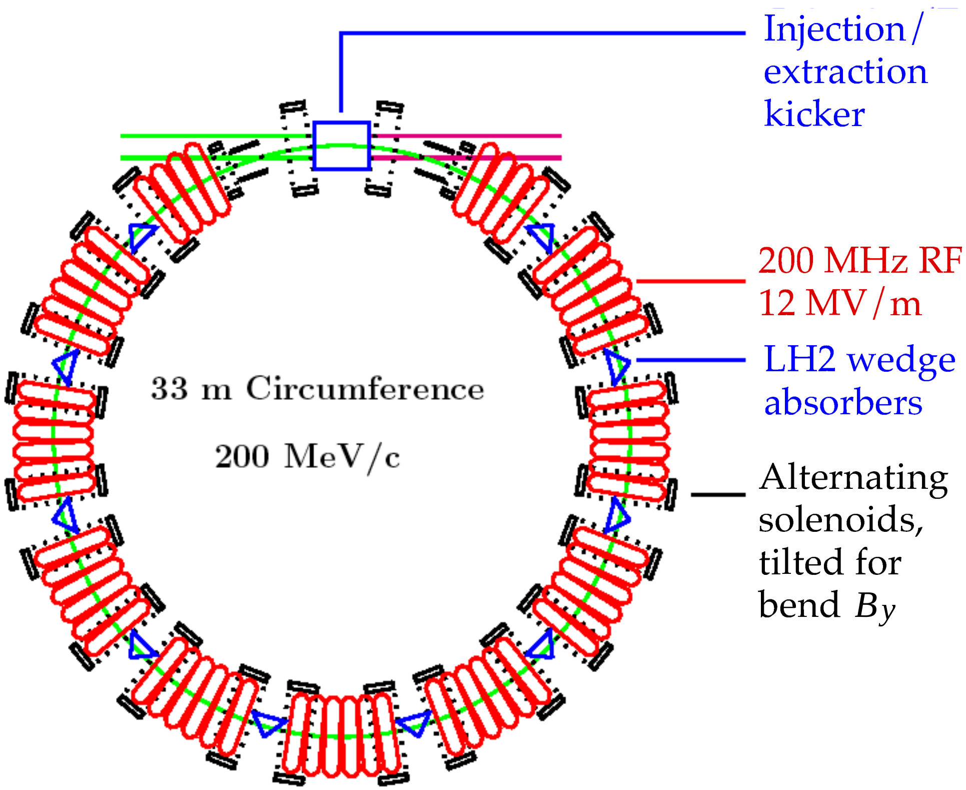
⇒ 0.1 volume change/s sufficient to keep $\Delta T \lesssim 0.1$ K

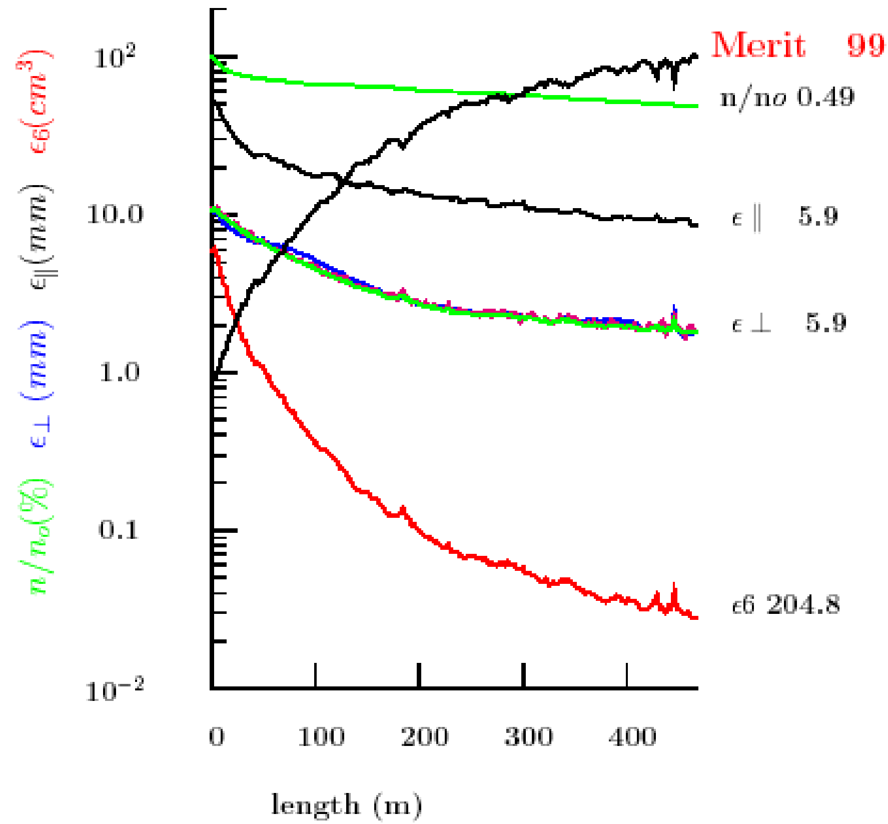
≈ 3 *l*/s for SFOFO 1 (35-cm) absorber

→ should be feasible **if** good transverse mixing, without eddies or dead zones

Ring Cooler

- Ring cooler:
  - does 6D cooling via simultaneous transverse cooling and emittance exchange
  - e.g. Palmer design:





- Requires muons to traverse each absorber 10–20 times

$\rightarrow \approx$20 kW/absorber power dissipation

- Is this feasible?

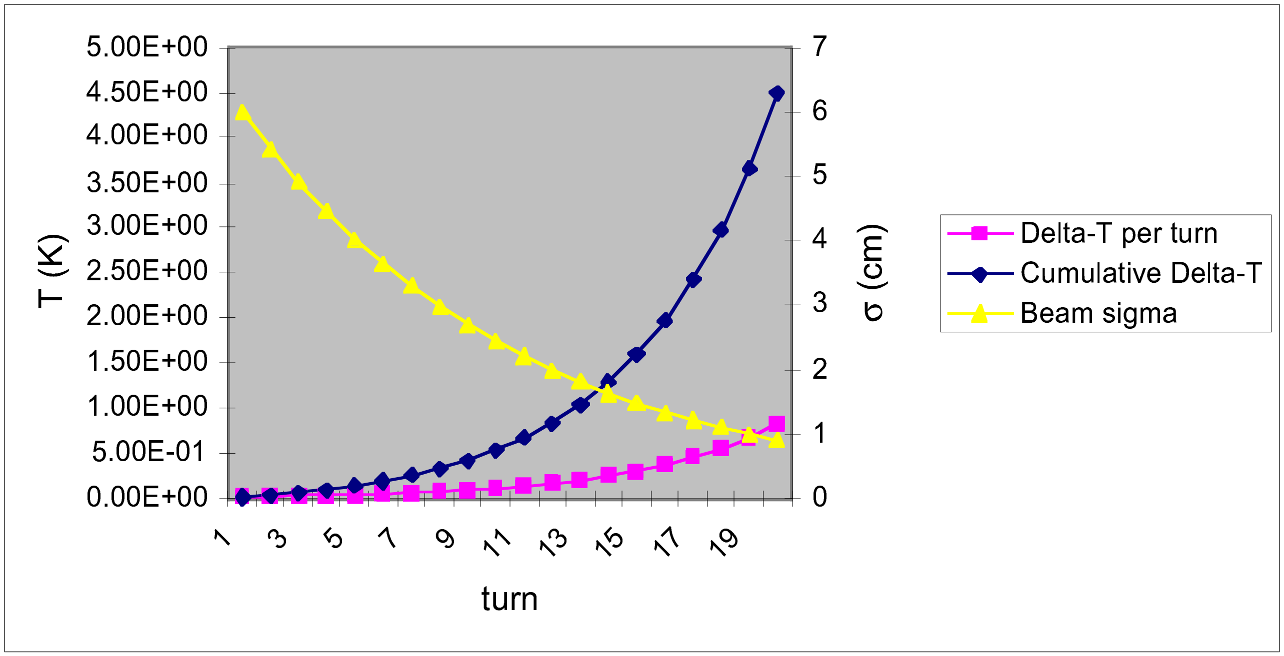
Ring Cooler Power Handling

- ΔT per turn at beam center neglecting heat xfer (T. Roberts, IIT):

$$\Delta T \approx \frac{N\frac{dE}{dx}}{\sigma^2 c_p} = \frac{N}{\sigma^2}\frac{4.2\ \mathrm{MeV/g\cdot cm^{-2}}}{11\ \mathrm{J/g\cdot K} \times 1.6\times 10^{13}\ \mathrm{MeV/J}}$$

(assuming Gaussian beam centered at origin – maybe poor approx for ring cooler)

- Assume N = 2.8e13 @ 15 Hz (4-MW 24-GeV p beam × 0.2 μ/p × 2 μ charges):



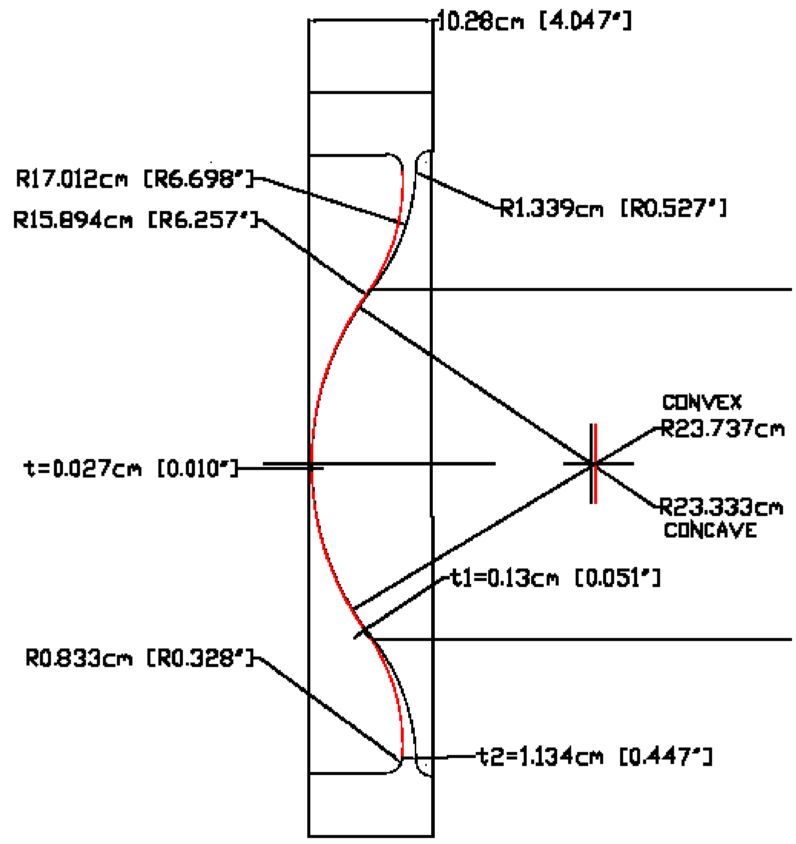
⇒ A single cycle does not boil the hydrogen, BUT
- can the heat be removed quickly enough? (need low ΔP due to thin windows!)
- maybe better than this:
  - in some designs wedge covers only half of beam
  - 2.8e13 μ/pulse maybe overestimate?
  - dispersion may lower peak intensity – need actual beam distribution from simulation

Absorber Windows

(E. Black, IIT, W. Lau, Oxford, M. Reep, D. Summers, UMiss)

- R&D issue: conventional designs for pressure-vessel windows too thick
  - especially true for ring cooler, which approaches scattering-dominated regime

→ Developing thin, tapered windows, custom-machined (with integral flange) out of a single block of material:



Impact of Safety Requirements

(D. Allspach, FNAL)

- Established FNAL liquid-hydrogen rules are explicit:

  1. must prevent oxygen contamination within hydrogen loop, AND
  2. must exclude ignition sources from vacuum vessel containing absorber

- Since RF cavities considered an ignition source,

  ⇒ must have "primary containment" vacuum vessel surrounding absorber vessel

  → twice as many windows as in Feasibility Study II simulation!

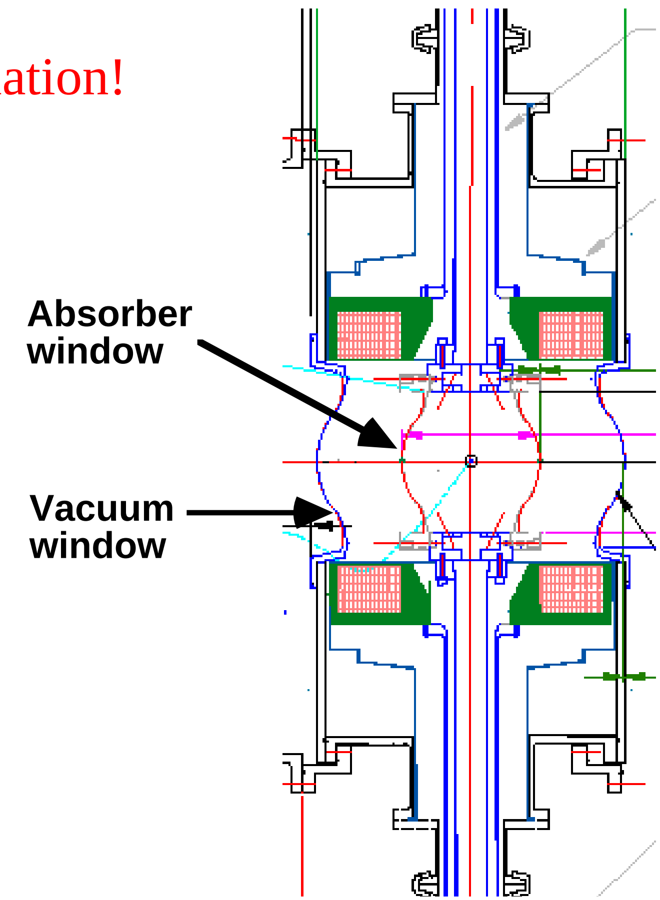
- Fortunately,

  vacuum window need not be as strong as absorber window (since not an LH_2 container)

  ⇒ total Al thickness per cell comparable to that in FS-II:

  2×360 µm "SFOFO 1" lattice

  2×220 µm "SFOFO 2" lattice



Even Thinner Windows?

(D. Summers, UMiss)

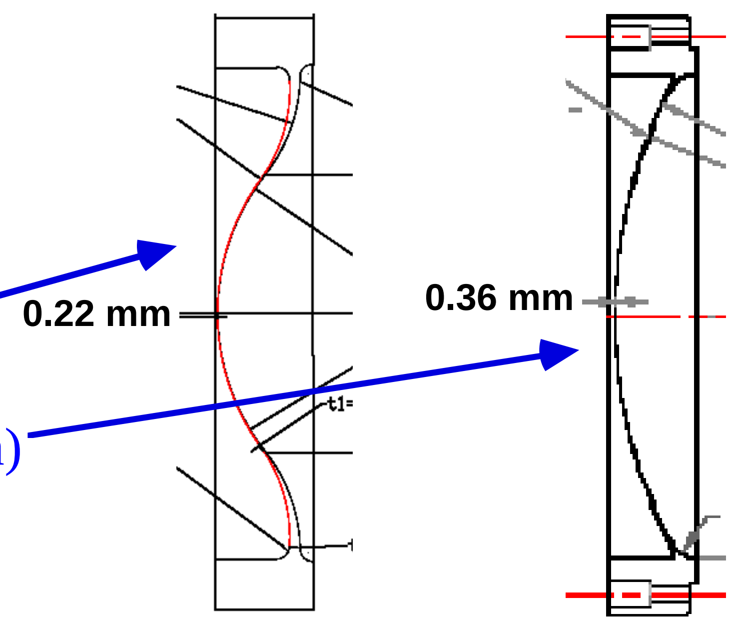
- “Aircraft alloys” (containing Li) are stronger & lighter than 6061:

Al alloy name	Composition	Density	Yield strength @300K	Tensile strength @300K	Tensile strength @20K	Rad. Length
	% by weight	(g/cc)	(ksi)	(ksi)	(ksi)	(cm)
6061-T6	1.0Mg 0.6Si 0.3Cu 0.2Cr	2.70	40	45	68	8.86
2090-T81	2.7Cu 2.2Li .12Zr	2.59	74	82	120	9.18

⇒Windows could be ≈45% thinner, **if**

- 2090-T81 has good machinability **and**
- such thin windows can be reliably machined

... to be tested soon at U. Miss.



(Note latest window shape already 40% thinner than previous iteration)

Summary

- Healthy progress developing LH_2 absorbers with thin windows
- Need to continue iterating towards optimal, self-consistent designs
- Need to document details of absorbers for MuCool, MICE
- Need to pass safety reviews
- Need to think about wedge absorbers and limits to power handling