A feasibility study of a neutrino source based on a muon storage ring — Source link

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Topics: Muon collider, Neutrino Factory, Neutrino, Neutrino oscillation and Neutrino detector

B. Appendix: Scaling of Cost with Energy and Intensity

With the two ongoing studies, one for the physics program, [1] and one for the accelerator and facilities [2] on the "Neutrino Factory Based on a Muon Storage Ring", a number of interesting suggestions and ideas came up. Almost immediately the question of scaling cost with the storage ring energy and with intensity came up. Nevertheless, it was impossible to explore all those questions in great detail, either in the report or in the preliminary cost estimate that is presented in Appendix A. During the study it became more and more clear, that one of the unique features of a neutrino source, namely the possibility to balance the cost of the accelerator with the cost of the detector, would urge the accelerator people to find an answer to this question sooner rather than later. This appendix is an attempt to give this answer, very short and very preliminary.

Scaling with Energy

The assumption at the beginning of this study was that accelerating muons would be the only cost driving factor of the facility, given the experience from other actual projects for pulsed high energy accelerators. This is emphasized in our case by the fact that the acceleration has to be done at low frequency with relatively high gradient—a very unfortunate combination from the technical point of view. The prejudice turned out to be right, although compared to a very early guess the result presented in Appendix A is not as obvious as it was assumed to be. The superconducting solenoids, especially in the cooling channel, are equally challenging from the technical point of view and certainly very expensive.

In the Introduction (chapter 2) it is described that over a large range of parameters the product of: the energy of the muon beam times the mass of the detector times the intensity should be kept constant for a given physics reach. The physics study on the other hand defined a lower energy limit of 20 GeV for the stored muon beam in order to have good muon detection in the long baseline detector. Changing the scope from 50 GeV to 11 GeV or so would have an obvious solution in that the second recirculating linac (RLA 2) would be abandoned. With 20 GeV being the target energy for the accelerator, this is not so obvious. The fast answer nevertheless is that doubling the acceleration per turn in RLA 1 would bring the energy up to 20 GeV. Optimization of the number of turns versus purely doubling the installed voltage would have to be done in a more detailed study, and could lead to a cheaper solution. The cost saving by taking out RLA 2 (~25%) and doubling the voltage in RLA 1 (~5%) would reduce the total by approximately 20%.

For the storage ring, the tunnel circumference will be constant to achieve the same decay ratio in the straight section. The magnets, given the 50 GeV arc radius, could now be normal conducting, which will not automatically lead to any savings, because the aperture has to increase at least proportional to $\sqrt{(1/\gamma)}$. The aperture in the straight section will be constant, because, as the decay angle increases with $1/\gamma$, the emittance increases with γ but the divergence of the muon beam only increases with $\sqrt{\gamma}$. The divergence of the muon beam should be smaller than the $1/\gamma$, which makes the product constant if the β-function scales proportional to γ. An interesting result. Nevertheless, the ring would have to handle a larger energy spread because of the smaller adiabatic damping. The cost savings using normal conducting magnets could easily be eaten up by the increased power consumption and the more complicated chromatic corrections that will be necessary. For the rest of the front end nothing would be saved

Scaling with Intensity

In the summary bar chart in Appendix A one can see, that the total investment cost for the cooling channel is approximately as much as for RLA2. The obvious conclusion is that increasing the energy will approximately cost as much as increasing the cooling. Reduction in cooling will decrease the intensity and decrease the cost as the cooling channel gets shorter (or disappears). Because emittance cooling scales exponentially with the length of the cooling channel and given the fact that, with the study presented here, we are very close to the theoretical cooling limit (2-3 e-foldings) reducing the length is an obvious choice. If we would decrease the length to one half (1/2 the cost) the intensity within the given acceptance would only go down by 20% or so. Approximately 12% could be saved. A minimal solution where no cooling is applied, is under investigation right now and the achievable intensity could be of interest for an entry level machine with an intensity of order 10^{19} per year. The total would be reduced by 20%.

Cost savings that will scale with intensity are usually made by reducing the installed rf power. Especially in a superconducting accelerator, where usually most of the rf power is transferred to the beam, this scales almost linearly. Unfortunately this does not work in our case. Due to the low frequency and the high gradient the stored energy in the cavity is large enough to accelerate the beam over many turns without refilling. By the same argument, the extracted energy is only a small fraction of the total and the rf peak power is required purely to build up the stored energy. The transfer to the beam is of the order of a few percent only. A reduction in beam intensity will therefore not save any money in the rf systems. On the other hand no upgrade of the rf system is required up to the point where the power extraction from the cavity becomes significant. At twice the design intensity this starts to happen and a different filling scheme, where the rf power going into the cavity has to be matched to the power extracted, is required. At this point the installed rf power has to be upgraded significantly. The power transfer to the beam is more efficient and the average ac power will not necessarily go up. The number of klystrons will have to be approximately doubled, increasing the cost for each of the accelerating systems (sc-linac, RLA 1 and RLA 2) by about 1/3, which again is approximately 20%. The tungsten shielding in the storage ring magnets, now designed for 70 Watts of power loss per meter (2×10^{20}/year) in the arcs due to decay electrons, will have to be increased. The inner beam pipe of the superconducting dipoles has to be exchanged and a smaller emittance muon beam is required (because of the reduced aperture) or new magnets have to build. This will add another 2-3%. This cost might be prudently spent initially to provide design and operating margin and to avoid a subsequent shutdown as the intensity increases.

Summary

The reduction in scope for a neutrino source based on a muon storage ring can be twofold: Decreasing the energy or decreasing the intensity or both. Each of the steps will reduce the primary investment significantly (approximately 20% each, more than 40% for both). The physics goal of an entry level facility will define which way to go.

REFERENCES

[1] Neutrino factory physics study coordinators: S. Geer and H. Schellman. See http://www.fnal.gov/projects/muon_collider/nu/study/study.html

[2] Neutrino factory technical study coordinators: N.Holtkamp and D. Finley. See http://www.fnal.gov/projects/muon_collider/nu-factory/nu-factory.html