MuCool Hardware R&D: Status and Prospects

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Outline:

1. MuCool Collaboration and Mission

2. High-gradient normal-conducting RF R&D

3. High-power LH_2-absorber R&D

4. Gaseous-absorber option

5. MuCool Test Facility

6. Summary

MuCool Collaboration

16 Institutions from US, Europe, and Japan:

RF Development
- ANL
- FNAL
- IIT
- LBNL
- Univ. Mississippi

Beam Diagnostics
- ANL
- FNAL
- IIT
- Univ. Chicago

Absorber R&D
- FNAL
- IIT
- KEK
- NIU
- UIUC
- Univ. Mississippi
- Univ. Osaka
- Univ. Oxford

Solenoids
- LBNL

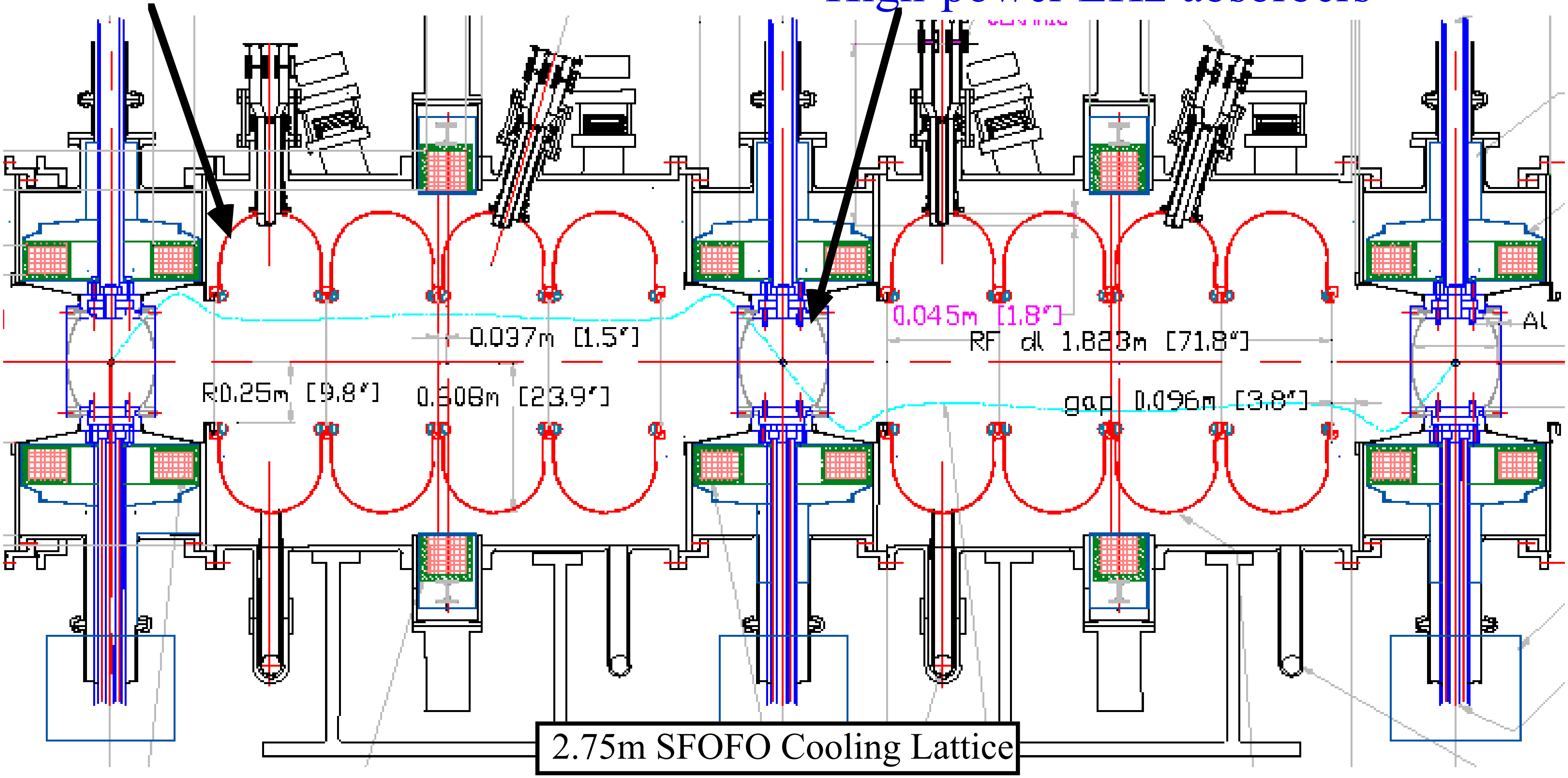
Cooling Experiment
- ANL
- BNL
- FNAL
- IIT
- LBNL
- Princeton
- UCLA
- UIUC
- Univ. Mississippi

Mission: Design, prototype, & bench-test all cooling-channel components & make an engineering beam test of a cooling section

MuCool R&D Projects & Facilities

High-gradient normal-conducting RF

High-power LH2 absorbers



Test facilities for the above:

- FNAL Lab G
- FNAL Linac-area MuCool Test Facility

Simulation studies in support of cooling R&D

Key R&D Issues

1. Can NCRF cavities be built that provide the required accelerating gradients, operating in multi-tesla fields?

2. Can the heat from dE/dx losses be adequately removed from the absorbers?

3. Can the channel be engineered with an acceptably low thickness of non-absorber material (absorber, RF, & safety windows) in the aperture?

4. Can the channel be designed & engineered to be cost effective?

High-Gradient-RF-Cavity R&D

ANL / FNAL / IIT / LBNL / UMiss

- Goal:

  201-MHz Cu cavity with > 20-MV/m on-axis accelerating gradient, operable in few-T solenoidal magnetic field

  – But rapid progress easier with smaller-scale prototypes → initial tests at 805 MHz
  – Pillbox cavity (cells closed with conducting windows) can save ≈ 50% in power

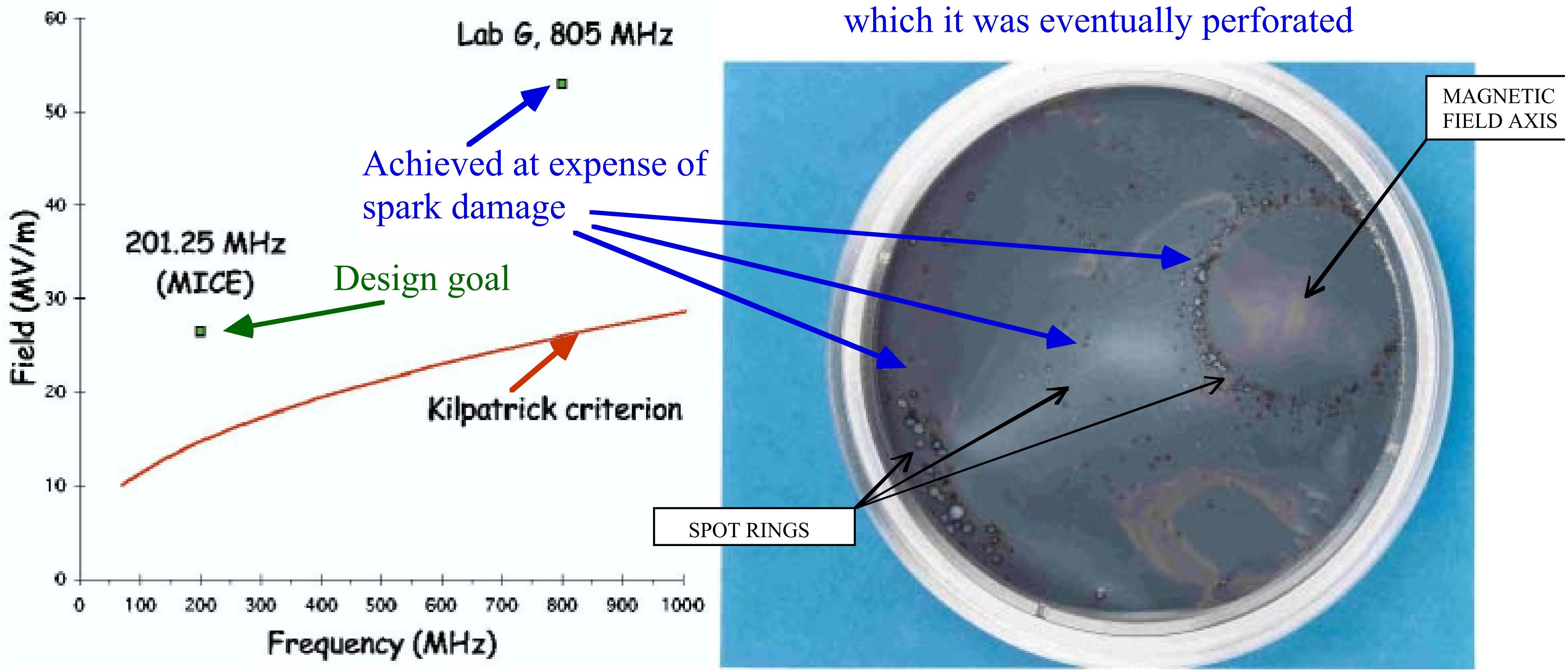
Open-cell 805-MHz prototype under high-power test in Lab G superconducting solenoid

Closed-cell 805-MHz prototype undergoing bake-out at LBL (now under high-power test in Lab G)

Beyond the Kilpatrick Criterion

- High-power open-cell 805-MHz tests in Lab G (Summer 2001):

125-µm titanium vacuum window after tests in which it was eventually perforated

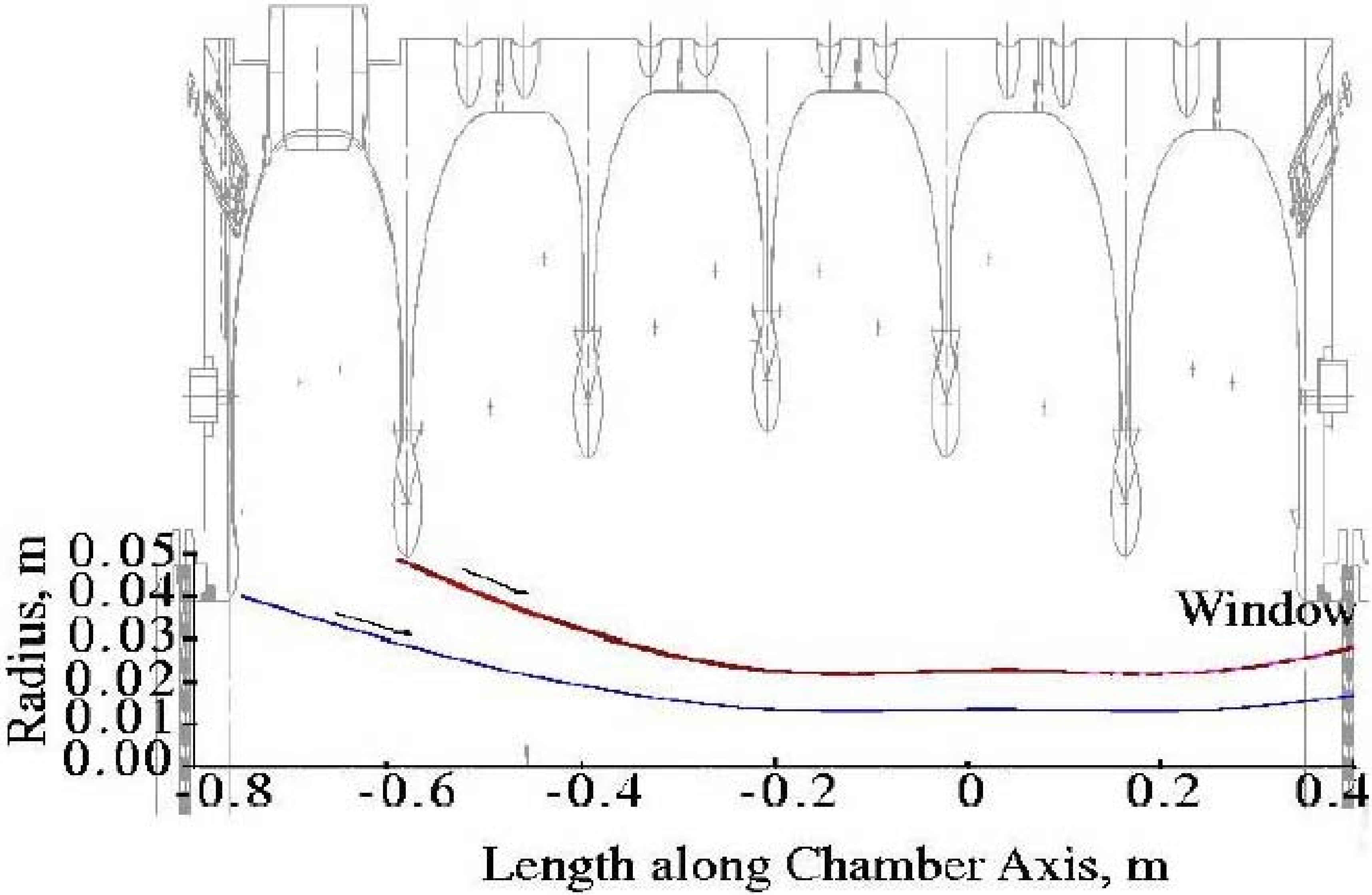


- Closed-cell prototype now up to 34 MV/m accelerating field at B = 0
  - tests with solenoidal field to be done in coming months

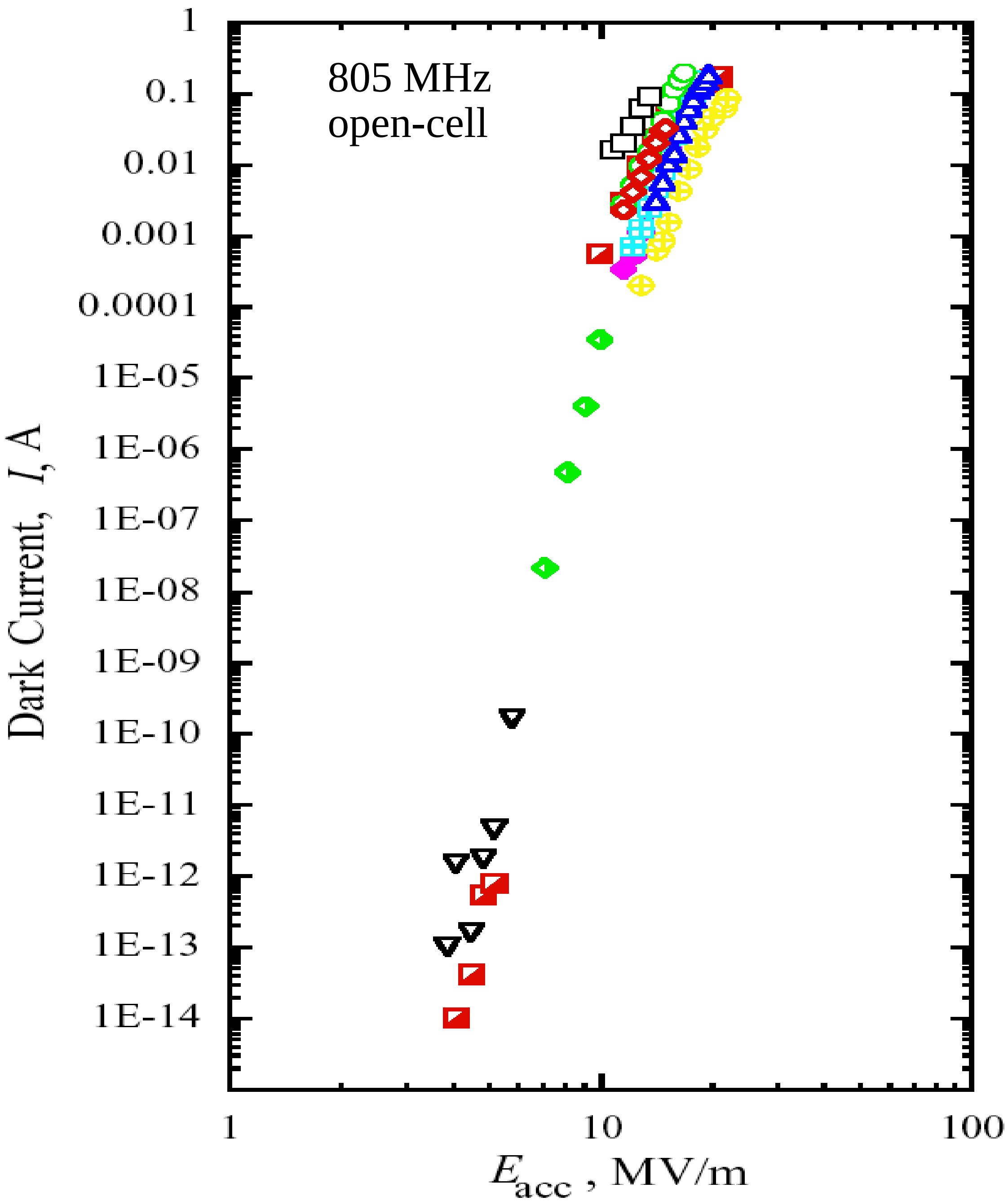
Rings due to magnetic focusing of emission from irises:

(J. Norem, ANL)

- Localized sharp emitters experience peak electrostatic force exceeding Cu tensile strength
  - ionized Cu globules ejected from surface accelerate towards vacuum window



See large dark current at high gradients:



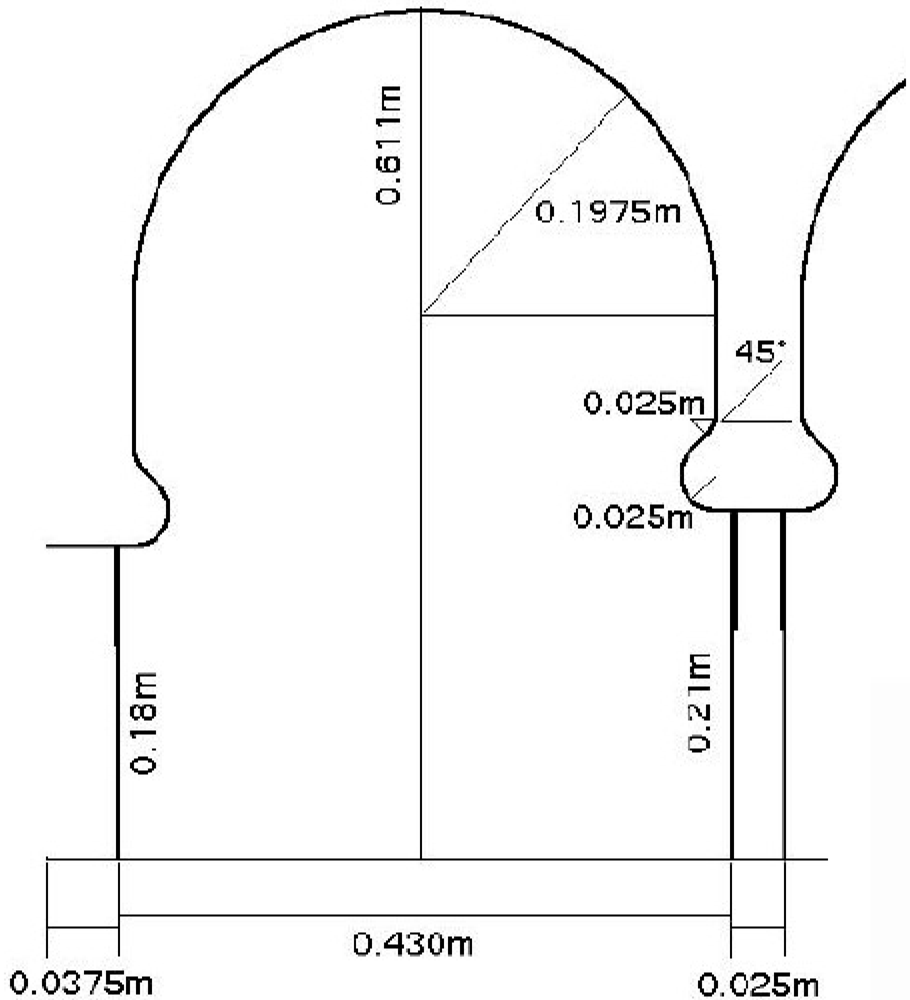
...along with high X-ray flux

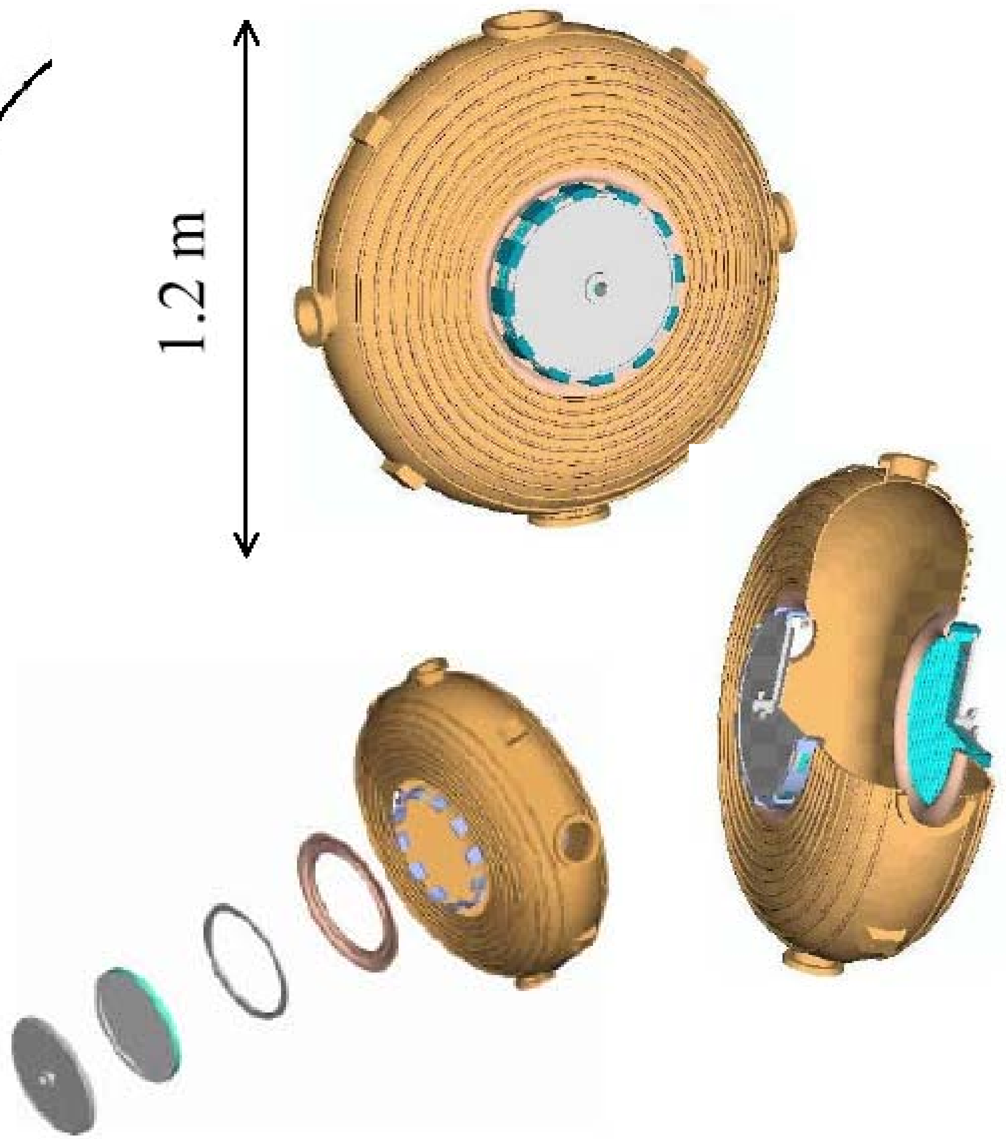
- Consistent as expected with Fowler-Nordheim equation, with local field enhancement ~10^3 compared to smooth, flat surface
  - approx. power-law parametrization gives $I \propto E^{9 \text{ to } 10}$
  - see J. Norem et al., submitted to Phys. Rev. ST Accel. Beams
- Note: these protoypes made with standard machining techniques
- Will now focus R&D on dark-current reduction
  - explore surface prep., coatings, treatment (á là niobium cavities)
  - lots of room for improvement!
  - area of general interest (e.g. NLC)
  - MICE requires single-particle detectors near cavities

201-MHz Design Work

(T. Ladran, D. Li, R. Rimmer, LBNL)

- Both electrical and mechanical design in progress:

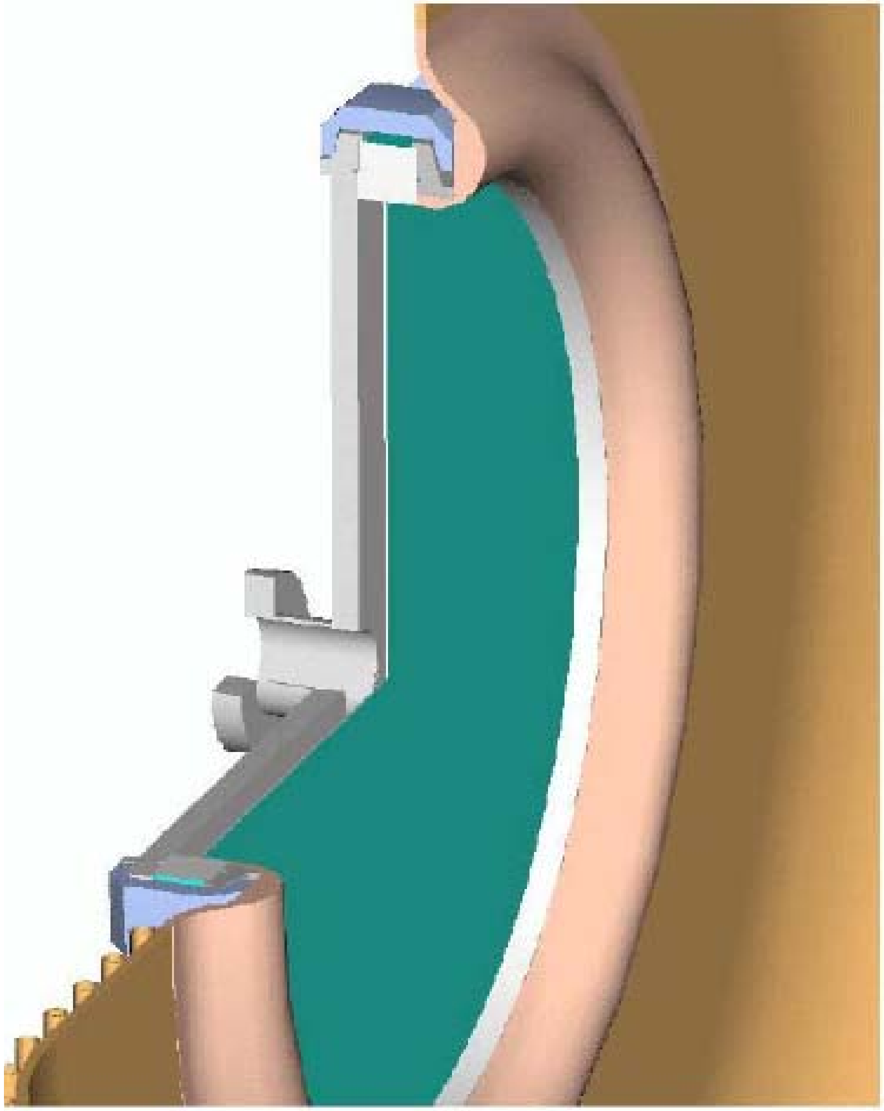




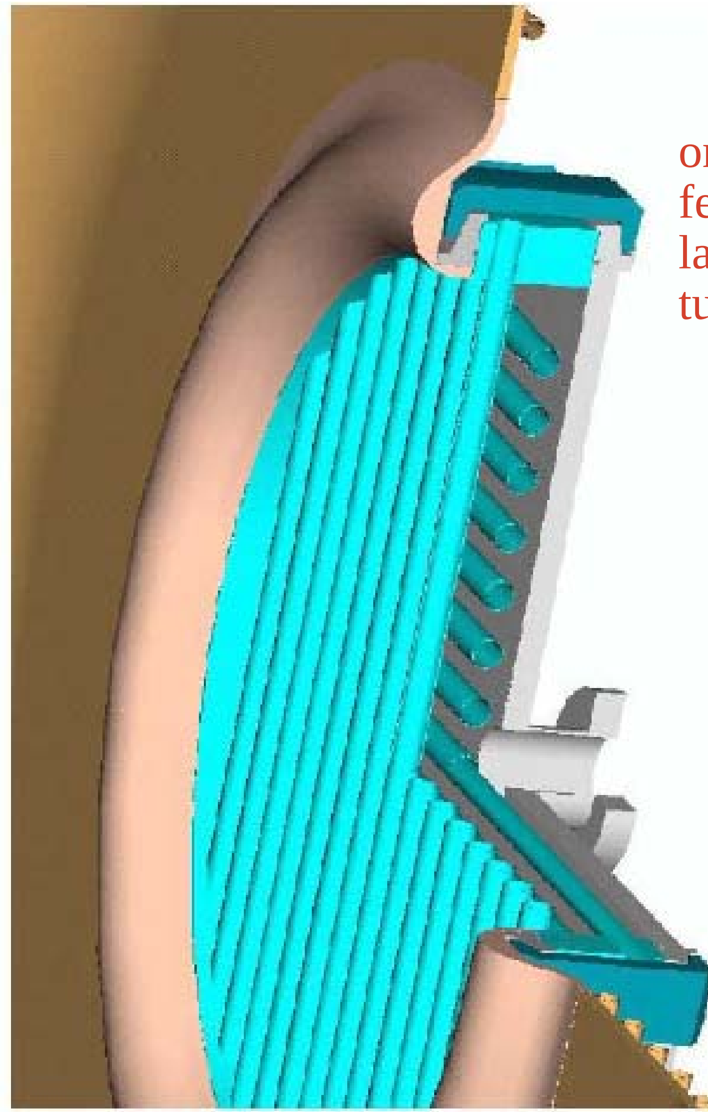
Cell Closure Details

(T. Ladran, D. Li, LBNL; A. Moretti, FNAL; M. Alsharoa, M. Gosz, IIT)

- Two alternatives under consideration:



Thin Beryllium foils



Grid of Thin Hollow Tubes

or possibly fewer, larger-diameter tubes

- Need foil suff. thick so no deflection under RF heating ⇒ gas-cooled tubes may be thinner

Absorber R&D Collaboration

E. Almasri, E. L. Black, K. Cassel, R. Johnson†, D. M. Kaplan, W. Luebke
*Illinois Institute of Technology**

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KEK High Energy Accelerator Research Organization

M. A. Cummings, A. Dychkant, D. Hedin, D. Kubik
*Northern Illinois University**

Y. Kuno
Osaka University

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*University of Illinois at Urbana-Champaign**

M. Reep, D. Summers
University of Mississippi

W. Lau
University of Oxford

in collaboration with

D. Allspach, C. Darve, S. Geer, C. Johnstone‡, A. Klebaner, B. Norris, M. Popovic,
A. Tollestrup
Fermilab

* member, Illinois Consortium for Accelerator Research   † also at Muons, Inc.   ‡ also at IIT

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/cm³)	(MeV/g·cm²)	(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 scattering-limited regime, as cooling/heating equilibrium approached (ring cooler, e.g.), LH_2 best by factor of at least ≈2

- Far from equilibrium (e.g. FS-II linear cooling channel), differences among materials (hence LH_2 advantage) small:
- Exploiting LH_2 advantage requires care in window design

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%

Absorber Power Handling

- νF Feasibility Study II absorbers (1 MW Proton Driver, μ^+ or μ^-):

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

(Not LH2)

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

– First, estimate rate of bulk temperature rise if no flow: $c_p = 1.1 \times 10^4$ J/kg·K

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

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

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

⇒ to keep ΔT $\lesssim$ 0.1 K takes 0.1 volume change/s ≈ 3 *l*/s for SFOFO 1 absorber

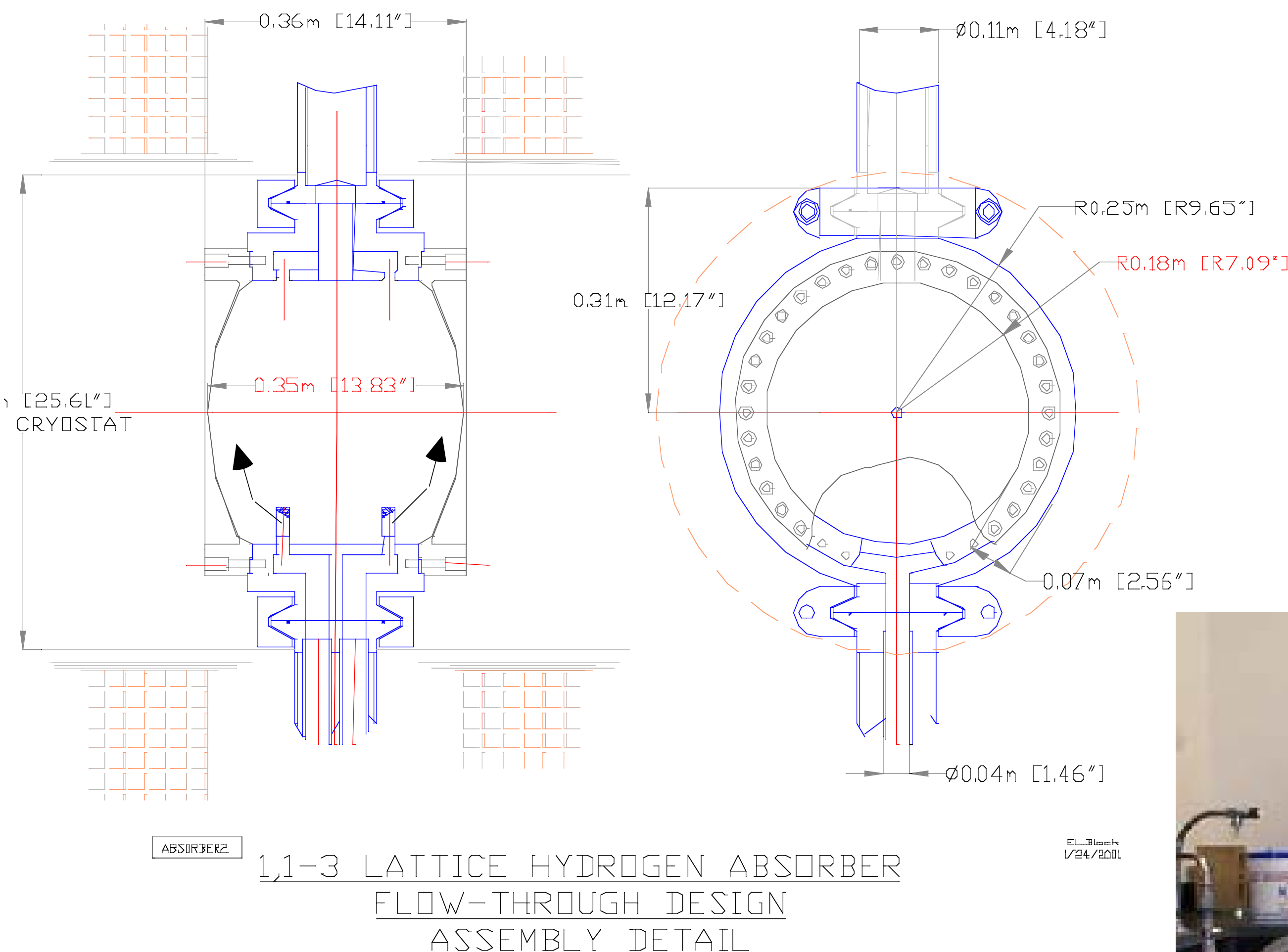
→ should be feasible **if** good transverse mixing, without eddies or dead zones

- Note ring cooler calls for ≈10 passes ⇒ ≈20 kW ⇒ **R&D issue**

Forced-Flow Absorber Design

(E. Black, IIT)

- Heat exchange carried out in cooling loop external to absorber
- Transverse mixing established by forced flow through nozzles:



R&D Issue:

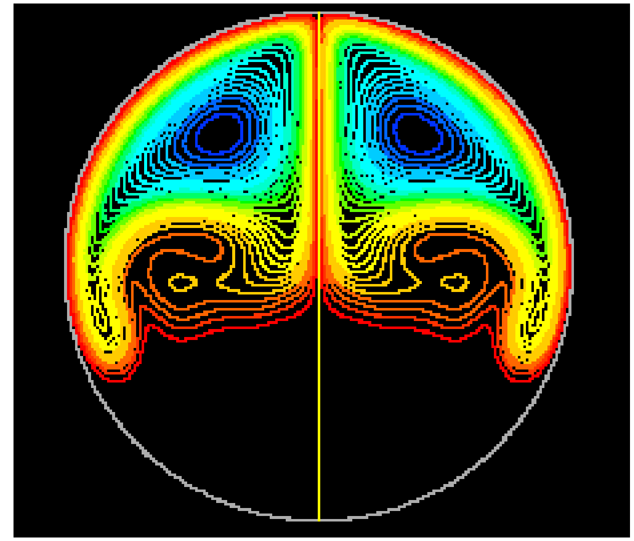
→ nozzle design must be worked out on bench

- Prototype built
- Flow pattern under study
- Absorber will be filled with LH_2 and tested at Fermilab

Flow study setup at NIU

Convection-Cooled Absorber Design

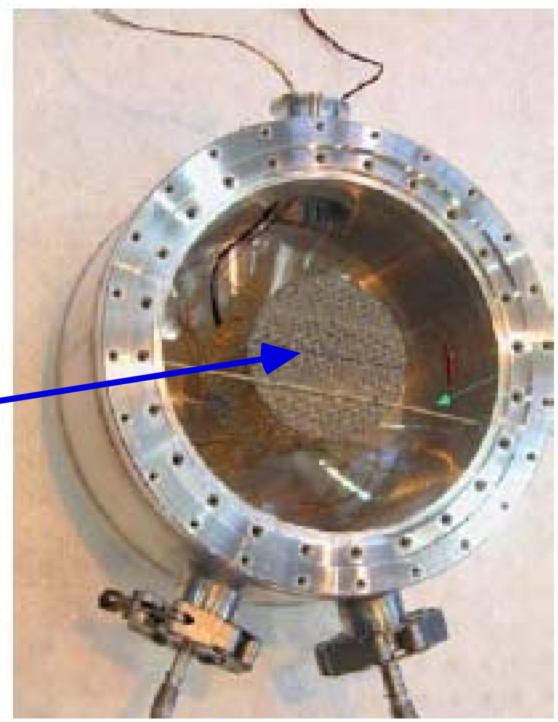
(S. Ishimoto, K. Yoshimura, KEK)



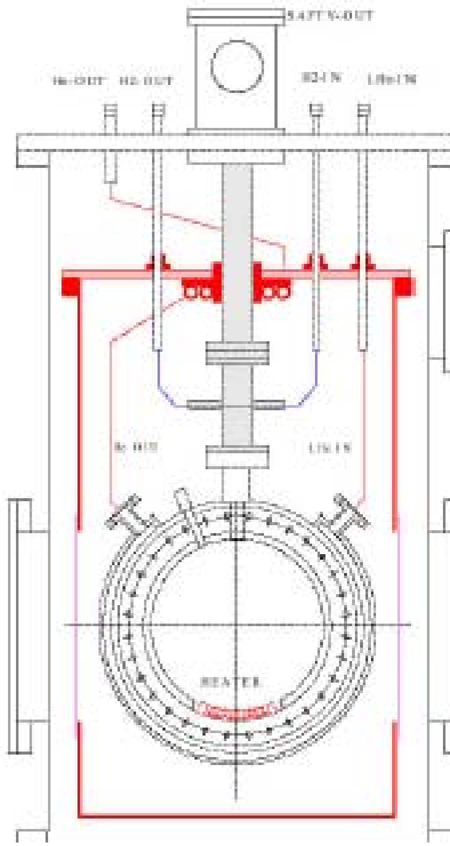
2D CFD flow calculation at IIT

- Heat exchanger built into absorber vessel
  - smaller total hydrogen volume
  - flow intrinsically transverse
  - simpler design (fewer moving parts)
  - **R&D issue: what is max power?**

- Prototype built and tested with LNe via resistance heating at KEK
  - pushed to 100 W at KEK, to be followed by LH2 tests at FNAL



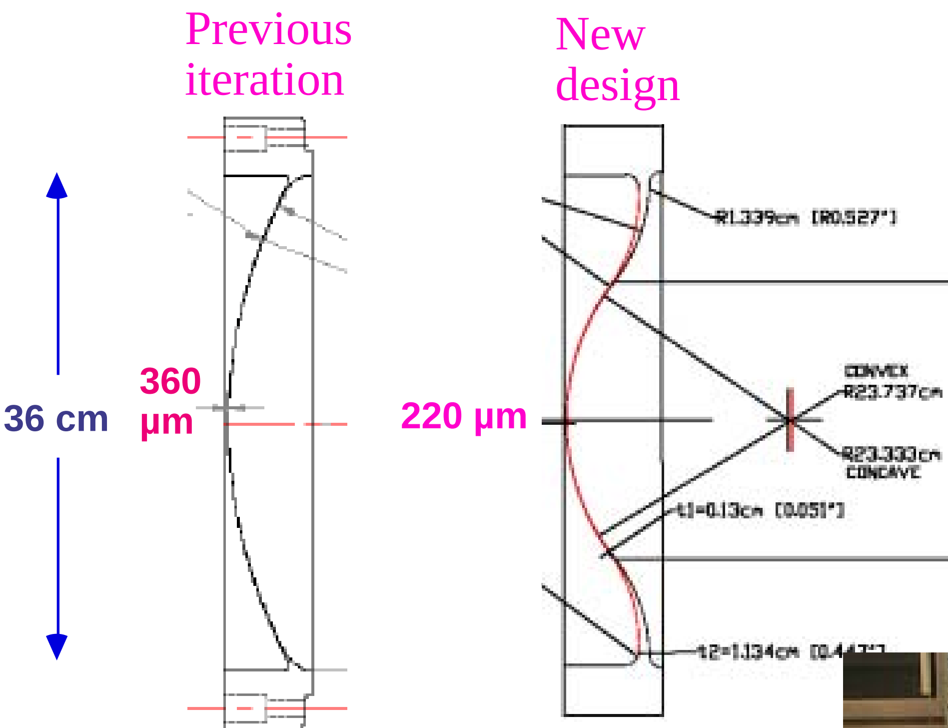
Array of heating wires



Absorber Windows

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

- **R&D issue:** conventional designs for pressure-vessel windows too thick
  - FS-II SFOFO 1 windows assumed 360 µm, vs. 530 µm for ASME torispherical
  - → Developing thin, tapered windows, custom-machined (with integral flange) out of a single block of material:



- New "inflected" design is 40% thinner in center (where most of beam goes) but thicker at edges
  - To assess effect on cooling requires simulation study (in progress)

- Design safety needs confirmation by destructive pressure tests, careful measurements, & FEA
  - require ×4 safety factor ⇒ 100 psid

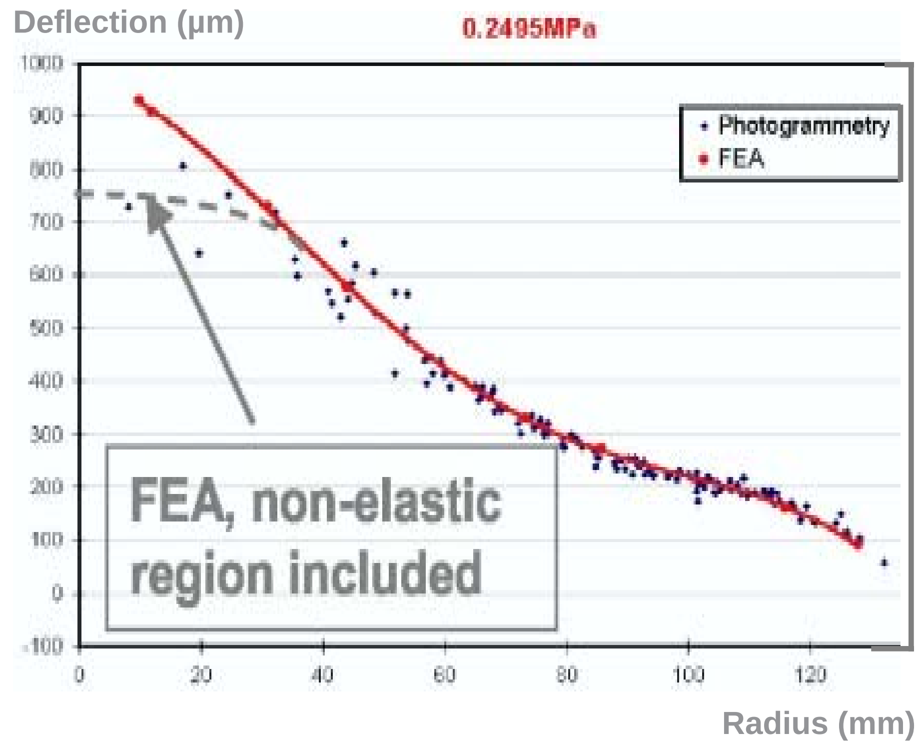
Non-Contact Precision Measurements

(M. A. Cummings, D. Kubik, NIU; J. Greenwood, FNAL)

- Projected-spot photogrammetry:
  - spot pattern projected onto object by strobe lamp
  - digital video camera records pattern from several vantage points

  - computer analysis finds 3D position of each spot to <10 μm by triangulation

- Good agreement with finite-element modeling of shape vs. pressure:



  - agreement improved by nonlinear FEA - takes inelastic behavior into account

- Now used also to measure window thickness profile by “shooting” from both sides

Impact of Safety Requirements

- 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

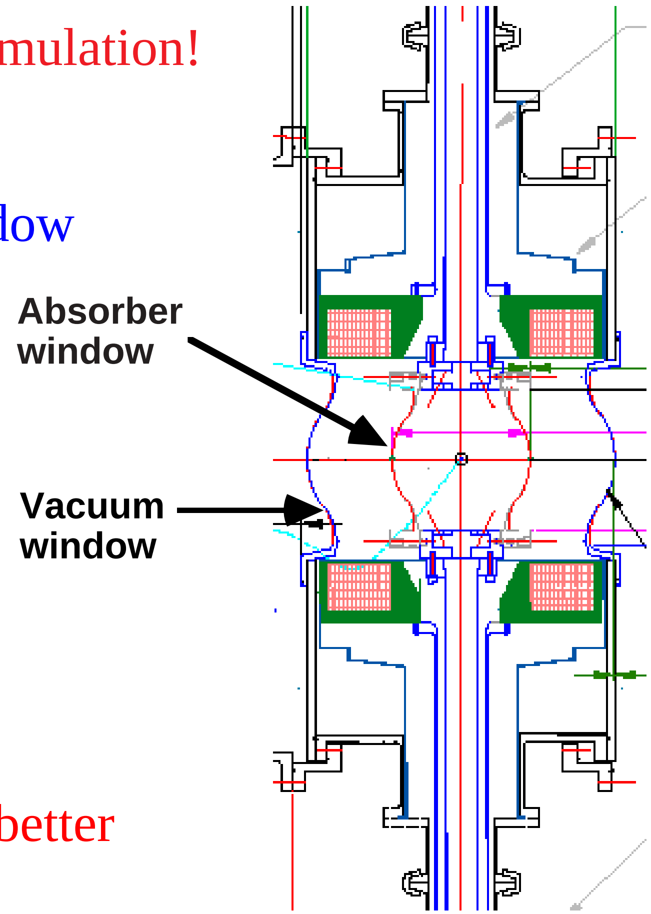
  → twice as many windows as in Feasibility Study II simulation!

- Fortunately,

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

  – must withstand 75 psid internal pressure
    25 psid external pressure

    w/o rupture or irreversible deformation



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

– "SFOFO 1" lattice: 360 μm → 220 μm + 160 μm

  assuming 6061-T6 Al alloy – can probably do even better with new alloy...

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**

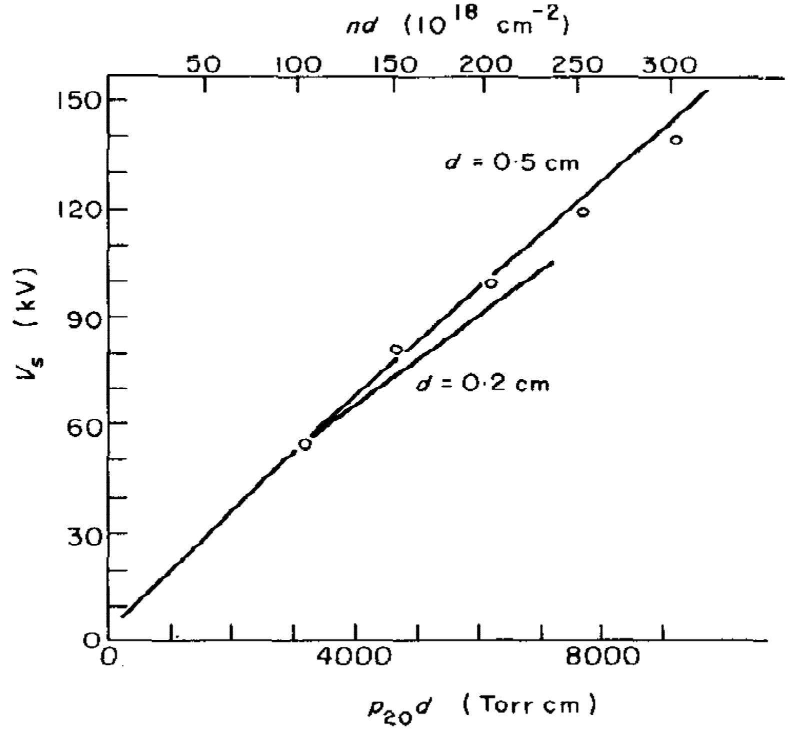
- 2090-T81 has good machinability and vacuum performance, **and**
- such thin windows can be reliably machined (125 μm thinnest attempted so far)

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

Gaseous Absorber?

(R. Johnson, Muons, Inc.; A. Moretti, M. Popovic, FNAL; D. Kaplan, IIT)

- Idea: why not eliminate (almost) all the windows?
  - Cooling channel becomes series of RF cavities (in suitable focusing field) filled with high-pressure gaseous H_2, protected against breakdown by the Paschen effect:



Breakdown voltages in hydrogen (Müller, 1966. permission of Springer–Verlag)

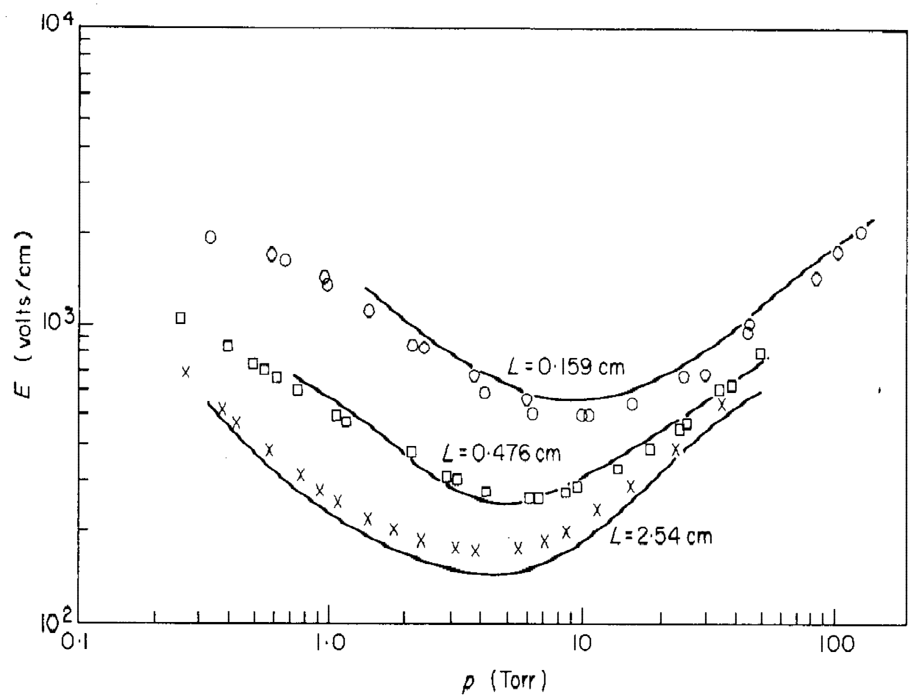


Figure 8.13. Theory and experiment compared for hydrogen at 2·8 GHz (MacDonald and Brown, 1949. Reproduced by permission of The America Physical Society)

- Paschen's Law: $V_s = 0.448\,(nd) + 0.6\,(nd)^{1/2}$ (need to confirm in our regime)

$\Rightarrow$ Breakdown suppressed for $P \gtrsim \begin{cases} 40 \text{ atm (room temp.)} \\ 10 \text{ atm (LN}_2\text{ temp.)} \end{cases}$

$\rightarrow$ To match absorption to RF gradient, need $P \approx 23$ atm at LN_2 temp.

Gaseous Absorber Update

- News since NuFact '01:

R. Johnson has formed Muons, Inc. and, in collaboration with IIT, successfully obtained a U.S. DOE Small-Business Technology Transfer grant to develop a practical, high-gradient, pressurized RF cavity that operates under the conditions needed for muon ionization cooling

- STTR Phase 1: awarded $100K, 6/2002 to 3/2003

Build a test cell at IIT and use it at FNAL Lab G to measure the Paschen curve (breakdown voltage vs. pressure) of helium at 805 MHz at 80K over many-atmosphere range in *P*

- STTR Phase 2: up to $500K, up to 2 years
(contingent on successful completion of Phase 1 & favorable review of Phase 2 proposal)

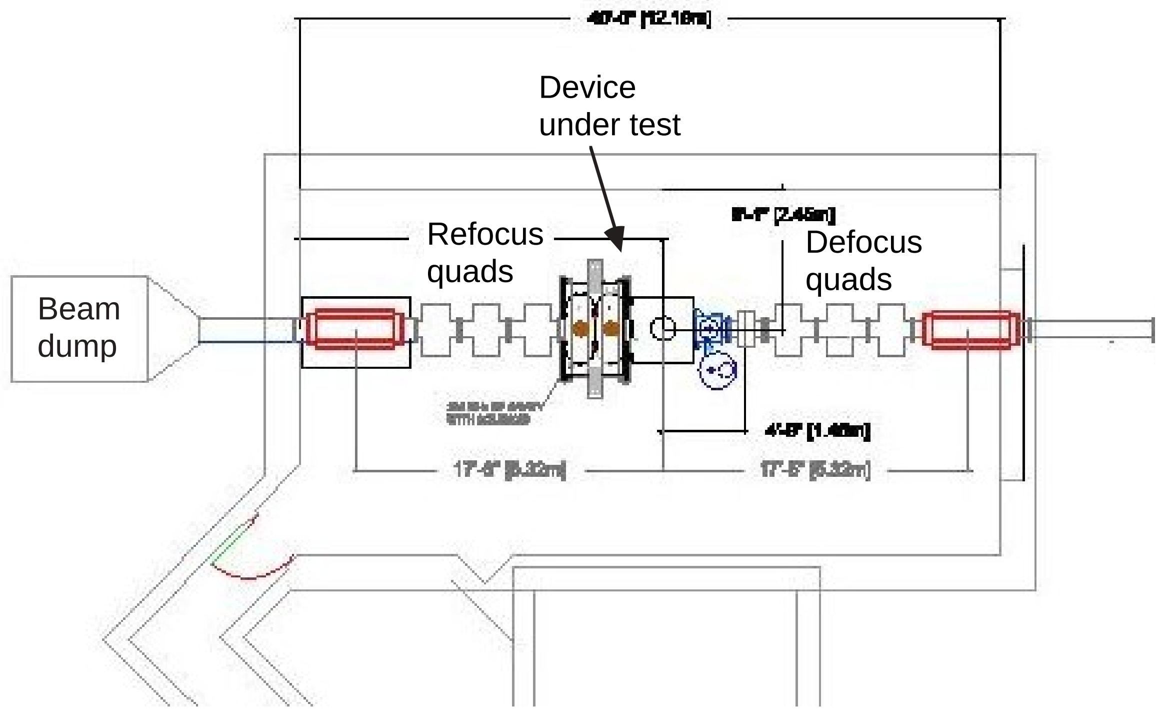
Extend measurements to hydrogen and 201 MHz, with and without solenoidal field and ionizing radiation, at the new MuCool Test Facility

- STTR Phase 3: (Requires another funding source)

Build a complete demonstration cooling channel to be tested at MICE

MuCool Test Facility

- Need facility in which to test
  - absorbers
  - RF cavities
  - solenoids
- Show that cooling cell is operable in an intense beam
  (engineering test, not cooling demo)
- ∃ convenient location: end of Linac has
  - space
  - 201 & 805 MHz RF power sources
  - 400 MeV beam up to 2.4×10^{14} *p*/s $\rightarrow$ 570 W in 35-cm LH_2 absorber (higher at lower E)



Summary

- Continued steady progress developing components for a cooling channel
- Ongoing 805 MHz RF R&D program will develop techniques required for low-dark-current, high-gradient NCRF cavities operable at high *B*
- Healthy progress developing LH_2 absorbers with thin windows
- Some open R&D issues:
  - How suppress dark current in NCRF cavities?
  - What are the limits to power-handling capability in LH2 absorbers?
  - How minimize effect of windows on cooling performance?
  - Are gaseous absorbers a viable alternative?
- Opportunities for Ph.D. and M.S. students in beam physics & engineering
  - already 1 Ph.D. & 1 M.S. completed, 2 Ph.D.'s in progress
- International participation in place
- More collaborators welcome!
  - contact Steve Geer <sgeer@fnal.gov>