The Muon Accelerator Program

Mark Palmer

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Fermilab

Introduction and Context

The focus of the Muon Accelerator Program (MAP) is on the R&D required to demonstrate feasibility of muon accelerators for HEP applications

- Neutrino Factories (NF)
  - Both long and short baseline
- Muon Colliders (MC)
  - Higgs Factory to multi-TeV Scale
- Also muon accelerator concepts that can support ongoing/planned experiments (eg, narrow band neutrino beam line & cooled muon sources)

Program scope spans near- to long-term facility concepts!

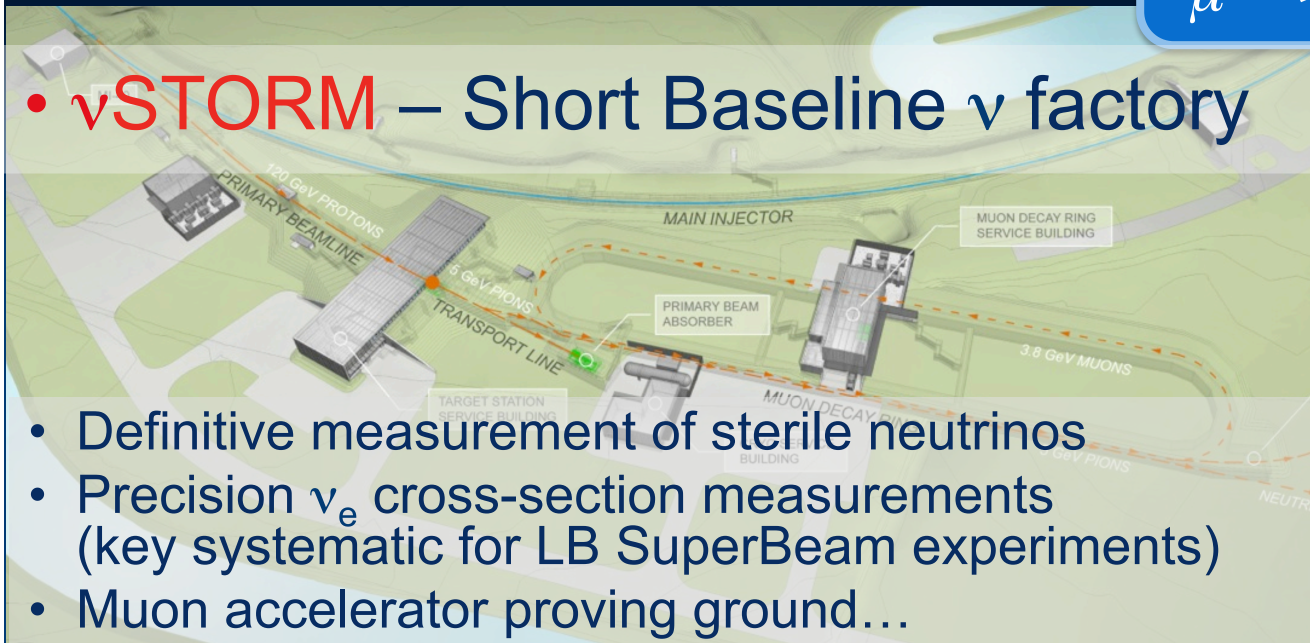
NF and MC Muon Accelerator capabilities are strongly linked

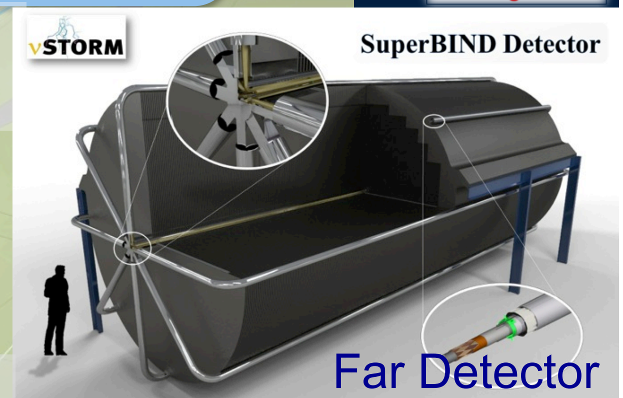
- With key synergies that can be exploited to control technical risk and cost
- A unique breadth of physics that can be supported

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…

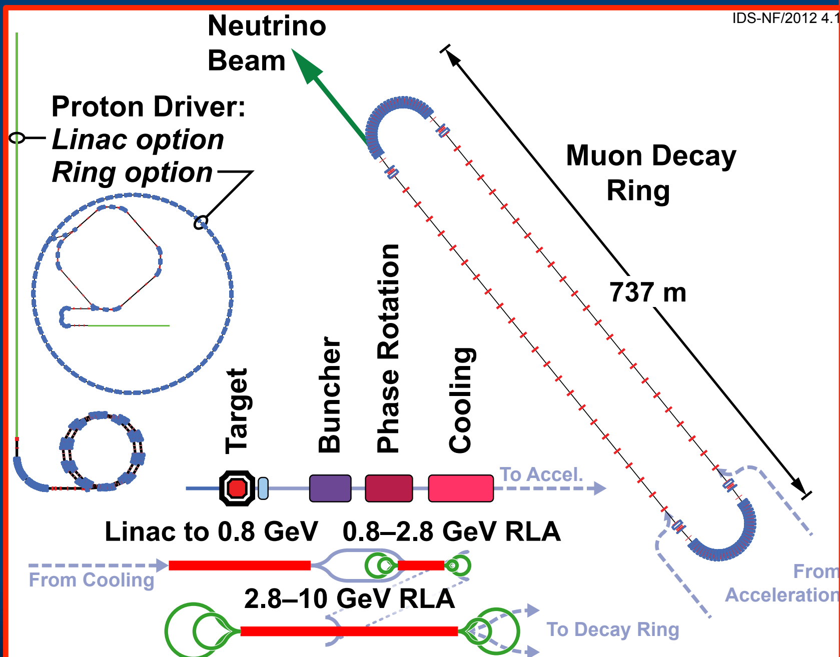
- **NuMAX** (Neutrinos from a Muon Accelerator CompleX)
  - Long baseline concept developed by MAP
    - As part of its Muon Accelerator Staging Study (MASS)
  - Evolutionary from IDS-NF Concept ⇨ FNAL to SURF baseline
    - Magnetized detector (MIND, Mag LAr?)
    - CP violation sensitivity optimal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

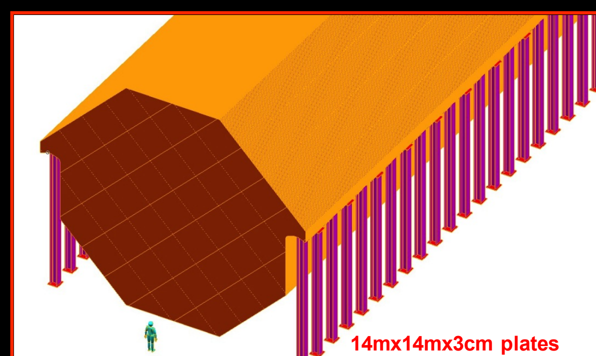
NuMAX@5 GeV⇨SURF

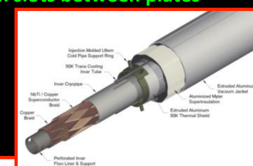
	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to long-baseline neutrino detector	1 500–2 500 km

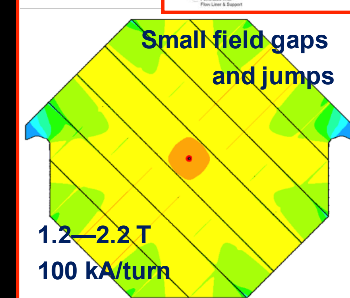


Magnetized Iron Neutrino Detector (MIND):

- **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





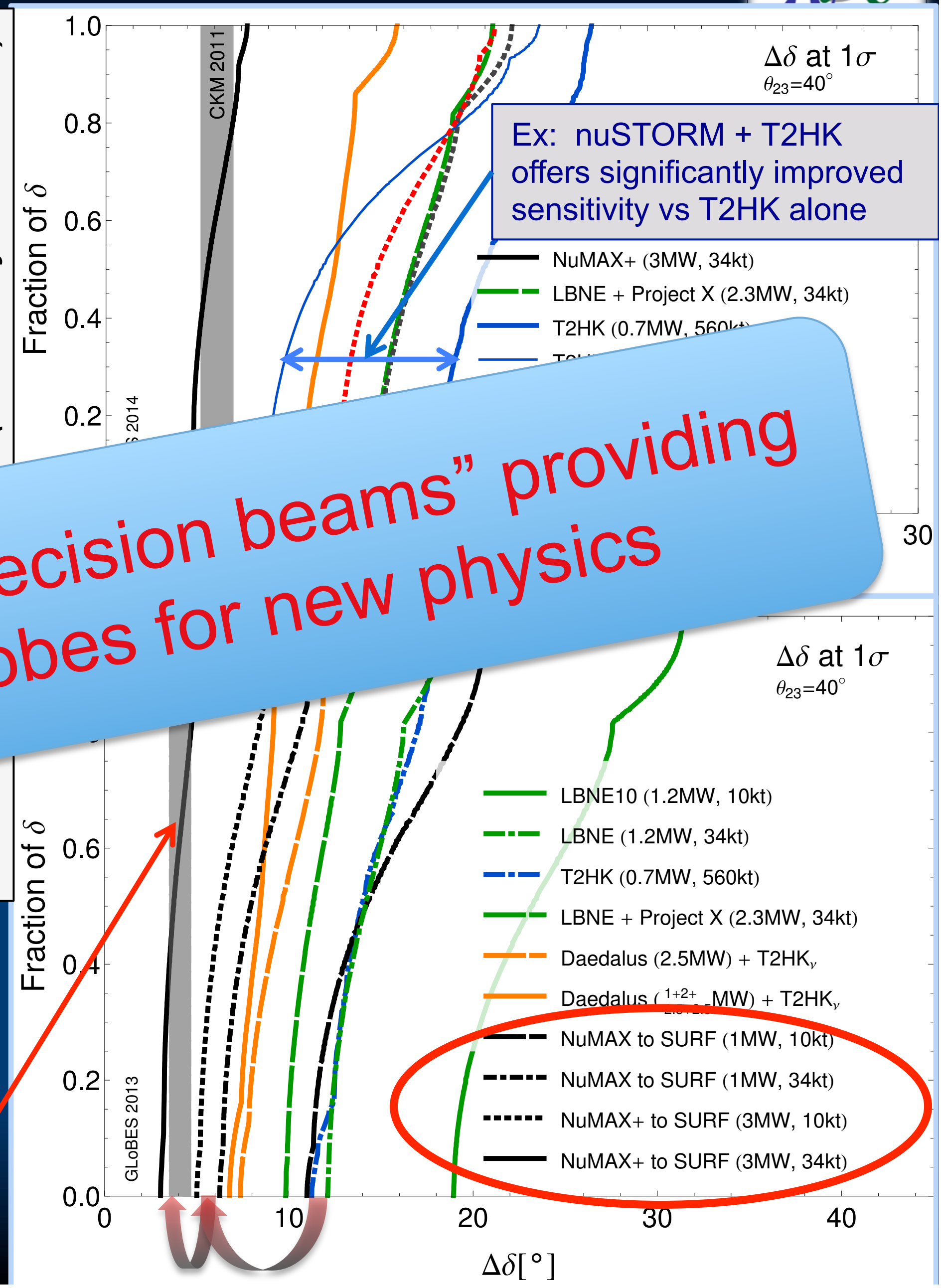


Bross, Soler

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 systematics
- NuMAX
  - Ultimate ... ν sector
  - Offers:
    - Well-characterized beam
    - Energy Flexibility
    - Discovery Potential!

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



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

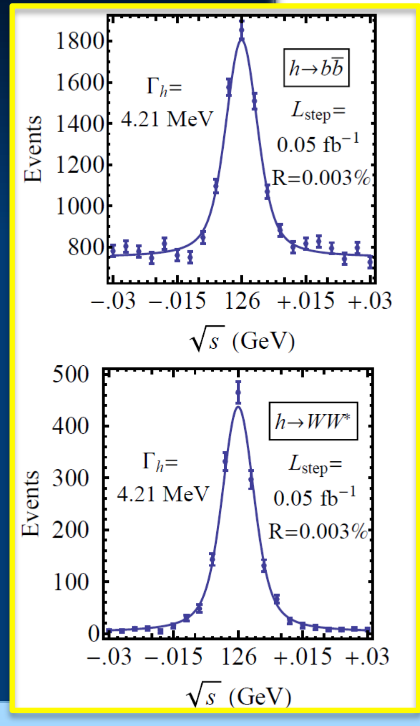
NuMAX+ targets equivalent sensitivity to CP violation in the ν sector as has been achieved in the flavor sector

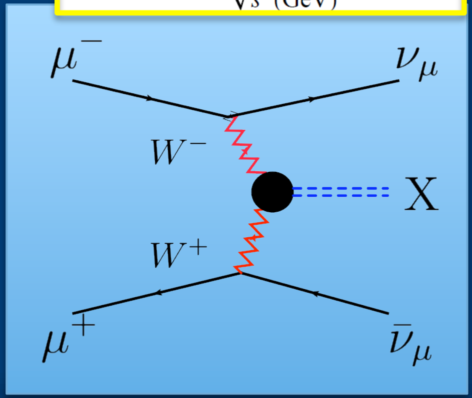
NF Staging (MASS)

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

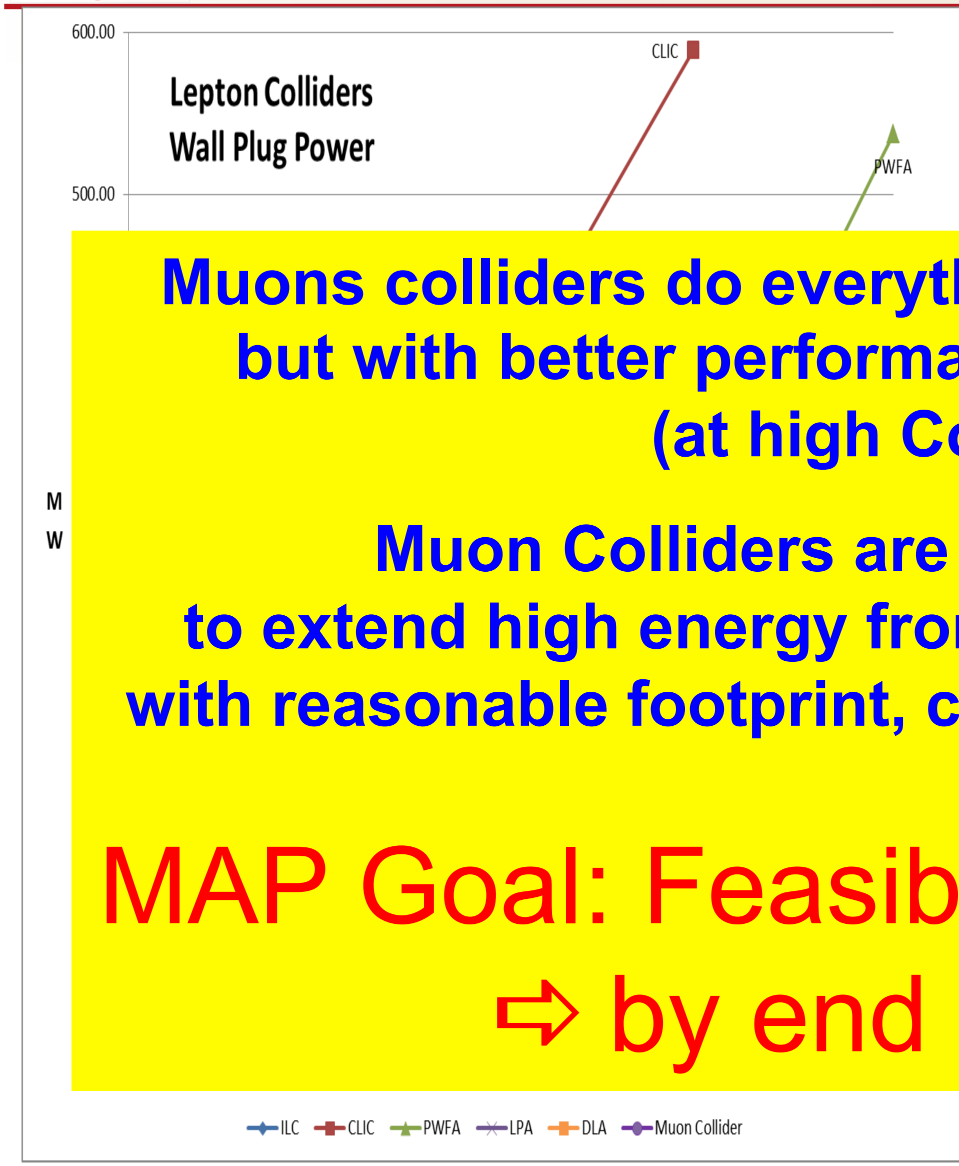
- Superb Energy Resolution
  - SM Thresholds and s-channel Higgs Factory operation
- Multi-TeV Capability (≤ 10TeV):
  - Compact & energy efficient machine
  - Luminosity > 10^{34} cm^{-2} s^{-1}
  - Option for 2 detectors in the ring
- For √s > 1 TeV: Fusion processes dominate
  - ⇨ an Electroweak Boson Collider
  - ⇨ a discovery machine complementary to a very high energy pp collider
  - At >5TeV: Higgs self-coupling resolutions of <10%

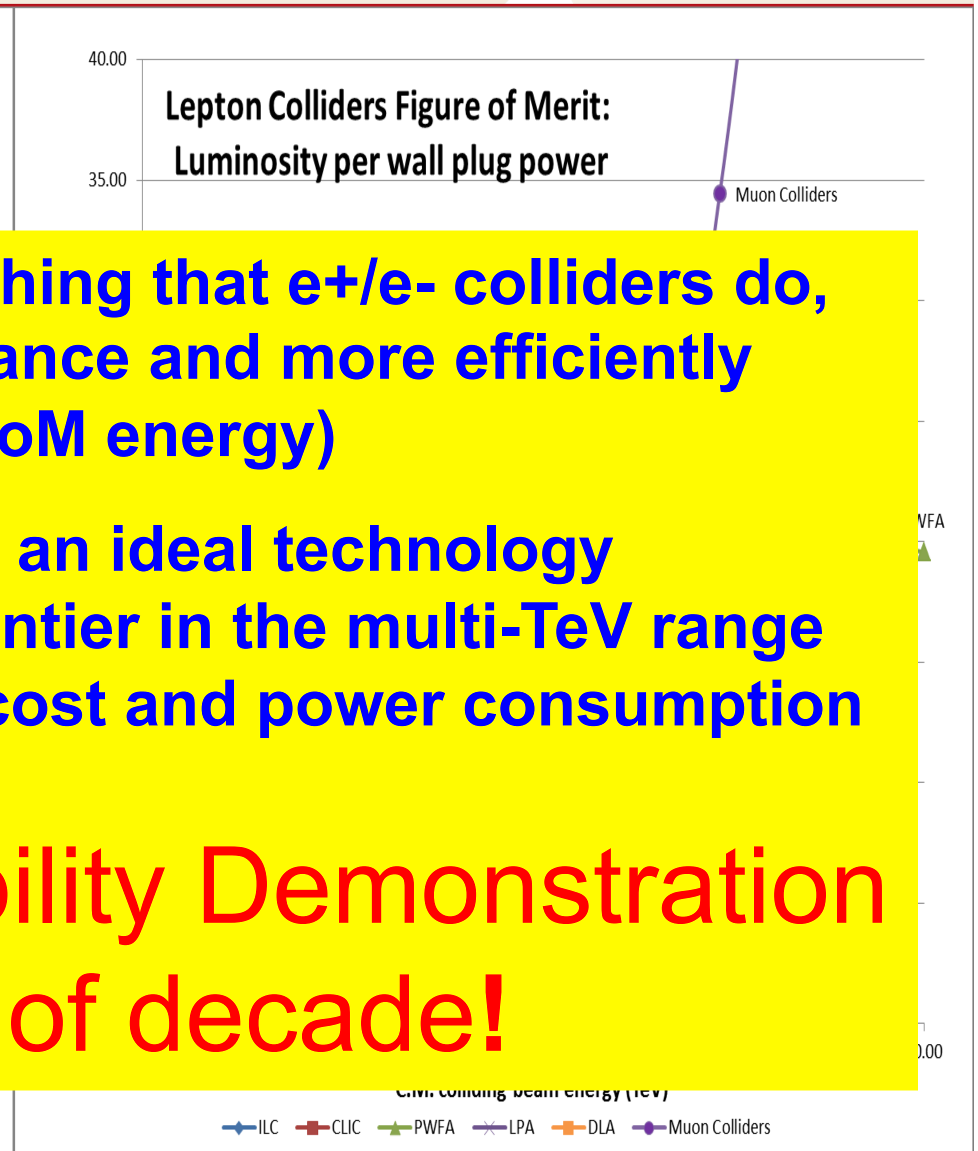




What are our accelerator options if new LHC data shows evidence for a multi-TeV particle spectrum?

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





Muons colliders do everything that e+/e- colliders do, but with better performance and more efficiently (at high CoM energy)

Muon Colliders are an ideal technology to extend high energy frontier in the multi-TeV range with reasonable footprint, cost and power consumption

MAP Goal: Feasibility Demonstration
⇨ by end of decade!

The Staging Study (MASS)

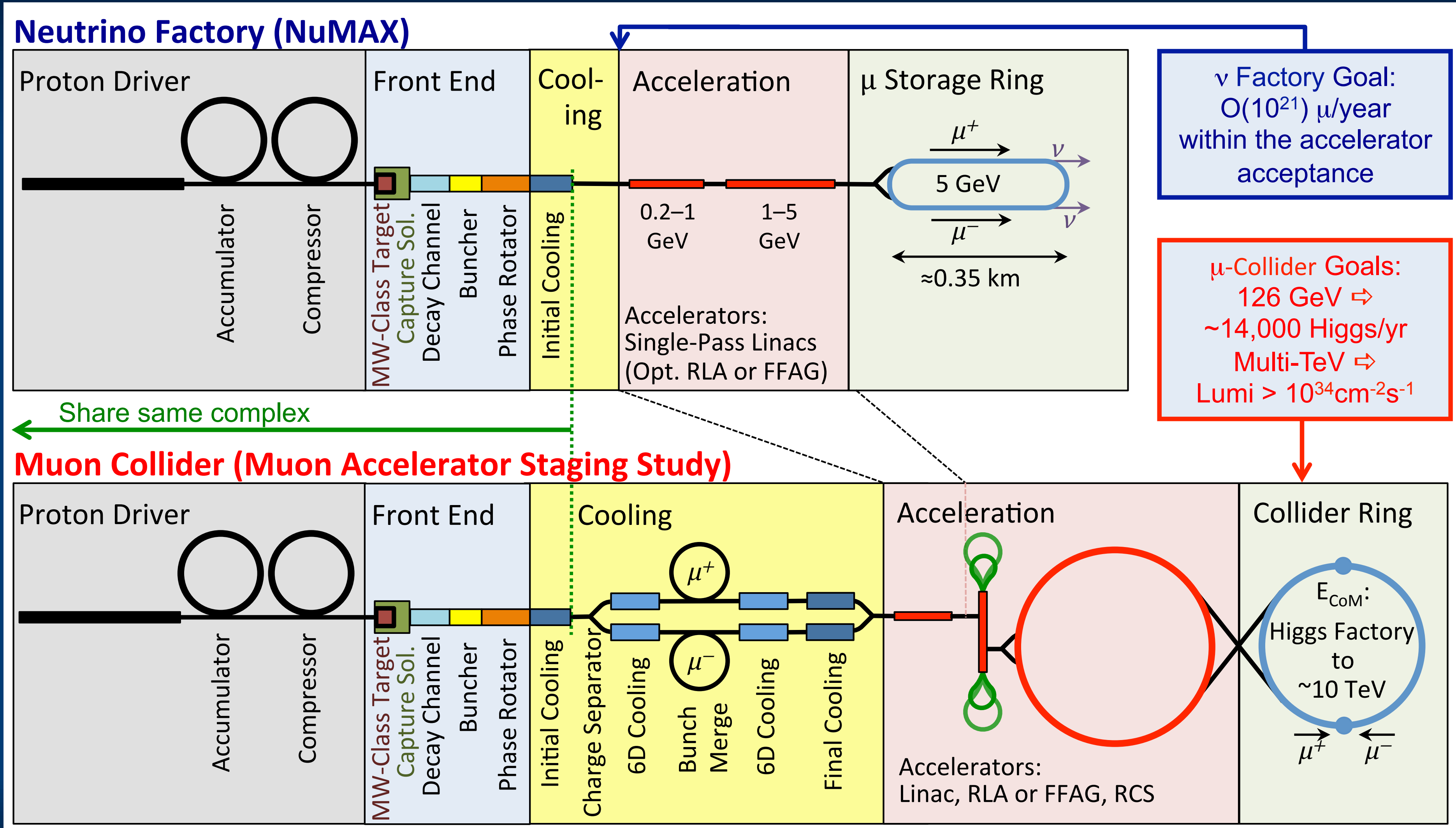
Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the US - http://arxiv.org/pdf/1308.0494

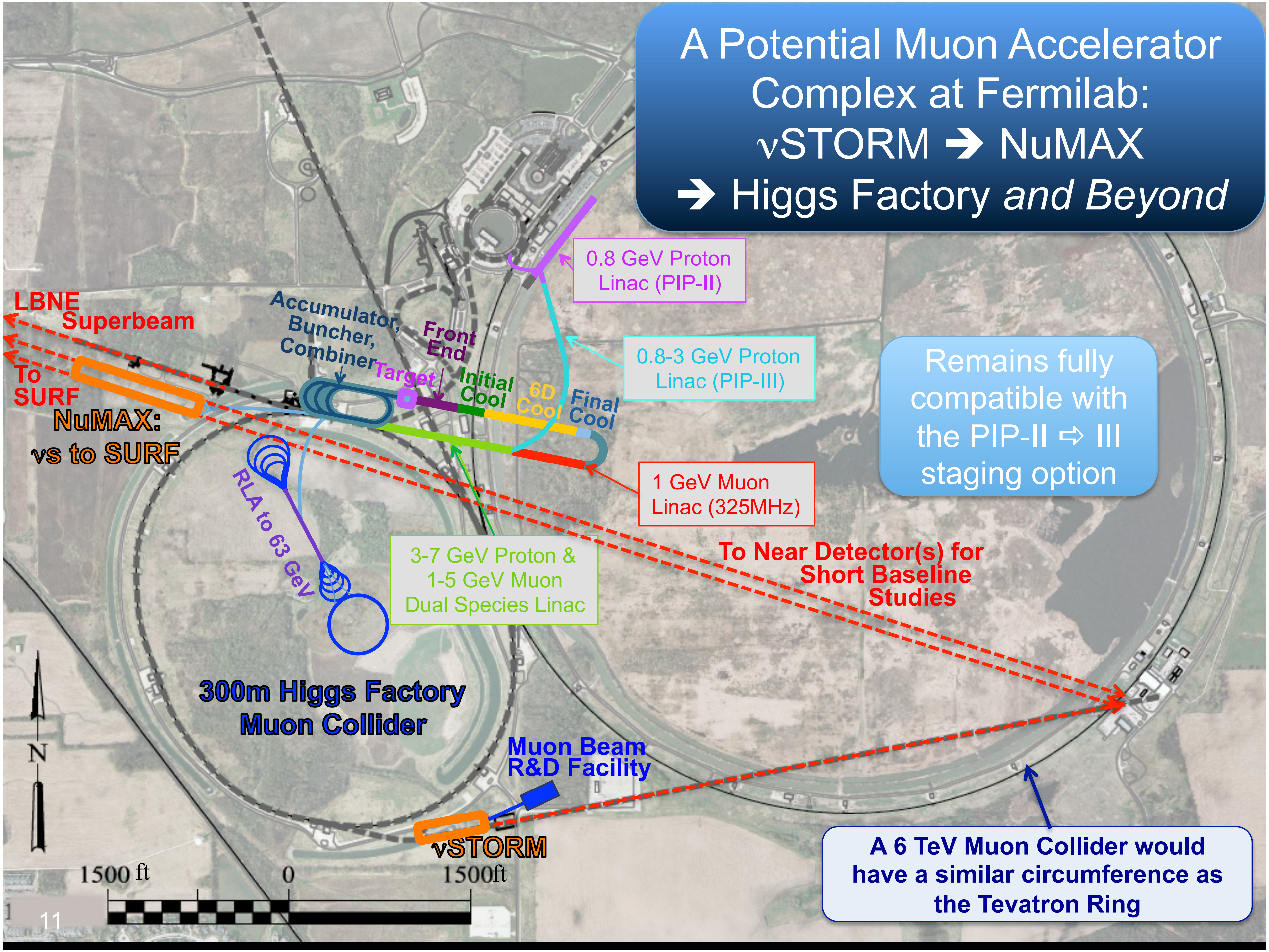
The plan consists of a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach:

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

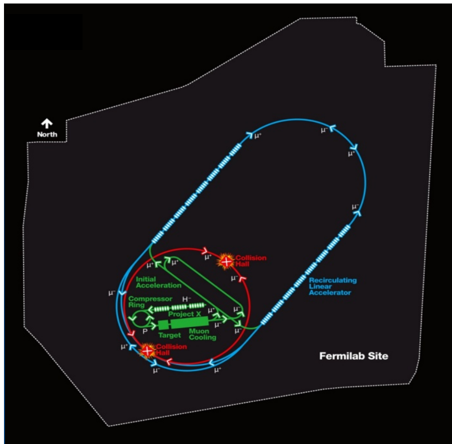
Ability to utilize some or all stages

NF/MC Synergies




A Potential Muon Accelerator Complex at Fermilab:
νSTORM ➔ NuMAX
➔ Higgs Factory and Beyond
0.8 GeV Proton Linac (PIP-II)
0.8-3 GeV Proton Linac (PIP-III)
Remains fully compatible with the PIP-II ⇨ III staging option
1 GeV Muon Linac (325MHz)
LBNE Superbeam
To SURF
NuMAX: νs to SURF
Accumulator, Buncher, Combiner
Front End
Target
Initial Cool
6D Cool
Final Cool
RLA to 63 GeV
3-7 GeV Proton & 1-5 GeV Muon Dual Species Linac
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

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	$10^{34}cm^{-2}s^{-1}$	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/10^7sec		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

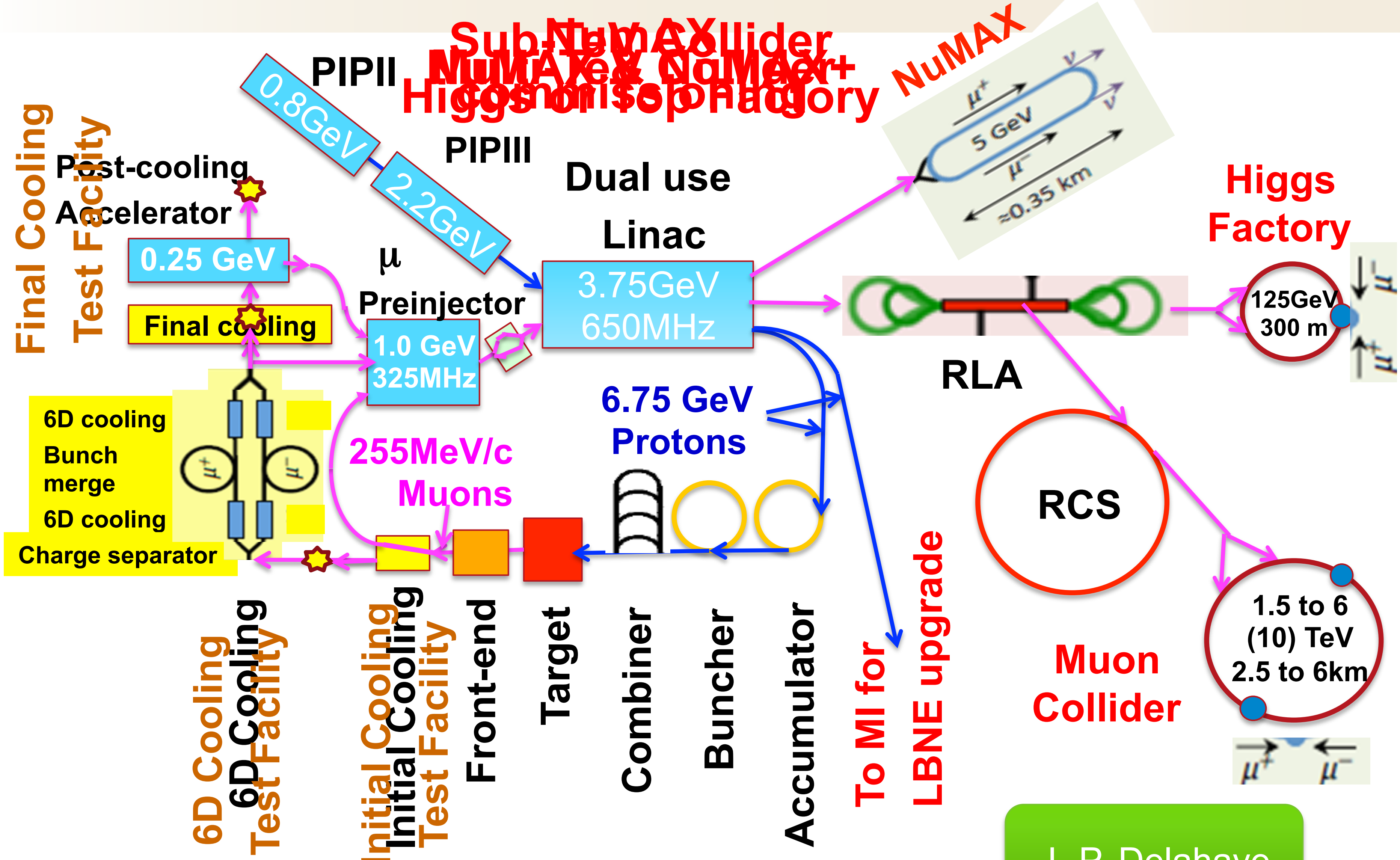
Could begin operation with Project X Stage II beam

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

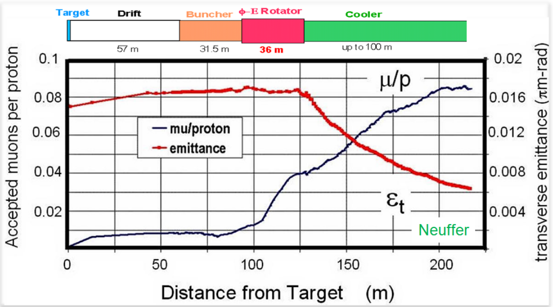
Progressive installation in stages with Physics and technology validation at each stage



J.-P. Delahaye

Technical Challenges

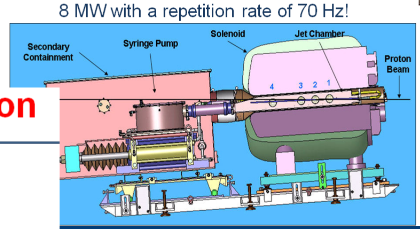
Technical Challenge: Tertiary Production

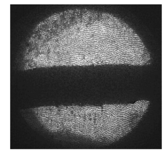


- A multi-MW proton source, *e.g.*, Project X, will enable O(10^{21}) muons/year to be produced, bunched and cooled fit within the acceptance of an accelerator.

Technical Challenges: Target

- The MERIT Experiment at the CERN PS
  - Proof-of-principle demonstration of a liquid Hg jet target in high-field solenoid in Fall `07
  - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!
  - ⇨ Technology OK for beam powers up to 8 MW with a repetition rate of 70 Hz!



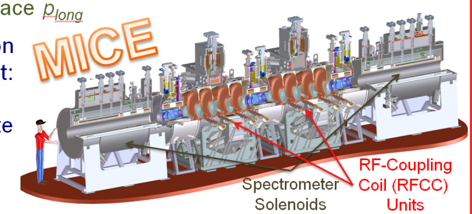


Hg jet in a 15 T solenoid with measured disruption length ~ 28 cm

Technical Challenges: Cooling

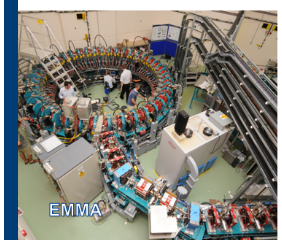
- Tertiary production of muon beams ⇨
  - Initial beam emittance intrinsically large
  - Cooling mechanism required, but no radiation damping
- Muon Cooling ⇨ Ionization Cooling
  - dE/dx energy loss in materials
  - RF to replace p_{long}

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



Technical Challenges: Acceleration

- Muons require an ultrafast accelerator chain
  ⇨ *Beyond the capability of most machines*
- Several solutions for a muon acceleration scheme have been proposed:
  - Superconducting Linacs
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient (FFAG) Machines
    - ➢EMMA at Daresbury Lab is a test of the promising non-scaling type
  - Rapid Cycling Synchrotrons (RCS)
  - Hybrid Machines



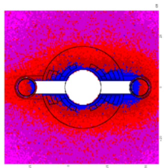
Technical Challenges: RF

A Viable Cooling Channel requires
- Strong focusing and a large accelerating gradient to compensate for the energy loss in absorbers
- ⇨ Large B- and E-fields superimposed

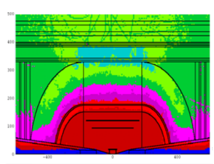
Operation of RF cavities in high magnetic fields is a necessary element for muon cooling
- Control RF breakdown in the presence of high magnetic fields
- The MuCool Test Area (MTA) at Fermilab is actively investigating operation of RF cavities in the relevant regimes
- Development of concepts to mitigate the challenges are being actively pursued

Technical Challenges: Ring, Magnets, Detector

- Emittances are relatively large, but muons circulate for ~1000 turns before decaying
  - Lattice studies for 1.5 TeV and 3 TeV CoM
- High field dipoles and quadrupoles must operate in high-rate muon decay backgrounds
  - Magnet designs under study
- Detector shielding & performance
  - Initial studies for 1.5 TeV, then 3 TeV
  - Shielding configuration
  - MARS background simulations



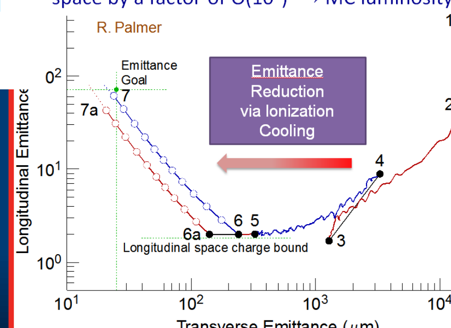
MARS energy deposition map for 1.5 TeV collider dipole



MAP Feasibility Assessment – By end of decade

Technical 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



Some components beyond state-of-art:
- Very high field HTS solenoids (30-40 T)
- High gradient RF cavities operating in multi-Tesla fields

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

MAP R&D Thrusts

Design Studies

- Proton Driver
- Front End
- Cooling
- Acceleration and Storage
- Collider
- Machine-Detector Interface
- Work closely with physics and detector efforts

Technology R&D

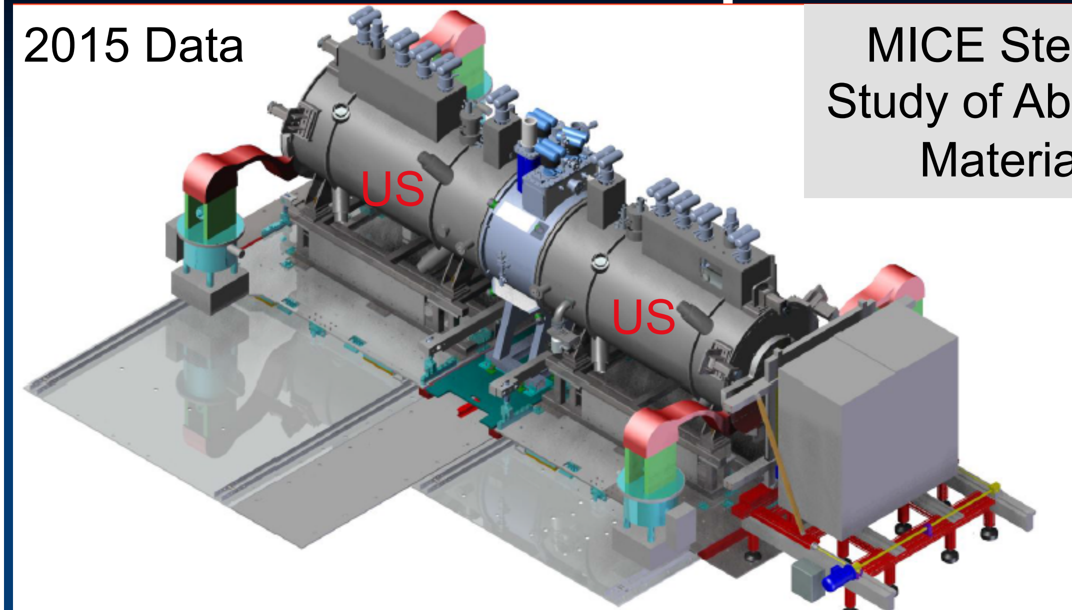
- RF in magnetic fields
- SCRF for acceleration chain (eg, 200 MHz cavities)
- High field magnets
  - Utilizing HTS technologies
- Targets & Absorbers
- MuCool Test Area (MTA)

Major System Demonstration

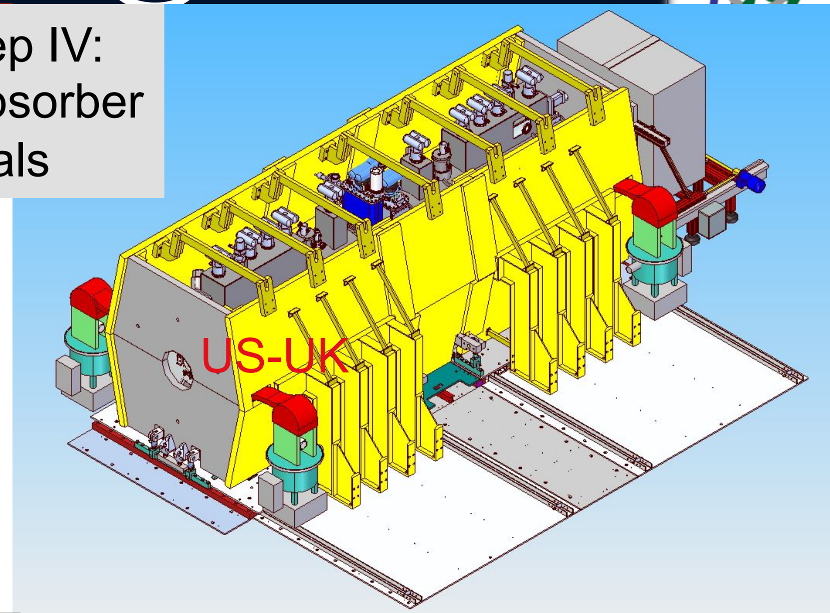
- The Muon Ionization Cooling Experiment – MICE
  - Major U.S. effort to provide key hardware: RF Cavities and couplers, Spectrometer Solenoids, Coupling Coil(s), Partial Return Yoke
  - Experimental and Operations Support

MICE Experiment @RAL

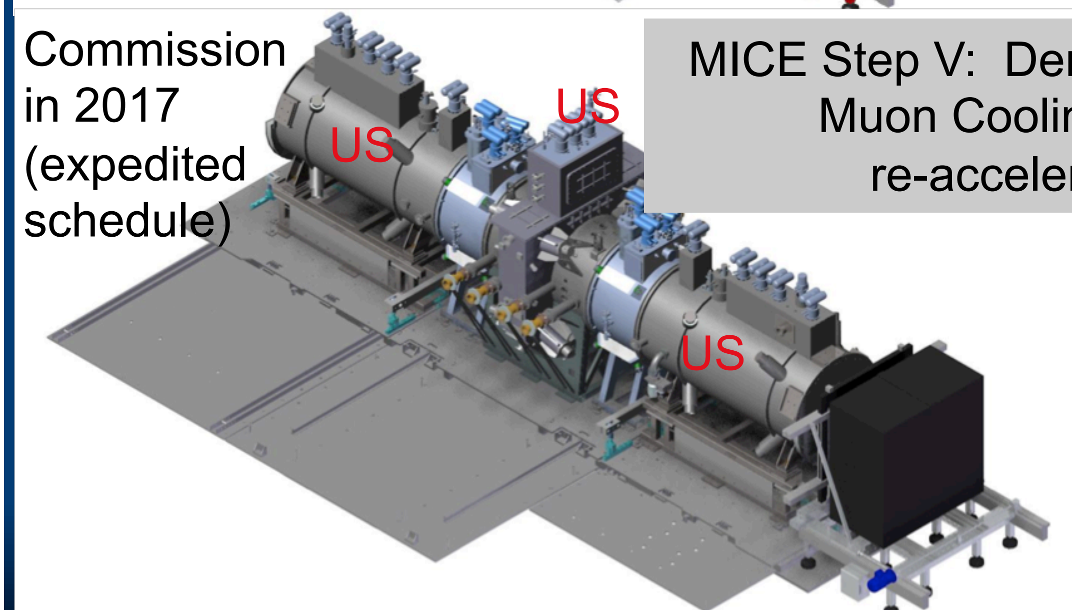
2015 Data



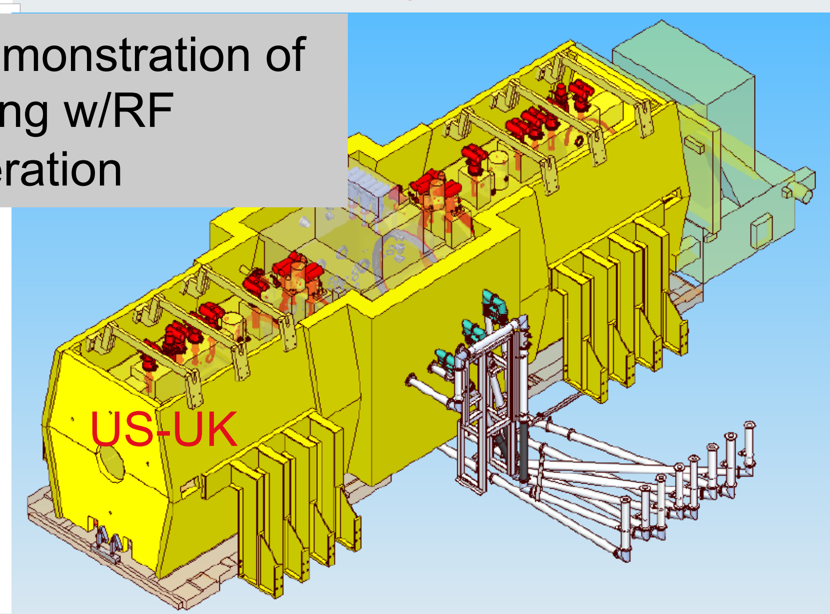
MICE Step IV:
Study of Absorber
Materials



Commission
in 2017
(expedited
schedule)

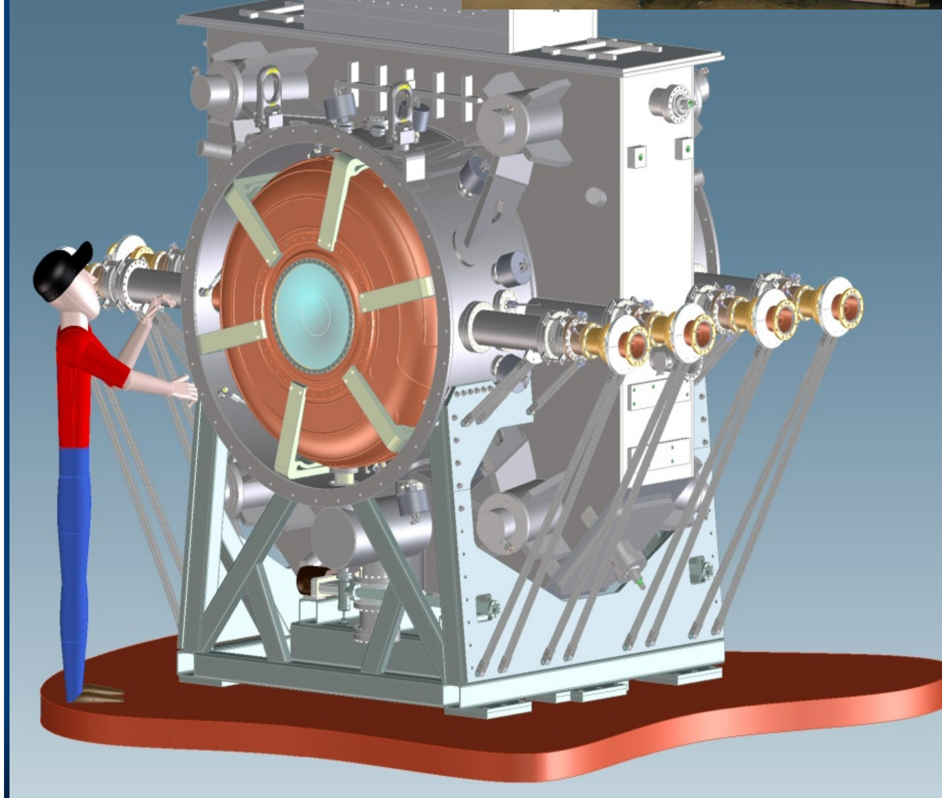


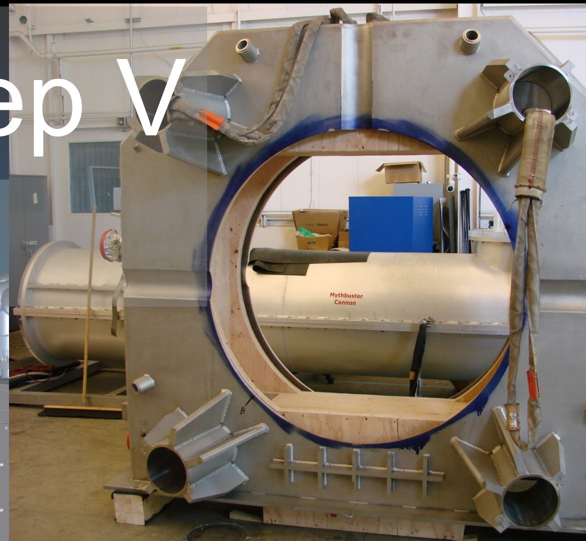
MICE Step V: Demonstration of
Muon Cooling w/RF
re-acceleration



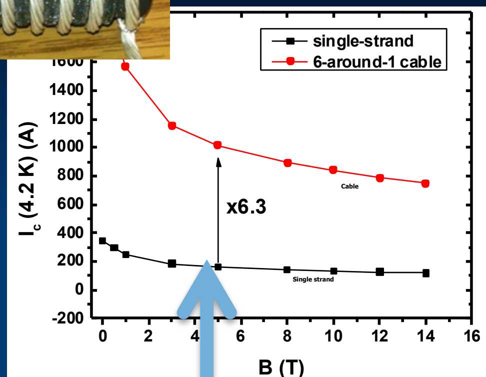
MICE Step IV Integration

MICE Step V
RFCC





Cooling Channel R&D Effort

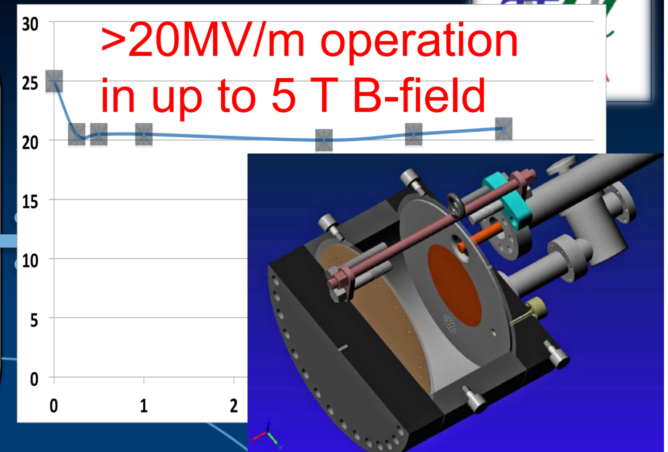


Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

FNAL-Tech Div
T. Shen-Early Career Award

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

MuCool Test Area/Muons Inc

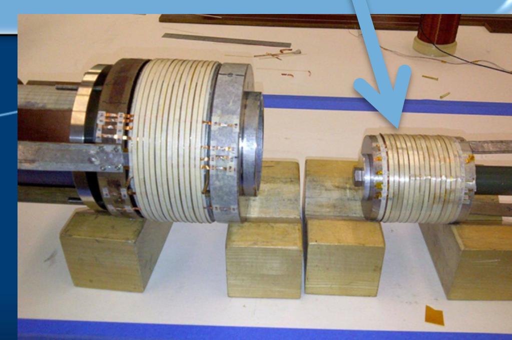


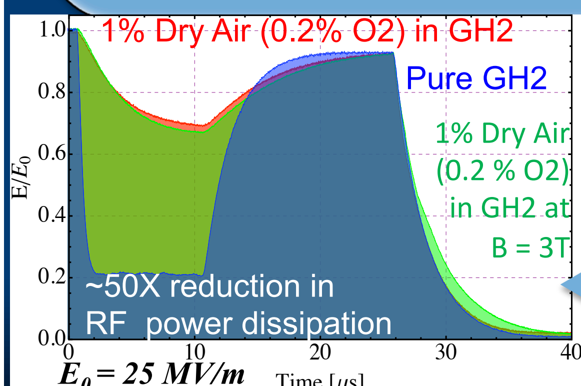
The Path to a Viable Muon Ionization Cooling Channel

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

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

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

- 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
    - 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