Muon Accelerators: R&D Towards Future Neutrino Factory & Lepton Collider Capabilities

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Fermilab

Muon Accelerators for HEP

- μ – an elementary charged lepton:
  - 200 times heavier than the electron
  - 2.2 μs lifetime at rest
- Physics potential for the HEP community using muon beams
  - Tests of Lepton Flavor Violation
  - Anomalous magnetic moment ⇨ hints of new physics (g-2)
  - Can provide equal fractions of electron and muon neutrinos at high intensity for studies of neutrino oscillations – the Neutrino Factory concept

$$m^{+} \to e^{+} n_{e} \bar{n}_{m}$$

$$m^{-} \to e^{-} \bar{n}_{e} n_{m}$$

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

Outline

- The U.S. Muon Accelerator Program
- Why Neutrino Factories?
  - Neutrino Factory Concepts
    - Short baseline ⇨ νSTORM
    - Long Baseline ⇨ IDS-NF and **NuMAX**

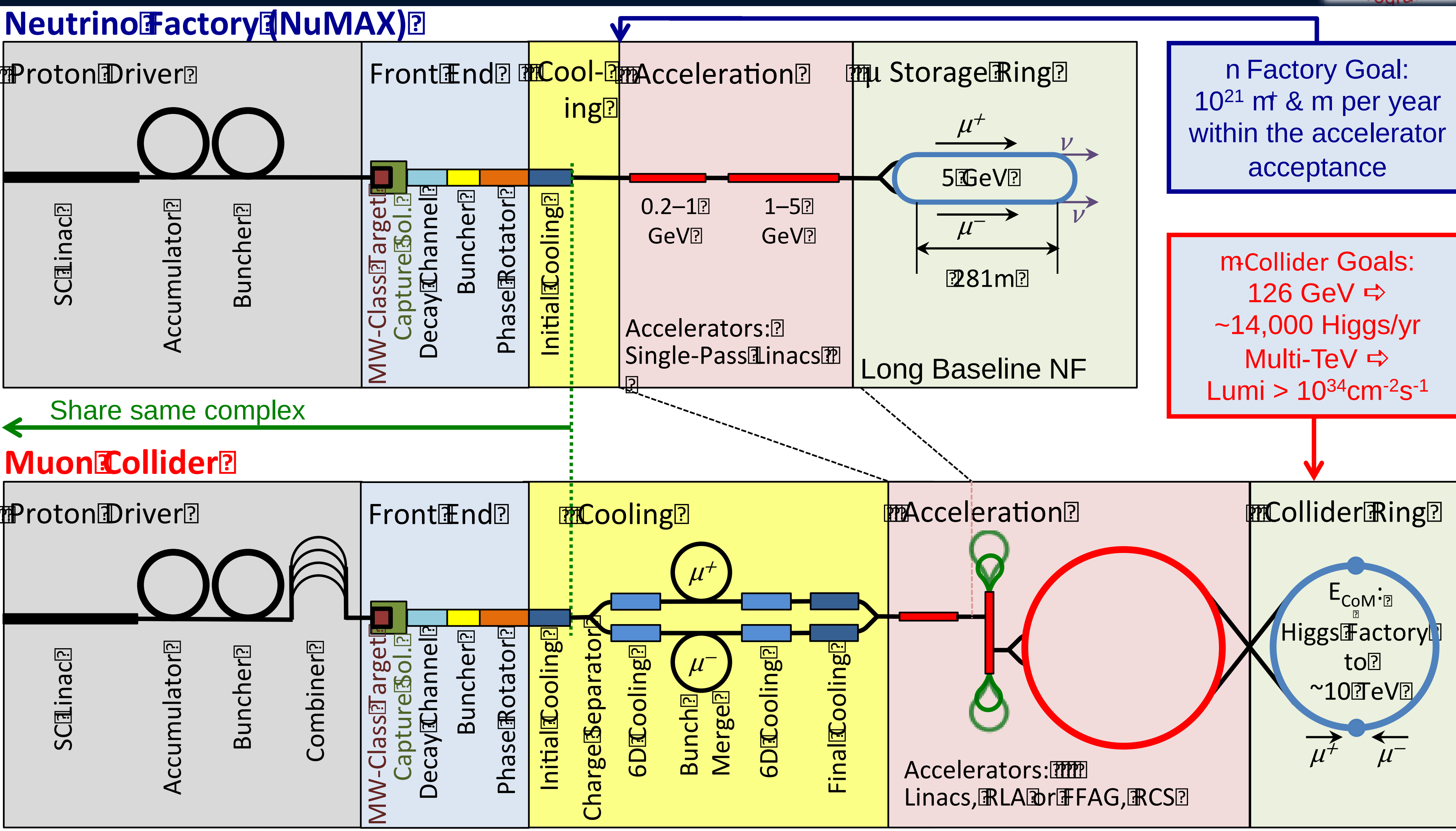
Will show highlights from ~50 MAP-related contributions to this conference

- Going Beyond a Neutrino Factory Facility
  - Possibilities for a future Muon Collider Capability
  - Higgs Factory to >5 TeV
- Key Accomplishments of the MAP R&D Effort
- Conclusion

The U.S. Muon Accelerator Program I

- The US Muon Accelerator Program was approved by DOE-OHEP in in 2011, in response to the 2008 P5 Panel Report Recommendation:
  - *The panel also recommends R&D for alternative accelerator technologies, to permit an informed choice when the lepton collider energy is established.*
- That report specifically noted:
  - *Finally, a muon collider may be an effective means to reach multi-TeV energies... Recent studies using a jet of mercury in a strong magnetic field have demonstrated that such a target is capable of surviving a four-megawatt proton beam. This first step toward providing muons is very encouraging. <u>The next step is the demonstration of cooling using a combination of ionization energy loss and dispersion in a low-energy, low-frequency acceleration system</u>. Support for R&D for this program has been very limited. Demonstrating its feasibility or understanding its limitations will require a higher level of support.*
- In 2012, DOE-OHEP requested development of a detailed plan for a ~6-year program to establish muon accelerator feasibility
  - *A detailed Feasibility Assessment Execution Plan was delivered to DOE-OHEP and endorsed by an OHEP-convened review panel in February 2014.*

The U.S. Muon Accelerator Program II

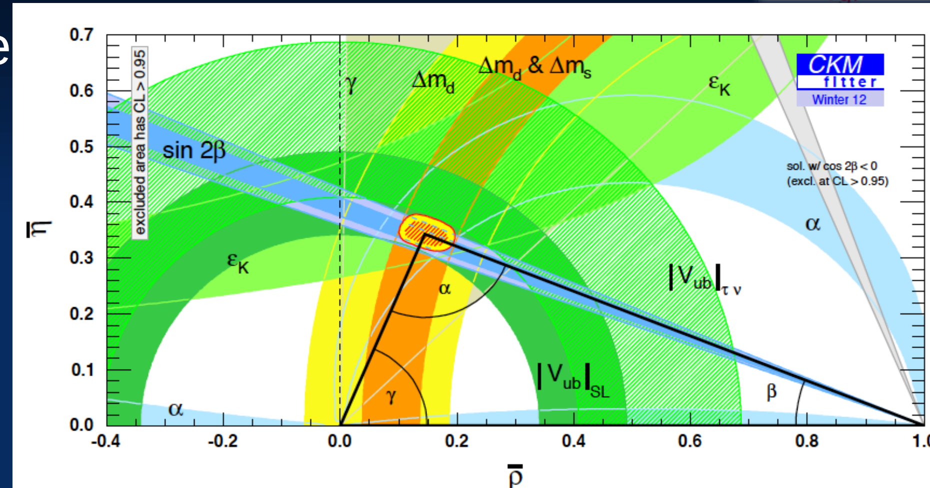


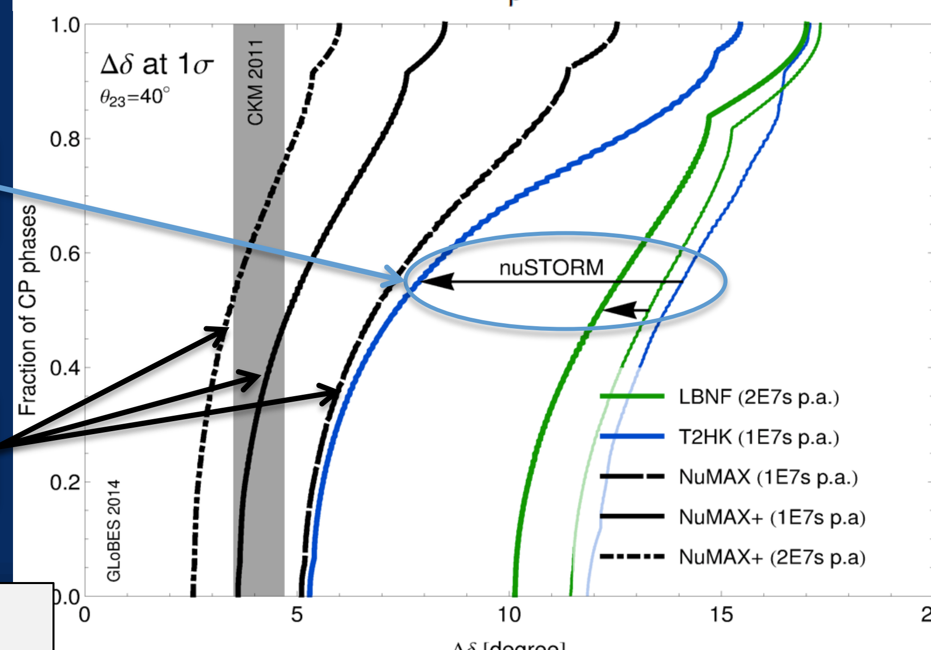
The program also targeted a short-baseline NF design for precision studies of σ_ν and the short baseline ν anomalies

WHY NEUTRINO FACTORIES?

The Critical Issues

- What must we understand in the neutrino sector?
  - δ_{CP}: Can this be done with the same precision as the quark sector???
  - The mass hierarchy
  - The value of θ_{23}-$\pi/4$: +, - or zero?
  - Resolve the LSND and other short baseline experimental anomalies
  - *And enable the search for new physics*





Impact of precision short-baseline NF capabilities

Impact of precision long-baseline NF capabilities

GLoBES Comparison of Potential Performance of the Various Advanced Concepts *(courtesy P. Huber)*

Microscopes for the ν Sector

- Superbeam technology will continue to drive initial observations in the coming years

- *However, anomalies and new discoveries will drive our need for precision studies to develop a complete physical understanding*

- Neutrino Factory capabilities (both long- and short-baseline) offer the route to *controlled systematics* and *precision measurements*, which are required to fully elucidate the relevant physics processes

⇨ *Precision Microscopes for the ν sector*

Neutrino Factory Development Under MAP

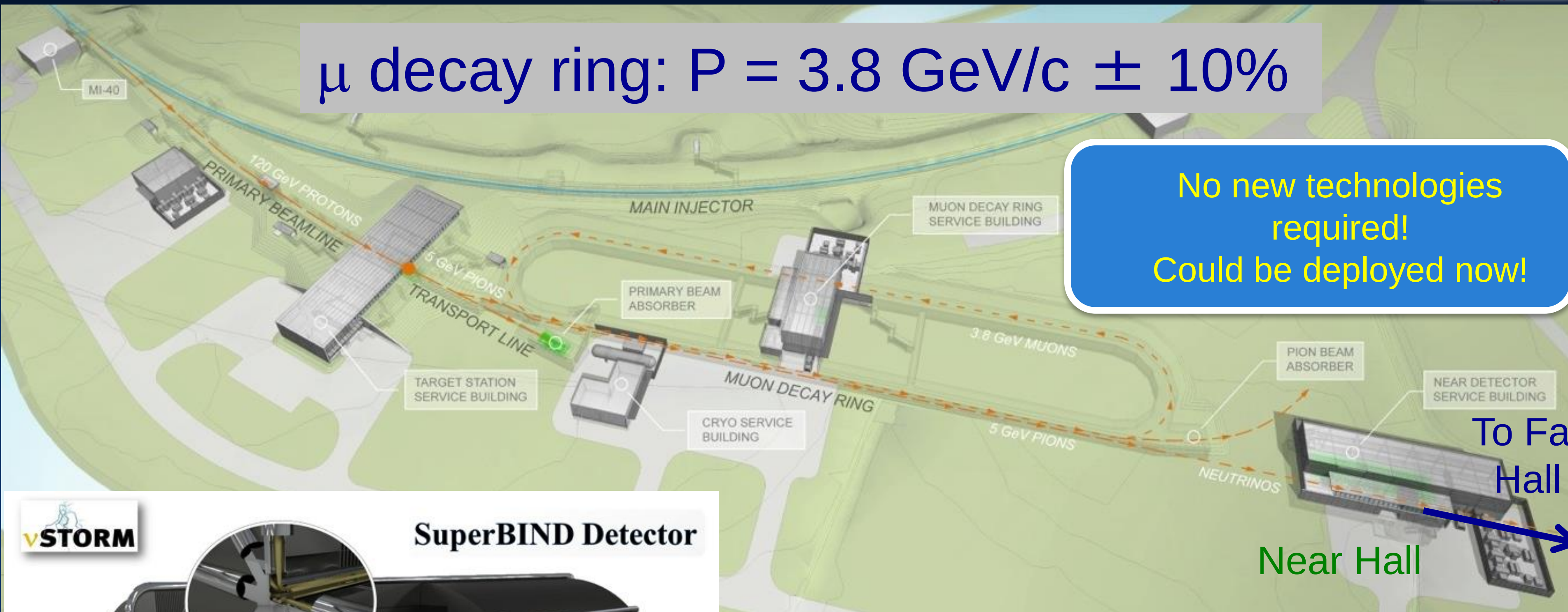
- Short Baseline NF
  - nuSTORM
    - Definitive measurement of sterile neutrinos
    - Precision ν_e cross-section measurements (systematics issue for long baseline SuperBeam experiments)
    - Would serve as an HEP muon accelerator proving ground…

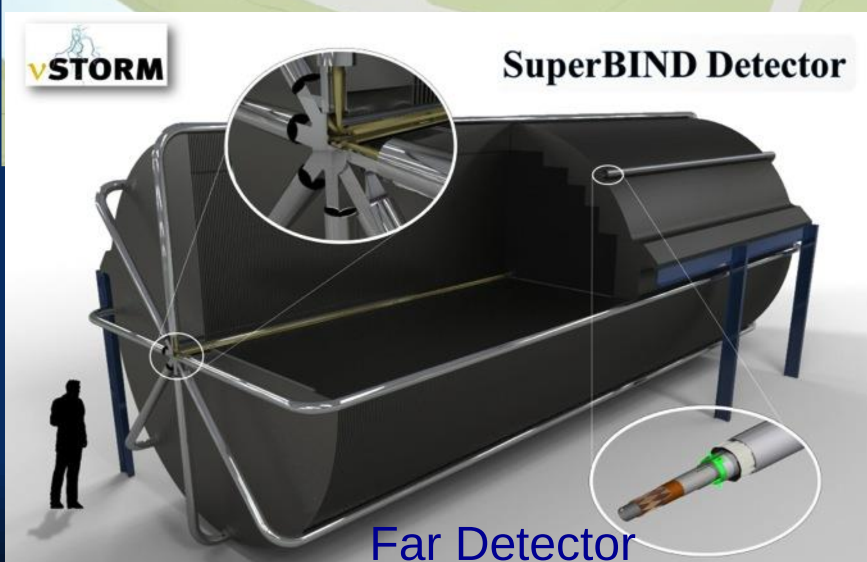
- Long Baseline NF with a Magnetized Detector
  - IDS-NF (International Design Study for a Neutrino Factory)
    - 10 GeV muon storage ring optimized for 1500-2500km baselines
    - “Generic” design (ie, not site-specific)
  - NuMAX (Neutrinos from a Muon Accelerator CompleX)
    - Site-specific: FNAL ⇨ SURF (1300km baseline)
    - 4-6 GeV beam energy optimized for CP studies
      - Flexibility to allow for other operating energies
    - Can provide an ongoing short baseline measurement option
    - Detector options
      - Magnetized LAr is the goal
      - Magnetized iron provides equivalent CP sensitivities using ~3x the mass

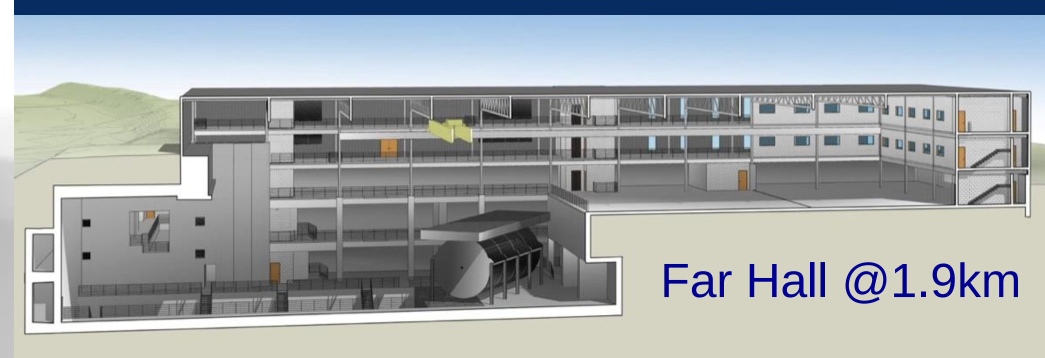
νSTORM – *the First NF?*

μ decay ring: P = 3.8 GeV/c ± 10%

No new technologies required!
Could be deployed now!



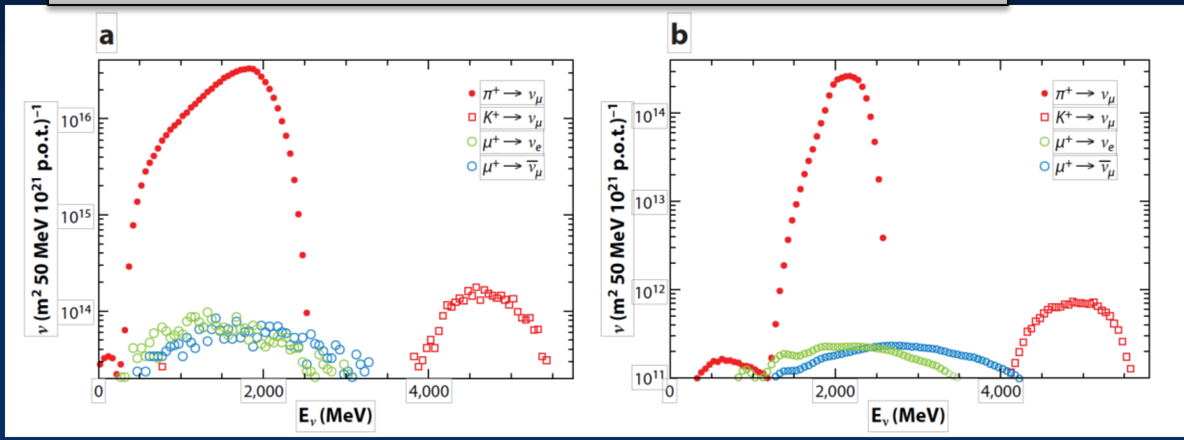




ν Beams at nuSTORM

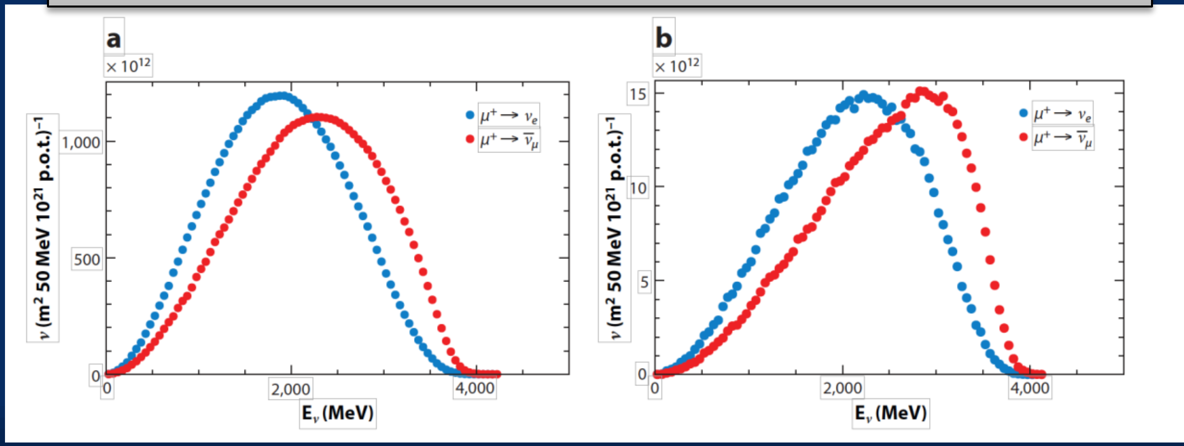
- ν beams from π^+ decay at nuSTORM
  - a: at 50 m from end of production straight
  - b: at 2000 m
- Flavor pure with flux known to <1%

$\pi^+ \rightarrow \mu^+ + \nu_\mu$, π decays in injection straight



- ν beams from μ decay at nuSTORM
  - a: at 50 m from end of production straight
  - b: at 2000 m
- Absolute flavor purity with flux known to <1%

$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$-bar, decays from stored muons



nuSTORM and δ_{cp} Coverage @ DUNE

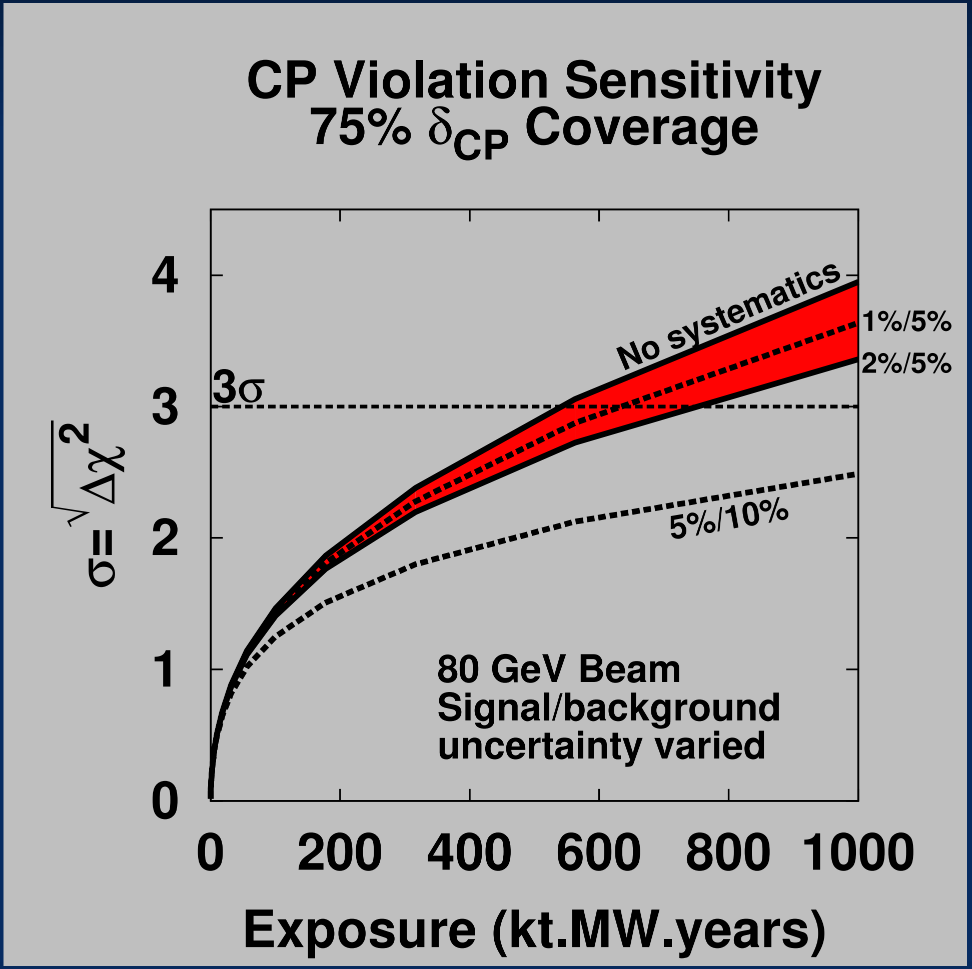
- 75% coverage of δ_{cp} in a LBL ν oscillation experiment (P5 requirement) in a reasonable exposure time

  ⇨ *Systematic uncertainties at the 1% level are required.*

- Degradation of systematic uncertainties to the ~5% level

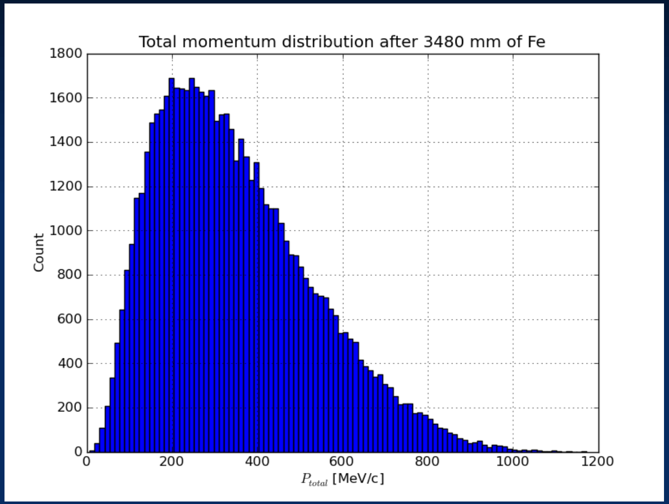
  ⇨ *exposure increase of 200-300% (very non-linear).*

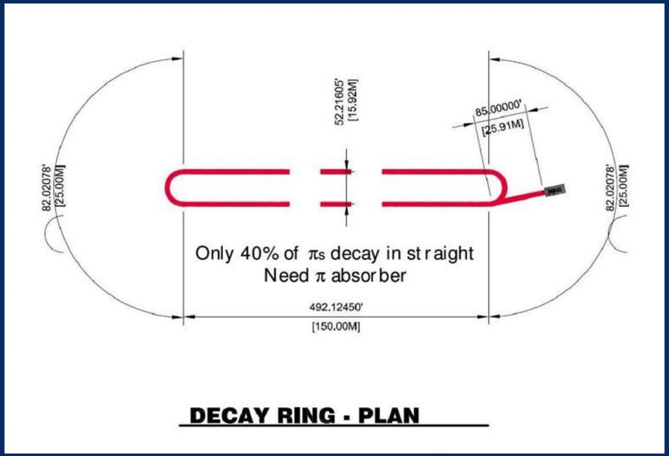
- *We have yet to achieve 2% uncertainty in ν experiments.*



νStorm as an R&D platform

- A high-intensity pulsed muon source
- 100<p_μ<300 MeV/c muons
  - Using extracted beam from ring
  - 10^{10} muons per 1 μsec pulse
- Beam available simultaneously with physics operation
- νSTORM also provides the opportunity to design, build and test decay ring instrumentation (BCT, momentum spectrometer, polarimeter) to measure and characterize the circulating muon beam



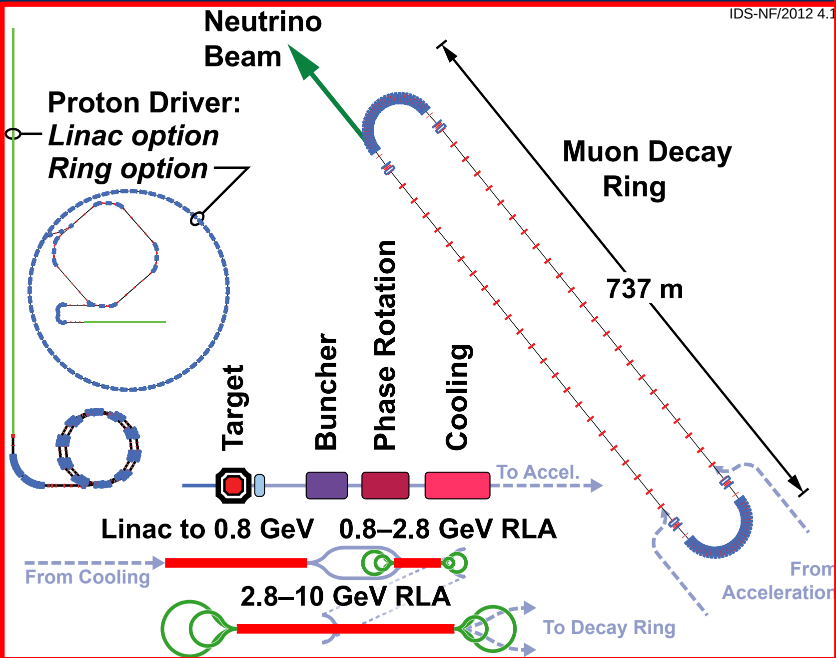


The Long Baseline Neutrino Factory

- IDS-NF: the *ideal* NF
  - Supported by MAP
- MASS working group:
  A staged approach -

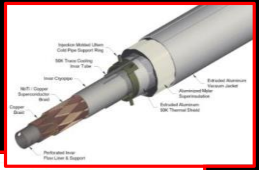
NuMAX@5 GeV⇨SURF

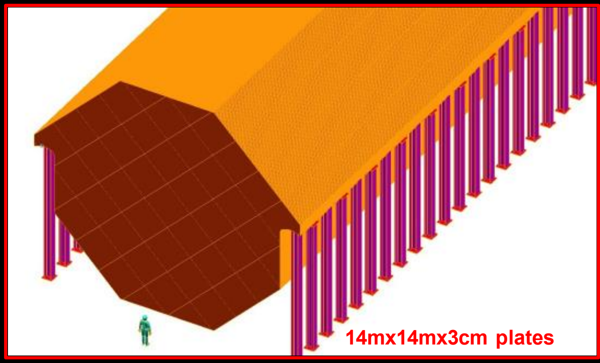
	Value
Accelerator facility	
Muon total energy	10 GeV
Production straight muon decays in 10^7 s	10^{21}
Maximum RMS angular divergence of muons in production straight	$0.1/\gamma$
Distance to long-baseline neutrino detector	1 500–2 500 km

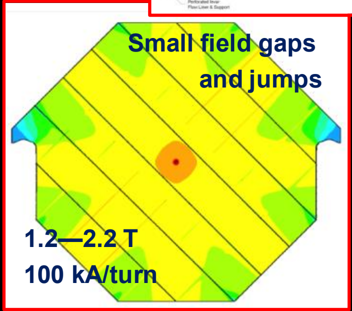


MagneHzed'Iron'Neutrino'Detector'(MIND):'

- IDS$NF'baseline:'
  - Intermediate'baseline'detector:'
    - 100'kton'at'2500—5000'km'
  - Magic'baseline'detector:''
    - 50'kton'at'7000—8000'km'
  - Appearance'of'"wrong$sign"'muons'
  - Toroidal'magneHc'field'>'1'T'
    - Excited'with'"superconducHng' transmission'line"'
  - SegmentaHon:'3'cm'Fe'+'2'cm' scinHllator'
  - 50$100'm'long'
  - Octagonal'shape'
  - Welded'double$sheet'
    - Width'2m;'3mm'slots'between'plates'

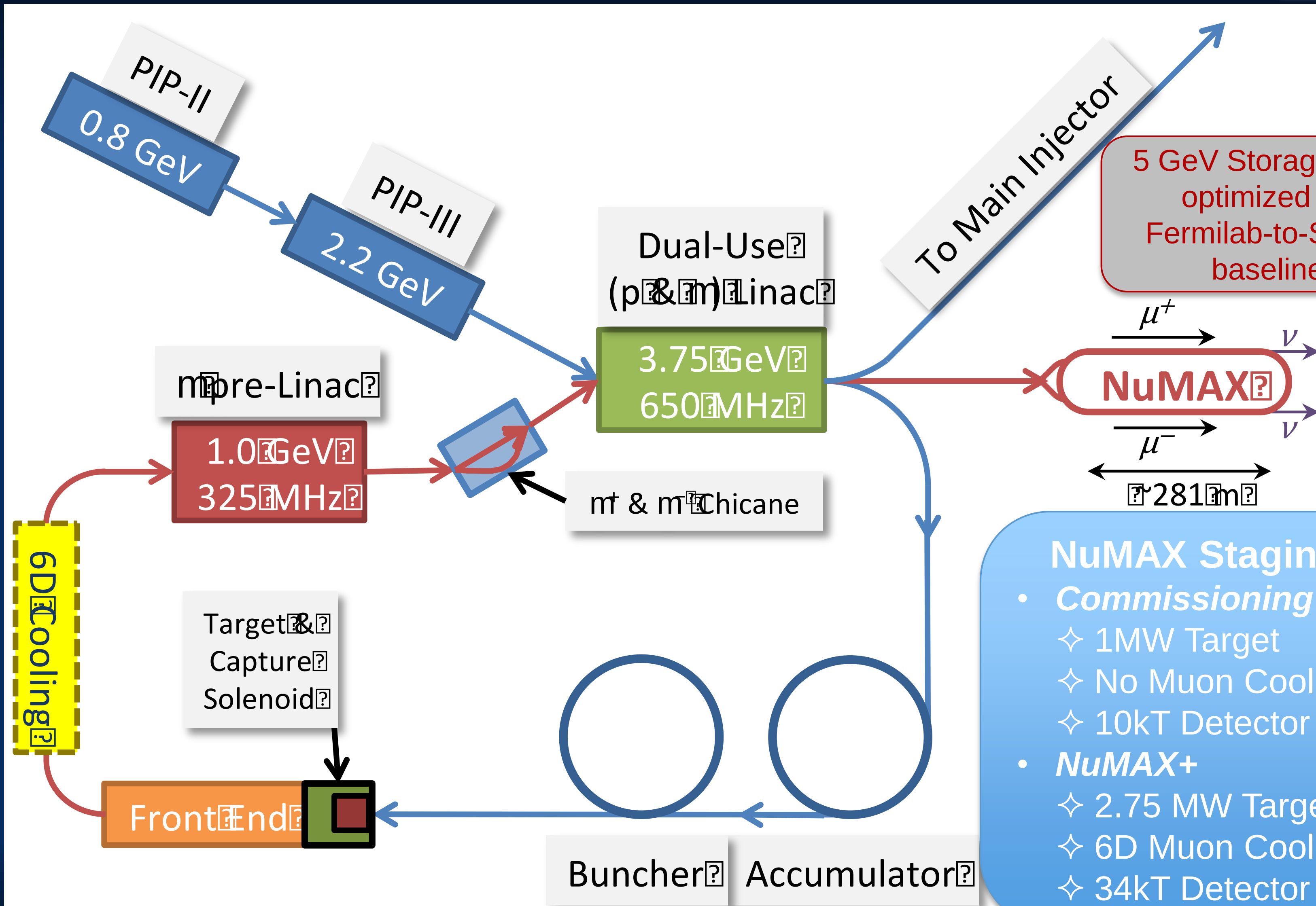






Bross,'Soler'

The MAP Muon Accelerator Staging Study ⇨ NuMAX



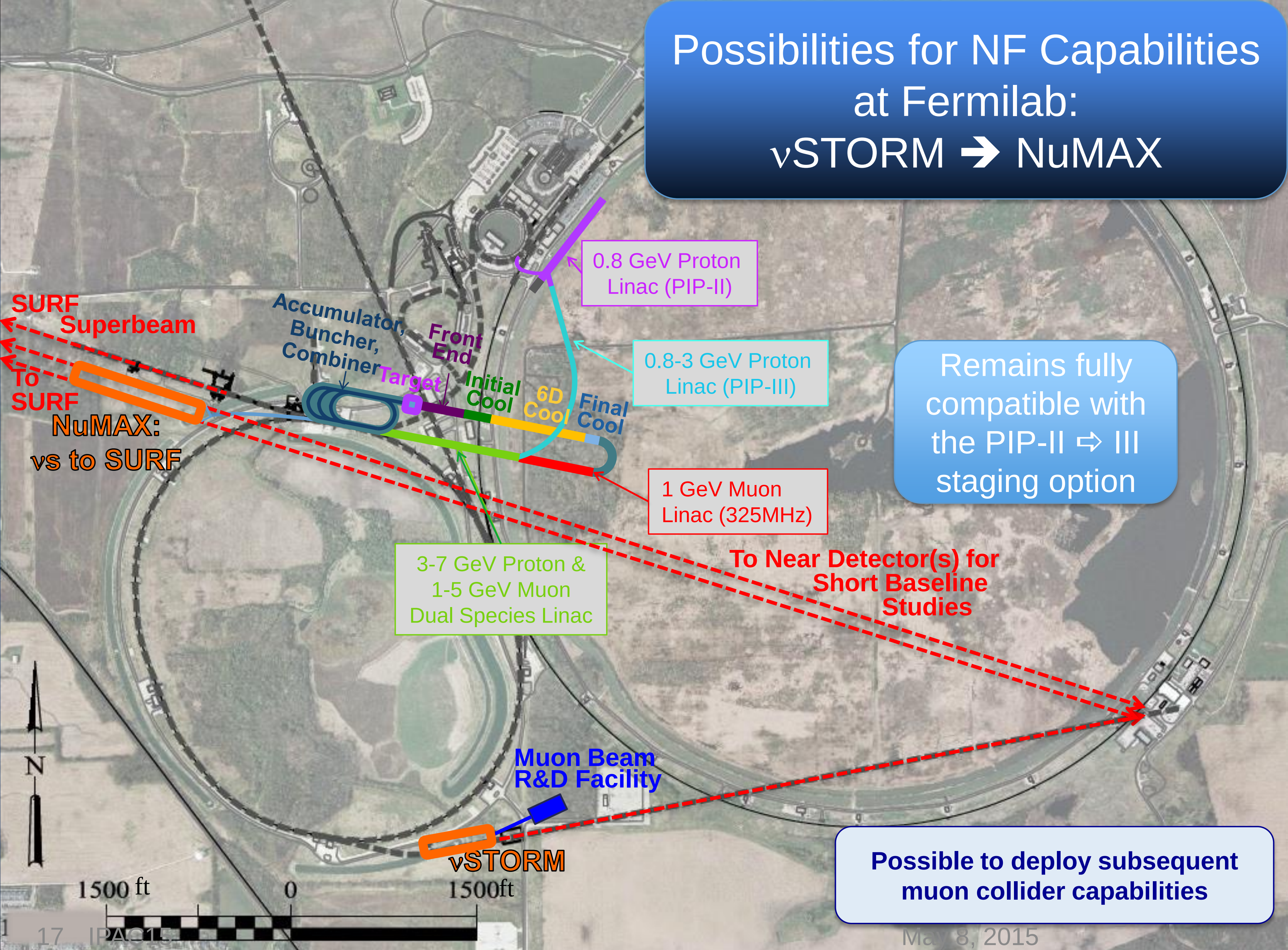
NuMAX Staging:

- ***Commissioning***
  - ✧ 1MW Target
  - ✧ No Muon Cooling
  - ✧ 10kT Detector
- ***NuMAX+***
  - ✧ 2.75 MW Target
  - ✧ 6D Muon Cooling
  - ✧ 34kT Detector

MASS NF Parameters

Neutrino Factory Parameters					
Parameters	**Unit**	**nuSTORM**	**NuMAX Commissioning**	**NuMAX**	**NuMAX+**
ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Far Detector:	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / Mag LAr
Distance from Ring	km	1.9	1300	1300	1300
Mass	kT	1.3	100 / 30	100 / 30	100 / 30
Magnetic Field	T	2	0.5-2	0.5-2	0.5-2
Near Detector:	Type	SuperBIND	Suite	Suite	Suite
Distance from Ring	m	50	100	100	100
Mass	kT	0.1	1	1	2.7
Magnetic Field	T	Yes	Yes	Yes	Yes
Accelerator: Ring Momentum (P_μ)	GeV/c	3.8	5	5	5
Circumference (C)	m	480	737	737	737
Ionization Cooling	-	No	No	**6D Initial**	**6D Initial**
Proton Beam Power	MW	0.2	1	1	2.75

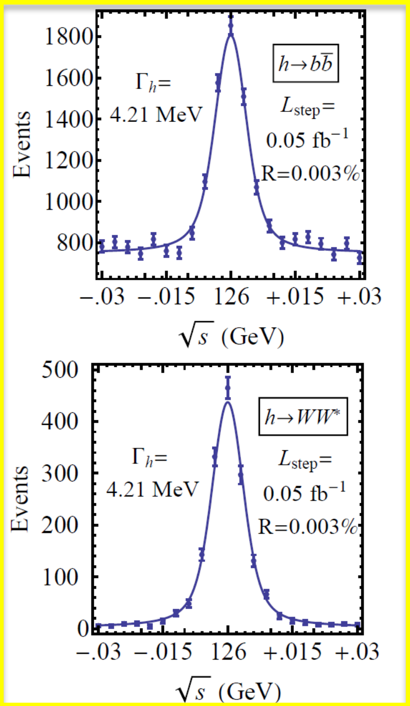
Possibilities for NF Capabilities at Fermilab: νSTORM ➔ NuMAX

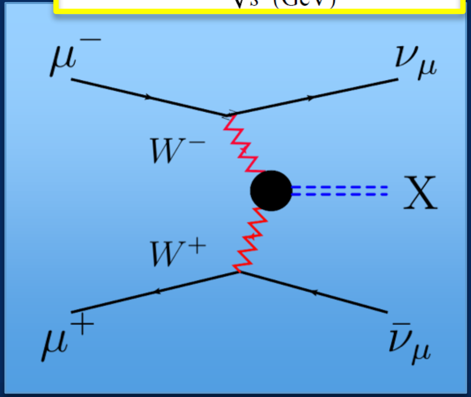


GOING BEYOND NEUTRINO FACTORY CAPABILITIES

Features of the Muon Collider

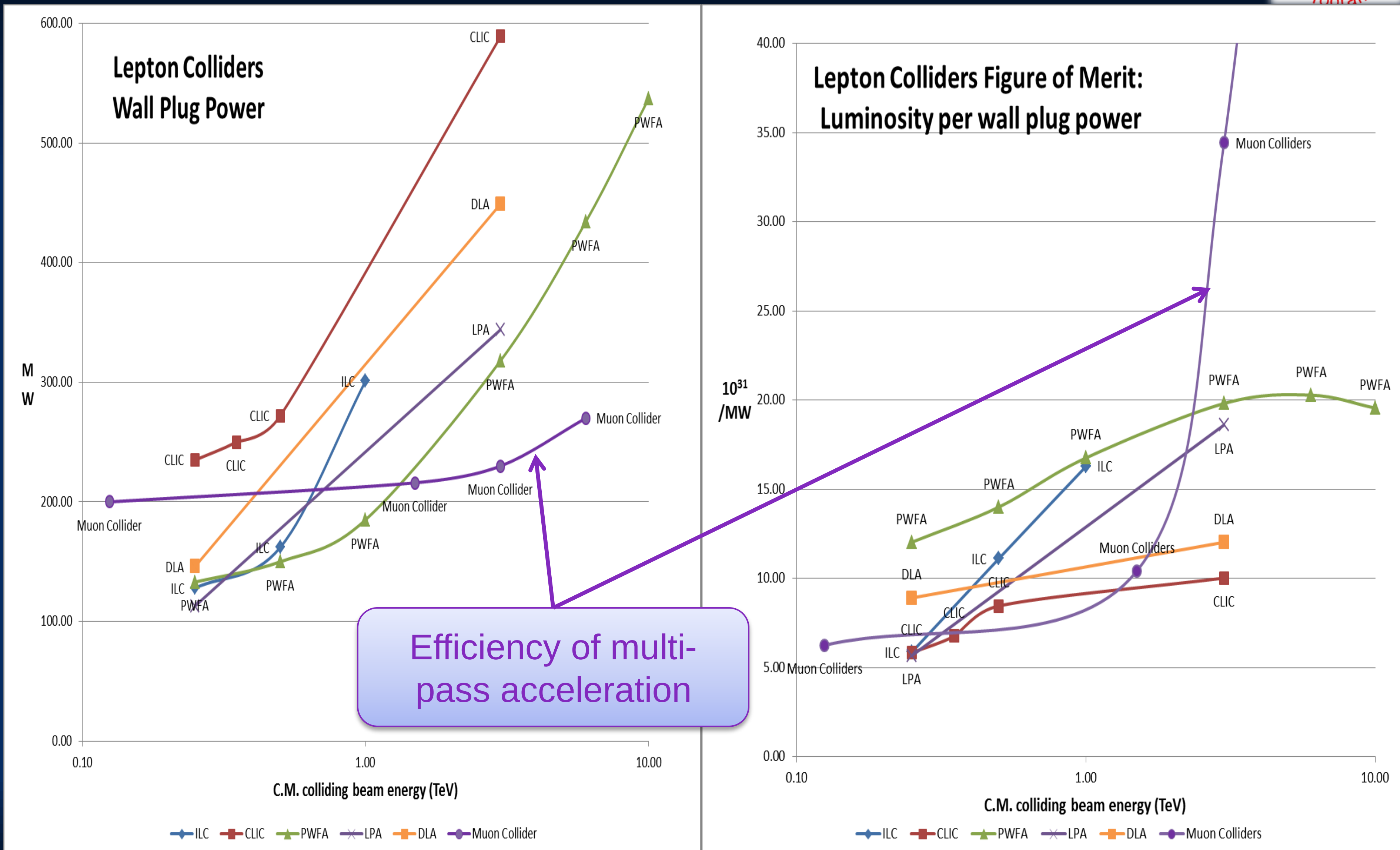
- Superb Energy Resolution
  - SM Thresholds and s-channel Higgs Factory operation
- Multi-TeV Capability (≤ 10TeV):
  - Compact & energy efficient machine
  - Luminosity > 10^{34} cm^{-2} s^{-1}
  - Option for 2 detectors in the ring
- For √s > 1 TeV: Fusion processes dominate
  - ⇨ an Electroweak Boson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



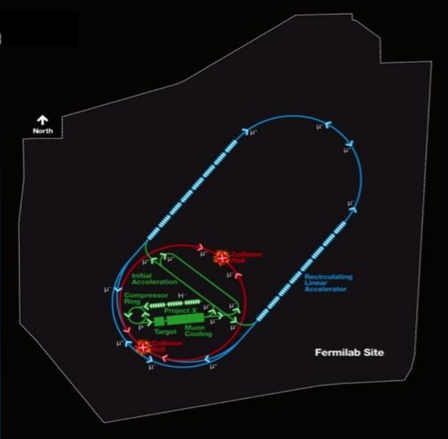


What is our most efficient accelerator option if new LHC data shows evidence for a multi-TeV particle spectrum?

Muon Colliders – Efficiency at the multi-TeV scale



Efficiency of multi-pass acceleration



Muon Collider Parameters

Muon Collider Parameters

		Higgs	Multi-TeV		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^{7}sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
b*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_{s}	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts ⇨ several ↙ 10^{32}

THE MAP R&D EFFORT

Accelerator R&D Effort (U.S. MAP)

Design Studies

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

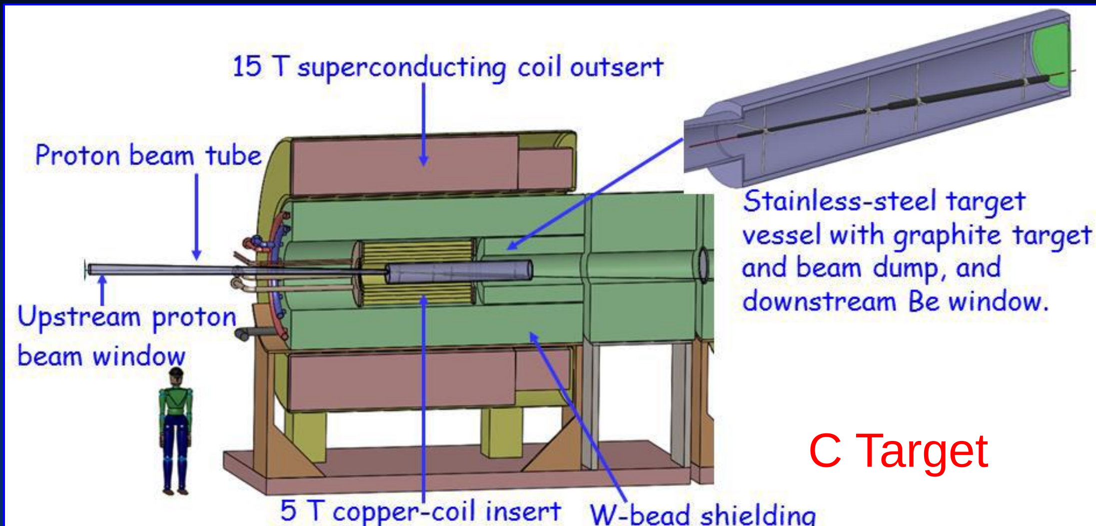
Technology R&D

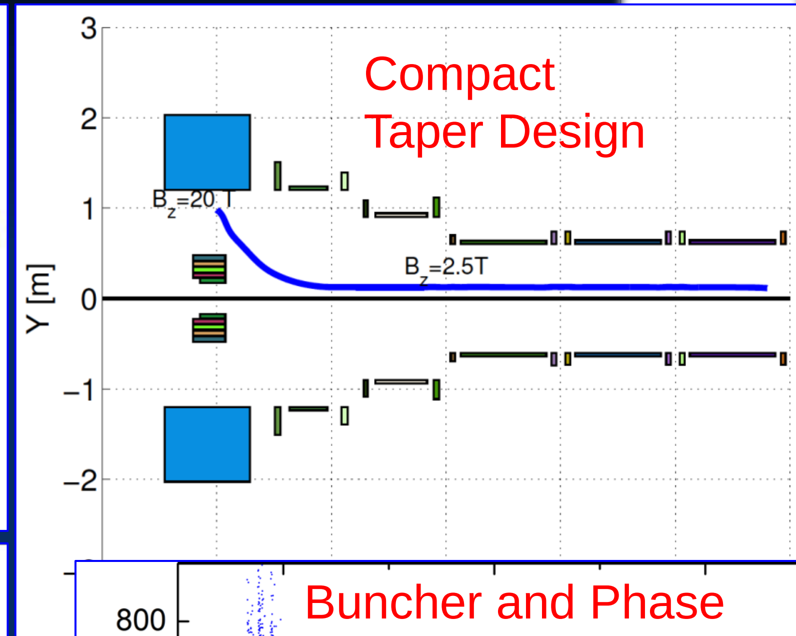
- RF in magnetic fields
- SCRF for acceleration chain (Nb on Cu technology)
- High field magnets
  - Utilizing HTS technologies
- Targets & Absorbers
- MuCool Test Area (MTA)

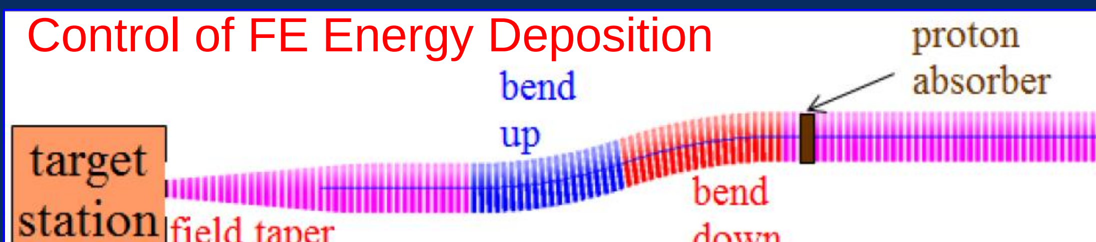
Major System Demonstration

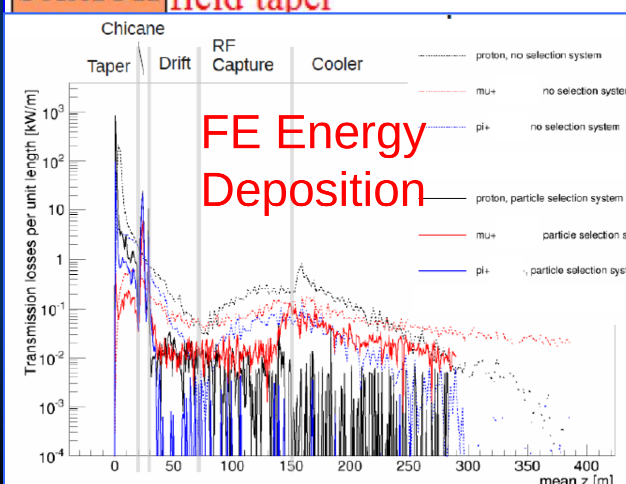
- The Muon Ionization Cooling Experiment – MICE
  - Major U.S. effort to provide key hardware: RF Cavities and couplers, Spectrometer Solenoids, Coupling Coil(s), Partial Return Yoke
  - Experimental and Operations Support

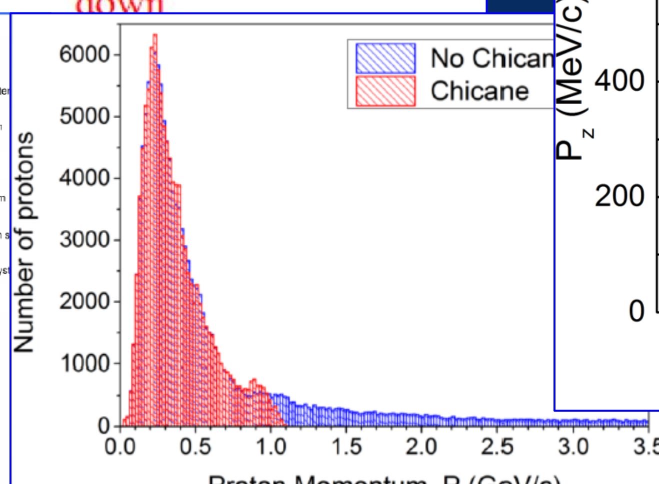
Target & Front End Progress

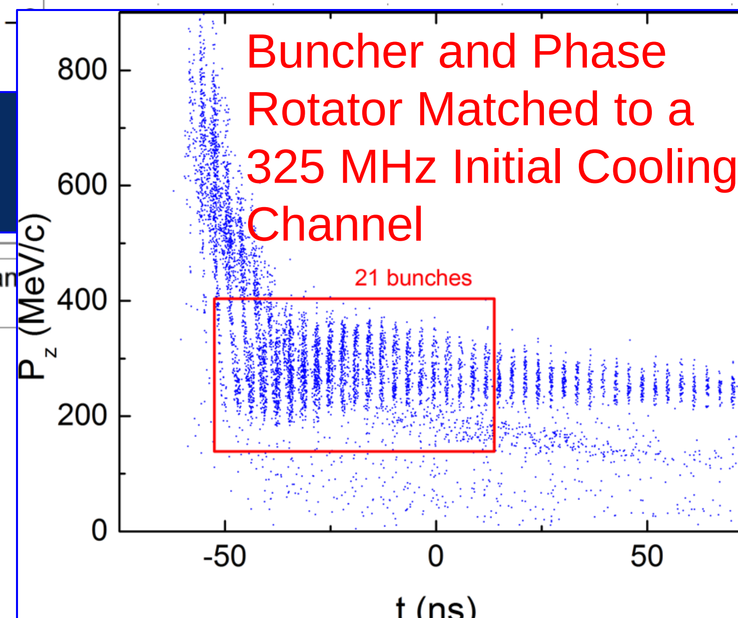




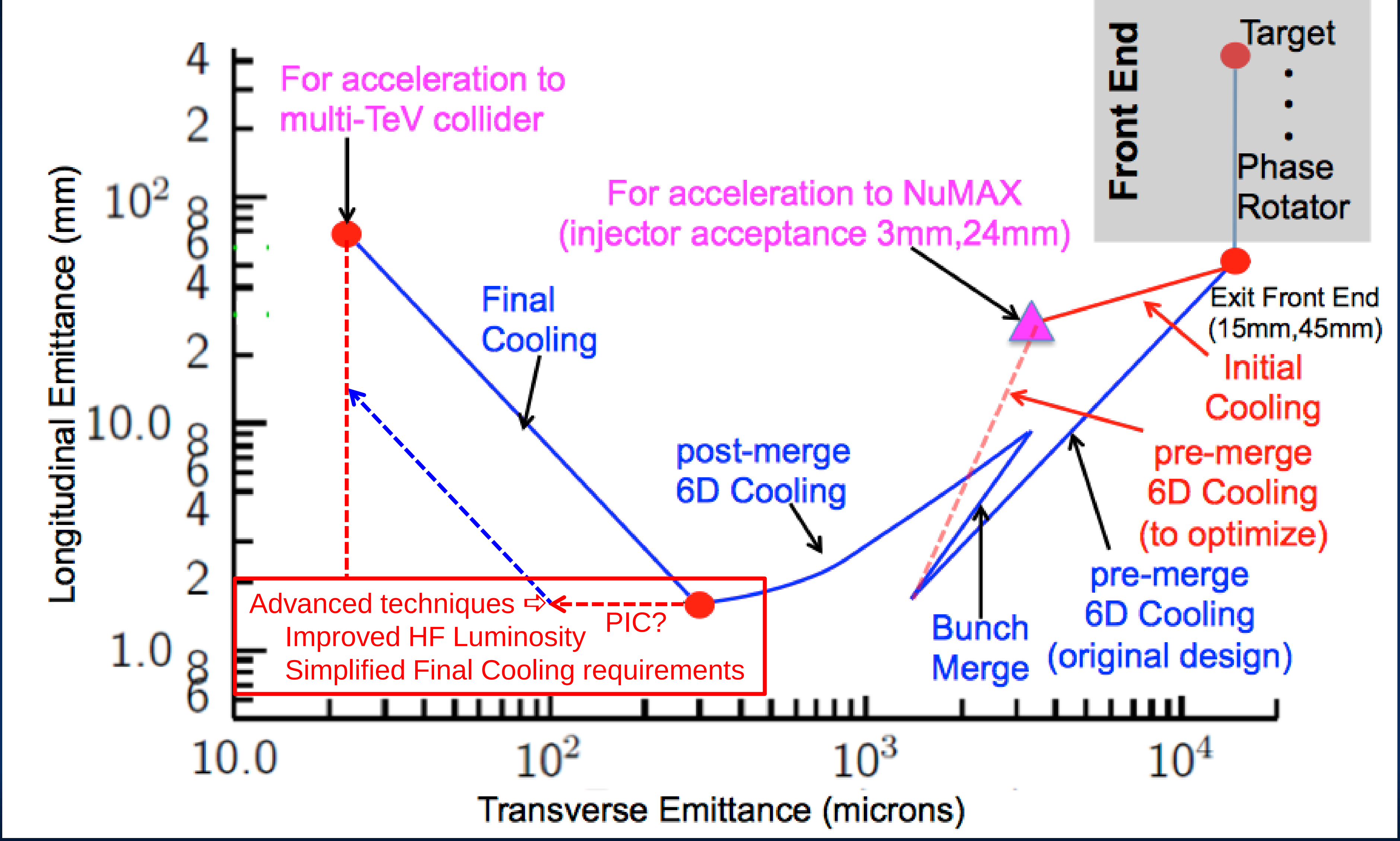




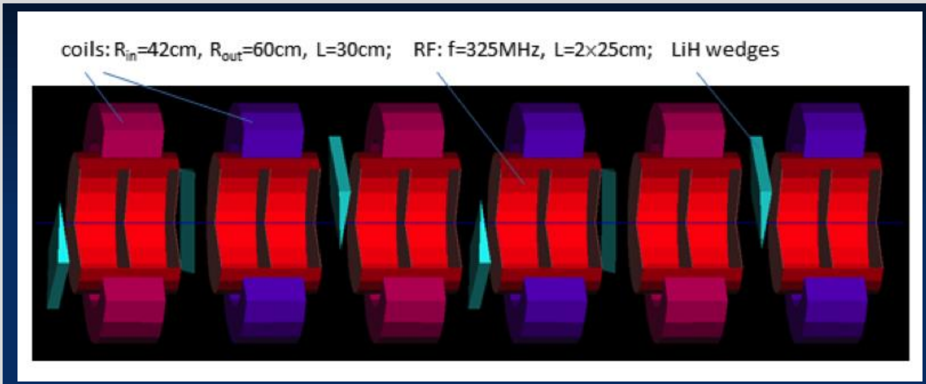


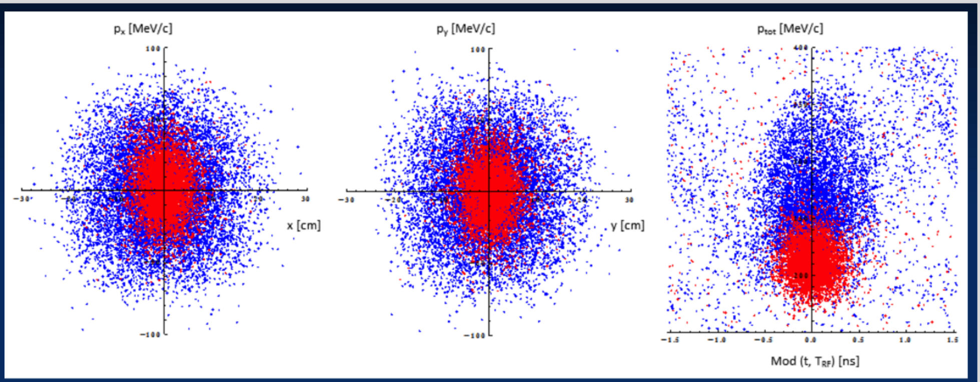


Muon Ionization Cooling

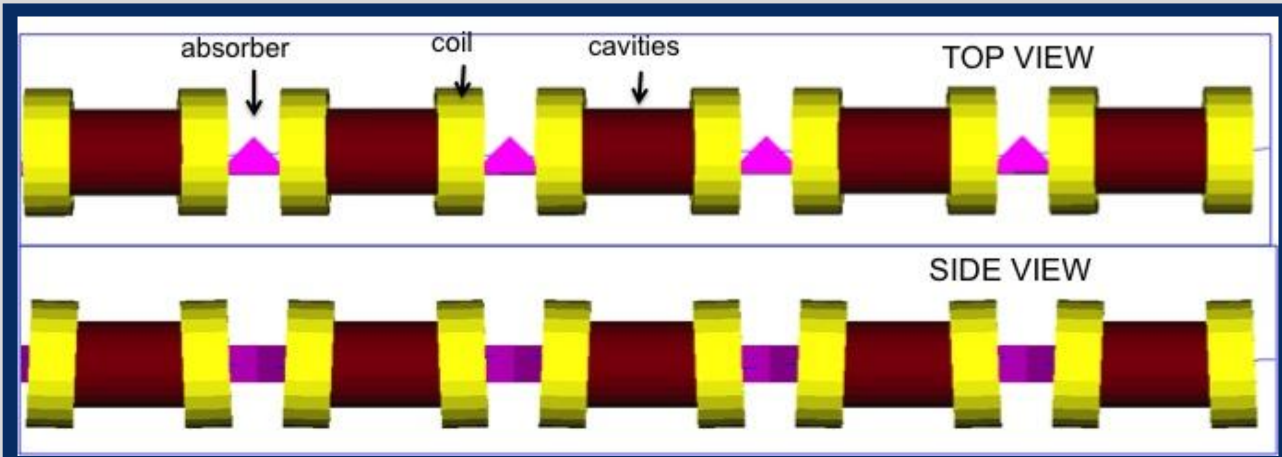


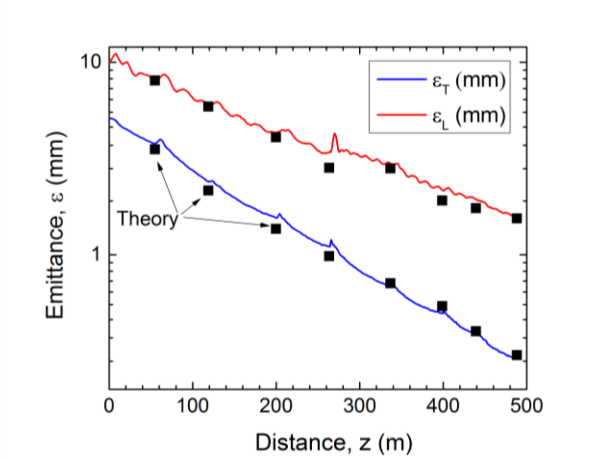
Muon Ionization Cooling (Design)





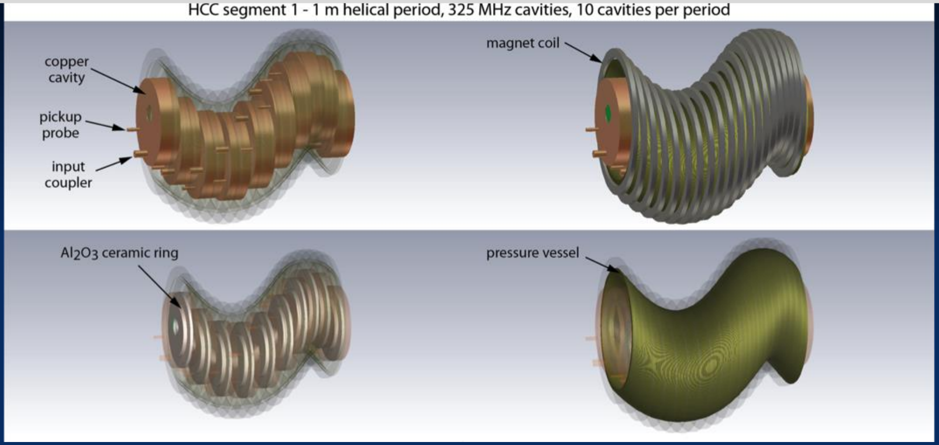
Initial 6D Cooling: ε_{6D} 60 cm^3 ⇨ ~50 mm^3; Trans = 67%

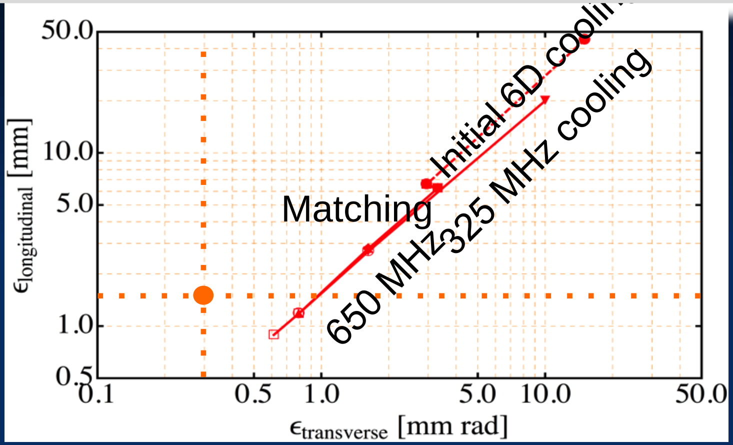




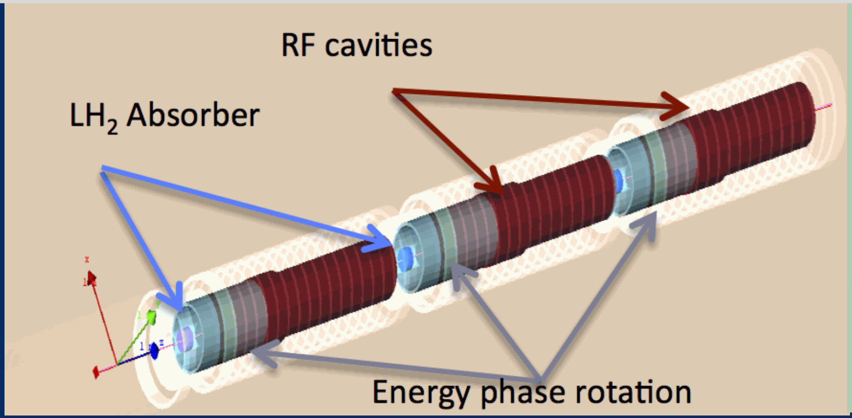
6D Rectilinear Vacuum Cooling Channel (replaces Guggenheim concept): Trans = 55%(40%) without(with) bunch recombination

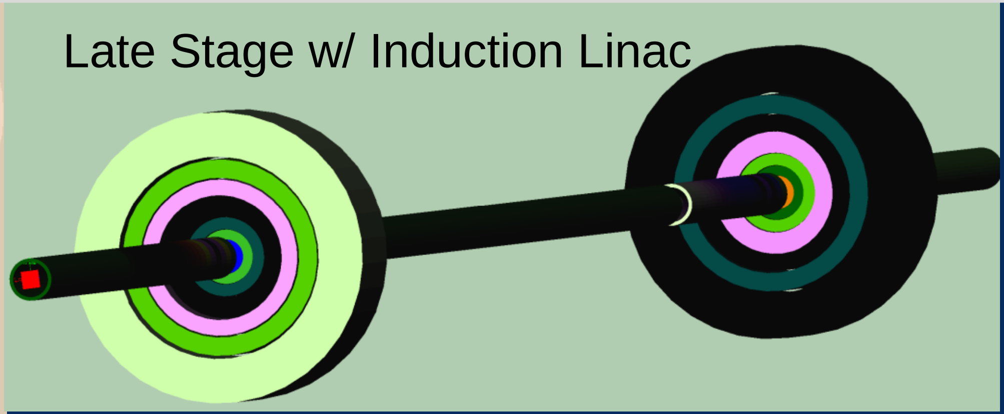
Muon Ionization Cooling (Design)





- Helical Cooling Channel (Gas-filled RF Cavities): $\varepsilon_T = 0.6$mm, $\varepsilon_L = 0.3$mm





- Final Cooling with 25-30T solenoids (emittance exchange): $\varepsilon_T = 55\mu$m, $\varepsilon_L = 75$mm

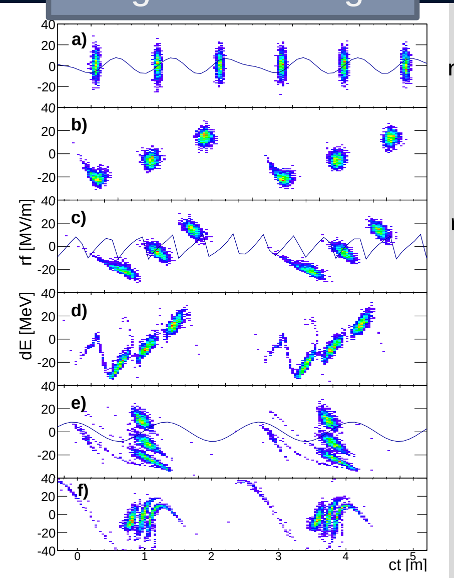
Muon Ionization Cooling (Design)

Bunch Merge

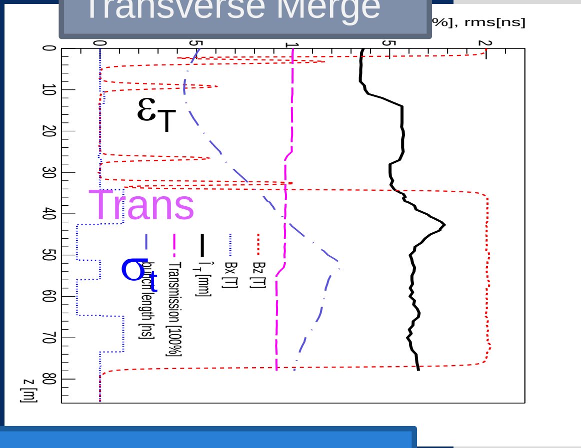
- MAP Baseline Designs offer
  - Factor >10^5 in emittance reduction
- Alternative and Advanced Concepts
  - Hybrid Rectilinear Channel (gas-filled structures)
  - Parametric Ionization Cooling
  - Alternative Final Cooling
    - ⇨ Early stages of existing scheme
    - ⇨ Round-to-flat Beam Transform
    - ⇨ Transverse Bunch Slicing
    - ⇨ Longitudinal Coalescing (at ~10s of GeV)

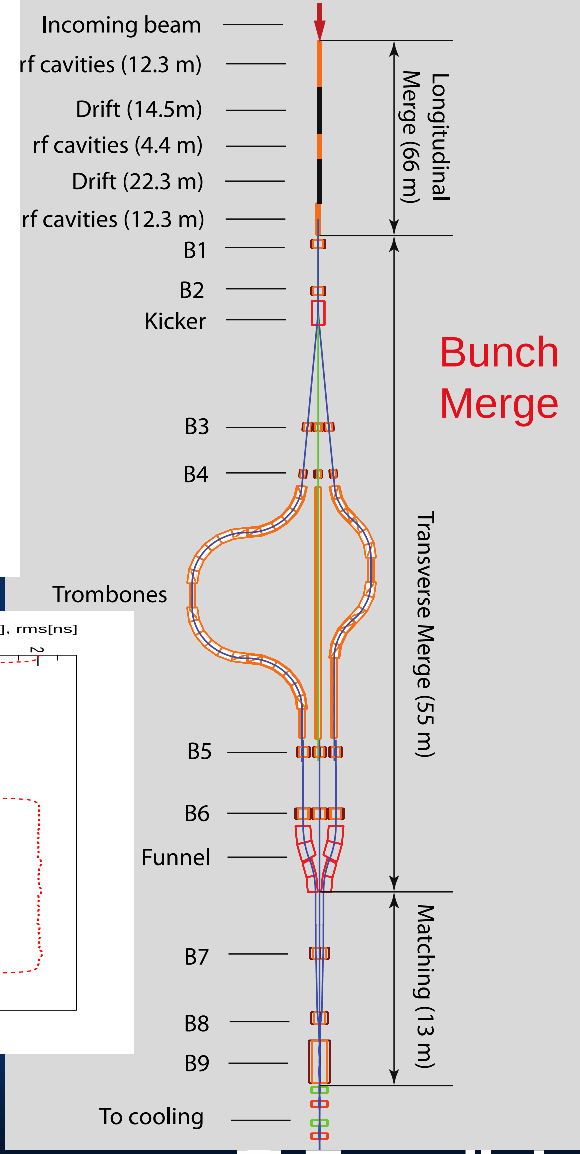
⇨ *Considerable promise to exceed our original target parameters*

Longitudinal Merge



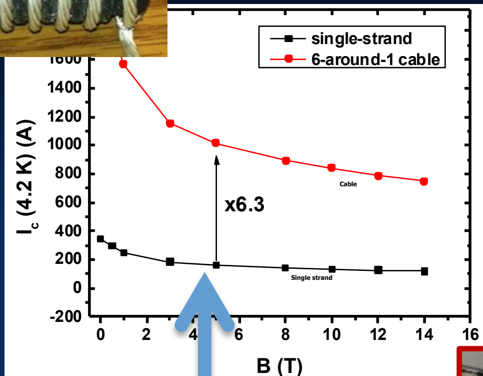
Transverse Merge





MASS identified extension of the 6D cooling concepts and modification of Final Cooling scheme to be one of most likely areas of performance improvement

Cooling Technology R&D

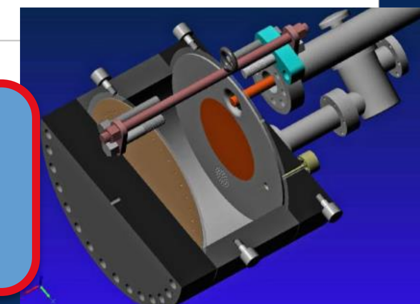


Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

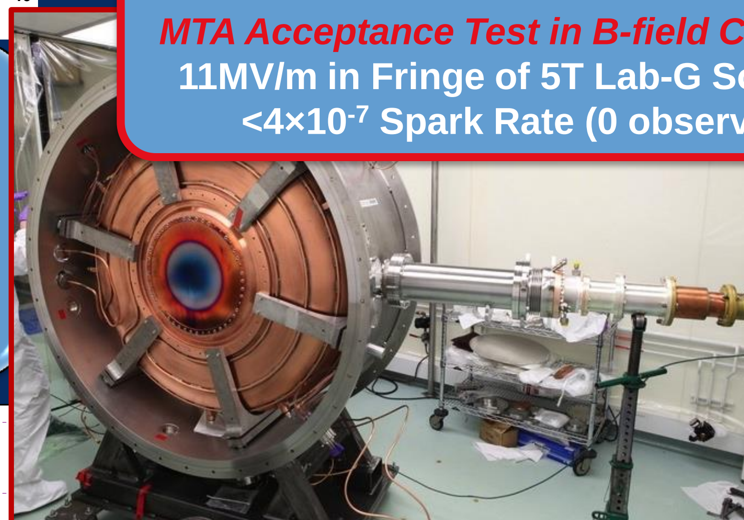
FNAL-Tech Div
T. Shen-Early Career Award

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

MuCool Test Area/Muons Inc



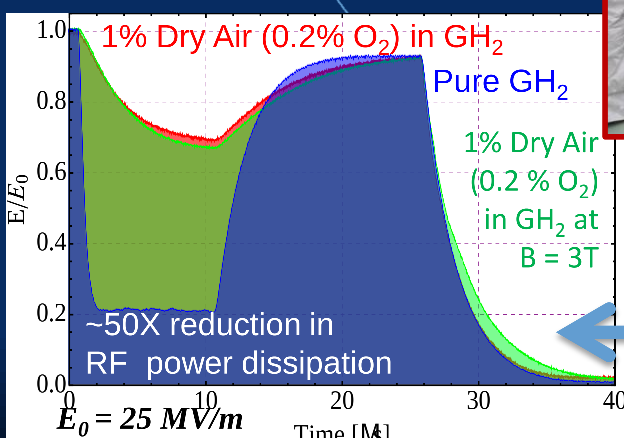
MICE 201 MHz RF Module –
MTA Acceptance Test in B-field Complete
11MV/m in Fringe of 5T Lab-G Solenoid
$<4\times10^{-7}$ Spark Rate (0 observed)



World Record HTS-only Coil

15T on-axis field (16T on coil)

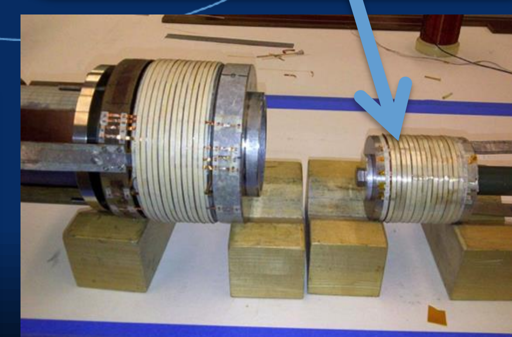
R. Gupta
PBL/BNL



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

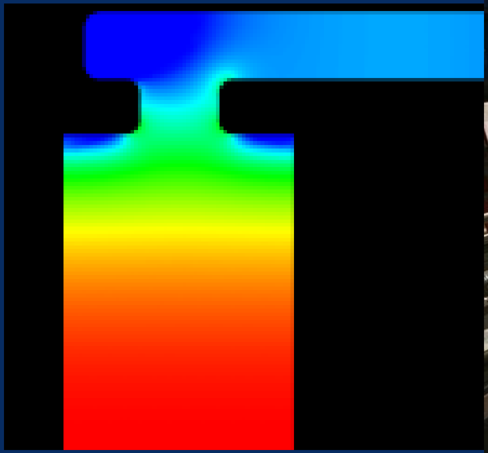
Extrapolates to required μ-Collider Parameters

MuCool Test Area



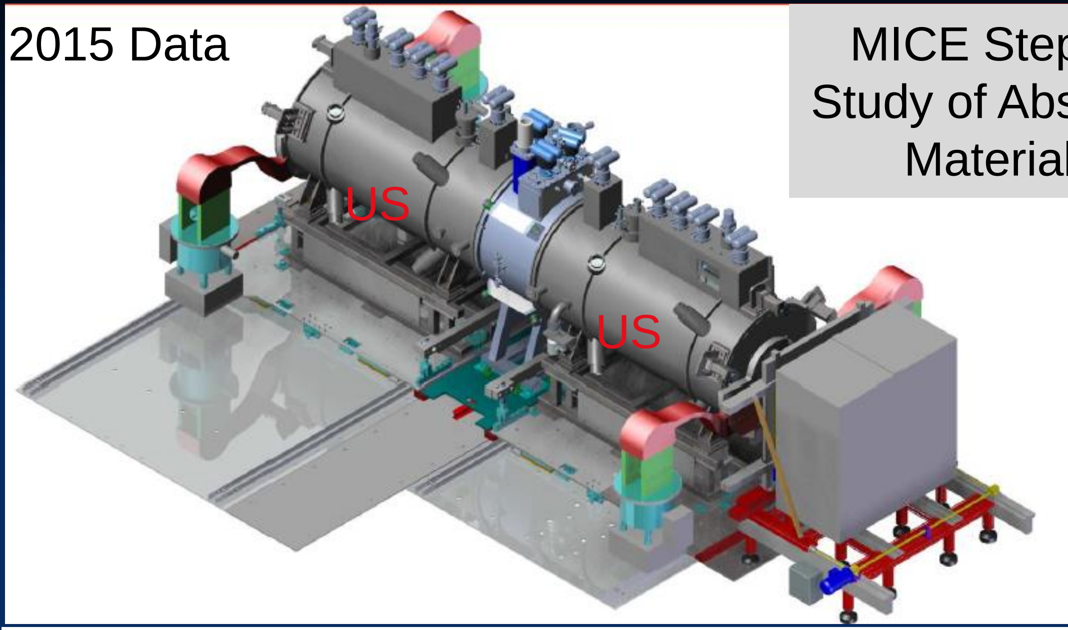
Cooling Technology R&D

- Cooling Technology Status
  - Magnets
    - MAP Initial Baseline Selection process has yielded 6D cooling baselines that do ***not*** require HTS magnets
    - HTS Solenoids may be required as part of a higher performance 6D Cooling Channel and for parts of the Final Cooling Channel
  - RF Cavities
    - The *successful test in magnetic field* of the MICE RF Module Prototype demonstrates
      - The importance of surface preparation
      - The importance of detailed simulation in magnetic field as part of the design process
    - High Pressure Gas-Filled RF Cavities provide a *demonstrated route to the required gradients with high intensity muon beams*
    - Recent results with vacuum RF cavities in magnetic field have shown results consistent with our physical models
      - **805 MHz "Modular" Cavity:** *A test vehicle to characterize breakdown effects in vacuum cavities*
        - » SCRF-style surface preparation
        - » Design optimized for use in magnetic field
        - » Data-taking has begun

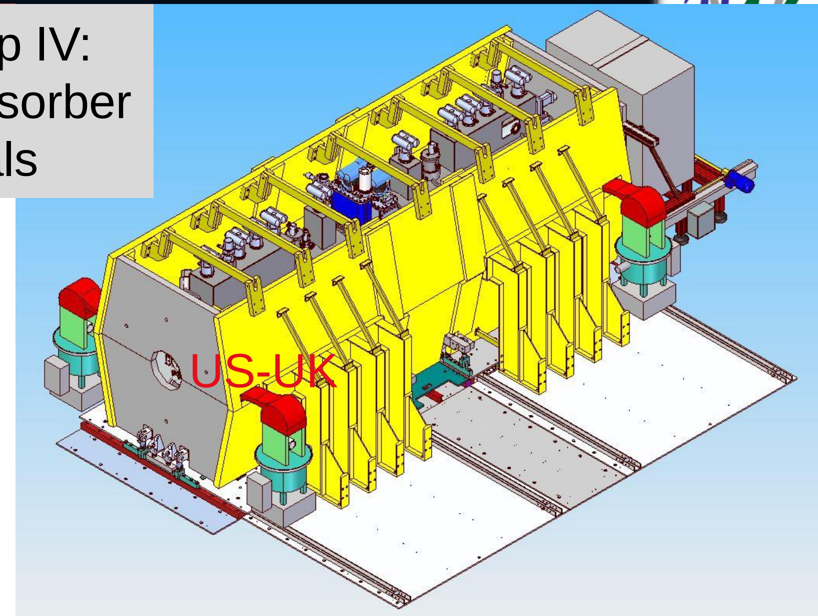


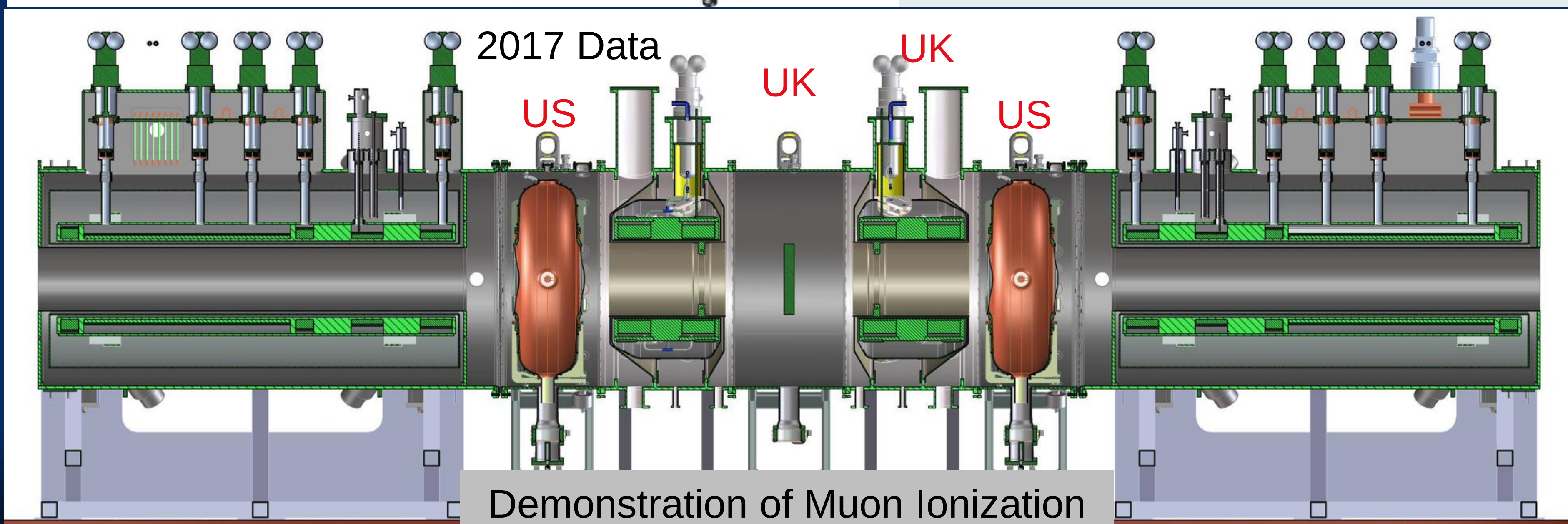
The MAP Feasibility Assessment aimed to provide a full 6D cell prototype for testing at high beam intensity in the MTA

MICE Demonstration @ RAL



MICE Step IV:
Study of Absorber Materials



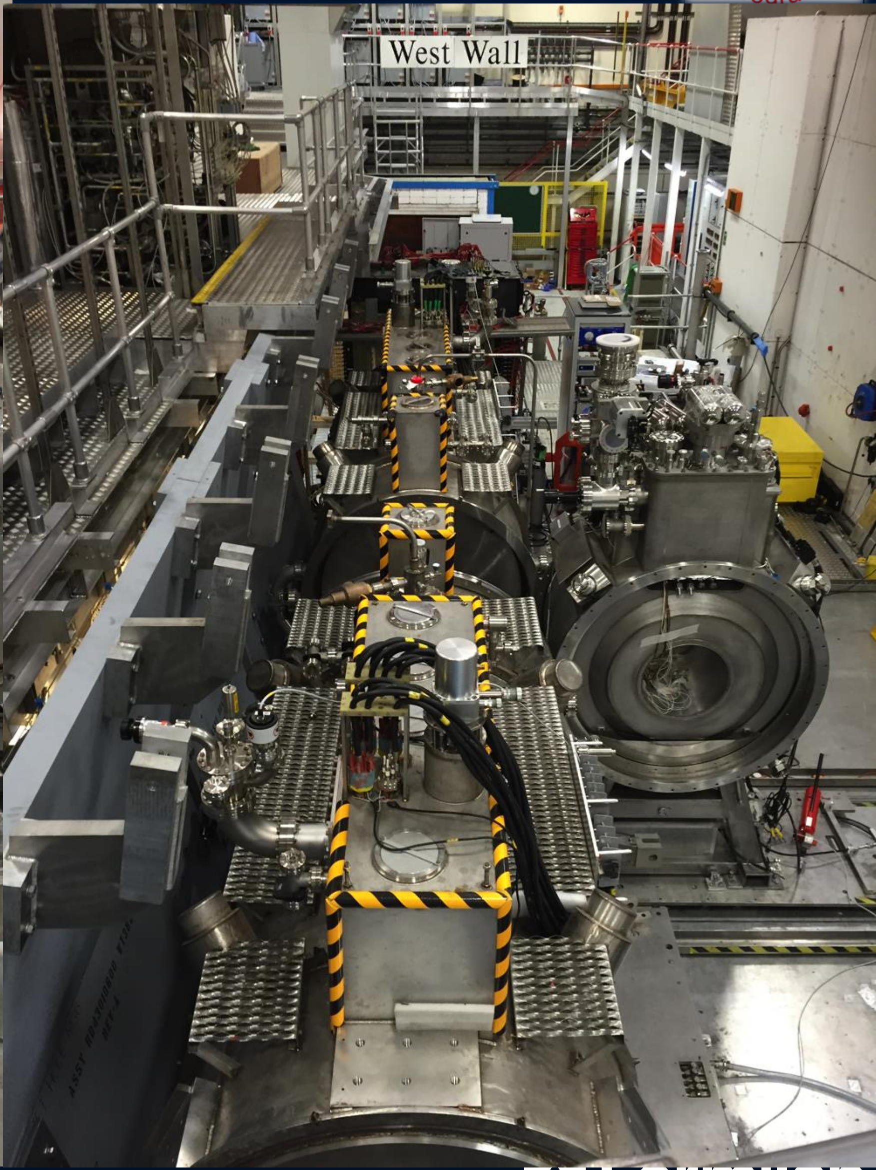


Demonstration of Muon Ionization Cooling (Re-baseline)

MICE Installation/Commissioning

Integration and Preliminary Commissioning Underway

Formal start of Channel Commissioning in June

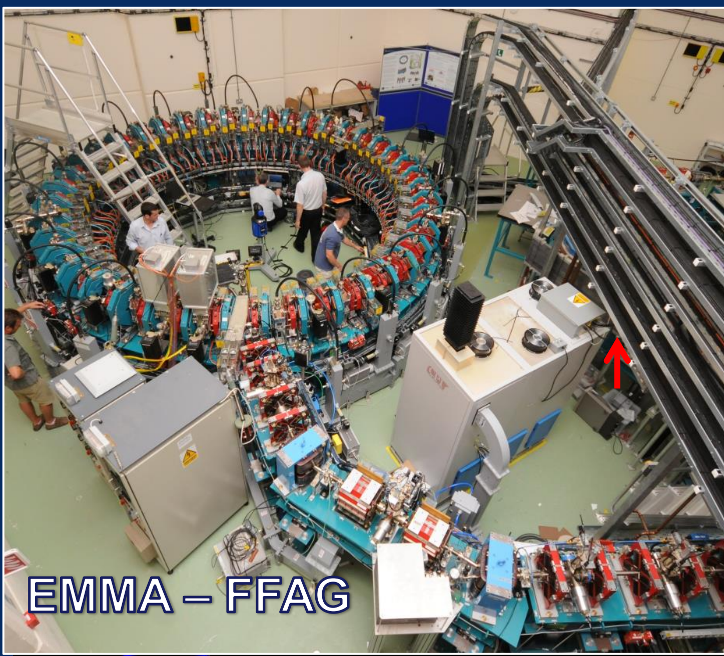


Technology Challenges - Acceleration

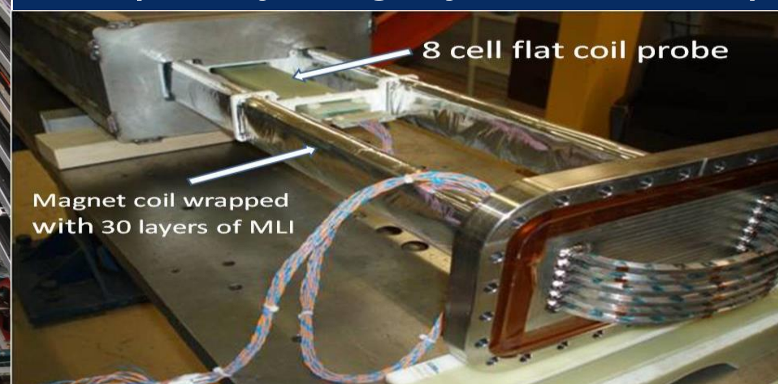
- Muons require an ultrafast accelerator chain

  ⇨ *Beyond the capability of "standard designs"*

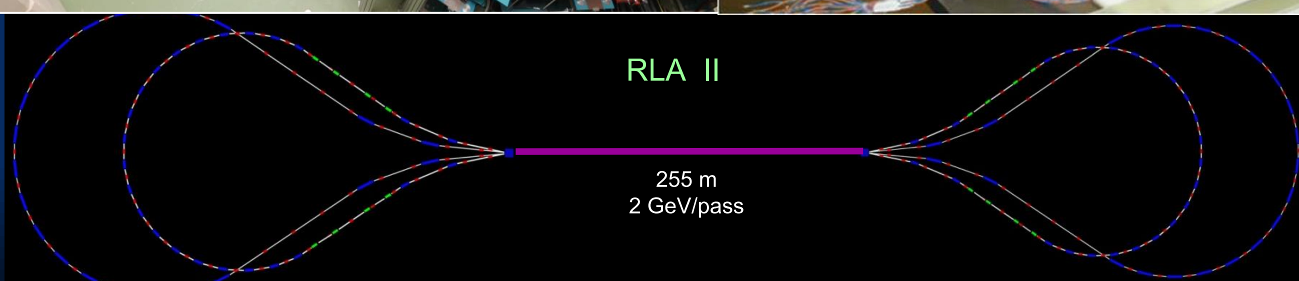
- Solutions include:



- Superconducting Linacs (NuMAX choice)
- Recirculating Linear Accelerators (RLAs)
- Fixed-Field Alternating-Gradient (FFAG) Rings
- Rapid Cycling Synchrotrons (RCS)



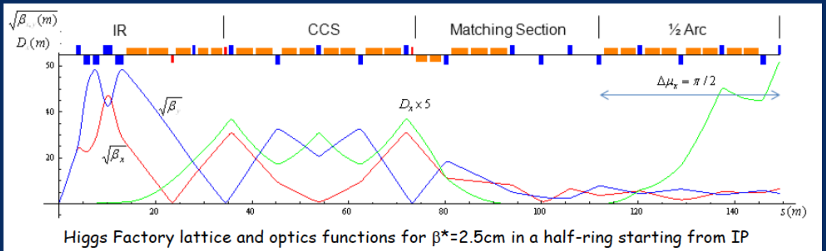
RCS requires
2 T p-p magnets
at f = 400 Hz
(U Miss & FNAL)



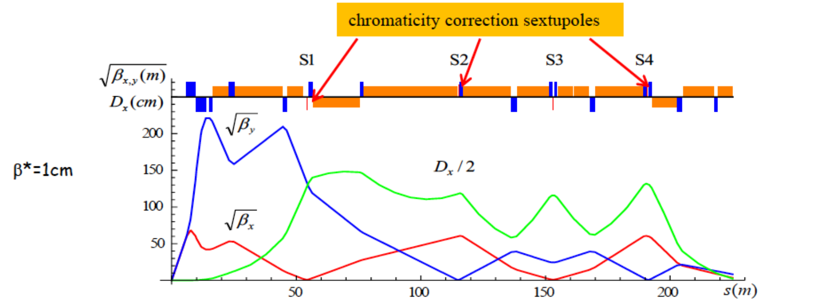
JEMMRLA Proposal:
JLAB Electron Model of
Muon RLA with Multi-pass
Arcs

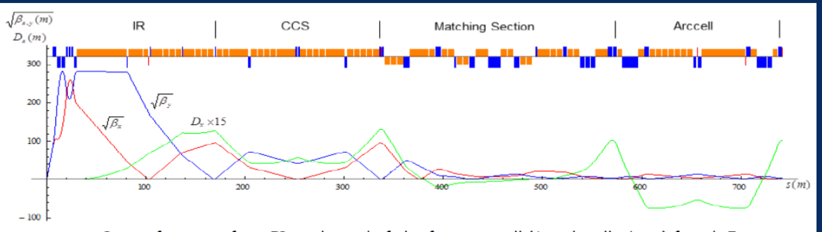
Muon Rings

- NF: nuSTORM and NuMAX designs
- Collider: Detailed optics studies for Higgs, 1.5 TeV, 3 TeV and now 6 TeV CoM
  - With supporting magnet designs and background studies
  - Detector occupancy similar to that seen in the LHC Luminoisty Upgrade

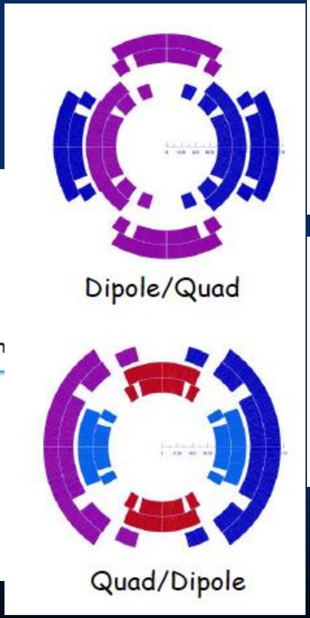


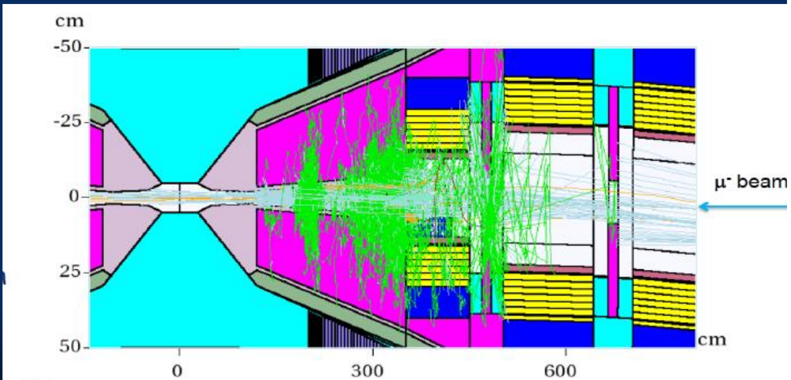
Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP





Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm





Particle tracks (> 0.1 - 0.5 MeV) for 15 mu- decays

CONCLUSION

Concluding Remarks

- Neutrino Factory capabilities offer a precision microscope that will likely be needed to fully probe the physics of the neutrino sector
- A multi-TeV muon collider may be the only cost-effective route to lepton collider capabilities at energies > 5 TeV
- For the last 3 years US Muon Accelerator Program has pursued options to deploy muon accelerator capabilities
  - Near-term (νSTORM)
  - Mid-term (NuMAX)
  - Long-term: a muon collider capability that would build on the NF complex

  and key technical hurdles have been addressed.
- In light of the 2014 P5 recommendations that this directed facility effort no longer fits within the budget-constrained US research portfolio, the US effort is entering a ramp-down phase

Nevertheless, muon accelerator capabilities offer unique potential for the future of high energy physics research