COOL`13
Mürren, Switzerland

An Overview of the U.S. Muon Accelerator Program

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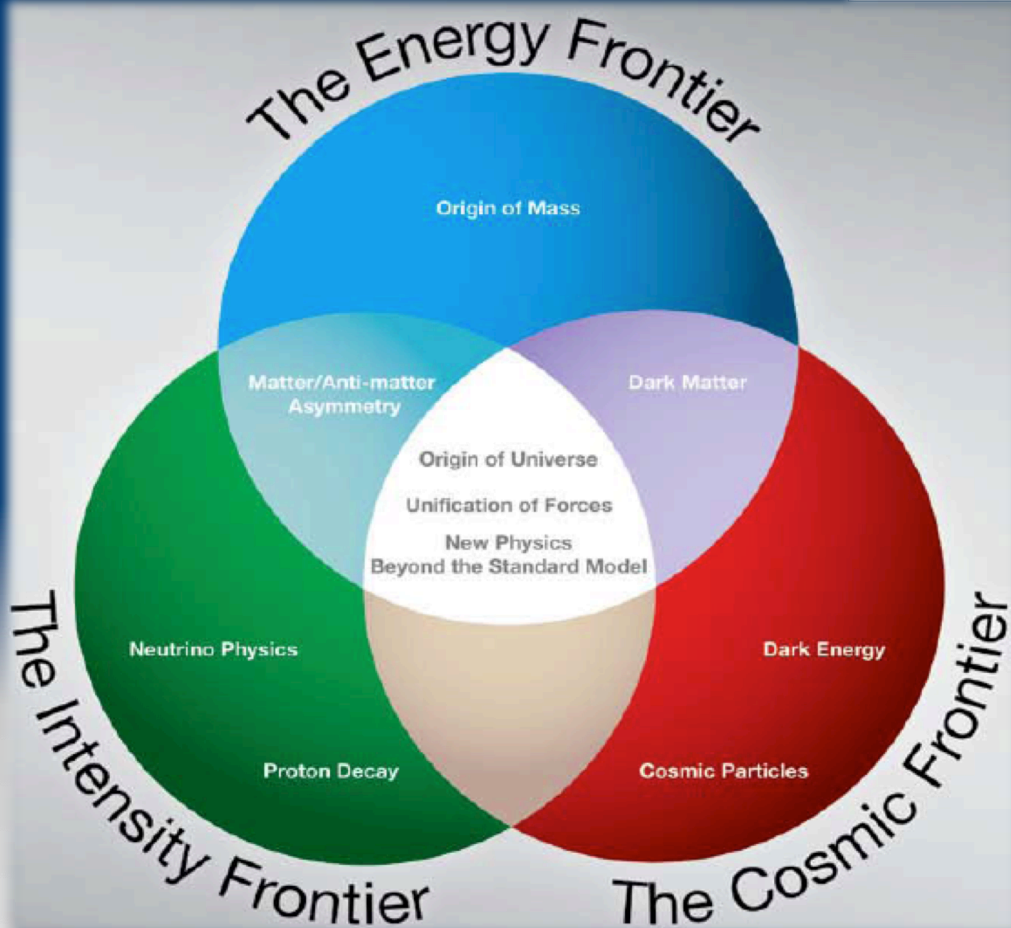
Fermilab

The Aims of the Muon Accelerator Program

Muon accelerator R&D is focused on developing a facility that can address critical questions spanning 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 multi-TeV CoM energies
and
*a **Higgs Factory** on the border between these Frontiers*



The unique potential of a facility based on muon accelerators is physics reach that SPANS 2 FRONTIERS

Outline

- The Physics Motivations
- The Muon Accelerator Program
- The R&D Challenges
- Some Recent R&D Highlights
- The Staging Study and Timelines
- Conclusion

THE PHYSICS MOTIVATIONS

The Physics Motivations

- μ – an elementary charged lepton:
  - 200 times heavier than the electron
  - 2.2 μs lifetime at rest

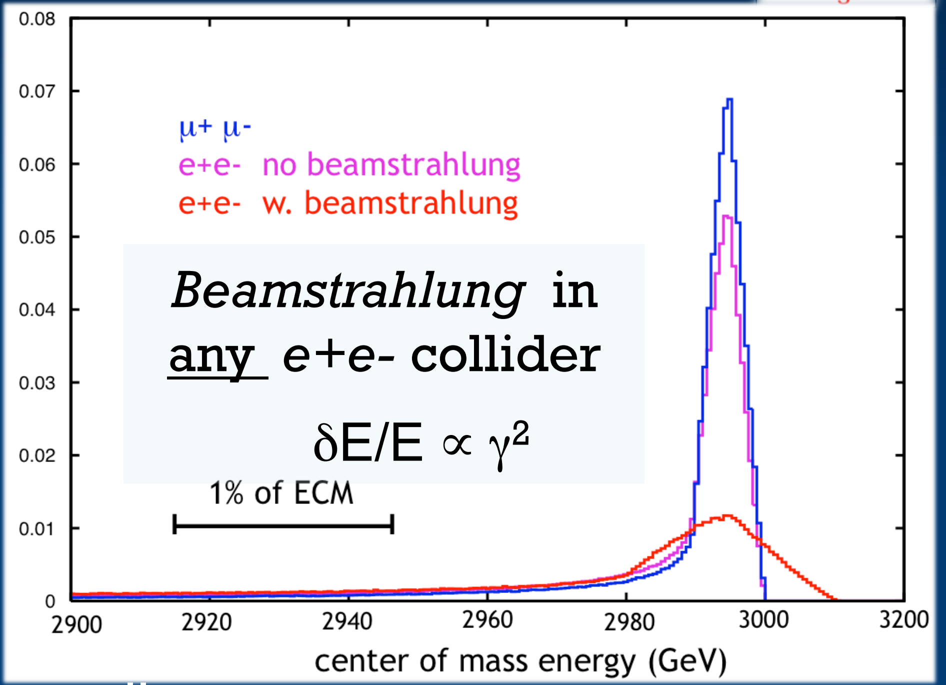
- Physics potential for the HEP community using muon beams
  - Tests of Lepton Flavor Violation
  - Anomalous magnetic moment ⇨ hints of new physics (g-2)
  - Can provide equal fractions of electron and muon neutrinos at high intensity for studies of neutrino oscillations – the Neutrino Factory concept

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

  - Offers a large coupling to the "Higgs mechanism" $\sim \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4 \times 10^4$
  - As with an e^+e^- collider, a $\mu^+\mu^-$ collider would offer a precision probe of fundamental interactions – in contrast to hadron colliders

Muon Accelerator Physics

- Large muon mass strongly suppresses synchrotron radiation
  - ⇨ Muons can be accelerated and stored using rings at much higher energy than electrons
  - ⇨ Colliding beams can be of higher quality with reduced beamstrahlung



- Short muon lifetime has impacts as well
  - Acceleration and storage time of a muon beam is limited
  - Collider ⇨ a new class of decay backgrounds must be dealt with
- Precision beam energy measurement by g-2 allows precision Higgs width determination
- Muon beams produced as tertiary beams: $p \rightarrow \pi \rightarrow \mu$
  - Offers key accelerator challenges…

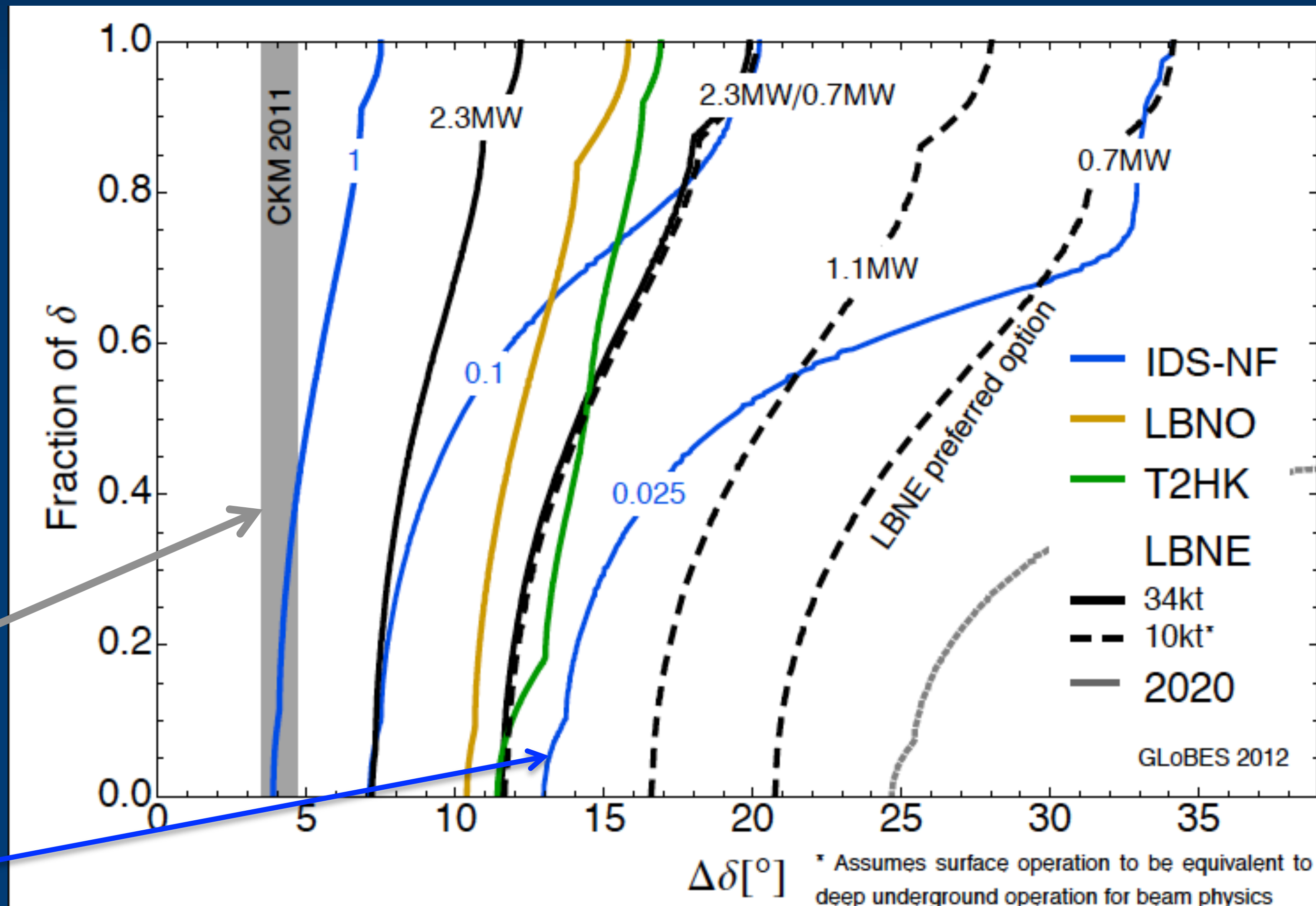
The Physics Needs: Neutrinos

- CP violation physics reach of various facilities

Can we probe the CP violation in the neutrino sector at the same level as in the CKM Matrix?

Measurement sensitivity in the quark sector

0.025 IDS-NF:
700kW target,
no cooling,
2×10[8] s running time
10-15 kTon detector

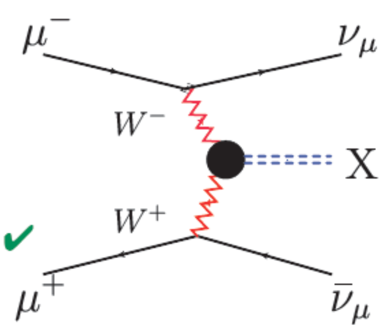


P. Coloma, P. Huber, J. Kopp, W. Winter – article in preparation

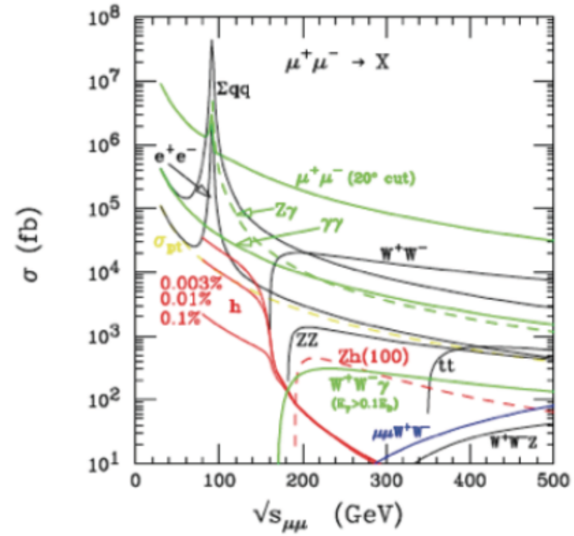
Muon Collider Reach

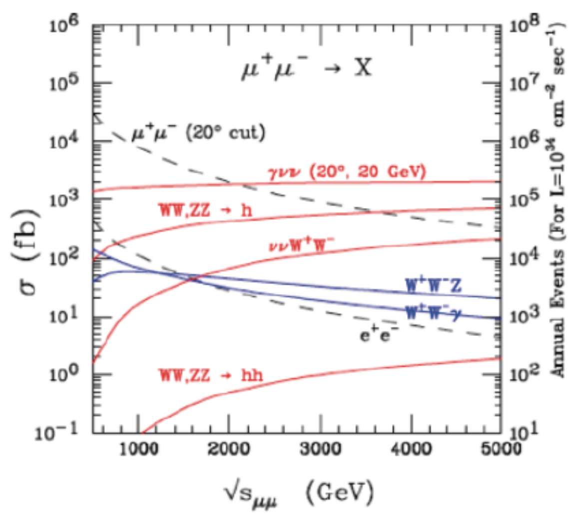
- For $\sqrt{s}$ < 500 GeV
  - SM thresholds: Z^0h, W^+W^-, top pairs
  - Higgs factory ($\sqrt{s} \approx 126$ GeV) ✔
- For $\sqrt{s}$ > 500 GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required. ✔
    - Cross sections for central ($|\theta| > 10°$) pair production ~ R × 86.8 fb/s(in TeV^2) (R ≈ 1)
    - At $\sqrt{s}$ = 3 TeV for 100 fb^{-1} ~ 1000 events/(unit of R)
- For $\sqrt{s}$ > 1 TeV
  - Fusion processes important at multi-TeV MC

$$\sigma(s) = C \ln\left(\frac{s}{M_X^2}\right) + \ldots$$



  - An Electroweak Boson Collider ✔





E. Eichten

MUON ACCELERATOR PROGRAM

The Muon Accelerator Program

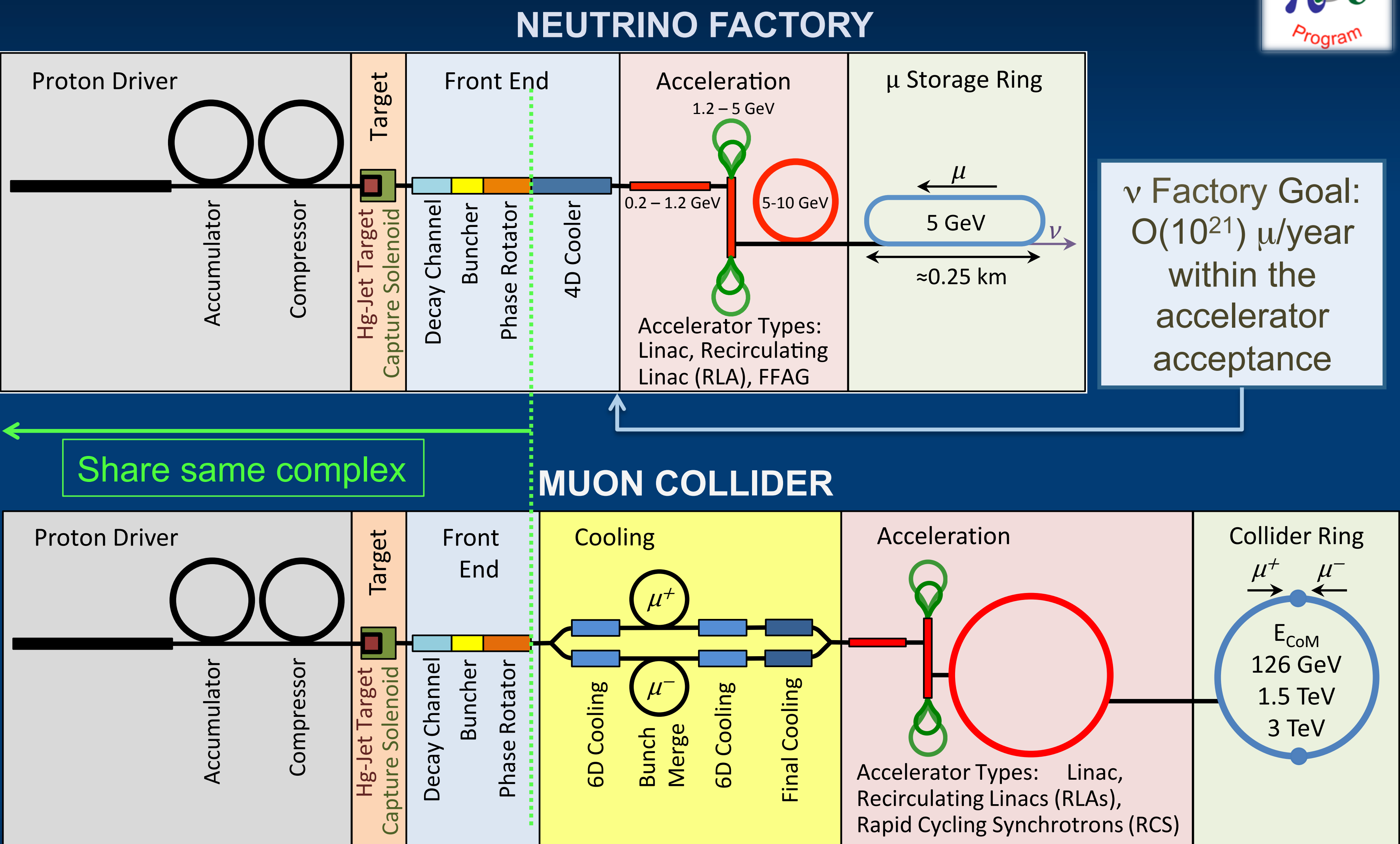
During this decade:

- *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-Neutrino Factory Comparison



The MAP Feasibility Assessment

Feasibility Assessment: Phase I

FY13 – FY15:
- Identify ***baseline*** design concepts
- Identify high leverage ***alternative*** concepts
- Identify key engineering paths to pursue:
  - RF
  - High Field Magnets
- Develop critical engineering concepts (eg, 6D Cooling Cell)
- Support major systems tests
  - MICE Step IV
  - MICE RFCC construction & testing

Feasibility Assessment: Phase II

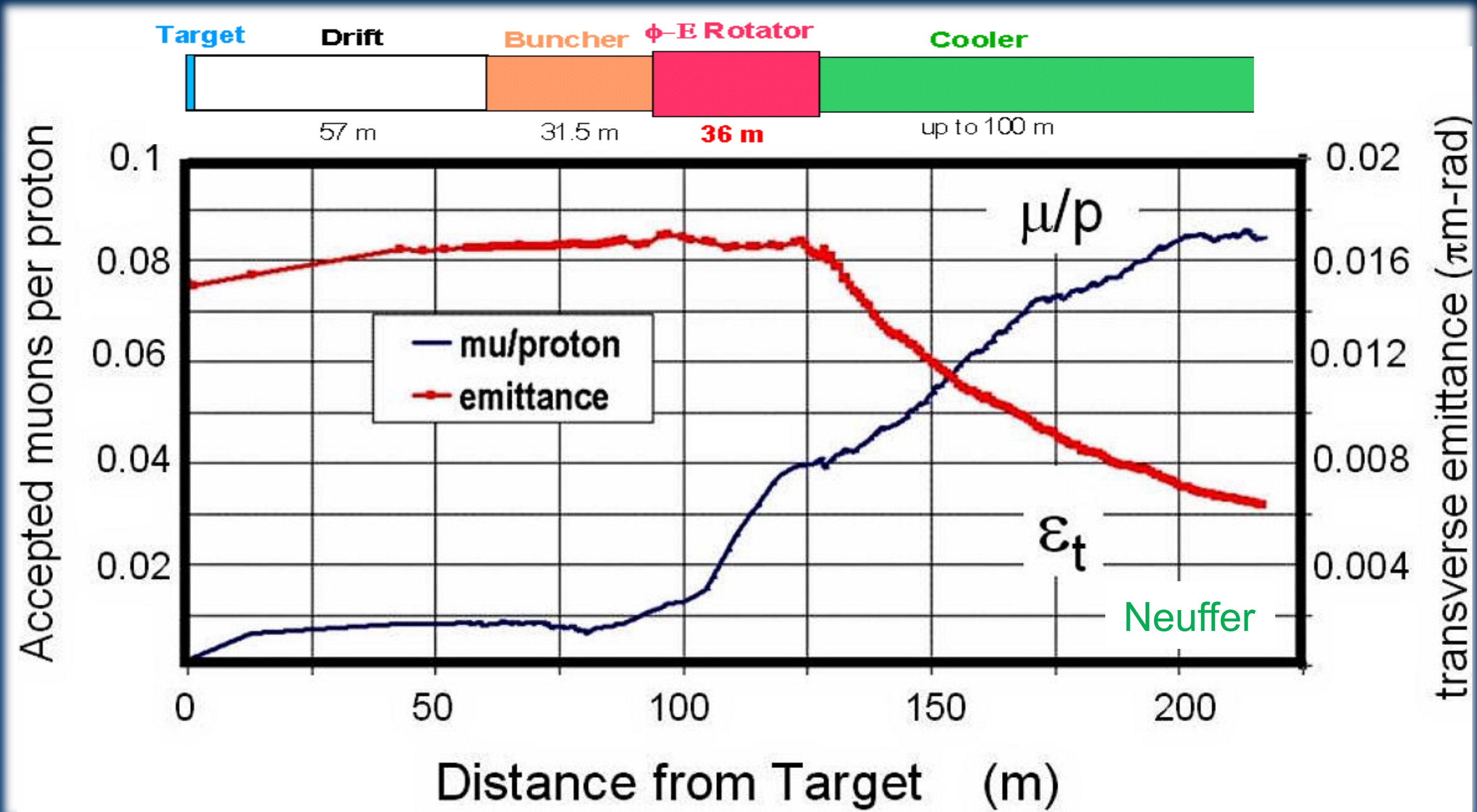
FY16 – FY18:
- Technical demonstration of critical ***baseline*** concepts
  - eg, 6D Cooling cell
- Pursue high leverage ***alternative*** concepts
- Assess technical and cost feasibility of ***baseline*** concepts
- Support major systems tests
  - MICE Step V/VI
  - 6DICE planning

Beyond Phases I & II

FY19 ➔
- Plan contingent on the conclusions from Phases I & II
- Goal is to launch the conceptual & technical design effort towards a staged implementation of a NF & MC?
- Advanced systems tests

THE R&D CHALLENGES

Technology Challenges – Tertiary Production

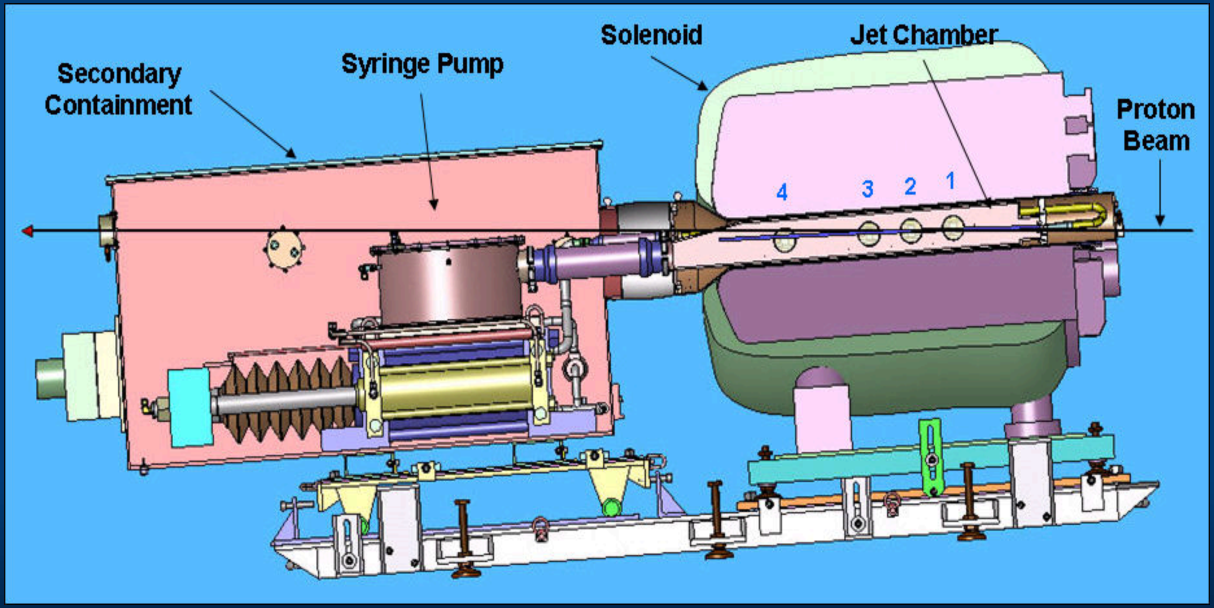


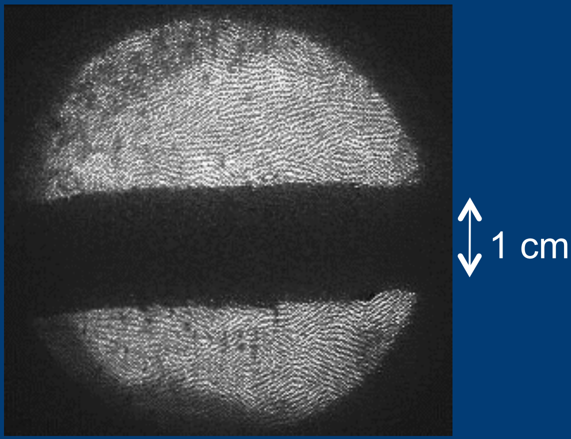
- A multi-MW proton source, *e.g.*, Project X, will enable $O(10^{21})$ muons/year to be produced, bunched and cooled to fit within the acceptance of an accelerator.

Technology 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

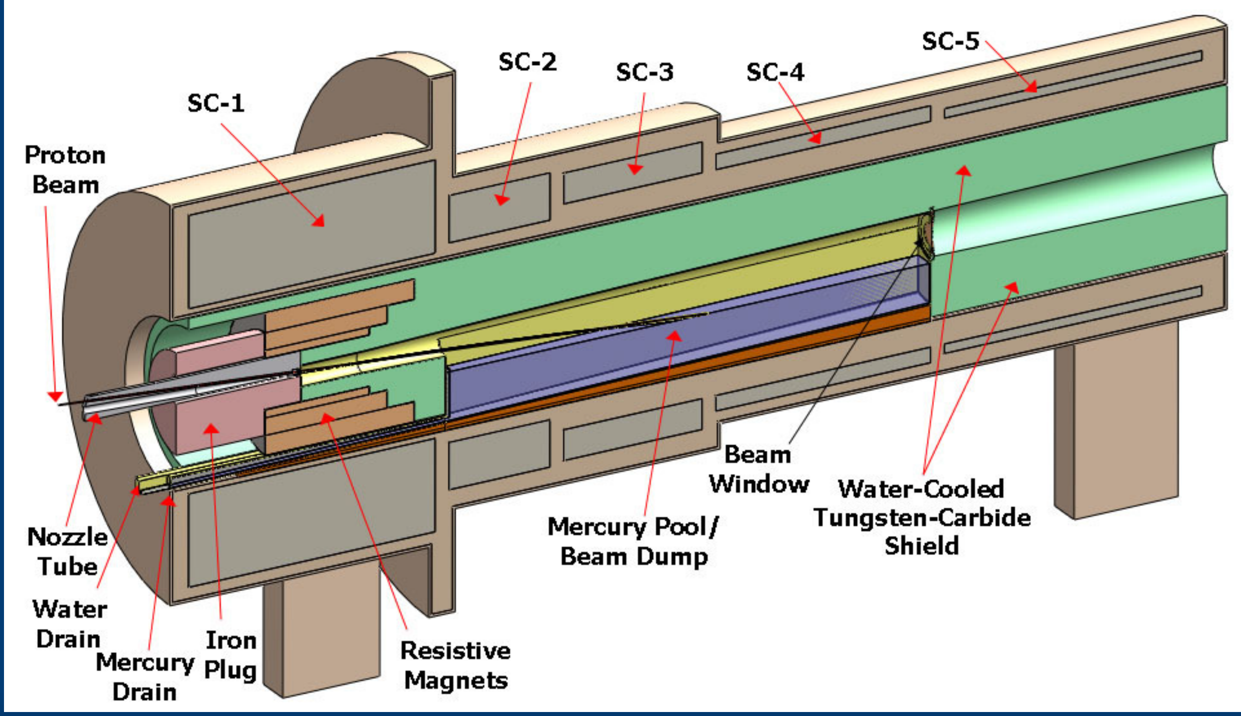
Technology Challenges – Capture Solenoid

- 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

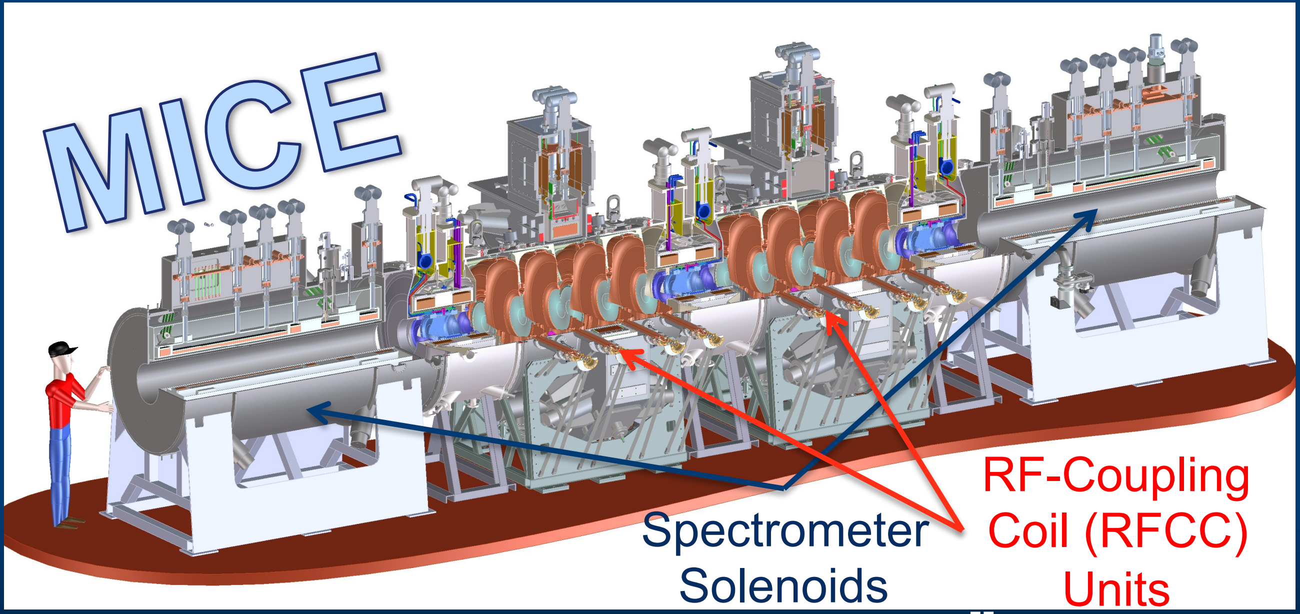
Possible application for High Temperature Superconducting magnet technology



Technology Challenges - Cooling

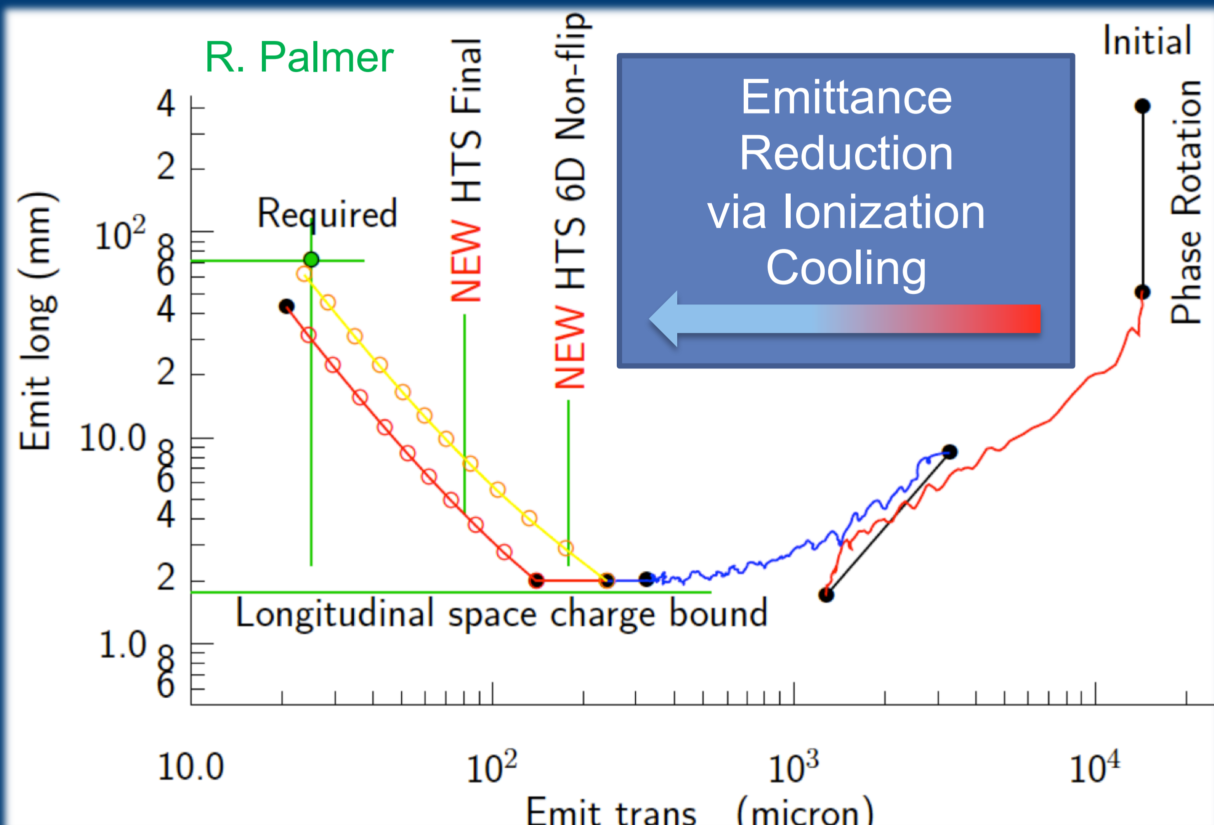
- Tertiary production of muon beams ⇨
  - Initial beam emittance intrinsically large
  - Cooling mechanism required, but no radiation damping
- Muon Cooling ⇨ Ionization Cooling
  - dE/dx energy loss in materials
  - RF to replace p_{long}

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



Technology Challenges - Cooling

- Development of a cooling channel design to reduce the 6D phase space by a factor of O(10^6-10^7) $\longrightarrow$ MC luminosity of O(10^{34}) cm^{-2} s^{-1}

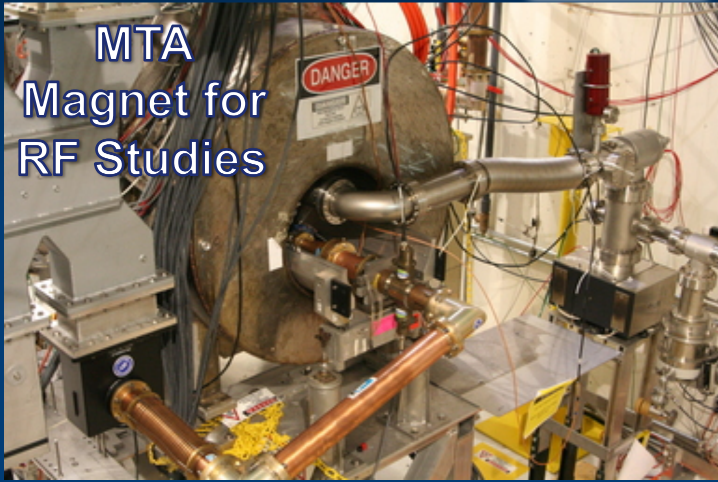


- Some components beyond state-of-art:
  - Very high field HTS solenoids (≥30 T)
  - High gradient RF cavities operating in multi-Tesla fields

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

Technology 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



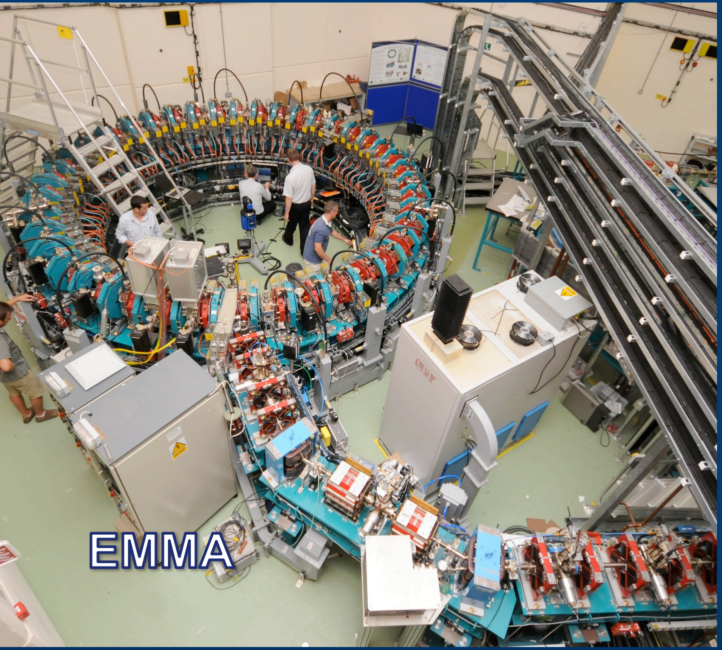
- Operation of RF cavities in high magnetic fields is a necessary element for muon cooling

  - 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
    - Breakdown mitigation techniques

Technology Challenges - Acceleration

- Muons require an ultrafast accelerator chain
  ⇨ *Beyond the capability of most machines*

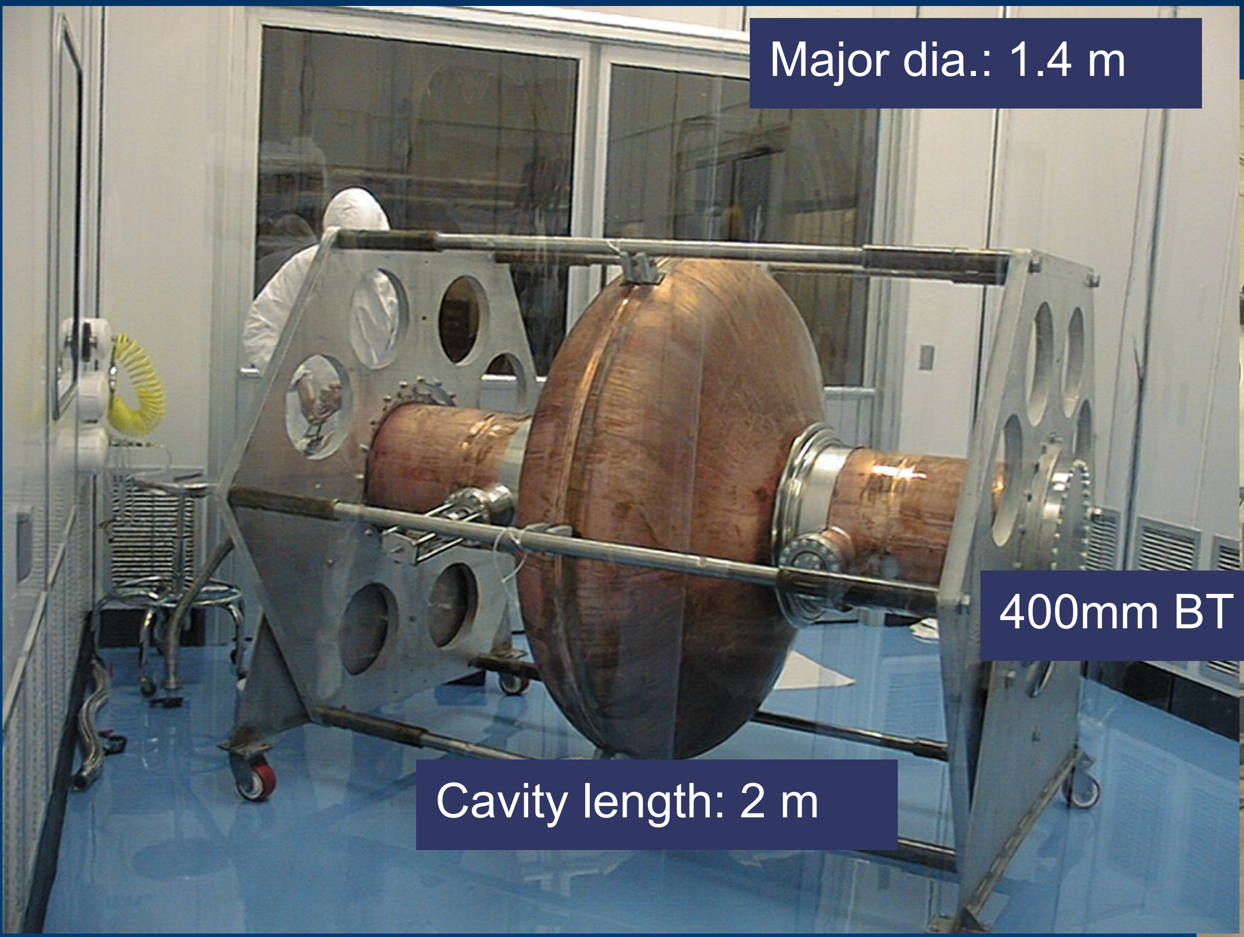
- The accelerator chain requires a range of accelerator technologies

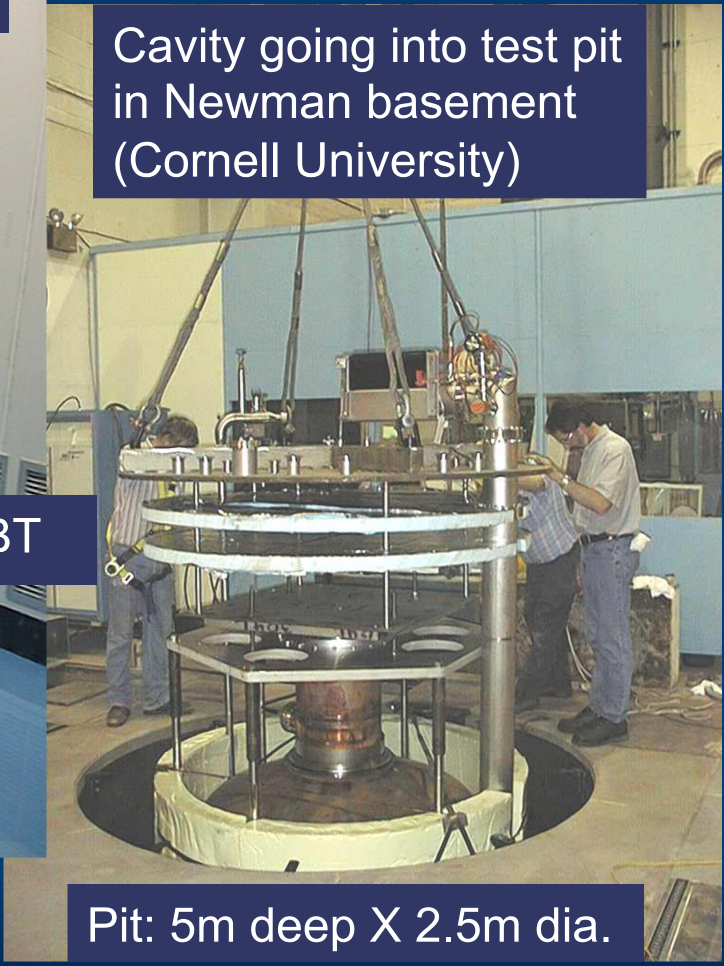


- Superconducting Linacs
- Recirculating Linear Accelerators (RLAs)
  - New designs: Utilize multi-pass arcs
  - Proposed electron demonstration (JEMMRLA)
- Fixed-Field Alternating-Gradient (FFAG) Machines
  - ➢ EMMA at Daresbury Lab is a test of the promising non-scaling type
- Rapid Cycling Synchrotrons (RCS/VRCS)

Superconducting RF Development

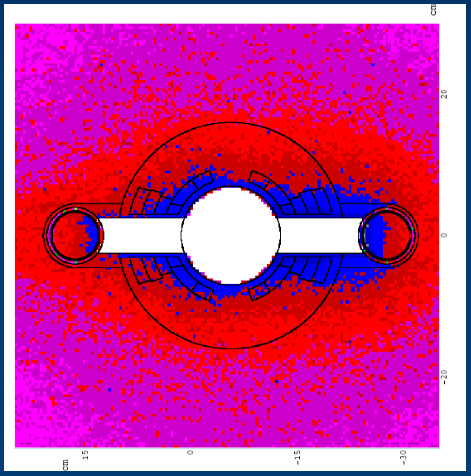
201 MHz SCRF R&D





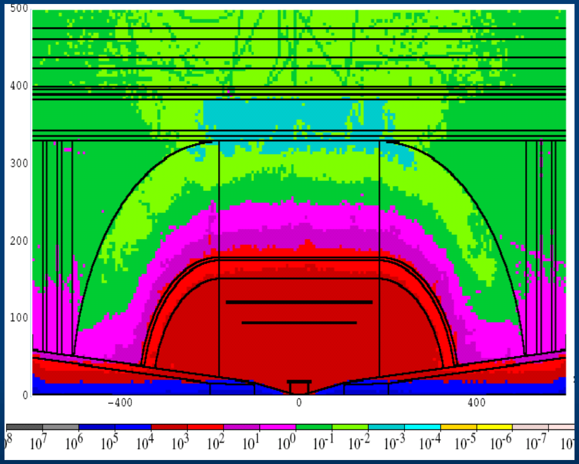
Technology & Design Challenges – Ring, Magnets, Detector

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



MARS energy deposition map for 1.5 TeV collider dipole

- High field dipoles and quadrupoles must operate in high-rate muon decay backgrounds
  - Magnet designs under study
- Detector shielding & performance
  - Initial studies for 126 GeV, 1.5 TeV, and 3 TeV using MARS background simulations
  - Major focus on optimizing shielding configuration

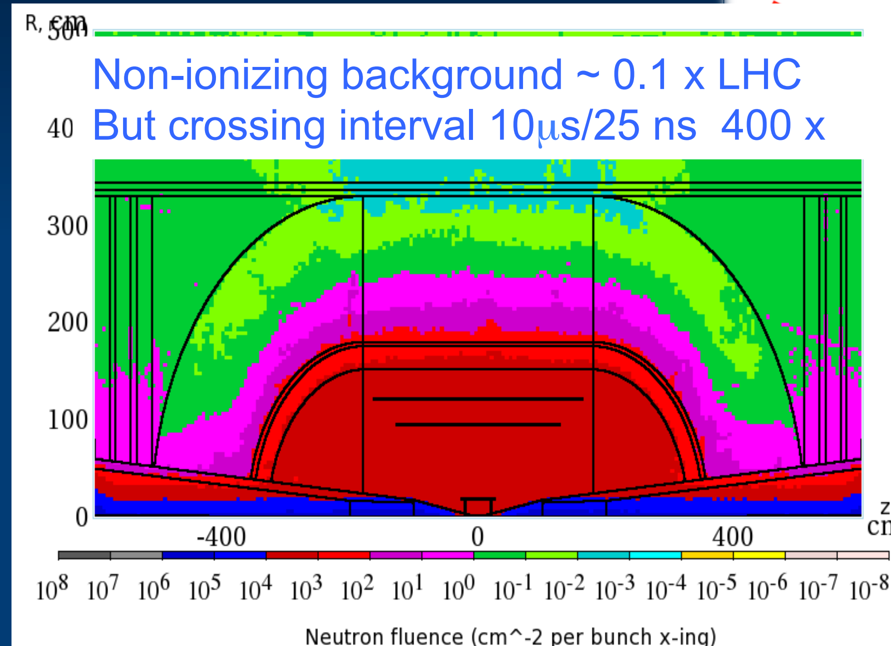


Backgrounds and Detector

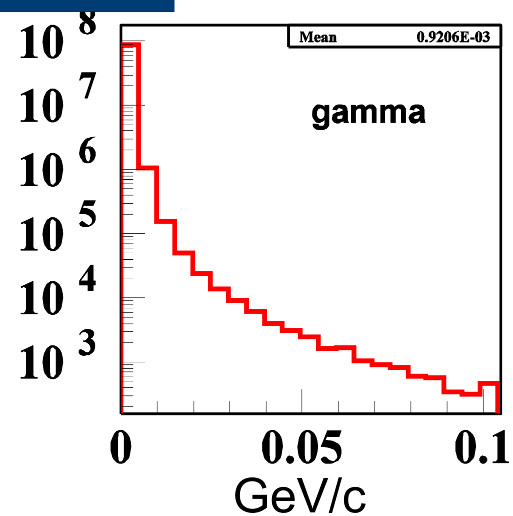
Much of the background is soft and out of time

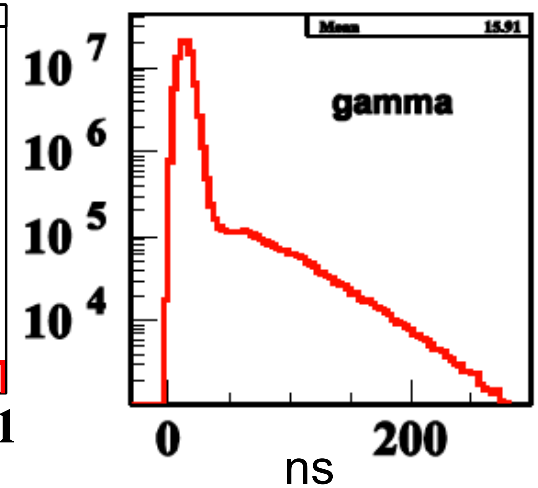
- Nanosecond time resolution can reduce backgrounds by three orders of magnitude

Requires a fast, pixelated tracker and calorimeter.



	Cut	Rejection
Tracker hits	1 ns, dedx	9×10^{-4}
Calorimeter neutrons	2 ns	2.4×10^{-3}
Calorimeter photons	2 ns	2.2×10^{-3}

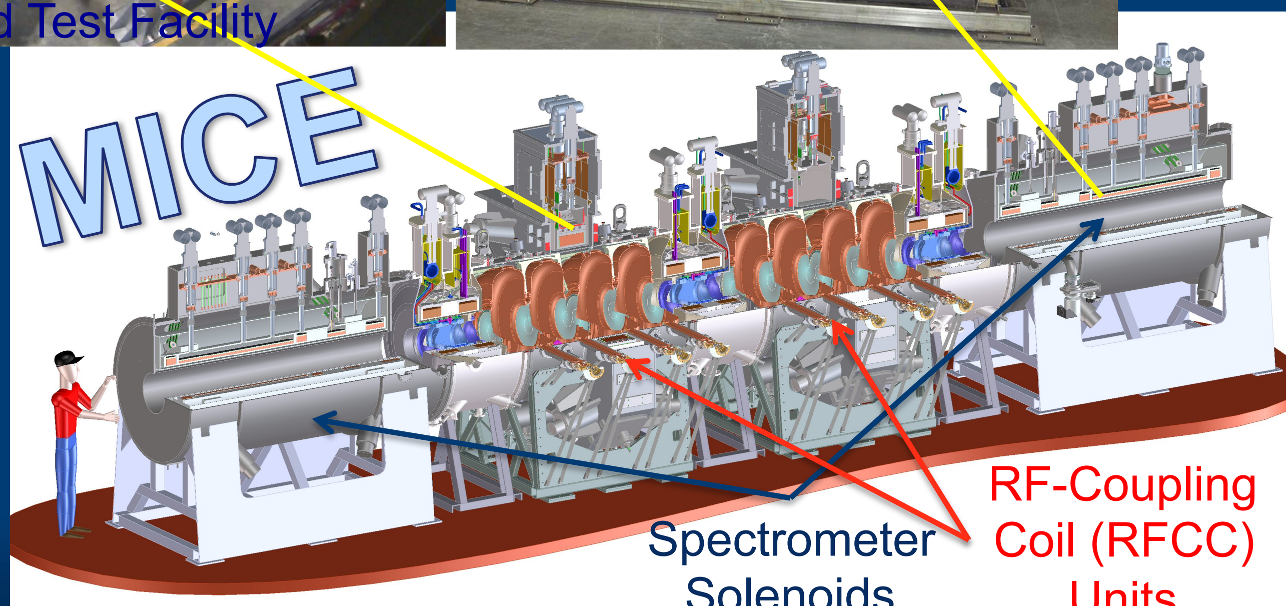




RECENT R&D PROGRESS – SOME HIGHLIGHTS

Recent Progress I - MICE

- Currently preparing for MICE Step IV
- Includes:
  - Spectrometer Solenoids
  - First Focus Coil
- Provides:
  - Direct measurement of interactions with absorber materials
  - Important simulation input

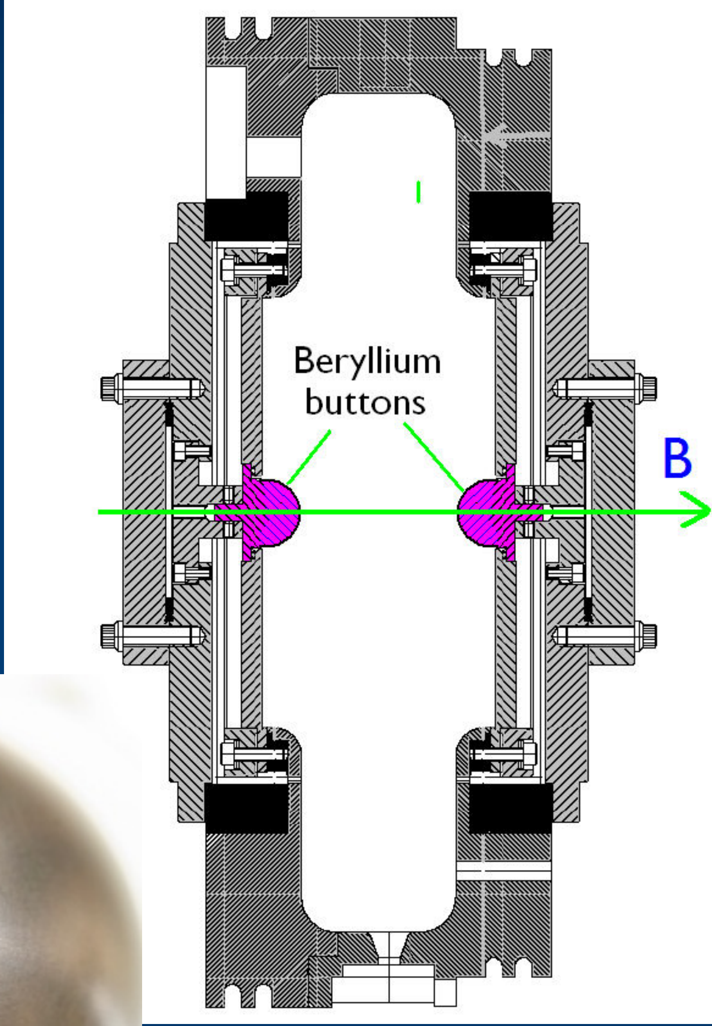


Recent Progress II – Cavity Materials

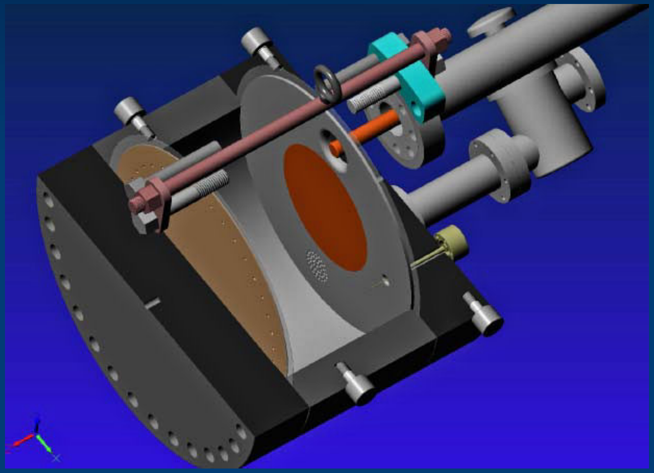
Breakdown tests with Be and Cu Buttons

- 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 mangetic fields

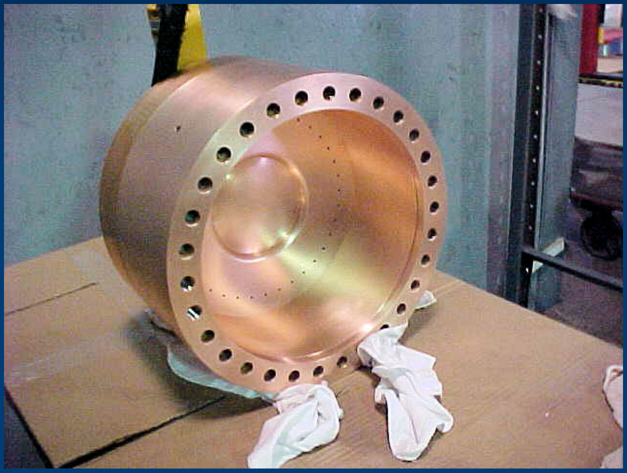


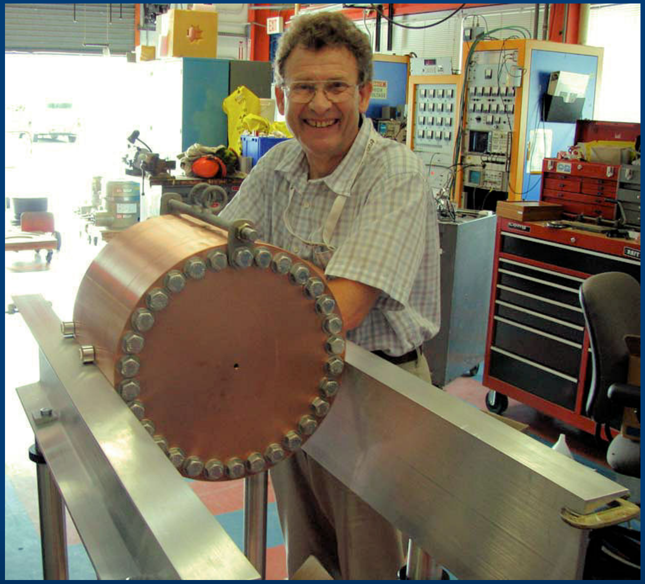
Recent Progress III – Vacuum RF



All-Seasons Cavity

(designed for both vacuum and high pressure operation)

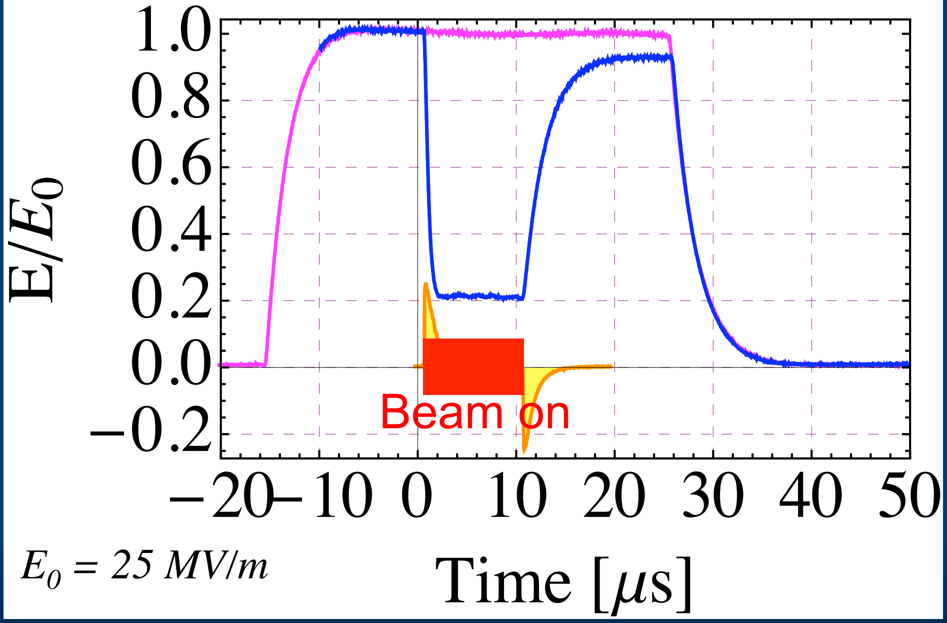


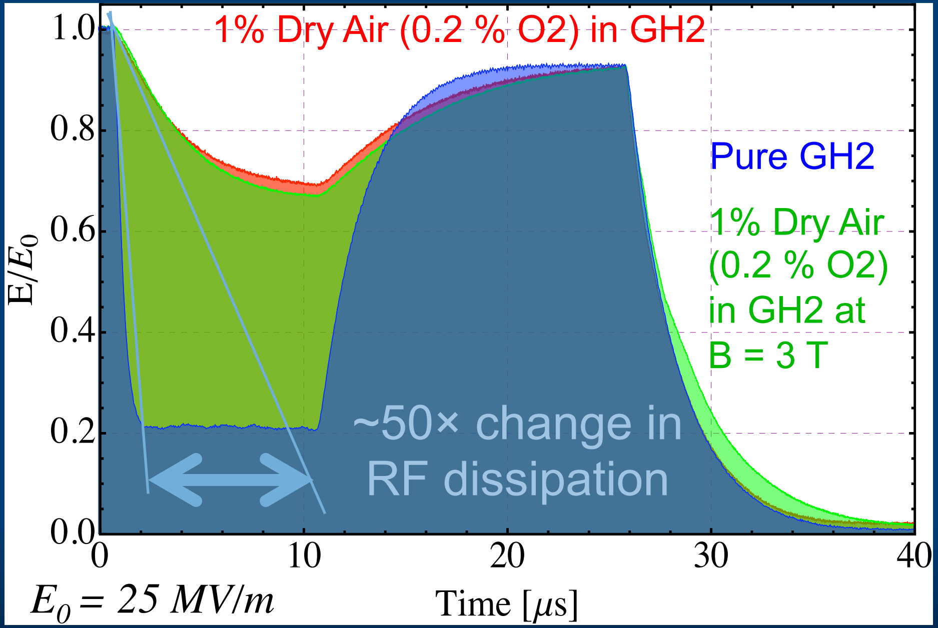


- Vacuum Tests at B = 0 T & B = 3 T
  - Two cycles: $B_0 \Rightarrow B_3 \Rightarrow B_0 \Rightarrow B_3$
- No difference in maximum stable operating gradient
  - Gradient $\approx$ 25 MV/m
- Demonstrates possibility of successful operation of vacuum cavities in magnetic fields with careful design

Recent Progress IV: 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



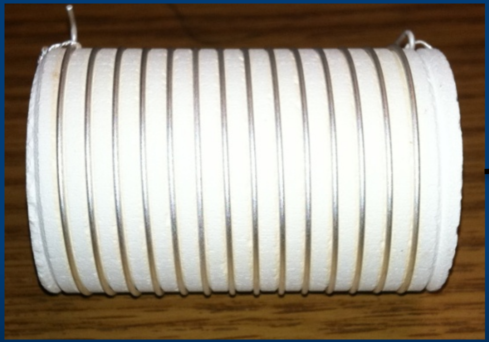


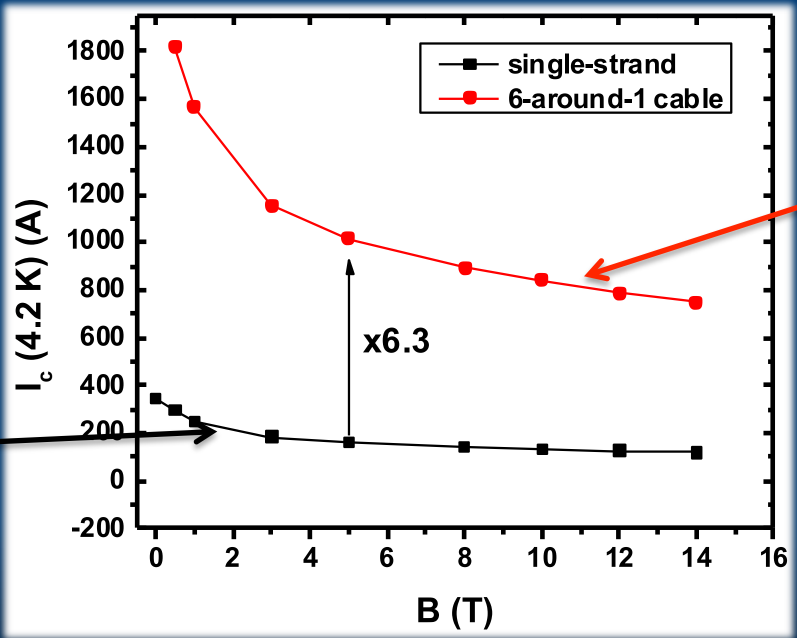
Recent Progress V: High Field Magnets

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)
- Will soon begin preparations for a test with HTS insert + mid-sert in NC solenoid at NHFML ⇨ >30 T

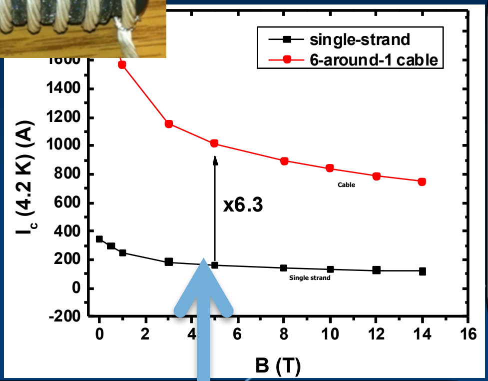
BSCCO-2212 Cable - Transport measurements show that FNAL cable attains 105% J_c of that of the single-strand





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

MAP: Recent Technology Highlights

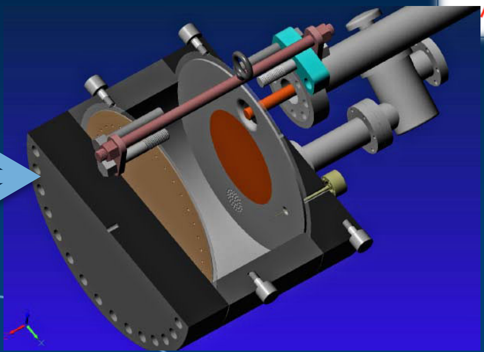


Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

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

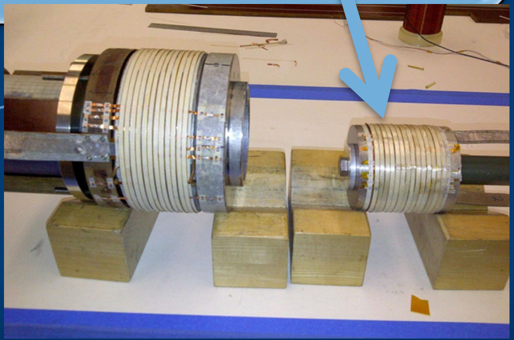


The Path to a Viable Muon Ionization Cooling Channel

World Record HTS-only Coil

15T on-axis field
16T on coil

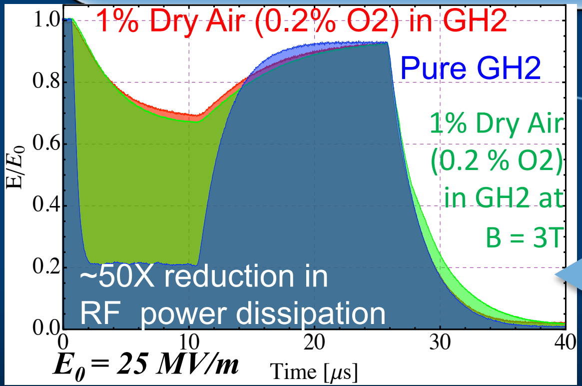
PBL/BNL



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

Extrapolates to
μ-Collider Parameters

MuCool Test Area



THE MUON ACCELERATOR STAGING STUDY (MASS) AND MAP TIMELINES

A Staged Muon-Based Neutrino and Collider Physics Program

The plan is conceived in four stages, whose exact order remains to be worked out:

- The "entry point" for the plan is the νSTORM facility proposed at Fermilab, which can advance short-baseline physics by making definitive observations or exclusions of sterile neutrinos. Secondly, it can make key measurements to reduce systematic uncertainties in long-baseline neutrino experiments. Finally, it can serve as an R&D platform for demonstration of accelerator capabilities pre-requisite to the later stages.
- A stored-muon-beam Neutrino Factory can take advantage of the large value of θ_{13} recently measured in reactor-antineutrino experiments to make definitive measurements of neutrino oscillations and their possible violation of CP symmetry.
- Thanks to suppression of radiative effects by the muon mass and the m^2_{lepton} proportionality of the s-channel Higgs coupling, a "Higgs Factory" Muon Collider can make uniquely precise measurements of the 126 GeV boson recently discovered at the LHC.
- An energy-frontier Muon Collider can perform unique measurements of Terascale physics, offering both precision and discovery reach.

Muon Accelerators

Accelerator	Energy Scale	Performance
Cooling Channel	**~200 MeV**	**Emittance Reduction**
MICE	*160-240 MeV*	*10%*
Muon Storage Ring	**3-4 GeV**	**Useable μ decays/yr***
νSTORM	*3.8 GeV*	*$3x10^{17}$*
Intensity Frontier ν Factory	**4-10 GeV**	**Useable μ decays/yr***
FNAL NF Phase I (PX Ph 2)	*4-6 GeV*	*$8x10^{19}$*
FNAL NF Phase II (PX Ph 2)	*4-6 GeV*	*$5x10^{20}$*
IDS-NF Design	*10 GeV*	*$5x10^{20}$*
Higgs Factory	**~126 GeV CoM**	**Higgs/yr**
s-Channel μ Collider	~126 GeV CoM	5,000-40,000
Energy Frontier μ Collider	**> 1 TeV CoM**	**Avg. Luminosity**
Opt. 1	*1.5 TeV CoM*	*$1.2x10^{34}cm^{-2}s^{-1}$*
Opt. 2	*3 TeV CoM*	*$4.4x10^{34}cm^{-2}s^{-1}$*
Opt. 3	*6 TeV CoM*	*$12x10^{34}cm^{-2}s^{-1}$*

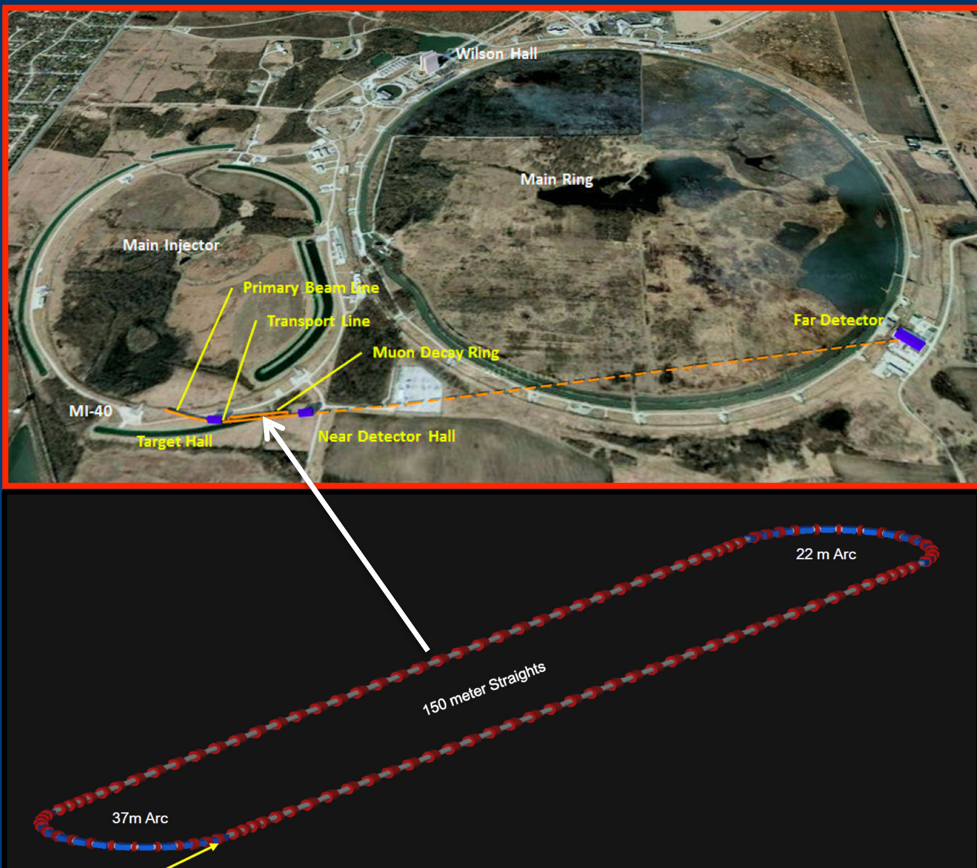
* Decays of an individual species (ie, μ^+ or μ^-)

Program Baselines

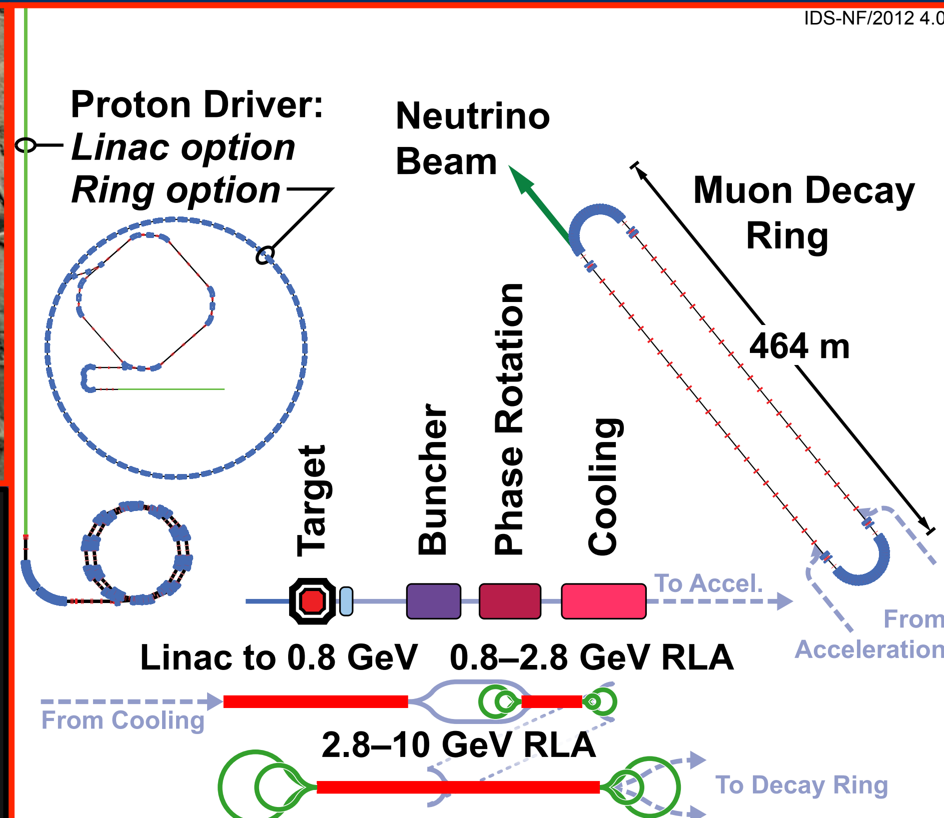
And Potential Staging Steps

All proposed muon-based accelerators would easily fit at Fermilab

νSTORM (entry level Neutrino Factory)



Intensity Frontier Neutrino Factory

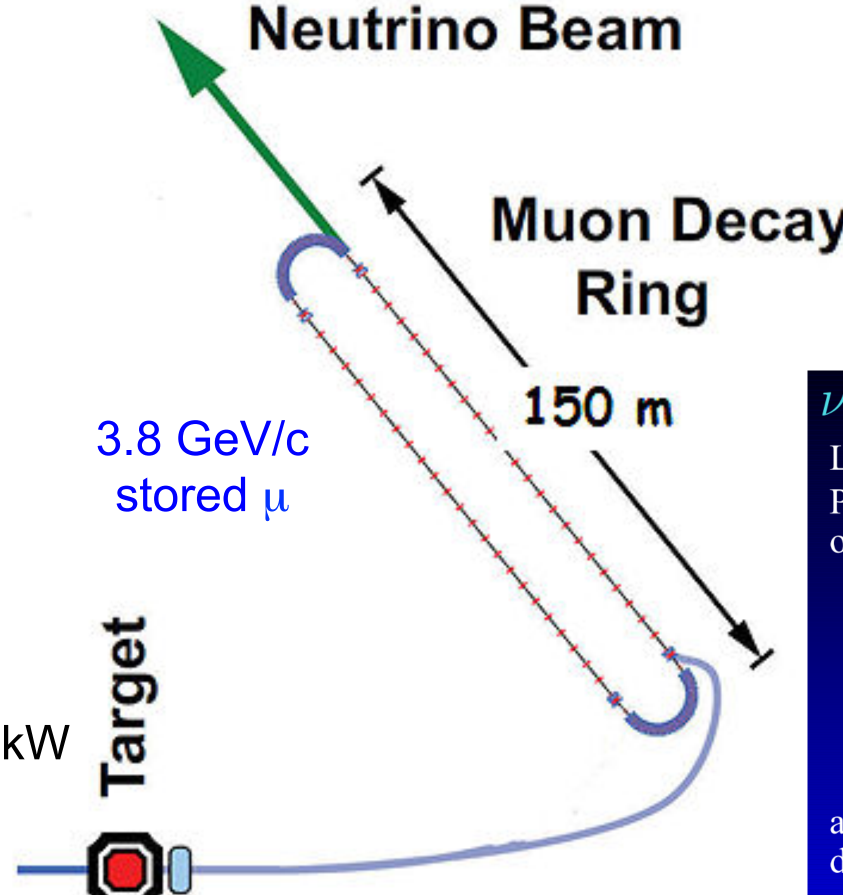


νSTORM would provide important physics output and critical R&D leverage

Also a muon-based Higgs Factory or Energy Frontier Muon Collider

Neutrinos from Stored Muons (arXiv: 1206.0294 (LOI), Fermilab P-1028)

A.Bross
NuFACT12



An entry-level NF?

DOES NOT
Require the Development of ANY New Technology

νSTORM

Low energy, low luminosity muon storage ring. Provides with 1.7×10^{18} μ^+ stored, the following oscillated event numbers

$\nu_e \to \nu_\mu$ CC	330
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47000
$\nu_e \to \nu_e$ NC	74000
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122000
$\nu_e \to \nu_e$ CC	217000

and each of these channels has a more than $10\,\sigma$ difference from no oscillations

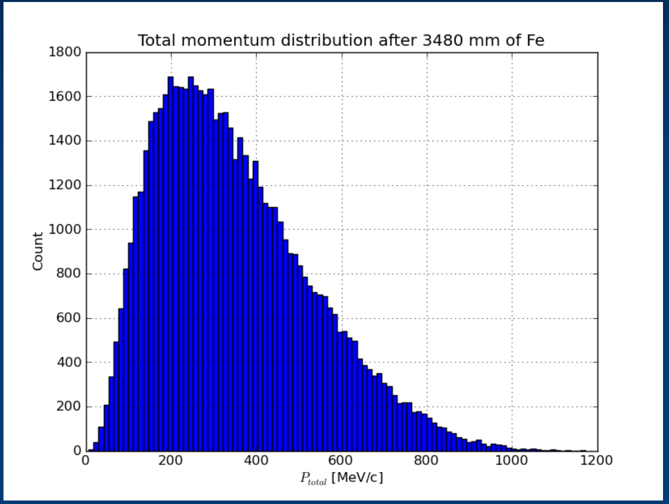
With more than 200 000 ν_e CC events a %-level ν_e cross section measurement should be possible

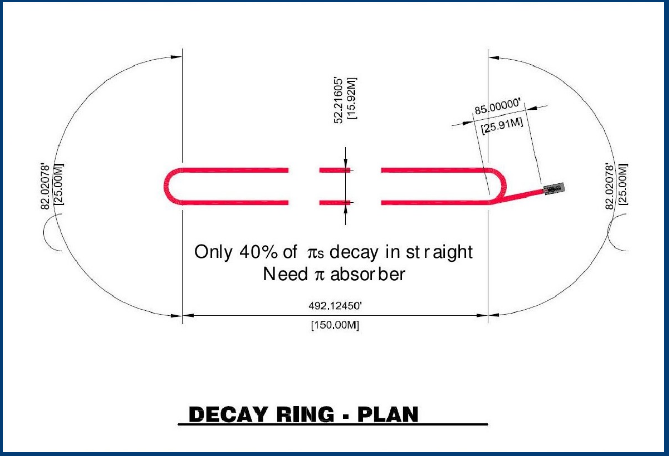
NuSTORM Workshop held Sept 21-22 @ FNAL:

(https://indico.fnal.gov/conferenceDisplay.py?confId=5710)

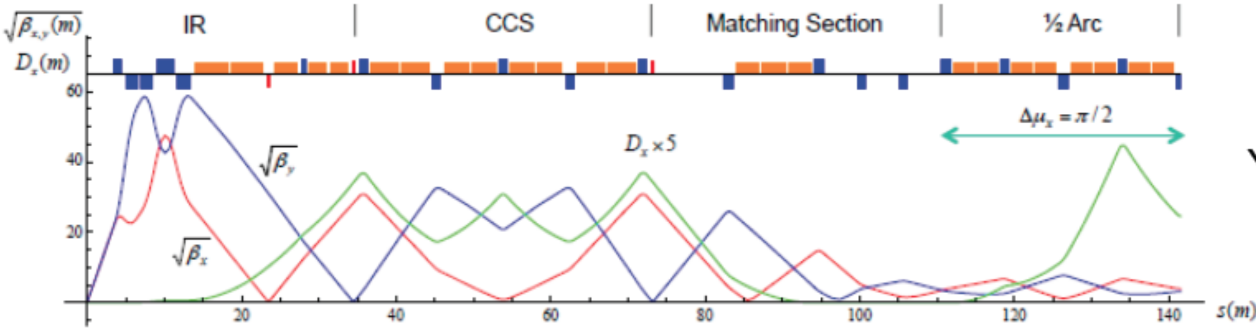
νStorm as an R&D platform

- A high-intensity pulsed muon source
- $100<p_\mu<300$ MeV/c muons
  - Using extracted beam from ring
  - 10^{10} muons per 1 μsec pulse
- Beam available simultaneously with physics operation
  - Sterile ν search
  - ν cross section measurements needed for ultimate precision in long baseline measurements
- νSTORM also provides the opportunity to design, build and test decay ring instrumentation (BCT, momentum spectrometer, polarimeter) to measure and characterize the circulating muon flux.





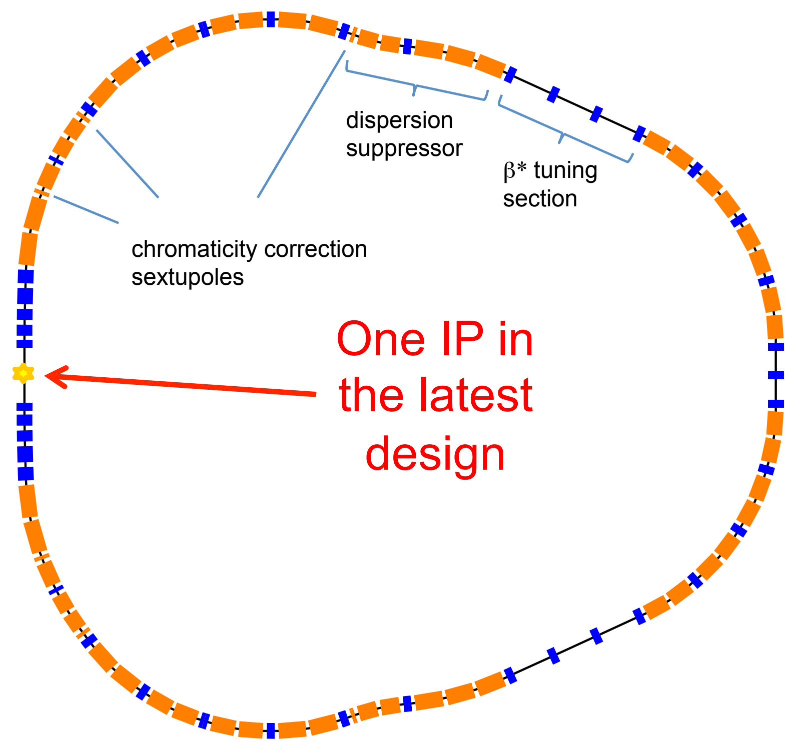
Updated 63 x 63 GeV Lattice



Optics functions in half ring for β*=2.5cm

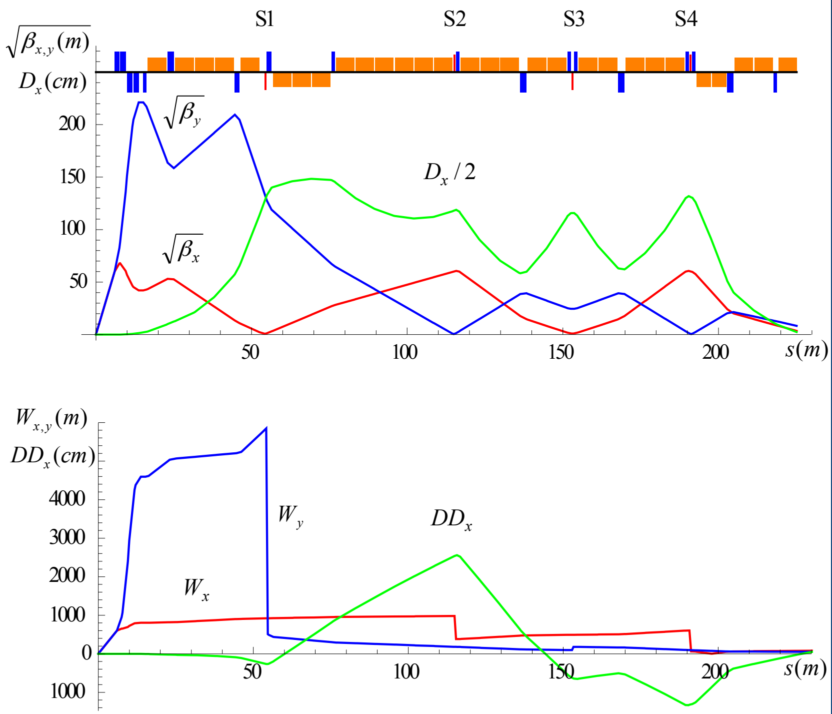
Y. Alexahin

Parameter			
Beam energy	GeV	63	63
Average luminosity	10^{31}/cm²/s	1.7	8.0
Collision energy spread	MeV	3	4
Circumference, C	m	300	300
Number of IPs	-	1	1
β*	cm	3.3	1.7
Number of muons / bunch	10^{12}	2	4
Number of bunches / beam	-	1	1
Beam energy spread	%	0.003	0.004
Normalized emittance, $\varepsilon_{\perp N}$	π·mm·rad	0.4	0.2
Longitudinal emittance, $\varepsilon_{\parallel N}$	π·mm	1.0	1.5
Bunch length, σ_s	cm	5.6	6.3
Beam size at IP, r.m.s.	mm	0.15	0.075
Beam size in IR quads, r.m.s.	cm	4	4
Beam-beam parameter	-	0.005	0.02
Repetition rate	Hz	30	15
Proton driver power	MW	4	4



Multi-TeV Collider – 1.5 TeV Baseline

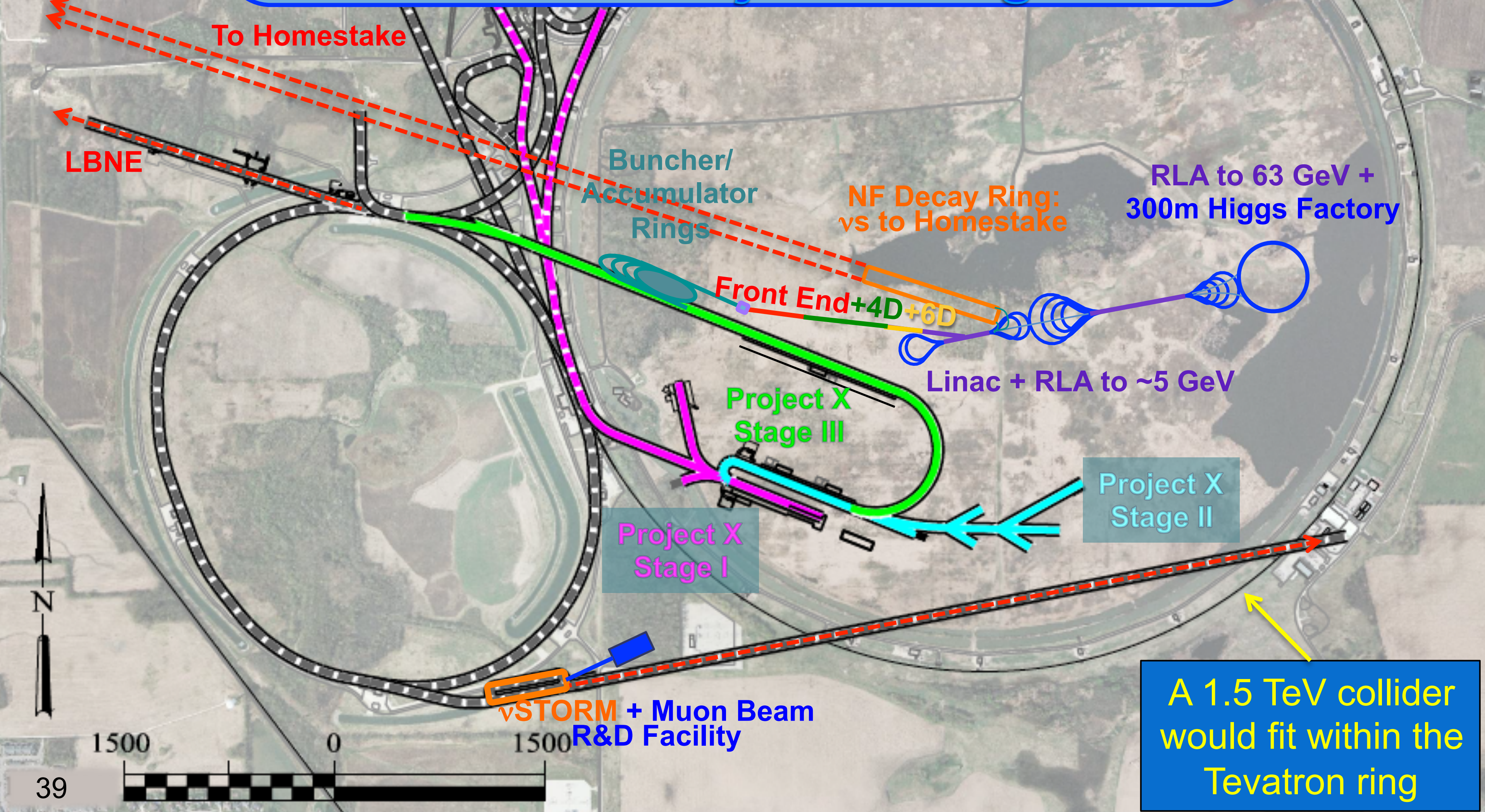
Y. Alexahin



Larger chromatic function (Wy) is corrected first with a single sextupole S1, Wx is corrected with two sextupoles S2, S4 separated by 180° phase advance.

Parameter	Unit	Value
Beam energy	TeV	0.75
Repetition rate	Hz	15
Average luminosity / IP	$10^{34}/cm^2/s$	1.1
Number of IPs, N_{IP}	-	2
Circumference, C	km	2.73
β^*	cm	1 (0.5-2)
Momentum compaction, α_p	10^{-5}	-1.3
Normalized r.m.s. emittance, $\varepsilon_{\perp N}$	π·mm·mrad	25
Momentum spread, σ_p/p	%	0.1
Bunch length, σ_s	cm	1
Number of muons / bunch	10^{12}	2
Number of bunches / beam	-	1
Beam-beam parameter / IP, ξ	-	0.09
RF voltage at 800 MHz	MV	16

A Muon Accelerator Facility for Cutting Edge Physics on the Intensity and Energy Frontiers Based on Project X Stage II



How Could the Staged NF to Homestake Perform?

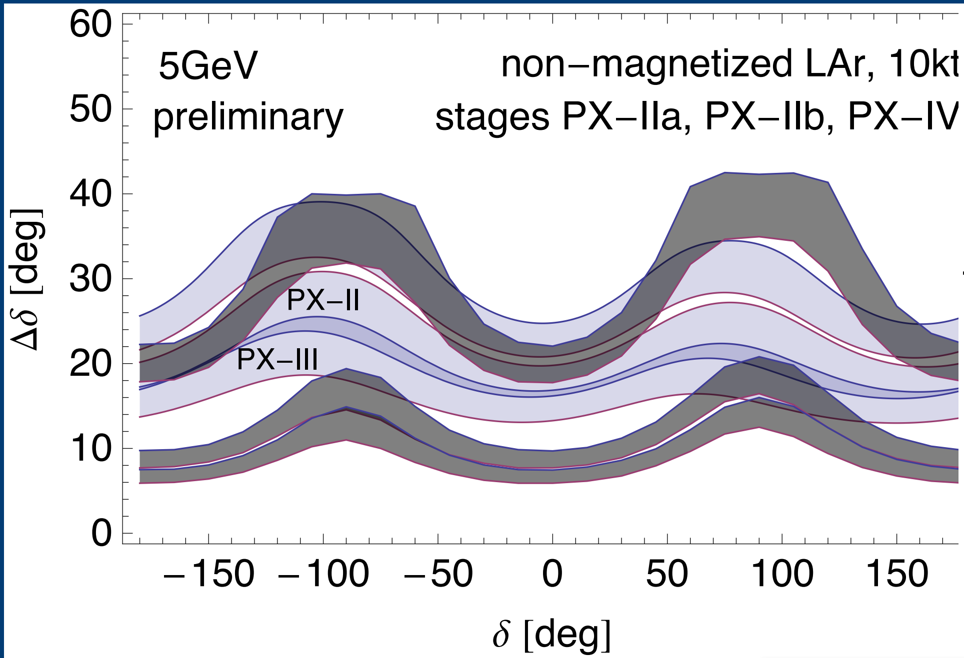
What if we send beam to LBNE?

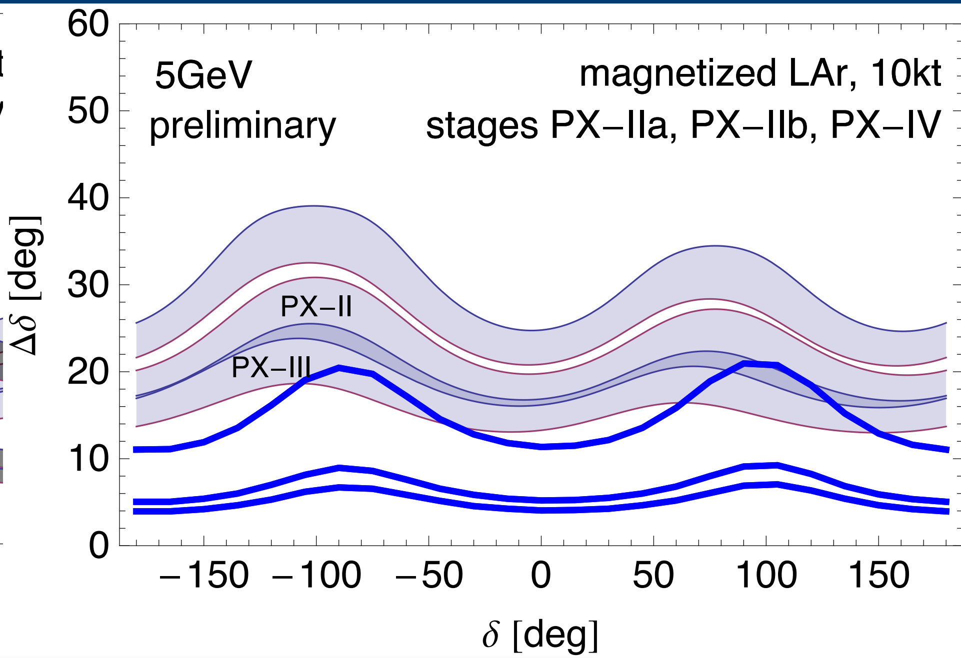
1 MW, no muon cooling

⇨ 3 MW, w/cooling

⇨ 4 MW, w/cooling

What if we were able to have a magnetized LAr detector?





Gray bands represent range of possible detector performance per arXiv:0805.2019

Plots courtesy of P. Huber

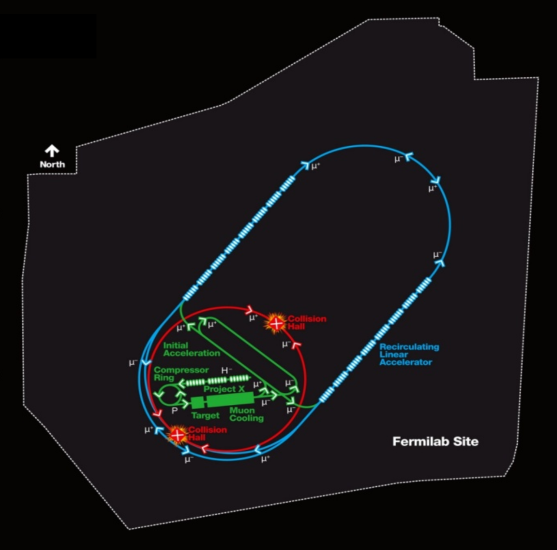
Plots assume 100 kt-years

Neutrino Factory Staging (MASS)

Preliminary Staging Plan Based on **Project X Phase 2**

System	Parameters	Unit	NuSTORM	L3NF	NF	IDS-NF
Performance	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**	**Super-Bind***	**Mag LAr**	**Mag LAr**	**Super-Bind**
	Distance from ring	**km**	**1.5**	**1300**	1300	2000
	Mass	**kT**	**1.3**	**10**	**30?**	**100**
	magnetic field	**T**	**2**	**0.5**	**0.5**	**1-->2 ?**
	Near Detector	**Type**	**Liquid Ar**	**Liquid Ar**	**Liquid Ar**	**Liquid Ar**
	Distance from ring	**m**	**50**	**100**	**100**	**100**
	Mass	**kT**	**0.1**	**1**	**2.7**	**2.7**
	magnetic field	**T**	**No**	**No**	**No**	**No**
Neutrino Ring	Ring Momentum P_μ	GeV/c	3.8	5	5	10
	Circumference C	m	350	600	600	1190
	Straight section Length	m	150	235	235	470
	Arc Length	m	25	65	65	125
Acceleration	Initial Momentum	GeV/c	3.8	0.22	0.22	0.22
	single pass Linac	GeV	None	0.9?	0.9?	0.9
	4.5-pass RLA	GeV	None	0.92?	0.92?	4
	NS-FFAG Ring	GeV	None	None	None	10
	SRF frequency linac/RLA	MHz	None	325/650	325/650	201
	Number of cavities		None	50 + 26?	50 + 26?	50 + 26 + 25
	Total Arc Length	m	50	550?	550?	550 +200
Cooling			No	No	4D	4D
Proton Source	Proton Beam Power	MW	0.2	1	3	4
	Proton Beam Energy	GeV	60	3	3	10
	protons/year	1×10^{21}	0.2	41	125	25
	Repetition Frequency	Hz	1.25	70	70	50

* supports multiple detector technologies



MAP Designs for a Muon-Based Higgs Factory and Energy Frontier Collider

Muon Collider Baseline Parameters

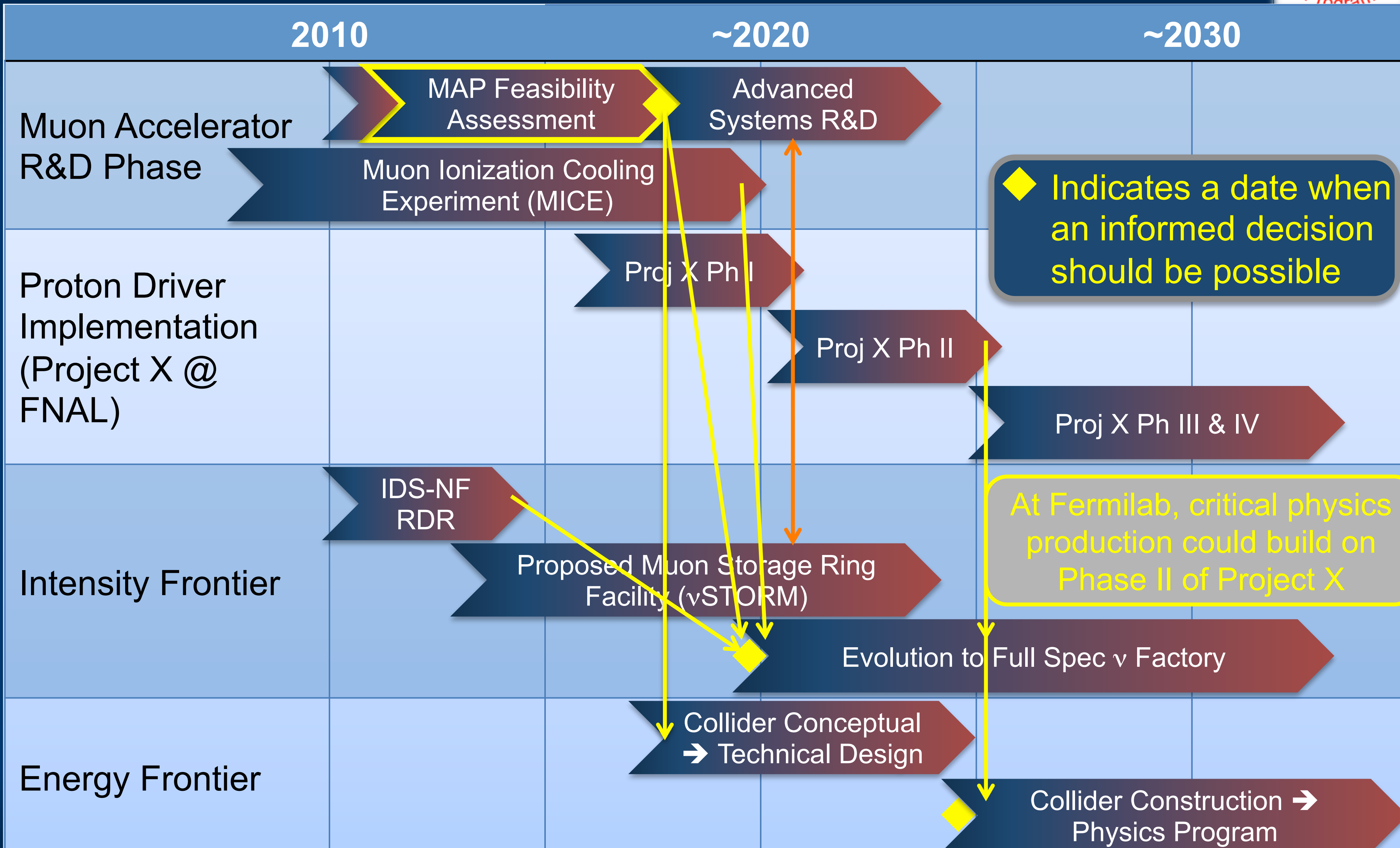
Parameter	*Units*	Higgs Factory: Initial Cooling	Higgs Factory: Upgraded Cooling / Combiner	Multi-TeV Baselines	Multi-TeV Baselines
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Circumference	km	0.3	0.3	2.5	4.5
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}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π 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

$^{\#}$Could begin operation with Project X Phase 2 beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

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

The Muon Accelerator Program Timeline



CONCLUDING REMARKS

Some Thoughts…

- The unique feature of muon accelerators is the ability to provide cutting edge performance on both the Intensity and Energy Frontiers
  - This is well-matched to the direction specified by the P5 panel for Fermilab
  - The possibilities for a staged approach make this particularly appealing in a time of constrained budgets
  - νSTORM would represent a critical first step in providing a muon-based accelerator complex

- World leading Intensity Frontier performance could be provided with a Neutrino Factory based on Project X Phase II
  - This would also provide the necessary foundation for a return to the Energy Frontier with a muon collider on U.S. soil

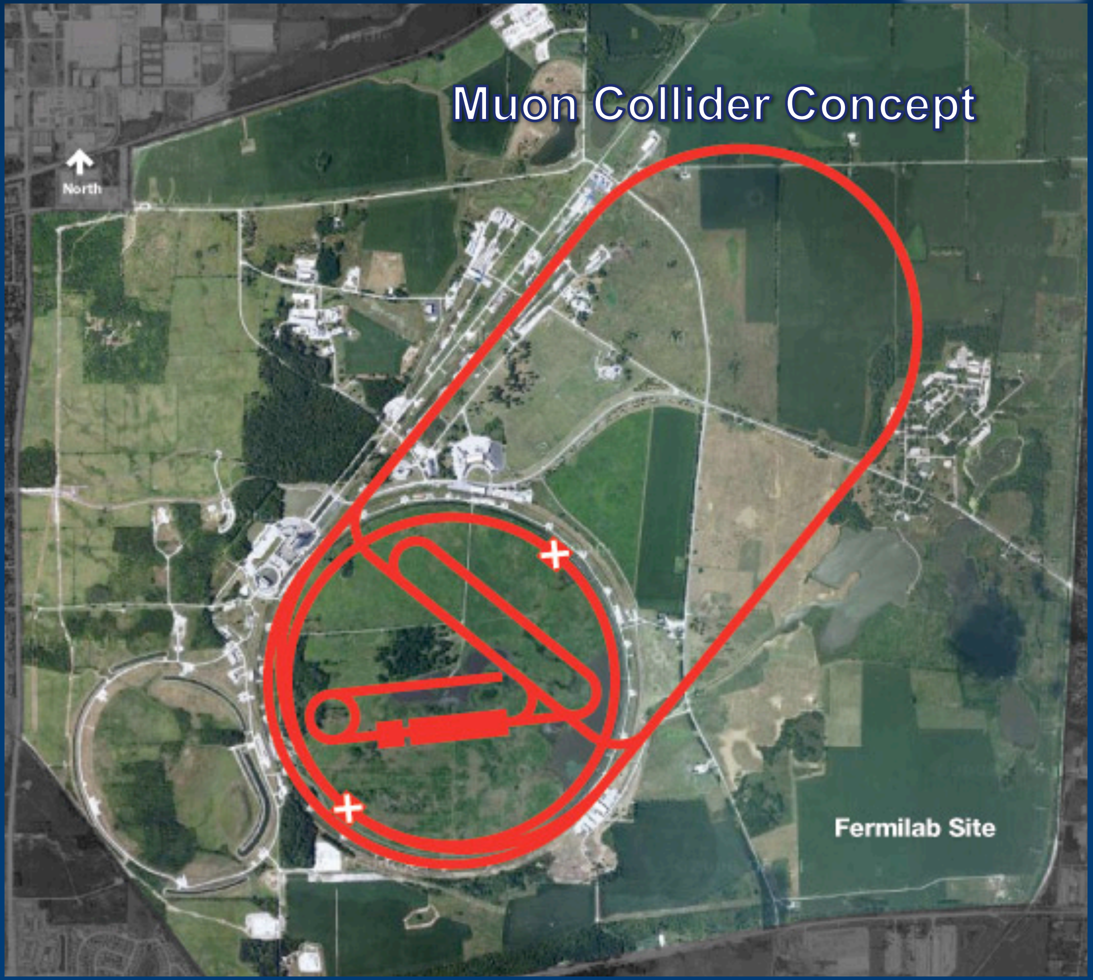
- A Muon Collider Higgs Factory
  - Would provide exquisite energy resolution to directly measure the width of the Higgs. This capability would be of crucial importance in the MSSM doublet scenario.

The first collider on the path to a multi-TeV Energy Frontier lepton machine?

Conclusion

- Through the end of this decade, the primary goal of MAP is demonstrating the feasibility of key concepts needed for a neutrino factory and muon collider

⇨ Thus enabling an informed decision on the path forward for the HEP community



A challenging, but promising, R&D program lies ahead!

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The MAP Effort -

- Labs: ANL, BNL, FNAL, JLAB, LBNL, ORNL, SLAC
- Universities: Chicago, Cornell, IIT, Princeton, UC-Berkeley, UCLA, UC-Riverside, UMiss
- Companies: Muons, Inc; Particle Beam Lasers