Fast-Cycling Superconducting Synchrotrons and Possible Path to the Future of US Experimental High-Energy Particle Physics

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We outline primary physics motivation, present proposed new arrangement for Fermilab accelerator complex, and then discuss possible long-range application of fast-cycling superconducting synchrotrons at Fermilab.

1. Motivation

During the past decade developments in the neutrino physics combined with progress in the cosmological models of dark matter and dark energy suggest that neutrinos play a very fundamental role in our universe. It has been determined through solar, atmospheric, reactor and accelerator experiments that neutrinos change flavor (oscillate) while passing through matter. This implies that at least two neutrino species have a non-zero mass [1], thus being in a striking contradiction to the Standard Model (SM), and therefore suggesting existence of the physics Beyond the Standard Model (BSM). In addition, the possibility of neutrinos having a small mass may provide a bridge (via e.g. a see-saw mechanism) to the GUT theories including the origin of mass in the universe. As a consequence of this new situation a need for the resolution to the neutrino physics has risen to a level that is not just complimentary to other high-energy particle physics programs but turns out to be absolutely necessary to further the understanding of the microscopic structure and workings of the universe.

In neutrino physics phenomenology neutrinos with physical flavors, ν_α (α = e, μ, τ), are assumed to be linear super-positions, through a unitarity matrix, of neutrino fields with definitive masses ν_i (i = 1, 2, 3). A common parameterization for this matrix uses mixing angles, θ_{ij} = (0, 2π) typically represented by $\sin^2\theta_{ij}$, and a CP-violating phase δ_{CP} = (0, 2π). The current neutrino phenomenology also implies that two of the neutrino species have relatively close masses while the mass of the third one is either much heavier (normal hierarchy) or much lighter (inverted hierarchy) of the "doublet". The lightest (heaviest) neutrino in the doublet is called ν_1 (ν_2) and their squared mass difference is defined as $\delta m^2 = m_2^2 - m_1^2 > 0$. The mass difference between m_3 and $m_{1,2}$ doublet is defined as $\Delta m^2 = |m_3^2 - (m_1^2 + m_2^2)/2|$. The recent global analysis [2] of solar, atmospheric,

reactor and accelerator neutrino data projects that within a 2σ boundary the $\delta m^2 = (7.92 \, ^{+0.09}_{-0.09}) \times 10^{-5}$ eV^2, and the $\Delta m^2 = (2.4 \, ^{+0.23}_{-0.23}) \times 10^{-3}$ eV^2 implying that mass of at least one of the neutrino species is likely to be in the range of $(0.01–0.05)$ eV. We should point out that in another neutrino data analysis [3] this neutrino mass is $(0.04 - 0.10)$ eV, and some individual experiments, e.g. [4], set the upper mass limit at (0.3) eV, significantly higher than those from the global fits. The higher mass value is mostly from terrestrial experiments while the lower one comes from the solar neutrino studies. In the analysis [2] the most likely values of the mixing angle parameters are also given with $\sin^2 2\theta_{13} = 0.036 \, ^{+0.0.09}_{-0.036}$ (at 2σ uncertainty level), so it can be even very close to zero.

The neutrino mass can not be directly measured, but as neutrinos pass through the matter they can change the flavor, the process that is described as oscillations. The detection of the oscillations would be a manifestation that neutrinos have mass. The probability of the oscillation is a function of all the mixing angles and other parameters, so the potential smallness of the $\sin^2 2\theta_{13}$ parameter has a strong impact on the probability of the oscillation, and consequently on the feasibility of the experiment. In addition, the complexity of the oscillation function produces typically up to eight-fold degenerate solutions to the experimental data, adversely affecting oscillation detection thresholds. As example of how degeneracy of theory parameters affects sensitivity of the experiment we show in figure 1 the predictions for the recently proposed NOvA experiment [5] at Fermilab. One can see that combination of the δ_{CP} degeneracy with that of the Δm^2 widens the projected neutrino oscillation detection thresholds in terms of the $\sin^2 2\theta_{13}$ by more than a factor of 2.
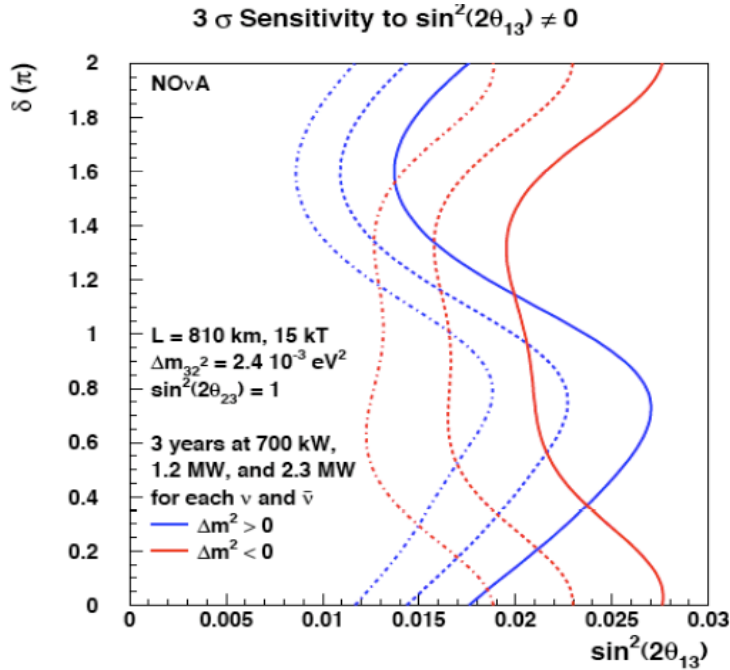

Fig.1. Sensitivity of NOvA experiment to $\sin^2 2\theta_{13}$ as a function of δ_{CP}, and for both the negative and the positive sign of Δm^2.

It has been shown recently [6], however, that there is an experimental condition when the degeneracy induced by the theory parameters can be strongly suppressed for the $\nu_e \to \nu_\mu$ or $\nu_\mu \to \nu_e$ appearance probability in matter. This appearance probability, $P_{e\mu}$, can be expanded in the small hierarchy parameter $\alpha = \Delta m^2_{21} / \Delta m^2_{31}$ and the small parameter $\sin2\theta_{13}$ as shown below:

$$
\begin{aligned}
P_{e,\mu} \sim &\ \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2[(1-A)\Delta]/(1-A)^2 \\
&+/-\ \alpha \sin2\theta_{13}\, \xi\, \sin(\delta_{CP)}\sin(\Delta)\sin(A\Delta)\, F(A,A\Delta) \\
&+\ \ \alpha \sin2\theta_{13}\, \xi\, \cos(\delta_{CP})\cos(\Delta)\sin(A\Delta)\, F(A,A\Delta) \\
&+\ \ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \sin^2(A\Delta)/A^2
\end{aligned}
\qquad (1)
$$

where $\Delta = \Delta m^2_{31} L / 4E$, $\xi = \cos\theta_{13}\sin2\theta_{12}\sin2\theta_{23}$, and $A = +/- (2\sqrt{2}\, G_F\, n_e\, E)/\Delta m^2_{31}$. The L is the baseline for the neutrino oscillation, and E is the neutrino energy. The G_F is the Fermi coupling constant and the n_e is the electron density in matter. The sign of the second term is determined by choosing either $\nu_e \to \nu_\mu$ (positive), or $\nu_\mu \to \nu_e$ (negative) oscillation channel in the formula (1). One can see that for the $\sin(A\Delta) = 0$ all but the first term disappear. This condition is for a nontrivial solution with $\sqrt{2}\, G_F\, n_e\, L = 2\pi$, or in terms of constant matter density, ρ, equivalent to a magic baseline, L_{magic}:

$$
L_{magic}\,[km] = 32726\ 1/\rho\ [g/cm^3] \qquad (2)
$$

With a standard value of $\rho = 4.3$ g/cm^3 the magic baseline is ~ 7630 km, but with the PREM (Preliminary Reference Earth Model) density it is ~ 7250 km long. Naturally, the experiment at magic baseline alone does not allow for measurement of other parameters. So, data from a second baseline are needed to fulfill this void. The authors of reference [6] provide analysis strongly suggesting that a combination of data from the magic baseline with those from the one of ~ 3000 km length would allow for the determination of the neutrino mass hierarchy (sign of Δm^2_{13}) and the CP violation (δ_{CP} phase) down to the values of the $\sin^2 2\theta_{13}$ parameter by several orders of magnitude below of those of any current experiment.

Following this observation new proposals are being considered for sending neutrino beam e.g. from CERN to India [7] and from Fermilab to Europe [8], both in 7200-7600 km range. Interestingly, Fermilab (contrary to CERN) appears also to be the best located for sending a neutrino beam to a detector at ~ 3000 km away [8]. The neutrino geographical beam paths from Fermilab to Gran Sasso (FNGS, ~7500 km), and from Fermilab to Mt Whitney, CA (FNMW, ~ 2700 km) is shown in figures 2a and 2b, respectively. The Gran Sasso is naturally of great interest because the CNGS detector is already residing there. The Mt Whitney is also a very interesting location because it is a very tall (4300 m) mountain of granite rock in a non-seismic area. The other potential sites at about 2700 km distance from Fermilab are: San Jacinto, CA and Icicle Creek, WA. Both these sites are considered for a National Underground Laboratory. All these locations are close to many West-coast US universities and HEP institutions that would be very helpful in designing, building and operating a neutrino detector there.

Fig.2a. Neutrino beam path from Fermilab to Gran Sasso, Italy

Fig.2b. Neutrino beam path from Fermilab to Mt Whitney, CA

The path of neutrinos through Earth's crust for FNGS and FNMW experiments is shown in figure3. The maximum depth of the neutrino beam into the Earth's crust is ~1660 km for the FNGS and ~185 km for the FNMW. For comparison, the maximum depth of the neutrino path to MINOS and CNGS experiments (both have baselines of ~ 735 km length) is ~ 10 km. The greater averaged depth of the neutrino path in FNGS and FNMW experiments has the advantage of a more uniform, and so more predictable, Earth's matter density which in turn helps in projections of the neutrino interactions while they are passing through the Earth's crest.
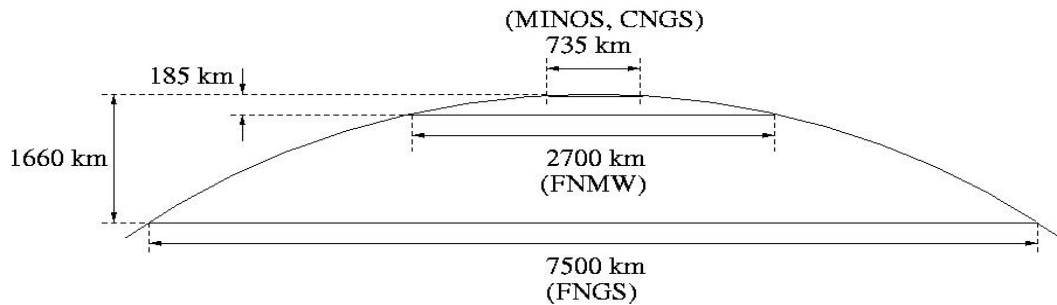

Fig.3. FNGS and FNMW neutrino beam paths through Earth's crest

The neutrino beam considered in ref. [6] is that of the proposed Neutrino Factory [9] at CERN. The extreme technological difficulties for construction of the neutrino factories, however, require very extensive prior R&D programs, making any practical realization of such a concept at least (15 - 20) years away. In this situation we proposed in [6] using the high-energy fast-cycling proton synchrotron as the source of high intensity neutrino beam for these long baseline experiments. We will show below that with a modest increase of the detector size relative to those used in the current experiments it will be possible to reach neutrino oscillation detection thresholds only by a factor of 6, or so, above the projected ones in [6] for the ultimate Neutrino Factory [9].

2. Dual Super-Ferric Main Ring as High Intensity Neutrino Source

2A. *Overview of the DSF-MR accelerator concept*

We assume that the acceptability of any proposed high intensity neutrino source at Fermilab for long baseline experiments is based on the following conditions:

- Allow for a non-interrupted continuity, and upon completion produce considerable improvement for the current (MINOS) and planned (NOvA) neutrino experiments.
- Ability to deliver satisfactory neutrino beam intensity for experiments with baselines of ~7500 km and ~3000 km.
- Allow for construction of the new neutrino production beam lines for these long baselines fully within the Fermilab proper.
- Ability to use the existing Fermilab accelerator infrastructure to suppress cost, and to speed-up the construction work.
- Utilize the decades-long experience and potential of Fermilab, BNL, LBL and SLAC scientific and technical personnel in synchrotron accelerator design, construction and operation.
- New accelerator complex with neutrino beam lines should be completed in a period of time that the followed-up long-term physics program will be viewed as much advanced relative to similar contemporary programs elsewhere.

We believe that Dual Super-Ferric Main Ring (DFSMR) accelerator as proposed in [8] fulfills well all the above conditions. The outline of the proposed new Fermilab accelerator complex with DSFMR is shown in figure 4. When the Tevatron stops its operations it would be replaced with two rings of fast-cycling synchrotrons (DSFMR).
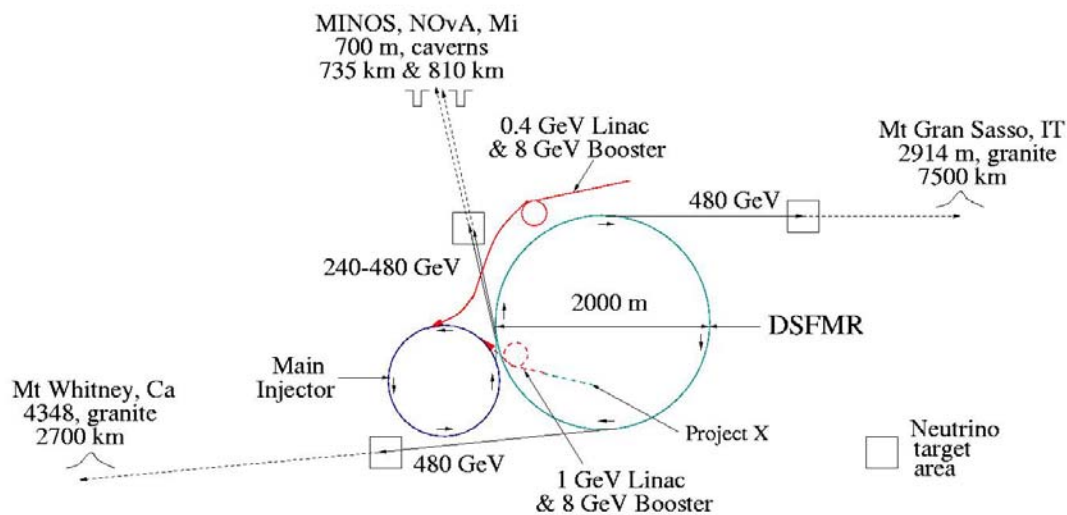

Fig.4. Proposed arrangement of DSFMR at the Fermilab accelerator complex

As the Main Injector is not only the latest addition to the Fermilab accelerator complex but it is also a well functioning fast-cycling synchrotron it remains a central part of the proposed new Fermilab accelerator complex. The main three components of the new accelerator complex are then: 8 GeV Pre-injector, (8-120) GeV Main Injector, and (48-480) GeV DSF-MR, all three synchrotrons being the fast-cycling machines.

The present Pre-injector consists of 0.4 GeV Linac and 8 GeV Booster that can be used as is for start up. However, both these machines are the oldest ones, and must be replaced if the proton beam based physics experiments are to continue at Fermilab into a far future. The most appealing proposal of a new Pre-injector is the one that consists of a new 1 GeV Linac with new 8 GeV Booster, both placed in a location that does not overlap with current Pre-injector. This will allow for the new machines construction while the physics program continues. As indicated in figure 3, the new injector is also proposed to become part of the Project X [10]. The Project X would expand the 1 GeV Linac to 8 GeV with a Booster serving only as the H$^-$ stripper ring.

Using two accelerator rings instead of one allows double the repetition rate for dumping the proton beam onto the neutrino production lines. The time sequence for beam stacking in Booster, MI and DSFMR accelerators together with their respected ramping times and beam extraction is shown in figure 5. The first set of proton pulses from Linac is stacked in the Booster and accelerated to 8 GeV. This beam batch is then transferred to
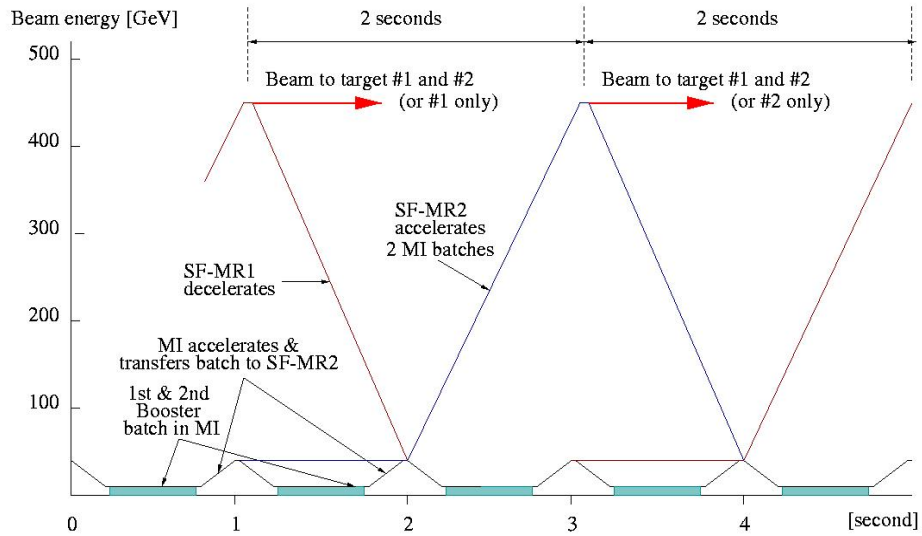

Fig.5. Time sequence for beam stacking, ramping and extraction onto neutrino production targets with DSFMR.

the Main Injector, accelerated immediately to 48 GeV, and then transferred to one of the DSFMR rings where it will await for a second proton beam batch from the Main Injector to arrive. The DSFMR ring will accelerate both batches up to 480 GeV, and then extract them into one or two neutrino beam production lines, as desired. Some technical details

of the main arc magnet, current leads and power supply designs were presented in [11, 12, 13]. Using the Main Ring tunnel for the DSFMR allows re-use the existing Tevatron infrastructure (power distribution, cryogenic support, etc.) for the new accelerator. Very importantly, the existing Tevatron RF system will also be re-used for the DSFMR after some necessary expansion and upgrades. In summary, this approach will save considerable amount of money as well as it will much shorten the overall DSFMR construction time.

2B. DSFMR neutrino production lines and the Fermilab proper

Possible arrangement of the neutrino production lines (shown in figure 6) has been discussed earlier [8]. The most important feature for the neutrino production lines based on the DSFMR accelerator is that these lines can fit well within the Fermilab proper (figure 7) which extends ~ 4 km east, and ~ 2.5 km west from the center of the main Ring. We assumed ~1000 m long meson decay pipes for each of the neutrino production lines but much longer decay pipes, both in the east and the west direction, are allowed if needed. The required depth (~ 240 m for Mt Whitney path, and ~ 700 m for Gran Sasso path) into which these decay pipes must go constitutes a great engineering challenge. The fact, however, that decay pipes are only about 1.5 m in diameter and there is no need for a human access along the entire pipe length should help the construction effort and keep the cost at some reasonable level. There will be shafts to the neutrino production target caves, and to the caves at the deep ends of each decay pipe where detectors identifying neutrino production will be located.
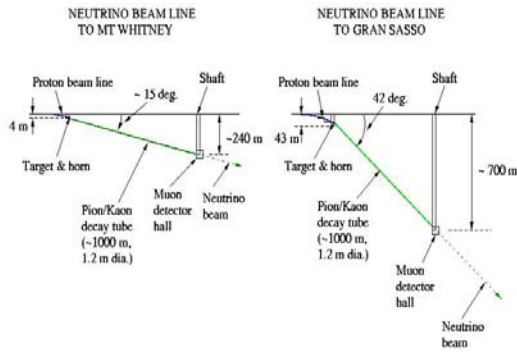

Fig.6. Arrangement of neutrino production beam lines to Mt Whitney and to Gran Sasso.

Fig.7. Birds view of the Fermilab proper. The Main Ring is 2 km in diameter. North is up red lines show foot-prints of neutrino beam lines.

2C. Projected neutrino beam flux and sensitivity limits with DSFMR

At present the Main Injector allows for proton bunch intensities, $N_b \sim 10^{11}$, without adversely affecting circulating beam phase space due to e.g. electron cloud effects [14]. With the $N_b \sim 10^{11}$ protons per bunch the maximum allowable number of stored protons in the Main Injector is $\sim 5.4 \times 10^{13}$. As the DSFMR ring circumference is double in size of the Main Injector and the beam pipe cross-sections are about the same, one should expect

to store ~1.08 x 10^{14} protons in each of the DSFMR rings. The neutrino beam flux is typically measured by beam power on production target which is expressed in the formula (3), where N_p is a number of protons on target in units of 10^{20}, E_p is the proton energy in units of GeV, and T is the time of exposure in units of 10^7 seconds.

$$\text{Beam Power [MW]} = (N_p \times 1.62\ E_p) / (1000 \times T) \qquad (3)$$

For proton beam energy of 480 GeV, cycle time of 2 seconds and with 1.08 x 10^{14} protons per cycle the projected DSFMR beam power on target (POT) is:

$$\text{POT} = (10^{-7} \times 1.62 \times 480) / (1000 \times 2 \times 10^{-7}) = 8.6\ \text{MW} \qquad (4)$$

The 8.6 MW exceeds by a factor of 2 the currently acceptable beam power on a neutrino production target [15]. There is a two-fold solution to this problem: (1) – reduce beam energy to 240 GeV while keeping the same cycle time, and (2) – split and extract 2 beam batches from DSFMR, each batch onto its own neutrino production target. The first option is suitable for operations with only one neutrino experiment, while the second option is suitable for simultaneous operations of two independent neutrino experiments which is a primary reason for the DSFMR proposal. Simultaneous extraction onto two production targets with accelerator cycle time of 2 seconds is equivalent to extracting a beam batch onto one production target every 1 second. The fact that 4 MW beam power can be simultaneously available for two neutrino production targets provides a factor 20 advantage over the current neutrino beam production at Fermilab (as of November 2006). With the MI beam intensity acceptable at present (5-6 x 10^{13} per cycle), the HINS would produce maximum beam power of only 0.8 MW [8]. The DSFMR beam power on neutrino production target also exceeds by factor 2 the proposed future J-PARC and CERN (SPL) upgrades [16].

As the purpose of this note is to provide only a qualitative analysis of what can be achieved with the DSFMR as a neutrino beam source we use the neutrino flux for the CNGS experiment with 400 GeV proton beam to project the neutrino flux with the DSFMR. As shown in [17] the projected neutrino flux at the CNGS detector site (735 km from source) is ~ 7.5 x 10^{-9} ν_μ/ pot_m^2. This makes ~ 4 x 10^{-3} ν_μ/p.o.t._m^2 at ~ 1000 m from the production target (excluding detector acceptance). For the DSFMR this rate increases by the ratio of 480/400 to ~ 4.8 x 10^{-3} ν_μ/p.o.t._m^2. Assuming 5 x 10^{13} p/s, and 2 x 10^7 seconds/y one obtains ~ 4.8 x 10^{18} ν_μ/y at ~ 1000 m from the production target for each neutrino beam to the far detectors. The 1000 m distance is a typical decay path for π -> μ + ν in direct production of a neutrino beam with proton synchrotrons and it can be compared to ~700 m path (one leg of a triangle) assumed for a neutrino production from μ -> e + ν + $\bar{\nu}$ decays in the Neutrino Factory. The π and μ decay paths for the neutrino beam production are illustrated in figure 8 which shows that with full acceptance of π and μ the neutrino beam rates per power on target would have to be the same in both cases. For DSFMR (5 x 10^{13} p/s at 480 GeV) the power on target is actually 20% higher than for a Neutrino Factory (10^{16} p/s at 2 GeV). It also appears that the μ-decay pipe is typically assumed to be of about the same cross-section (~ 1 m^2) as the π-decay pipe suggesting expectation of a similar emittance growth of neutrino beams for both cases.
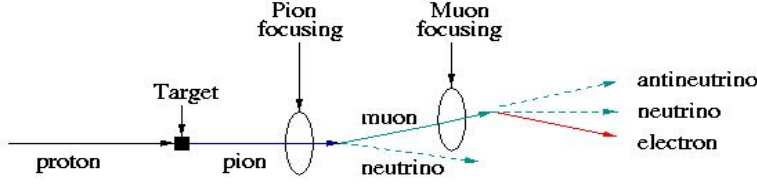
Fig.8. Neutrino production in one step process (π-focusing, DSFMR), and in two-step process (π-focusing followed by μ-focusing, Neutrino Factory)

Neutrino Factories [18, 19] project typically a useful flux of ν_e and ν_μ neutrinos $\sim 10^{20}$ /y with the most optimistic expectations of ~ 1.8 x 10^{20} $\nu_{\mu,e}$/y (this latter value was assumed for the sensitivity limits estimation in [6]). So, the DSFMR would have the ν_μ flux about (20-40) times lower than that of the ultimate Neutrino Factory. It is interesting to observe that with the μ cooling system off in the neutrino factory [20] the projected neutrino beam rate there is lowered by a factor of 16, but still it would be (1.5-3) times higher than with DSFMR. This implies that perhaps in the Neutrino Factory the π meson focusing system is more efficient, or that the overall neutrino production rate is simply overestimated as there are no actual measurements yet.

The sensitivity limits scale with the luminosity, L, as $1/\sqrt{L}$. The luminosity is a product of a total neutrino flux and detector acceptance. With the same detector acceptance the limits scale then as $\sim 1/ (N\nu_\mu)^{1/2}$, which means that the projected limits with the DSFMR will be higher by no more than a factor of $\sqrt{40} \approx 6$ with respect to those with a Neutrino Factory. We use the sensitivity projections in reference [6] to scale down the sensitivity reach with DSFMR. The far-away detectors used in reference [6] are of 25 kt fiducial mass. We note that with some 100 kt fiducial mass for the DSFMR detectors the sensitivity reach would be only a factor of 3 lower than the one projected in [6]. The expected sensitivity limits with DSFMR, and their comparison to those of the ultimate Neutrino Factory are shown in figure 9.
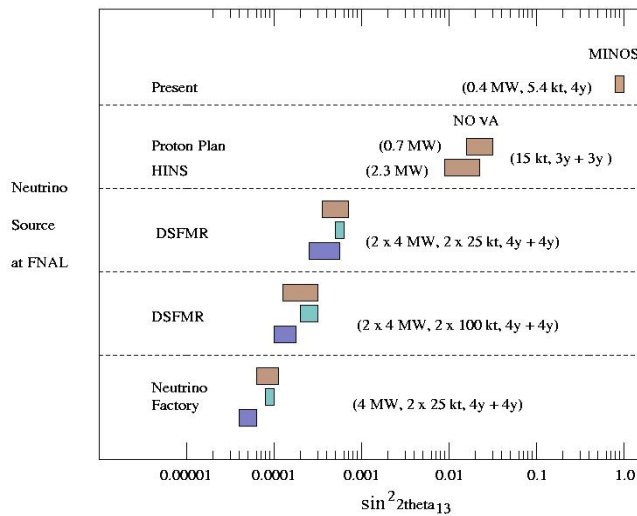

Fig.9. Sensitivity reaches as function of $\sin^2 2\theta_{13}$ for $\sin^2 2\theta_{13}$ (brown), sign of Δm^2_{31} (green), and CP violation (blue) with DSFMR and Neutrino Factory [6]. Sensitivity of MINOS and NOvA are also shown.

The sensitivity limits for $\sin^2 2\theta_{13}$ projected for the MINOS [21] and NOνA [5] experiments are also shown in figure 9. For the DSFMR and the Neutrino Factories the running times of 4 years with each, neutrino and antineutrino beams were assumed. The running times with NOνA experiment is assumed 3 years with each, the neutrino and the antineutrino beams, and for MINOS 4 years of running is assumed. The sensitivity projections in figure 9 show that the DSFMR based experiments exceed by far the sensitivity reach with NOνA experiment and both MINOS and NOνA experiments are also degenerate by the CP violation and the sign of Δm^2 parameter. The sensitivity limits with DSFMR are higher though than with Neutrino Factory but the DSFMR can be put into the operation at least 10 years ahead. The Neutrino Factory has the advantage over the DSFMR as it also allows study the $\nu_e \to \nu_\mu$ oscillations. Consequently, Neutrino Factory may be considered as a successor to the DSFMR.

2D. Far-away neutrino detectors with DSFMR

The detector choice depends on the neutrino energy, which in turn depends on the energy of the proton beam. In figure 10 we show the mean neutrino beam energy as a function of the proton beam energy. The higher the energy of the neutrino the denser the detector can be used. This is very important because as pointed out in [22] it allows for the neutrinos in the 20 GeV range use the iron based calorimeters, saving space while increasing the fiducial mass. Most of the current neutrino experiments apply low-density
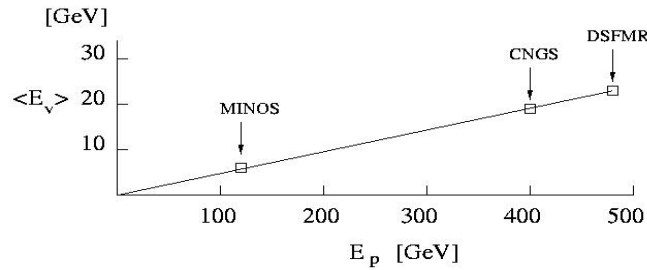

Fig.10. Mean neutrino energy for MINOS (E_p = 120 GeV), CNGS (E_p= 400 GeV) and projected for DSFMR (E_p = 480 GeV)

medium, such as water, scintilator or liquid argon (NOνA). Such approach requires large detector volumes for a fiducial mass necessary to satisfy the required detection efficiency. The iron based calorimeters will be smaller in size, and so much simpler to build, and they tend to have lower cost and easier operations. In addition, the neutrino detectors must be placed in the deep caverns, or caves inside the mountain, making use of cryogens such as liquid argon very difficult. Consequently, if e.g. the NOνA experiment should proceed it would not only benefit from the 10 times increased neutrino beam intensity but one perhaps could also consider using a much less expensive iron-based calorimeter as a neutrino detector.

The DSFMR can only meet the ultimate limit expectations with a Neutrino Factory if the fiducial size of the far-away detectors is considerably increased. This is actually possible with detectors of 1 Mt size as the proposed ones for the J-PARC-HK and UNO

experiments [23]. Such detectors can be constructed as composition of the modular detectors of a smaller size, e.g. 100 kt over extended period of time while the physics data are being taken. Using the iron-based calorimeters (instead of the water Cerenkov detector) certainly facilitates such undertaking.

3. Dual Super-Ferric Main Ring as Pre-Injector to VLHC

The determination of existence (or non-existence) of SM Higgs is the most important high-energy particle physics goal at present. The LHC is very well set to discover and investigate Higgs up to mass of 0.8 TeV, which is nearly an order of magnitude more than the 0.09 TeV mass of SM highest likelihood. Already the results from the Tevatron suggest that Higgs mass lower limit is likely to be above 150 GeV, and therefore on the fringes of acceptability within the Standard Model. In the past decade developments in the neutrino physics combined with cosmological theories strongly suggest that neutrinos have mass, a hypothesis that can not be accommodated within the Standard Model. Consequently, there is a consensus now that there is a new physics beyond the Standard Model. Naturally one would like to know the energy scale at which this new physics occurs. As neutrinos do not carry charge (unlike other fermions) they can be assumed to have the Majorana mass. Based on this assumption a model-independent upper bound on the scale, Λ_{Maj}, of Majorana-neutrino mass generation was outlined in [24] as follows:

$$\Lambda_{Maj} = 4\pi v^2 / \sqrt{3}\, m_v \qquad (5)$$

where $v = (\sqrt{2}\, G_F)^{-1/2} \sim 246$ GeV is the SM weak scale, and m_v is a neutrino mass. By substituting the $v = 0.25$ TeV with 1, 2 and 5 TeV scales of BSM range we project value of the m_N mass as function of the m_v mass at these higher weak scales. Then by imposing the high and the low limits on the neutrino mass, m_v, such as e.g. given in [2,3,4], one can project the range of the Majorana neutrino mass, m_N, as a function of strength of the weak scale from the BSM model mass range. The result is shown in figure 11.
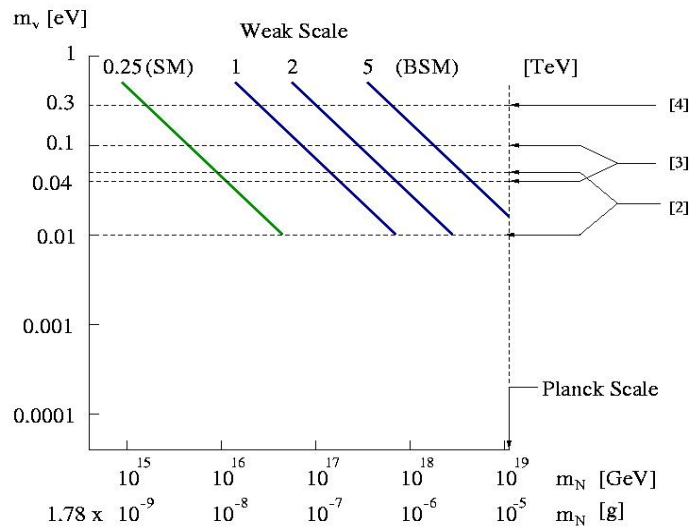

Fig.11. Majorana neutrino mass m_N for weak scales of 0.25 TeV to 5 TeV with bounds on neutrino mass m_v as deduced in Refs. [2], [3] and [4]

For the weak scale of 0.25 TeV the maximum reach of the Majorana neutrino mass m_N is $\sim 10^{16}$ GeV, three orders of magnitude below the Planck scale. The stronger the weak scale the closer the m_N mass gets to the Planck scale, but interestingly the weak scale does not need to be higher than ~ 5 TeV to reach the ultimate high m_N mass range of $(10^{18}-10^{19})$ GeV. Most theorists believe indeed, that the new physics will open at ≥ 1 TeV mass threshold [25]. This is an interesting observation because it suggests that the mass reach of a future accelerator may not necessarily need to be much higher than that of the LHC to begin thorough investigation of the physics from Beyond the Standard Model. This is, in fact, a primary reason for considering the DLHC (Double Energy of LHC) as an option for the LHC upgrade in the future. The LHC energy upgrade, however, will require development of 20 Tesla accelerator magnets which may be very difficult to achieve. In this situation building the entirely new accelerator with longer circumference (thus allowing use of LHC type magnets) may be considered as a reasonable option. One obvious idea is built a scaled-down VLHC accelerator aiming at mass reach of (5-10) TeV. This would require the collision energy to be at (50-100) TeV.

At the time the VLHC proposal [26] was conceived the adopted guiding principle was building an accelerator in a tunnel of a largest feasible circumference to study proton-proton collisions at as high as possible energy. This approach may have, however, backfired as it has lead to a project that may have been much too difficult, too expensive, and of too large a scale to manage. Assuming use of the LHC type magnets in the final VLHC accelerator stage the collision energy of 56 TeV (4 times the LHC) is achieved in a circumference of 106 km. A possible placement of such a new VLHC accelerator in the Chicago area is shown in figure 12.The new VLHC ring is very far away from the areas
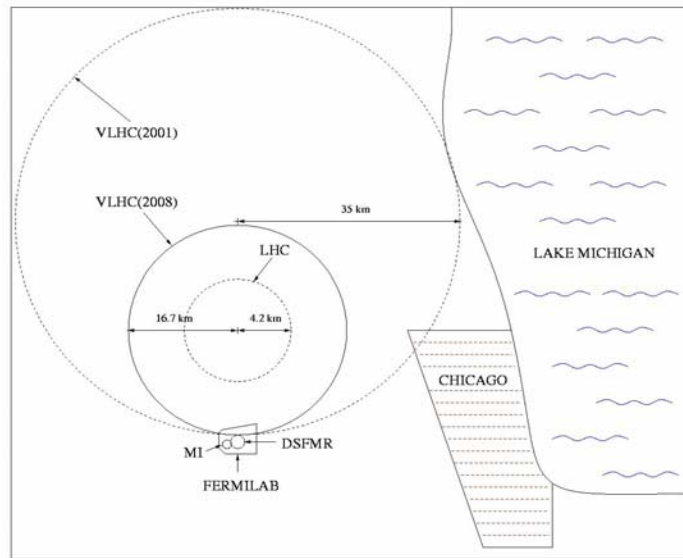

Fig.12. Possible location of VLHC ring in Chicago area. The rings of
VLHC-2001 and LHC are also shown for comparison.

geologically difficult such as the Troy Bedrock Valley, the Sandwich Fault, the Michigan Lake, and it does not interfere with the Chicago city. This makes the construction of the

tunnel more feasible from the civil engineering point of view, and more likely acceptable by the populace.

The VLHC tunnel will host two accelerator rings, the Low Energy Ring (LER) and the High Energy Ring (HER). Two 0.5 TeV proton beams from DSFMR will be simultaneously stacked in the LER ring. Both the LER and the HER rings use two-bore magnets. After stacking is complete the energy of both LER beams will ramp to 7.5 TeV, and then beams will simultaneously transfer to the HER ring. The two beams in the HER ring will then ramp to the ultimate VLHC energy. At present we assume the HER ring will use the LHC-type 8 Tesla magnets (VLHC-HER-1). There is, however, a long-term but realistic possibility of 16 Tesla, and even 20 Tesla accelerator magnets. Such magnets could replace in the future the 8 Tesla magnets allowing for115 TeV (VLHC-HER-2), or 140 TeV (VLHC-HER-3) of the collision energy, or 10 times that of the LHC.

The VLHC accelerator ring within Fermilab site and the transfer lines from DSFMR to LER ring are shown in figure 13. For beam transfer from the LER ring to the HER ring we adopted the concept developed for the LHC luminosity upgrade with the LER injector accelerator [27] sharing the LHC tunnel. Such arrangement allows for a two-beam single batch transfer from the low energy ring to the high energy ring inside the tunnel without by-passing the detectors. Consequently, no transfer lines in the outside area of the LHC (or VLHC) ring are required.
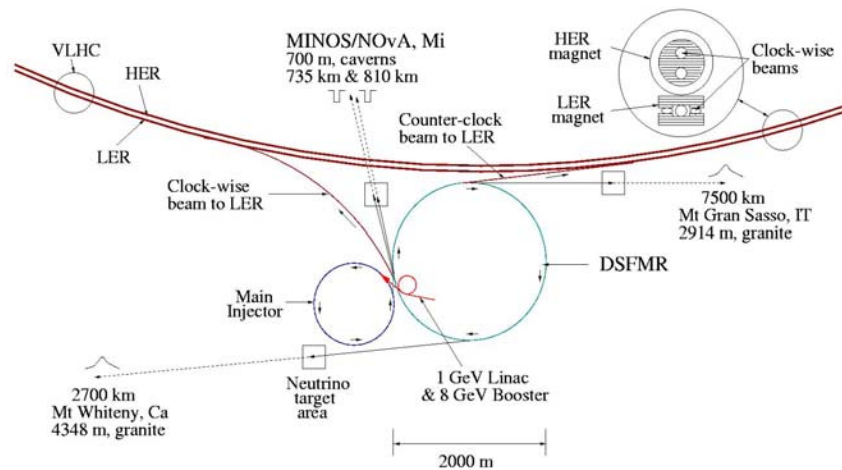

Fig.13. VLHC accelerator rings and DSFMR to VLHC transfer lines

The proposed arrangement of the new VLHC does not affect the long-baseline neutrino physics program, and it allows its continuation during the construction period as well as after VLHC was built. Naturally there can be more beam lines originating from the DSFMR for other fixed target physics programs, or for the detector testing.

A summary of some basic parameters of all synchrotrons involved in the proposed above new Fermilab accelerator complex is presented in Table 1. We assume that there will be a new Linac and new Booster built, if the long range plans for the Fermilab are

adopted. For the Booster we consider both the normal conducting (NC) and the super-conducting (SC) options. For the latter one the ring circumference would have to be a bit longer to lower the dipole B-field, so the ramp rate would not exceed 4 T/s. At 4 T/s the power losses are 4 times higher than with 2 T/s, but they may be considered as practical for a small accelerator such as the Booster. The new 1 GeV Linac can use either warm or superconducting cavities. If the warm cavities were chosen their design could be based on the ones used at present in 0.4 GeV Linac. The superconducting cavities, on the other hand, require a considerable R&D effort before considering them for any practical implementation.

Table1. Basic parameters of the synchrotrons in new Fermilab accelerator complex

Synchrotron	Circumference [km]	Injection/Extraction Energy [GeV]	Max. B-Field [T]	Ramp rate [T/s]	Cycle Time [s]
Booster NC / SC	0.474 / 0.830	1 / 8	0.7 / 0.4	7 / 4	0.2
Main Injector	3.4	8 / 48	1.8	2	1.4
DSFMR	6.8	48 / 480	2.0	2	2
VLHC-LER	106	480 / 7200	2.0	0.2	-
VLHC-HER-1	106	7200 / 28800	8.0	0.005	-
VLHC-HER-2	106	7200 / 57600	16.0	-	-
VLHC-HER-3	106	7200 / 69100	20.0	-	-

4. Magnet and Power Supply R&D, Cost Estimate, Timeline

The fast-cycling superconducting magnets for the DSFMR (and for the Booster, if desired) are of the most concern. Following the successful development of the VLHC low-field magnet a design effort was initiated for a superconducting transmission line that would be suitable for the fast ramping/fast-cycling magnets. Some preliminary studies of 2 Tesla magnets operating with a 2 T/s ramp rate [11], including the associated power supply [12] and the current leads [13] were recently presented at the MT-20 Conference. It was estimated in [11] that the cryogenic power losses associated with 2 T/s B-field ramping speed would not exceed some 4 kW for an accelerator of 7 km circumference (e.g. one ring of the DSFMR). So, for the two rings of DSFMR the projected cryogenic power loss is of the order of 8 kW, or 1/3 of that of the Tevatron cryoplant of 24 kW. This means that the existing cryoplant at Fermilab will be sufficient to support also the 8 GeV Booster if the superconducting magnets were chosen for this machine as well. The R&D effort for the transmission line conductor including magnet prototyping is certainly required to produce necessary technical data for designing the DSFMR magnet. This R&D effort must also comprise of the power supply and the quench detection/protection systems. Recently, a strong interest was generated at CERN to develop superconducting fast-cycling magnets for the PS2 accelerator (a replacement for the PS). A workshop [28] dedicated in part to the superconducting magnets operating in Hz range is organized at CERN, and Fermilab was invited to participate in a joint collaborative R&D effort for the

fast cycling superconducting magnets. This development will certainly help to initiate the R&D for the DSFMR magnet.

In [8] a preliminary cost estimate for the construction of the DSFMR accelerator was given at about $M300, in the same range (if not much lower) than the cost of the 8 GeV Linac for the HINS. The cost of two new neutrino production beam lines was estimated at about $M200 (most of the cost is due to the civil engineering work). So, the total cost was estimated to be in the range of $M500. By adding some 30% contingency the overall cost rises to ~ $M700. With a construction time spanning over 5-6 years it would mean $M(120-150) per year on average. So, even during the tight budget times, such as at present, the funding agencies may be able to support the DSFMR construction.

5. Summary and Conclusions

At present any new truly large-scale HEP project must wait until physics data coming from the LHC get sorted out. The LHC is well set to investigate the Higgs up to 0.8 TeV mass, well beyond the expectations of the Standard Model. The determination of the Higgs mass is the key to the prospect for the CLIC/ILC as well as for the Muon Collider. If the mass Higgs turns out to be only moderately high the LHC will be able to examine it very thoroughly, and so the basic physics prospect for the CLIC/ILC or Muon Collider will be to study the spectroscopy of flavor. Such a study is certainly important to solidify and expand our understanding of particle interactions, but not yet of a high priority. On the other hand if the Higgs mass turns out to be very high, or not even observed at LHC, the required collision energy for the CLIC/ILC as well as for the Muon Collider will be beyond their technological feasibilities contemplated at present, and consequently these projects would be pushed into a very remote future.

It is of utmost importance to continue the experimental high-energy particle physics program in the US during the LHC era which will be characterized for some time by uncertainty about options for the future of HEP. From all the US laboratories it is the Fermilab that has a unique opportunity to embark on a research program that is both very important to the high-energy particle physics and also truly complementary to that of the LHC. The search for the neutrino oscillations in "7500 km + 3000 km" baselines with DSFMR can be certainly viewed as such a program. It is likely that the achievable neutrino theory parameters with DSFMR will in fact turn out satisfactory for the resolution of the neutrino physics which appears to play a very fundamental role in understanding the workings of the universe. This includes not only the microscopic structure of the matter but also the dark matter and the dark energy of the astrophysics theory. In his recent remarks to Congress NASA Administrator M. Griffin observed [29]: *"Truly, we study the brush strokes of physics in our particle accelerators, and (in astrophysics) the grand portrait of those strokes as it is painted on the night sky"*. We believe that the long-baseline neutrino experiments based on DSFMR accelerator will provide considerably much more than the "brush strokes" with a reasonable chance that they will actually paint a masterpiece of physics.

The DSFMR project does not require carry-out R&D effort on a very fundamental level, or on a large scale. The required magnet R&D and the prototyping is rather straightforward, inexpensive, and it can be accomplished in a time span of less than 3 years. One should consider the use of both the LTS and HTS conductors. The LTS may be more practical for the smaller machines (Booster or PS2) that must have a very large bore. Larger bore magnets require a larger core which in turn may help hide the conductor from the sweeping B-field as suggested in [30], and so the total cryogenic power loss may be acceptable. For the large machines, such as DSFMR or SFSPS, where the magnetic bore is small the HTS conductor is preferable [11] allowing to substantially reduce the cryogenic power losses with respect to those with the LTS conductors suppressing in this way the cost of long term operations. Very importantly, the DSFMR project will utilize the existing Main Ring tunnel with Tevatron infrastructure allowing to begin DSFMR construction at any time. The DFSMR accelerator components and required actions are listed in Table 2.

Table2. Principal components of DSFMR accelerator

Component	Comment
Linac (NC, but SC ok)	Can use existing, preferred new ,1 GeV
Booster (NC, but SC if new)	Can use existing, preferred new, 8 GeV
Dual Super-Ferric Main Ring (SC)	New, replaces Tevatron magnets
RF System	Use expanded Tevatron RF system
Injection/Extraction Beam Lines	New transfer lines to be constructed

Because of necessity to implement as soon as possible a strong high-energy physics program in the US (after the Tevatron closing) the new project should demonstrate its ability to be successfully built within next 6-8 years, and to be of a moderate cost in the same time. We believe that the DSFMR project can be proven to be just that.

As the DSFMR can extend in a natural way into the VLHC era we present in Table 3 expectations for maximum energy per parton for the current and possible future colliders.

Table3. Maximum available energy per parton at various colliders

Accelerator	CMS energy [TeV]	Maximum energy per parton [TeV]
Tevatron	1.8	0.3
LHC	14	2.3
ILC (CLIC)	1 (3-5)	0.5 (1.5-2.5)
Muon Collider	1.5	0.375
VLHC-HER-1	57.6	9.6
VLHC-HER-2	115	19
VLHC-HER-3	138	23

Some arbitrary comparison of the scales of: (1) Physics reach, (2) R&D effort, (3) Construction effort, (4) Cost, and (5) Time to begin physics with various possible future HEP projects is shown in Table 4.

Table4. Arbitrary comparison of various possible HEP projects

HEP Project	Physics Reach	R&D Effort / Time [Y]	Civil Construction Effort	Cost	Lapsed Time to Physics [Y]
HINS	Average	High / 5	Average	High	> 8
DSFMR	High	Minor / 3	Average	Average	< 8
Nu-Factory	High	Very high / 10	Very high	Very high	> 20
CLIC/ILC	Average	Very high / 10	Very high	Very high	> 20
Muon Collider	Average	Very high / > 10	Very high	Very high	> 20
VLHC	High	Minor / 3	Very high	Very high	10

We believe that the DSFMR project is likely to be the best choice for the US HEP community during the LHC era. It satisfies the necessary high minded physics goals and it can be put to operation in a rather short period of time at affordable cost. There are no fundamental technological issues that must be resolved before embarking on such a project. This is contrary to the Neutrino Factory, ILC, CLIC and Muon Collider proposals which seem to be not only technologically very difficult but likely of the exuberant expectations, with cost and timeline to be determined only after extensive, long term and costly R&D programs. The Neutrino Factory parallels, and if its technology permits, it will exceed the physics reach of DSFMR. The problem is that it has to succeed in achieving low-emittance muon beam production, and fast-cycling synchrotron with 10^{16} protons/sec (DSFMR will use $\sim 10^{14}$ protons/sec). The failure to achieve either of these goals will put Neutrino Factory on par (or possibly even worse) with DSFMR. In addition, the civil construction effort for the Neutrino Factory is extremely difficult as it requires building a 2000 m long muon decay tunnel (in which beam also re-circulates) of a triangular shape that has two different and large inclination angles, so the neutrino beams can be send to both the 3000 km and the 7500 km baselines simultaneously.

One should mention that since the LHC is already built the cost and the timeline of the VLHC based on the same magnets can be very reasonably predicted now. This is important because it would bring some stability to what actually the US HEP can do, and how much support it would be required to accomplish that goal. In figure 14 possible timelines for the LHC, DSFMR and possibly the VLHC are shown.
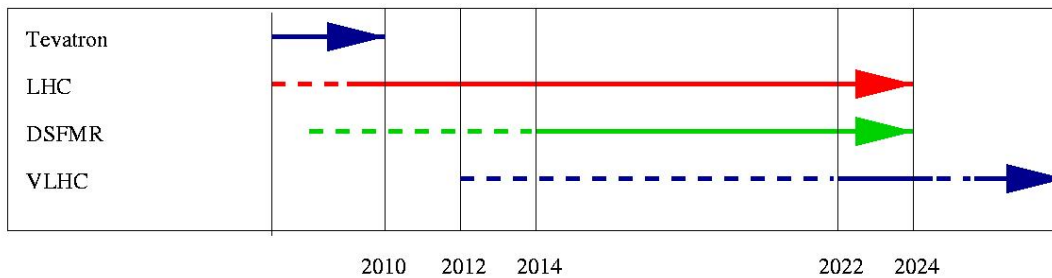

Fig.14. DSFMR timeline relative to LHC with possible extension to VLHC

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