

The NuMAX Long Baseline Neutrino Factory Concept*

J-P. Delahaye^a, C. Ankenbrandt^b, A. Bogacz^c, P. Huber^d, H. Kirk^e, D. Neuffer^f,
M.A. Palmer^f, R. Ryne^g, and P. Snopok^h

^a SLAC,
Menlo Park, California, USA

^b Muons, Inc.,
552 N. Batavia Avenue, Batavia, IL 60510, USA

^c JLAB,
Newport News, Virginia 23606, USA

^d Virginia Tech.,
Virginia Polytechnic Institute, Blacksburg, Virginia 24061, USA

^e BNL,
Upton, Long Island, New York 11973, USA

^f FNAL,
Batavia, Illinois 60510, USA

^g LBNL,
Berkeley, California 94720, USA

^h ITT,
Illinois Institute of Technology, Chicago, Illinois 60616, USA

E-mail: jean-pierre.delahaye@cern.ch

ABSTRACT: A Neutrino Factory where neutrinos of all species are produced in equal quantities by muon decay is described as a facility at the intensity frontier for exquisite precision providing ideal conditions for ultimate neutrino studies and the ideal complement to Long Base Line Facilities like LBNF. It is foreseen in to be built in stages taking advantage of existing or proposed facilities at an existing laboratory like Fermilab. A tentative layout based on a recirculating linac providing opportunities for considerable saving is discussed. Tentative parameters of the various stages are presented as well as the necessary R&D to address the technological issues and demonstrate their feasibility.

KEYWORDS: Neutrino, Factory, Accelerator, Detector

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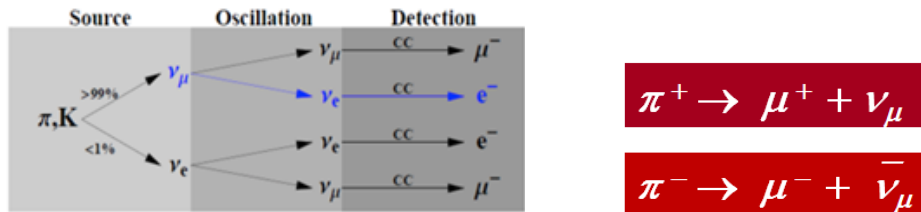
1. Overview

The 2012 major discoveries of the large flavour mixing angle θ_{13} at Daya Bay in China and of the Higgs boson by 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 physics Beyond Standard Model (BSM) has (yet) been detected at LHC, BSM physics is necessary to address basic questions which the SM cannot, especially dark matter, dark energy, matter-antimatter asymmetry, and neutrino mass. Therefore the quest for BSM physics is a high priority for the future of High Energy Physics. It requires facilities at both the high energy and high intensity frontiers. Neutrino oscillations are irrefutable evidence for BSM physics with the potential to probe up to extremely high energies. Although neutrinos studies in Long Base Line Neutrino Facilities (LBNF) as the one foreseen at FNAL are presently sufficient due to the unexpected large measured value of the flavour mixing angle, Neutrino Factories with an intense and well defined flux of neutrinos from muon decay will be required in the future to provide an ideal tool for high precision flavour physics at the intensity frontier. At the energy frontier, a multi-TeV lepton collider will be necessary as a precision facility to complement the LHC, for physics beyond the Standard Model if and when such physics is confirmed.

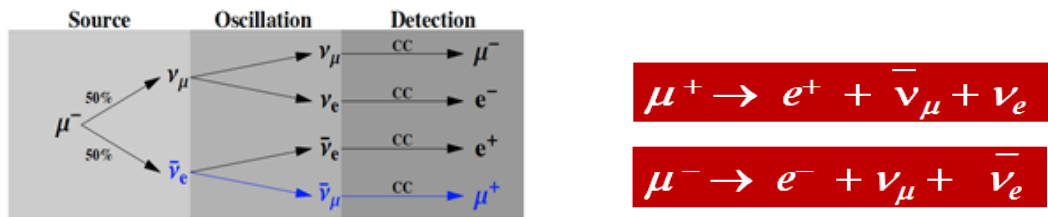
A Neutrino Factory where neutrinos are produced as tertiary particles by muons decay would then constitute the ideal complement to Long Base Line Facilities based on a more standard technology where neutrinos are produced as secondary particles by pion decay as reminded below, and would provide very attractive improvements especially:

- the production of all neutrino species allowing physics with multiple channels,
- a neutrino beam constitution defined with a precision of about 1% improving systematic precision
- a clean muon detector with a magnetic field to distinguish μ^+ from μ^- , as discussed in section 2.2.

Neutrinos produced by pion decay in Long Base Line Facilities following the scheme below :



Neutrinos produced by muon decay in Neutrino Factories following the scheme below:



The concept of a Neutrino Factory on the FNAL site, so called NuMAX standing for “**N**eutrino from **M**uon Accelerator comple**X**”, has been defined in the frame of the Muon Accelerator Program (MAP) [1]. It is strongly inspired from the IDS-NF study [2] of an ideal Neutrino Factory on a green site. Nevertheless, its concept is significantly modified to take into account and take advantage of the specificities of the FNAL site in order to mitigate its cost and maximize the synergies with the FNAL existing or planned systems and programs.

In particular, it envisions using the Sanford Underground Research Facility (SURF) foreseen to house the Deep Underground Neutrino Experiment (DUNE) detector of the Long Base Line Facility (LBNF). Because its distance of 1300kms from FNAL is shorter than the 2000kms considered in the IDS-NF, the optimum neutrino energy is around 1 to 2 GeV such that the muon energy is reduced from 10 to about 5 GeV with considerable savings of the accelerating system as described in the Fast Acceleration Systems sub-section and the muon decay ring as described in the Neutrino Factory Storage Ring sub-section. In spite of the reduced energy, the physics performance of NuMAX with a similar neutrino flux is similar to the one of IDS-NF as discussed in section 4.

NuMAX is foreseen to be built in phases to make the project as realistic as possible and favor its possible future evolution towards a Muon Collider [3] taking advantage of the strong synergies between Neutrino Factory and Muon Collider layouts as shown on Fig. 1, thus enabling facilities at both the intensity and the energy frontiers.

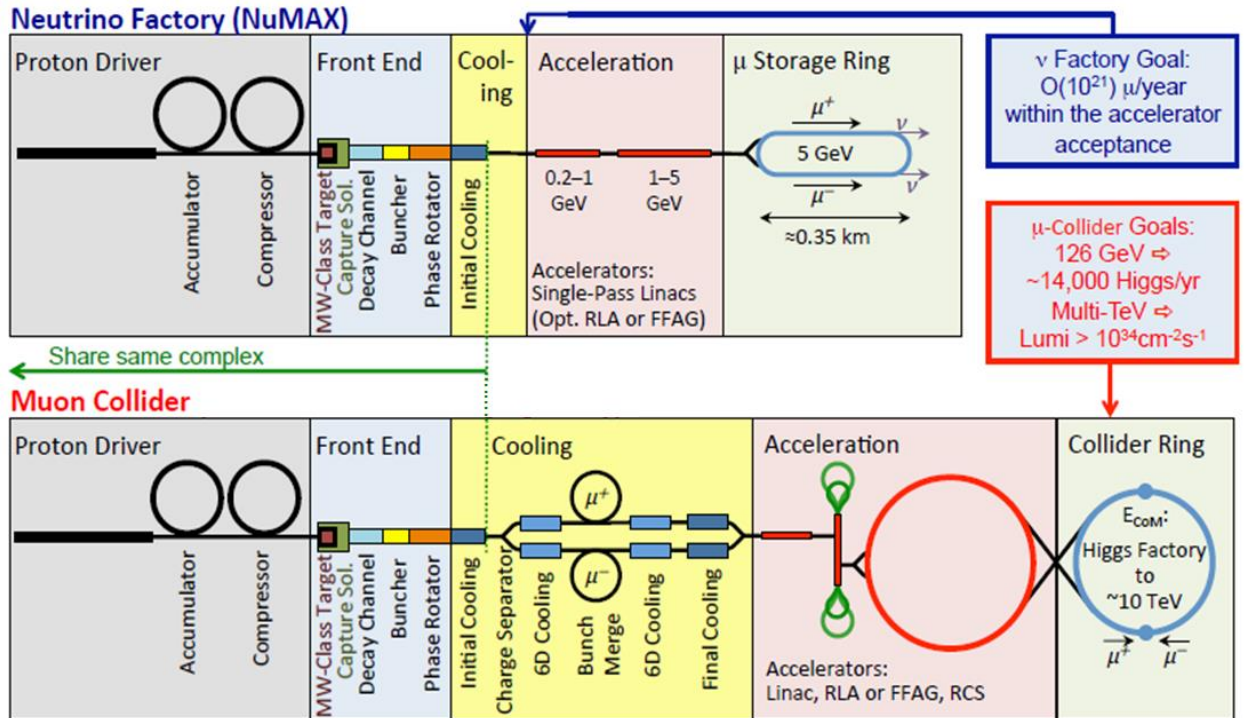


Figure 1: Neutrino Factory and Muon Collider layouts emphasizing synergies between the various sub-systems especially concerning the muon production and initial cooling stage.

2. NuMAX

2.1 The accelerator complex

Like IDS-NF, NuMAX uses a high-power proton beam to produce charged pions. The majority of the produced pions have momenta of a few hundred MeV/c, with a large momentum spread, and transverse momentum components that are comparable to their longitudinal momentum. Hence, the daughter muons are produced within a large longitudinal and transverse phase-space. This initial muon population must be confined transversely, captured longitudinally, and have its phase-space manipulated to fit within the acceptance of an accelerator. These beam manipulations must be done quickly, before the muons decay ($\tau_0 = 2.2 \mu\text{s}$). Finally, muons are stored in the decay ring to produce neutrino beams in the ring's straight sections pointing towards short and long base-line detectors where neutrinos are analyzed.

The functional elements of a Neutrino Factory, illustrated schematically in Figure 1, are as follows:

- A proton source producing a high-power multi-GeV bunched proton beam [4].
- A pion production target that operates within a high-field solenoid. The solenoid confines the pions radially, guiding them into a decay channel [5, 6].
- A front-end made of a solenoid decay channel equipped with RF cavities that captures the muons longitudinally into a bunch train, and then applies a time-dependent acceleration that increases the energy of the slower (low-energy) bunches and decreases the energy of the faster (high-energy) bunches [7, 8].
- A cooling channel that uses ionization cooling to reduce the transverse phase space occupied by the beam, so that it fits within the acceptance of the first acceleration stage [9, 10, 11, 12].
- An acceleration scheme that accelerates the muons to 5 GeV [13].
- A 5 GeV “racetrack” storage ring with long straight sections [14].
- Short and long base line detectors, described in the section 2.2 below

A tentative block diagram of the NuMAX complex is displayed on Fig. 2

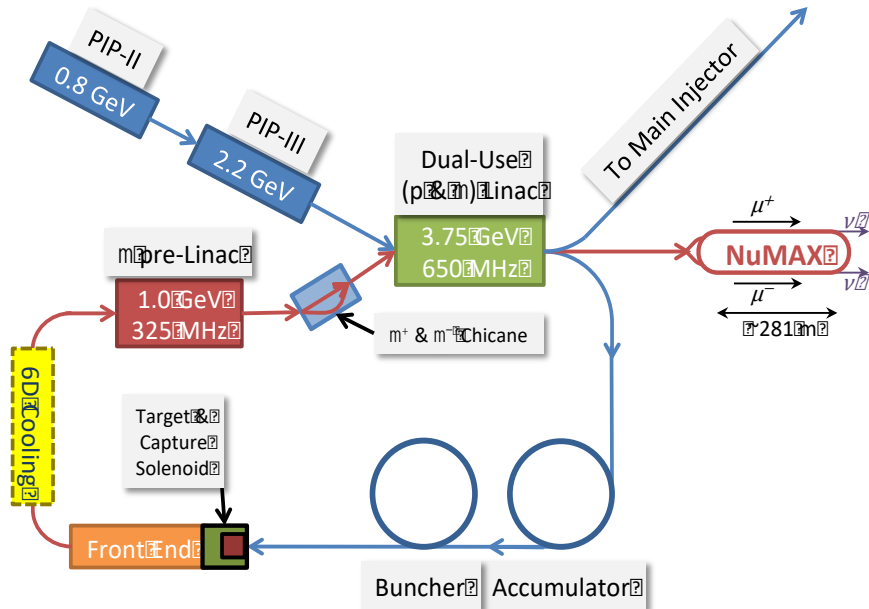


Figure 2: Tentative block diagram of the NuMAX complex based on a dual use linac accelerating both proton & muons particles

It is based on an extension of the PIP-II linac accelerating the proton beam in two stages up to 3 GeV and further accelerated by a straight dual 650 MHz linac before hitting the target for pion production. The muons produced by pion decay, captured and bunched in the front end are recirculated to the dual linac for further acceleration up to 5 GeV as required by NuMAX. The dual use linac concept accelerating both the proton and muon beams provides an opportunity for considerable savings as described in the Fast acceleration systems subsection. It requires initial cooling to match muon beam emittances to the linac acceptances at the 325 and 650 MHz RF standards adopted by the FNAL PIP-II program. The initial cooling specifications result from a cost optimization as the best trade-off between linac and cooling.

2.2 The detector

With a baseline of 1300 km, the relevant neutrino energies for oscillation measurements (dictated by Δm_{32}^2) lie in the 1–2 GeV range. The MIND technology preferred in the International Design Study for the Neutrino Factory (IDS-NF) starts to become inefficient at these low energies and it is anticipated that a change of detector technology will be needed. Two candidates suggest themselves at this point in time: magnetized, fully active, plastic scintillator and magnetized liquid argon TPCs. Since the DUNE of the LBNF facility has chosen a liquid argon (LAr) TPC (

Figure 3) as its far-detector technology, a staged approach to a Neutrino Factory using a magnetized liquid argon detector seems the way to go, with possibly 10 kt fiducial mass (twice as much for the whole detector) at the initial phases of NuMAX upgradable to 30 kt at the final phase of NuMAX+.

A 12 meter diameter by 60 meter long liquid argon detector requires a coil with 400,000 amps per meter to generate a half Tesla magnetic field. One might use NbTi carrying 40,000 amps in a 10 cm diameter cryostat [15]. This would require 23,000 meters of cable or 920,000 kiloAmp-meters. Flux return would require 14 kilotons of steel.

There is considerable liquid argon TPC R&D taking place worldwide with the primary goal of providing input to the detailed design of the LBNE far detector(s). There have been some R&D efforts in Europe toward a magnetized LAr TPC, but considerable R&D remains to be done. Pending that R&D, it is not yet clear whether a non-magnetized LAr TPC for LBNE could be economically retrofitted with a magnetic field or whether an entirely new detector would need to be built.

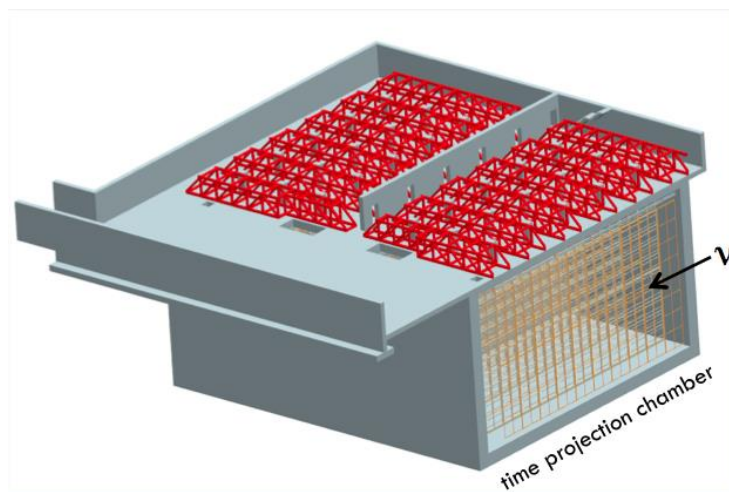


Figure 3: Preliminary design of a 10 kt liquid argon DUNE detector [15]

With such detector, the physics performance [16] compares well with the performance of other facilities even in the early NuMAX phases as shown in Figure 4. The gradual upgrade of the facility and the detector allows to progressively improve the performance of the facility towards the required precision of a few degrees of CP violating phases.

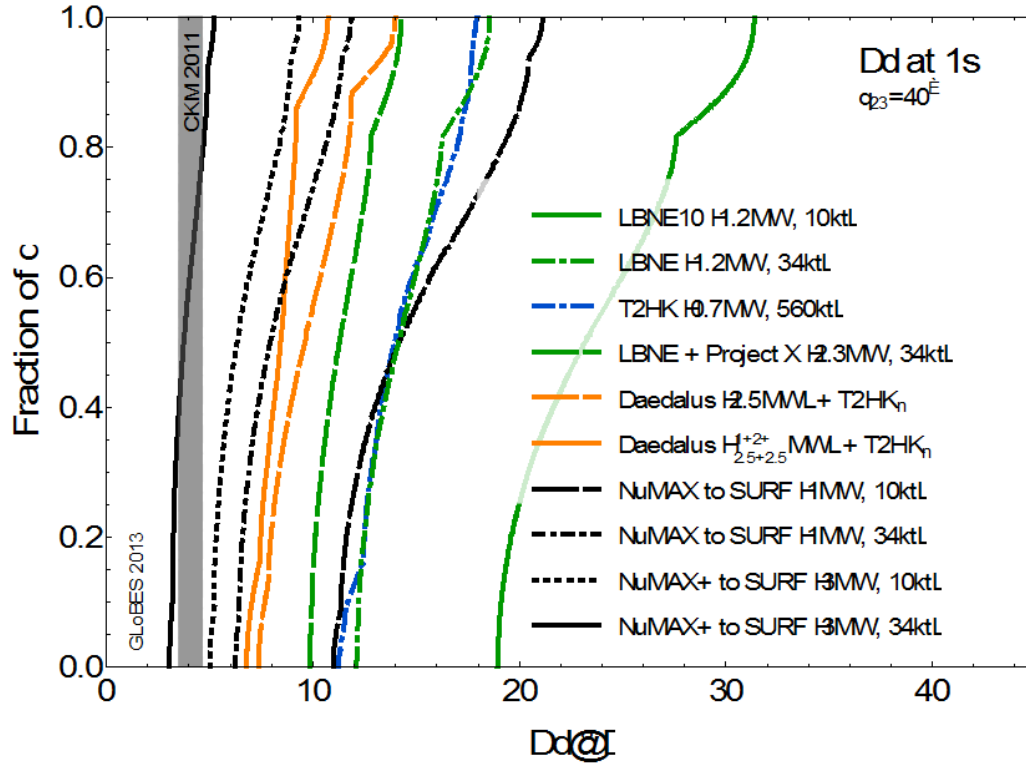


Figure 4: NuMAX stages Physics performance compared with other neutrino facilities where each line corresponds to a facility as described in the legend [16]

3. Phased approach

3.1 Rationale

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 specially designed to address the major issues. Although very convenient, these test facilities 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.

An alternative approach is considered 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.

The staging plan builds on, and takes advantage of, existing or proposed facilities at FNAL, thus maximizing the synergies between the existing FNAL program and the Muon program, specifically:

- Existing tunnels and other conventional facilities;
- Proton Improvement Program (PIP) presently developed at Fermilab 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 (which could initially be the LBNE detector itself).

3.2 Staging scenario

A complete staging scenario has been identified in the frame of the MAP Accelerator Staging Study (MASS) [17]. It consists of a series of facilities with increasing complexity, each with performance characteristics providing unique physics reach:

- **nuSTORM** [18]: a short-baseline Neutrino Factory-like ring 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 (Neutrino from Muon Accelerator Complex)**: a long-baseline 5 GeV 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, 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 [2] 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.

Such a staging scenario 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. Obviously, some parts of the plan could be skipped depending on Physics needs.

A tentative block diagram of the overall complex in a phased approach emphasizing the evolution and synergies from Neutrino Factory to Muon collider is shown in Annex II. The systems installed for each phase is re-used in the following phases for which specific equipment or sub-systems are added after tests and validation in the previous phase.

4. Main parameters

Preliminary parameters of the three NuMAX phases with progressing complexity and performance are presented in Annex I and compared with nuSTORM. In particular, the final phase of NuMAX+ provides a neutrino flux similar to the one obtained by IDS-NF.

In order to achieve the required flux of $5 \cdot 10^{20}$ neutrinos per year at the far detector, 60 bunches of 3.5×10^{10} muons/bunch are stored in the muon decay ring at a 15Hz repetition rate. Taking into account reasonable transmission including muon decay losses along the NuMAX complex and a production of 0.08 muon /6.75 GeV proton on target, it requires a high but not unreasonable proton beam power of 2.75MW on target for muon production and a modest amount of 6D cooling by a factor 50 (5 in each transverse plane and 2 in the longitudinal direction) in order to match the muon beam emittances to the acceptances of a reasonable accelerating system.

The early NuMAX commissioning phase without any cooling and a proton beam power of 1MW corresponding to the present state of the art, already provides an attractive flux although one order of magnitude lower than the one provided by IDS-NF. The flux is then improved by about a factor 4 by implementing the 6D cooling in the NuMAX phase.

5. R&D

Since the initial-stage Neutrino Factory, NuMAX, relies on a proton beam power of 1 MW at 3 GeV provided by the envisioned third phase of the FNAL proton improvement plan (PIP3) without any cooling, its critical challenges are limited to

- Proton driver and target corresponding to the state of the art in operation at SNS and therefore no specific development needed;
- A 15–20 T solenoid to efficiently capture the pions produced in the target. One would try to limit the field to so that Nb₃Sn might be used;
- Accelerating gradient in low frequency (325–975 MHz) RF structures immersed in high magnetic field as required by the front end;
- High efficiency recirculating linear accelerators (RLA);
- 10 kt magnetized liquid argon (LAr) or magnetized fully active plastic-scintillator detector.

The high-field solenoid and RF cavities immersed in large magnetic fields have been major subjects of development during the MAP Feasibility Assessment phase. The novel RLA technology involves multi-pass arcs based on linear combined-function magnets, which allow two consecutive passes with very different energies to be transported through the same string of magnets. Such a solution combines compactness with all of the advantages of a linear non-scaling

FFAG, namely, the large dynamic aperture and momentum acceptance essential for large-emittance muon beams. The dogbone RLA with 2-pass arcs is the subject of a specific proof-of-concept electron test facility, JEMMRLA (JLab Electron Model of Muon RLA [19]), proposed to be built and operated at Jefferson Lab. The NuMAX facility could thus be built soon after the completion of the MAP feasibility study.

The full-intensity Neutrino Factory, NuMAX+, is upgraded from NuMAX by additional proton beam power on target and modest cooling of the beam emittances by a factor 2.5 in both transverse planes. Its major technical challenges therefore consist of:

- A multi megawatt Proton driver which is being validated by the European Spallation Source (ESS).
- Corresponding upgrade of the target possibly by adopting Hg-jet target technology from which the feasibility has successfully been demonstrated by the MERIT experiment at CERN.
- Ionization Cooling for which the principle is being studied in the MICE experiment at RAL with first results expected in 2018 from MICE “. As described in Sec. 2.2.6, ionization cooling at reasonable intensity (10^8 muons/bunch) could be further tested using the proposed nuSTORM facility as a muon source. In parallel, cooling at full Muon Collider intensity (10^{12} muons/bunch) could be tested with protons in the proposed ASTA test facility at FNAL.

The NuMAX+ facility could then be progressively upgraded from NuMAX by the middle of next decade.

NuMAX could also be used to validate the technology required for the following phases:

- A lower-intensity Neutrino Factory, NuMAX, could be used as a long-baseline neutrino source and an R&D platform to test and validate transverse cooling (4D) at full muon intensity (10^{12} /pulse) as required by the full-intensity Neutrino Factory, NuMAX+. In addition, it would validate the injector complex at the 1 MW level as well as the corresponding target, front end and 5 GeV RLA.
- A high-intensity Neutrino Factory can be obtained from NuMAX by upgrading the proton driver to the nominal power of 3 MW at 3 GeV. The corresponding target and muon capture sections would need to be modified accordingly. Performance would benefit from the 4D cooling validated as R&D at NuMAX. This facility does not require any longitudinal cooling but would be used as a muon source and an R&D platform to test and validate transverse and longitudinal (6D) cooling to full specification and nominal muon bunch intensity (10^{12} /bunch) as required by Muon Colliders.

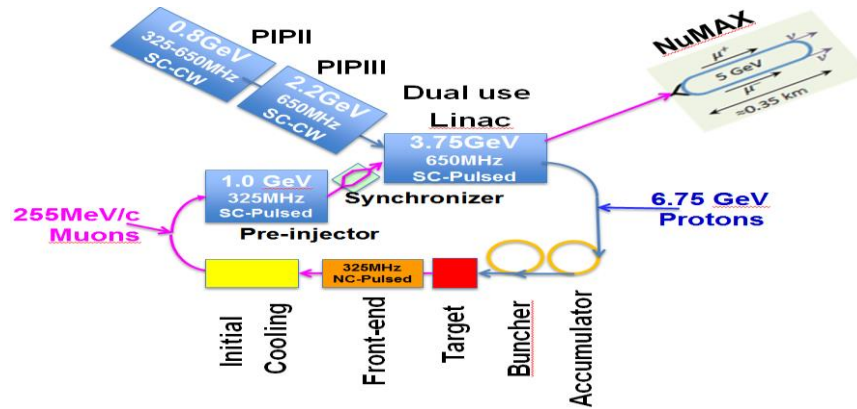
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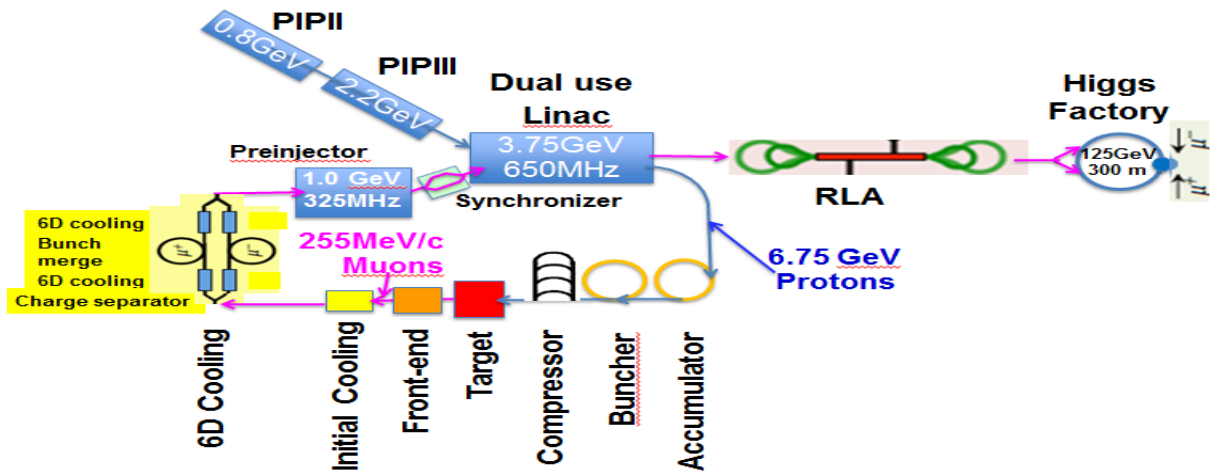
**Annex I: Main beam and machine parameters of the various stages of the NuMAX
Neutrino Factory compared with the preliminary nuSTORM facility**

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	<i>Far Detector:</i>	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
	<i>Near Detector:</i>	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 (P_μ)	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 Frequency	Hz	-	30	30	60
Cooling	Hor.*Vert.*Long.		No	No	5*5*2	5*5*2
Proton Driver	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam Energy	GeV	120	6.75	6.75	6.75
	Protons/year	1×10^{21}	0.1	9.2	9.2	25.4
	Repetition Frequency	Hz	0.75	15	15	15

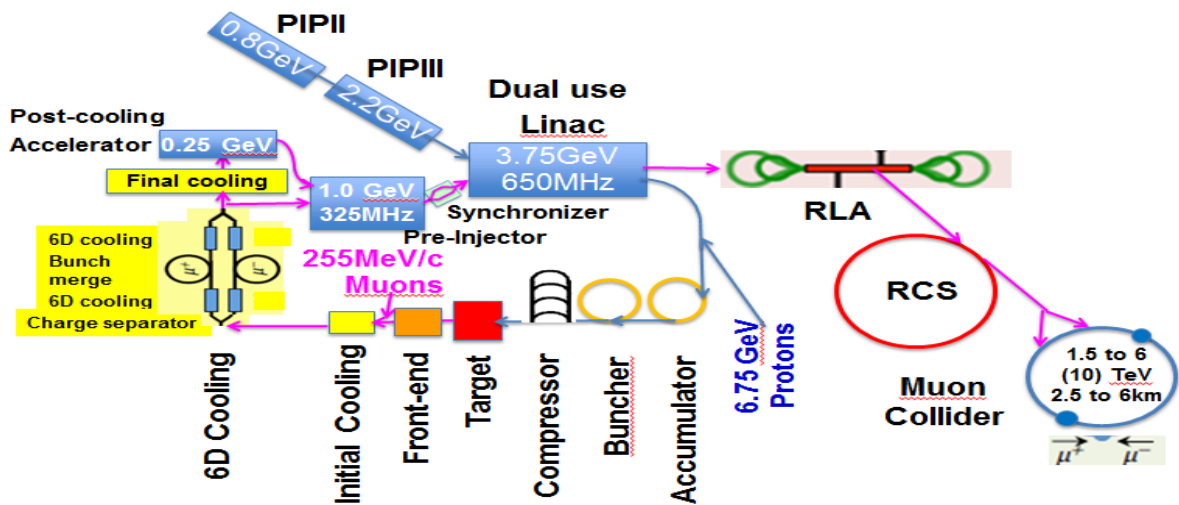
Annex II: Evolution in stages of the muon complex from a Neutrino Factory (a) to a HIGGS factory (b) and a multi-TeV Muon Collider (c) by reusing the systems of the previous stage and adding specific systems for the following stage



a) Layout of a Muon based Neutrino factory



b) Layout of a Muon based Higgs factory



c) Layout of a multi-TeV Muon Collider