Muon Collaboration

Absorber: Introduction & Design Issues

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ICAR

Muon Collaboration Meeting
Shelter Island, NY
5/10/02

MuCool Absorber R&D Collaboration:

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Key Issues:

1. Power handling
2. Minimization of multiple scattering: design of thin windows
3. Safety
4. Alternative materials

Absorber Power Dissipation

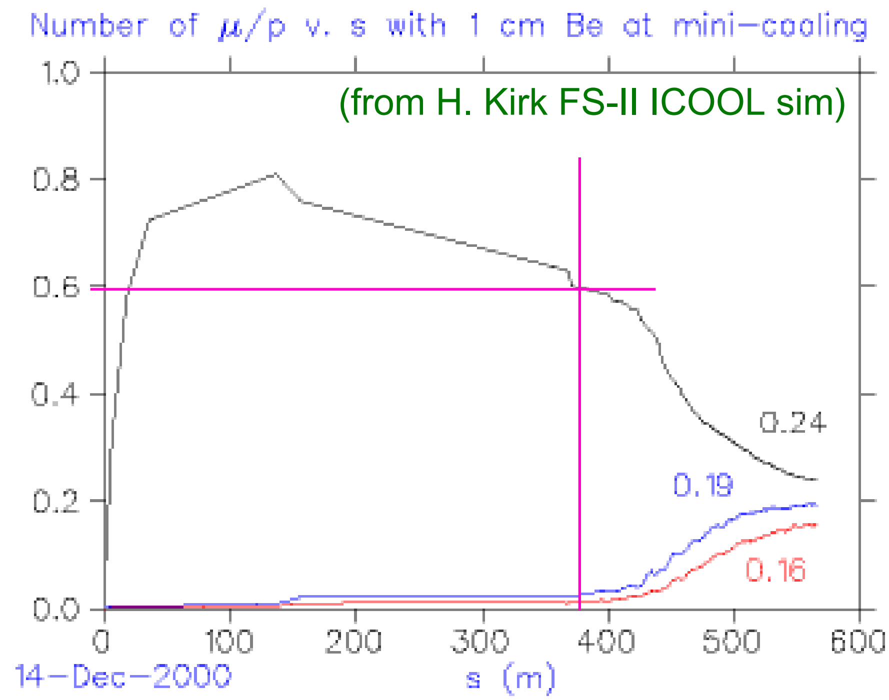
Worst case (?): "Revised FS-II" SFOFO1 Absorber:

- Lose 0.3 MeV/cm/$\mu \times$ 35 cm $\approx$ 11 MeV/μ
- 4 MW beam $\Rightarrow 1.0 \times 10^{15}$ p/s at 24 GeV
- FS-II: $\approx$ 0.6 μ/p at entrance to SFOFO lattice 1

  $\times$ 2 (get both signs with Neuffer ϕR)

$\Rightarrow 1.2 \times 10^{15}$ μ/s $\times$ 11 MeV/$\mu \times 1.6 \times 10^{-13}$ J/MeV

= 2 kW/absorber



SFOFO2 Absorber:

- $\approx$ 2/3 as many muons, 60% as long $\Rightarrow \approx$ 40% as much

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
SFOFO 1	35	18	360	16	≈0.27	≈2
SFOFO 2	21	11	220	36	≈0.1	≈0.9

Absorber-Medium Options

- 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	**M.P.**	**B.P.**	***dE/dx***	***dE/dx*/cm**	L_R	**merit**
	(g/cm^3)	(K)	(K)	(MeV/g·cm^2)	(MeV/cm)	(cm)	$(L_R\ dE/dx)^{-2}$
LH_2	0.0708	14	20	4.05	0.29	866	1
LHe	0.125		4	1.94	0.24	755	1.95
LiH	0.78	956		1.94	1.59	106	2.28
Li	0.53	454	1615	1.64	0.88	155	3.54
CH_4	0.42	91	112	2.42	1.03	46.5	5.15
Be	1.848	1560	2744	2.95	2.95	65	6.02

– "merit" $\propto$ rate of increase of (4D) transverse phase-space density

$\Rightarrow$ Hydrogen is best by factor ≈2, IF cooling channel reaches scattering-dominated regime

LH_2 Cooling @ 2 kW

- Flow-through absorber
  - First, estimate rate of bulk temperature rise if no flow:

$c_p = 1.1 \times 10^4$ J/kg·K

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

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

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

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

≈ 3 l/s SFOFO1 (35-cm) absorber

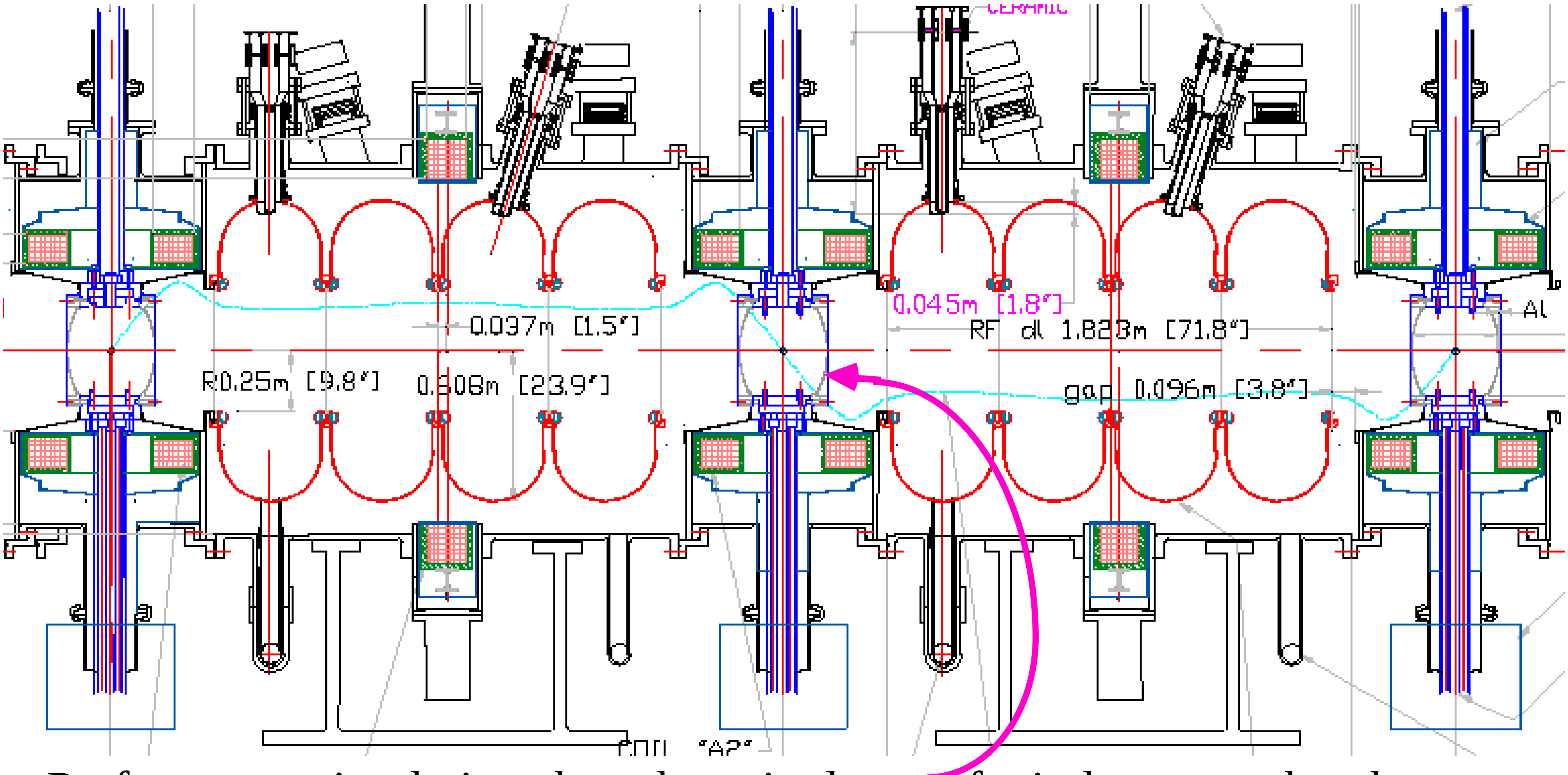
$\rightarrow$ should be feasible

(also need good mixing without eddies or dead zones)

- Convection-cooled absorber harder to analyze
  - may need boiling to achieve high enough rate of heat transfer within fluid

FS II Cooling Channel

2.75-m SFOFO ("Lattice 1"):



- Performance simulations based on single set of windows per absorber at ≈1 atm operating pressure:

2.75-m SFOFO (lattice 1): 360 μm Al

1.65-m SFOFO (lattice 2): 220 μm Al

Safety Considerations

- Established FNAL LH_2 guidelines:
  1. Vacuum vessel enclosing LH_2 flask must contain neither oxygen nor ignition sources
  2. OK for absorber to operate at ≈15 psi, but vacuum vessel enclosing LH_2 flask must be rated for 30 psid (to handle pressure rise from evaporating LH_2 in case of flask rupture)
  3. Despite intended ≈15-psi absorber operating pressure, guidelines require absorber windows to have adequate safety margins at 25 psid MAWP

- RF cavity is ignition source!

  → Especially if cells closed by grids rather than windows

  (In any case, Be RF windows not rated for 30 psid so wouldn't satisfy guidelines)

⇒ **Need vacuum vessel around absorber with additional set of windows that are "twice as strong" as absorber windows themselves:**

Window	**Max int. pressure (psid)**	**Max ext. pressure (psid)**	**Safety factor (rupture)**	**Safety factor (yield)**	**Min rupture pressure (psid)**
Absorber	25	-	4	1.5	100
Vac. vessel	30	15	2.5	1.5	75

Meeting Safety Requirements

- FS-II-design absorber windows have been shown by FEA and prototype tests to burst at >100 psid

  (FNAL/IIT/NIU/Oxford/UIUC/UMiss)

- Now adopting more conservative criterion:
  burst pressure >120 psid

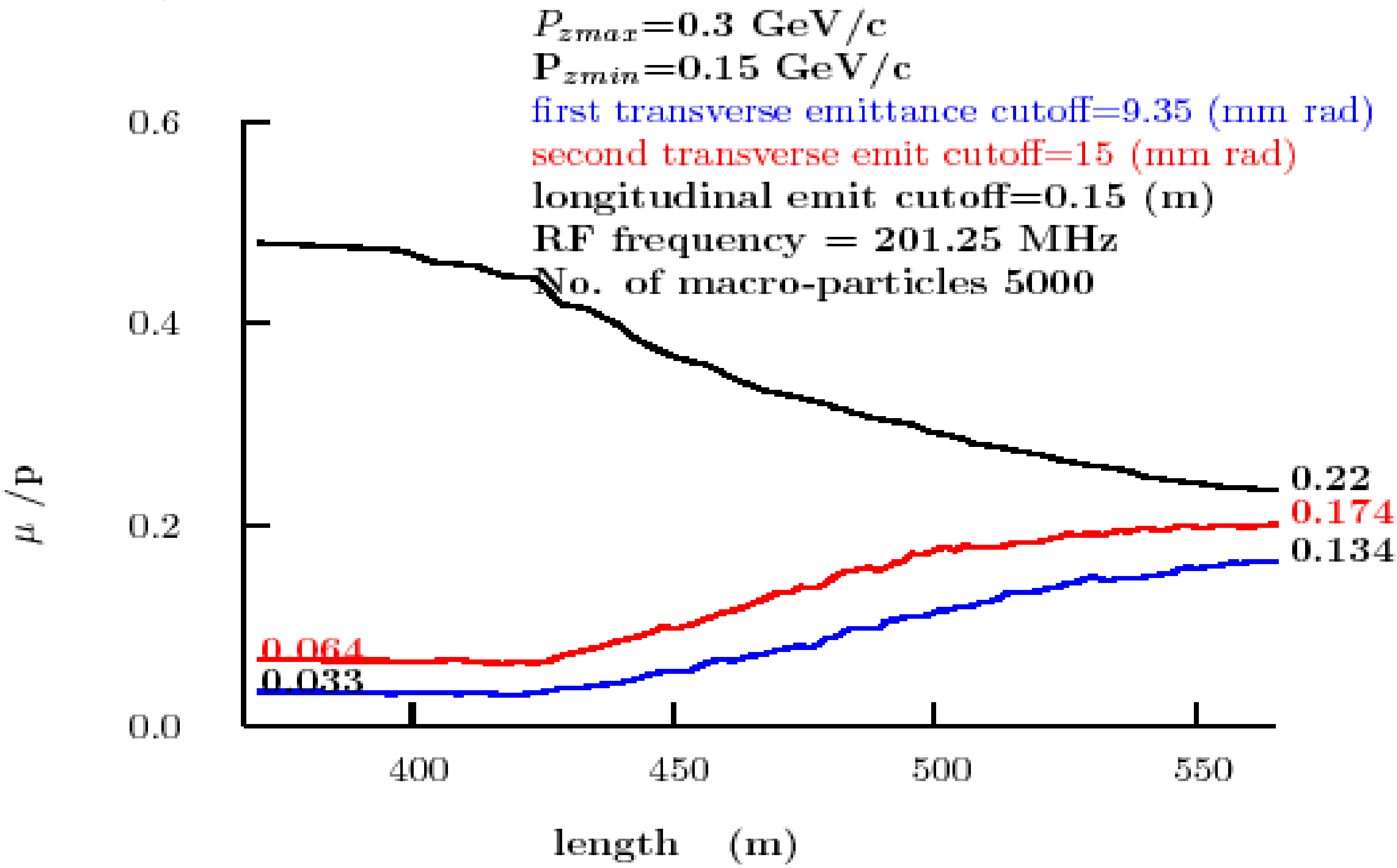
  – Allows margin for manufacturing tolerances on window thickness

  ⇒ FS-II SFOFO1 windows would be 400 μm
  FS-II SFOFO2 windows would be 240 μm

- Now working through design details incorporating vacuum vessel per absorber

ICOOL Studies of Absorber Options

- Cooling performance (FS II report):



- Updated *μ/p* within 15-cm longitudinal cutoff (Palmer/Gallardo/Fernow MUC-NOTE 233):

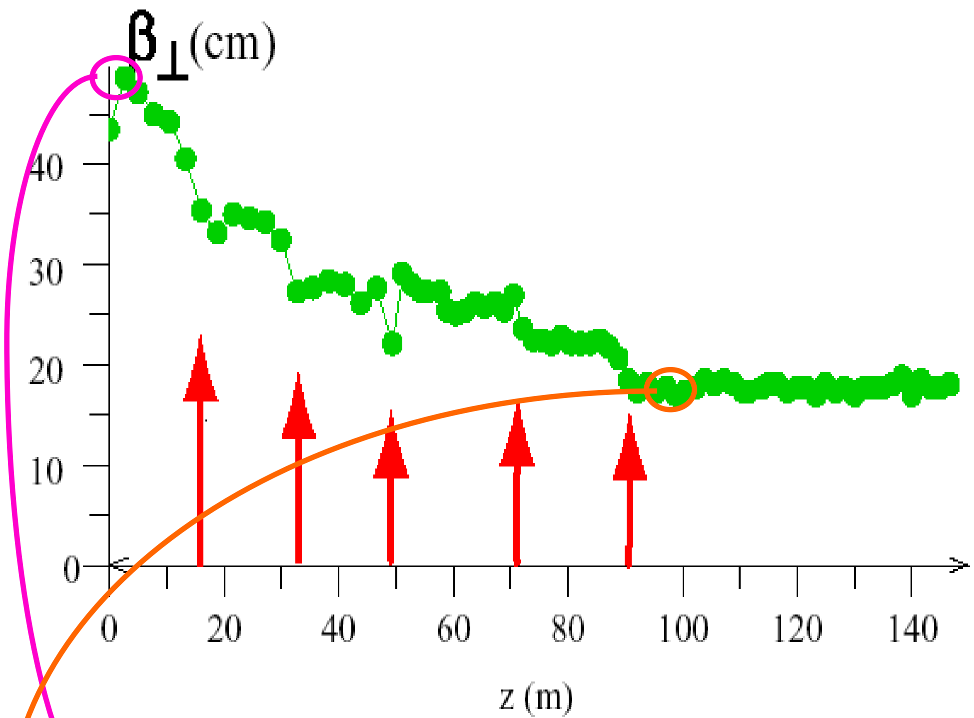
Case	Final μ/p	Loss
"FS II"	0.139 ± 0.04	-
+ 2x Al	0.127 ± 0.02	8.6%
LHe	0.121 ± 0.02	12.9%
LiH	0.121 ± 0.02	12.9%

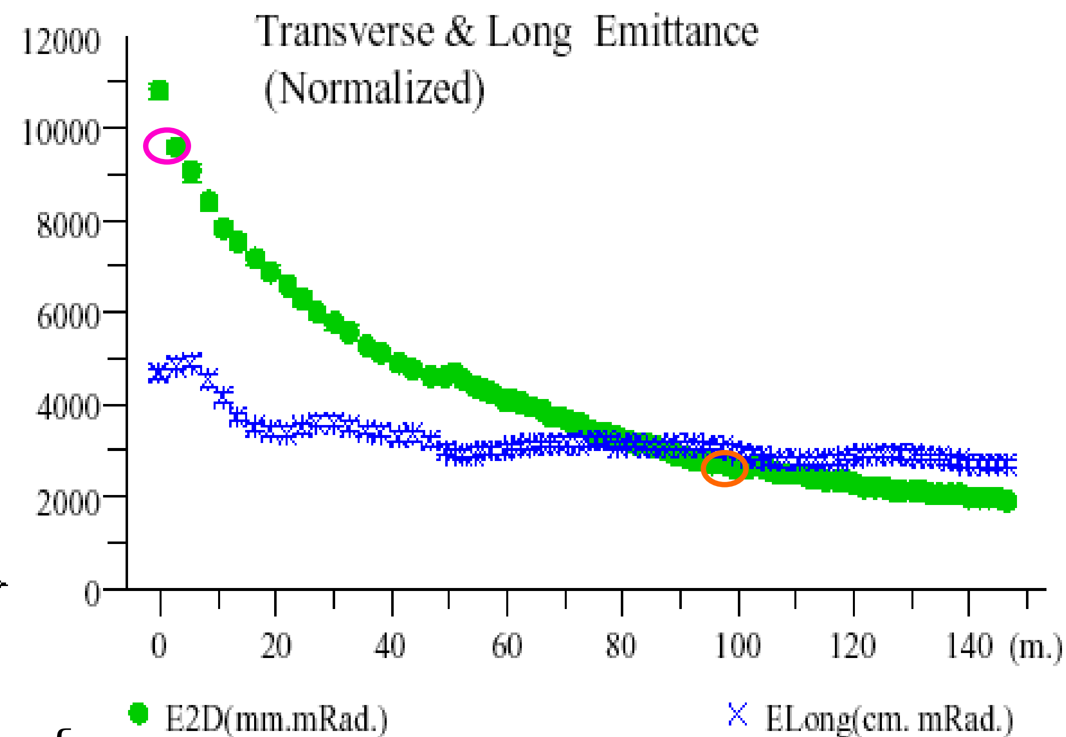
central Al thickness = 0.72 mm/SFOFO1 absorber

central Al thickness = 2.16 mm/SFOFO1 absorber (based on "twice as strong means twice as thick")

Why are effects so small?

- FS II report:





$$\beta = 48\text{ cm}, \varepsilon_{x,N} = 9.6\text{ cm} \Rightarrow \frac{d\varepsilon_{x,N}}{\varepsilon_{x,N}} \approx \begin{cases} 5.74\%/\text{cell} & 35\text{ cm LH}_2\text{ (no scattering)} \\ 5.62\%/\text{cell} & 35\text{ cm LH}_2 \\ 5.55\%/\text{cell} & 35\text{ cm LH}_2 + 6 \times 360\ \mu\text{m Al} \\ 5.52\%/\text{cell} & 6.4\text{ cm LiH} \end{cases}$$

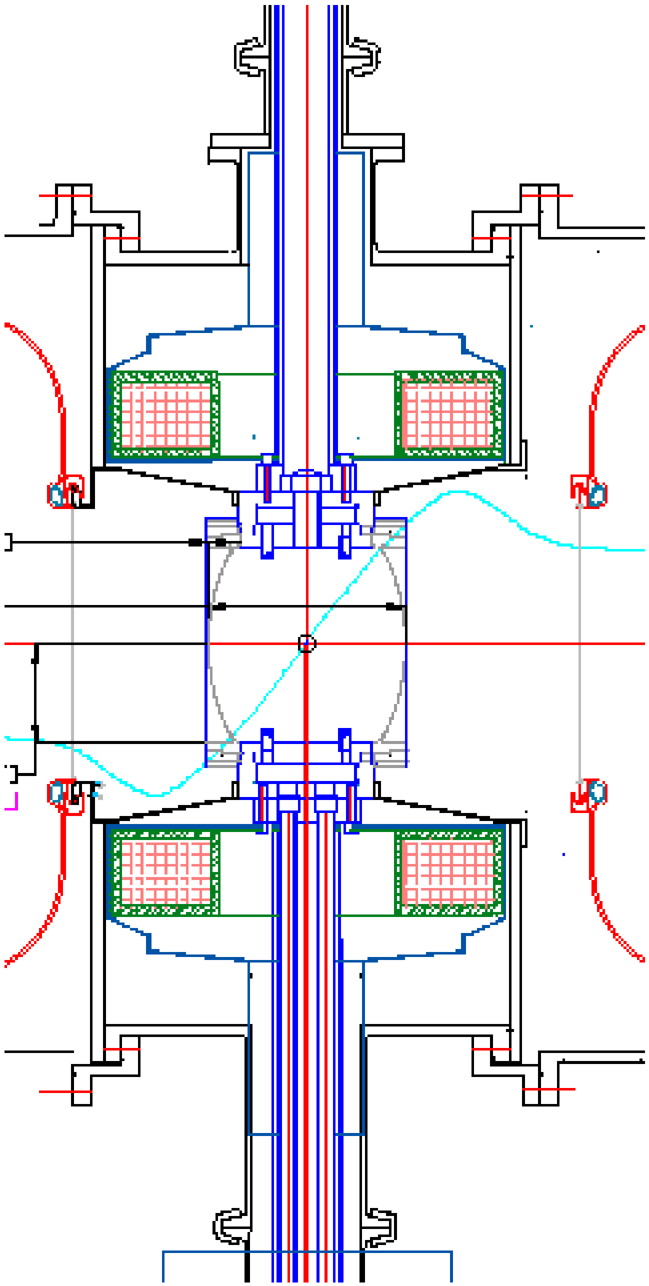
$$\beta = 17\text{ cm}, \varepsilon_{x,N} = 2.6\text{ cm} \Rightarrow \frac{d\varepsilon_{x,N}}{\varepsilon_{x,N}} \approx \begin{cases} 3.44\%/\text{cell} & 21\text{ cm LH}_2\text{ (no scattering)} \\ 3.35\%/\text{cell} & 21\text{ cm LH}_2 \\ 3.29\%/\text{cell} & 21\text{ cm LH}_2 + 6 \times 220\ \mu\text{m Al} \\ 3.28\%/\text{cell} & 3.8\text{ cm LiH} \end{cases}$$

→LiH costs only 1% (5%) in cooling rate near start of Lattice 1 (end of Lattice 2)

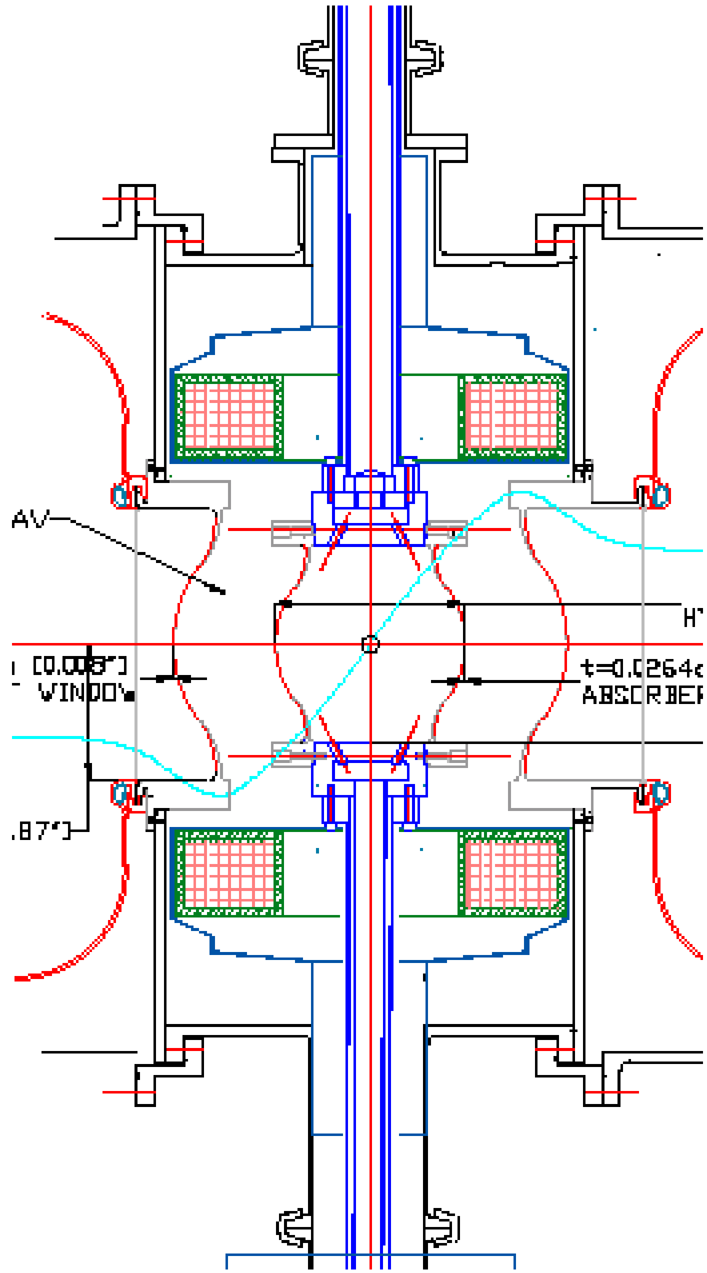
Incorporating Vacuum Vessel

(E. Black, W. Lau)

Old layout



New layout



New Window Shape

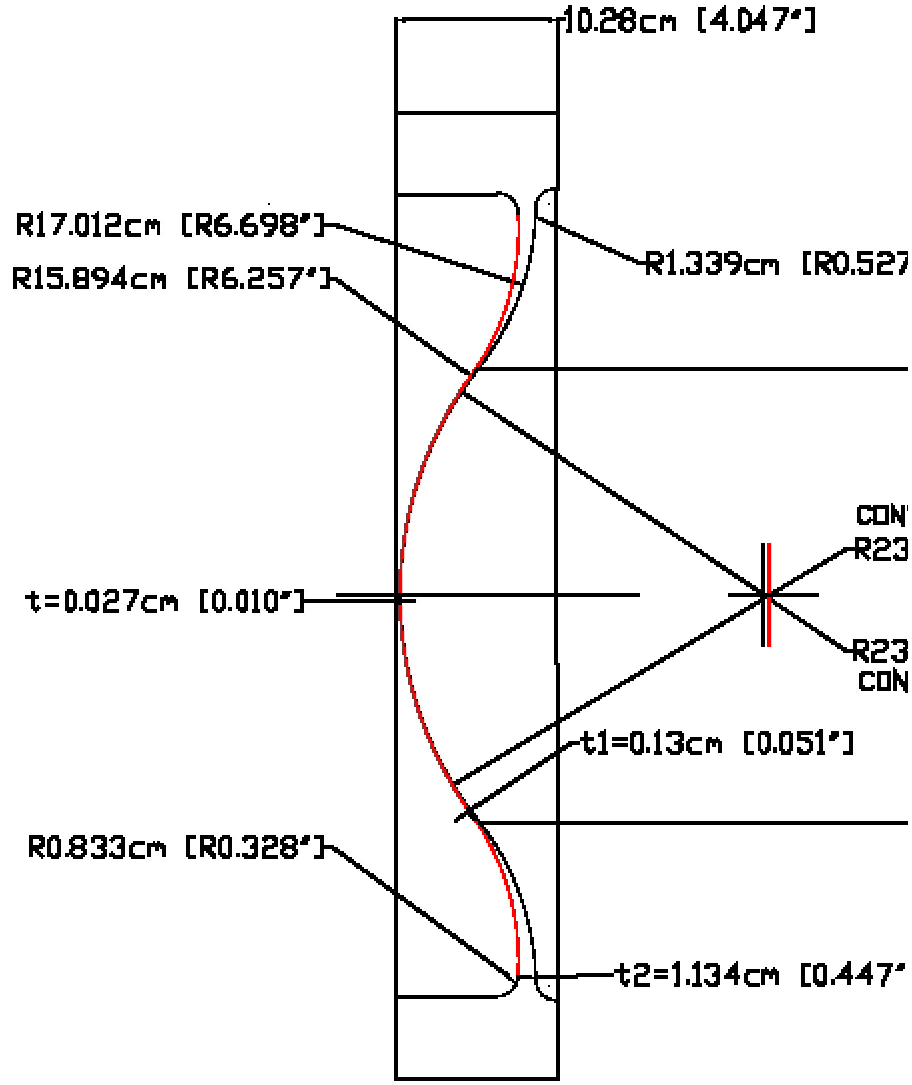
(Wing Lau, Oxford U.)

- Inflected or “bellows” shape:
  - Significantly stronger for same central thickness
  - Significantly thicker well away from center
- Preliminary FEA results (SFOFO1):
  - absorber-window central thickness = 210 µm
  - vac-vessel-window central thickness = 270 µm

→960 µm 6061-T6 per SFOFO1 absorber

(vs. 2,160 µm in ICOOL study above)

- If 2090-T81 a practical, machinable alloy (D. Summers investigating @ U. Miss)
  - Total thickness → ≈ 530 µm per SFOFO1 absorber



LHe Issues

- Absorber cryoplant ≈ \$10M in FS II
  - M. Green: refrigerator cost scaling ~ $(1/T)^{0.7}$ ⇒ LHe cost ~ LH_2 cost × ≈2.5
    - not show stopper
  - BUT:
    - Neuffer bunched φR → ×2 (keeps both signs)
    - Palmer: 4 MW *p* beam more cost effective than more cooling → × 4

⇒ Power ×10, LHe cryoplant cost $\times 10^{0.7}$ ~ \$130M?

LiH Issues

1. LiH is hazardous stuff:

   - violently reacts exothermically with H_2O

     $\rightarrow$ hydrogen gas + lithium hydroxide (highly corrosive)

     $\Rightarrow$ incompatible with H_2O coolant or fire extinguishers

   - released hydrogen may ignite explosively if air present

   - Fermilab safety group has no experience with LiH (though other labs do)

2. Will most likely need to

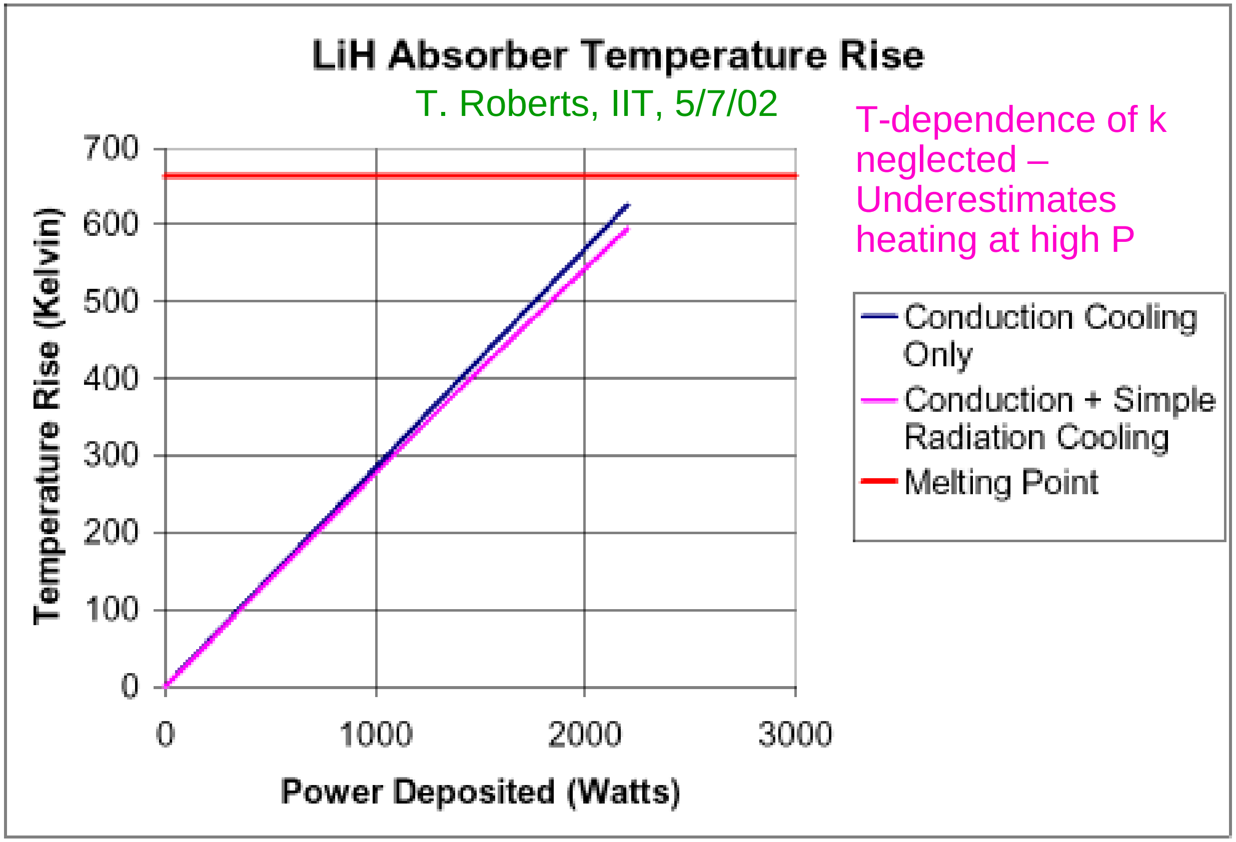
   - encase it in metallic box (≈1-mil SS adequate?)

   - cool around edge with non-H_2O-filled cooling tubes

   - pump box interior down to vacuum to prevent outgassing-induced overpressure

LiH Issues (cont'd)

3. Center-to-edge ΔT for ≈250W heating ≈75K (need to refine calculation)



4. At highest power (≈2kW), edge-cooled LiH may melt; liquid absorber may be easier to cool than nonmetallic solid (though still a challenge)

5. Making contacts with experts at Oak Ridge, BNL, etc. (ORNL and some private companies can cast disks)

Conclusions:

- Effort to design, prototype, and beam-test an absorber is teaching us valuable lessons about real-world safety engineering
- LH_2 may still be best material (especially in potential applications with longer absorbers $\Rightarrow$ relatively less window thickness, ring coolers, etc.)
- Need to prototype stronger window materials (2090-T81)
- Approaching realistic design including vacuum vessel per absorber
- Learning about LiH (for emittance exchange if not transverse cooling)