A COMPUTATIONAL MODEL FOR MUONS PASSING GAS AND PLASMA TARGETS: BEAM EMITTANCE

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Abstract

A good understanding of interaction of muon beams with gas targets is crucial for attaining high acceleration gradients in gas pressured RF cavities. This physics includes a number of challenging problems. Our objective has been to develop a computational model for studying the effects of some of these physics processes, within the same level of accuracy. The computational model simulates scattering of a bunch of charged particles on multiple atomic, molecular and ionic centers. The interaction potentials have been calculated using Hartree-Fock method for atomic targets. Target particles are populated randomly to simulate either a gas in a pressured RF cavity with a particular material density, or liquid hydrogen. In the present work the following effects on beam emittance have been studied: effect of simultaneous scattering (comparing to single particle tracking models), effect of various degree of target ionization (beam-plasma interaction), space charge screening in plasma, effect of strong magnetic fields. Our preliminary results demonstrate that the degree of plasma ionization has a strong effect on the beam emittance.

INTRODUCTION

The idea of neutrino factory and a muon collider is the motivation for development of new muon accelerator technology. The design of these facilities is affected by the need to fit a diffuse muon beam inside the typical accelerating aperture and at the same time to fit it longitudinally into an RF cavity for acceleration.

A new approach was recently developed resulting in the design of a high pressure RF cavity, a novel device capable of achieving extreme muon cooling. To support these new ideas and developments and to validate a technical design of these new accelerating facilities, accurate and comprehensive simulations are required long before their construction. Since muon cooling is achieved by passing a muon beam through low-Z absorbing materials, the interaction between the two must be accounted for in the supporting simulations. The GEANT4 [1] and G4beamline [2], are able to simulate particle passing through matter, and as such are among the best candidates for muon tracking. However, the needs of muon accelerating facilities simulations may require the upgrade of these tool kits with some new physics processes and features that include but are not limited to multiple scattering and collective effects in matter, space charge, etc [3].

The aim of this work is to study some of the mentioned physical processes and estimate how large their effects are on the muon beam emittance.

MULTIPLE SCATTERING

"Multiple scattering occurs whenever travelling particles or waves undergo successions of similar processes that change the direction of their motion and the successive scatterings are statistically independent or almost independent [4]." This definition of multiple scattering implies multiple binary collisions of projectile and target atoms, that occur one at the time without any influence of surrounding target atoms. It also assumes that the target is unlimited and that it stays unchanged and that there is no interaction among the particles in a bunch (single tracking) [5, 6].

The multiple Coulomb Scattering model in GEANT4 is based on the *Lewis's theory* [8]. This theory, under all the mentioned approximations, offers a solution of the diffusion equation of the multiple scattering problem without using small angle approximation [6]. This solution, however, requires the scattering cross sections for each particular absorbing material. In GEANT4 cross sections are not used directly, rather the spatial and angular distributions are described by the model functions that are fitted with number of parameters. Recent reports on Muscat [7] experiment showed that GEANT4 has a tendency to overestimate the tails in low-Z materials that would affect the design of the cooling channel.

Whether this overestimation is coming from the inadequacy of the multiple scattering model in GEANT4 is still unclear. So the question remains: should the influence from the rest of the target atoms be neglected, or could it be necessary to account for the target response and for the interaction between particles inside the bunch?

Here, with our modified molecular dynamic simulation method, we want to study the collective effects on a simple model of muons passing through matter, and estimate under which conditions these processes can be important for muon acceleration and cooling.

PHYSICAL MODEL

We start our study with a simple classical scattering of positive muons on multiple centres. Centres are described by realistic potentials, which are calculated quantum mechanically from the first principles. We use *Hartree-Fock* method for atomic targets. Target particles are populated randomly to simulate hydrogen target with a particular material density and a degree of ionisation. In the present simulation scattering centres were kept fixed. The muons were propagated trough the target one by one or as a bunch, and the interaction between them in a bunch was described by the Coulomb's force.

SIMULATION PARAMETERS AND RESULTS

Simulation results are given for a μ^+ passing through target of arbitrary size L, that is determined by the number of centers in the target and the target density.

First we compare the effects of multiple simultaneous scattering versus the multiple binary scattering for different target densities and degrees of ionisation Fig.(1). From these functional dependences it is obvious that the influence of the rest of target atoms/ions is significant especially if the projectile momentum is exceeding the $100\frac{MeV}{c}$.

In our study of the importance of type of the potential used to describe target centers we concluded that the long range Coulomb's potential widens the particles' distributions due to its long range property [9]. Thus our next concern was how would the presence of ions in the target affect a muon beam. The question of ions in the target is relevant since it is expected that when an intense muon beam bunch enters the absorber material, the particles in the head of the bunch ionise the atoms in the material so the particles in the tail of the bunch will scatter off of both neutral atoms and ions. We have discovered that in the case of scattering processes the significance of their effects depend on the ratio of the scattering length and the distance between the target centers. It also depends on the projectile velocity, or how much time the projectile spends in the vicinity of the target center. Fig.(2) shows the effect of ionisation of the target on the angular distribution of the muon beam, and as expected the distribution gets wider as we go from neutral (screened potential) to ionic target (Coulomb's potential).

Another issue that we wanted to address in this work is the space charge. We simulated the bunch evolution in vacuum and in the presence of the target while considering mutual Coulomb's repulsion between the particles in the bunch. We have also tracked the bunch in the target excluding the interaction between the particles. We observed that the Coulomb's repulsion contributes to the spreading of the bunch in the direction of motion. Also we saw that when Coulomb's repulsion was present it suppressed the spread of the bunch in the transverse direction that occurs due to the interaction with the target atoms Fig.(3). In addition we looked at the difference in angular distributions of the single particle tracking and bunch tracking simulation Fig.(4). One can see that the bunch tracking gives a wider angular distribution of the particles and this discrepancy is also in favour of the fact that the space charge effects should be investigated further.

We have also investigated the influence of the external magnetic field on the collective effects of muon beam passing through material. In the present calculation the external magnetic field is introduced only trough the orientation of the target along the direction of the field. The preliminary results show that if the field is along the direction of motion that the angular distribution of muons in the beam is narrower meaning that it has focusing effect on the beam, Fig.(5). The effect is, however, dependent on the projectile velocity, i.e. it is more significant for lower projectile velocities.

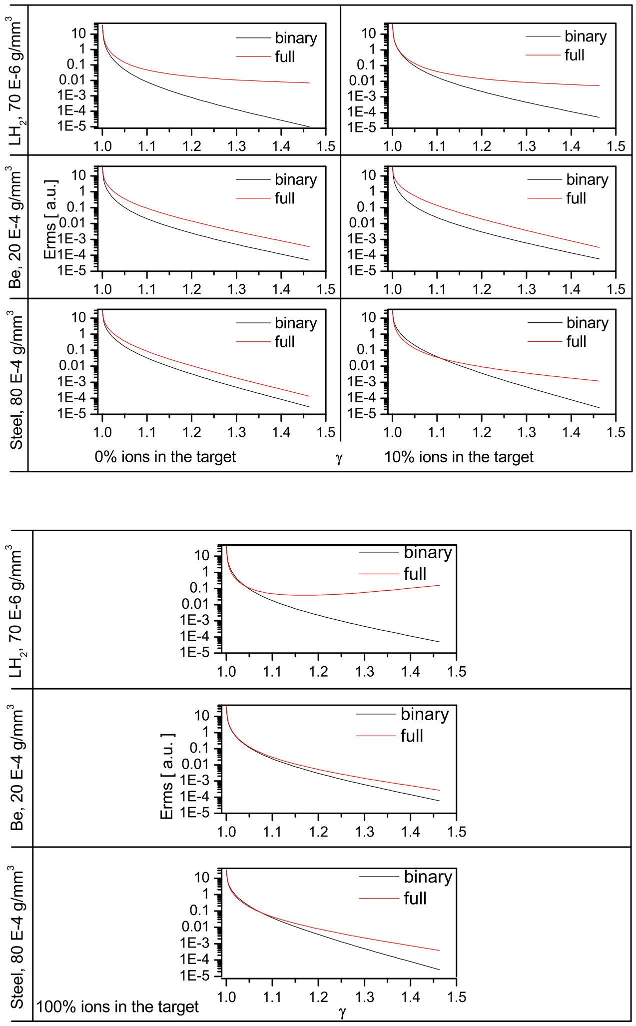

Figure 1: Emittance as a function of projectile velocity under different target conditions.

DEVELOPMENT PLANS

We currently plan on investigating and implementing the following physical processes into our simulation, in order to understand their importance and significance to muon cooling:

- Energy straggling in target material.
- Low energy electron production from materials.
- Effects of applied external magnetic field on multiple scattering.

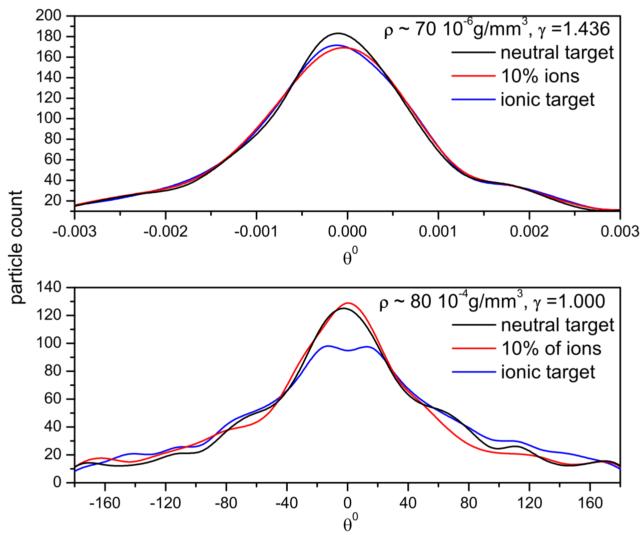

Figure 2: Angular muon distributions in two extreme cases: Sparse target and $\gamma = 1.436$, dense target and $\gamma = 1.000$.

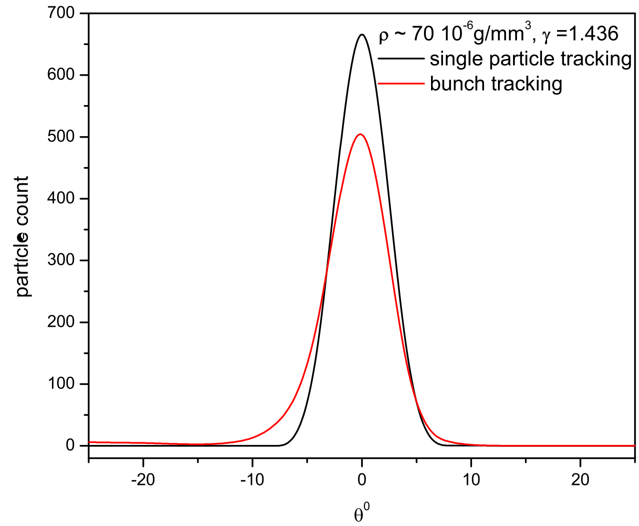

Figure 4: Angular distribution for the single particle tracking and the bunch.

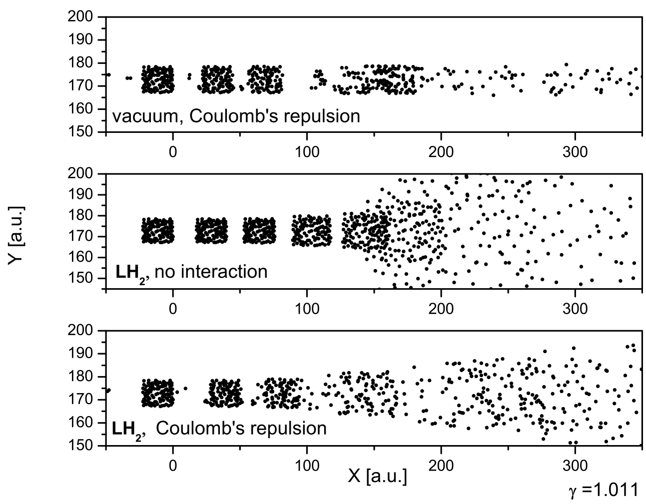

Figure 3: Bunch evolution in vacuum and absorber for different projectile velocities.

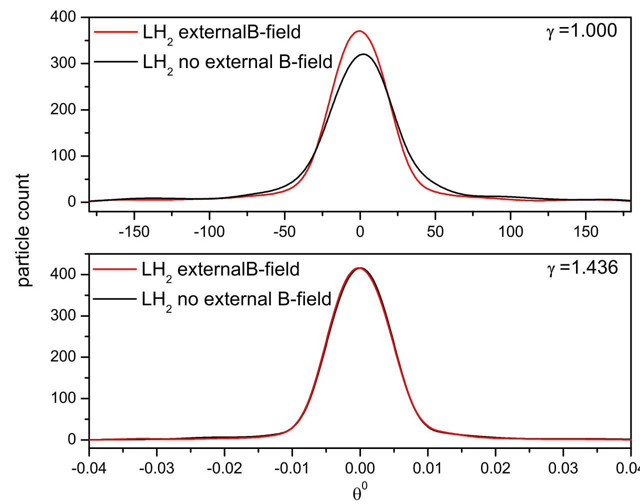

Figure 5: Effects on external magnetic field on angular particle distribution.

SUMMARY

We developed a simulation to study the multiple scattering and collective effects of muon passing through matter. The current results demonstrate the conditions under which the effects of certain physical processes are significant. For muon accelerator purposes the simultaneous scattering, ionisation of the target and interaction of particles in the bunch are the processes that should be taken into consideration for further detail analysis and possible implementation in the existing simulation tools. The future plan is to extend the simulation with features such as energy loss, low-energy electron production from the material and the effects of applied magnetic field, with the purpose to investigate their effects on muon cooling, in order to maintain accurate and complete simulation for muon accelerating facilities.

REFERENCES

[1] `http://geant4.web.cern.ch/geant4/`.

[2] `http://g4beamline.muonsinc.com`.

[3] T.Roberts *et al.*, "Particle Tracking In Matter Dominated Beam Lines", PAC'09 Proceedings, Canada, May 2009.

[4] W.T. Scott, Rev. Mod. Phys., 35 (1963) 231.

[5] S. Goudsmit and J.L. Saunderson, Phys. Rev., 57 (1940) 24.

[6] H.W. Lewis, Phys. Rev., 78 (1950) 526.

[7] W.J. Murray, Nucl. Phys. B, 155 (2006) 282.

[8] `http://geant4.web.cern.ch/geant4/collaboration/workshops/users2002/talks/lectures/multiplescattering.pdf`.

[9] A.Samolov and A. Godunov *et al.*, " Computational Modeling of Muons Passing Through Gas Pressured RF Cavities", IPAC'10 Proceedings, Japan, May 2010.