MASS preliminary recommendations for MAP Initial Baseline Selection

by the MASS working group[1]

Following the mandate of the **M**uon **A**ccelerator **S**taging **S**tudy (**MASS**)[2], a preliminary set of recommendations on possible staging options for a realistic and cost optimized implementation of muon based facilities at Fermilab is provided below for consideration and possible validation by the upcoming MAP **I**nitial **B**aseline **S**election (**IBS**) process.

Introduction

A preliminary staging scenario[3] has been presented at the Snowmass workshop. It takes advantage of the unique potential of muon based facilities to provide capabilities at both the Intensity Frontier with Neutrino Factories and the Energy Frontier with Muon Colliders ranging from the Higgs energy to the multi-TeV energy range (Figure 1). The updated staging scenario and corresponding preliminary recommendations presented below corresponds to an adaptation to the evolving ideas of the **P**roton **I**mprovement **P**lan (**PIP**) at Fermilab.

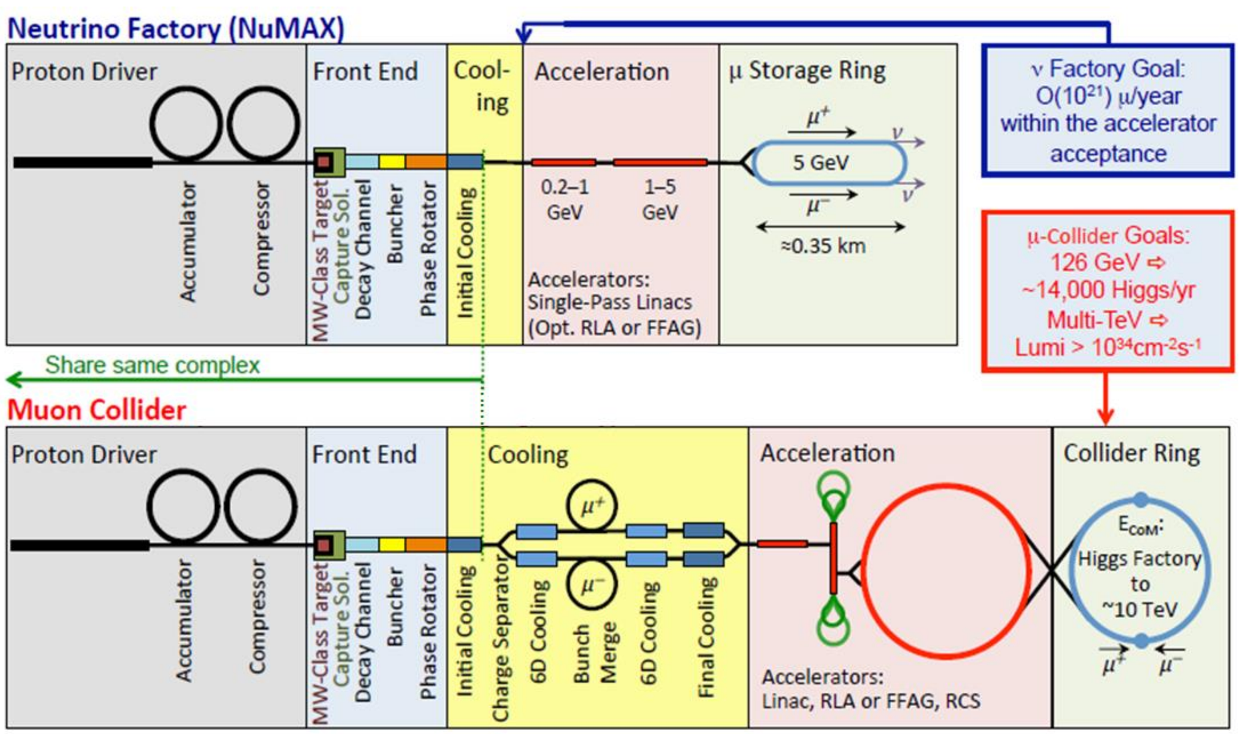


Figure 1: Neutrino Factory and Muon Collider layouts emphasizing synergies

The staging scenario

The updated staging scenario consists of a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach:

- **nuSTORM**[4]: a short-baseline Neutrino Factory-like facility enabling a definitive search for sterile neutrinos, as well as neutrino cross-section measurements that will ultimately be required for precision measurements at any long-baseline experiment.
- **NuMAX (N**eutrino from **M**uon **A**ccelerator Comple**X):** a long-baseline 5GeV Neutrino Factory, optimized for a detector at the **S**anford **U**nderground **R**esearch **F**acility (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, while already providing very attractive physics parameters.
    - **NuMAX** upgraded from the commissioning phase by adding a limited amount of 6D cooling, affording a precise and well-characterized neutrino source that exceeds the capabilities of conventional superbeams.
    - **NuMAX+**: a full-intensity Neutrino Factory, upgraded progressively from NuMAX by multiplying the proton beam power on target when it becomes available, and upgrading correspondingly the detector for performance similar to the IDS-NF[5] as the ultimate source to enable precision CP-violation measurements in the neutrino sector
- **Higgs Factory**: a collider capable of providing between 3500 (startup) and 13,500 Higgs events per year (10^7 sec) with exquisite energy resolution enabling direct Higgs mass and width measurements.
    - Possible upgrade to a **Top Factory** with production of up to 60000 top particles per year (10^7 sec) for precise top properties measurements.
- **Multi-TeV Collider**: if warranted by LHC results, a multi-TeV Muon Collider, with an ultimate energy reach up of to 10 TeV, likely offers the best performance, least cost and power consumption of any lepton collider operating in the multi-TeV regime.

The series of facilities is proposed to be built in stages, where each stage offers:

- Unique physics capabilities such that the corresponding facility obtains support and is funded.
- In parallel with the physics program, integration of an R&D platform to develop, test with beam, validate and get operational experience with a new technology that is necessary for the following stages.
- Construction of each stage as an add-on to the previous stages, extensively reusing the equipment and systems already installed, such that the additional budget of each stage remains affordable.

Such a staging plan provides clear decision points before embarking upon each subsequent stage. It is especially attractive at FNAL building on, and taking advantage of, existing or proposed facilities, thus maximizing the synergies between the existing FNAL program and the proposed MAP program, specifically:

- Existing tunnels and other conventional facilities;
- The Proton Improvement Plan (PIP) as the MW-class proton driver for muon generation;
- The Sanford Underground Research facility (SURF) as developed for the LBNE detector, which could then house the detector for a long-baseline Neutrino Factory.

Preliminary parameters of the various facilities with progressing complexity are presented in Annex I: a) for muon colliders and b) for neutrino factories. A tentative block diagram of the overall complex in a phased approach based on the recommendations below and emphasizing the evolution and synergies from Neutrino Factory to Muon collider is shown in Annex II. A possible implementation of the complex on the FNAL site is sketched in Annex III.

Recommendations for MAP IBS

1. nuSTORM as first stage

1.1. Building-up experience on muon accelerators at FNAL

1.2. Providing an ideal beam for R&D platform on muon based technology

1.3. Design and implementation to be reviewed

- maximizing synergies with LBNE and/or with NuMAX at similar energy
- allowing cost optimized evolution from nuSTORM to NuMAX
- optimizing nuSTORM Physics and integration in the MASS staging scenario

2. Proton driver

2.1. PIPII (0.8GeV) as presently envisaged and eventually PIPIII (2.2GeV) if decided in the future as the 3 GeV injector of the Proton Driver

2.2. Further proton acceleration by a 650MHz dual use linac of both PIP (H^-) and MAP (μ) programs with potential of considerable overall cost savings

2.3. Energy gain of the dual use linac (tentatively 3.75 GeV) optimized as best trade–off between linac saving and cooling additional cost (see 4.2)

2.4. Providing a >6.75 GeV proton beam

- At MI injection for LBNE beam power upgrade
- On target for close to optimum muon production

2.5. Common design of the dual use linac and coherent layout of PIP and MAP complexes on FNAL site in close collaboration between PIP & MAP teams.

3. Target for muon production

3.1. Focus the target design and development effort on a technology suitable to 1MW upgradable to about 2.3MW beam power with Neutrino Factory and Muon Collider time structures.

3.2. Proton beam power on target initially limited to 1MW for an early and realistic start of NuMAX initial phases based on "conventional" technology taking advantage of available experience on existing facilities as much as possible.

3.3. MAP ultimate proton beam power and target specifications aligned to FNAL plans for LBNE: 2.3 MW

- Maximizing synergy with and taking advantage of the development at FNAL towards the LBNE improvement program
- NF and MC designs to be reviewed accordingly:
  - ✓ $NuMAX^+$ would provide $4.2\ 10^{20}$ neutrinos of each kind per year (10^7 s) to the SURF detector corresponding to 80% of the IDS-NF performance. A $NuMAX^+$ performance equivalent to the one of IDS-NF would require a proton beam power of 2.75 MW (Annex 1b)
  - ✓ The 6 TeV collider design is unchanged since already limited to a proton beam power of 1.6MW by neutrino background (Annex 1a)
  - ✓ At lower colliding beam energies, preserve luminosity as much as possible by maintaining the charge per bunch and scaling down the repetition rate thus reducing proportionally both the power consumption and the luminosity by a ratio of 4/2.3=1.74, if acceptable. The corresponding $2.5\ 10^{34}\ cm^{-2}s^{-1}$ luminosity of a 3TeV muon collider would still be larger than the one proposed by CLIC at the same energy.

4. Cooling

4.1. NuMAX commissioning phase without any cooling for an early and realistic start

- NuMAX commissioning phase as an R&D platform, in parallel with the Physics program, to demonstrate the integration & performance of the first cells of initial cooling prior to their use in operation to progressively improve the performance of subsequent NuMAX phase

4.2. Introduce an initial 6D cooling stage prior to beam acceleration for improved performance by matching the muon beam emittances at the exit of the front-end to the longitudinal & transverse acceptances of the NuMAX acceleration system

- Cost savings allowing maximum use of high(er) RF frequency linacs
  - ✓ Moderate cooling of the beam emittances (by a factor 5 in transverse and 2 in longitudinal) allows a 1 GeV pre-injector linac with 325MHz RF frequency and a 3.75 GeV dual use linac with 650MHz RF frequency

- ✓ More aggressive cooling would allow additional savings by eliminating the (expensive) 325MHz pre-injector and extending the 650MHz dual use linac to 4.75 GeV. The proton beam energy on target would then be increased to 7.75 GeV close to optimum muon production.

- Cooling specification optimized as the best trade–off between linac and cooling cost

4.3. Introduce the initial cooling of the Neutrino Factory as pre-cooler of the Muon Collider 6D cooling path

- Facilitating the charge separation scheme and the pre-merge 6D cooling
- Allowing re-optimization of the overall Muon Collider 6D cooling path (fig. 2).

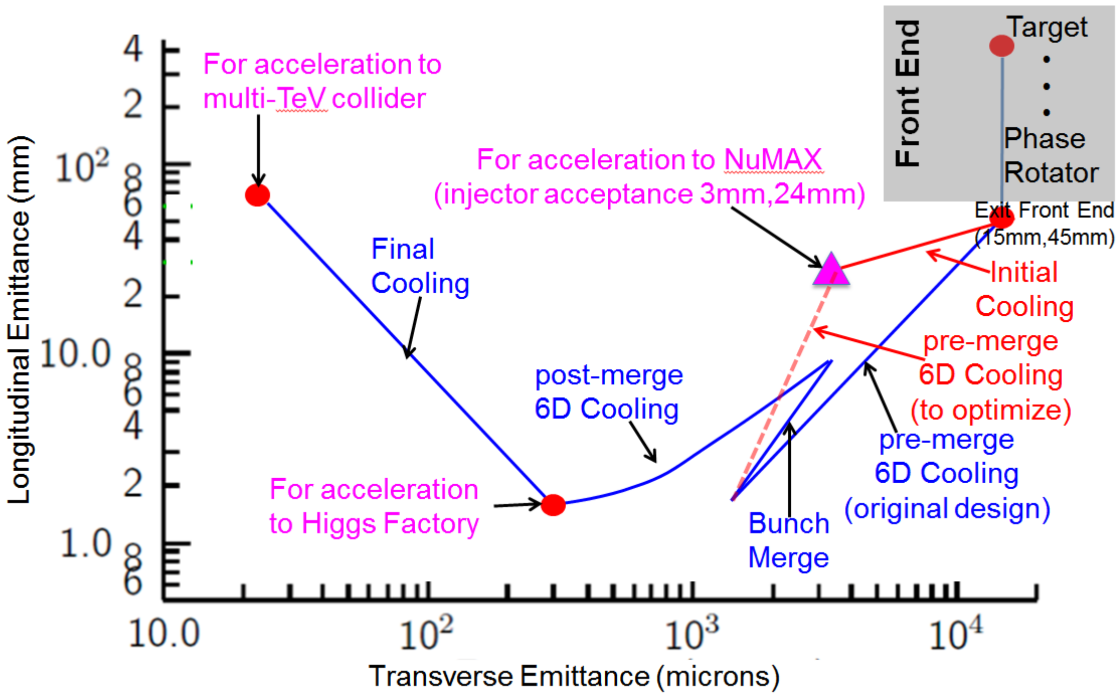


Figure 2: 6D cooling path to be re-optimized with initial cooling

4.4. 6D cooling path and final cooling

- Review the 6D cooling and final cooling paths aiming at a lower longitudinal emittance after final cooling, thus reducing the presently high cost of the low energy acceleration by induction linac by exploring for example an alternative 6D cooling path as shown in red on Figure3:
  - ✓ pursue post-merge 6D cooling by additional cooling towards lower tranverse emittances by using solenoids made with High Temperature Superconductors (HTS) providing stronger focusing fields.
  - ✓ The final cooling thus ends with lower longitudinal emittance for identical transverse emittances

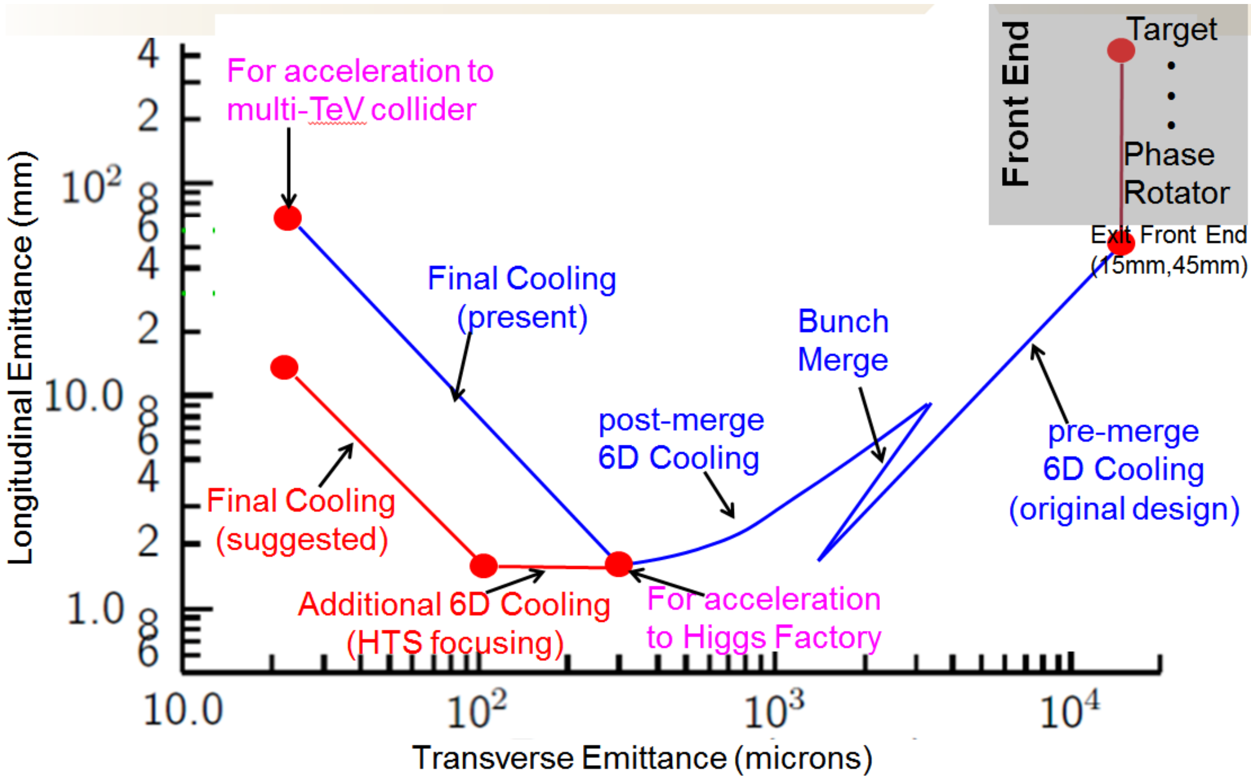


Figure 3: Alternative cooling path (in red) with additional post-merge 6D cooling for reduced longitudinal emittance after final cooling

4.5. Envisage a 6D cooling experiment at FNAL with significant muon beam intensity in complement to the MICE experiment presently ongoing at RAL:
- at nuSTORM or
- existing facilities (AP0, g-2)

4.6. Integrate at each stage of the facilities an R&D platform of technology development (6D cooling, etc) necessary for next stage

5. Accelerating systems

5.1. Adopt FNAL standard RF frequencies coherent with PIP: 325 and 650MHz

5.2. Replace the 4 GeV Recirculating Linac Accelerator (RLA) with 4.5 passes and 325MHz RF frequency structures presently foreseen in the accelerator chain to the Neutrino Factory by a 650MHz straight dual use linac for proton and muon acceleration (fig 2 of Annex II).
- saving of one 4GeV linac in the overall MAP and PIP programs
- higher muon transmission efficiency due to larger effective accelerating field of the straight linac without the additional length and complexity of the arcs

- cost saving by use of higher RF frequency structures but at the expense of additional 6D cooling
- accelerating gain to be optimized as best trade–off between linac saving and cooling additional cost (as described under 4.2)

5.3. Consider reduced repetition frequency (30Hz) of first two NuMAX phases for the sake of power saving

6. 5 GeV Neutrino factory (NuMAX) in stages pointing towards SURF

6.1. Launch design of a 5 GeV storage ring with one single muon bunch train per cycle and potential of significant cost reduction in respect with IDS-NF

6.2. Maximize synergies with nuSTORM and cost effective upgrade from nuSTORM to NuMAX by exploring the option below, pending compatibility with LBNE:

- nuSTORM ring location close to the NuMAX ring possibly sharing building and facilities
- using as proton driver on target, the 120 GeV proton beam delivered by the Main Injector through the LBNE extraction system thus maximizing synergies with LBNE and taking advantage of its future upgrade in power,
- nuSTORM target close to the LBNE target and possibly to the NuMAX target thus creating a "target campus" sharing facilities as much as possible
- providing an attractive staged path from LBNE to nuSTORM to NuMAX

7. SURF as host of the NuMAX long baseline detector

7.1. Launch R&D and feasibility study of magnetized MIND or LAr detector

7.2. Launch compatibility study with LBNE maximizing synergies

7.3. Physics comparison with IDS-NF

9. Muon Collider

9.1. Launch the design of a multi-TeV (> 5 TeV) Collider

- Muon technology more favorable at very high energy (cost and power efficiency, luminosity with narrow energy spread)
- Energy range without any alternative technology for a lepton collider with reasonable power consumption
- Attractive schedule with possible availability by 2035 as a complement with ILC in the TeV range if built by the time and with HL-LHC for BSM physics if required

9.2. Prioritization of Muon Collider design and documentation

- Document the work already done on the design of a muon collider at various energies especially the Higgs factory and at 1.5 TeV colliding beam energy
- Focus future resources on muon collider design at the most appealing colliding beam energies:
  - ✓ at 3 TeV for comparison with CLIC and emphasizing the advantages of muon collider in respect with linear collider especially the absence of beamstrahlung during collision and the very favorable power consumption
  - ✓ at > 5TeV (for example 6 TeV) in preparation for a possible future request for Physics Beyond the Standard Model (BSM) if and when identified by LHC and at which no alternative realistic collider technology is currently available.

10. Design and technology development focused on feasibility issues related to initial phases of staging scenario, especially NuMAX:

10.1. Dual use straight linac

10.2. Target: initially 1MW upgradable to a few (2 to 2.3?) MW

10.3. 20T Capture solenoid:

10.4. Front end: Performance of NC cavities embedded in strong magnetic fields

10.5. Initial and 6D cooling:

10.6. Muon Accelerating system: Heat loss deposited in SC environment by muon decay

10.7. Magnetized MIND or LAr detector

Annex I a: Muon Colliders main parameters

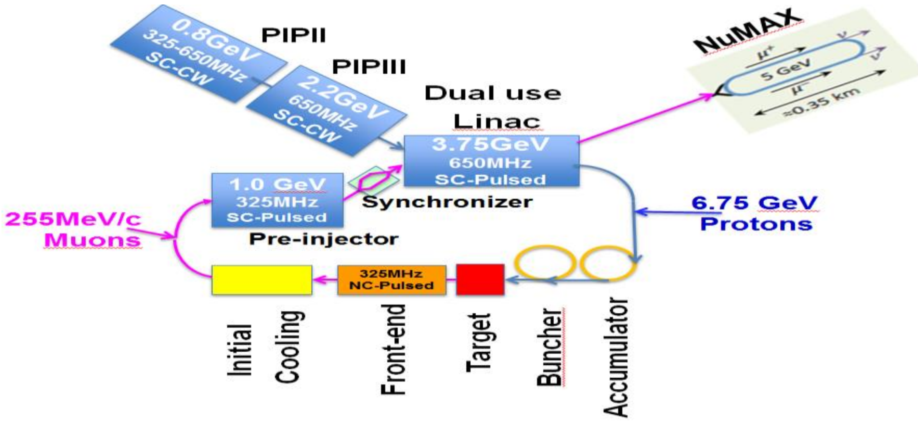
Muon Collider Parameters								
		Higgs Factory		Top Threshold Options		Multi-TeV Baselines		
Parameter	***Units***	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	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)	2.5
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	2
Proton Driver Power	MW	4#	4	4	4	4	4	1.6

Could begin operation with Project X Stage II beam

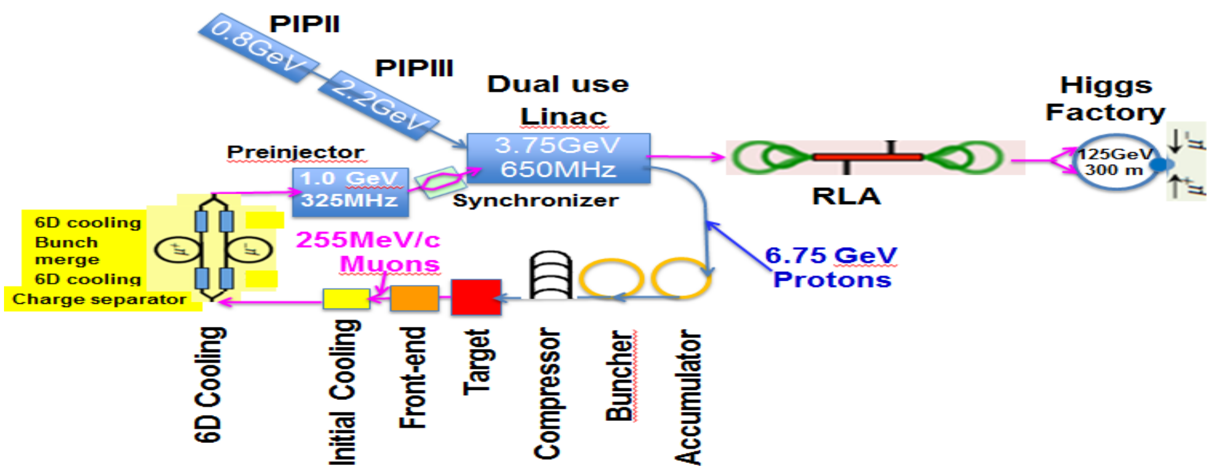
Annex I b: Neutrino Factories main parameters

System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Perfor-mance	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
Accelerati on	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

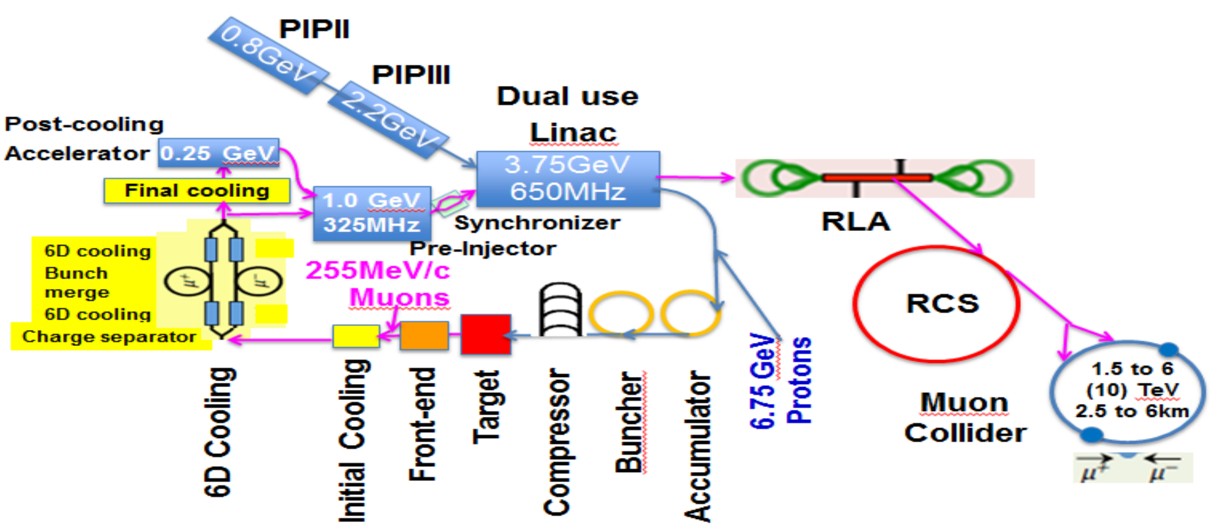
Annex II: Evolution of Muon based complex from Neutrino Factory to Muon Collider



a) Layout of a Muon based Neutrino factory

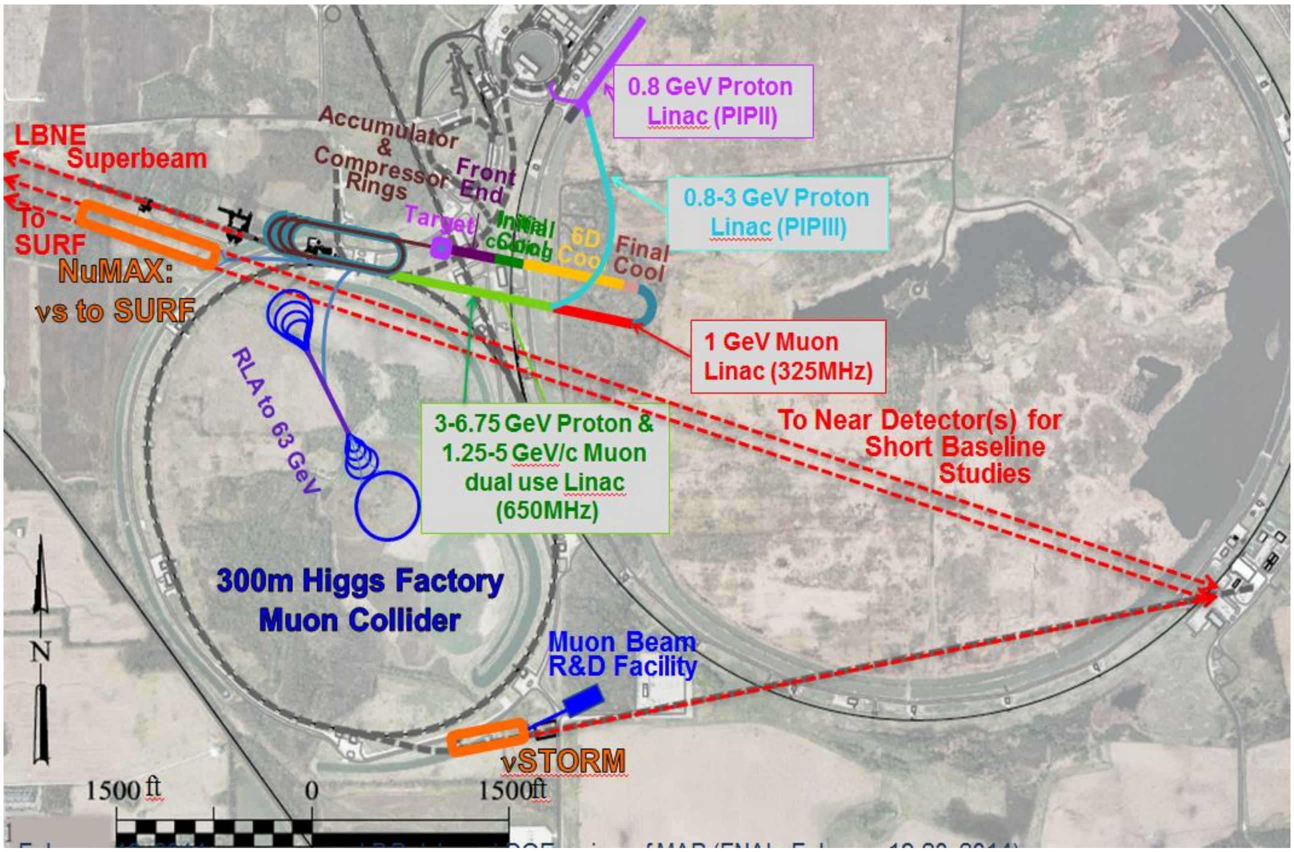


b) Layout of a Muon based Higgs factory



c) Layout of a multi-TeV Muon Collider

Annex III: A possible implementation of NuMAX and Higgs Factory on FNAL site. A 6 TeV Muon Collider would fit in a tunnel with the size of the Tevatron but deep underground.



Footnotes

[1] MASS members: C. Ankenbrandt (FNAL), A.Bogacz (JLAB), S,Brice (FNAL), J.P.Delahaye (SLAC), D.Denisov (FNAL), E.Eichten (FNAL), D.Hartill (Cornell), S.Holmes (FNAL), P.Huber (VT), D.Neuffer (FNAL), M.A.Palmer (FNAL), R.Ryne (LBNL), P.Snopok (IIT/FNAL)

[2] MASS mandate: Memo M.A.Palmer, August 10, 2012

[3] MAP White Paper at CSS2013: arXiv:1308.0494

[4] NuSTORM: arXiv: 1308.6228 (proposal) and arXiv: 1309.1389 (Project Definition Report)

[5] IDS-NF: https://www.ids-nf.org/wiki/FrontPage