Study of the performance of the SPL-Fréjus Super Beam using a graphite target

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The simulations developed so far for the SPL-Fréjus Super Beam foresee the use of a liquid mercury-jet target in order to efficiently dissipate the heat produced by the 4 MW incoming proton beam from the HP-SPL [1]. Due to the low energy of incoming protons (4 GeV) the emission angle of secondary pions is large enough to force the use of a horn-embedded target in order to preserve a good collection efficiency. It should be noted that recent results from the MERIT collaboration [2] support the importance of a high magnetic field to mitigate the explosion of the mercury jet. This can be achieved by using superconducting solenoids for the capturing system. This solution is acceptable for the neutrino factory design but not for a Super Beam due to the lack of charge discrimination. In the current scenario the focusing system is composed of two concentric magnetic horns. Recent efforts [3–5] have then been focused on the study of a solid target option which would greatly simplify the problem of the integration of the target and the focusing system and more importantly would avoid the difficult issues related to the mercury jet handling in a magnetic field free region. The impact of using a solid target has been studied in terms of both technical aspects (the power dissipation in the target) and physics performance related aspects (pion and kaon yields, pion collection efficiency with a long target, ν fluxes and sensitivity to δ_{CP} and θ_{13}).

A graphite target was chosen since it is already an adopted technology in current experiments. As a first attempt the graphite (ρ = 1.85 g/cm^3) target was chosen to have the same radius of the previous mercury target (0.75 cm) and a length of 78 cm (instead of 30 cm for mercury) to roughly preserve the prescription of having $\sim 2\lambda_I$ of material.

The power released in the target has been estimated using FLUKA2008.3[1] and GEANT4. At 4 GeV the deposited power is $\sim$ 250 kW for the graphite target and 700 kW for the mercury one.

The evolution of absolute particle yields for different particles ($K^{\pm}$, $K^0(\bar{K}^0)$, $\pi^{\pm}$, n) has been studied as a function of $E_k(p)$ from 2 to 10 GeV with FLUKA working at constant power. The pion yield for the mercury target is reasonably stable with energy at $2.5 \cdot 10^{15}$ π^-/s and $\sim 3 \cdot 10^{15}$ π^+/s. The graphite target gives a rather flat rate of $\sim 2.5 \cdot 10^{15}$ π^-/s while the larger π^+ flux decreases from $\sim$ 4.5 to $\sim$ 3 $\cdot 10^{15}$ π^+/s at 10 GeV. The most striking difference between the two targets is the neutron yield which is about a factor $\times$ 15 larger in the case of mercury. A reduced neutron flux is highly beneficial in terms of aluminum radiation damage. At 5 GeV a structure occurs in the yields of π^- and neutrons. At this energy the matching of different inelastic hadron-nucleus production models (Glauber-Gribov multiple scattering + GINC model below and PEANUT model above) occurs. A similar structure used to be observed in kaon spectra at 3.5 GeV in FLUKA2002.4 [1].

Neutrino fluxes have been computed with GEANT3 and the standard horn for kinetic energies of 2.2, 3.5, 4.5 and 8.0 GeV for both both positive and negative focusing [4]. The obtained fluxes reflects the pion yields and thus resulting graphite fluxes are of the same order or even larger than the ones obtained with graphite depending on energy [3]. On the other hand a quite larger contamination of $\bar{\nu}$ in the neutrino beam and particularly ν in the $\bar{\nu}$ beam is observed due to the fact that with the standard horn many wrong charge pion emerging in the downstream part of the target and at low angles are not effectively defocused.

The $\sin^2 2\theta_{13}$ sensitivity curves (at 3σ C.L.) have been re-evaluated after the substitution of the standard mercury target with the graphite one. A worsening of the limit with graphite in the $\delta_{CP} < \pi$ region which is driven by $\bar{\nu}$ running (π^- focusing) has been observed. The effect was found to be related

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[1] FLUKA 2002.4 was used in previous studies

	+ focusing	- focusing
ν_μ (%)	88.9 → **95.6**	26.1 → **11.2**
$\bar{\nu}_\mu$ (%)	10.5 → **3.9**	73.4 → **88.4**
ν_e (%)	0.60 → **0.56**	0.17 → **0.09**
$\bar{\nu}_e$ (%)	0.052 → **0.025**	0.340 → **0.352**

Table 1: Standard horn → **test horn** both with a 78 cm long graphite target.

to a sizable ν_e^{CC} background with the $\bar{\nu}$ beam from cascade decays of defocused $\pi^+ \rightarrow \mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$. The same behavior is not as evident in the ν running driven region ($\delta_{CP} > \pi$) due to the combined effect of the reduced cross section of $\bar{\nu}_e$ and the fact that π^- are less abundantly produced than π^+. This consideration motivated an optimization of the horn shape in view of using a graphite target taking into account in particular the need for a reduced contamination from wrong–charge π.

The horn optimization has been performed after a full rewriting of the simulation from GEANT3 [1] to GEANT4 in order to easily change the geometrical parameters and have a quick feed-back. Two horn geometries have been implemented in GEANT4: the standard one reproducing the existing CERN prototype and a more general one based on a parametric model inspired by the shape of the MiniBOONE horn. In order to debug and validate the new GEANT4–based software, a comparison has been done with the fluxes obtained with GEANT3 using the standard horn geometry and the graphite target. Good agreement has been achieved. The parametric model is flexible enough to reproduce also the standard conical geometry with an appropriate choice of the parameters. This possibility has also been used to cross check the parametric model by comparison with the standard horn geometry.

A subset of the nine available geometrical parameters were sampled uniformly. The horn currents and the horn+reflector structure for the moment were maintained as in the original design. The resulting fluxes were analyzed and ranked according to the requirement of having low enough “wrong-CP” neutrino contamination and high flux for the signal component. More sophisticated selection techniques (i.e. based on final sensitivity on physical parameters and energy spectrum shape) and further tuning would be possible but has not yet been fully pursued.

One of the horn shapes selected with the outlined heuristic procedure has been studied in more detail (will be denoted as “test horn” in the following). The most evident modifications with respect to the previous design are the presence of a forward “end-cap” in the horn (effective in removing low–angle wrong–sign pions) and the thickness of the reflector which is larger by $\sim$ 10 cm [3]. The radius of the inner conductor is as in the previous design (3.7 cm). With the test horn the ν_μ and ν_e energy spectra are shifted to higher energies with an increase in statistics particularly around 5-600 MeV. The wrong-CP component on the other hand is reduced by more than a factor two. The beam composition for the standard and test horn is detailed in Tab.1 for positive and negative focusing.

Profiting of the relative horn ($r = 0.5$ m) and tunnel ($L = 40$ m, $r = 2$ m) compactness the idea of using a battery of four horns in parallel has been proposed. This arrangement would imply reduced stress on the targets via lower frequency (12.5 Hz) or lower proton flux depending on the injection strategy. This choice would bring the incoming beam power in the regime which is currently considered as a viable upper limit for solid targets operations ($\sim$ 1 MW). This scenario has been implemented and tested with the GEANT4 simulation. Small flux losses even up to big lateral displacements (r) are found. In the extreme case of putting the four horns at the tunnel edge ($r = r_{TUNNEL} - r_{HORN}$) the flux of ν_μ is reduced by 13% at 4.5 GeV. The baseline configuration with horns as central as possible ($r \sim r_{HORN}\sqrt{2}$) causes an almost negligible loss of ν_μ. The presence of a magnetic field in all the horns simultaneously or in each horn separately does not change significantly the predicted fluxes.

Sensitivity limits on $\sin^2 2\theta_{13}$ calculated with GLoBES 3.0.14 are shown in Fig.1 (left). The performance of the MEMPHYS Water Cherenkov detector [8] at the level of physics performance (efficiencies, background rejection, etc.) is implemented in the AEDL file `SPL.glb` which is distributed with GLoBES [7]. A mass of 0.44 Mton and a data taking of 8+2 years $\bar{\nu}$+ν-running has been assumed. The dashed curves refer to the standard horn design in combination with the graphite target while the continuous ones refer to the test horn. A significant improvement is observed in the $\bar{\nu}$ running driven region as wanted. The graphite limits after the horn upgrade are in general even better performing than those obtained with the standard liquid mercury design [3]. It must be noted that this result is still to be considered as preliminary since the NC-π^0 background has not yet been corrected for the change in the neutrino energy spectrum. This correction anyway will not alter the conclusions of this study since the bulk of the background is coming from the intrinsic ν_e+$\bar{\nu}_e$ beam contamination which has been exactly taken into account. Increasing the background by 30% induces a worsening in the limit which is $\lesssim$ $1{\cdot}10^{-4}$ (mainly in the $\bar{\nu}$ driven δ region). The CP violation discovery potential is shown in Fig.1 (right). Parameter regions for which a $\Delta\chi^2 > 9$ is obtained when fitting under the CP conserving hypotheses ($\delta_{CP} = 0, \pi$) allow the CPV discovery at more than 3σ. Also in this case a sizable improvement is obtained (lowest $\sin^2 2\theta_{13}$ passes from $\sim 8\cdot 10^{-4}$ to $\sim 5\cdot 10^{-4}$). It can be noticed than in general the 3.5 GeV and 4.5 GeV energies are still the preferred ones also within the test focusing.

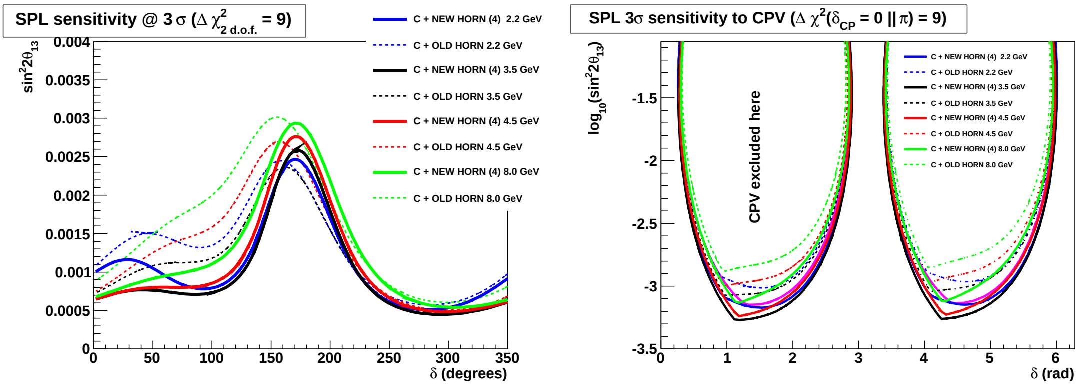

Fig. 1: The standard (dashed) and the test horn (continuous) are compared (both with the graphite target). Left: 3σ sensitivity to $\sin^2 2\theta_{13}$ vs δ. Right: regions for CP violation discovery at 3 σ.

In summary the possibility to use a solid target looks very appealing for the SPL-Fréjus Super Beam. Further steps which are in progress include the use of the HARP experiment “thick target” data to put the results on pion yields in graphite on a stronger experimental basis.

References

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