A STAGED MUON-BASED FACILITY TO ENABLE INTENSITY AND ENERGY FRONTIER SCIENCE IN THE US*

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Abstract

Muon-based facilities offer a unique potential 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. They rely on novel technology with challenging parameters, for which the feasibility is currently being assessed by the U.S. Muon Accelerator Program (MAP) [1]. A realistic scenario for a complementary series of staged facilities with increasing complexity and significant physics potential at each stage has been developed. It takes advantage of and leverages the capabilities already planned at Fermilab, especially Project X and LBNE. Each stage is defined in such a way as to provide an R&D platform to validate the technologies required for subsequent stages. The rationale and sequence of a realistic staging process are presented.

INTRODUCTION

The major discoveries made in 2012, namely the large flavour mixing angle θ_{13} measured at Daya Bay in China and the Higgs boson by the LHC at CERN dramatically modified the Particle Physics landscape. Although the Higgs discovery corresponds to a splendid confirmation of the Standard Model (SM) and no sign of new physics Beyond the Standard Model (BSM) has (yet) been detected at LHC up to at least 1 TeV, BSM physics is necessary to address basic questions which the Standard Model cannot address especially the dark matter, the matter-antimatter asymmetry and the neutrino mass. Therefore the quest for BSM physics constitutes a high priority for the future of High Energy Physics. It requires facilities at both high energy and high intensity frontiers. Neutrino oscillations are irrefutable evidence for BSM physics with the potential to probe up to an extremely high energy range. Neutrino Factories with an intense and well defined flux of neutrinos from muon decay provide an ideal tool for high precision flavour physics at the high intensity frontier. At the high energy frontier, a multi-TeV lepton collider will be necessary as a precision facility to complement the LHC, if and when confirmed, for Physics exploration beyond the Standard Model.

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THE BEAUTY AND CHALLENGES OF MUON-BASED FACILITIES

Muon-based facilities [2] offer the unique potential to provide the next generation of capabilities and world-leading experimental support spanning physics at both the Intensity and Energy Frontiers. Building on the foundation of Project X at FNAL, muon accelerators can provide that next step with a high-intensity and precise source of neutrinos to support a world-leading research program in neutrino physics. Furthermore, the infrastructure developed to support such an Intensity Frontier research program can also enable the return of the U.S. high energy physics program to the Energy Frontier. This capability would be provided in a subsequent stage of the facility that would support one or more Muon Colliders, which could operate at center-of-mass energies from the Higgs resonance at 126 GeV up to the multi-TeV scale.

An ensemble of facilities built in stages is made possible by the strong synergies between Neutrino Factories and Muon Colliders, both of which require a high power proton source and target for muon generation followed by similar front-end and ionization cooling channels. These muon facilities rely on a number of systems with conventional technologies whose required operating parameters exceed the present state of the art as well as novel technologies unique to muon colliders. An R&D program to evaluate the feasibility of these technologies is being actively pursued within the framework of the U.S. Muon Accelerator Program (MAP) [1] with impressive R&D results already achieved and a definitive answer expected by 2018 as to whether or not muon-based facilities built in stages can be realistically contemplated.

RATIONALE FOR A STAGED APPROACH

The feasibility of the technologies required for Neutrino Factories and/or Muon Colliders must be validated before a facility based upon these could be proposed. Such validation is usually made in dedicated test facilities which are rather expensive to build and to operate over several years. They are therefore difficult to justify and fund, given especially that they are usually useful only for technology development rather than for physics.

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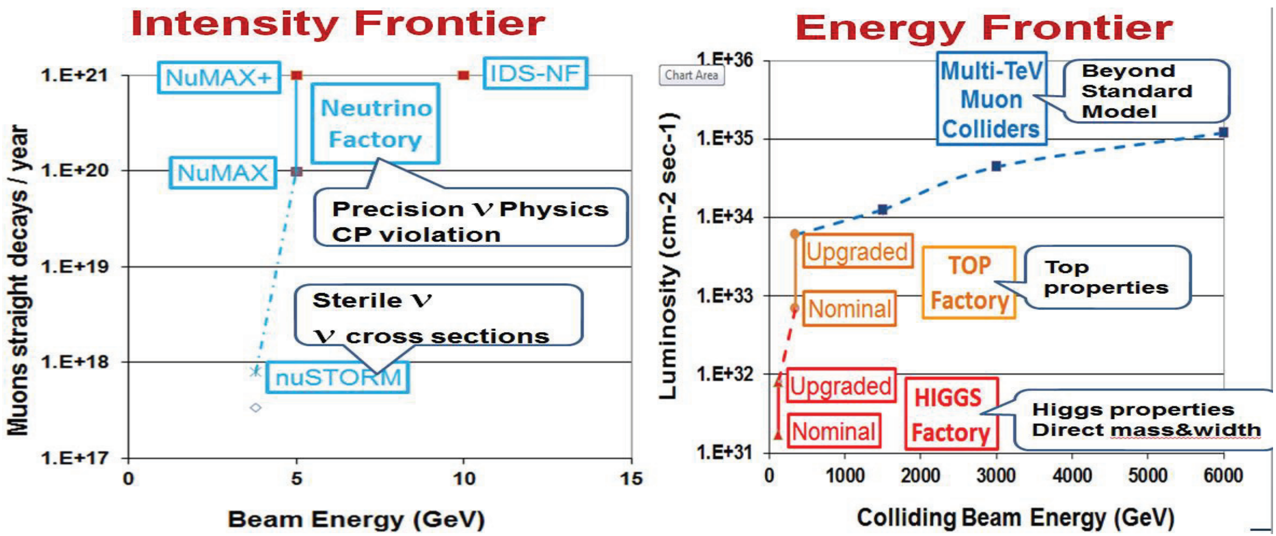

Figure 1: Performance and Physics of muon-based facilities over two frontiers and a wide energy range.

An alternative approach is proposed here. It consists of a series of facilities 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 [3] thus 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, specifically:

- Existing tunnels and other conventional facilities;
- Project X as the MW-class proton driver for muon generation;
- SURF as developed for the LBNE detector, which could then house the detector for a long-baseline Neutrino Factory.

It consists of a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach (Fig.1):

- 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: an initial long-baseline 5GeV Neutrino Factory, optimized for a detector at SURF, affording a precise and well-characterized neutrino source that exceeds the capabilities of conventional superbeams.
- NuMAX+: a full-intensity Neutrino Factory, upgraded from NuMAX, with performances similar to IDS-NF [5] as 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.
- 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 and least cost and power consumption for any lepton collider operating in the multi-TeV regime.

Their main parameters are described in Table 1. A complex integrating all of the above facilities in a staged approach on the FNAL site is shown in Figure 2.

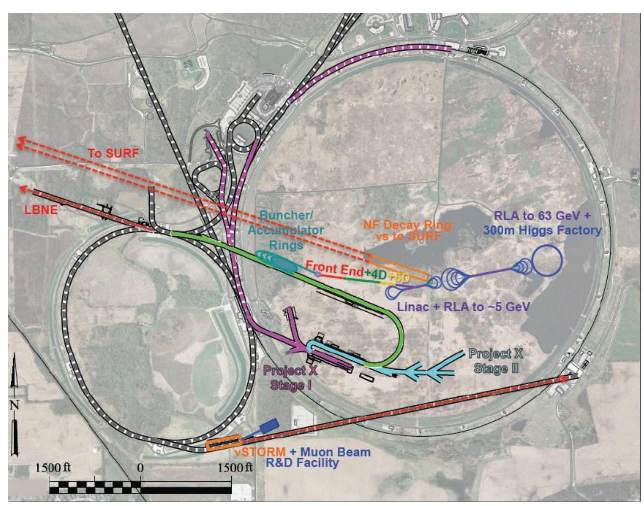

Figure 2: Footprint of Neutrino Factory and Higgs Factory Muon Collider facilities on the FNAL site.

Table 1: Main arameters of the arious Muon-based acilities in a hased pproach

System	Parameters	Unit	nuSTORM	NuMAX	NuMAX+
Perfor-mance	Stored μ+ or μ-/year		8×10^{17}	2×10^{20}	1.2×10^{21}
	ν_e or ν_μ to detectors/yr		3×10^{17}	8×10^{19}	5×10^{20}
Detector	***Far Detector:***	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr
	Distance from Ring	km	1.9	1300	1300
	Mass	kT	1.3	30 / 10	100 / 30
	Magnetic Field	T	2	0.5-2	0.5-2
	Near Detector:	Type	SuperBIND	Suite	Suite
	Distance from Ring	m	50	100	100
	Mass	kT	0.1	1	2.7
	Magnetic Field	T	Yes	Yes	Yes
Neutrino Ring	**Ring Momentum (P_μ)**	GeV/c	3.8	5	5
	Circumference (C)	m	480	600	600
	Straight section	m	184	235	235
	Arc Length	m	56	65	65
Acceleration	**Initial Momentum**	GeV/c	-	0.22	0.22
	Single-pass Linac	GeV/pass	-	0.95	0.95
		MHz	-	325	325
	4.5-pass RLA — **RLA I**	GeV/pass	-	0.85	0.85
		MHz	-	325	325
	4.5-pass RLA — **RLA II**	GeV/pass	-	-	-
		MHz	-	-	-
Cooling			No	No	4D
Proton Source	**Proton Beam Power**	MW	0.2	1	3
	Proton Beam Energy	GeV	120	3	3
	Protons/year	1×10^{21}	0.1	41	125
	Repetition	Hz	0.75	70	70

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	$4^\sharp$	4	4	4	4	4	1.6

TENTATIVE STAGED SCENARIO AND SCHEDULE

Three major items on the critical path have been clearly identified: i) MAP technology feasibility demonstration with results expected by 2018, ii) 6D cooling performance with beam validation by 2022 possibly using nuSTORM as an R&D platform in complement to the cooling principle and feasibility demonstration at MICE [6], iii) Proton beam power availability of 3 MW at 3 GeV from Project X (phase 2) by 2024 and 4MW at 8 GeV (phase 4) by 2032. A technically limited schedule could then be tentatively defined.

nuSTORM as the first stage could be launched as soon as funding is available since it does not require any technology development. A first beam could be provided by the end of the decade. It would serve as an R&D platform to test and validate the 6D cooling with a 10^8 muon beam. NuMAX which does not require any cooling could be launched by 2018 when the MAP technology feasibility will have been demonstrated. It would initially be driven by a proton beam power of 1MW at 3 GeV provided from 2024 by Project X phase 2 in parallel with its other users. This facility would then be upgraded to NuMAX+ by adding a limited amount of 4D cooling validated in NuMAX when used as an R&D platform with a beam of 10^{11} muons and by increasing the proton driver to the full power of 3 MW provided by Project X phase 2 at 3 GeV. The NuMAX+ injector & acceleration up to 5 GeV could then be used to drive a Muon Collider at the energy and luminosity as required by Physics at the time, possibly a Higgs factory, which could be launched by 2025. It would have to be upgraded by i) implementing a 6D cooling previously validated at full intensity using NuMAX+ as an R&D platform with a beam of 10^{12} muons, ii) upgrading the proton driver to 4 MW by the project X phase 4 at 8 GeV available from 2032, iii) extending the acceleration system up to 62.5GeV. A multi-TeV muon collider could then be launched if and when required by Physics for BSM studies by using the previously built injector system and adding the necessary final cooling, acceleration system and collider ring.

CONCLUSION

A staging approach for muon-based facilities has been developed with physics interest and technology validation at each phase taking advantage of the present and proposed facilities at Fermilab. Each stage is built as an addition to the previous stages, reusing as much as possible the systems already installed such that the additional budget of each stage remains affordable. Thanks to the great synergies between Neutrino Factory and Muon Collider technologies, these facilities are complementary and allow capabilities and world-leading experimental support spanning physics at both the Intensity and Energy Frontiers. Rather than building an expensive test facility without physics use, the approach uses each stage as an R&D platform at which to test and validate the technology required by the following stage. The critical issues of this novel and promising technology are thus all addressed in the most efficient and practical way within reasonable funding and scheduling constraints.

As deduced from the components on the critical path and a technically limited schedule, such a staging approach with integrated R&D would allow informed decisions by 2020 about Neutrino Factories at the Intensity Frontier and by 2025 about Muon Colliders at the Energy Frontier.

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