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Detector Geometry Simulation Using GEANT4

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Abstract: Neutrino oscillation is an important phenomenon to explain the massive nature of neutrinos. This quantum mechanical phenomenon can be understood as mixing in quark sector just like the one we have in lepton sector. Observed deficit of solar neutrino flux is explained through neutrino oscillations and this study is the only way to investigate for small difference of neutrino masses thus gives signatures for the physics beyond Standard Model. Experimental results by Superkamiokande put a huge interest of experimentalists in neutrino field. In the present article after discussing the theoretical background of neutrinos and their status in standard model, latest important long baseline neutrino oscillations experiments as NOvA and LBNE has been discussed. Straw Tube Detector, an important part of LBNE-near detector, has been reviewed the geometry of which is studied through a software Geometry and Tracking (Geant4). Using Geant4, an important aspect of detector geometry and simulation has been studied.

Keywords: Straw-tubes Phenomenology with Geant4 geometry

1. INTRODUCTION

Neutrinos are neutral elementary particles thus interacting only through weak forces and categorized as fermion. Neutrinos came into picture when conservation of energy and angular momentum in beta decay was in danger. So, to conserve these two Wolfgang Pauli postulated a new particle which takes away missing energy silently and that particle was named neutrino by Enrico Fermi. Neutrinos are produced through many different ways and thus depending upon their mode of production neutrinos are named as - Solar neutrinos (one produce inside the Sun), Atmospheric neutrinos (through cosmic rays), Reactor neutrinos (through nuclear reactions), and Beam neutrinos. Existence of neutrinos was first confirmed by Cowan and Reines. Later, to conserve lepton number different neutrino flavors corresponding to each lepton flavor came into existence – electron, muon and tau neutrino.

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Table 1: Sensitivity to $Sin^2\theta_{13}$ is tabulated for various Reactor based experiments.

Experiments	$sin^2\theta_{13}$ Sensitivity
Double Chooz	0.03
RENU	0.02
Daya Bay	0.01
T2K	0.06
MINOS	0.08

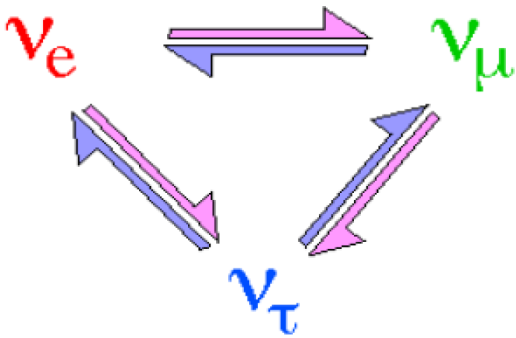

Figure 1: Pictorial representation of neutrino oscillations.

Each neutrino flavor is associated with its anti-particle and the difference between these two lies in helicity. As per Standard Model, neutrinos are considered to be massless but later studies and experiments proved the massive nature of neutrinos and this is one of the reasons that physicists go beyond Standard Model. The phenomenon through which we came to know about neutrinos massive nature is the Neutrino Oscillation suggested by Bruno Pontecorvo in which neutrino with definite flavor is found to be the mixture of different flavor states after travelling certain distance which arises due to the mixture of flavor and mass eigenstates of neutrinos. The mixing between these two states is represented by unitary mixing matrix known as Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS). Exact mass of the neutrino species is not known to us but experiments have given the values of mass squared difference between three mass eigenstates.

PMNS matrix is characterized by three mixing angles and one phase. Out of these angles associated with Solar (θ_{12}) and atmospheric (θ_{23}) neutrino oscillation have been measured well experimentally but not the value of θ_{13} which describes the magnitude of overlap between ν_3 and ν_e. If this angle is zero then there will be no CP-violation but as CP-violation is necessary to

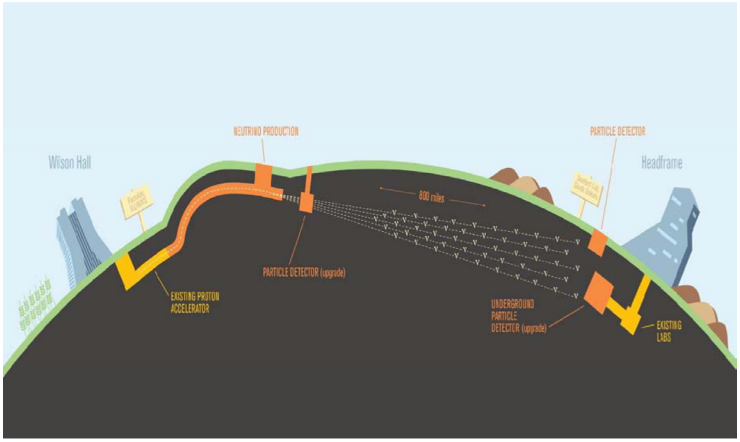

Figure 2: Schematics of LBNE baseline (near and far detector).

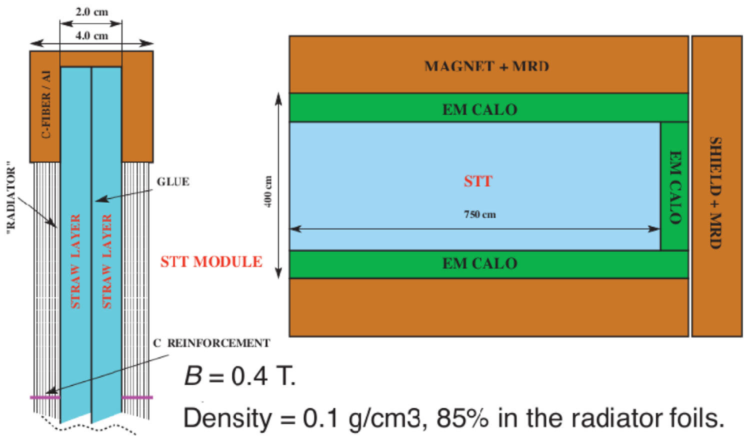

Figure 3: Schematics of HIRESMNU (near detector).

explain the matter-antimatter asymmetry in the Universe so this demands the angle to be non-zero. Many experiments have provided some constraints on the value of θ_{13}. In the table given below, sensitivity to $\mathrm{Sin}^2\theta_{13}$ is shown for various Reactors (Daya Bay, Double Chooz, RENU) and Accelerator (T2K, MINOS) experiments.

1.1 Experiments for the study of neutrino oscillation

In addition to above mentioned experiments, to improve the sensitivity, physicists are looking for more experiments as NuMI off-axis neutrino (electron neutrino)

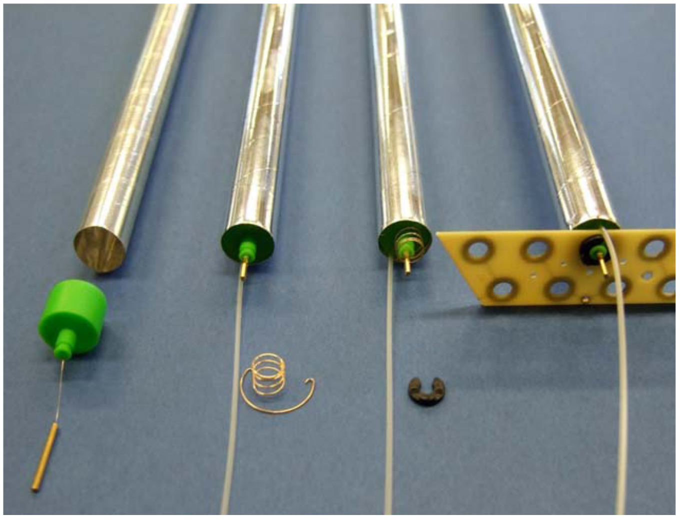

Figure 4: Pictures of STT modules and preparation steps.

appearance **(NOvA)** and Long Baseline Neutrino Experiment (**LBNE**). These experiments are considered to be more sensitive than the others. NOvA is a particle physics experiment which will study the appearance of electron neutrino starting from a beam of muon neutrino and hopes to accomplish three things: measurement of mixing angle θ_{13}, measurement of CP-violating phase $\delta$and determination of neutrino mass hierarchy. The baseline length is 810 km and neutrino will travel this distance in less than three milli-seconds.

1.2 LBNE (Long Baseline Neutrino Experiment)

This experiment is being designed primarily to explore the neutrino oscillation parameters. With a proposed baseline of 1300 km the experiment will be especially capable in searching for CP violation and determining the neutrino mass hierarchy. It is critical to determine the experimental requirements in terms of physics goals of sensitivity to CP violation, mass hierarchy and θ_{13} in a muon neutrino to an electron neutrino analysis. LBNE uses near and far detector for measuring neutrino fluxes and to study neutrino oscillations. Near Detector uses the concept of HIRESMNU (High Resolution Neutrino Experiment in Magnetic field) in which it is proposed to use Straw Tube Detector.

LBNE plans to use straw tube based fine grained tracker .The FGT has excellent position and angular resolutions due to its lower-density ($\sim$ 0.1 g/cm^2) and high-precision Straw tube tracker. This high resolution is important for determining the neutrino whether the neutrino interaction occurs in the water or argon target. The proposed 2.5×2.5×4m^3 tracker will be positioned inside a dipole magnet with magnetic field, B = 0.4T for particle tracking. The nominal fiducial volume corresponds to 2.5 tons of mass.

1.3 Straw Tube Detector

Straw Tube Detector or Straw Tube Tracker (STT) uses straw tubes as basic detector element Straws are gas-filled cylindrical tubes with a conductive inner layer as cathode and an anode wire stretched along the cylinder axis. An electric field between the wire and the outer conductor separates electrons and positive ions produced by a charged particle along its trajectory through the gas volume. Usually the wire is on positive voltage of a few kV and collects the electrons while the ions drift to the cathode. By choosing thin wires, with a diameter of few tens of μm, the electric field strength near the wire is high enough to start further gas ionizations by electron collisions with gas molecules. Tasks of Straw tube detector is the precise spatial reconstruction of particles in a broad momentum range, the measurement of particle momentum by the reconstructed trajectory and measurement of specific energy loss (dE/dx) for particle identification (PID).

1.4 GEANT4 (Software Work done)

Geant4 stands for geometry and tracking 4. It is software package i.e. a detector simulation toolkit based on Monte Carlo Method, which is used to simulate the passage of particles through the matter. Geant4 uses three mandatory classes which the user must have to define –

- G4VDetectorConstruction,
- G4VPhysicsList
- G4VPrimaryGeneratorAction

In addition to these, many optional classes are there which can be included as per need –

- G4UserEventAction
- G4UserRunAction
- G4UserSteppingAction
- G4UserTrackingAction.

Above all these, there is a class G4RunManager which controls the flow of program and manages the event loop within a run. It manages the procedure of run. All of user initialization classes and user action classes defined by the user should be assigned to G4RunManager before starting initialization of the Geant4 kernel. Through the run manager all the information must be given which is necessary to build and run the simulation including the information that

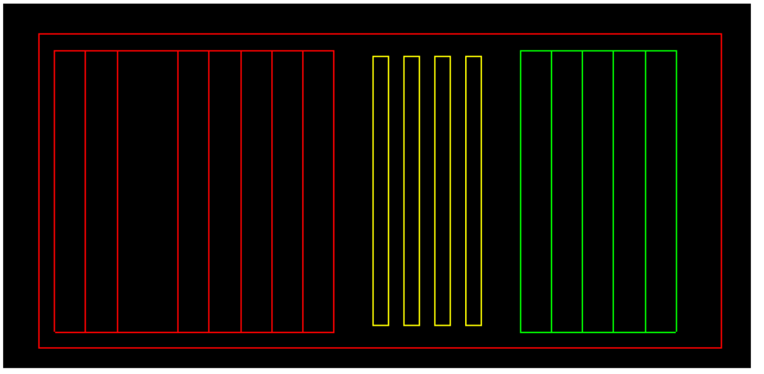

Figure 5(a)

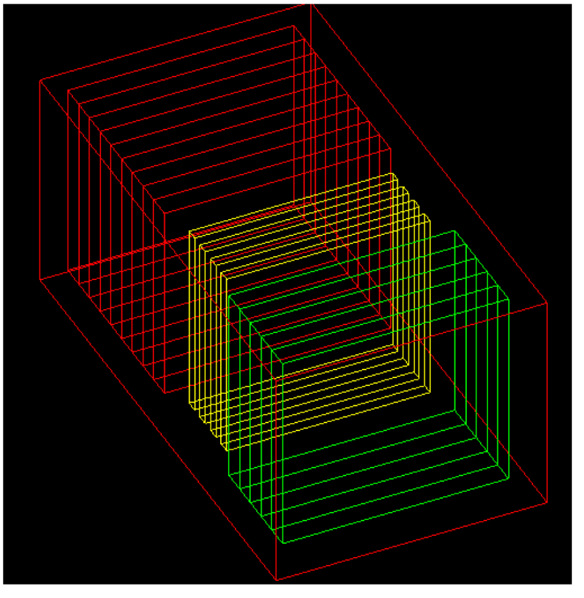

Figure 5(b)

- How the detector should be constructed,
- If all the particles and all the physics processes to be simulated or not,
- How the primary particles in an event should be produced and
- Any additional requirements of the simulation.

Every initialization needed by the Geant4 kernel is triggered by Initialize() method in run manager. Various geometries are constructed using geant4. Using Geant4, one can visualize detector components, particle trajectories,

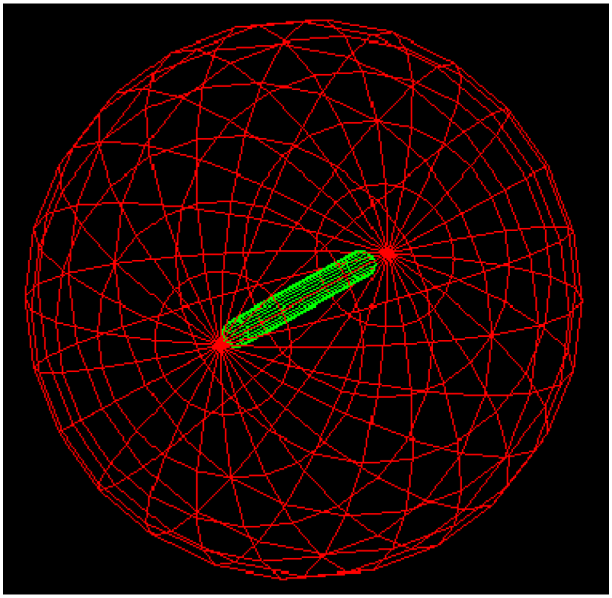

Figure 6:

hits, texts etc. and there are varieties of requirements for this to which Geant4 is able to respond but is difficult with only one built-in visualizer. So, Geant4 supports an abstract interface to many kinds of graphics systems. Visualization procedures are controlled by the "Visualization Manager" described under the class G4VisManager. Below some geometry are constructed and viewed through this software.

Fig. 5(a) shows the placement of layer of boxes inside a box where former is called as daughter volume and latter is the mother volume. Fig. 5(b) shows the same geometry but through different angle. Fig. 6 is the placement of a cylindrical tube inside a sphere. Fig. 7(a) is the polyclone and Fig. 7(b) is the same with different viewpoint.

Using Geant4, geometry of straw tubes has been constructed. Above in Fig.8 (a) and (b), single and replica of straw tube is shown. Here, pink colored cylindrical tube is made up of Aluminium and it will act as a cathode and inside it red colored structure is wire made up of tungsten and will act as anode. End-caps are green colored and made up of thermoplastic. These are some simple geometry which can be constructed using Geant4. In addition to constructing geometries, various physics processes can also be studied. In Fig. 9(a), light green colored cylindrical structure is the tracker tube filled with Argon gas and the red colored box is calorimeter block made of lead which has 19 layers of Aluminium plates inside and the whole

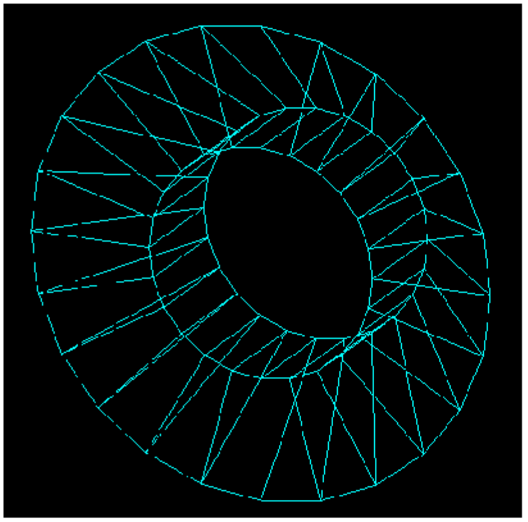

Figure 7(a)

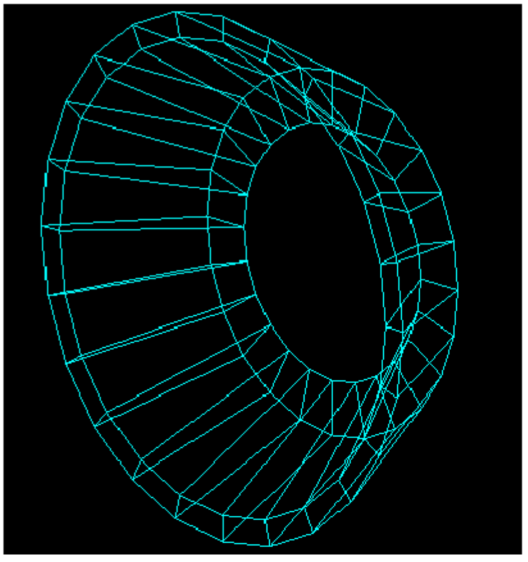

Figure 7(b)

setup is placed in the experimental hall filled with Argon gas and it is a box. Below Fig. 9(a) shows neutral particle going straight without suffering any interactions and only physics process studied is transportation and Fig. 9(b) is the electromagnetic shower studied using the same geometry. So, using geant4 complete simulation study can be done.

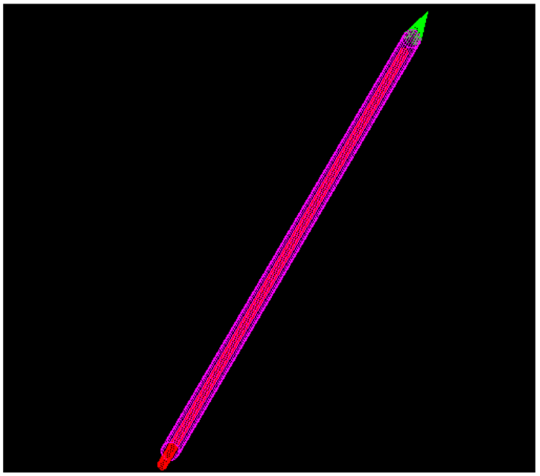

Figure 8(a)

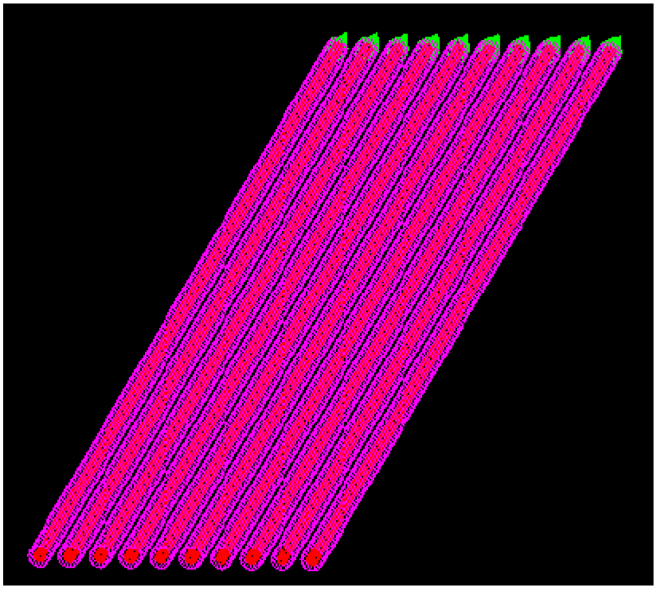

Figure 8(b)

1.5 Hardware work done with straws and wire (as anode) used in STT

1.5.1 Straw Fabrication

Fabrication of straws using ordinary plastic sheet and a glass tube, of a certain diameter (8mm to 1 cm) is shown in figure 10 (a & b) . Plastic cap is used as

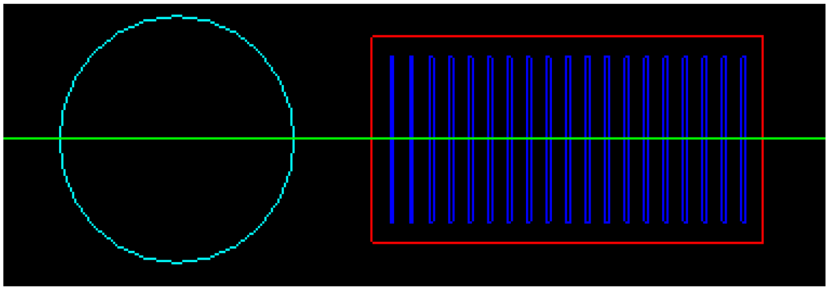

Figure 9(a)

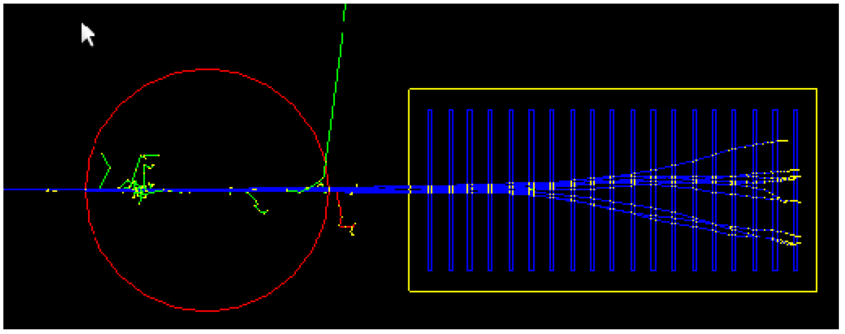

Figure 9(b)

end plug on one side. 20 micron wire is inserted in the straw with the help of needle.

1.6 Tension measurement of a wire used as anode in STT

Experimental setup to measure the tension a wire can hold is shown in fig.6. Wire used is 20 micron Gold Plated Tungsten having density 19.22 g/cc and specific resistance of the wire is 0.092Ω-mm2/m. Experiment has been performed in our lab to measure the maximum tension the wire can hold.

The principle behind the experiment is when a current is passed through a conductor in a direction perpendicular to that of magnetic field, the conductor experiences a force

$$F = BIL.$$

Where, B is magnetic field, I is current, L is length of the conductor. The wire was stretched across the two ends of the sonometer board and masses of the order of grams were hanged. Resonant frequencies were observed for a particular mass and the masses were increased gradually.

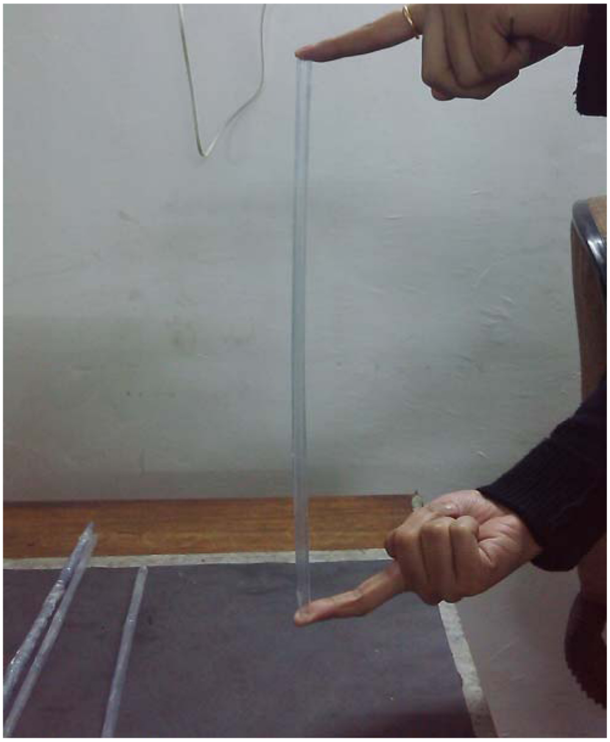

Figure 10(a): Fabrication of Straws (as a practice).

Figure 10(b): Fabrication of Straws (as a practice).

From this experiment we came to know that the wire we used can support a mass of approximate 60 g and below table shows the experimental observations.

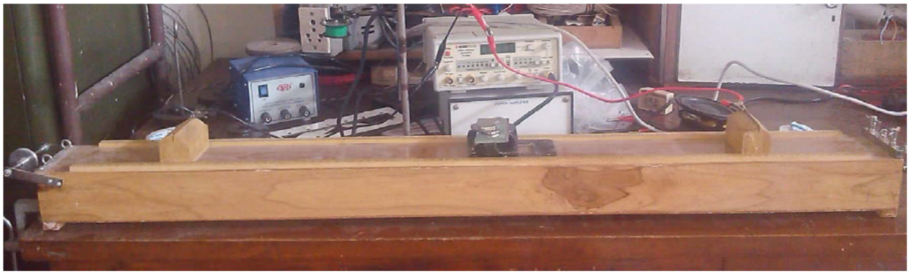

Figure 11: Experimental Setup for testing of STT.

Table I (Observations)

Mass (g)	I Harmonic (Hz)	II Harmonic (Hz)	III Harmonic (Hz)
20	124	250	376
30	145	299	450
40	162	326	491
50	188	372	559
60	204	411	614

These observations are also checked theoretically using the formula

$$f = 1/2l \sqrt{T/ml} = 1/2l \sqrt{T/(\varpi r2dlw/lw)}.$$

Where ml is mass per unit length, lw is length between two bridges and T is the tension in g-cm/sec^2.

$$f = 1/2rl \sqrt{T/\varpi d} = 0.56/2rl \sqrt{T/d}$$

$$f = 0.56/2rl \sqrt{(1000\ gm)/d}$$

$$f = 17.67/2rl \sqrt{m/d}\ Hz$$

Using radius (r) = 10 micron = 10 e^{-3} cm, density (d) = 19.22 g/cc, length (l) = 75 cm f = 26.84 $\sqrt{m}$ Hz.

Thus, experimentally observed values are in accordance with the theoretically calculated values.

2. SUMMARY

Geant4 is a complete and very useful simulation toolkit i.e. it simulates the passage of particles through matter. It provides a complete set of tools for all domains of radiation transport:

Table II

Mass (g)	Frequency
20	120
30	147
40	169
50	189
60	204

- Geometry and tracking
- Physics processes and models
- Graphics and user interfaces
- Propagation in fields

Geant4 physics processes describe electromagnetic and nuclear interactions of particles with matter at energies from eV to TeV. It provides a powerful tool to do full three flavor analyses of future long baseline experiments. Not only this in collider experiments and in many other fields this simulation toolkit can be used.

Straw tube geometry has been constructed and various physics processes which it can undergo can be studied. In addition to this, a simple straw tube using ordinary plastic sheet has been manufactured in our lab and tension of the wire (used as an anode) has been measured to minimize the gravitational sag. Using this concept a technique can be developed to measure tension of the wire inside the straw tube. There should be more R and D for a large scale application of this technique in areas of manufacturing of straw tubes and also for measuring tension in multi-wires collectively.

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