A FEW WORDS ON THE MUON ACCELERATOR PROGRAM (MAP)

Program Mission

The mission of the Muon Accelerator Program (MAP) is to develop and demonstrate the concepts and critical technologies required to produce, capture, condition, accelerate, and store intense beams of muons for Muon Colliders and Neutrino Factories. The goal of MAP is to deliver results that will permit the high-energy physics community to make an informed choice of the optimal path to a high-energy lepton collider and/or a next-generation neutrino beam facility. Coordination with the parallel Muon Collider Physics and Detector Study and with the International Design Study of a Neutrino Factory will ensure MAP responsiveness to physics requirements.

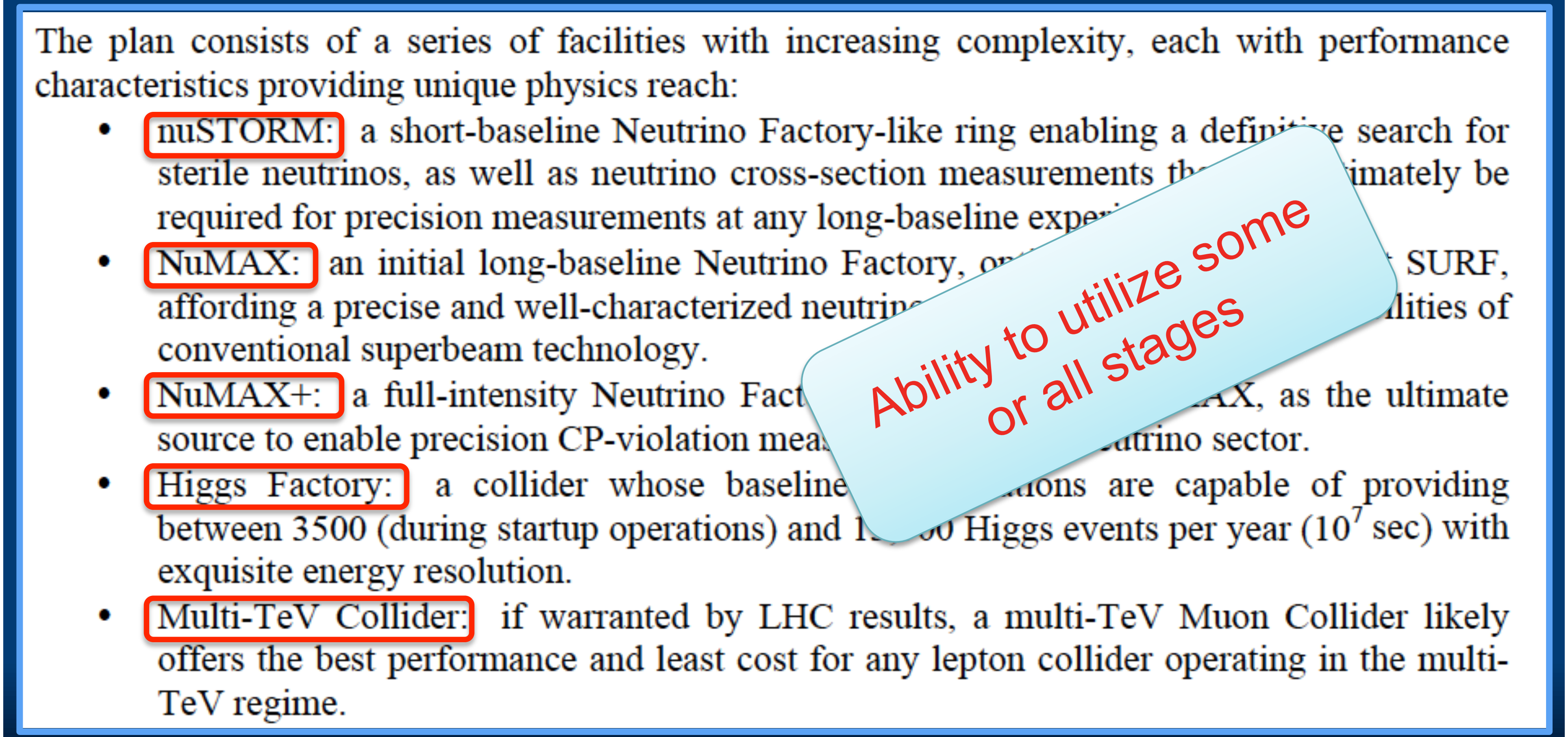
How we are executing this mission?

By supporting the development of muon accelerator technologies for the full range of capabilities described:

- Short baseline neutrino factory:
  - nuSTORM design, costing and proposal – a design for which *no new technology requirements exist*
- Long baseline neutrino factory:
  - IDS-NF design – *aimed at optimal physics reach*
  - Staged complex at Fermilab – *aimed at a **realistic** (ie, staged) deployment of NF capabilities ⇨ **NuMAX** concept*
    - *Starting with a 1 MW proton driver and no ionization cooling…*
- Collider options:
  - From a *Higgs Factory* to…
  - A *multi-TeV Collider* (extending up to energy ranges that may be required by LHC results)
  - Again utilizing a staged complex at Fermilab…

The Staging Study (MASS)

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:

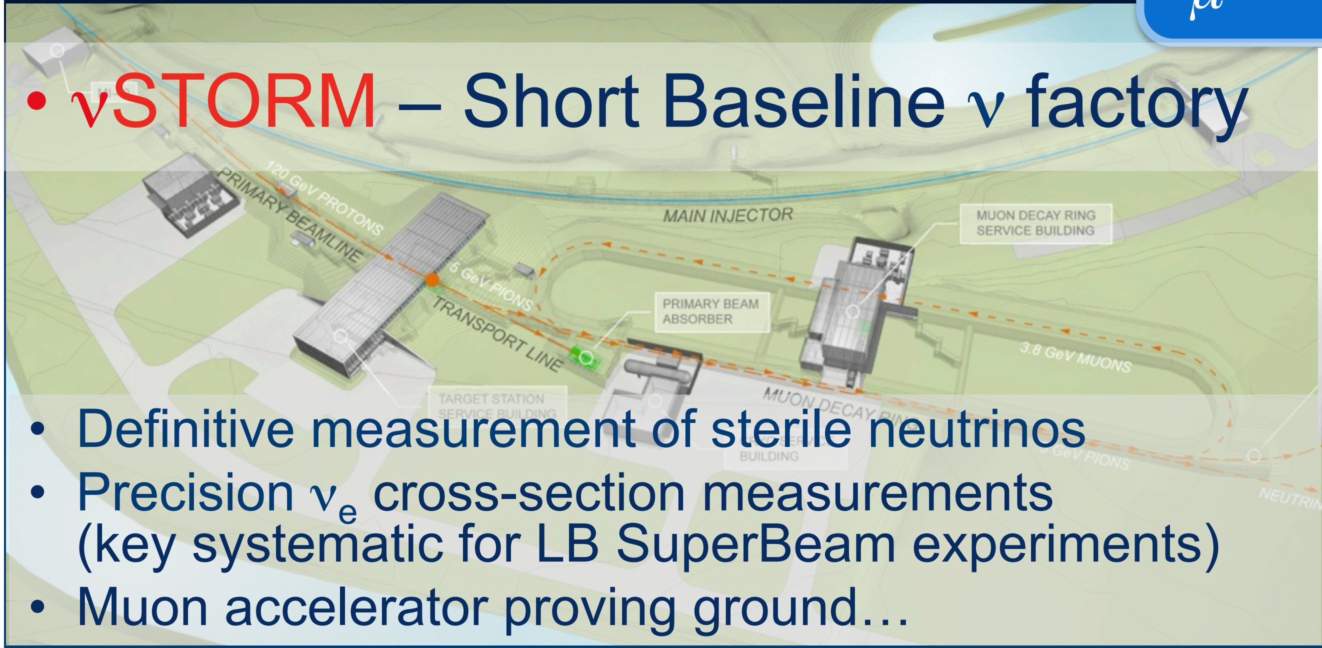
- nuSTORM: a short-baseline Neutrino Factory-like ring enabling a defin ve search for sterile neutrinos, as well as neutrino cross-section measurements th imately be required for precision measurements at any long-baseline exper
- NuMAX: an initial long-baseline Neutrino Factory, o t SURF, affording a precise and well-characterized neutrin lities of conventional superbeam technology.
- NuMAX+: a full-intensity Neutrino Fact AX, as the ultimate source to enable precision CP-violation meas utrino sector.
- Higgs Factory: a collider whose baseline ations are capable of providing between 3500 (during startup operations) and 1 00 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.

Ability to utilize some or all stages

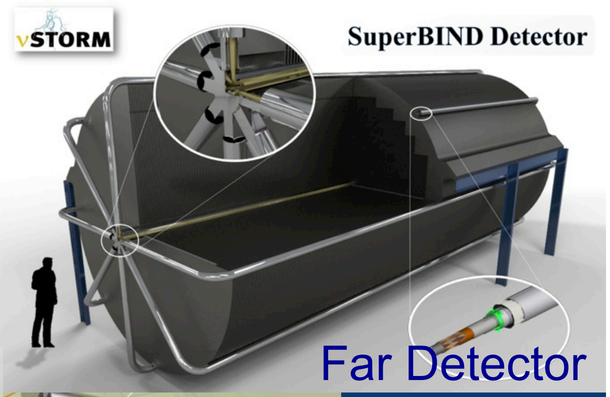
Neutrino Factories

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

- νSTORM – Short Baseline ν factory



- Definitive measurement of sterile neutrinos
- Precision ν_e cross-section measurements (key systematic for LB SuperBeam experiments)
- Muon accelerator proving ground…



Far Detector

To Far Detector

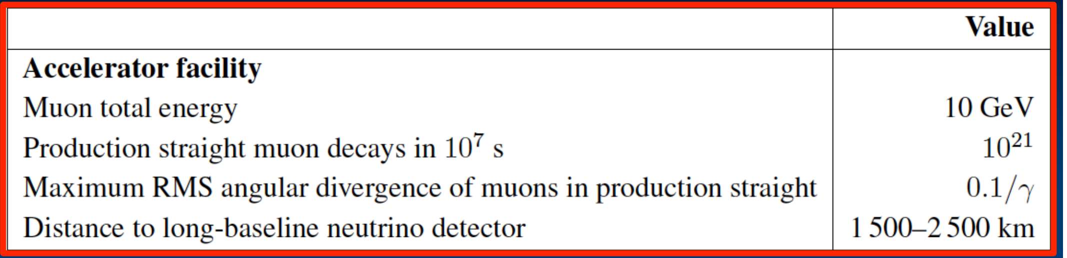
- **NuMAX** (Neutrinos from a Muon Accelerator CompleX)
  - Long baseline concept developed by MAP
    - As part of its Muon Accelerator Staging Study (MASS)
  - Evolutionary from IDS-NF Concept ⇨ FNAL to SURF baseline
    - Magnetized detector (MIND, Mag LAr?)
    - CP violation sensitivity optimal for 4-6 GeV beam energy
    - Provides ongoing short baseline capabilities

The Long Baseline Neutrino Factory

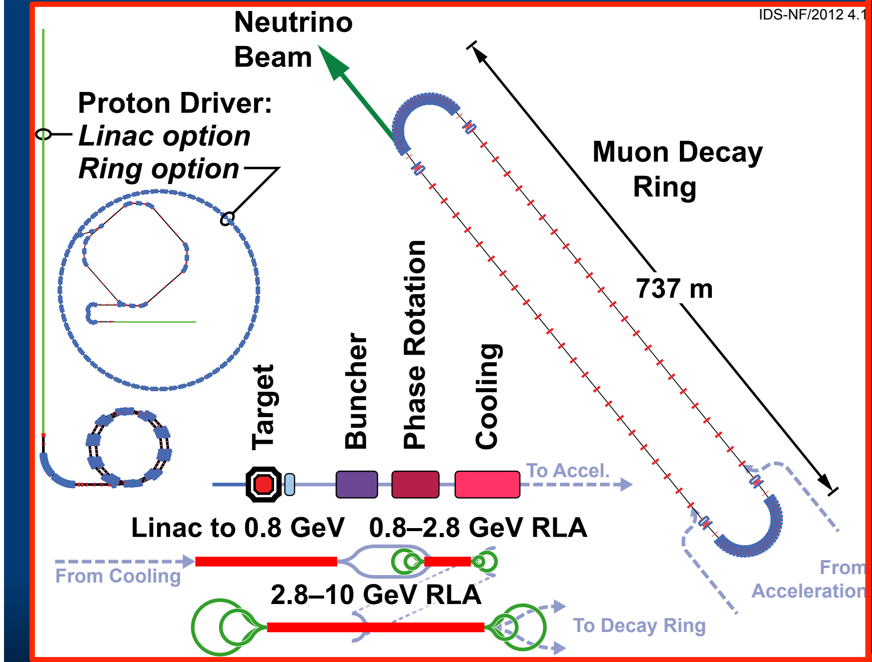
- IDS-NF: the *ideal* NF
  - Supported by MAP
- MASS working group:

  A staged approach -

NuMAX@5 GeV⇨SURF

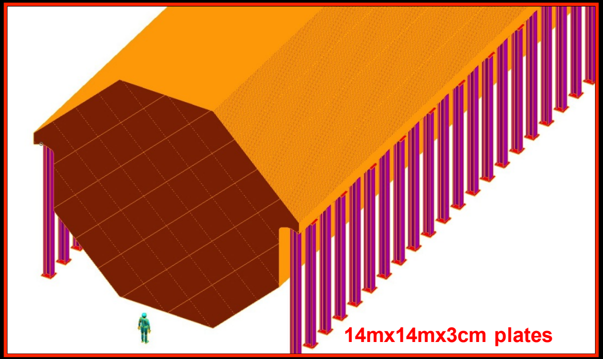


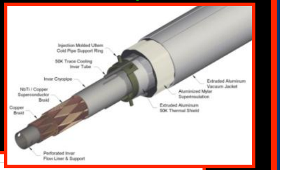
	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to long-baseline neutrino detector	1 500–2 500 km

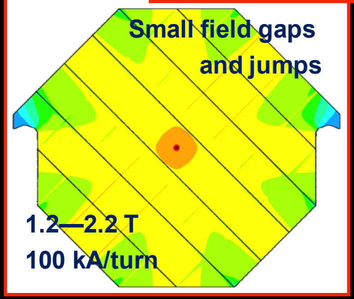


Magnetized Iron Neutrino Detector (MIND):

- 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





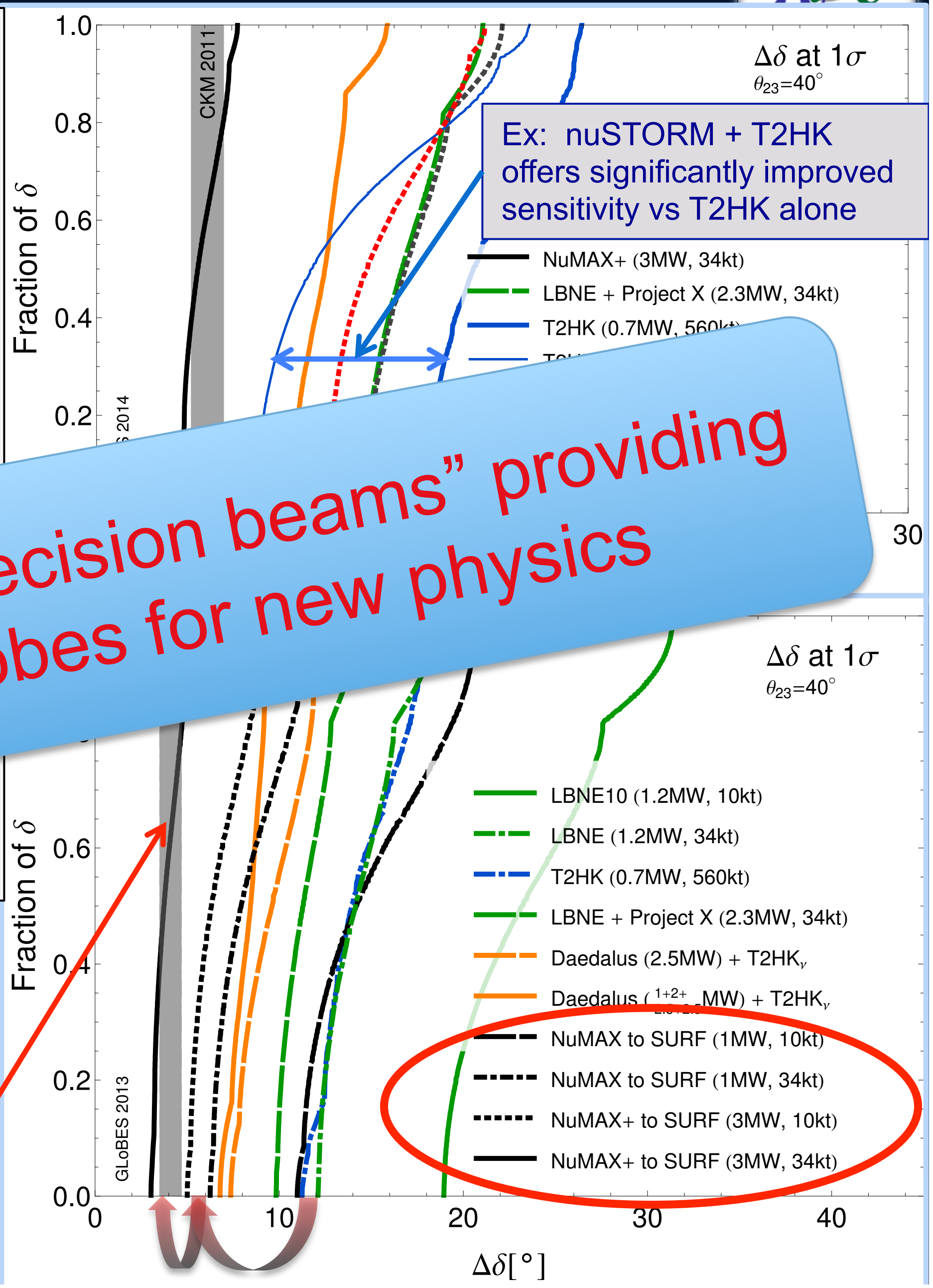


Bross, Soler

Precision Capabilities for the ν Sector

- Both short- (νSTORM) and long-baseline (NuMAX) options provide routes to high precision measurements in the ν sector with very well understood systematic
- NuMAX
  - Ultimate
    ν sector
  - Offers:
    - Well-characterized beam
    - Energy Flexibility
    - Discovery Potential!

G…arison of Potential
…e of the Various
Adva…s (courtesy P. Huber)

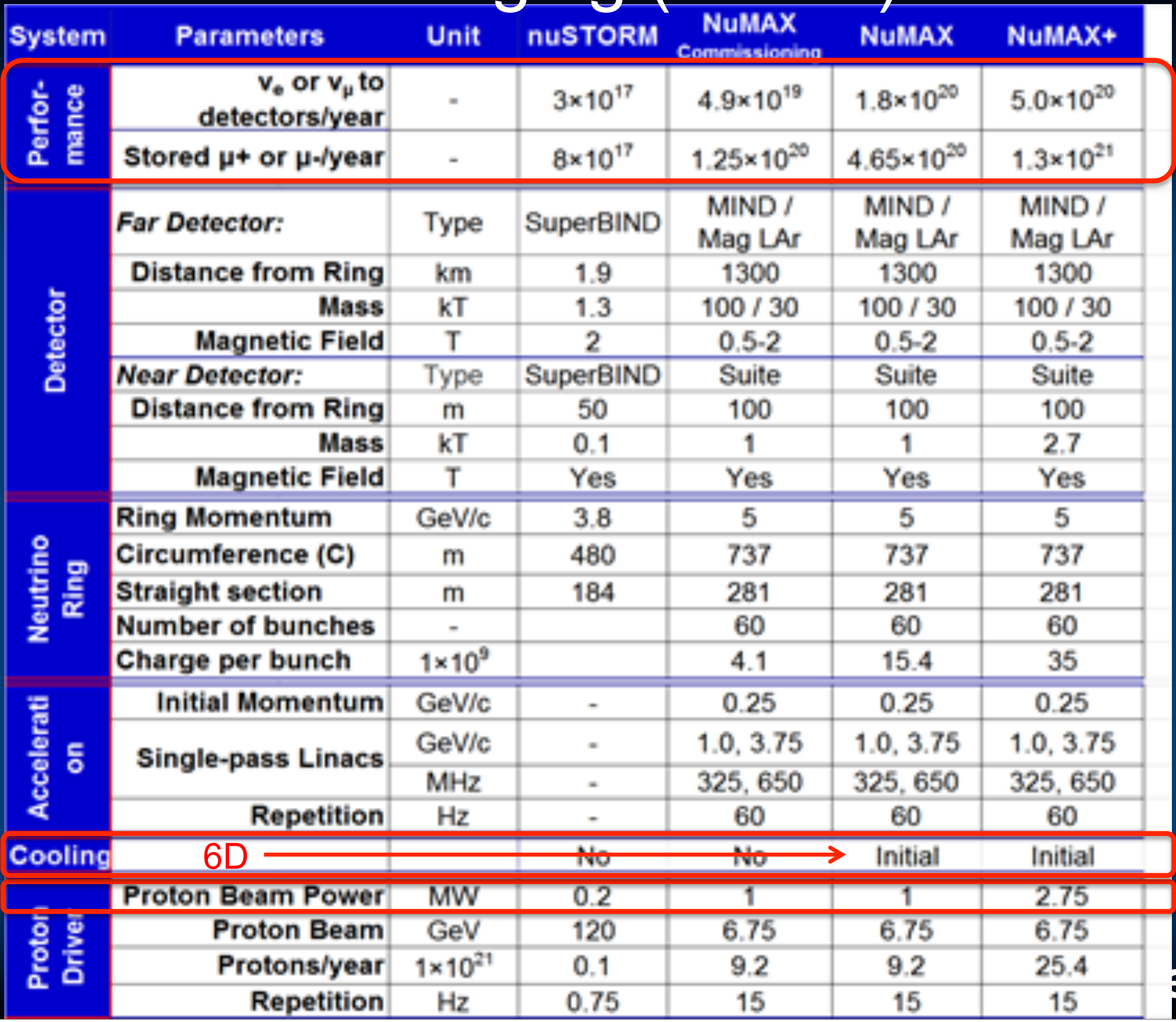


Ex: nuSTORM + T2HK offers significantly improved sensitivity vs T2HK alone

High intensity "precision beams" providing sensitive probes for new physics

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

NF Staging (MASS)



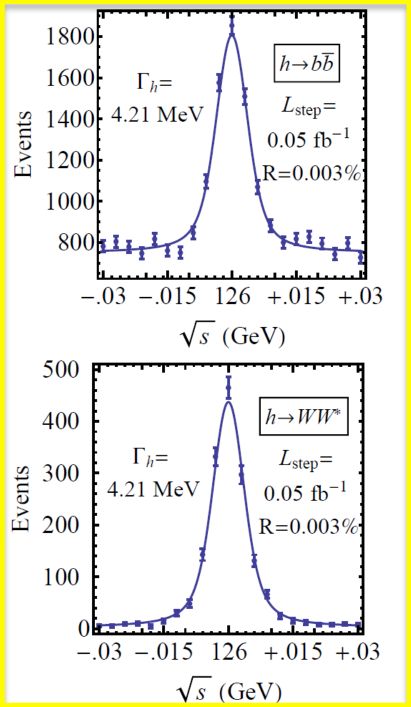
System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Performance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Detector	*Far Detector:*	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / Mag LAr
	Distance from Ring	km	1.9	1300	1300	1300
	Mass	kT	1.3	100 / 30	100 / 30	100 / 30
	Magnetic Field	T	2	0.5-2	0.5-2	0.5-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	1	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	Ring Momentum	GeV/c	3.8	5	5	5
	Circumference (C)	m	480	737	737	737
	Straight section	m	184	281	281	281
	Number of bunches	-		60	60	60
	Charge per bunch	1×10^{9}		4.1	15.4	35
Acceleration	Initial Momentum	GeV/c	-	0.25	0.25	0.25
	Single-pass Linacs	GeV/c	-	1.0, 3.75	1.0, 3.75	1.0, 3.75
		MHz	-	325, 650	325, 650	325, 650
	Repetition	Hz	-	60	60	60
Cooling	6D		No	No	Initial	Initial
Proton Driver	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam	GeV	120	6.75	6.75	6.75
	Protons/year	1×10^{21}	0.1	9.2	9.2	25.4
	Repetition	Hz	0.75	15	15	15

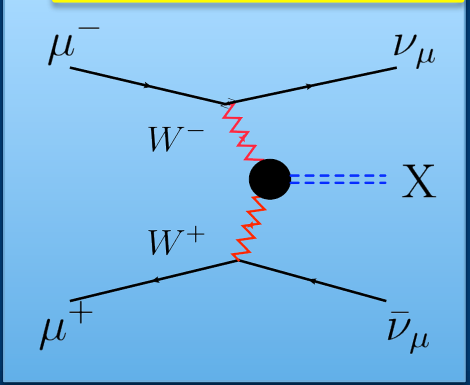
Features of the Muon Collider

- Superb Energy Resolution
  - SM Thresholds and s-channel Higgs Factory operation
- Multi-TeV Capability (≤ 10TeV):
  - Compact & energy efficient machine
  - Luminosity > 10^{34} cm^{-2} s^{-1}
  - Option for 2 detectors in the ring
- For √s > 1 TeV: Fusion processes dominate

  ⇨ an Electroweak Boson Collider

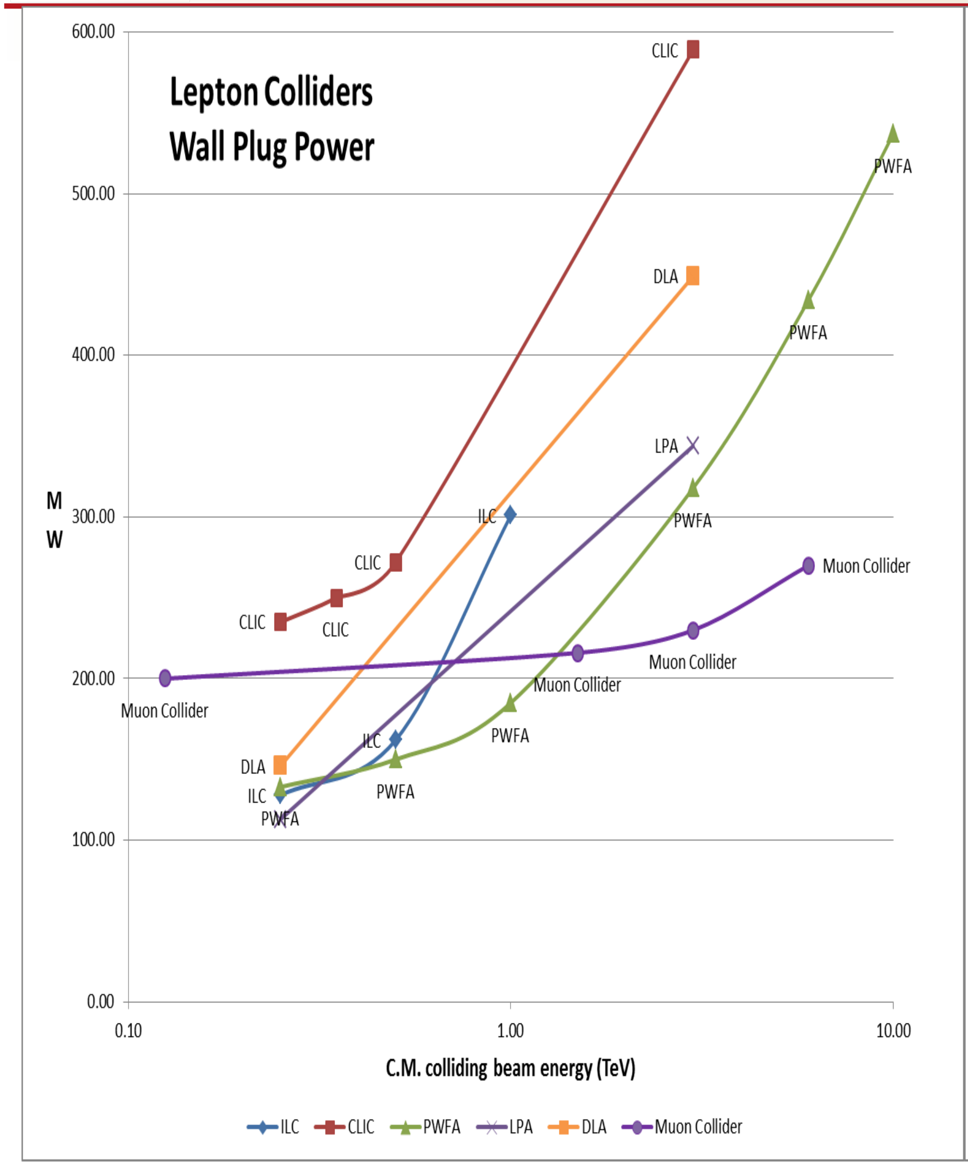
  ⇨ a discovery machine complementary to a very high energy pp collider
  - At >5TeV: Higgs self-coupling resolutions of <10%

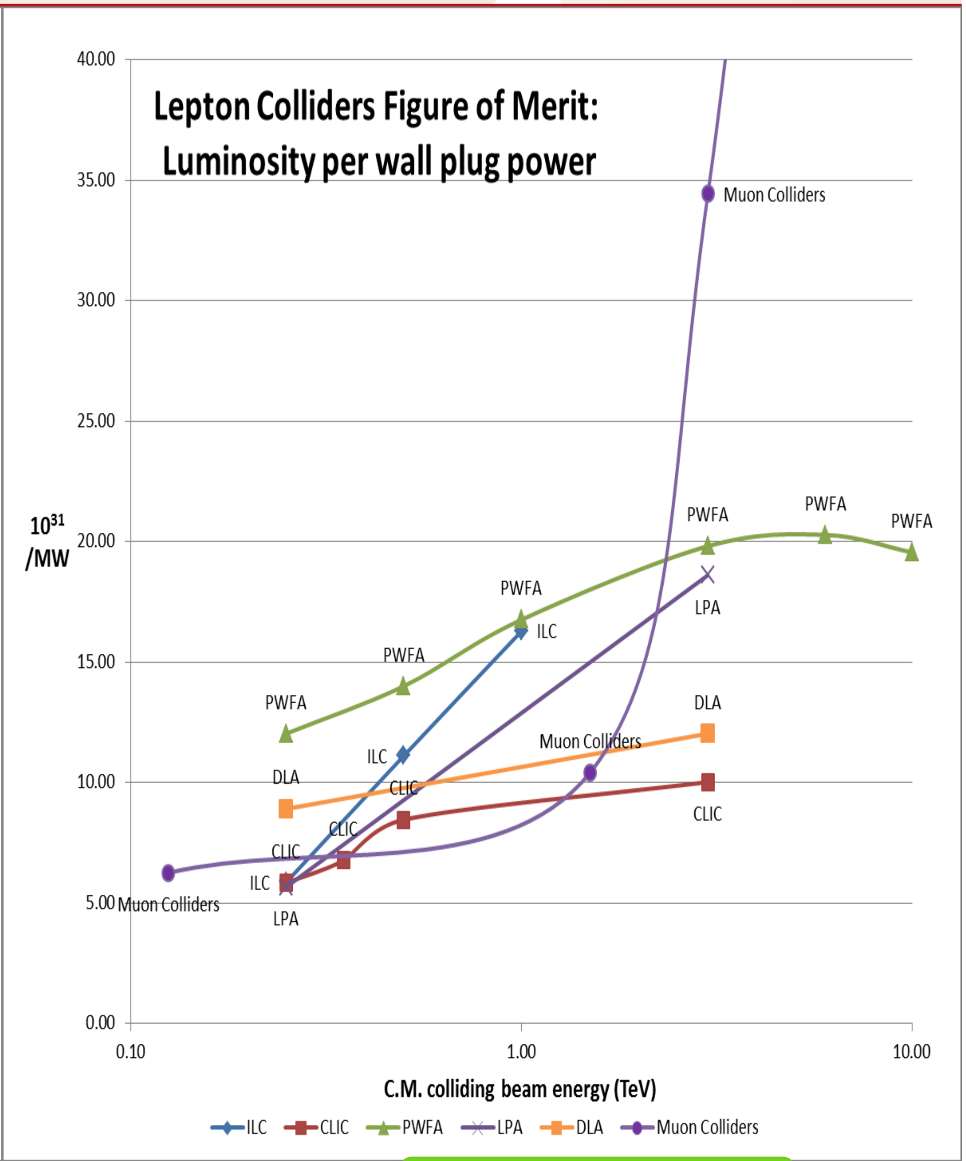




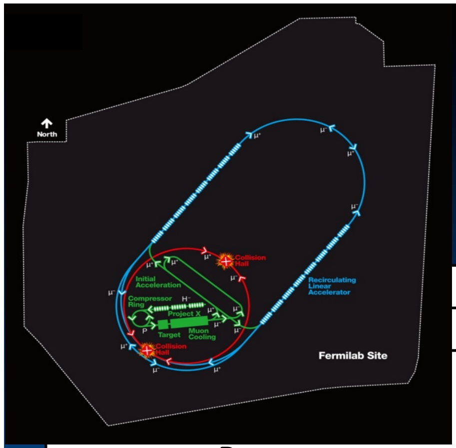
What are our accelerator options if new LHC data shows evidence for a multi-TeV particle spectrum?

Muon Colliders extending high energy frontier with potential of considerable power savings


Lepton Colliders Wall Plug Power


Lepton Colliders Figure of Merit: Luminosity per wall plug power

Muon Collider Parameters



Muon Collider Parameters

		Higgs Factory		**Top Threshold Options**		**Multi-TeV Baselines**		
Parameter	***Units***	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top^{+} Production/10^{7}sec		3,500*	13,500*	7,000^{+}	60,000^{+}	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	4$^{\#}$	4	4	4	4	4	1.6

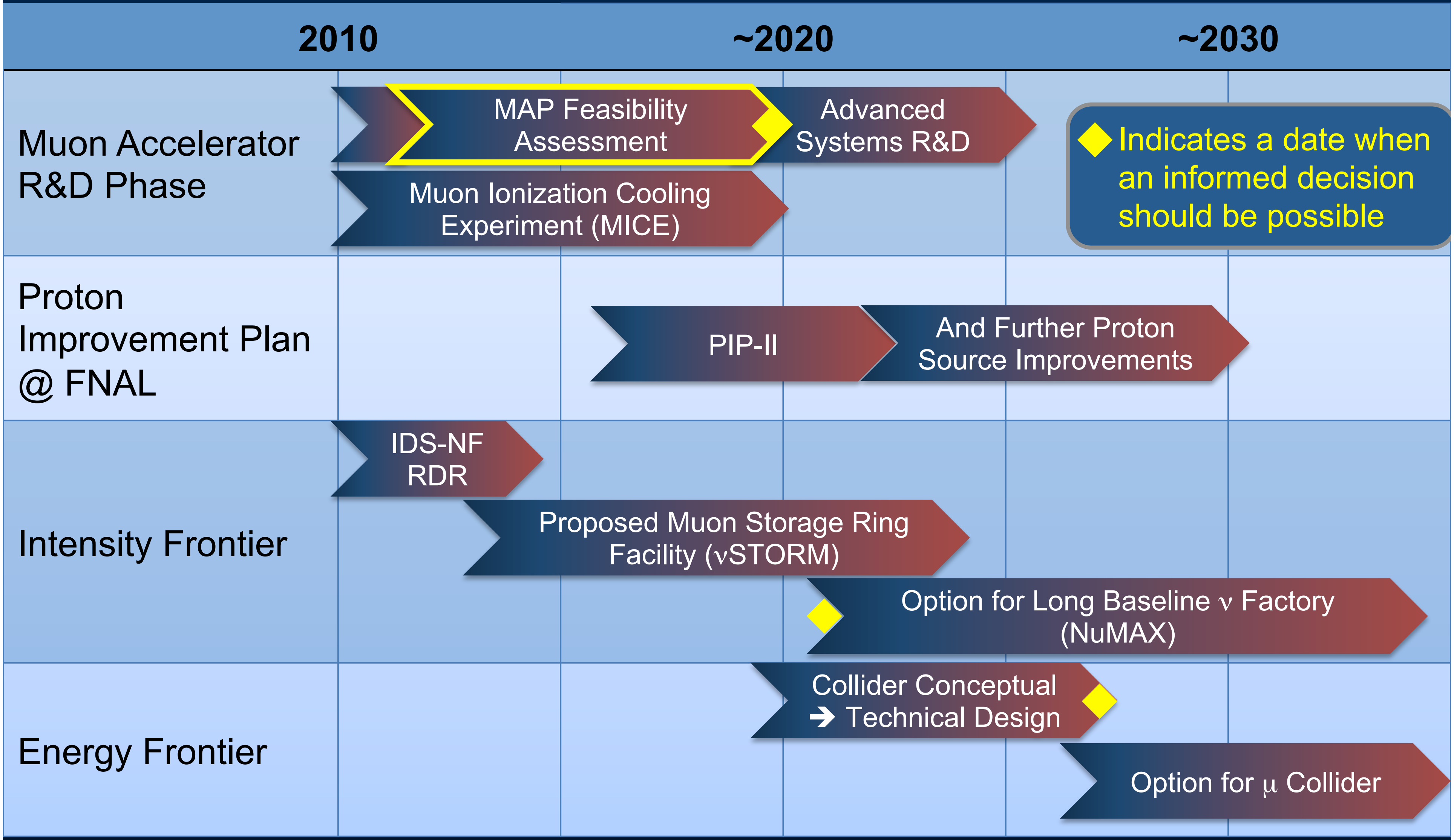
Could begin operation with Project X Stage II beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts ⇨ several × 10^{32}

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

MAP Timeline ⇨ Provide Informed Decision Points



2010

~2020

~2030

Muon Accelerator R&D Phase

MAP Feasibility Assessment ◆

Advanced Systems R&D

Muon Ionization Cooling Experiment (MICE)

◆ Indicates a date when an informed decision should be possible

Proton Improvement Plan @ FNAL

PIP-II

And Further Proton Source Improvements

Intensity Frontier

IDS-NF RDR

Proposed Muon Storage Ring Facility (νSTORM)

◆ Option for Long Baseline ν Factory (NuMAX)

Energy Frontier

Collider Conceptual → Technical Design ◆

Option for μ Collider

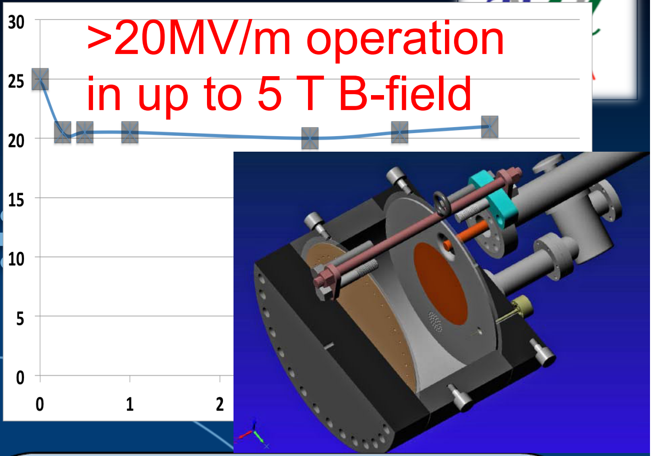
R&D Effort

- Scope – *A focused effort to demonstrate feasibility*
  - Provide:
    - Specifications for all required technologies
    - Baseline design concepts for each accelerator system (see block diagram to follow)
  - 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

Cooling Channel R&D Effort

Successful Operation of 805 MHz "All Seasons" Cavity in 5T Magnetic Field under Vacuum

MuCool Test Area/Muons Inc

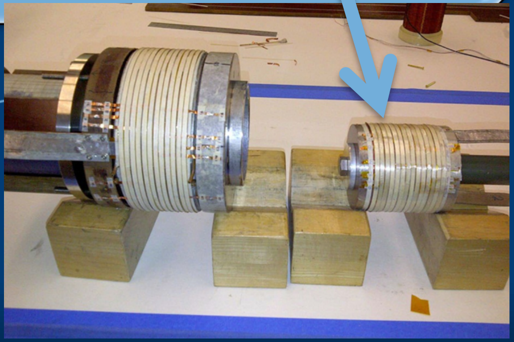


>20MV/m operation in up to 5 T B-field

World Record HTS-only Coil

15T on-axis field
16T on coil

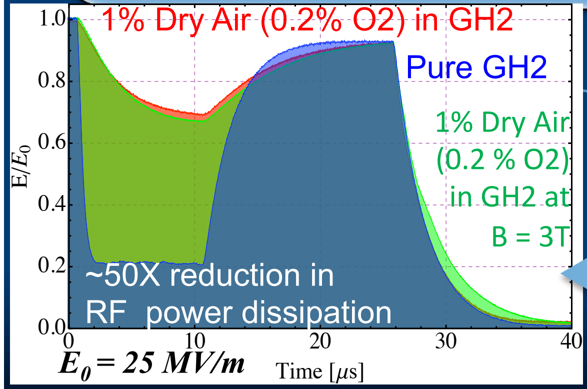
PBL/BNL



Demonstration of High Pressure RF Cavity <u>in 3T Magnetic Field with Beam</u>

Extrapolates to
μ-Collider Parameters

MuCool Test Area

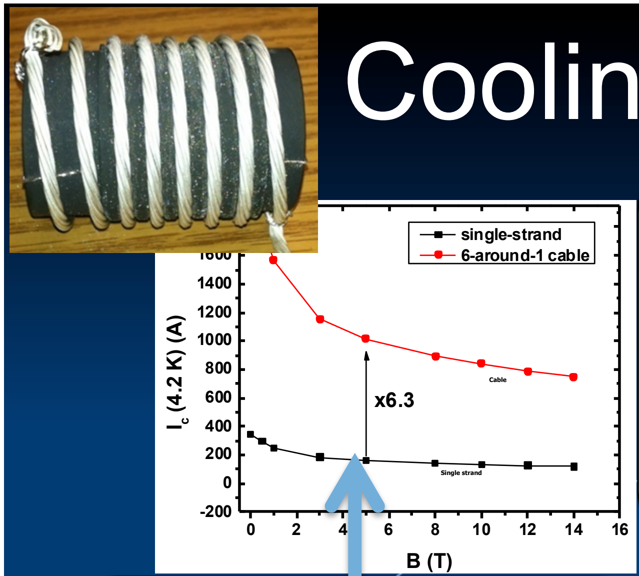


~50X reduction in RF power dissipation

$E_0 = 25$ MV/m

Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

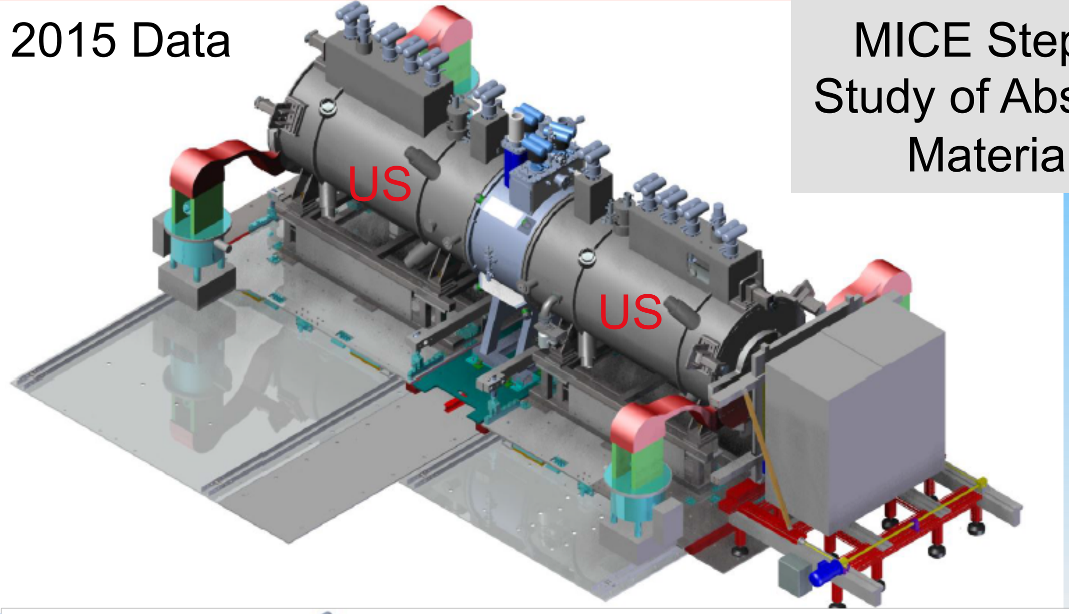
FNAL-Tech Div
T. Shen-Early Career Award



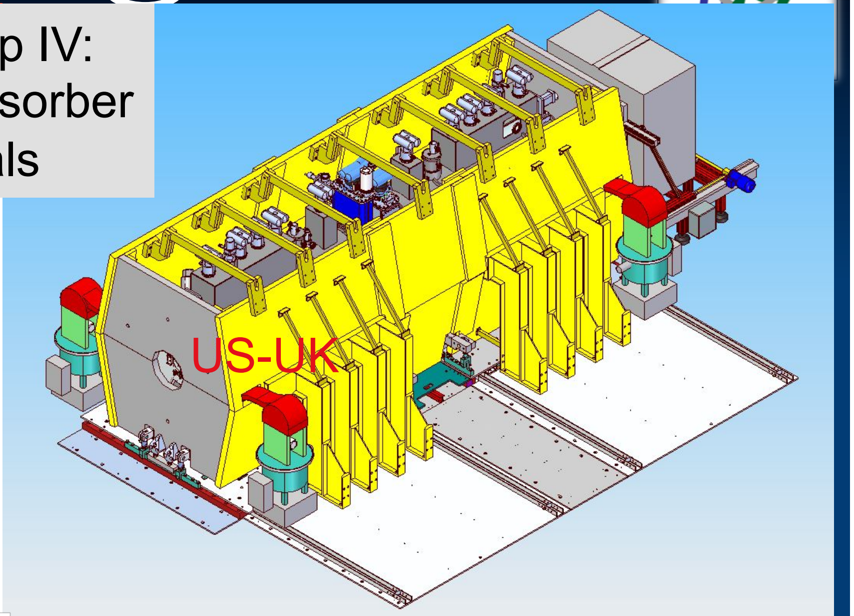
The Path to a Viable Muon Ionization Cooling Channel

MICE Experiment @RAL

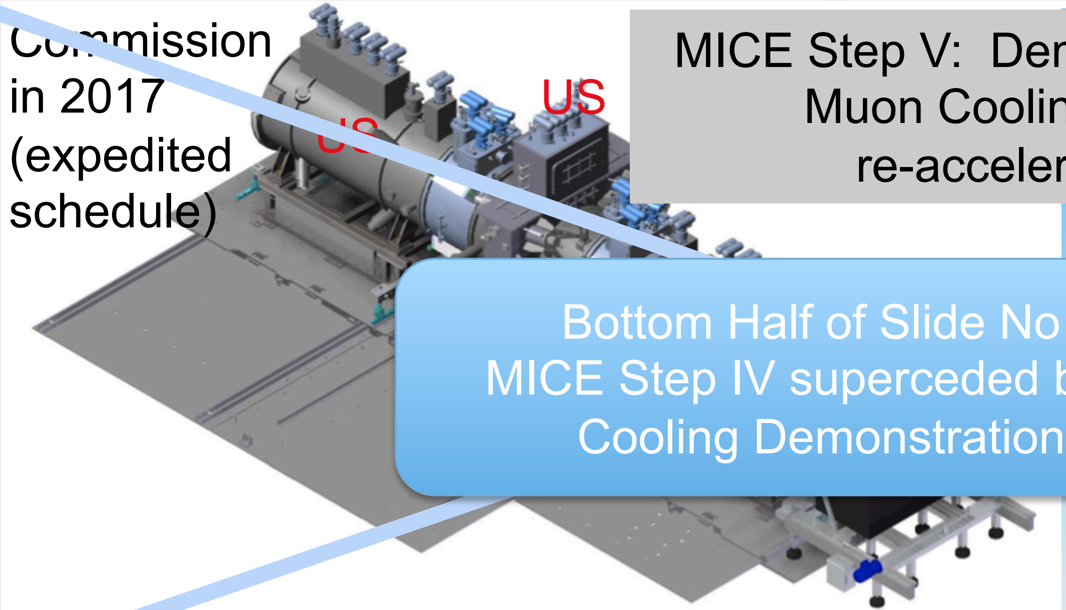
2015 Data



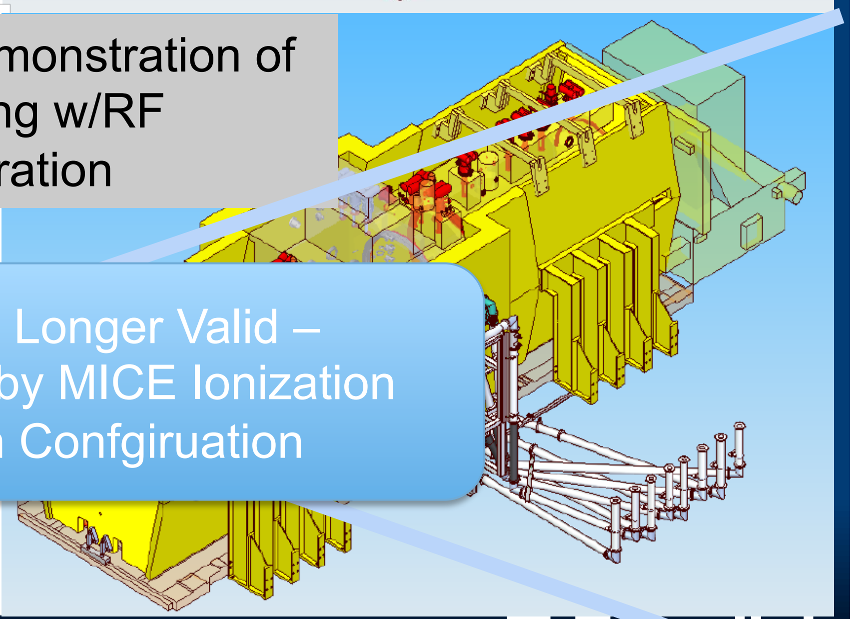
MICE Step IV: Study of Absorber Materials



Commission in 2017 (expedited schedule)



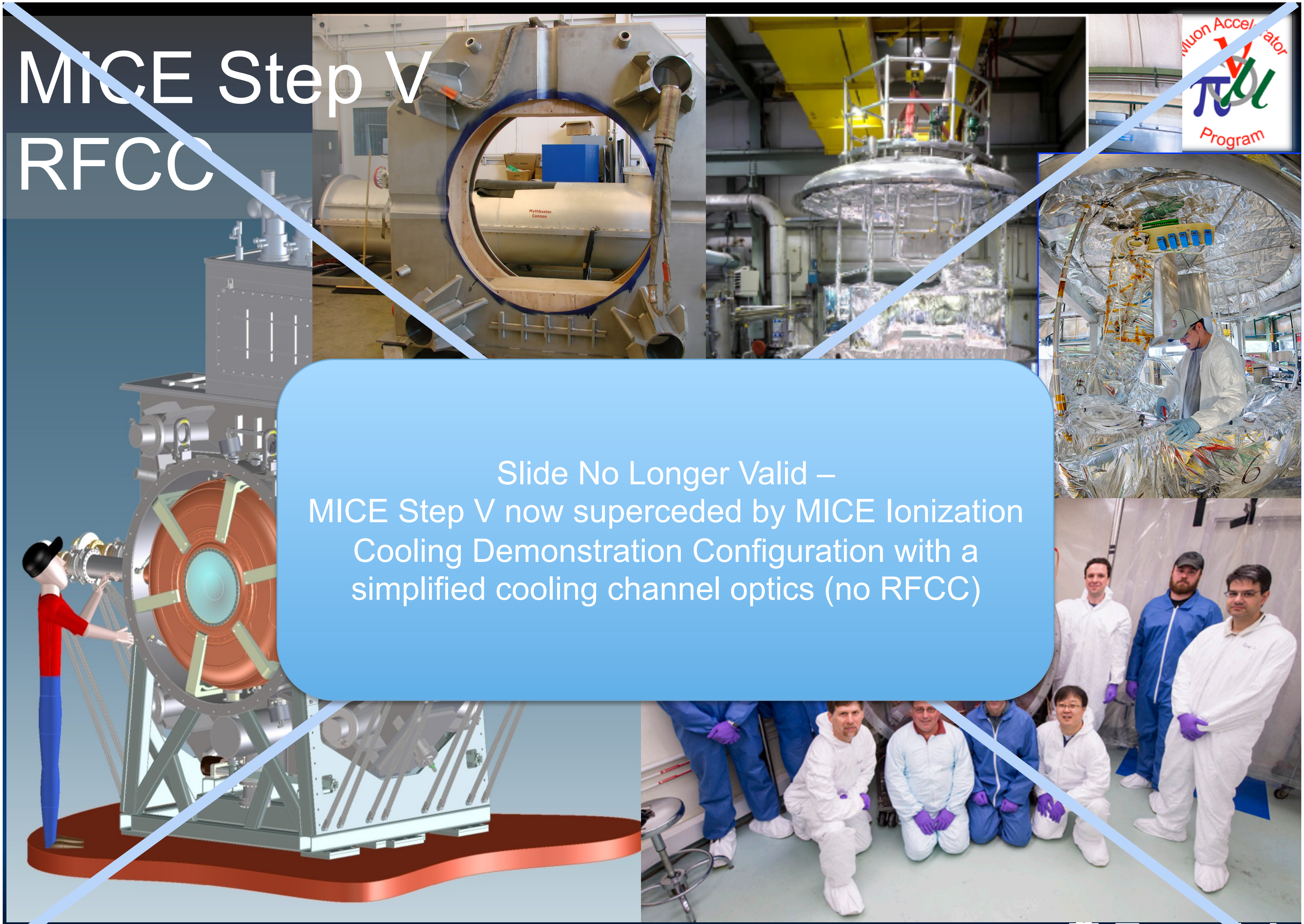
MICE Step V: Demonstration of Muon Cooling w/RF re-acceleration



Bottom Half of Slide No Longer Valid –
MICE Step IV superceded by MICE Ionization Cooling Demonstration Confgiruation

MICE Step IV Integration

MICE Step V RFCC



Slide No Longer Valid –
MICE Step V now superceded by MICE Ionization Cooling Demonstration Configuration with a simplified cooling channel optics (no RFCC)

The Key Choices

- The breadth of science that can be supported by a muon accelerator capability argues for continued support of the directed national accelerator R&D program (integrated with a global R&D effort) which is now in its 3rd year
  - Feasibility Assessment available by the end of the decade
- NF:
  The R&D would support future high precision capabilities with well-understood systematics
- MC:
  The R&D would prepare for the possibility that LHC running reveals the lowest states of a new particle spectrum

  Note that the MC may be the only viable route to a several TeV lepton collider capability in the next 20 years

Comments

- Where are we heading now? P5 Recommendations…
  - A plan for expedited completion of MICE was already presented to the MICE Project Board in April – *endorsed*
    - Includes *Step IV measurements in 2015-16* and deployment of Step V configuration by 2017 (*demonstration of "cooling with RF"*)
  - Have been requested by DOE to prepare a transition plan
    - Preserve critical investments – both technical and human resources
    - Sensitivity to international commitments
    - 3 Major Thrusts:
      - MICE Conclusion
      - Critical activities that should be preserved within the GARD program
      - Lower priority items that will be deferred
    - Review planned in several weeks
      - Will serve as input to the Accelerator R&D Panel
      - Will determine FY15 budget while awaiting the panel's report

BACKUP SLIDES

Summary I

- Muon accelerators can provide unique options for a facility at the intensity and energy frontiers
  - Precision neutrino measurements ⇨ sensitivity to new physics
  - A promising path to a multi-TeV lepton collider:
    - if required by (new) physics results
    - with reasonable footprint, cost & power consumption
  - A TeV-scale collider has complementary discovery potential to a 100TeV pp FCC
    - See talk by Estia Eichten: https://indico.fnal.gov/getFile.py/access?contribId=16&sessionId=0&resId=0&materialId=slides&confId=8326)
  - MAP Program Execution Plan endorsed by DOE Review in Feb 2014 for completion of feasibility assessment by 2020.

Summary II

- MASS: An attractive Staging Path for Muon Accelerators
  - A series of facilities with increasing complexity and physics reach – *with manageable budget and risk for each stage*
  - Provides an integrated R&D platform at each stage for validation of the technologies required by subsequent stages
  - Dates for informed technical decisions for specific facilities:
    - Early 2020s for a long-baseline Neutrino Factory (NuMAX)
    - Late 2020s for a Muon Collider
  - *A facility capable of flexibility in adapting to a range of physics requirements*
- Uniquely suited to the accelerator complex at Fermilab
  - A natural extension of the LBNF concept
  - Ability to respond to various physics thrusts

Comments

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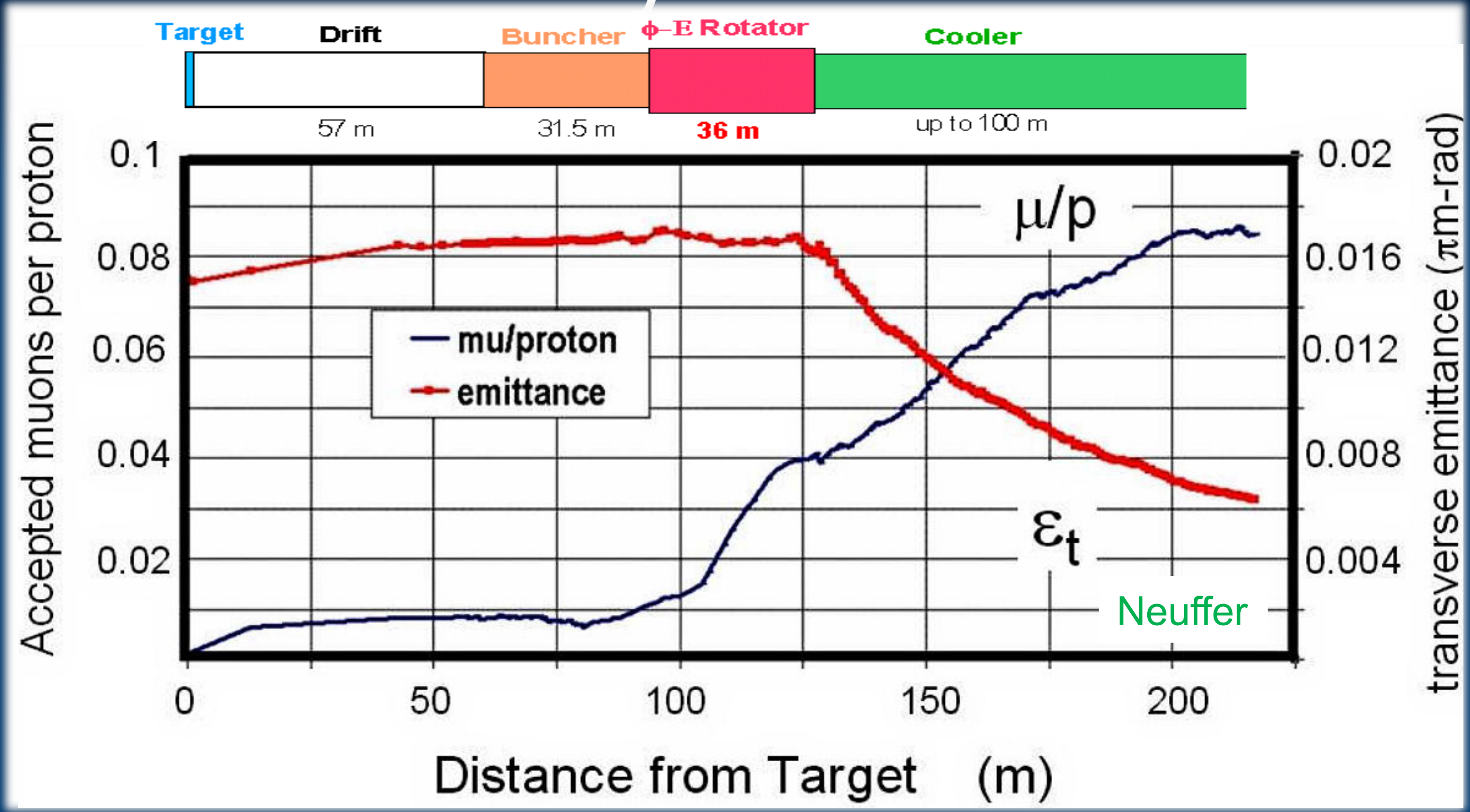
MAP Initial Baseline Selection Process

- Now to 2016:
  - Explore, develop, and select the **Initial Baseline Design (IBS)** of all accelerator subsystems
    - Clear specifications are absolutely critical to the technology demonstrations that are being undertaken to establish the feasibility of high intensity muon accelerators
    - The coupling between design and technology is clearly iterative
    - However, given the knowledge that we presently have, it is crucial to clearly define the design concepts for individual systems
  - To enhance the quality of the designs, the IBS process will focus primarily on a site-specific implementation at Fermilab which would build on the superconducting linac upgrade presently being planned
    - It will also focus on specifications that are compatible with the conclusions of the Muon Accelerator Staging Study (MASS)
- In the 2016-2020 timeframe, will launch the next set of feasibility R&D activities (on the basis of the IBS-specified designs)

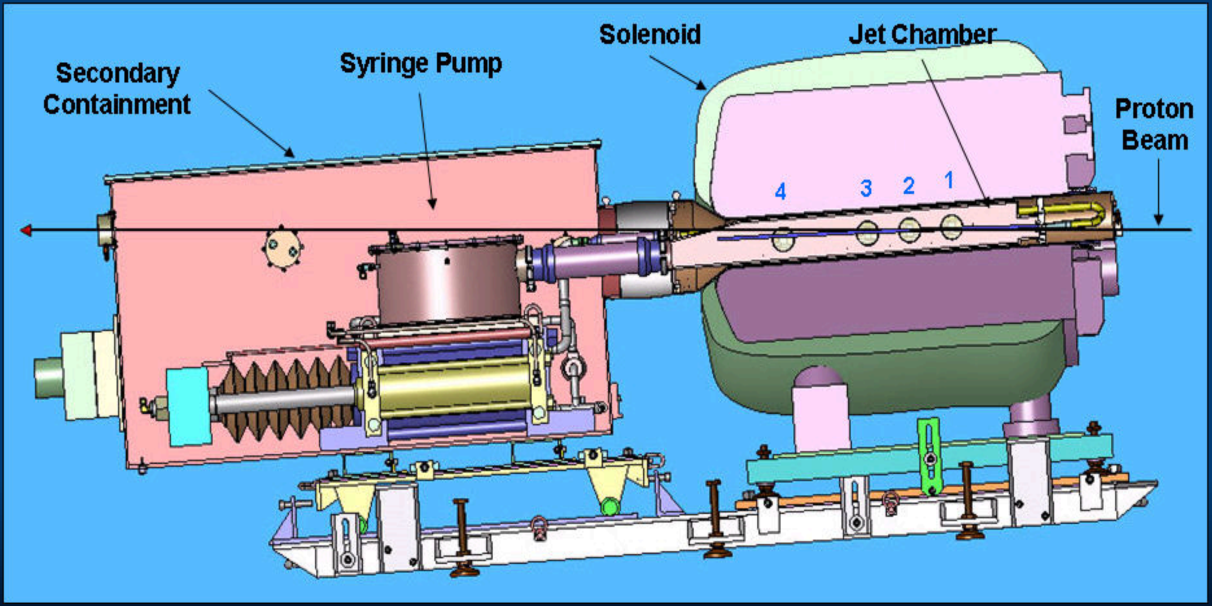
Technology Challenges – Tertiary Production

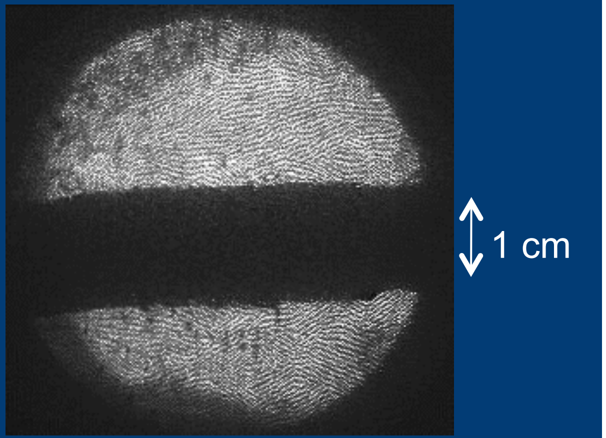


- A multi-MW proton source, *i.e.*, the extension of PIP-II, will enable O(10^{21}) muons/year to be produced, bunched and cooled to fit within the acceptance of an accelerator.

Key Technologies - Target

- The MERIT Experiment at the 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





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

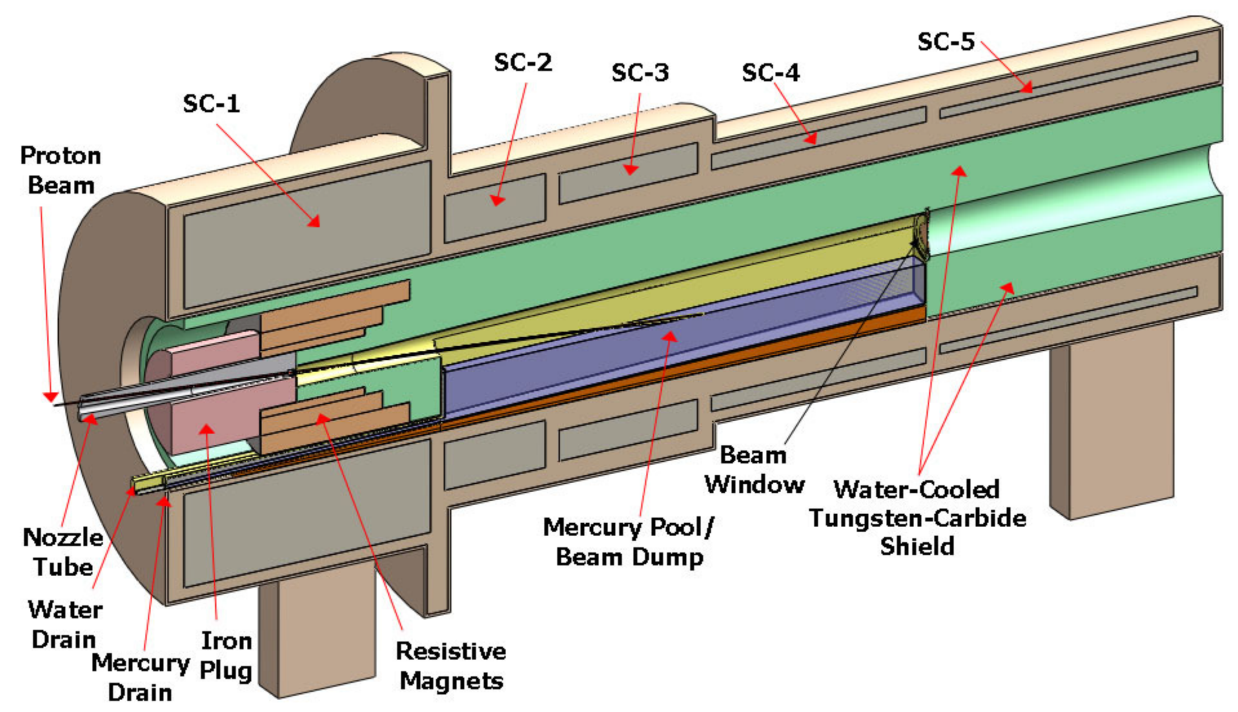
Technology Challenges – Capture Solenoid

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

$E_{stored} \sim 3$ GJ

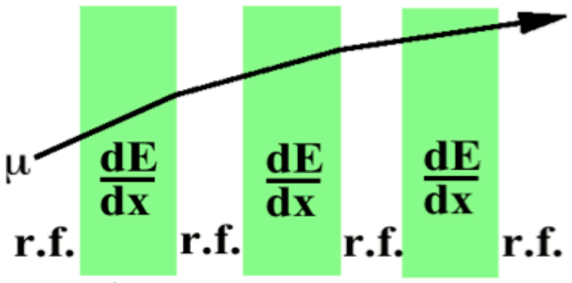
O(10MW) resistive coil in high radiation environment

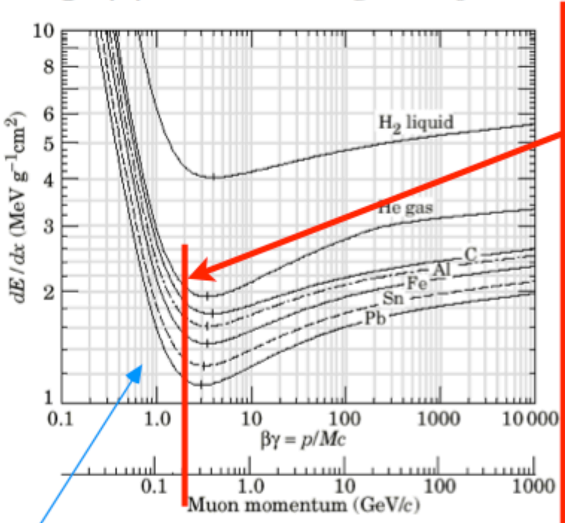
Possible application for High Temperature Superconducting magnet technology



Ionization Cooling

- Muons cool via dE/dx in low-Z medium





- ionization minimum is ≈ optimal working point:
  - longitudinal +ive feedback at lower *p*
  - straggling & expense of reacceleration at higher *p*

  – Absorbers:

$$\begin{cases} E \to E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

- 2 competing effects ⇒ ∃ equilibrium emittance

  – RF cavities between absorbers replace ΔE

  – Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

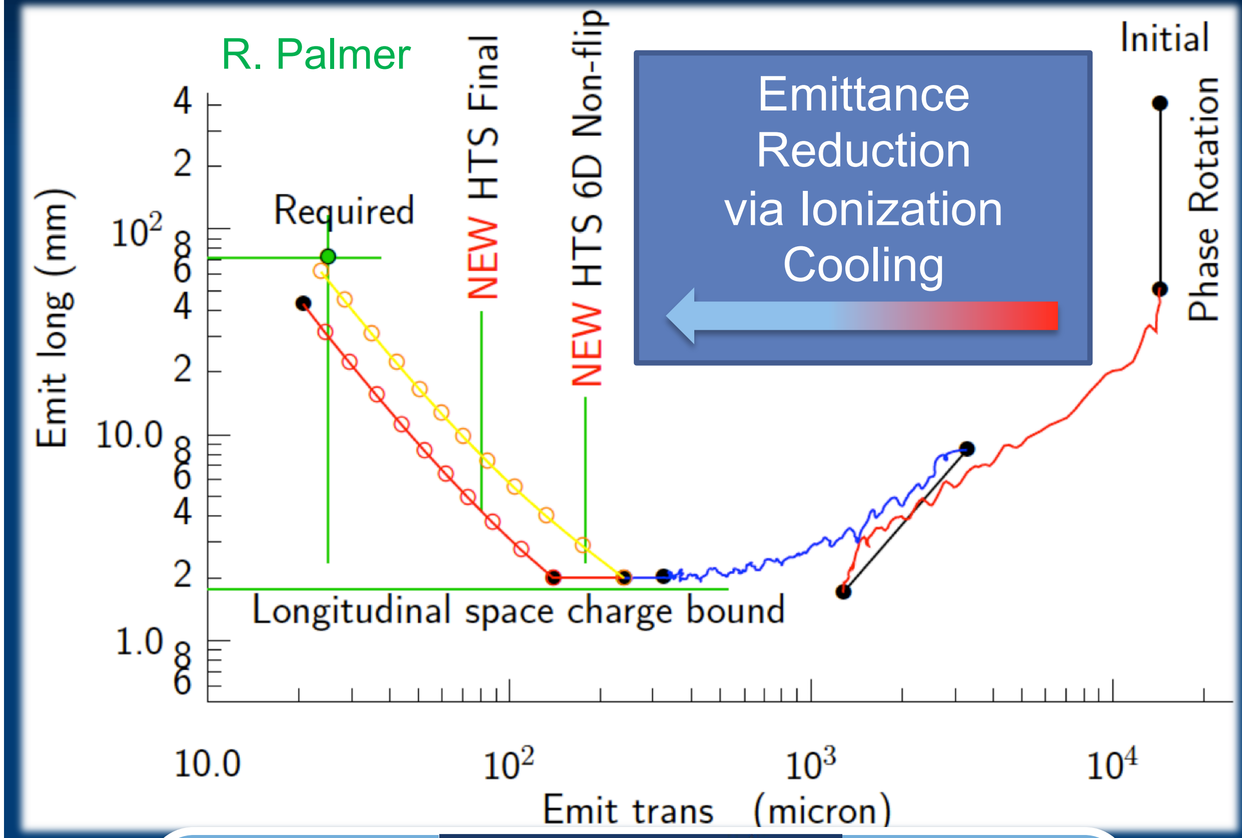
$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\text{ GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

(emittance change per unit length)

D. Kaplan

Technology Challenges - Cooling

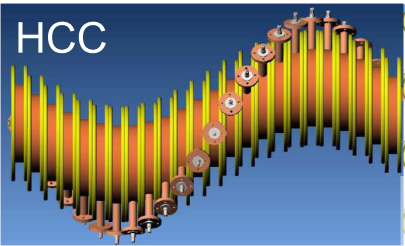
Development of a cooling channel design to reduce the 6D phase space by a factor of O(10^6) → MC luminosity of O(10^{34}) $cm^{-2}\ s^{-1}$



- Some components beyond state-of-art:
  - Very high field HTS solenoids (≥30 T)
  - High gradient RF cavities operating in multi-Tesla fields

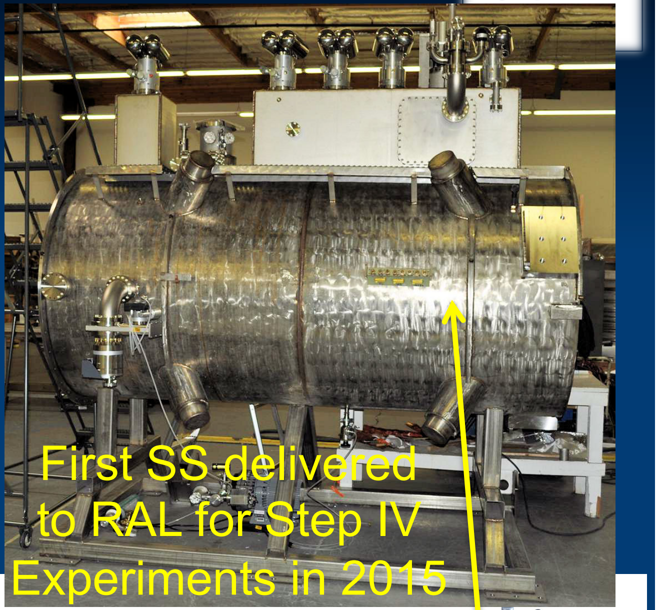
The program targets critical magnet and cooling cell technology demonstrations within its feasibility phase.

Cooling Channel Concepts



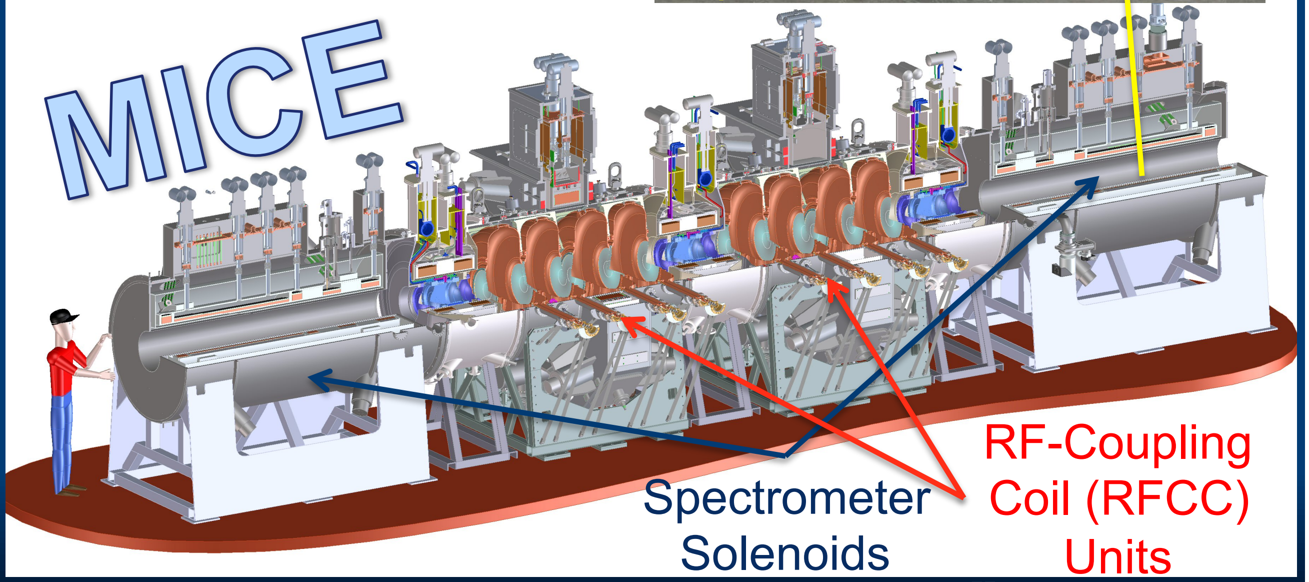
Technology Challenges - Coolin

- 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}



First SS delivered to RAL for Step IV Experiments in 2015

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

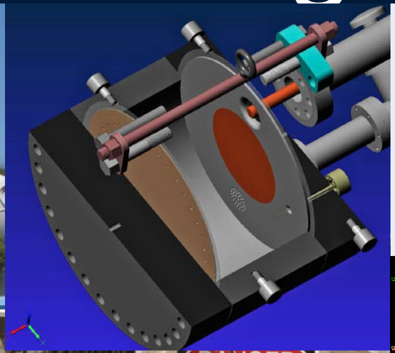


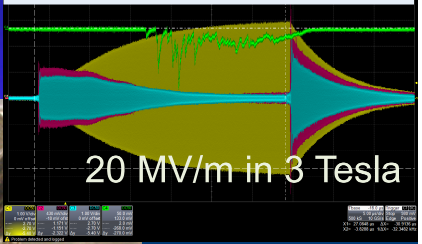
Elements of the R&D Program

MuCool Test Area

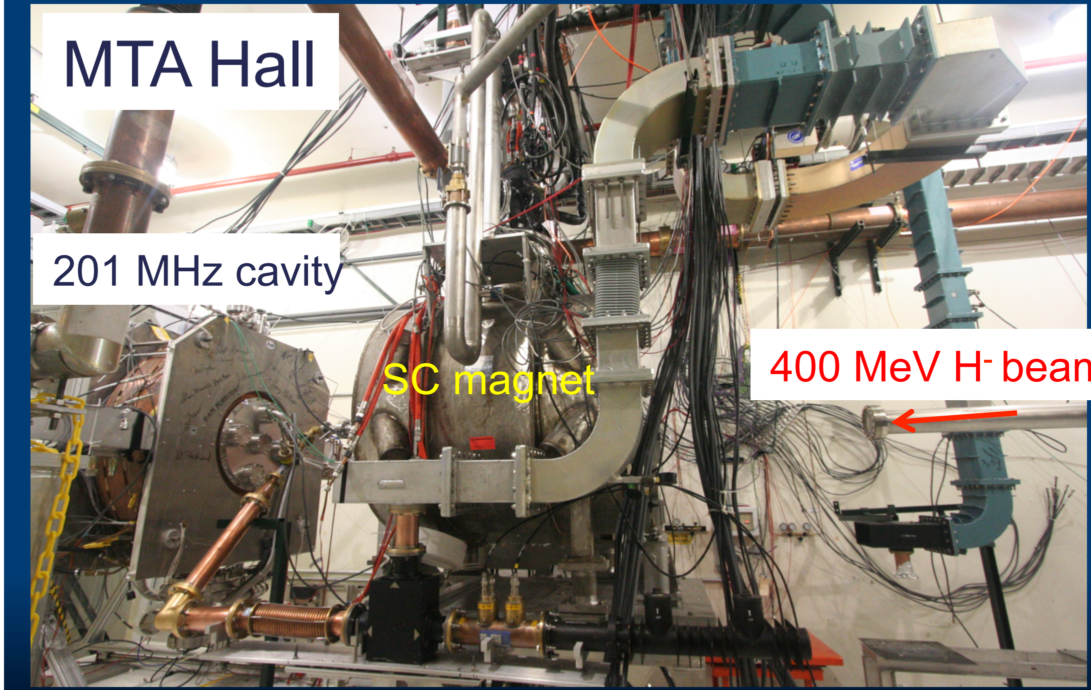

Entrance of MTA exp. hall

Compressor + refrigerator room


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

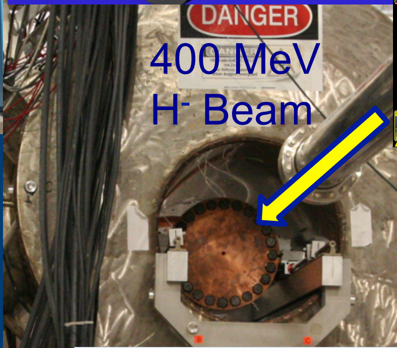

20 MV/m in 3 Tesla

MTA Hall


201 MHz cavity

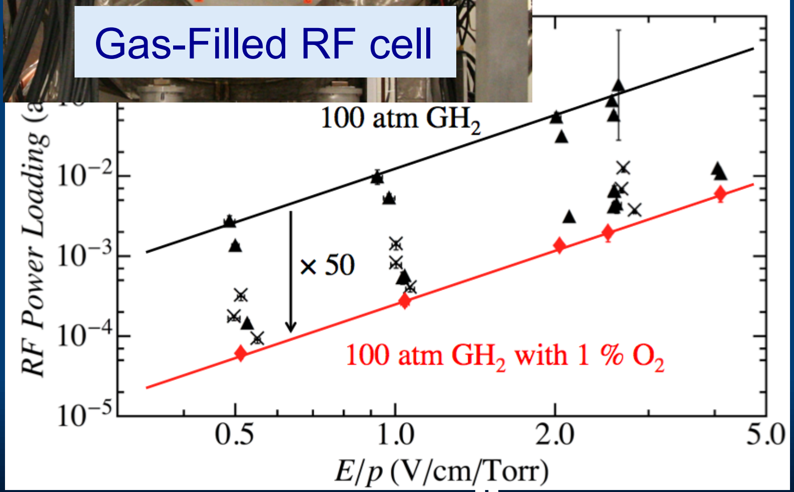
SC magnet

400 MeV H$^-$ beam

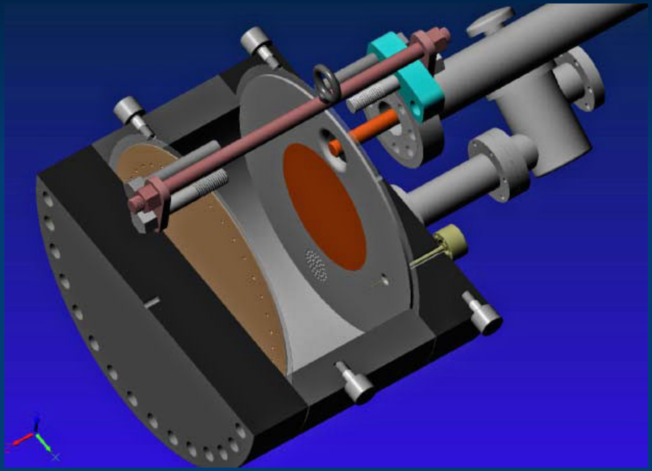


400 MeV H$^-$ Beam

Gas-Filled RF cell

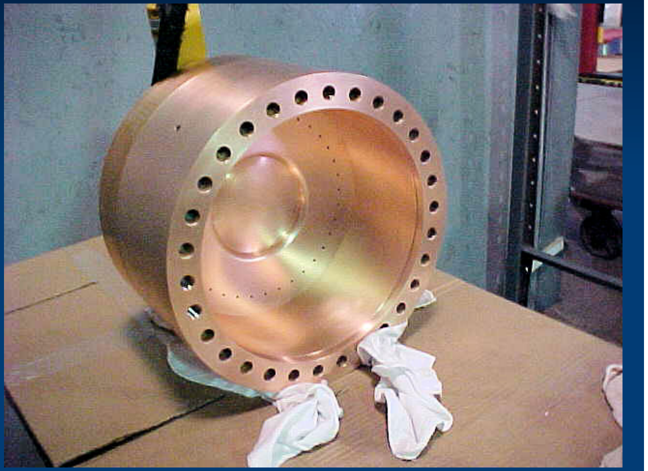


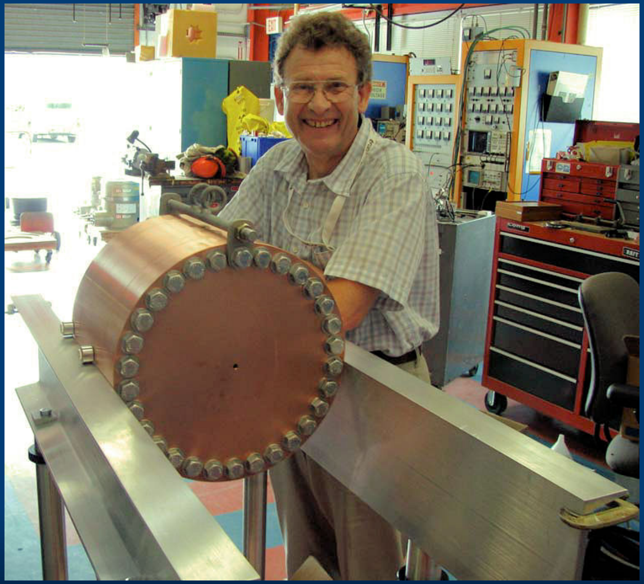
Recent Progress – Vacuum RF



All-Seasons Cavity

(designed for both vacuum and high pressure operation)

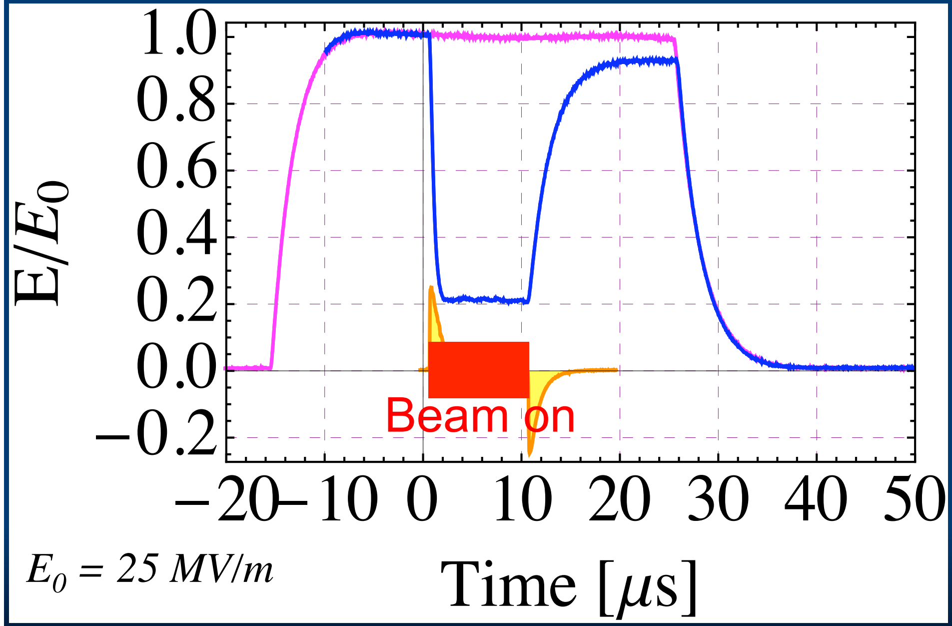


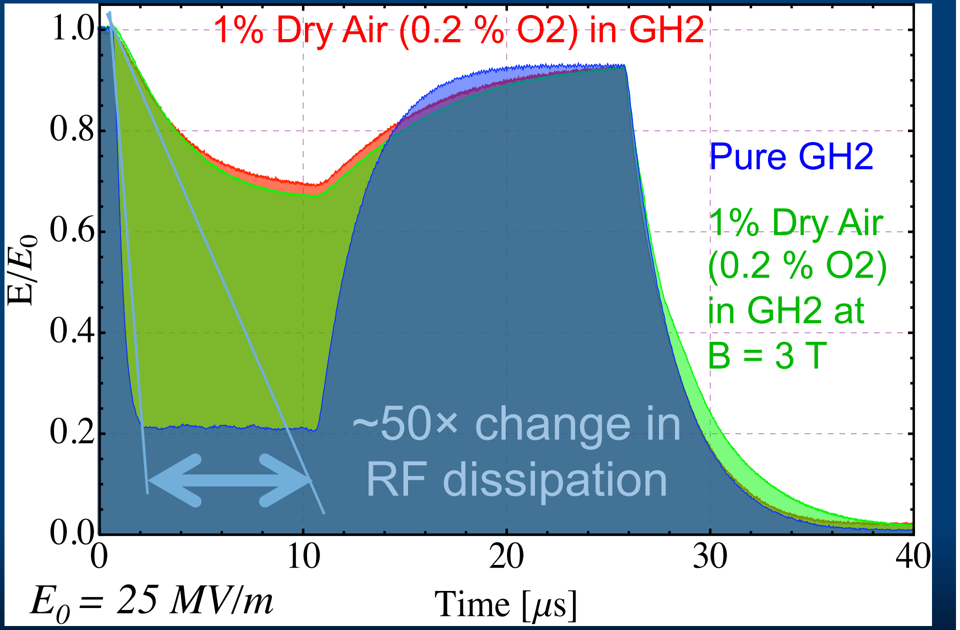


- Now operated in magnetic fields up to 5T:
  - Gradients > 20 MV/m
- Demonstrates possibility of successful operation of vacuum cavities in magnetic fields with careful design
- Successor design (the *805 MHz Modular Cavity*) will be ready for testing during FY14
- *Also progress on alternative cavity 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
  - Can moderate the loading effects of beam-induced plasma by scavenging the relatively mobile electrons





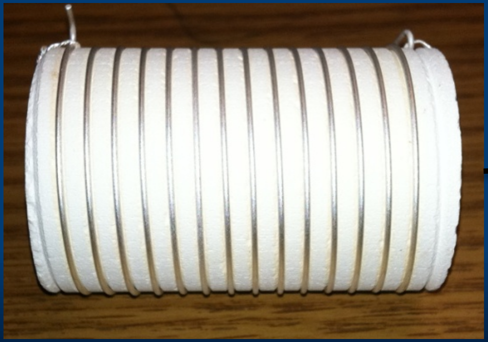
Recent Progress - High Field Magnets

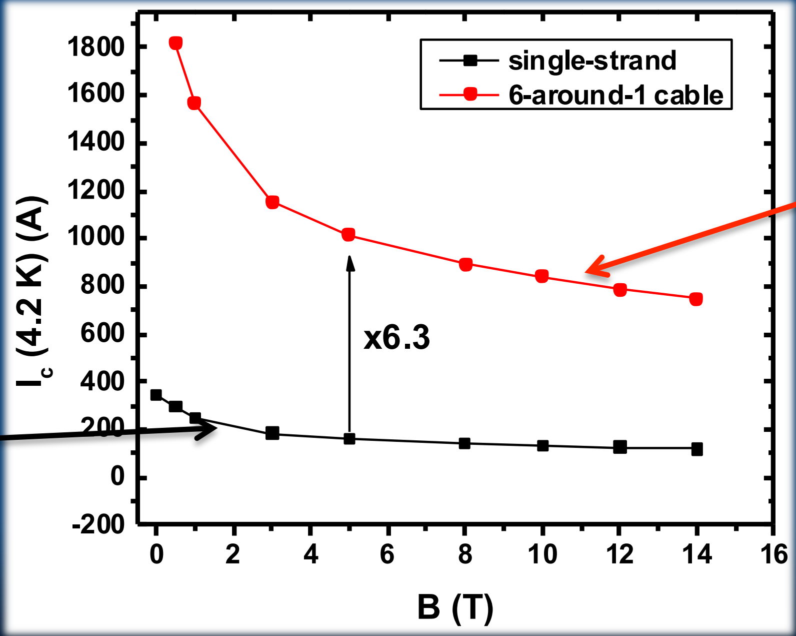
Progress towards a demonstration of a final stage cooling solenoid:

- Demonstrated 15+ T (16+ T on coil)
  - ~25 mm insert HTS solenoid
  - BNL/PBL YBCO Design
  - Highest field ever in HTS-only solenoid (by a factor of ~1.5)
- Developing a test program for operating HTS insert + mid-sert in an external solenoid ➪ >30 T

BSCCO-2212 -

- New cable fabrication methods with demonstrated J_E
- Hyperbaric processing to avoid strand damage





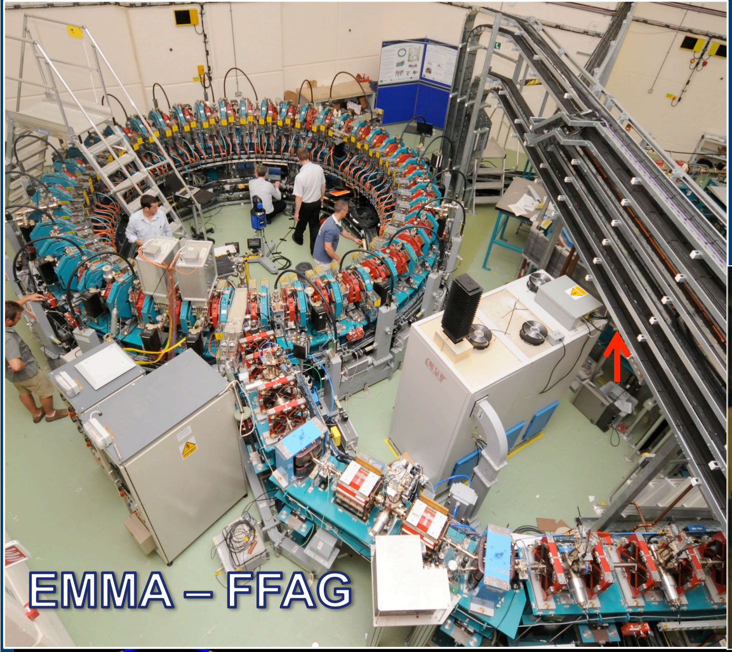
Multi-strand cable utilizing chemically compatible alloy and oxide layer to minimize cracks

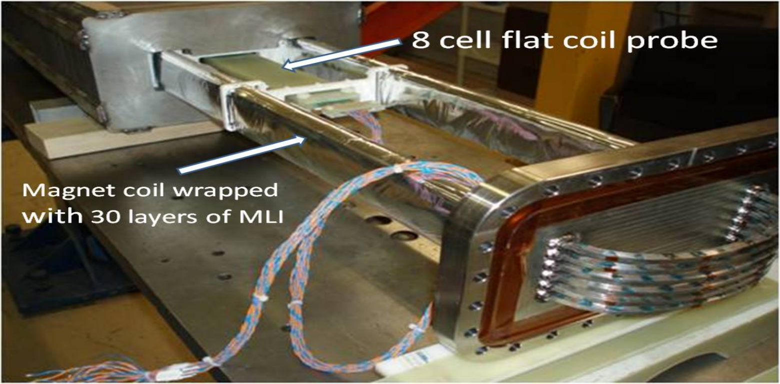
Technology Challenges - Accelerati

- Muons require an ultrafast accelerator chain

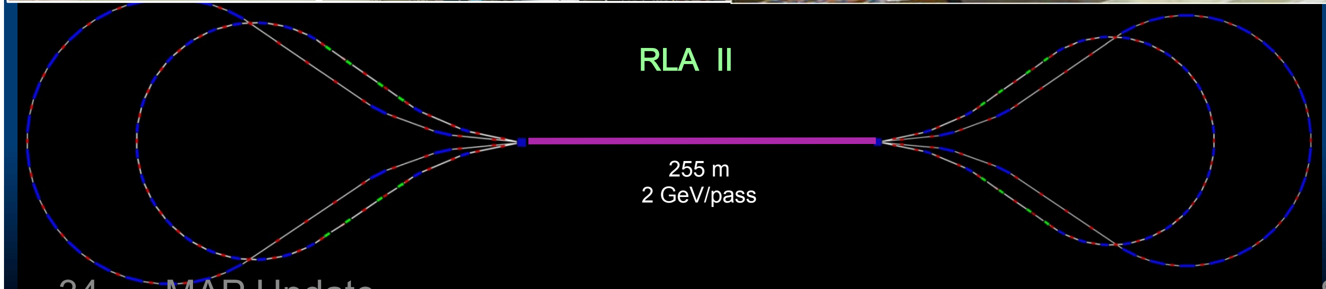
  ⇨ *Beyond the capability of most machines*

- Solutions include:
  - Superconducting Linacs
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient (FFAG) Machines
  - Rapid Cycling Synchrotrons (RCS)



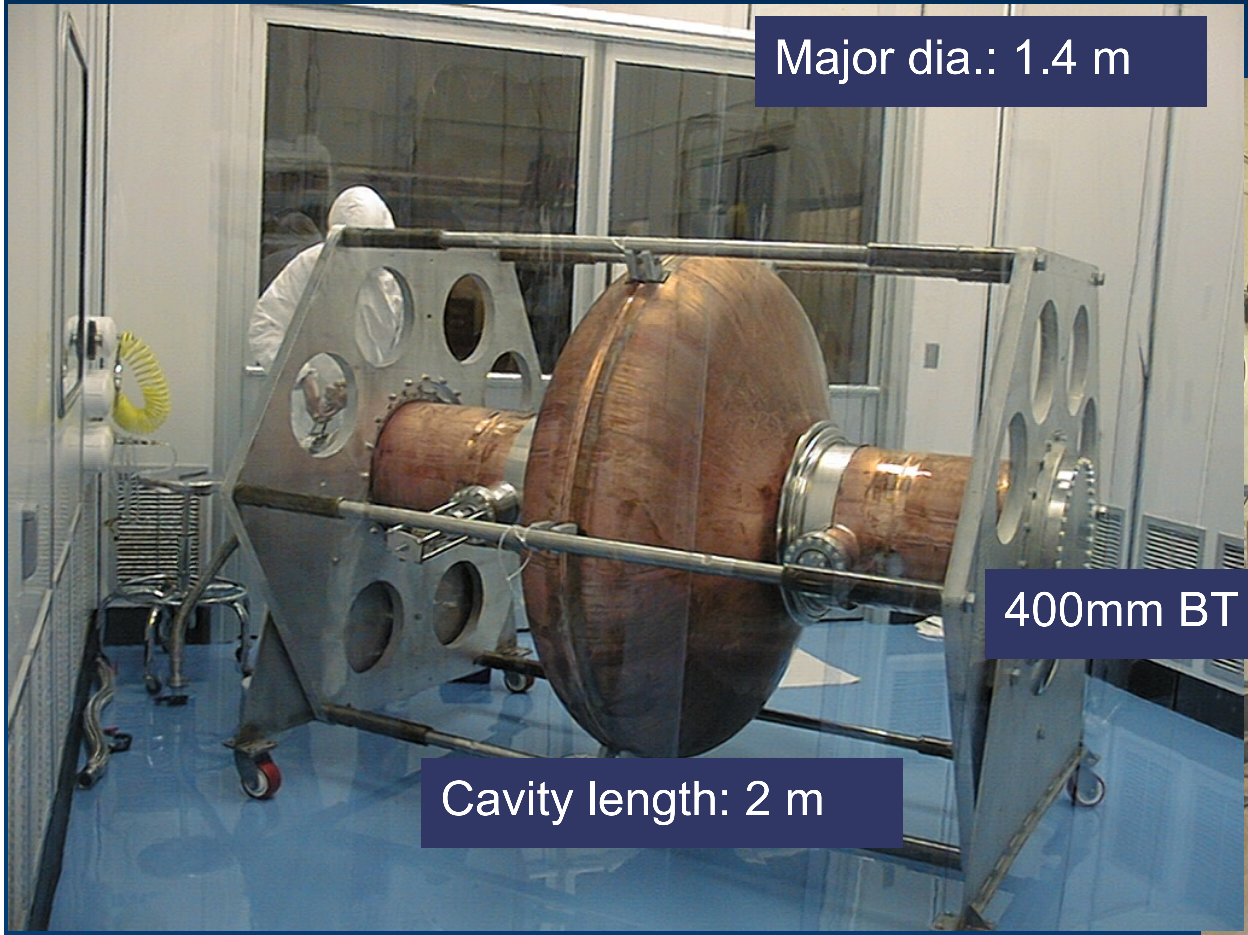


RCS requires
2 T p-p magnets
at f = 400 Hz
(U Miss & FNAL)



JEMMRLA Proposal: JLAB Electron Model of Muon RLA with Multi-pass Arcs

Superconducting RF Development

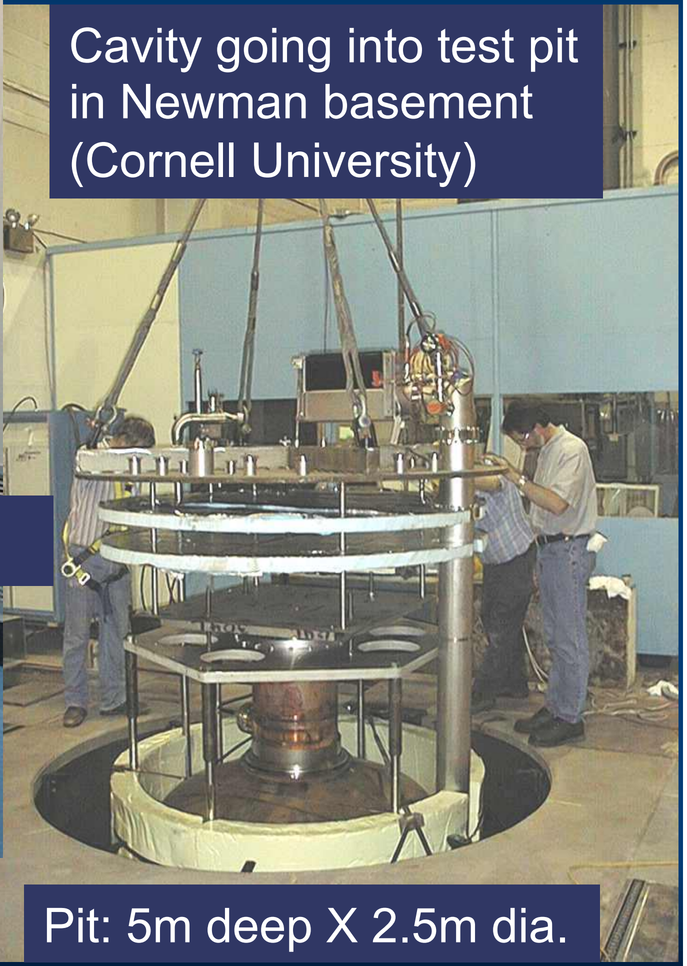


Major dia.: 1.4 m

400mm BT

Cavity length: 2 m

201 MHz SCRF R&D

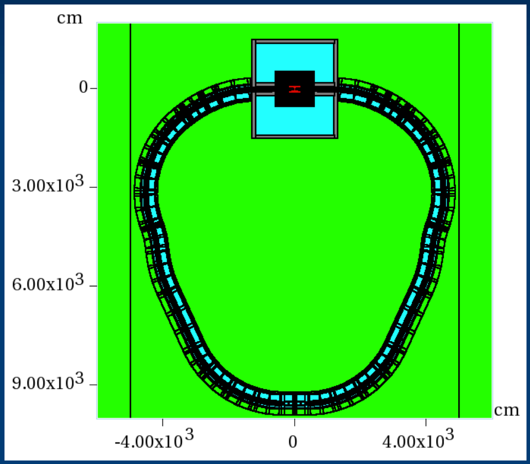


Cavity going into test pit in Newman basement (Cornell University)

Pit: 5m deep X 2.5m dia.

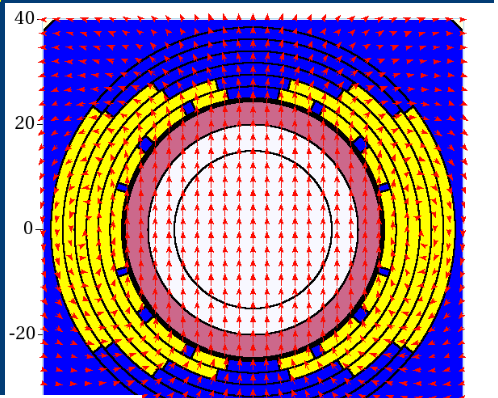
Technology & Design Challenges – Ring, Magnets, Detector

- Emittances are relatively large, but muons circulate for ~1000 turns before decaying
  - Lattice studies for 126 GeV, 1.5 & 3 TeV CoM

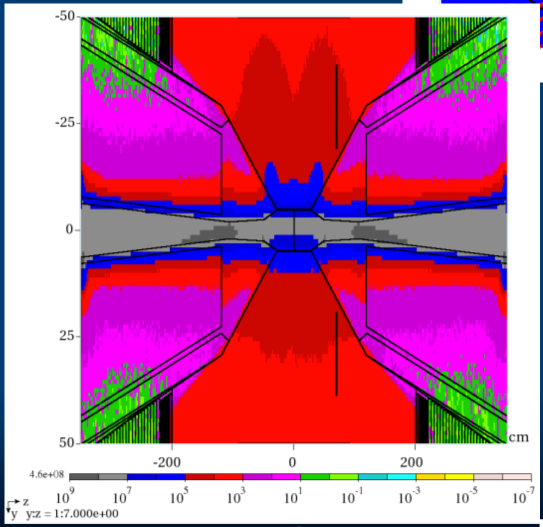


- High field dipoles and quadrupoles must operate in high-rate muon decay backgrounds
  - Magnet designs under study

MARS energy deposition studies for Higgs Factory magnets and IR



- Detector shielding & performance
  - Initial studies for 1.5 TeV, then 3 TeV and now 126 GeV
  - Shielding configuration
  - MARS background simulations



Backgrounds and Detector

Much of the background is soft and out of time

- Nanosecond time resolution can reduce backgrounds by three order

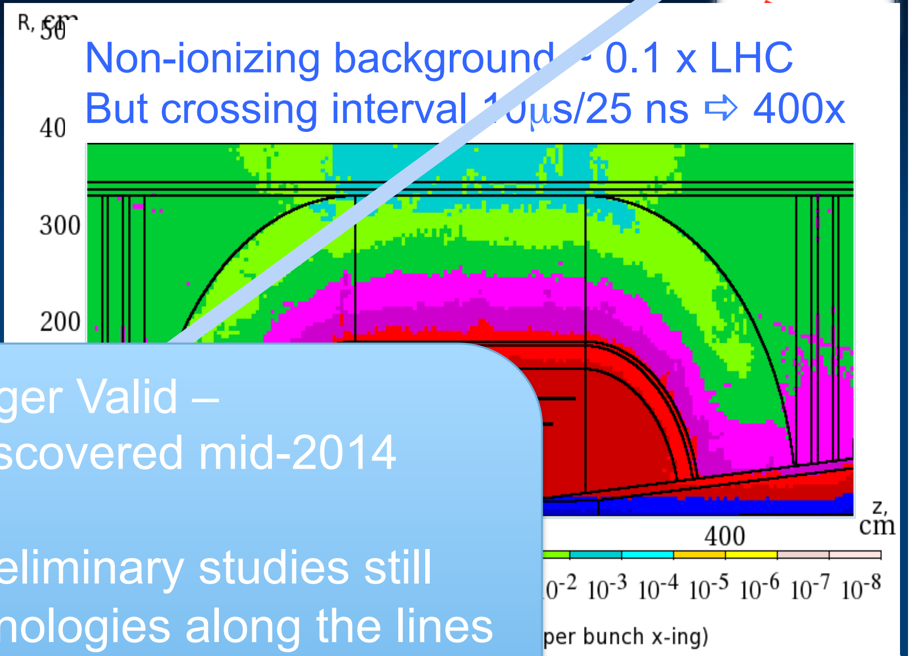
Requires a fa

tracker and ca

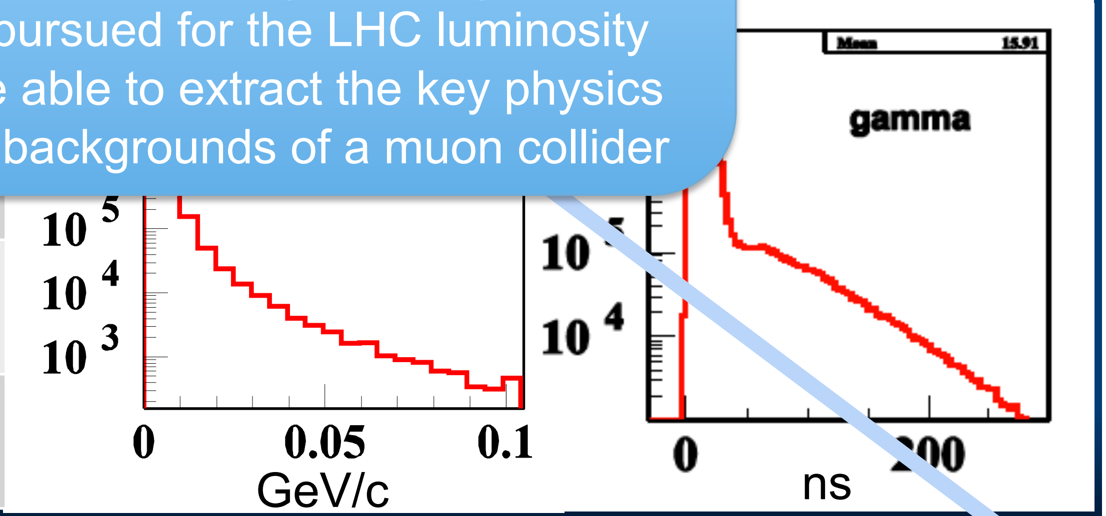
Slide No Longer Valid –
MARS Timing Bug Discovered mid-2014

Not yet updated, but preliminary studies still indicate that detector technologies along the lines of those being pursued for the LHC luminosity upgrades will be able to extract the key physics from the unique backgrounds of a muon collider

	Cut	
Tracker hits	1 dedx	
Calorimeter neutrons	2 ns	2.4×10^{-3}
Calorimeter photons	2 ns	2.2×10^{-3}



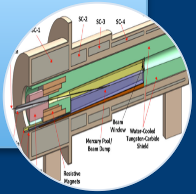
Non-ionizing background ~ 0.1 x LHC
But crossing interval 10μs/25 ns ⇨ 400x



Overview of MAP Magnet Pull

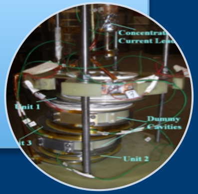
- Characteristics:
  - High field (15-20T)
  - Large bore (meter-scale)
  - Intense radiation environment – NC or HTS insert coil

Capture Solenoid for Simultaneous mu+ & mu- Beams



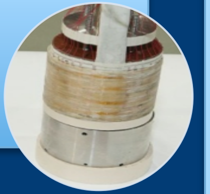
- Characteristics:
  - Solenoid-based cooling channel (LH_2/LiH absorbers)
  - RF cavities integral to focusing channel
  - Fields ranging from LTS to HTS conductor regime

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

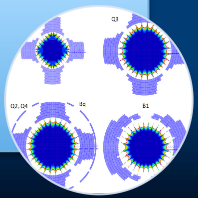


- Characteristics:
  - Present baseline based on the use of Rapid Cycling Synchrotrons
  - Requires magnets capable of ~400Hz operation with >1.5T peak fields

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



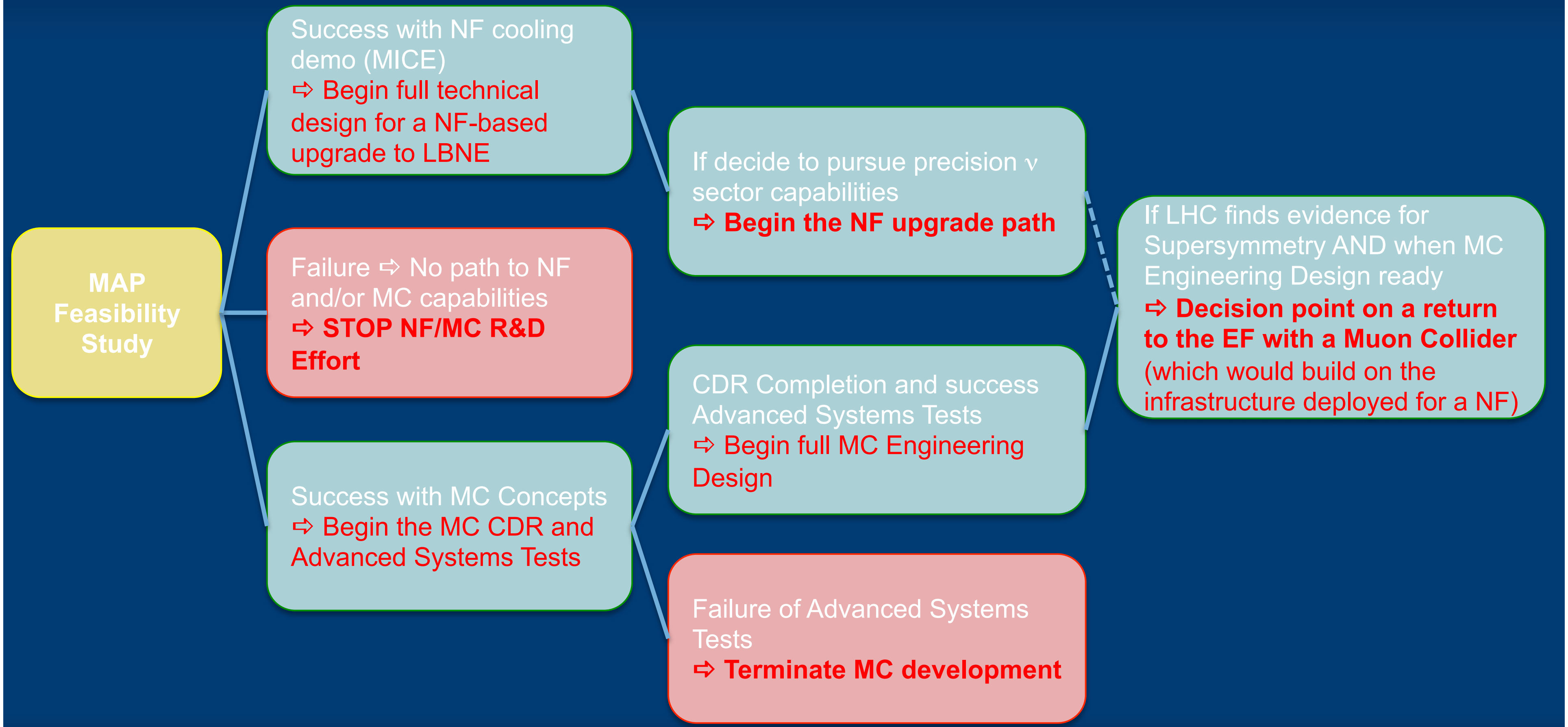
- Characteristics:
  - A MC (w/decaying beams) obtains the greatest performance enhancement of any HEP collider from HTS magnet technology
  - High quality HTS cables and magnets must be a priority

HTS Magnet Development

Feasibility R&D through End of Decade

A Muon Accelerator Capabilities Technical Decision Tree

| Thru ~2020 | ~2020 | ~2025 | Late 2020s |



MAP Feasibility Study

Success with NF cooling demo (MICE)
⇨ Begin full technical design for a NF-based upgrade to LBNE

Failure ⇨ No path to NF and/or MC capabilities
⇨ STOP NF/MC R&D Effort

Success with MC Concepts
⇨ Begin the MC CDR and Advanced Systems Tests

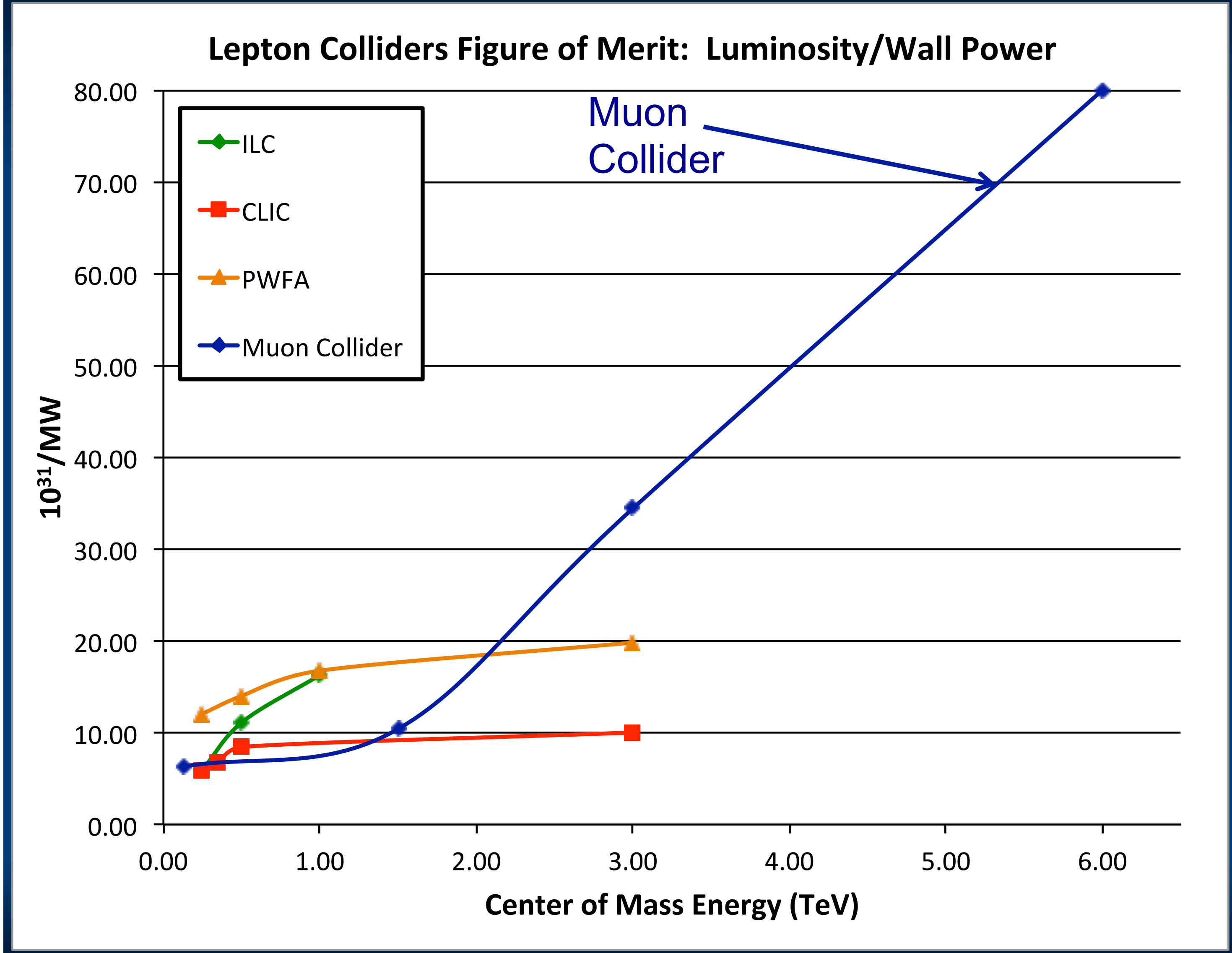
If decide to pursue precision ν sector capabilities
⇨ Begin the NF upgrade path

CDR Completion and success Advanced Systems Tests
⇨ Begin full MC Engineering Design

Failure of Advanced Systems Tests
⇨ Terminate MC development

If LHC finds evidence for Supersymmetry AND when MC Engineering Design ready
⇨ Decision point on a return to the EF with a Muon Collider
(which would build on the infrastructure deployed for a NF)

Luminosity Production Metric



Luminosity Metric:

$N_{det} \times L_{avg} / P_{tot}$