COOL'15

Workshop on Beam Cooling and Related Topics

Sept. 28 - Oct. 2, 2015

Jefferson Lab

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

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September 27, 2015

with acknowledgments to the MAP, MICE and IDS-NF Collaborations

Fermilab

Why Muons?

Physics Frontiers

- **Intense and cold muon beams ⇨ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos ⇨ **Neutrino Factories**
  - Next generation lepton collider

$$m_\mu = 105.7\, MeV/c^2$$
$$\tau_\mu = 2.2 \mu s$$

Colliders

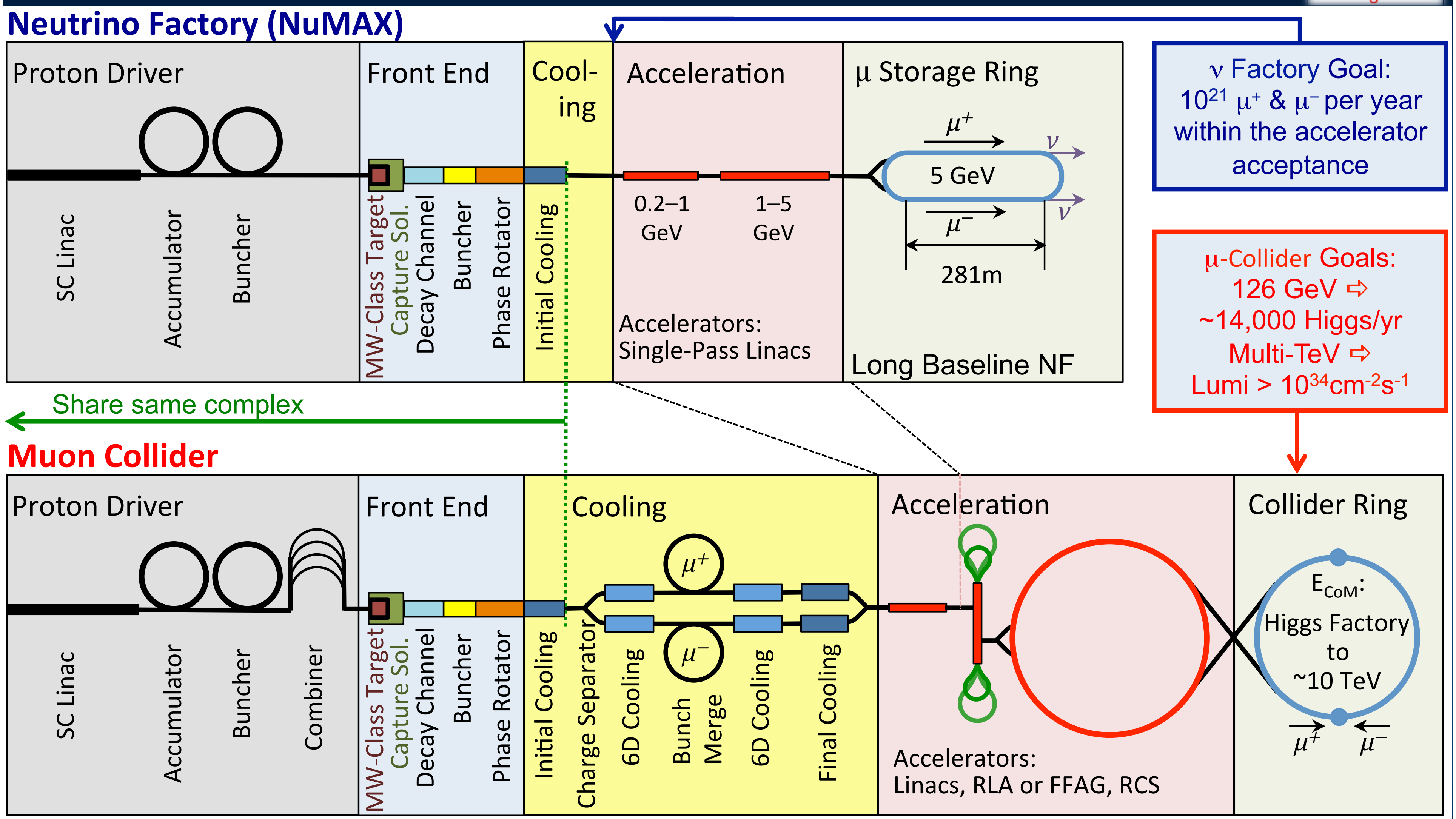
- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to the Higgs → $\sim \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times10^4$
  - Reduced synchrotron radiation ⇨ multi-pass acceleration feasible
  - Beams with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT* accelerator complex/detector must be able to handle the impacts of μ decay**

NF + Collider Synergies

- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations (Muon Accelerator Staging Study – MASS)

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

Muon Accelerator Capabilities for HEP



Outline

- The Muon Accelerator Program
- MAP Neutrino Factory Thrusts
  - Short baseline ⇨ νSTORM
  - Long Baseline ⇨ IDS-NF and **NuMAX**
- Beyond Neutrino Factories
  – Possibilities for a future Muon Collider Capabilities
  – Higgs Factory to >5 TeV
- Key Accomplishments of the MAP R&D Effort
- Conclusion

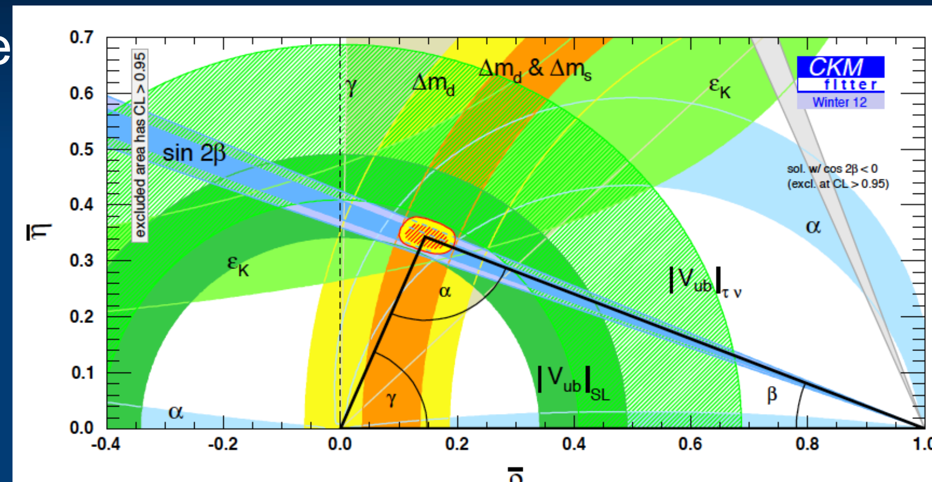
MAP Feasibility Assessment: 2012-2015

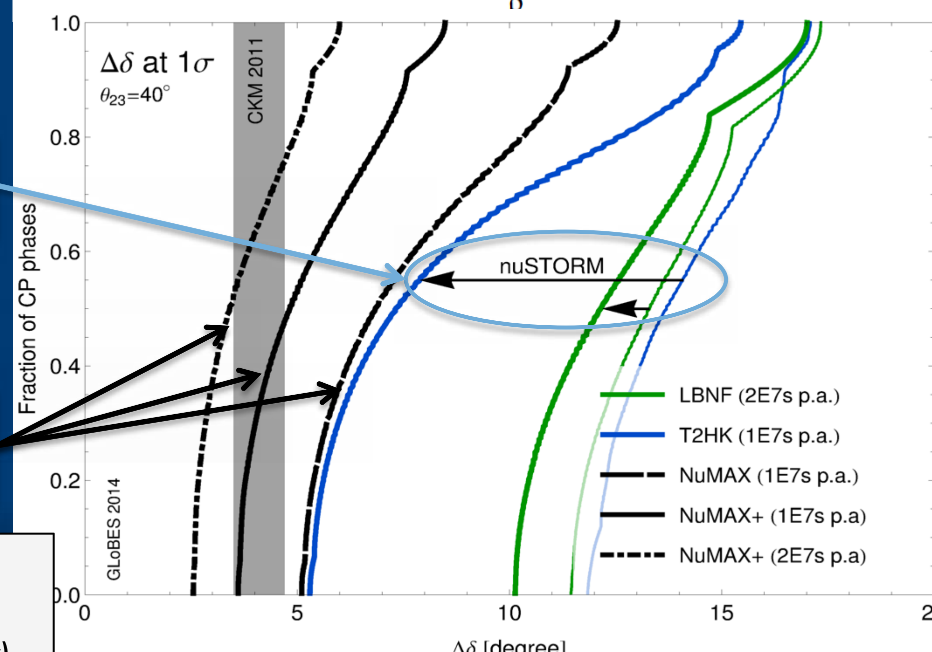
- Scope – *A focused effort to demonstrate feasibility*
  - Provide:
    - Baseline design concepts for each accelerator system (cf. block diagram on slide 3)
    - ⇨ Specifications for all required technologies to guide the R&D effort
  - For novel technologies:
    - Carry out the necessary design effort and technology R&D to assess feasibility
    - ***Note: a program of advanced systems R&D required after completion of the feasibility assessment***
  - Technology R&D and feasibility demonstrations have included:
    - MERIT@CERN (pre-MAP): Demonstration of high power liquid metal jet target concepts
    - MuCool Test Area (MTA) research program (FNAL): RF in high magnetic fields
    - Muon Ionization Cooling Experiment (MICE@RAL):
      - Demonstration of transverse cooling
      - Validation of cooling channel codes and parameters
    - Advanced magnet R&D
      - Very high field magnets (cooling channel and storage rings)
      - Rapid cycling magnets for acceleration of short-lived beams

MAP NEUTRINO FACTORY THRUSTS

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
  - <u>*And enable the search for new physics*</u>





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 observations in the coming years

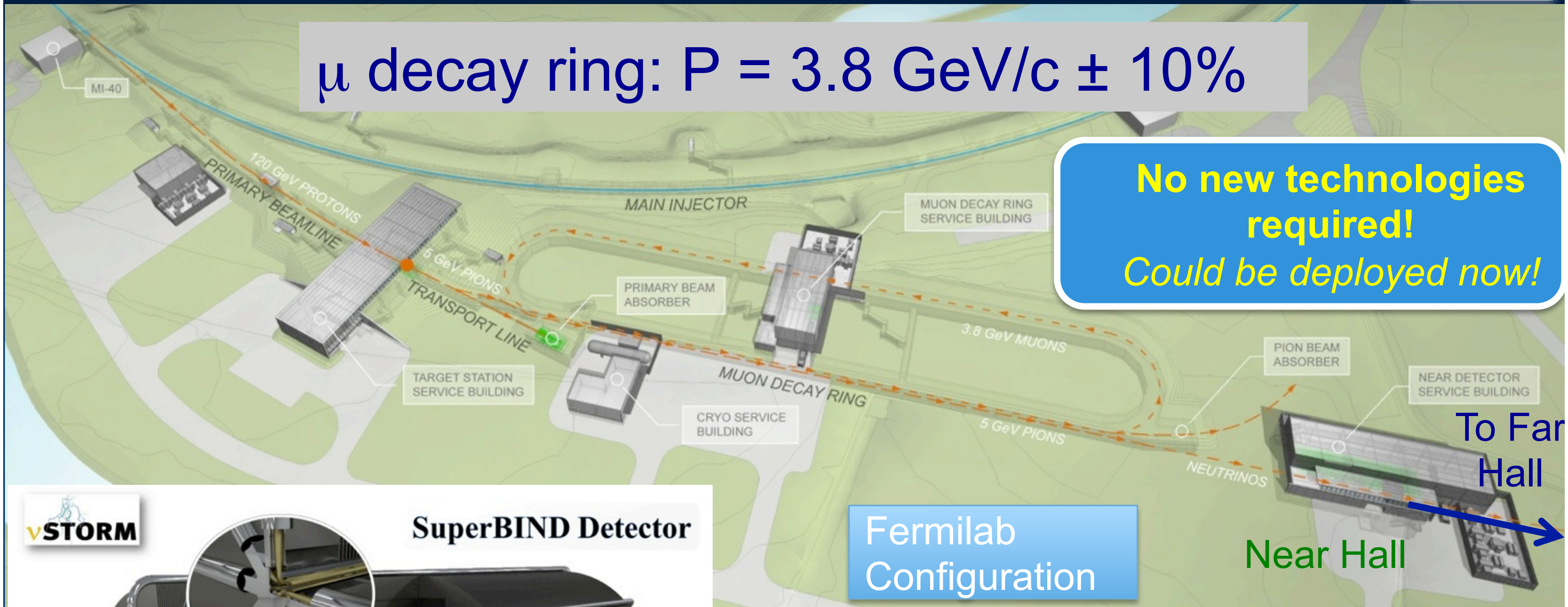
- *However, anomalies and new discoveries will drive our need for precision studies to develop a complete physical understanding*

- ***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*

νSTORM – *the First NF?*

μ decay ring: P = 3.8 GeV/c ± 10%

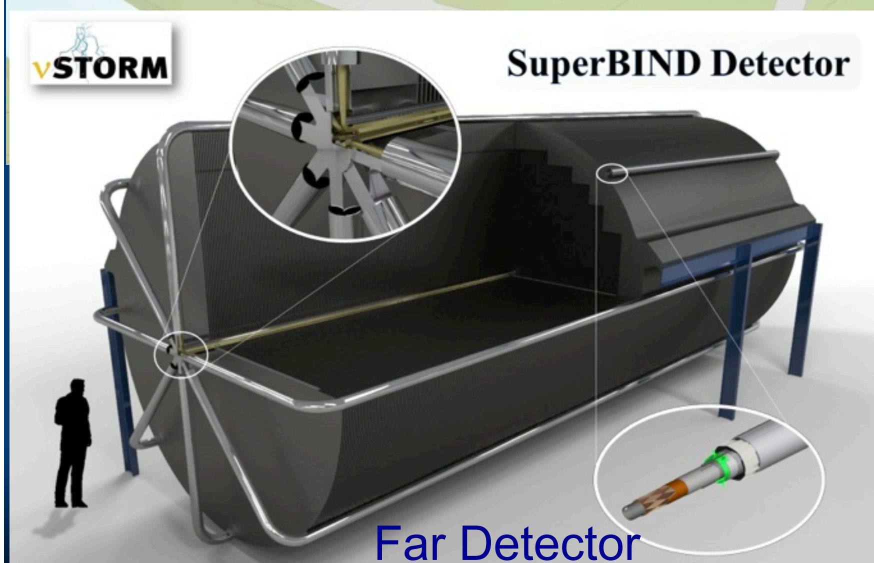


No new technologies required!
Could be deployed now!

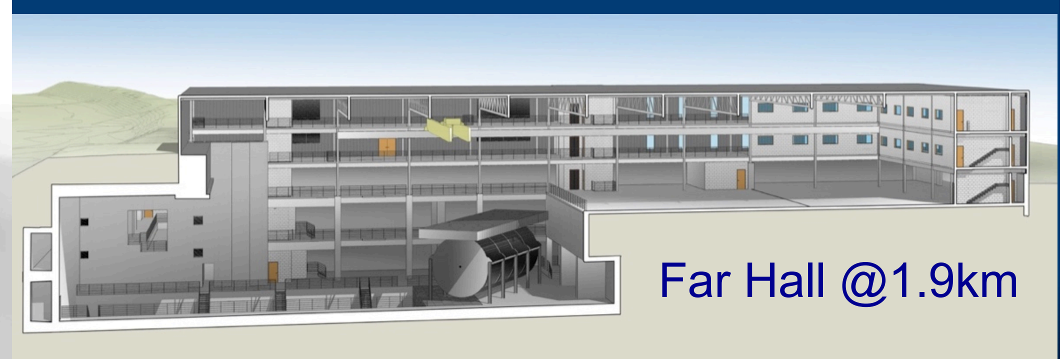
Fermilab Configuration

Near Hall

To Far Hall



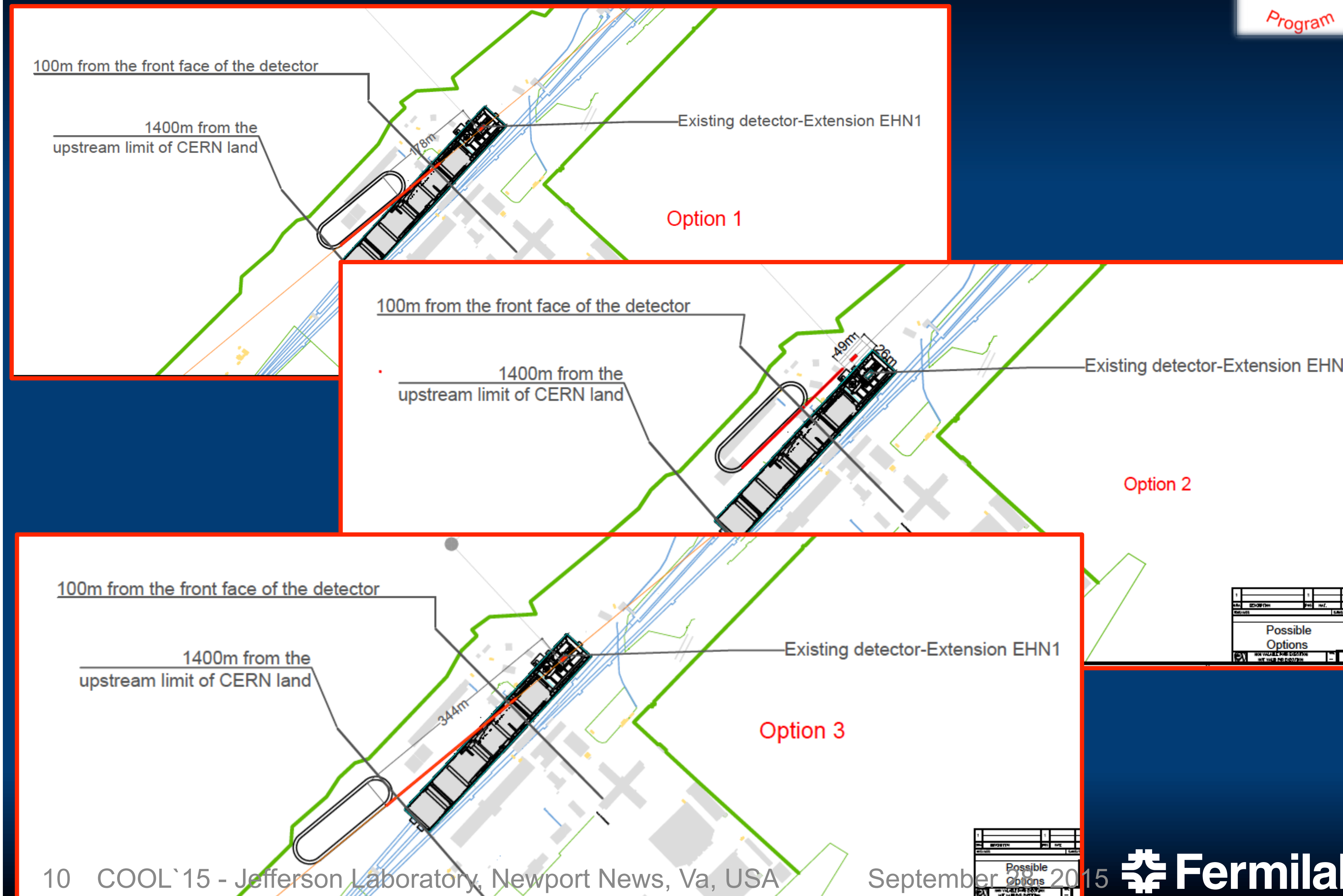
Far Detector



Far Hall @1.9km

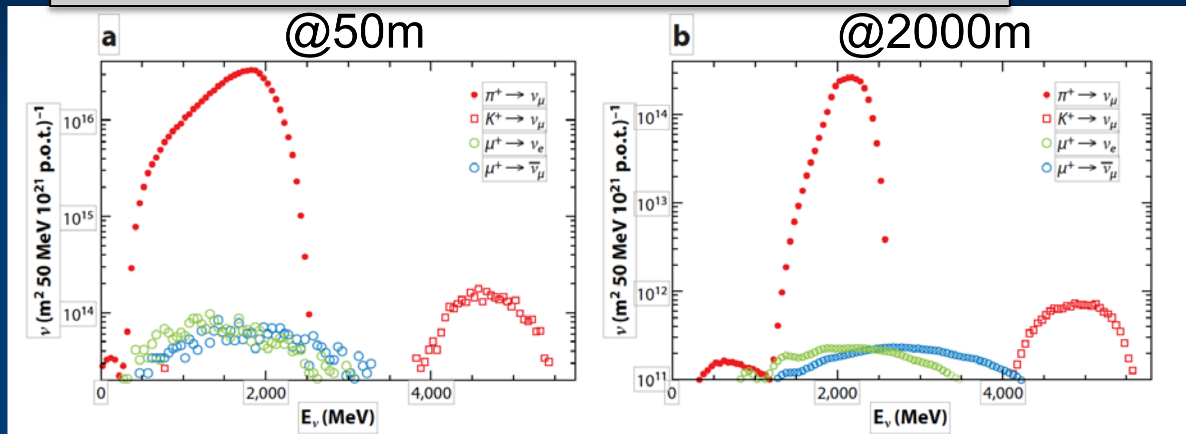
νSTORM Option for the CERN Neutrino Platform

under study: M. Nessi, et al.



ν Beams at nuSTORM

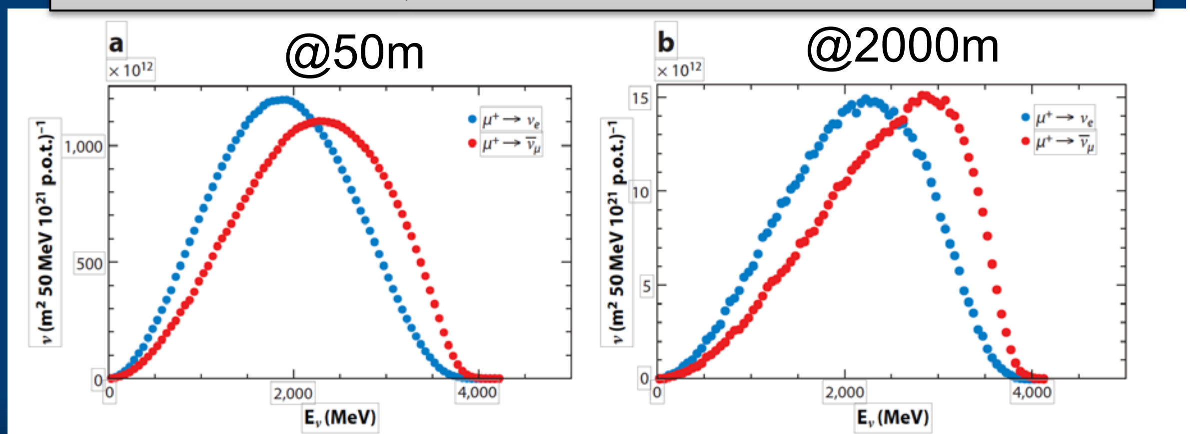
$\pi^+ \rightarrow \mu^+ + \nu_\mu$, π decays in injection straight



- ν beams from π decay at nuSTORM:
  High flavor purity with flux known to <1%

Now providing new concepts for higher purity beamlines for superbeam sources ⇨ NuPIL, enhanced MOMENT

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

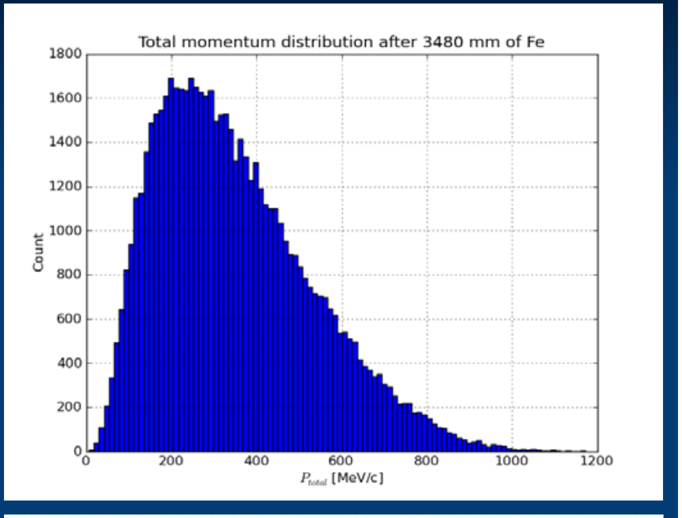


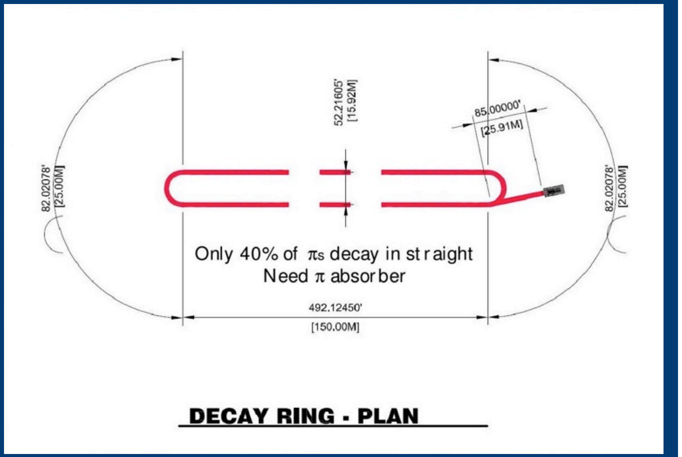
- ν beams from μ decay at nuSTORM:
  Absolute flavor purity with flux known to <1%

νStorm as an R&D platform

- A *high-intensity pulsed muon source* for accelerator R&D
  - 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

- A platform to test instrumentation for characterizing high intensity muon beams

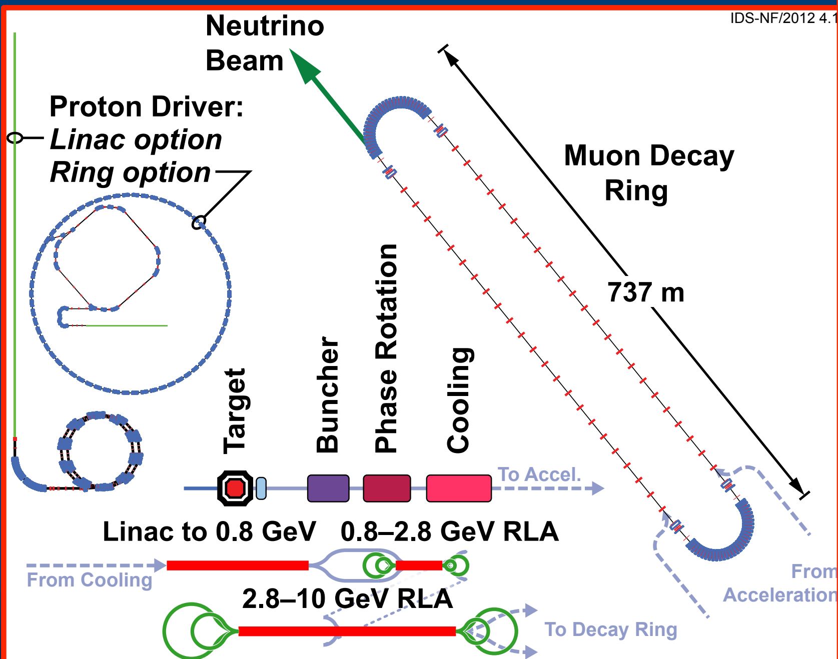




The Long Baseline Neutrino Factory

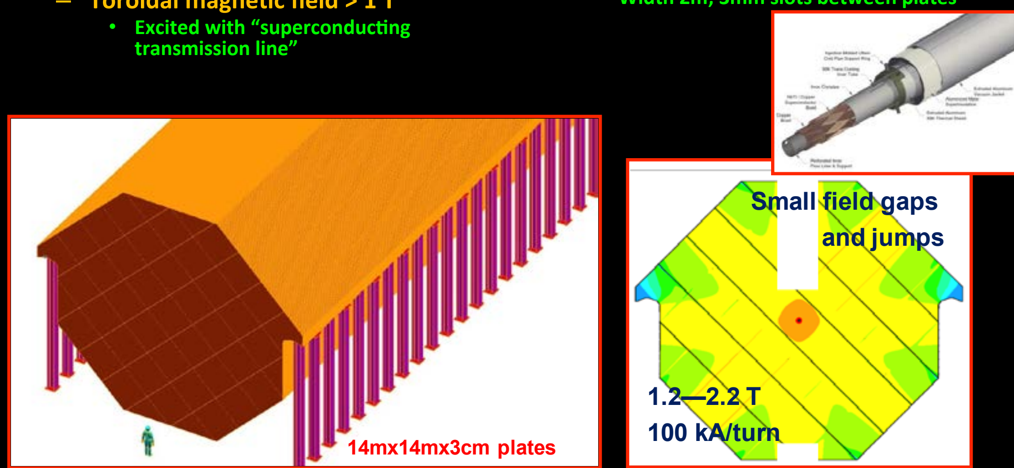
- IDS-NF: an *idealized* NF
- Muon Accelerator Staging Study:
  An incremental approach - NuMAX@5 GeV⇨SURF

	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



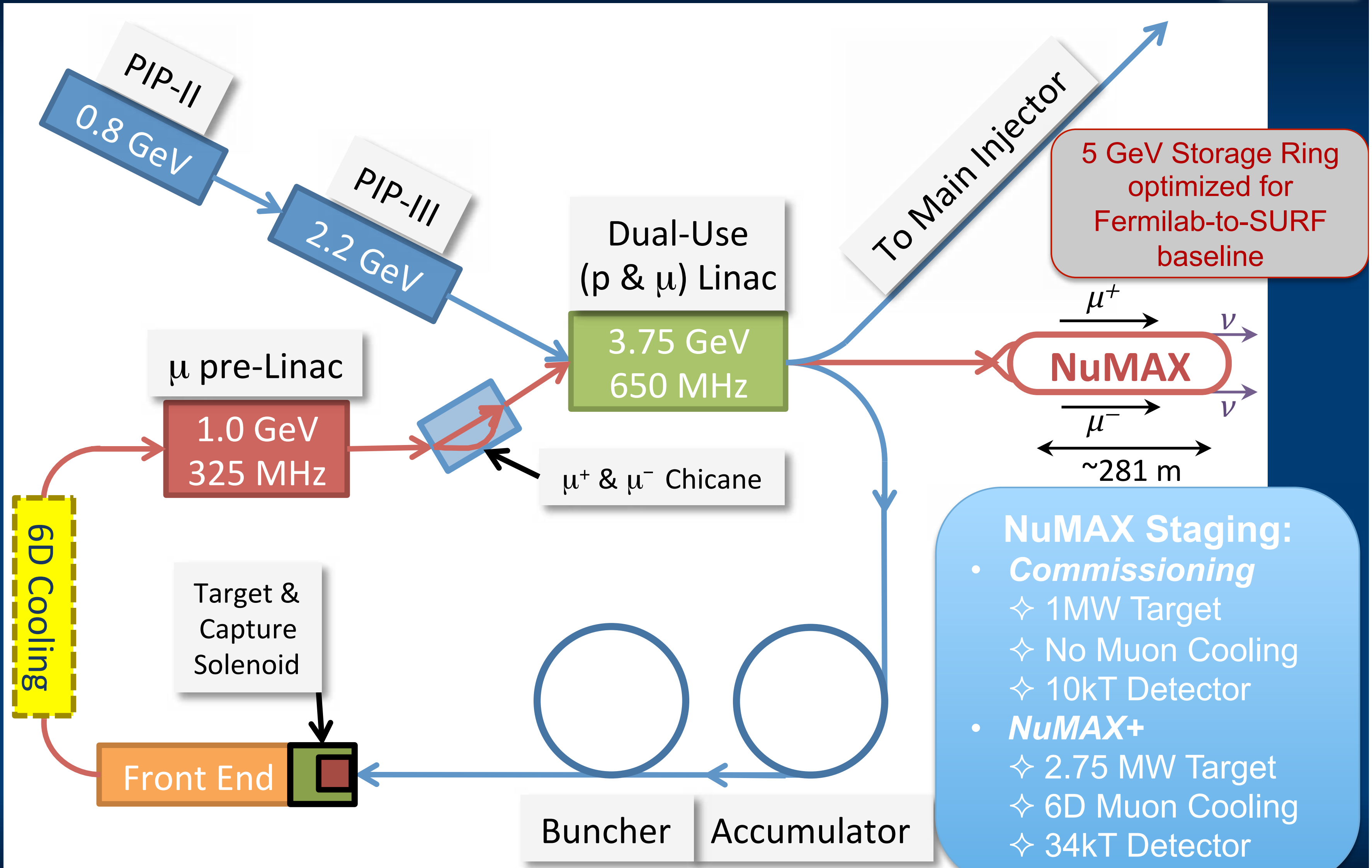
Magnetized Iron Neutrino Detector (MIND):

- **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 magnetic field > 1 T
    - Excited with "superconducting transmission line"
  - Segmentation: 3 cm Fe + 2 cm scintillator
  - 50-100 m long
  - Octagonal shape
  - Welded double-sheet
    - Width 2m; 3mm slots between plates



Bross, Soler

The MAP Muon Accelerator Staging Study ⇨ NuMAX



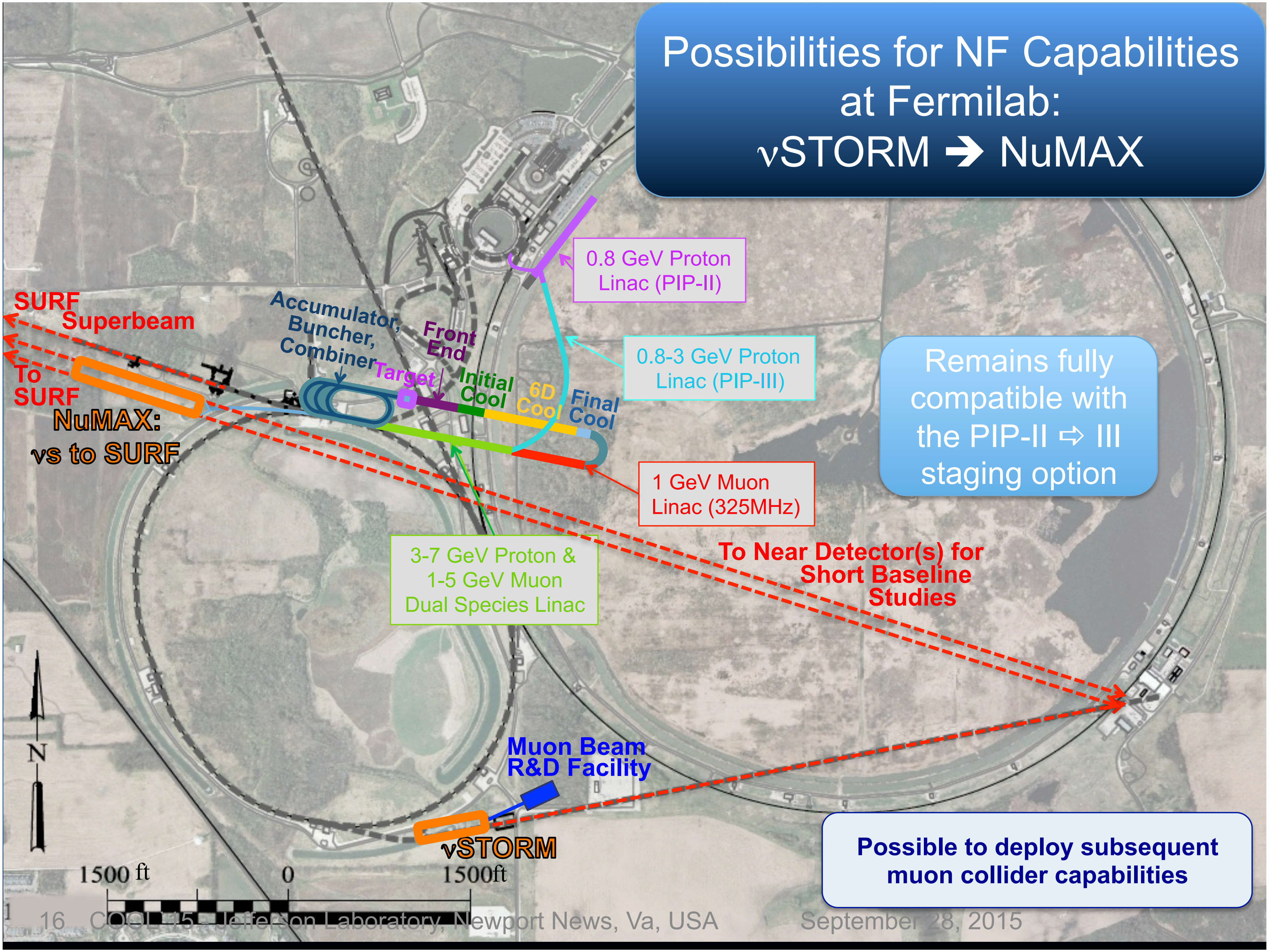
NuMAX Staging:
- ***Commissioning***
  - ✧ 1MW Target
  - ✧ No Muon Cooling
  - ✧ 10kT Detector
- ***NuMAX+***
  - ✧ 2.75 MW Target
  - ✧ 6D Muon Cooling
  - ✧ 34kT Detector

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



Remains fully compatible with the PIP-II ⇨ III staging option

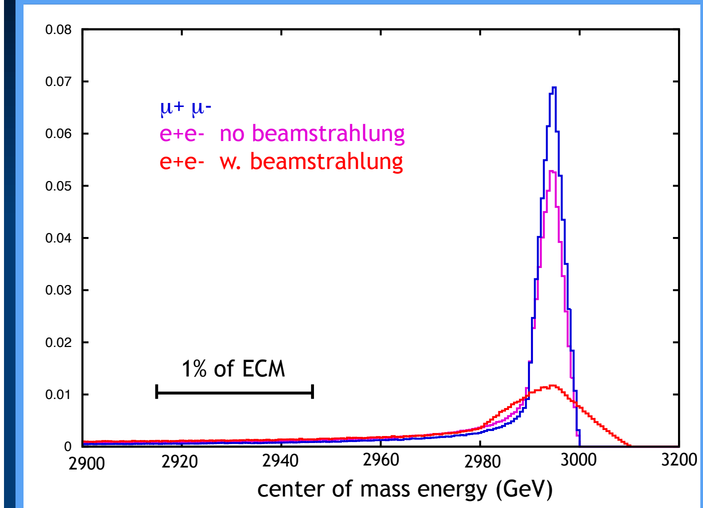
Possible to deploy subsequent muon collider capabilities

Summary of Neutrino Factory Thrusts

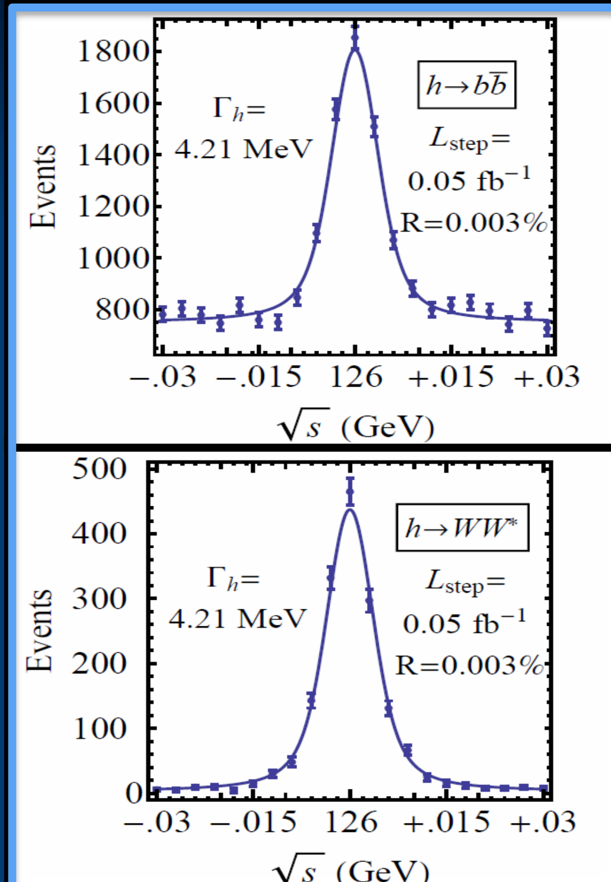
- ***Short Baseline NF***
  - nuSTORM
    - Definitive measurement of sterile neutrinos
    - Precision ν_e cross-section measurements (systematics issue for long baseline SuperBeam experiments)
    - *Beam line concept ⇨ higher purity beams for current experimental program*
    - HEP muon accelerator 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 1500-2500 km baselines
    - "Generic" design (ie, not site-specific)
  - NuMAX (Neutrinos from a Muon Accelerator CompleX)
    - Site-specific: FNAL ⇨ SURF (1300 km baseline)
    - 4-6 GeV beam energy optimized for CP studies
      - Flexibility to allow for other operating energies
    - Can provide an ongoing, high statistics, short baseline measurement option
    - Magnetized Detector
      - LAr is the goal but magnetized Fe provides equivalent CP sensitivity with ~3x the mass

GOING BEYOND NEUTRINO FACTORY CAPABILITIES

Collider Physics with $\mu^+\mu^-$

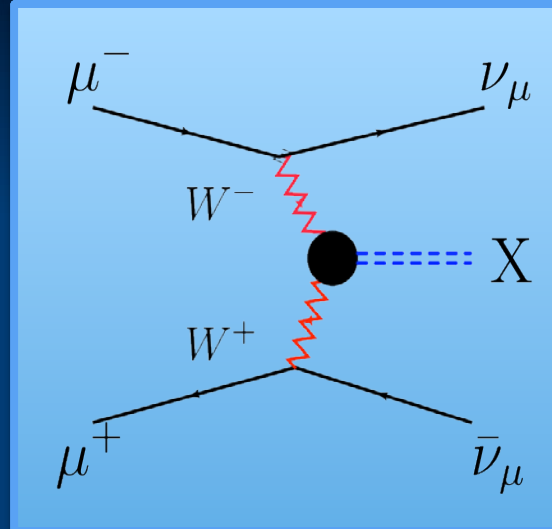


Effect of Beamstrahlung on CoM Energy Distribution at 3 TeV



Energy Resolution:

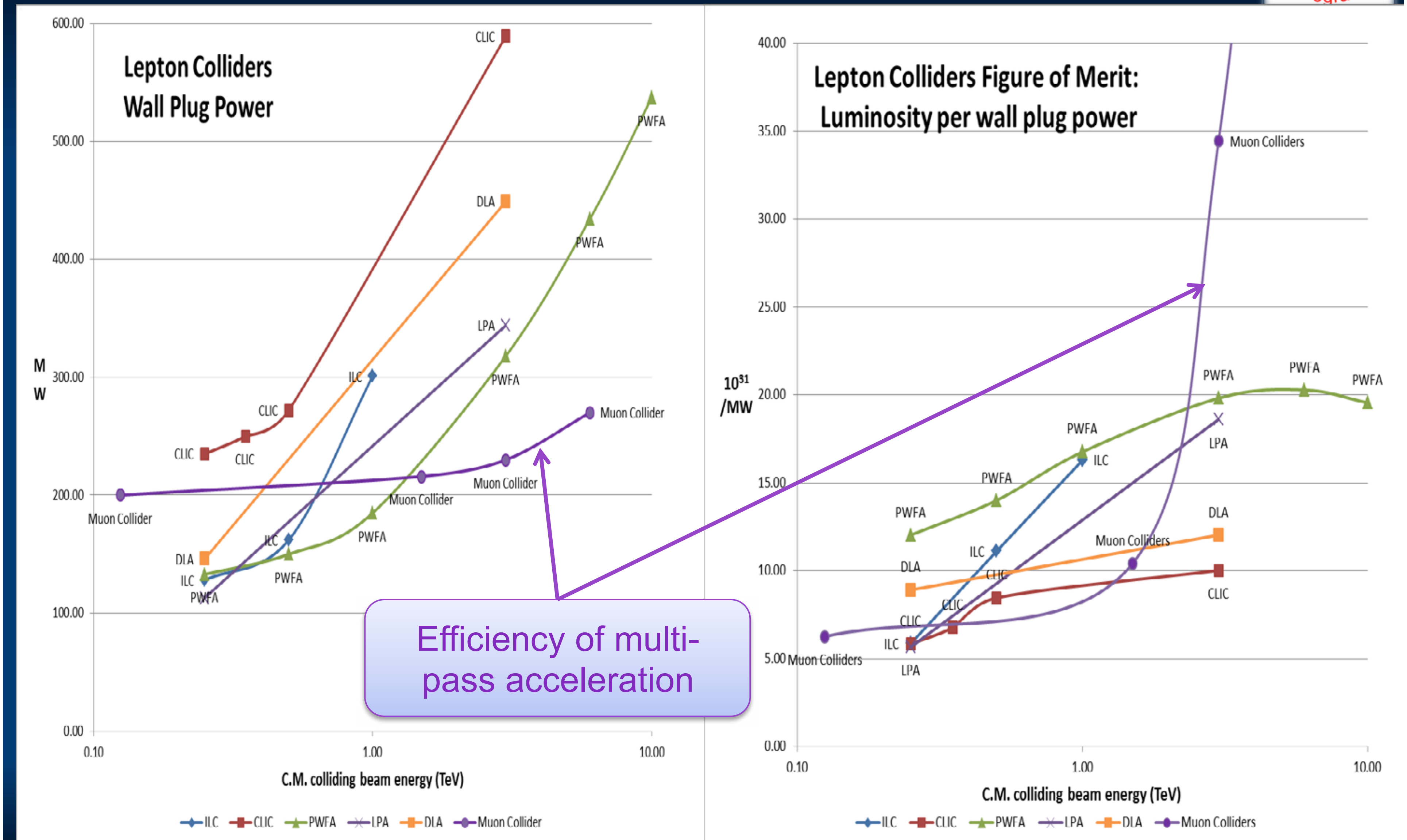
- $\delta E_b/E_b \sim 4\times10^{-5}$ @Higgs
- $\delta E_b/E_b \sim 1\times10^{-3}$ @TeV-scale

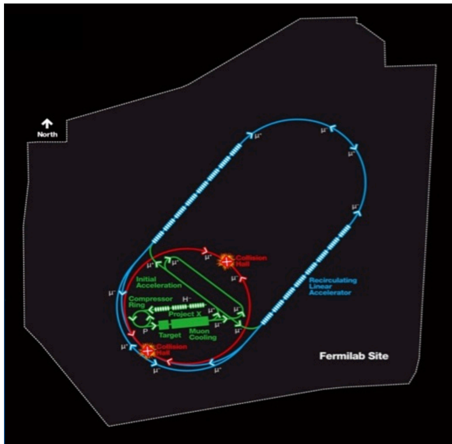


√s > 1 TeV: Fusion processes dominate

- EW Boson Collider
- Discovery machine complementary to very high energy pp
- At >5TeV: Higgs self-coupling resolution <10%

Muon Colliders –
Efficiency at the multi-TeV scale





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/10^7sec		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
β^*	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, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_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}

A number of detailed updates will be covered in COOL`15 talks and posters

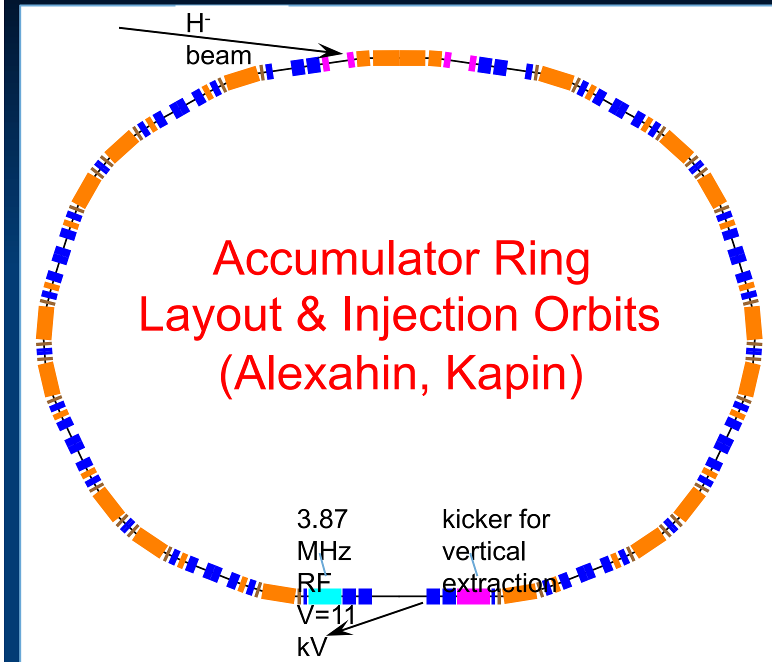
MUON ACCELERATOR R&D

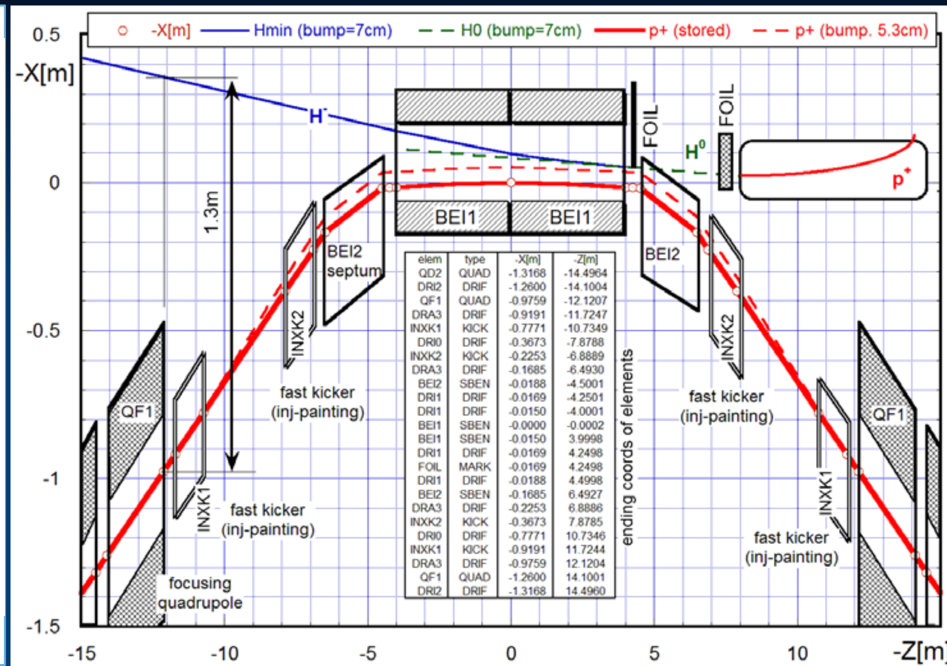
Key Accomplishments

Critical Feasibility Issues

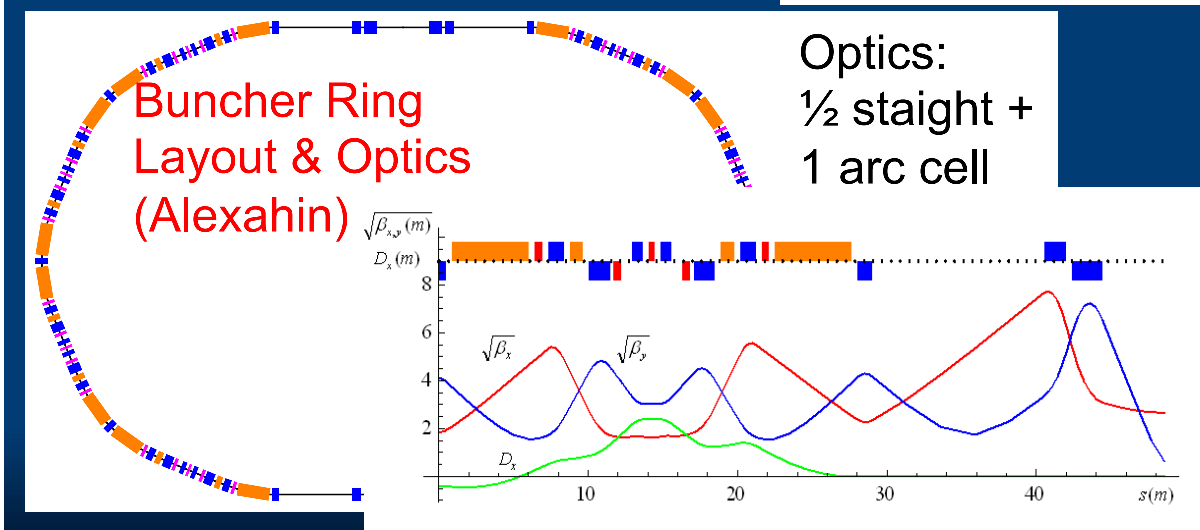
- Proton Driver
- Target — High Power Target Station; Capture Solenoid
- Front End — Energy Deposition
- Cooling — RF in Magnetic Fields; Magnet Requirements (Nb_3Sn vs HTS)
- Acceleration — >400 Hz AC Magnets
- Collider Ring — IR Magnet Strengths/Apertures
- MDI — SC Magnet Heat Loads (μ decay)
- Detector — Backgrounds (μ decay)

Proton Driver



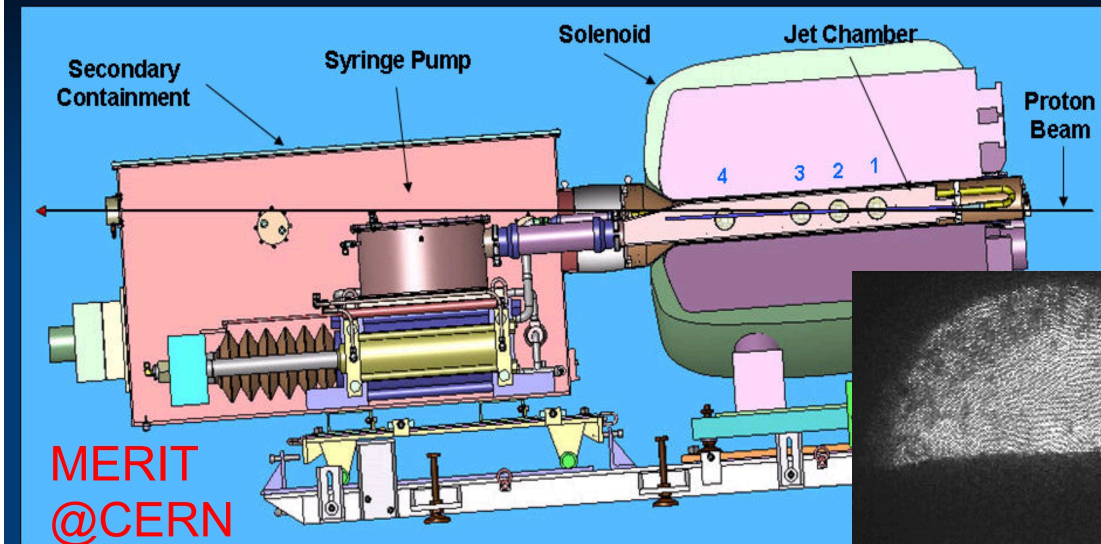


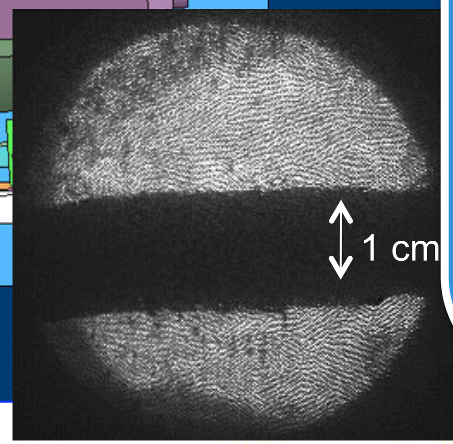
elem	type	-X[m]	-Z[m]
QD2	QUAD	-1.3168	-14.4964
DRI2	DRIF	-1.2600	-14.1004
QF1	QUAD	-0.9759	-12.1207
DRA3	DRIF	-0.9191	-11.7247
INXK1	KICK	-0.7771	-10.7349
DRI0	DRIF	-0.3673	-7.8788
INXK2	KICK	-0.2253	-6.8889
DRA3	DRIF	-0.1685	-6.4930
BEI2	SBEN	-0.0188	-4.5001
DRI1	DRIF	-0.0169	-4.2501
DRI1	DRIF	-0.0150	-4.0001
BEI1	SBEN	-0.0000	-0.0002
BEI1	SBEN	-0.0150	3.9998
DRI1	DRIF	-0.0169	4.2498
FOIL	MARK	-0.0169	4.2498
DRI1	DRIF	-0.0188	4.4998
BEI2	SBEN	-0.1685	6.4927
DRA3	DRIF	-0.2253	6.8886
INXK2	KICK	-0.3673	7.8785
DRI0	DRIF	-0.7771	10.7346
INXK1	KICK	-0.9191	11.7244
DRA3	DRIF	-0.9759	12.1204
QF1	QUAD	-1.2600	14.1001
DRI2	DRIF	-1.3168	14.4960



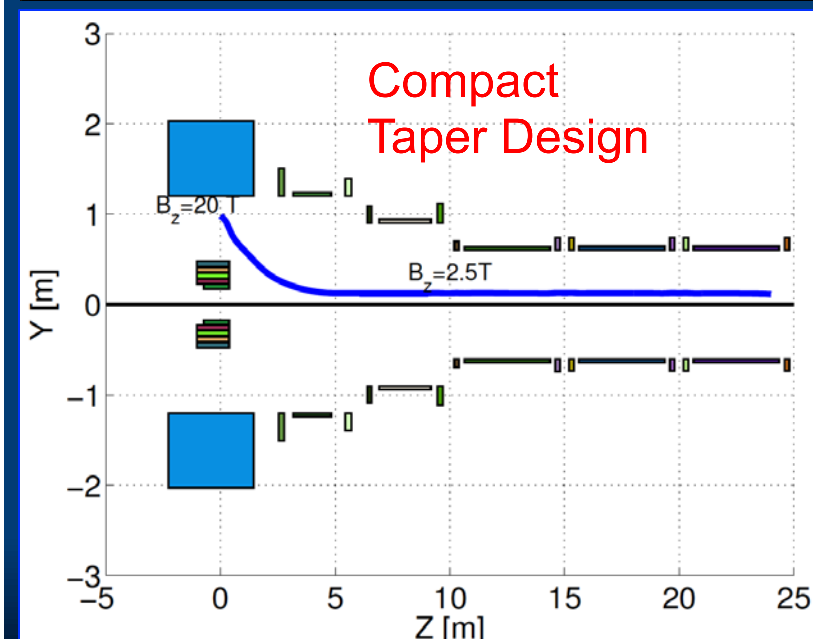
- ✓ Based on 6-8 GeV Linac Source
- ✓ Accumulator & Buncher Ring Designs in hand
- ✓ H- stripping requirements same as those established for Fermilab's Project X

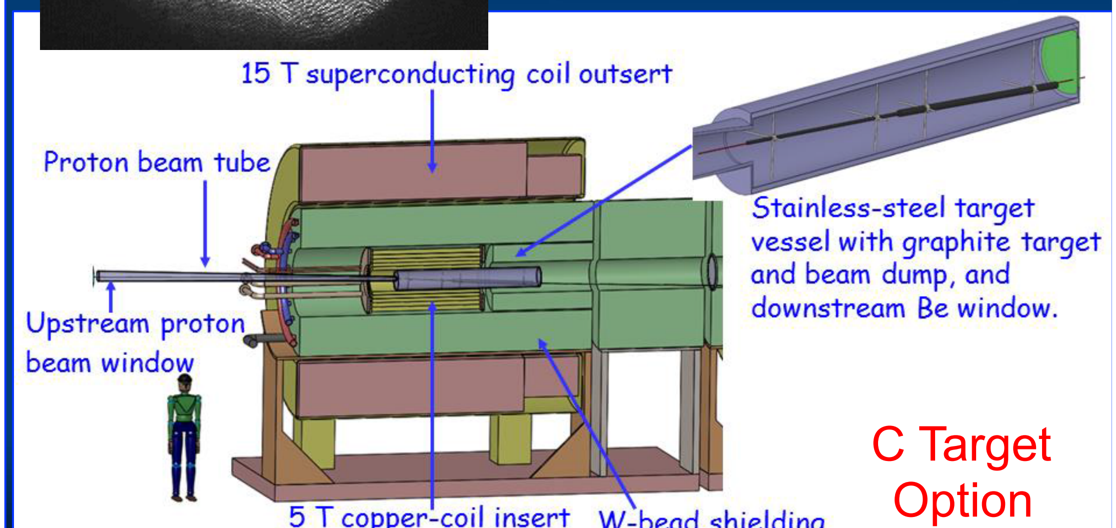
High Power Target





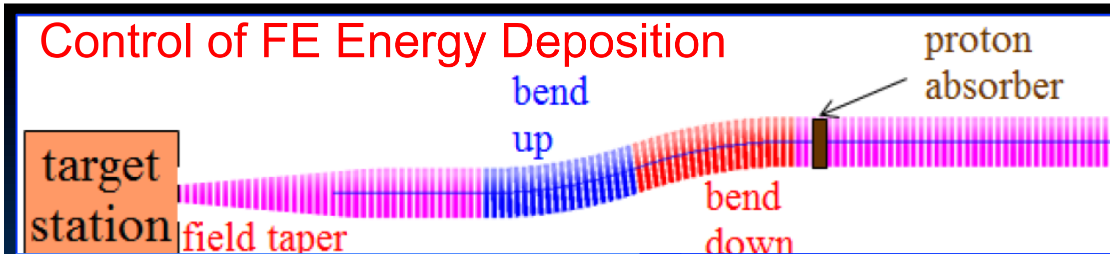
- ✓ MERIT Expt:
  - LHg Jet in 15T
  - Capability: 8MW @70Hz
- ✓ MAP Staging aims at 1-2 MW ⇨ C Target
- ✓ Improved Compact Taper Design
  - Performance & Cost

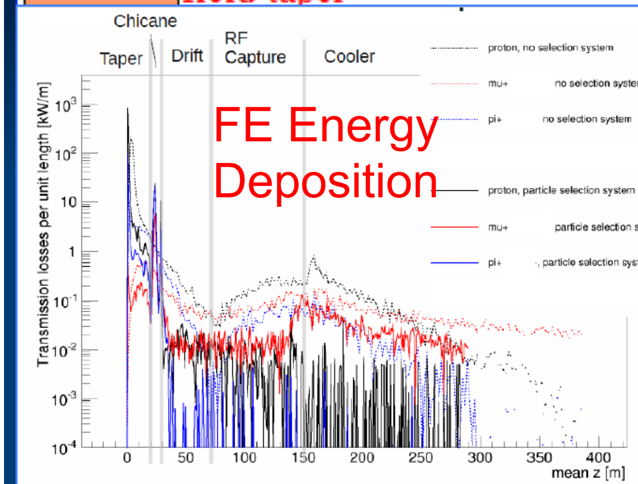


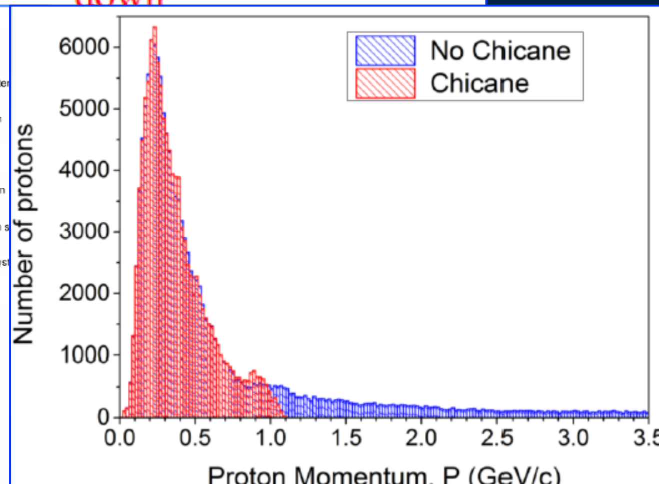


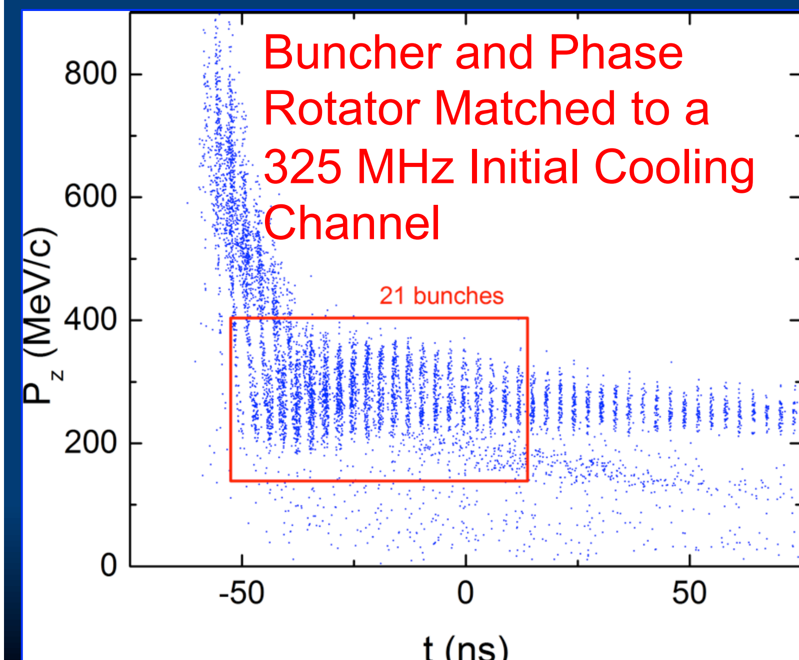
Front End

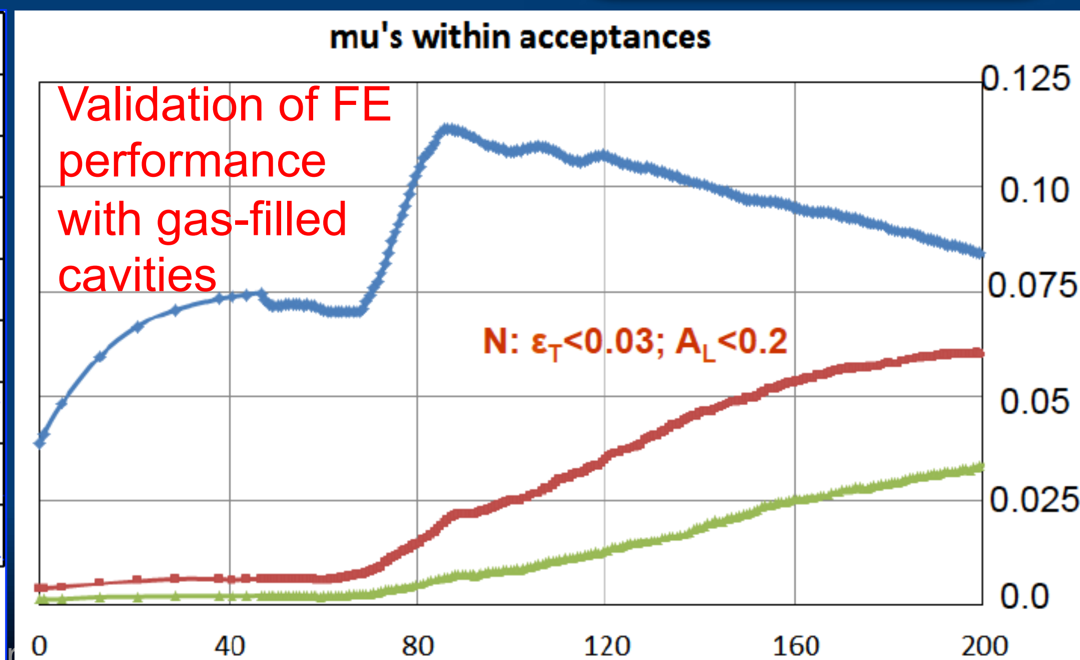
- ✓ Energy Deposition
- ✓ Full 325 MHz RF Design
- ✓ Validation of gas-filled RF cavity performance



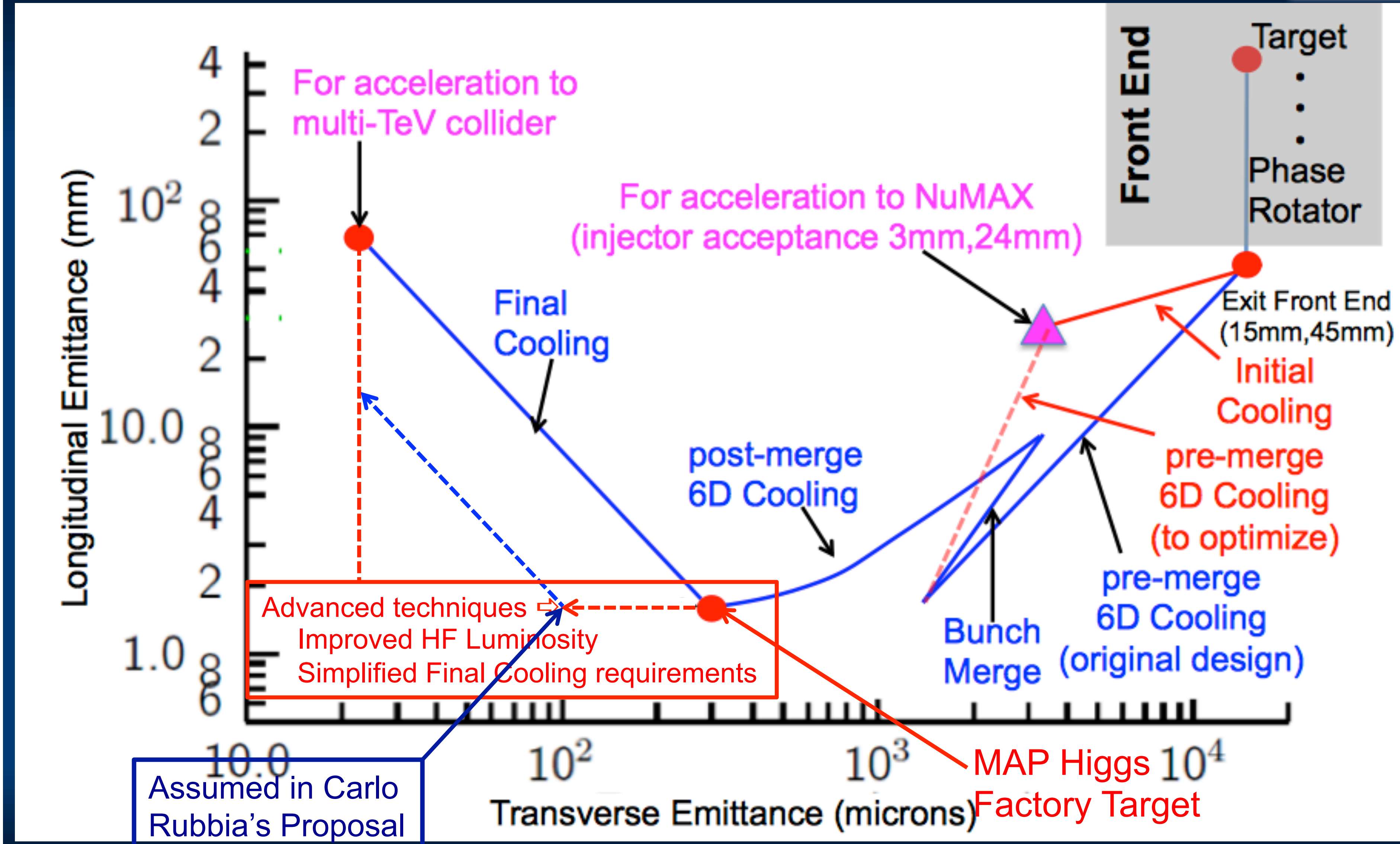




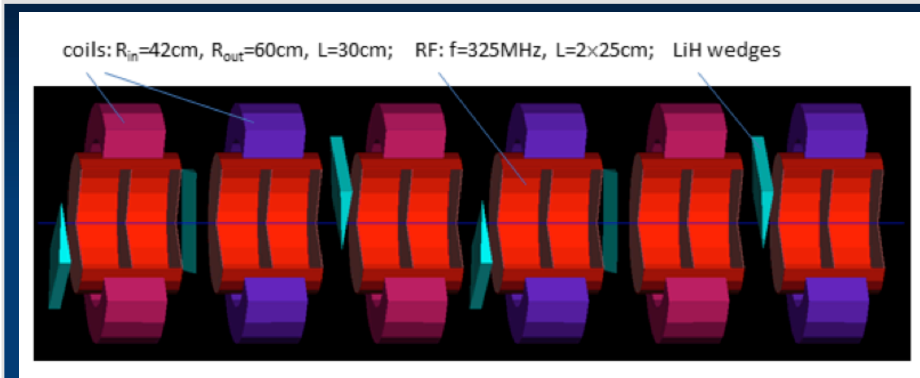


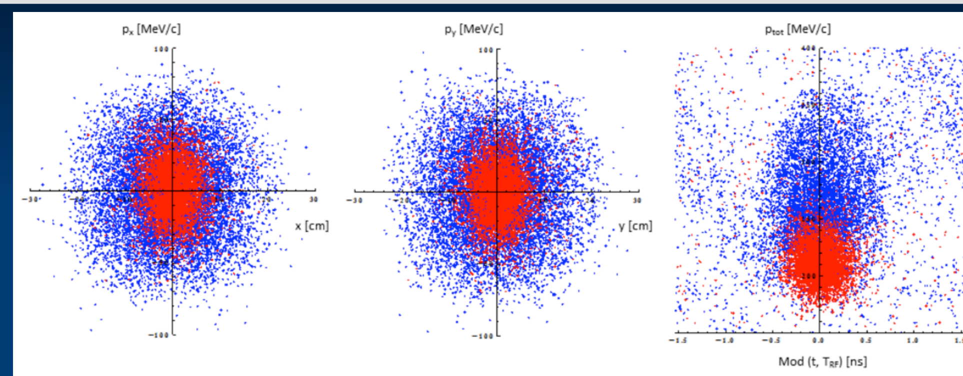


Muon Ionization Cooling

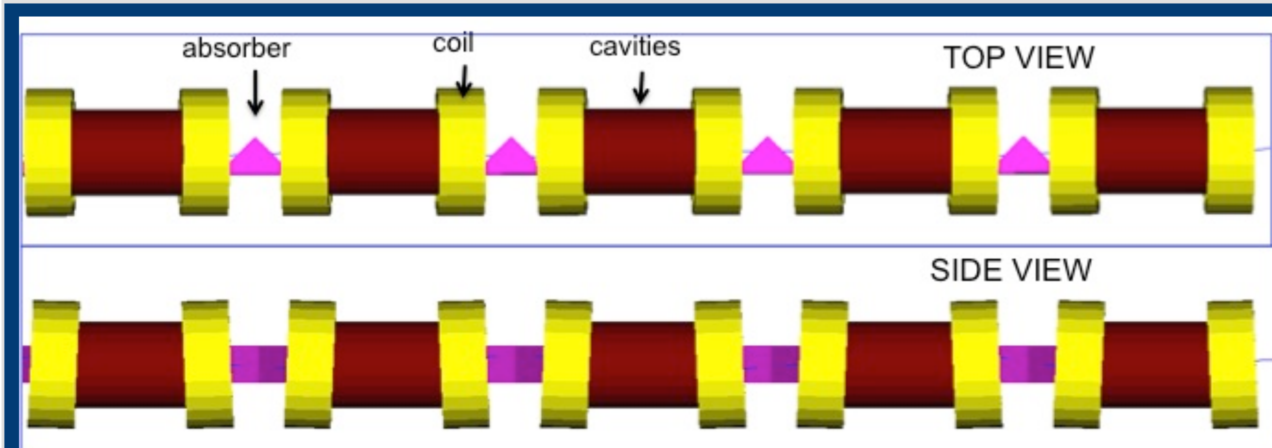


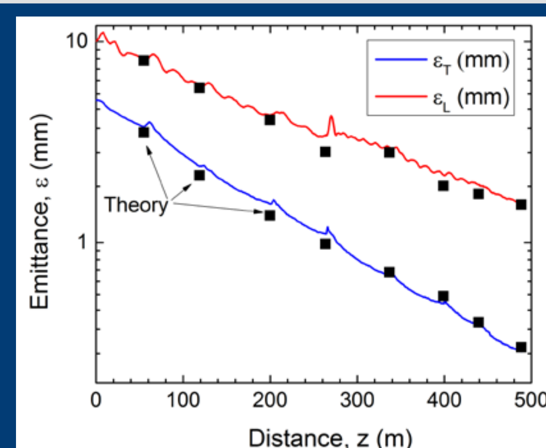
Muon Ionization Cooling (Design)





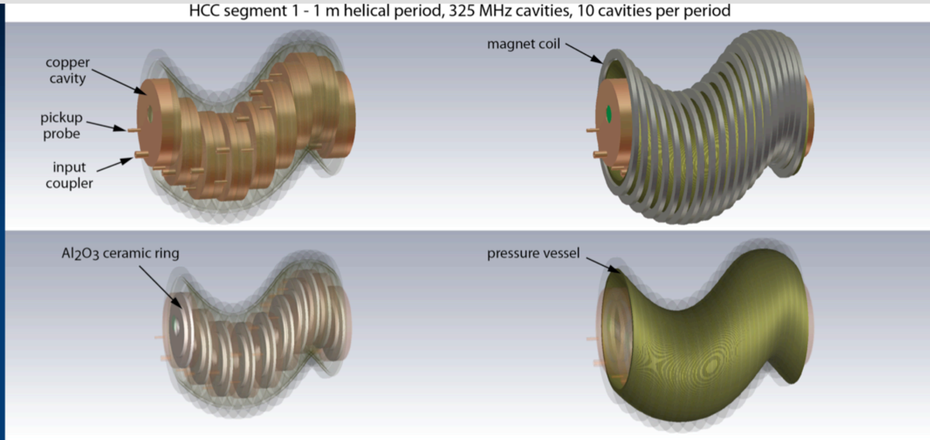
Initial 6D Cooling: ε_{6D} 60 cm^3 ➪ ~50 mm^3; Trans = 67%

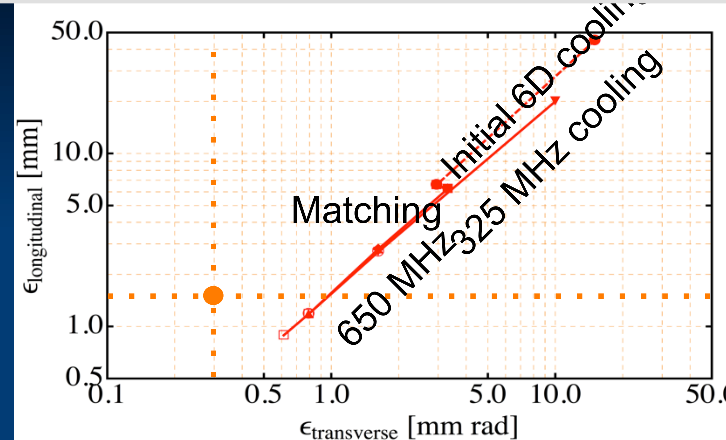




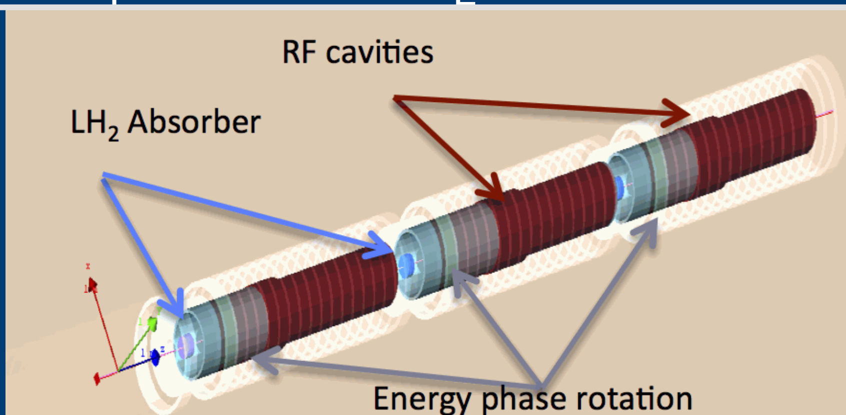
6D Rectilinear Vacuum Cooling Channel (replaces Guggenheim concept):
ε_T = 0.28mm, ε_L = 1.57mm @488m
Transmission = 55%(40%) without(with) bunch recombination

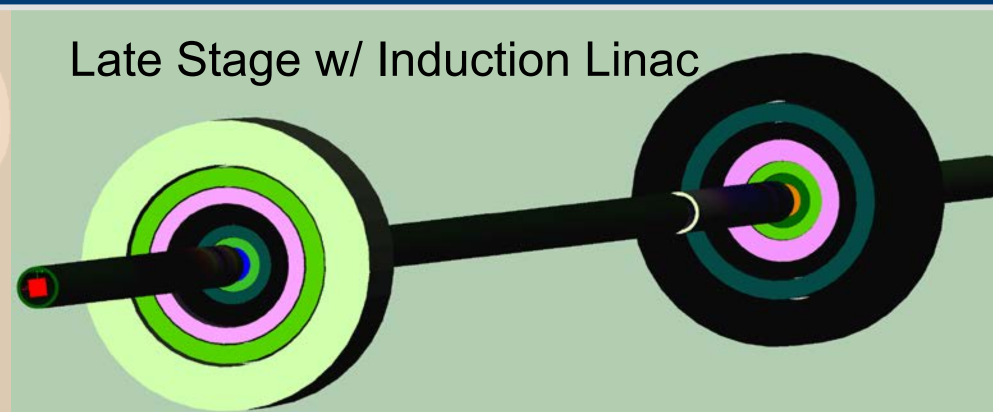
Muon Ionization Cooling (Design)





- Helical Cooling Channel (Gas-filled RF Cavities):
  ε_T = 0.6mm, ε_L = 0.3mm





- Final Cooling with 25-30T solenoids (emittance exchange):
  ε_T = 55μm, ε_L = 75mm

Muon Ionization Cooling (Design)

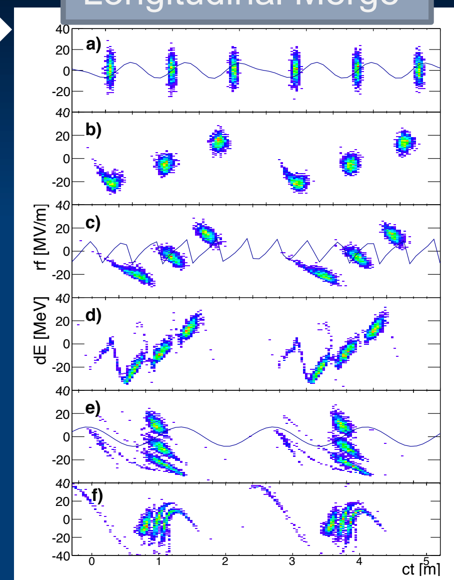
- MAP Baseline Designs offer
  - Factor >10^5 in emittance reduction
- Alternative and Advanced Concepts
  Higgs Factory
  - Hybrid Rectilinear Channel (gas-filled structures)
  - Parametric Ionization Cooling
  - Alternative Final Cooling

One example:
⇨ Early stages of existing scheme
⇨ Round-to-flat Beam Transform
⇨ Transverse Bunch Slicing
⇨ Longitudinal Coalescing (at ~10s of GeV)

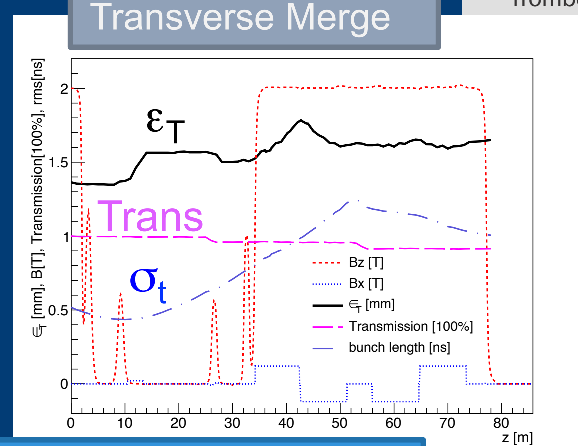
⇨ *Considerable promise to exceed our original target parameters*

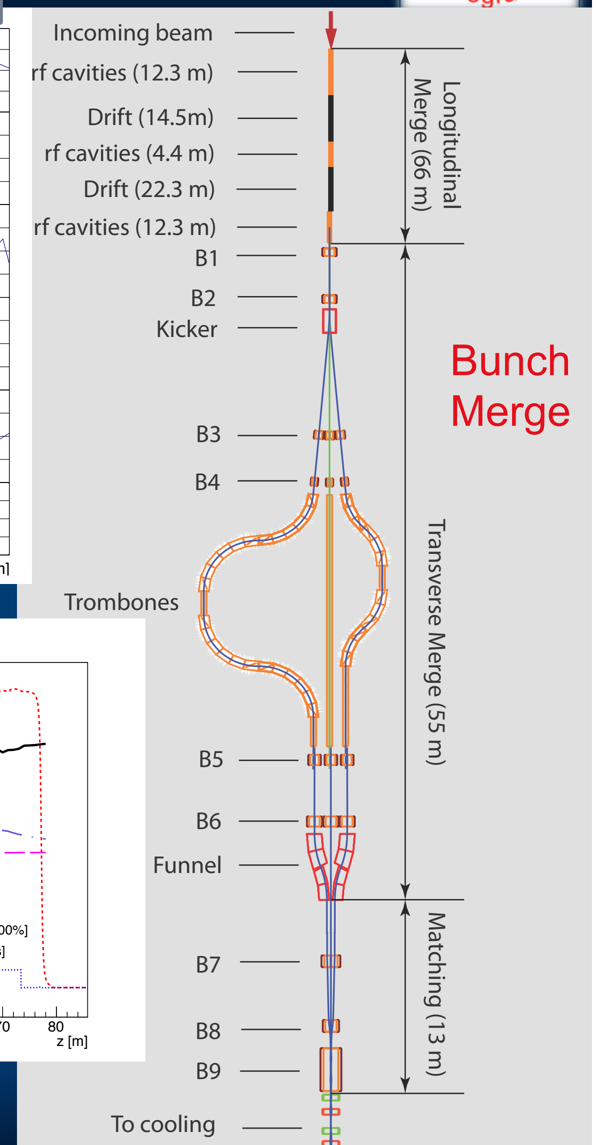
Bunch Merge ➡

Longitudinal Merge



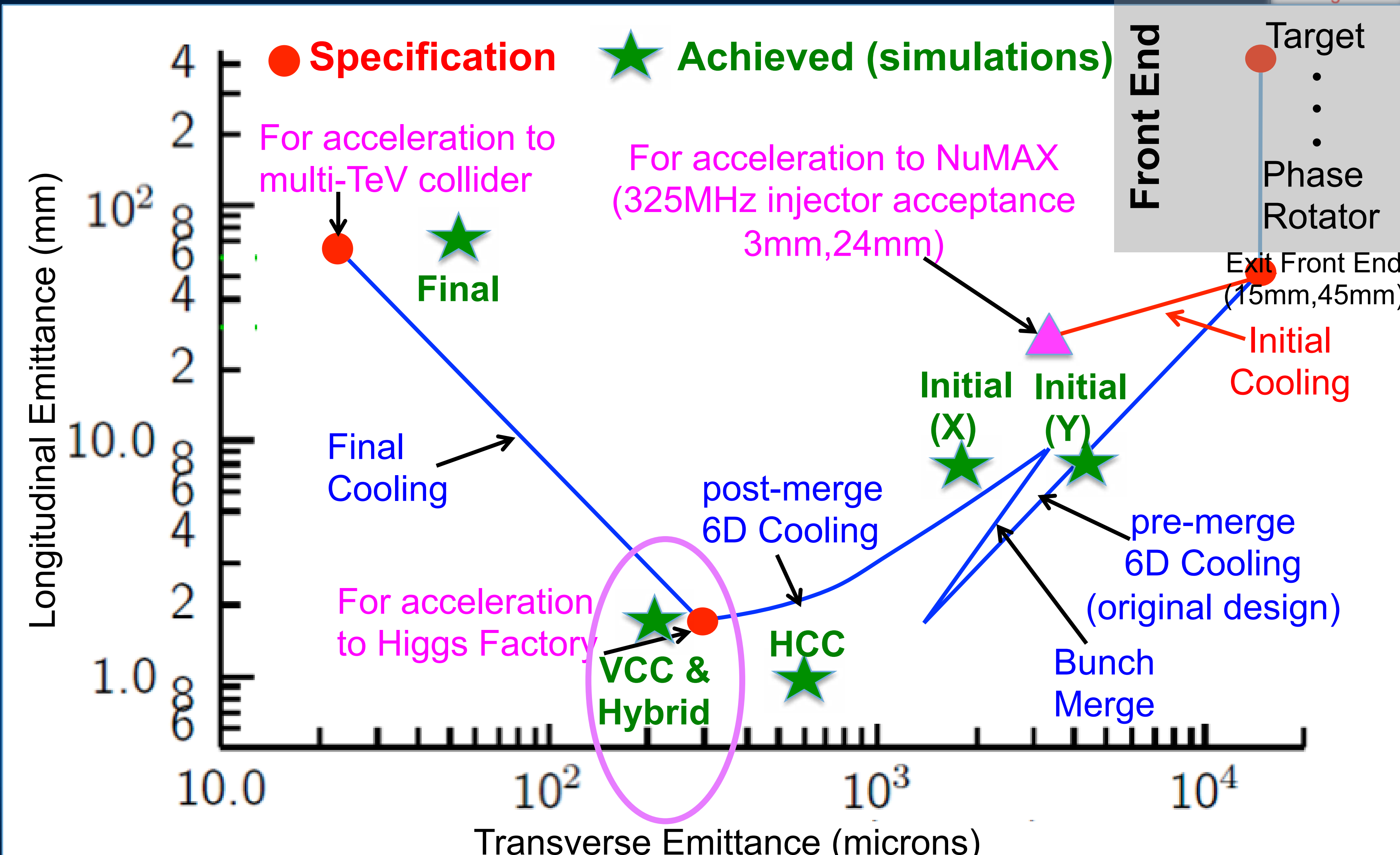
Transverse Merge



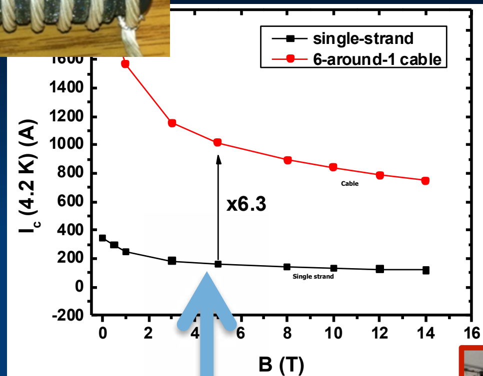


MASS identified extension of the 6D cooling concepts and modification of Final Cooling scheme to be one of most likely areas of performance improvement

Cooling: The Emittance Path



Cooling Technology R&D

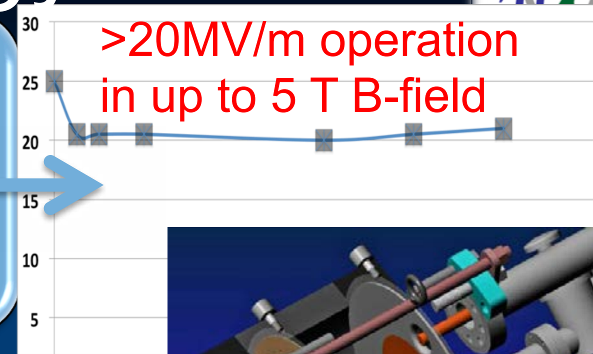


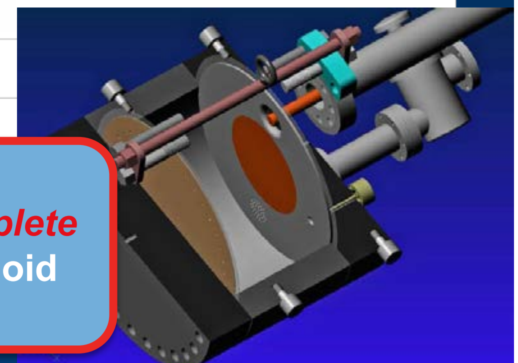
Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

FNAL-Tech Div
T. Shen-Early Career Award

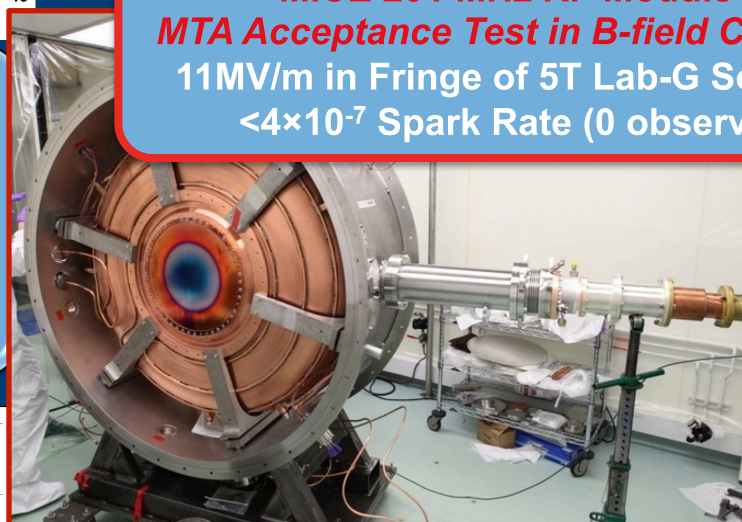
Successful Operation of 805 MHz "All Seasons" Cavity in 5T Magnetic Field under Vacuum

MuCool Test Area/Muons Inc



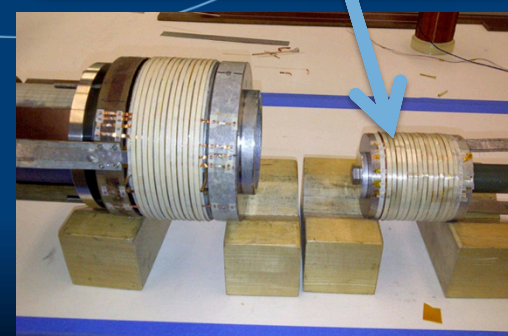


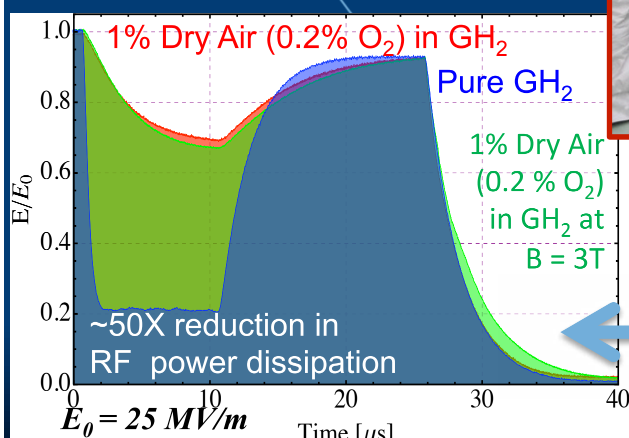
MICE 201 MHz RF Module –
MTA Acceptance Test in B-field Complete
11MV/m in Fringe of 5T Lab-G Solenoid
<4×10^{-7} Spark Rate (0 observed)



World Record HTS-only Coil
15T on-axis field (16T on coil)

R. Gupta
PBL/BNL





Demonstration of High Pressure RF Cavity in 3T Magnetic Field with Beam

Extrapolates to required
μ-Collider Parameters

MuCool Test Area

Muon Ionization Cooling Experiment

Cooling Channel Commissioning Underway for MICE Step IV

Ionization Cooling Summary

✓ 6D Ionization Cooling Designs
- Designs in hand that meet performance targets in simulations with stochastic effects
- Ready to move to engineering design and prototyping
- Able to reach target performance with Nb_3Sn conductors (NO HTS)

✓ RF operation in magnetic field (MTA program)
- Gas-filled cavity solution successful and performance extrapolates to the requirements of the NF and MC
- Vacuum cavity performance now consistent with models
- MICE Test Cavity significantly exceeds specified operating requirements in magnetic field

✓ MICE Experiment now in commissioning phase

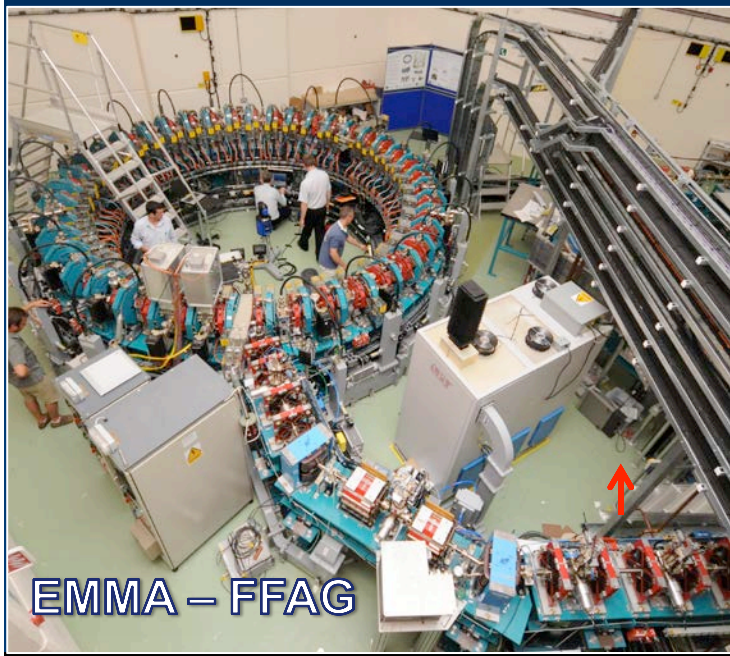
~ Final Cooling Designs
- Baseline design meets Higgs Factory specification and performs within factor of 2.2× of required transverse emittance for high energy MC (while keeping magnets within parameters to be demonstrated within the next year at NHMFL).
- Alternative options under study

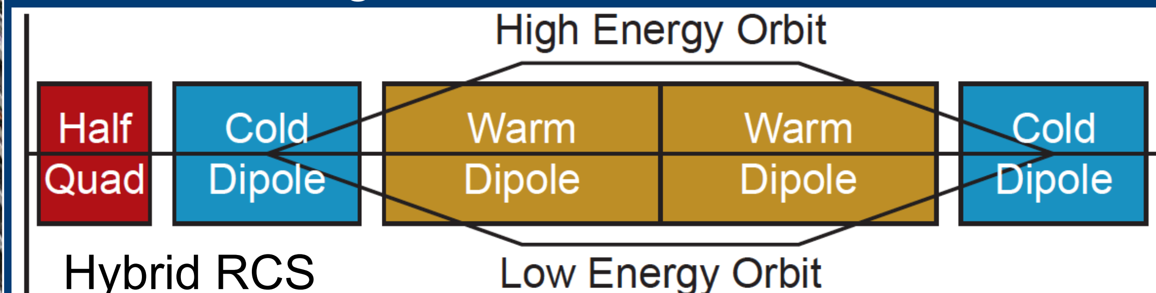
Acceleration

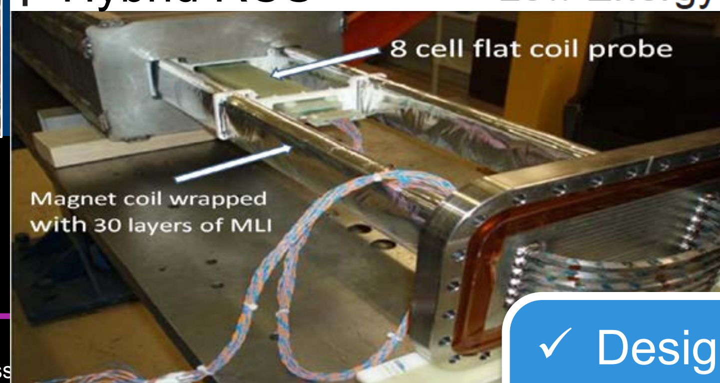
- Muons require an ultrafast accelerator chain

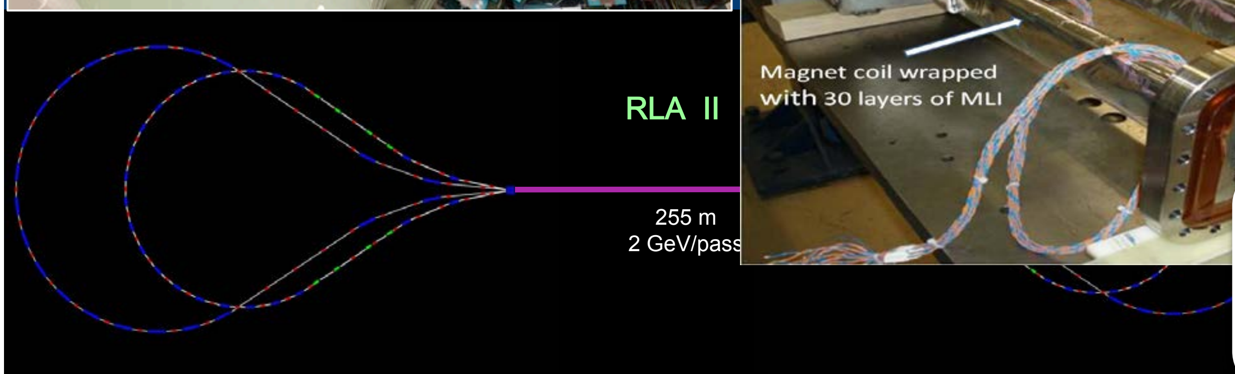
Technologies include:

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







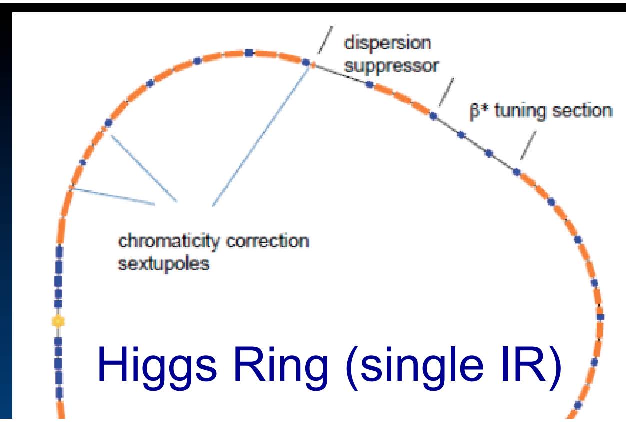


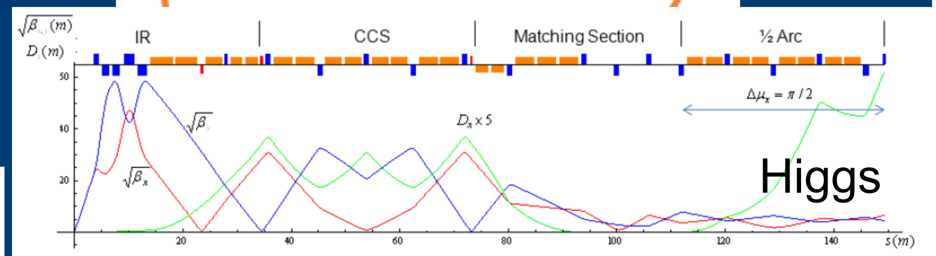
RCS requires 2 T p-p magnets at f > 400 Hz (U Miss & FNAL)

- ✓ Design concepts in hand
- ✓ Magnet R&D indicates parameters achievable

Collider Rings

- Detailed optics studies for Higgs, 1.5 TeV, 3 TeV and now 6 TeV CoM
  - With supporting magnet designs and background studies

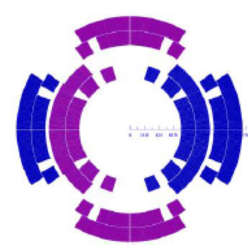




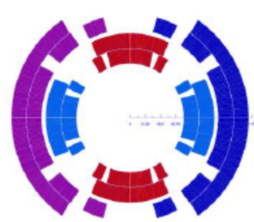
Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP

✓ Higgs, 1.5 TeV CoM and 3 TeV CoM Designs
  - With magnet concepts
  - Achieve target parameters

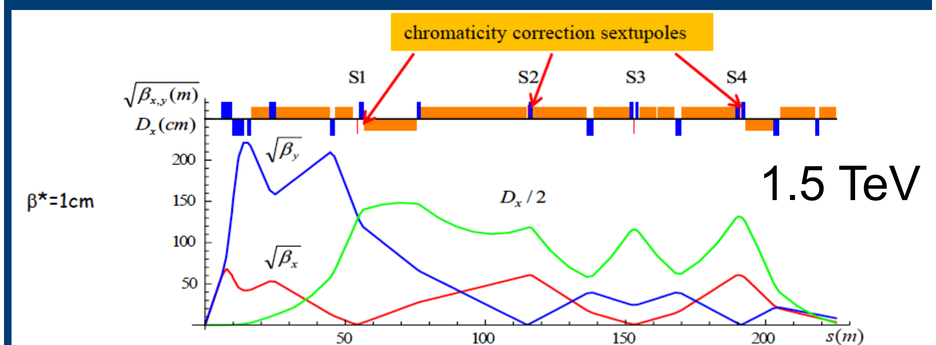
✓ Preliminary 6 TeV CoM design
  - Key issue is IR design and impact on luminosity
  - Utilizes lower power on target

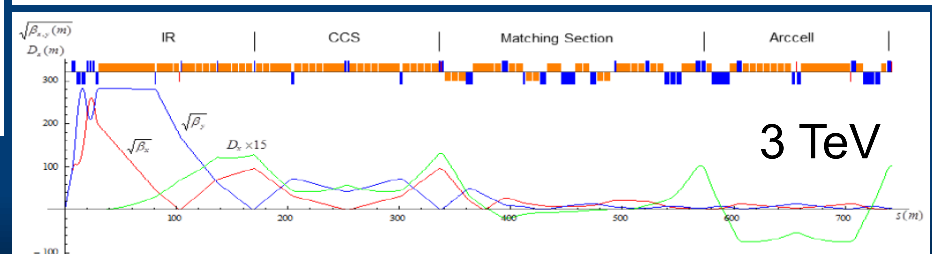


Dipole/Quad



Quad/Dipole

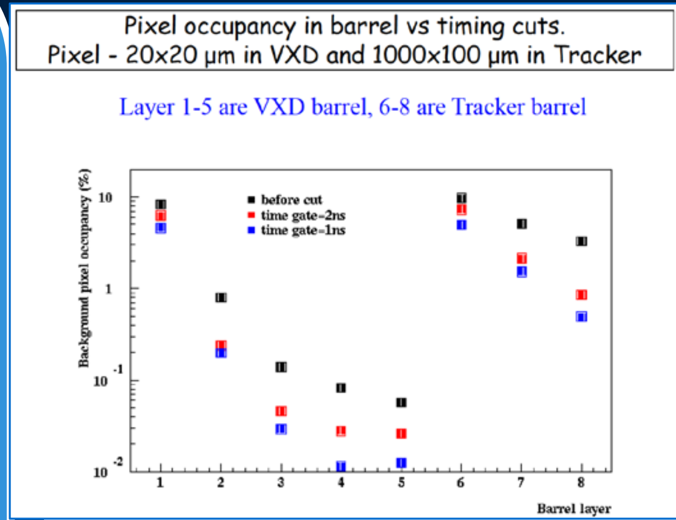


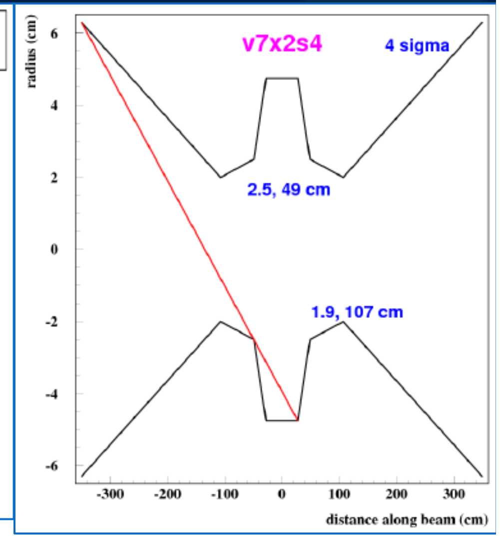


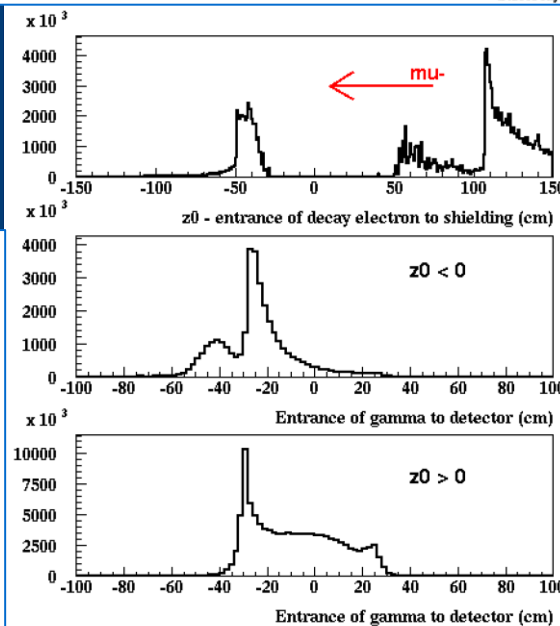
Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm

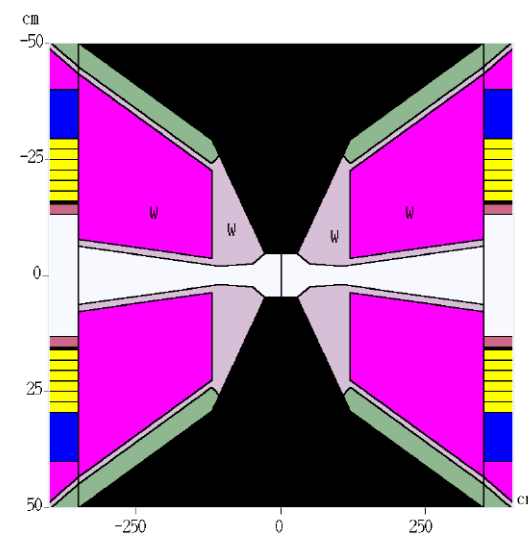
Machine Detector Interface

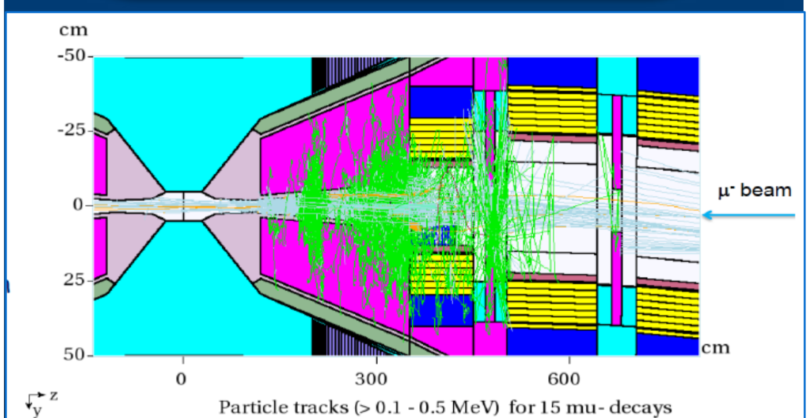
- ✓ Backgrounds appear manageable with suitable detector pixelation and timing rejection
- ✓ Recent study of hit rates comparing MARS, EGS and FLUKA appear consistent to within factors of <2
  - ⇨ Significant improvement in our confidence of detector performance





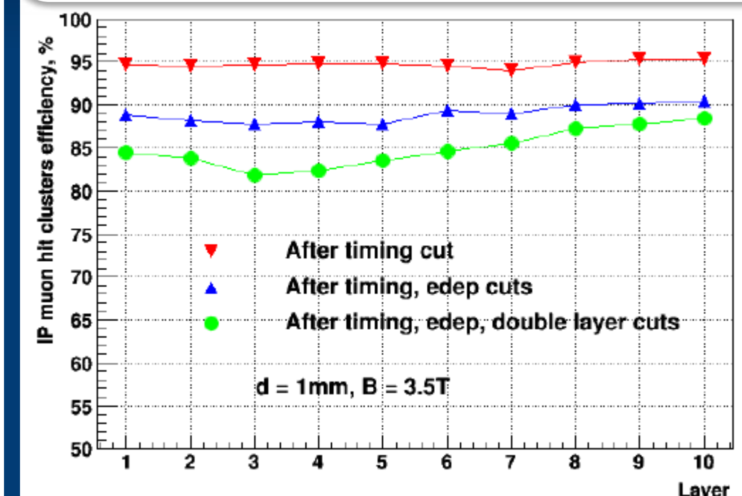


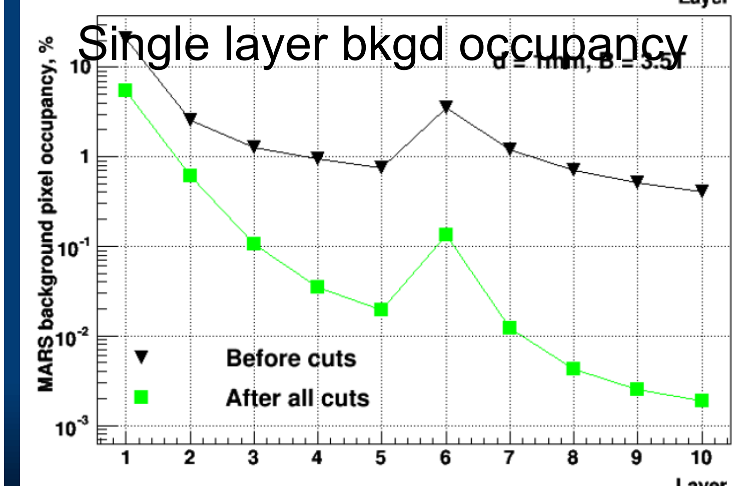




Detector Backgrounds & Mitigation

Trackers: Employ double-layer structure with 1mm separation for neutral background suppression

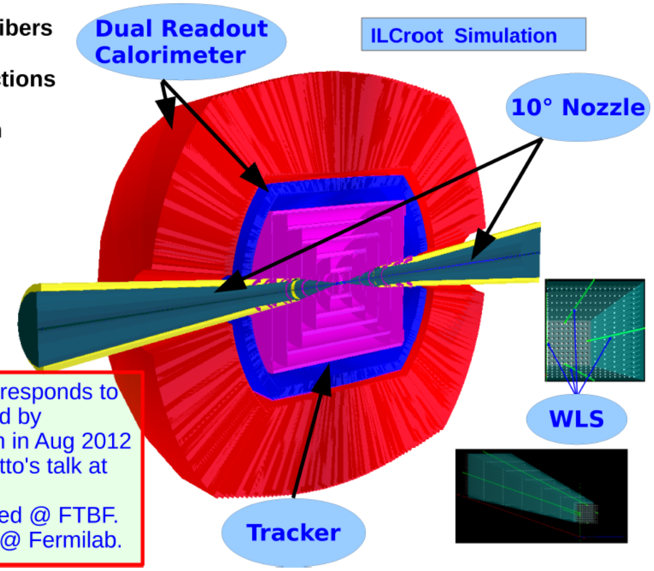




MARS Bkgds ⇨ ILCRoot Det Model

Dual Readout Projective Calorimeter

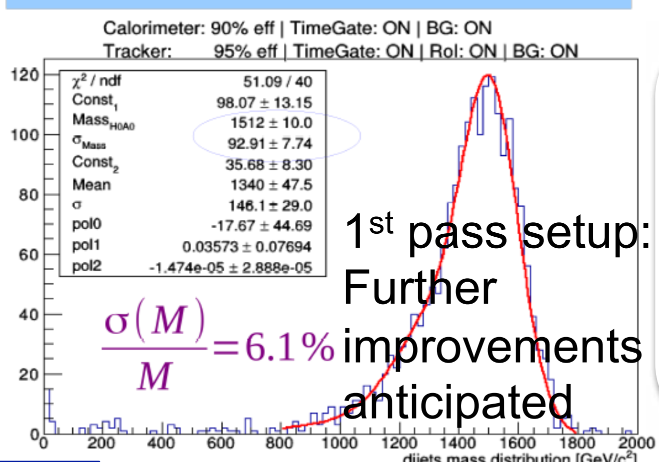
- Lead glass + scintillating fibers
- ~1.4° tower aperture angle
- Split into two separate sections
- Front section 20 cm depth
- Rear section 160 cm depth
- ~ 7.5 λ_{int} depth
- >100 X_0 depth
- Fully projective geometry
- Azimuth coverage down to ~8.4° (Nozzle)
- Barrel: 16384 towers
- Endcaps: 7222 towers



- All simulation parameters corresponds to ADRIANO prototype #9 tested by Fermilab T1015 Collaboration in Aug 2012 @ FTBF (see also T1015 Gatto's talk at Calor2012)
- Several more prototypes tested @ FTBF.
- New test beam ongoing now @ Fermilab.

- Fermilab 7

Time gate & RoI ON – BG ON



1st pass setup: Further improvements anticipated

- ✓ Preliminary detector study promising
  - Real progress requires dedicated effort, which MAP was not allowed to fund

Conclusion

- 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 4 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
- Key technical hurdles have been/are being addressed
  - Realizable cooling channel designs with acceptable performance
  - Breakthroughs in cooling channel technology
  - MICE commissioning is now underway

Muon accelerator capabilities offer unique potential for the future of high energy physics research

Since COOL`13, we have lost three key contributors to Muon Accelerator R&D

David Cline, UCLA
June 27, 2015

Andy Sessler, LBNL
April 27, 2014

Mike Zisman, LBNL
August 30, 2015

They will be sorely missed