Muon Accelerators:
An Integrated Path to Intensity and Energy Frontier Physics Capabilities

Mark Palmer

March 21, 2013

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:

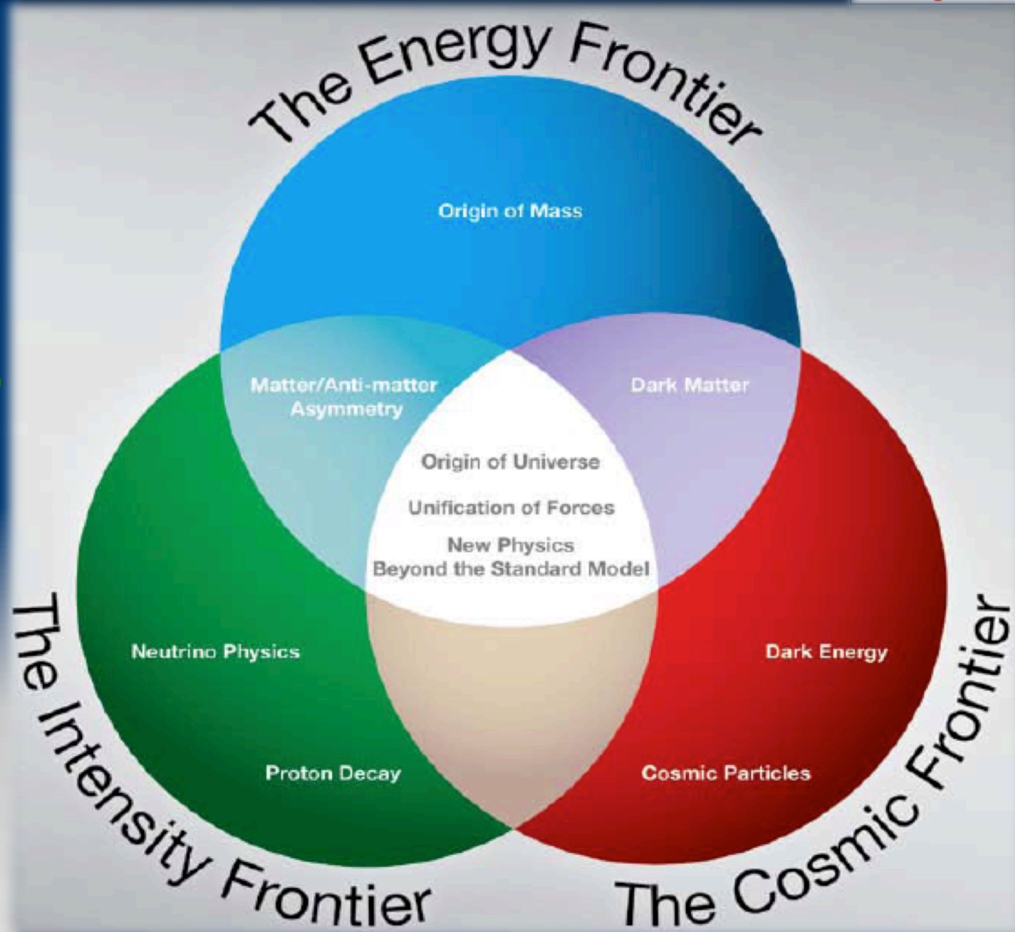
with a ***Neutrino Factory*** producing well-characterized n beams for precise, high sensitivity studies

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

- Physics Motivations
- Muon Collider Concept
- Muon Collider and Neutrino Factory Synergies
  - Staging Scenarios
  - The Proposed Timeline
  - Parameters
- The R&D Challenges
- The MAP Feasibility Assessment
- Concluding Remarks

THE PHYSICS MOTIVATIONS

The Physics Motivations

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

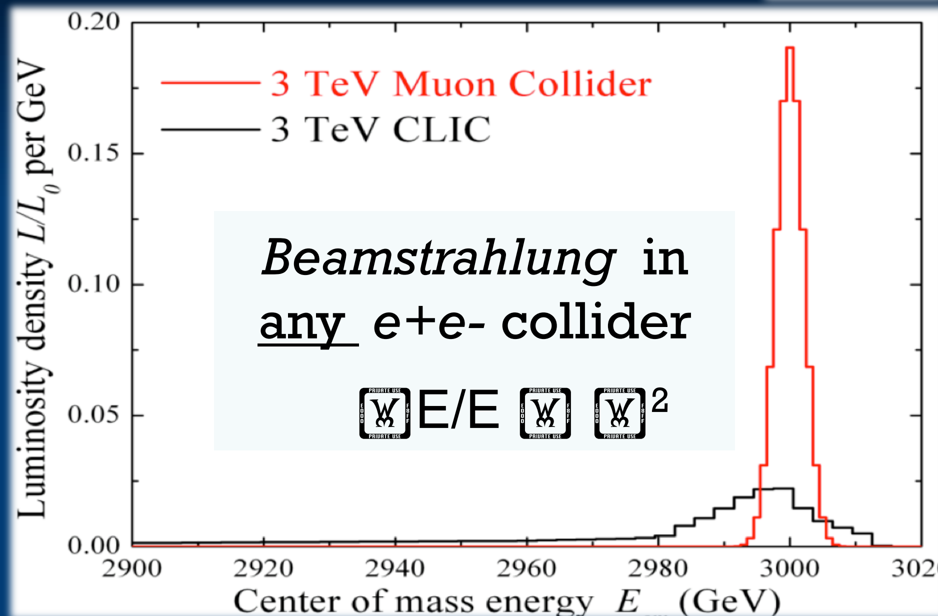
- Physics potential for the HEP community using muon beams
  - Tests of Lepton Flavor Violation
  - Anomalous magnetic moment ⇨ hints of new physics (g-2)
  - Can provide equal fractions of electron and muon neutrinos at high intensity for studies of neutrino oscillations – the Neutrino Factory concept

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

  - 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 m^+m^- 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

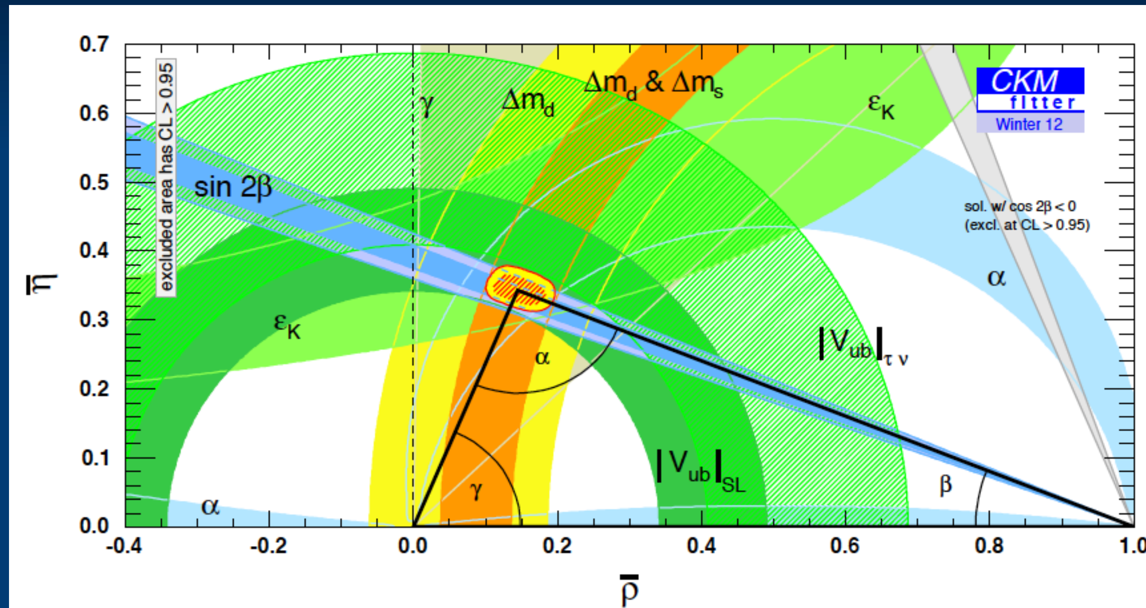


- Short muon lifetime has impacts as well
  - Acceleration and storage time of a muon beam is limited
  - Collider ⇨ a new class of decay backgrounds must be dealt with
  - Precision beam energy measurement by g-2 allows precision Higgs width determination

- Muon beams produced as tertiary beams: $p \rightarrow \pi \rightarrow \mu$
  - Offers key accelerator challenges…

The Physics Needs: Neutrinos (I)

- In the neutrino sector it is critical to understand:
  - d_{CP}
  - The mass hierarchy
  - $q_{23} = p/4$, $q_{23} < p/4$ or $q_{23} > p/4$



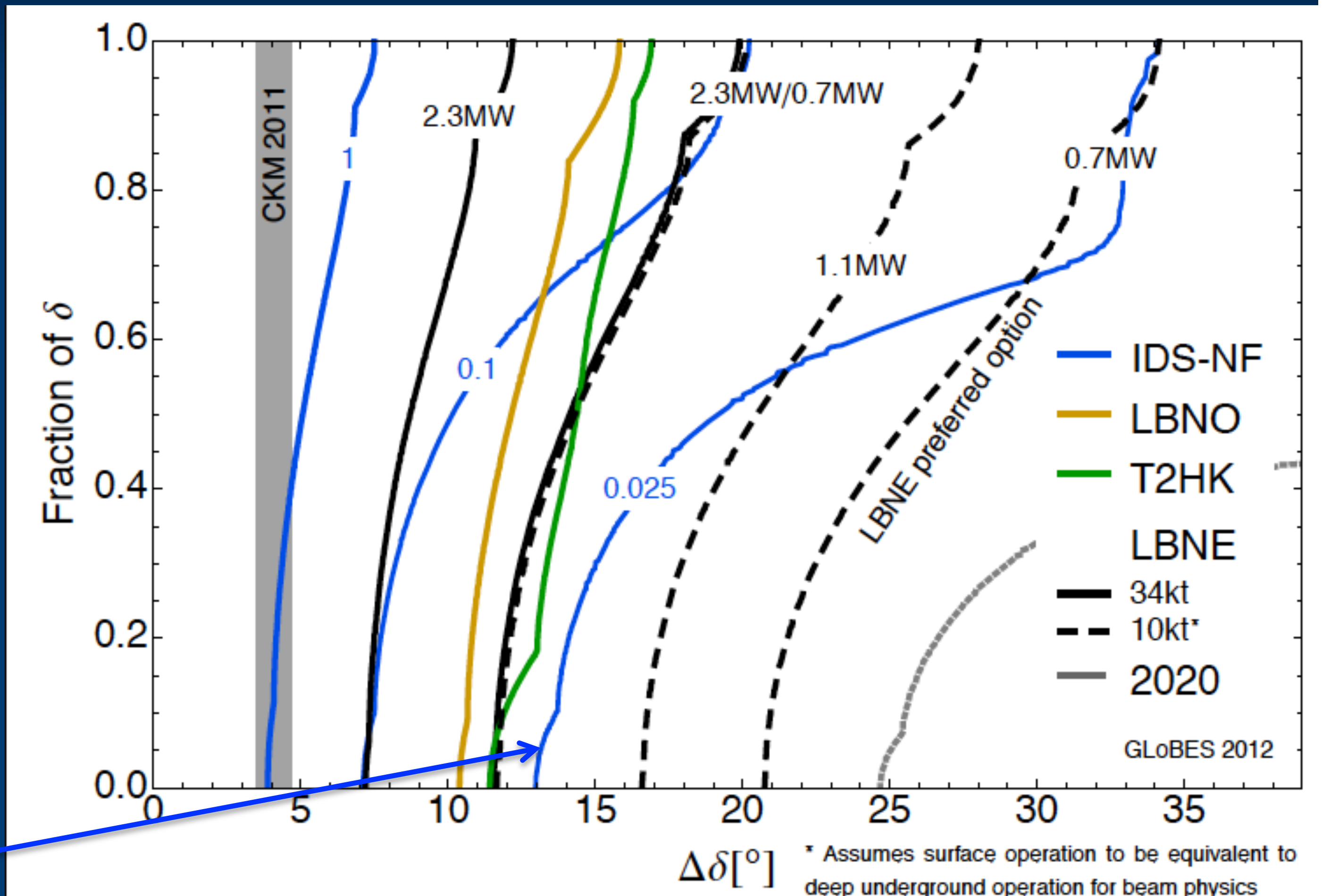
  - Resolve the LSND and other short baseline experimental anomalies [perhaps using beams from a muon storage ring (nSTORM) in a short baseline experiment]
  - And continue to probe for signs new physics

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?

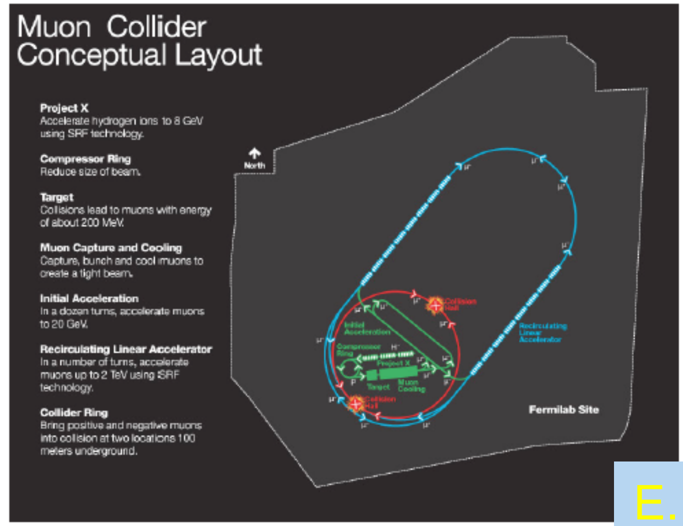


0.025 IDS-NF:
700kW target,
no cooling,
2×10^8 s running time
10-15 kTon detector

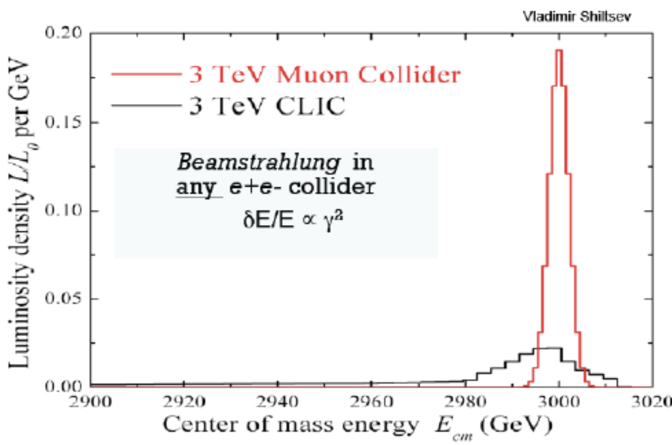
P. Coloma, P. Huber, J. Kopp, W. Winter – article in preparation

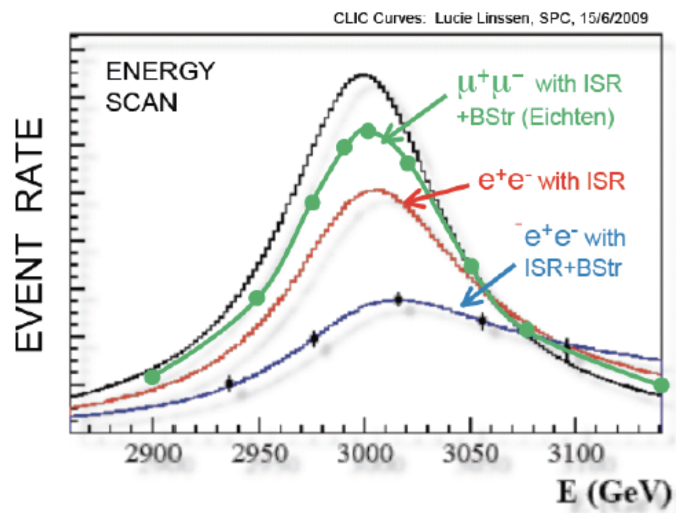
The Physics Needs: Colliders

- $\mu^+\mu^-$ 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%



E. Eichten

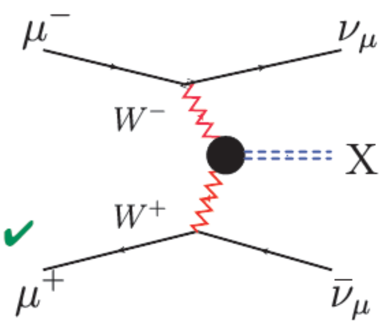




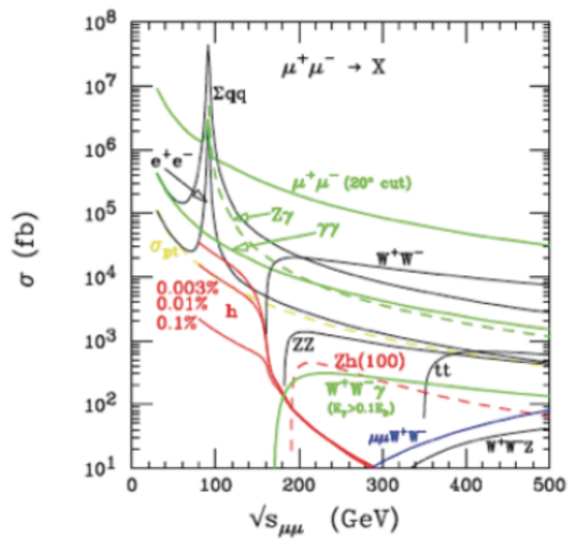
Muon Collider Reach

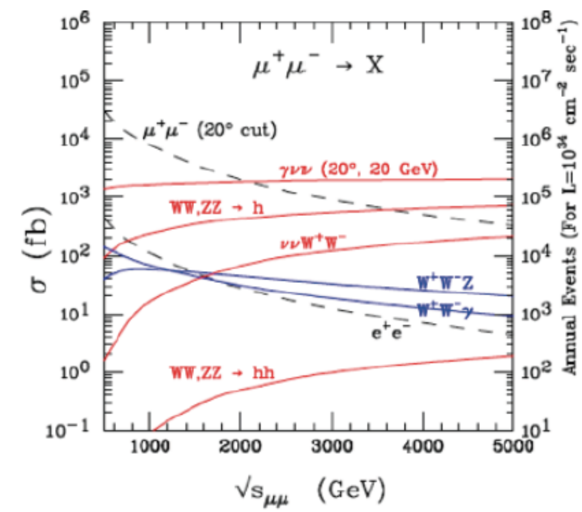
- For $\sqrt{s}$ < 500 GeV
  - SM thresholds: Z^0h, W^+W^-, top pairs
  - Higgs factory ($\sqrt{s} \approx$ 126 GeV) ✔
- For $\sqrt{s}$ > 500 GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required. ✔
    - Cross sections for central ($|\theta| > 10°$) pair production ~ R × 86.8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





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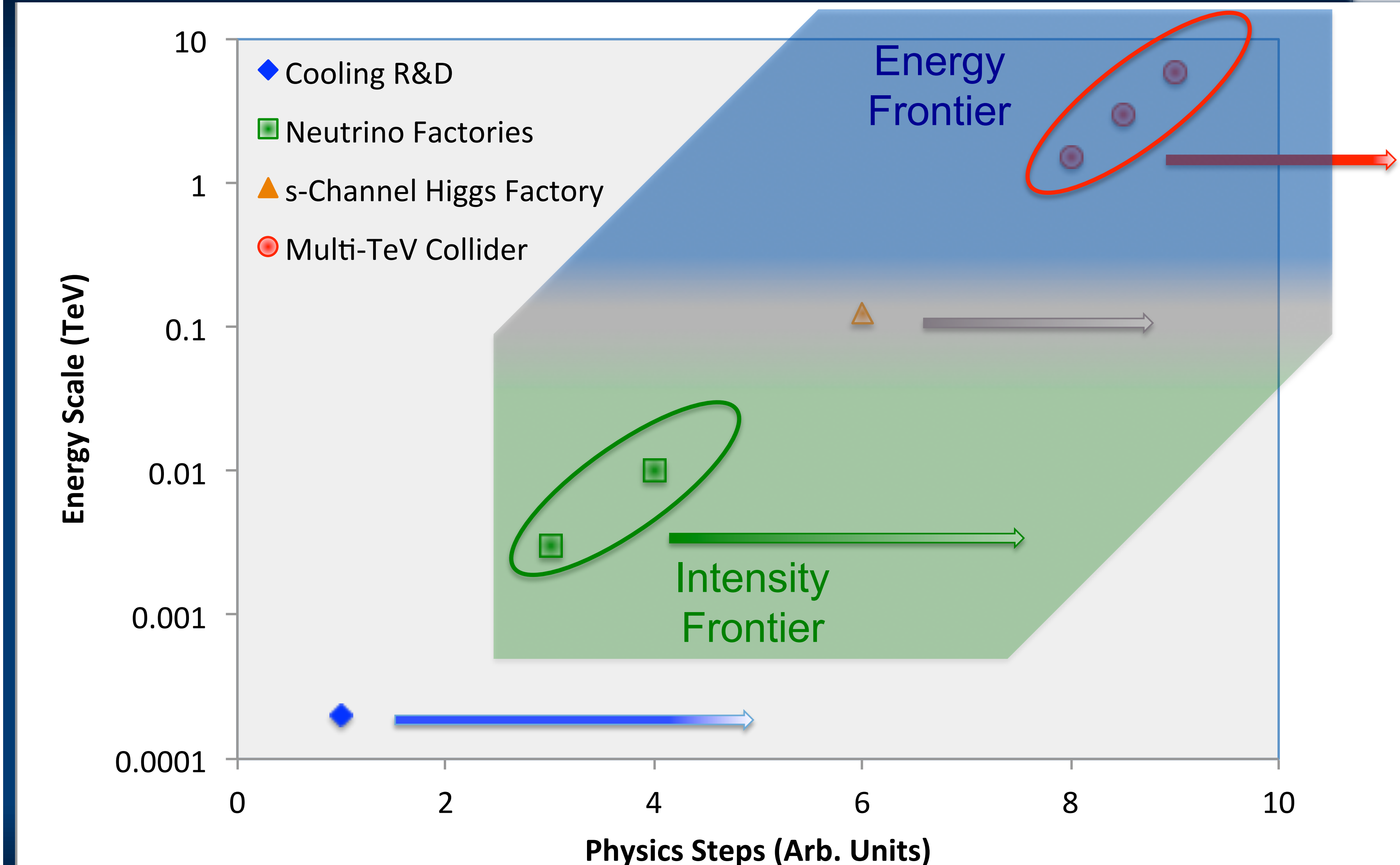
Muon Accelerator Physics Scope



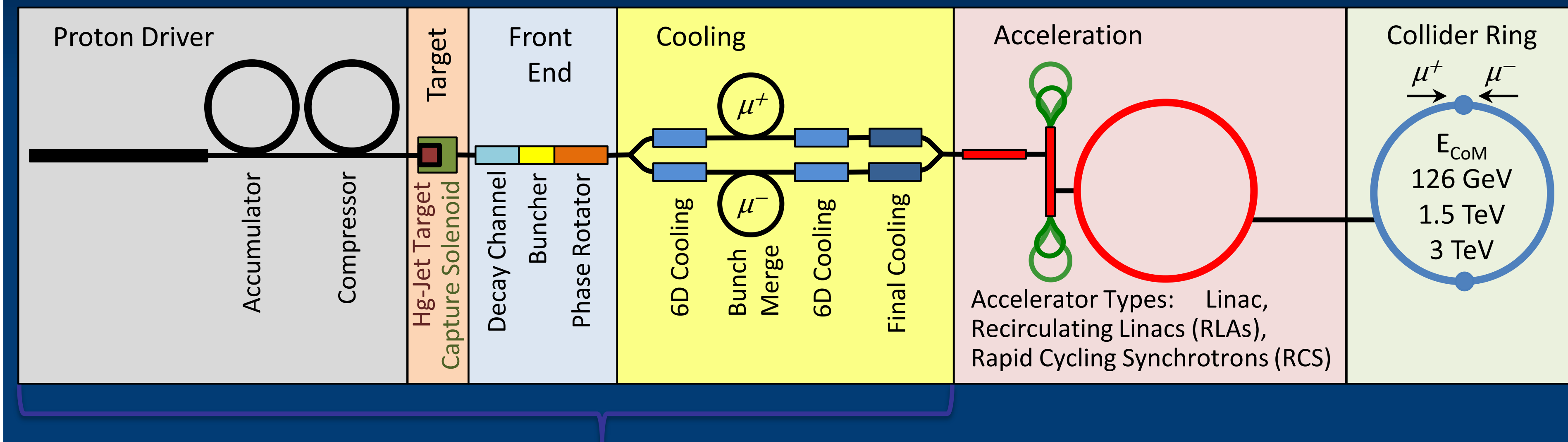
Muon Accelerators

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

Muon Collider Concept

Muon Collider Block Diagram



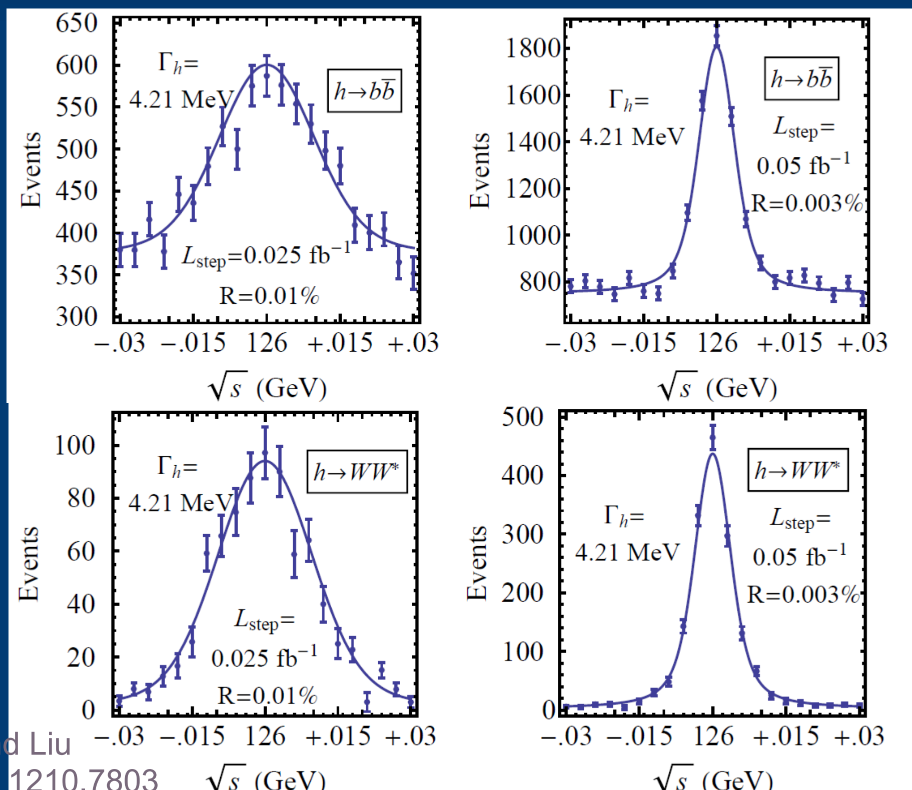
Proton source:
For example PROJECT X at 4 MW, with 2±1 ns long bunches

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

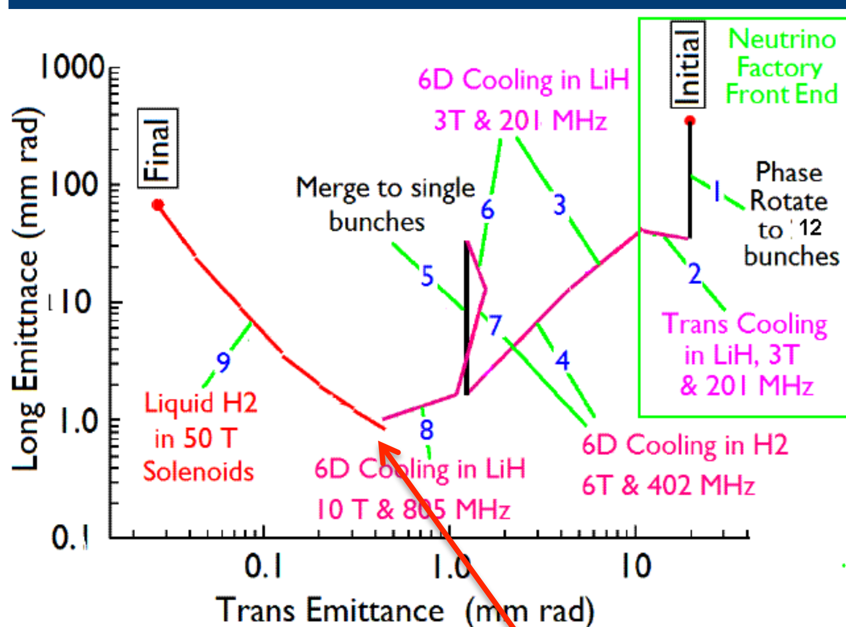
Collider: √s = 3 TeV
Circumference 4.5km
$L = 3\times10^{34}$ cm^{-2}s^{-1}
m/bunch = 2x10^{12}
$s(p)/p$ = 0.1%
$e_{\perp N}$ = 25 mm, $e_{//N}$=72 mm
b^* = 5mm
Rep. Rate = 12 Hz

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}



Han and Liu
hep-ph 1210.7803

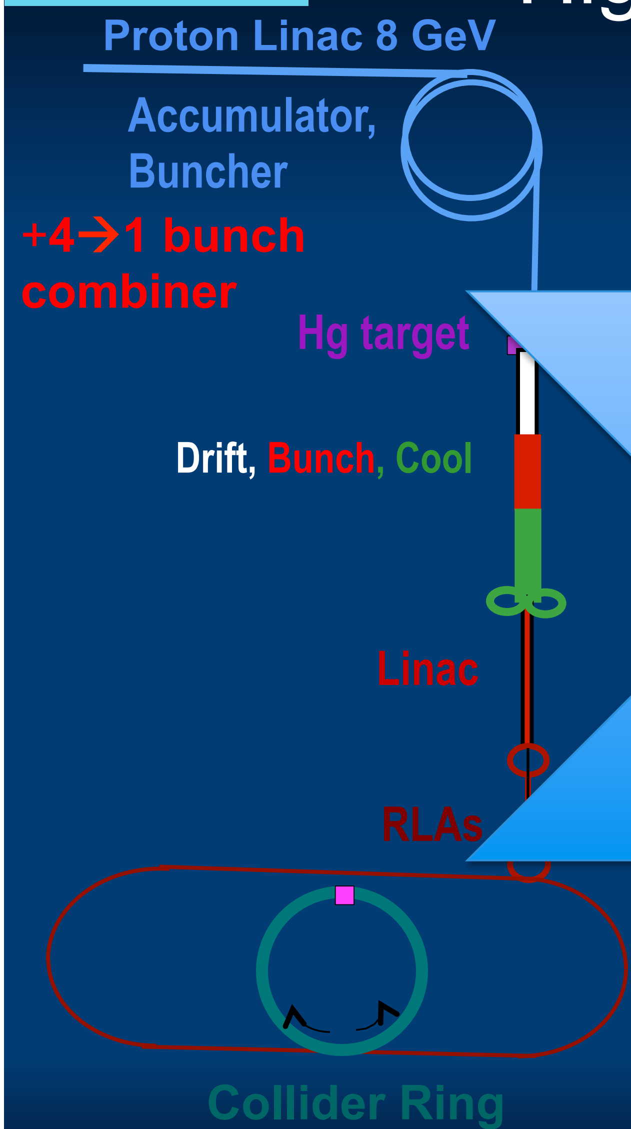


Major advantage for Physics of a $\mu^+\mu^-$ Higgs Factory: possibility of direct measurement of the Higgs boson width (Γ~4MeV FWHM expected)

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

D.Neuffer
AAC12
NuFACT12

Preliminary Muon Collider Higgs Factory Parameters



$\delta\nu_{BB} = 0.027$

Parameter	Symbol	Value
Proton Beam Power	P_p	4 MW
Bunch frequency	F_p	15 Hz
[illegible]	[illegible]	[illegible]5×10^{13}
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]cm
Beam size (arc)	$\sigma_{x,y}$	0.3cm
Beam size IR quad	σ_{max}	4cm
Collision Beam Energy	$E_{\mu+}, E_{\mu-}$	62.5(125geV total)
Storage turns	N_t	1000
Luminosity	L_0	10^{32}

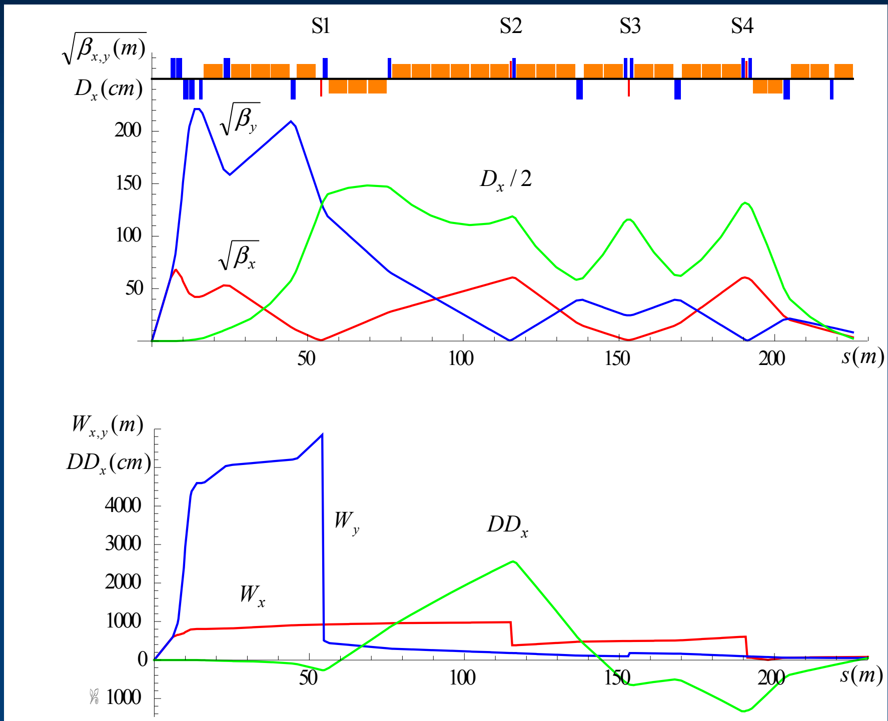
Updated designs now underway which leverage developments in our multi-TeV collider designs –Y. Alexahin, etal.

Alternate staging scenarios also being developed in the context of the MAP Muon Accelerator Staging Study – J-P. Delahaye, etal.

Fermilab

Multi-TeV Collider – 1.5 TeV Baseline

Y. Alexahin



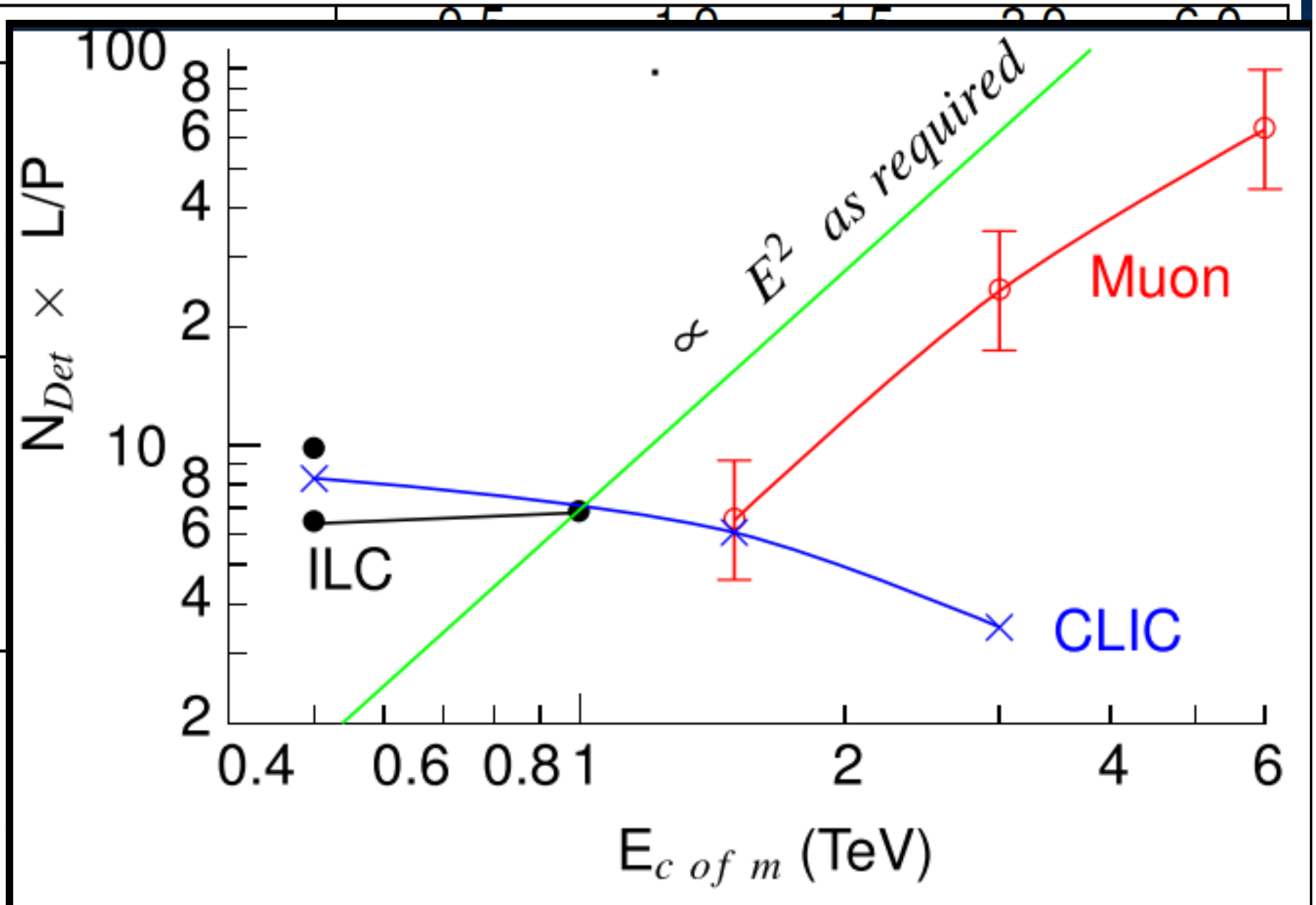
Larger chromatic function (Wy) is corrected first with a single sextupole S1, Wx is corrected with two sextupoles S2, S4 separated by 180° phase advance.

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, ε_N	[illegible][illegible]mm[illegible] 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

Luminosity Production Metric vs E_{CM}

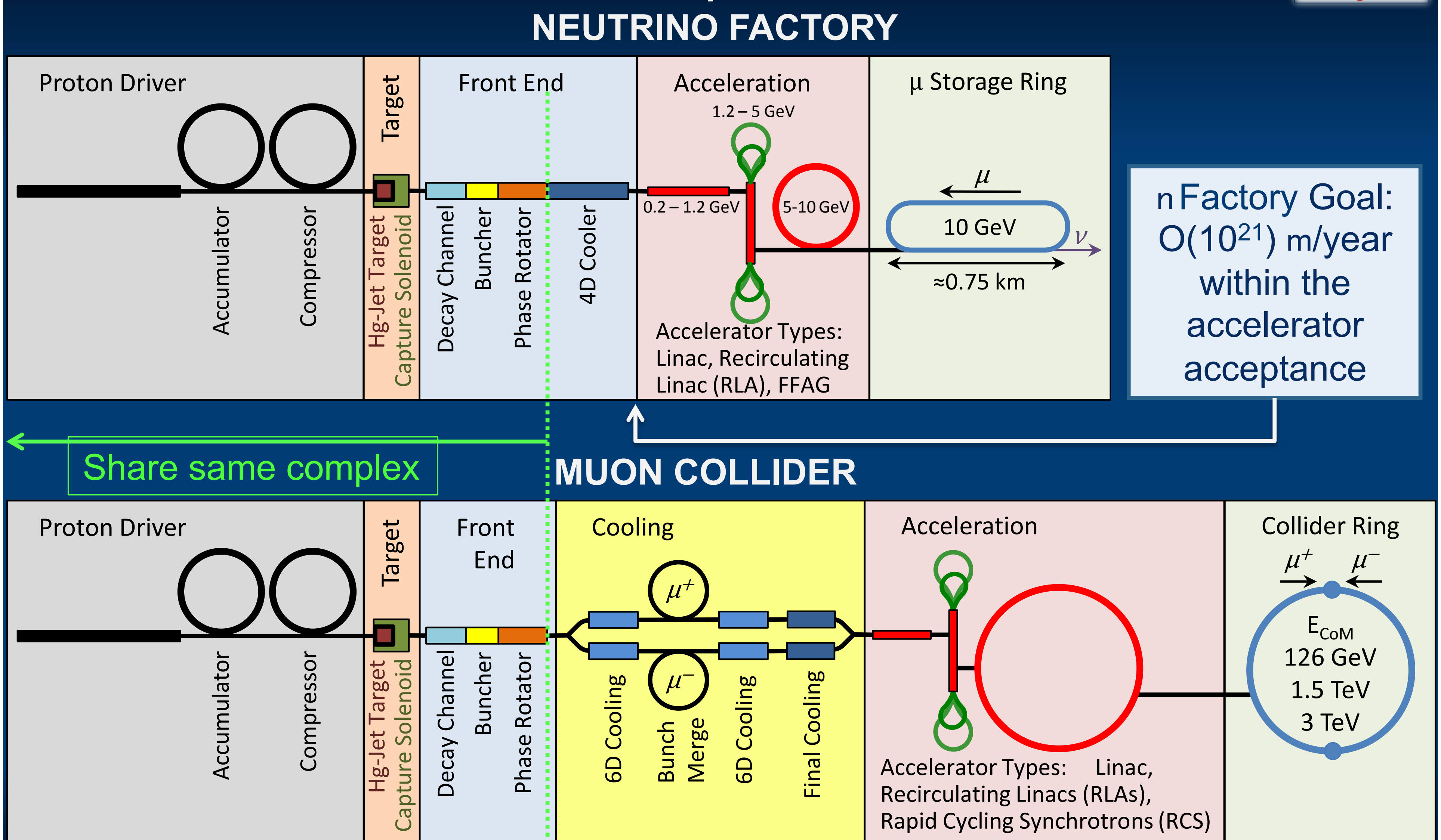
R. Palmer
MAP DOE Review 2012

$E_{c\ of\ m}$	TeV
ILC	
Detectors N_{Det}	
Luminosity	10^{34}
Wall Power	MW
$N_{Det} \times L/P$	10^{34}
CLIC	
Detectors N_{Det}	
Luminosity	10^{34}
Wall Power	MW
$N_{Det} \times L/P$	10^{34}
Muon	
Detectors N_{Det}	
Luminosity	10^{34}
Wall Power	MW
$N_{Det} \times L/P$	10^{34}



MUON COLLIDER AND NEUTRINO FACTORY SYNERGIES

Muon Collider - Neutrino Factory Comparison



Muon Accelerator Staging Study (MASS)

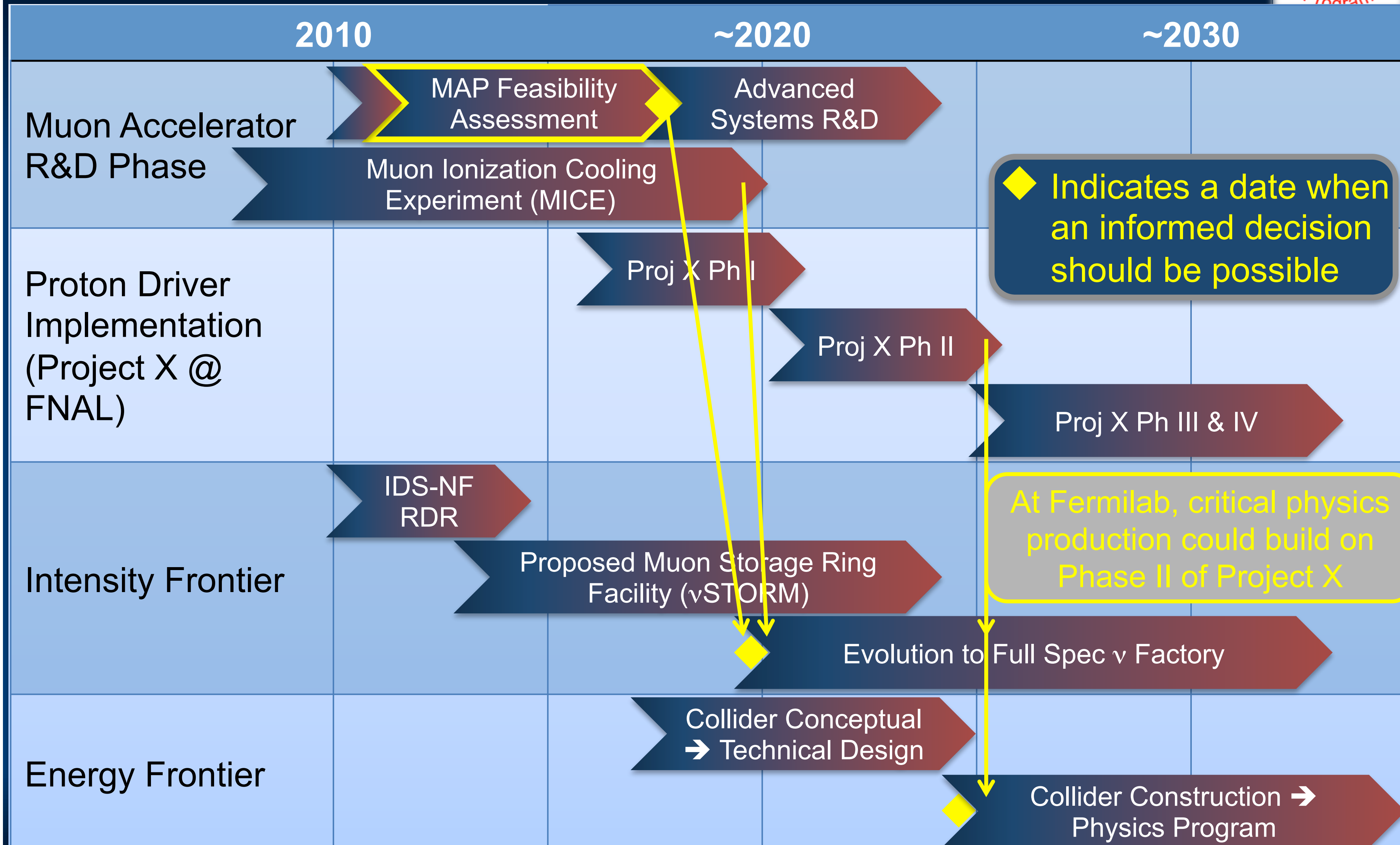
- Two approaches exist:
  - A dedicated “green field” construction project
  - A staged development based on evolving capabilities at an existing facility
    - Desirable if high quality physics can be produced along the way…
    - Can provide clear decision points with well-understood risks for moving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

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.

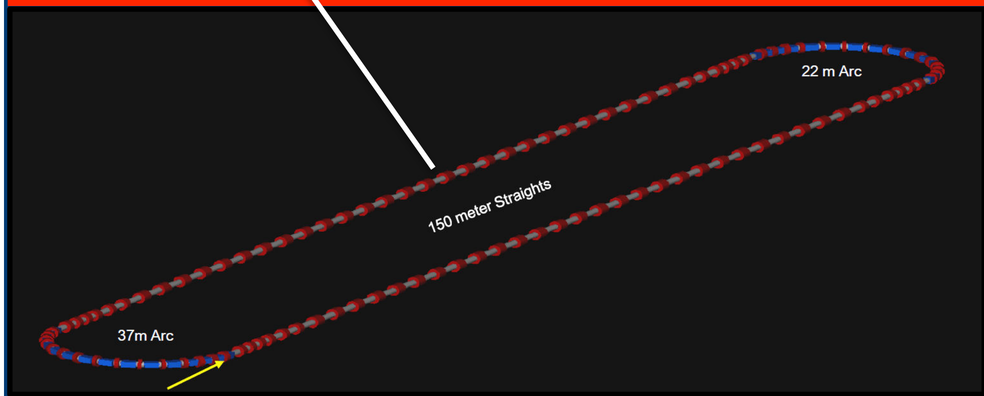
The Muon Accelerator Program Timeline

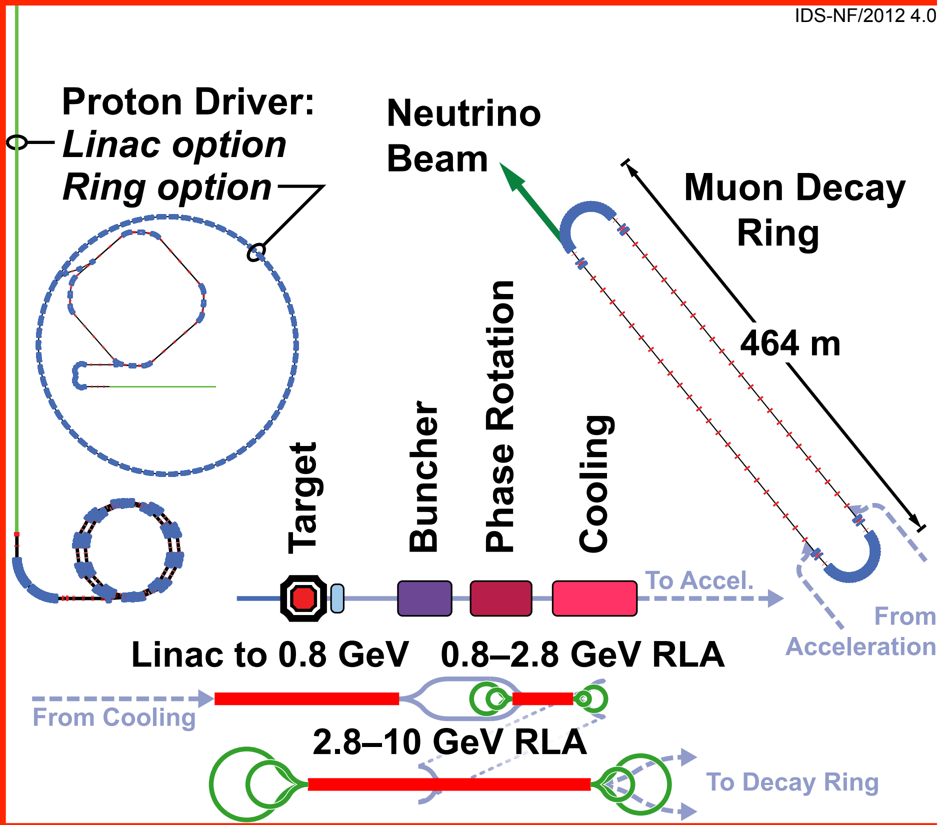


All proposed muon-based accelerators would easily fit at Fermilab

nSTORM (entry level Neutrino Factory)

Intensity Frontier Neutrino Factory





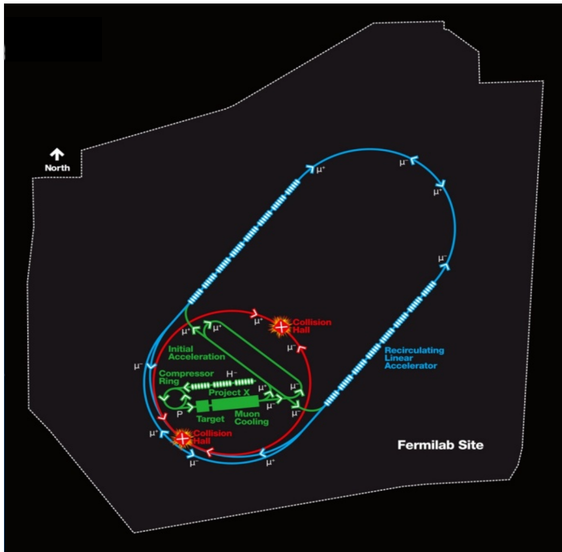
nSTORM would provide important physics output and critical R&D leverage

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

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}	1.25×10^{21}	1×10^{21}
	ν_e or ν_μ^* to detectors/yr		3×10^{17}	9.4×10^{19}	5.6×10^{20}	5×10^{20}
Detector	**Far Detector**	**Type**		**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	4	4	10
	Circumference C	m	350	1190	1190	1190
	Straight section Length	m	150	470	470	470
	Arc Length	m	25	125	125	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	4	4	4
	NS-FFAG Ring	GeV	None	None	None	10
	SRF frequency	MHz	None	201	201	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



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

Muon Collider Baseline Parameters

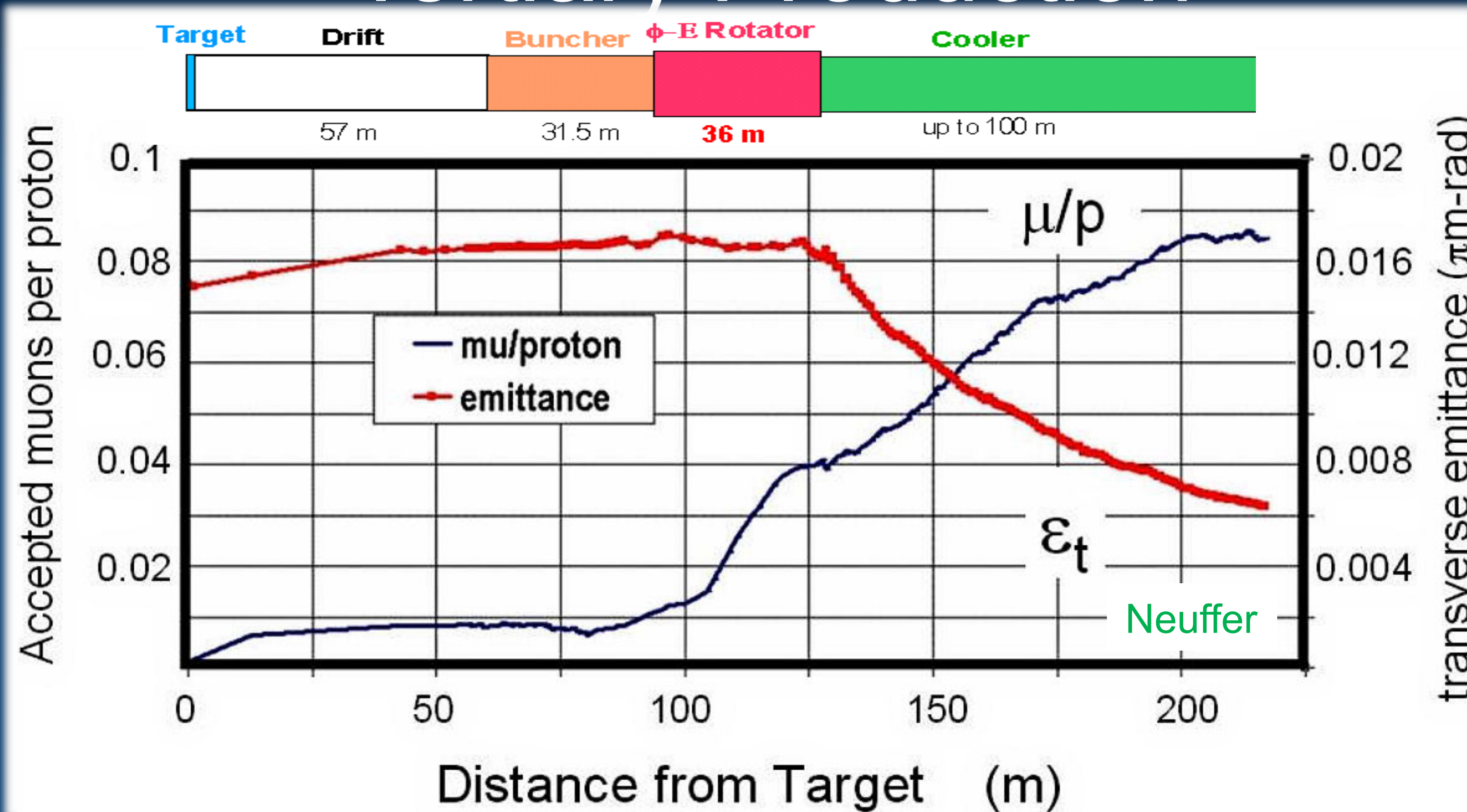
		Higgs Factory		Multi-TeV Baselines	
Parameter	***Units***	Initial Cooling	Upgraded Cooling / Combiner		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
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

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

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

THE R&D CHALLENGES

Technology Challenges – Tertiary Production

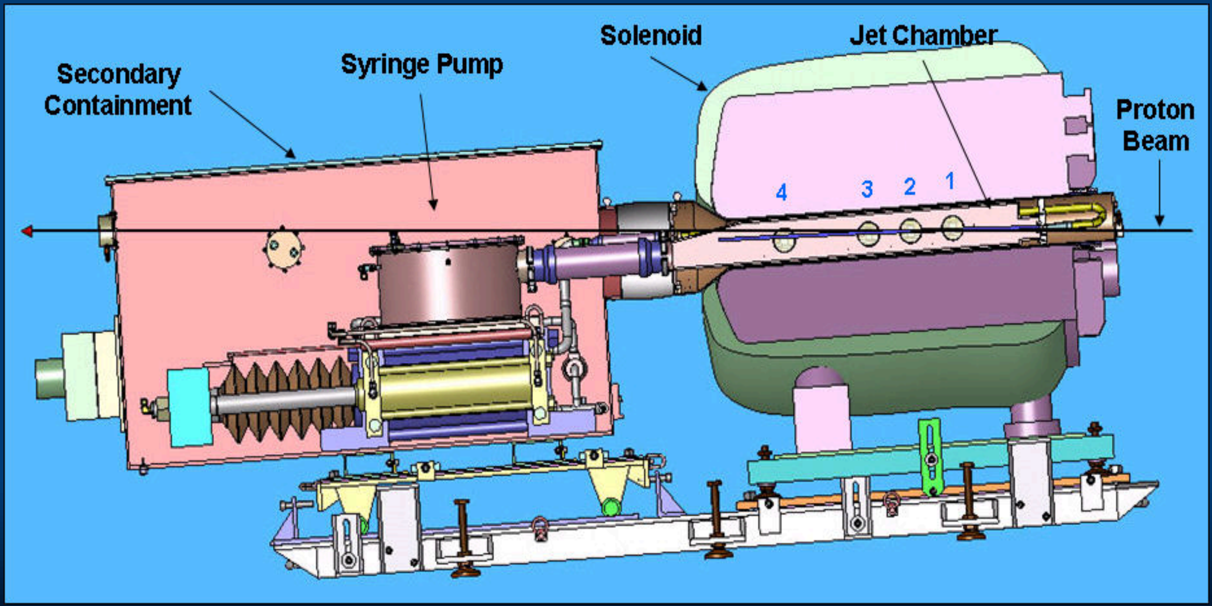


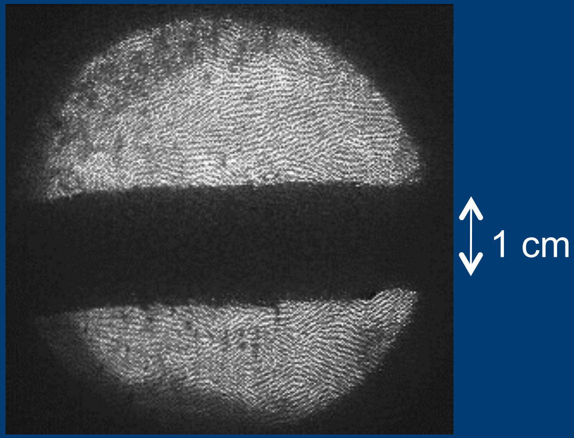
- A multi-MW proton source, *e.g.*, Project X, will enable O(10^{21}) muons/year to be produced, bunched and cooled to fit within the acceptance of an accelerator.

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

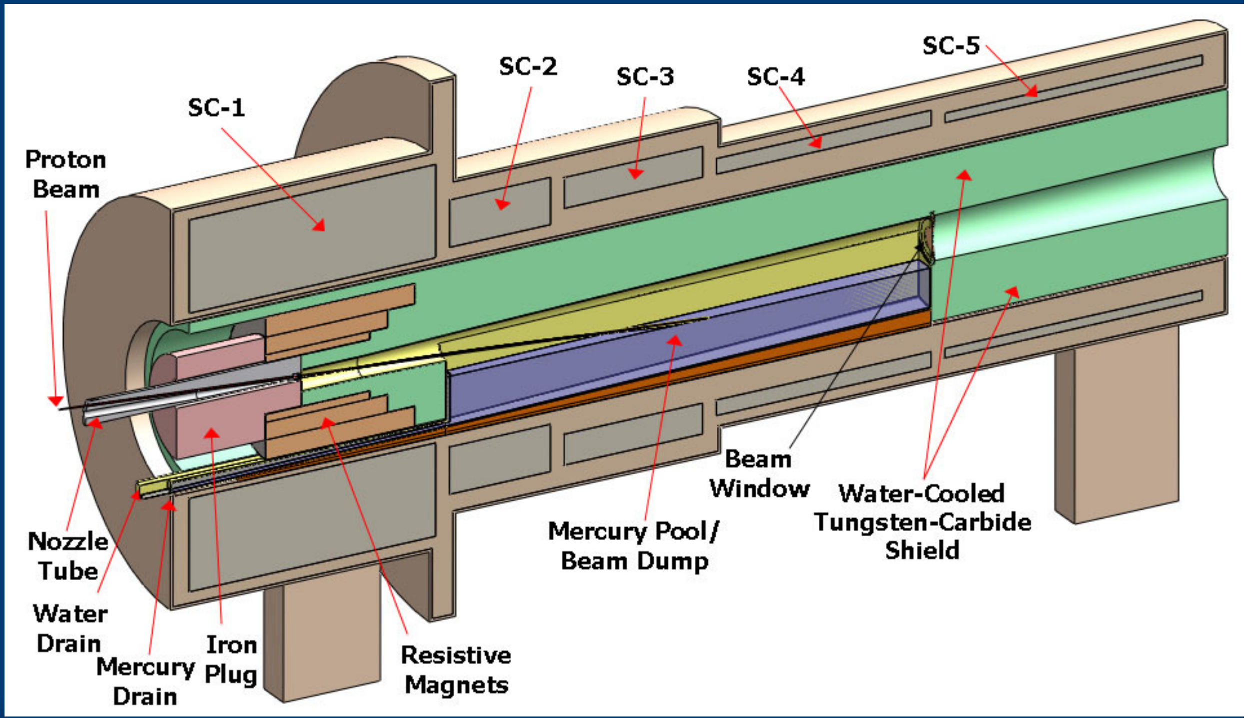
Technology Challenges – Capture Solenoid

- 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

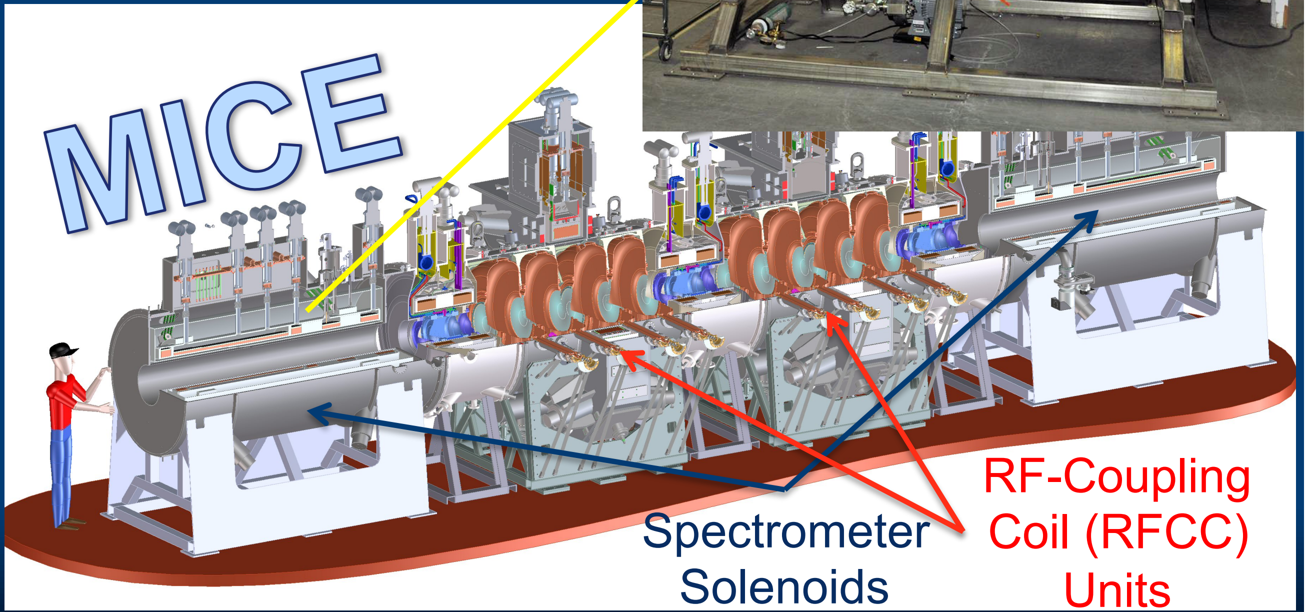
Possible application for High Temperature Superconducting magnet technology



Technology Challenges - Cooling

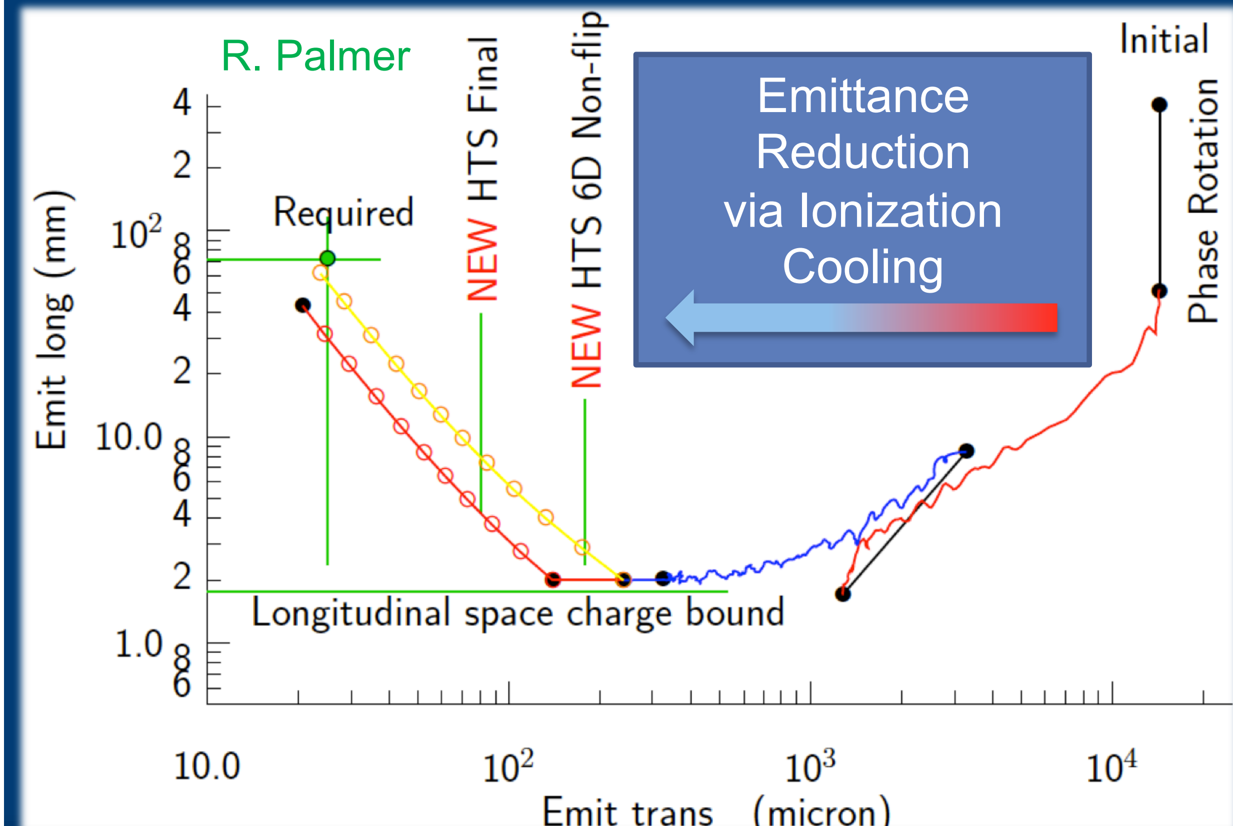
- Tertiary production of muon beams
  – Initial beam emittance intrinsically large
  – Cooling mechanism required, but no radiation damping
- Muon Cooling ⇨ Ionization Cooling
  - dE/dx energy loss in materials
  - RF to replace p_{long}

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



Technology Challenges - Cooling

- Development of a cooling channel design to reduce the 6D phase space by a factor of O(10^6-10^7) → 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 technical 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

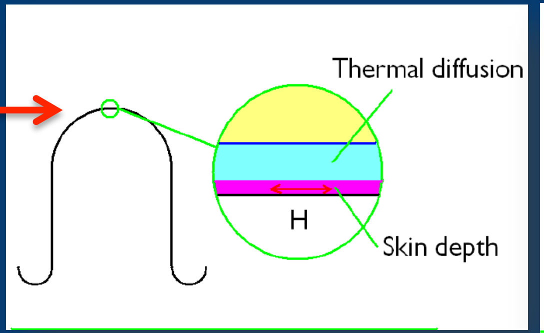
- Operation of RF cavities in high magnetic fields is a necessary element for muon cooling

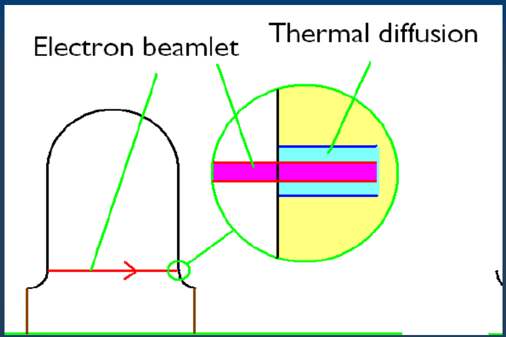
  - Control RF breakdown in the presence of high magnetic fields
  - The MuCool Test Area (MTA) at Fermilab is actively investigating operation of RF cavities in the relevant regimes
  - Development of concepts to mitigate the challenges are being actively pursued

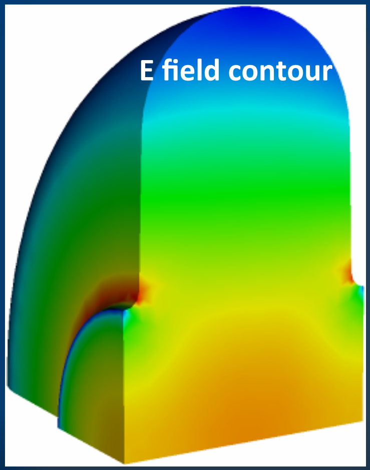
RF Breakdown in Magnetic Fields

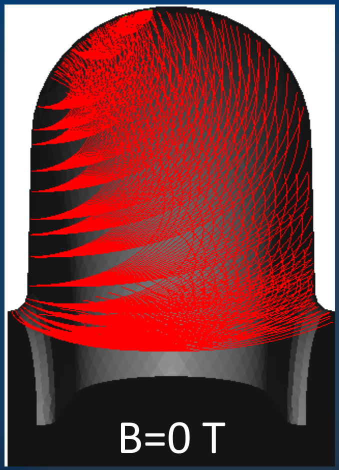
- The RF breakdown could be related by heating through field emission with external magnetic field and RF field:
  - External magnetic field
  - Ohmic heating
- Possible solutions
  - *ExB*
  - Choice of materials
  - Lower initial temperatures

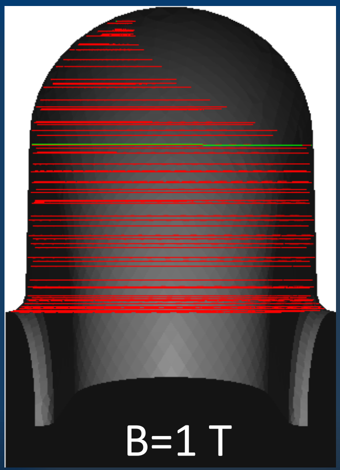
D. Li

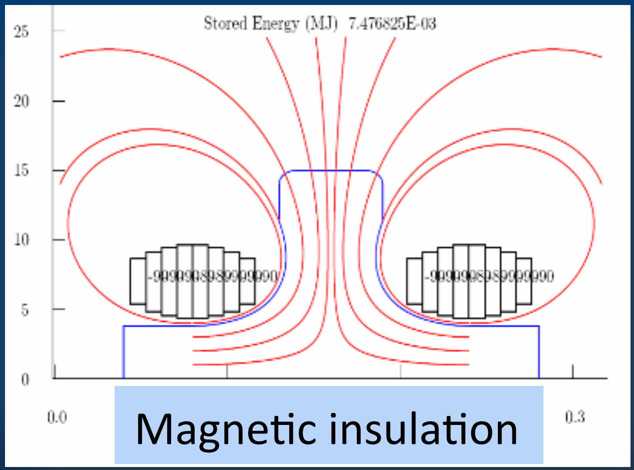




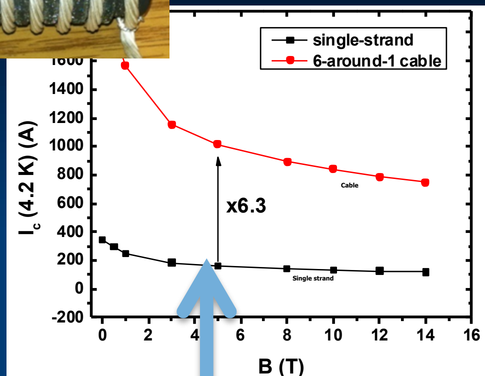








Recent Technology Highlights



Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

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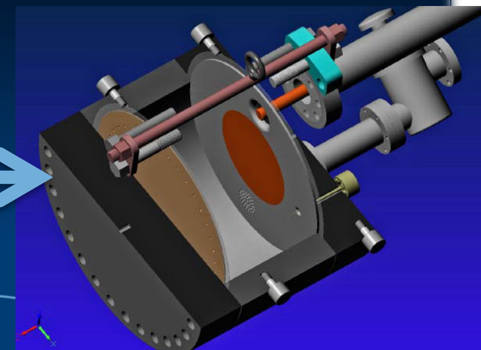
T. Shen-Early Career Award

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

MuCool Test Area/Muons Inc

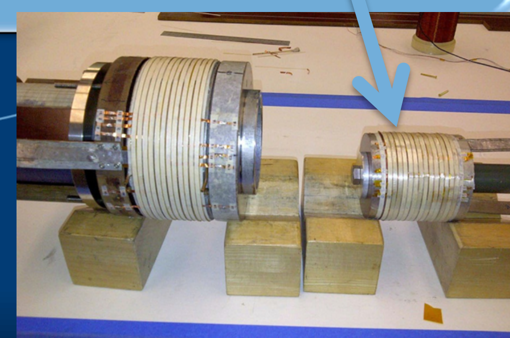


The Path to a Viable Muon Ionization Cooling Channel

World Record HTS-only Coil

15T on-axis field
16T on coil

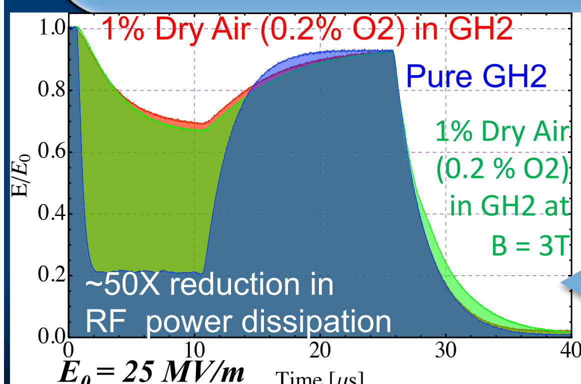
PBL/BNL



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

Extrapolates to m-Collider Parameters

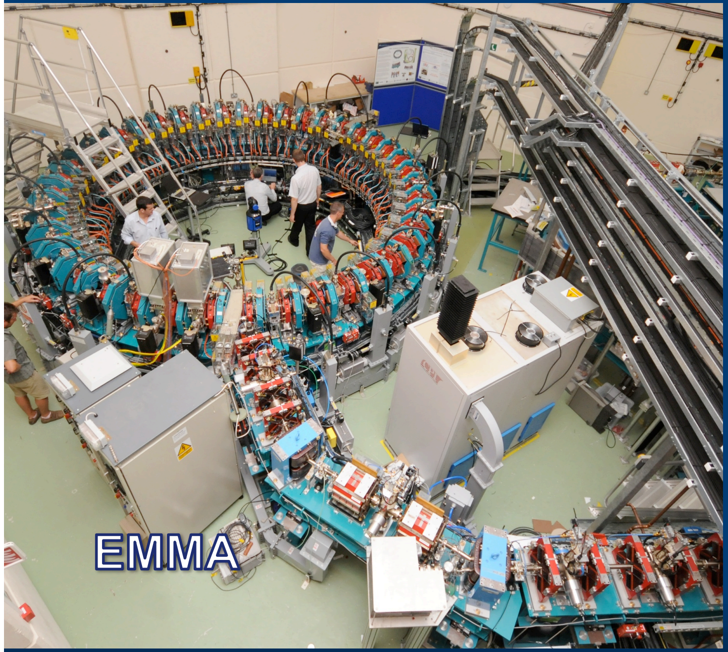
MuCool Test Area



Technology Challenges - Acceleration

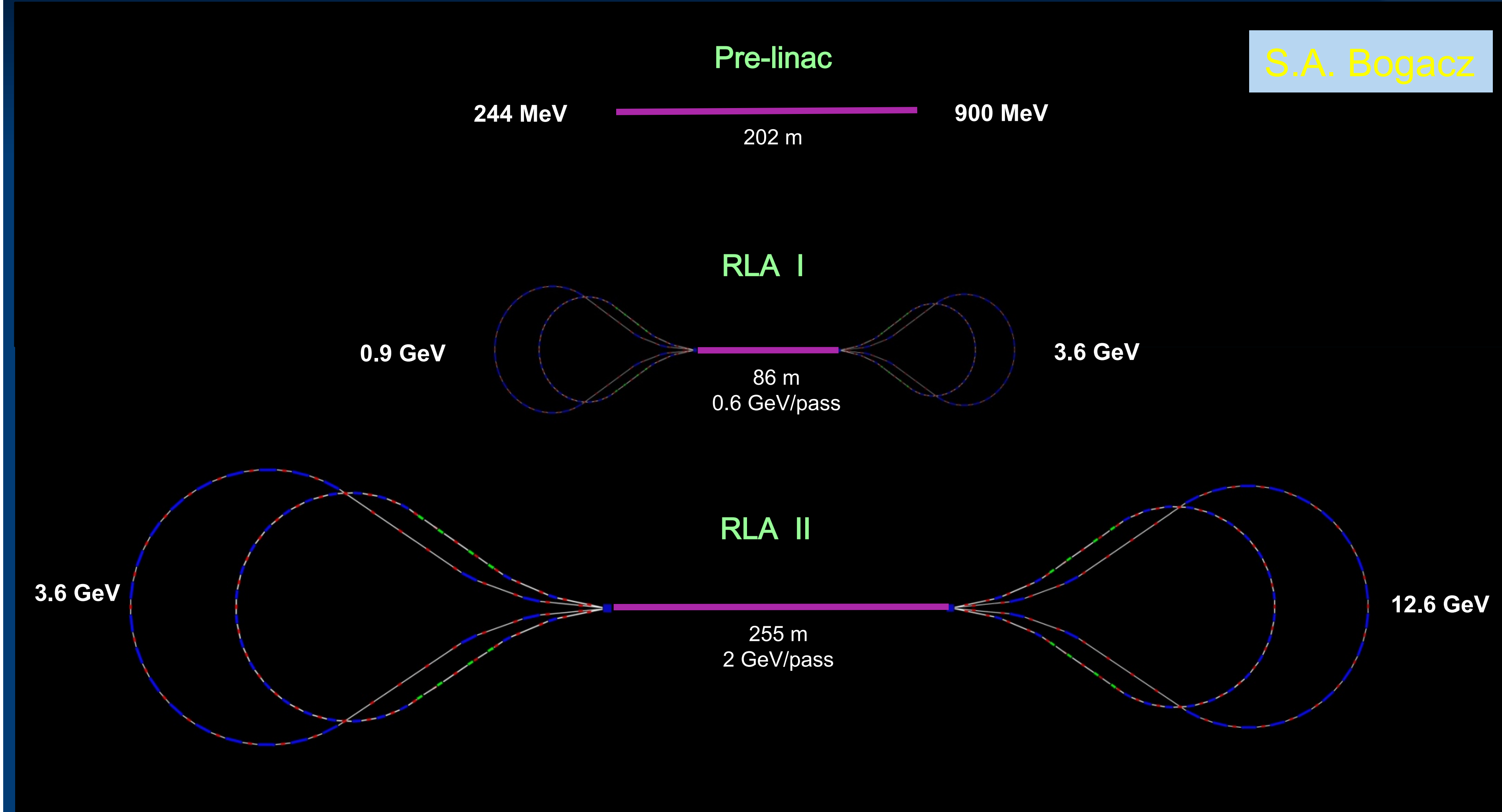
- Muons require an ultrafast accelerator chain
  - ⇨ *Beyond the capability of most machines*

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



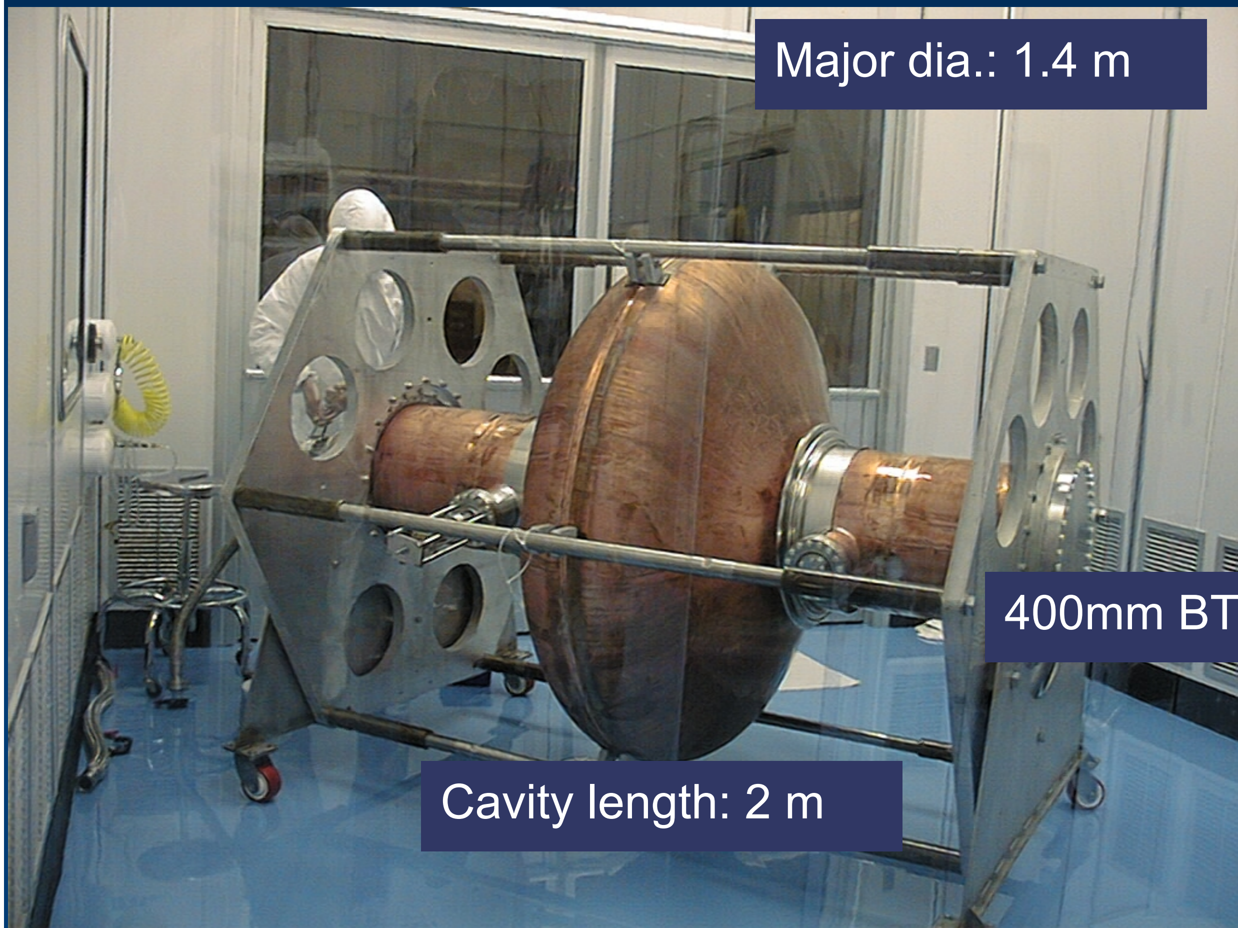
  - Superconducting Linacs
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient (FFAG) Machines
    - EMMA at Daresbury Lab is a test of the promising non-scaling type
  - Rapid Cycling Synchrotrons (RCS/VRCS)
  - Hybrid Machines

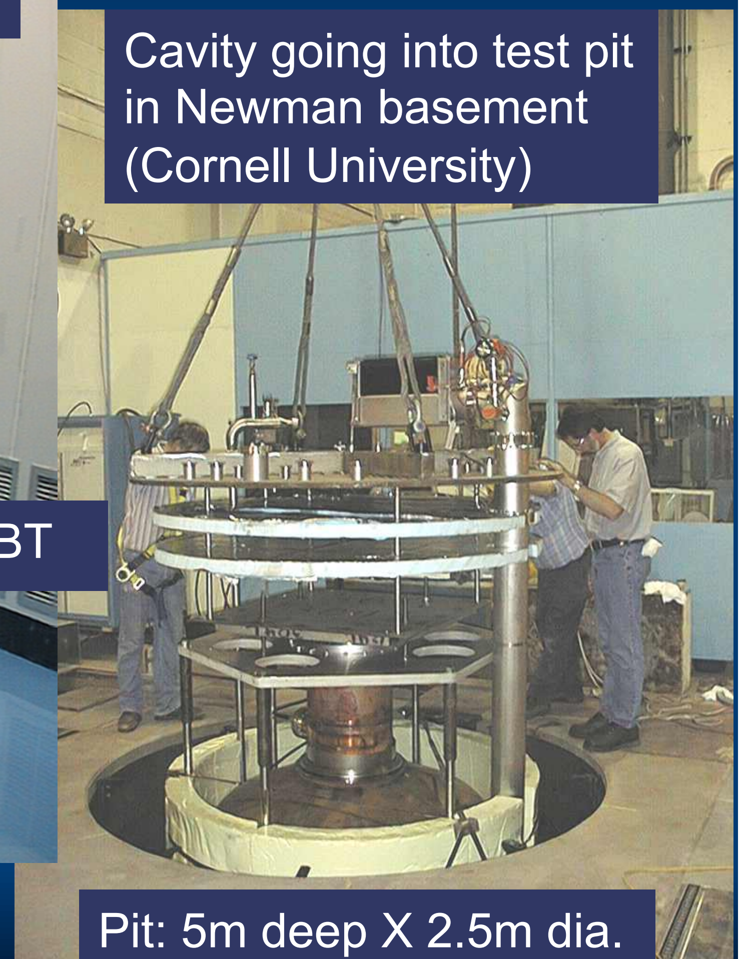
An Initial Acceleration Scheme: RLAs



Superconducting RF Development

201 MHz SCRF R&D
Nb on Cu Cavities



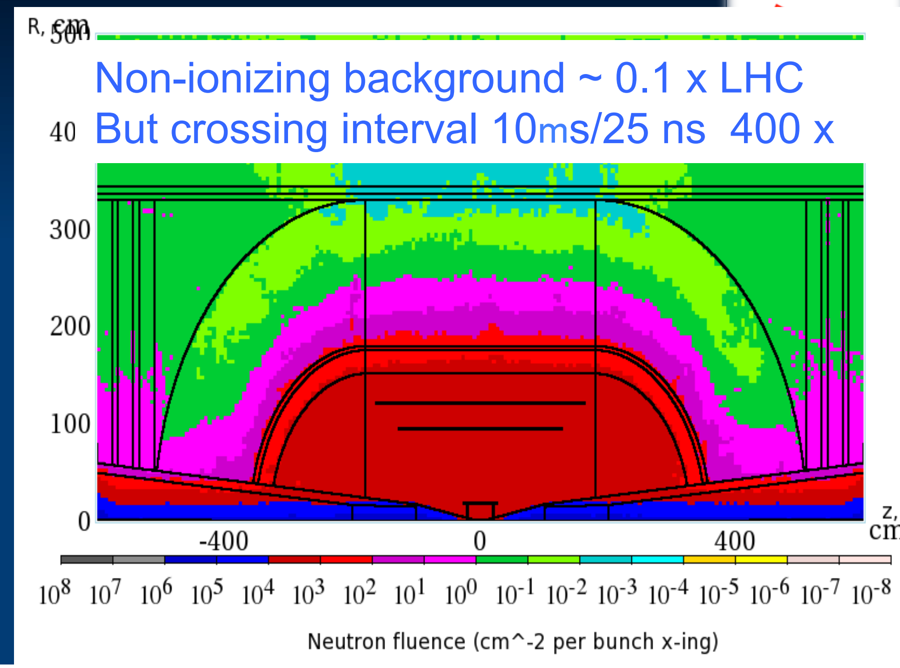


Backgrounds and Detector

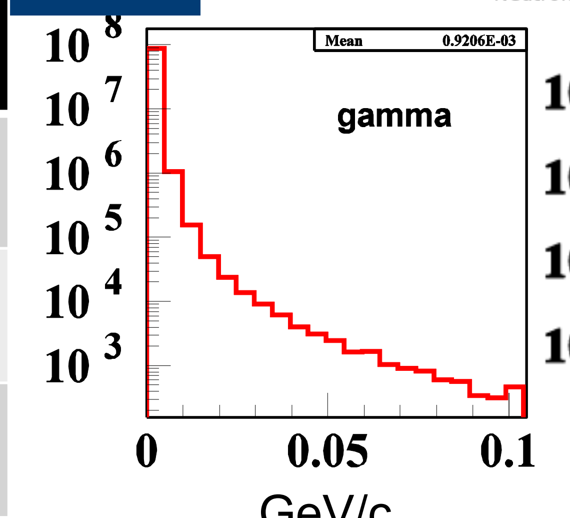
Much of the background is soft and out of time

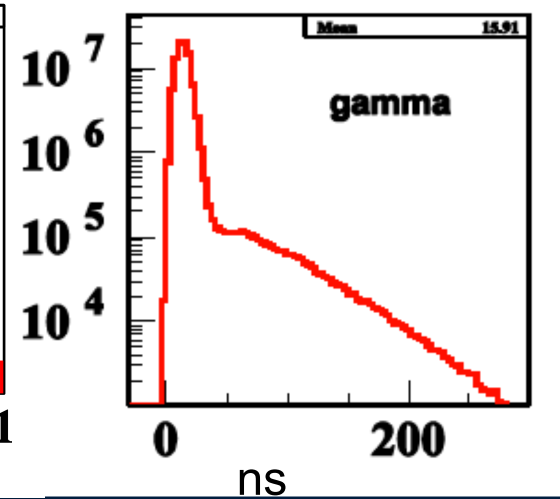
- Nanosecond time resolution can reduce backgrounds by three orders of magnitude

Requires a fast, pixelated tracker and calorimeter.



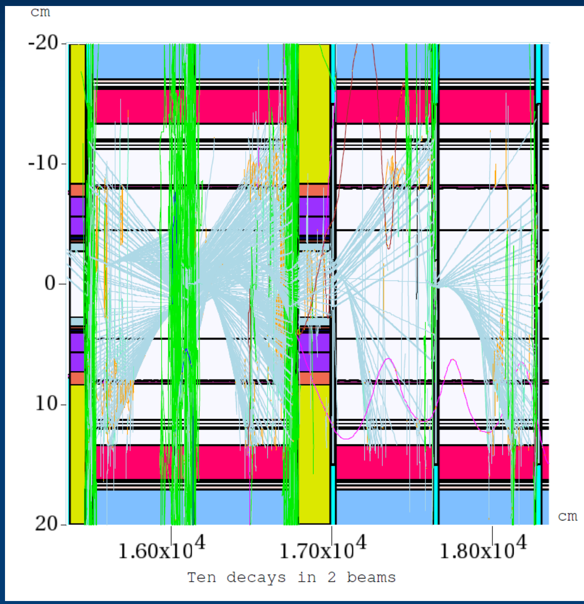
	Cut	Rejection
Tracker hits	1 ns, dedx	9×10^{-4}
Calorimeter neutrons	2 ns	2.4×10^{-3}
Calorimeter photons	2 ns	2.2×10^{-3}



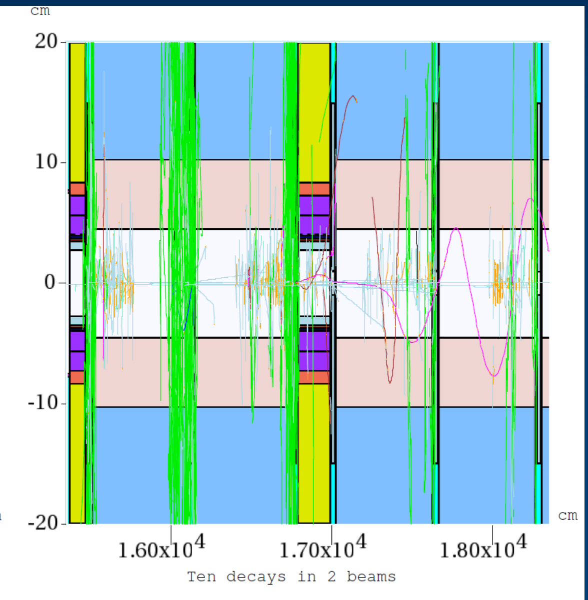


Technology Challenges: Heat Load in Arc Magnets (N.Mokhov)

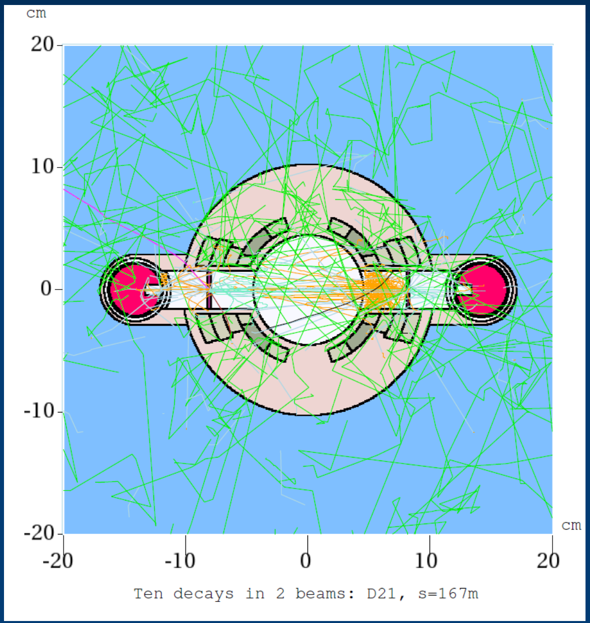
Decay products trajectories :



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

THE MAP FEASIBILITY ASSESSMENT

MAP Feasibility Assessment Phases

Feasibility Assessment: Phase I

FY13 − FY15:

- Select an ***initial baseline*** design and technologies; provide *realistic* performance assessments
- Identify high leverage ***alternative*** concepts
- Identify key technology/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:

- Technology 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 RFCC & MICE Step VI
  - 6DICE planning

MAP Feasibility Assessment 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*

Concluding Remarks…

- The unique feature of muon accelerators is the ability to provide cutting edge performance on both the Intensity and the 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
- 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
- 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 along the path to a multi-TeV Energy Frontier machine?

BACKUP SLIDES

The Feasibility Assessment I

- MAP was originally proposed as a 5-7 year effort to evaluate the feasibility of Neutrino Factory and Muon Collider Technologies
  - Feasibility Assessment Phase in 2 parts
    - Phase I: FY13-15
    - Phase II: FY16-18
  - Approach
    - Establish baseline concepts for each segment of the complex
      - Prepare baseline design specifications that can be employed in the MAP Technical Demonstrations
      - Evaluate realistic performance parameters from those baselines
      - ***Verify feasibility***
    - Continue to pursue alternative options
      - In particular, there exist alternative designs that hold the promise of significantly enhanced performance
      - However, the capability (and funds) to implement demonstrations may well be beyond the reach of the feasibility assessment phase of the program

The Feasibility Assessment II

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

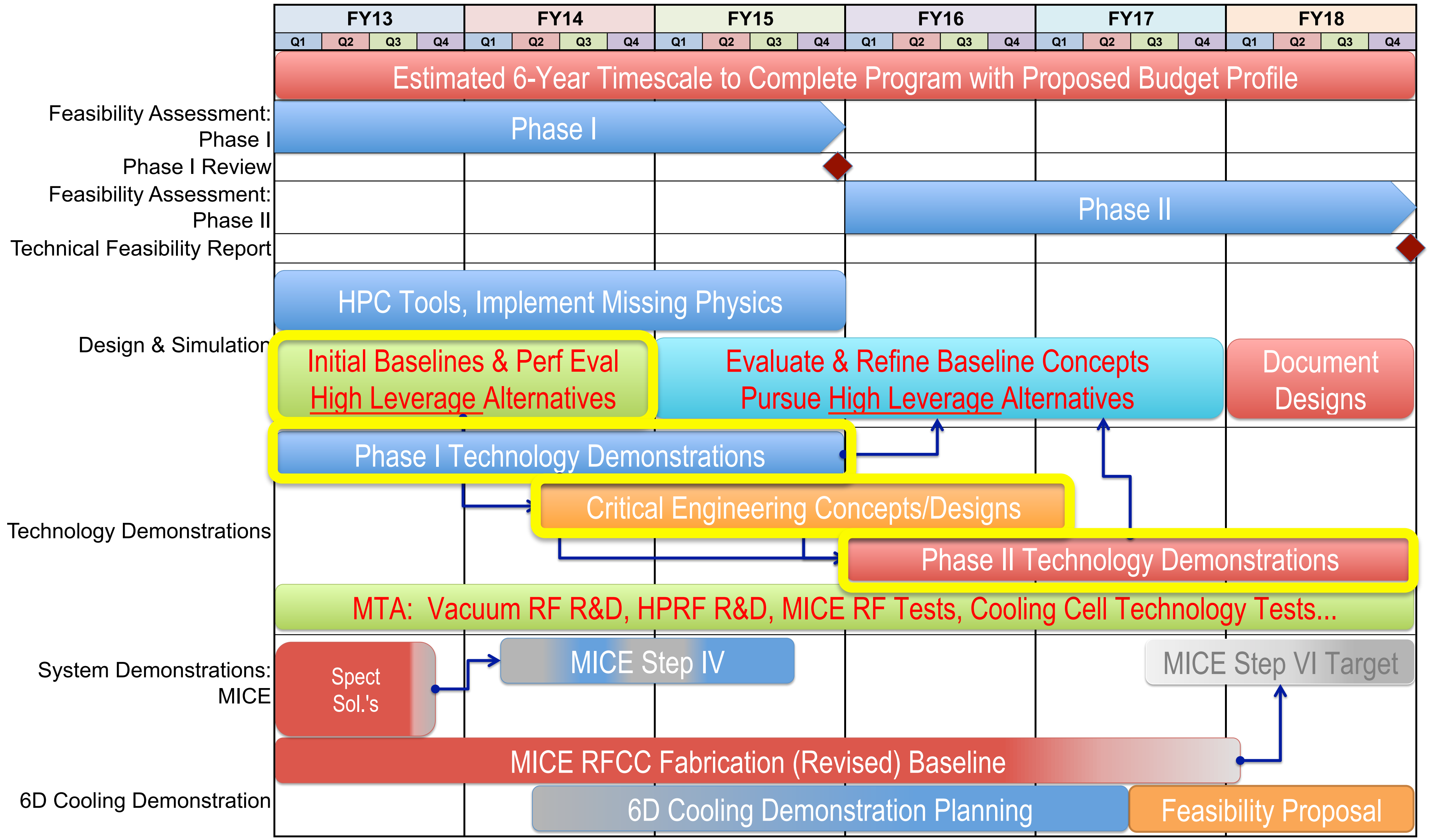
Feasibility Assessment: Phase II

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?

The US MAP Feasibility Assessment



Moving Forward with a Muon-based Program

- Assuming that we meet our Phase I and Phase II Feasibility Goals, we hope to move forwards a full conceptual design effort including:
  - Advanced systems studies may include
    - A beam-based 6D ICE
    - Front End concepts
    - Demonstration of acceleration concepts
  - Ideally this involves a staged R&D program coupled to physics needs
    - Start providing intensity frontier physics results within the next decade
    - Support R&D towards a collider
    - Develop a staged approach that takes us to the Intensity Frontier and subsequently onwards to the Energy Frontier
- We are very interested in pursuing an expanded international collaboration for this effort!

RECENT R&D PROGRESS – SOME HIGHLIGHTS

–
MICE Magnets

Spectrometer Solenoids

1st SS

- Cooldown and preliminary operational tests complete
- Ready for full current training and field mapping

2nd SS

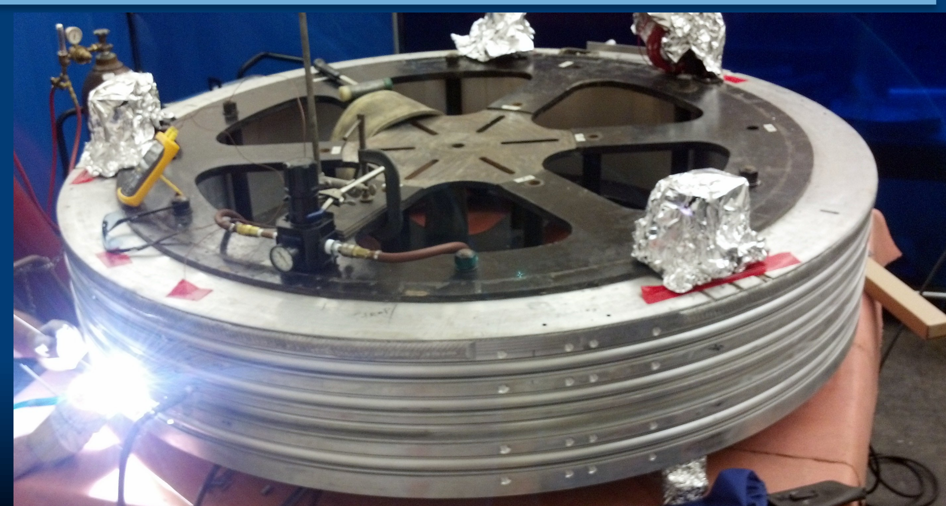
- Cold mass and shield being assembled into vacuum vessel

⇨ Support MICE Step IV (2013-)

Coupling Coils

- First Coupling Coil cold mass being prepared (at LBNL) for training (at FNAL) in new Solenoid Test Facility

⇨ Support MICE Step V/VI (2017-)

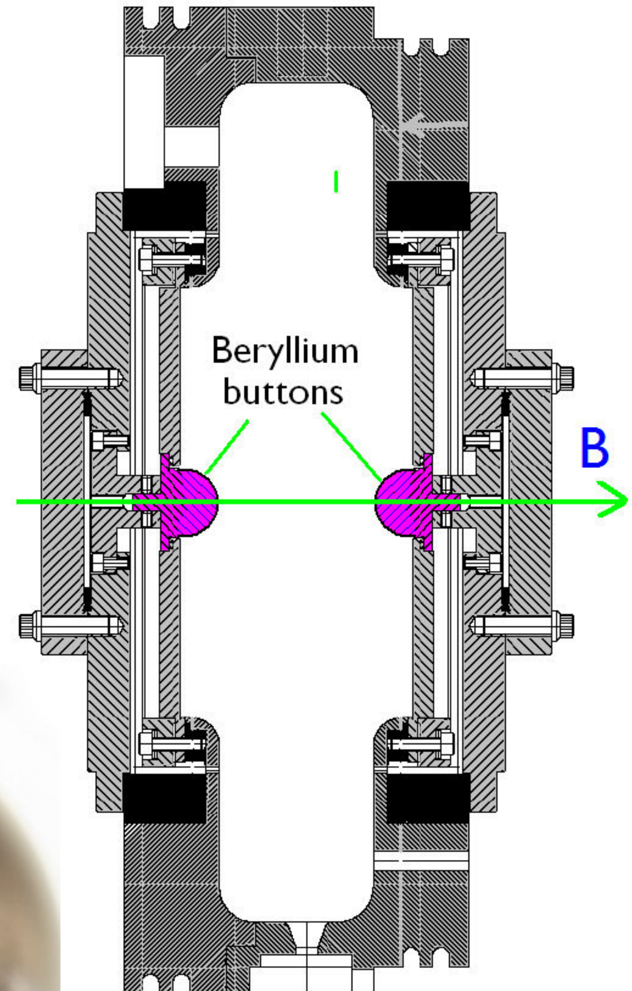


Recent Progress II – Cavity Materials

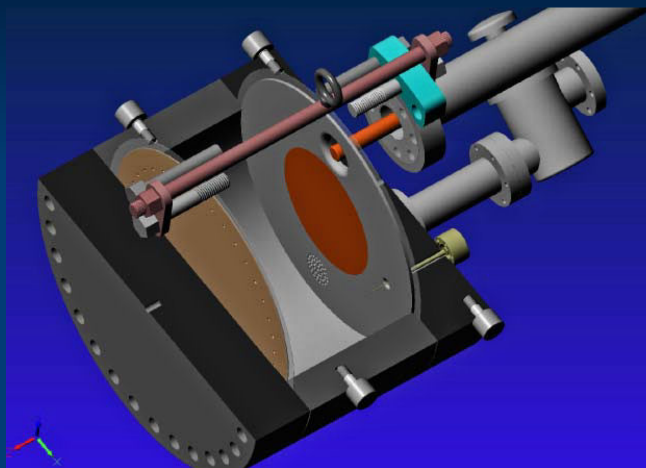
Breakdown tests with Be and Cu Buttons

- 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

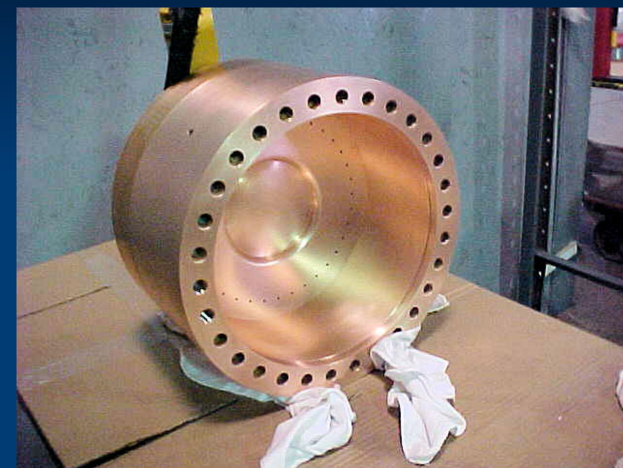


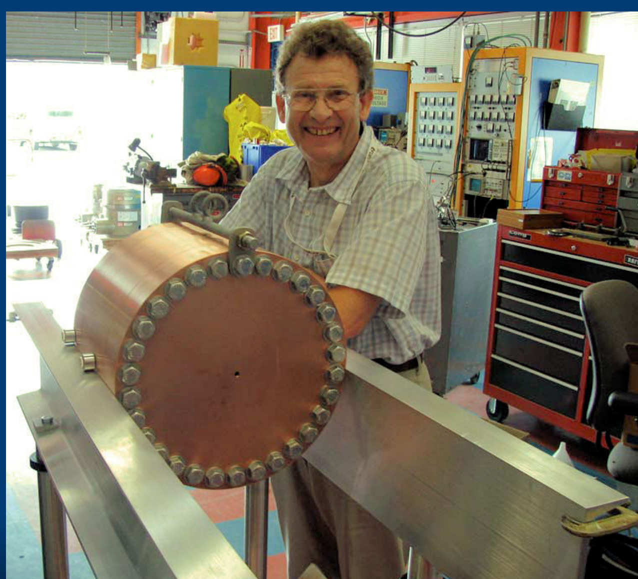
Recent Progress III – Vacuum RF



All-Seasons Cavity

(designed for both vacuum and high pressure operation)

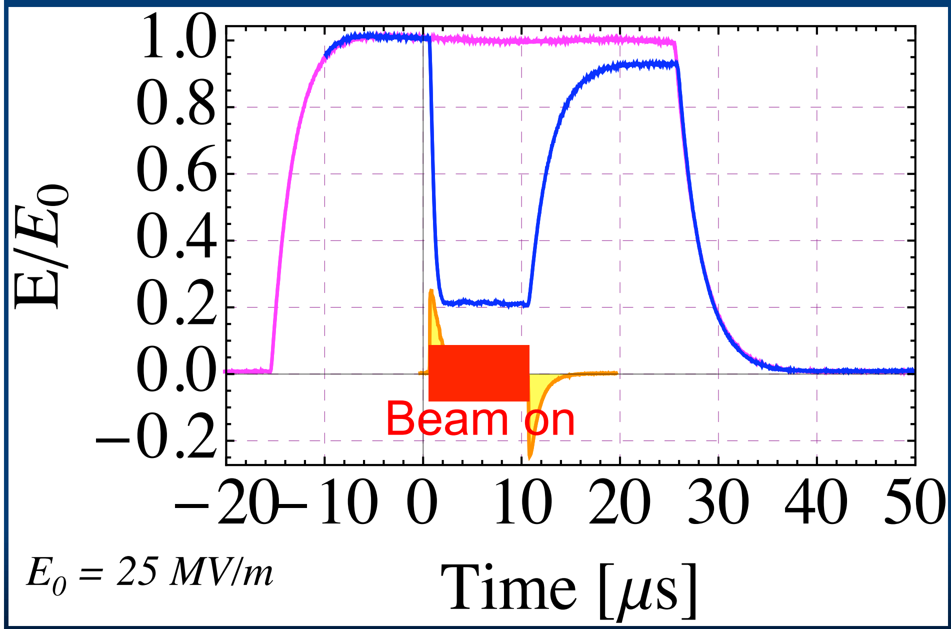


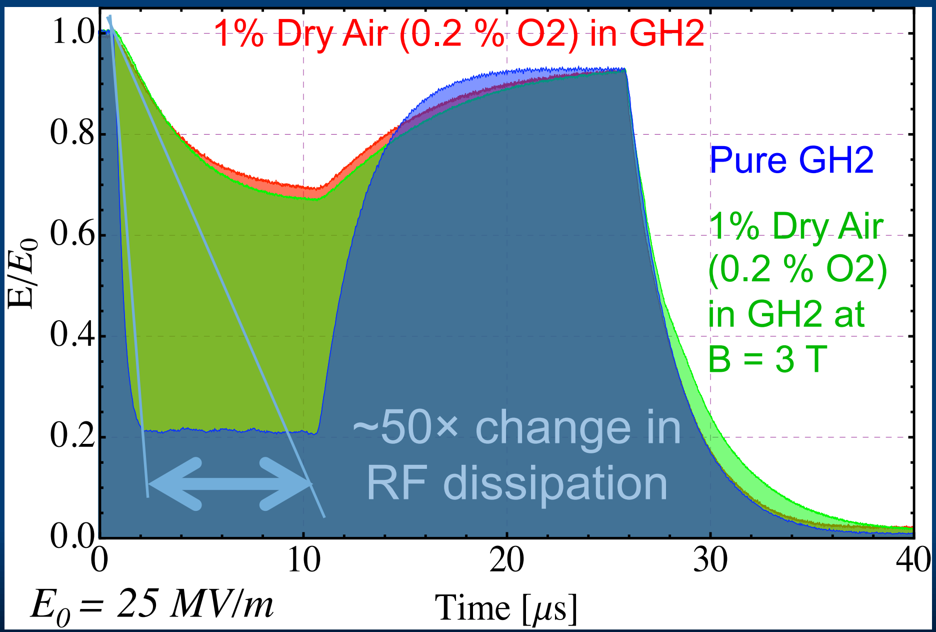


- Vacuum Tests at B = 0 T & B = 3 T
  - Two cycles: $B_0 \Rightarrow B_3 \Rightarrow B_0 \Rightarrow B_3$
- No difference in maximum stable operating gradient
  - Gradient $\gg$25 MV/m
- Demonstrates possibility of successful operation of vacuum cavities in magnetic fields with careful design

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



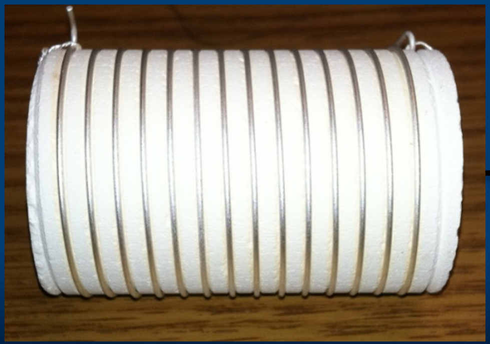


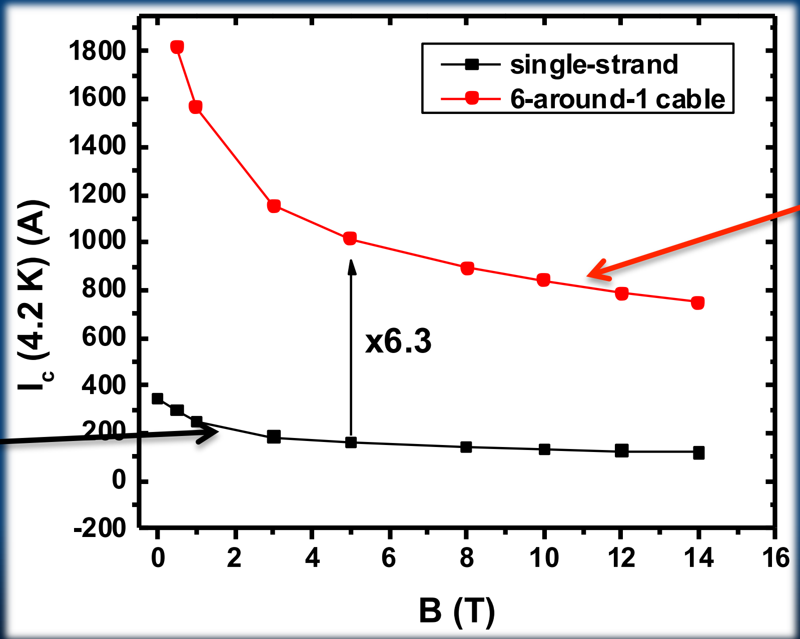
Recent Progress V: High Field Magnets

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

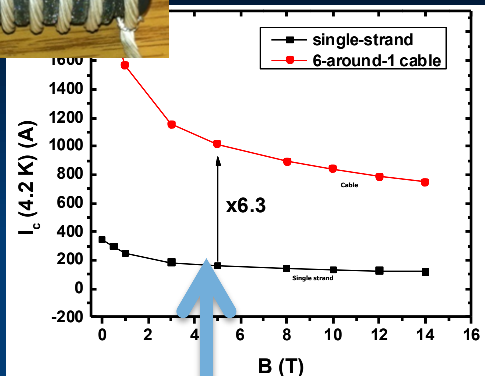
BSCCO-2212 Cable - Transport measurements show that FNAL cable attains 105% J_c of that of the single-strand





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

MAP Recent Technology Highlights



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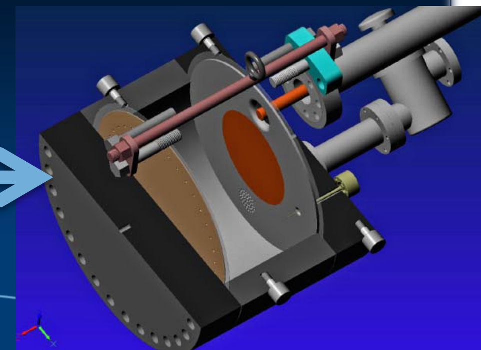

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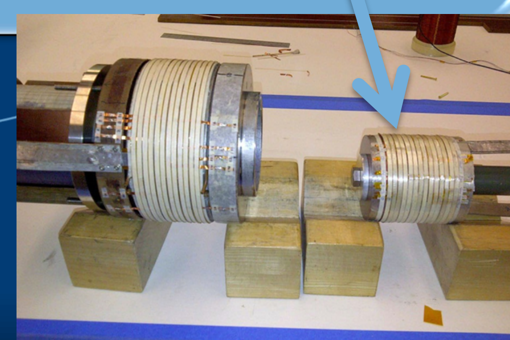
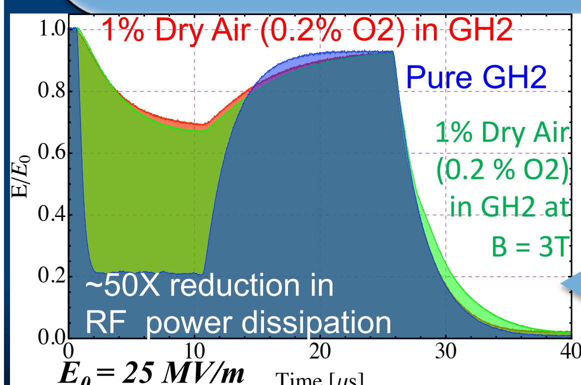




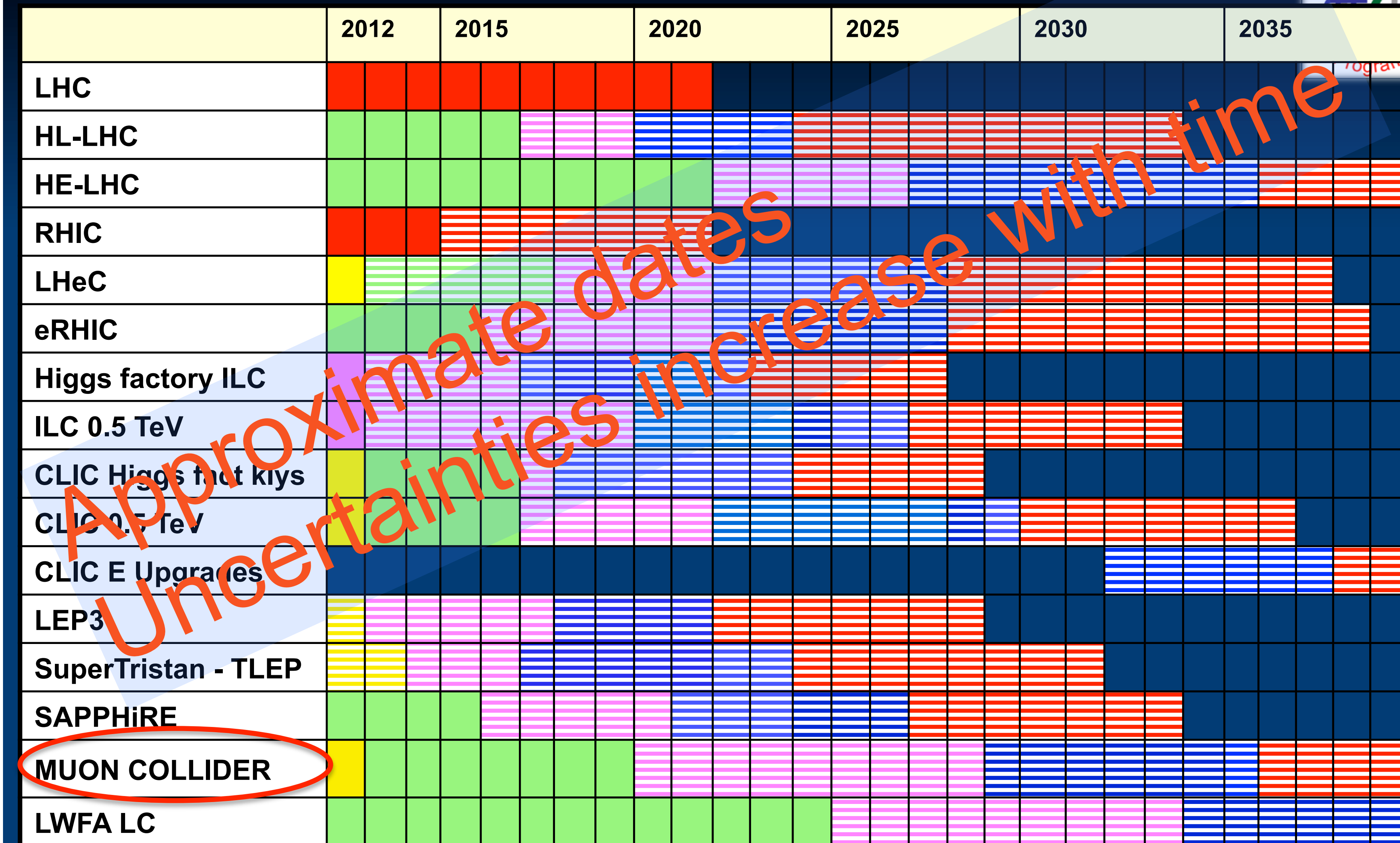
Demonstration of High Pressure RF Cavity <u>in 3T Magnetic Field with Beam</u>

Extrapolates to m-Collider Parameters

MuCool Test Area

CONCLUDING REMARKS

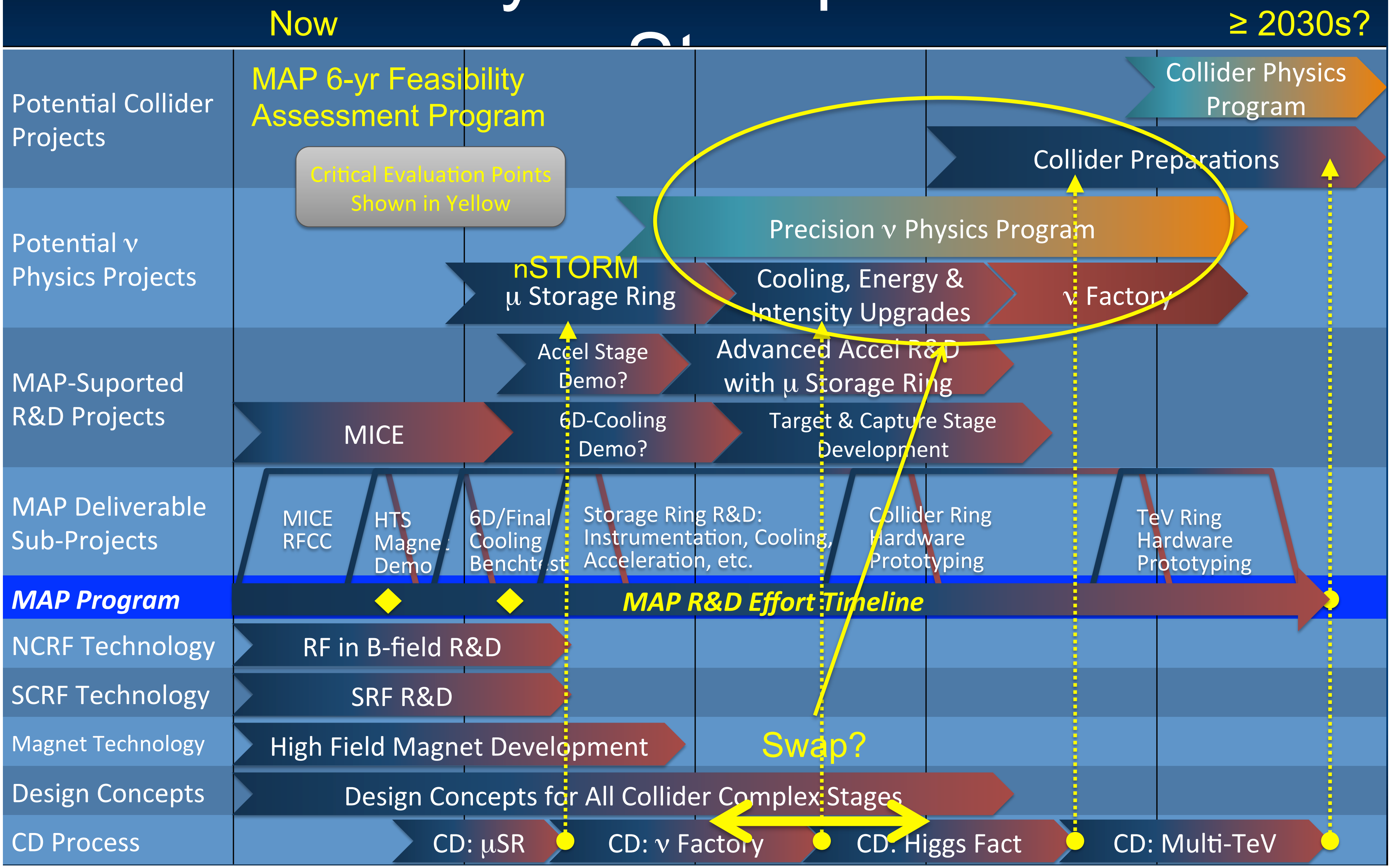
Timelines of HE projects (C.Biscari@European Strategy: Sept 2012)



RDR (CDR) R&D TDR/Preparation
Construction Operation

PROPOSE APPROVED

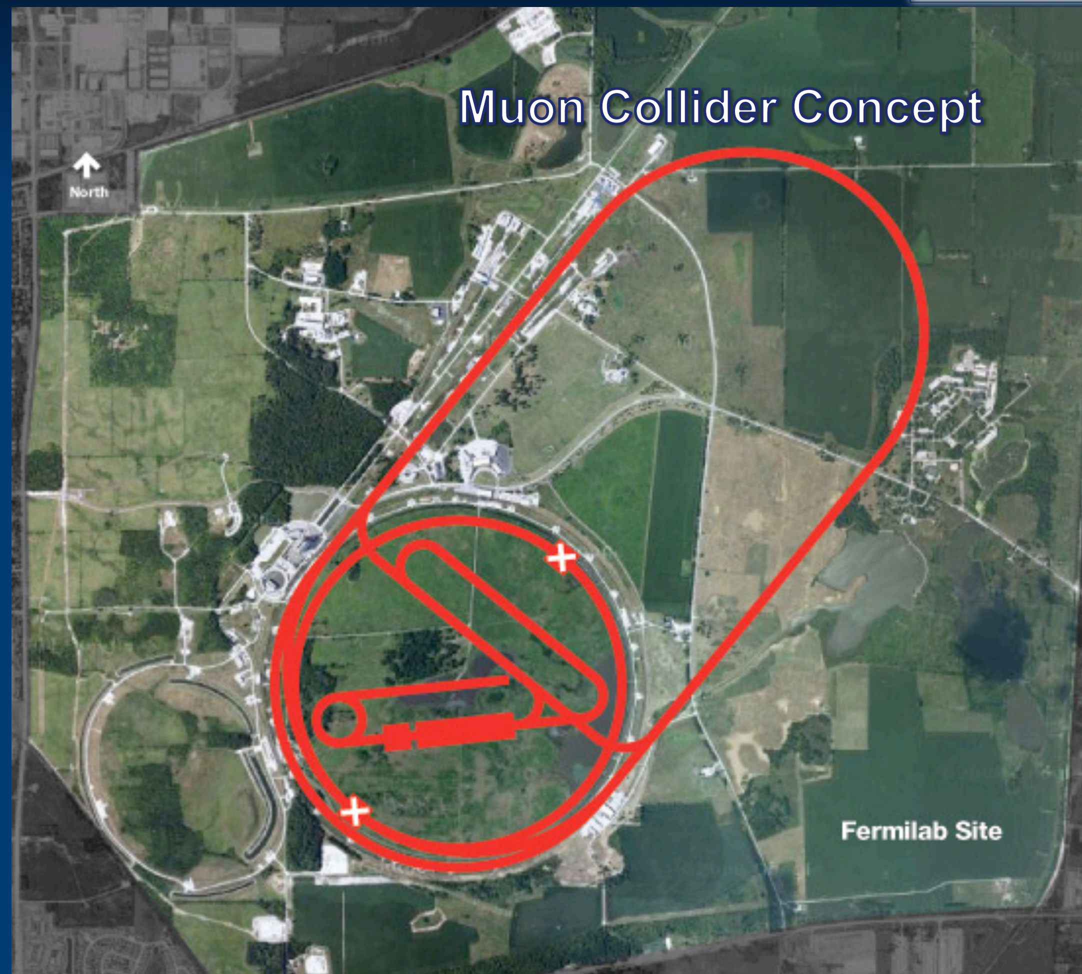
Staging Scenario with Physics Output at Each St



Conclusion

- Over the next 6 years 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!

Muon Accelerator Program Contacts

- MAP Web-Site: http://map.fnal.gov/
- MAP Management Team:

  Mark Palmer, Director: mapalmer@fnal.gov

  Robert Ryne, L1 Manager for Design and Simulation: rdryne@lbl.gov

  Alan Bross, L1 Manager for Technology Development: bross@fnal.gov

  Daniel Kaplan, L1 Manager for Systems Demonstrations: kaplan@iit.edu

  Ron Lipton, L1 Manager for Detectors and Physics: lipton@fnal.gov

- US HEP Community Planning Effort

  Jean-Pierre Delahaye, Muon Accelerator Staging Study jpd@slac.stanford.edu

Acknowledgments

I would personally like to thank Steve Geer, Mike Zisman, Bob Palmer as well as the MAP L1 & L2 managers for their help in familiarizing me with the program since I took over as director earlier this year

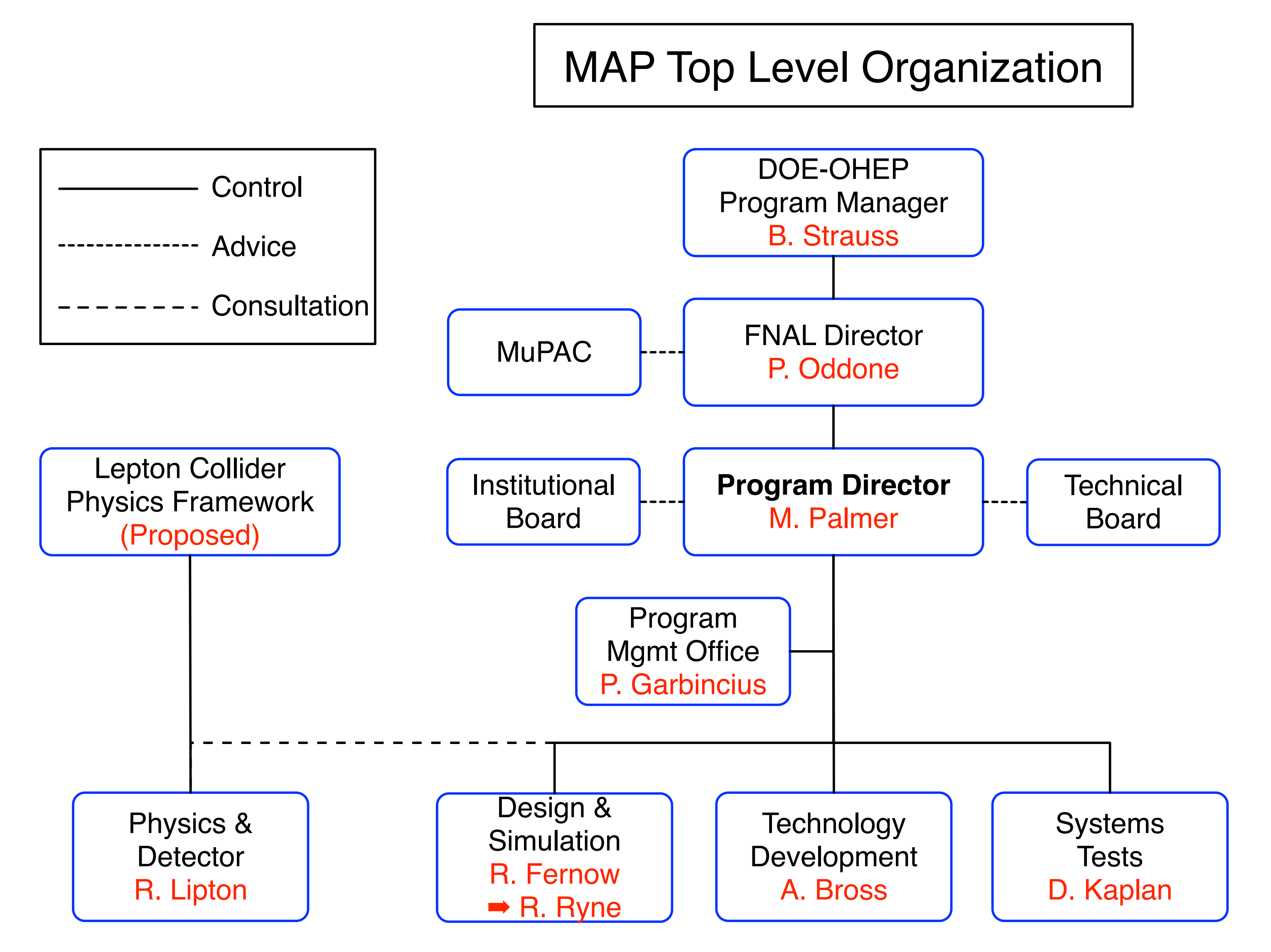
The MAP Effort -

- 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

ADDITIONAL SLIDES

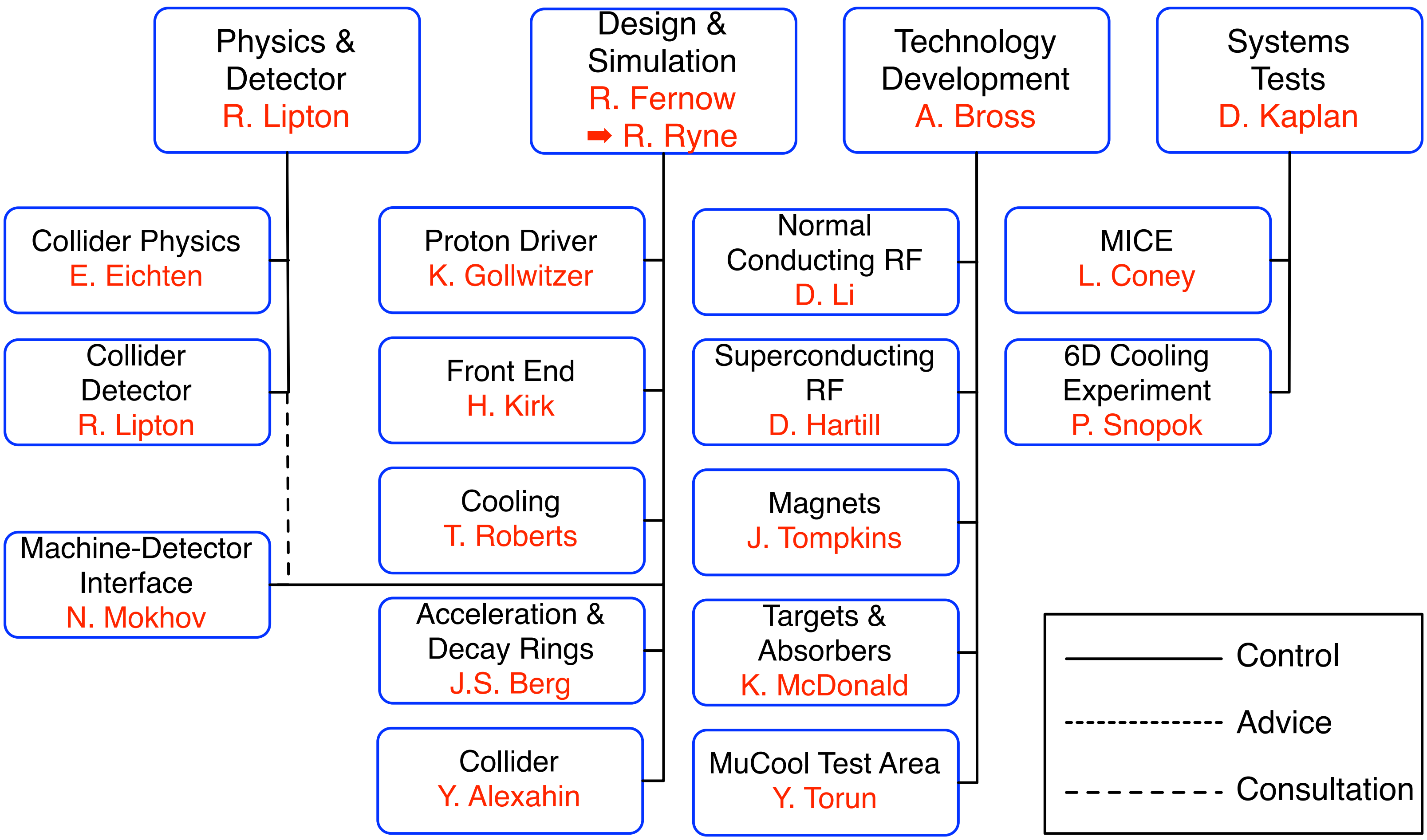
MAP ORGANIZATION

MAP Organization

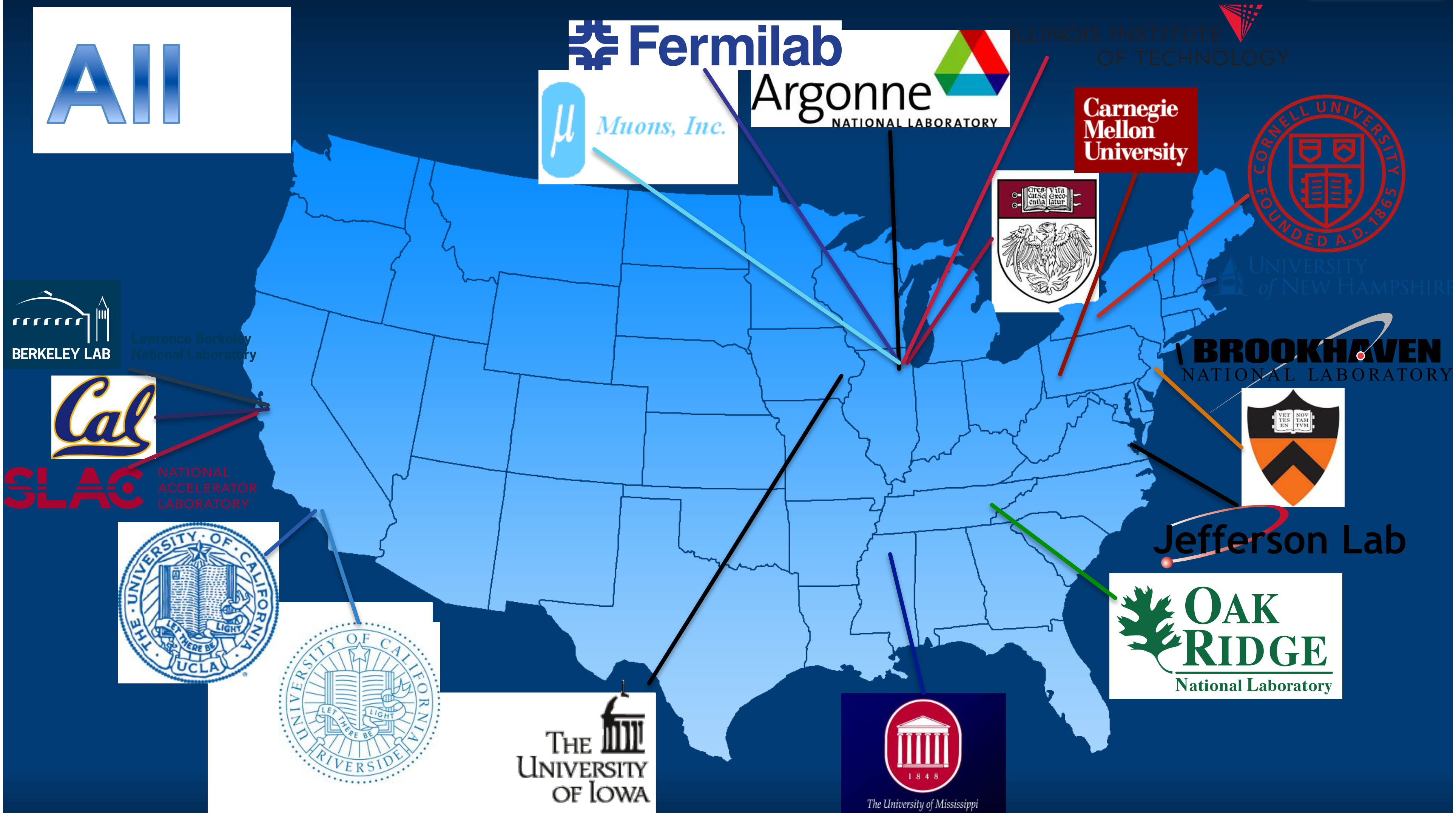


MAP Organization (cont'd)

MAP Level 1 & 2 Management Structure



Participating Institutions



MAP STRATEGIC PLANNING

Strategic Plan for FY13-15 (I)

- Feasibility Demonstrations (major efforts)
  - Muon Ionization Cooling Experiment
    - Magnet Prototyping, Production, and Testing Effort ***thru at least FY15***
    - RF Production and Testing Effort
    - Experimental Support
  - RF Test Program
    - Ongoing effort to validate likely solutions for cavity operation in B-field
    - Need increased effort to fully characterize and understand the breakdown process in magnetic fields (vacuum and gas-filled cavities)
      ⇨ enable *reliable* projections to viable configurations in each stage of a muon collider accelerator chain
  - Preparations for the Next Major Feasibility Demonstration (eg, 35 T HTS Solenoid)
    - Identify most critical feasibility issue
    - A small number of technical challenges now identified for evaluation
    - Effort to ramp up as MICE hardware is delivered
  - Design Studies to Specify a 6D Cooling Feasibility Demonstration

Dependent on funding profile

Strategic Plan For FY13-15 (II)

- Technology Development
  - Continued NCRF, SCRF and magnet development efforts are essential
  - Must maintain key expertise and progress in all areas (eg, HTS development)
    - Target the addition of key individuals to critical tasks
  - While scheduling tasks must accommodate funding constraints, *maintaining the required intellectual breadth is essential for program success*
- Accelerator Design Concepts
  - Concepts at each stage of the accelerator complex challenge state of the art solutions
  - Design concepts ***must receive effort now*** to provide specifications for feasibility evaluations in the FY16-FY18 time frame
    - Target the addition of key individuals to critical tasks
  - This effort also provides the interface to our most important stakeholders – the HEP community!

Constraints

- MAP has a broad effort underway in Muon Collider and Neutrino Factory R&D
  - We must show feasibility of a range of key concepts on the few year timescale
  - The MICE Experimental Program remains a fundamental element of our planning
- Budget Challenges are Looming
  - FY13 President's Budget Request (PBR) will leave key efforts within MAP unfunded
  - Have prepared 3 scenarios:
    - PBR – Requires de-scoping for the near-term
    - "Baseline" – Could continue key efforts but with schedule stretch
    - "Augmented" – Tries to balance scope against budget realities
      ⇨ stages critical efforts with viable schedules while deferring new efforts and stretching "ongoing" efforts

THE MUON ACCELERATOR STAGING STUDY

Open Symposium - European Strategy Preparatory Group

European Strategy for Particle Physics

Contribution ID : 135

A Staged Muon-Based Neutrino and Collider Physics Program

Content :

We sketch a staged plan for a series of muon-based facilities that can do compelling physics at each stage. Such a plan is unique in its ability to span both the Intensity and Energy Frontiers as defined by the P5 sub-panel of the US High Energy Physics Advisory Committee. This unique physics reach places a muon-based facility in an unequaled position to address critical questions about the nature of the Universe.

Primary authors : KAPLAN, Daniel (Illinois Institute of Technology)

Co-authors : COLLABORATION, MAP (MAP)

The Muon Accelerator Staging Study

- Working group led by Jean-Pierre Delahaye (SLAC)
- Preparing a detailed response for the U.S. Community Planning Effort (2013 summer study)

Why the Muon Accelerator Staging Study?

- Explore our options for a staged physics strategy based on Muon Accelerators
- Provide inputs to the US MAP response being prepared for "Snowmass 2013"
- To provide guidance to MAP which will help determine the shape and scope of a proposal to the U.S. DOE to move forward with a conceptual design and project
  - Assumes that we are successful with the necessary technology demonstrations (but may influence priorities somewhat)
  - Acknowledges a particular focus on developing the framework for a U.S. facility for High Energy Physics
- An advisory panel to the MAP Director to enhance both the national and international dialogue for a muon-based facility for the ***Intensity and Energy Frontiers***

Framework: August 13, 2012 Memorandum

U.S. Muon Accelerator Program Memorandum

August 13, 2012

From: Mark Palmer, Director, U.S. Muon Accelerator Program

To: The Muon Accelerator Staging Study (MASS) Working Group

Subject: Establishment of the Muon Accelerator Staging Study

The Muon Accelerator Staging Study (MASS) working group is being established by the U.S. Muon Accelerator Program (MAP) to provide key program planning inputs during the MAP Feasibility Assessment Phase. The updated MAP plan, which will be reviewed by the U.S. Department of Energy later this year, envisions this feasibility assessment occurring in two parts – Phase I (FPI) covering the period FY13-15 and Phase II (FPII) covering the period FY16-18. During this time, the principal focus of the program is to validate the design concepts and technologies that will enable a project to build a neutrino factory and/or muon collider. The results of these assessments will enable the HEP community to make an informed decision on its path forward.

In addition to the design and technical demonstrations required for this assessment, it is necessary to understand how a path forward that incorporates a progressive program of accelerator R&D along with the production of key physics results might evolve. The MASS working group will be the body within MAP tasked with the development of an overarching vision for the program that can enable the U.S. High Energy Physics Program to achieve its goals at Intensity Frontier and provide a path to a new Energy Frontier facility. Thus the working group will be established to provide such guidance during Phase I of the MAP Feasibility Assessment, and will be expected to present its conclusions as one of the deliverables of the Phase I effort.

The working group is requested to evaluate the following issues:

- A review of possible intermediate facilities and physics capabilities that could be targeted in a staged approach to reaching a neutrino factory and/or muon collider – this should include an evaluation of both the physics and the accelerator R&D potential at each stage.
- An assessment of how such facilities could be coupled with an ongoing machine-based R&D program to improve and refine the concepts and technologies that will support the development of subsequent stages in the program.
- An assessment of the minimum physics performance required at each stage in such a plan to ensure that the community's physics goals can be achieved.
- An assessment of the physics performance that might be expected from such facilities based on the baseline technical concepts that are being designated by MAP over the course of Phase I of the feasibility program.

U.S. Muon Accelerator Program Memorandum

- An assessment of the potential physics performance improvements that might be expected from alternative concepts identified by MAP for continued development.
- Identification of the key synergies between the neutrino factory and muon collider development paths.

Key deliverables for the working group are as follows:

- During FPI, the working group is asked to prepare a yearly report, which will be included in the MAP Annual Report, describing the staging scenarios that it has examined.
- In the context of the upcoming 2013 Community Summer Study, the working group will take the lead in developing a program statement which addresses the following questions:
  - What are the unique capabilities of a muon-accelerator based program?
  - What are the most useful staging scenarios that could be supported by a laboratory facility based on muon accelerators?
  - What are the plausible timescales on which such a facility could be developed?
- Prior to the conclusion of FPI, the working group is requested to provide a set of recommendations on potential staging options and an evaluation of how those may couple to the MAP research program planned for FPII and beyond. These recommendations should be provided as early as possible in FPI, but no later than the conclusion of 2014.
- The working group will present its conclusions and recommendations as part of the final review of the MAP FPI effort.

The working group will report to the MAP Director and is charged with advising the director on the options for a staged physics and R&D program based on muon accelerator technology, which can address the current questions associated with the Intensity and Energy Frontiers of High Energy Physics. Since MAP is a U.S. program, the working group is asked to, in particular, review the options for a facility based at the single remaining U.S. HEP laboratory, Fermilab. It is anticipated that the working group will assign tasks to sub-committees that it appoints and which are led by one or more members of the working group. The working group is encouraged to pursue international participation in these evaluations. MAP will make every effort to provide the resources and expertise necessary to pursue the questions that are raised by these sub-committees. Since this represents a special draw on program resources, the chair of the MASS is expected to become a member of the MAP Management Council and provide regular updates on progress as well as resource requests during the Council's weekly meetings.

cc: Pier Oddone, Director, FNAL
Bruce Strauss, Program Manager, U.S. DOE, OHEP
Stuart Henderson, Assoc. Director for Accelerators, FNAL

Working Group Charge

- A review of possible intermediate facilities and physics capabilities that could be targeted in a staged approach to reaching a neutrino factory and/or muon collider – this should include an evaluation of both the physics and the accelerator R&D potential at each stage.
- An assessment of how such facilities could be coupled with an ongoing machine-based R&D program to improve and refine the concepts and technologies that will support the development of subsequent stages in the program.
- An assessment of the minimum physics performance required at each stage in such a plan to ensure that the community's physics goals can be achieved.
- An assessment of the physics performance that might be expected from such facilities based on the baseline technical concepts that are being designated by MAP over the course of Phase I of the feasibility program.
- An assessment of the potential physics performance improvements that might be expected from alternative concepts identified by MAP for continued development.
- Identification of the key synergies between the neutrino factory and muon collider development paths.

Working Group Deliverables

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- The working group will present its conclusions and recommendations as part of the final review of the MAP FPI effort.

Working Group Membership

- Chuck Ankenbrandt (Muons Inc)
- Alex Bogacz (JLab)
- Jean-Pierre Delahaye (SLAC) - Chair
- Dmitry Denisov (FNAL)
- Estia Eichten (FNAL)
- Debbie Harris (FNAL)
- Don Hartill (Cornell)
- Patrick Huber (Virginia Tech)
- David Neuffer (FNAL)
- Pavel Snopok (IIT)
- Ex Officio
  - Young-Kee Kim
  - Mark Palmer
- Possibly another 1-2 additions over time…
- Also international liaisons…

Conclusion

- MASS presently reviewing *"configurations of interest"* for both neutrino factory and collider options
- Next major activity: Coordinating the program for a muon collider Higgs Factory mini-workshop
  - Tuesday, November 13 at Fermilab
  - Day before HF2012
    - ICFA: Accelerators for a Higgs Factory: Linear vs. Circular
    - November 14-16 at Fermilab
- WG will take the lead in coordinating evaluations of the basic options under consideration
- WG will initiate additional international points of contact as soon as basic framework for discussions is in place

MAGNET TECHNOLOGY R&D AND MAP

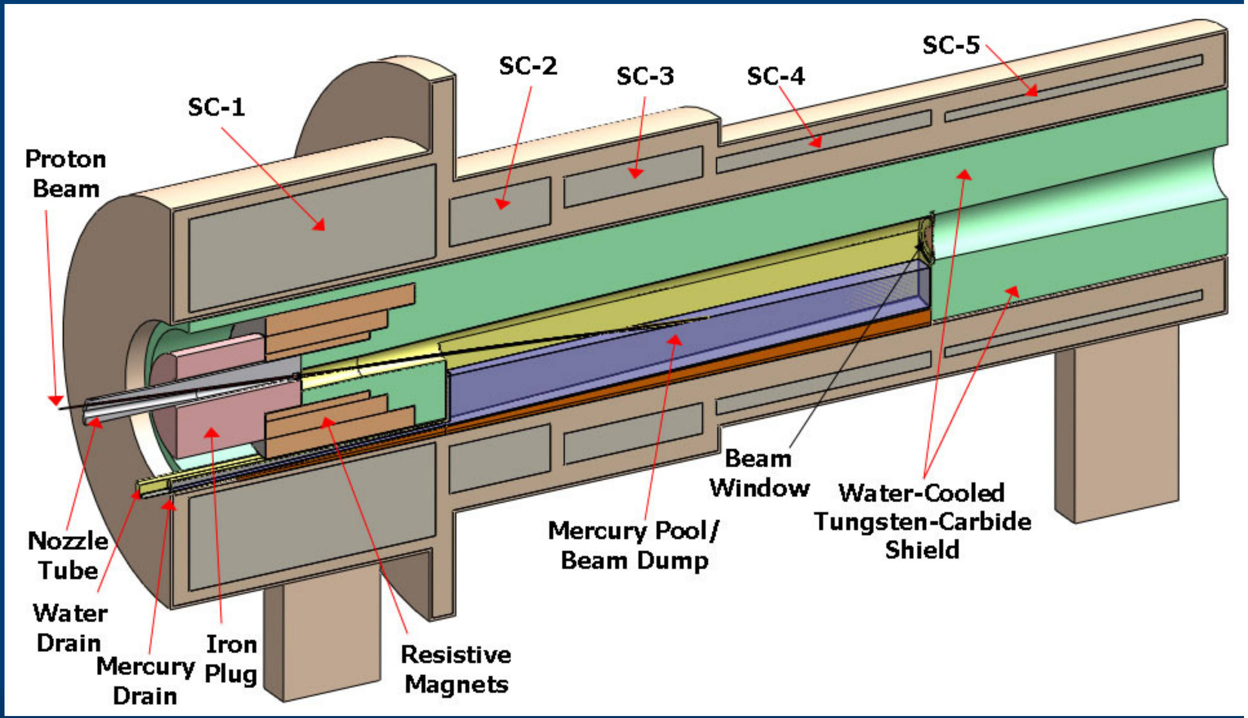
Key Areas of Magnet Pull - I

- 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

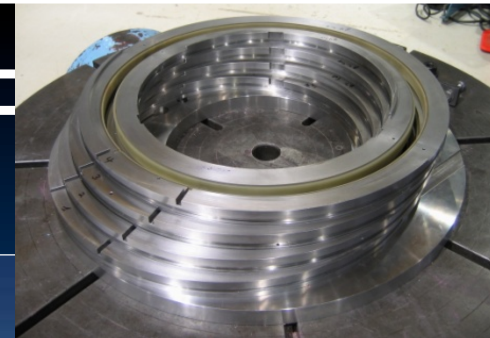
O(10MW) resistive coil in high radiation environment

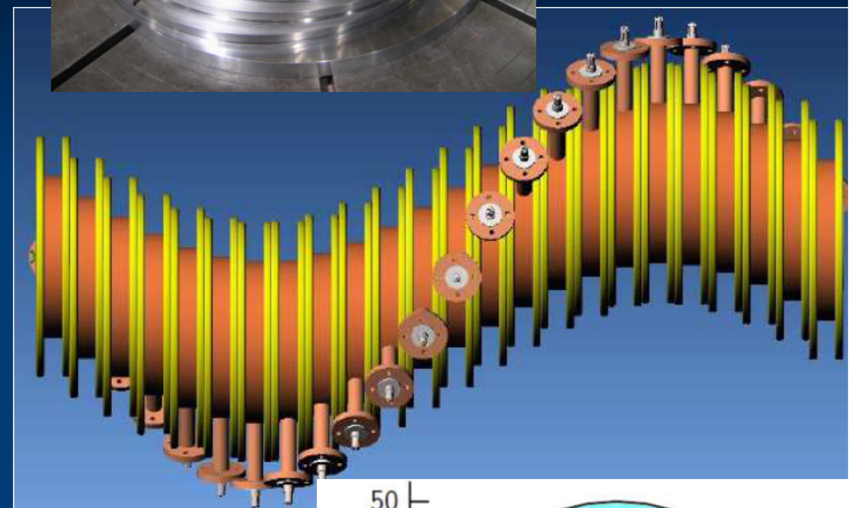
Possible application for HTS magnet technology

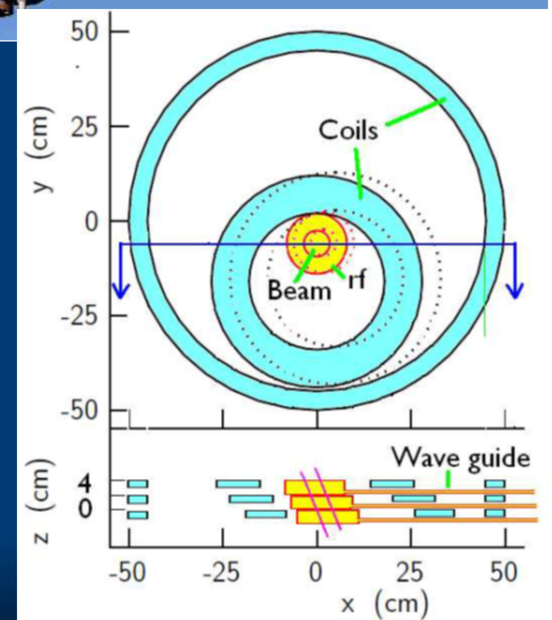


Key Areas of Magnet

- The Ionizaton Cooling Channel
  - 6D Beam Cooling Stage – 2 principal design concepts under consideration: Helical Cooling Channel (HCC) and Guggenheim Channel
  - Final Cooling – VHF Solenoids
- HCC: Dielectric-Loaded RF cavities filled with high pressure hydrogen





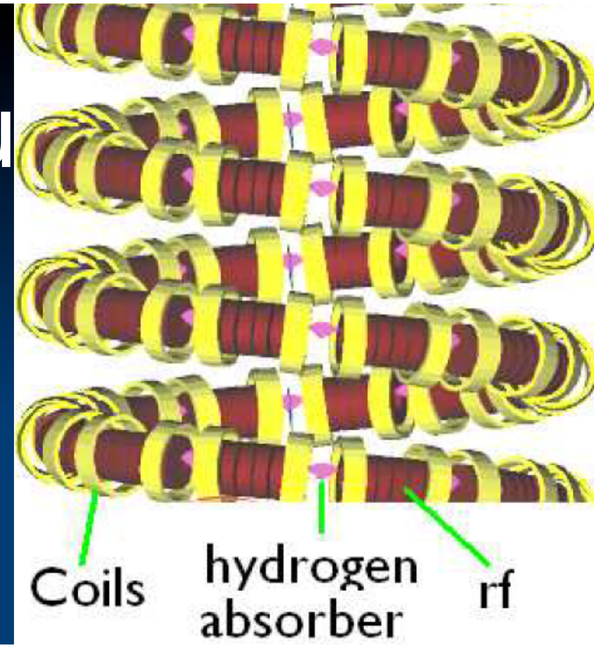


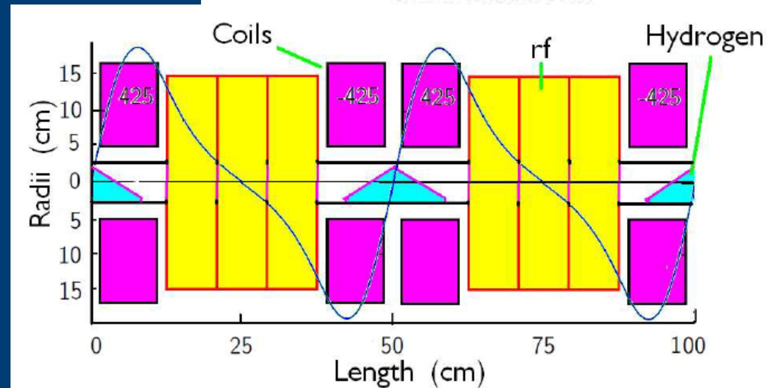
stage	R_c	λ	B_z	R1	R2	n	L_K	j	$\epsilon_\perp$	
	m	m	T	m	m		m	A/mm^2	mm	
2	.28	1	.55	.35	.4	20	.025	194	10	Kashikin
6	.16	.4	6.73	.18	.28	20	.01	332.9	0.4	Kashikin
7	.12	.3	8.97	.135	.21	20	.0075	592	0.3	Extrapolated

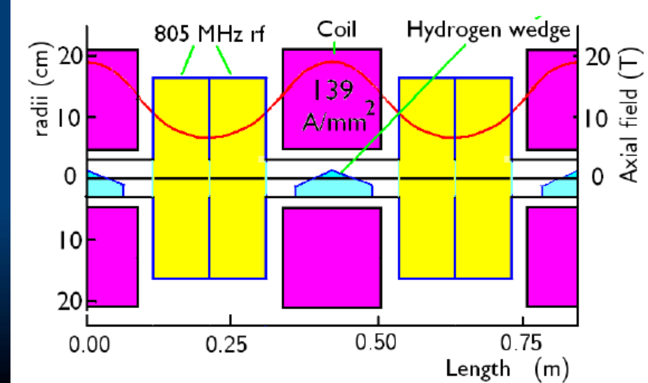
Key Areas of Magnet Pu

- Guggenheim cooling channel
  - Vacuum RF cavities
  - Studying both “Flip” and “Non-Flip” lattices
  - Challenging geometry constraints
  - High J_E required in final stages

- Demonstration magnets required on the 3 year timescale for RF tests (see talk by R. Gupta)

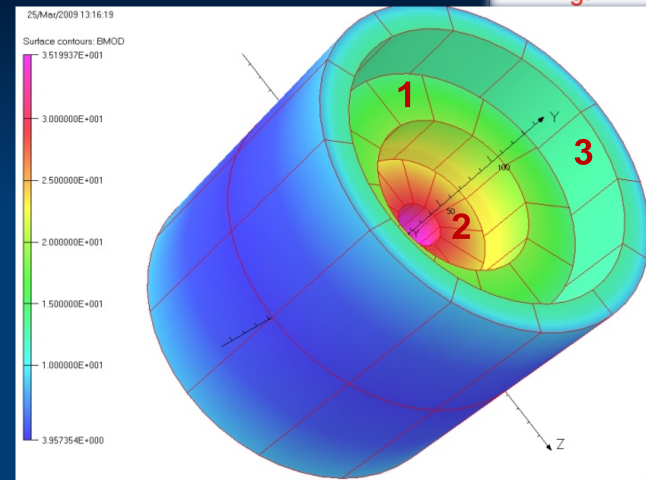




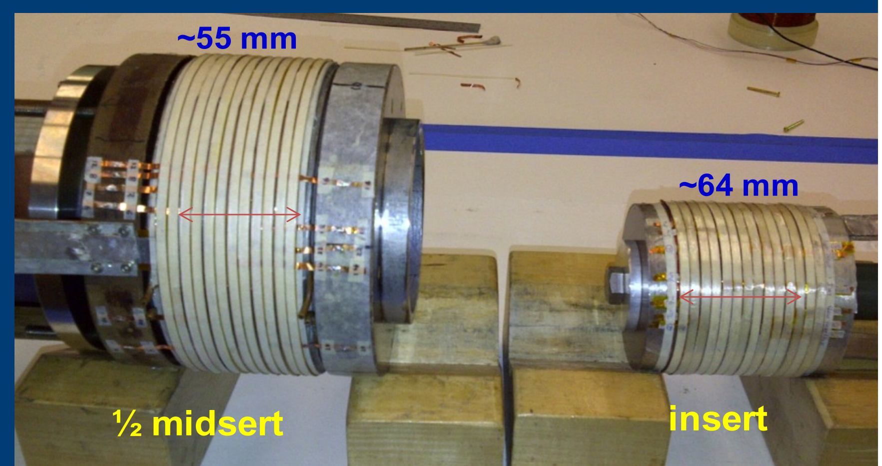


Key Areas of Magnet Pull - IV

- Final Cooling
  - Requires > 30T Class Solenoids
  - May 2012 Review
    - YBCO recommended for moving forward with MAP demonstration effort
    - Working in close collaboration with SBIR program (PBL/BNL)
  - Demonstration program exploring critical magnet issues
    - High J_E
    - Quench Protection
    - Stress
    - Piece Length Constraints



HTS (1&2, funded) and LTS (3, not funded)



HTS solenoids – built and tested

Key Areas of Magnet Pull - V

- Fast Ramping Magnets utilized in rapid-cycling synchrotron for final acceleration for the MC
- Collider Ring
  - Magnet design R&D for collider ring and IR magnets that have to deal with the expected high level of energy deposition from m decay electrons
  - As with the LHC, pushing the field limits for magnets can impact the energy reach
  - What is the optimal design for the collider ring magnets that will enable them to operate in the presence of the decay electrons? Paper studies only.
  - Requires high field quality designs and hence the necessary cable development

Critical Technology Challenges for Muon Accelerator Magnets

- Magnet needs for the Muon Accelerator Program offer a strong pull on technology development
  - High engineering current densities
  - Extreme radiation environments
    - Damage
    - Heat Load
  - Quench protection
    - A major challenge for HTS
  - Stress management
    - A major challenge for the very high field designs desired
  - Piece Lengths
    - Conductors still under development
- A well-integrated and coordinated R&D plan is required

HEP: Community Summer Study 2013

- APS Division of Particles & Fields coordinating a year long planning exercise for the US HEP community

  http://www.snowmass2013.org/tiki-index.php

- Inputs currently being solicited
  - Facilities subgroup covers accelerator options and technologies
  - I am a sub-convener for the Lepton Collider topical area
- Would like to propose the formation of a group to provide input to the Facilities sub-group on the technology and industrial connections for magnet technology

Conclusion

- MAP is entering a 6-year Feasibility Assessment
  - Presently heavily reliant on collaboration with SBIR companies for moving forward with HTS technology
    - High Field Solenoid demonstration – focused on YBCO
    - Broader review of HTS applications, including those where high field quality is required
  - Critical accelerator baseline choices to be made over the next 3 years ⇨ basic engineering designs
  - Anticipate supporting key technology demonstrations during final 3-year period
  - Detailed planning is underway
    - John Tompkins (FNAL) is the MAP coordinator for the magnet R&D effort
    - Goal is a detailed plan including input from stakeholders and contributors
- The US HEP Community Planning effort is underway
  - Am soliciting input for the technology/industrial connections to go with the physics planning effort