PRELIMINARY DESIGN OF A 4 MW PROTON BEAM SWITCHYARD FOR A NEUTRINO SUPER BEAM PRODUCTION FACILITY

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Abstract

The feasibility of the distribution of 4 MW proton beam power onto a 4-targets horn system for neutrino Super Beams production is discussed. A preliminary solution using a pair of bipolar kickers to route the beam onto the targets at a repetition rate of 50 Hz (12.5 Hz per beam line) is proposed. Magnetic fields induced by these optical elements would not exceed 0.96 T. Studies of the beam envelopes with the code TRANSPORT suggest the use of three quadrupoles per beam line located after the dipoles to focus the 4 mm rms beam onto each target. The length of this switchyard system is estimated to be 29.9 m for 6 m width.

INTRODUCTION

For the next generation of neutrino beams based on MW power scale proton drivers, 2 projects have been proposed in Europe: the Superconducting Proton Linac (SPL) neutrino Super Beam from CERN to Fréjus laboratory [1] and the European Spallation Source (ESS) Super Beam [2] where a water Cherenkov detector with a Mt scale fiducial mass is used to detect the neutrinos [3]. In the recent EUROnu Design Study [4], the neutrino source would benefit from the SPL upgrade and would produce a high intensity proton beam with 4 MW power pulsed at a repetition rate of 50 Hz [1].

For high-power applications the SPL will provide a 4-5 GeV proton beam (5.5×10^{15} pps) with time-structure according to each application. The bunch duration foreseen for the production of neutrino Super Beams will be ~1 µs (compared to the SPL pulses of ~500 µs) to limit the current sent to the horn to a reasonable level [3]. This requires the use of an accumulator ring.

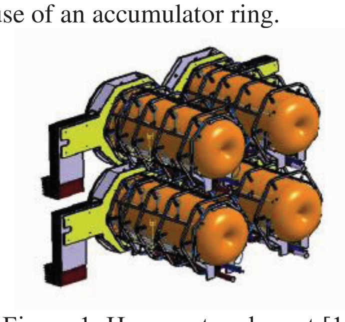

Figure 1: Horn system layout [1].

To minimize power dissipation and radiation problems, the target/horn system is composed of 4 targets (Fig.1) onto which the proton beam is distributed via four beam lines. Each target receives then 1MW proton beam at a frequency of 12.5Hz. To ensure the distribution of the proton beam onto such a target/horn system, a suitable optical system has to be defined.

BEAM DISTRIBUTION ONTO THE HORN SYSTEM

Technical Requirements

The proton beam is assumed to have a Gaussian charge distribution, a circular shape and an rms of 4 mm. Each target is considered to be 780 mm long and to have a radius of 15 mm (Table 1). The 4 targets are separated by a distance of 2000 mm (center-to-center). This value is a key parameter in the design of the beam distribution system as it determines the angle of deflection and thus the magnetic field mandatory for the splitting of the proton beam.

Table 1: Parameters Required for the Target [1]

Parameter	Value
Target Length (mm)	780
Target Radius (mm)	15
Charge distribution	Gaussian
rms (mm)	4
Rep. Rate per line (Hz)	12.5
Pulse Duration (µs)	1
Distance Between Target Centers (mm)	2000

Beam Rigidity

To efficiently define the necessary magnetic induction, the beam rigidity is determined as a function of the particle type and the envisaged beam energy. The beam rigidity is defined as [4]:

$$B \cdot \rho = \frac{1}{q \cdot c}\sqrt{E_k(E_k + 2E_0)} \qquad (1)$$

where ρ is the radius of the particle's trajectory, E_0 is equal to 938 MeV (protons), E_k is the kinetic energy of the incoming proton beam (4.5 GeV), q is the electric charge and c the speed of light. The beam rigidity is calculated to be 17.85 T.m.

A Two-Bipolar Kicker Solution

General Configuration The primary proton beam is assumed to propagate along the z-axis centred onto the 4-targets/horn system; 4 angles of deflection are therefore needed to bring the protons to the axis of each target. 2 bipolar kickers would then perform this task.

The principle of such configuration is presented in Fig. 2. The kickers make an angle of ±45 degrees with respect to the central beam axis. This rotation already introduces a first angle of deflection. Therefore, according to the polarity of the magnetic field of kicker 1 (kicker 2), the proton beam is distributed diagonally to the compensating dipoles 1 or 3 (2 or 4) which deviate the beam to the corresponding target 1 or 3 (2 or 4).

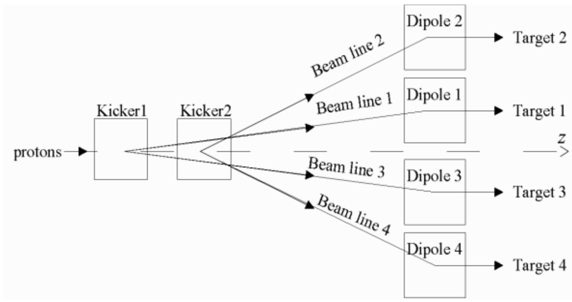

Figure 2: Beam switchyard principle.

Compensating dipoles aim at applying symmetry to the optical system and at avoiding chromaticity in the bend.

Parameters As a first approach, the distance between the kicker 1 and the compensating dipoles has been set to 15 m. For this distance, the deflection angle of the kicker is 85.45 mrad. The magnetic field, *B,* needed to deflect the proton beam is expressed as [5]:

$$B = \frac{\sin(\alpha)}{0.2998 \cdot L_{eff}} \cdot E \qquad (2)$$

where E is the energy (GeV) of the incoming proton beam, L_{eff} (m) is the effective length of the magnet (set to 1.5 m). At a distance of 15 m and at proton energy of 4.5 GeV, the kickers must induce a magnetic field of 0.86 T to deflect the beam to the axis of the compensating dipoles.

Beam Optics Simulations The code TRANSPORT [6] was used to estimate the size of the beam envelope from the kickers to the compensating dipoles travelling through the 4 beam lines. As the protons travel close to the speed of light ($\beta = \upsilon/c = 0.98$) the space-charge forces are assumed to be negligible here. Preliminary simulations showed that the radius of the beam at the horn location expands to 7 times the radius of each target. Therefore it is mandatory to focus the beam before it reaches the horn system. This is done by adding quadrupoles.

Beam Focussing

Quadrupoles (QP) have the function of focusing the beam on one plan and defocusing it on the other. In other words, more than 1 quadrupole is actually necessary to focus the beam in this present system. Several configurations were then investigated with TRANSPORT. The use of two or three quadrupoles located between the kicker and the dipole and/or between the dipole and the target were considered.

The transverse size and the emittances of the proton beam entering the switchyard are considered to be σ = 2 mm and the rms emittances $\varepsilon_x = \varepsilon_y = 3\pi$ mm.mrad (Gaussian). To simulate 3 σ (99.8% of the beam shape), the geometrical radius of the beam when entering the system is considered to be X = Y = 6 mm. The geometrical emittances become then
$(\varepsilon_{geo})_x = (\varepsilon_{geo})_y = 3\,\sigma_x \times 3\,\sigma_y = (9\,\varepsilon_{RMS})_{x,y} = 27\,\pi$.mm.mrad.
The error margin on the emittances was considered to be 20% [7] and was included in the simulations.

Different alternative layouts have been studied with TRANSPORT. The baseline configuration chosen uses three quadrupoles located after each dipole (Fig 3). The distance between kicker 1 (kicker 2) and dipoles 1-3 (dipoles 2-4) is 17 m (14.7 m). The beam focuses at 29.9 m from the kicker 1 and its dimensions (3 σ) reaches closely the values needed at this point. The quadrupoles have a reasonable magnetic length (1 m) and generate magnetic fields that are quite common to provide (Table 2).

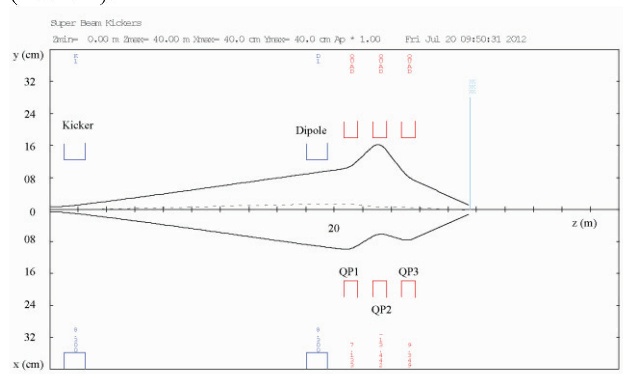

Figure 3: Transverse envelops of the beam along one beam line (horizontal plane on top, vertical plane on bottom).

To take into account 99.999% of the beam size, an extension of the standard deviation to 5 σ is necessary. In such a case, a σ of 4 mm implies the probability of having the beam being larger than the target (5 σ > 15 mm). A lower value of width should be then proposed (i.e. 2 mm) at the target. Further investigations on this will be done in the design phase.

Error Analysis

To properly design an optical system, beam and equipment parameter fluctuations must be carefully foreseen.

Magnetic fields The magnetic field generated by the kickers is one of the first parameters to be considered, as it is the key parameter in the deflection process towards the dipoles. A 1%-tolerance on this magnetic field is considered in this configuration. To prevent the beam from hitting the magnets and generate safety issues, a tolerance higher than 1% is not recommended. Moreover, 1% of the magnetic field represents 14.7 mm beam shift to the dipole, which would affect the target. Therefore a collimator placed before the targets will cut the beam halo due to these fluctuations as used in the T2K experiment [8].

Beam size As discussed earlier, the fluctuations that may vary the size of the beam were taken into account for the TRANSPORT simulations. 20% error was included in the emittances.

Energy During the distribution process, a variation in the beam energy, due to instabilities, may arise. In this case it is considered to be less than 200 MeV [7], which represents 4.5% of the total energy. Such a variation

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would introduce an asymmetry in the shape of the beam and also a fluctuation of 4.5% in the deflection angle applied by the kickers and the dipoles as is inversely proportional to the kinetic energy of the beam. It is assumed that the optical elements would be able to correct those fluctuations if necessary.

Additional Beam Instrumentation

During the experiment, the quality and the position of the beam must be controlled at several positions along the beam lines and mainly at the entrance and the exit point of the switchyard system. Beam collimation may be needed upstream the kicker 1 to cut off any eventual halo of the beam when leaving the accumulator. Any alignment tuning (steering) or remote control (position correction) might be also defined if required.

Physical Parameters and Power Supply Requirements

Characteristics of the optical elements The functional drawing of the switchyard and the distances between the optical elements are shown in Fig. 4. The radius of the whole system is estimated to be 3 m. This gives a total volume of 845 m^3.

Table 2 summarizes the physical parameters calculated for the kickers (K1, K2), dipoles (D1, D2, D3, D4) and the three quadrupoles (QP1, QP2 and QP3) for each beam line of the switchyard system. According to the high values of the intensity needed for the coils, the use of superconducting magnets can be considered here and will be investigated in further studies.

Table 2: Physical Parameters

	K1 / K2	D 1- 3 / D 2- 4
Field strength (T)	0.83 / 0.96	0.83 / 0.96
Angle of deflection (mrad)	± 83 / ± 96	-
Magnetic length (m)	1.5	1.5
Aperture H - V (mm)	250- 350 / 250- 600	250- 250 / 250- 250
Total intensity (kA)	115.6 / 152.6	82.6 / 95.4

	QP 1	QP 2	QP 3
Field gradient (T/m)	0.71	1.34	0.93
Aperture radius (mm)	180	180	180
Magnetic length (m)	1	1	1
Total intensity (kA)	20.3	38.4	26.6

Power supply requirements The power supply unit (PSU) of theses optical elements will be located in a room beside the switchyard system. The total surface needed is 180 m² (15 m long, 12 m large) and 4 m for the height. The weight of the PSU will be of 1 t/m^2. The total electrical current is estimated to have a maximum rms value of 1440 A with an average consumption of 720 A under 400 V. The power to dissipate by water is 240 kW and 50 kW using the air conditioning system [9].

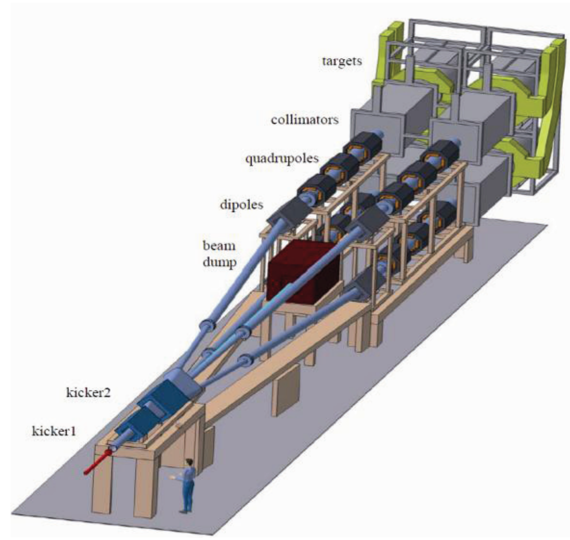

Figure 4: Beam switchyard layout.

Beam Dump A beam dump located after the pair of kickers and made of graphite and iron is necessary to stop the beam in case of kicker's dysfunction.

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