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# GEANT4 Simulation of Phase Rotation for Neutrino Factory

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**Abstract**

We discuss a GEANT4 simulation of the phase rotation system for a neutrino factory. The comparison with the beam transport code PATH shows a good agreement. Preliminary result for the energy deposition in the cryostat of the superconducting 1.8 T solenoid is briefly presented.

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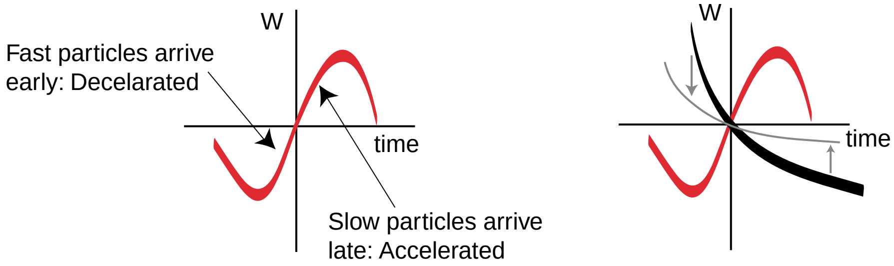

Figure 1: *This sketch shows the principle of how the phase rotation works. Since muons in the energy window considered are not ultra-relativistic, an energy spread corresponds to a velocity spread. More energetic muons arrive early at the RF section and they are decelerated while low energetic muons arrive late at the RF and they are accelerated.*

# 1 Brief description of simulation program

The phase rotation is the section of the neutrino factory whose aim is to reduce the muon energy spread by a factor of two. Muons coming from pion decay are spreaded in a kinetic energy interval between 1 GeV down to few MeV, while the interesting muons are the one around 200 MeV. One desires to capture particles in a energy acceptance of 200 ± 100 MeV and reduce the energy spread to ±50 MeV. This is possible using a set of 21 RF (Radio Frequency) cavities that slows down high energy particles and accelerate low energy particles. This process is shown in figure 1.

## 1.1 Geometry and materials

A GEANT4 world physical volume of cylindrical shape (G4Tube) with the length of 29.4 m and the radius of 1.3 m consists of 21 RF. One 44 MHz RF cavity at 2 MV/m is 1.4 m long and the geometry is taken from [2](see figure 2). The fieldmap of the solenoid surrounding one RF was generated by POISSON [5]. The field was normalised to have the same focusing power as for an hard edge solenoid of 2 Tesla and 1 meter long (see figure 3 for the un-normalised field distribution).

The world volume was filled with air of the following contents (here and below we use weight concentrations) $0.7537N + 0.2315O + 0.0128Ar$ at a pressure of $10^{-8}$ atm. The pressure roughly corresponds to technical vacuum that can be provided for big hermetical volumes. Each sections consists of stainless steel cover $(0.73Fe + 0.16Cr + 0.09Ni)$ surrounding a cryostat filled with liquid helium. Inside the liquid helium a superconducting niobium solenoid generates the field of figure 3. For providing better program performance all section parts were described by cylinders (G4Tube). A small gap of 1 micron was provided for touching surfaces.

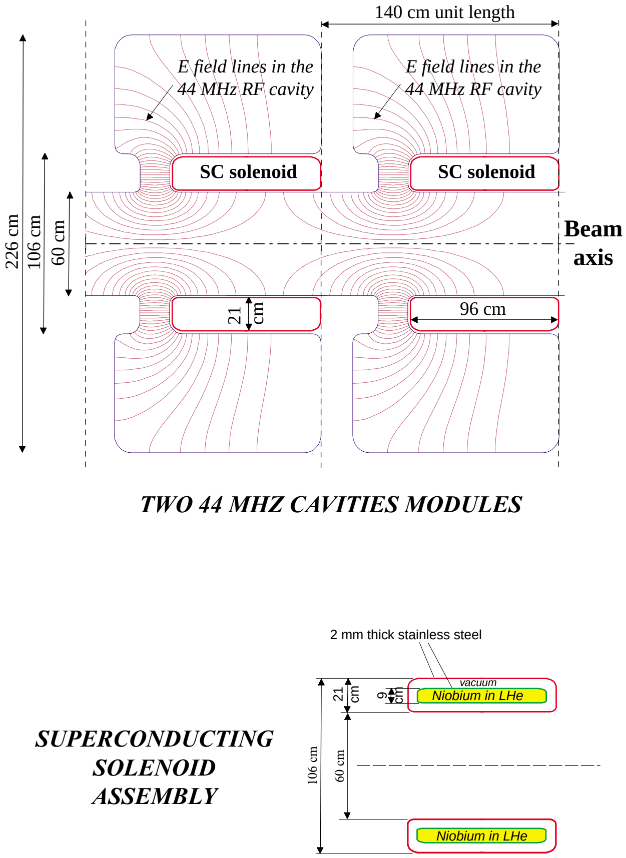

Figure 2: *Cavity design from [2]. This geometry is described “as it is” in the* Geant4 *simulation.*

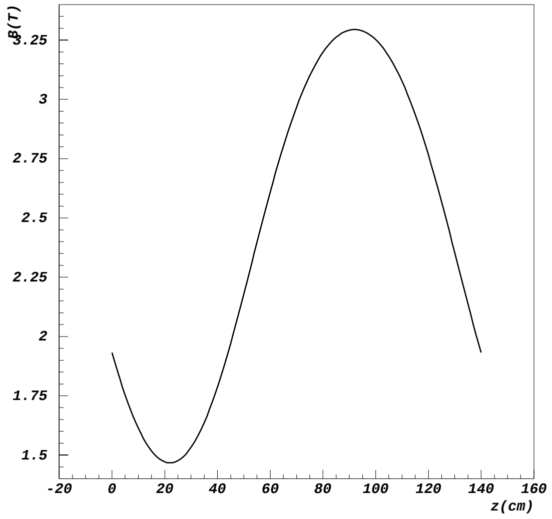

Figure 3: *Un-normalised longitudinal magnetic field component for along the beam axis of one RF cavity.*

## 1.2 Interactions of particles with materials

The geometry was irradiated by a flux of positive muons selected in a kinetic energy interval between 100 and 300 MeV. The incoming particle spectra were calculated by a MARS [4] simulation that includes pion production, pion focusing and decay. The muons interact with matter by ionization energy loss, bremsstrahlung and pair creation. In addition they experience multiple scattering.

Secondary electrons experience ionization energy loss, bremsstrahlung and multiple scattering. Secondary X-ray and gamma quanta experience photoabsorption, Compton scattering and conversion.

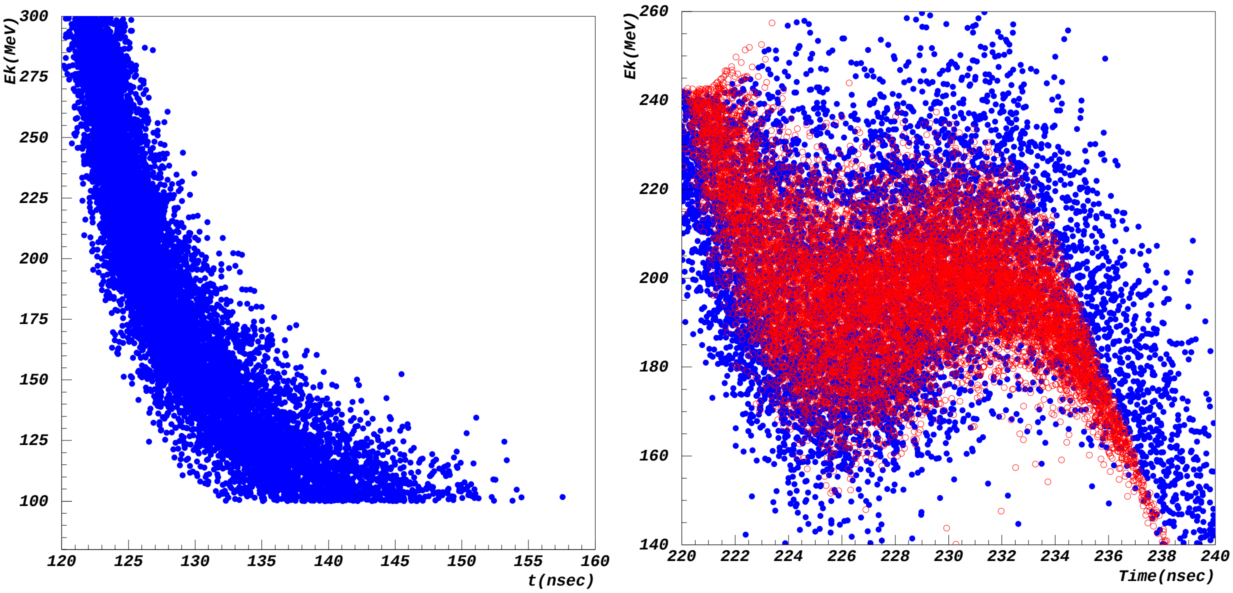

Figure 4: *Longitudinal phase space for muons produced by pion decay channel (right) at the beginning of the phase rotation. The left figure shows the* Geant4 *simulation (full dots, blue), and* PATH *(open dots, red) after the phase rotation.*

# 2 Results of simulation

The Geant4 simulation was compared to a PATH [7] simulation of the phase rotation reference scheme [6] to validate the RF implementation in Geant4 . Table 1 shows the nice agreement between the two simulations for transmission coefficients, while a small difference, discussed in the following, could be noticed in the longitudinal plane (figure 4).

| | Input | Transmission | In cut |
|---|---|---|---|
| PATH | 15222 | 100% | 77% |
| GEANT4 | 10436 | 94% | 79% |

Table 1: *Particles "In cut" are calculated as the percent of the input muons selected in a window defined by 140 MeV<* $E_{kinetic}$ *<260 MeV and in one RF period of 44 MHz.*

The two distributions of figure 4 differ for the tail due to the following reasons:

- in the GEANT4 simulation the phase of the reference particle is chosen by injecting a 200 MeV muon in the center of the beam line. The arrival time of this particle at the different RF fixes the synchronous phase. This procedure is good enough only in first approximation, while codes like PATH calculate the average particle before each RF. The average particle takes into account the evolution of the whole bunch in the channel, which is ignored by a single particle approach. To improve the GEANT4 RF implementation, one could imagine to use the GEANT4 stack facility. All the muons could be tracked just before one RF where the particles are stored into the stack. Once all the particles reach the RF, the average muon is evaluated and then the tracking restarts until the next RF, where this process is repeated[2].
- the particles used for the two simulation are not the same, but the average quantities like spot size, time and energy distribution are the same.
- the RF length was 1 m for the PATH simulation (as in the CERN reference scenario), while in the GEANT4 simulation the cavity is 1.4 m long, according to the very last design from [2]. The average gradient per meter was kept constant.

# 3 Energy deposition in the superconducting solenoids

The energy deposition in the cryostat was calculated by the GEANT4 simulation using the full geometry shown in figure 2. All positive muons produced by pion decay (see figure 5) and accepted by the previous channel are tracked in the phase rotation, where part of them are lost due to mismatch. The phase rotation channel was optimise to transport with the higher possible efficiency the muons described in table 1. Only 6% of them are lost in the channel for mismatch or decay, while if one considers the whole muon distribution, then the transmission decreases from 94% to 69%. The energy deposited in the

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[2] The implementation of this procedure is under development

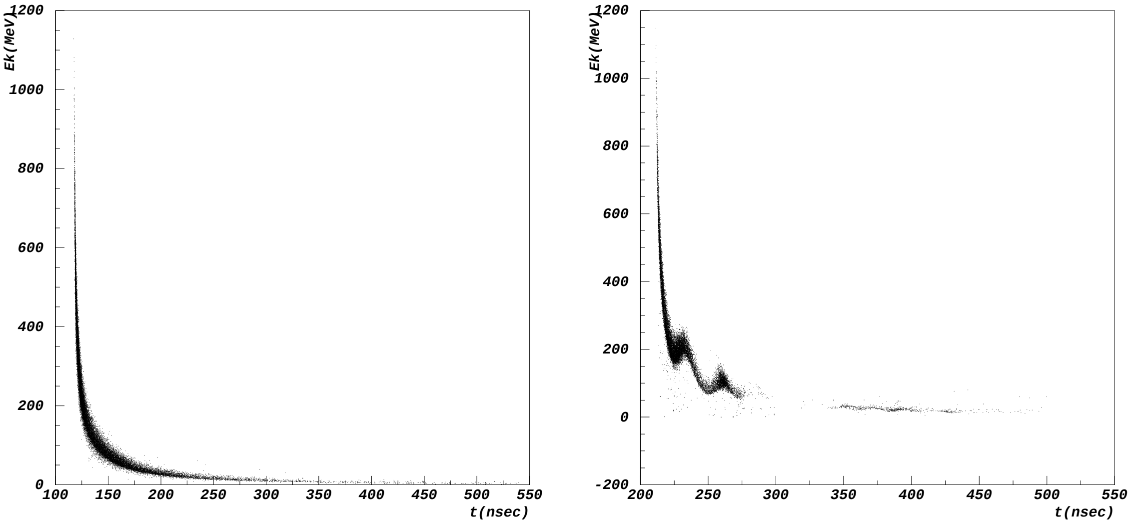

Figure 5: *All muon spectra at the beginning of the phase rotation(left) and at the end of the channel(right)*

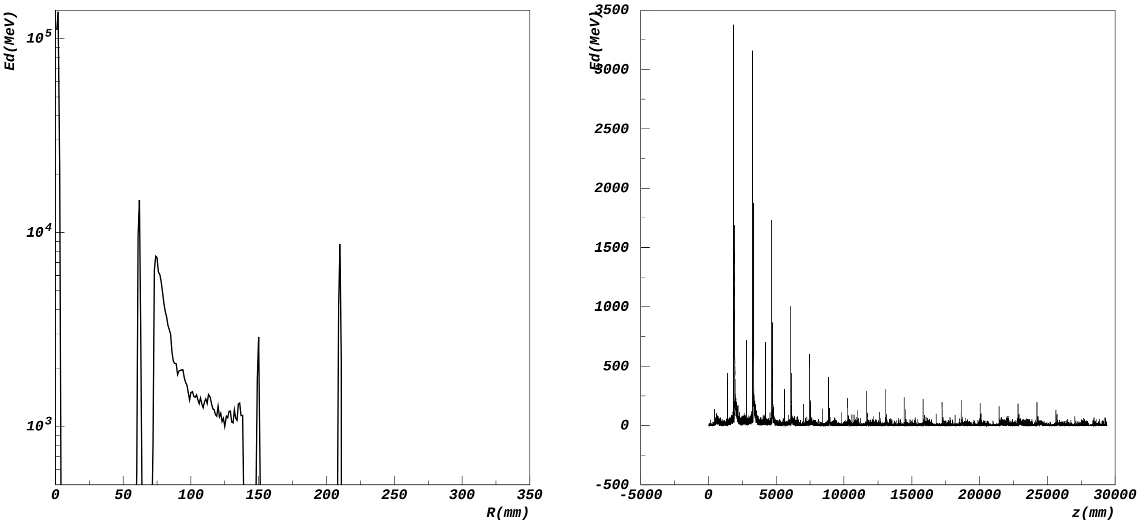

Figure 6: *Integrated energy deposited versus radius (left) and versus position in the channel(right)*

cryostat+solenoid is calculated by GEANT4 . In figure 6 on left one could see the energy deposited versus the radius and integrated versus the $z$ coordinate. The spikes correspond to the energy deposited in the 2 mm thick steel surfaces of the cryostat, which are visible also in right histogram where the energy deposited is integrated versus the radius and plotted versus the position along the beam axis. From this figure one could see that most of the power losses are due to the mismatch of the beam in the first four cells,

after which it decreases and stays constant along the channel.
The energy deposition integrated versus the radius and $z$, normalised to one cell, gives 30.8 W/m, which is twice the recommended limit for a traditional cryogenic system. As solution, the beam losses could be diluted in the decay channel, of which a careful redesign could be envisaged.

## 4 Discussion and conclusions

A simulation of the CERN reference scheme for the phase rotation using GEANT4 was presented in this note. The RF implementation in GEANT4 is validated by the nice agreement with the simulation of the same channel using the PATH code. The energy deposition in the cryostat+solenoid of the RF system calculated by GEANT4 is 30.8 W/m.

## 5 Acknowledgements

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## A Introduction to GEANT4

GEANT4 is an object-oriented toolkit for simulation in High Energy Physics, Space, and Medical applications [1].

The GEANT4 software has been developed by a world-wide collaboration of about 100 scientists from over 40 institutions and laboratories participating in more than 10 experiments in Europe, Russia, Japan, Canada and the United States. GEANT4 has exploited advanced software engineering techniques and Object Oriented technology to improve the validation of physics results and in the same time to make possible the distributed software design and development in the world-wide collaboration. The first GEANT4 production version was released by the end of 1998, as it was scheduled in the DRDC P58 project proposal at the end of 1994. Since then, regular biannual releases have been performed, maintained and supported for the users. GEANT4 has a multi-disciplinary nature, providing functionality in a set of different scientific fields. The GEANT4 Object-Oriented design allows the user to understand, extend, or customise the toolkit in all the domains. At the same time, the modularity of the GEANT4 software allows the user to load and use only the components he needs. The main functionality of the different domains is outlined here.

The GEANT4 physics processes exploit Object-Oriented Technology to make transparent how physics results are produced. The way cross sections are calculated (via formulas, data files, etc. and eventually using different data-sets with restricted applicability by particle, energy, material) is clearly exposed via Object-Oriented design and it is separated from the way they are accessed and used in the algorithms. The user can overload both these features. The way the final state is computed is again separated from the tracking and is split into alternative or complementary models, according to, for example, the energy range, the particle type, the material. Multiple implementations of physics processes and models are possible and have been made available. No numbers should be hard-coded in formulas and algorithms, but only variables and constants should be used. An extensive set of units is defined in GEANT4 and all the numerical quantities are expressed through units explicitly, thus making the GEANT4 physics independent from the units chosen by the user.

The Electromagnetic physics manages lepton physics, gamma, x-ray and optical photon physics, and muon physics. It includes various implementation of ionization and Bremsstrahlung (both with differential treatment for energy loss and with integration of cross-sections in function of energy), the latter with LPM effect, as well as multiple scattering (with lateral displacement and without any path length restriction), and annihilation. It includes as well multiple implementations of the photoelectric (also with fluorescence) and Compton (also with polarisation) effects, pair conversion, synchrotron and transition radiation, scintillation, refraction, reflection, absorption and Rayleigh effect. Low energy extensions, down to 1 KeV and below, are implemented and will continue to be produced in the framework of a joint project with the European Space Agency. The validity range of all the muon processes (based on theoretical models) scales up to the PeV region, allowing the simulation of ultra-high energy and cosmic physics.

The Hadronic physics offers both a data parameterisation-driven set of models, and a variety of theory- driven models for physics beyond test-beams energies, as well as treatment of low energy neutron transport. Parameterisation-driven models include high energy inelastic scattering, as well as low energy inelastic and elastic scattering, fission, capture and dedicated processes for stopping kaons and pions physics. The theory-driven models provide two string parton models in the high energy regime (with the possibility to interface to Pythia7 for the hard-scattering), as well as intra-nuclear transport models and pre-equilibrium, and a variety of de-excitation models, including evaporation, photo-evaporation, fission, Fermi break-up and multifragmentation. The low energy neutron transport is based on best selections of evaluated data (such as ENDF-B VI, JENDL, CENDL, ENSDF, JEF, BROND, IRDF, exploiting the file system to maximise a granular and transparent access to the data sets for the user) and it offers event biasing options, allowing radiation background studies. Lepton-hadron interactions, such as muon-nuclear interactions, photo-fission and general gamma-meson conversion are also implemented. Object-Oriented technology allows to plug-and-play models, for example a theory-driven evaporation model is also used by a parameterised stopping-pion model.

The Geometry provides an ISO STEP compliant solid modeller, allowing exchange of models from CAD systems, and provides the equation of motion solvers in different fields and geometrical boundaries conditions for the propagation of particles. Multiple solid representations, such as Constructive Solid Geometry, Boundary Represented Solids (including NonUniformRationalBSplines), Swept Solids, Boolean Operations, are supported according to the ISO STEP standard. Thus GEANT4 can perform physics simulation in CAD detector models. Different navigation algorithms in the geometrical data bases allow an high degree of automation in the optimisation of flat or hierarchical volumes structures. Different integrators, beyond classical Runge-Kutta, and including multi-turn perturbative methods, allow a correct treatment for various fields of variable non-uniformity and differentiability. A proper integration is also performed to update the particles time of flight during transportation.

The Tracking manages the evolution of the track's status determined by the physics interaction occurring at a given time, at a given location, or distributed in space-time. The tracking system manages any of these kinds of interactions, or any combination of them, leading to a closed generalisation of the traditional classification in discrete and continuous physics processes (which is found back as a special case). In order to fully exploit the validity ranges of the physics models, GEANT4 does not apply any tracking cuts, but relies only on production thresholds, thus all particles are tracked down to zero range. In addition, GEANT4 can ensure a consistent and material-independent accuracy of the simulation because the production cuts are set in range, rather than in energy (and the tracking allows automatic correct treatment of near-boundary regions via the capability of processes to produce secondaries below threshold). Of course, the user can optionally define cuts in energy, path length, time-of-flight, for special treatment of selected areas in the experimental set-up.

The Run, Event and Track management allows the simulation of the event kinematics, together with primary and secondary tracks, and it provides the functionality to perform studies of anything from pile-up to trigger and loopers via a triple stacking mechanism. A fast parameterisation framework (which can be triggered on particle type, volume, etc.) is integrated with the full simulation, allowing independent and simplified detector descriptions and at the same time a correct treatment near cracks. Fast parameterisations allow the direct production of hits corresponding to a full shower development for several detector types. Finally the Hits and Digi domains provide the functionality to reproduce the read-out structure of the detector and its electronic response, independently from the geometry used for the tracking.

Visualisation and User Interface make use of abstract Object-Oriented interfaces to allow drivers of multiple standard and specialised graphics systems, and interaction with sophisticated GUIs or command line and batch systems. The implemented visualisation drivers allow the use of X11, PostScript, OpenGL, OpenInventor, VRML, and DAWN, which allows engineering quality drawings and automatic detection of volumes overlaps. The implemented user interfaces allow batch sessions (including the processing of macro files), interactive sessions based on command lines interfaces, as well as fully graphical user interface sessions such as with OPACS or MOMO, the latter including automatic code generation for detector description and materials definition. The VRML2 driver also allows interactive picking of physics objects, such as tracks and hits, visualising in real time the associated physics information.

Particle Data Group compliant particle definitions, including hundreds of baryonic and mesonic resonances and ions) and decay processes and modes, have been implemented and are available. Extensive possibilities of interaction with the GEANT4 system are offered to the user via a kit of dedicated user-action classes. A wide set of utilities, including a complete set of random number generators, physics units and constants, as well as isotopes, elements, compounds definitions, and interface to event generators and to ODBMS, complete the toolkit.

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