PRECISION ENERGY MEASUREMENTS IN A MUON COLLIDER USING POLARIZATION

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Abstract

It was shown in a previous paper that polarized muons beams can be obtained in a muon collider [1]. R. Raja and A. Tollestrup [2] pointed out that the polarization can be used to determine the energy of the muons in the collider with high accuracy in a similar way as in electron accelerators. The proposed technique is similar to the famous muon (g-2)/2 experiments performed in various labs [3]. In this paper the limits of this technique from a spin dynamics point of view are discussed and the difference to the well known electron spin based energy calibration is shown.

1 INTRODUCTION

Muon-muon colliders are under consideration for the multi-100 GeV and the TeV energy range [4]. The idea is based on the fact that muons are heavy leptons which emit a negligible amount of synchrotron radiation even at the highest energies. Therefore the muon collider can be a circular collider despite the fact that muons are “pointlike“ leptons which behave in a circular accelerator like protons. Before a muon collider is feasible, several problems have to be solved.

Comparing the muon collider with the other canditates for TeV colliders (proton colliders, proton-antiproton colliders and linear electron-positron colliders) one advantage is obvious: both the muon and the anti-muon beam can be polarized. It was shown in a previous paper that the naturally born polarized muons can maintain their polarization up to the highest energies.

The technique of controlling the energy by polarization is nowadays used in almost all electron machines from the sub-GeV range up to about 60 GeV. It was first pointed by R. Raja and A. Tollestrup [2] that in a muon collider the absolute energy of narrow resonances can be measured and calibrated by using the polarization. This is a clear advantage over other types of multi-100 GeV or TeV colliders.

In principle two types of high precision energy measurements using polarization are known: the above already mentioned depolarization method in electron (positron) accelerators and the (g-2)/2 experiments with muons. Both techniques are similar but differ in the way the energy spread is handled. In the following the difference will be discussed in more detail. Afterwards conclusions are performed how to calibrate the energy in muon colliders.

2 GENERATION OF POLARIZED MUONS AND MUON SPIN DYNAMICS

Muons are generated at low energy from a decaying pion. The pion decays via the weak interaction into a muon and a muon neutrino (fig. 1). The muons are born polarized.

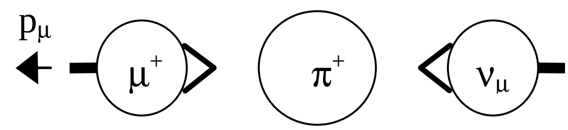

Fig. 1: The generation of a muon from a pion decay. The muon is polarized opposite to its direction of motion.

The rest mass of the muon is 105.66 MeV and therefore about 207 times larger than the rest mass of the electron. The anomalous magnetic moment of muon and electron is [3].

$$\left(\frac{g-2}{2}\right)_\mu = 1.166\text{x}10^{-3}$$

$$\left(\frac{g-2}{2}\right)_e = 1.16\text{x}10^{-3}$$

Since the lifetime of the muon is relatively short (γ.2.2 x10^{-6} sec), a selfpolarization mechanism at high energies is almost excluded: the muons have to be collected polarized and polarization has to be maintained during acceleration and storage.

During acceleration the integer resonances occur when (n = integer)

$$\left(\frac{g-2}{2}\right)\gamma = \text{n}$$

The distance between two integer resonances is 94.62 GeV compared to ca. 440 MeV with electrons and ca. 470 MeV with protons. The figures clearly show that the muon spin is extremely insensitive to magnetic fields.

This has a positive aspect. Polarization is far more stable than it is in the case of electrons and protons. However, there is also a negative aspect: in the relativistic limit an integrated field of 492 Tesla.m is

required to rotate the muon spin by 90 degrees. In comparison, 2.3 T.m are required to rotate the spin of an electron by 90 degrees and 2.7 Tm for rotating the spin of a proton by 90 degrees.
The clear advantage is that even at an end energy of 2 TeV the spin tune is only 21.13 and comparable to a circa 10 GeV electron storage ring.

3 RESOLUTION OF THE (g-2)/2 MUON MEASUREMENTS

It is well known that it is possible to measure (g-2)/2 with a high accuracy. The basic technique is the following: polarized muons are generated according to fig. 1 and injected into a homogenous field. The muons circle in this field B with the cyclotron frequency

$$\omega_{cyclotron} = \frac{eB}{\gamma m_o c}$$

The spin precession

$$\omega_{spin} = \left(\frac{g-2}{2}\right)\gamma \,.\omega_{cyclotron} = \left(\frac{g-2}{2}\right).\frac{eB}{m_0 c}$$

is independent of γ. Particles with an energy deviation $\gamma+\Delta\gamma$ have different revolution frequencies and therefore different spin frequencies. But, and this is an important feature, at a certain point of the circumference the spins aim into the same direction independent of $\Delta\gamma$. The price which is paid for this feature: even when the beam is bunched at the beginning the bunches are smeared out during the decay time.

A muon collider will be a strong focusing machine where the revolution frequency is almost independent of the energy. This allows to keep the bunches together (by keeping the momentum compaction factor α low) and allows to obtain high luminosity. But, as a result, the beam becomes depolarized due to the energy spread.

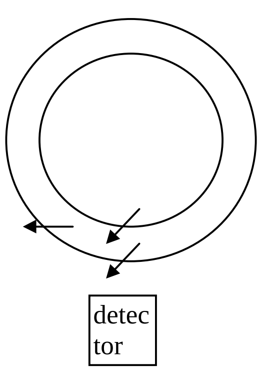

Fig. 2: Principle of the g-2/2 experiment for muons. The storage ring has no focusing elements. The spins of particles with different energies rotate differently, but so does the particle itself (cyclotron frequency is energy dependent). Two parallel spins always stay parallel independent of their energy difference.

The effect can be explained by an example. A circa 95 GeV beam [((g-2)/2).$\gamma \cong 1$] and an energy spread of 3.10^4 leads to a spin spread of $1000 \times 3.10^{-4} \times 360$ degrees = 108 degrees after 1000 turns. At 2 TeV (spin tune around 21) the beam will be completely depolarized after circa 84 revolutions. A high resolution can only be obtained within the first revolutions. A classical (g-2/2) experiment as shown in fig. 2 is not possible in such a machine.

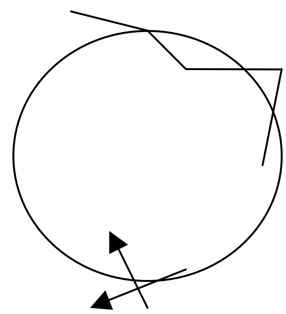

Fig. 3: Situation as in fig. 2 with the only difference that the storage ring is a strong focusing machine. The revolution frequency of the energy deviating particle schematically sketched by the zig-zag line (symbolizing the focusing by quadrupoles) is almost energy independent and the polarization decays more and more from revolution to revolution

3 RESOLUTION OF THE ENERGY MEASUREMENTS IN ELECTRON STORAGE RINGS

The energy calibration technique in electron storage rings is in completely different to the muon (g-2)/2 experiment. The beams remain bunched (the revolution frequency is almost independent from the energy deviation) and the polarization direction is vertical. The spins are bent by a radial RF field away from the vertical. As soon as the spins leave the vertical direction they begin to precess around the vertical direction with a speed depending on their actual energy deviation. In first order the energy deviation is given by

$\Delta\gamma/\gamma = A\, e^{-t/\tau} \sin \omega_s t$
where τ is the synchrotron damping time and ω_s is the synchrotron frequency. The magnitude $\Delta\gamma/\gamma$ is driven by synchrotron emission. Due to the fact that

$\langle\Delta\gamma/\gamma\rangle \cong A/\tau$

(< > means averaging over the time) is a small number, depolarization is a rather weak effect and takes place over many synchrotron periods. During this depolarization process each particle changes many times its energy deviation $\Delta\gamma/\gamma$, so that the beam finally appears almost monochromatic. Energy resolutions of several times of 10^{-5} are possible, even when the actual energy spread $\Delta\gamma/\gamma$ is in the order of 10^{-3}.

Depolarization in an electron storage ring is a highly nonlinear process and has therefore, fortunately, a sharp energy resolution.

4 THE INFLUENCE OH THE SOLENOID FIELDS ON THE SPIN TUNE

Similar to electron accelerators the spin tune is influenced by the solenoid fields of the detectors. At each passage through the solenoid the spin position changes. In the case of electrons the solenoids cause depolarization and in the case of the muon system a change of the spin precession frequency. It is therefore assumed in the following that the solenoid fields of the experiments are locally compensated by so-called anti-solenoids so that the integrated solenoid field is zero.

5 MINIMIZING THE DEPOLARIZATION IN A MUON COLLIDER WITH A LOW MOMENTUM COMPACTION FACTOR

In order to obtain a good energy resolution both ideas (the muon g-2/2 idea and the electron energy calibration can be combined. This is shown in fig. 4.

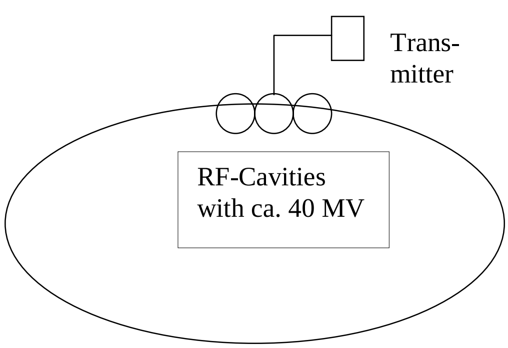

Fig. 4: The basic idea how to obtain a good energy resolution in a muon collider by using the longitudinal polarization. The finite momentum compaction factor together with the cavities let particles with an energy deviation oscillate around the central energy.

The cavities shown in fig. 4 generate undamped synchrotron radiations with the result that the spins only deviate by a small amount. This of course is only possible due to the high mass of the muons and the relatively low spin precession frequency.

5 SUMMARY

Without considering energy calibration by polarization muon colliders will operate without cavities and a low momentum compaction factor. Both effects will influence the degree of polarization. From revolution to revolution the polarization will smear out and the energy calibration will become more and more uncertain. On the other hand can the precise energy calibration of the beam be an enormous advantage of a muon collider compared to other types of collider especially during the search for new particles. Therefore it is proposed to introduce especially for this case an RF system. The phase is chosen in such a way that a particle with the central energy sees zero accleration field. All the energies of the other particles oscillate around this position.

7 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] B. Norum and R. Rossmanith, Nuclear Physics B (Proc. Suppl.) 51A(1996) 191
[2] R. Raja and A. Tollestrup, Proc. Workshop, Fermilab Nov. 1997
[3] J. Bailey, Il Nuovo Cimento, Vol. 4, N. 4 (1972)369
[4] For a summary see A. Sessler, Physics Today, March 1998, 48