A Staged Muon Accelerator Facility for Neutrino and Collider Physics

J.P Delahaye / SLAC
on behalf of the MAP collaboration
(and the MASS team)

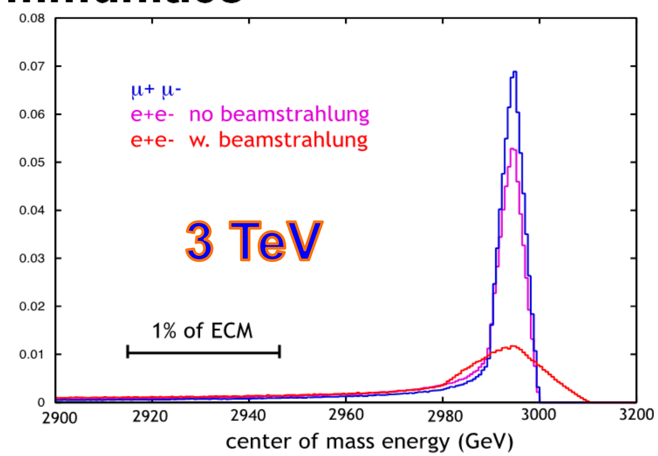
Muon Accelerator Program

U.S. DEPARTMENT OF ENERGY
Office of Science

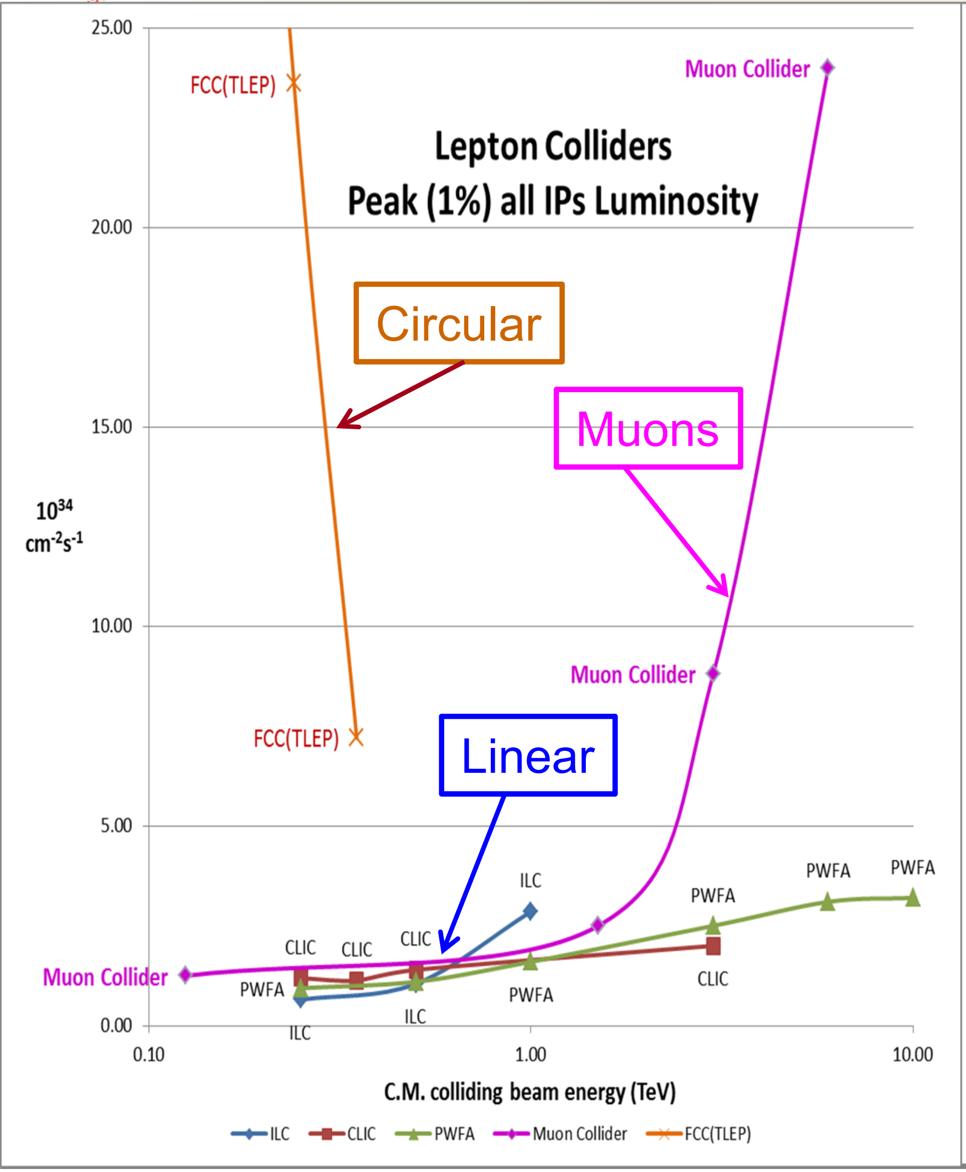
Muons based facilities a novel and attractive technology

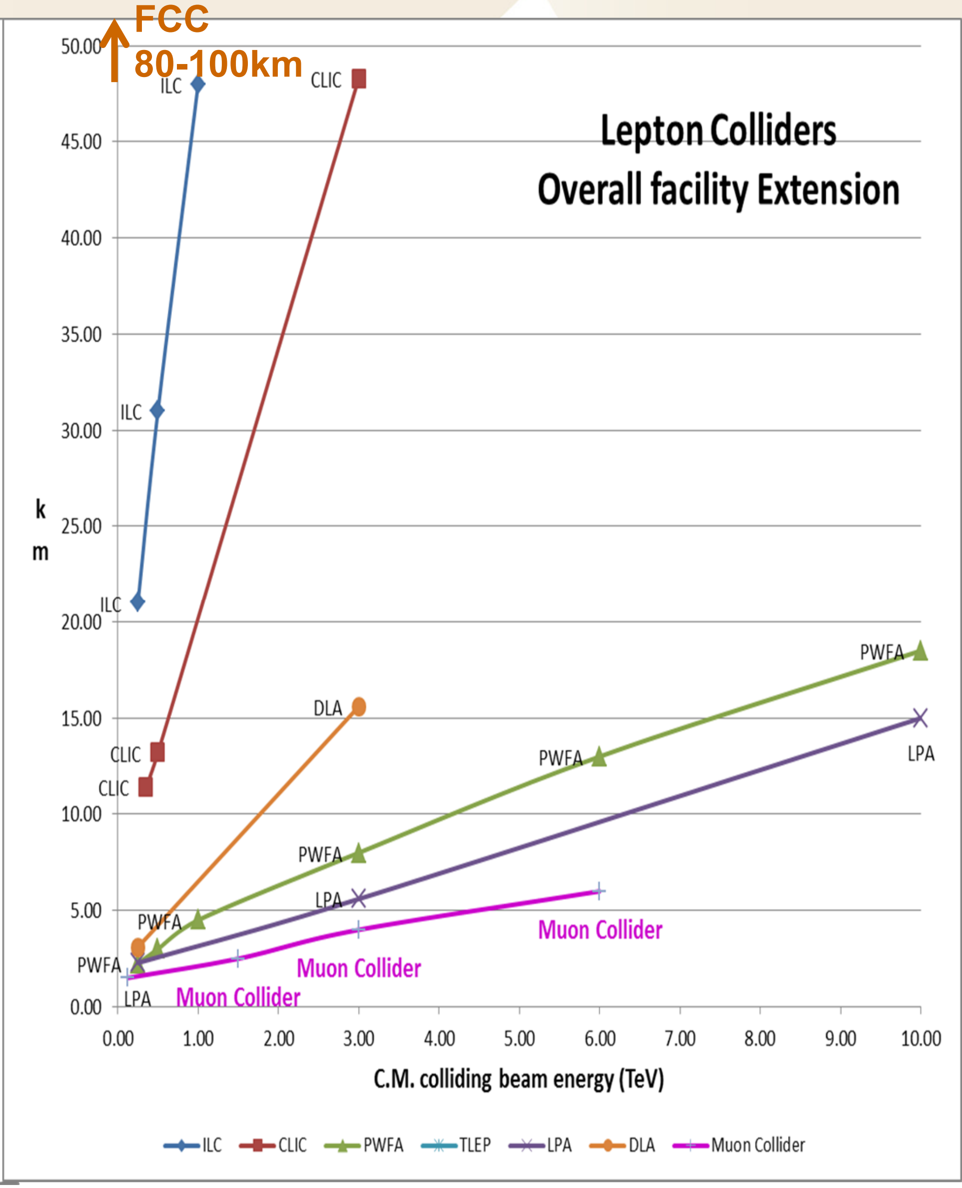
Muons are leptons like electrons & positrons but with a mass 207 times larger

- Negligible synchrotron radiation emission ($\alpha\ m^{-2}$)
  - Multi-pass collisions (1000 turns) in ring
    - High luminosity with reasonable beam power and power consumption
      - relaxed beam emittances & sizes, alignment & stability
    - Multi-detectors supporting broad physics communities
    - Large time (15 μs) between bunch crossings
  - No beam-strahlung at collision:
    - narrow luminosity spectrum
  - Multi-pass acceleration:
    - Cost effective construction & operation
    - Compact acceleration system and collider
  - No cooling by synchrotron radiation in standard damping rings
    - Requires development of novel cooling method

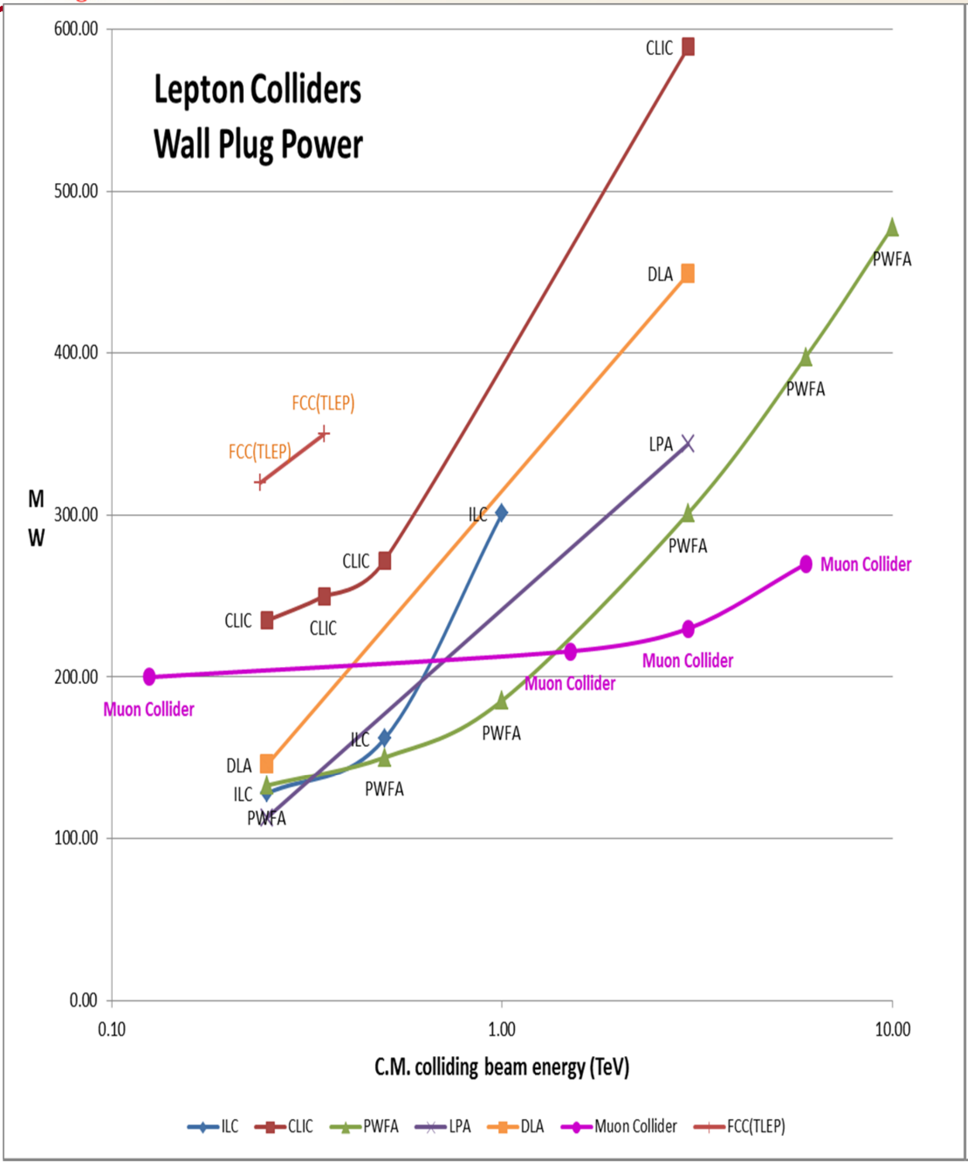


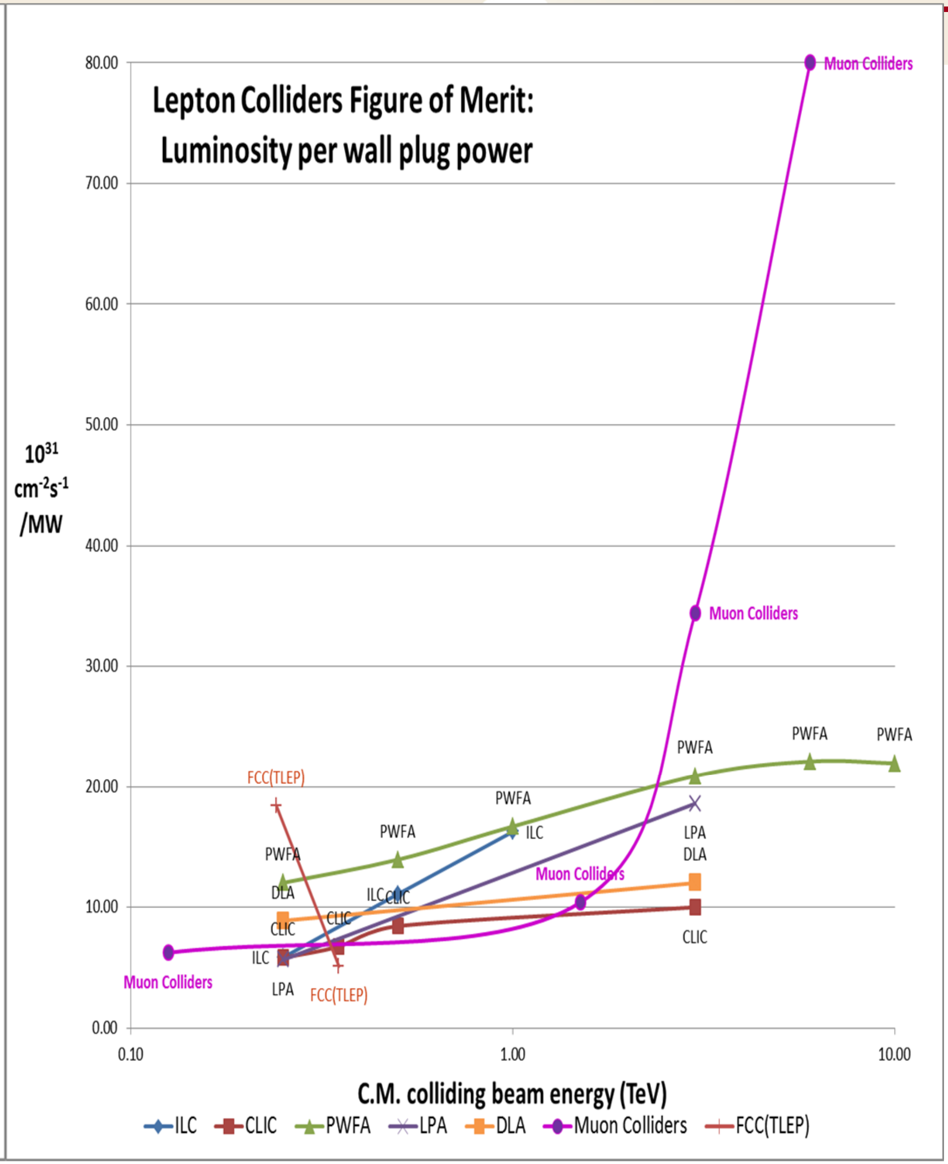
Muon Colliders extending high energy frontier with potential of considerable cost savings



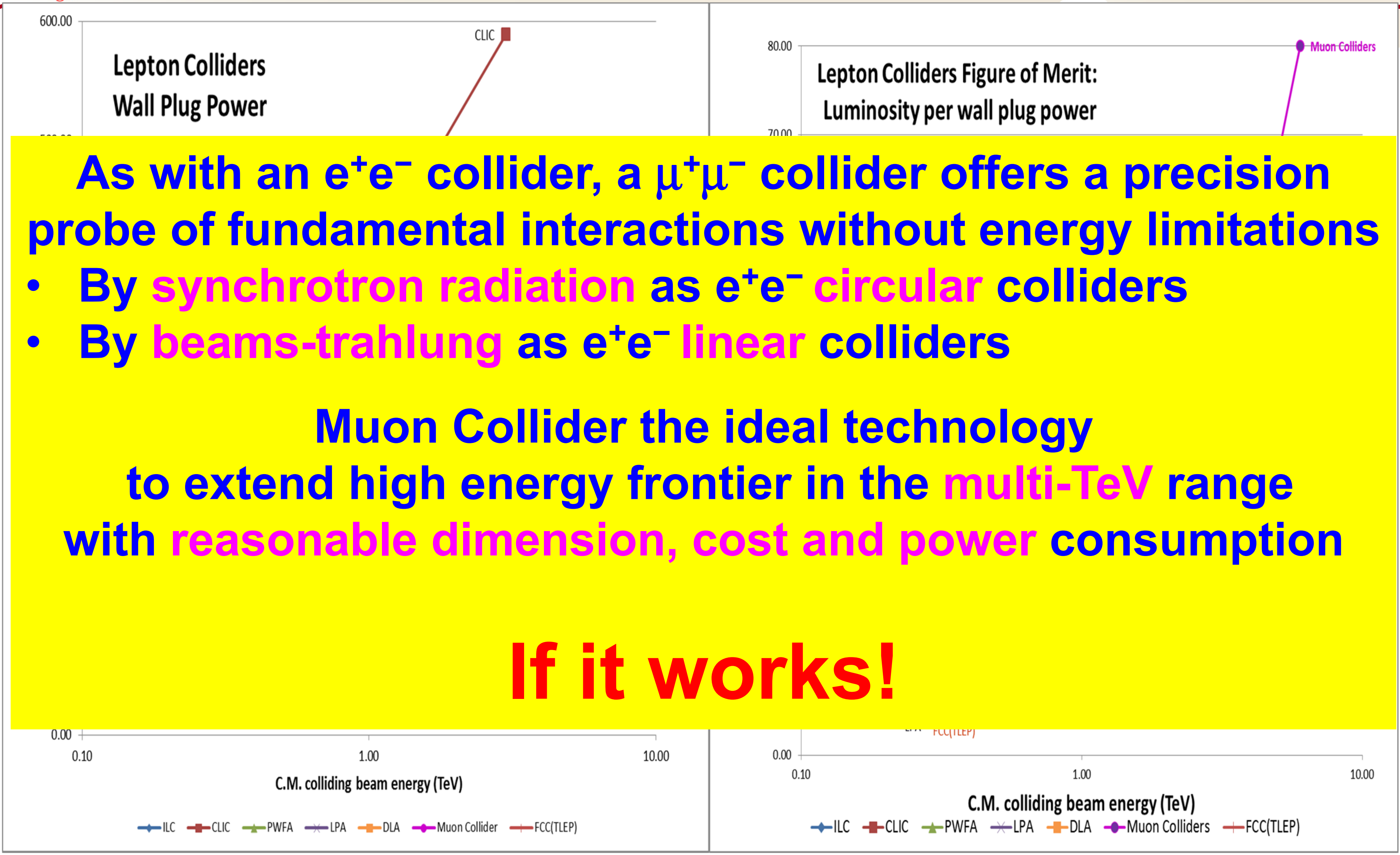


Muon Colliders extending high energy frontier with potential of considerable power savings





Muon Colliders extending high energy frontier with potential of considerable power savings



As with an e^+e^- collider, a $\mu^+\mu^-$ collider offers a precision probe of fundamental interactions without energy limitations

- **By synchrotron radiation as e^+e^- circular colliders**
- **By beams-trahlung as e^+e^- linear colliders**

Muon Collider the ideal technology to extend high energy frontier in the multi-TeV range with reasonable dimension, cost and power consumption

If it works!

Muons: Issues & Challenges

- **Limited lifetime: 2.2 μs at rest**

☹
  - Race against death: generation, acceleration & collision before decay
  - Muons decay in accelerator and detector
    - Shielding of detector and facility irradiation
    - Physics feasibility with large background?
  - Decays in neutrinos:
    - Ideal source of well defined electron and muon neutrinos in equal quantities :

☺

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

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

The neutrino factory concept

- **Generated as tertiary particles in large emittances**

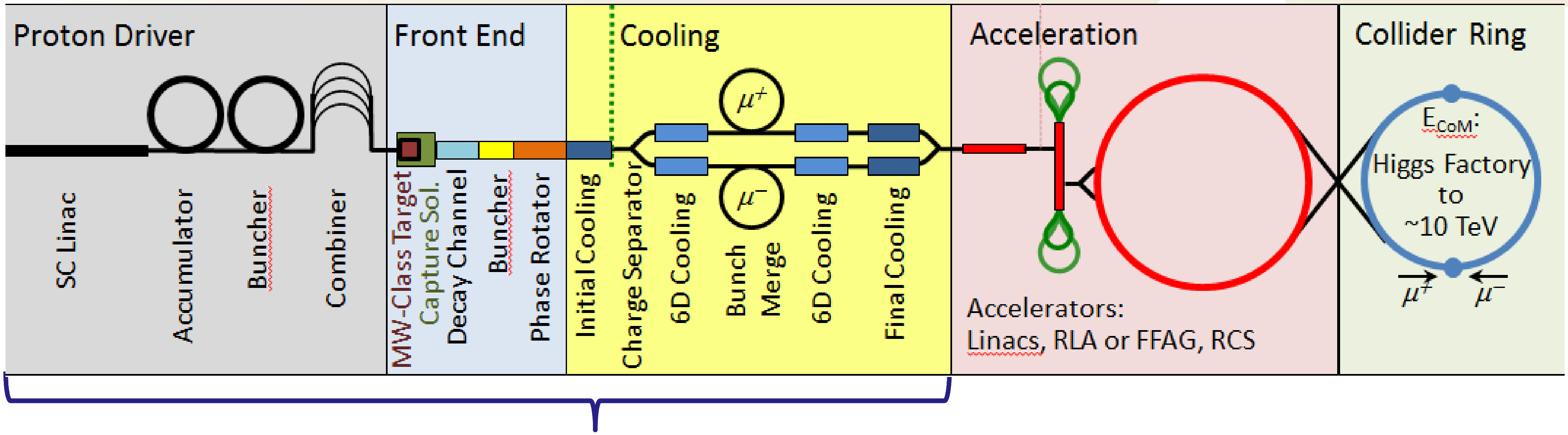
☹
  - powerful MW(s) driver
  - novel (fast) cooling method

Development of novel technologies
with key accelerator and detector challenges

Muon Collider Concept
Muon Accelerator Program (MAP)

M.A.Palmer

TUPME012



Proton source:
Up to 4 MW,
with 2±1 ns long bunches

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

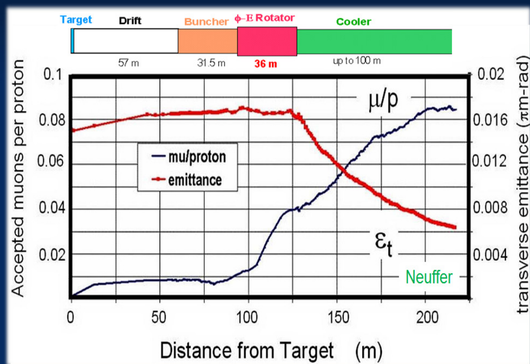
Fast acceleration mitigating muon decay

Collider up to 6-10TeV
2 detectors:

$\sqrt{s}$ = 3 TeV
Circ: 4.5km
$L = 3\times10^{34}$ $cm^{-2}s^{-1}$

Technical challenges Feasibility addressed by MAP

Technology Challenges – Tertiary Production

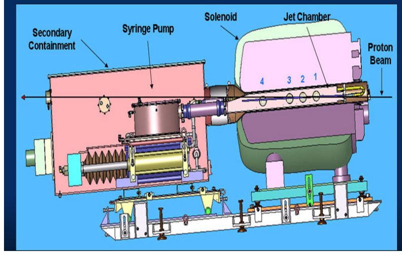


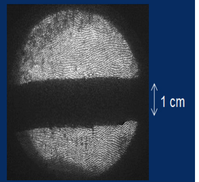
- A multi-MW proton source, *e.g.*, Project X, will enable O(10^{21}) muons/year to be produced, bunched and cooled to fit within the acceptance of an accelerator.

Technology challenges - Target

THPRI089

- The MERIT Experiment at the CERN PS
  - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!
  - ⇨ Jets could operate with beam powers up to **8 MW** with a repetition rate of 70 Hz
- MAP staging aimed at initial 1 MW target





Hg jet in a 15 T solenoid with measured disruption length ~ 28 cm

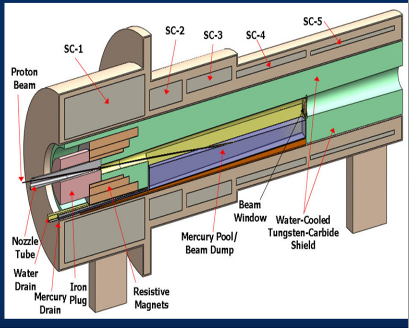
Technology Challenges – Capture Solenoid

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

E_{stored} ~ 3 GJ

O(10MW) resistive coil in high radiation environment

Possible application for High Temperature Superconducting magnet technology

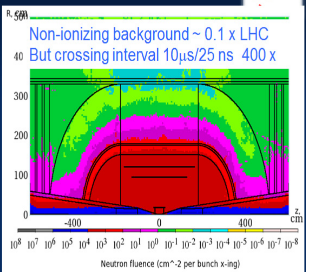


Backgrounds and Detector

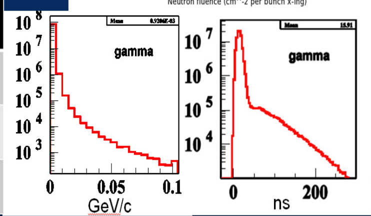
Much of the background is soft and out of time

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

Requires a fast, pixelated tracker and calorimeter.

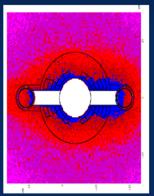


	Cut	Rejection
Tracker hits	1 ns, dedx	9×10^{-4}
Calorimeter neutrons	2 ns	2.4×10^{-3}
Calorimeter photons	2 ns	2.2×10^{-3}

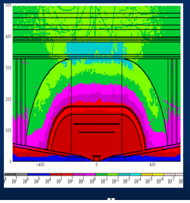


Technology & Design Challenges Ring, Magnets, Detector

- Emittances are relatively large, but muons circulate for ~1000 turns before decaying
  - Lattice studies for 126 GeV, 1.5 & 3 TeV CoM
- High field dipoles and quadrupoles must operate in high-rate muon decay backgrounds
  - Magnet designs under study
- Detector shielding & performance
  - Initial studies for 126 GeV, 1.5 TeV, and 3 TeV using MARS background simulations
  - Major focus on optimizing shielding configuration

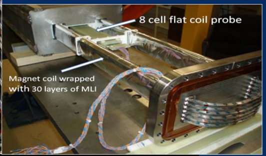


MARS energy deposition map for 1.5 TeV collider dipole



Technology Challenges - Acceleration

- Muons require an ultrafast accelerator chain
  - ⇨ *Beyond the capability of most machines*
- Solutions include:
  - Superconducting Linacs
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient (FFAG) Machines
  - Rapid Cycling Synchrotrons (RCS)

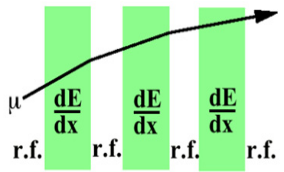


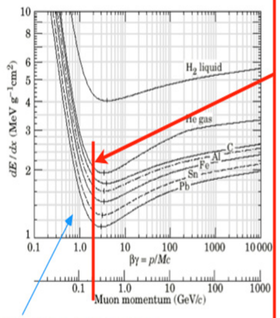
RCS requires 2 T p-p magnets at f = 400 Hz (U Miss & FNAL)

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

Novel Ionization Cooling Method

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





- Absorbers:

$$\begin{cases} E \to E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta_{space}^{rms} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

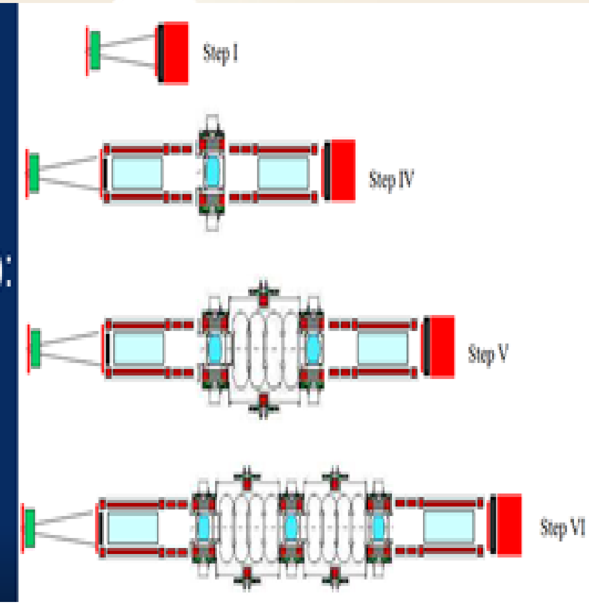
- RF cavities between absorbers replace ΔE
- Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

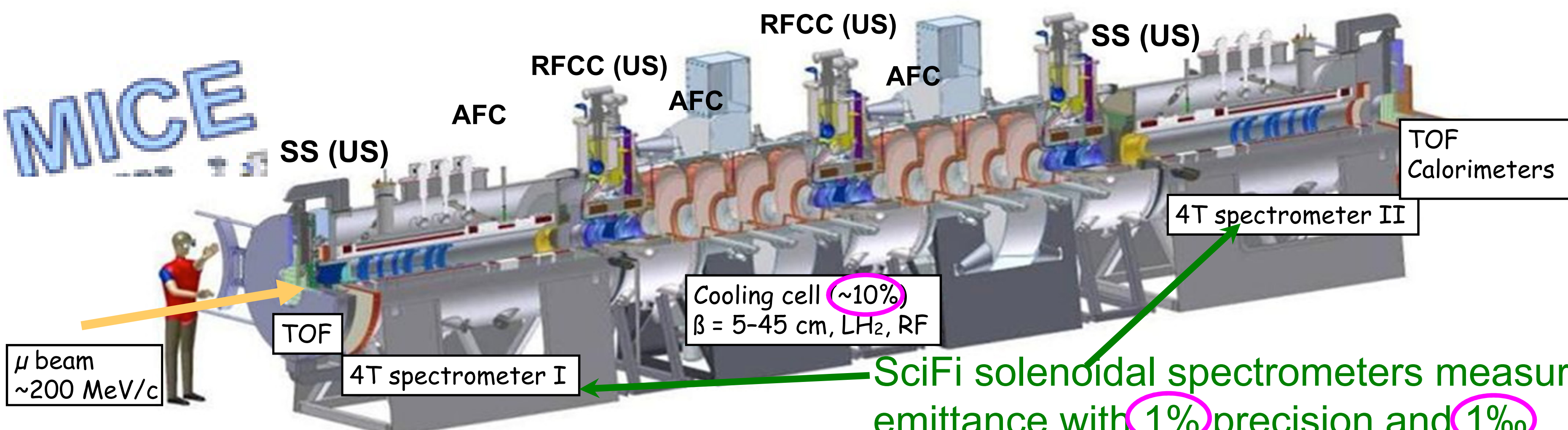
$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle \frac{dE_\mu}{ds} \right\rangle \frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$ (emittance change per unit length)

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

- 2 competing effects ⇒ ∃ equilibrium emittance

The Muon Ionization Cooling Experiment (MICE) in Rutherford (UK): Demonstrate in steps the method and validate the cooling simulations





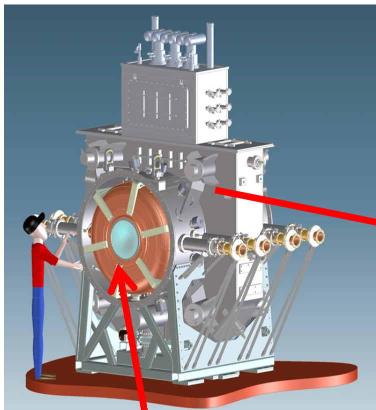
SciFi solenoidal spectrometers measure emittance with 1% precision and 1‰ resolution (muon by muon)

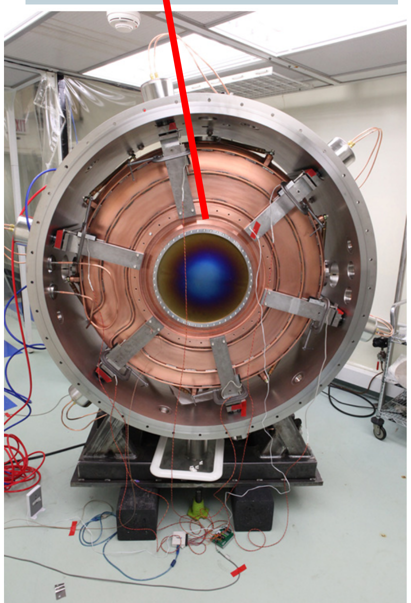
Progress on MICE @ RAL (Int. Collaboration) Muon Ionization Cooling Experiment

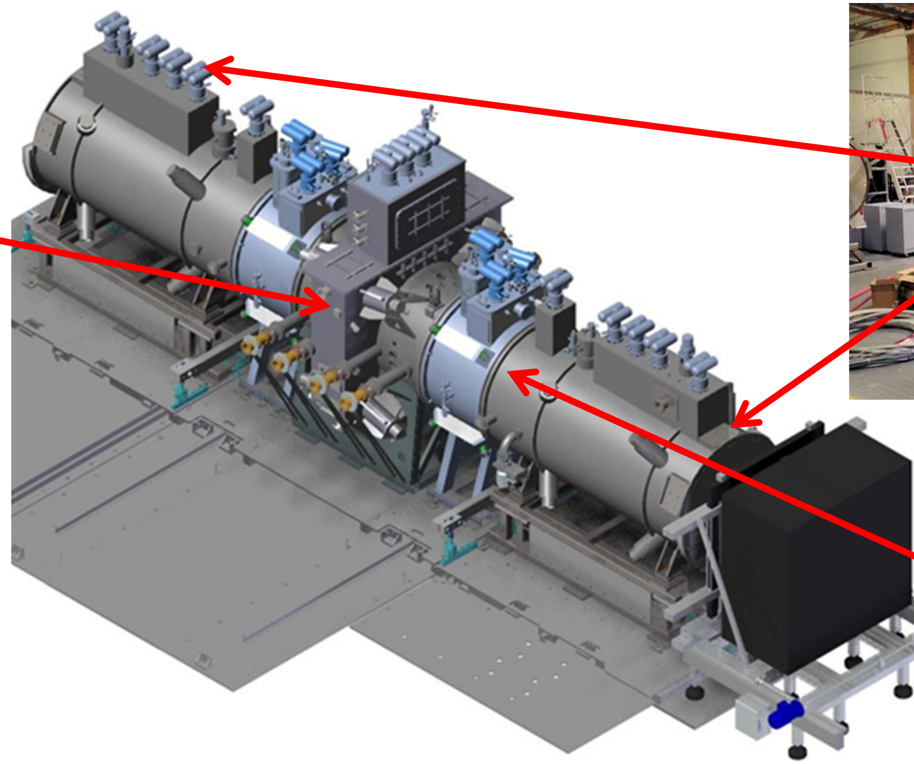
All detectors have been built and tested

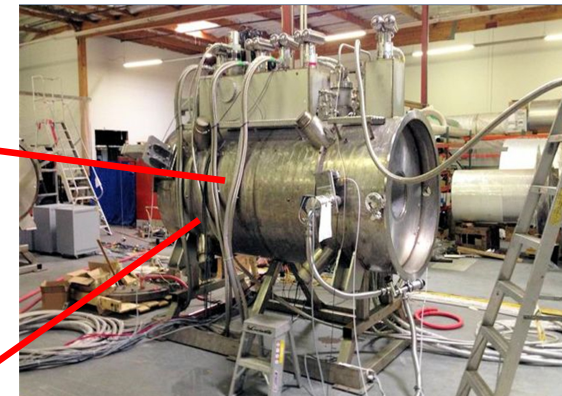
Construction of magnets, RF, RF power system..

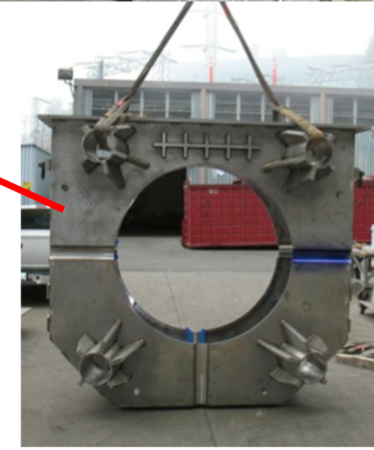
TUPME010
TUPME011
THPRI030









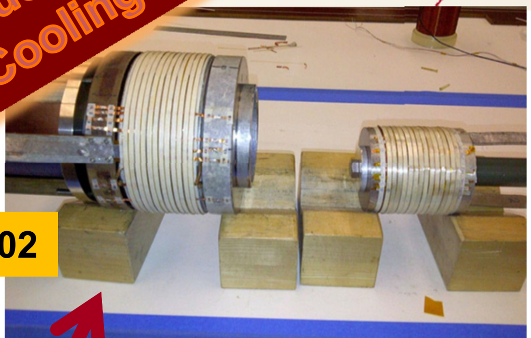


Step IV without acceleration completed by March 2015
Step V with acceleration completed by 2017

R&D outstanding achievements

S.A.Gourlay

The Path to a Viable Muon Ionization Cooling Channel



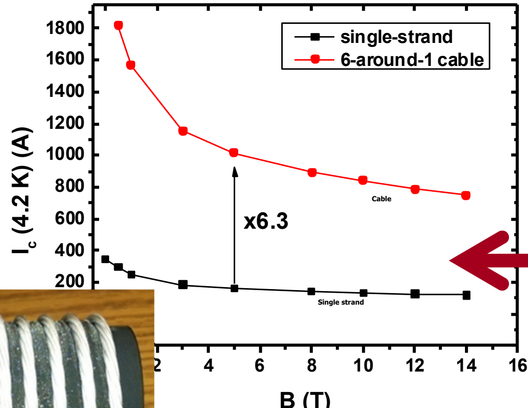
TUZB02

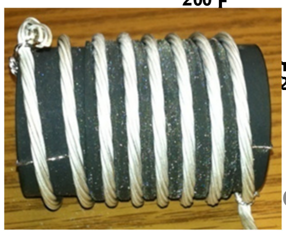
World Record HTS-only Coil

15T on-axis field

16T on coil

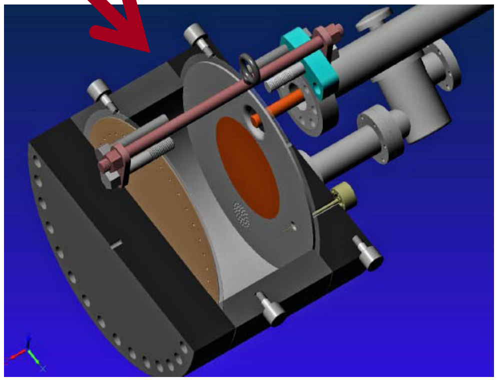
PBL/BNL

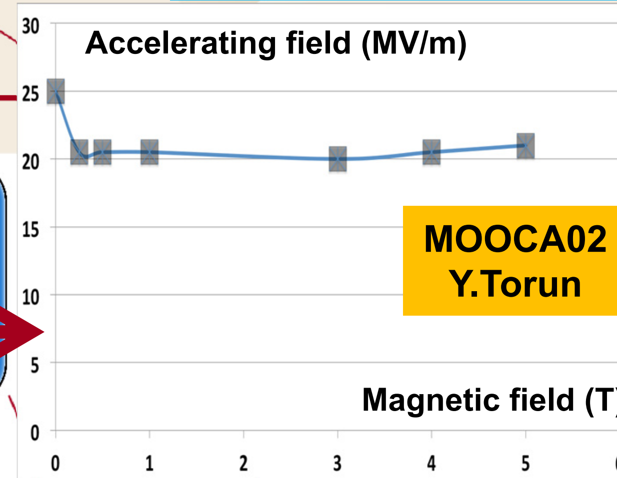




Successful Operation of 805 MHz Cavity in 3T Magnetic Field

MuCool Test Area/MuonsInc





MOOCA02
Y.Torun

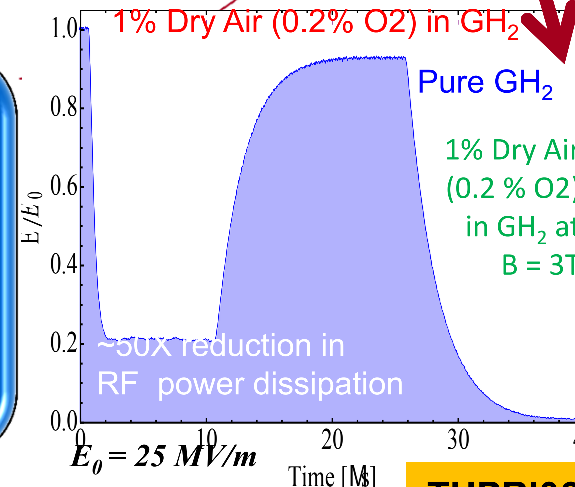
Breakthrough in cable fabrication with High Temperature Super-Conductor (HTS)

FNAL-Tech Div

T. Shen-Early Career Awarde

High Pressure RF Cavity in 3T Magnetic Field with Beam

MuCool Test Area



THPRI065

Muon-based Accelerator Staging Scenario (MASS)

exploring the feasibility of staged facilities

- **Intermediate facilities and physics capabilities in staged approach including evaluation of Physics and accelerator R&D at each stage.**
- **In the specific FNAL context**

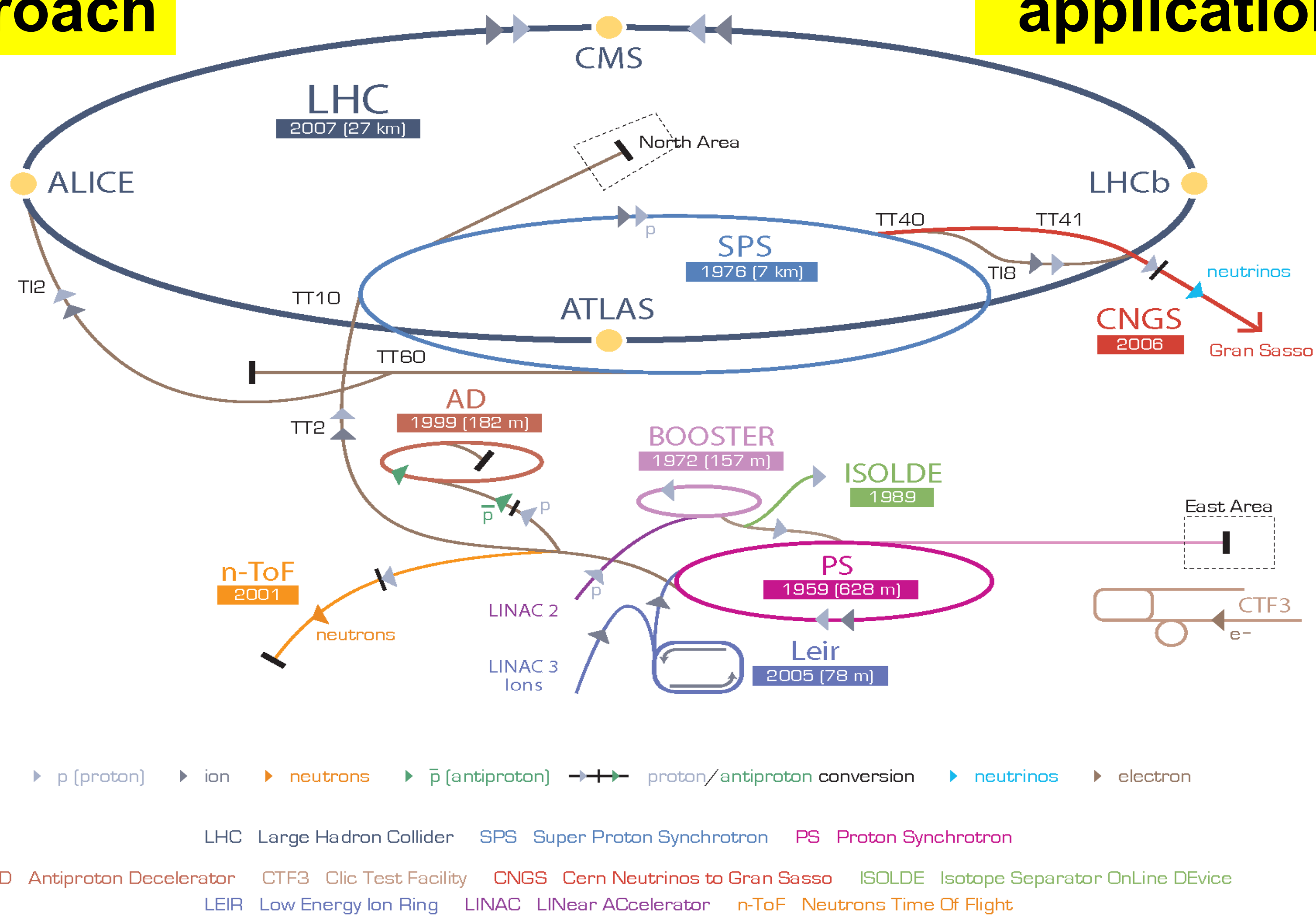
Charles M. ANKENBRANDT	Muons Inc	Parameters/Technical
Dr. Alex BOGACZ	Jefferson Lab	Accelerator technology
Dr. Steve BRICE	Fermilab	Neutrino Experimental
Dr. Jean-Pierre DELAHAYE	SLAC	Chair
Dr. Dmitri DENISOV	Fermilab	Collider experimental
Dr. Estia EICHTEN	Fermilab	Collider Physics
Prof. Don HARTILL	Cornell Universit	General
Dr. Steve HOLMES	Fermilab	Proton Improvement (PIP)
Prof. Patrick HUBER	Virginia Tech	Neutrino Physics
Dr. David NEUFFER	Fermilab	Parameters
Dr. Mark PALMER	Fermilab	Ex-Officio
Dr. Robert Ryne	LBLN	Design & Simulations
Dr. Pavel SNOPOK	IIT/Fermilab	Systems tests

CERN, a success story

Staged approach

Multi-purpose applications

CERN Accelerator Complex



Principles of an ideal project scenario

Series of STAGED facilities

- physics interest at each stage
- Technology with increasing complexity progressively developed and validated

Preferably MULTIPURPOSE

- maximizing supported physics community and funding!

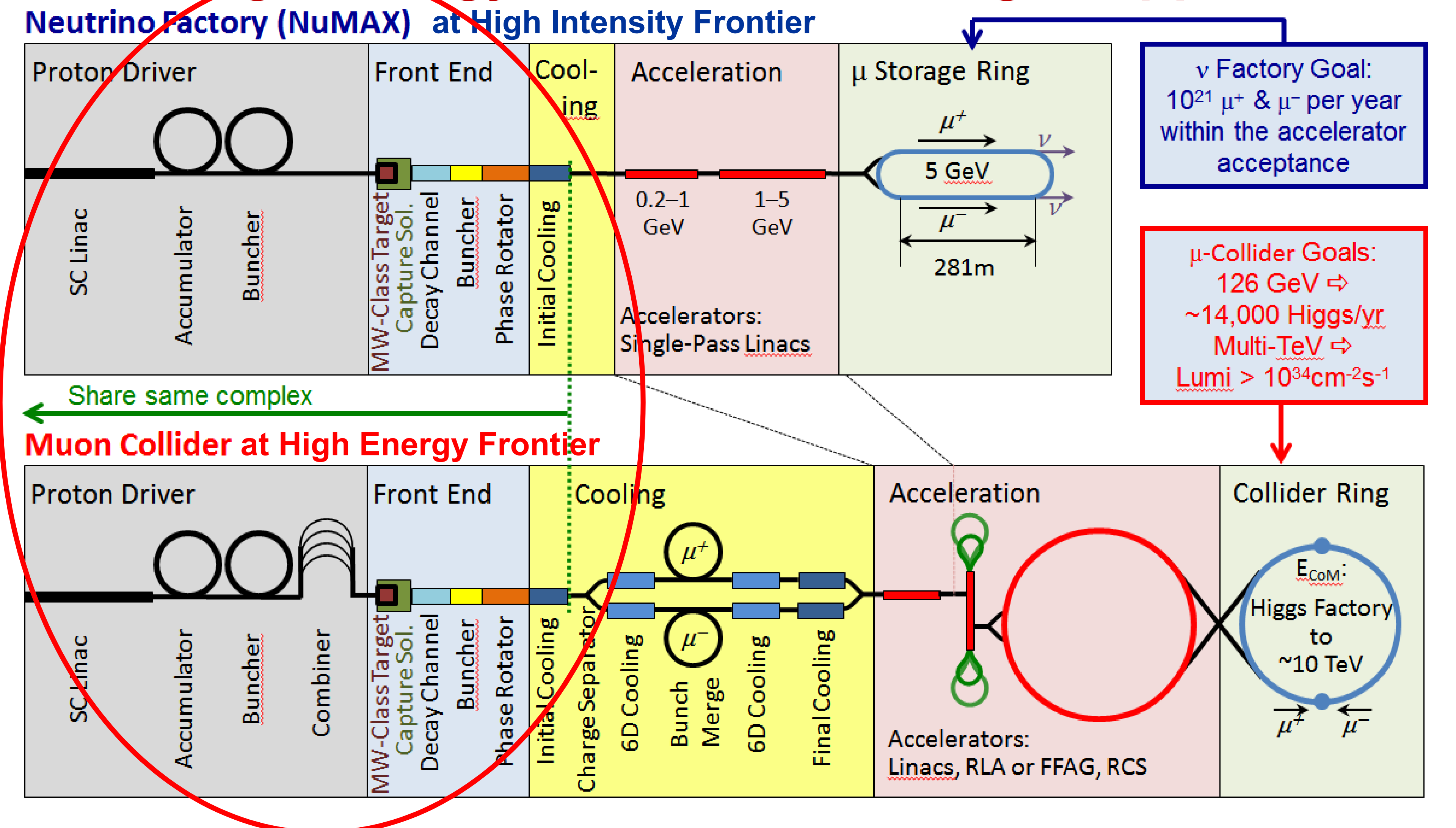
Affordable budget (< 1B$) from one facility to next

- Stage built-on previous stage with additional facilities

Taking advantage of existing facilities

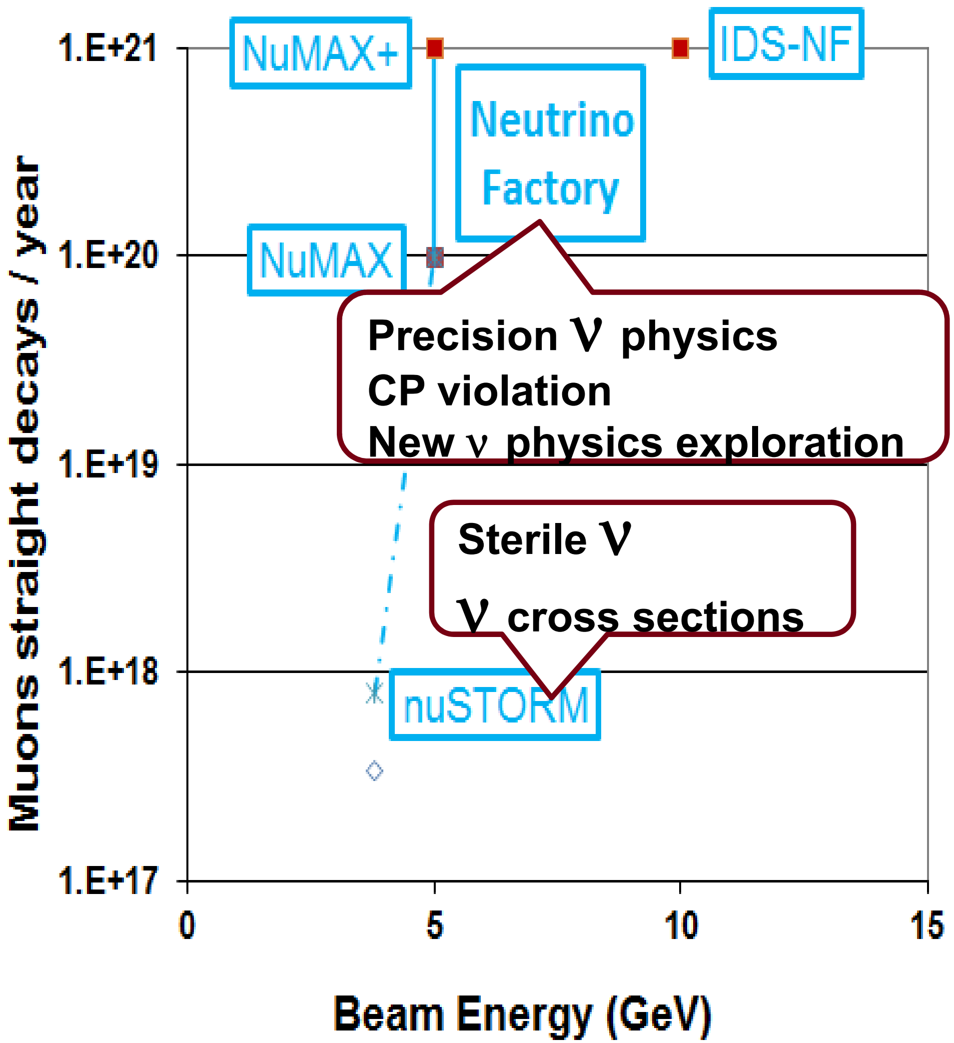
- synergy between present and future program

Unique opportunity of Muon based accelerators to enable facilities at both High Intensity and High Energy Frontiers in a staged approach

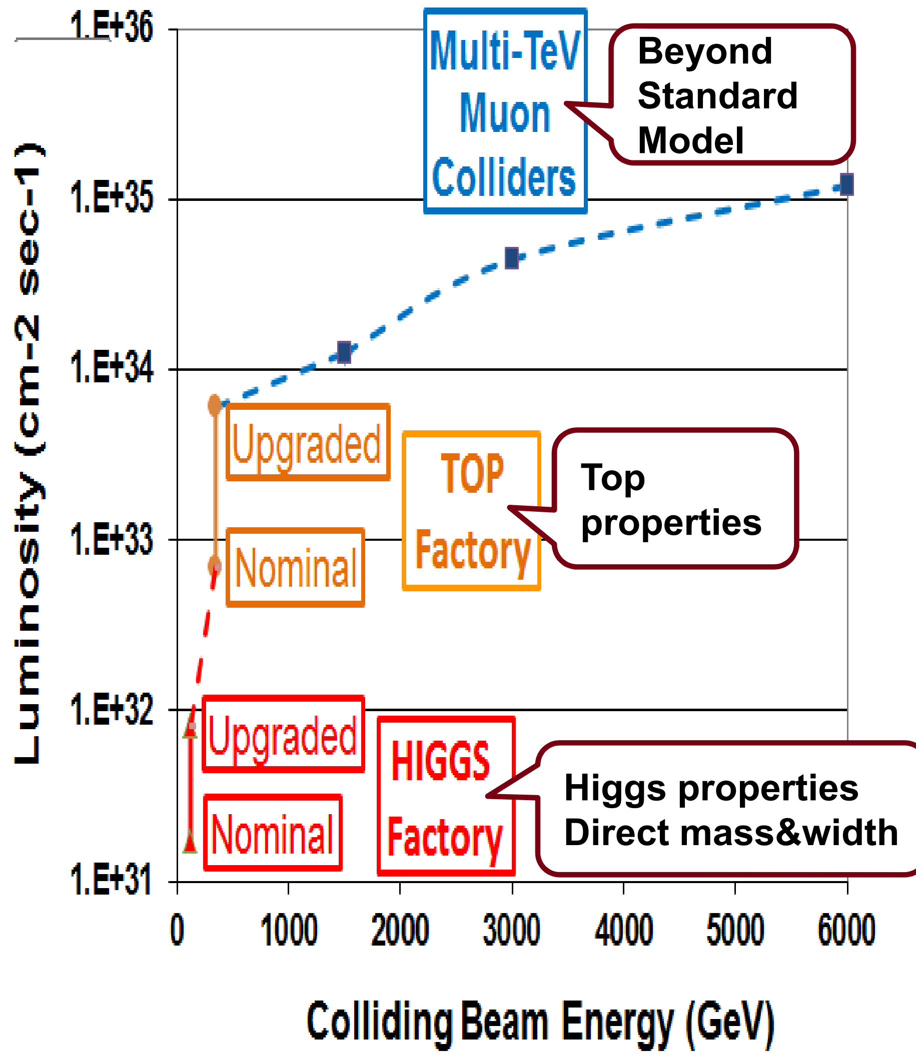


An attractive staging scenario of facilities with physics interest at each stage

Intensity Frontier



Energy Frontier



A cost effective staging scenario in the FNAL context

Taking advantage of and leveraging FNAL future projects:

- Proton Improvement Plan (PIP), TUOAA01
- Long Baseline Neutrino Facility (LBNF) TUOAA02

Proton Improvement Program (PIP) as proton driver

- Starting with 1MW for an early and realistic start (beam power, target…..)
- Upgradable to the highest beam power when available

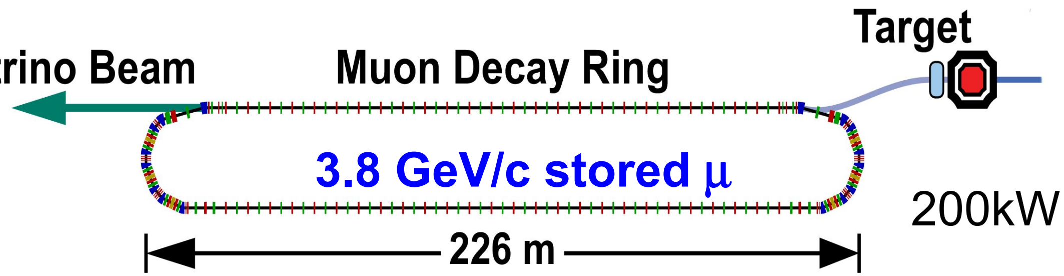
Sanford Underground Research Facility (SURF) host of long distance detector of a Neutrino Factory

- Great synergy with LBNF about detector and facility
- Neutrino Factory energy of 5 GeV compatible with 1300 km distance of FNAL to Sanford

nuSTORM

A.Bross

neutrinos from STOred Muons



An entry-level NF?

DOES NOT
Require Development of ANY New Technology

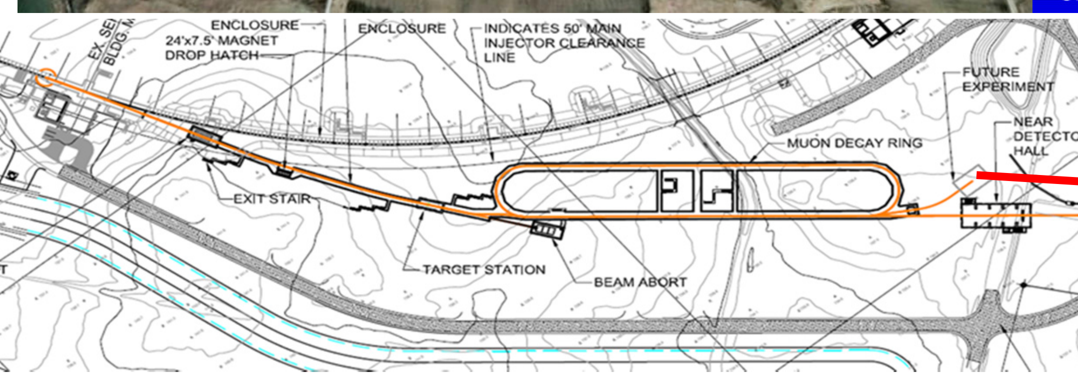
νSTORM

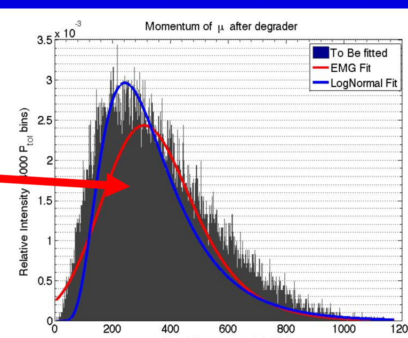
Low energy, low luminosity muon storage ring.
Provides with 1.7×10^{18} μ^+ stored, the following oscillated event numbers

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

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

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

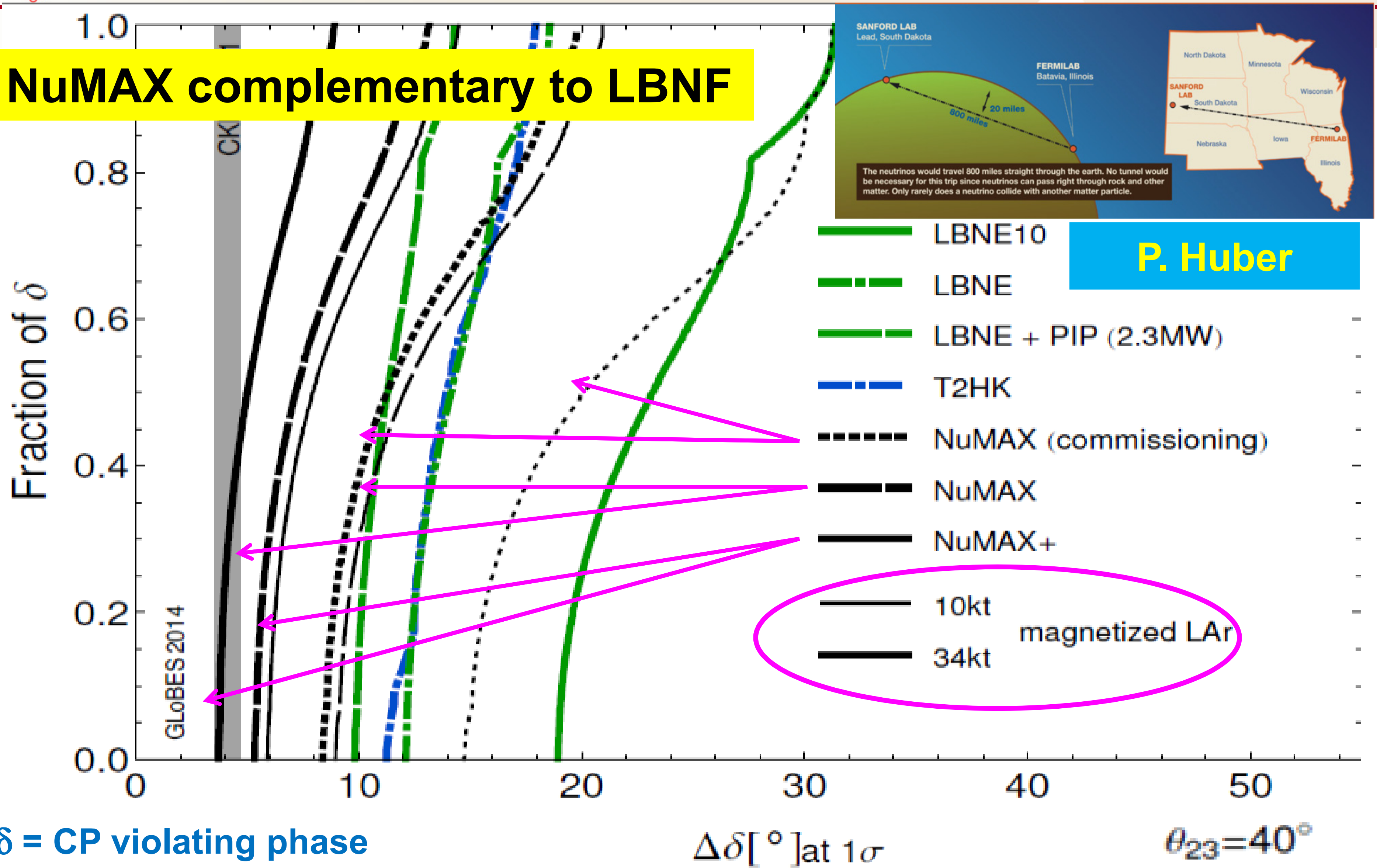




10^{10} μ / 1μs pulse
Ideal R&D platform to get experience, test & validate muon technology

NuMAX (Neutrinos from Muon Accelerator CompleX)
5GeV staged Neutrino Factory with far detector at SURF

NuMAX complementary to LBNF



P. Huber

δ = CP violating phase

Staged Neutrino Factory and Muon Colliders
Increasing complexity and challenges
main parameters

Neutrino Factory at intensity frontier

System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Performance	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}
Detector	*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
Neutrino Ring	Ring Momentum	GeV/c	3.8	5	5	5
	Circumference (C)	m	480	737	737	737
	Straight section	m	184	281	281	281
	Number of bunches	-		60	60	60
	Charge per bunch	1×10^{9}		6.9	26	35
Acceleration	Initial Momentum	GeV/c	-	0.25	0.25	0.25
	Single-pass Linacs	GeV/c	-	1.0, 3.75	1.0, 3.75	1.0, 3.75
		MHz	-	325, 650	325, 650	325, 650
	Repetition	Hz	-	30	30	60
Cooling			No	No	Initial	Initial
Proton Driver	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam	GeV	120	6.75	6.75	6.75
	Protons/year	1×10^{21}	0.1	9.2	9.2	25.4
	Repetition	Hz	0.75	15	15	15

Muon Collider at the energy frontier

		Higgs Factory		Top Threshold Options		Multi-TeV Baselines		
Parameter	*Units*	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top† Production/10^7sec		3,500*	13,500*	7,000†	60,000†	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	$4^{\ddagger}$	4	4	4	4	4	1.6
Cooling		**6D no final**		**Full 6D**				

R&D platform at each Physics stage

Principle:

- MAP novel technologies to be tested and validated
- Dedicated test facilities usually very expensive and not useful for Physics
- Novel concept of test facility integrated into actual facility stage aiming at development & validation of technology required by next stage

nuSTORM as R&D platform for 6D cooling at moderate intensity

- Source of 10^{10} muons per pulse
- 6D cooling validation for HIGGS factory and/or Muon Collider

NuMAX as R&D platform for initial cooling

- Source of 10^{11} muons per pulse
- Initial cooling validation for NuMAX+

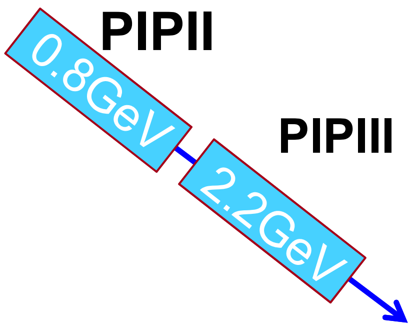
NuMAX+ as R&D platform for 6D cooling at high intensity

- Source of 10^{12} muons per pulse
- complementary to cooling experiment @ MICE at (very) low intensity
- 6D cooling validation for HIGGS factory and Muon Collider

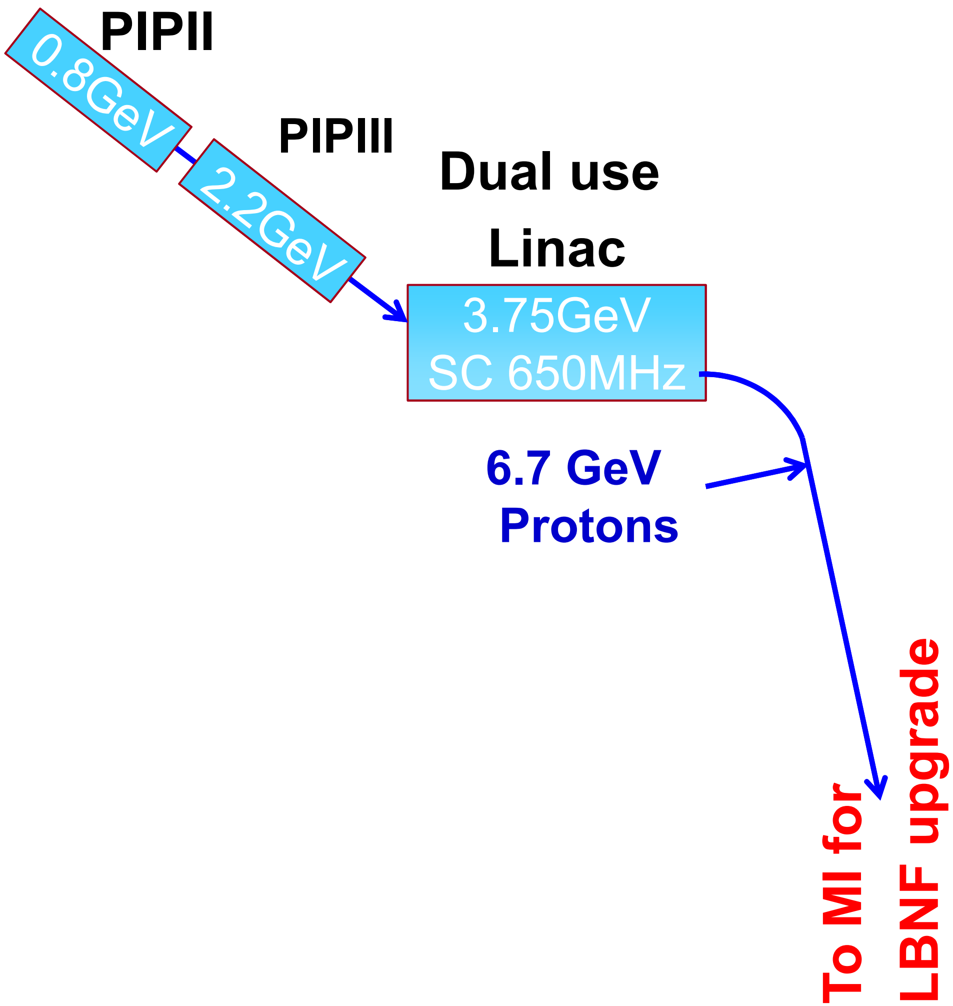
HIGGS factory as R&D platform for final cooling

- Final cooling validation for Muon Collider

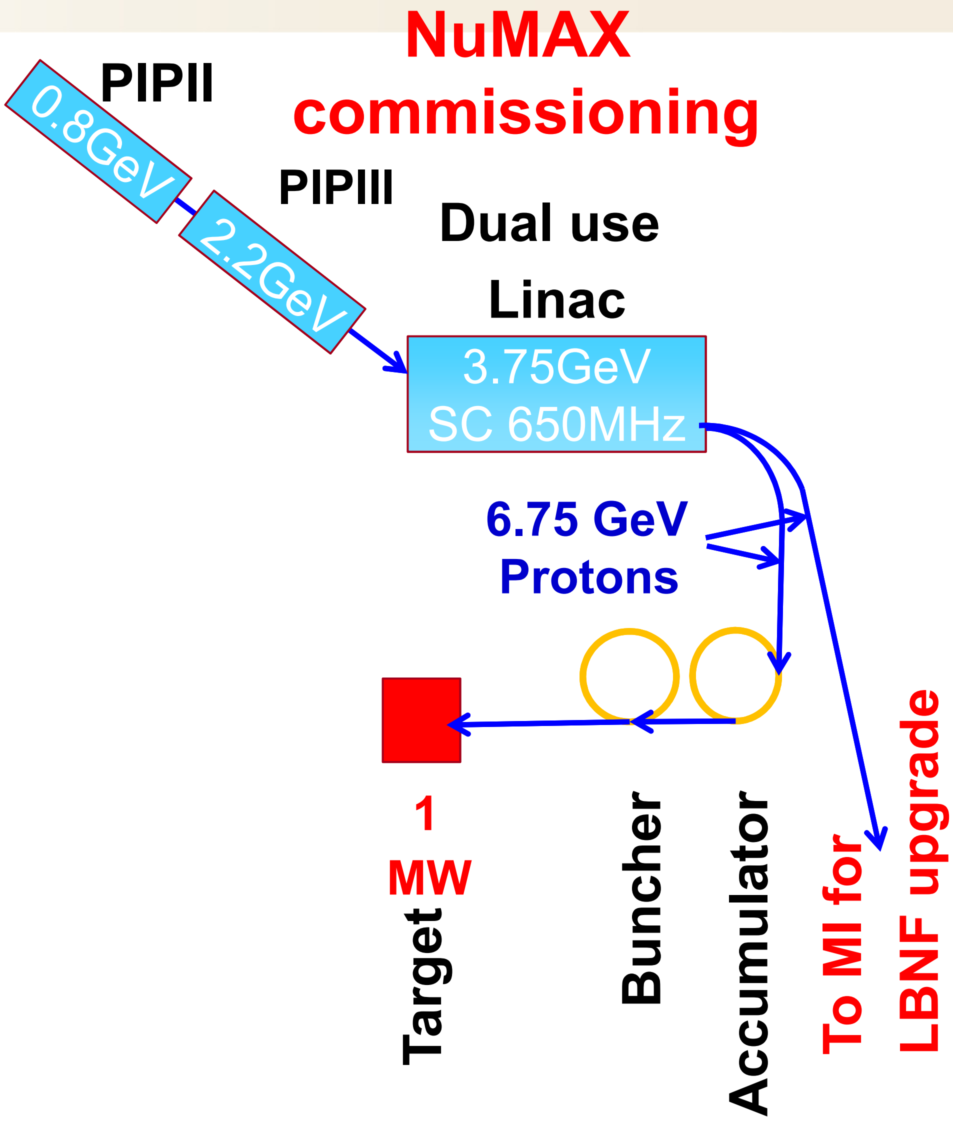
Progressive installation in stages with technology validation at each stage



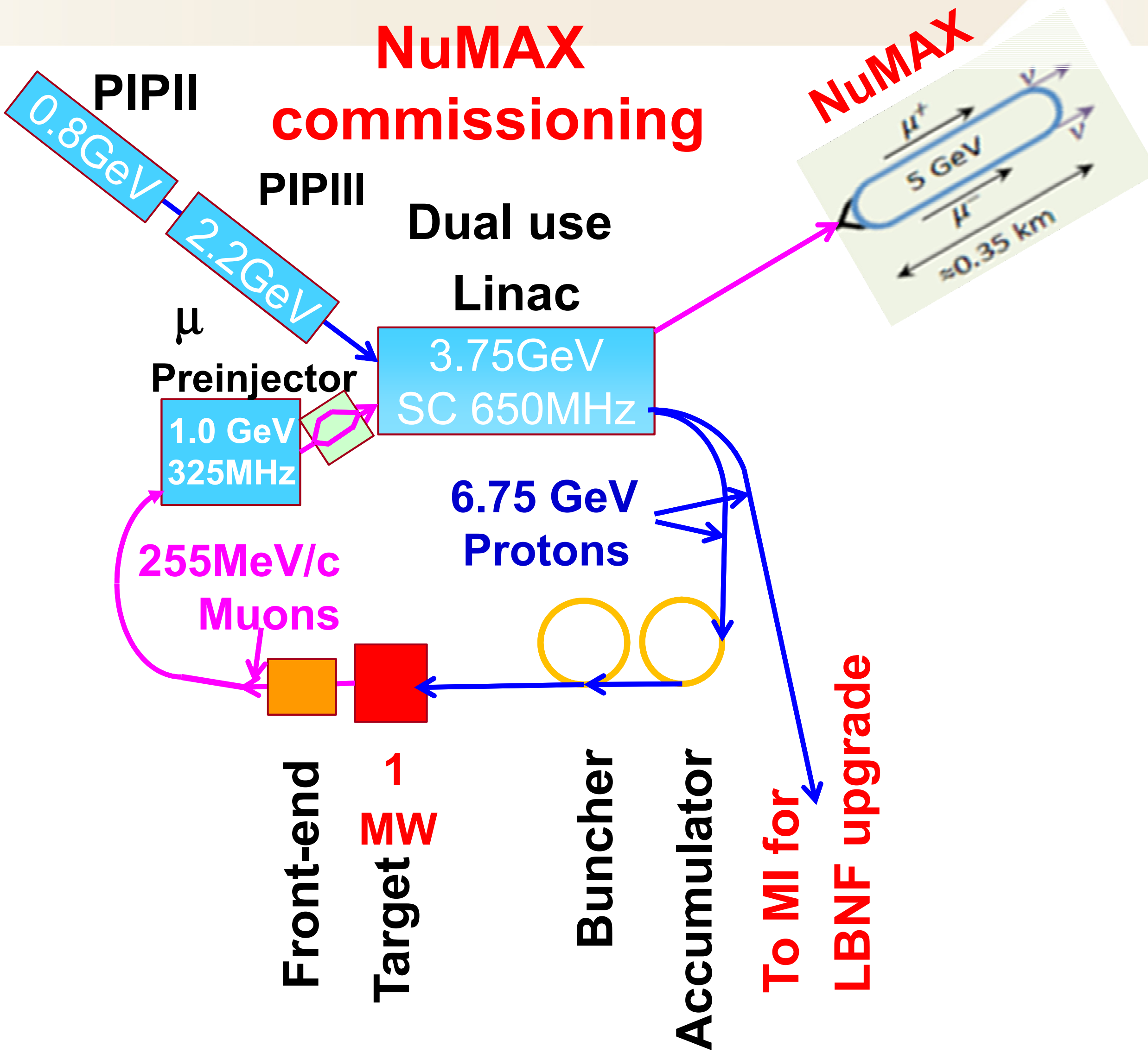
Progressive installation in stages with technology validation at each stage



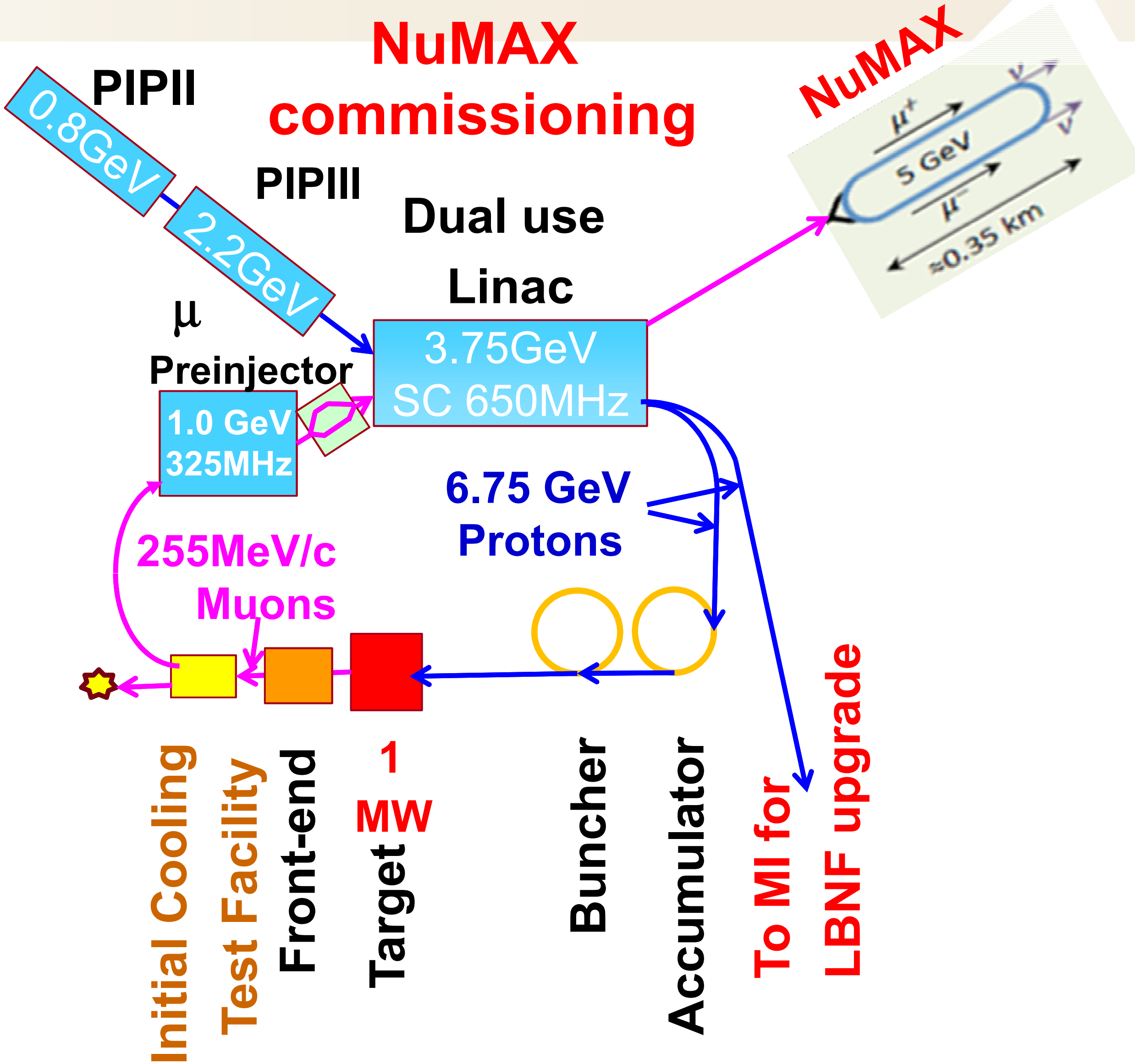
Progressive installation in stages with technology validation at each stage



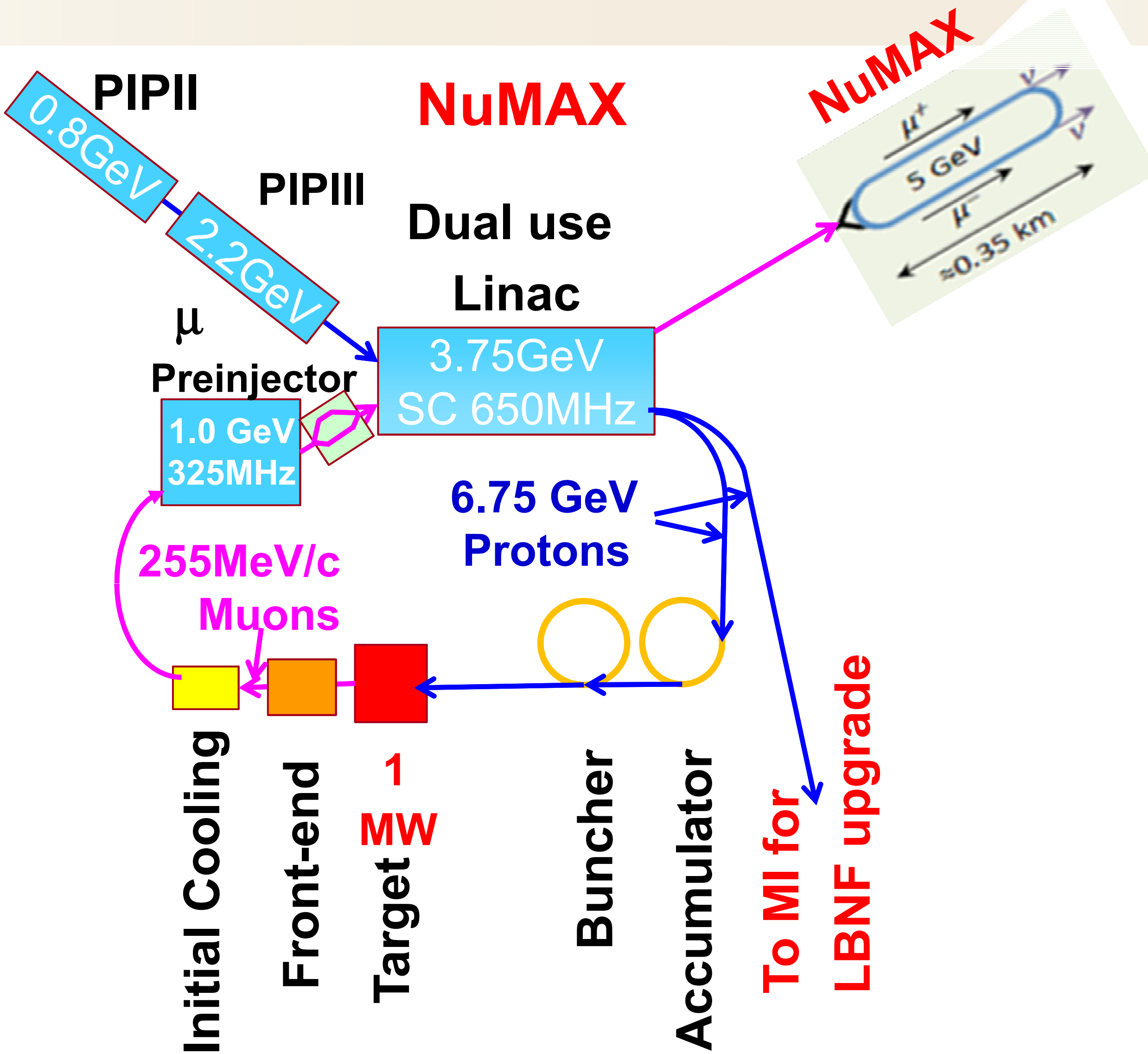
Progressive installation in stages with technology validation at each stage



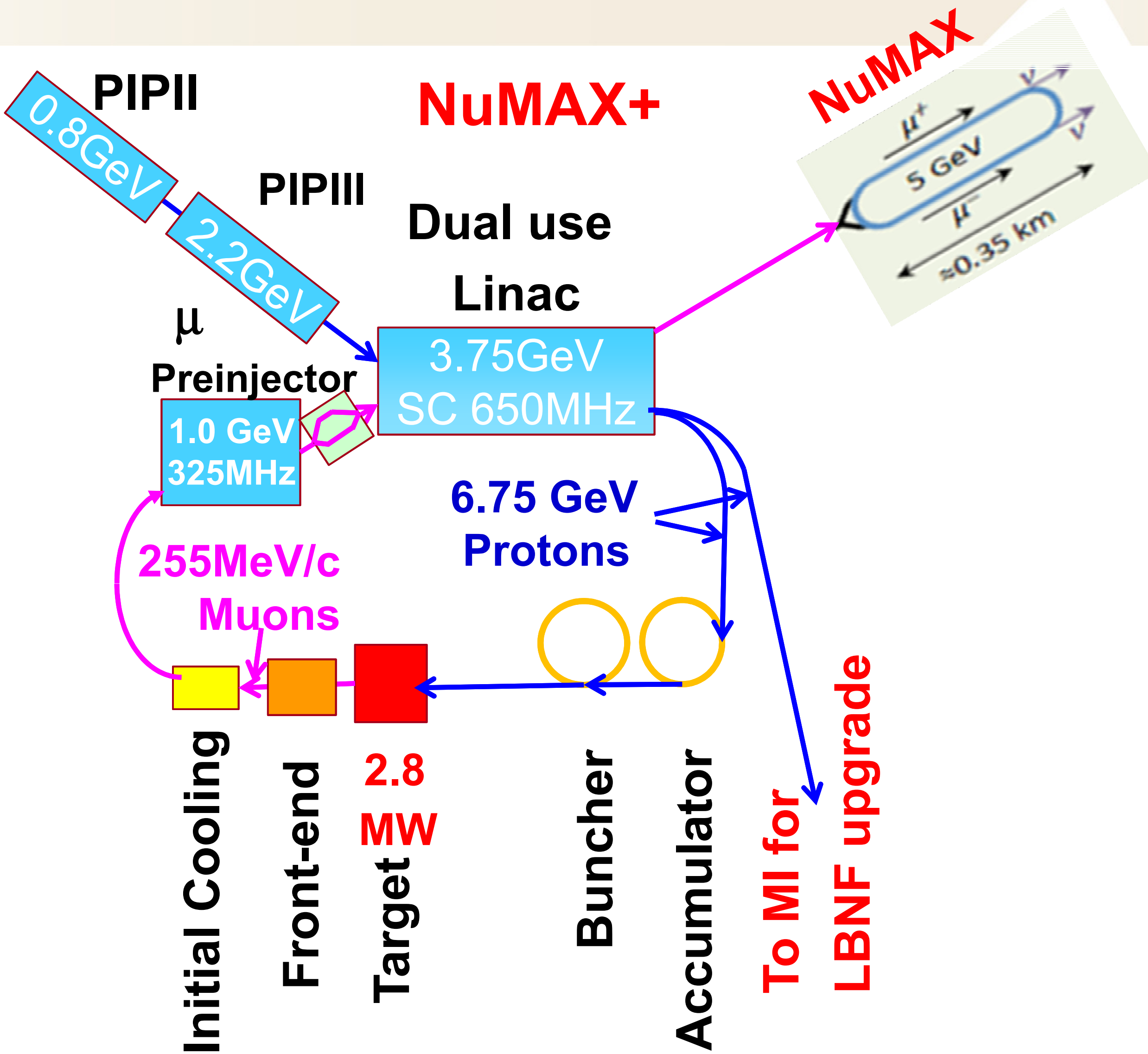
Progressive installation in stages with technology validation at each stage



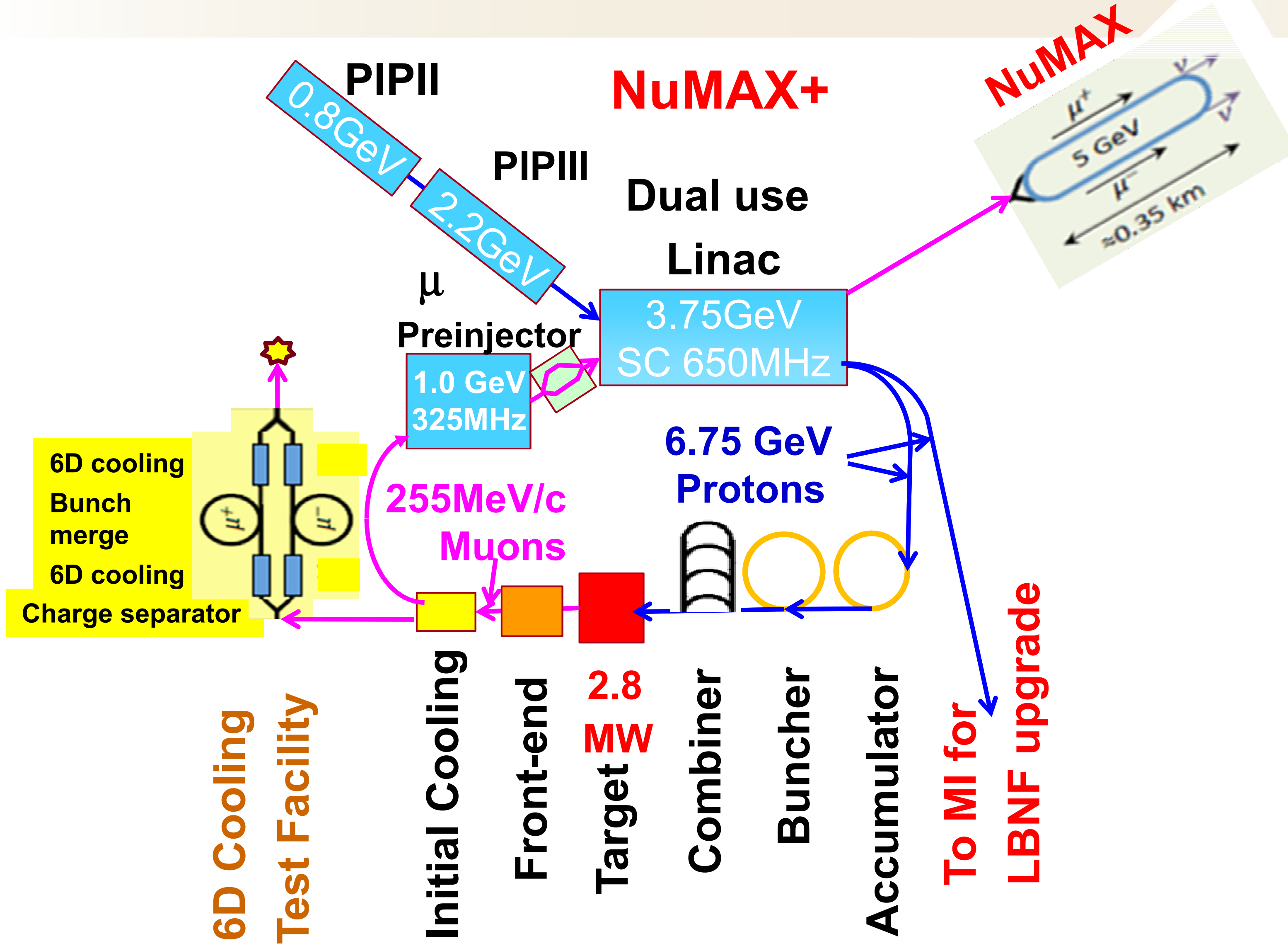
Progressive installation in stages with technology validation at each stage



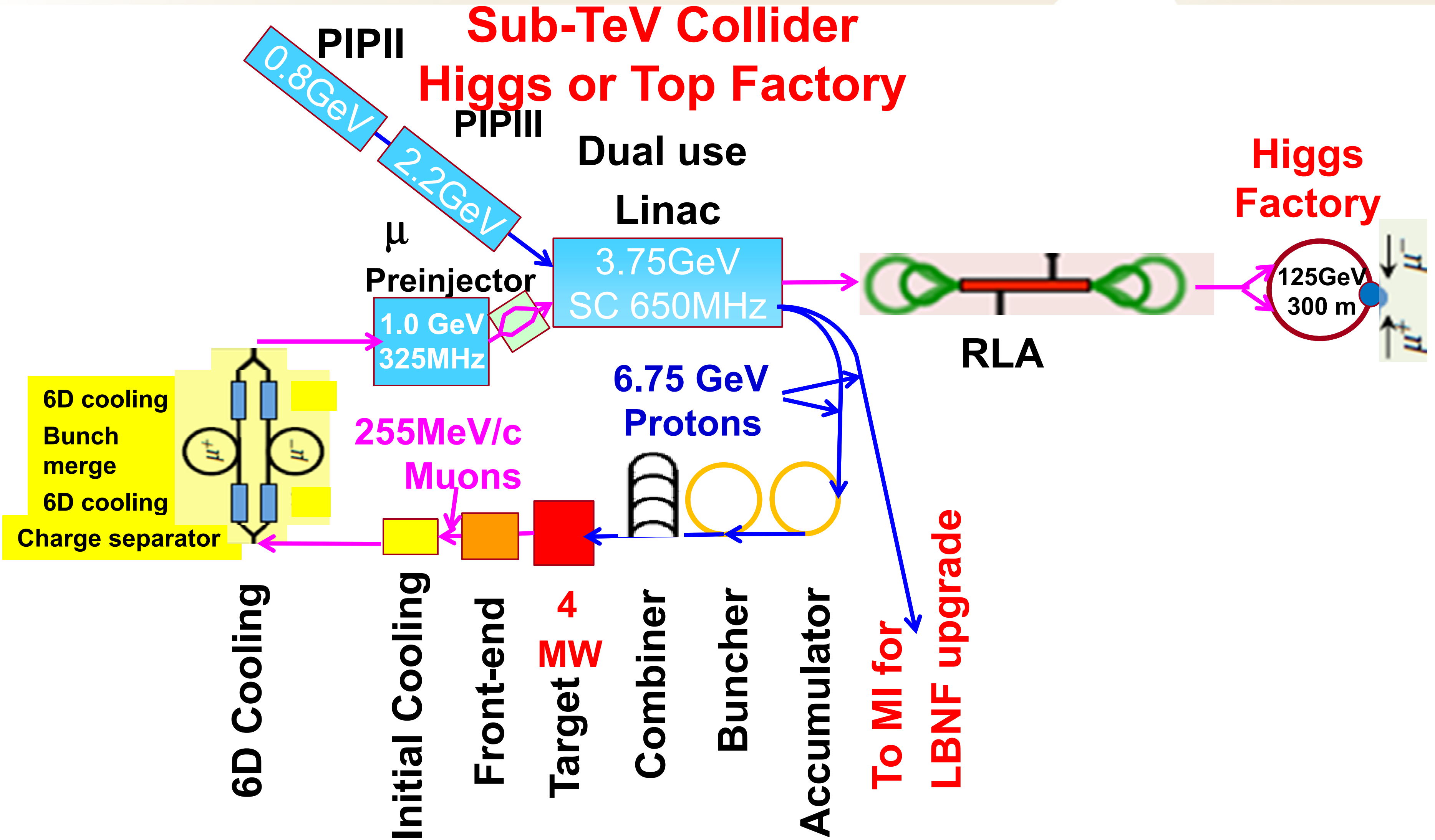
Progressive installation in stages with technology validation at each stage



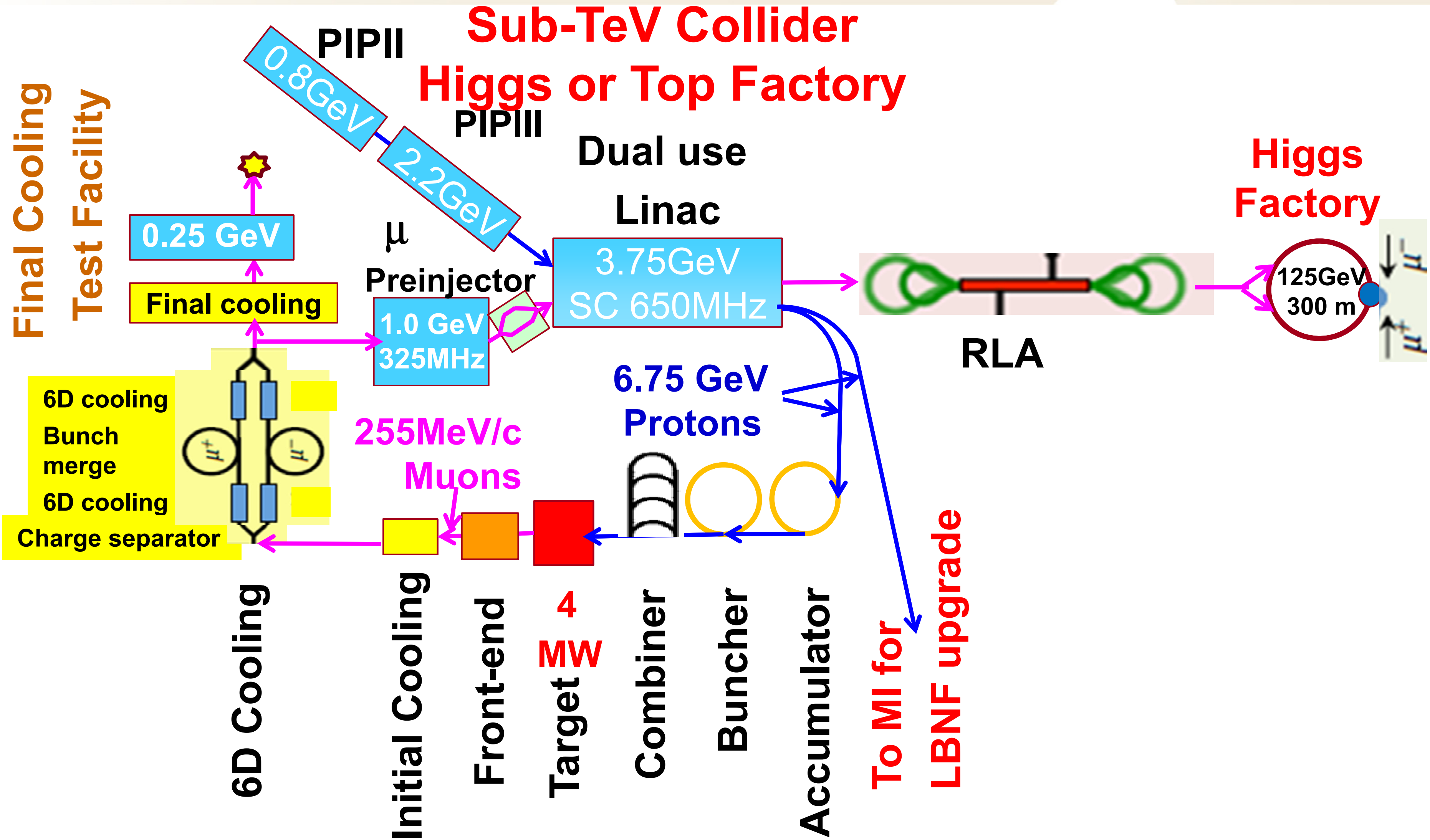
Progressive installation in stages with technology validation at each stage



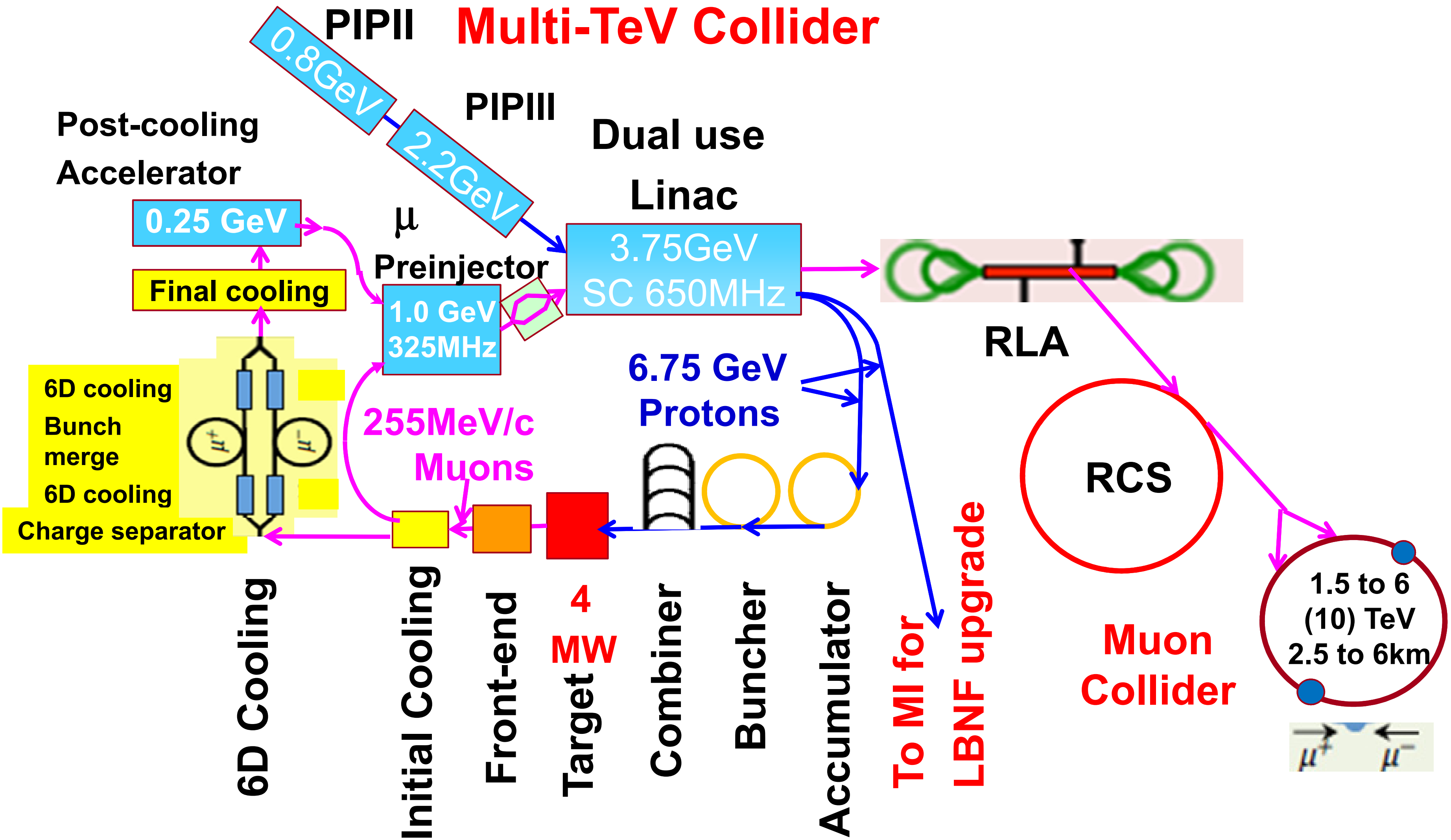
Progressive installation in stages with technology validation at each stage



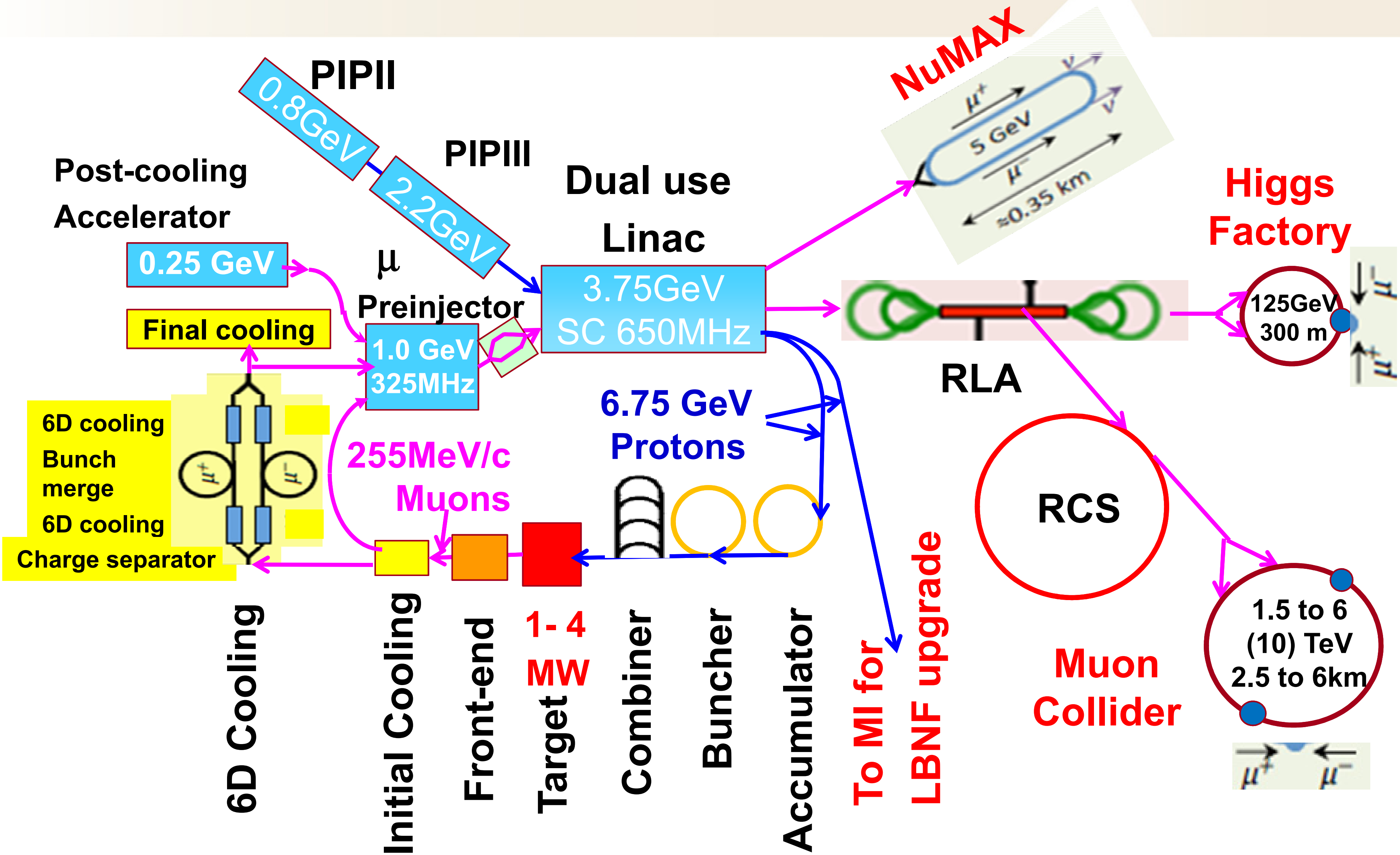
Progressive installation in stages with technology validation at each stage



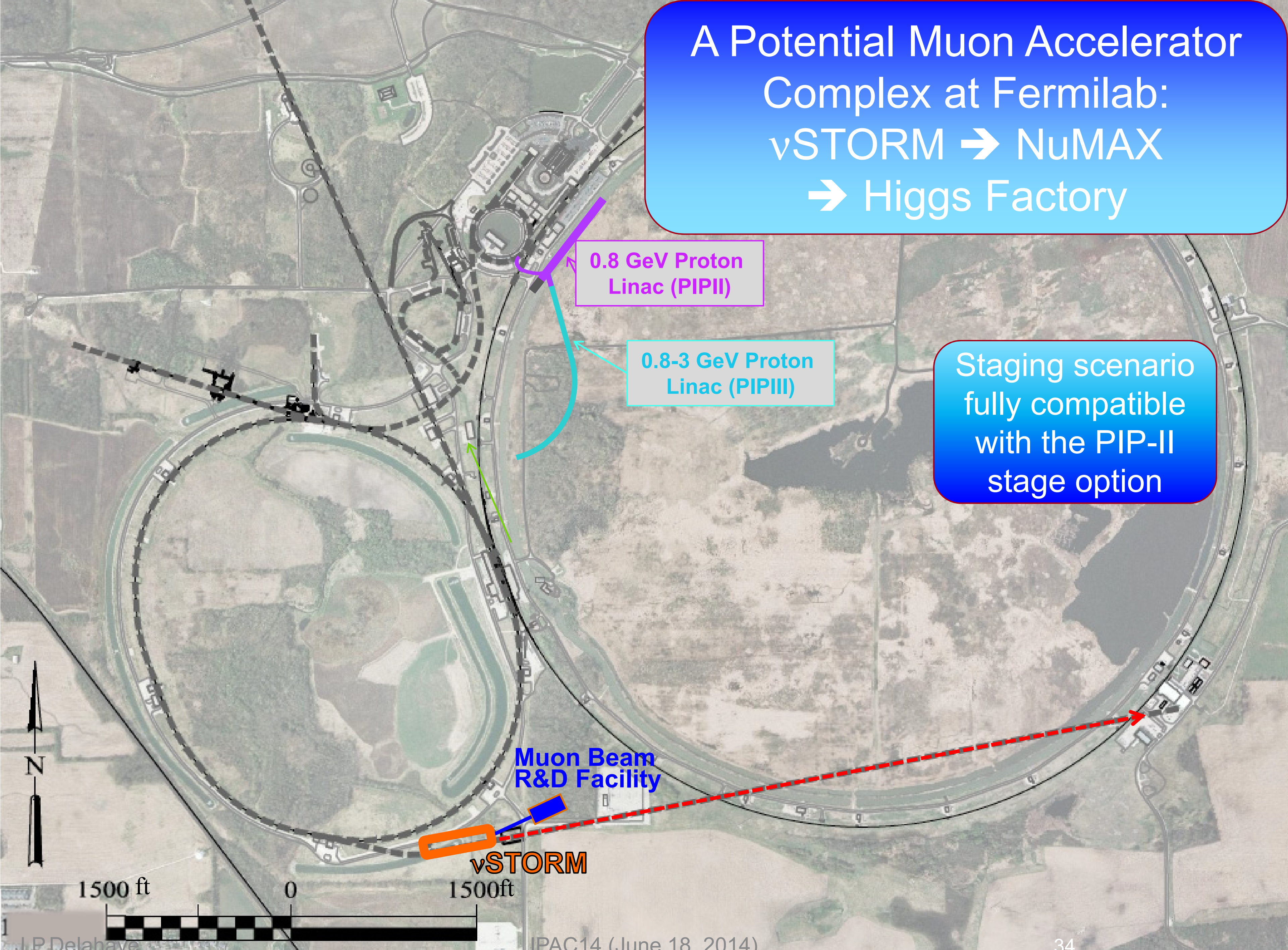
Progressive installation in stages with technology validation at each stage



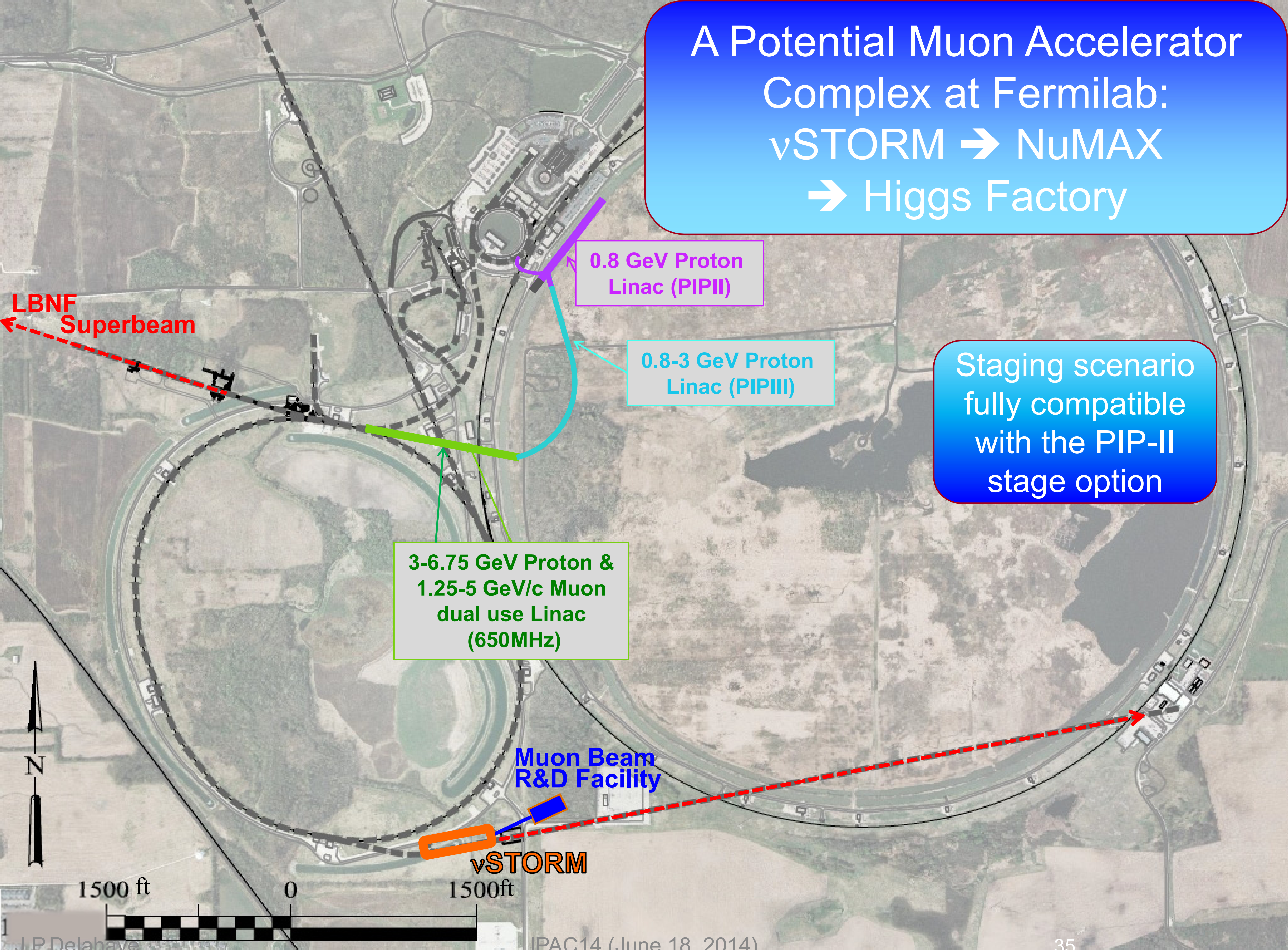
Progressive installation in stages with technology validation at each stage



A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory

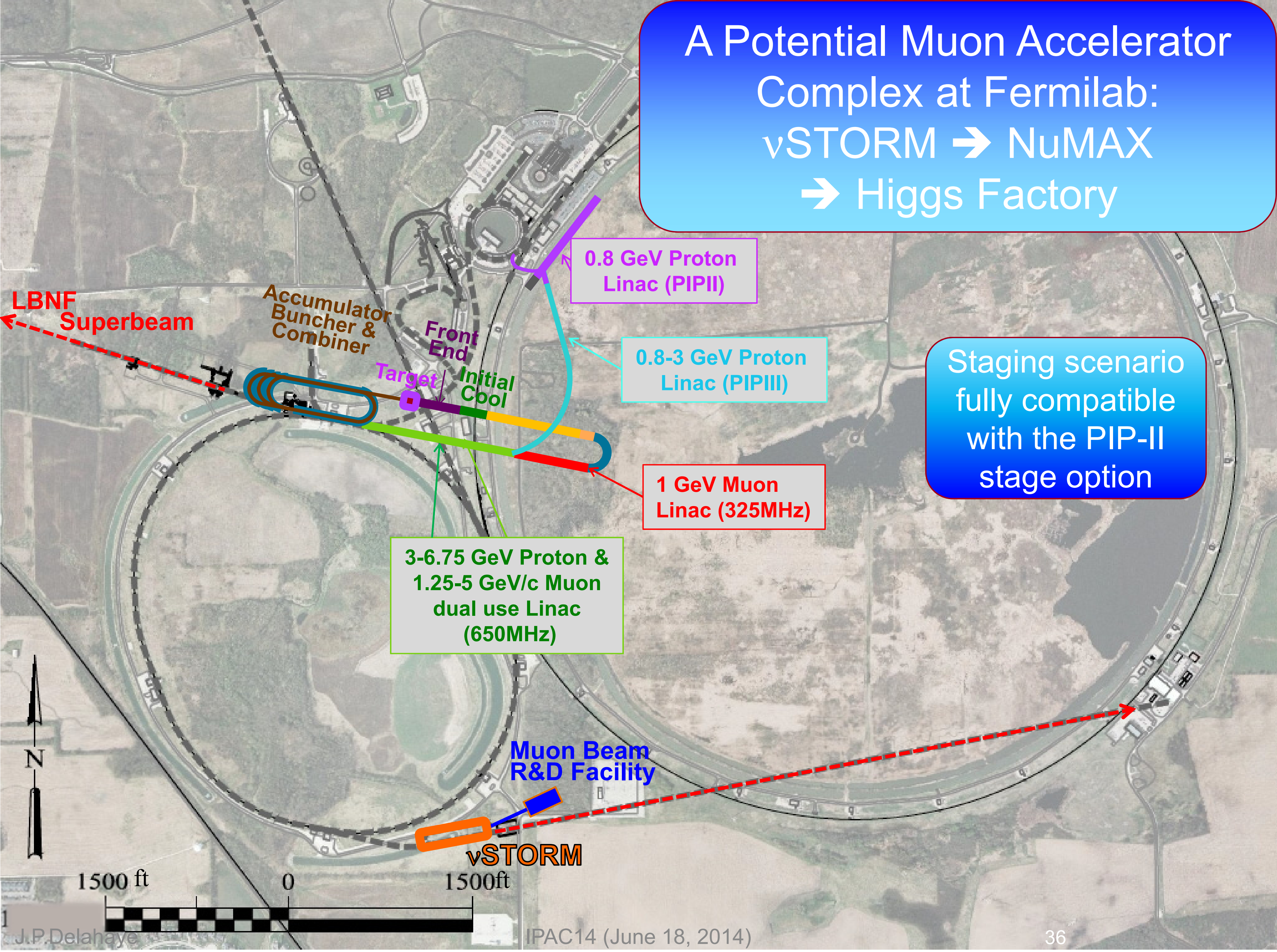


A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory

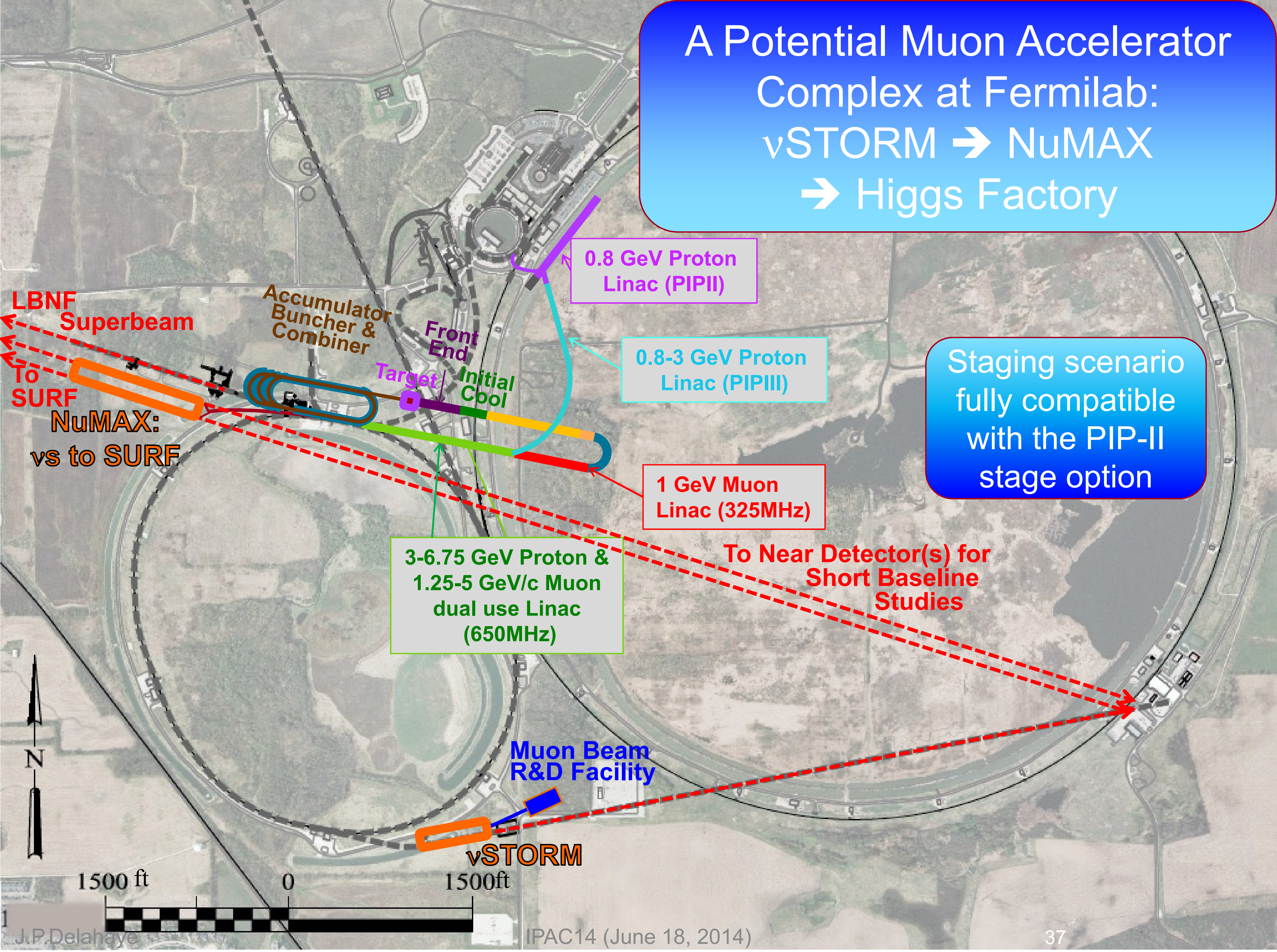


Staging scenario fully compatible with the PIP-II stage option

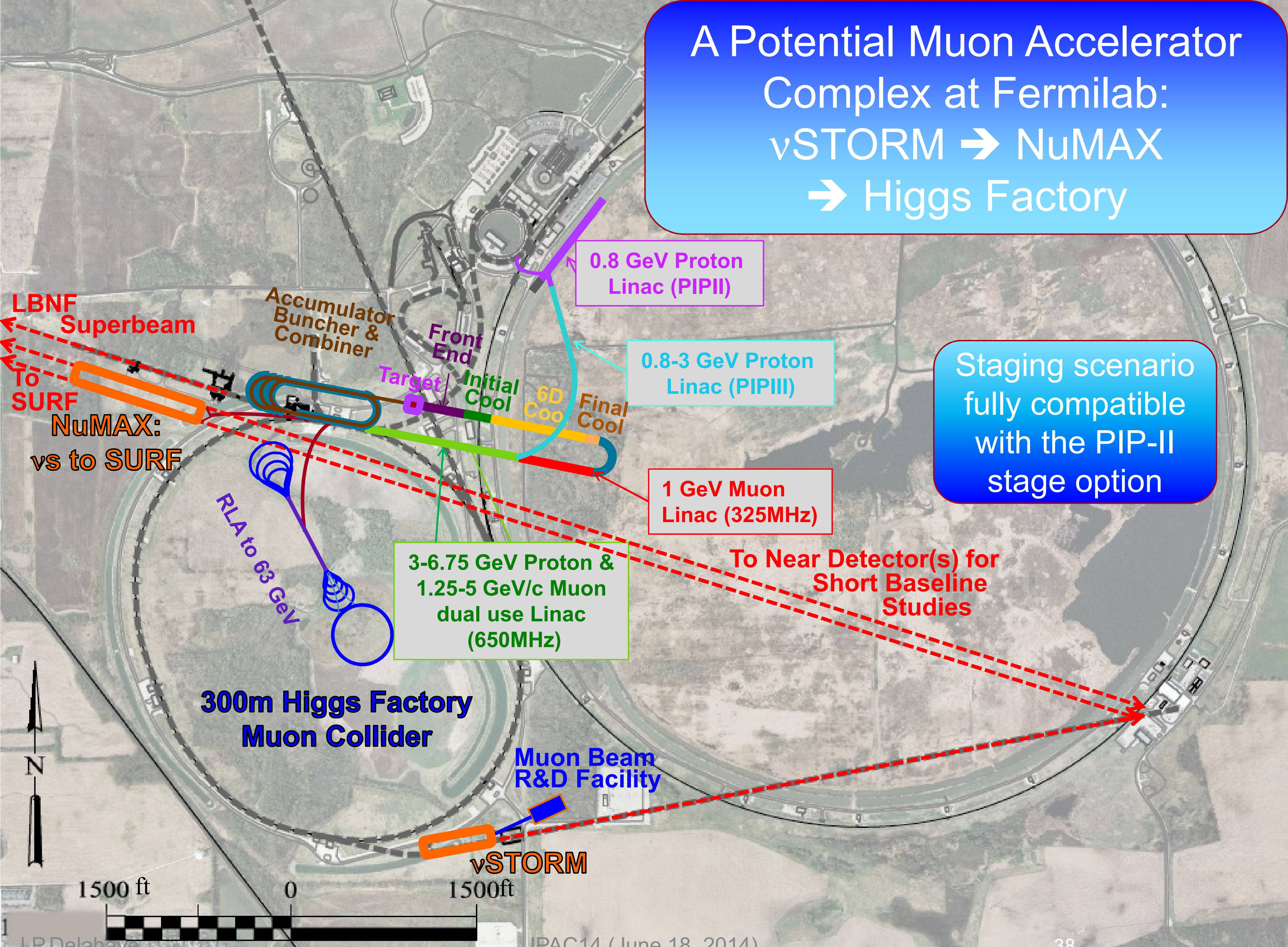
A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory

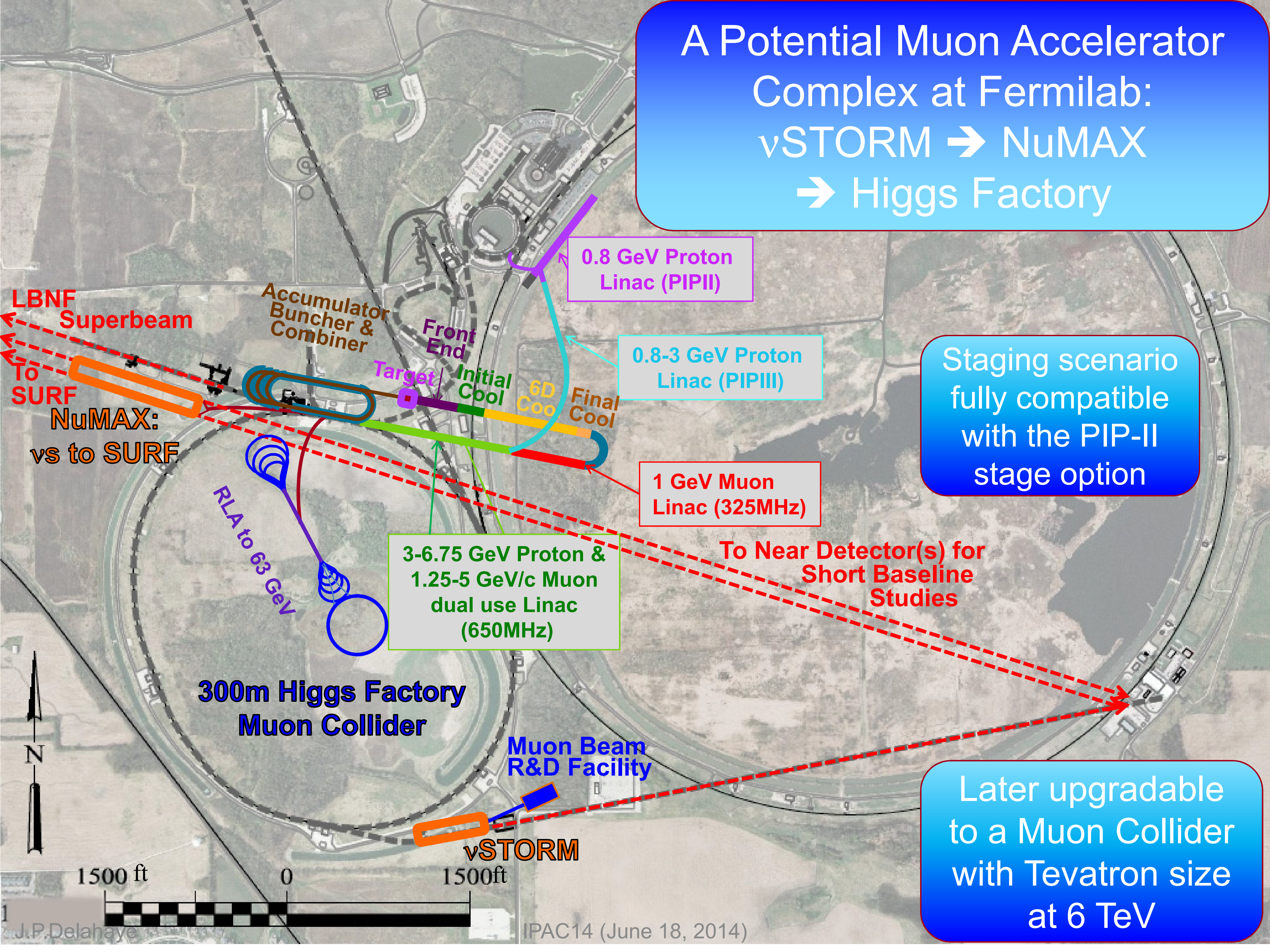


A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory



A Potential Muon Accelerator Complex at Fermilab: νSTORM ➔ NuMAX ➔ Higgs Factory




A Potential Muon Accelerator Complex at Fermilab:
νSTORM ➔ NuMAX ➔ Higgs Factory
0.8 GeV Proton Linac (PIPII)
0.8-3 GeV Proton Linac (PIPIII)
Staging scenario fully compatible with the PIP-II stage option
LBNF Superbeam
To SURF
Accumulator Buncher & Combiner
Front End
Target
Initial Cool
6D Cool
Final Cool
NuMAX: νs to SURF
1 GeV Muon Linac (325MHz)
RLA to 63 GeV
3-6.75 GeV Proton & 1.25-5 GeV/c Muon dual use Linac (650MHz)
To Near Detector(s) for Short Baseline Studies
300m Higgs Factory Muon Collider
Muon Beam R&D Facility
νSTORM
Later upgradable to a Muon Collider with Tevatron size at 6 TeV
N
1500 ft
0
1500ft
J.P.Delahaye
IPAC14 (June 18, 2014)

MAP timeline ⇨ providing informed decisions points

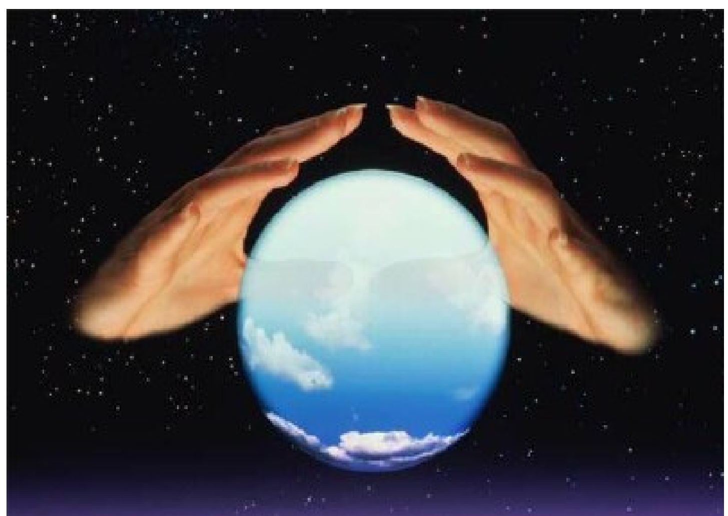
M.A.Palmer

2010	~2020	~2030

Muon Accelerator R&D Phase

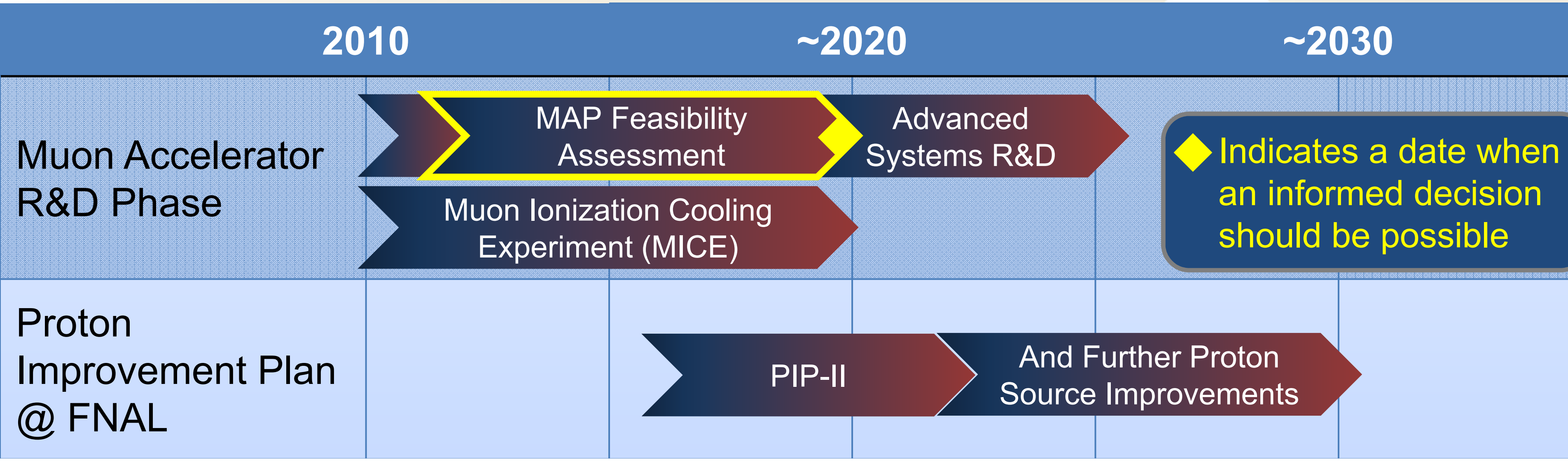
- MAP Feasibility Assessment
- Advanced Systems R&D
- Muon Ionization Cooling Experiment (MICE)

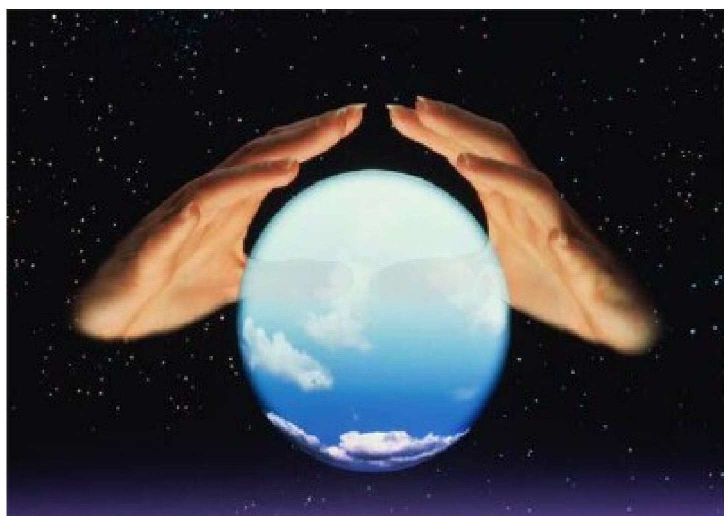
◆ Indicates a date when an informed decision should be possible



MAP timeline ⇨ providing informed decisions points

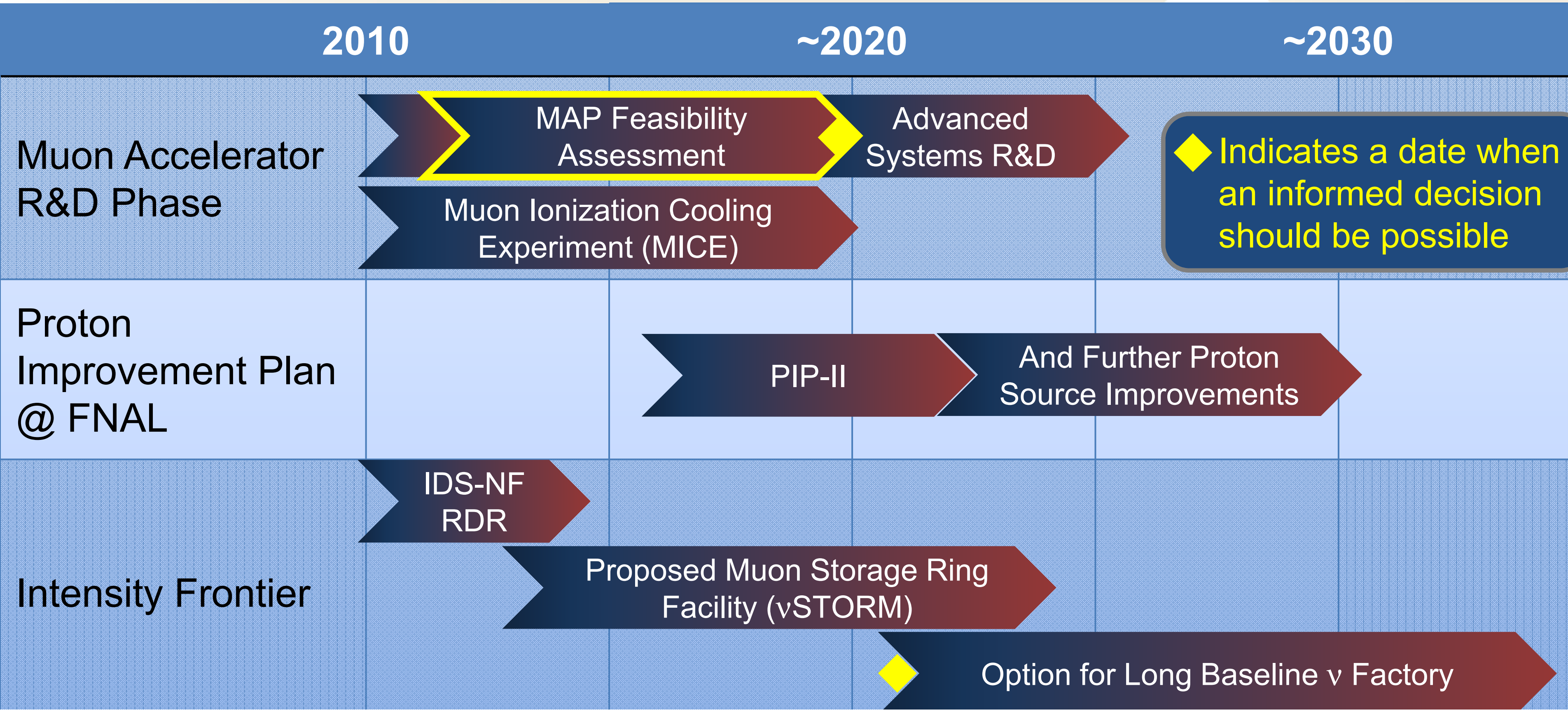
M.A.Palmer





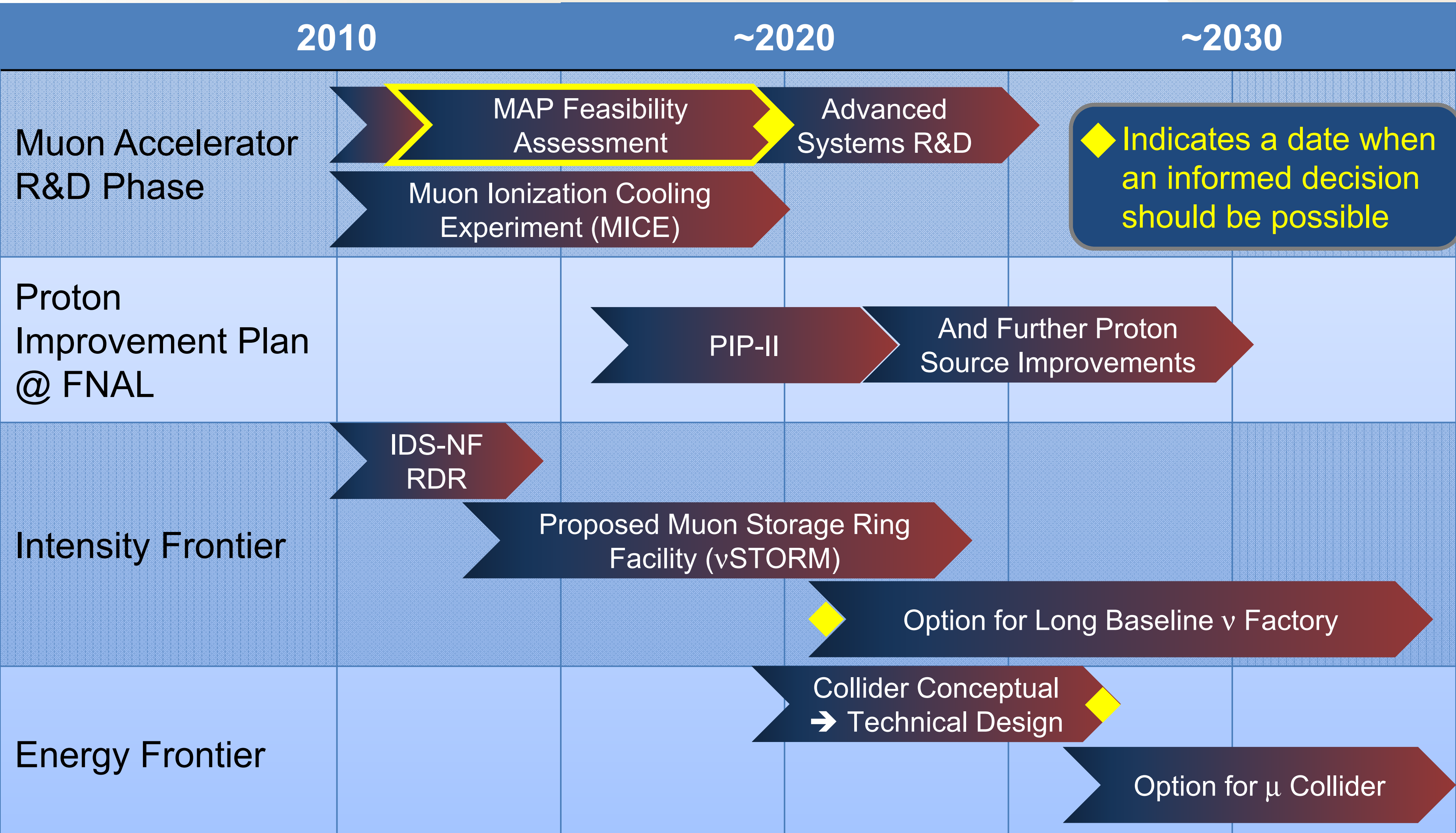
MAP timeline ⇨ providing informed decisions points

M.A.Palmer



MAP timeline ⇨ providing informed decisions points

M.A.Palmer



Conclusion

Muon based technology unique opportunity to enable facilities at both the high intensity and the high energy frontiers

- High precision neutrino physics and lepton colliders extension into multi-TeV range with reasonable dimensions, cost & power consumption
- MAP focused on feasibility demonstration of novel & challenging technology

Attractive Muon based Accelerators Staged Scenario

- Series of facilities with increasing complexity built-up on previous stage
- Integrated R&D platform at each stage for validation of novel technology
- Informed decision on following stages with risk mitigation
- Flexibility of adaptation to physics requirements

Especially appealing at FNAL taking advantage & leveraging of projects or then existing facilities: PIP, LBNF

- Neutrino Factory (NuMAX) natural complement of Long Baseline Neutrino Facility (LBNF) if warranted by Neutrino Physics at the time
- Multi-TeV lepton collider when and if required by (new) Physics in the future

Plea for long term R&D support

MAP related contributions to IPAC14

Posters

MOPME036 Plasma Effects and Simulation Tools for Muon-based Accelerators – P. Snopok, *etal.*

MOPME038 Space Charge Simulation in COSY using the Fast Multipole Method – P. Snopok, *etal.*

MOPME043 Modeling and Simulation of Beam-Induced Plasma in Muon Cooling Devices – R. Samulyak, *etal.*

MOPRI007 Design and Simulation of High Intensity Muon Beam Production for Neutrino Experiments – D. Stratakis, *etal.*

TUPME010 The Physics Programme of Next MICE Step IV – J.C. Nugent, *etal.*

TUPME011 The Status of the Construction of MICE Step IV – P. Snopok, *etal.*

TUPME012 The U.S. Muon Accelerator Program – M.A. Palmer

TUPME014 Development of Six-Dimensional Helical Muon Beam Cooling Channel for Muon Colliders – K. Yonehara, *etal.*

TUPME015 Study of Cooling Performance in a Helical Cooling Channel for Muon Colliders – K. Yonehara, *etal.*

TUPME016 Status of the Complete Muon Cooling Channel Design and Simulation – C. Yoshikawa, *etal.*

TUPME017 Design and Simulation of a Matching System into the Helical Cooling Channel – C. Yoshikawa, *etal.*

TUPME019 Design and Simulation of a High Field-low energy Muon Ionization Cooling Channel – D. Stratakis, *etal.*

TUPME020 A Complete Six-dimensional Muon Cooling Channel for a Muon Collider – D. Stratakis, *etal.*

TUPME021 Theoretical Framework to Predict Efficiency of Ionization Cooling Lattices – D. Stratakis, D. Neuffer

TUPME022 Design and Optimization of a Particle Selection System for Muon-based Accelerators – D. Stratakis, *etal.*

TUPME023 Overview of a Muon Capture Section fro Muon Accelerators- D. Stratakis, *etal.*

TUPME024 A Hybrid Six-Dimensional Muon Cooling Channel with Gas Filled Cavities – D. Stratakis, *etal.*

TUPRI002 The EUROnu Sudy for Future High Power Neutrino Oscillation Facilities – T.R. Edgecock, *etal.*

TUPRI003 Simulating the Production and Effects of Dark Currents in MICE Steps V and VI – C. Hunt, *etal.*

TUPRI004 The Design and Implementation of the Radiation Monitors for the Protection of the MICE Tracker Detectors – C. Hunt, *etal.*

TUPRI008 Target System Concept for a Muon Collider/Neutrino Factory – K.T. McDonald, *etal.*

TUPRO029 Reducing Backgrounds in the Higgs Factory Muon Collider Detector – S. Striganov, *etal.*

TUPRO030 Mitigating Radiation Impact on Superconducting Magnets of the Higgs Factory Muon Collider – S. Striganov, *etal.*

TUPRO116 Conceptual Design of the Muon Cooling Channel to Incorporate RF Cavities – M. Lopes, *etal.*

WEPME020 Commissioning of the MICE RF System – A. Moss, *etal.*

WEPRI100 Magnetic Design Constraints of Helical Solenoids – M. Lopes, *etal.*

WEPRI103 Magnet Design for a Six-dimensional Rectilinear Cooling Channel – Feasibility Study – D. Stratakis, *etal.*

THPME054 RF Cavity Design Aspects for a Helical Muon Beam Cooling Channel – F. Marhauser, *etal.*

THPRI028 Acoustic Spark Localization for the 201 MHz RF Cavity – P. Snopok, *etal.*

THPRI029 Acoustic Localization of Breakdown in the MICE Single-cavity Module – P. Snopok, *etal.*

THPRI030 Progress Towards Completion of the MICE Demonstration of Muon Ionization Cooling – P. Snopok, *etal.*

THPRI064 Plasma Chemistry in a High Pressure Gas Filled RF Test Cell for Use in a Muon Cooling Channel – K. Yonehara, *etal.*

THPRI065 Effects of Beam Loading and Higher-Order Modes in RF Cavities for Muon Ionization Cooling – K. Yonehara, *etal.*

THPRI067 Installation and Commissioning of the MICE Single-Cavity Module – Y. Torun, *etal.*

THPRI068 Extended RF Testing of the 805-MHz Pillbox “All-Season” Cavity for Muon Cooling – Y. Torun, *etal.*

THPRI069 Tube-grid Windows for Pillbox Cavities – Y. Torun, *etal.*

THPRI070 Tuner System Simulation and Tests for the 201-MHz MICE Cavity – Y. Torun, *etal.*

THPRI071 Instrumentation for Characterizing 201-MHz MICE Cavity at Fermilab – Y. Torun, *etal.*

THPRI072 The Fermilab MuCool Test Area and Experimental Program – Y. Torun, *etal.*

THPRI087 Magnet Design for the Target System of a Muon Collider/Neutrino Factory – K.T. McDonald, *etal.*

THPRI088 Energy Deposition in the Target System of a Muon Collider/Neutrino Factory – K.T. McDonald, *etal.*

THPRI089 Optimization of Particle Production for a Muon Collider/Neutrino Factory with a 6.75 GeV Proton Driver – K.T. McDonald, *etal*

Presentations

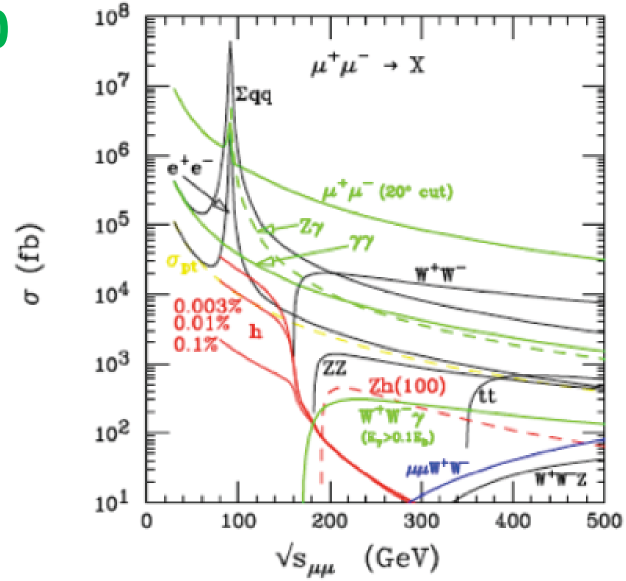
MOOCA02 RF Design and Operation of a Modular Cavity for Muon Ionization Cooling R&D – Y.Torun, *etal.*

WEZA02 A Staged Muon Accelerator Facility for Neutrino and Collider Physics – J-P. Delahaye, *etal.*

Supporting slides

The beauty of Muons

- **Strong coupling to Higgs mechanism by s channel**
  - **Cross section enhanced by $(m_\mu/m_e)^2$ =40000 with sharp peak at 126GeV resonance**
    - **Higgs factory allowing energy scan with high energy resolution for direct mass and width measurements at half colliding beam energy and 10^3 less luminosity than with e+/e-**
    - **Requires colliding beam with extremely small momentum spread (4 10^{-5}) and high stability**



As with an e^+e^- collider, a $\mu^+\mu^-$ collider offer a precision probe of fundamental interactions

without limitations in energy:

- **By synchrotron radiation as e^+e^- circular colliders**
- **By beams-trahlung as e^+e^- linear colliders**

An attractive staging scenario in the FNAL context

a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach:

nuSTORM (neutrinos from STOred Muons): a short-baseline 3.8 GeV Neutrino Factory-like facility enabling a definitive search for sterile neutrinos, as well as neutrino cross-section measurements

NuMAX (Neutrinos from Muon Accelerator compleX): a long-baseline 5GeV Neutrino Factory, optimized for a detector at the Sanford Underground Research Facility (SURF) to be built in phases,

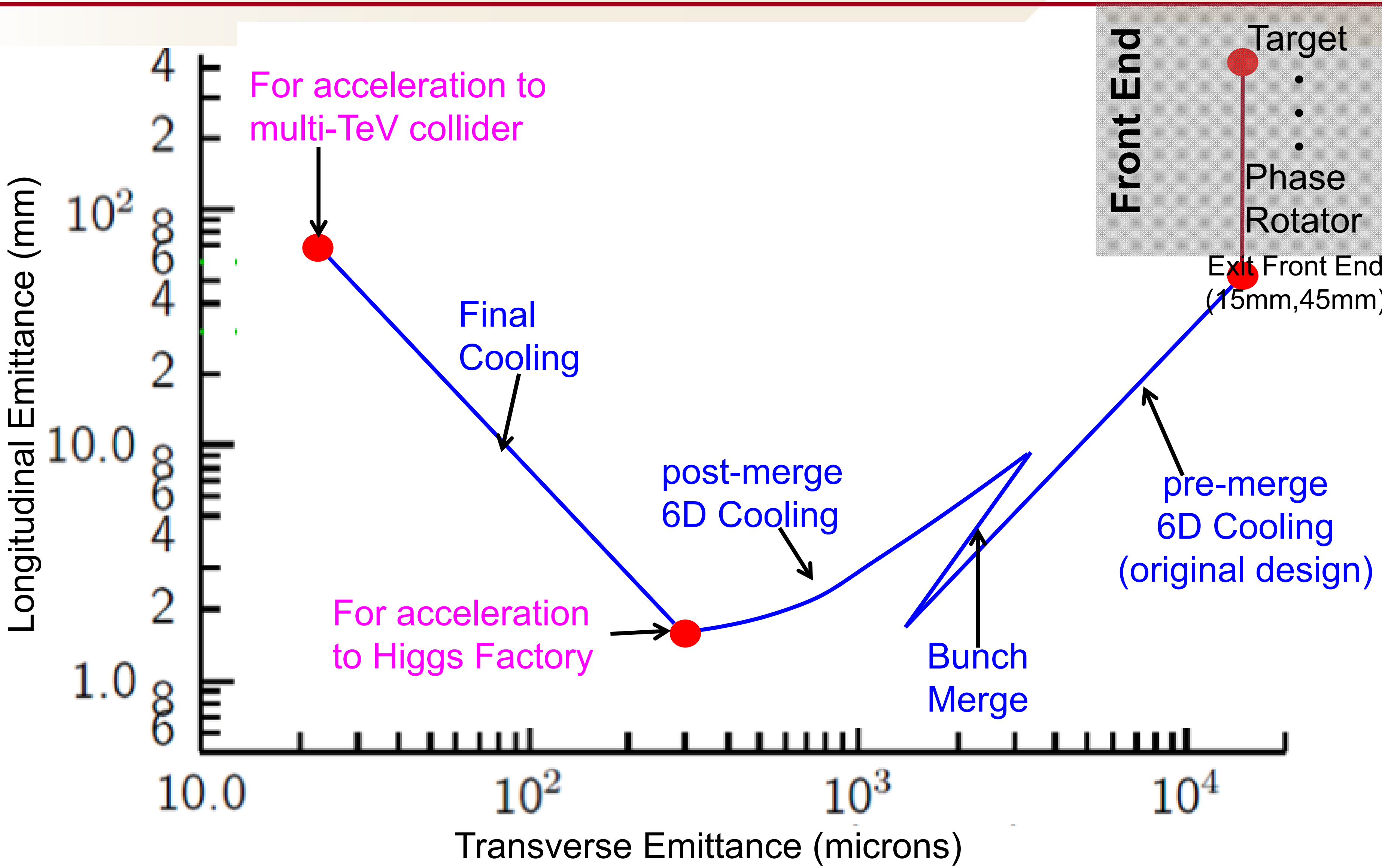
- **A commissioning phase based on a limited proton beam power of 1MW on the muon production target with no cooling for an early and realistic start with conventional technology**
- **NuMAX upgraded from the commissioning phase by adding a limited amount of 6D cooling (by a factor 50), affording a precise and well-characterized neutrino source**
- **NuMAX+: a full-intensity Neutrino Factory, upgraded from NuMAX by multiplying the proton beam power on target and detector upgrade for performance as the ultimate source for precision CP-violation measurements and potential exploration of new physics in the neutrino sector**

Higgs Factory: 125 GeV collider providing up to 13,500 Higgs events per year (10^7 sec) with exquisite energy resolution enabling direct Higgs mass and width measurements (s channel coupling).

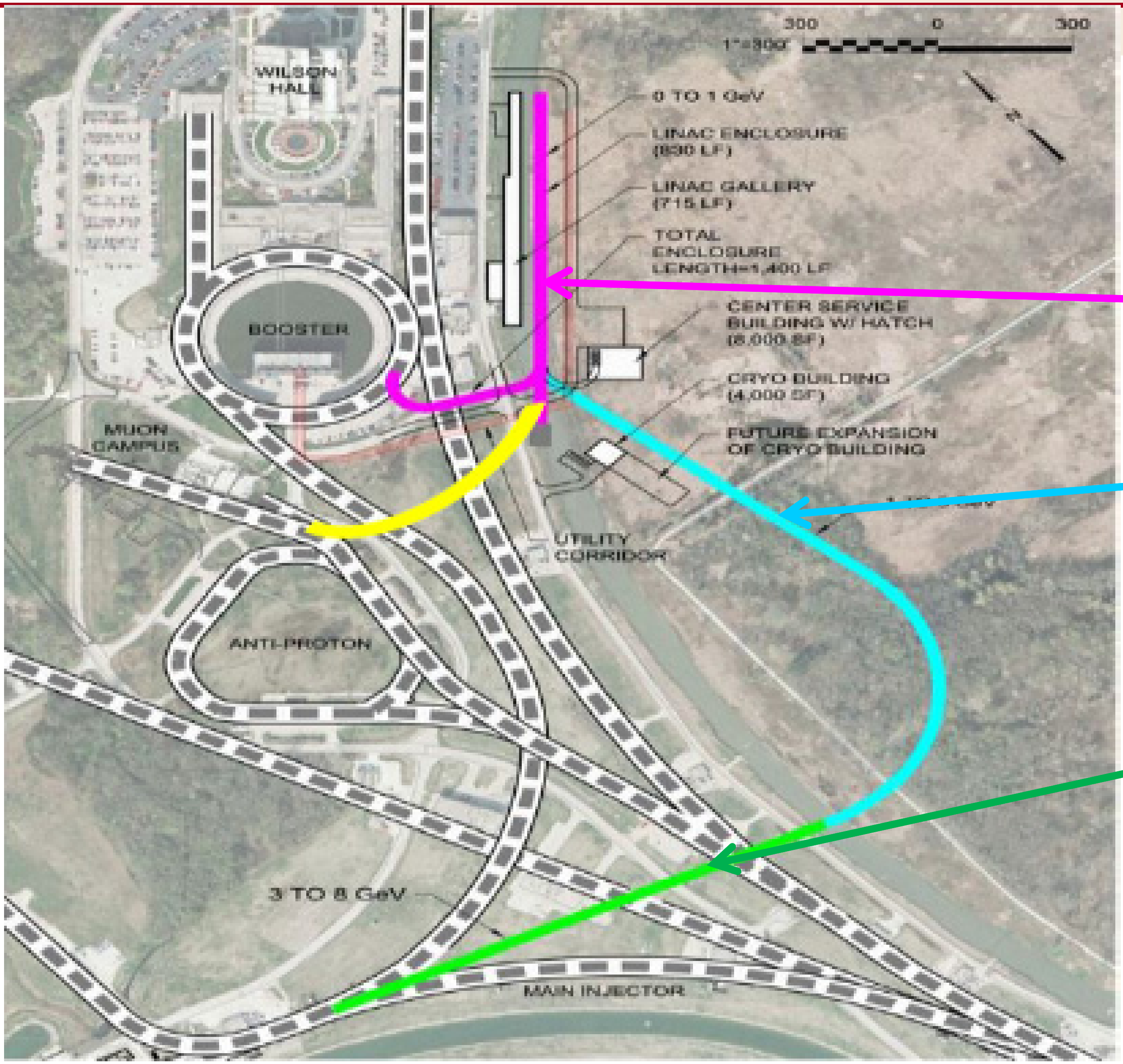
- **Possible upgrade to a Top Factory with production of up to 60000 top particles per year (10^7 sec).**

Multi-TeV Collider: if warranted by LHC results, with an ultimate energy reach up to 10 TeV, offering the best performance, least cost and power consumption of any lepton collider in the multi-TeV regime.

Cooling System: Emittance path
6 orders of magnitude in 6 Dimensions



FNAL Proton Improvement Plan (PIP)
Possible future upgrade



S.Holmes @ P5
Dec16, 2013