CHOICE OF PROTON DRIVER PARAMETERS FOR A NEUTRINO FACTORY*

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Abstract

We discuss criteria for designing an optimal "green field" proton driver for a neutrino factory. The driver parameters are determined by considerations of space charge, power capabilities of the target, beam loading and available RF peak power.

INTRODUCTION

A neutrino factory may be the best experimental tool to unravel the physics involved in neutrino oscillation and CP violation phenomena [1]. To have sufficient neutrino flux for acceptable physics results within 5 years requires about 10^{22} protons on target per year, which corresponds to 1-4 MW of proton beam power from the proton driver depending on the beam energy.

In the past, there were individual proposals from different laboratories of a particular design of proton driver capable of delivering beam power from 2 to 4 MW, without consistent attention paid to the needs or requirements from the downstream systems. In this study, we try to identify the requirements from those down stream systems first, then see whether it is possible to design a proton driver to meet those needs. Such a study will also assist site specific proposals to further improve on their designs to better serve the need of a proton driver for neutrino factory applications.

As shown in Fig. 1, after the proton driver, there are several major subsystems comprising the complete configuration of a neutrino factory [2]. They are the target and capture, bunch rotation, cooling, and acceleration systems, and finally the decay ring. Each of these systems requires the proton driver to have certain beam qualities for optimal performance.

The beam power *P* of a proton driver is given by the relation P = E N e f, where E is the beam energy, N is the number of protons per pulse, e is the proton charge, and f is the repetition rate. To achieve 4 MW, possible examples of beam intensities required at given energies and repetition rates are shown in Table 1. It is important to realize that typically it requires a beam intensity at the level of 5 10^{13} per pulse, which from our past experience is at the current limit of what can be reasonably achieved, due to limitations from space charge and other coherent instabilities. Therefore, special attention has to be paid to the choice of beam energy and the number of bunches.

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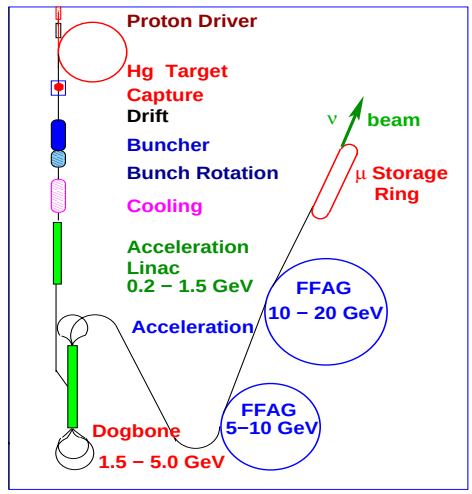

Figure 1: Schematic layout of a neutrino factory.

Table 1: Protons per pulse required for 4 MW. 1 Tp is 10^{12} protons.

	10 Hz	25 Hz	50 Hz
10 GeV	250 Tp	100 Tp	50 Tp
20 GeV	125 Tp	50 Tp	25 Tp

ENERGY CHOICE

We wish to determine the kinetic energy of the proton beam that is most efficient for the production of the soft-pions, which will lead to the maximal collection of muons in a pion decay channel. We process the produced pions through the entire front end of the neutrino factory front end using the Study 2a [3] configuration from the target module to the conclusion of the cooling section. As a figure of merit, we select those surviving muons which are fully contained within the capture transverse acceptance (30 π mm-rad) and the longitudinal acceptance (150 π mm-rad) of the assumed subsequent accelerating section.

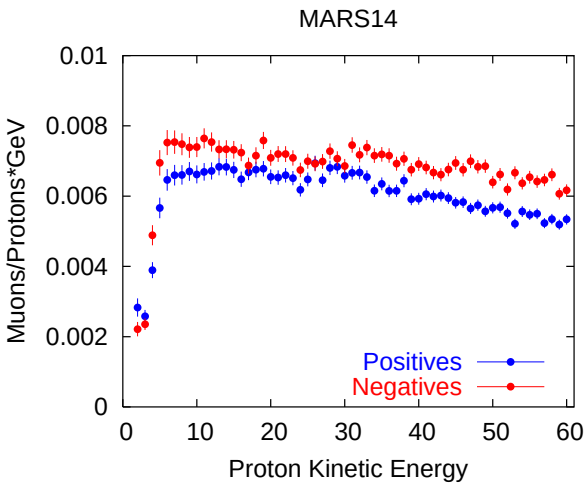

Figure 2: Efficiency of muon collection at the exit of the Study 2a front end versus proton driver energy.

The particle production model used was MARS V14 [4] and the propagation of the particles though the neutrino factory front end was done utilizing the ICOOL code [5]. The efficiency of the muon capture was computed by evaluating the number of collected muons at the end of the neutrino factory front end and normalizing the results to the power of the proton beam such that a beam of e.g. 20 GeV kinetic energy is assumed to contain twice the number of protons as an equivalent beam with 40 GeV kinetic energy. Results of this analysis utilizing a mercury-based target are shown in Fig. 2. The target parameters such as radius, tilt angle, and longitudinal placement have been previously optimized in Study 2a [3].

We also investigated other candidate target types with elements of various Z content with the result that the high-Z materials show the highest efficiency for soft-pion production which will lead to the greatest number of captured muons. In evaluating the most efficient kinetic energy region we found that 6 to 38 GeV protons gave the sum of positive and negative pions within 10% of the maximum efficiency.

TARGET ISSUES

The challenge of delivering 4 MW of beam power on a target (solid or liquid) is governed by two sets of parameters. The first set relates to the production target and specifically the choice of material, as well as its integrated design that allows it to operate as a functional unit. The second set is linked with the proton pulse structure delivered to the target and the parameter choices have a direct impact on the survivability of the target. Whether liquid or solid, the target feasibility issues stem from the inherent material limits that in turn depend on the deposited energy density. This energy density is a function of the proton energy, intensity and spatial structure, as well as the material properties.

Solid vs. Liquid Targets

The issues associated with each of these two target types are distinctively different. On one hand, solid targets are vulnerable to thermo-mechanical shock induced by high energy densities that can lead to failure even with a single pulse on target. Fatigue due to the cyclic nature of the problem can lead to premature failure of the target. Most importantly, solid targets are susceptible to irradiation damage manifesting itself in altering the key properties of the material, both physical and mechanical, that are responsible for behavior under shock and heat diffusion towards the heat sink. The onset of irradiation damage is always expected to compromise the longevity and functionality of a solid target. In addition, solid targets, even under the best of circumstances, must enable the removal of the significant heat load through a feasible and "smart" design. This is particularly challenging because of the constraints brought onto the target by physics requirements that limit the size of the target to avoid re-absorption of secondary particles and thus limiting the available target surface area for heat transfer to the heat sink. Solid targets seem capable of withstanding powers of 2 MW at best and only with low Z, high performance materials.

Liquid targets, on the other hand, either in the form of jets or contained volumes, do not suffer from thermal shock, fatigue or irradiation damage. While these serious limitations are avoided altogether, liquid targets face challenges of a different kind. Specifically, interaction of the proton beams with a high Z liquid jet target will lead to an explosive destruction that, while of no consequence to the secondary particle production, could have serious consequences to the target container. The ability to replenish a liquid jet to meet the repetition requirement of the high power proton driver and the difficulties of adopting a feasible jet scheme to tight geometrical constraints pose additional challenges. In the case of a contained liquid, the generation of high cavitational pressures can induce damage on the target infrastructure. Liquid targets seem capable of supporting a 4 MW proton driver.

Proton Energy

While the energy density distribution in a given solid target will vary within the target depending on the energy of the incoming protons, an important parameter in transferring deposited heat from the target, the maximum energy density increases with increasing energy. Table 2 depicts peak energy densities on a Cu target intercepting proton pulses with the same intensity and pulse shape.

Table 2: Energy Density in Cu Targets at Different Beam Energies (MCNPX Code).

proton energy (GeV)	8	16	24
energy density (J/g)	234	351	377

Repetition Rate

The benefit of increased repetition rate of the proton driver is two-fold. For a given proton driver power an increased rep-rate will lower the demand on the target (especially the solid target) in that the pulse intensity will be decreased. For the same pulse intensity and increased repetition rate the proton driver power increases but the demand on the target increases as well. Specifically, the thermal load of each pulse on the target must, under the higher rep-rate, be removed by the heat sink in a shorter time and the rep-rate limit will be controlled by the ability to remove the dynamic stresses entirely between pulses.

Pulse Length, Intensity and Structure

The survivability of the target depends on the above three parameters. Specifically, the pulse intensity, combined with the beam spot size, controls the quasi-static conditions of pressure and temperature generated in the target upon beam interception. Energy densities of up to 400 J/g, corresponding to ~ 24 10^{12} protons per pulse and σ_r = 1mm, may be tolerated by some high performance solid materials. The pulse length controls the ensuing dynamic stresses and can play a significant role in the way the solid target survives the induced shock. Solid targets favor longer pulses because of the ability to relax during deposition. On the other hand, liquid jet targets will perform best at very short pulses (a few ns) where the onset of jet destruction has not occurred. A pulse structured not as a Gaussian but as a uniform distribution over the same (i.e., 3σ spot) and same intensity will reduce the stress and temperature demand on the target by approximately a factor of three.

BUNCH LENGTH

The proton bunch length has a strong influence on the muon density produced at the end of the front end. The accepted muon density at the end of the cooling channel falls off with increasing proton driver bunch length on the target. This behavior can be partially understood by a simple theory that models the longitudinal dynamics of the muon beam through the RF components of the front end. Longer proton bunches produce initial longitudinal phase space areas that exceed the longitudinal acceptance of the front end.

REPETITION RATE

The primary downside of a higher repetition rate is the average power consumption for the RF systems. There are two sources of this: the first is the energy to fill the RF cavities for each pulse (the unused portion of which we have no good way of storing for the next pulse), and the second is the cryogenic costs for cooling the dynamic heat load (the heat from the absorption of the cavities' stored energy) in the superconducting cavities.

In Study II [6], the average power required for these systems was 44 MW for a 15 Hz average repetition rate. This portion of the machine's power consumption will be proportional to the repetition rate.

Higher repetition rates will reduce the amount of current per bunch train, which will reduce the beam loading in the RF cavities. The primary effect of beam loading is that the bunches toward the head of the train will gain more energy than those at the tail of the train, since the earlier bunches have extracted energy from the cavities. This would be corrected, at least partially, if particles were undergoing synchrotron oscillations, but they do not do so in scenarios involving FFAGs, and they undergo a relatively small number of synchrotron oscillations in the RLAs and initial linac. Furthermore, some schemes for the storage ring require (superconducting) RF cavities to keep the beam bunched, and higher currents might require more RF power (and possibly more cavities) to compensate for beam loading there.

REFERENCES

[1] C. Albright et al., "Neutrino factory and beta beam experiments and development", FNAL-TM-2259 (2004)

[2] M. Zisman, "International scoping study of a future accelerator neutrino complex", these proceedings.

[3] J.S. Berg et al., "Cost-effective design for a neutrino factory", Phys. Rev. Spec. Top.-Acc. Beams 9 (2006) 011001.

[4] N.V. Mokhov et al., Fermilab-Conf-98/379; LANL Report LA-UR-98-5716(1998); http://www-ap.fnal.gov/MARS.

[5] R.C. Fernow, "Recent developments on the muon-facility design-code ICOOL", PAC'05, Knoxville, TN, 2005, p. 2651, http://www.jacow.org.

[6] M. Alsharo'a et al., "Recent progress in neutrino factory and muon collider research within the Muon Collaboration", Phys. Rev. Spec. Top.-Acc. Beams 6 (2003) 081001