Muon Accelerators for the Next Generation of High Energy Physics Experiments

Katsuya Yonehara

on behalf of MAP

Accelerator Physics Center, Fermilab

June 08, 2013

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:

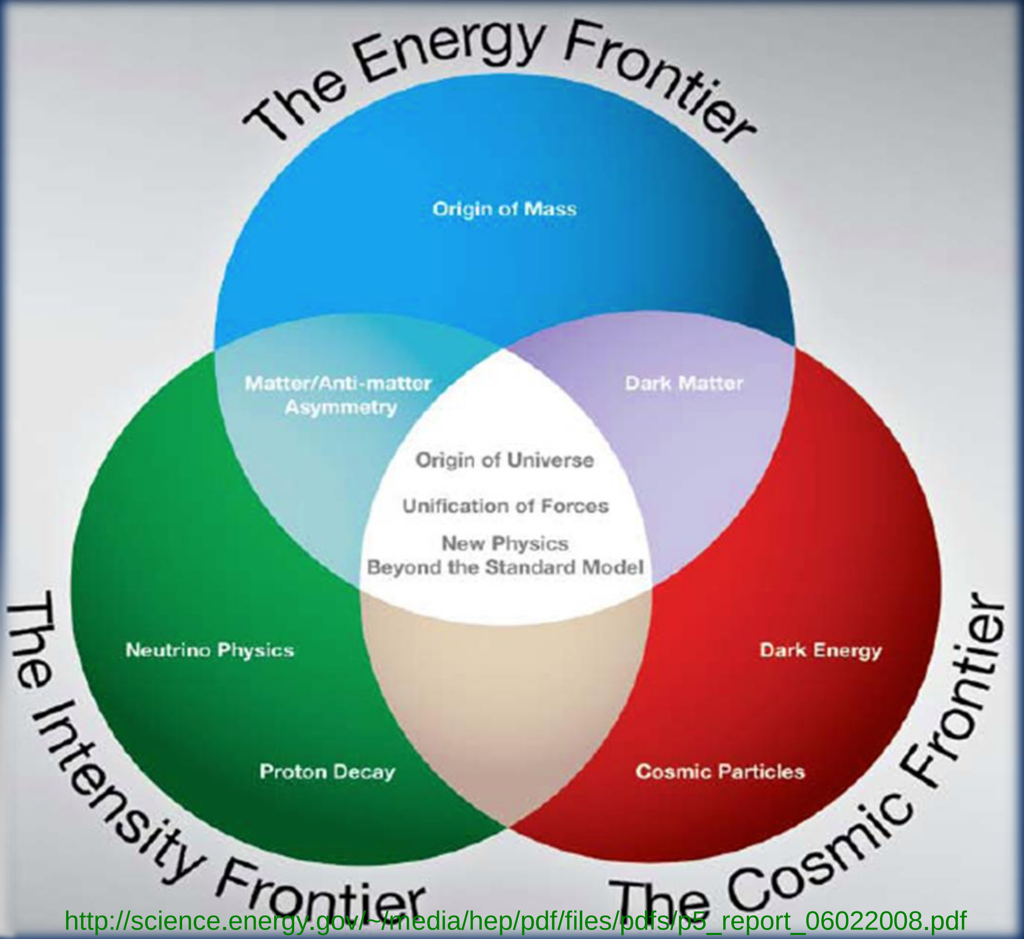
with a ***Neutrino Factory*** producing well-characterized ν beams for precise, high sensitivity studies

The Energy Frontier:

with a ***Muon Collider*** capable of reaching multi-TeV CoM energies

and

*a **Higgs Factory** on the border between these Frontiers*



http://science.energy.gov/~/media/hep/pdf/files/pdfs/p5_report_06022008.pdf

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

Outline

- Physics Motivations
- Muon Collider Concept
- Muon Collider and Neutrino Factory Synergies
- The MAP Feasibility Assessment
- Concluding Remarks

Backup item (Central part of MAP R&D)

- R&D Challenges
- Recent R&D Highlights

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 (mu2e conversion)
  - 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

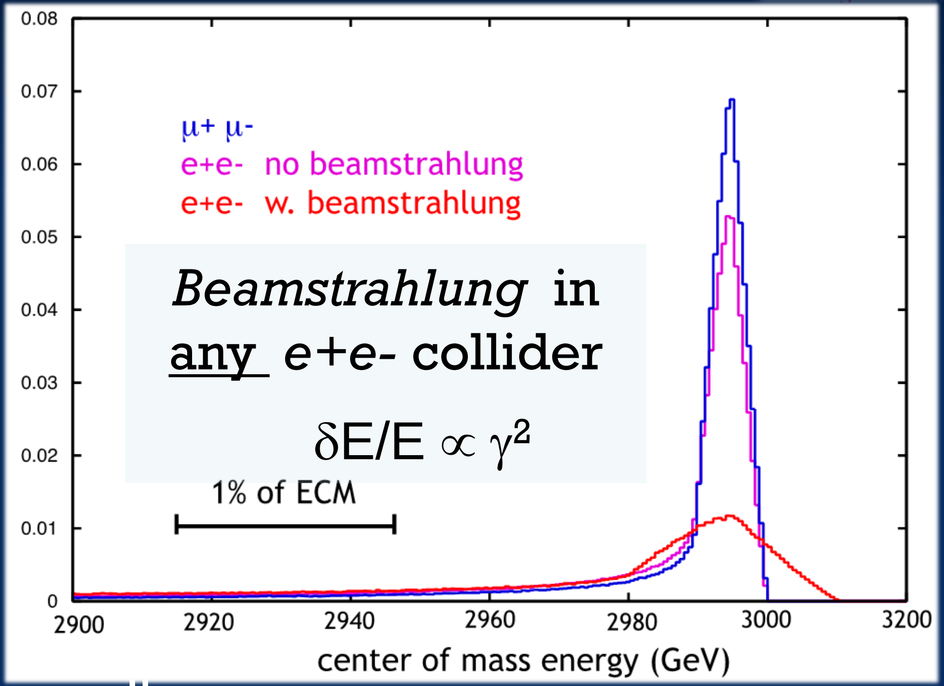
$$m^+ \to e^+ n_e \bar{n}_m$$

$$m^- \to e^- \bar{n}_e n_m$$

  - Offers a large coupling to the “Higgs mechanism” $\sim \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times10^4$
  - 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

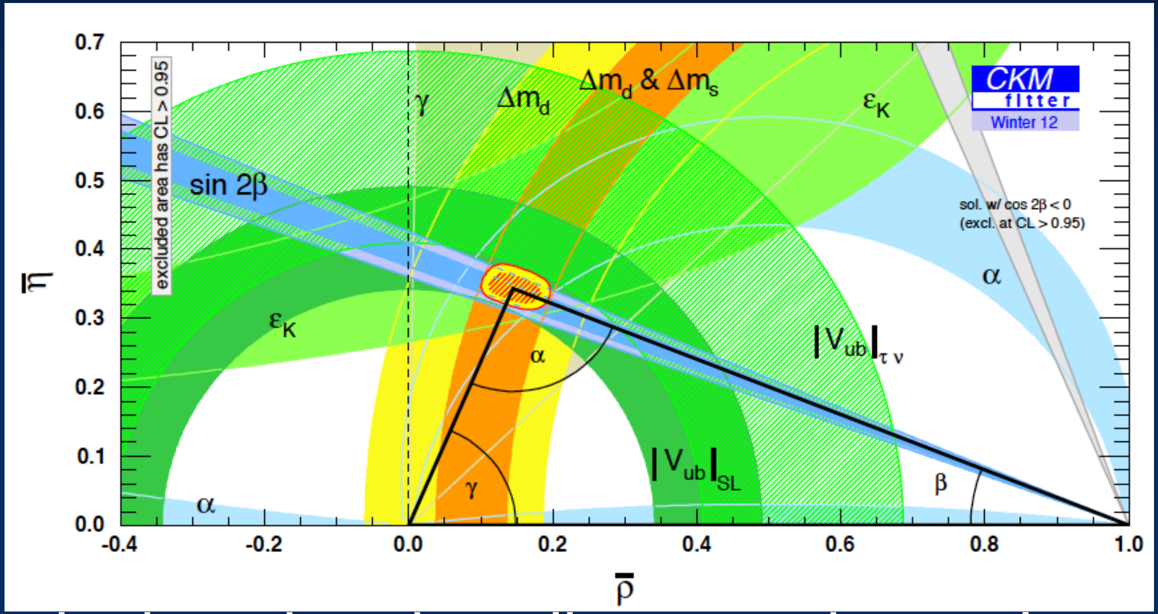
- Large muon mass strongly suppresses synchrotron radiation
  - ⇨ Muons can be accelerated and stored using rings at much higher energy than electrons
  - ⇨ Colliding beams can be of higher quality with reduced beamstrahlung



- 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: $p \rightarrow p \rightarrow n$
  - – Offers key accelerator challenges… Beam Cooling

The Physics Needs: Neutrinos (I)

- In the neutrino sector it is critical to understand:
  - δ_{CP}
  - The mass hierarchy
  - $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$



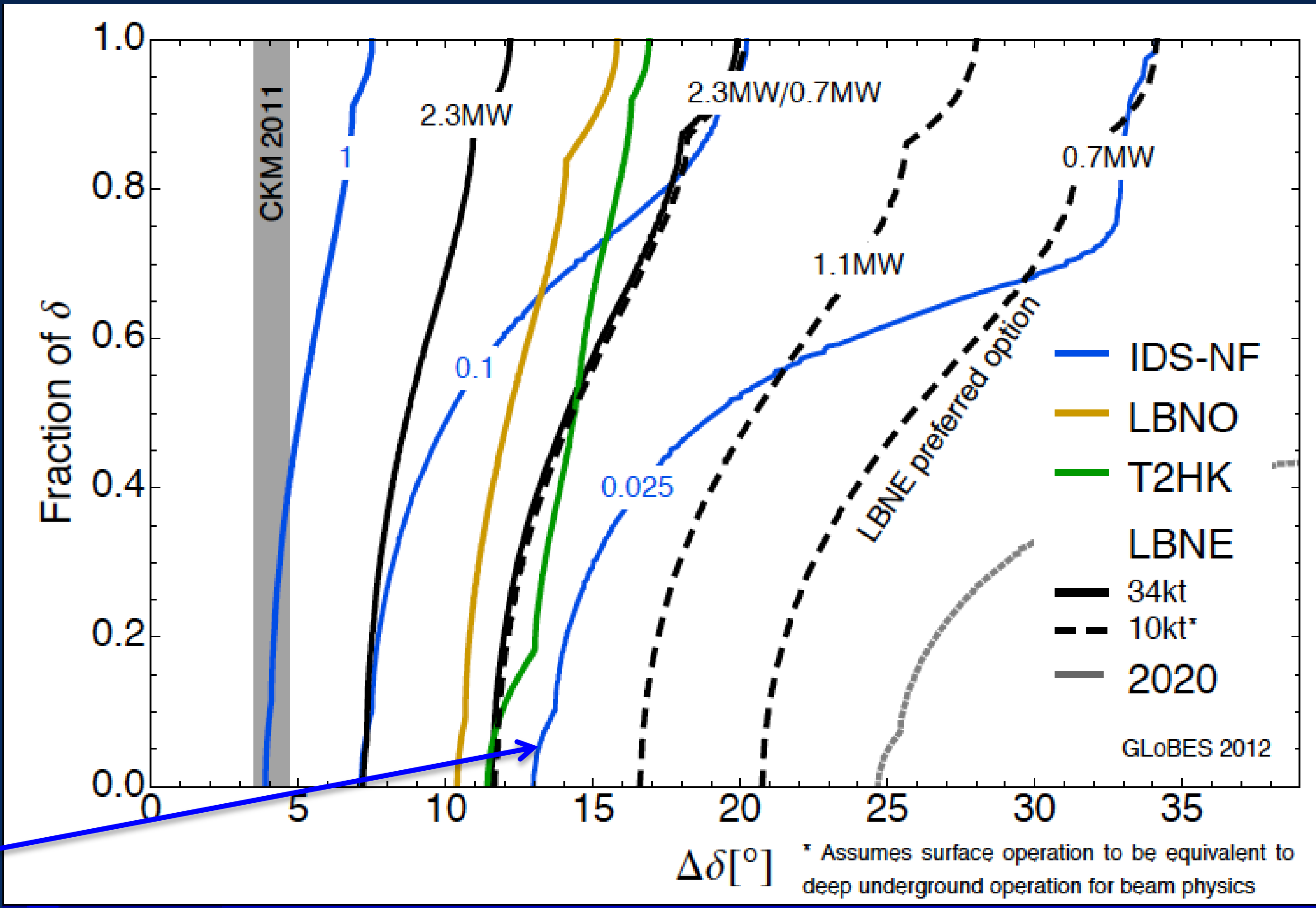
  - Resolve the LSND and other short baseline experimental anomalies [perhaps using beams from a muon storage ring (νSTORM) in a short baseline experiment]
  - And continue to probe for signs new physics

P. Huber

The Physics Needs: Neutrinos (II)

- 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?



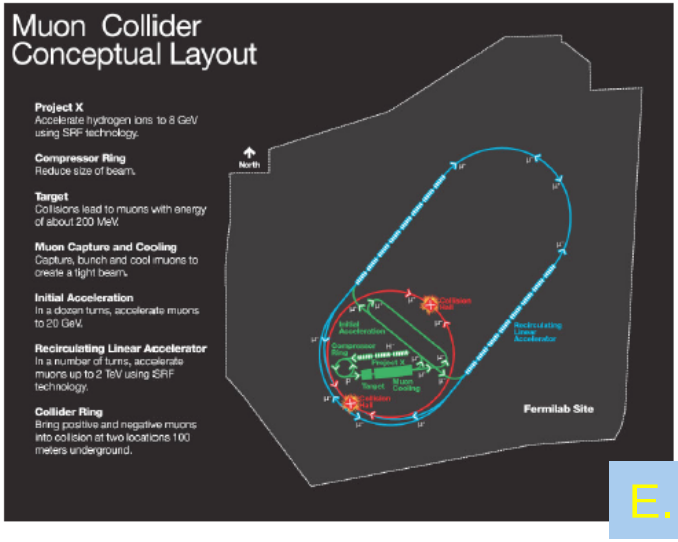
* Assumes surface operation to be equivalent to deep underground operation for beam physics

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

The Physics Needs: Colliders

- $\mu^+\mu^-$ Collider:
  - Center of Mass energy: 1.5 - 6 TeV (3 Tev)
  - Luminosity > 10^{34} cm^{-2} sec^{-1} (350 fb^{-1}/yr)
  - Compact facility
    - 3 TeV - ring circumference 3.8 km
    - 2 Detectors
  - Superb Energy Resolution
    - MC: 95% luminosity in dE/E ~ 0.1%
    - CLIC: 35% luminosity in dE/E ~ 1%


Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

Target
Collisions lead to muons with energy of about 200 MeV.

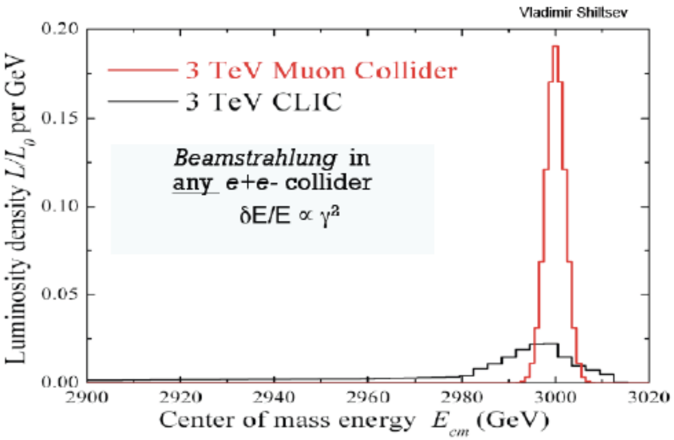
Muon Capture and Cooling
Capture, bunch and cool muons to create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

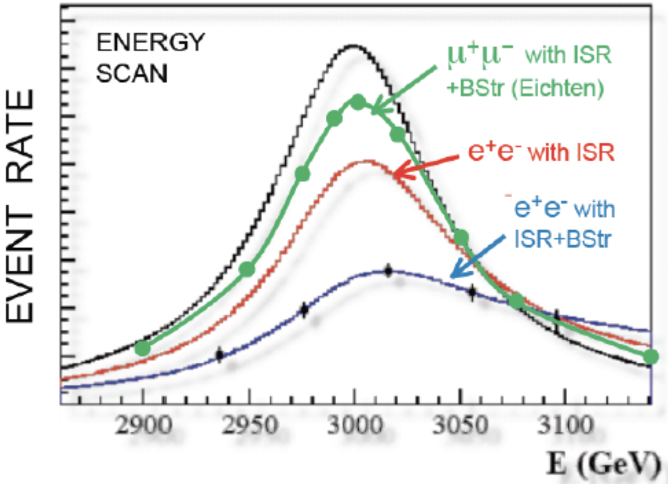
Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring
Bring positive and negative muons into collision at two locations 100 meters underground.

E. Eichten


Vladimir Shiltsev

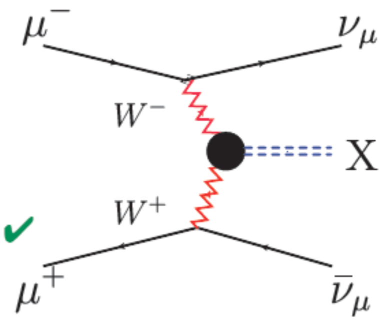
CLIC Curves: Lucie Linssen, SPC, 15/6/2009



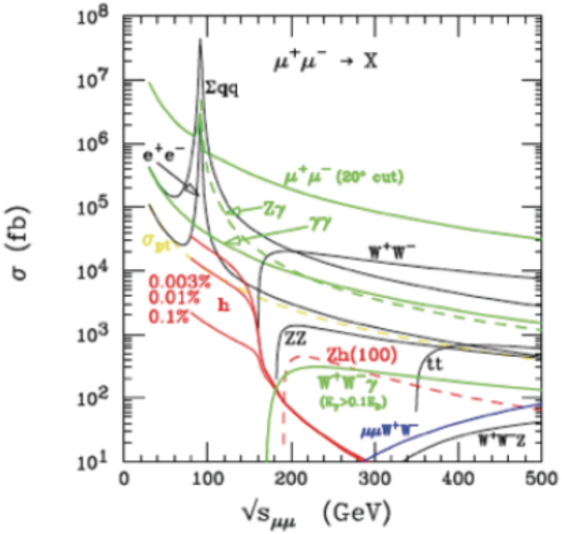
Muon Collider Reach

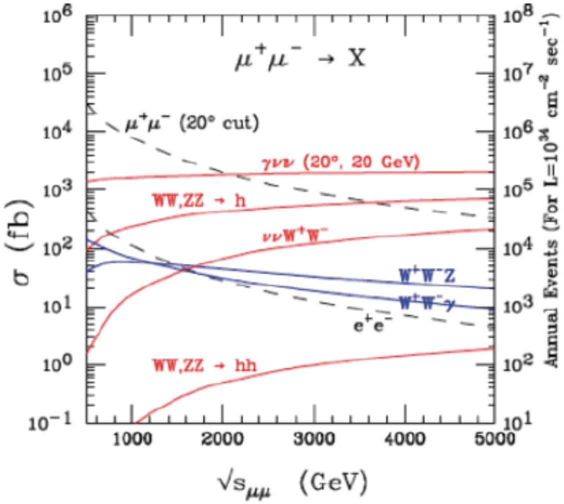
- For $\sqrt{s}$ < 500 GeV
  - SM thresholds: Z^0h, W^+W^-, top pairs
  - Higgs factory ($\sqrt{s} \approx 126$ GeV) ✔
- For $\sqrt{s}$ > 500 GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required. ✔
    - Cross sections for central ($|\theta| > 10°$) pair production ~ R × 86.8 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

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



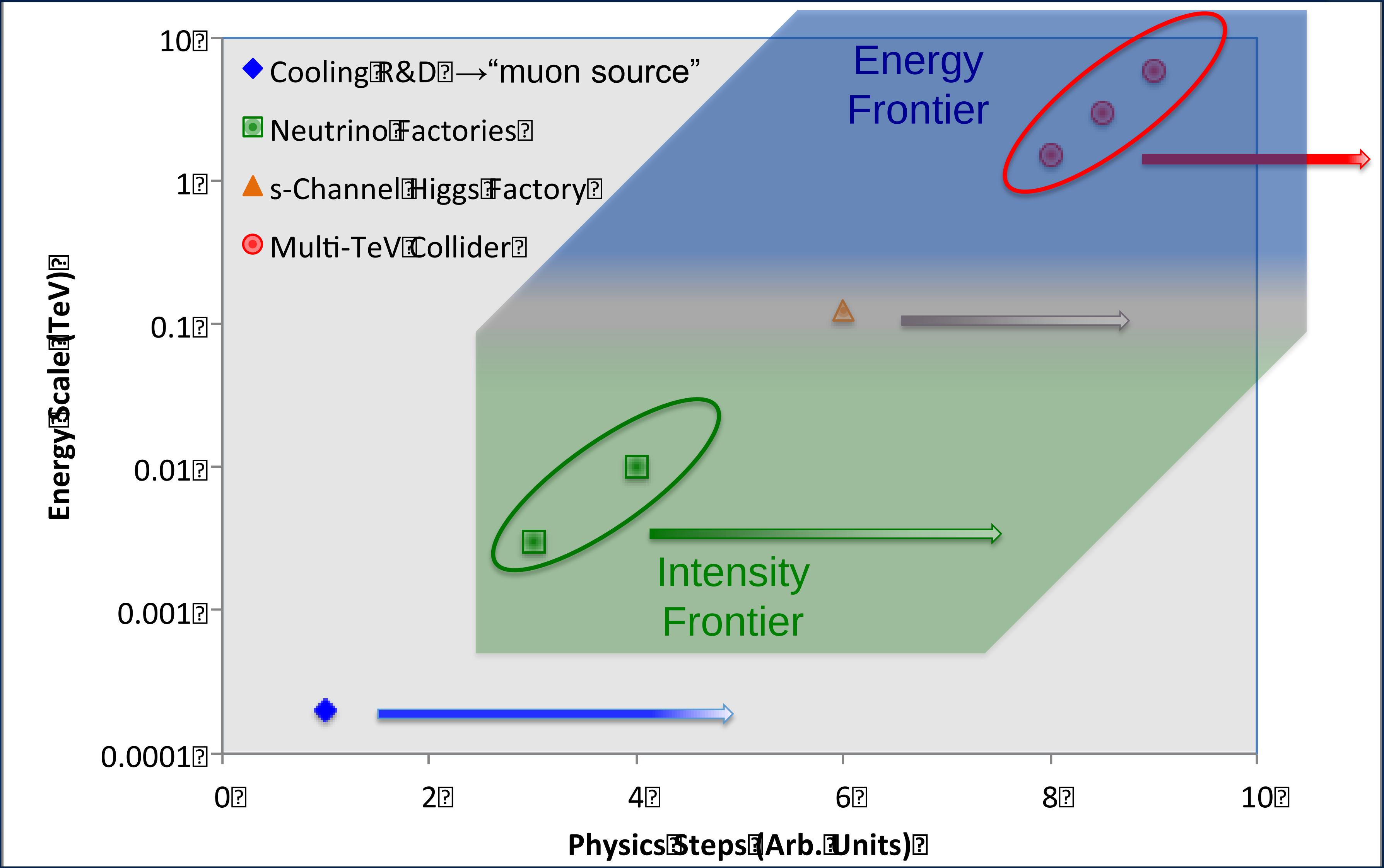
  - An Electroweak Boson Collider ✔





E. Eichten

Muon Accelerator Physics Scope



Muon Accelerators

Accelerator	Energy Scale	Performance	
Cooling Channel	**~200 MeV**	**Emittance Reduction**	
(muon source) *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}*	

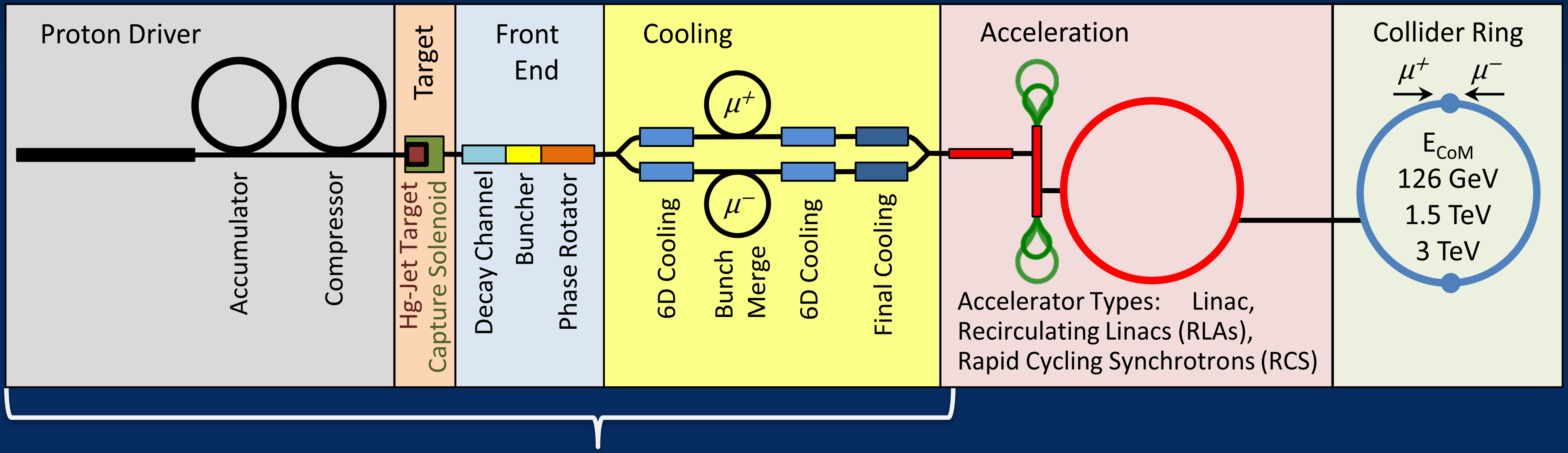
*Decays of an individual species (ie, μ^+ or μ)

Program Baselines

And Potential Staging Steps

Muon Collider Concept

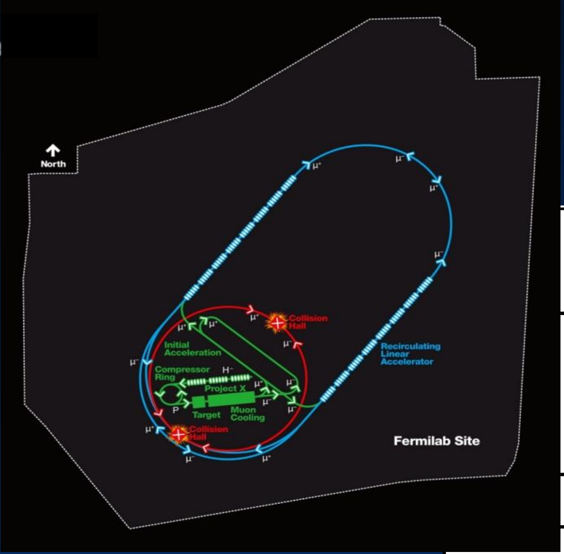
Muon Collider Block Diagram



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
$L = 3\times10^{34}\ \mathrm{cm^{-2}s^{-1}}$
μ/bunch = 2×10^{12}
$\sigma(p)/p = 0.1\%$
$\varepsilon_{\perp N} = 25\ \mu\mathrm{m}$, $\varepsilon_{//N} = 72\ \mathrm{mm}$
$\beta^* = 5\mathrm{mm}$
Rep. Rate = 12 Hz



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

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
b*	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, e_{TN}	p mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1	1.5	70	70
Bunch Length, s_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	mm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4$^{\#}$	4	4	4

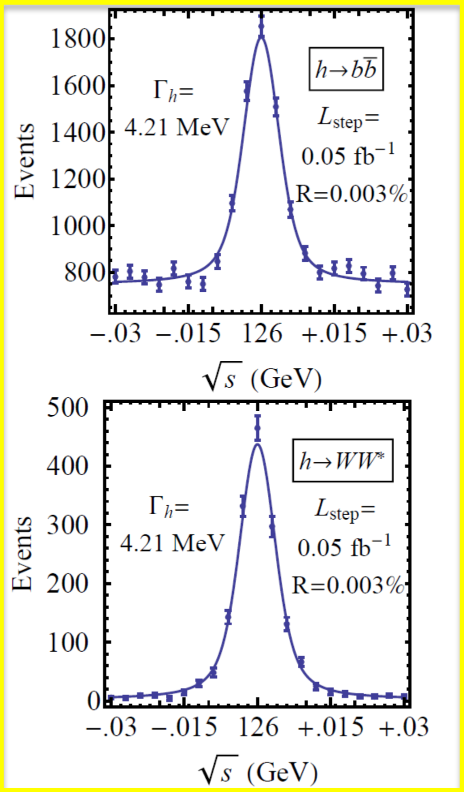
$^{\#}$Could begin operation with Project X Phase 2 beam

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

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

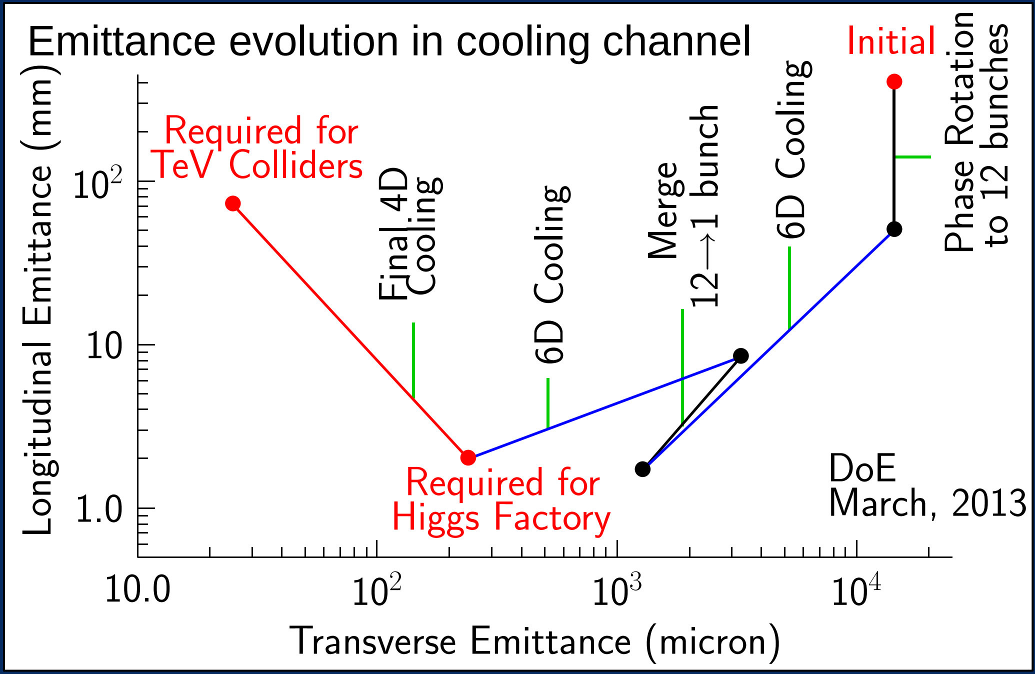
126 GeV Higgs Factory

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
Sharp resonance: momentum spread of a few × 10^{-5}



Precision energy measurement provided by g-2 effect and residual polarization in muon beams

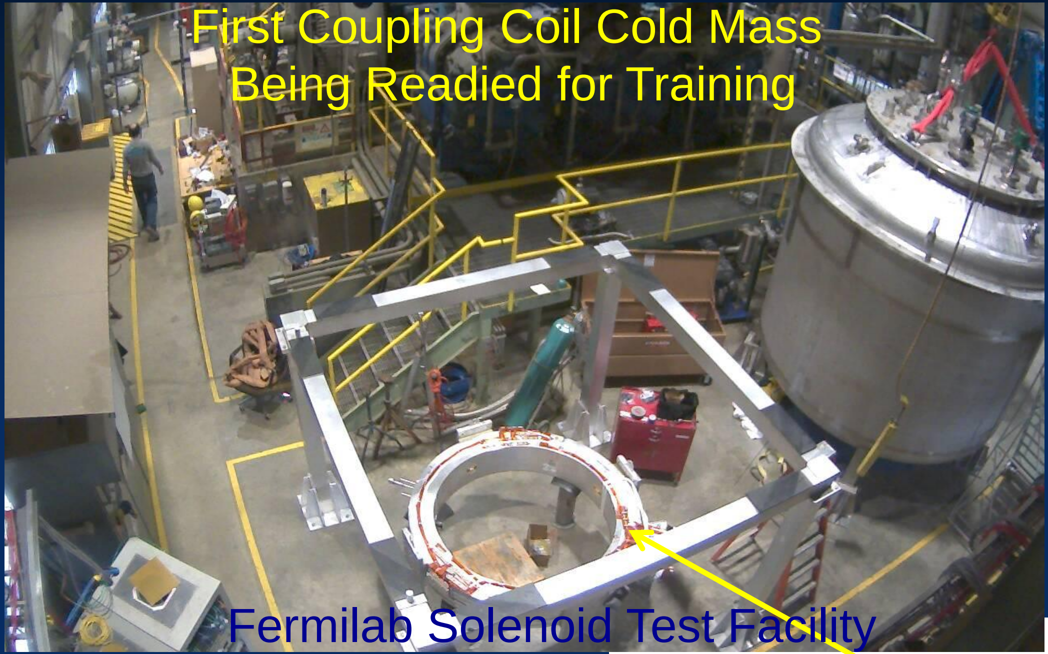
Han and Liu
hep-ph 1210.7803



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

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

Demonstration of cooling channel - MICE

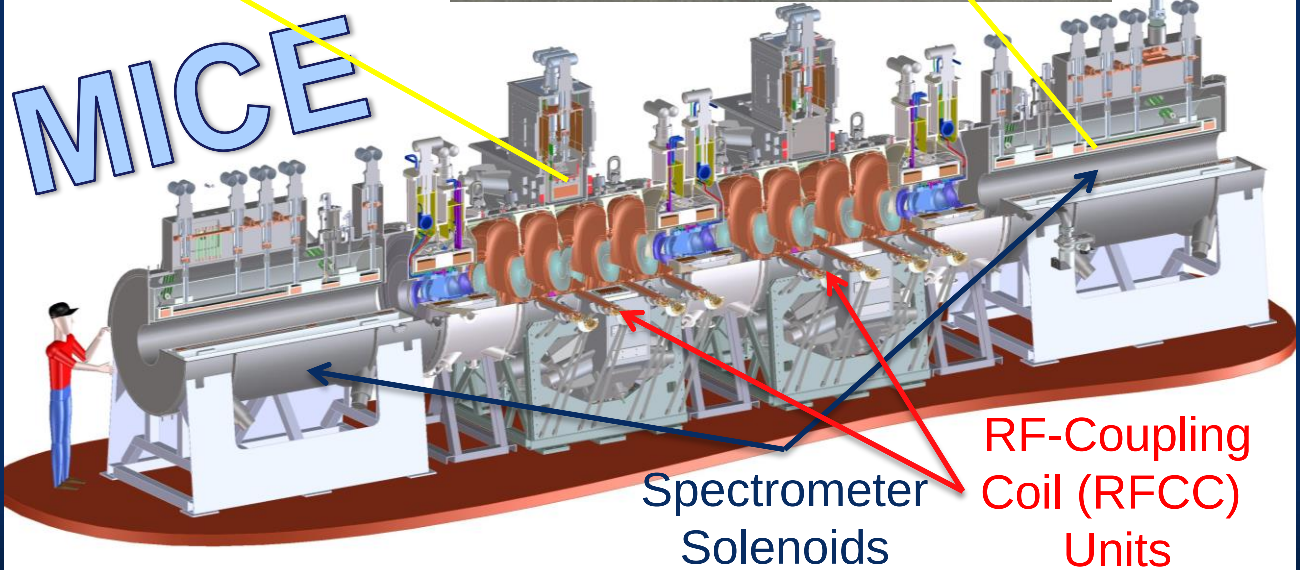


First Coupling Coil Cold Mass Being Readied for Training

Fermilab Solenoid Test Facility

First Spectrometer Solenoid Now Commissioned!

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

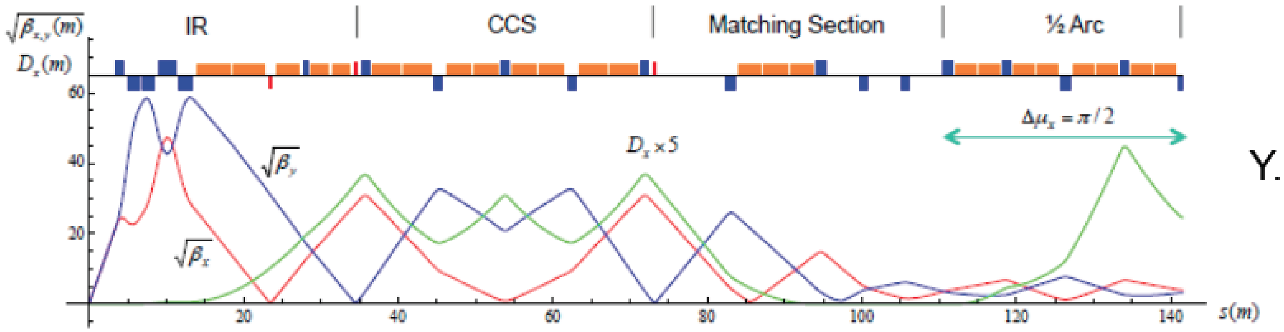


MICE

Spectrometer Solenoids

RF-Coupling Coil (RFCC) Units

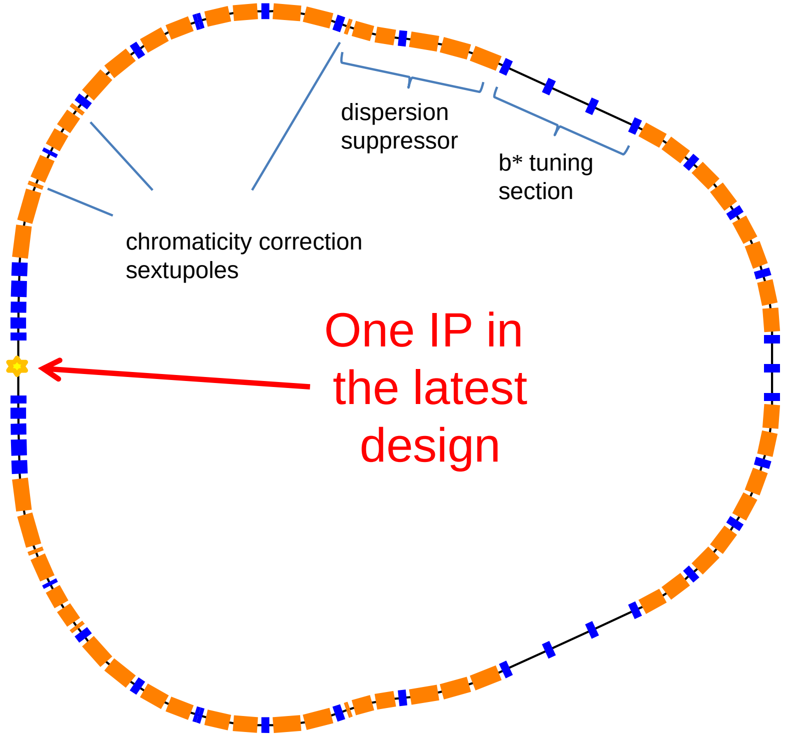
Updated 63 x 63 GeV Lattice



Y. Alexahin

Optics functions in half ring for β*=2.5cm

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



dispersion suppressor

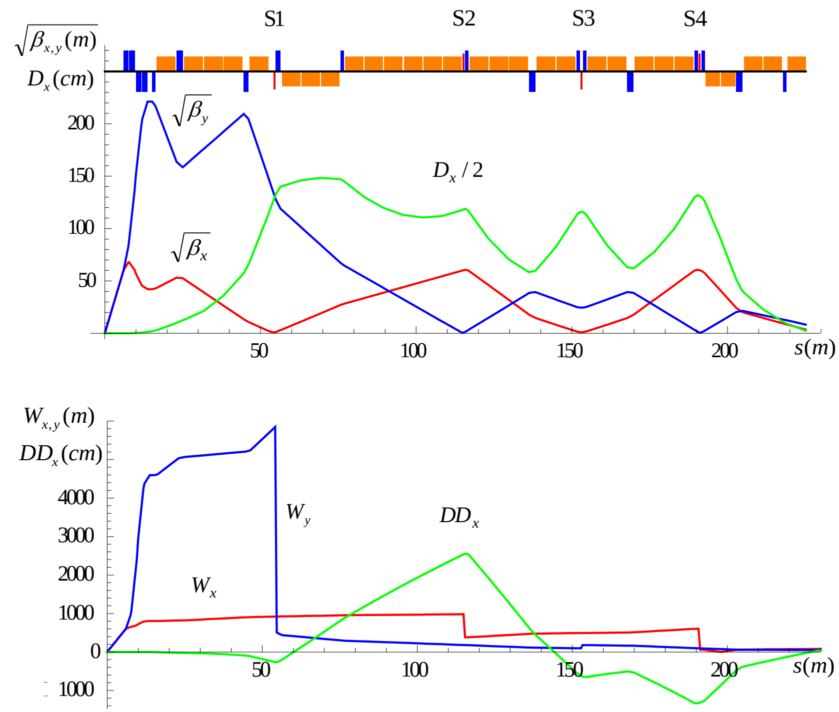
b* tuning section

chromaticity correction sextupoles

One IP in the latest design

Multi-TeV Collider – 1.5 TeV Baseline

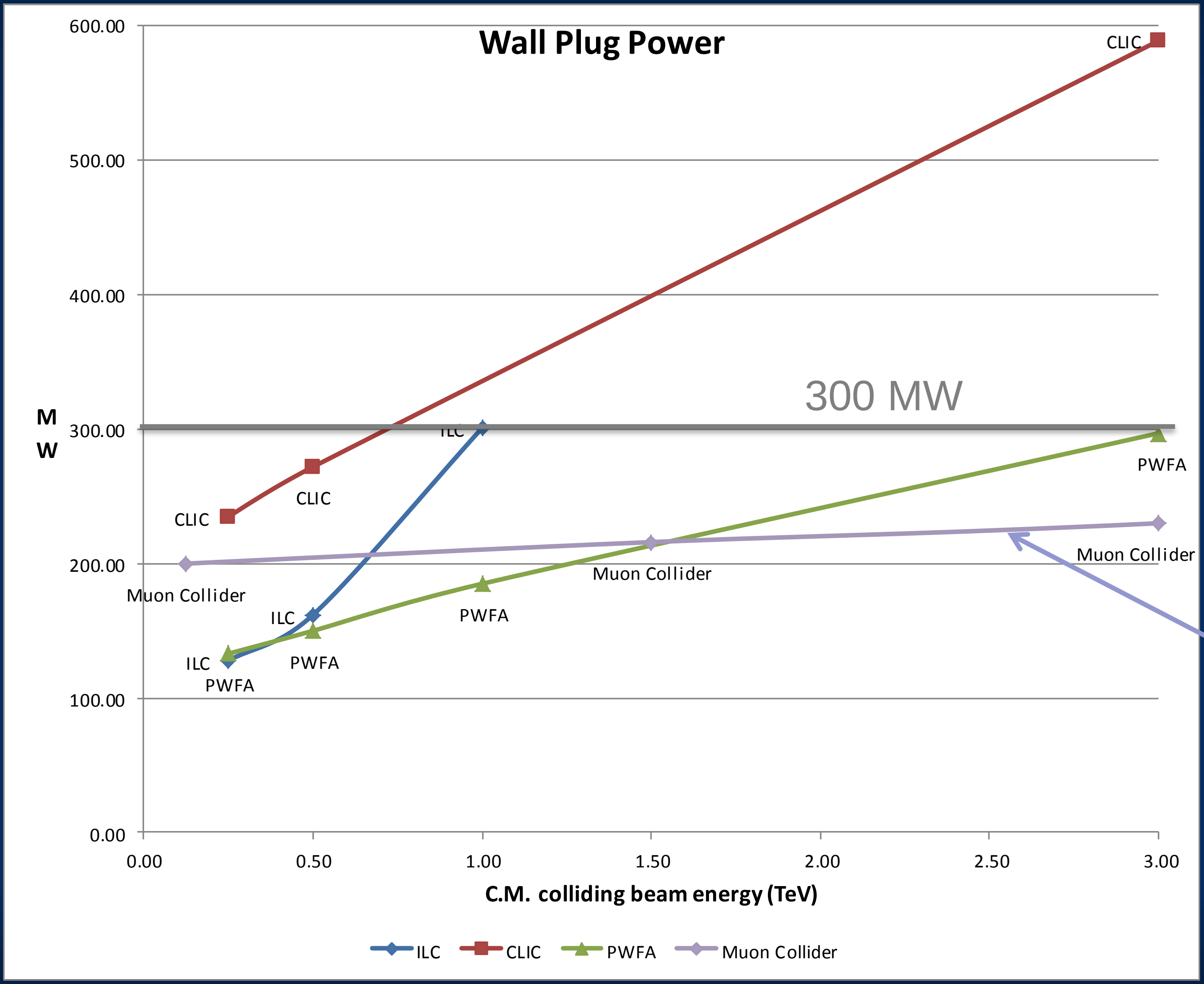
Y. Alexahin



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

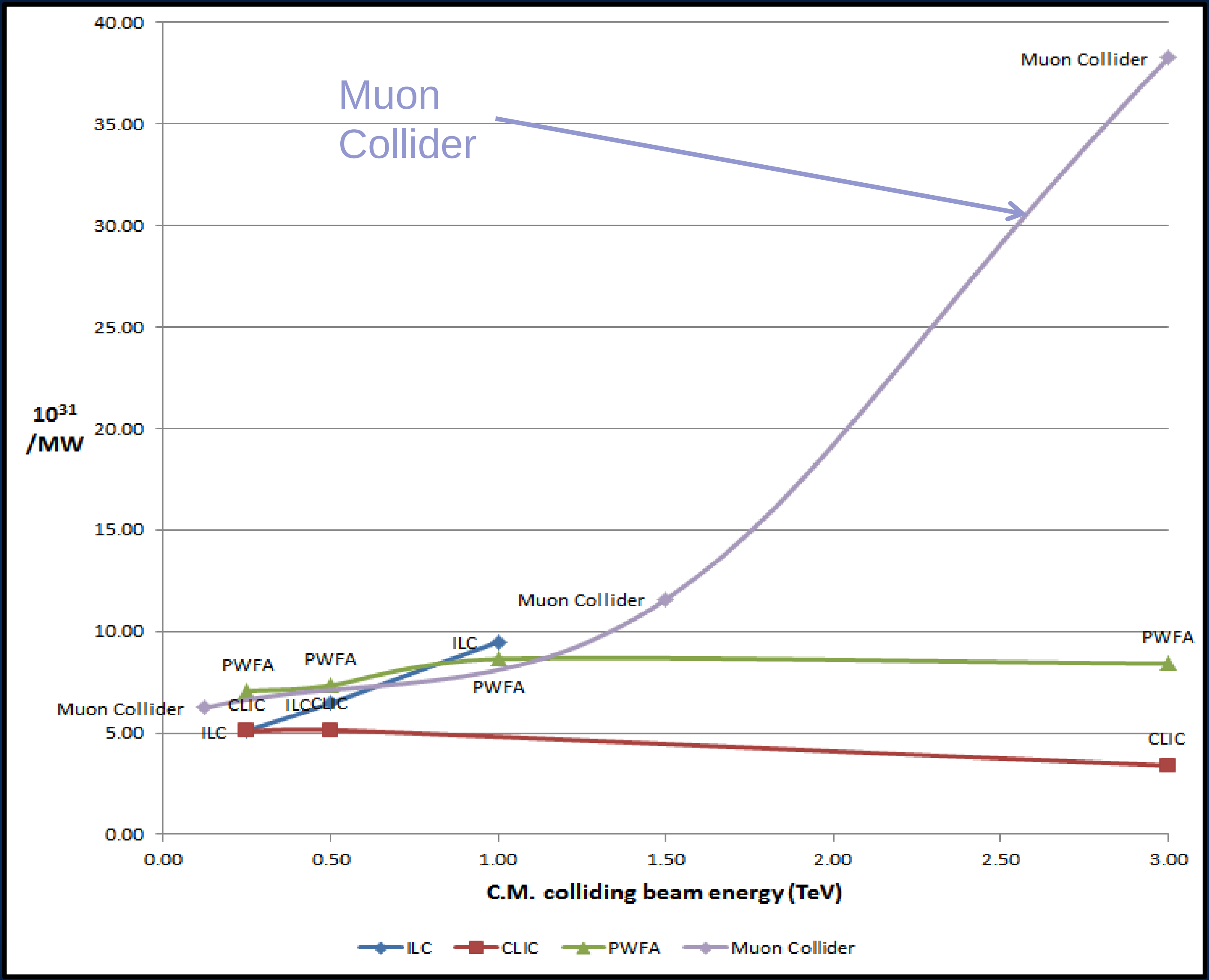
Wall Plug Power Estimates



Estimate assumes a base 70MW Facility Power requirement as in LC analyses.

Muon Collider

Luminosity Production Metric

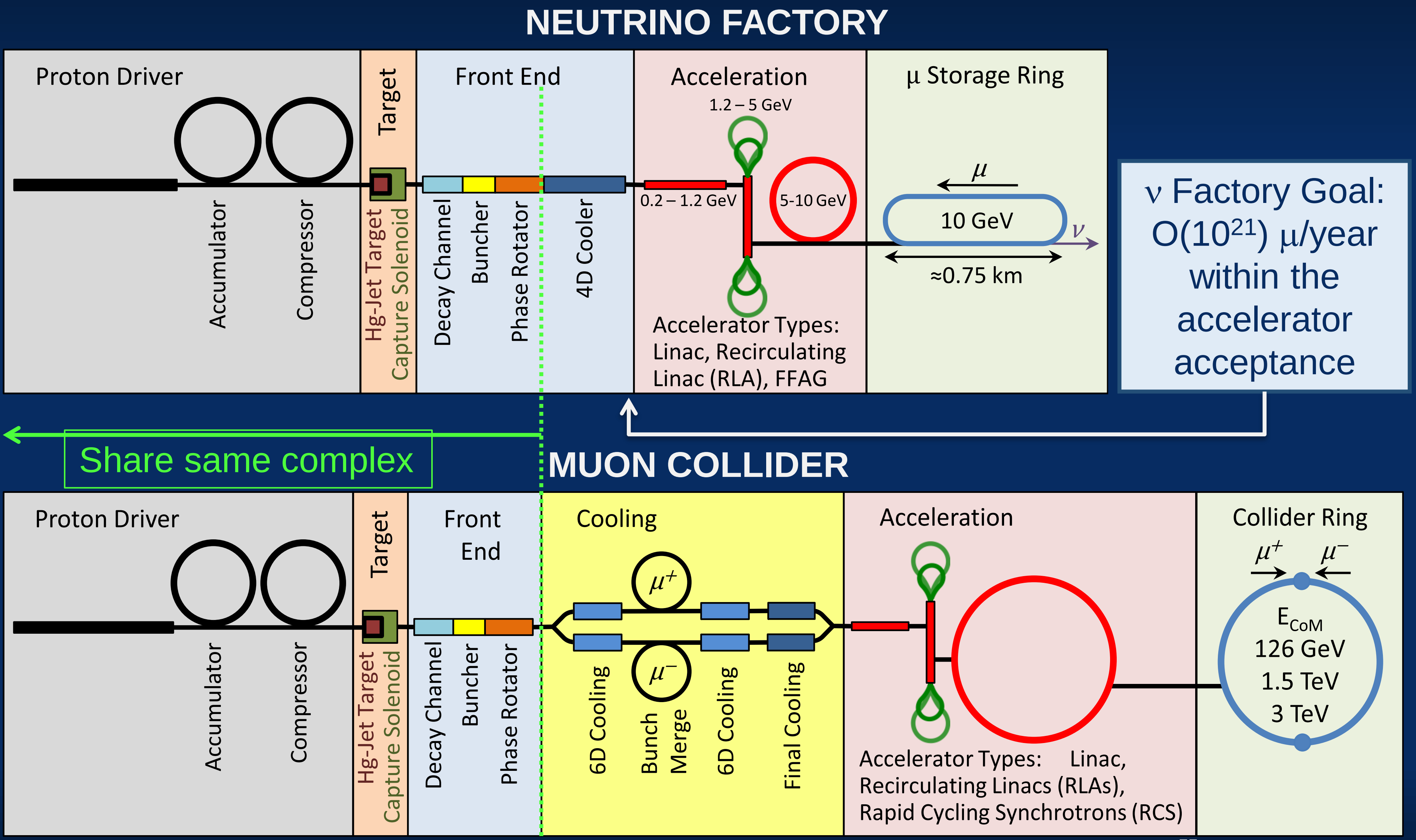


Luminosity Metric:

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

MUON COLLIDER AND NEUTRINO FACTORY SYNERGIES

Muon Collider - Neutrino Factory Comparison



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

Share same complex

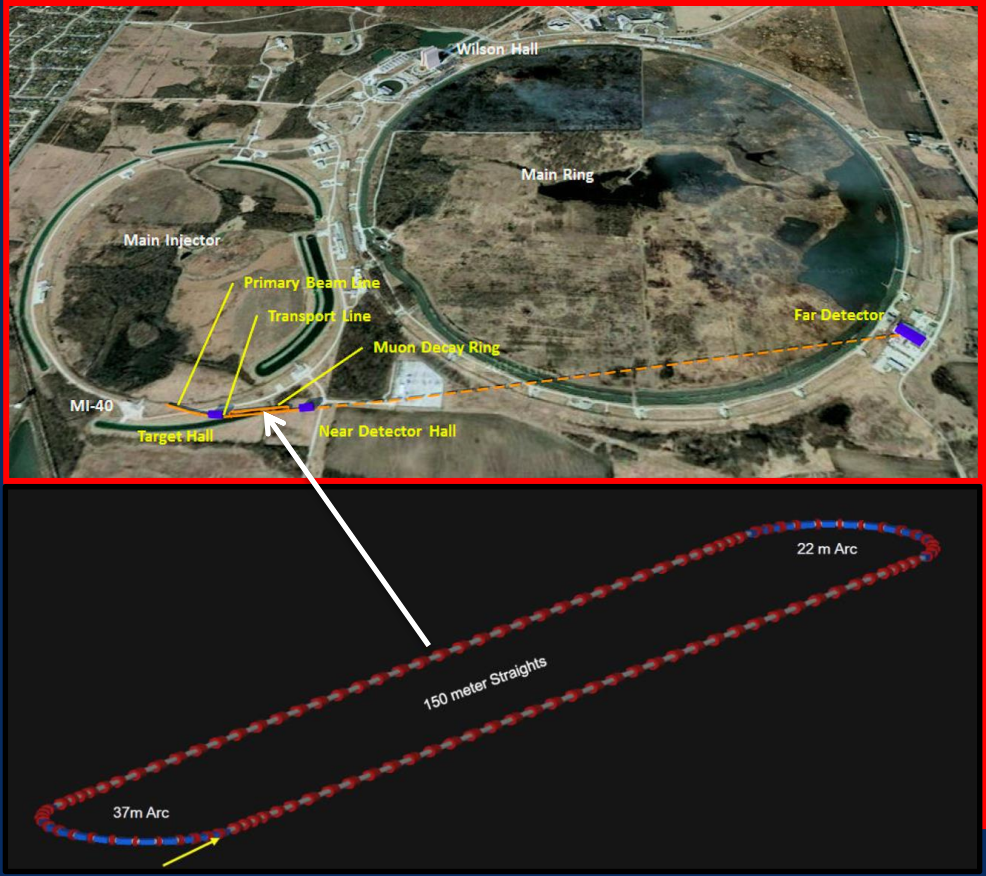
Muon Accelerator Staging Study (MASS)

- Two approaches exist:
  - A dedicated “green field” construction project
  - A staged development based on evolving capabilities at an existing facility
    - Desirable if high quality physics can be produced along the way…
    - Can provide clear decision points with well-understood risks for moving forward
    - Incremental deployment of expensive or technically challenging elements

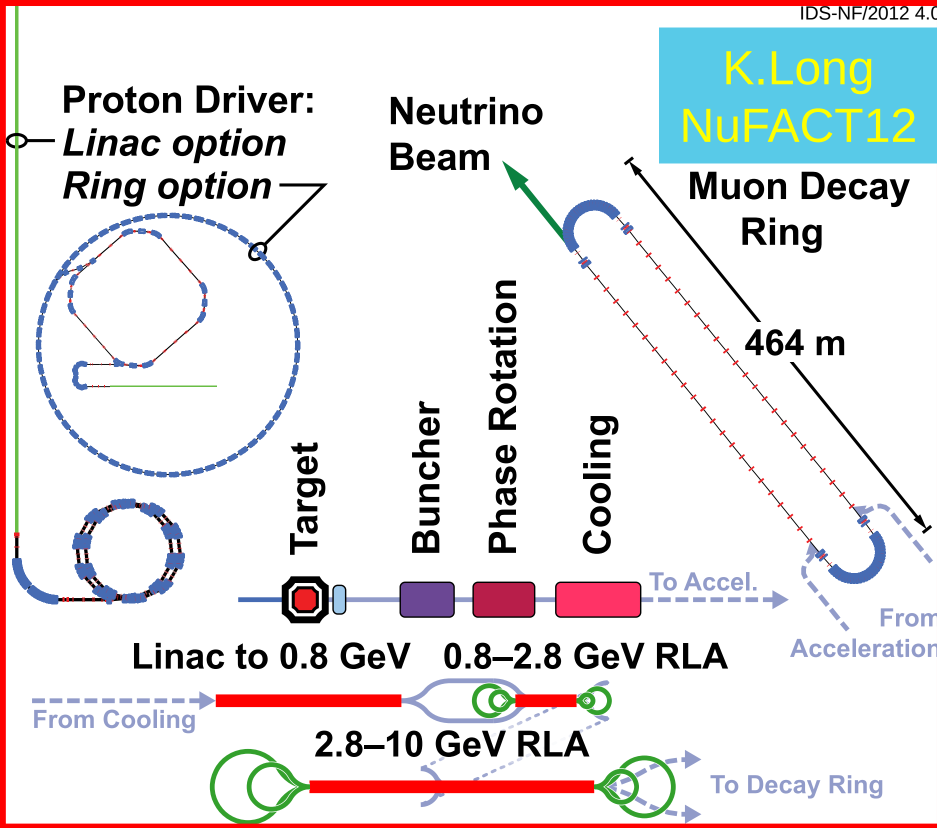
- 2008 P5 Roadmap called for a “world-leading Intensity Frontier program centered at Fermilab”
  - Can a Muon Accelerator effort support this goal as well as provide a path to return to an Energy Frontier facility in the US?
  - Can a staged Muon Accelerator effort provide both physics output and the necessary accelerator R&D along the way?
  - What are the timescales associated with such an effort?

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

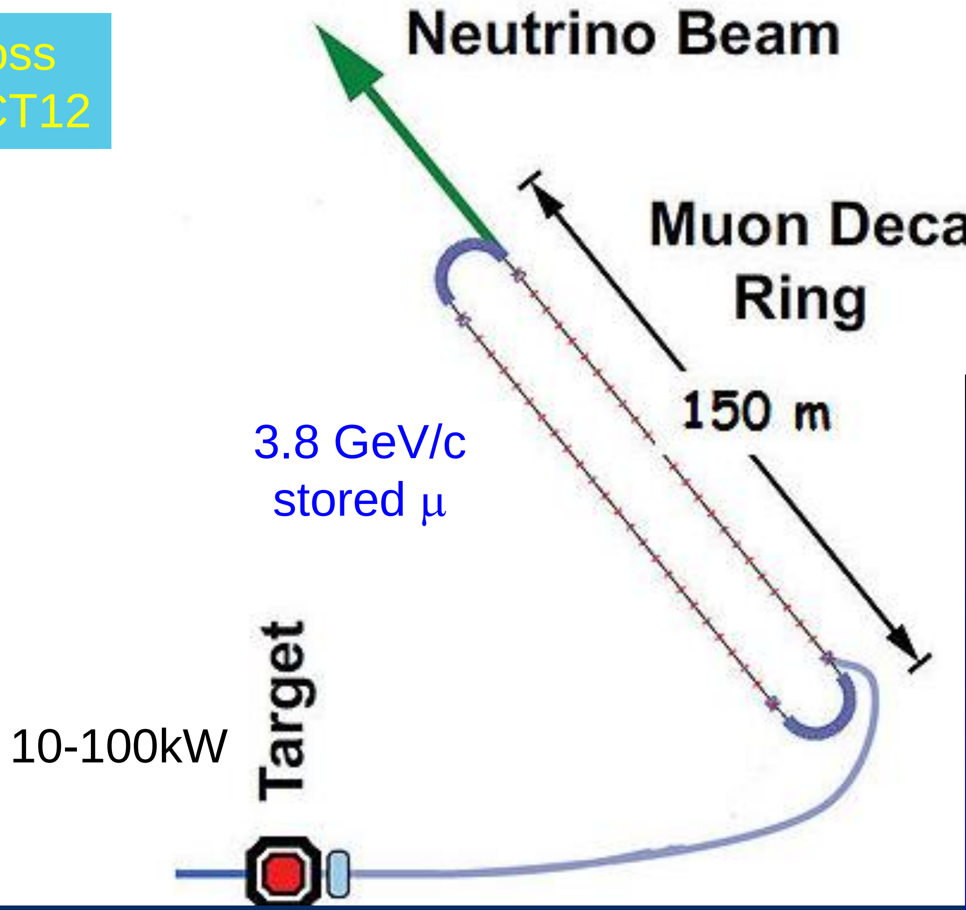
Also a muon-based Higgs Factory or Energy Frontier Muon Collider

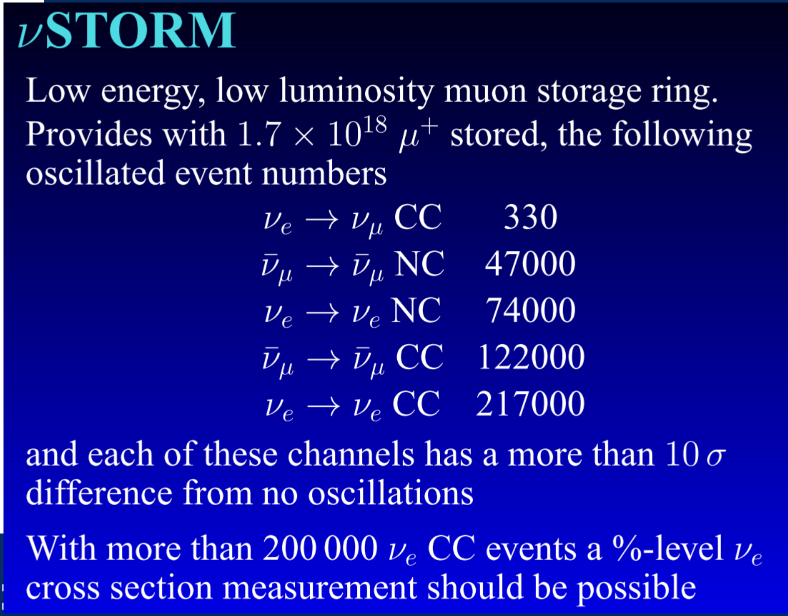
Neutrinos from Stored Muons
(arXiv: 1206.0294 (LOI), Fermilab P-1028)

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:

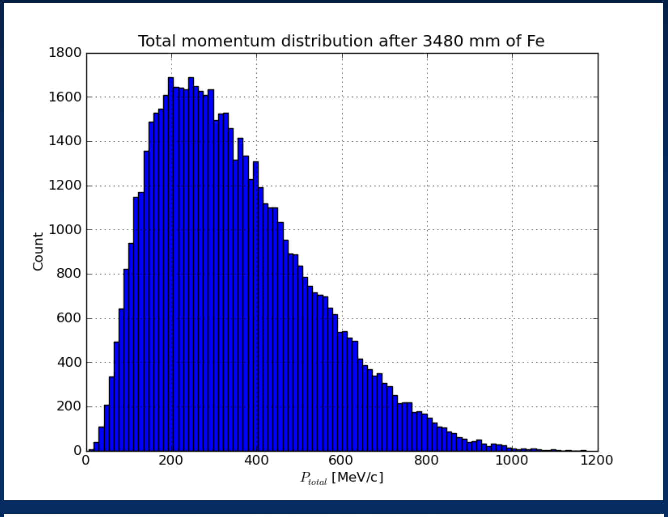
(https://indico.fnal.gov/conferenceDisplay.py?confId=5710)

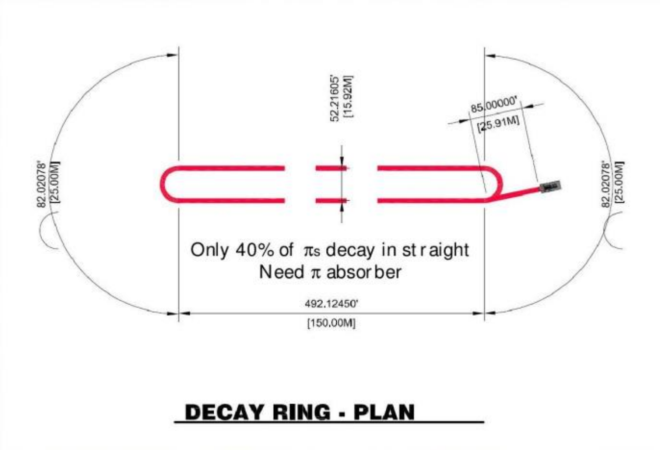
νStorm as an R&D platform

- 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

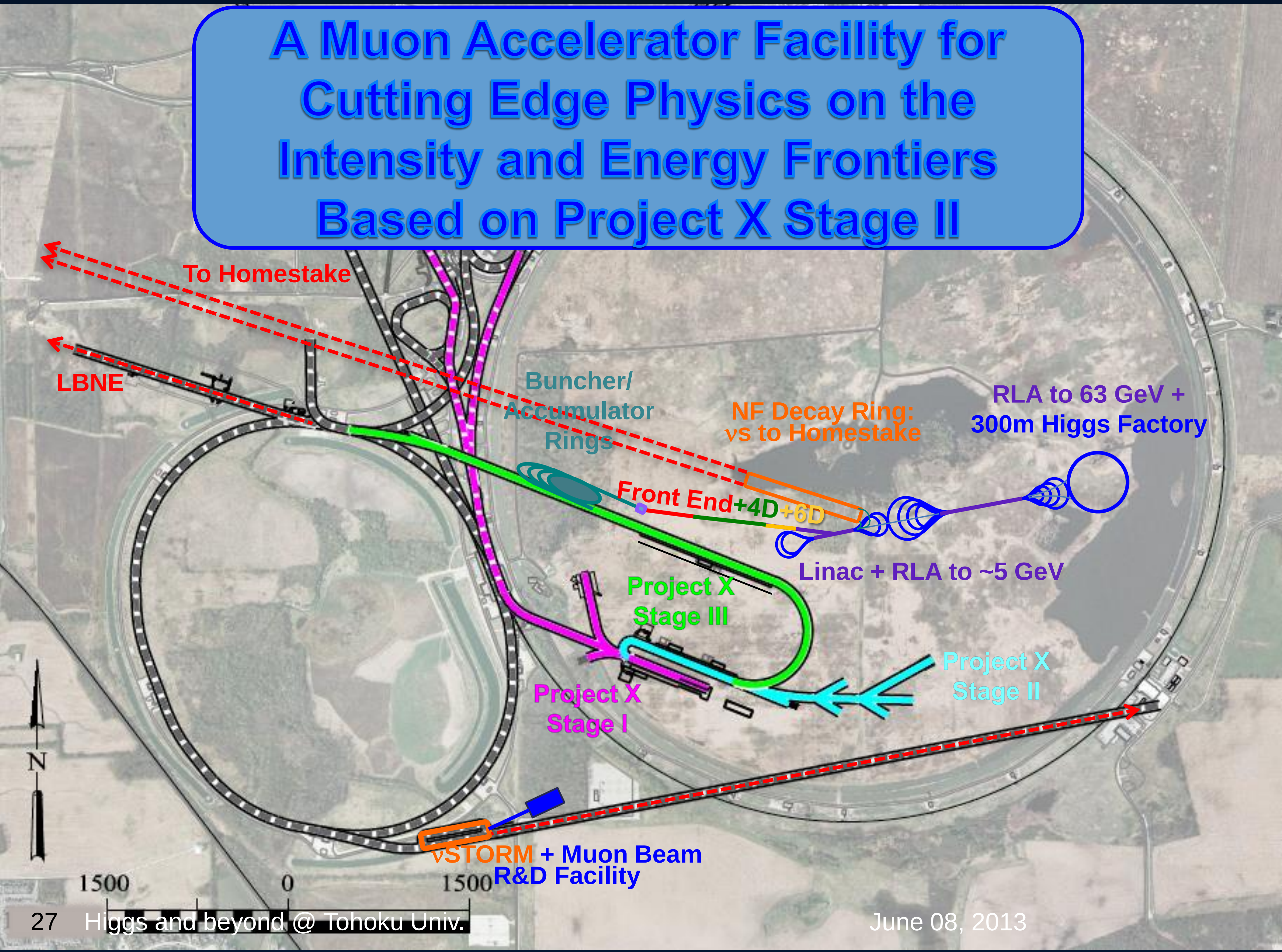
- Beam available simultaneously with physics operation
  - Sterile ν search
  - ν cross section measurements needed for ultimate precision in long baseline measurements

- 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.

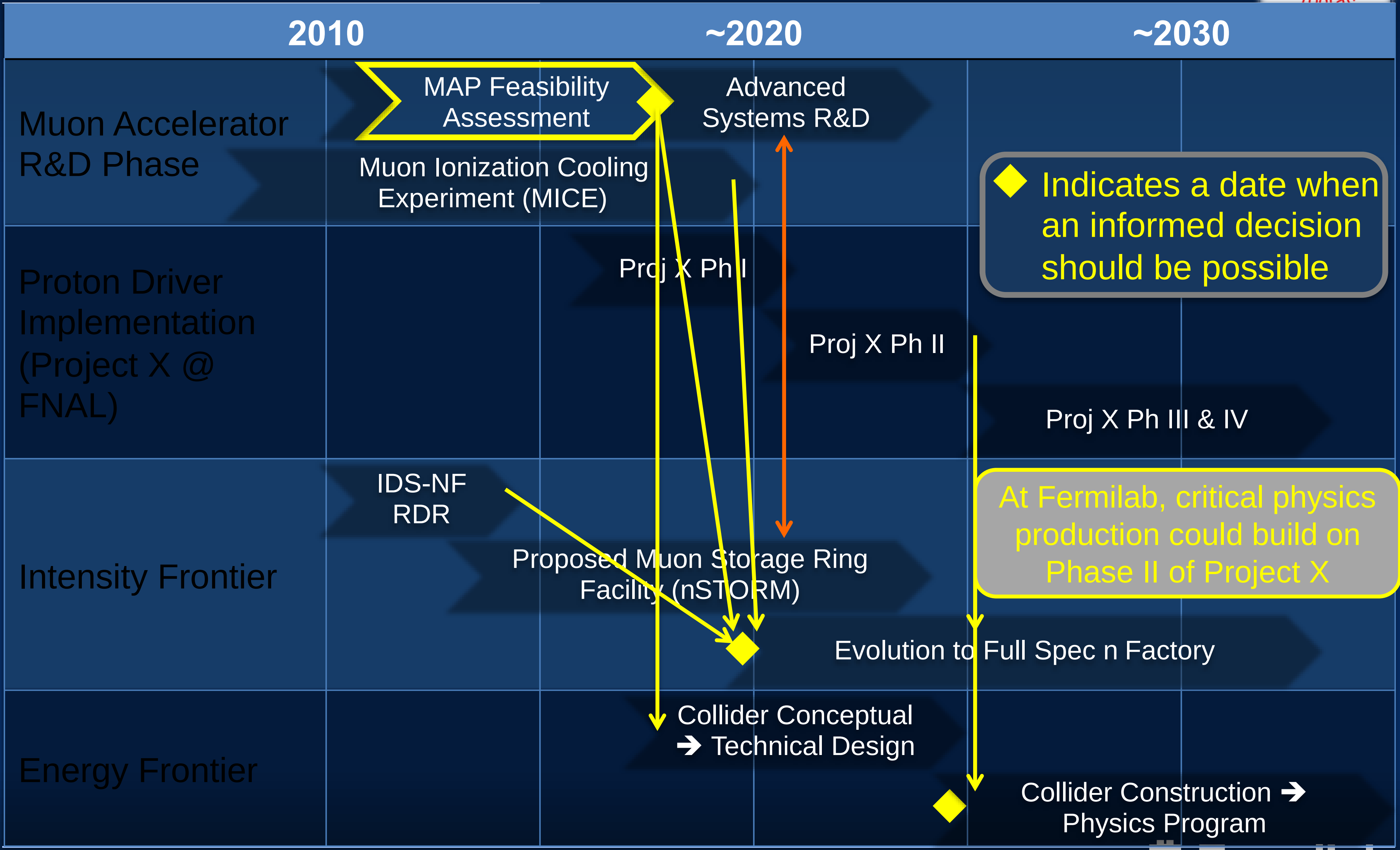




A Muon Accelerator Facility for Cutting Edge Physics on the Intensity and Energy Frontiers Based on Project X Stage II



The Muon Accelerator Program Timeline



2010 | ~2020 | ~2030

Muon Accelerator R&D Phase

- MAP Feasibility Assessment
- Advanced Systems R&D
- Muon Ionization Cooling Experiment (MICE)

Proton Driver Implementation (Project X @ FNAL)

- Proj X Ph I
- Proj X Ph II
- Proj X Ph III & IV

Intensity Frontier

- IDS-NF RDR
- Proposed Muon Storage Ring Facility (nSTORM)
- Evolution to Full Spec n Factory

Energy Frontier

- Collider Conceptual → Technical Design
- Collider Construction → Physics Program

◆ Indicates a date when an informed decision should be possible

At Fermilab, critical physics production could build on Phase II of Project X

THE MAP FEASIBILITY ASSESSMENT

The 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 the Feasibility Assessment

FY19 ➔

- Plan contingent on the feasibility assessment!
- Can we launch the design effort towards a staged implementation of a NF & MC?
- Advanced systems tests
  - 6DICE?
  - Support physics?

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

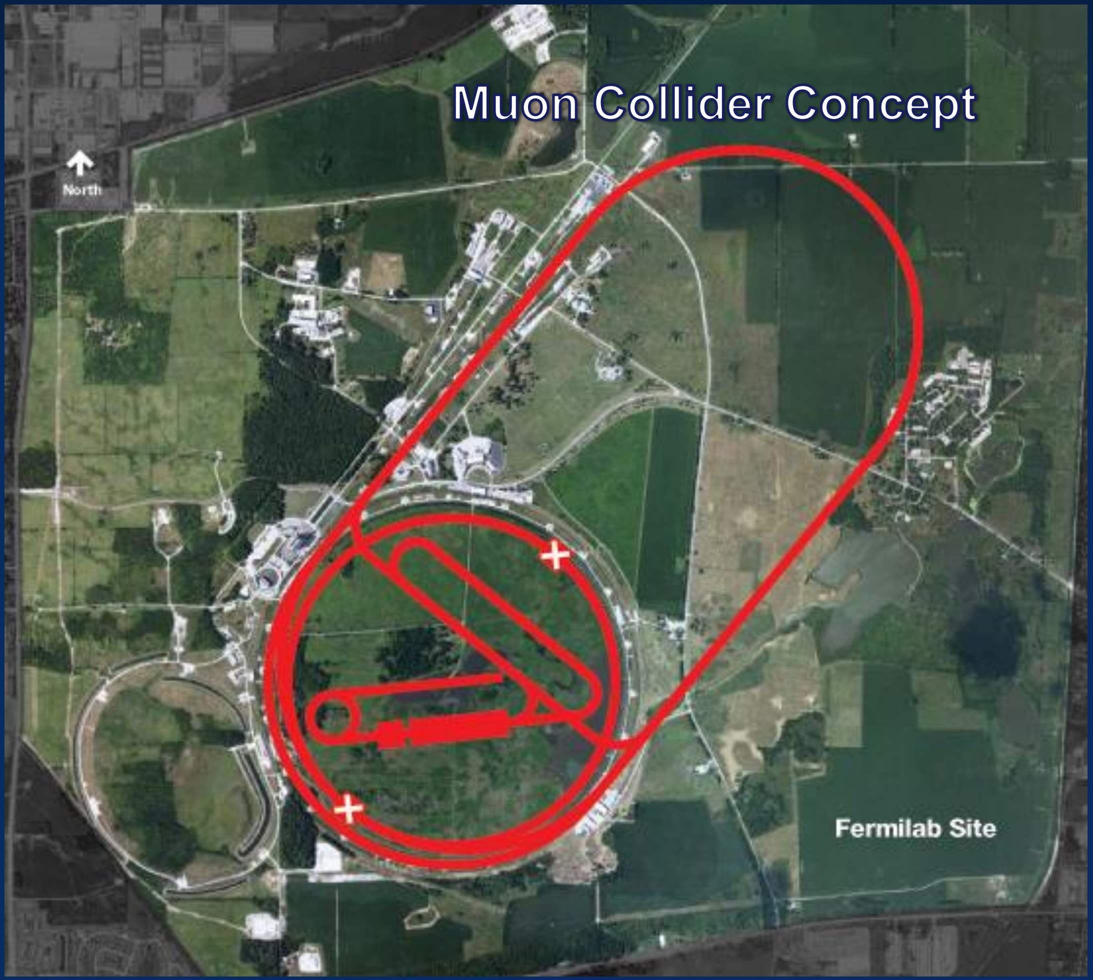
- A Muon Collider Higgs Factory
  - Would provide exquisite energy resolution to directly measure the width of the Higgs. This capability would be of crucial importance in the MSSM doublet scenario.

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

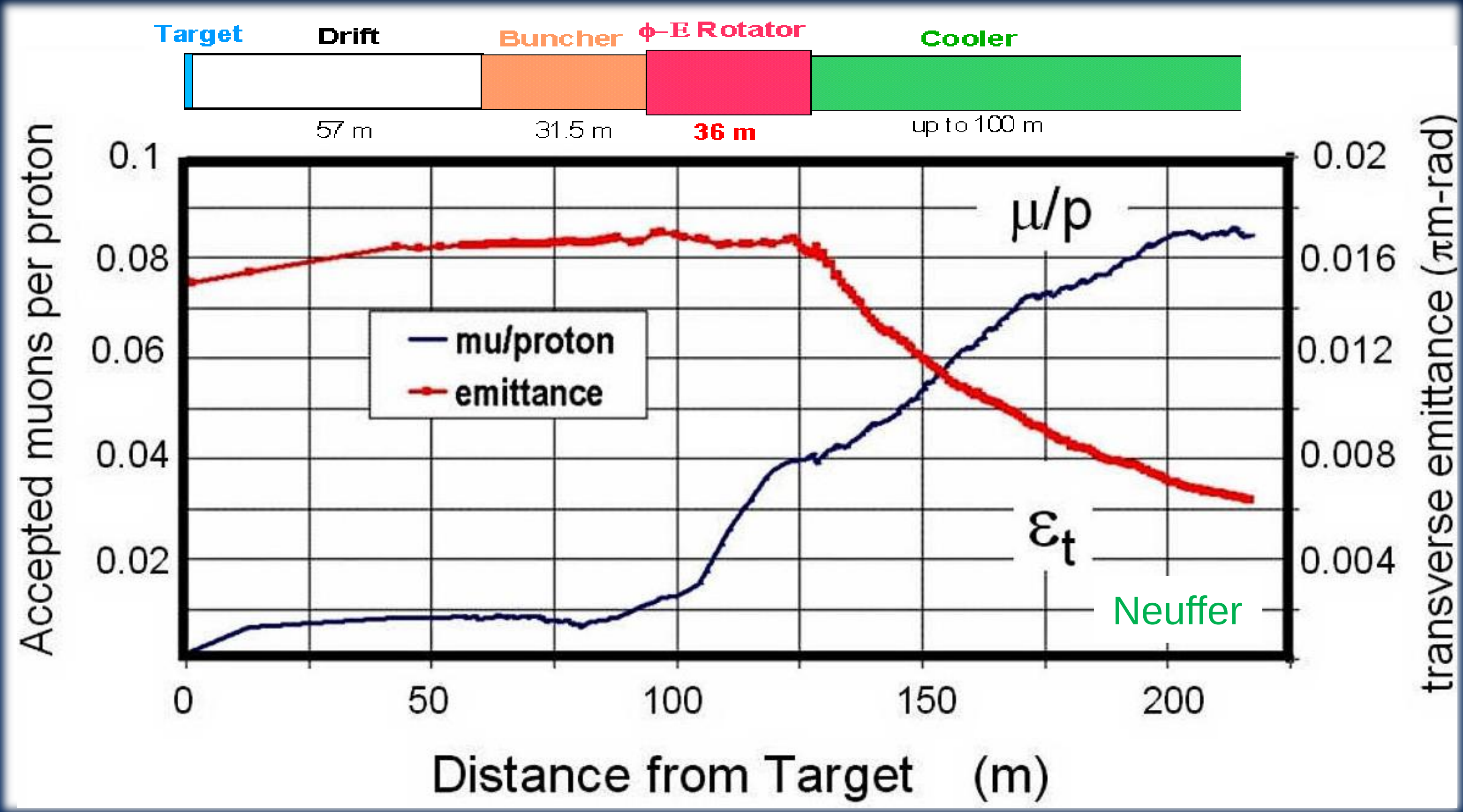


A challenging, but promising, R&D program lies ahead!

Backup slide

THE R&D CHALLENGES

Technology Challenges – Tertiary Production

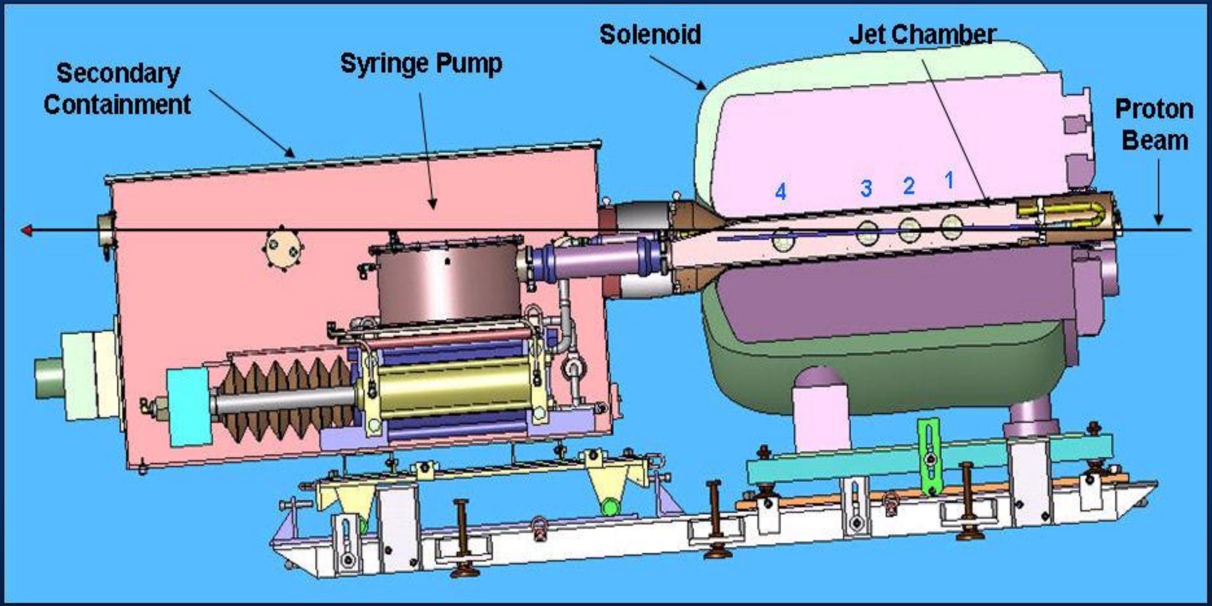


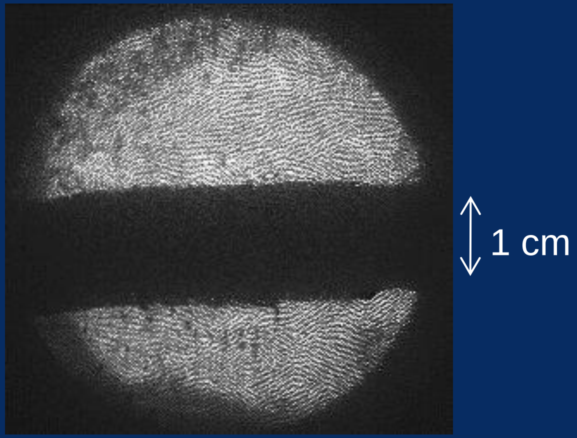
- A multi-MW proton source, *e.g.*, Project X, will enable O(10^{21}) muons/year to be produced, bunched and cooled to fit within the acceptance of an accelerator.

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

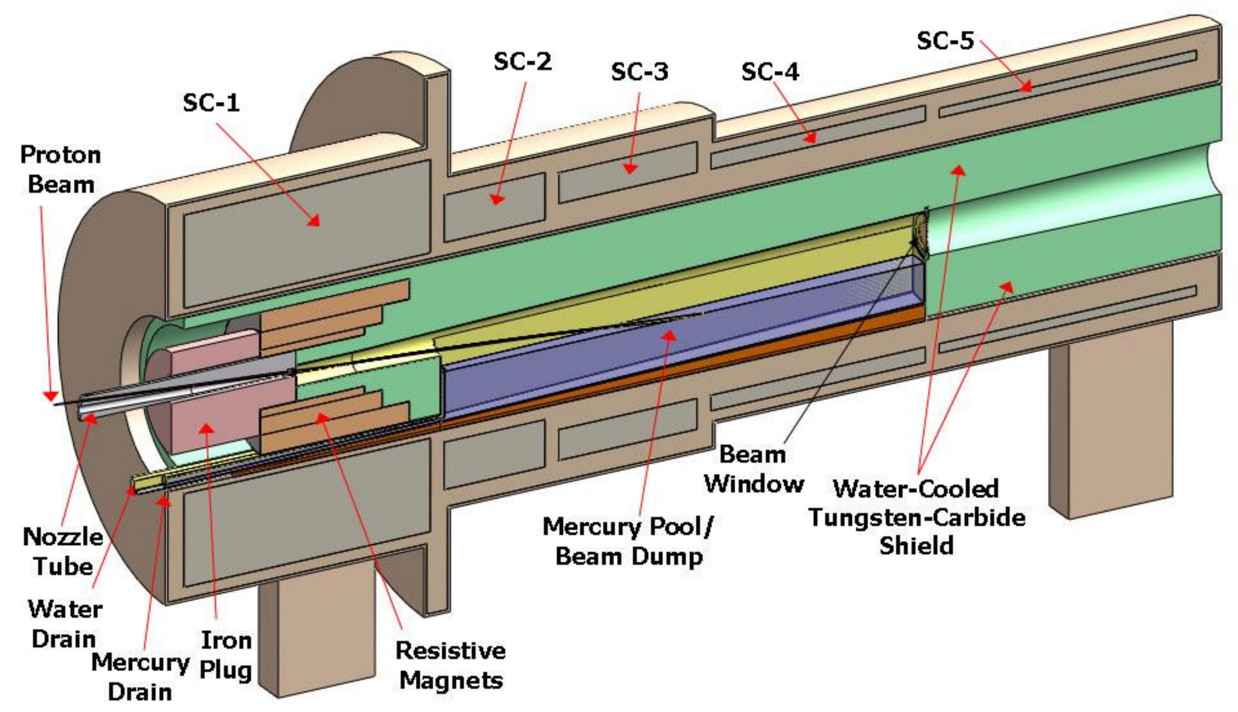
Technology Challenges – Capture Solenoid

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

$E_{stored} \sim 3$ GJ

O(10MW) resistive coil in high radiation environment

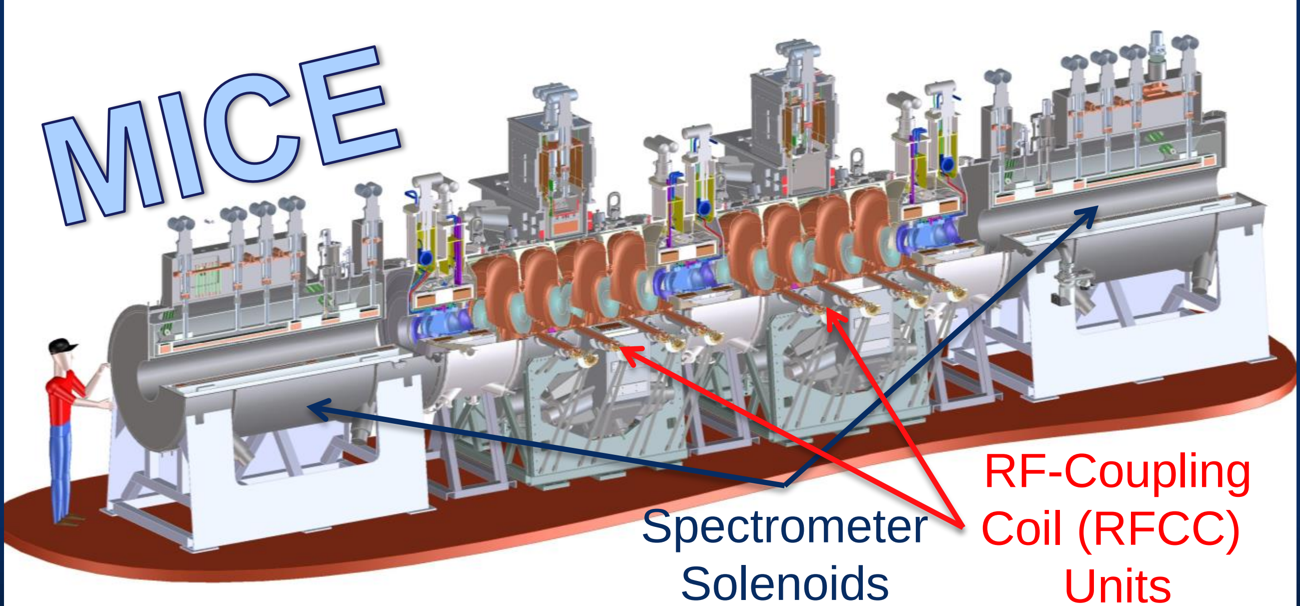
Possible application for High Temperature Superconducting magnet technology



Technology Challenges - Cooling

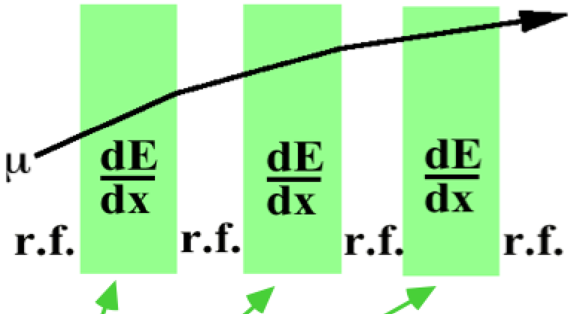
- Tertiary production of muon beams ⇨
  - Initial beam emittance intrinsically large
  - Cooling mechanism required, but no radiation damping
- Muon Cooling ⇨ Ionization Cooling
    - dE/dx energy loss in materials
    - RF to replace p_{long}

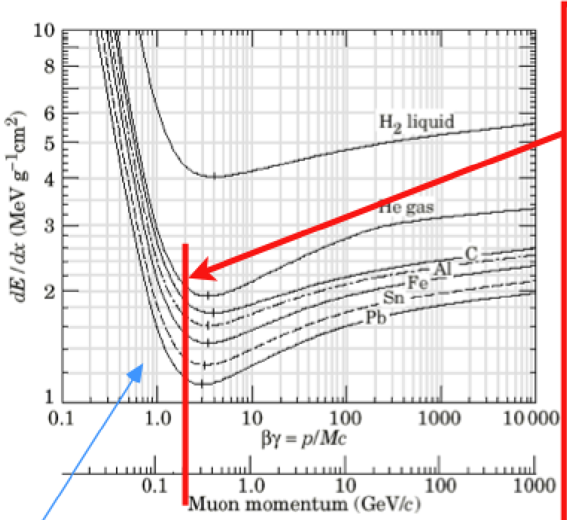
The Muon Ionization Cooling Experiment: Demonstrate the method and validate our simulations



Ionization Cooling

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





- Absorbers:

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

ionization energy loss

multiple Coulomb scattering

- RF cavities between absorbers replace ΔE
- Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

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

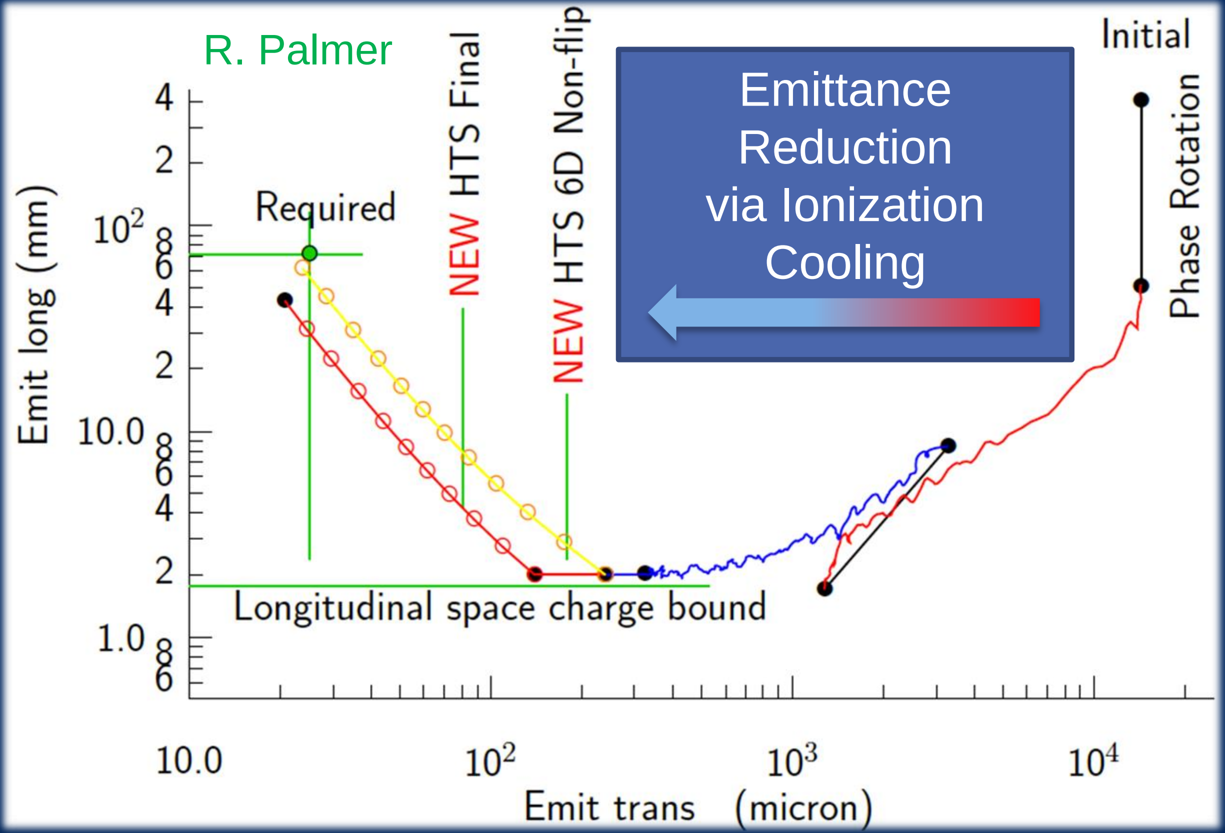
(emittance change per unit length)

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

- 2 competing effects ⇒ ∃ equilibrium emittance

Technology Challenges - Cooling

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



R. Palmer

Emittance Reduction via Ionization Cooling

- 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.

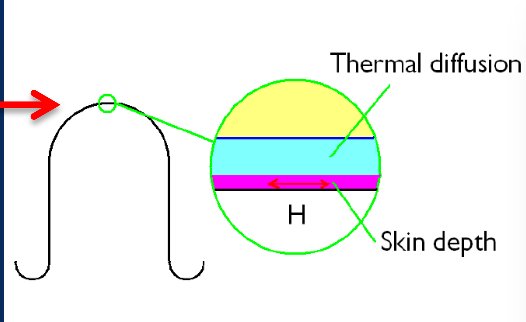
Technology Challenges – RF

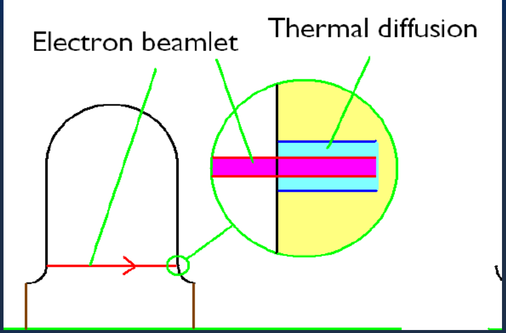
- A Viable Cooling Channel requires
  - Strong focusing and a large accelerating gradient to compensate for the energy loss in absorbers
  - ⇨ Large B- and E-fields superimposed
- Operation of RF cavities in high magnetic fields is a necessary element for muon cooling
  - Control RF breakdown in the 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

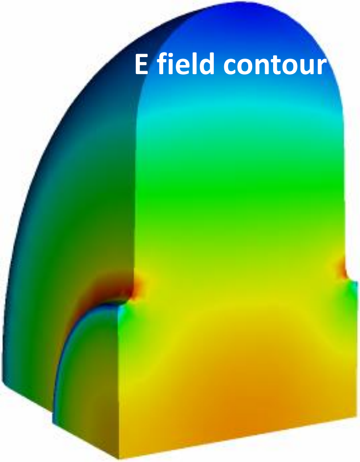
RF Breakdown in Magnetic Fields

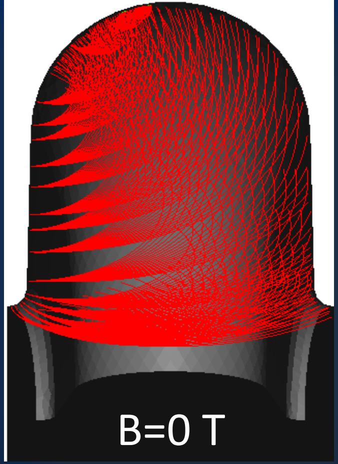
- The RF breakdown could be related by heating through field emission with external magnetic field and RF field:
  - External magnetic field
  - Ohmic heating
- Possible solutions
  - ***ExB***
  - Choice of materials
  - Surface preparation
  - Lower initial temperatures

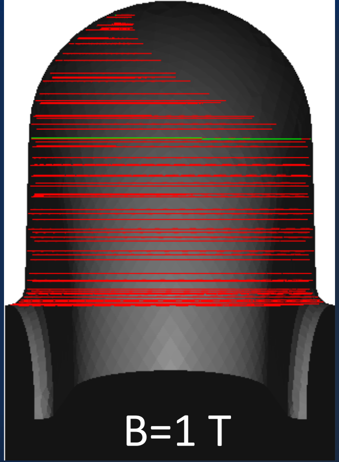
D. Li

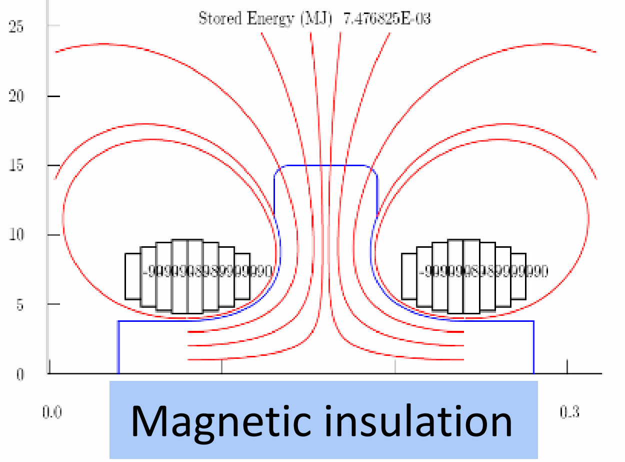







B=0 T


B=1 T



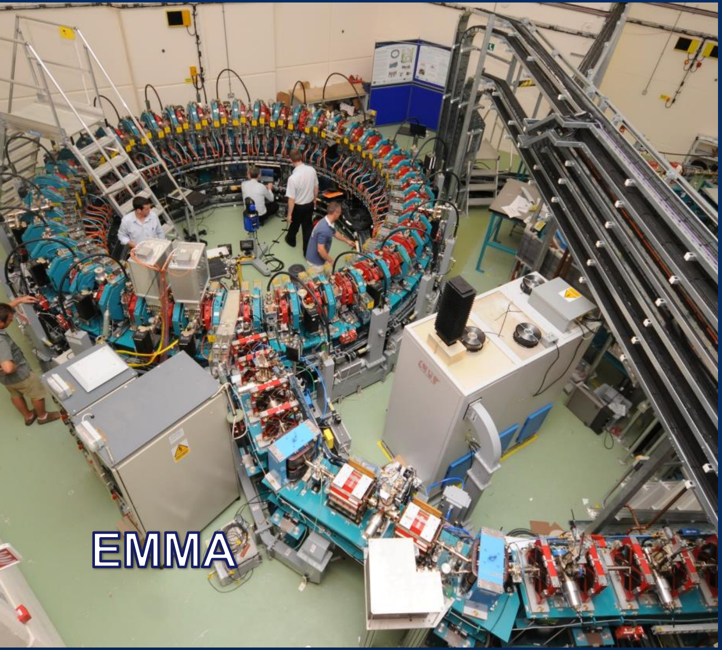
Magnetic insulation

Technology Challenges - Acceleration

- Muons require an ultrafast accelerator chain

  ⇨ *Beyond the capability of most machines*

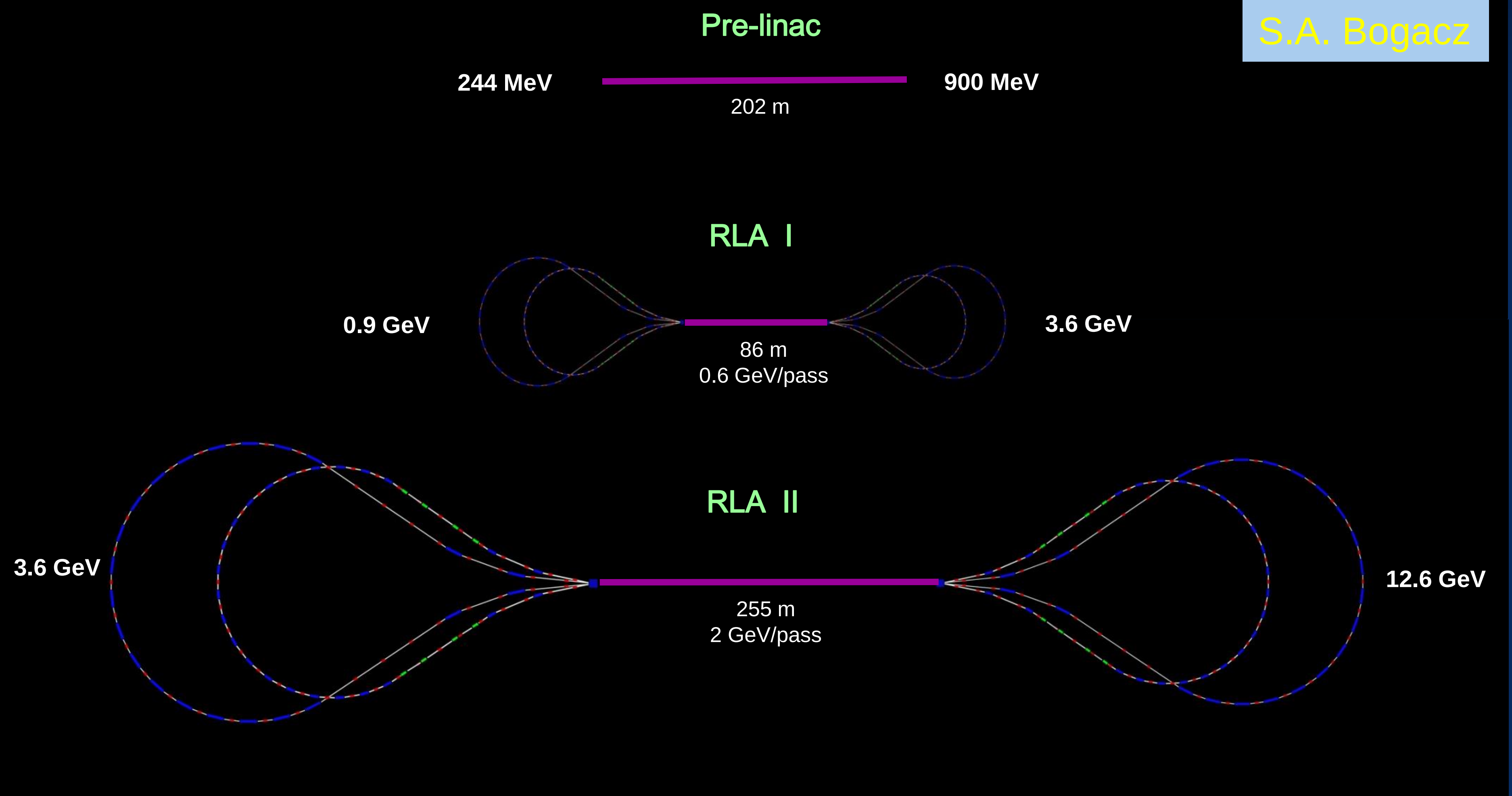
- Several solutions for a muon acceleration scheme have been proposed:



  - 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/VRCS)
  - Hybrid Machines

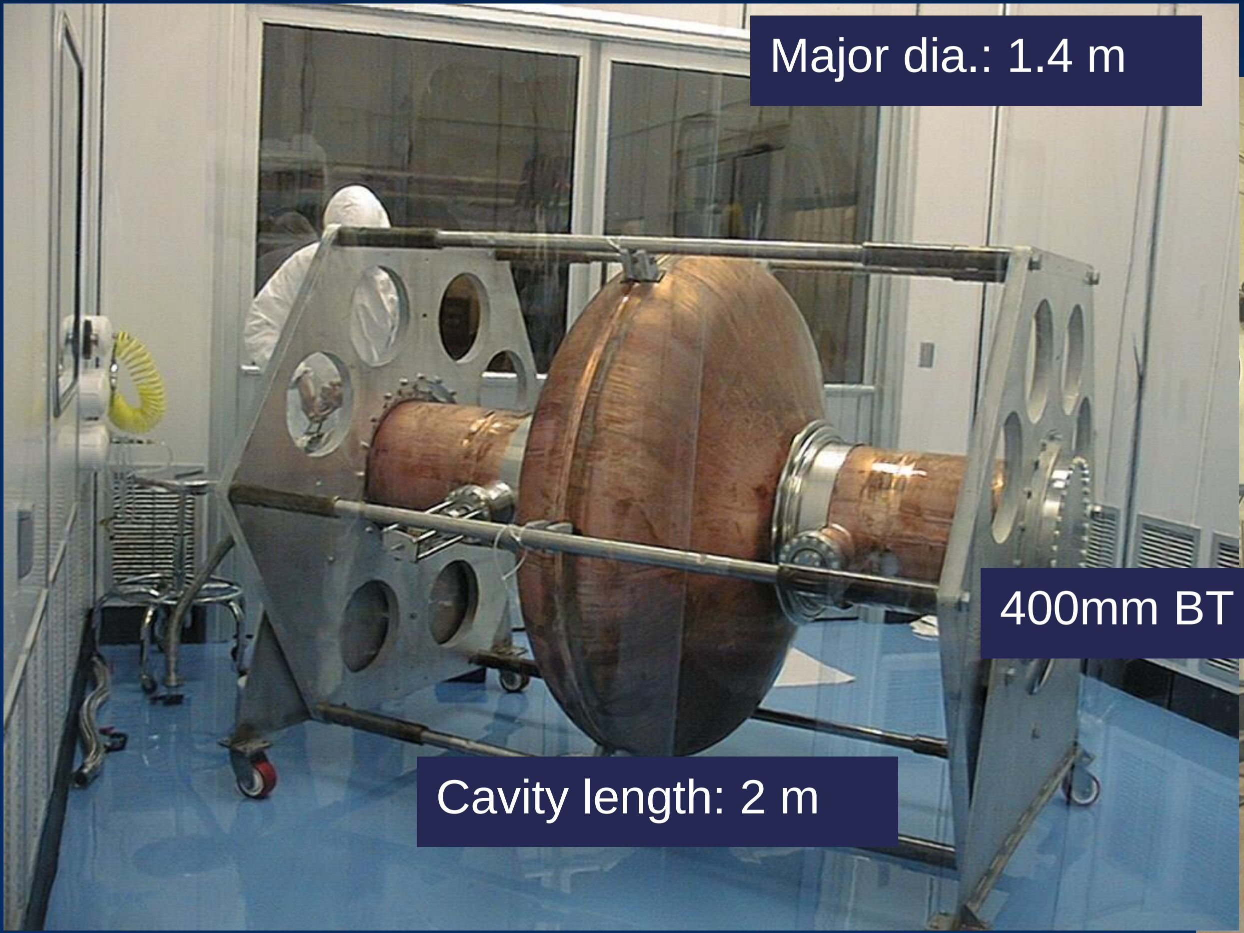
An Initial Acceleration Scheme: RLAs

S.A. Bogacz



Superconducting RF Development

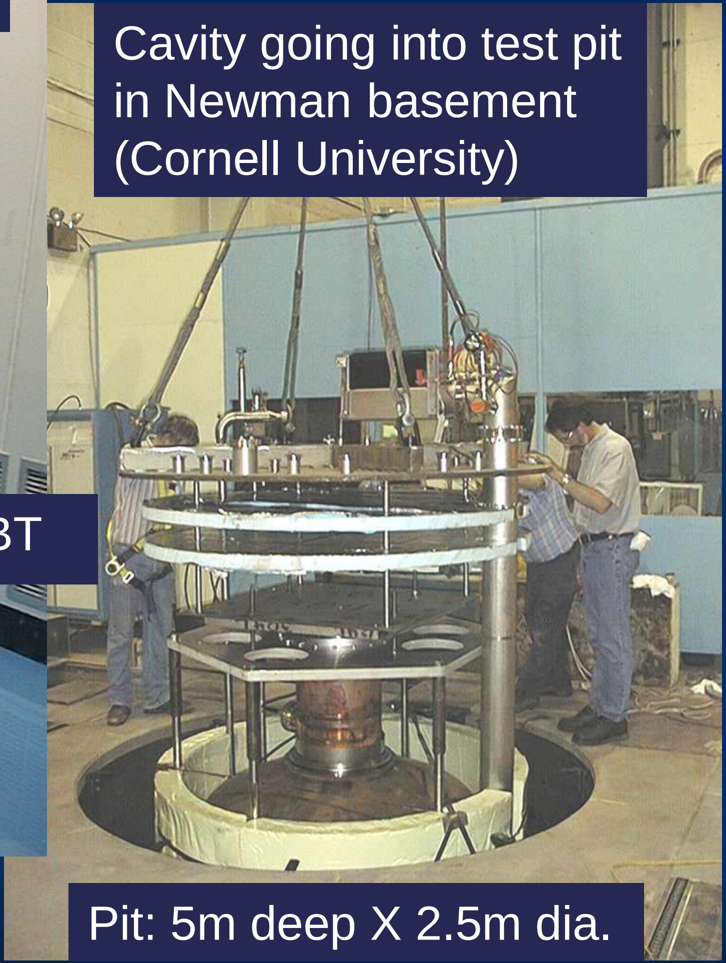
201 MHz SCRF R&D



Major dia.: 1.4 m

400mm BT

Cavity length: 2 m

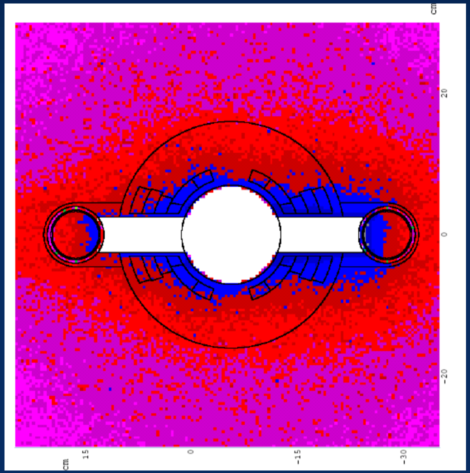


Cavity going into test pit in Newman basement (Cornell University)

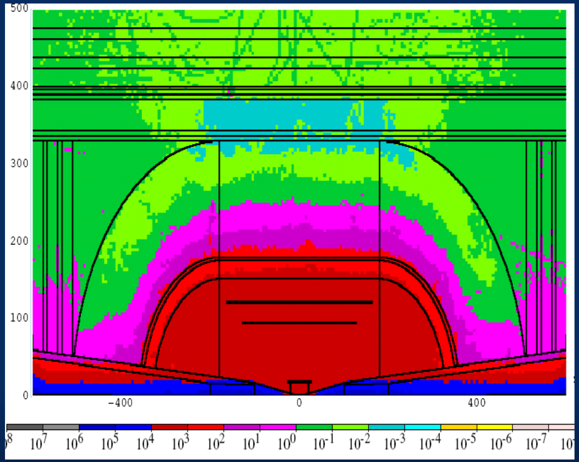
Pit: 5m deep X 2.5m dia.

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

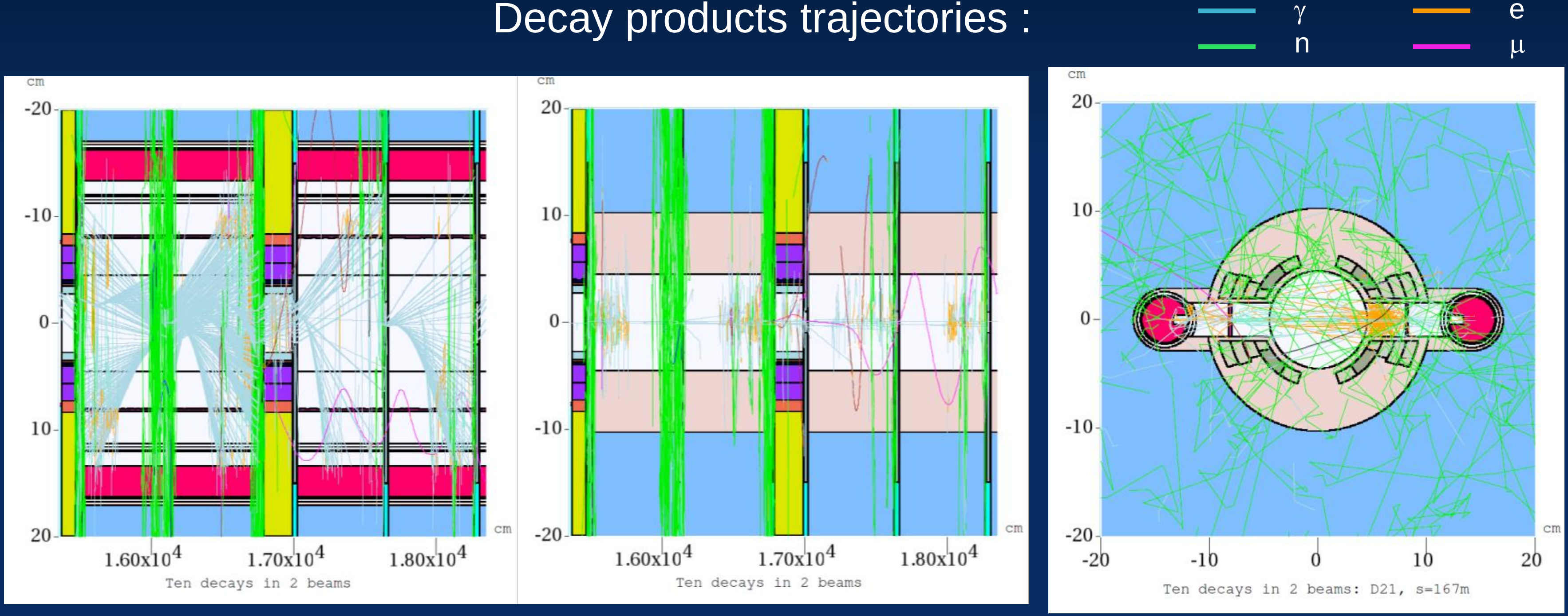


MARS energy deposition map for 1.5 TeV collider dipole



Technology Challenges:
Heat Load in Arc Magnets (N.Mokhov)

Decay products trajectories :



Horizontal view

Vertical view

Cross-section view

Energy deposition: in the ring dipole cold mass @LHe temp 25 W/m - a factor of ~5 too high!
W rods 80 W/m
in the quadrupole cold mass @LHe temp 38 W/m
in masks between magnets 1.5-3 kW/m

Solutions:

– abandon the open-midplane design, put W absorber inside the dipole bore

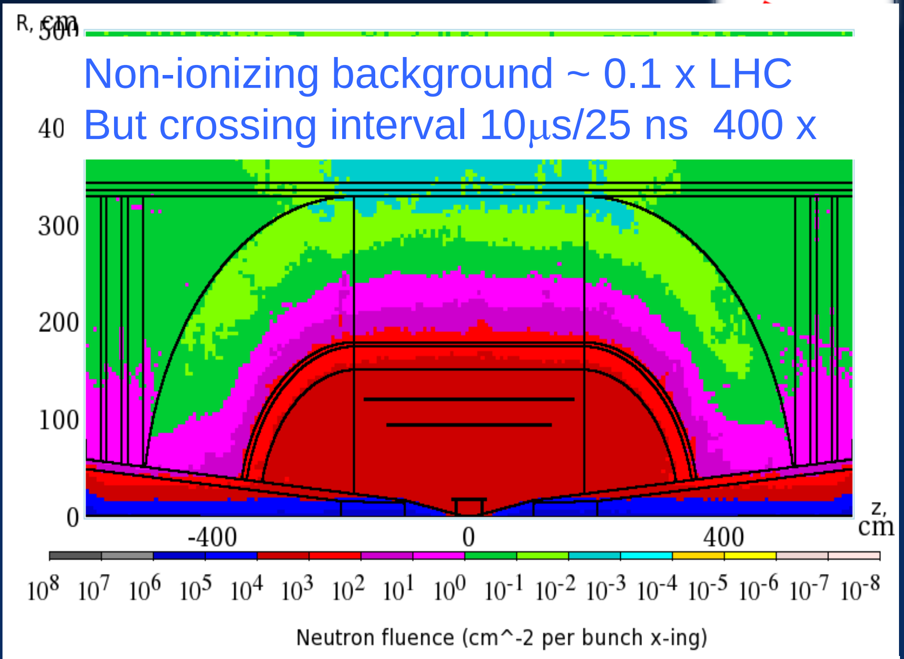
– sweep away the decay electrons before they obtain considerable vertical displacement: use combined-function magnets

Backgrounds and Detector

Much of the background is soft and out of time

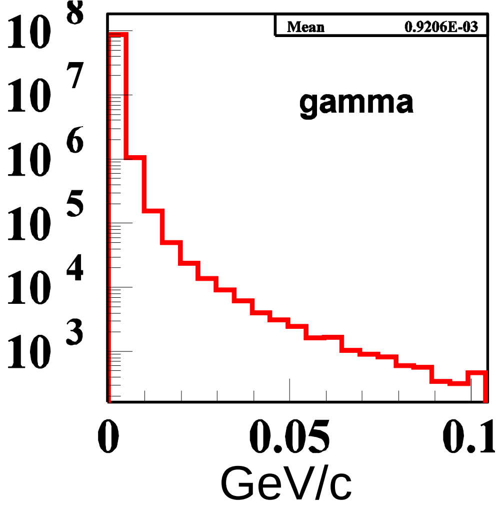
- Nanosecond time resolution can reduce backgrounds by three orders of magnitude

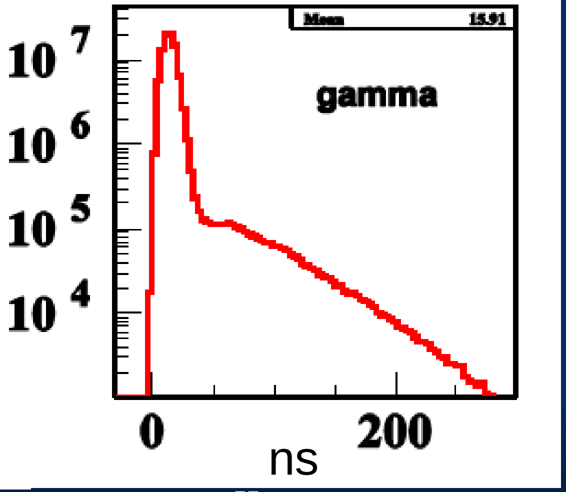
Requires a fast, pixelated tracker and calorimeter.



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

	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}





Backup slide

RECENT R&D PROGRESS – SOME HIGHLIGHTS

MAP Design & Simulation

MAP Design Efforts

Accelerator	Energy Scale	Performance
Cooling Channel	**~200 MeV**	**Emittance Reduction**
MICE	*160-240 MeV*	*10%*
Muon Storage Ring	**3-4 GeV**	**Useable m decays/yr***
nSTORM	*3.8 GeV*	*$3x10^{17}$*
Intensity Frontier n Factory	**4-10 GeV**	**Useable m decays/yr***
FNAL NF Phase I (PX Ph 2)	*4-6 GeV*	*$9x10^{19}$*
FNAL NF Phase II (PX Ph 2)	*4-6 GeV*	*$1x10^{21}$*
IDS-NF Design	*10 GeV*	*$5x10^{20}$*
Higgs Factory	**~126 GeV CoM**	**Higgs/yr**
s-Channel m Collider	~126 GeV CoM	4,000-40,000
Energy Frontier m 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*	*$12x10^{34}cm^{-2}s^{-1}$*

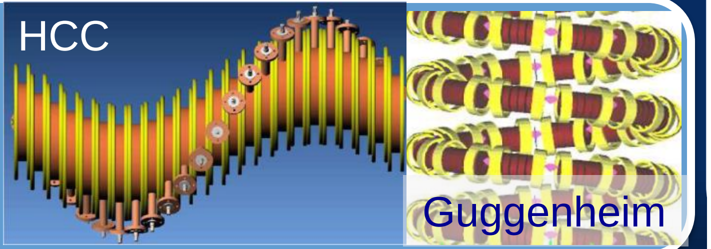
* Decays of an individual species (ie, m+ or m-)

- Program Baselines
- Staging Study (MASS) Contributions

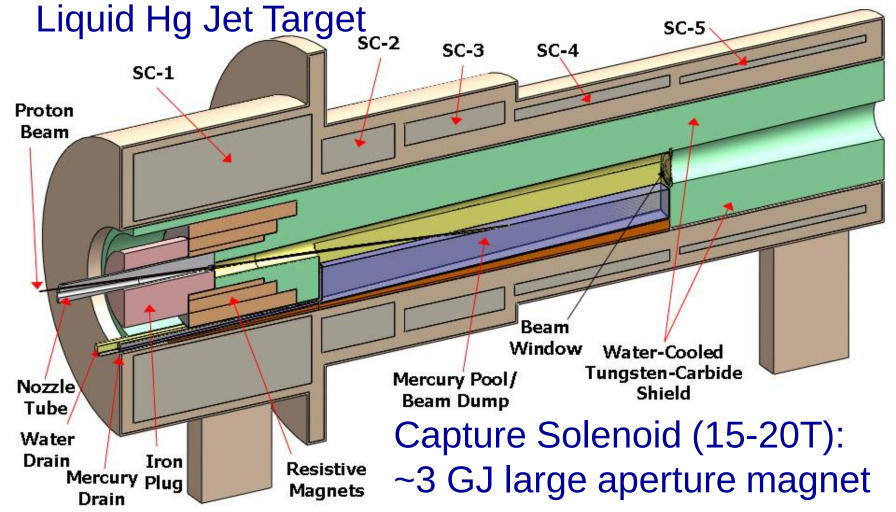
High Performance Computing

- Code Parallelization (G4Beamline, ICOOL)
  - Performance improvements > 10^4
- Enables Multi-Objective Parallel Optimization of Accelerator Designs

Cooling Channel Concepts

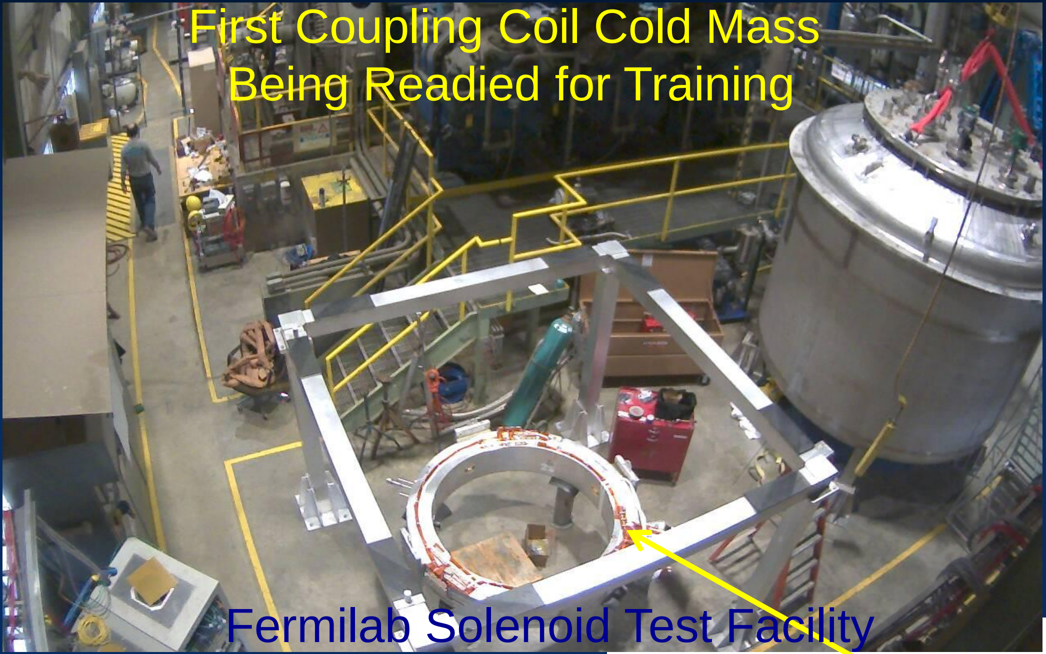


Liquid Hg Jet Target



Capture Solenoid (15-20T):
~3 GJ large aperture magnet

Recent Progress I - MICE

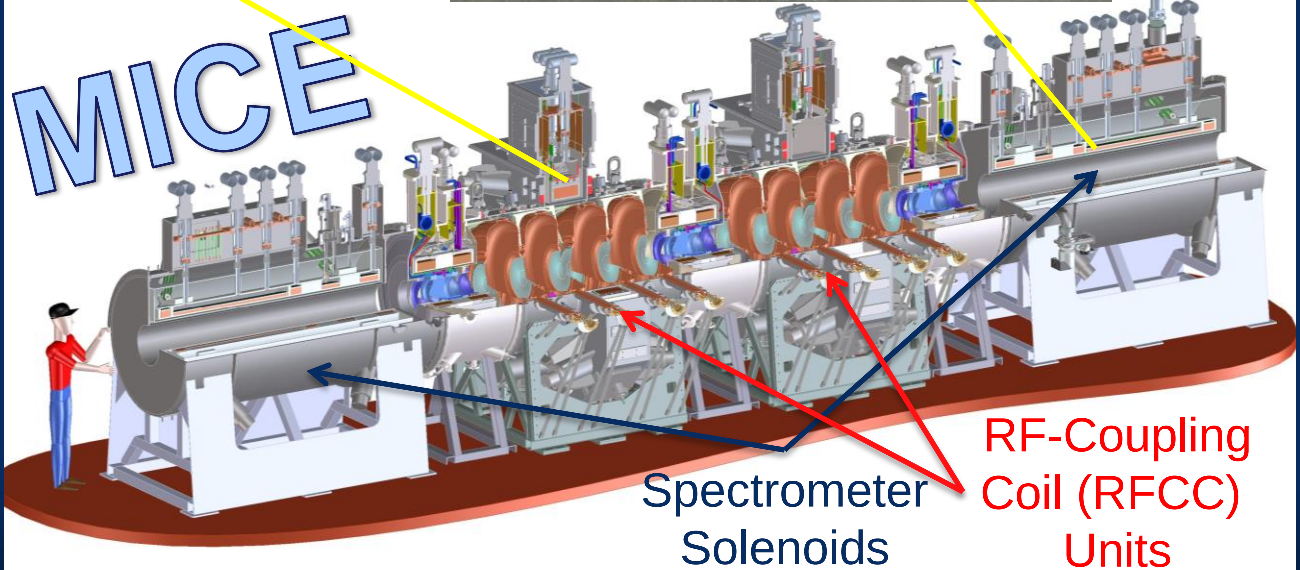


First Coupling Coil Cold Mass Being Readied for Training

Fermilab Solenoid Test Facility

First Spectrometer Solenoid Now Commissioned!

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



Spectrometer Solenoids

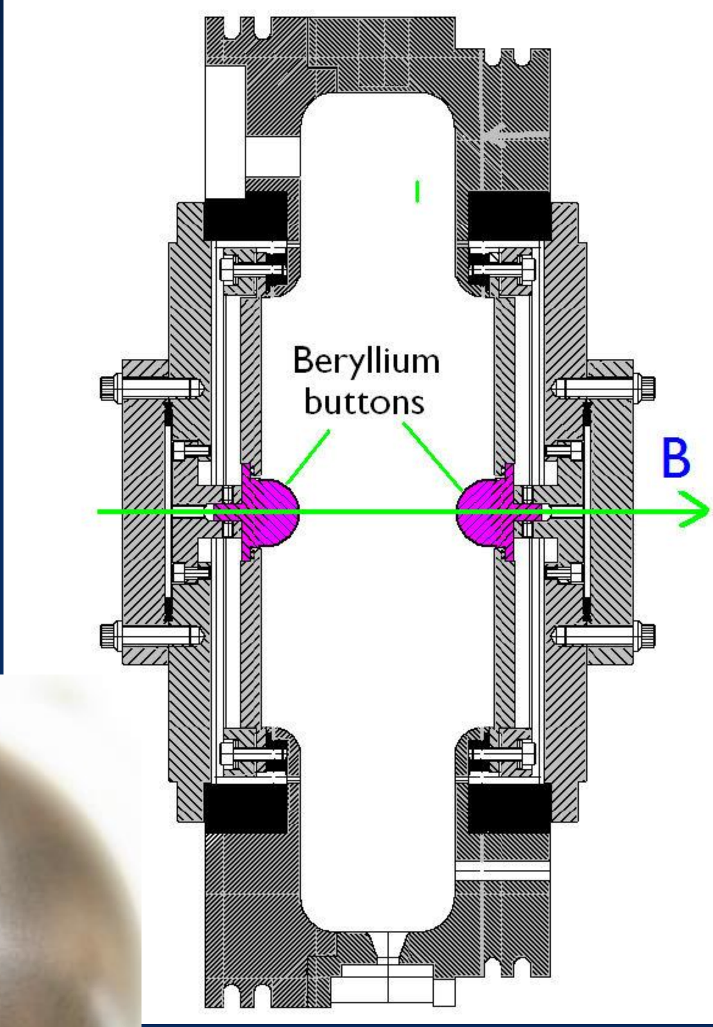
RF-Coupling Coil (RFCC) Units

Recent Progress II – Cavity Materials

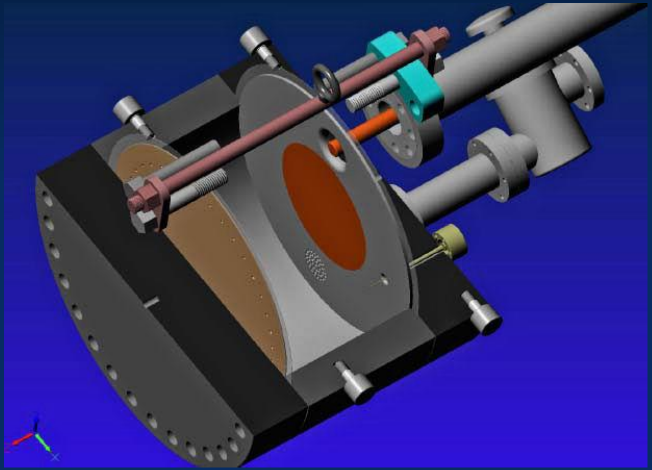
Breakdown tests with Be and Cu Buttons

- 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

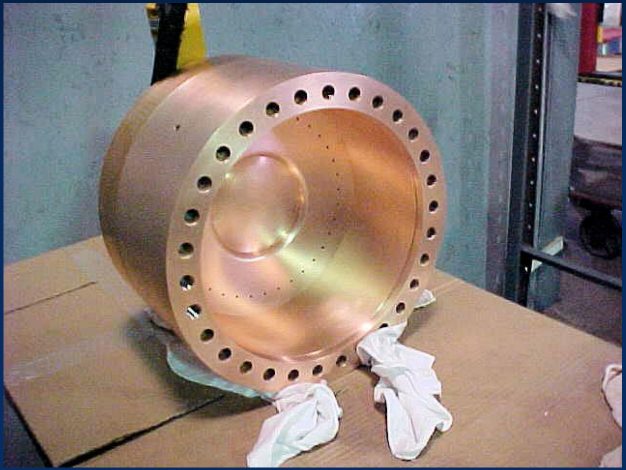


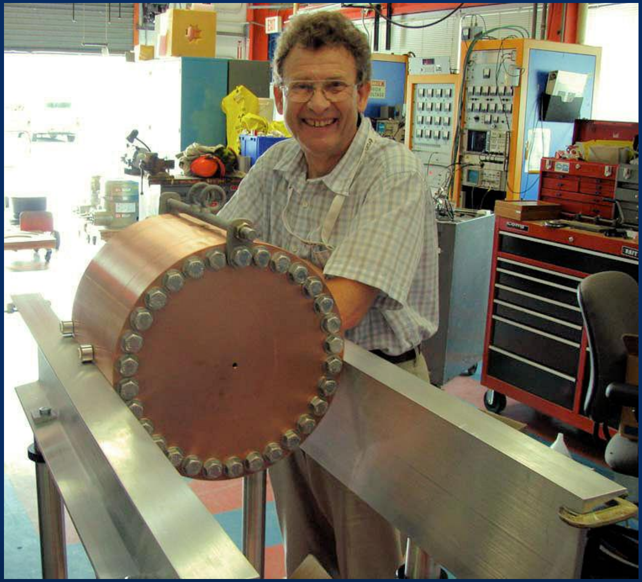
Recent Progress III – Vacuum RF



All-Seasons Cavity

(designed for both vacuum and high pressure operation)

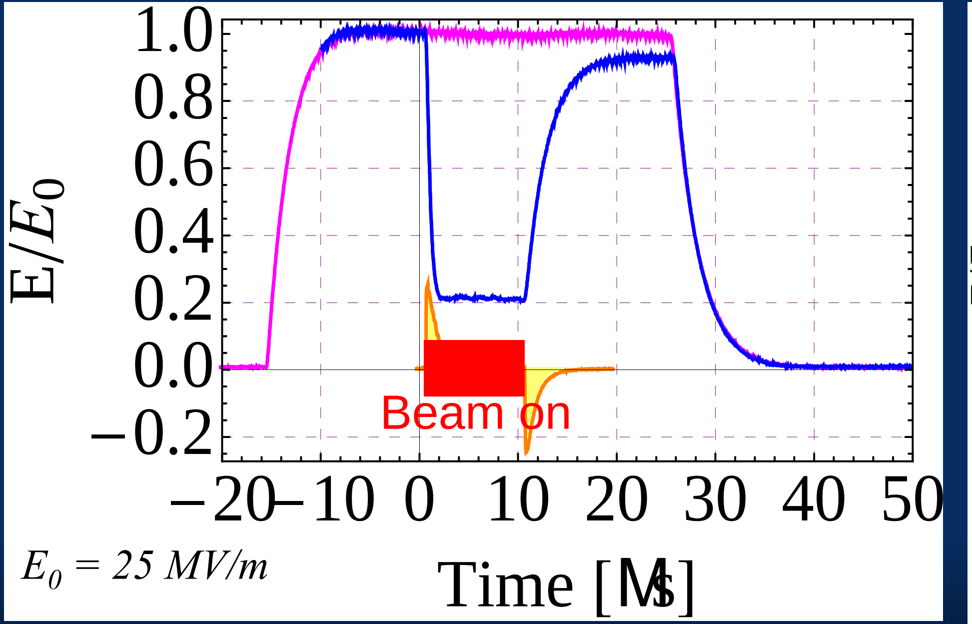


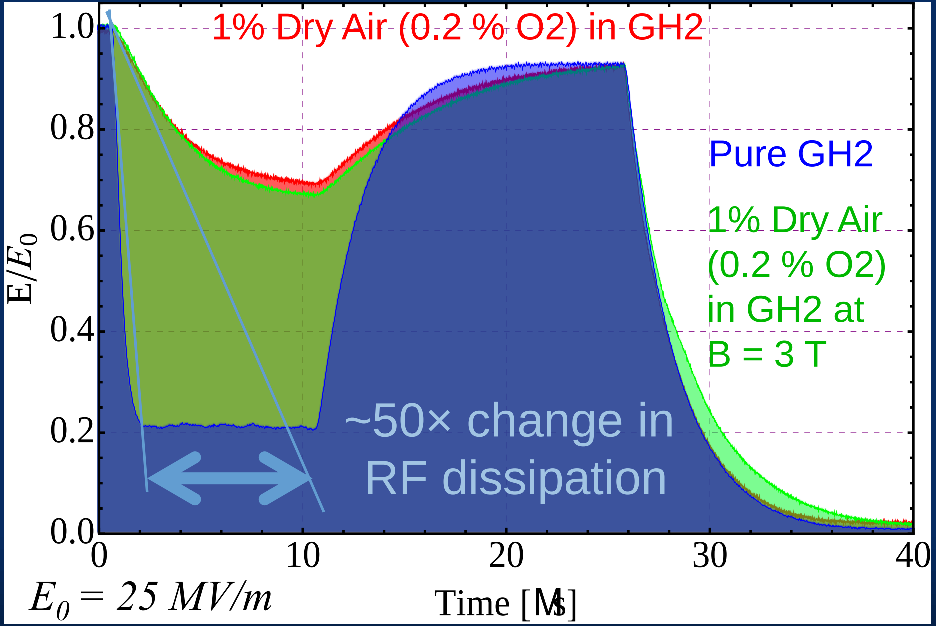


- Vacuum Tests at B = 0 T & B = 3 T
  - Two cycles: B_0 ⇨ B_3 ⇨ B_0 ⇨ B_3
- No difference in maximum stable operating gradient
  - Gradient ≈ 25 MV/m
- Demonstrates possibility of successful operation of vacuum cavities in magnetic fields with careful design

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



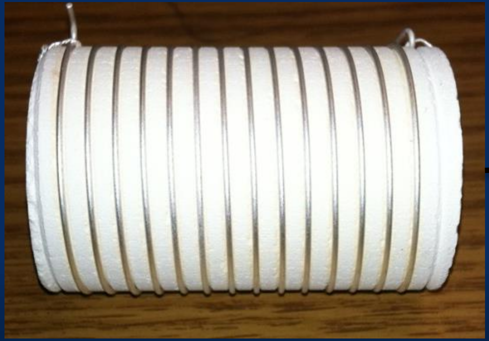


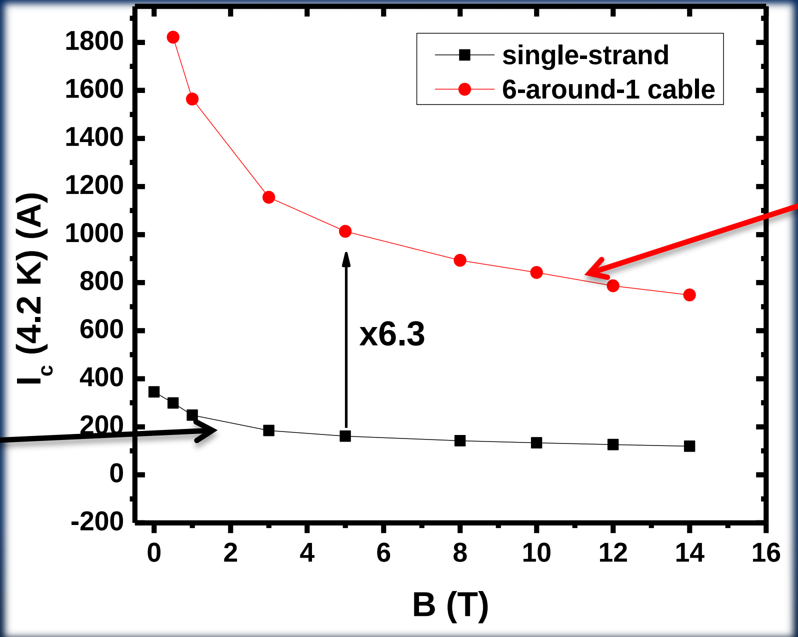
Recent Progress V: High Field Magnets

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

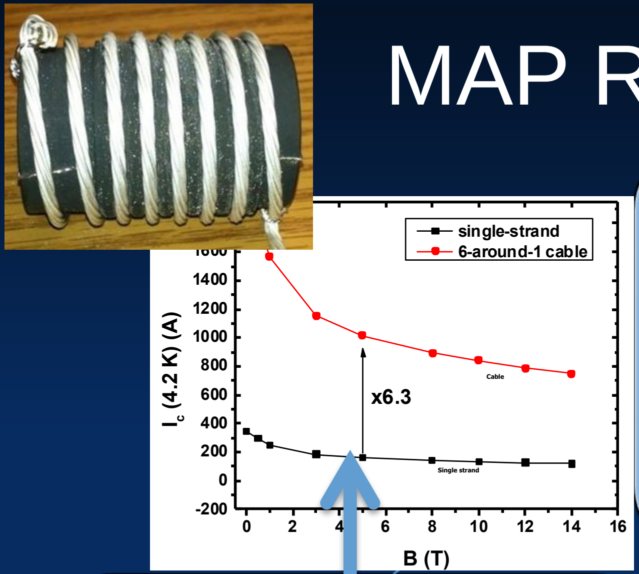
BSCCO-2212 Cable - Transport measurements show that FNAL cable attains 105% J_c of that of the single-strand





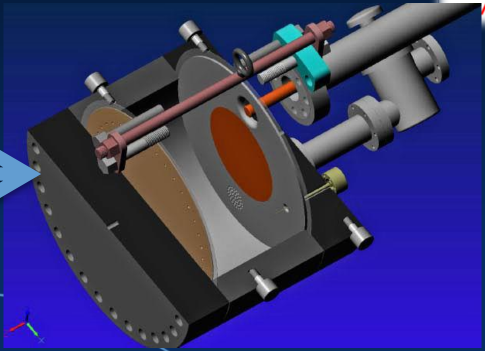
Multi-strand cable utilizing chemically compatible alloy and oxide layer to minimize cracks

MAP Recent Technology Highlights



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

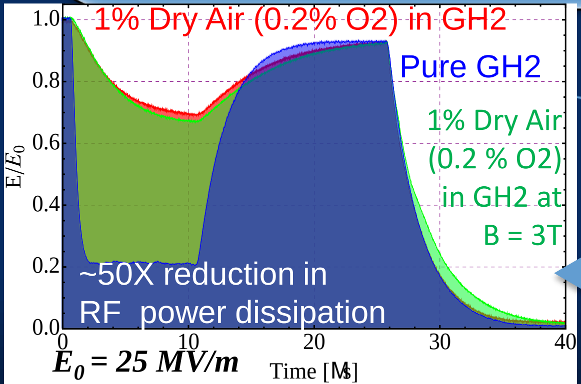
Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

FNAL-Tech Div
T. Shen-Early Career Award

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