The U.S. Muon Accelerator Program

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University of Chicago

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PROGRAM OVERVIEW

Why a Muon Accelerator Program?

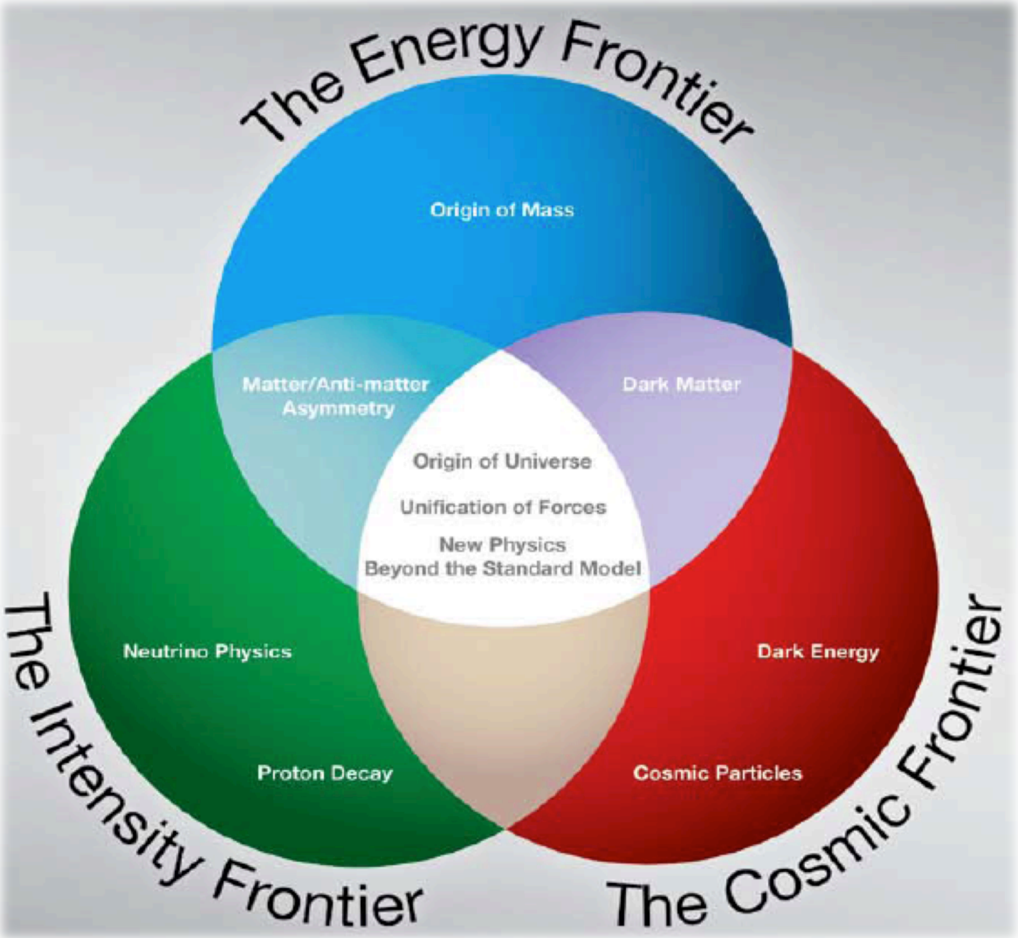
Muon accelerator R&D is focused on developing facilities that can address critical questions on two frontiers…

The Intensity Frontier:

with a ***Neutrino Factory*** producing well-characterized ν beams for precise, high sensitivity studies

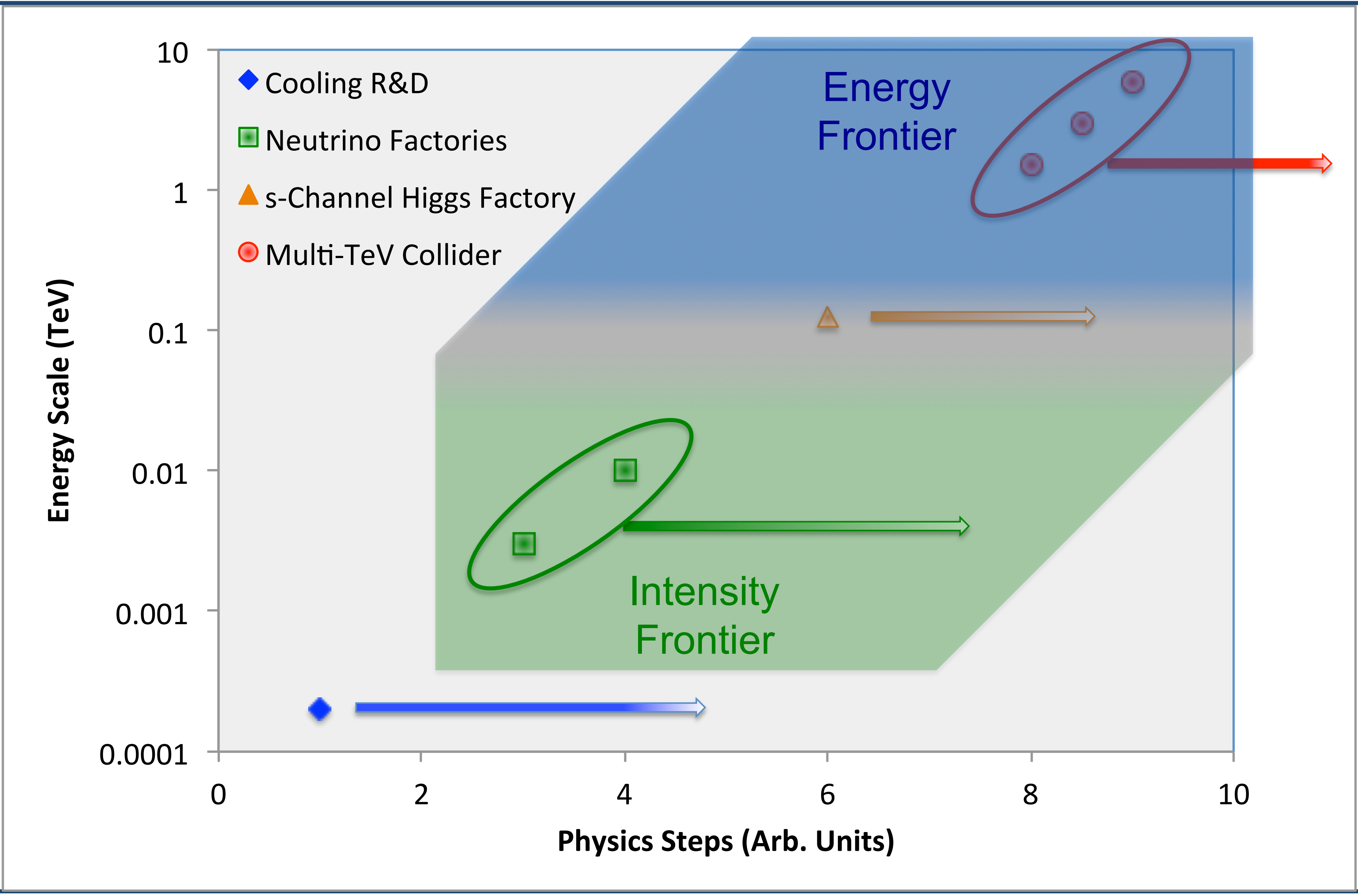
The Energy Frontier:

with a ***Muon Collider*** capable of reaching the multi-TeV center-of-mass energies



The unique potential of a facility based on muon accelerators is physics reach that spans 2 frontiers

Fermilab Muon Accelerator Physics Scope

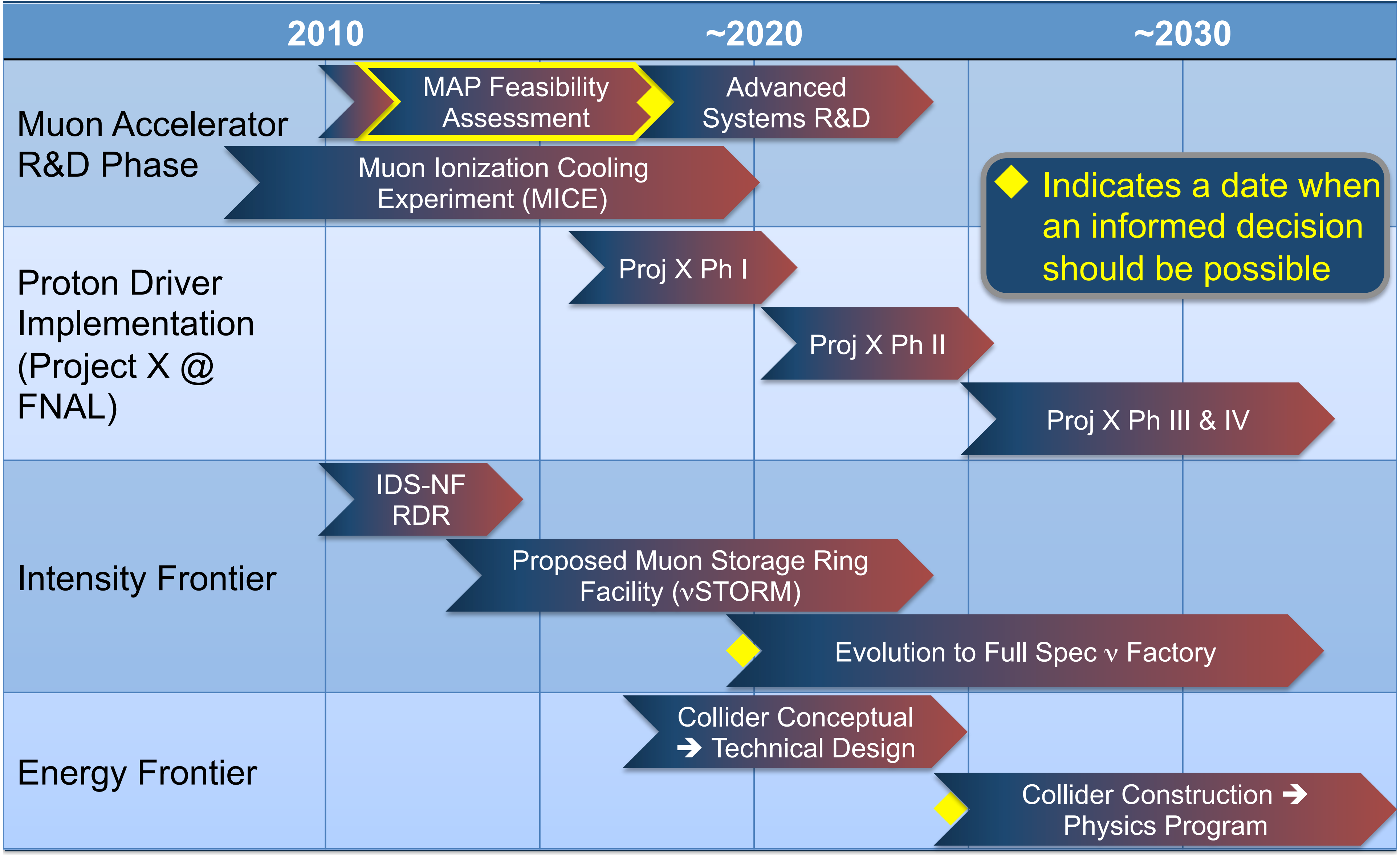


Muon Accelerators

Accelerator	Energy Scale	
Cooling Channel	**~200 MeV**	
MICE	*160-240 MeV*	←
Muon Storage Ring	**3-4 GeV**	
νSTORM	*3.8 GeV*	
Intensity Frontier ν Factory	**10-25 GeV**	
Low Energy NF	*10 GeV*	
IDS-NF 2.0	*25 GeV*	
Current IDS-NF	*10 GeV*	←
s-Channel Higgs Factory	**~126 GeV CoM**	←
Energy Frontier μ Collider	**> 1 TeV CoM**	
Opt. 1	*1.5 TeV CoM*	←
Opt. 2	*3 TeV CoM*	←
Opt. 3	*6 TeV CoM*	

Program Baselines

The Muon Accelerator Program Timeline



◆ Indicates a date when an informed decision should be possible

MAP Goals

Within the 6-year time frame:

- *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*

As well as…

- *To explore the path towards a facility that can provide cutting edge performance at both the Intensity Frontier and the Energy Frontier*
- *To validate the concepts that would enable the Fermilab accelerator complex to support these goals*

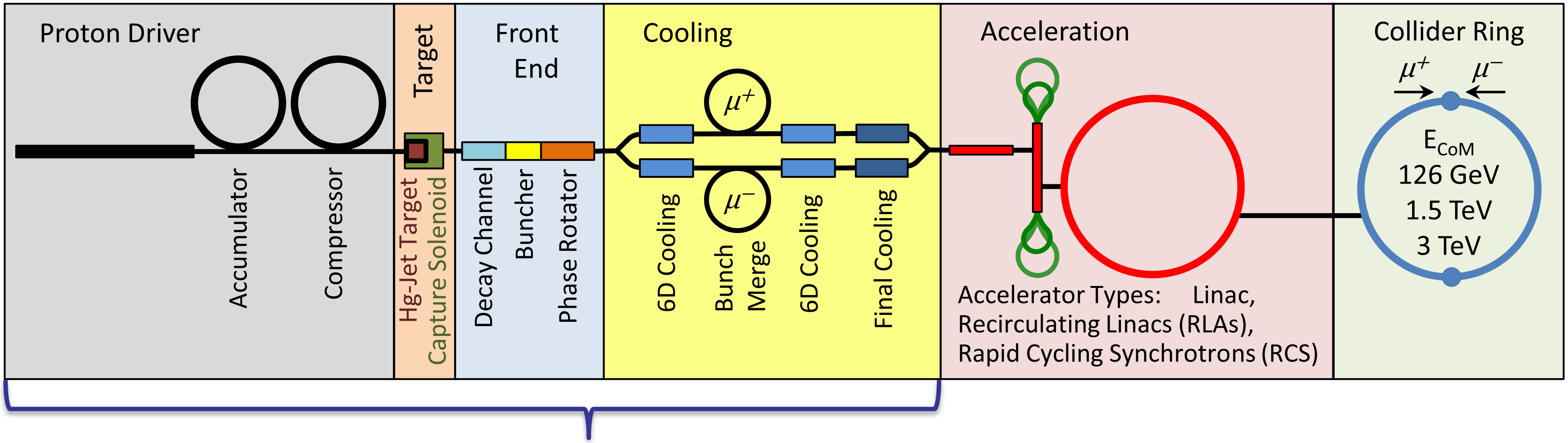
MUON COLLIDER

Fermilab

Muon Collider Concept

Muon Accelerator Program

Muon Collider Block Diagram



Proton source:
For example PROJECT X at 4 MW, with 2±1 ns long bunches

Goal:
Produce a high intensity μ beam whose 6D phase space is reduced by a factor of ~10^6-10^7 from its value at the production target

Collider: $\sqrt{s}$ = 3 TeV
Circumference 4.5km
$L = 3\times10^{34}$ cm^{-2}s^{-1}
μ/bunch = $2\text{x}10^{12}$
$\sigma(p)/p$ = 0.1%
$\varepsilon_{\perp N}$ = 25 μm, $\varepsilon_{||N}$=70 mm
β^* = 5mm
Rep. Rate = 12 Hz

Muon Collider Parameters

Muon Collider Baseline Parameters

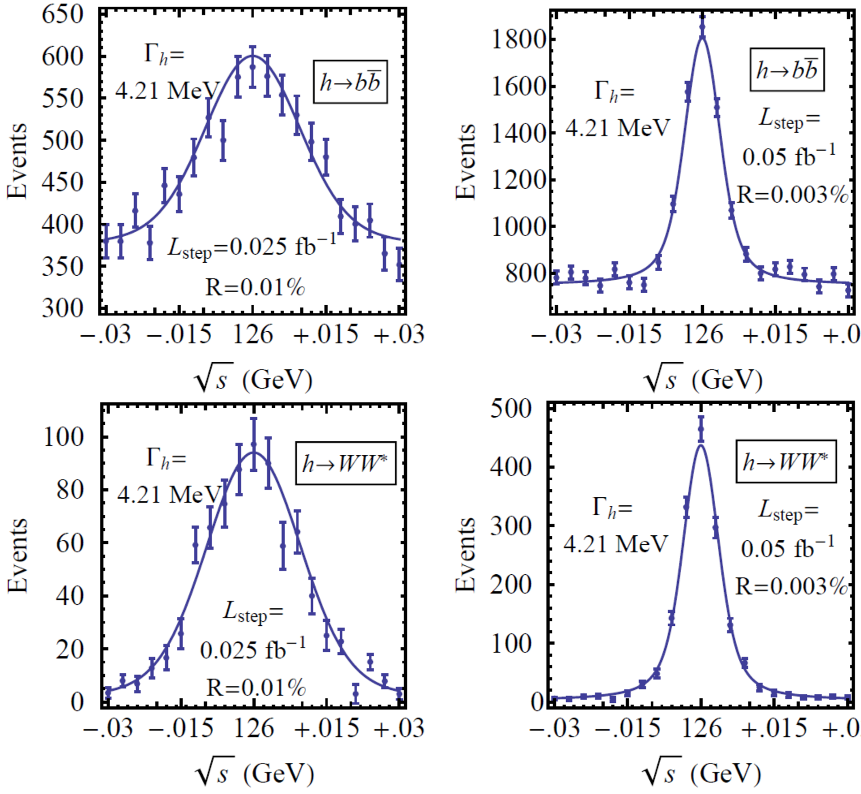
		Higgs Factory		**Multi-TeV Baselines**	
Parameter	***Units***	Initial Cooling	Upgraded Cooling / Combiner		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	$4^{\#}$	4	4	4

3-4 MeV CoM Energy Spread

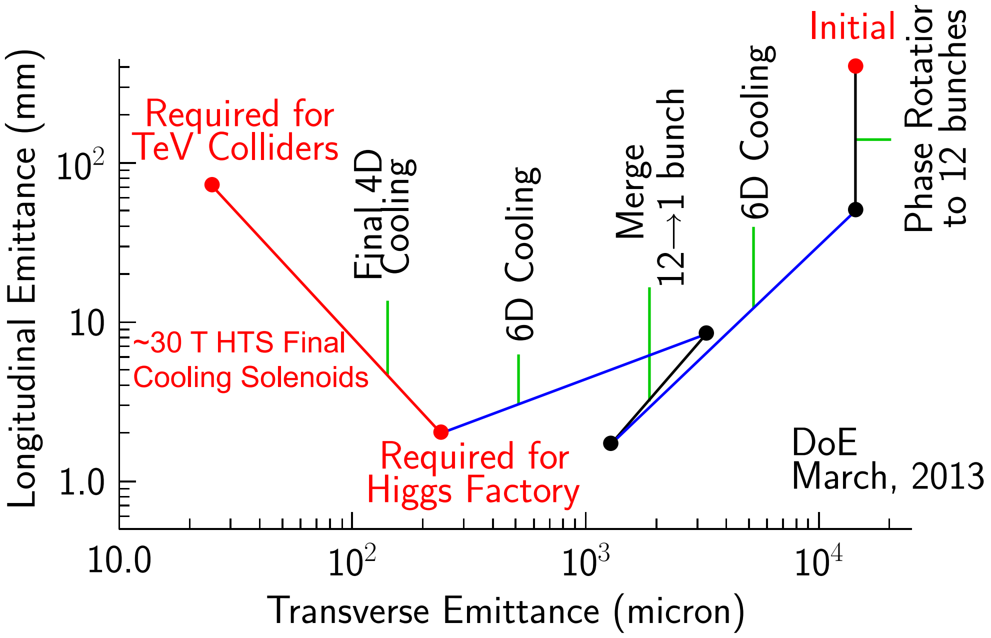
$^{\#}$Could begin operation at lower beam power (eg, with Project X Phase 2 beam)

126 GeV Higgs Factory

s-channel coupling of Muons to HIGGS with high cross sections:
Muon Collider of with L = 10^{32} cm^{-2}s^{-1} @ 63 GeV/beam (50000 Higgs/year)
Competitive with e+/e- Linear Collider with L = 2. 10^{34} cm^{-2}s^{-1} @ 126 GeV/beam



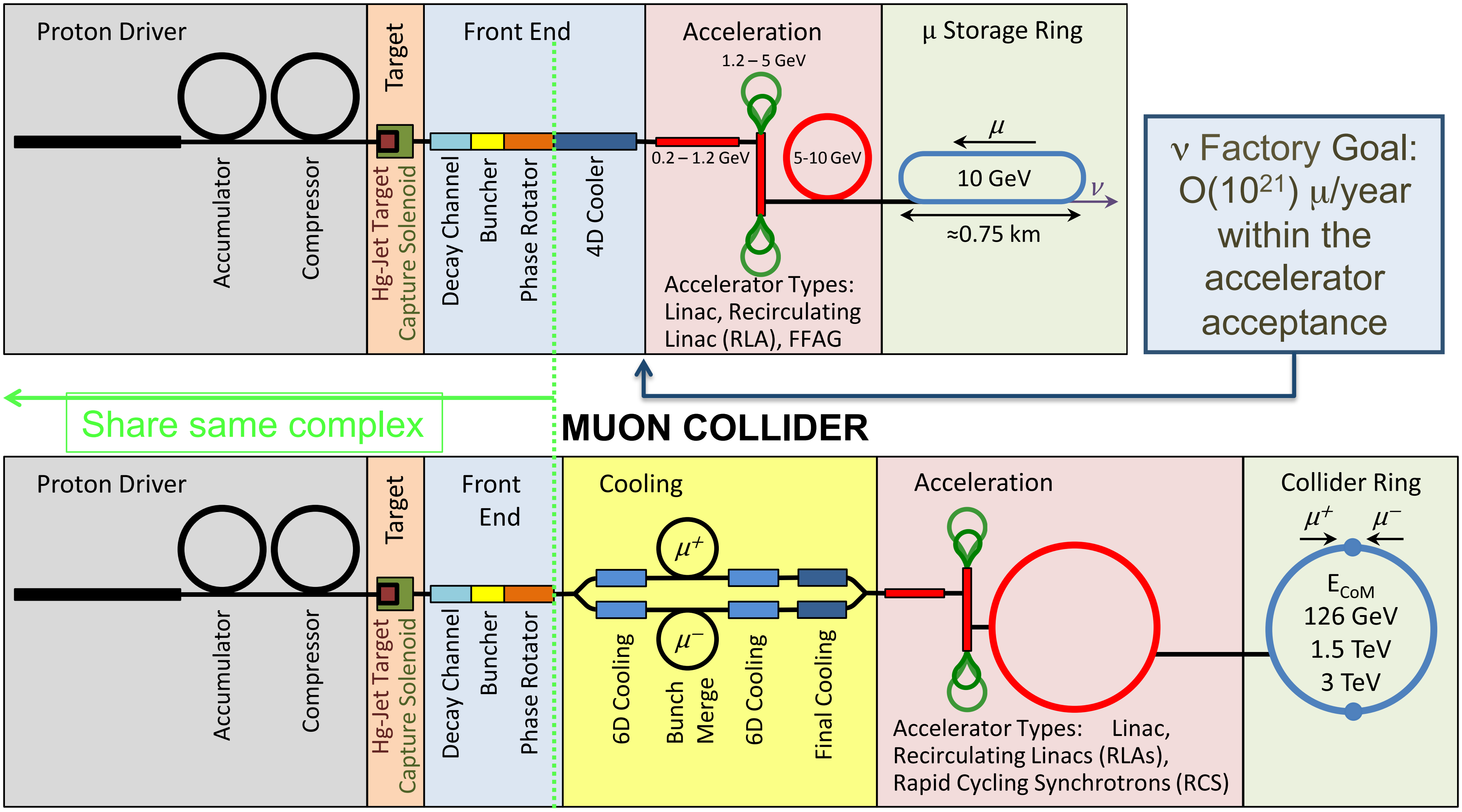
Han and Liu
hep-ph 1210.7803



Major advantage for Physics of a $\mu^+\mu^-$ Higgs Factory: possibility of direct measurement of the Higgs boson width (Γ~4MeV FWHM expected)

Reduced cooling:
$\varepsilon_{\perp N}$ =0.3π·mm·rad,
$\varepsilon_{||N}$ =1π·mm·rad

Muon Collider - Neutrino Factory Comparison



NEUTRINO FACTORY

Proton Driver
Accumulator
Compressor

Target
Hg-Jet Target
Capture Solenoid

Front End
Decay Channel
Buncher
Phase Rotator
4D Cooler

Acceleration
1.2 – 5 GeV
0.2 – 1.2 GeV
5-10 GeV

Accelerator Types:
Linac, Recirculating
Linac (RLA), FFAG

μ Storage Ring
μ
10 GeV
ν
≈0.75 km

ν Factory Goal:
O(10^{21}) μ/year
within the
accelerator
acceptance

Share same complex

MUON COLLIDER

Proton Driver
Accumulator
Compressor

Target
Hg-Jet Target
Capture Solenoid

Front
End
Decay Channel
Buncher
Phase Rotator

Cooling
μ^+
μ^-
6D Cooling
Bunch
Merge
6D Cooling
Final Cooling

Acceleration

Accelerator Types: Linac,
Recirculating Linacs (RLAs),
Rapid Cycling Synchrotrons (RCS)

Collider Ring
μ^+ μ^-
E_{CoM}
126 GeV
1.5 TeV
3 TeV

CRITICAL R&D AREAS

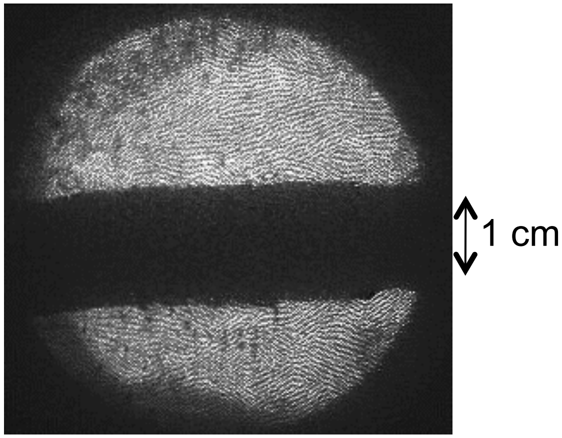
Overview of R&D Areas

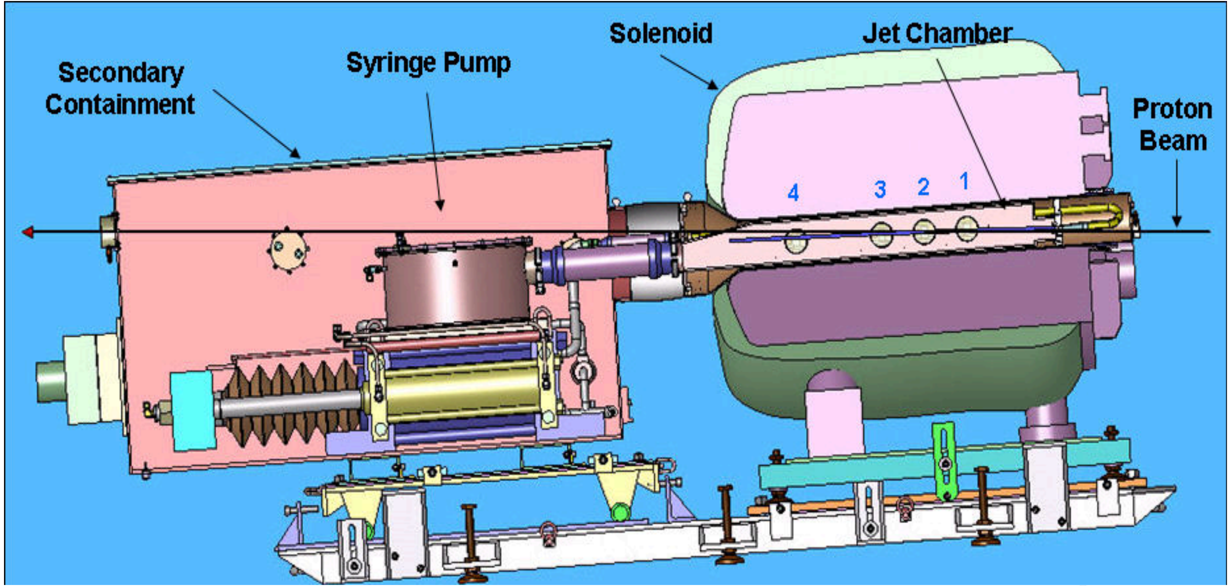
- Design Studies
  - Proton Driver
  - Front End
  - Cooling
  - Acceleration and Storage
  - Collider
  - Machine-Detector Interface
  - Work closely with physics and detector efforts
- Major System Demonstration
  - The Muon Ionization Cooling Experiment – MICE
    - Major U.S. effort to provide key hardware: RF Cavities and couplers, Spectrometer Solenoids, Coupling Coils
    - Experimental and Operations Support

- Technology R&D
  - Normal Conducting RF
    - Vacuum RF Cavities with reduced breakdown rates in high magnetic fields
    - Cavity Materials
    - RF Cavities filled with high pressure gas
  - Superconducting RF
    - Demonstrating good Q_0 performance with Niobium on Copper cavities
      - Performance
      - Fabrication techniques
  - Magnets
    - High field solenoids for cooling channel application
    - 10T dipole design (synergistic with LHC upgrade activities)
    - Rapid cycling magnets for high energy hybrid synchrotron
    - Shielded magnets for μ decay in rings
  - Target and Absorbers
    - Liquid jet targets capable
    - Capture solenoid technology

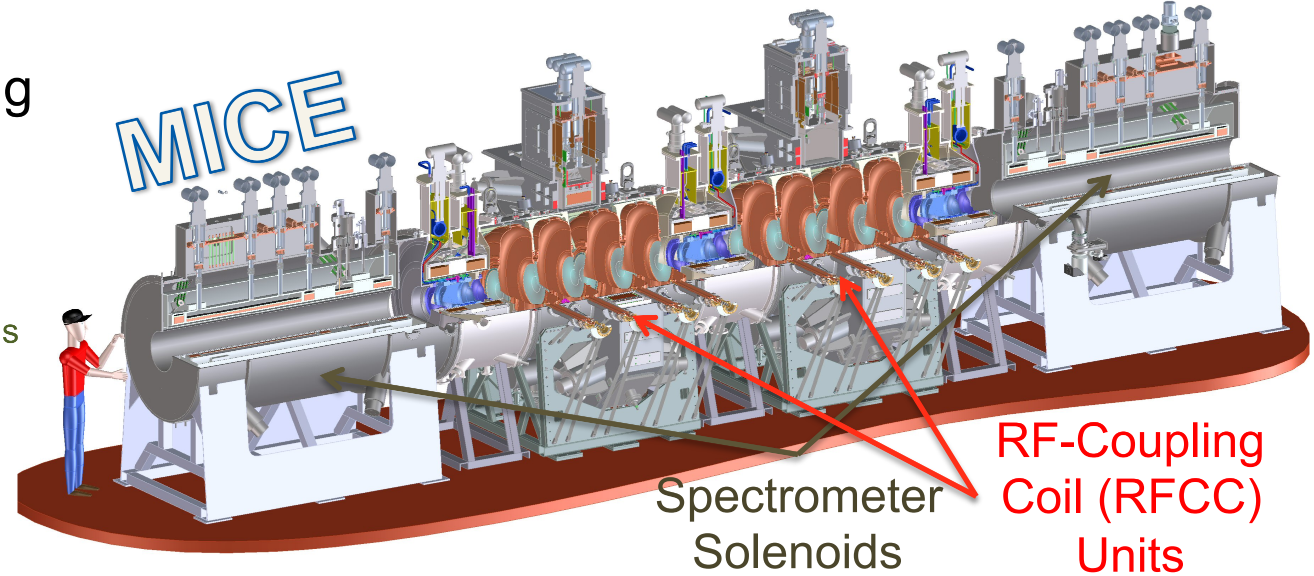
R&D Capabilities I (Completed, Current or Underway)

- Target Technology: MERIT Experiment
  - Liquid Hg jet ➩ 8MW with 70Hz rep. rate



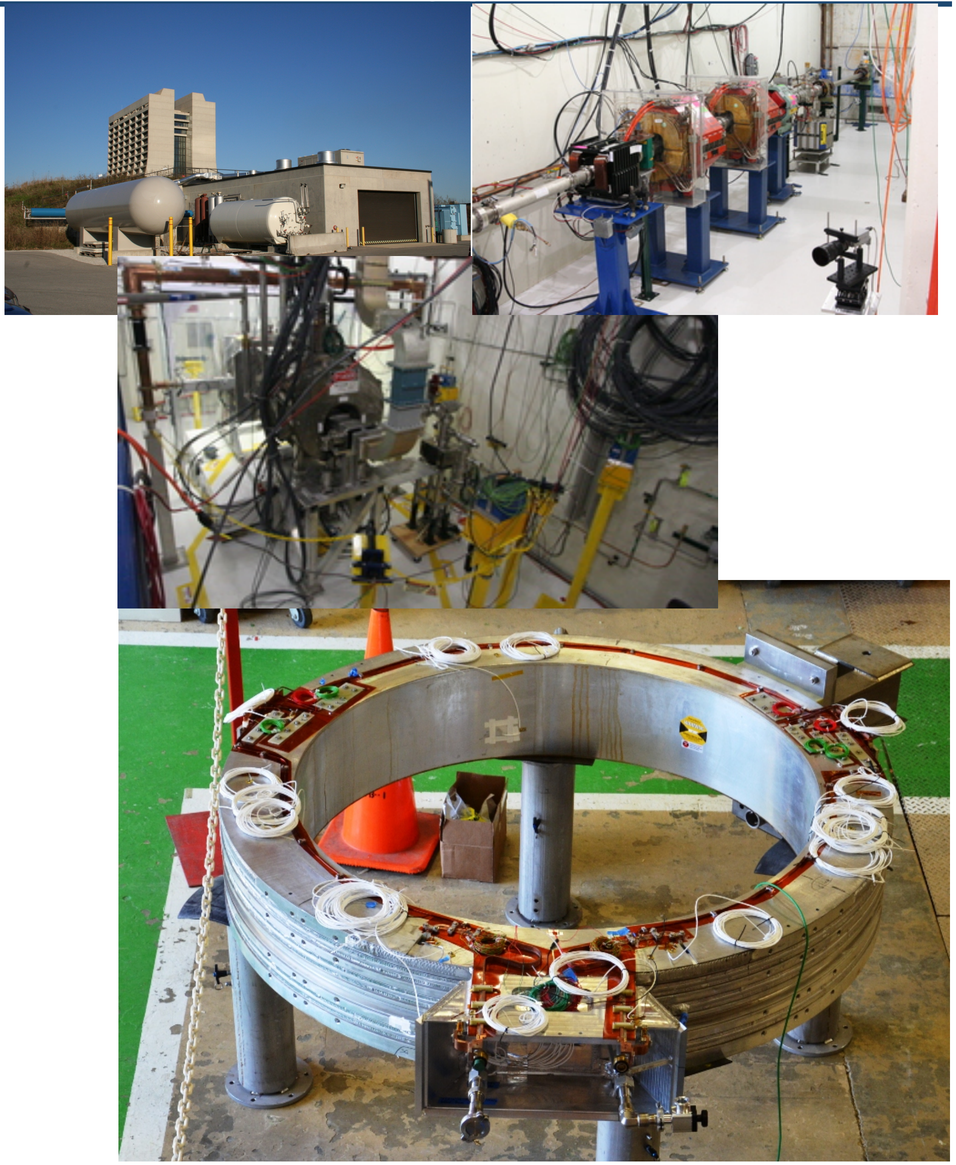


- Muon Ionization Cooling Experiment (MICE)
  - Cool beams produced with tertiary production mechanism
    - dE/dx energy loss in materials
    - RF to replace p_{long}
  - Employs Guggenheim Cooling Channel Technology



R&D Capabilities II (Completed, Current or Underway)

- MuCool Test Area (MTA)
  - RF power (12MW @ 805MHz, 4.5MW @ 201MHz)
  - Large-bore 5T superconducting solenoid
  - Cryogenic plant
  - 400-MeV H- beamline
  - Class-100 portable clean room
  - Hydrogen safety infrastructure
  - 805- and 201-MHz cavities
  - Radiation detectors
- Solenoid Test Facility
  - Utilizes Fermilab Central Helium Liquefier (CHL) Facility
  - First MICE CC Coldmass ready for testing

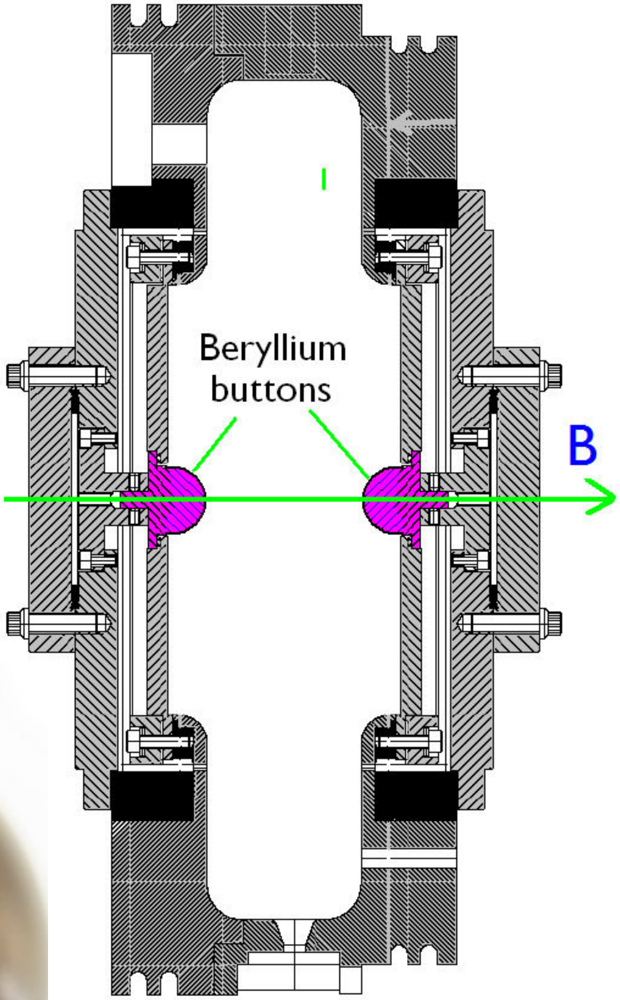


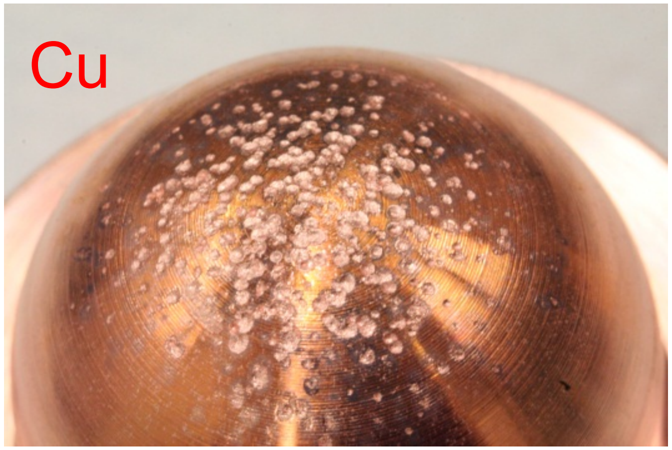
R&D Activities: Cavity Materials

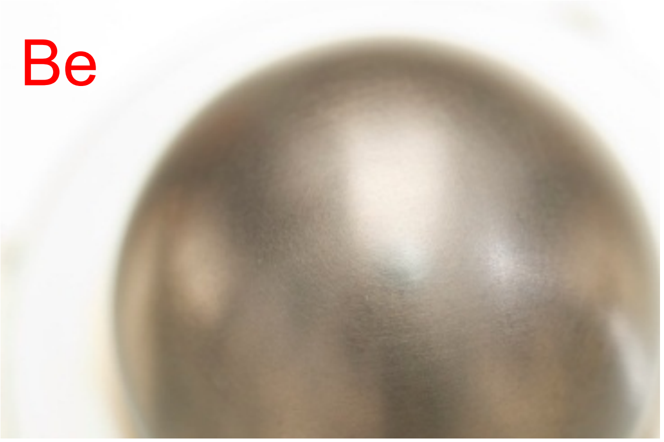
Breakdown tests with Be and Cu Buttons

- Both reached ~31 MV/m
- Cu button shows significant pitting
- Be button shows minimal damage

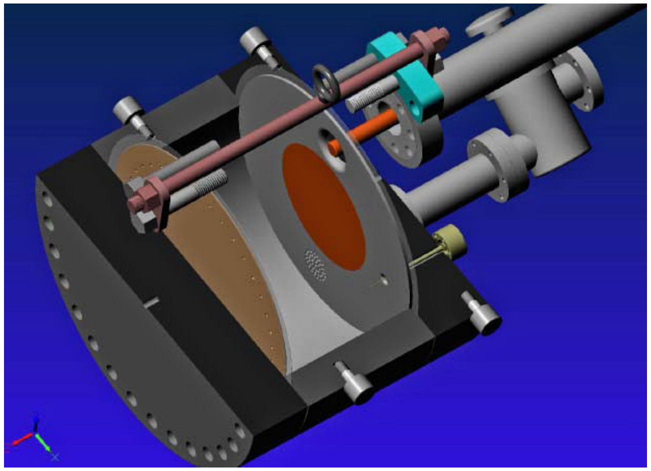
⇨ Materials choices offer the possibility of more robust operation in magnetic fields (increased operating lifetime)





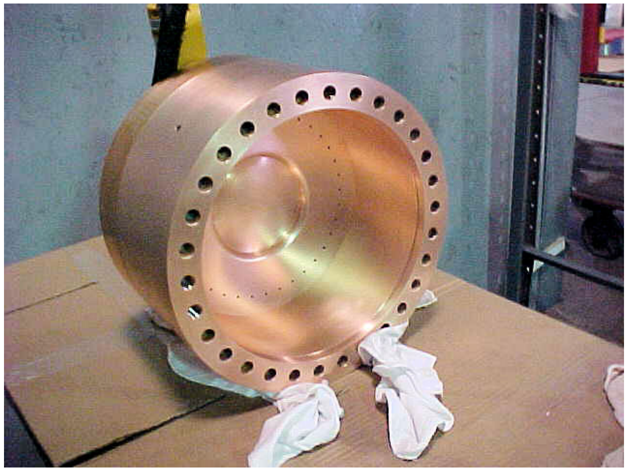


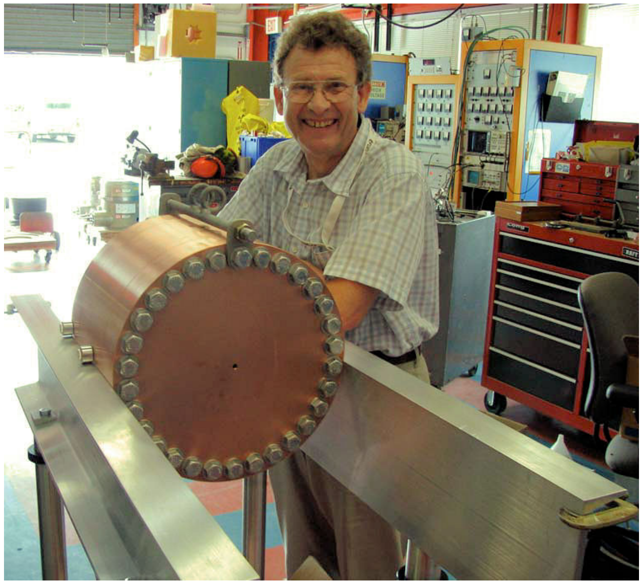
R&D Activities: Vacuum RF



All-Seasons Cavity

(designed for both vacuum and high pressure operation)

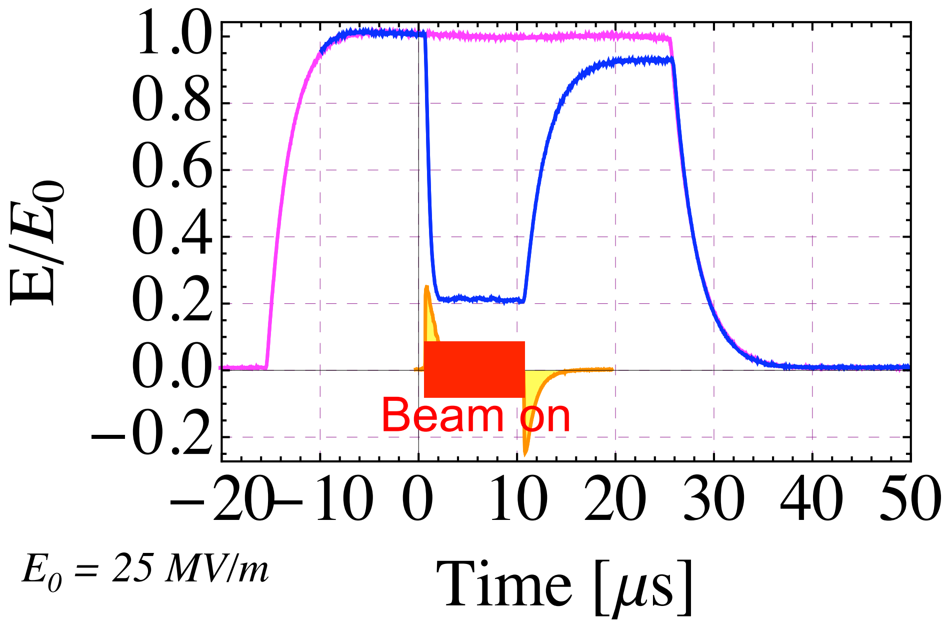




- Vacuum Tests at B = 0 T & B = 3 T
  - ~25 MV/m operating gradient in each configuration
- Demonstrates possibility of successful operation of vacuum cavities in magnetic fields with careful design

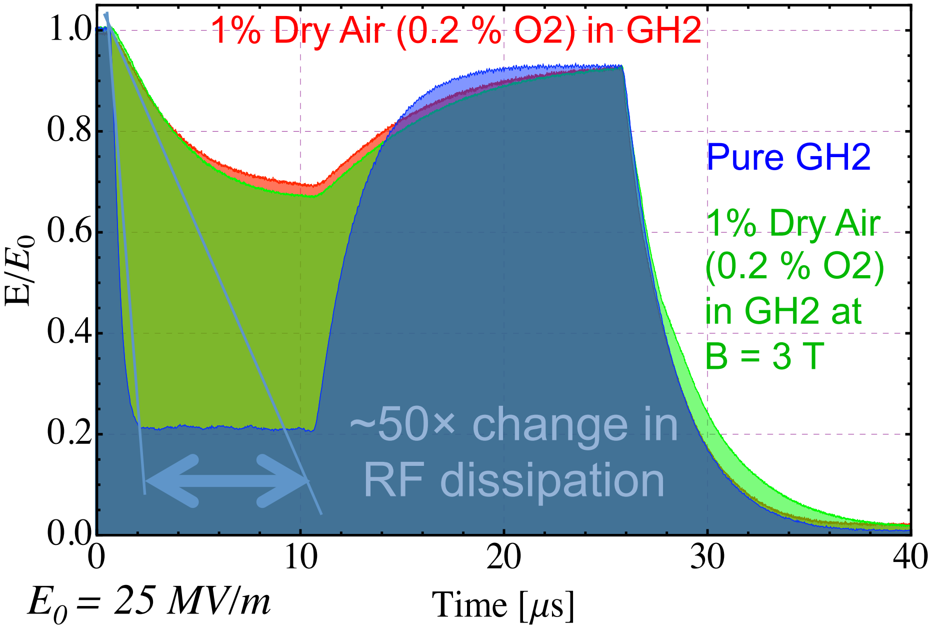
R&D Activities: High Pressure RF

- Gas-filled cavity
  - Can moderate dark current and breakdown currents in magnetic fields
  - Can contribute to cooling
  - Is loaded, however, by beam-induced plasma



$E_0 = 25\ MV/m$

- Electronegative Species
  - Dope primary gas
  - Can moderate the loading effects of beam-induced plasma by scavenging the relatively mobile electrons

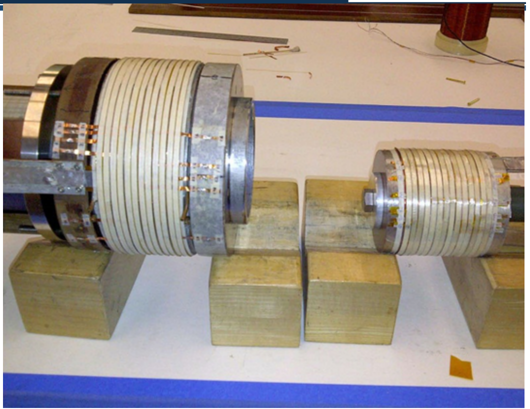


$E_0 = 25\ MV/m$

R&D Activities: HTS High Field Magnets

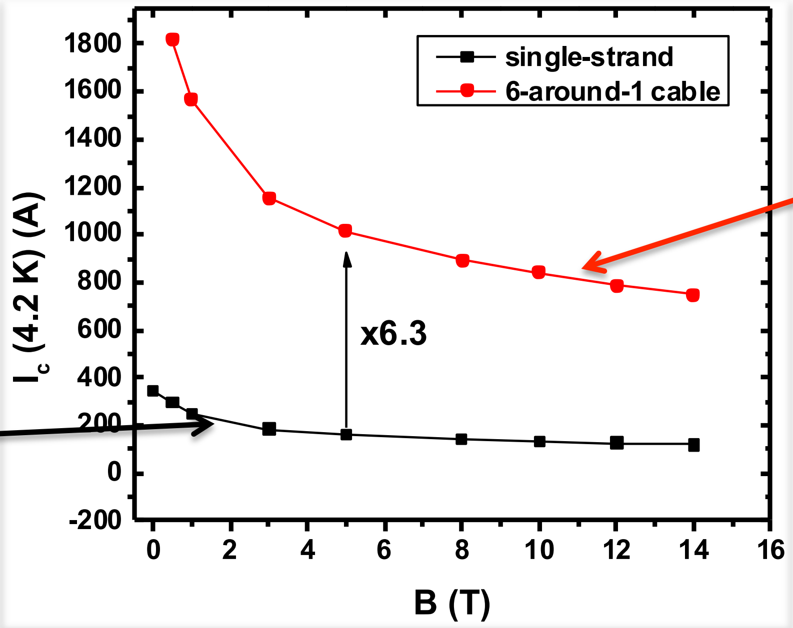
Progress towards a demonstration of a final stage cooling solenoid:

- 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)
- Preparing for high field tests utilizing various outsert options (20+ T followed by 30+ T demonstrations)



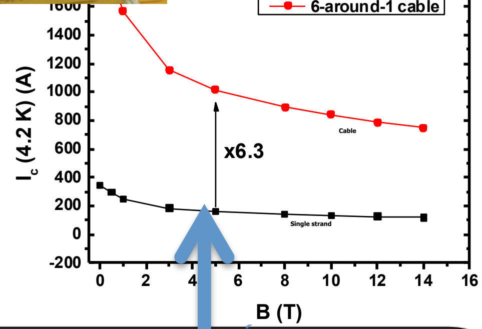
BSCCO-2212 Cable -

Long piece-length obtained by hyperbaric fabrication process to reduce bubble formation



Multi-strand cable utilizing chemically compatible alloy and oxide layer to minimize cracks. Cable achieving full current density of single strand

MAP Technology Highlights

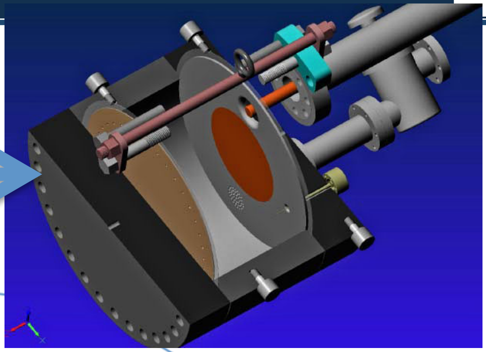


Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

FNAL-Tech Div
T. Shen-Early Career Award

Successful Operation of 805 MHz "All Seasons" Cavity in 3T Magnetic Field under Vacuum

MuCool Test Area/Muons Inc

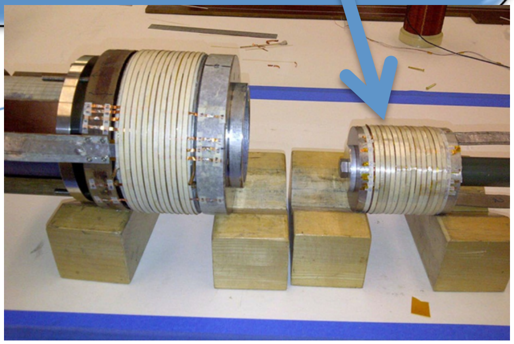


The Path to a Viable Muon Ionization Cooling Channel

World Record HTS-only Coil

15T on-axis field
16T on coil

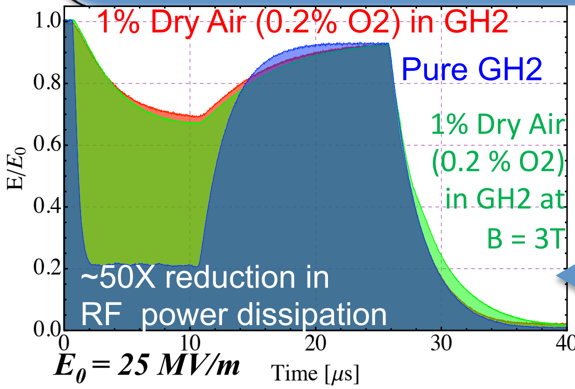
PBL/BNL



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

Extrapolates to μ-Collider Parameters

MuCool Test Area

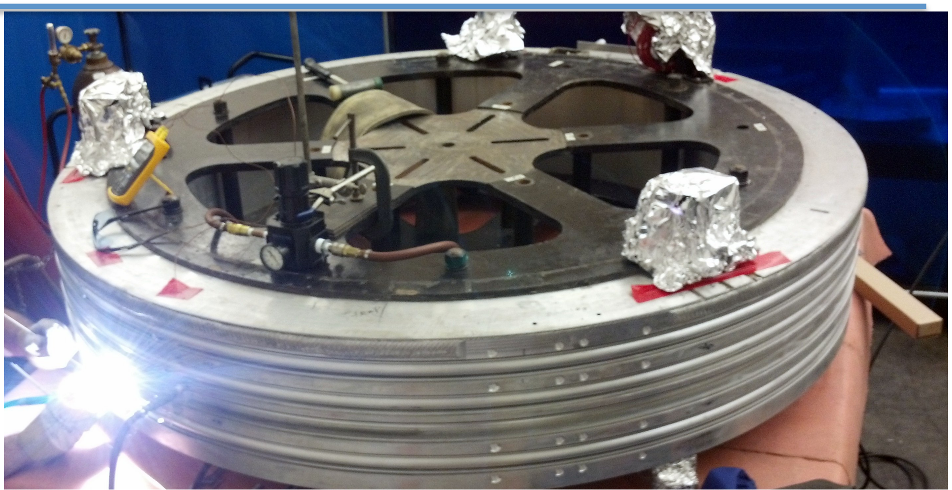


R&D Activities: MICE Magnets

Spectrometer Solenoids @ LBNL

- 1st SS
  - Has reached 100% of target current
- 2nd SS
  - Assembly nearing completion with training and acceptance tests scheduled to begin immediately after 1st unit testing complete

➪ Support MICE Step IV (2014-15)



Coupling Coils

- First Coupling Coil cold mass delivered to FNAL from LBNL for testing in new Solenoid Test Facility

➪ Support MICE Step V/VI (2017-)

R&D Capabilities (Continuing and Future)

- Continuing
  - – MTA (FNAL): RF cavity R&D
  - – MICE (RAL): ionization cooling demonstration
- New possibilities
  - – νSTORM (Neutrinos from Stored Muons): Ring instrumentation, energy calibration methods, and R&D beams
  - – ASTA (FNAL): Novel cooling techniques: optical stochastic cooling, carbon-based crystal structures
  - – FACET II (SLAC): Potential studies with polarized muons

νSTORM – Physics + Critical Accelerator R&D

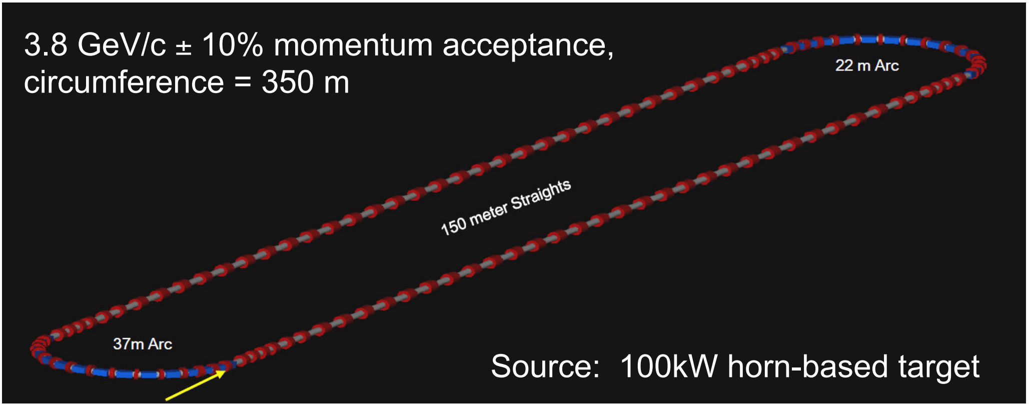
Well-understood neutrino source:

μ Decay Ring:

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

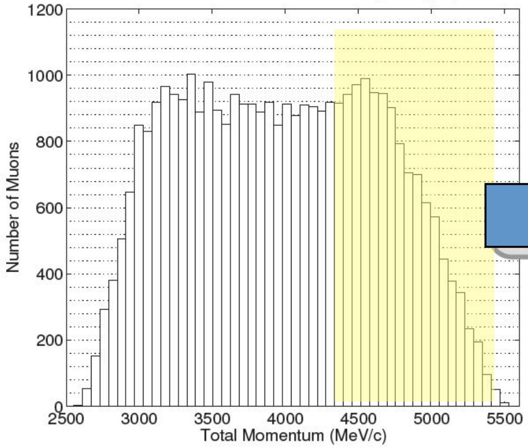
$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

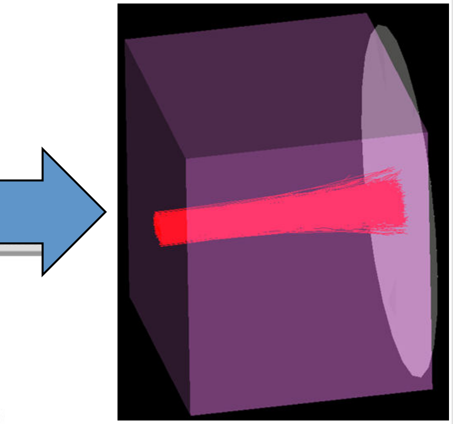
Provides important physics output (ν cross sections and sterile ν search) as well as critical R&D leverage (ring instrumentation and a beam well-suited for advanced cooling R&D).

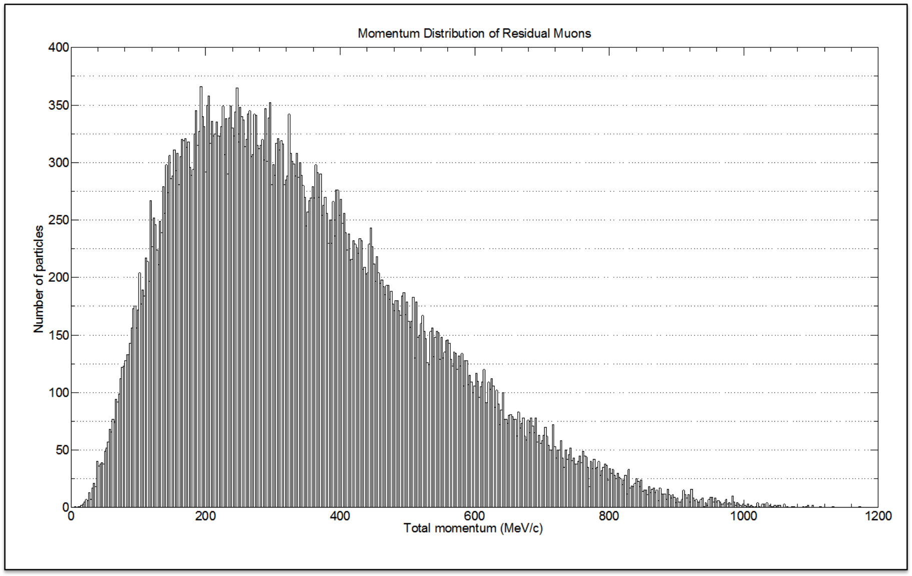


3.8 GeV/c ± 10% momentum acceptance, circumference = 350 m

Source: 100kW horn-based target







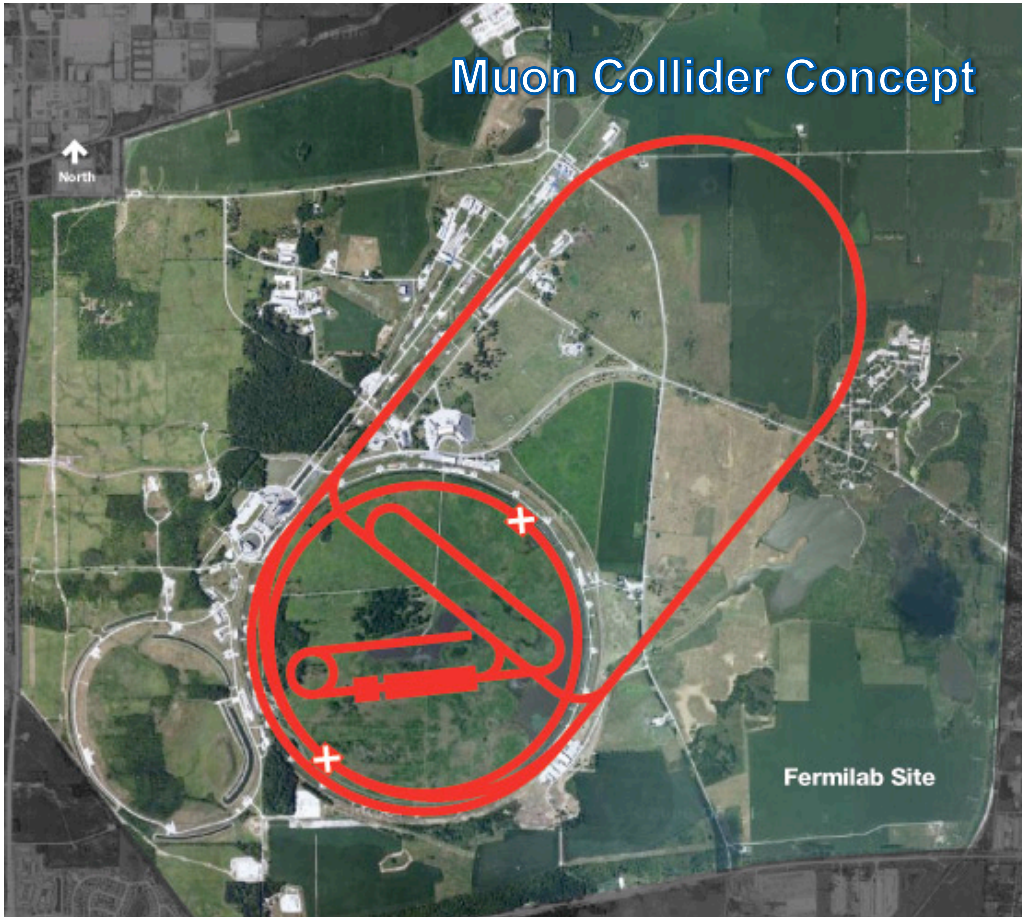
At end of straight we have a lot of πs, but also a lot of μs with 4.5 < P(GeV/c) < 5.5

After 3.48m Fe, we have ≈ 10^{10} μ/pulse in 100 < P(MeV/c) < 300

Conclusion

- MAP is working towards a 6-year Feasibility Assessment to be delivered in 2018:
  - Feasibility of key concepts needed for a Muon Collider and Neutrino Factory
  - Provide the foundation for a facility that can support unsurpassed Intensity and Energy Frontier research

⇨ ***A robust R&D program will enable an informed decision on the path forward for HEP***



An effective muon accelerator R&D program will rely on the availability of high capability test facilities