

Preliminary Consideration of a Double, 480 GeV, Fast Cycling Proton Accelerator for Production of Neutrino Beams at Fermilab

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We propose to build the DSF-MR (Double Super-Ferric Main Ring), 480 GeV, fast-cycling (2 second repetition rate) two-beam proton accelerator in the Main Ring tunnel of Fermilab. This accelerator design is based on the super-ferric magnet technology developed for the VLHC, and extended recently to the proposed LER injector for the LHC and fast cycling SF-SPS at CERN. The DSF-MR accelerator system will constitute the final stage of the proton source enabling production of two neutrino beams separated by 2 second time period. These beams will be sent alternately to two detectors located at ~ 3000 km and ~ 7500 km away from Fermilab. It is expected that combination of the results from these experiments will offer more than 3 order of magnitudes increased sensitivity for detection and measurement of neutrino oscillations with respect to expectations in any current experiment, and thus may truly enable opening the window into the physics beyond the Standard Model. We examine potential sites for the long baseline neutrino detectors accepting beams from Fermilab. The current injection system consisting of 400 MeV Linac, 8 GeV Booster and the Main Injector can be used to accelerate protons to 45 GeV before transferring them to the DSF-MR. The implementation of the DSF-MR will allow for an 8-fold increase in beam power on the neutrino production target. In this note we outline the proposed new arrangement of the Fermilab accelerator complex. We also briefly describe the DSF-MR magnet design and its power supply, and discuss necessary upgrade of the Tevatron RF system for the use with the DSF-MR accelerator. Finally, we outline the required R&D, cost estimate and possible timeline for the implementation of the DSF-MR accelerator.

1. Motivation

The expected startup of the LHC in the late 2007 brings the Tevatron collider physics program to a close by 2009. The ILC with its primary motivation to investigate the Higgs bosons of the Standard Model must wait for the LHC to discover the Higgs, or the very least to determine its most probable mass range, so the required energy reach can become a firm parameter in the ILC accelerator design and cost estimate. The current Higgs mass limit from CDF and D0 experiments [1] at Fermilab is already at the fringes of the Standard Model expectations for a connection all the way up to the Max Planck scale. The highest allowed mass scale for the Higgs boson (or some other electroweak symmetry breaking mechanism), however, is around 0.8 TeV. At this mass range the Standard Model becomes inconsistent, and as expected by most theorists, the new physics will likely emerge at the order of TeV mass scale.

It will take some time for the LHC to confirm or deny the existence of the Standard Model Higgs thus giving time for the ILC to determine its achievable parameters, R&D program and cost estimate. In the meantime, we believe that it is of the utmost importance for the high-energy physics community in the US to have intermediate, but scientifically high-profiled, accelerator based physics program at Fermilab. Such a program will strengthen the Laboratory predisposition as a host to any future large-scale, high-energy particle physics accelerator center, including the ILC. To comply with a need for construction of the ILC (or other large-scale next HEP project) such a program should be of a moderate cost, not exceeding some 10 % of e.g. the projected ILC cost. In this note we show that the DSF-MR accelerator for producing neutrino beams for truly long-baseline neutrino oscillation search experiments is feasible, low cost, and it will provide the HEP community (in US and elsewhere) with a high-profile particle physics research in the same time.

2. Physics potential with long baseline neutrino experiments

There has been a decades-long quest for the evidence of physics beyond the Standard Model in neutrino oscillation experiments. The neutrino oscillations, if detected, would constitute most direct evidence of the new physics as they are not allowed in the Standard Model. As the observed limits of mass difference, $\Delta m^2 (v_\alpha - v_\beta)$, of various neutrino flavors ($\alpha, \beta = 1, 2, 3$ for e, μ , τ) are pushed to lower and lower values the baselines to observe neutrino oscillations are being increased in order to enhance the neutrino oscillation probability. This probability, $P (v_\alpha \rightarrow v_\beta)$, is expressed in the following formula:

$$P (v_\alpha \rightarrow v_\beta) = \sin^2 (2\theta_{\alpha,\beta}) \times \sin^2 (1.27 \Delta m^2 (\text{eV}^2) L (\text{km}) / E_\nu (\text{GeV}))$$

The current neutrino oscillation experiments: KEK-PS, FNAL-NUMI and CERN-CNGS, use the baselines of 250, 735 and 732 km, respectively. All these experiments, however, face data analyses that are strongly affected by the degeneracy of theory parameters such as δ_{CP} , $\sin^2 2\theta_{13}$, $\text{sgn}(\Delta m_{31}^2)$, etc. This limits significantly the experimental reach of the tested neutrino oscillation physics. It has been shown recently [2], however, that there exists a “magic” baseline length for the neutrino oscillation experiment for which the analysis of observed data is not biased by the degeneracy of theory parameters, and especially the measurement of the $\sin^2 2\theta_{13}$ and the $\text{sign}(\Delta m_{31}^2)$ is degeneracy free. This magic baseline depends primarily only on the density of the traversed matter and it is given in the formula below:

$$L_{\text{magic}} [\text{km}] = 32726 / (\rho [\text{g/cm}^3])$$

For the average Earth matter density $\rho = 4.3 \text{ g/cm}^3$ the $L_{\text{magic}} = 7630 \text{ km}$, or about 7250 km using a more realistic model for the Earth density profile (PREM).

It was also shown in [2] that a combination of the measurements at this magic baseline with those at ~ 3000 km would provide as well very high sensitivity to the CP phase thus allowing to achieve sensitivities to theory parameters down to $\sin^2 2\theta_{13} \sim O(5e^{-5})$. For comparison, MINOS and CNGS experiments [3,4] are expected to be by more than 3 orders of magnitude less sensitive. This means that even if observation of neutrino oscillations was made in these experiments the long baseline experiments would actually allow for a high precision measurement of theory parameters, including determination of mass hierarchy and CP violation. The summary of experimental limits and expectations is shown in the Table below.

Experiment	Baseline [km]	$\sin^2 \theta_{13}$	δ_{CP}	Mass Hierarchy
MINOS	735	0.05	NO	NO
CNGS	732	0.02	NO	NO
NEW EXP.	7500 + 3000	0.00005	YES	YES

3. Possible sites for detectors to satisfy ~ 7500 and ~ 3000 km baselines for neutrino beams from Fermilab

For the neutrino beam produced at Fermilab (N 41.48° , W 88.32°) a detector at ~ 7500 km baseline can only be placed in Europe (that is excluding far-east Russia, north of the arctic circle, e.g. South Chukotka). As observed in [2] the baseline from Fermilab to Gran Sasso (N 42.45° , E 13.7°), where the CNGS neutrino detector in Italy is located, appears to be almost exactly matching the magic distance of ~ 7500 km though the current detector orientation is not appropriate for the Fermilab neutrino beam. In Figure 1 we show the Fermilab - Gran Sasso neutrino beam path through the north-south cross-section of the Earth (left) and through the cross-section at the 42° latitude (right) which is about common to both locations. The neutrino path is far away from the Earth's core but well below the Atlantic Ocean floor helping to make more reliable assumption of the earth's matter density profile for this path. Naturally any location in Europe within the longitude range of E ($13^\circ - 15^\circ$) and latitude range of N ($40^\circ - 50^\circ$) can be used for the detector site of the Fermilab neutrino beam. One should notice, however, that the neutrino production beam line must be built at $\sim 42^\circ$ relative to the laboratory surface creating a significant technical challenge. The same is true for the detector orientation at the European location.

The 3000 km long neutrino beam path must be found within the US. For that distance it is only possible to go west of Fermilab. The problem is that the western part of the US is typically prone to the seismic activities, and so not suitable for the underground detector. In the mountain chain of Sierra Nevada, however, there is a seismic-free area. In addition, this mountain chain is built of granite thus facilitating digging the cave for the detector. One possible location would be at the foothills of the Mt Whitney (36.6° N, 118.7° W, Lone Pine, CA 93545, airport, hotels, golf courses). Mt Whitney is the tallest peak (4348 m) in the US with exception of Alaska, and it is located ~ 2700 km south-west of

Fermilab. A possible neutrino beam path is shown in Figure 2. The Sierra Nevada mountain range, with Mt Whitney in the center, is shown in Figure 3.

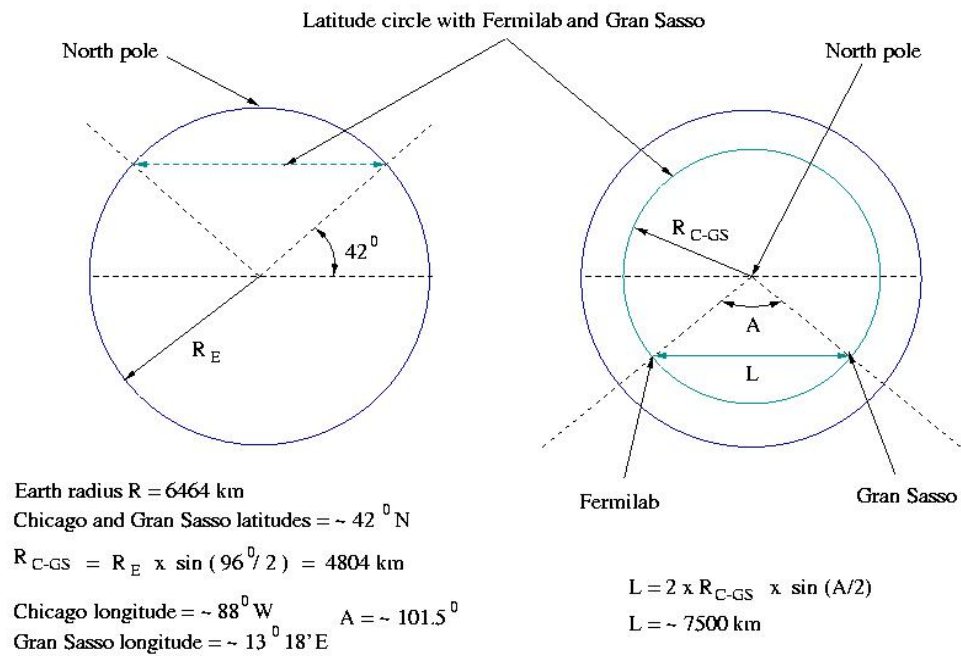


Figure 1. A neutrino beam path from Fermilab to Gran Sasso



Figure 2. A neutrino beam path from Fermilab to MT Whitney



Figure 3. A look at the Sierra Nevada mountain range with Mt Whitney (center)

In order to match the ~ 7500 km baseline requirement CERN is considering sending neutrino beam to either of two locations in India: (1) Ramman, N 27.4° , E 88.1° , or (2) Pushep, N 11.5° , E 76.6° where the INO (Indian Neutrino Observatory) is proposed [5]. For the ~ 3000 km baseline the following detector sites are considered: (1) Santa Cruz, Spain – 2750 km, (2) Longyearbyen, Iceland – 3590 km, and (3) Pyhaesalami, Finland – 1995 km [6].

4. Proposed new accelerator complex at Fermilab

The neutrino beams are produced in secondary reactions following the proton beam striking a needle-like production target. Although the energy of neutrinos may not need to be very high (3 – 20) GeV, the long-baseline neutrino beams require highest possible energy of the protons at the target to enhance the beam power as well as the pion and kaon production in the forward direction. Both factors are important for increasing the projected neutrino detection sensitivity [7]. For this purpose CERN is using 450 GeV protons from the SPS for the long baseline neutrino experiments.

After the Tevatron closedown we propose to replace the old Main Ring accelerator in the Tevatron tunnel with two rings of the SF-MR1 and SF-MR2 (DSF-MR) accelerators, placing one on the top of the other. The 1.9 Tesla super-ferric magnets that will operate at 1 second rise and 1 second decay time, or 2

seconds cycle time, will be used for these accelerators. These new accelerators will accept 45 GeV beam from the Main Injector and accelerate this beam to 480 GeV. The proton beams will be then extracted sequentially to two different, or to the same neutrino production target, if desired.

A schematic view of this arrangement is shown in Figure 4. The 8 GeV proton beam from the current injection system with 400 MeV Linac and 8 GeV Booster (or the new H^- , 8 GeV beam from the recently proposed Linac [8]) is transferred to the Main Injector and then ramped to 45 GeV. The 45 GeV beam is then transferred to one of the DSF-MR accelerators where it is ramped to 480 GeV. The DSF-MR accelerator ring length is double of that of the Main Injector, so two proton beam batches from the Main Injector can be stacked in each of the DSF-MR ring.

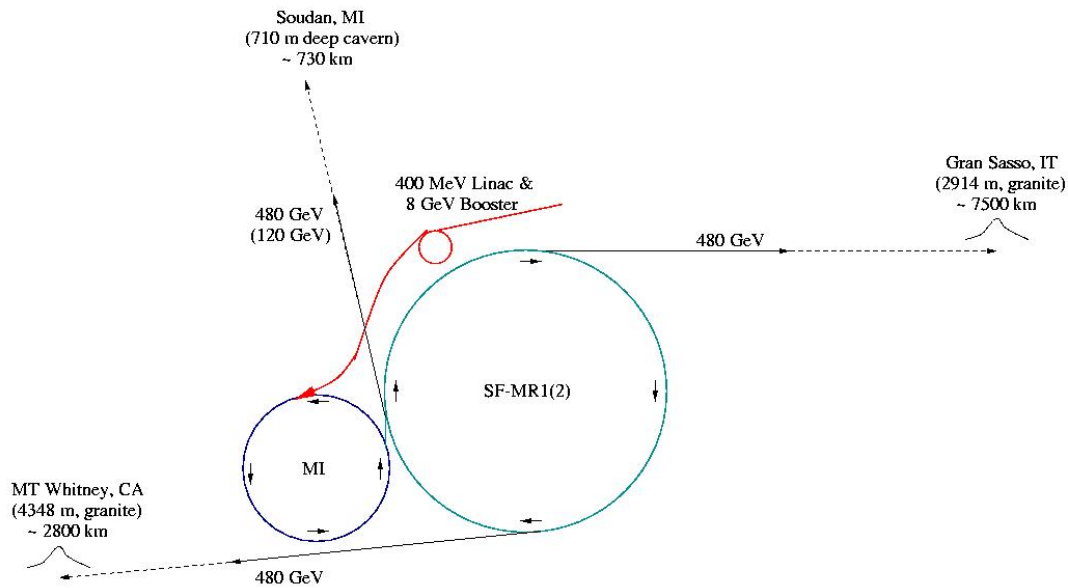
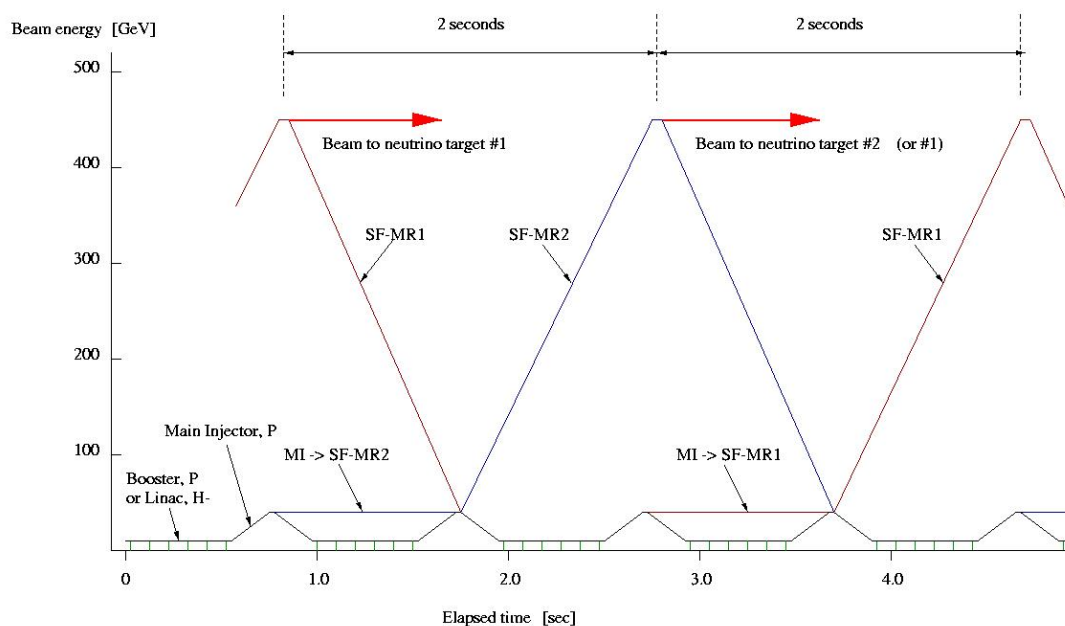


Figure 4. Proposed new arrangement of the accelerator complex at Fermilab for production of neutrino beams to MT Whitney and a site in Europe

The DSF-MR allows for the optimal use of the Fermilab injector system. The idea of operation with two SF-MR accelerators is illustrated in Figure 5. The overall timing sequence is determined by the Main Injector and the DSF-MR ramping times. As discussed in Chapter 5, a 2-second cycle time of the DSF-MR



magnets is proposed, but even shorter cycle may be possible depending on the required quality of magnetic field for the fast cycling mode of operation. The Main Injector cycle time at 45 GeV is about 0.4 second, thus requiring ~0.8 seconds to stack two beam batches. This leaves about 1.2 second for stacking and accelerating beam from the Booster (or the Linac) in the DSF-MR accelerator ring. For the H^- ion source operating at 15 Hz it would be possible to stack 7 beam pulses per one Main Injector beam batch, or total of 14 pulses per each of the DSF-MR accelerators. As the ramping of the magnets in each of the DSF-MR rings is successive, one can envision sharing of the required power system between the two accelerators.

Fermilab Accelerator System	Ion Source Rep. Rate [Hz]	Pulse Length [msec]	Protons per Cycle $\times 10^{14}$	Proton Energy [GeV]	Beam Power on Target [MW]
Present (proton plan)	15	0.09	0.45	8 - 120	0.40
Present + DSF-MR	15	0.09	0.90	45-480	3.20
SNuMi I	15	0.09	0.49	8 - 120	0.70
SNuMi II	15	0.09	0.83	8 - 120	1.20
8 GeV Linac + MI + - Current H^- Source - Heavy-duty H^- Source	15	0.09	0.31	8 - 120	0.28
	10	1	2.17		2.00

5. Main arc magnet for the DSF-MR accelerator

For the main arc magnet of the DSF-MR fast-cycling accelerator we propose to use the magnet based on a modified super-ferric magnet technology developed for the VLHC [11]. This new magnet concept is briefly described in [12], and a more detailed design of this magnet system will be presented at MT-20 Conference [13, 14, 15]. The magnet uses laminated, Fe3%Si, core to form the magnetic field. The accelerator magnet string is powered by a single, transmission-line conductor with the NbTi, or the HTS - 344S superconductor strands. The eddy current effects in both magnet core and the conductor are small enough to allow for operations with 1-2 second cycle mode.

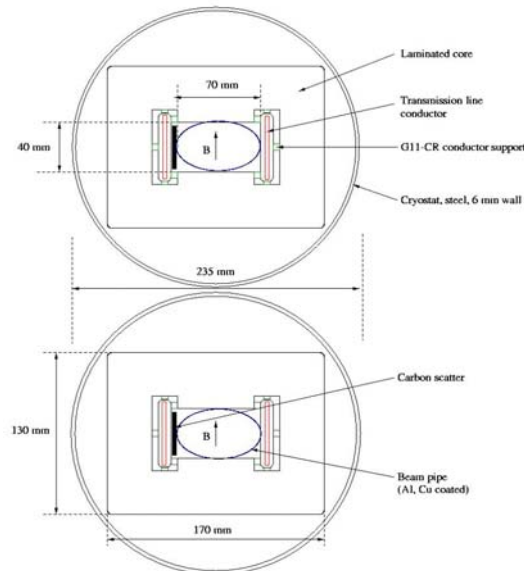


Figure 6. The arrangement of the SF-MR1 (top) and SF-MR2 (bottom) magnets

As shown in Figure 6 the two magnet rings are placed one on the top of the other to keep the identical circumferences. The carbon scatter blocks are placed along the entire length of the conductor to prevent its damage from the failed beam.

The proposed arrangement of the transmission line conductors for these magnets is shown in Figure 7. The whole magnet assembly (including its cores) is placed inside the cryostat pipe to minimize the outside heat load on the conductors. Other source of the heat load to the conductors comes from the eddy currents effect but it appears to be very minimal especially with the 344S HTS conductor. The total projected heat load is estimated at about 0.16 W/m, or ~ 2.3 kW for the two SF-MR magnet rings. This is about 1/10 of the existing cryogenic system capacity for the Tevatron. The conductors can be cooled using the supercritical helium (5 K @ 2 Bar) or two-phase liquid helium at 4.2 K.

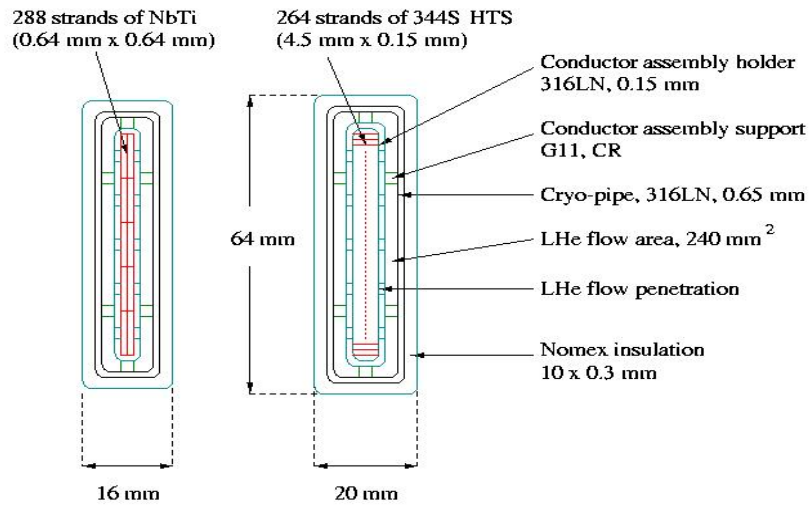


Figure 7. Arrangement of the transmission line conductor with NbTi, and HTS-344S superconductor strands

The main arc magnet list is shown in Table below. It is the same as the one proposed for the SF-SPS [12]. There will be total of 804 magnets in each ring, or 1608 magnets for the DSF-MR accelerator.

Cell type	Magnet type	L magnet [m]	B [T]	B' [T/m]	Number
Arc sections	GF/GD	7.165	1.9	+/- 4.7	744
	QF	0.660		+/- 70.00	6
	QTF	0.339		+/- 70.00	6
Straight sections	QF/QD	0.660		+/-70.00	48
Total					804

6. The DSF-MR accelerator magnet power system

A new power supply system will have to be developed for the SF-MR1 and SF-MR2 magnet rings. Each supply will be ± 2 kV ramping supply at 100 kA current, and 198 MVA peak power. Each supply will ramp out of phase with each other and therefore will share common harmonic filter and feeder system. The power demand for the DSF-MR rings is illustrated in Figure 8. There exists harmonic filter between the Tevatron A2 and A3 locations that provides 5 MVAR leading power factor with a frequency roll off 720 Hz and 1440 Hz traps. At that location there is also additional equipment for a second harmonic filter if more damping power is needed for the high pulse rate. The present Tevatron power transformer is a 40 MVA pulsed duty, and so it will be able to support the DSF-MR operation without any modification but we can reconfigure a second existing transformer for a total of 80 MVA RMS. The feeder system enters the Tevatron ring at the same above location and it is fanned out to twelve locations. The DSF-MR power supply will require three parallel feeders to supply the rings. So, the A2 and A3 are good places for the power supplies from the point of view of the feeder installation. The C0 detector hall, however, is a better location for the construction of the power supplies as it allows placing high-power current leads close to the magnet ring. In this case the power leads could extend through the shield wall to the output filter summing bus. One may need to reconfigure part of the feeder system to extend a third cable to C0 building.

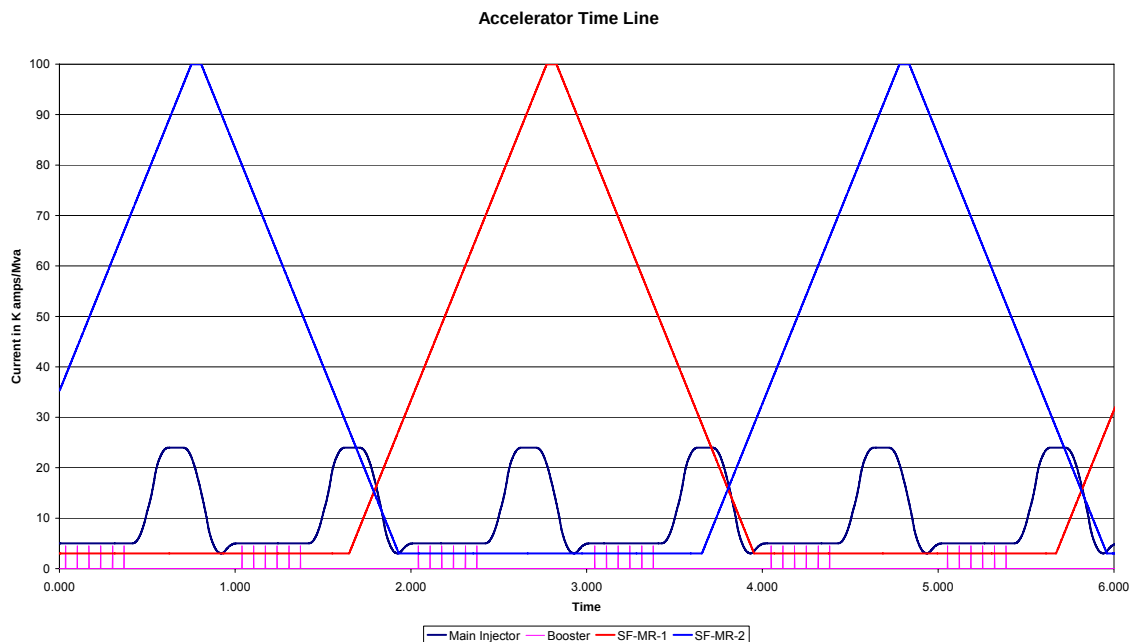


Figure 8. A power cycle for the DSF-MR accelerator

The Main Injector power supply will be used as a base design of the 100 kA, DSF-MR ramping power supply. The MI supplies are 1kV/5kA paralleled devices that utilize filter chokes and bus-work to share current. The DSF-MR supply design will be of twice the power of the present MI supply. We will use experience with operation of a 30 kA supply at the FNAL MTF magnet test facility. The current regulation for each DSF-MR magnet system will use parallel DCCT's, one at each of four filter chokes, summed together. In Figure 9, a conceptual schematic of the $\frac{1}{4}$ of 100 kA supply is shown.

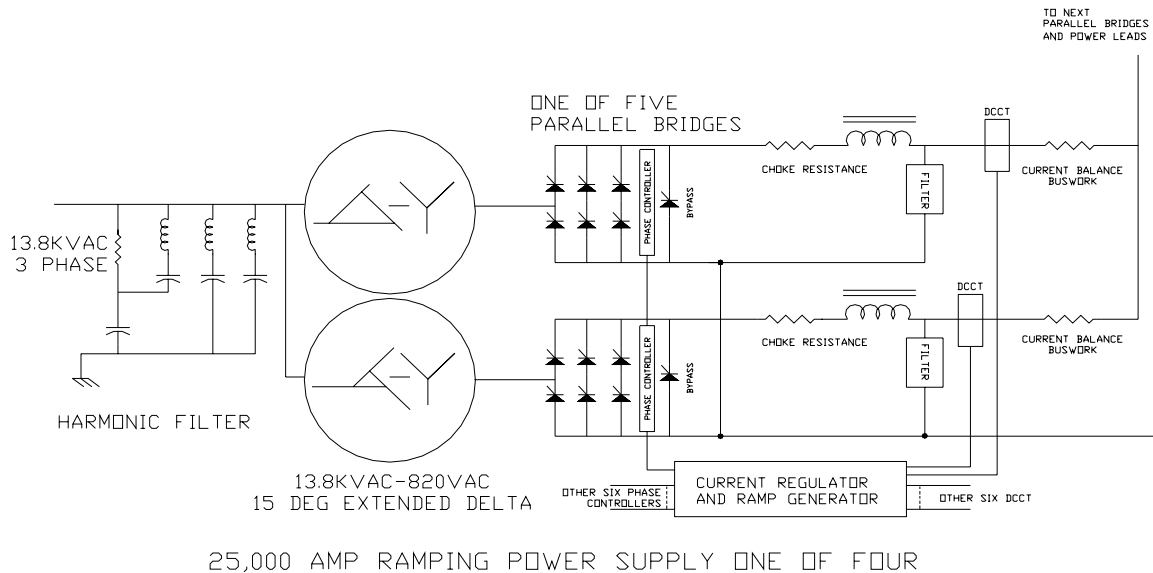


Figure 9. A simplified schematic of 1/4 of 100 kA DSF-MR supply

Each of the DSF-MR ring ramping power supplies will be constructed using paralleled 12.5 kA, ± 2000 V phase controlled 12 pulse full-wave bridges. These full-wave bridges are summed through the filter choke impedance to provide a 25 kA supply current. Then four of these 25 kA supplies are paralleled using the bus-work impedance and summed at the power leads. Measuring the total output current would be done by summing the output of the DCCTs from each of the 12.5 kA bridges after the filters. There are two large benefits from using this paralleling scheme, first the fault current is limited by the filter choke to a manageable level, second we do not need a 100 kA DCCT for regulation. The implementation of this type of system has been in operation at the FNAL magnet test facility with slower ramping magnets. In this installation all bridge SCR's are controlled from only one voltage regulator, and the bus-work impedance controls the balance. We parallel 5 kA and 10 kA bridges in the Main Injector [16] using this topology; however with the high currents in this system we expect to implement a control loop to ensure balance at the 12.5 kA level. Using a control loop to assist the balance will help reduce the current spread caused by differences in the forward drops of the SCR's, cable impedance, transformer

phase to phase balance and the system impedance. Even though the phase control changes to correct for imbalance are small we expect that the current regulator will be a learning system for us with a goal of keeping the cycle to cycle balance under 1%.

Power supplies of this size and speed will cause large swings at the power distribution and a harmonic filter will be necessary to level the power load for the site. We have harmonic filters of this type [17] installed in both the MI and the Tevatron. The Tevatron system is installed on the feeder system that would be used for the DSF-MR power supplies.

The R&D effort for the magnet testing and main ramping power supplies will need to be completed. The magnet testing can use the 1.5 V, 100 kA switcher power supply developed for the VLHC. This would allow for testing a 5 m long magnet at full current and ramp rate. The main ramping power supply will require the construction of at least one of the 25 kA supplies with the full regulation systems.

Although the DSF-MR magnets have much lower inductance than the Tevatron ones the Quench Protection Monitor (QPM) can be reused for the DSF-MR accelerators. The QPMs will be split into two systems, one for each of the rings but since the magnets share common refrigeration system both rings may need to be turned off if one of them quenches. The ramping computer, TECAR, will have to be upgraded for a DSF-MR faster ramp and to support both rings.

Possibly up to three beam extraction systems may be needed for the DSF-MR accelerators: one to the East, one to the West and, if desired, one to the NuMi at F0. These systems may also be dual systems that allow for both DSF-MR machines to extract beams into the same location. The power equipment of the present low-Beta systems can be reused for these new extraction lines. In addition also the Tevatron magnets can be used for the DSF-MR transfer lines to neutrino production targets. They would operate in the DC mode at 480 GeV, and depending on the descending proton beam line angle may require less current than presently being operated. The Tevatron magnets have a poor history when used in the ramping mode but they have a very good record for the DC operations. The injection kicker systems in the Tevatron, now used for protons and p-bars, can be reused for the injection to DSF-MR rings. In addition, the Tevatron abort extraction kickers can be relocated to the DSF-MR rings and serve as the extraction kickers there.

7. Main Injector and DSF-MR operations

The Main Injector power system does not require any modifications. It will ramp only to 45 GeV, but it will use all the MI power supplies. Consequently, the MI will be able to support the 120 GeV operations for a slow spill, NuMi, as well as the P-bar production, if desired, even after the DSF-MR installation. If the DSF-MR accelerator will be used for NuMi operations the A150 line will have to

be extended up to the NuMi present line, and the additional power supplies will be needed at MI-62 to power these magnets.

8. The DSF-MR RF system

The Tevatron RF system can be reused for the DSF-MR accelerators but it will require upgrade from the current maximum ramp rate of 100 GeV to 480 GeV per second. The present TeV RF system uses 8 stations that can be configured to allow for 10^{14} ppp acceleration at 100 GeV per second for 1.6 MW beam power requiring 2.28 MW wall power. We will need to add more RF stations to increase the total power for each ring to 9.92 MW. Also only one RF system may be used for both rings but at the expense of a longer time in the ramp cycle. It will not be possible to inject beam from the Main Injector to one of the DSF-MR machines until the beam was extracted from the other one. This increases the time per cycle by about 0.5 second. However, it may be possible to develop a system with two cavities (one above the other to line up with two-ring magnet systems) to share the power amplifiers. It will increase the RMS power needed from each amplifier but reduce the arc magnet complications by not having the beam to change the elevation.

9. Neutrino production lines

There is a significant experience with building the neutrino production lines. In Figure 10, we illustrate possible arrangement of such lines for detectors

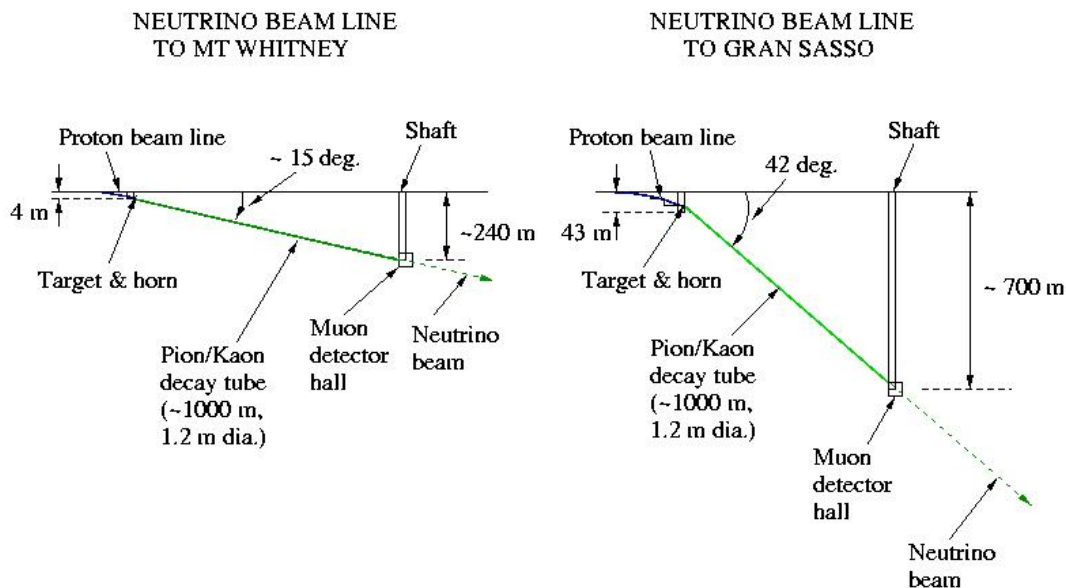


Figure 10. A sketch of neutrino production lines for Mt Withney and Gran Sasso

at ~2700 km (case #1), and ~7500 km (case #2) away from Fermilab. Each line consists of a proton beam line pointing at the far-away detector, the pion/kaon

production target, the focusing horn, the pion/kaon decay tube with the neutrino identifying muon detector at the end. The Tevatron 4 Tesla magnets can be used for the proton beam lines to the targets but new 8 Tesla dipoles would allow for shorter beam path and so a shallower descent of the beam line. For the case #1, the proton beam line length would be ~ 40 m, and it would descend by ~ 4 m. For the case #2, the beam path would be ~ 120 m with a descent of ~ 43 m.

The most challenging part is the installation of a decay tube that may be 1000 m long. With the 480 GeV proton momentum, however, the muons from the meson decays are emitted very strongly in the forward direction allowing for the decay tube diameter to be moderately narrow, e.g. ~ 1.2 m, and so the decay tube tunnel may need to be only of about 2 m in diameter, making it easier to construct. It is very important that the decay tubes, muon detector and shafts are within the Fermilab site (Figure 11). One can see that using the DSF-MR rather



Figure 11. Fermilab site with MR (radius ~ 1000 m) in the center

than the Main Injector for the extraction of the proton beams to the neutrino production targets will put a 1000 m long (or even much longer, if needed) decay tube at east, west, north, north-west and south-west directions well inside the Fermilab borders.

10. Sizing detectors for the long baseline neutrino experiments

The sensitivity, L , of a neutrino oscillation search experiment is typically expressed as a product of the beam power on target, detector mass and the available running time:

$$L = \text{Target power (MW)} \times \text{Detector mass (kton)} \times \text{Running time (y)}$$

With the projected beam power for the DSF-MR (Chapter 4) we will use the NUMI beam operation to MINOS experiment at 735 km away from Fermilab as a reference for the scaling-down, or up, the required detector size for distances such as: (1) 810 km to NovA (MI) (2) 1500 km to the Underground Neutrino Observatory in Henderson Mine (CO), (3) 2700 km to Mt Whitney (CA), and (4) 7500 km to Gran Sasso (Italy). The detection efficiency falls down as a square of the neutrino beam path. The results are shown in a Table below. The size of the MINOS and NovA detectors is naturally scaled down due to drastic increase of the beam power with the DSF-MR. The detector sizes much smaller than MINOS, however, are probably unrealistic as a necessary detector depth has to be taken into account as well.

Detector or Location	Distance [km]	Detector size (Proton Plan) [kton]	Detector size (Proton Plan+ DSF-MR) [kton]
MINOS, MI	735	5.4	(0.7)
NOvA, MI	810	25	3.1
Henderson, CO	1500		2.8
Mt Whitney, CA	2700		10
Gran Sasso, IT (or EU)	7500		66

We conclude that up to 1500 km neutrino beam path the detector can be of a size smaller than MINOS. For the 2700 km distance the detector size is double of the MINOS one, and for the 7500 km beam path it needs to be ~2.5 times larger than the NOvA detector for the “off-axis” neutrino experiment at Fermilab. It is interesting to note that the INO detector for the CERN-SPS 7250 km baseline experiment has been proposed to be of the 50 kton mass [5].

The above Table suggests also that if the DSF-MR was implemented one could collect in just a few month statistics for the MINOS or the NovA experiments that require at present many years to complete.

11. Tentative schedule and preliminary cost estimate

A list of activities and a tentative time to conclude them are shown in Table below. Most of the new R&D effort will be related to the fast cycling magnets. The R&D effort for these magnets will focus on the B-field quality and mechanical strength required in long-term operations of a fast-cycling magnet. There is a significant experience gained in building the high-power neutrino production beam lines and targets but the steep descent of these lines for the long baseline experiments (especially the one to Europe) is of a strong concern, and so serious studies of the feasibility and the cost are required. As suggested in the Table below, the DSF-MR project could be completed in a span of 5 to 6 years. The fabrication of the DSF-MR components and the superconducting magnet accelerator system assembly work will profit from multi-decade long experience of Fermilab technical, engineering and scientific personnel. In addition, the MR tunnel that would host the DSF-MR is already fit with the basic infrastructure consisting of power and cryogenic distribution systems, multiple access and ventilation. The MR magnets are mostly removed from the tunnel, and the Tevatron magnets can stay there, if desired, as there will be enough space left to install the DSF-MR magnet rings.

	Activity	Time [Y]	Lapsed time [Y]
1	DSF-MR accelerator design, including MI to DSF-MR transfer lines and neutrino beam production lines	1	1
2	Fast cycling magnet R&D and prototyping (includes current leads and power system)	2	2
3	DSF-MR magnet & component production	3	5
4	Magnets, power, RF & cryogenic systems installation	2	5
5	Neutrino production lines and targets installation	2	5
6	DSF-MR subsystems commissioning	1	5
7	DSF-MR accelerator system commissioning	1	6

The true cost estimate of any new accelerator project requires a considerable engineering effort. For the purpose of this preliminary note we based the projected cost estimate of the DSF-MR on the studies performed for the VLHC [11] and updated recently for the LER accelerator in LHC ring as well as the fast-cycling SF-SPS accelerator [12] at CERN. The DSF-MR cost is estimated to be about \$M 300. Adding 30% of contingency, the overall cost of the proposed new Fermilab accelerator system is projected to be less than \$M 400 which is approximately 5% of the estimated Sub-TeV ILC project. The average per year spending over the 6 years of the R&D and construction effort would be ~ \$M 65.

	DSF-MR Subsystems	[\$M]
1	Main arc magnets including transmission line conductors, current leads and power supplies	200
2	Main arc corrector magnets	10
3	Main Injector to DSF-MR transfer line magnets	10
4	DSF-MR RF systems	40
5	Beam pipe vacuum system	15
6	Upgrade of cryogenic plant and distribution lines	10
7	Magnet and power supply R&D and prototyping	5
	Grand total	300

The DSF-MR cost estimate does not include the cost of the neutrino production lines, targets and muon trigger detectors. The civil engineering work required for the tunnels of the descending neutrino production lines, especially the one for the beam to Europe will strongly dominate this cost. Scaling much upward from the NuMi project we expect though this cost not to exceed \$M 200 (\$M50 for 15⁰ tunnel, and \$M150 for 42⁰ tunnel), so the overall cost of a long baseline neutrino project would be ~ \$M 600, thus remaining in the 10 % bracket of e.g. the ILC accelerator cost.

12. Summary and conclusions

The combined 3000/7500 km baseline neutrino oscillation experiments offer unprecedented opportunity to investigate the high-energy particle physics theories well beyond the Standard Model. The about three order of magnitude increased detection sensitivity and the independence of interpretation of the results on the theory parameters, makes these experiments worthwhile independently of the outcome of any current oscillation search experiment. The DSF-MR project allows for an 8-fold increase of the proton power on the neutrino production target regardless of the choice of the injection scheme, and thus strongly enhancing potential success of the long baseline neutrino experiments.

We believe that for any large scale accelerator project one should use technologies that are readily available for a practical application. Such approach will lead to predictable time-line and cost. The technology of the superconducting transmission-line super-ferric magnets recently pioneered at Fermilab has proven to match the expectations of the manufacturing simplicity, low cost and high-performance standards as required for the accelerator magnets. A small scale R&D followed by the prototyping of the fast cycling magnets with matching them current leads and power supplies will be sufficient to prove applicability in the fast-cycling accelerator design. Therefore one could begin now making plans for the new powerful neutrino beams at Fermilab with the DSF-MR accelerator in the final stage.

The overall cost of the proposed DSF-MR accelerator system for the long baseline neutrino beams production, when averaged over 6 years, is at a very acceptable level without endangering any future US large scale HEP project. The construction of the DSF-MR will also benefit from in-depth experience of the Fermilab personnel with the superconducting accelerators. The construction of a neutrino detector in the Sierra Nevada mountain range will greatly benefit from the experience of many West Coast Universities with advanced HEP programs. By the time the DSF-MR comes to life the Gran Sasso detector in Italy may be due for an upgrade, or a new detector for the neutrino beam from Fermilab could be built at another location in Europe. A possible timeline for the major HEP projects in the world is shown in Figure 12. This timeline may stretch by 3-5 years depending on the available funding. Without the new powerful neutrino beams at Fermilab there will be a long gap (at least 10 years) for the accelerator based HEP physics in the US. Such a gap may have a devastating effect on the implementation of any future large-scale HEP project in the US, including the ILC.

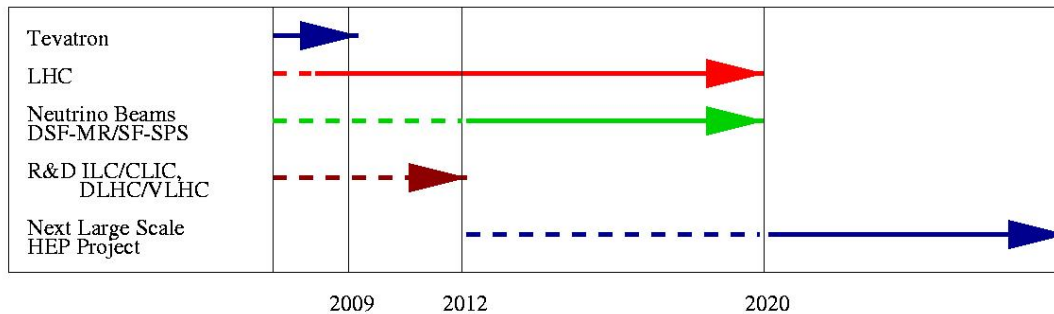


Figure 12. Possible timeline for major HEP projects

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