Muon Accelerator Activities for the General Accelerator R&D Portfolio

presented to the HEPAP Accelerator R&D Sub-Panel

Mark Palmer

Fermilab

August 27, 2014

Outline

- P5 Context and MAP
- Context of Proposed Work
- Proposed Activities
  - Advanced Concepts for Muon and Neutrino Sources
  - RF in Magnetic Field
- Conclusion

P5 CONTEXT AND MAP

Muon Accelerator Activities in GARD

- P5 Recommendations Relevant to Muons
  - Recommendation 25:
    Reassess MAP. Incorporate into the GARD program the MAP activities that are of general importance to accelerator R&D, and consult with international partners on the early termination of MICE.
  - Recommendation 26:
    Pursue accelerator R&D with high priority at levels consistent with budget constraints. Align the present R&D program with the P5 priorities and long term vision, with an appropriate balance among general R&D, directed R&D, and accelerator test facilities and among short-, medium-, and long-term efforts. Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators.

Other Relevant P5 Comments

- Neutrino Factories in the Report:
  - *Neutrino factories based on muon storage rings could provide higher intensity and higher quality neutrino beams than conventional high power proton beams on targets. This concept would be attractive for an international long-baseline neutrino program offering more precise and complete studies of neutrino physics beyond short-term and mid-term facilities.*
  - The construction of PIP-II and the beamline for LBNF will be major advances in accelerator technology in the areas of SCRF and targetry *and lay the foundation for a possible future neutrino factory.*
- Comments from Joe Lykken addressing the MAP Collaboration https://indico.fnal.gov/getFile.py/access?contribId=13&sessionId=0&resId=0&materialId=slides&confId=8326
  - *"This was a programmatic recommendation about the advisability of carving out MAP as a directed R&D program, versus supporting MAP activities within GARD"*
  - *"The P5 plan launches the U.S. toward a long term comprehensive neutrino program"*
    - *"This program should include a home for people thinking about neutrino factories"*

CONTEXT OF PROPOSED WORK

The Issues I

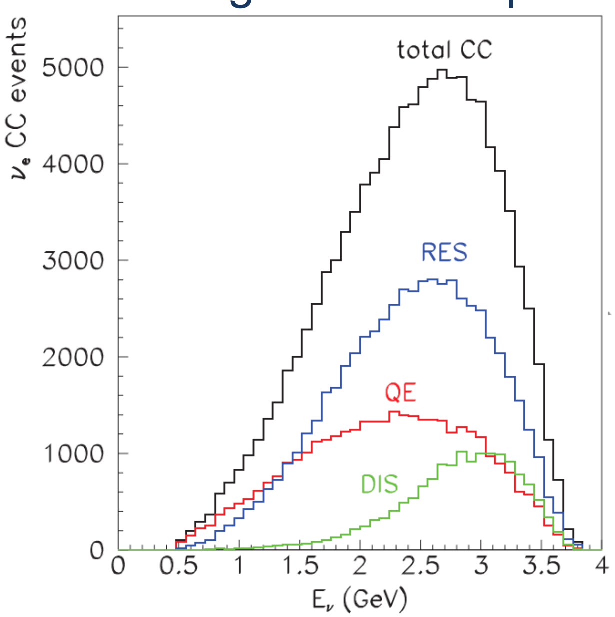
Precision and Accuracy

- The usual metric for a neutrino experiment:
  Beam Power × Detector Mass × Operation Time
- Ultimately, the validity of our oscillation measurements is determined by our:
  - Understanding of the source (ie, the beam)
  - Understanding of the interactions in the detector

    And neutrino oscillation experiments are targeting understanding at the <1% scale
- In disappearance measurements, strong cancellation of systematics can be achieved by measuring:
  1. The event rate before oscillation at near detector
  2. The oscillated event rate at a far detector which has identical technology and acceptance
- In appearance measurements, this cancellation does not apply, and one requires:
  1. Precise knowledge of the source flux
  2. Precise knowledge of the energy-dependent cross-section × efficiency, $\sigma_\alpha(E)\varepsilon_\alpha(E)$, for each mode

The Issues II

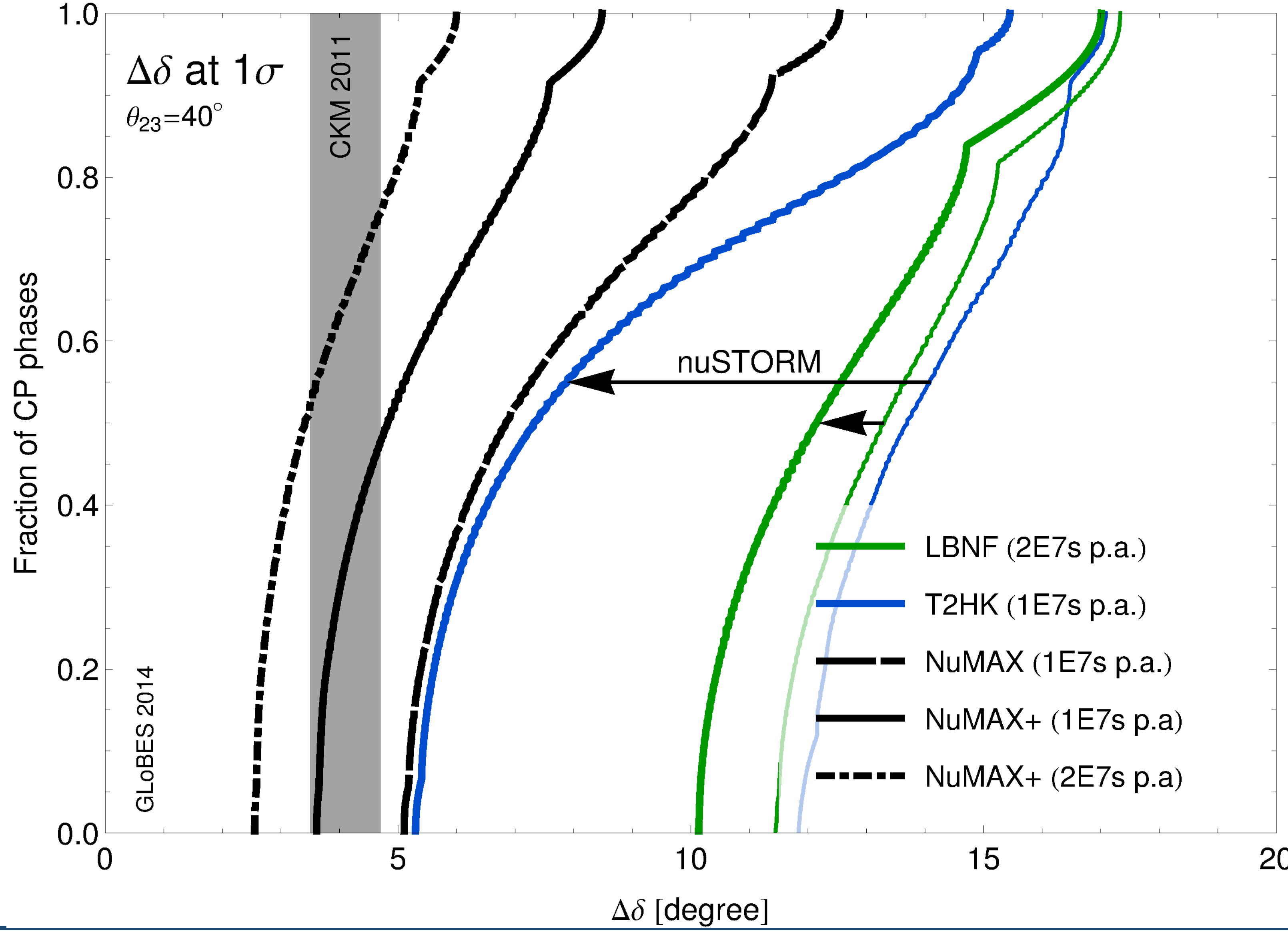
- Generally, 1% level understanding appears to be a significant challenge for ν superbeams
- Muon beams can provide sources of neutrinos that have both precision and accuracy
  - High production rates
  - Well-understood source systematics
    - Precisely measured beams (to <1%)
  - With automatic cross-checks
    - Interlocking appearance, disappearance and conjugate modes
  - Thus leading to the best possible measurements…



μ^+ Channel	N_{evts}	μ^- Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

Example: nuSTORM Collaboration, 2013

Performance Benefits from Precision ν Sources



PROPOSED ACTIVITIES

The Proposed Activities

- While a directed facility R&D effort no longer fits within the US HEP portfolio, MAP management feels that two component activities that are key to enabling a long-term neutrino factory capability deserve consideration for GARD funding starting in FY16:

  1. MAP's Muon Accelerator Staging Study has identified a staged and more cost-effective approach to achieving NF capabilities. The design effort for these capabilities is closely aligned with plans for US long baseline neutrino capabilities. Thus, research into *Advanced Concepts for Muon and Neutrino Sources* should be continued to ensure an optimal path beyond LBNF.

  2. Key progress has been made over the last 3 years to provide the necessary technology solutions for the cooling channels required to provide high brightness muon beams. The *RF in magnetic field R&D program* is at a critical junction in terms of developing our understanding of operating high field RF cavities in magnetic fields. Thus, these efforts should be continued to obtain the next set of experimental results and enable an option for muon accelerator based capabilities beyond LBNF.

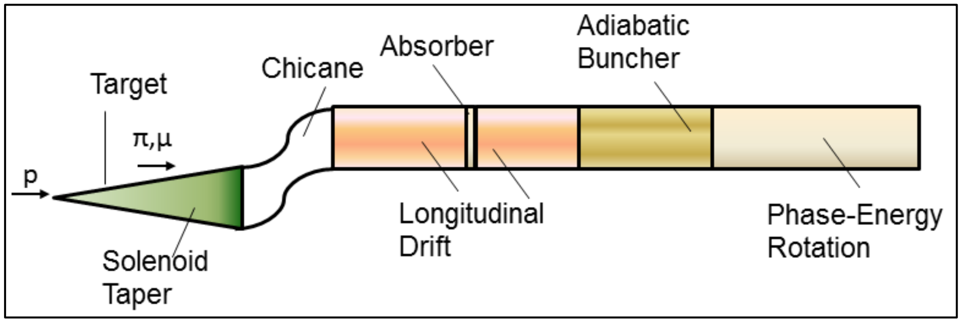
Activity 1: Advanced Concepts for Muon and Neutrino Sources

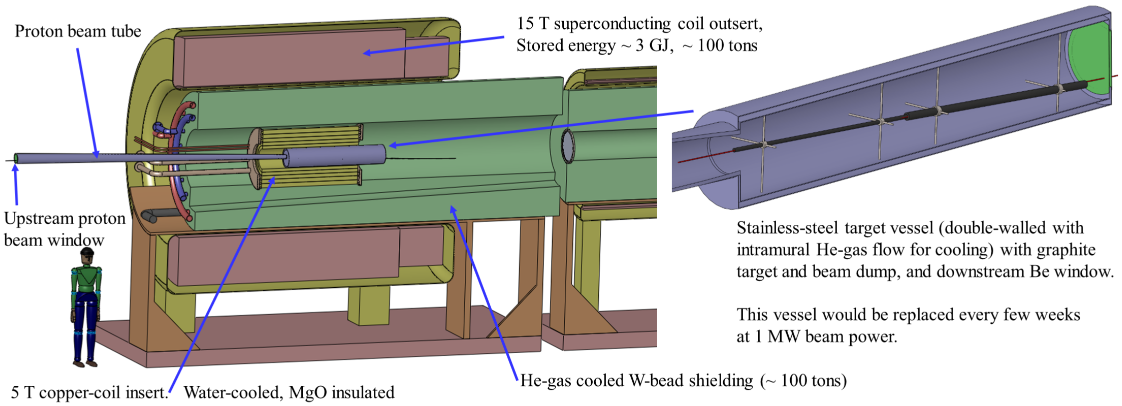
- The long-term future of our domestic HEP program is now firmly focused on short- and long-baseline neutrino physics capabilities

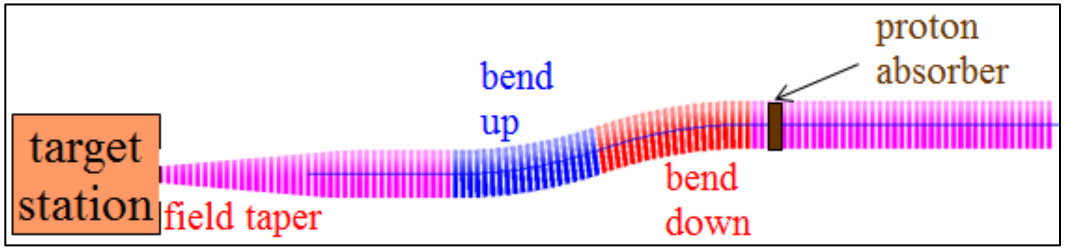
- As noted by P5, while the near-term effort may not require NF capabilities, these capabilities point the way to controlling systematics, thus providing the ultimate high precision and accuracy measurements for the field.

- Thus we feel that there should be a GARD-supported activity to
  - Continue to develop these concepts;
  - Ensure that a viable path to these capabilities is preserved within the US program; and
  - Enable their implementation when they are needed

High Intensity Muon Sources





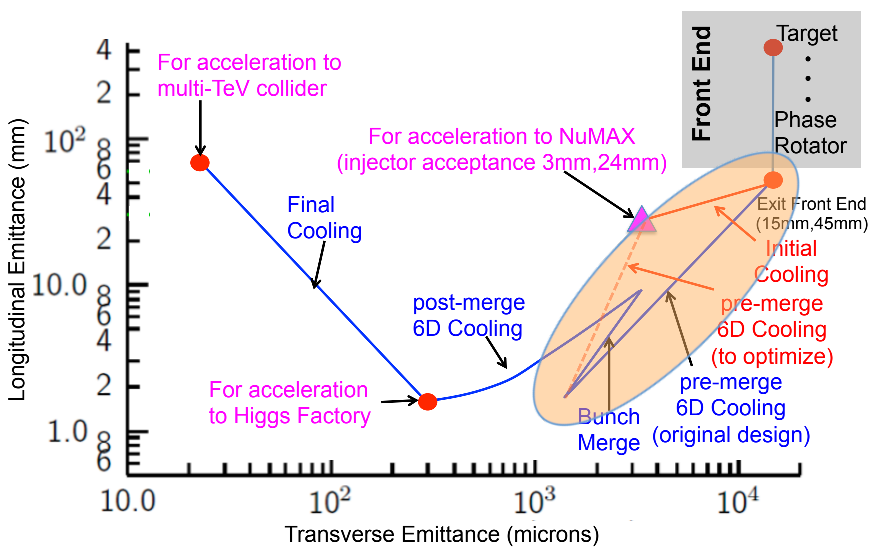


High Intensity R&D Activities:

- Energy deposition
- Gas-filled cavities in buncher/rotator
- Cost/performance tradeoffs

Bright Muon Sources

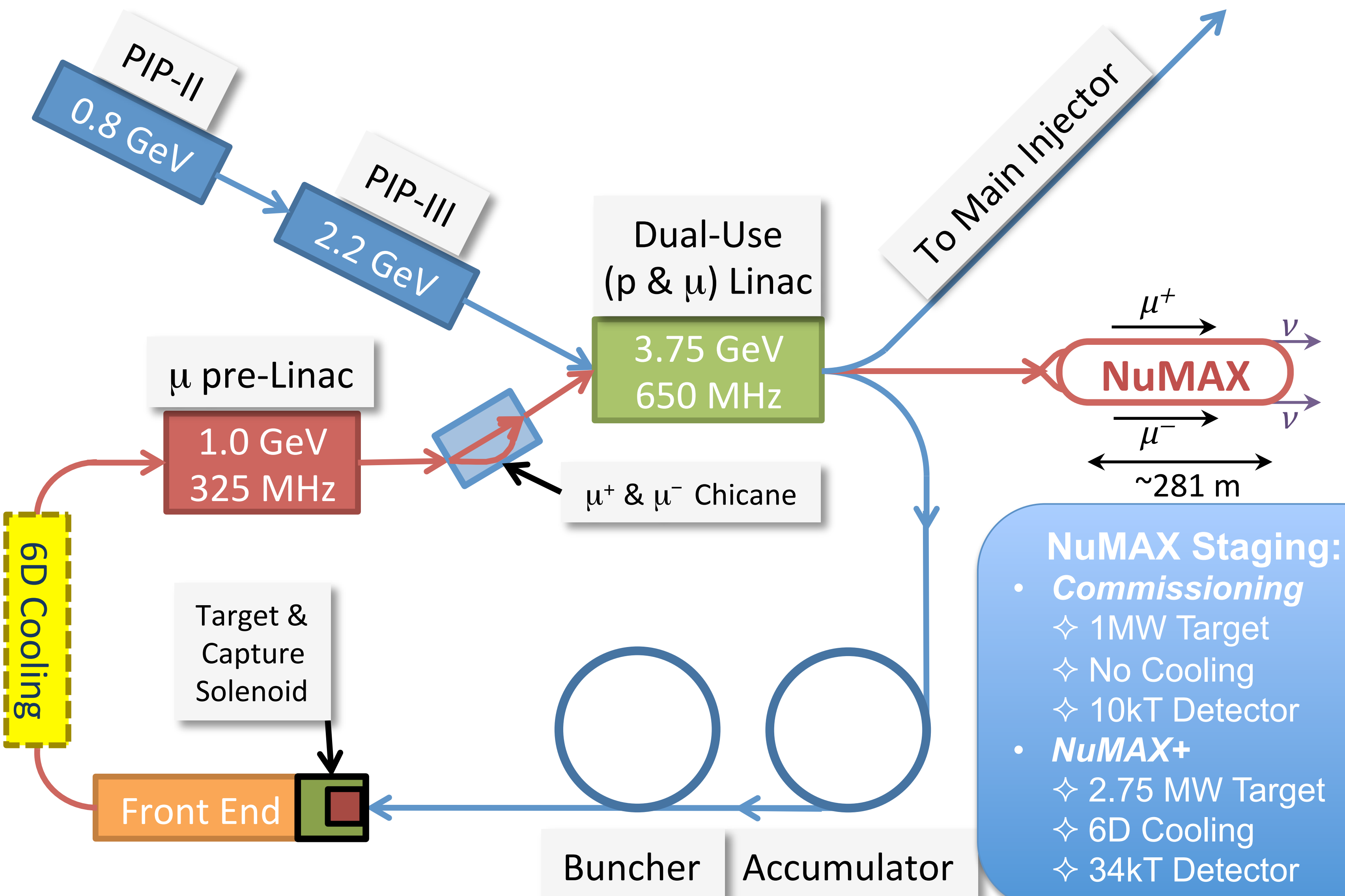
- MAP cooling effort has been remarkably successful
  - Technology: experiments show
    - HPRF can prevent breakdown & operate at high beam intensity
    - dielectrics have the potential to reduce cavity size in cooling systems
    - careful cavity design prevents continuous gradient loss at high B
  - Design:
    - realistic designs to "bottom" of cooling diagram cool ε_{6D} by 5 orders of magnitude!



In contrast to MAP cooling effort which considered entire cooling system for collider, the refocused effort under GARD would emphasize this region which impacts the cost, staging and performance of a future neutrino factory

Would also enable consideration of other potential applications of cold muons such as a Mu2e upgrade

An Advanced Neutrino Source



NuMAX Staging:

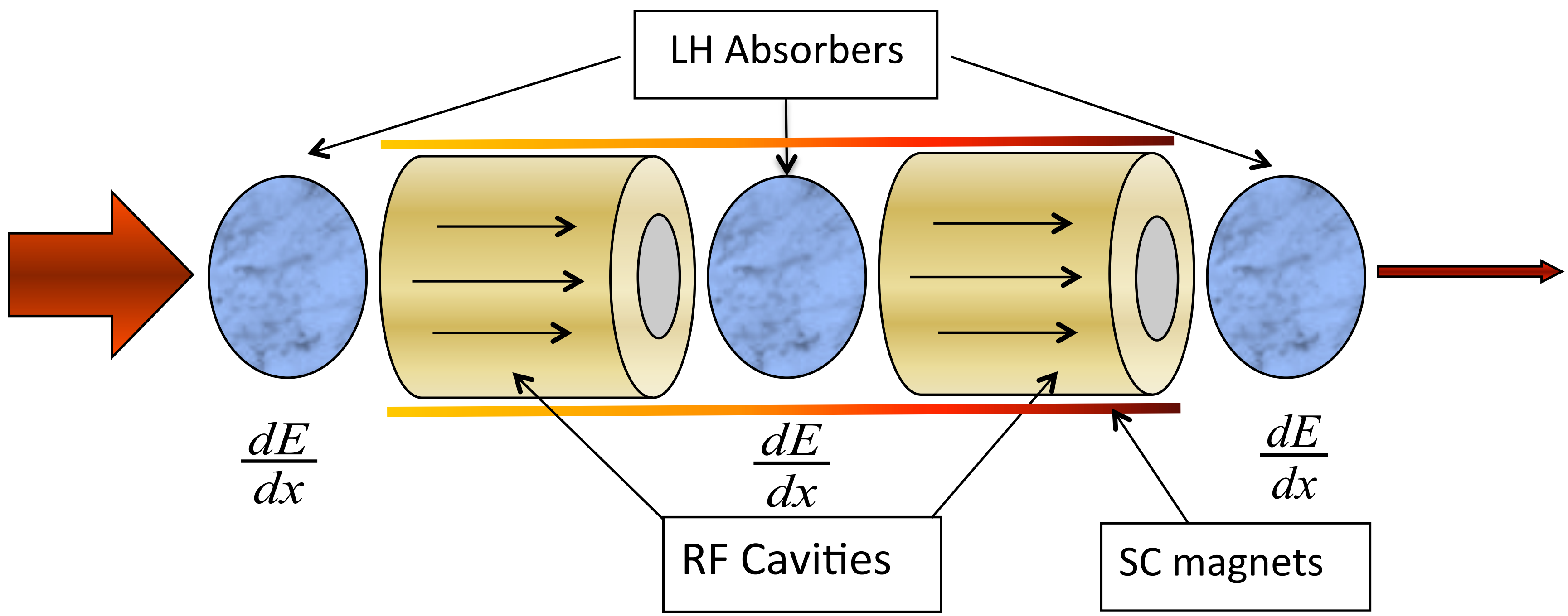
- ***Commissioning***
  - ✧ 1MW Target
  - ✧ No Cooling
  - ✧ 10kT Detector
- ***NuMAX+***
  - ✧ 2.75 MW Target
  - ✧ 6D Cooling
  - ✧ 34kT Detector

Summary: Advanced Concepts for Muon and Neutrino Sources

- Bright muon sources serve as the basis for the ultimate neutrino source capabilities
- A small and tightly focused effort to continue the design and simulation efforts warrants consideration in the GARD portfolio
  - Estimated effort in FY16: 8 FTEs
- This effort will also serve to ensure that plans maintained in a consistent fashion with the evolution of the Fermilab accelerator complex
  - Thus ensuring that a viable option to achieve these capabilities is preserved

Activity 2: RF in Magnetic Field R&D

- Muons have short lifetime (2.2 μs @ rest) and must be manipulated quickly
- High gradient RF cavities compensate for lost longitudinal energy in low Z absorbers
- Strong magnetic field to confine muon beams



RF Thrusts in MAP

- **Mission:**
  - Design, construction and testing of high gradient NCRF cavities and demonstrate their RF operation in strong magnetic field.
  - Goals:

    ~ 25 MV/m at 805 MHz @ 3T

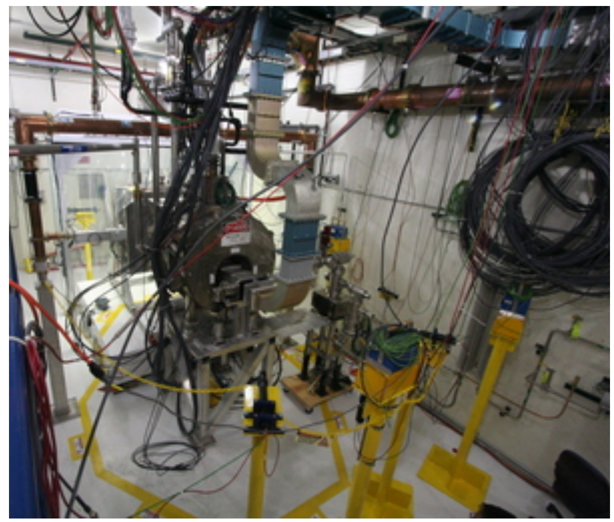
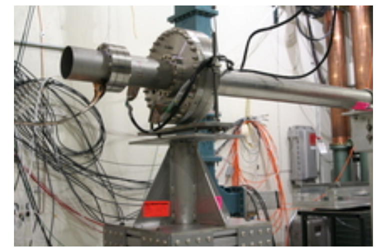
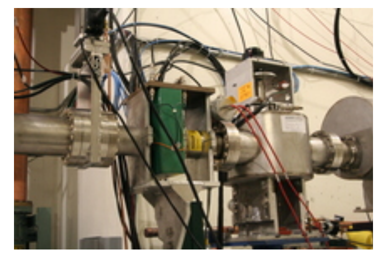
    ~ 16 MV/m at 201 MHz @ 3T
- **Thrusts:**
  - Vacuum RF cavity development
    - Utilize SCRF surface preparation
    - Detailed simulation to characterize performance-limiting issues in magnetic field
  - High Pressure gas RF cavity
    - Suppress the effects of dark current with HP H_2 gas
    - Using HP H_2 gas to cool muons
  - Support for the implementation of the MICE RF system

MuCool Test Area

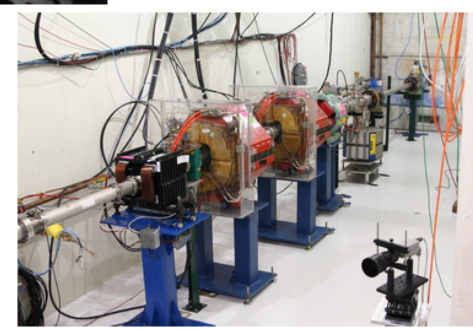
(http://mice.iit.edu/mta/)

- **Dedicated facility at the end of the Linac for MuCool R&D**
  - **RF power**
    - 12 MW @ 805 MHz
    - 4.5 MW @ 201 MHz
  - **Large-bore 5T SC solenoid**
    - Larger one (CC) on the way
  - **Cryogenic plant**
  - **400-MeV H^- beamline**
  - **Class-100 portable clean room**
  - **H_2 safety infrastructure**
  - **Extensive diagnostics**
- **Combination of capabilities unique in the world**
- **Well-matched to the proposed program**



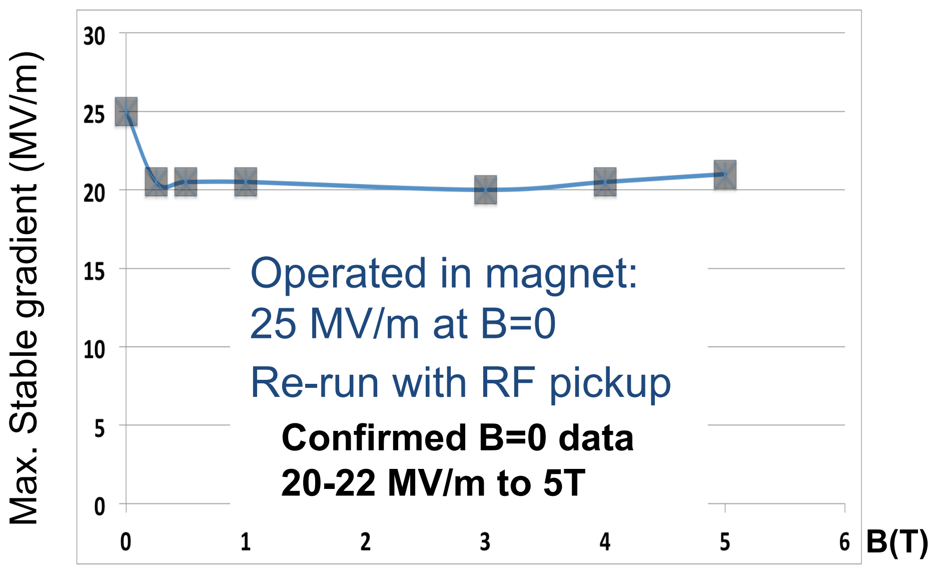


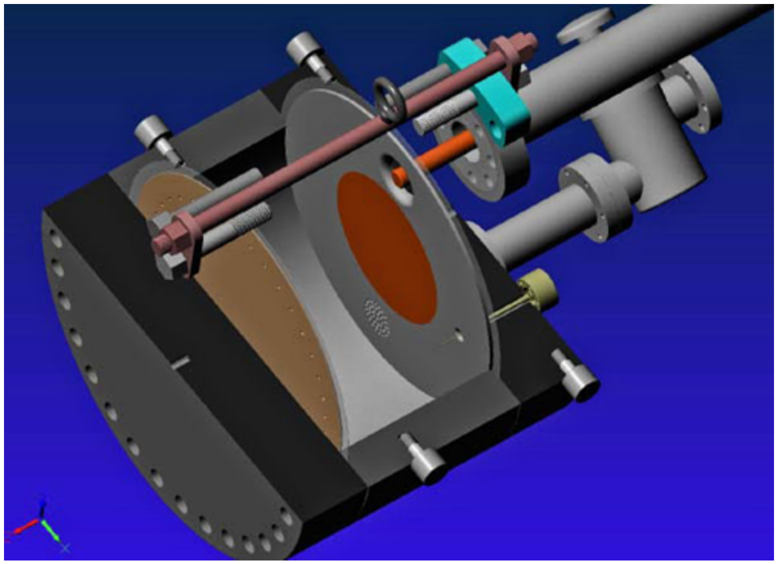


Recent Vacuum RF Cavity R&D Results

- Study a new structure: All Seasons Cavity (ASC)
  - Modular pillbox with replaceable endplates
    - Designed for both vacuum and high pressure
    - 316SS with 25-um Cu coating and 3.9/6.6/2.7-cm-thick center ring/outer/inner plates
  - Q ~ 28k, frequency 810.+ MHz and 1.2 MW @ 25 MV/m

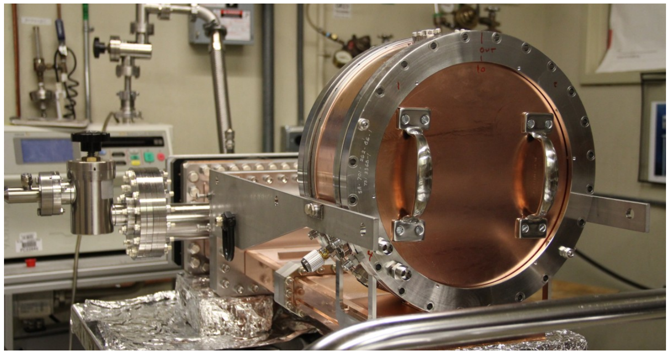
In contrast to tests with earlier cavities, the ASC performance is consistent with our basic physics model for cavity operation in magnetic fields

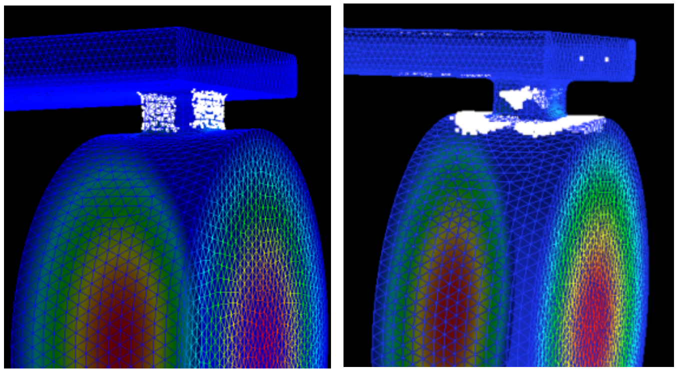




The Modular Cavity Design

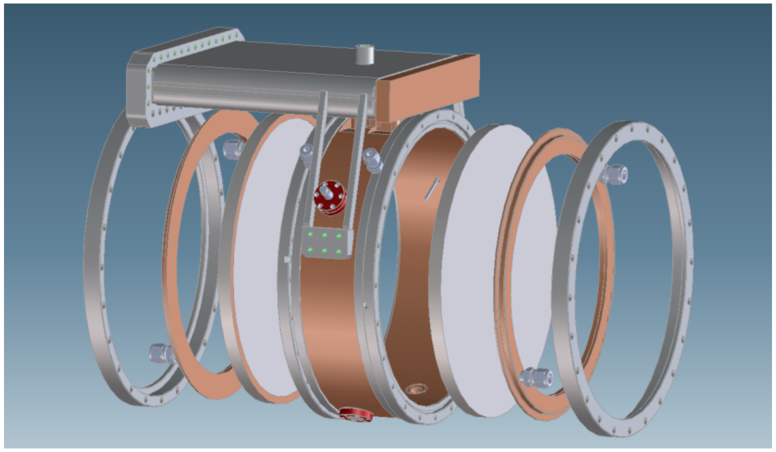
- Previous vacuum cavity experimental results limited by field emission/dark current at high peak field regions (coupling slot and iris)
  - Surface damage at coupling slot and beam iris regions
  - Contaminated coaxial & loop coupler/ceramic RF windows (201-MHz)
- Develop a **new** cavity to enable a systematic experimental study of the gradient-limiting and damage effects
  - Modular design for easy assembly, inspection, parts replacement
  - Replaceable endplates (vary materials and surface treatments)
  - Coupling iris moved to center ring and field reduced (*more realistic design for a cooling channel*)
  - RF design validated by detailed simulation
- ***Design incorporates all lessons learned***
- ***Ready to begin systematic test program***

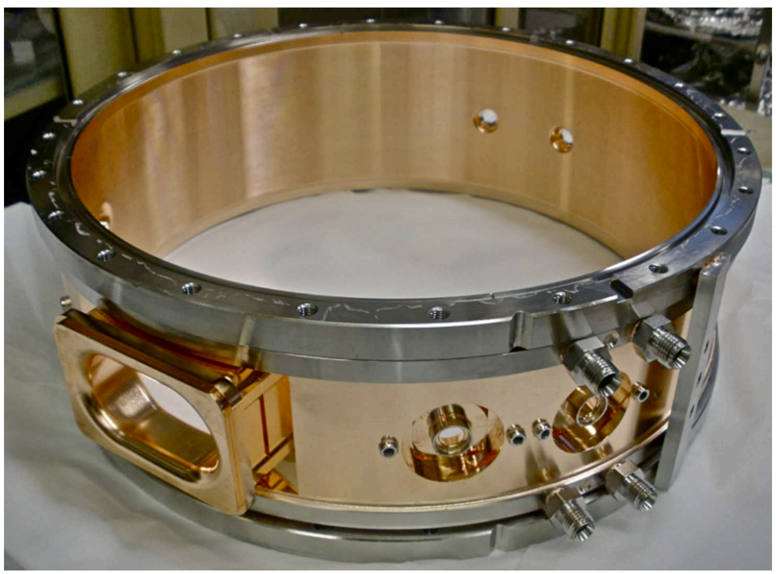


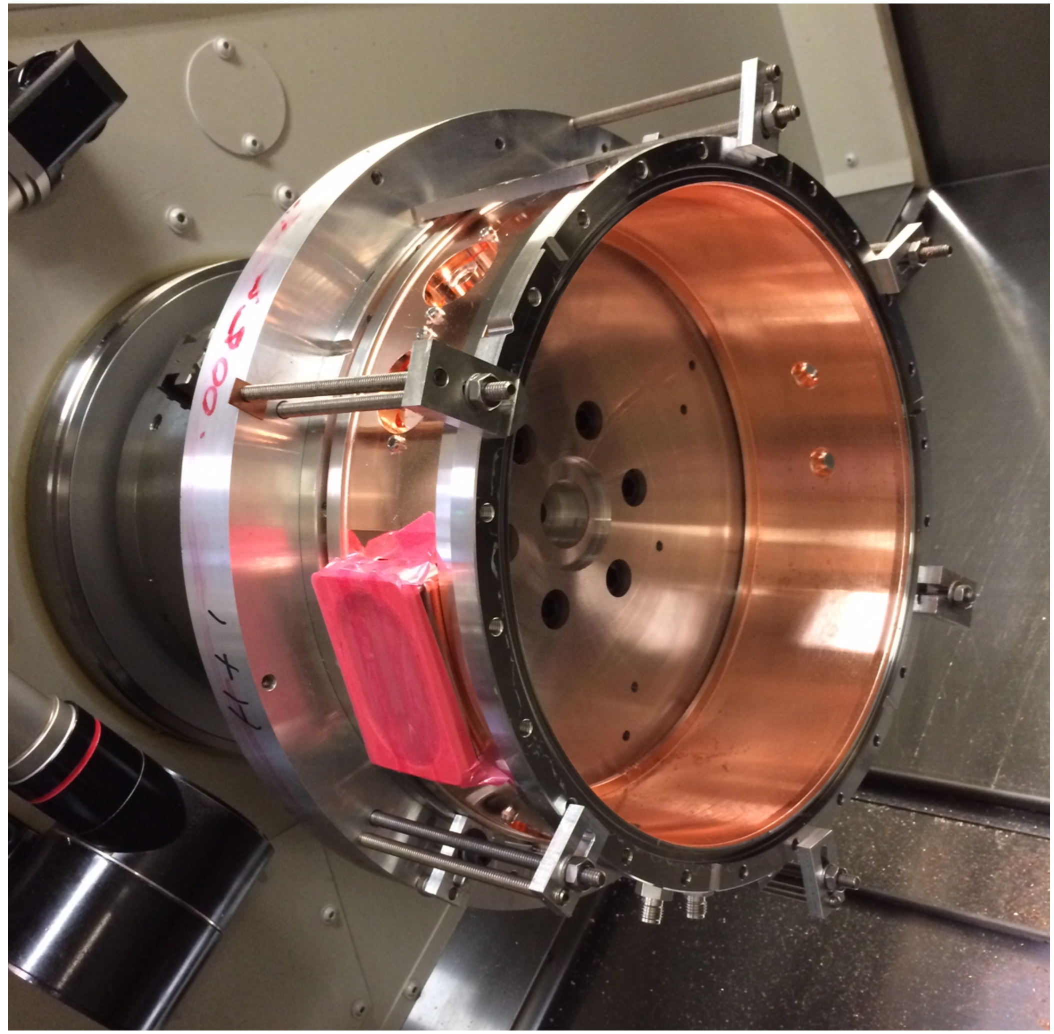


MP with & without external B field

Cavity Preparation at SLAC
[Now at FNAL being prepped for operation at the MTA]





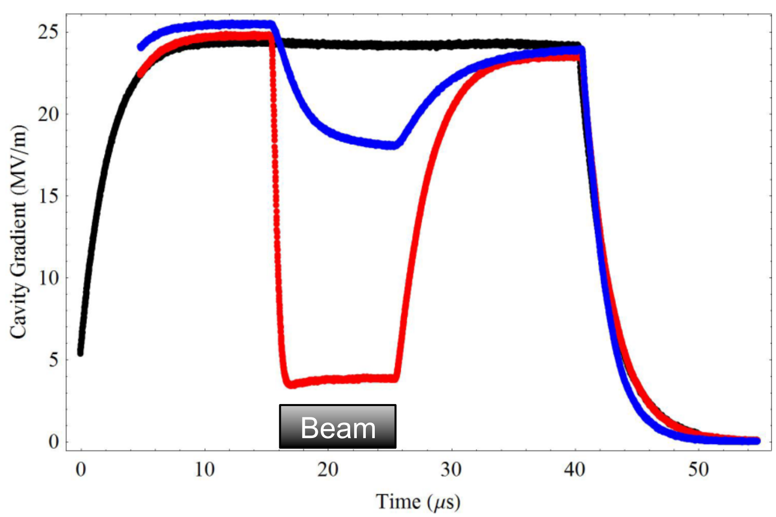


High Pressure H_2 Filled RF Cavity

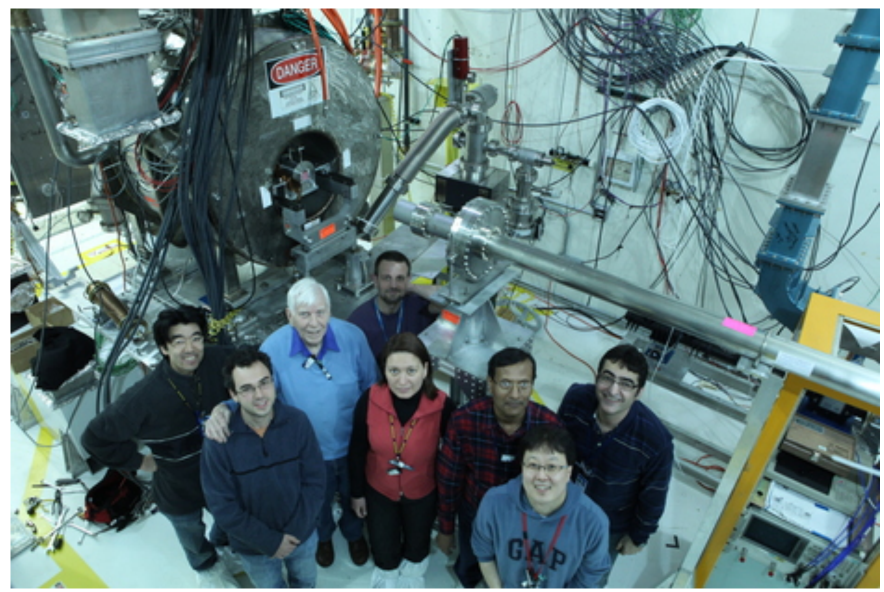
- **HPRF demonstrated a solution for RF in a strong magnetic field**
- Fundamental Question: *"What happens when intense beam passes through cavity?"*.
  - Beam testing at MTA and testing results published
    - M. Chung et al., ***PRL 111, 184802, 2013***
  - Quantitative theory validated by measurement of energy in H2/D2+dopant
  - Electronegative dopants turn mobile ionization electrons into heavy ions, reducing RF losses by large factor

Phys. Rev. Lett. 111, 184802 (2013) [5 pages]

Pressurized H_2 rf Cavities in Ionizing Beams and Magnetic Fields



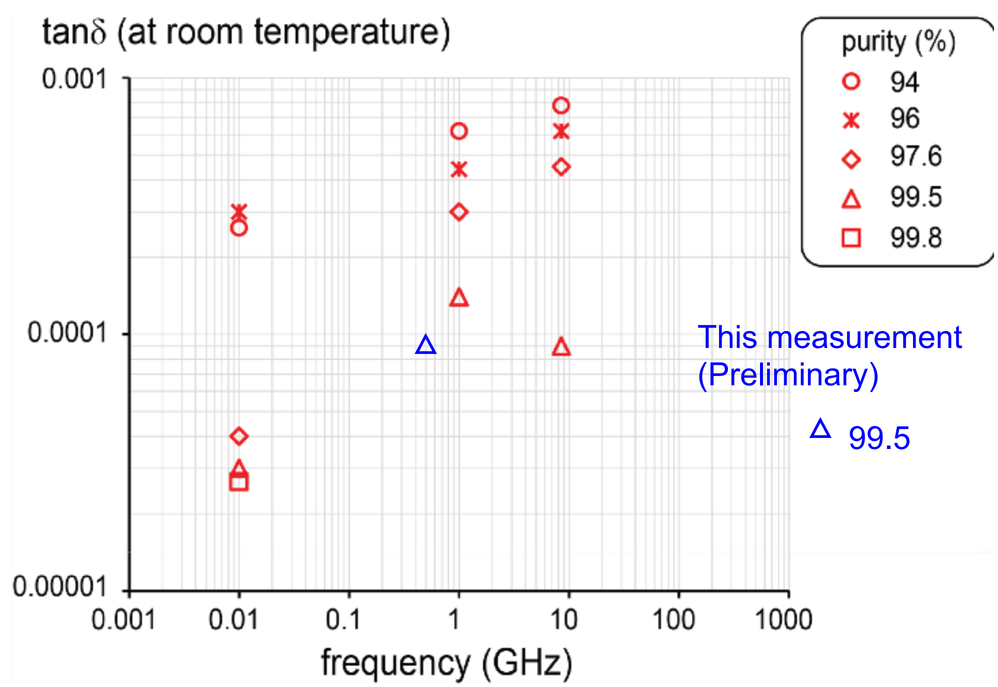
1470psi H_2 ⇨ w/beam ⇨ add 1% dry air



High Pressure H_2 Filled RF Cavity

- **We have demonstrated an ionization cooling solution using HPRF cavities**
- The results extrapolate well to Neutrino Factory operation (and to a range of MC beam parameters)
  - Includes beam-induced plasma loading of the RF system
  - Bunch intensity limits evaluated
- Compact dielectric-loaded HPRF cavity structures represent the next key step in development
  - Dielectric material tested up to equivalent of ~ 25 MV/m on axis acceleration gradient with 99.8 % Al2O3 (Alumina) (Dr. K. Yonehara)

New Test Result (FY14): Alumina



Summary: RF in Magnetic Field R&D

- Completing key elements of the MAP-developed experimental program in the MTA are key to enabling a future muon accelerator capability ⇨ NF option as noted by P5

- Furthermore these studies will expand our fundamental understanding of breakdown behaviors in RF cavities
  - Important fundamental knowledge for accelerator physics

- Taking the present opportunity to leverage the investment in capabilities that has been made in the MTA would be a wise GARD investment
  - Estimated FY16 Effort: ~10 FTEs
  - Re-constituting the full range of MTA capabilities non-trivial if abandoned
  - Critical results achievable on the 2-3 year timescale

Conclusion

- With the recent P5 recommendations, the US HEP program is focused on the delivery of long- and short-baseline neutrino oscillation capabilities
- Enabling the precise and accurate measurements required for a long-term future likely rests on the development of muon accelerator capabilities
- The two activities that we have proposed for inclusion in the GARD portfolio starting in FY16 both represent enabling research to be able to deploy those capabilities when required
  - Recommendation from August 12-14, 2014 DOE Review: *"Move forward with Non-MICE MAP activities according to normal DOE R&D guidelines within the advanced concepts activities of GARD."*

[Also see the supporting materials uploaded along with this talk]