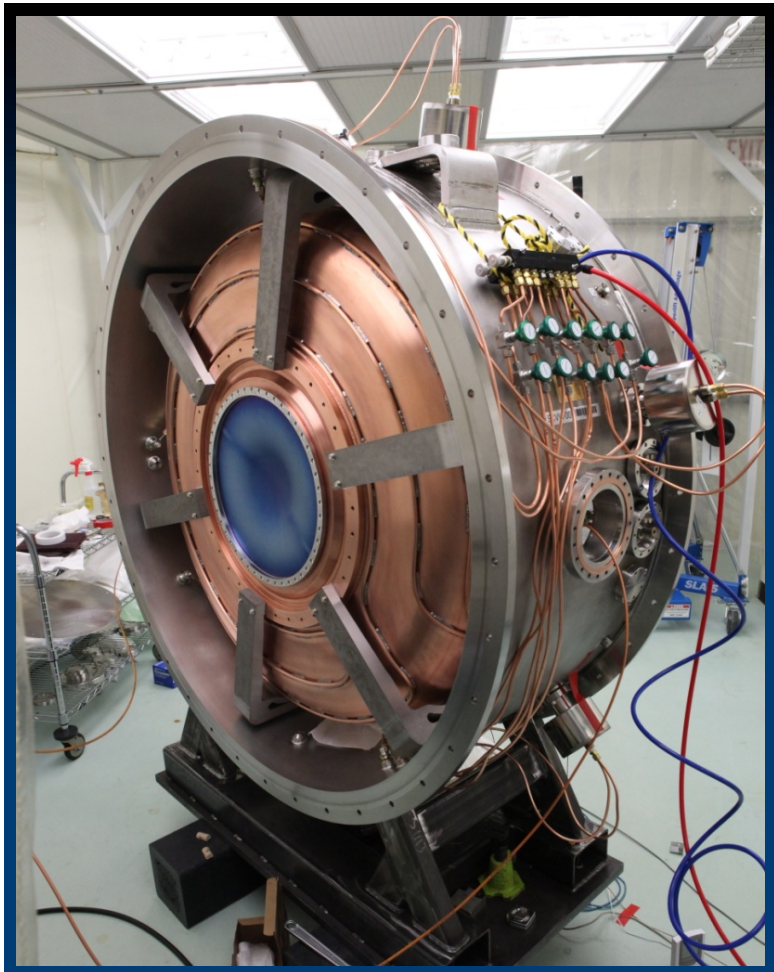


Muon Accelerator R&D Opportunities

Mark Palmer

ICFA Neutrino Panel Mini-Workshop, FNAL

January 30-31, 2014

Fermilab

Introduction and Context

The US Muon Accelerator Program (MAP) is one of two DOE HEP Facilities R&D efforts

- The other is LARP
- Both are *directed* **accelerator R&D** efforts
  ⇨ next generation capabilities for deployment at existing HEP facilities

MAP's focus is on the R&D required to demonstrate feasibility of muon accelerators for HEP applications

- Neutrino Factories (NF) on the Intensity Frontier
  - Both long and short baseline
- Muon Colliders (MC) on the Energy Frontier
  - Higgs Factory to multi-TeV

The two Muon Accelerator capabilities are strongly linked

- With key synergies that can be exploited to control technical risk and cost
- A unique breadth of physics that can be supported

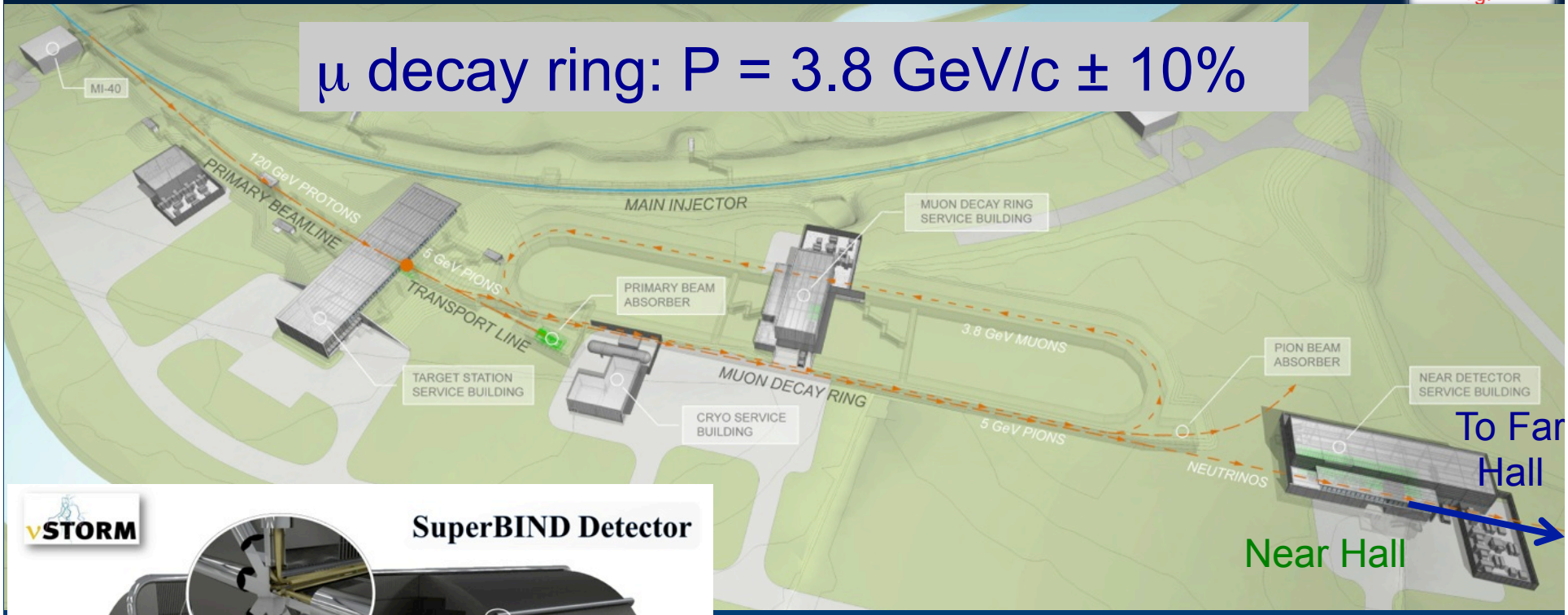
Physics Case for the Neutrino Factory

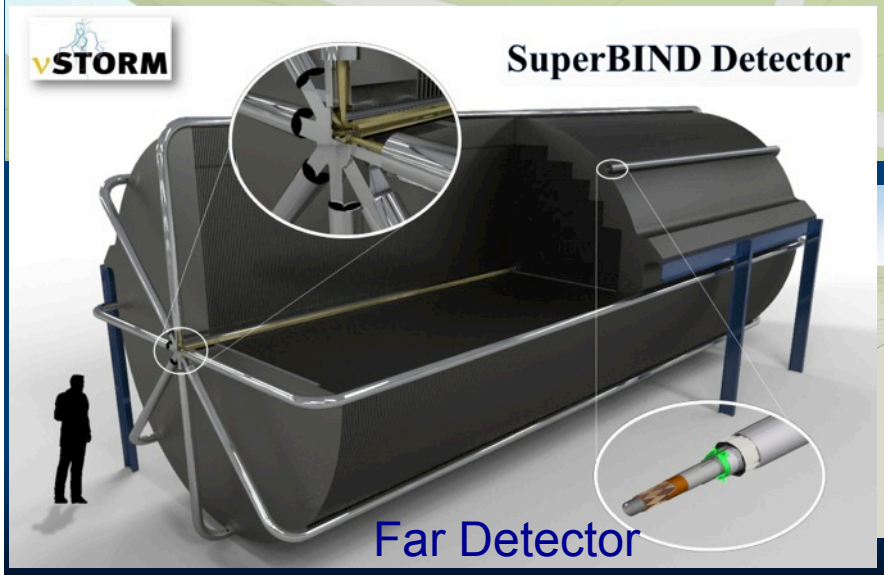
- Short Baseline Neutrino Factory
  - nuSTORM
    - Definitive measurement of sterile neutrinos
    - Precision ν_e cross-section measurements (systematics issue for long baseline SuperBeam experiments)
    - Would serve as an HEP muon accelerator proving ground…

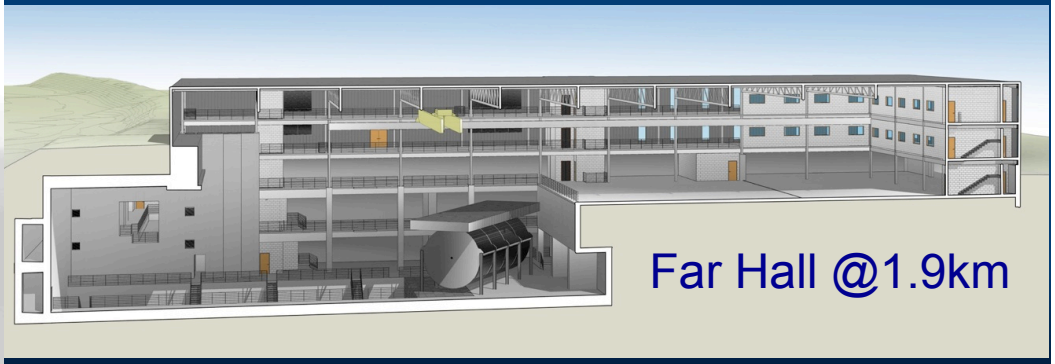
- Long Baseline Neutrino Factory with a Magnetized Detector
  - IDS-NF (International Design Study for a Neutrino Factory)
    - 10 GeV muon storage ring optimized for 1500-2500km baselines
    - "Generic" design (ie, not site-specific)
  - NuMAX (Neutrinos from a Muon Accelerator CompleX)
    - Site-specific: FNAL ⇨ SURF (1300km baseline)
    - 4-6 GeV beam energy
    - Can provide an ongoing short baseline measurement option
    - Detector options
      - Magnetized LAr is the goal
      - Magnetized iron provides equivalent CP sensitivities using ~3x the mass
  - Both options provide a route to high precision measurements in the ν sector with very well understood systematics

⇨ The advantage of high intensity "precision beams"

νSTORM





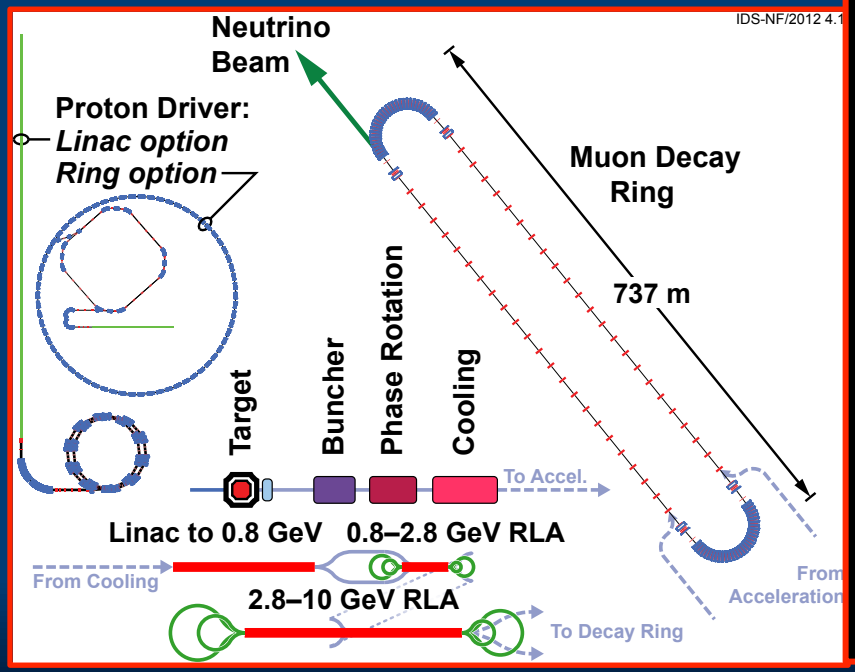


Fermilab

The Neutrino Factory

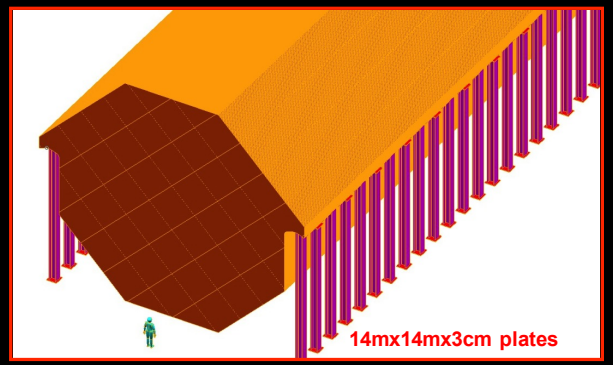
- IDS-NF: the *ideal* NF
  - Supported by MAP
- MASS working group
  ⇨ a staged approach

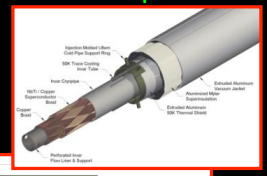
	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to long-baseline neutrino detector	1 500–2 500 km

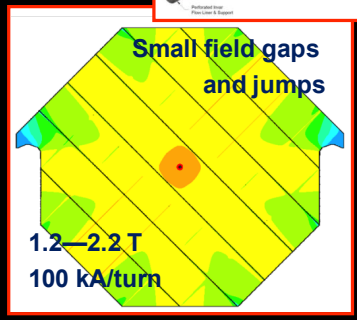


Magnetized Iron Neutrino Detector (MIND):

- IDS-NF baseline:
  - Intermediate baseline detector:
    - 100 kton at 2500—5000 km
  - Magic baseline detector:
    - 50 kton at 7000—8000 km
  - Appearance of "wrong-sign" muons
  - Toroidal magnetic field > 1 T
    - Excited with "superconducting transmission line"
  - Segmentation: 3 cm Fe + 2 cm scintillator
  - 50-100 m long
  - Octagonal shape
  - Welded double-sheet
    - Width 2m; 3mm slots between plates







Bross, Soler

The Muon Accelerator Staging Study (MASS)

MAP working group charged with:

- Developing a realistic staging plan for a muon accelerator facility
- Examining synergies and optimizations for a facility that could support both NF and MC capabilities
  ⇨ new design approaches
- Identifying critical R&D demonstrations that are required

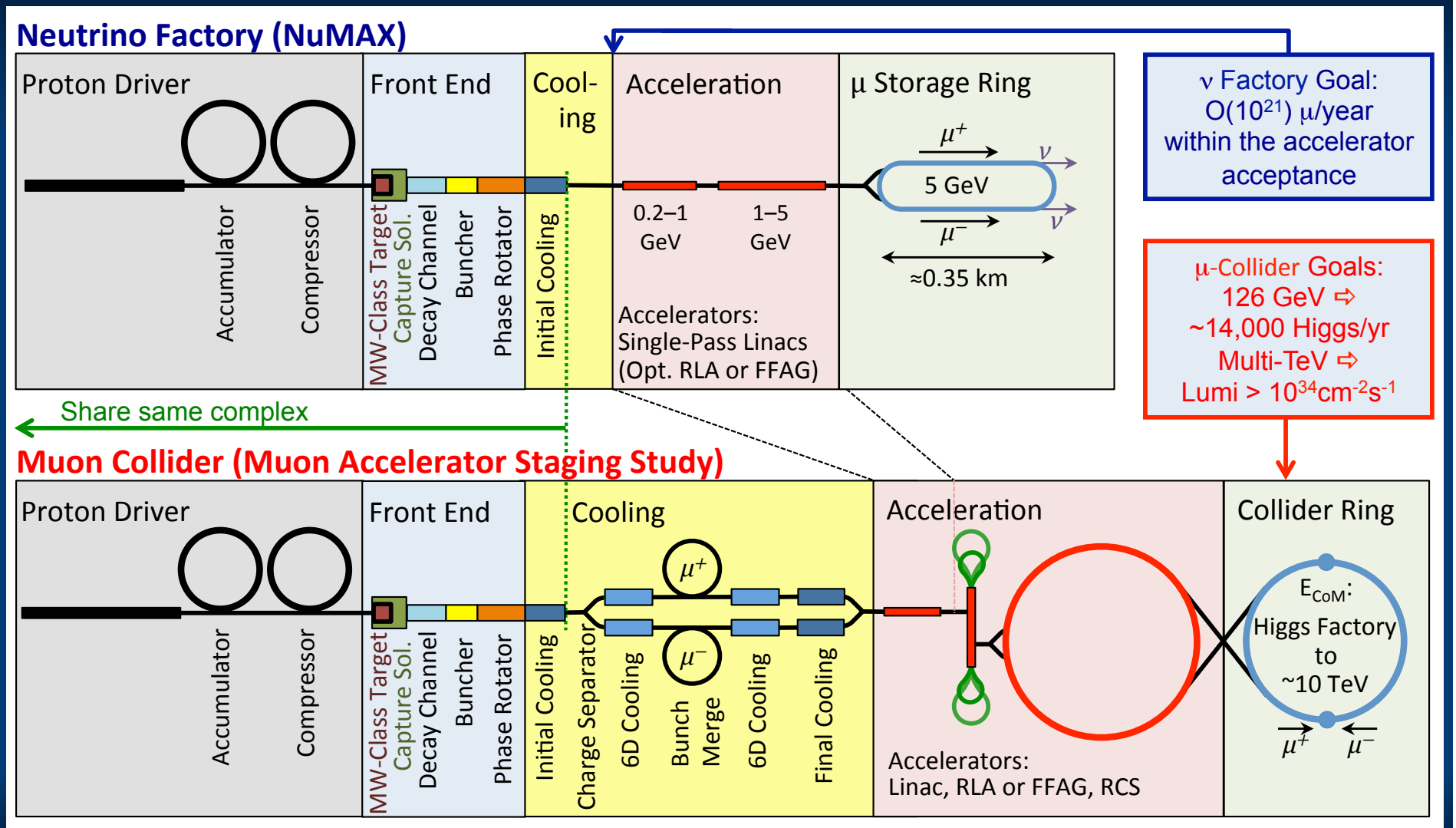
MASS Contribution to Snowmass

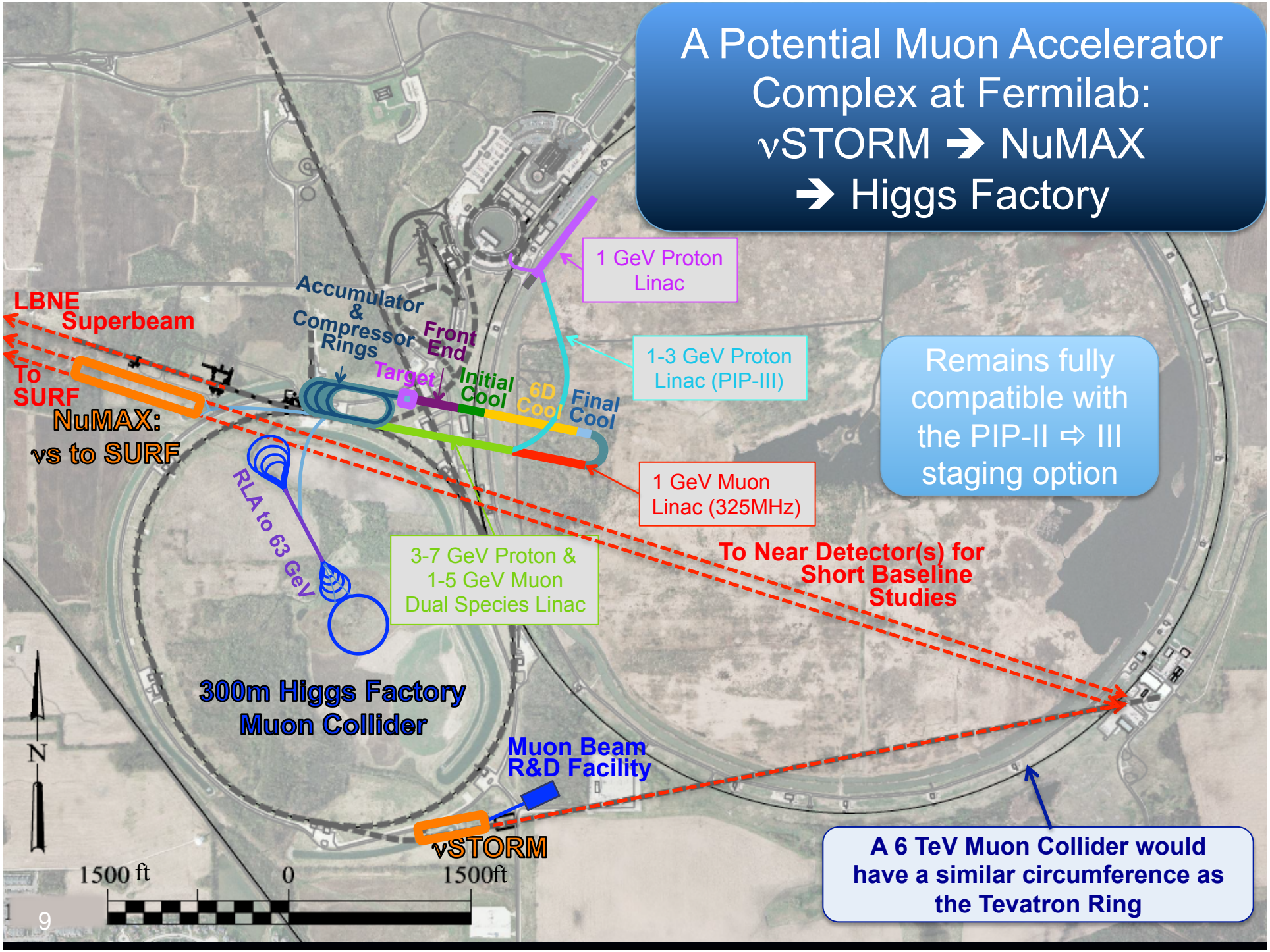
Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the US - http://arxiv.org/pdf/1308.0494

The plan consists of a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach:

- nuSTORM: a short-baseline Neutrino Factory-like ring enabling a definitive search for sterile neutrinos, as well as neutrino cross-section measurements that will ultimately be required for precision measurements at any long-baseline experiment.
- NuMAX: an initial long-baseline Neutrino Factory, optimized for a detector at SURF, affording a precise and well-characterized neutrino source that exceeds the capabilities of conventional superbeam technology.
- NuMAX+: a full-intensity Neutrino Factory, upgraded from NuMAX, as the ultimate source to enable precision CP-violation measurements in the neutrino sector.
- Higgs Factory: a collider whose baseline configurations are capable of providing between 3500 (during startup operations) and 13,500 Higgs events per year (10^7 sec) with exquisite energy resolution.
- Multi-TeV Collider: if warranted by LHC results, a multi-TeV Muon Collider likely offers the best performance and least cost for any lepton collider operating in the multi-TeV regime.

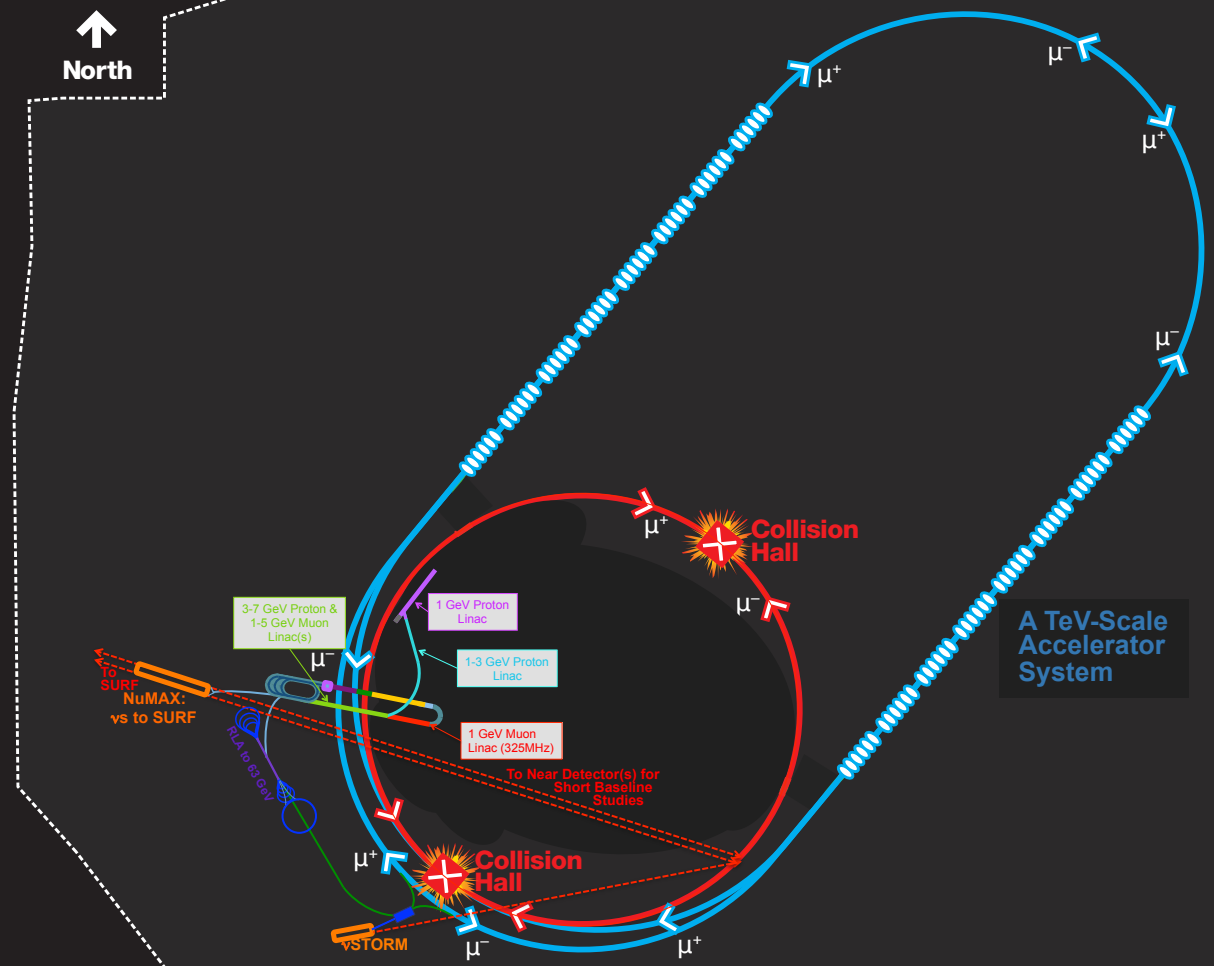
MC/NF Synergies




A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory
1 GeV Proton Linac
1-3 GeV Proton Linac (PIP-III)
Remains fully compatible with the PIP-II ⇨ III staging option
1 GeV Muon Linac (325MHz)
3-7 GeV Proton & 1-5 GeV Muon Dual Species Linac
RLA to 63 GeV
Accumulator & Compressor Rings
Front End
Target
Initial Cool
6D Cool
Final Cool
LBNE Superbeam
To SURF
NuMAX: νs to SURF
To Near Detector(s) for Short Baseline Studies
300m Higgs Factory Muon Collider
Muon Beam R&D Facility
νSTORM
A 6 TeV Muon Collider would have a similar circumference as the Tevatron Ring
N
1500 ft
0
1500ft

A Potential Muon Accelerator Complex at Fermilab:

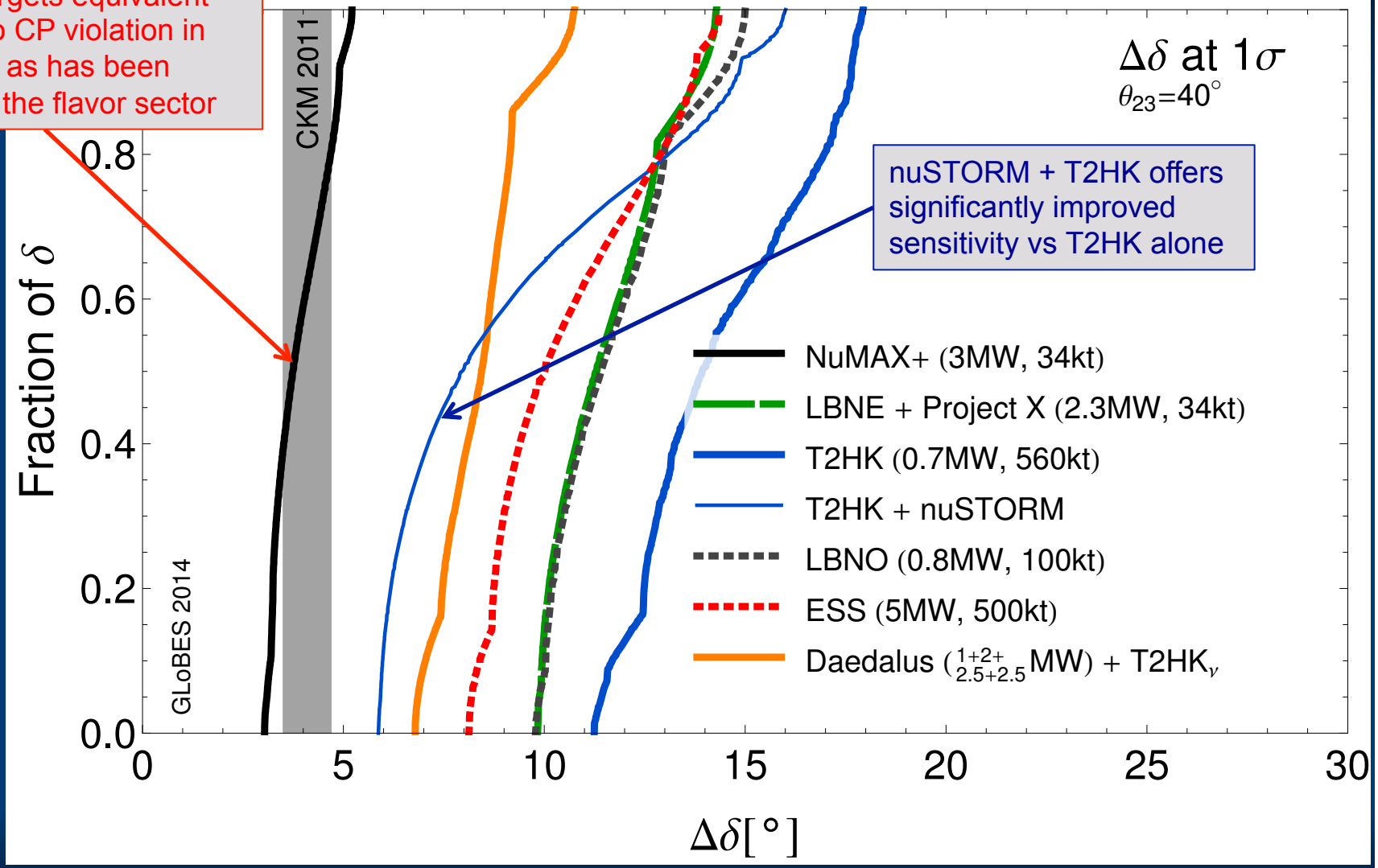
➔ Multi-TeV Collider



CP Violation Sensitivity

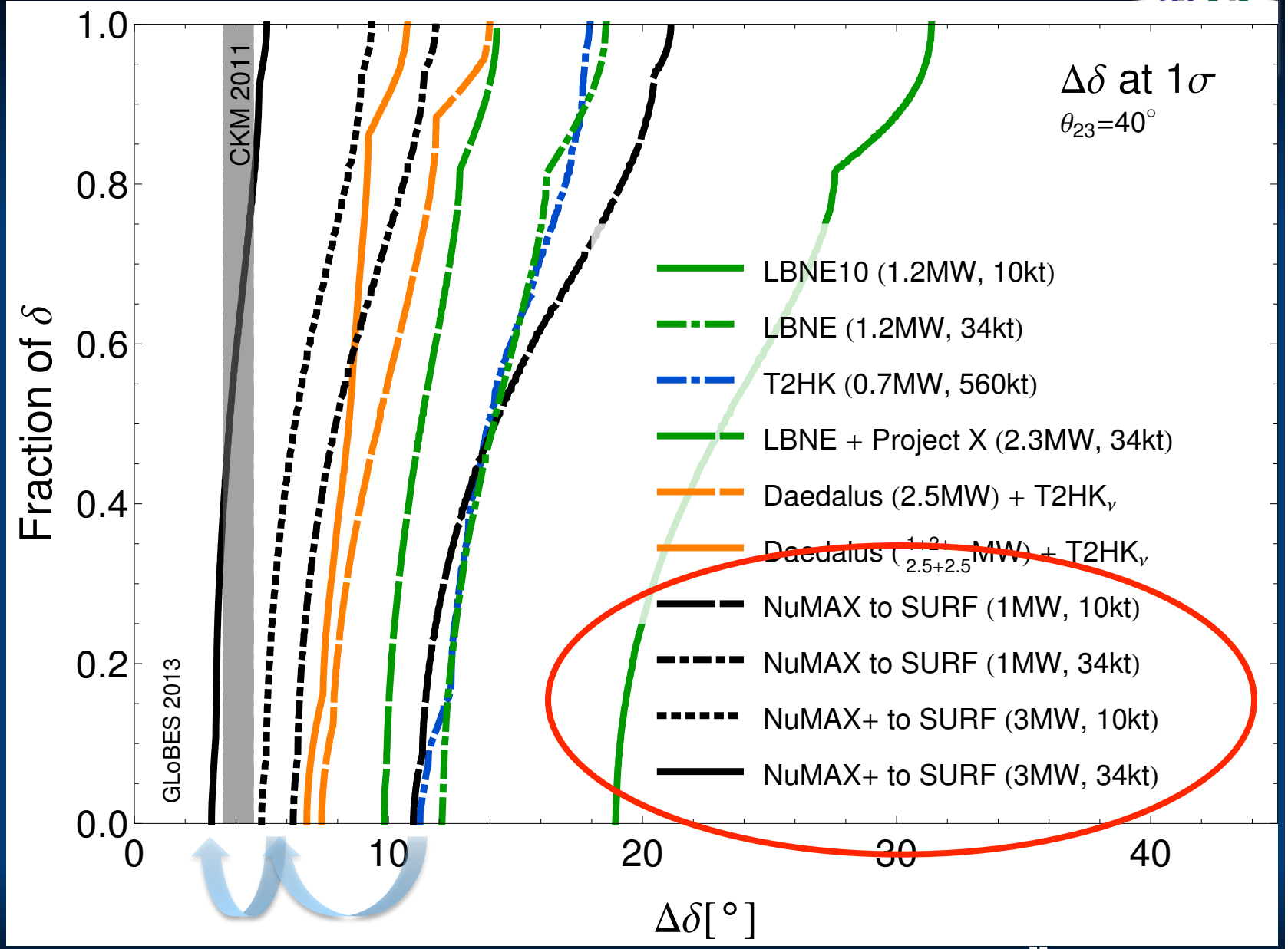
NuMAX+ targets equivalent sensitivity to CP violation in the ν sector as has been achieved in the flavor sector

GLoBES Comparison of Potential Performance of the Various Advanced Concepts (*courtesy P. Huber*)



A Staged Plan with NuMAX at Fermilab

GLoBES Comparison of Potential Performance of the Various Advanced Concepts *(courtesy P. Huber)*



NF Staging (MASS) for Snowmass

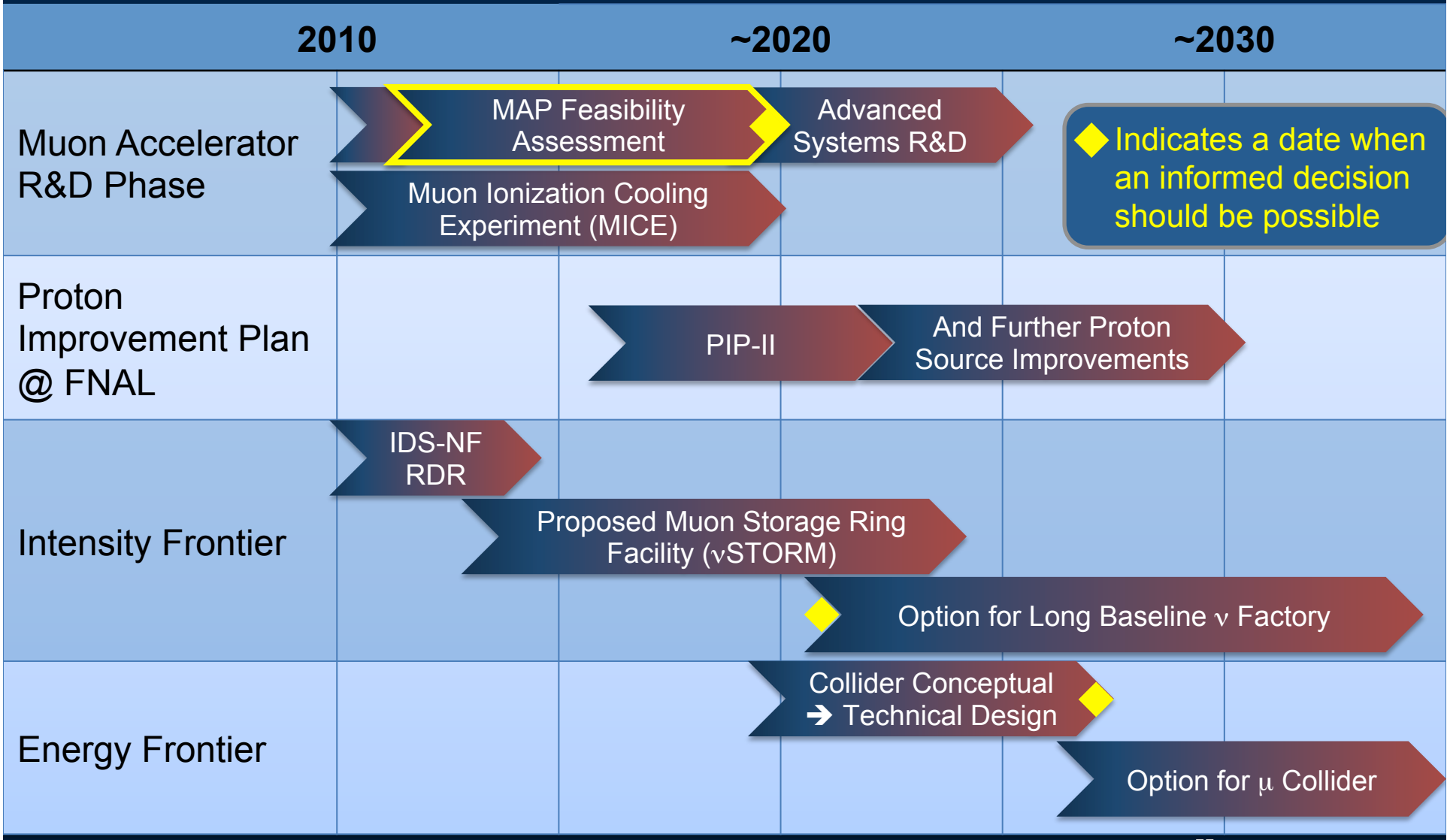
Preliminary Staging Plan Based on PIP-III Project X Stage 2

System	Parameters	Unit	nuSTORM	NuMAX	NuMAX+	IDS-NF
Perfor-mance	Stored μ+ or μ-/year		8×10^{17}	2×10^{20}	1.2×10^{21}	1×10^{21}
	ν_e or ν_μ to detectors/yr		3×10^{17}	8×10^{19}	5×10^{20}	5×10^{20}
Detector	***Far Detector:***	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND
	Distance from Ring	km	1.9	1300	1300	2000
	Mass	kT	1.3	30 / 10	100 / 30	100
	Magnetic Field	T	2	0.5-2	0.5-2	1-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	2.7	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	**Ring Momentum (P_μ)**	GeV/c	3.8	5	5	10
	Circumference (C)	m	480	600	600	1190
	Straight section	m	185	235	235	470
	Arc Length	m	50	65	65	125
Acceleration	**Initial Momentum**	GeV/c	-	0.22	0.22	0.22
	Single-pass Linac	GeV/pass	-	0.95	0.95	0.56
		MHz	-	325	325	201
	4.5-pass RLA **RLA I**	GeV/pass	-	0.85	0.85	0.45
		MHz	-	325	325	201
	RLA II	GeV/pass	-	-	-	1.6
		MHz	-	-	-	201
Cooling			No	No	4D	4D
Proton Source	**Proton Beam Power**	MW	0.2	1	3	4
	Proton Beam Energy	GeV	120	3	3	10
	Protons/year	1×10^{21}	0.1	41	125	25
	Repetition Frequency	Hz	0.75	70	70	50

6D

For reference

MAP Timeline ⇨ Provide Informed Decision Points



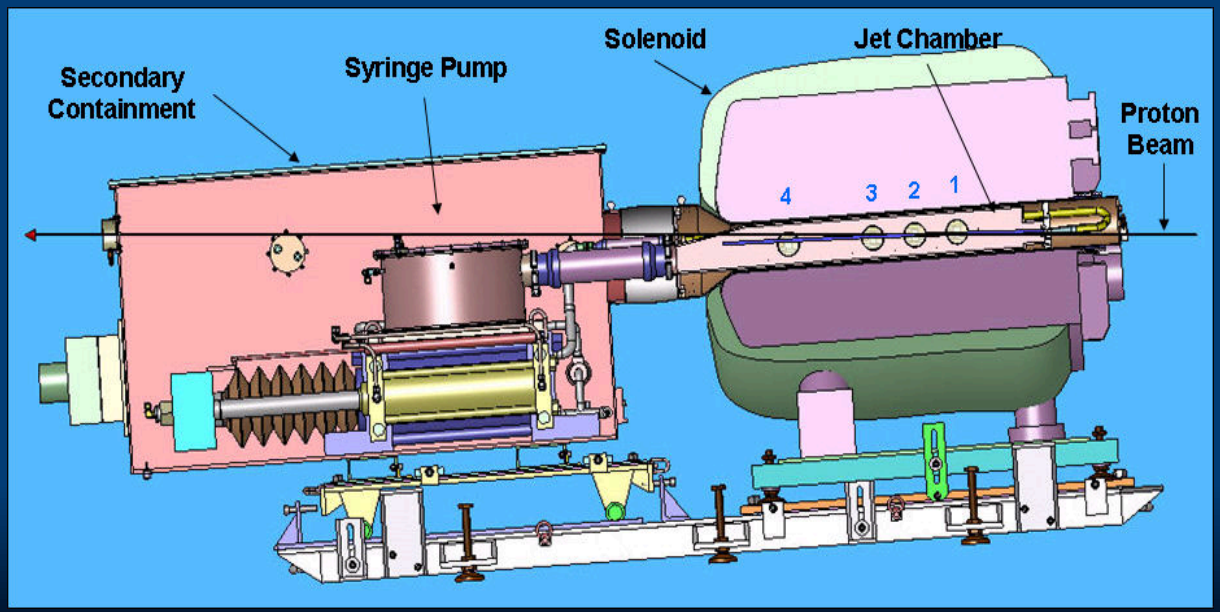
MAP R&D EFFORTS

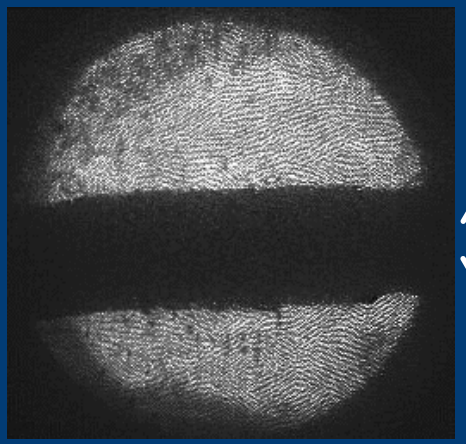
R&D Effort

- Scope of the MAP Feasibility Assessment:
  - Provide:
    - Specifications for all required technologies
    - Baseline design concepts for each accelerator system
  - For novel technologies:
    - Carry out the necessary design effort and R&D to assess feasibility
    - Note: a program of advanced systems R&D is anticipated ***after*** completion of the feasibility assessment
  - Ongoing Technology R&D and feasibility demonstrations include:
    - MuCool Test Area experimental program (FNAL): RF in high magnetic fields
    - The Muon Ionization Cooling Experiment (MICE@RAL):
      - Demonstration of emittance reduction
      - Validation of cooling channel codes
    - Advanced magnet R&D
      - Very high field magnets (cooling channel and storage rings)
      - Rapid cycling magnets for acceleration of short-lived beams

Key Technologies - Target

- The MERIT Experiment (2007@CERN PS)
  - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!
    - ⇨ Jets could operate with beam powers up to **8 MW** with a repetition rate of 70 Hz
- MAP staging aimed at initial 1 MW target capability (carbon)





Hg jet in a 15 T solenoid with measured disruption length ~ 28 cm

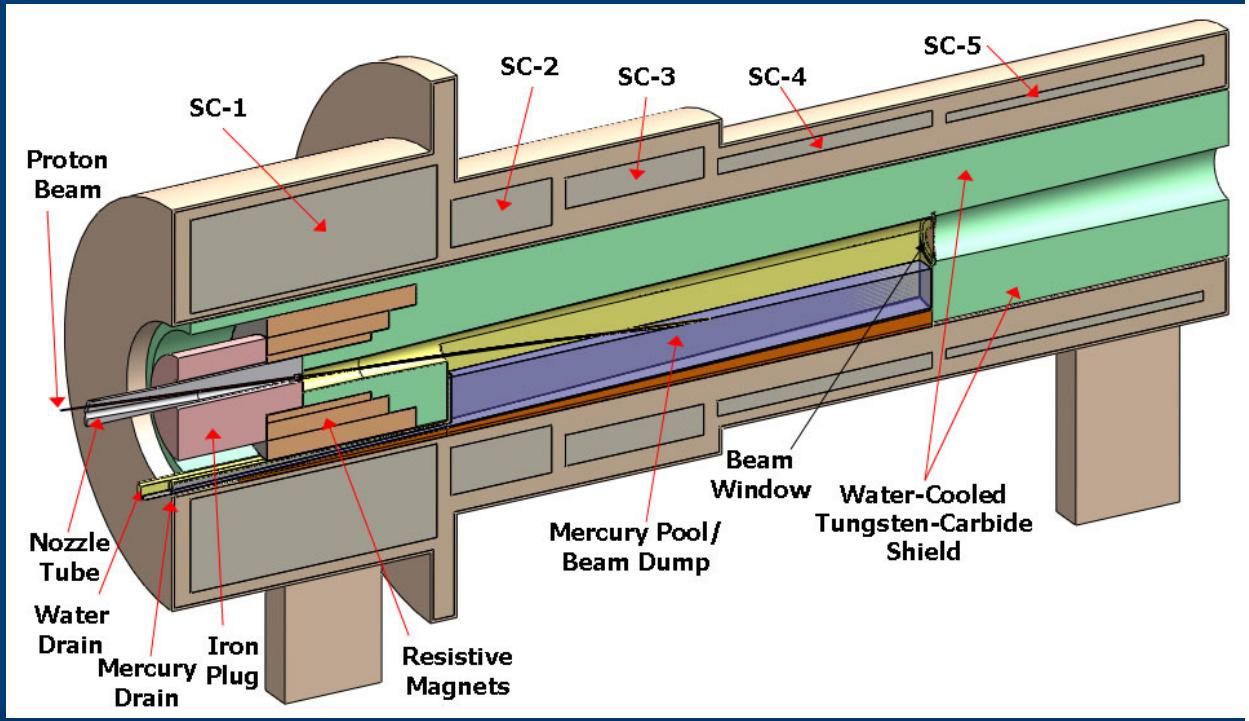
Technology Challenges – Capture Solenoid

- A Neutrino Factory and/or Muon Collider Facility requires challenging magnet design in several areas:
  - Target Capture Solenoid (15-20T with large aperture)

E_{stored} ~ 3 GJ

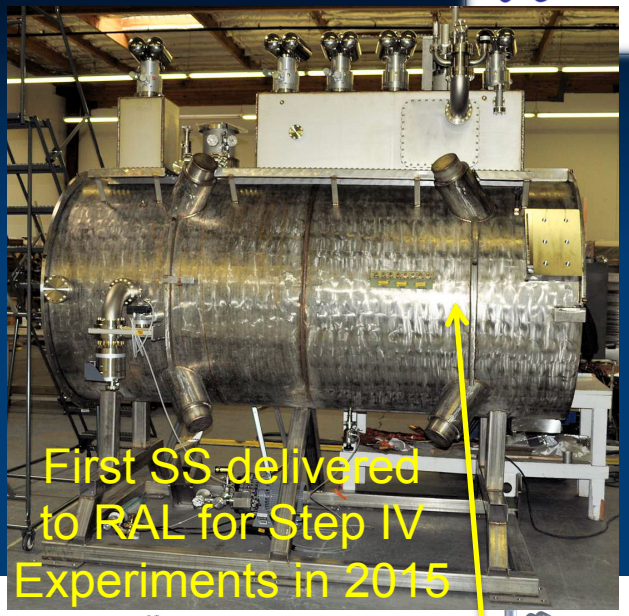
O(10MW) resistive coil in high radiation environment

Possible application for High Temperature Superconducting magnet technology

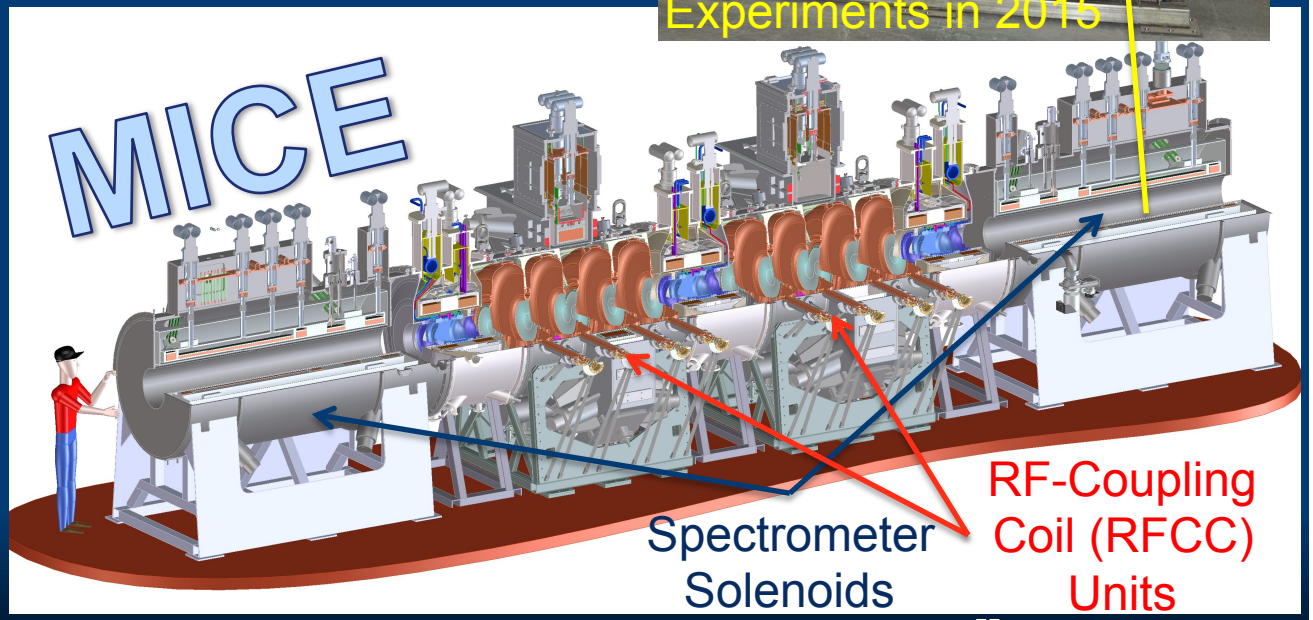


Technology Challenges - Cooling

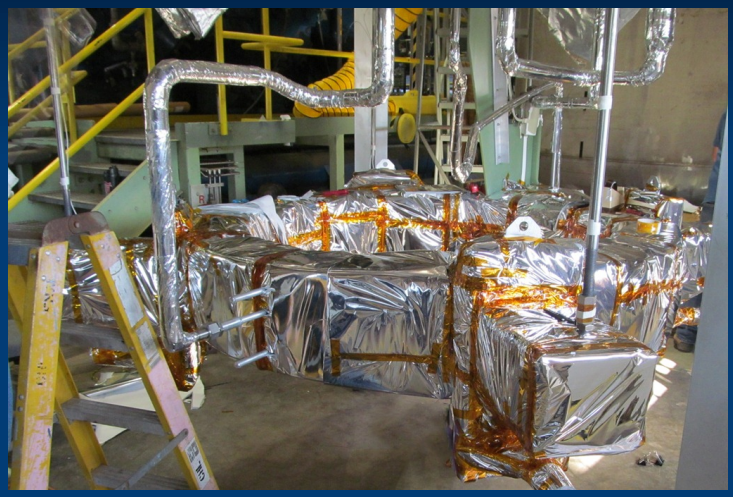
- Tertiary production of muon beams
  - Initial beam emittance intrinsically large
  - Cooling mechanism required, but no radiation damping
- Muon Cooling ⇨ Ionization Cooling
  - dE/dx energy loss in materials
  - RF to replace p_{long}

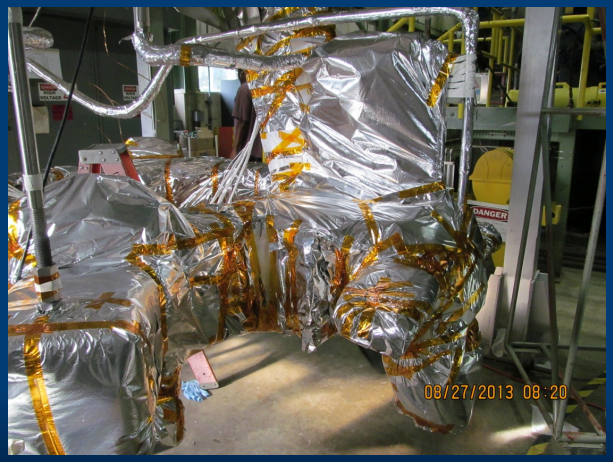


The Muon Ionization Cooling Experiment: Demonstrate the method and validate our simulations



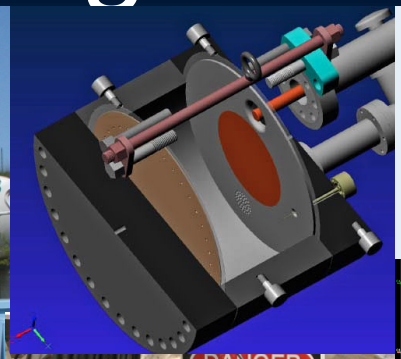
MICE CC Cold Mass 1 at the STF (FNAL)



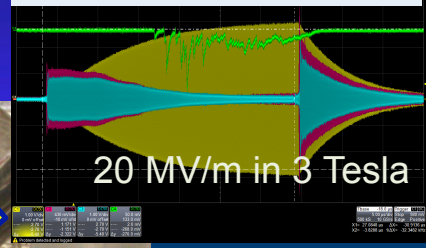


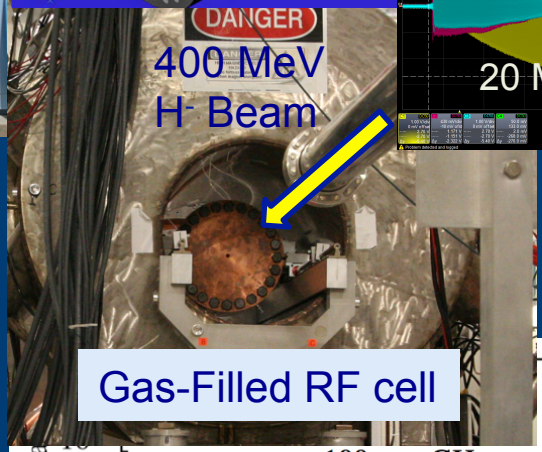
The RF R&D Program

MuCool Test Area

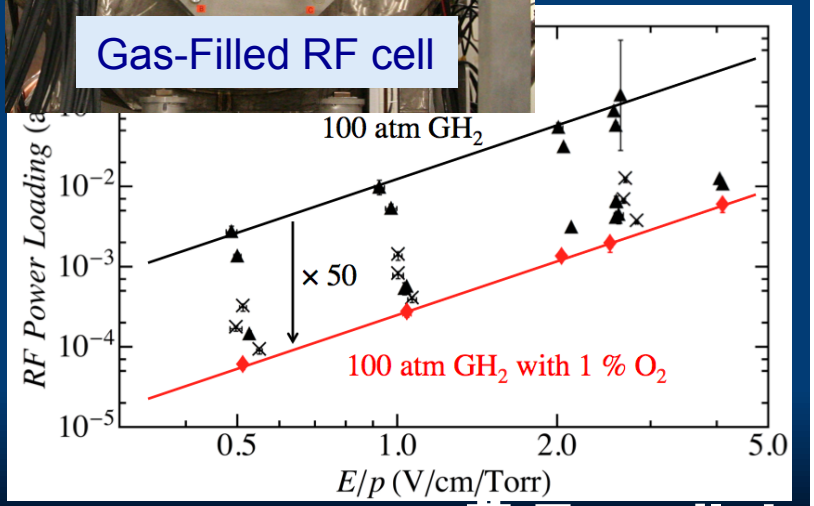


Vacuum RF Cavity – now operational in 5T B-field

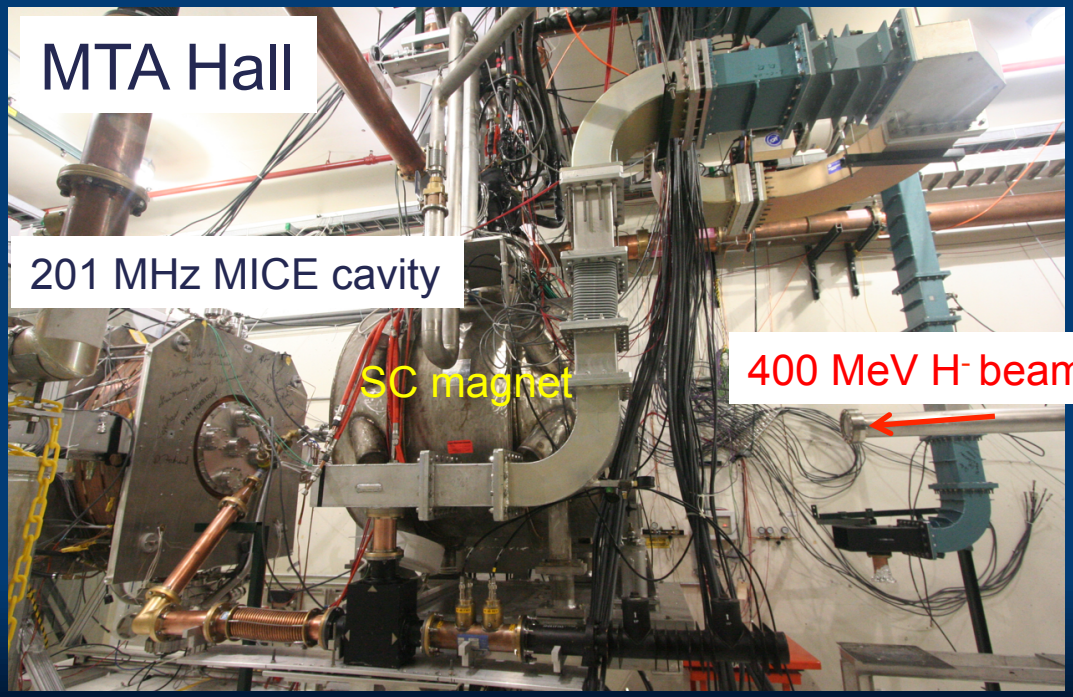




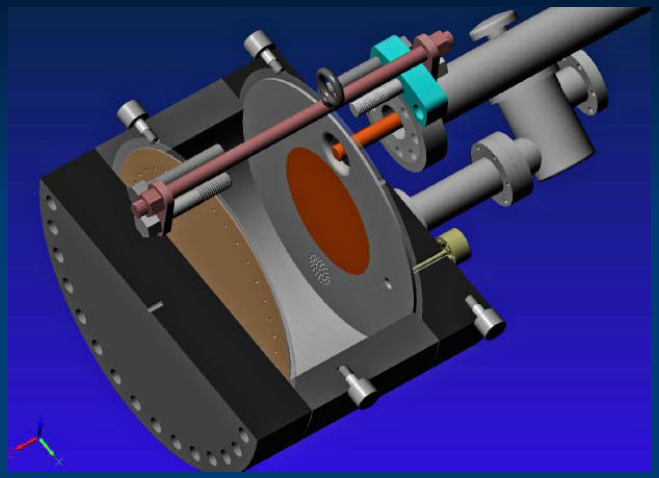
Gas-Filled RF cell



MTA Hall

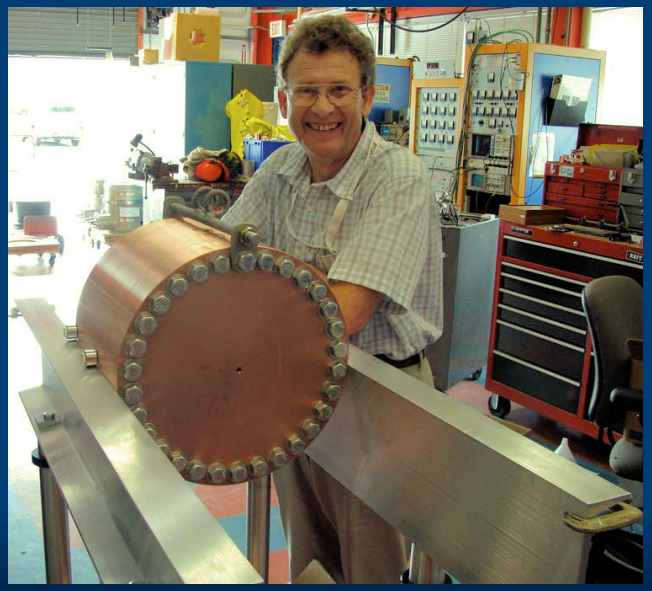


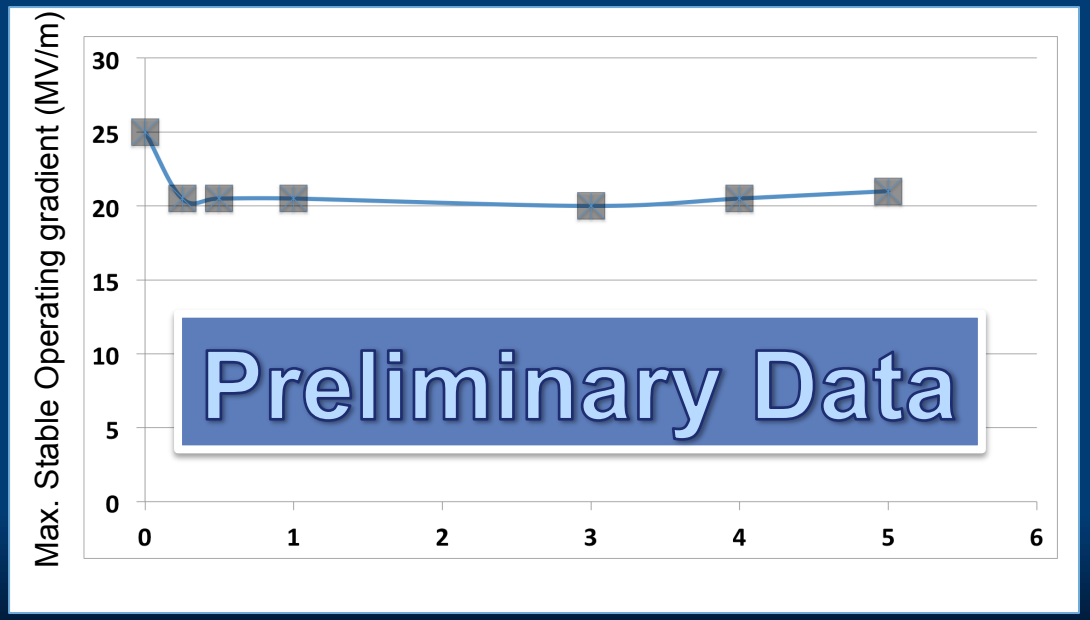
Recent Progress – Vacuum RF



All Seasons Cavity
(designed for both vacuum and high pressure operation)

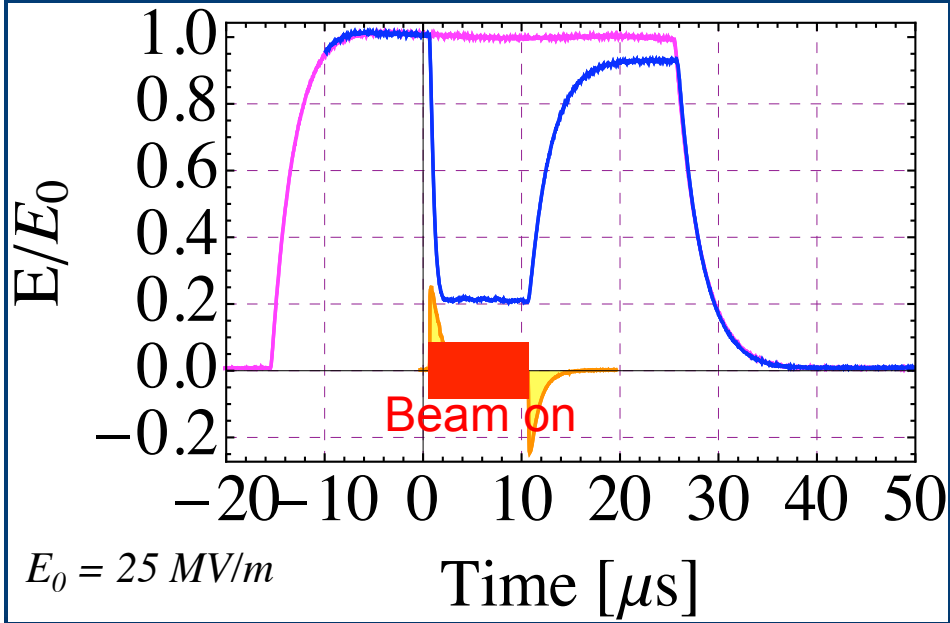
- Now operated in magnetic fields up to 5T:
  - Gradients > 20 MV/m
- Demonstrates possibility of successful operation of vacuum cavities in magnetic fields with careful design
- Successor design (the *805 MHz Modular Cavity*) will be ready for testing during FY14
- *Also progress on alternative cavity materials*

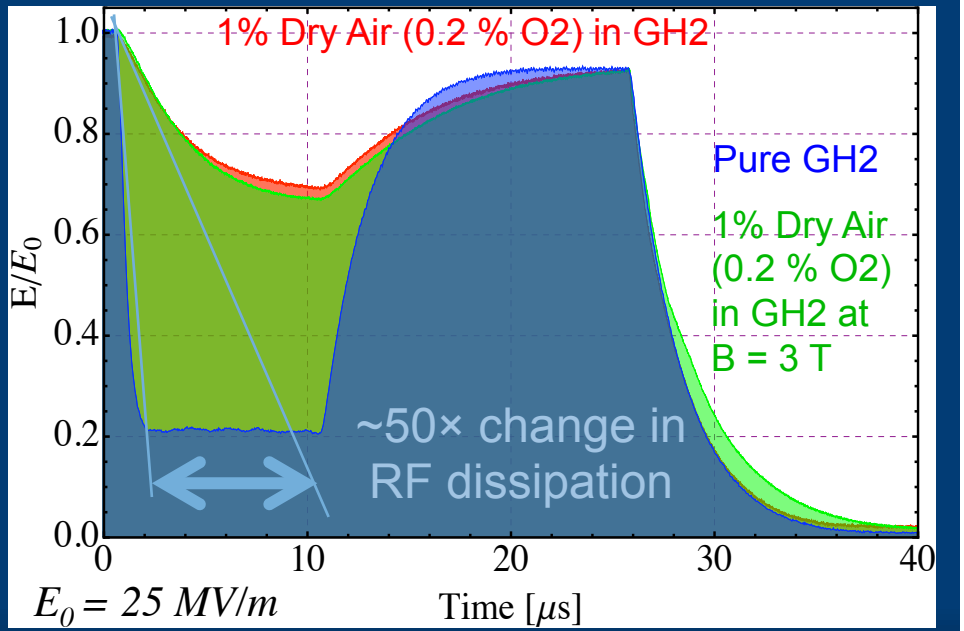




Recent Progress - High Pressure RF

- Gas-filled cavity
  - Can moderate dark current and breakdown currents in magnetic fields
  - Can contribute to cooling
  - Is loaded, however, by beam-induced plasma
- Electronegative Species
  - Dope primary gas
  - Moderates the loading effects of beam-induced plasma by scavenging the relatively mobile electrons



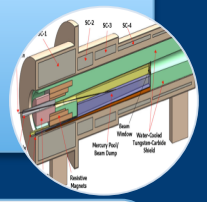


Results extrapolate well to NF operation and a range of MC beam parameters

Overview of MAP Magnet Pull

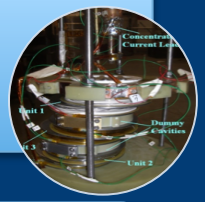
- Characteristics:
  - High field (15-20T)
  - Large bore (meter-scale)
  - Intense radiation environment – NC or HTS insert coil

Capture Solenoid for Simultaneous mu+ & mu- Beams



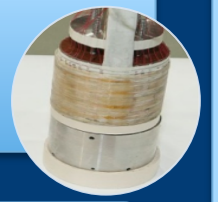
- Characteristics:
  - Solenoid-based cooling channel (LH_2/LiH absorbers)
  - RF cavities integral to focusing channel
  - Fields ranging from LTS to HTS conductor regime

Muon Ionization 6-Dimensional Cooling Channel



- Characteristics:
  - Emittance exchange channel for TeV-scale colliders (trade increased longitudinal beam emittance for smaller transverse emittance
  - Baseline: 30T class HTS solenoids with a>25mm

Muon Ionization Final Cooling Channel

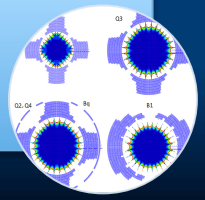


- Characteristics:
  - Present baseline based on the use of Rapid Cycling Synchrotrons
  - Requires magnets capable of ~400Hz operation with >1.5T peak fields

Acceleration to the TeV Energy Scale for Muon Colliders

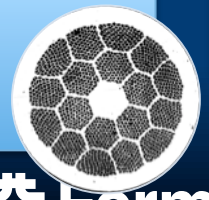
- Characteristics:
  - Decaying muon beams mean that luminosity is inversely proportional to circumference
  - 10T dipole ⇨ 15-20T dipoles improves luminosity
  - Radiation environment
  - Challenging IR magnets

Muon Collider Magnet Needs



- Characteristics:
  - A MC (w/decaying beams) obtains the greatest performance enhancement of any HEP collider from HTS magnet technology
  - High quality HTS cables and magnets must be a priority

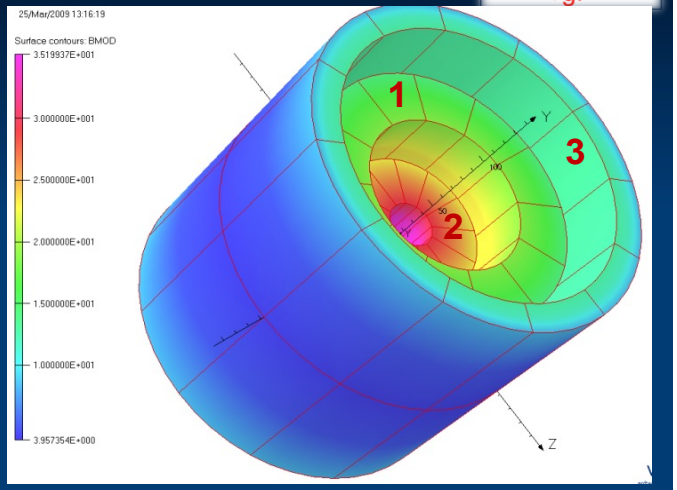
HTS Magnet Development



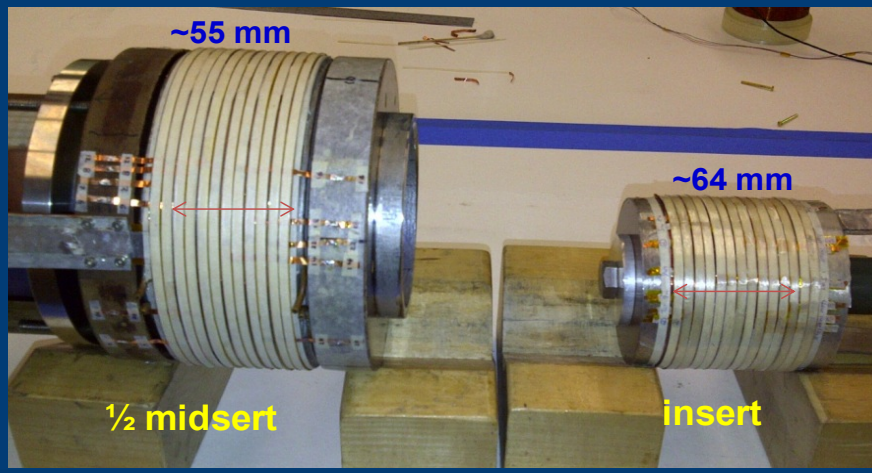
Feasibility R&D through End of Decade

Final Cooling Channel

- Final Cooling
  - Requires > 30T Class Solenoids
  - Demonstration program exploring critical magnet issues (R. Gupta at BNL)
    - High J_E
    - Quench Protection
    - Stress
    - Piece Length Constraints
- Anticipate a Final Cooling concept review in 2016



HTS (1&2, funded) and LTS (3, not funded)

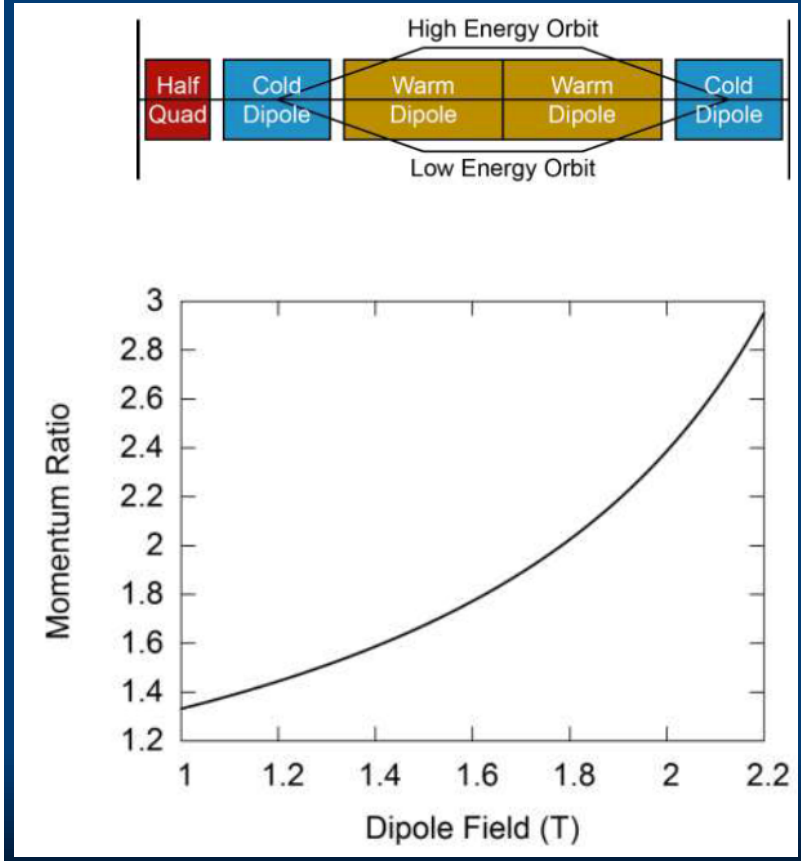


HTS solenoids – built and individually tested

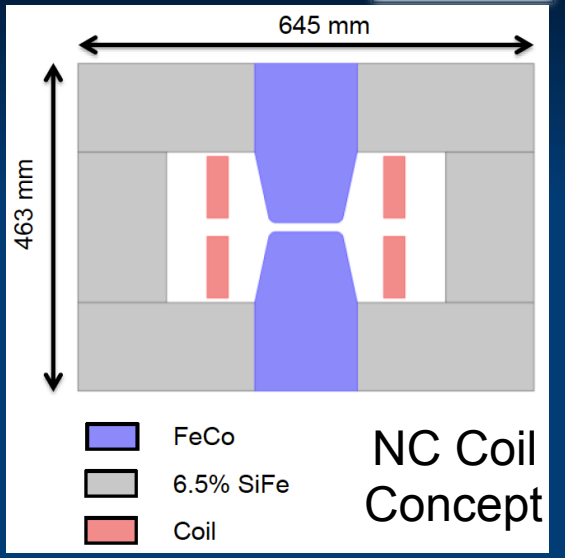
Magnets for the Acceleration Chain

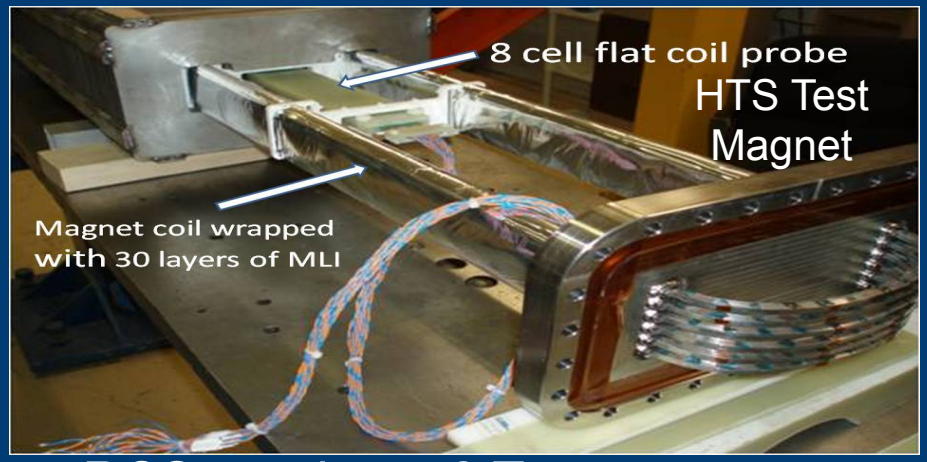
- Muons require an ultrafast accelerator chain

  ⇨ *Beyond the capability of most machines*



For 100's of GeV to the TeV-scale, Rapid Cycling Synchrotrons (RCS) offer the most efficient scheme



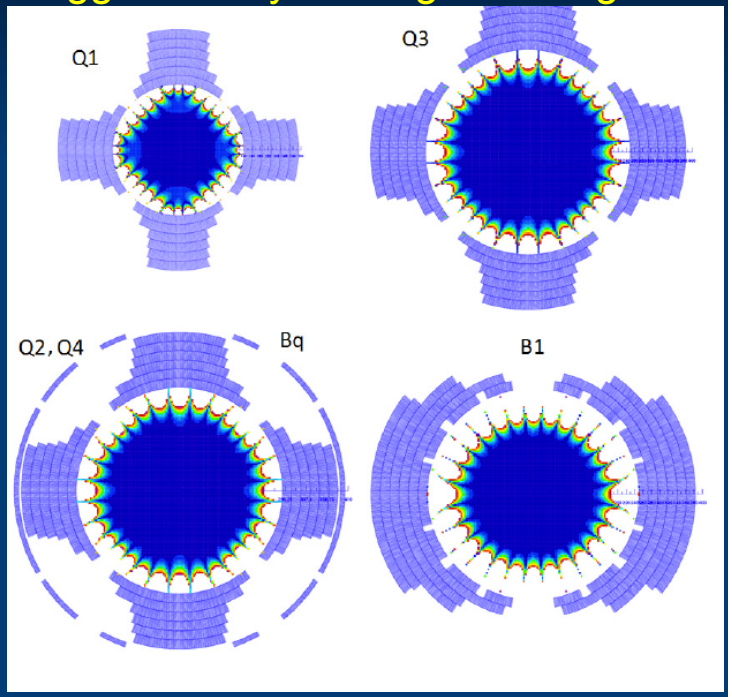


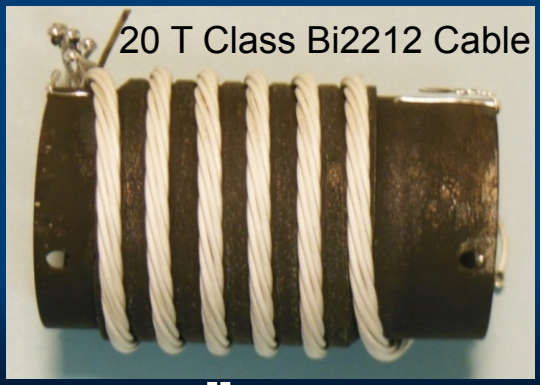
RCS requires ~2 T p-p magnets at f = 400 Hz (BNL, U Miss & FNAL)

Collider Ring Magnets

- Magnet design R&D for collider ring and IR magnets that have to deal with the expected high level of energy deposition from μ decay electrons
- Pursuing design concepts that allow for suitable shielding
- As with the LHC, pushing the field limits for magnets can impact the energy reach. *For the MC, this also directly impacts the luminosity performance!*
- Requires high field quality designs and hence the necessary cable development. Substantial progress in Bi2212 over the past year.

Higgs Factory IR Magnet Designs





The MAP Collaboration

- Participants in FY14
  - People:

    ~150 individuals

    ~50 FTEs
  - International Efforts:
    - International Design Study for a Neutrino Factory (IDS-NF)
    - Muon Ionization Cooling Experiment (MICE at RAL)
  - Participating Institutions (21)

    FNAL (host), ANL, BNL, Cornell, CMU, Chicago, ICL, IIT, JLAB, LBNL, Mississippi, Muons Inc, ORNL, PBL, Princeton, SLAC, SUNY-SB, UC-Berkeley, UCLA, UC-Riverside, VT
- MAP supports a broad accelerator R&D effort

  ⇨ Many opportunities exist for expanded collaboration