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Simulation of target particles emission for Neutrino Factory using FLUKA

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The goal of the Neutrino factory project [1] is to design an intense neutrino source. The first stage of the neutrino production is the production of pions by hitting a mercury target with a 4 MW proton beam. This papers presents target simulations performed with FLUKA, a hadronic cascade code. The main objective of theses simulations is to optimize the target parameters (geometry, incident protons energy) considering particle production efficiency and radioprotection issues.

1 – Introduction to FLUKA

FLUKA is a hadronic cascade simulation code: from initial parameters (geometry and beam) it computes every interaction with materials, particles production and trajectories. A built-in library (updated yearly), which comprises experimental results and theoretical cross sections, is used to deal with all possible interactions between particles and materials.

2 – Set-up

The FLUKA procedure consists in modeling the geometry of the problem by combination of simple elements (cylinders, boxes, spheres…) to which we assign materials. Then the user defines the beam parameters (particle type, emission location, direction and energy), and virtual detectors to view the results of the run, where we can score the number of crossing particles, their types and their energy, and the deposited energy.

The target is a liquid mercury jet placed in a 20 T magnetic field. In FLUKA it is modeled by a mercury cylinder (diameter 1.5 cm, length 30 cm, density 13.456 g/cm^3). To avoid pion absorption in the target, it has a 100 mrad angle with the magnetic field. The proton beam (pencil beam, monoenergetic) is parallel to the target. The solenoid is modeled with a 30 cm thick copper ring with an internal diameter of 15 cm.

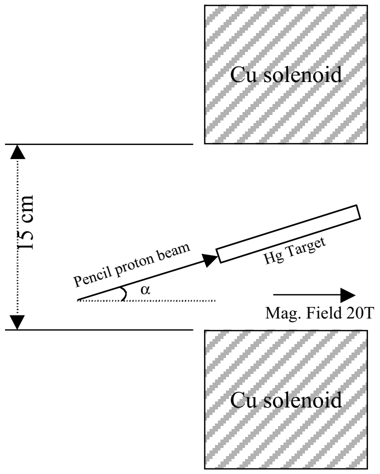

Fig. 1 – Simulated geometry

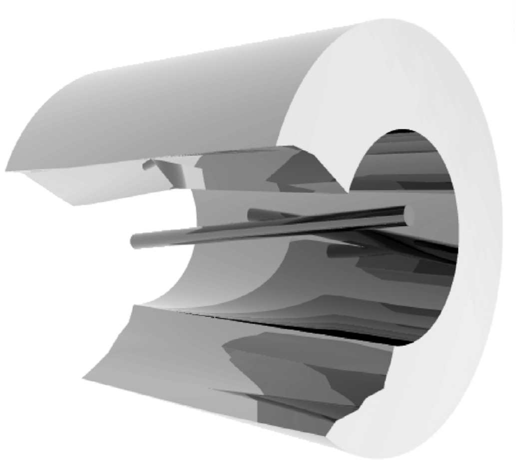

Fig. 2 – 3D view of the simulated geometry

3 – Particle production

The goal of this chapter is to evaluate the best incident proton energy, taking into consideration the production rate (the number of produced pions per proton) and secondary particles. We must also take into consideration the pion energy spectrum: with higher incident proton energy, the pions are distributed in a larger energy spectrum and the proportion of captured pions decreases. In actual design, the phase rotation system can only capture pions within a limited energy range of 100 MeV-300 MeV [2]. As this design can still be subject to modifications, we will consider that “interesting” pions have their energy between 80 MeV and 450 MeV. The following curve represents the result of 15 dedicated runs at different energies ranging from 1.5 GeV to 32 GeV, where the pion production efficiency is the number of produced positive pions per incident proton and per GeV of kinetic energy of theses protons. This indicates the “energy price” of the pions. Note that the particles energy values in this report are for kinetic energy.

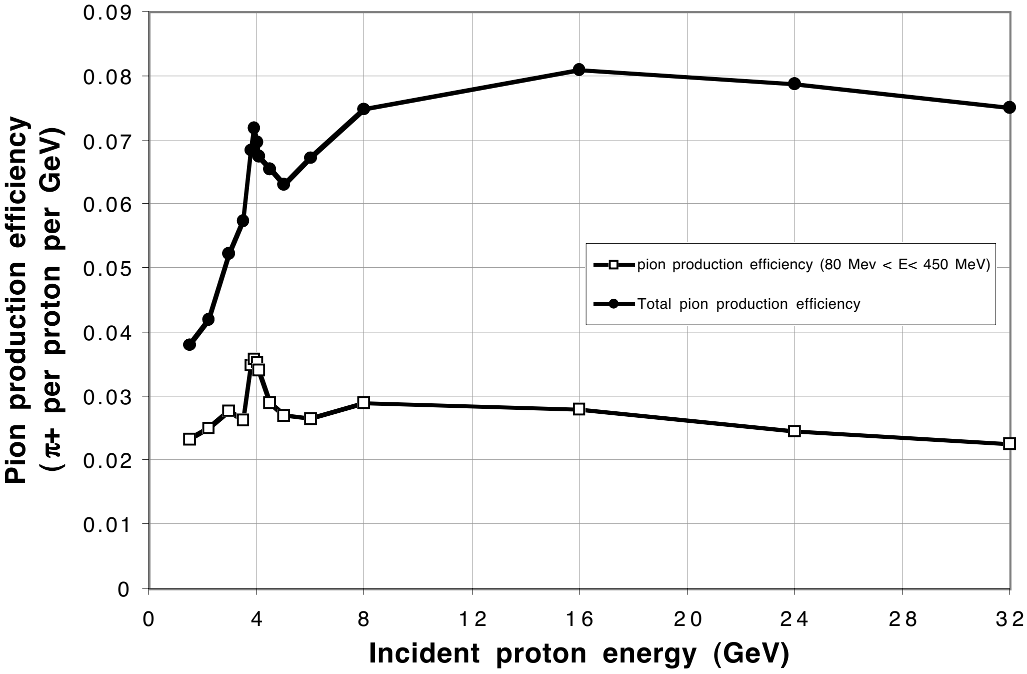

fig. 3 – Pion production efficiency vs incident proton kinetic energy

On this graph we can see that if the total pion production slightly increases with the energy; the production efficiency of captured pions ranges from 0.025 to 0.035 π per proton per GeV. The energy price of pions is almost constant, regardless the proton energy. We can notice a production peak at 3.9 GeV, which takes its origin in the theoretical model used by the FLUKA code. As there is no available experimental data for this reaction, we cannot be sure that this production increase is real. This point will be checked with the HARP experiment [3].

To choose the energy, we have to take into consideration the production of other particles. The following table gives the number of particles emitted in the forward direction. Two sets of data are reported, assuming a proton beam energy of 2.2 GeV (CERN SPL) and 16 GeV (FNAL) [4].

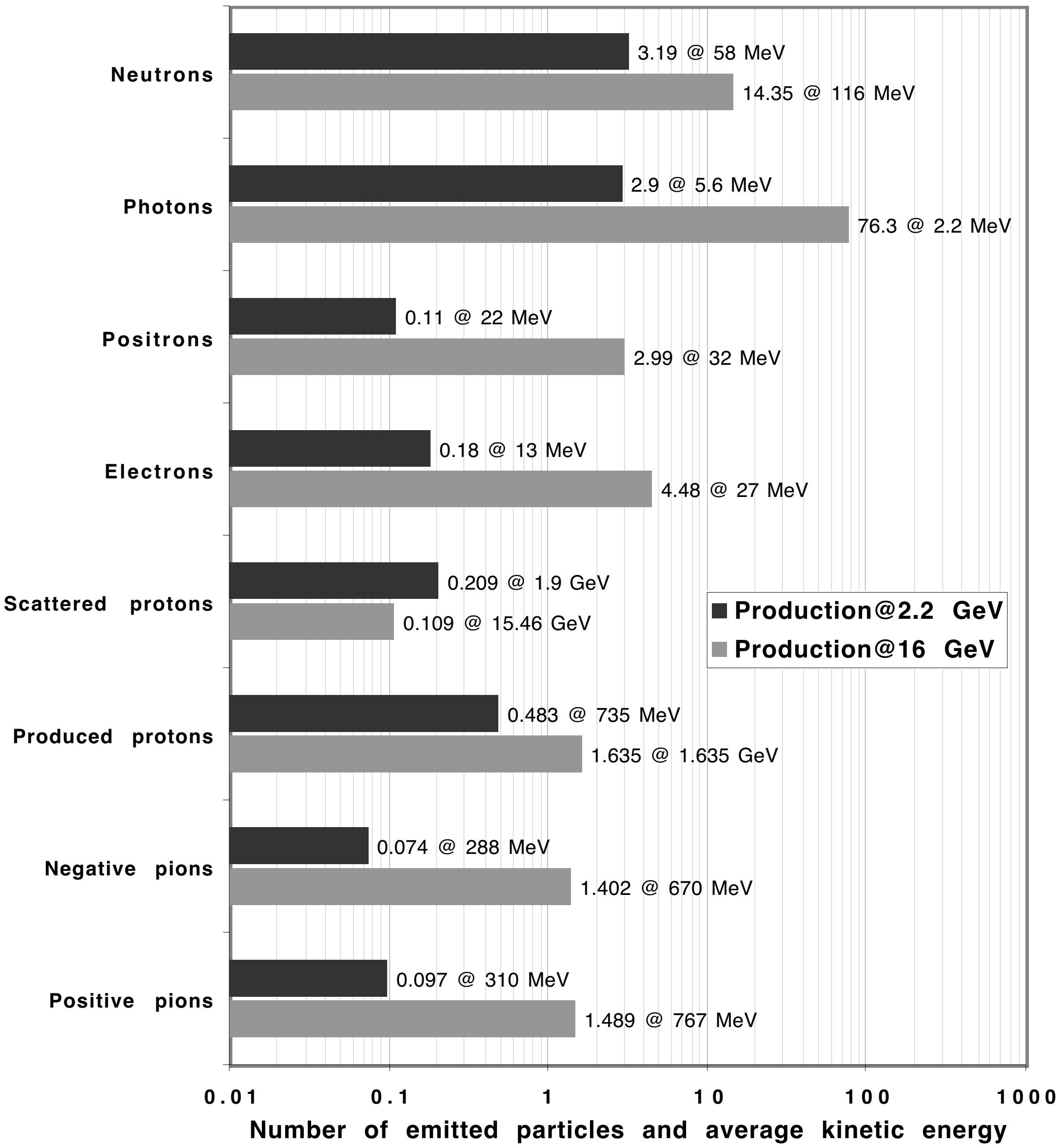

fig. 4 – Produced particles for 2.2 GeV and 16 GeV proton beam

Scattered protons are incident protons, which cross the target with only elastic collisions. Their emission cone is smaller and the average energy is higher than those of produced protons. With a 2.2 GeV proton beam (CERN SPL), one megawatt on the target would produce each second 7.10 x 10^7 "interesting" pions, plus 1.4 x 10^9 other charged particles in the capture system. With a 16 GeV beam (FNAL), the same power on the target would produce each second 8.23 x 10^7 "interesting" pions, but it would also send 2.04 x 10^9 other charged particles, with higher energies. The total number of protons is constant, but their average kinetic energy would be twice more. This indicates that for similar performance, a 16 GeV proton beam system would induce a more complex capture system (it would have to eliminate more particles) and more radioprotection problems than a 2.2 GeV proton beam system.

4 – Produced pions with a 2.2 GeV beam

The CERN neutrino factory reference design assumes that the pions are produced by a 2.2 GeV proton beam on a mercury target. The three following graphs (fig. 5, 6 and 7) give the characteristics of the produced pions.

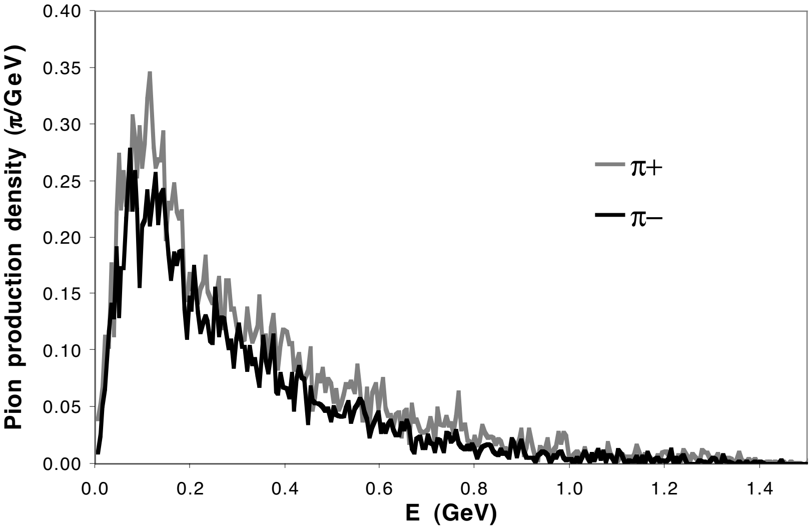

fig. 5 – Pion kinetic energy spectrum for a 2.2 GeV proton beam

We can note that the production rate is higher for positive pions than for negative pions, and that the energy distribution is similar.

To score the angular repartition of produced pions, a virtual detector is put in the solenoid, at one meter from the target, and the average positive pions flux is scored. The two following figures (6 and 7) represent the results scored by this detector.

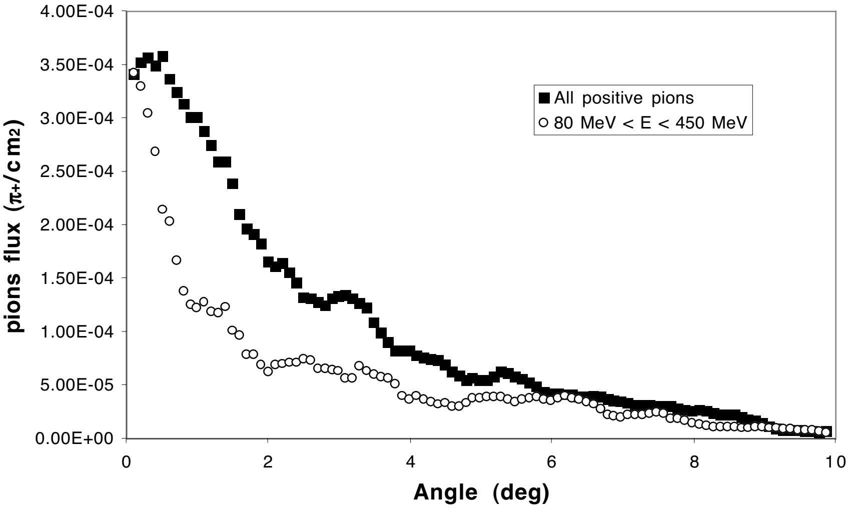

fig. 6 – Pions radial distribution at 1m of target (values for 1 incident proton on the target)

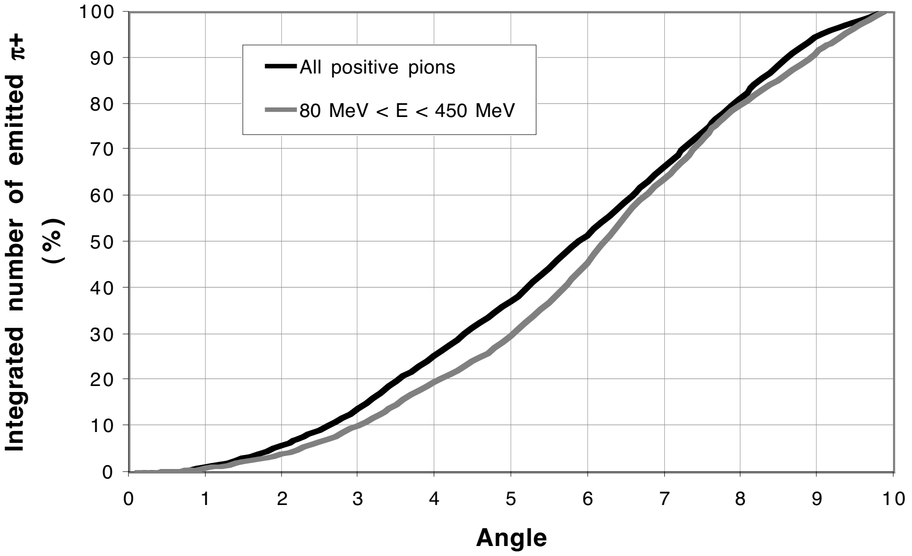

fig. 7 – Integrated number of pions vs angle (values normalized for one incident proton on target)

The pion flux is higher in a 2° cone in the magnetic field axis, but it only represents 5% of the total of emitted pions.

5 – Radioprotection issues

We are here interested in the energy deposition in the solenoid, which can generate magnet damages and material activations. A specific FLUKA geometry with the whole solenoid has been designed, and the magnetic field is fully simulated as described in [5]: its value ranges from 20 T (target) to 1.25 T (end of solenoid). The calculations are performed using copper as solenoid material. The energy deposition (neutron and electromagnetic) and the neutron flux are scored. The neutral particles (neutrons and photons) are emitted isotropically. The following table and graph (fig. 8) summarizes the results of this run.

Parameter	Value
Max. neutron flux in the solenoid	$3.18\ 10^{14}$ n/cm^2/s
Max. neutron dose in the solenoid	7 kGy/s
Max. γ dose in the solenoid	1.4 kGy/s

Table 1 – Radioprotection parameters for the solenoid

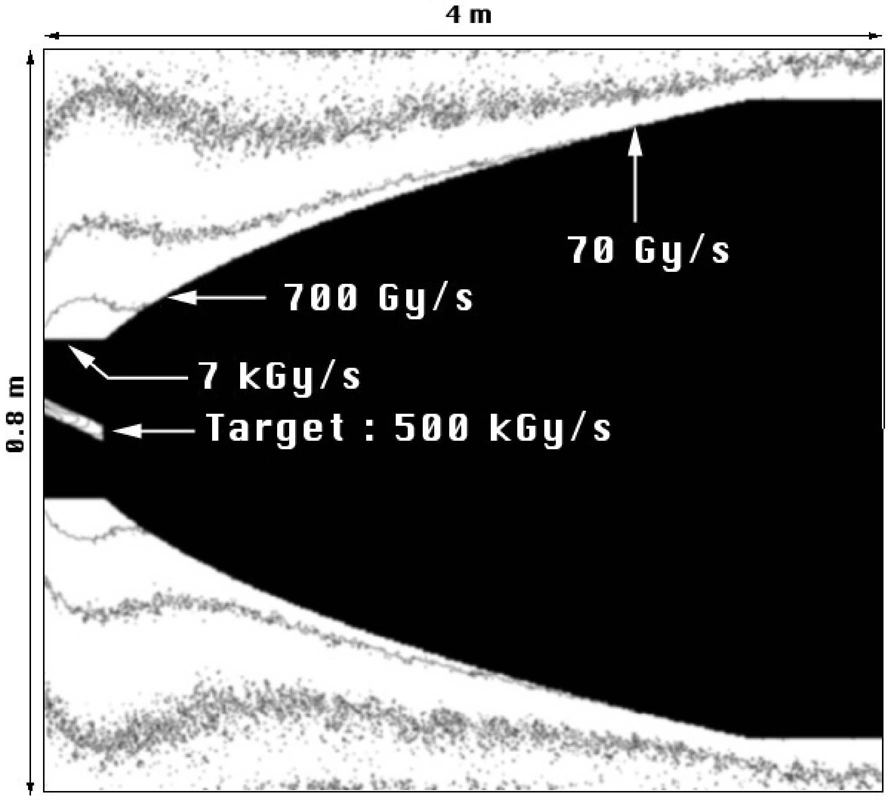

fig. 8 – Deposited neutron dose in the solenoid with a 2.2 GeV proton beam. The scale is logarithmic: there is a factor of 10 between each zone.

6 - Conclusion and comments

According to these results the pion production fits the expected machine parameters, and the target efficiency seems to be only slightly dependant from the proton beam energy, so it should be more interesting to work at low energy to limit radioprotection problems. The production peak at 4 GeV could be interesting if it appears to be experimentally verified by HARP.

The pion production efficiency values given in this report must be considered as a first approximation: the proton-mercury interaction is still experimentally undocumented. This lack of data should be solved with the HARP experiment.

References

1. H. Haseroth, Status of studies for a neutrino factory at CERN, CERN NUFACT-note 29 (July 2000)
2. B. Autin, J-P. Delahaye, R. Garoby, H. Haseroth, K. Hübner, C.D. Johnson, E. Keil, A. Lombardi, H. Ravn, H, Schönauer and A.Blondel, The CERN Neutrino Factory Working Group Status Report and Work Plan, CERN NUFACT-note 28 (August 2000)
3. http://harp.web.cern.ch/harp/
4. Norbert Holtkamp and David Finley (editors), A feasibility study of a neutrino source based on a muon storage ring (FNAL, May 2000)
5. Pion yield vs. geometry of target and 20 T pulse solenoid for a muon collider experiment, R.J. Weggel (BNL) and N.V. Mokhov (FNAL)