“All Things Muon”

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ILLINOIS INSTITUTE OF TECHNOLOGY
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ICAR

ICAR Workshop
ANL
19–20 May 2004

Outline

1. What’s a Neutrino Factory?

2. Neutrino Factory & Muon Collider physics

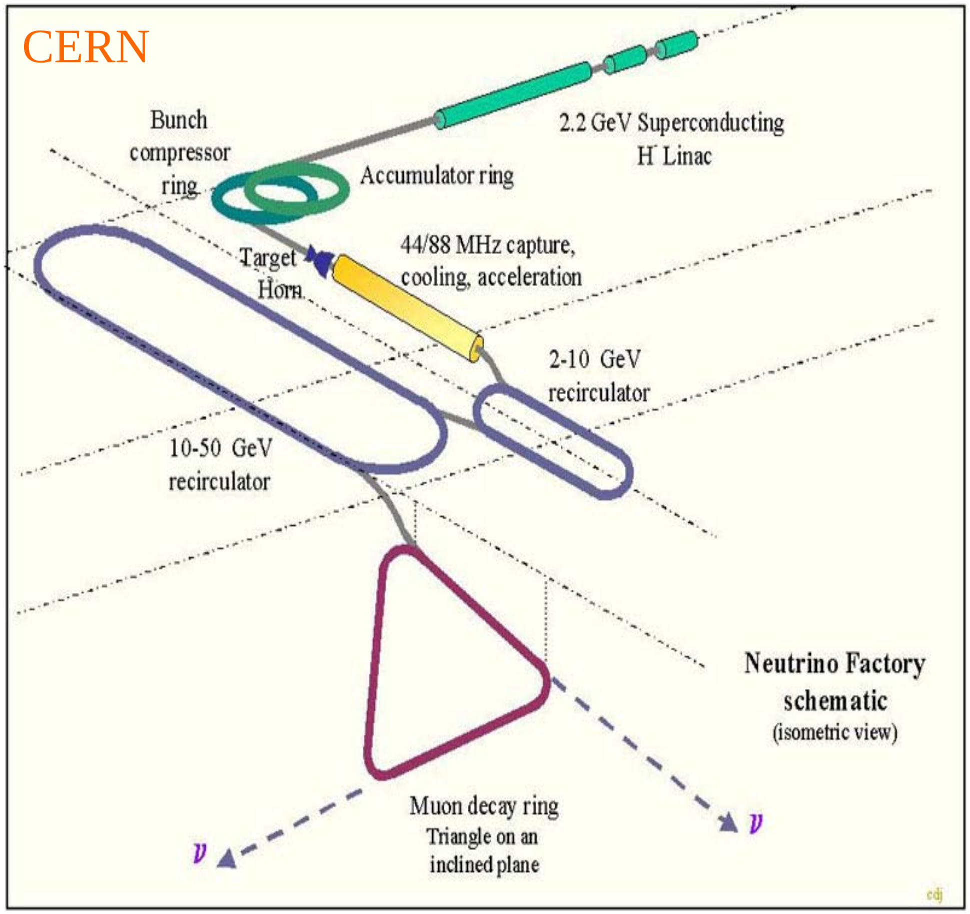
3. Ionization cooling

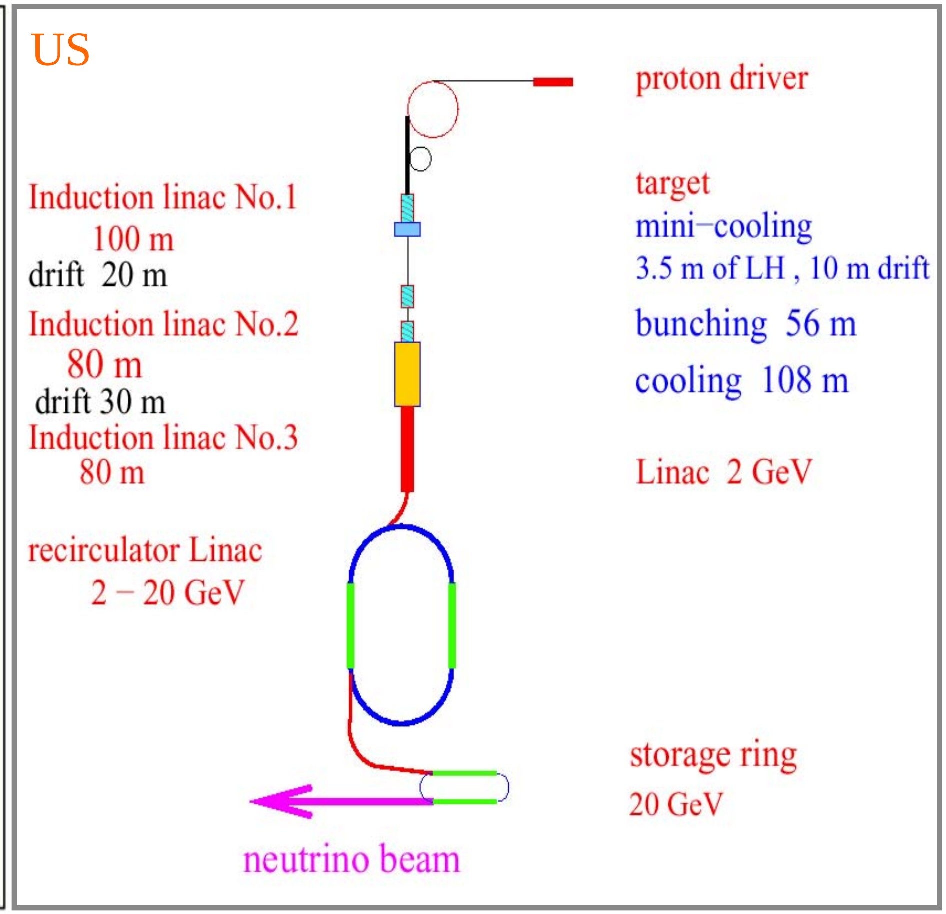
4. Muon Collaboration R&D program

What's a Neutrino Factory?

S. Geer, Phys. Rev. D **57**, 6989 (1998)

- A muon storage ring producing intense beams of high-energy electron and muon neutrinos:





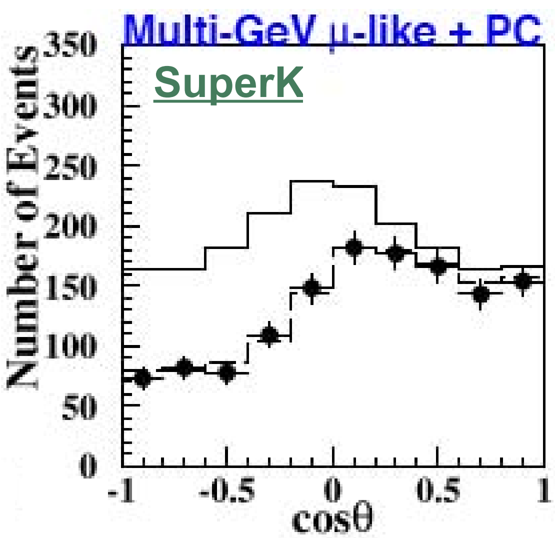
~ MW *p* beam → high-power target → pions, focused & decay → muons
muons bunched, cooled, accelerated, & stored in decay ring w/ long straights

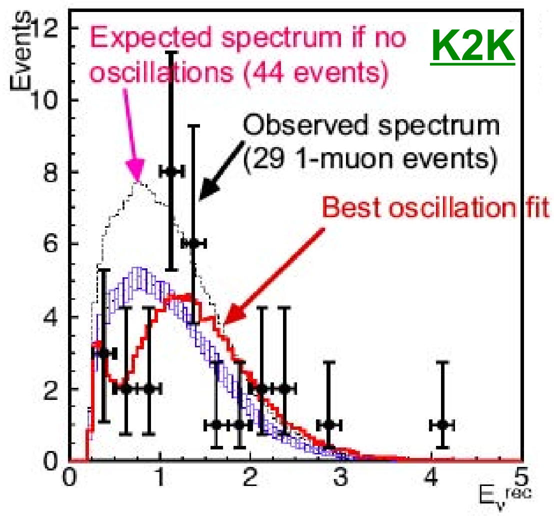
(Also ∃ Japanese design – does not require cooling but could benefit from it)

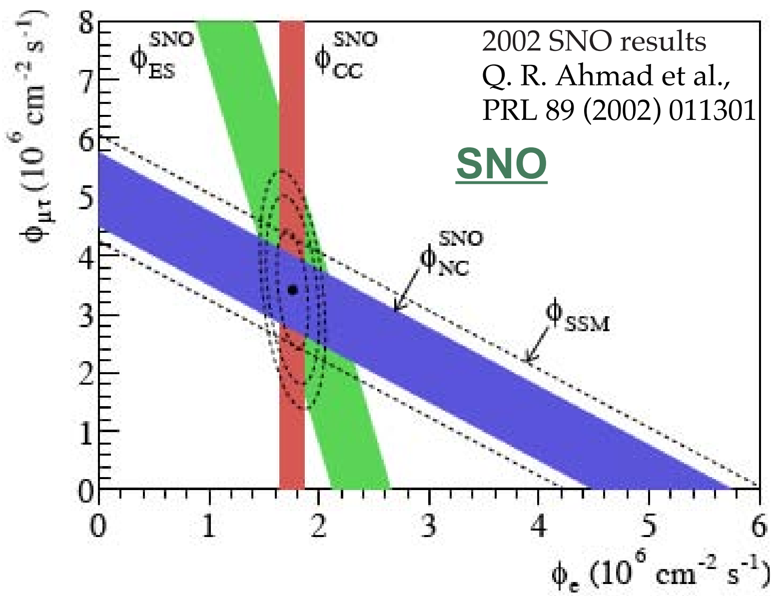
Neutrino Factory Physics

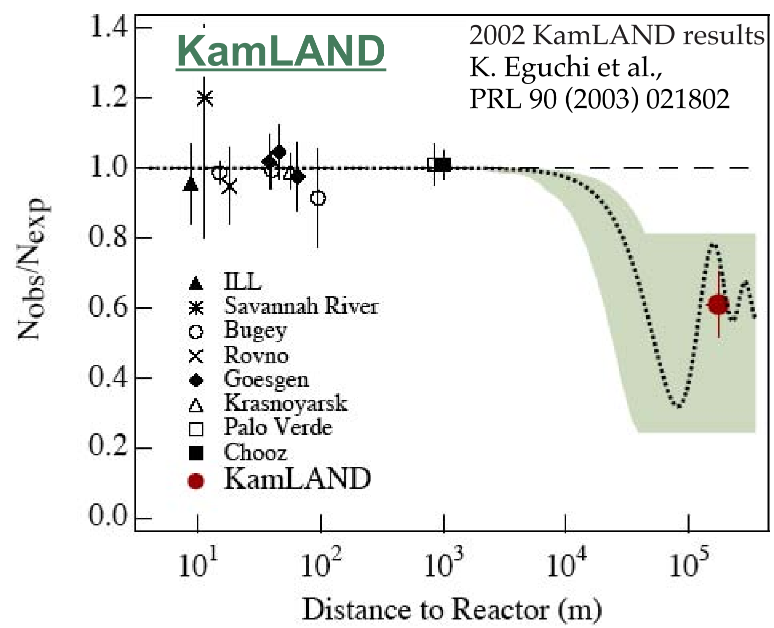
- Most fundamental particle-physics discovery of past decade:

☞ **neutrinos mix!**









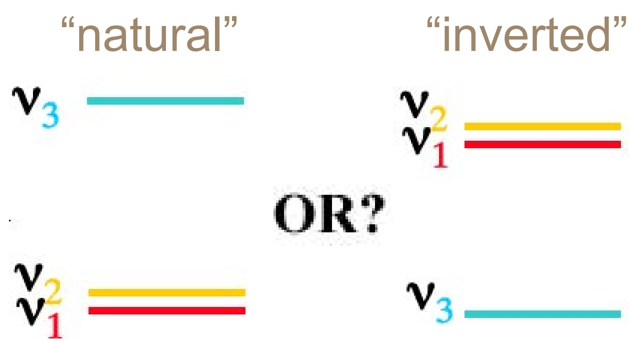
...arguably the leading explanation for the cosmic baryon asymmetry

M. Fukugita and T. Yanagida,
Phys. Lett. B174, (1986) 45.

Neutrino Factory Physics (cont'd)

- Raises fundamental questions:

1. What is the neutrino mass heirarchy? (Has e.g. cosmological consequences...)



2. Why is pattern of neutrino mixing so different from that of quarks?

CKM matrix:

$\theta_{12} \cong 12.8°$
$\theta_{23} \cong 2.2°$
$\theta_{13} \cong 0.4°$
} nearly diagonal

PMNS matrix:

$\theta_{12} = 30°$ (solar)
$\theta_{23} = 45°$ (atmospheric)
$\theta_{13} < 13°$ (Chooz limit)

$$\begin{pmatrix} \sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin\theta_{13}\, e^{i\delta} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\ \sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2} \end{pmatrix}$$

3. How close to zero are the small PMNS parameters θ_{13}, δ?

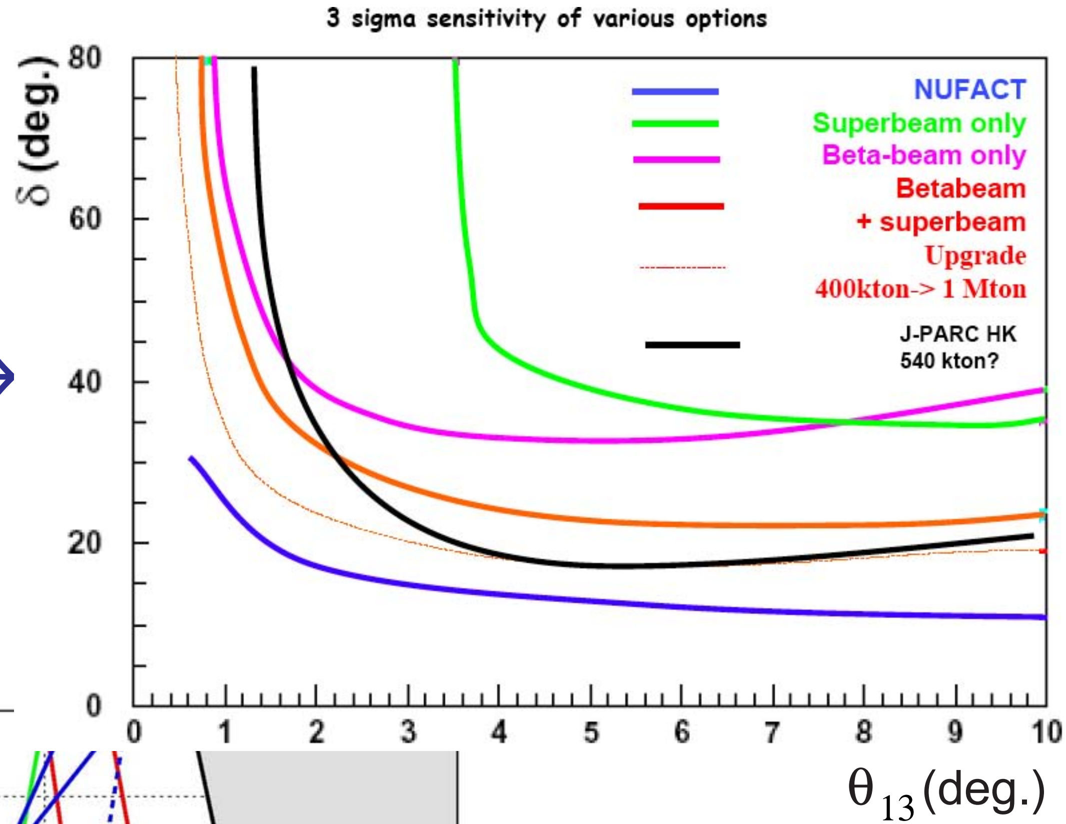
$\longrightarrow$ are they suppressed by underlying dynamics? symmetries?

These call for a program to measure the PMNS elements as well as possible

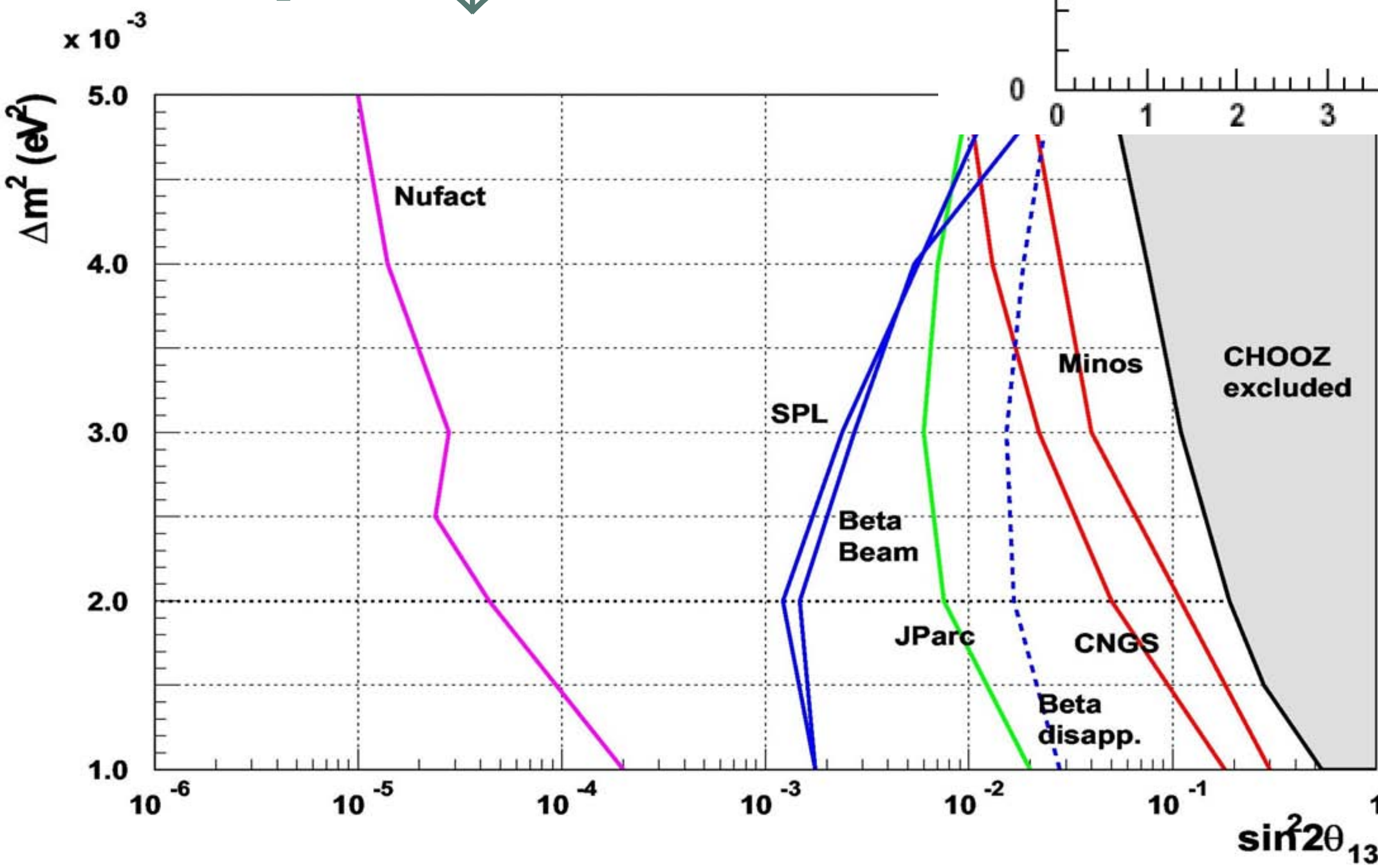
Neutrino Factory Sensitivity

- Neutrino Factory is most sensitive technique yet devised
  see e.g. M. Lindner, hep-ph/0209083

CP-sensitivity comparison →



Oscillation-parameter comparison ↓

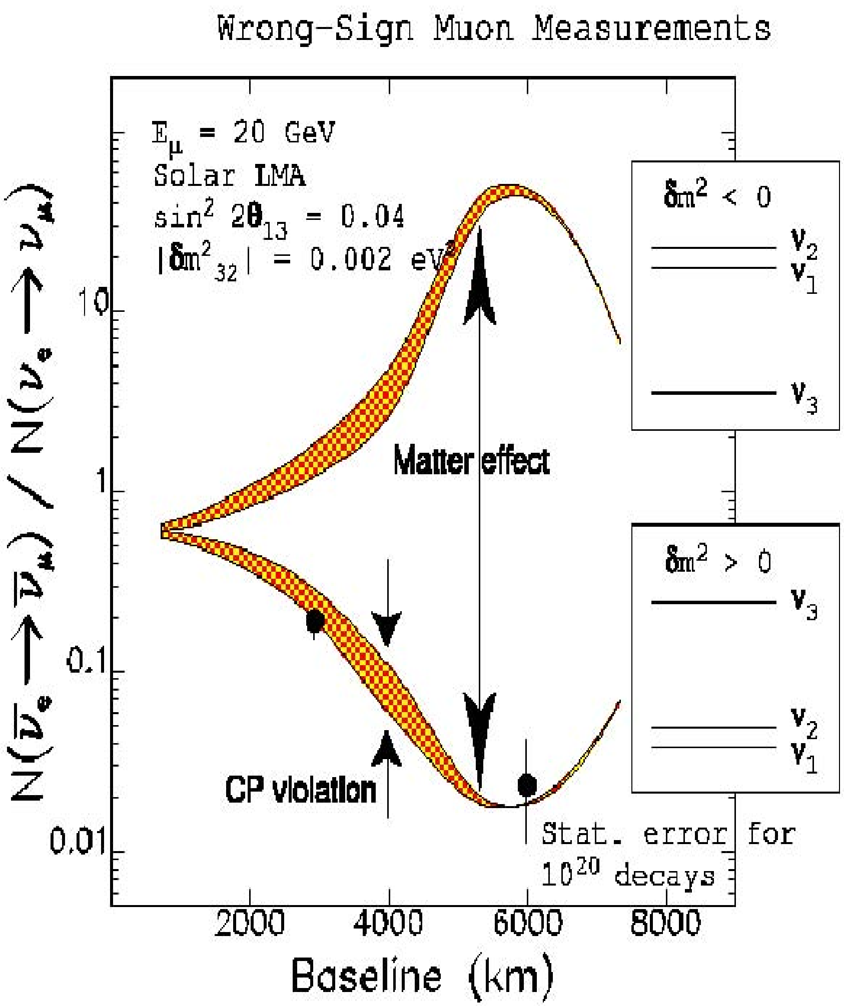


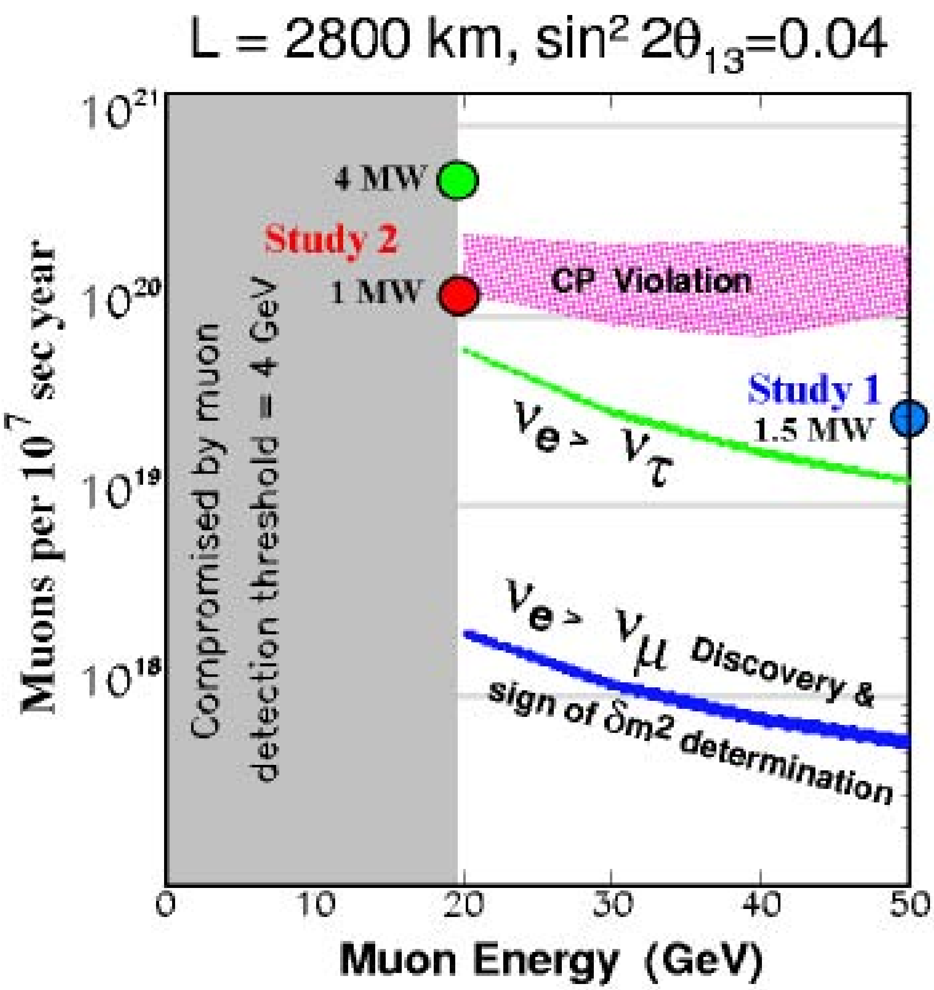
(plots from A. Blondel, NO-VE Workshop, Venice, Dec. 03)

NB: NuFact estimates assume "modest" (40-kton) detector

Neutrino Factory Physics Strategy

- With suitably chosen baseline(s), comparing $\nu_e \to \nu_\mu$ & $\bar{\nu}_e \to \bar{\nu}_\mu$ determines mass heirarchy and CP phase δ:





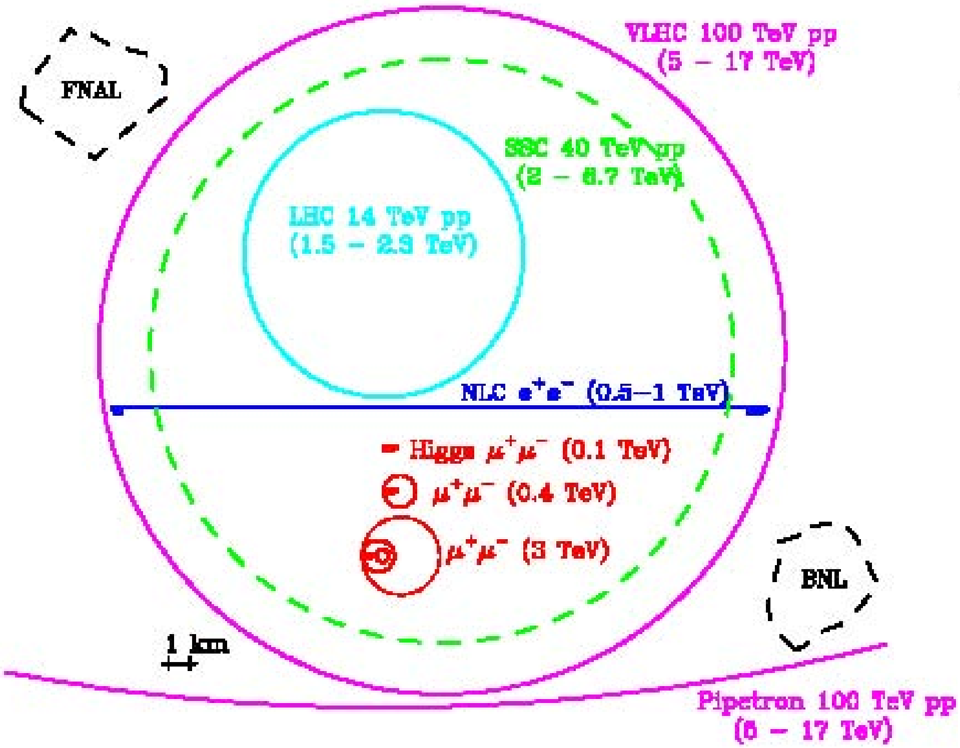
- To set scale, 10^{20} decays with 50-kT detector sees δ down to 8°

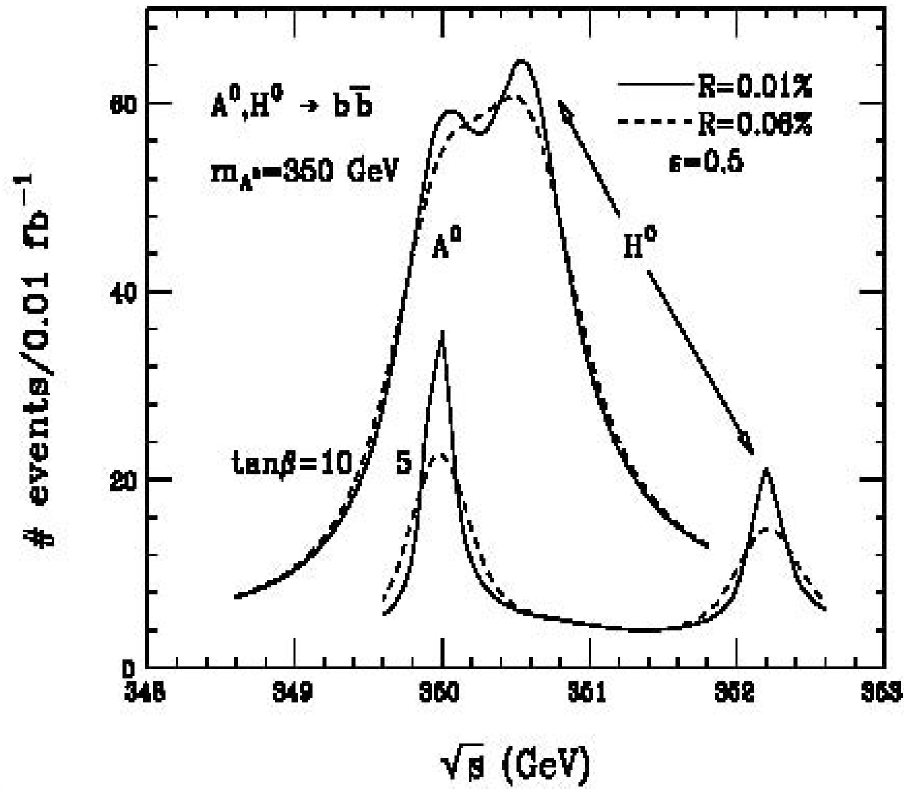
  ⇒ important to maximize flux!

Muon Collider Physics

- A pathway to *high-energy* lepton colliders
  - unlike e^+e^-, $\sqrt{s}$ not limited by radiative effects
  - a muon collider can fit on existing laboratory sites even for $\sqrt{s}$ > 3 TeV

- s-channel coupling of Higgs to lepton pairs $\propto m^2_{\mathrm{lepton}}$





- E.g., μμ-collider resolution can separate near-degenerate scalar and pseudo-scalar Higgs states of high-tanβ SUSY

Why Muon Cooling?

Neutrino Factory:

- need $\gtrsim$ 0.1 μ/p-on-target $\Rightarrow$ **very** intense μ beam from π decay

  $\Rightarrow$ must accept large (~10π mm·rad rms) beam emittance

- No acceleration system yet demonstrated with such large acceptance

  $\Rightarrow$ must cool the muon beam or develop new, large-aperture acceleration

  – in current νF studies, cooling $\rightarrow \times 3 - 10$ in accelerated muon flux

Muon Collider:

- $\mathcal{L} \propto I^2/\sigma_x\sigma_y \Rightarrow$ big gain from smaller beam

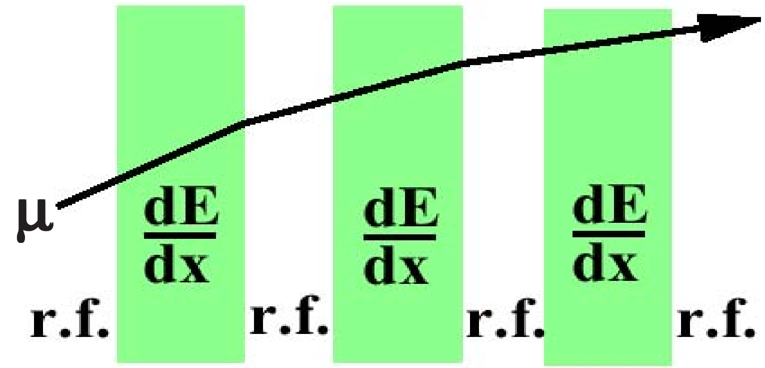
  $\Rightarrow$ to achieve useful luminosity, must cool the muon beam

The Challenge: $\tau_\mu = 2.2\ \mu s$

- What cooling technique works in microseconds?

  – there is only one, and it works only for muons:

Ionization Cooling



G. I. Budker and A. N. Skrinsky, Sov. Phys. Usp. **21**, 277 (1978)
A. N. Skrinsky and V. V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981)

- **A brilliantly simple idea:**
  1. Muons lose energy by ionizing absorber medium
     – reduces all 3 momentum components
  2. Longitudinal momentum restored in RF cavities

  → Net effect: beam divergence reduced at constant average energy

- 2D transverse-cooling rate:

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

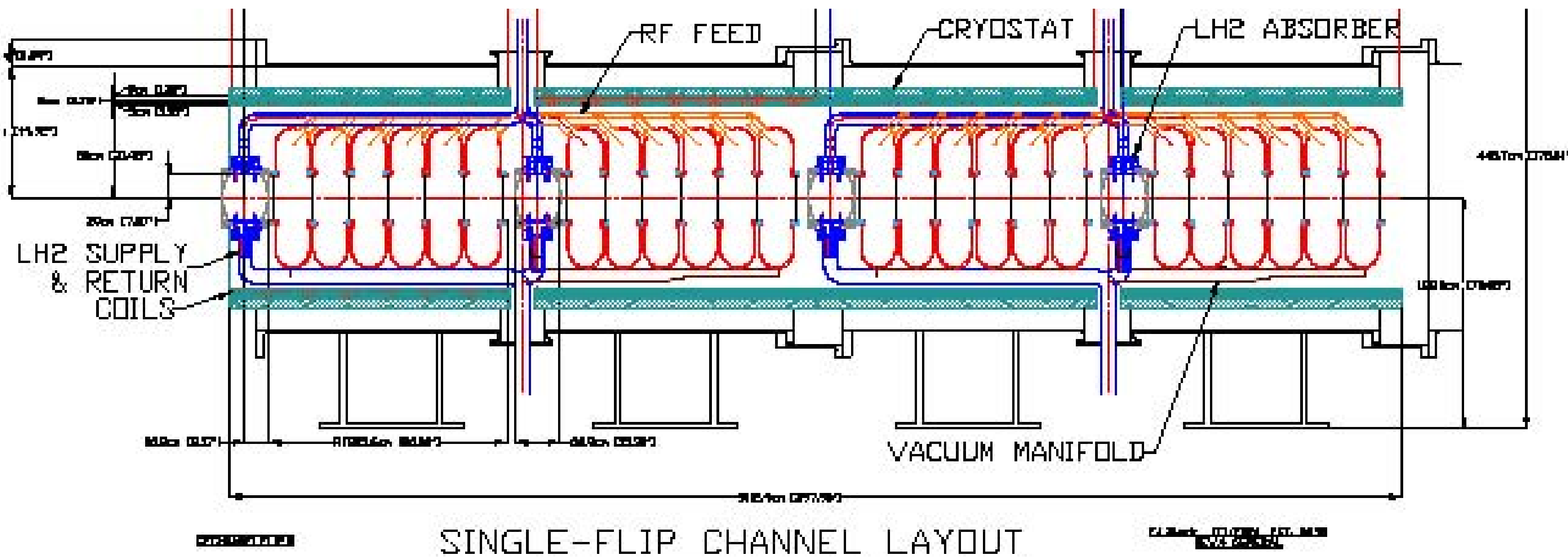
Competition between energy loss and Coulomb scattering

Note SR analogy

Optimizing Ionization-Cooling Performance

- Locate absorbers at low-β lattice points so that scattering in absorber medium negligible w.r.t. beam divergence
- Focus beam w/ superconducting solenoids for lowest β with most compact lattice (but quads may be cost-effective for large ε @ start of cooling channel)
- Reaccelerate beam with highest-gradient normal-conducting RF cavities (superconducting would quench due to multi-tesla focusing field)
  - minimizes losses due to muon decay

"Simple" (not nec. cheap!) example: absorbers & RF cavities inside long superconducting solenoids:



Analytical Theory of Ionization Cooling

- Approximate 6D ionization-cooling theory worked out and published:

  Chun-xi Wang and Kwang-Je Kim, Phys. Rev. Lett. 88, 184801 (2002);
  Kwang-Je Kim and Chun-xi Wang, Phys. Rev. Lett. 85, 760 (2000);
  G. Penn and J. S. Wurtele, Phys. Rev. Lett. 85, 764 (2000)

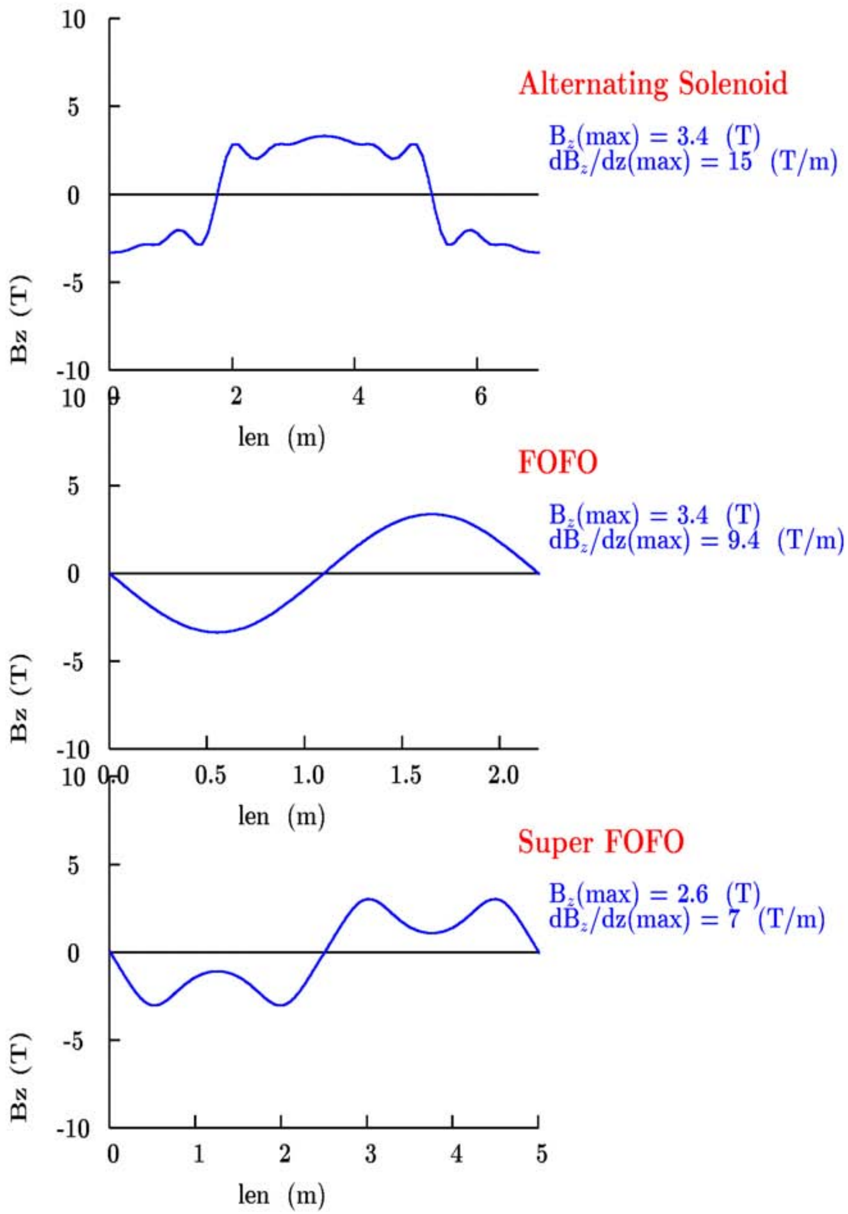
- Predictions similar to those shown above based on particle-tracking codes

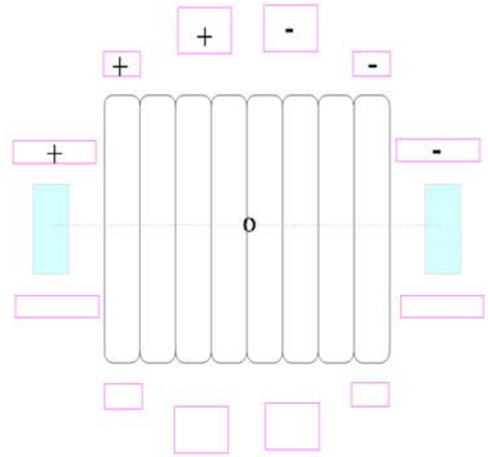
⇒ Muon cooling not a "fluke," say due to delicate choice of parameters

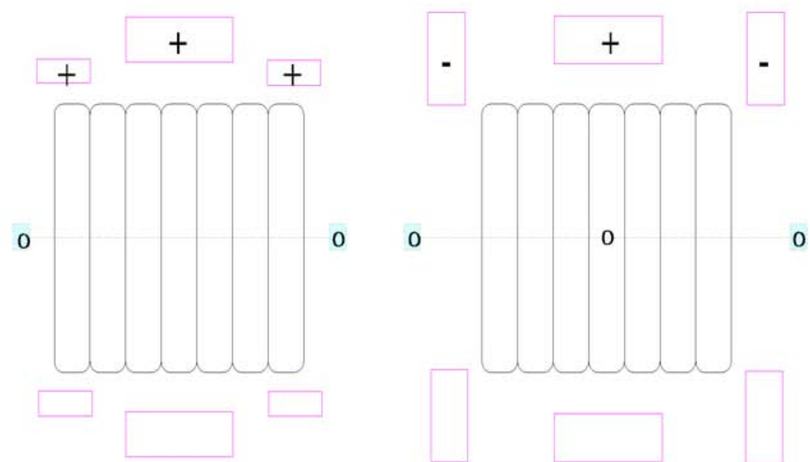
  – on the contrary, it is expected, and with the performance claimed

- Various possible lattices:

Cooling Lattices

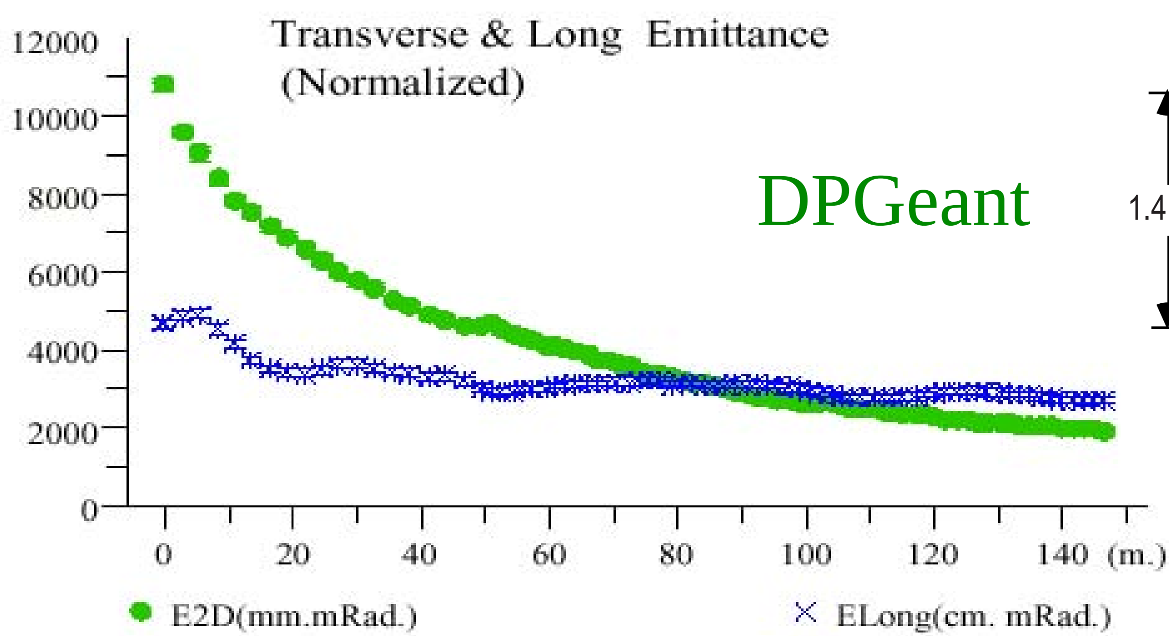


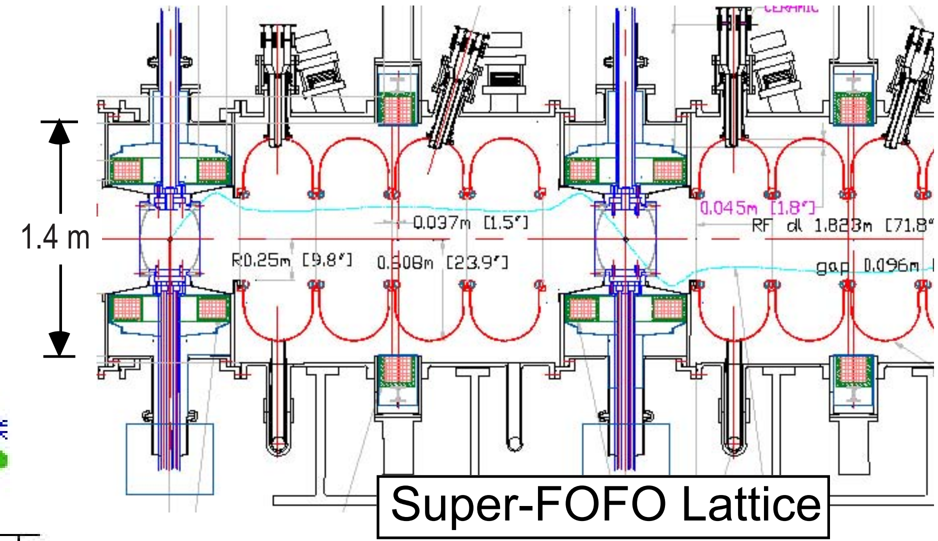




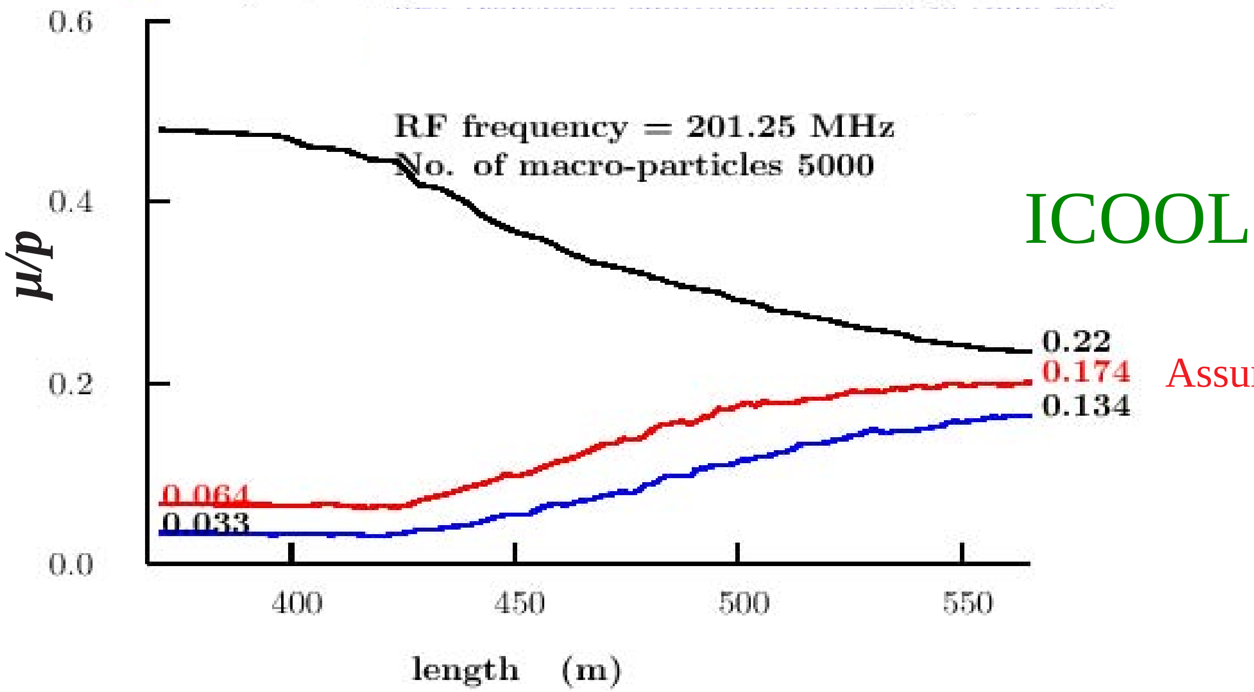
→ Periodic (alternating-gradient) focusing allows low β w/ much less superconductor

SFOFO Cooling Performance (νF FS-II)





2 indep. sim codes



Assuming 15mm trans. acceptance
9.5mm

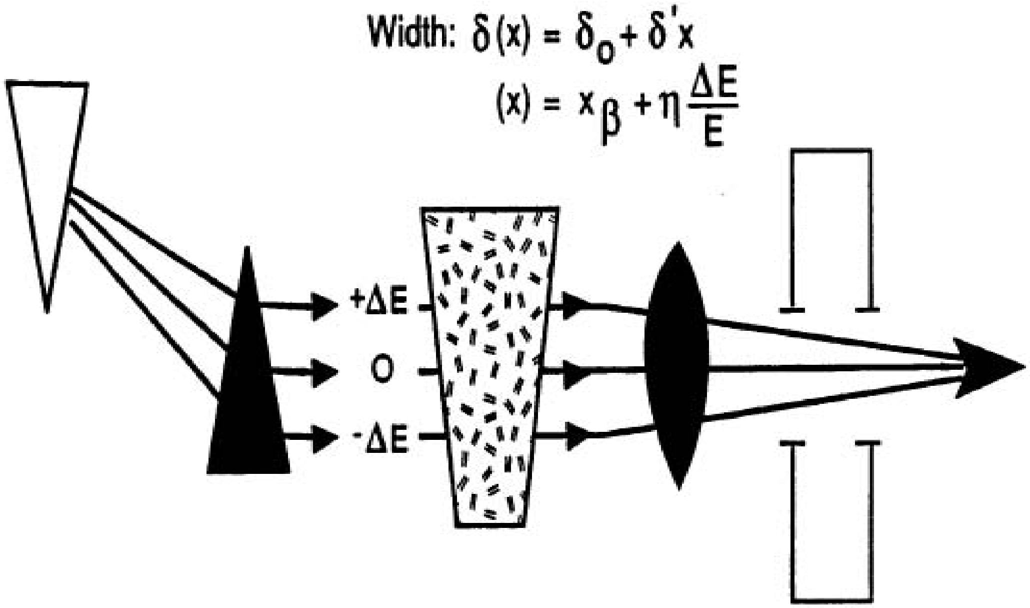
Longitudinal Cooling?

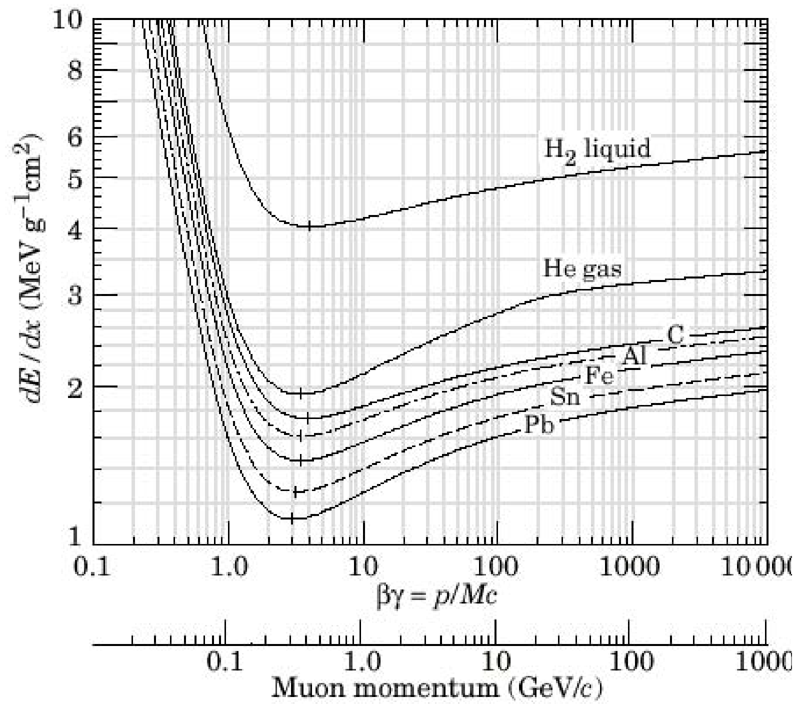
- Transverse ionization cooling self-limiting due to longitudinal-emittance growth

  ⇒ need longitudinal cooling for muon collider; could also help for νF

- Possible in principle by ionization above ionization minimum, but inefficient due to small slope *d(dE/dx)/dE* and straggling

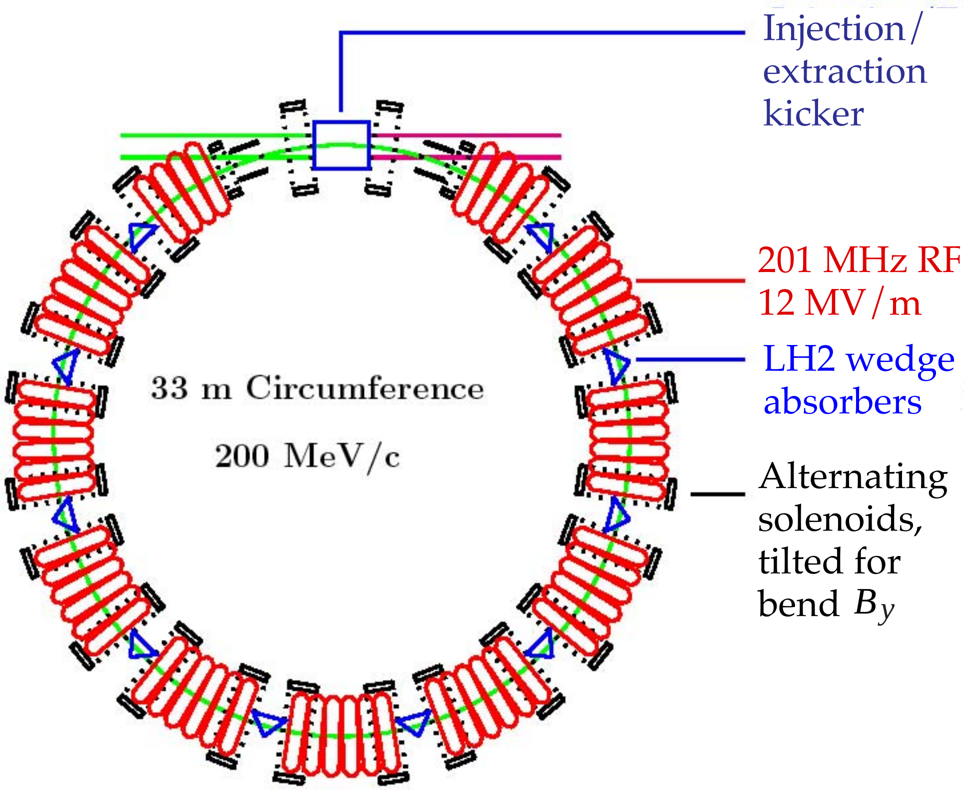
→ Emittance-exchange concept:



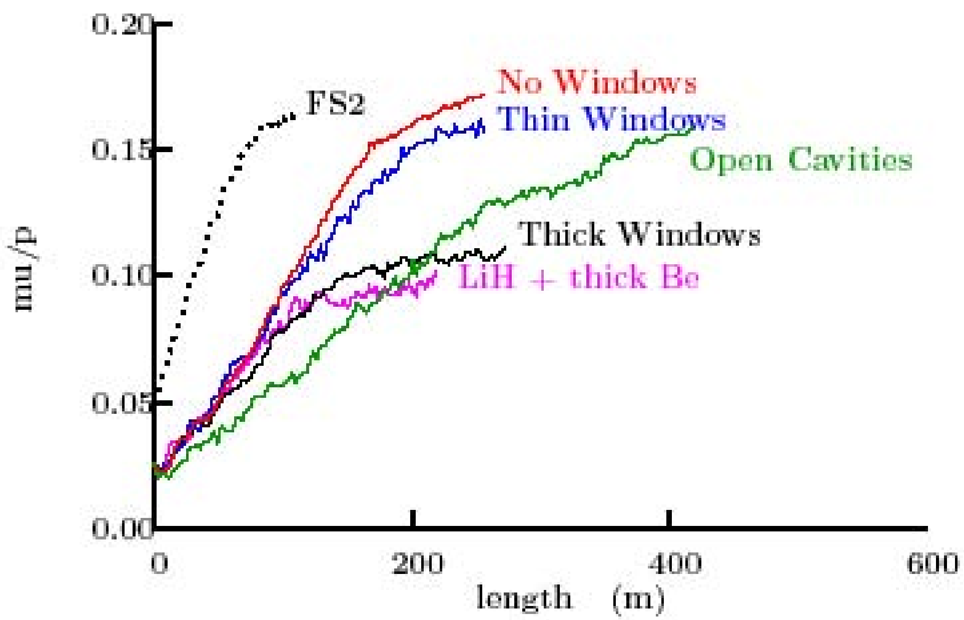


Ring Coolers

- Combine transverse cooling with emittance exchange
- Allow re-use of (expensive) cooling hardware via multiple passes



Ring Cooler Performance:



(from Palmer MuTAC Review talk 1/14/03)

- could lead to νFac or μ collider that is both cheaper and higher-performance
- injection & extraction appear soluble but require very fast, large-aperture kicker
- performance very sensitive to scattering: LH_2 absorbers with thin windows crucial
- or eliminate interior windows with high-*P* gas absorber?

Key Muon Cooling R&D Issues

- For either cooling approach (linear or circular),

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?

- We are working within the MuCool Collaboration on all of these issues

High-Gradient-RF-Cavity R&D

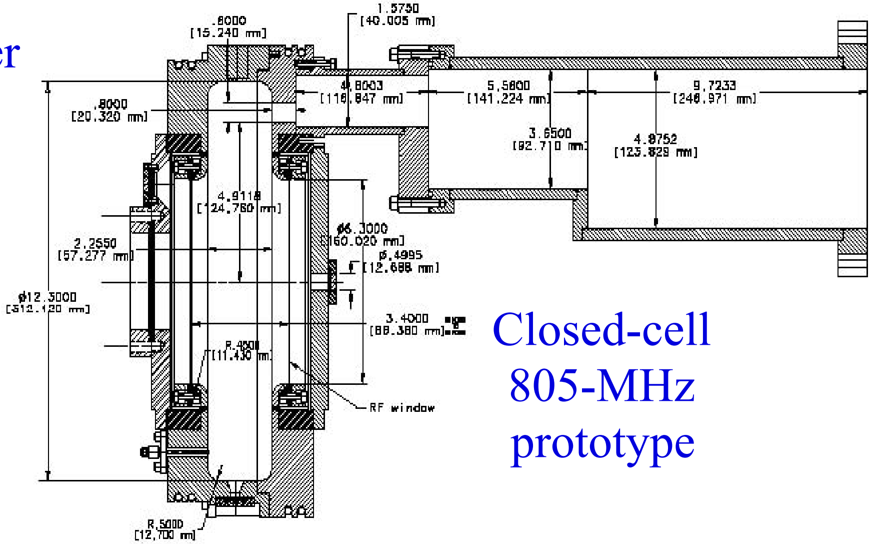
ANL / FNAL / IIT / LBNL / UMiss

- Goal:

  201-MHz Cu cavity with > 15-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 peak power

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



Closed-cell 805-MHz prototype

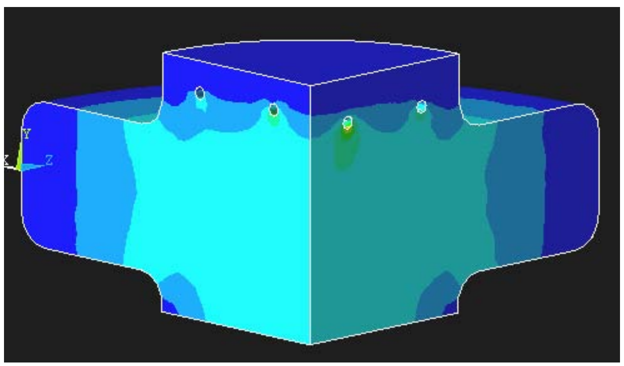
During bake-out at LBL (now under high-power test in Lab G)

Tube Grid Design Studies

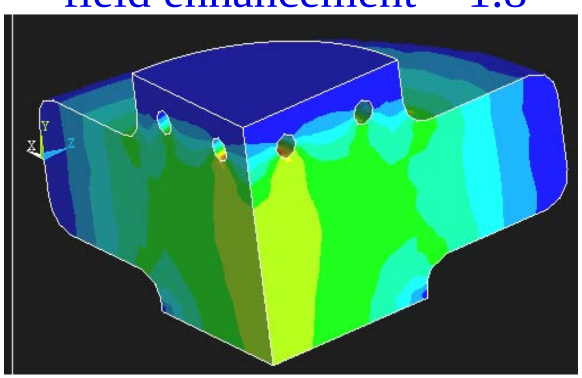
LBNL / FNAL / IIT (Alsharoa, Gosz)

- Flat windows may be sub-optimal at 201 MHz
- Grids of gas-cooled Al tubing might be thinner (in rad. len.) & cheaper
- Finite-element-analysis studies in progress at IIT & LBNL
  - Current goal: find manufacturable grid configuration with manageable field enhancement factor at tube surface (work in progress)

4x4 grid of 0.5-cm x & y tubes
field enhancement = 3.6



4x4 " waffle" grid of 1-cm tubes
field enhancement = 1.8



Field enhancement factors* for cases studied to date:

Grid \ Tube diam. (cm)	0.50	1.00	1.25	1.50
4×4 regular connected	3.60			
4×4 regular waffle	2.30	1.80		
6×6 regular waffle		1.64	1.40	1.39
6×6 center-concentrated waffle		1.40		

*enhancement factor = ratio of max tube surface field to on-axis accelerating field

Absorber R&D Collaboration

E. Almasri, E. L. Black, D. Bockenfeld, K. Cassel, D. M. Kaplan, A. Obabko
*Illinois Institute of Technology**

S. Ishimoto, K. Yoshimura
KEK High Energy Accelerator Research Organization

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

Y. Kuno
Osaka University

D. Errede, M. Haney
*University of Illinois at Urbana-Champaign**

M. Reep, D. Summers
University of Mississippi

W. Lau, S. Yang
University of Oxford

ICAR groups working cohesively with each other (& with external groups)

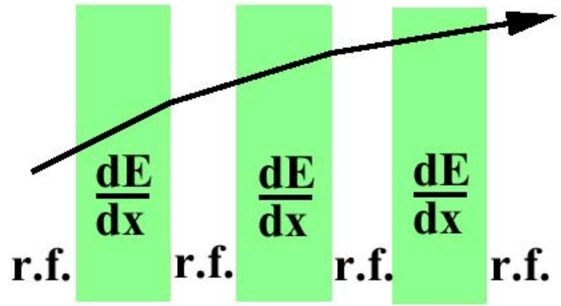
in collaboration with

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

* member, Illinois Consortium for Accelerator Research

Absorber R&D

ANL / FNAL / IIT / KEK / Osaka / Oxford / NIU / UIUC



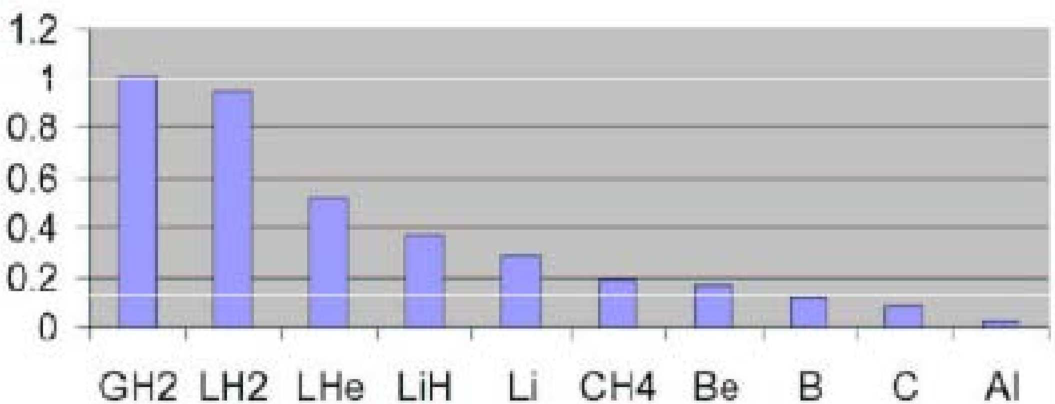
- 2D transverse-cooling rate:

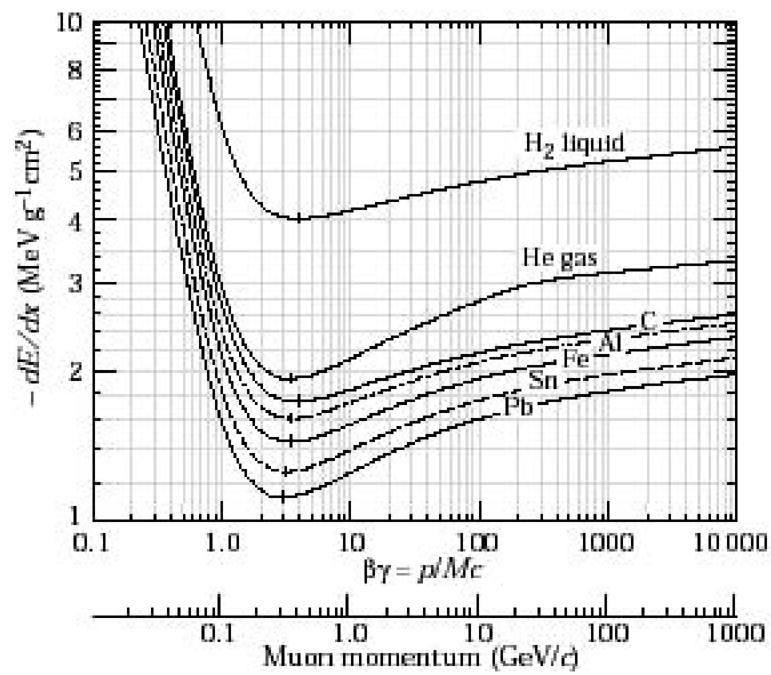
$$\frac{d\varepsilon_{x,N}}{dz} \approx -\frac{1}{\beta^2}\frac{\varepsilon_{x,N}}{E}\left|\frac{dE}{dz}\right| + \beta_\perp \frac{(0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu L_R}$$

Competition between energy loss and Coulomb scattering

⇒ Absorber material comparison:

$\perp$ cooling merit factor $\propto (L_R\, dE/dx)^2 \sim (Z+1)^{-2}$





- Hydrogen is best material by factor $\gtrsim 2$

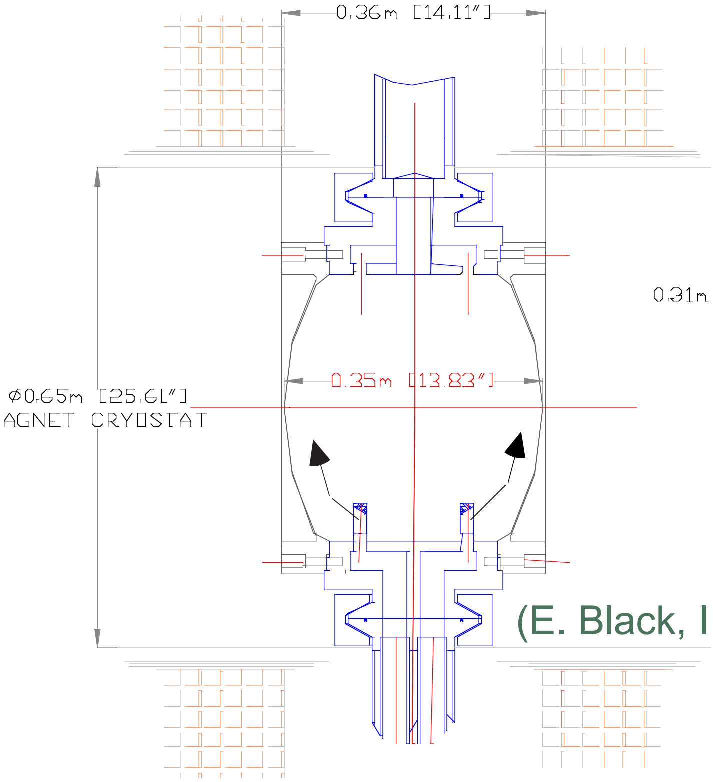
(...all other things being equal, e.g., neglecting effect of containment windows)

Absorber Power Handling

IIT / KEK / NIU / Osaka

- Need to handle 100s of watts per absorber in Study-II scenario
  - → ~ kW with more ambitious Proton Driver (4 MW instead of 1 MW *p*-beam power) and/or Neuffer phase rotation (keeps both μ^+ and μ^- simultaneously)
  - → ~ 10 kW in ring cooler with ≈10 passes
  - – State of the art is several hundred W in e.g. SLAC E-158 LH_2 target
- Two possible solutions (both proposed by IIT) being pursued:

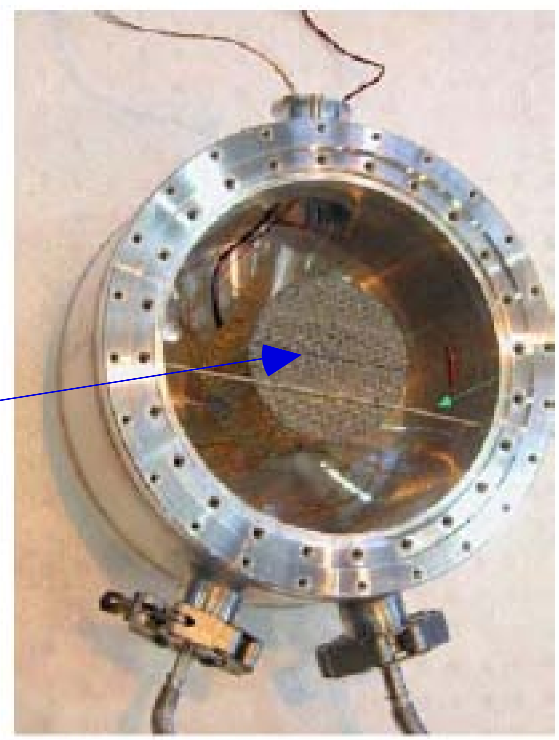
IIT/NIU: Forced-flow absorber with external cooling loop

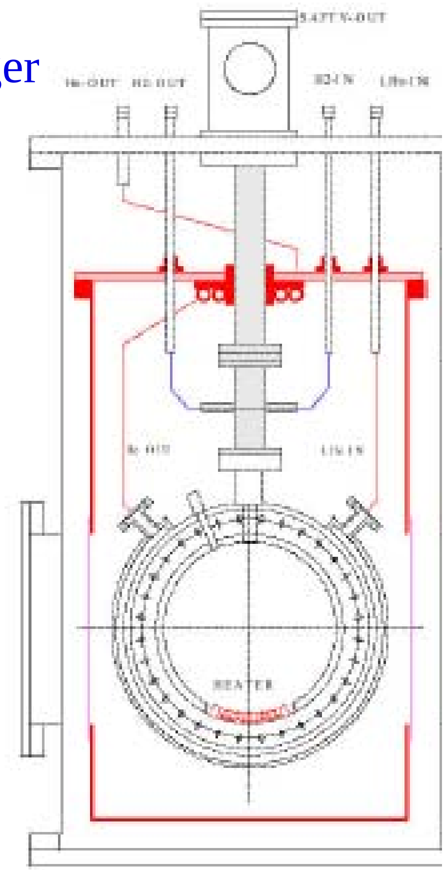


(E. Black, IIT)

KEK/Osaka: Convection-cooled absorber with internal heat exchanger

Array of heating wires for tests





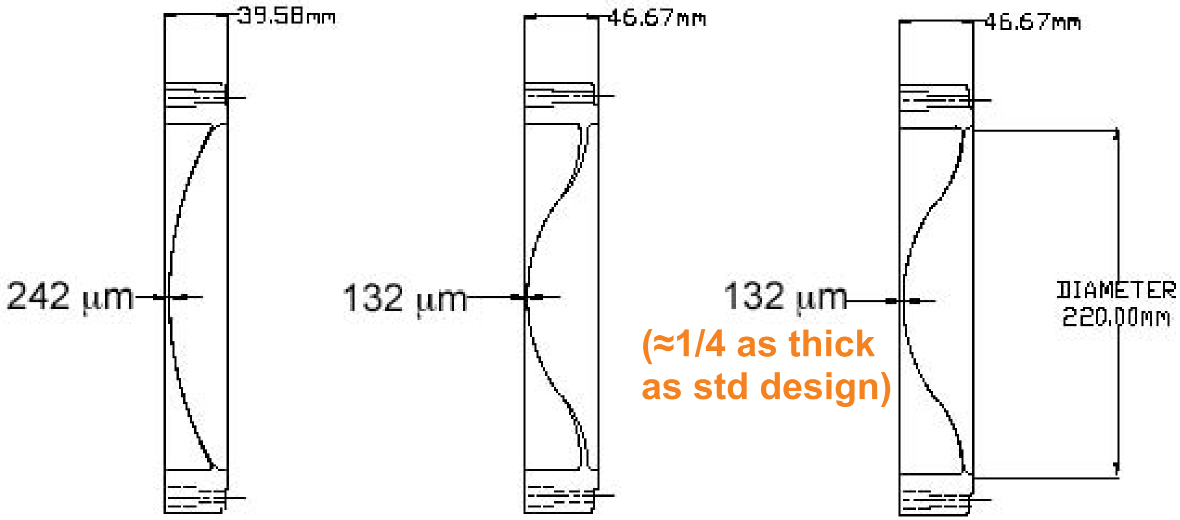
- Power-handling limit yet to be established for either approach

Progress in Absorber Windows: 1

IIT / NIU / Oxford / UIUC / UMiss

- To avoid compromising hydrogen's low Coulomb scattering, need containment windows as thin as possible:

3 iterations of absorber window design:

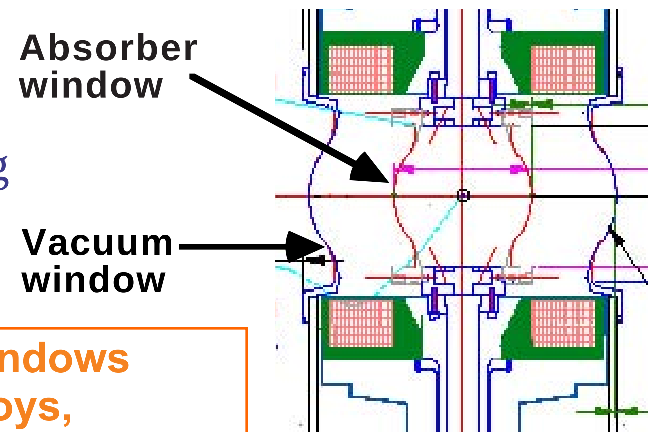


(E. Black, IIT)

Windows machined w/ integral flange out of single disk of Al alloy

Developed non-contact "photogrammetry" for window measurement and certification

Established need for containment vacuum surrounding absorber, to satisfy safety guidelines



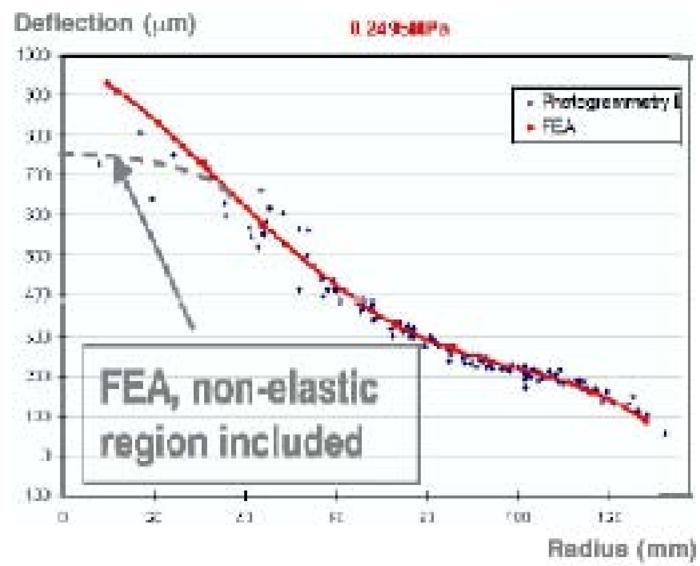
(E. Black, IIT)

With "inflected" windows & modern Al alloys, merit factor can be as high as ≈ 0.8

Progress in Absorber Windows: 2

- FNAL requirement for nonstandard LH_2 containment windows:
  - Series of 4 windows must be destructively pressure-tested
- This was carried out for windows of the “1st-iteration” design:

- Reliability of photogrammetry established
  - ≈10 µm precision in 3D
  - Can measure both thickness profile and shape
  - Good agreement w/ FEA predictions
  - Good agreement w/ strain-gage data
  - Good agreement w/ CMM data
  - Good agreement w/ micrometer measurements

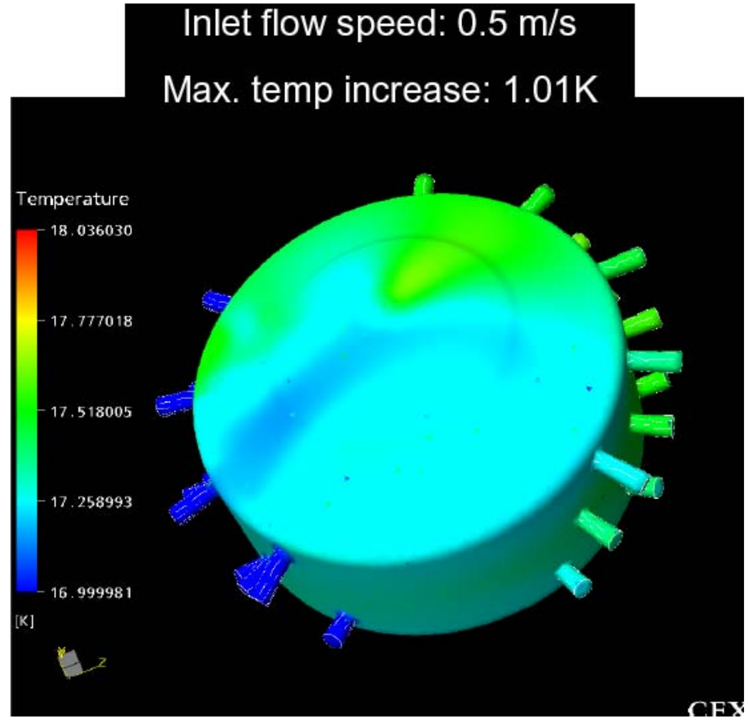


- Prototypes of latest design now in fabrication at UMiss

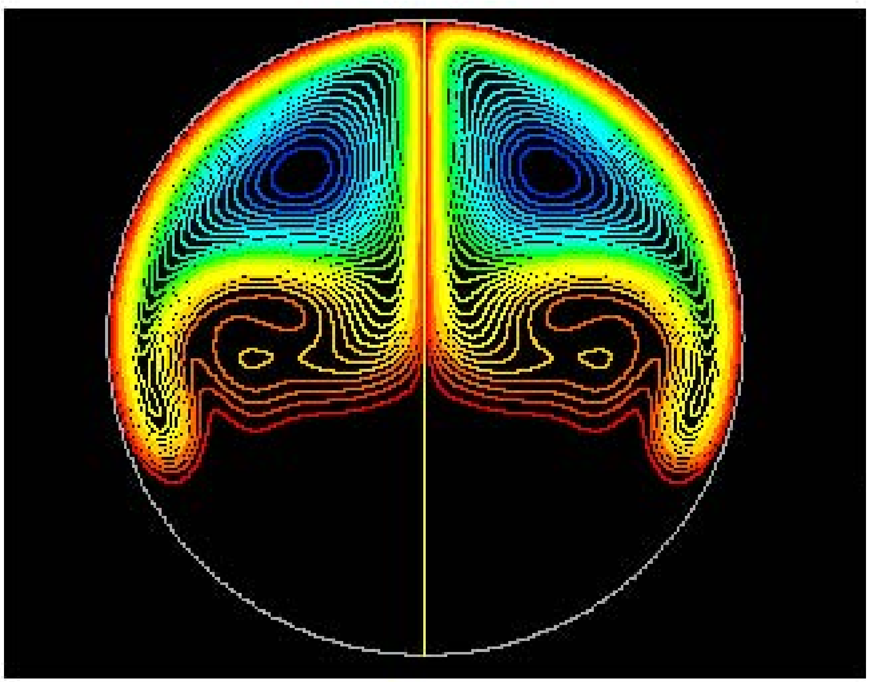
LH2 Flow Studies

ANL / IIT / Oxford / NIU / UIUC

- Need to optimize LH_2 flow for maximum heat transfer and temperature uniformity
  - Challenging engineering problem
  - Approach:
    - 2D & 3D FEA (flow-through design)
    - 2D CFD (convection-cooled design)
    - exp'tal tests



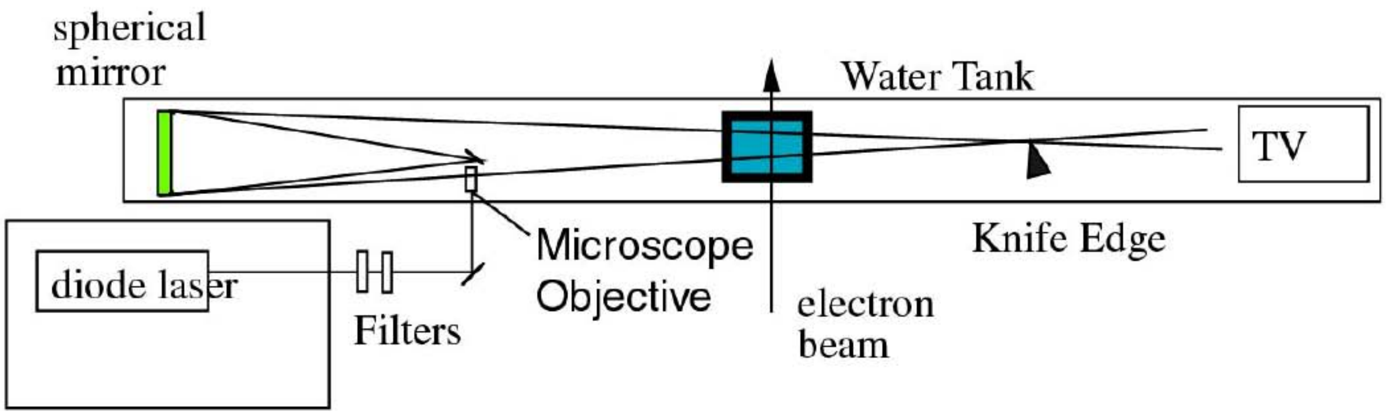
(Lau/Yang, Oxford)



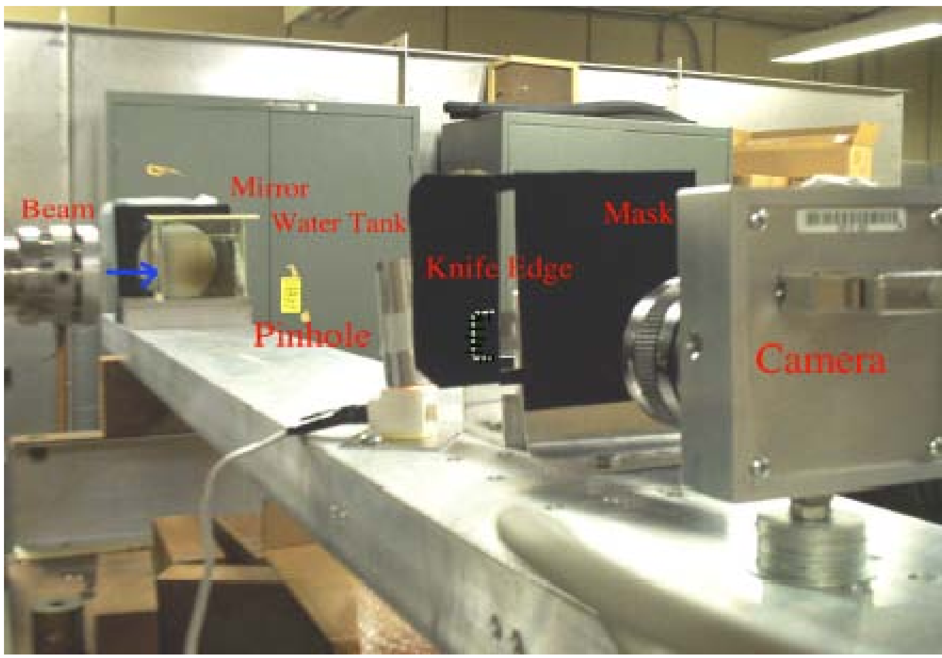
(Almasri/Cassel/Obabko, IIT)

LH2 Flow Studies (cont'd)

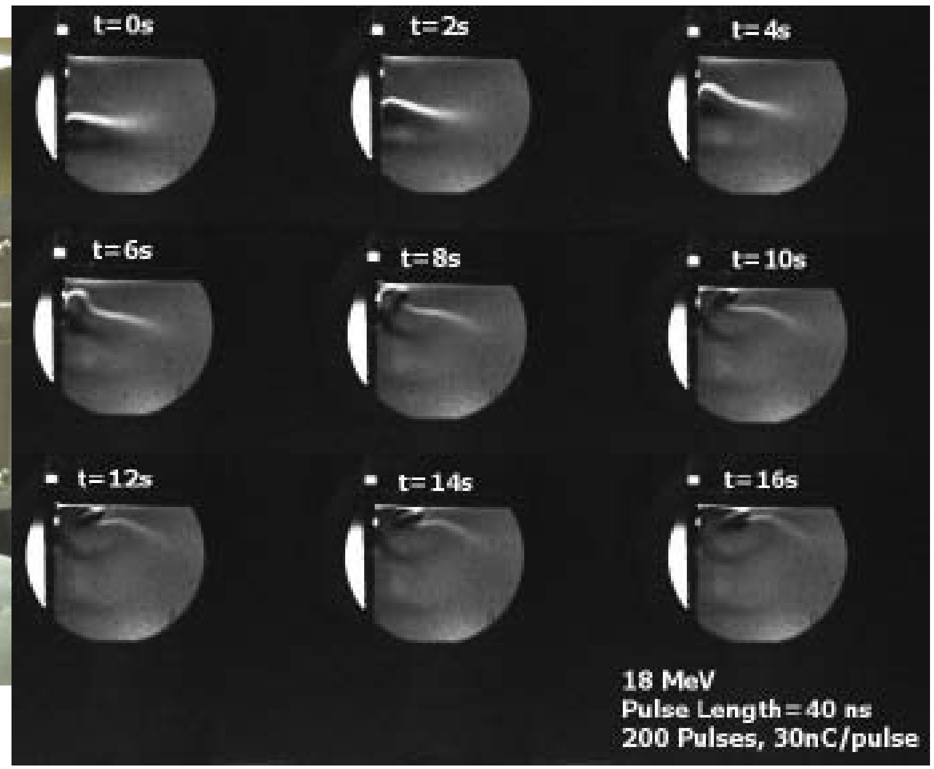
- Schlieren & Ronchi techniques tested at Argonne using 20 MeV e^- beam:



  - Schlieren setup:



  - Density fluctuations measurable:



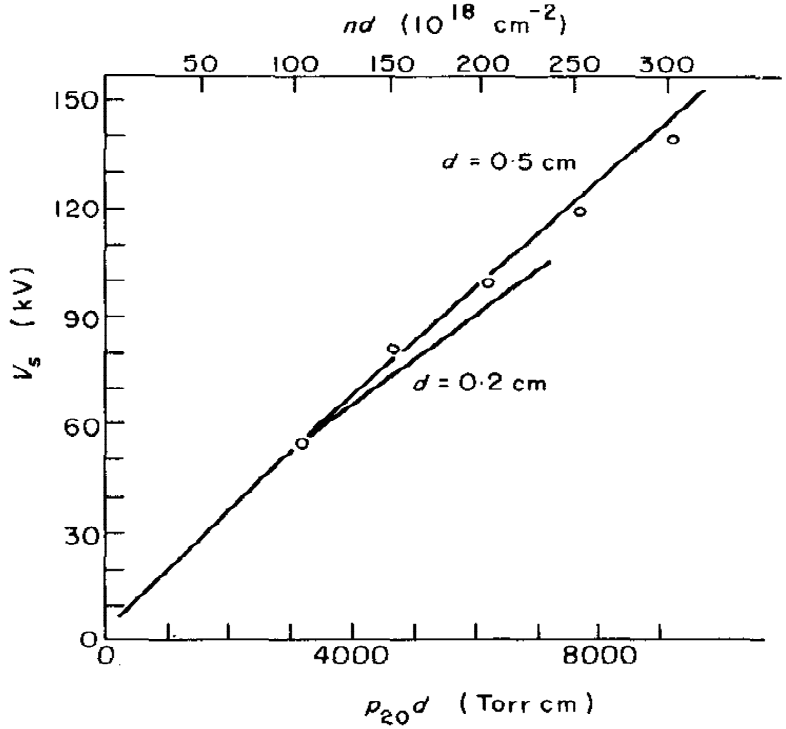
- Plan: take data in more configurations & compare with predictions

Gaseous Absorber?

Muons, Inc. / FNAL / 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:

  static case: $V_s = 0.448\,(nd) + 0.6\,(nd)^{1/2}$ (n = density of atoms or molecules in 10^{18}/cm)



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

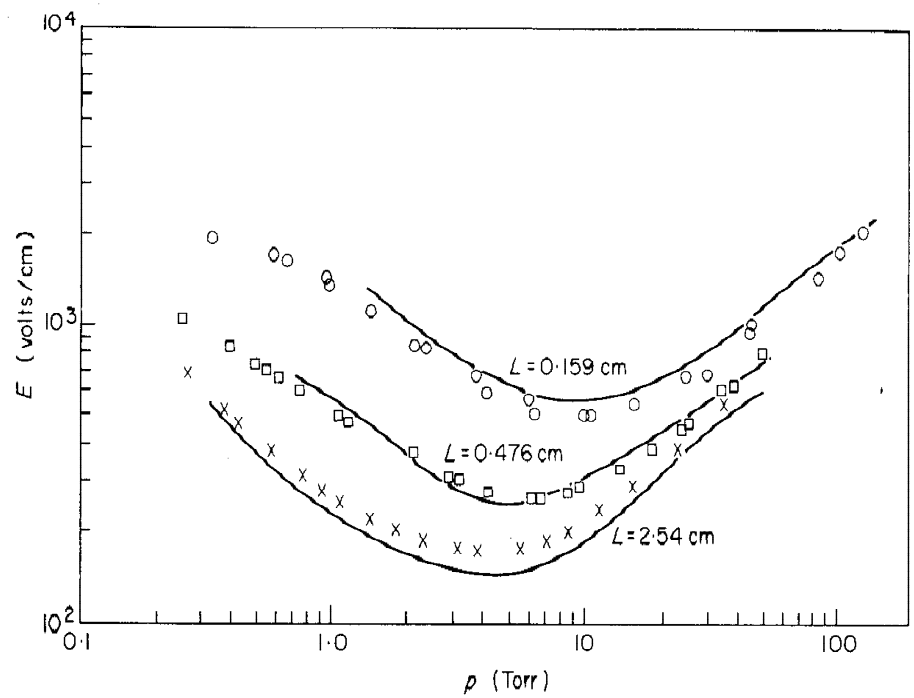


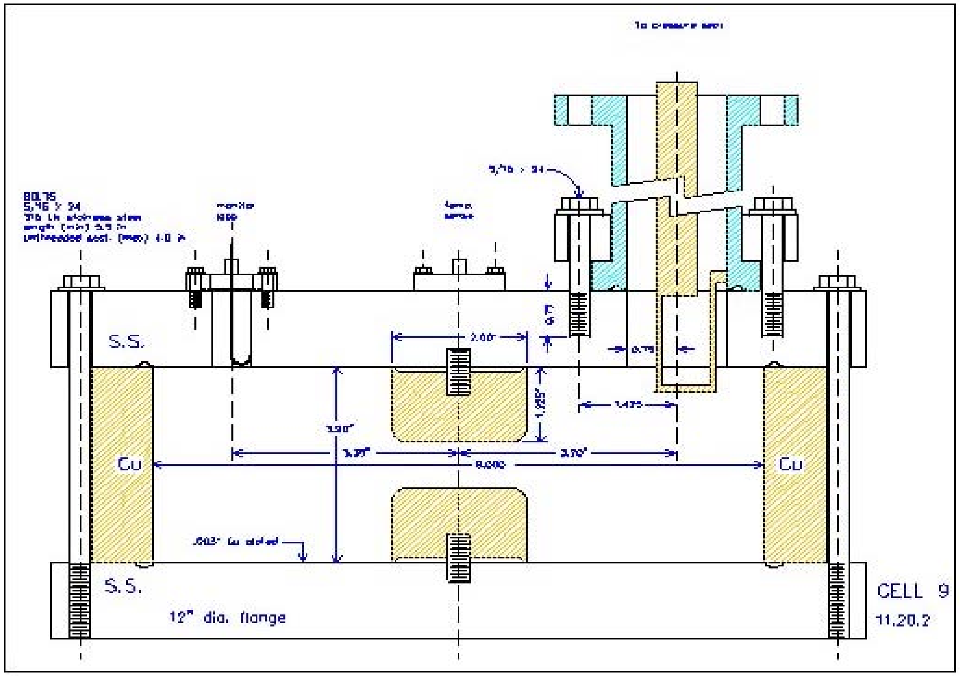
Figure 8.13. Theory and experiment compared for hydrogen at 2·8 GHz (MacDonald and Brown, 1949. Reproduced by permission of The America Physical Society)

- With low-temp operation, could take advantage of reduced Cu resistivity
- Could lead to higher-performance, shorter, cheaper cooling channel with higher-gradient RF cavities

Muons, Inc.

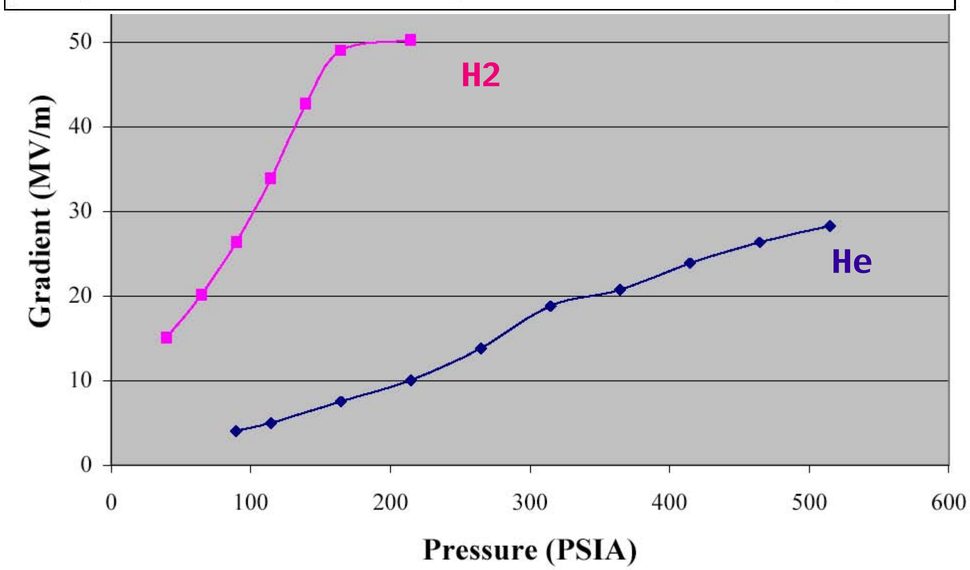
- Muons, Inc. formed 2002 w/ Phase I STTR funding from DOE, designed 805-MHz test cell and took measurements @ FNAL Lab G

805-MHz test cell design



Partially-assembled test cell
(Copper-plated SS Conflat disk with electrode)

Note: electrode shape adjusted to tune resonance



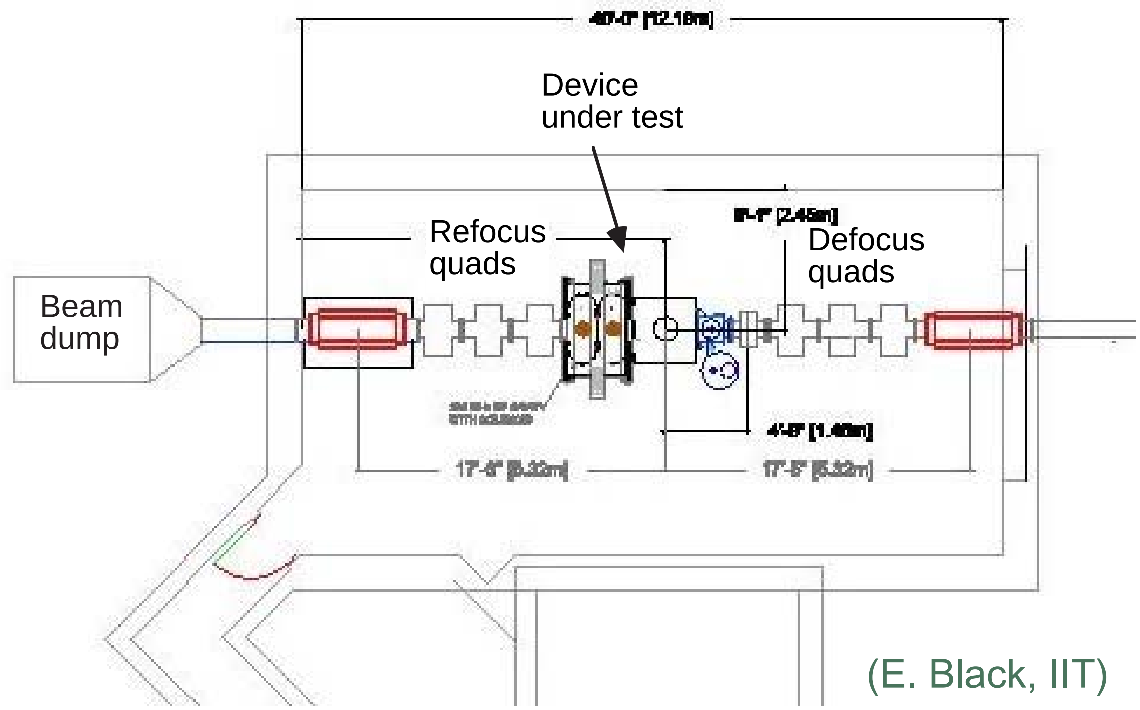
- Demonstrated 50 MV/m operation at 805 MHz in ≈12-atm GH2 at 77K
- STTR proposals submitted for Phase II* (201 MHz) and other possible applications of high-pressure RF cavities, e.g.
  - pulse compression*
  - 6D cooling*
  - gaseous-absorber cooling exp't (MANX)

* funded in FY03

- Beginning to influence other MC efforts

MuCool Test Area

- Need facility in which to test
  - absorbers
  - RF cavities
  - solenoids



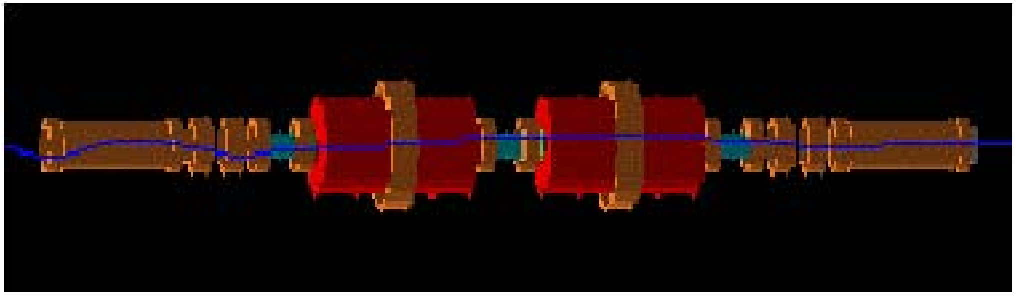
- Show that cooling cell is operable in an intense beam
  (engineering test, not cooling demo)

- ∃ convenient location:
  end of FNAL Linac has
  - sufficient space
  - 201 & 805 MHz RF power sources (Linac RF test stands)
  - 400 MeV beam up to $2.4{\times}10^{14}\ p$/s $\rightarrow$ 570 W in 35-cm LH_2 absorber (higher at lower E)

Design Studies & Simulations

(Black, DMK, Roberts, Torun)

- Feasibility Study II:
  - DMK led absorber design study & served as "editor for absorbers"
  - Black responsible for channel integration
- Geant Study-II simulations:
  - Established acceptable range of heat-induced absorber density fluctuations (±5%)
  - Confirmed that "iteration 2" window design was improvement over Study-II performance (not obvious → window was thinner at center but much thicker at edges)
  - Code improvements in progress (speed, usability)
- MICE Geant simulation:
  - Geant4 framework developed, now being applied to MICE design issues



  - Most recent work in progress: include beamline (for optimization studies)

“Targetry”

- To optimize design of stored-muon facility, need to understand how best to produce muons
- Need to understand how to target multi-MW proton beam safely
  - US-based R&D program centered @ BNL
  - also work in UK & CERN
- Need to know pion-production cross sections at various potential Proton Driver energies
- Goes roughly as P_{beam}
- Reliable data surprisingly sparse
- Experiments to improve this knowledge: E910@BNL, HARP@CERN, MIPP@FNAL

“Study-IIa”

- Study-II νF design cost estimate ≈1.9 G$
- Desirable to seek more cost-optimized design
- APS 6-month study provides opportunity
- BNL iterating/optimizing design including
  - Neuffer RF phase rotation
  - simpler cooling channel
  - larger-aperture acceleration using cheaper technology

Summary

- Continued progress developing components for a muon cooling channel
- Ongoing 805 MHz RF R&D program developing techniques required for low-dark-current, high-gradient NCRF cavities operable at high *B*
- Healthy progress developing LH_2 absorbers with thin windows
- MuCool Test Area ~~will soon be~~ available
- We are training Ph.D. and M.S. students in beam physics & engineering
  - already 1 M.S. completed, several Ph.D. and M.S. degrees in progress
- Benefiting greatly from international collaboration
  - Japan contribution to absorbers
  - UK contribution to absorber and cavity windows and flow sims
  - Cooling experiment proceeding via international MICE Collaboration
- IIT ICAR group has had substantial impact on progress & viability of muon cooling R&D
- Muon R&D is important "fallback" in case LC not built @ FNAL
- Preserves option for US to continue to lead in neutrino physics