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FERMILAB-Conf-97/114

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April 1997

Presented at the *Particle Accelerator Conference PAC 97*,
Vancouver, Canada, May 12-16, 1997

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An Asymmetric Muon-Proton Collider: Luminosity Consideration

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Abstract

An asymmetric muon-proton collider is proposed as an instrument for possible quark structure search. Energy of proton beam is supposed to be some 5-6 times of muon energy. Estimated luminosity of the collider with two rings – the Tevatron accelerator and μ -ring – is found to be of the order of $10^{33} \text{ s}^{-1} \text{ cm}^{-2}$.

1 INTRODUCTION

Several proposals of $\mu^+ - \mu^-$ and $\mu - p$ colliders were made in recent years (the past and present status of these ideas can be found, e.g., in Ref. [1]). Here we discuss a modification of existing plans of muon facilities which would fit to the requirements of a search for quark structure. This could be an asymmetric muon-proton collider in which the momenta of colliding quarks and muons are roughly the same in value but opposite. This condition will ease the observation of the events with large transverse momentum transfer which involve destruction of quarks or where quark structure may manifest itself. As an example, one can consider 1000 GeV protons of the Tevatron facilities which confine quarks with broad momentum spectra around the mean value of some 160 GeV/c. Therefore, an appropriate muon momentum should be about 100-200 GeV/c. This paper is devoted to brief consideration of the possibilities of such a collider, beam parameters and luminosity of the machine, and comparison with other probable competitive accelerator schemes.

2 BEAM PARAMETERS AND COLLIDER LUMINOSITY

Let us consider possible scheme of the $\mu - p$ collider which consists of two rings. Parameters of the ~ 200 GeV muon ring are taken from [2] where it is assumed that muon production and acceleration systems can provide $M = 2$ bunches of $N_\mu = 2 \cdot 10^{12}$ particles within transverse normalized rms emittance of $\epsilon_{n\mu} = 50 \text{ mm} \cdot \text{mrad}$ with a rate of $f_L = 30 \text{ Hz}$. These muons decay in the ring after a characteristic number of turns of $n_s = 300 \cdot B[T]$ in the bending field of B in Tesla. Here we will consider $B \sim 6T$ and, therefore, $n_s \sim 2000$.

A good candidate to deliver the beam of protons could be Tevatron. In the upgraded regime of “TeV33” [3] the length of the bunch of $E_p = 1000 \text{ GeV}$ protons will be about $\sigma_z = 15 \text{ cm}$, while the number of protons depends on the transverse normalized emittance as $N_p \simeq 10^{11} \cdot \epsilon_{np} [\text{mm} \cdot \text{mrad}]$.

* Operated by Universities Research Association, Inc., under contract with the U.S. Department of Energy

The last relation assumes limiting factors for proton beam population are low-energy space charge effects at injector stages and intrabeam scattering.

Transverse sizes σ_μ^* , σ_p^* of the beams at the $\mu - p$ collider interaction point should be approximately the same, thus, under the condition on beta-functions $\beta_\mu^* \sim \beta_p^* \sim \sigma_z$ we have following relation between transverse emittances:

$$\epsilon_{np} = \left(\frac{\gamma_p}{\gamma_\mu} \right) \left(\frac{\beta_\mu^*}{\beta_p^*} \right) \epsilon_{n\mu}, \quad (1)$$

here $\gamma_p \approx 1000$ and $\gamma_\mu \approx 2000$ denote relativistic factors of particles.

Taking for definiteness $\beta_p^* = 2\beta_\mu^* = \sigma_z = 15 \text{ cm}$, we obtain $\sigma_{IP} = \sqrt{\epsilon_{n\mu} \beta_\mu^* / \gamma_\mu} \approx 40 \mu\text{m}$ and $\epsilon_{np} = 12.5 \cdot 10^{-6} \text{ m}$. Consequently, the expected maximum number of protons is $N_p = 1.25 \cdot 10^{12}$.

Now we can estimate the luminosity of the muon-proton collider as:

$$L = \frac{f_L n_s N_\mu N_p M}{4\pi \sigma_{IP}^2} \approx 1.3 \cdot 10^{33} \text{ s}^{-1} \text{ cm}^{-2}. \quad (2)$$

As protons are supposed to live for a long time in the ring, one should consider beam-beam effects. With the parameters mentioned above, the proton tune shift due to opposite muon beam is:

$$\xi_p = \frac{N_\mu r_p}{4\pi \epsilon_{np}} \approx 0.02, \quad (3)$$

that seems acceptable (here $r_p = 1.53 \cdot 10^{-18} \text{ m}$ is the proton classical radius). The decay of muons leads to changing (reduction) of the shift within characteristic time of 2000 turns, therefore some external stabilization of the proton ring tune probably would be useful.

Beam-beam tune shift for muons is equal to

$$\xi_\mu = \frac{N_p r_\mu}{4\pi \epsilon_{n\mu}} \approx 0.026, \quad (4)$$

again far away of limiting values ($r_\mu = 1.36 \cdot 10^{-17} \text{ m}$).

Concluding this section, we would note that the key parameters for the $\mu - p$ collider luminosity are the muon production rate and the muon emittance. As these parameters are presently under detailed study, somewhat “pessimistic” variant II [1] with smaller N_μ , smaller repetition rate of μ production f_L , and larger emittance $\epsilon_{n\mu}$ is considered and put into summarizing Table 1, while high μ -production option is marked as variant I in the Table. For proton beam-beam tune shift estimations with smaller repetition rate f_L ,

Table 1: Two Options of $\mu - p$ Collider

Parameter	I	II
Muon Energy, E_μ , GeV	200	200
Proton Energy, E_p , GeV	1000	1000
μ Intensity, N_μ/bunch	$2 \cdot 10^{12}$	$5 \cdot 10^{11}$
μ Emittance, $\epsilon_{n\mu}$, $10^{-6} m$	50	200
Storage turns, n_s	~ 2000	~ 2000
μ Pulse rate, f_L	30	10
N bunches (p, μ), M	2	2
Beta at IP β_μ^* , cm	7.5	7.5
β_p^* , cm	15	15
Waist size σ_{IP} , μm	~ 40	~ 90
p Emittance ϵ_{np} , $10^{-6} m$	12.5	50
p Intensity, N_p/bunch	$1.25 \cdot 10^{12}$	$5 \cdot 10^{12}$
Beam-beam shift ξ_p	0.02	0.0005
ξ_μ	0.026	0.026
Luminosity L , $s^{-1} cm^{-2}$	$1.3 \cdot 10^{33}$	$1.1 \cdot 10^{32}$

the ‘duty factor’ of collisions was taken into account: $< \xi_p > \approx \xi_p (f_L n_s / f_0)$ where $f_0 \simeq 47$ kHz is the Tevatron revolution frequency, and ξ_p is given by Eq.(3). Let us remark also, that inasmuch as beta functions at the interaction point are of the order of bunch length, the ‘hour-glass’ effect can slightly decrease luminosity (by some dozen percents).

3 DISCUSSION

It is interesting to compare the proposed proton-muon collider with other lepton-hadron machines presently under study, namely, possible $e - p$ facilities of LEP+LHC at CERN and TESLA+HERA-p at DESY(Hamburg). Table 2 demonstrates main features of these machines: momenta of quarks ($p_q \sim E_p/6c$) and leptons p_l , maximum momenta transfer $Q \simeq 2\sqrt{p_q p_l}$ (all momenta in GeV/c), and luminosity in $s^{-1} cm^{-2}$.

Table 2: Quark-Lepton Collider Projects

Project	Q	p_l	p_q	L , 10^{31}
TESLA+HERA-p	350	250	140	~ 1.0
LEP+LHC	700	90	1300	1–10
μ -ring+Tevatron	350	200	160	10–100

The TESLA+HERA-p project [4] with use of superconducting linear accelerator of electrons can provide momenta-symmetric quark-lepton collisions, but its luminosity is limited by power of electron beam. The luminosity of the LEP+LHC is somewhat higher and limited by beam-beam instabilities into both beams of electrons and protons, but momenta asymmetry of the order of 15 is not convenient for the experiment. As it is mentioned in the Table 2, the luminosity of the muon-proton collider at FNAL could be

the highest one, depending mostly on the μ -production and cooling.

It seems reasonable to consider the proposed $\mu - p$ machine as the first step toward a large scale 4 TeV c.m. energy $\mu^+ \mu^-$ collider. With respect to the full-scale set up such a testing facility does not require production of both charge muons, allows large longitudinal emittance of μ -beam and, therefore, gives some freedom in obtaining lower transverse emittance (see in Refs. [1, 2]). Due to ability to operate with μ bunches as long as proton ones, one expects no troubles with single bunch instabilities in the muon ring, and at the same time it could substantially simplify focusing optics of the ring and the interaction region.

Further increase of the $\mu - p$ collider luminosity can be obtained with larger number of bunches M , or with implementation of ‘traveling focus’ regime [4] in order to decrease effective beam sizes at interaction point while bunch length is larger than the value of beta function. Formally speaking, quark-muon luminosity is some 3 times the obtained value, because number of quarks is triple number of protons we used in our estimations.

4 CONCLUSIONS

The asymmetric $\mu - p$ collider with energies of 200 GeV in muon beam and 1 TeV for protons is considered as a tool for quark structure search. The option with intersecting Tevatron accelerator and μ -ring allows to obtain luminosity of the order of $10^{33} s^{-1} cm^{-2}$. The key issues for high luminosity are large number and small transverse emittance of muons, while the muon bunch length can be as large as proton one’s. The beam-beam effects are found to give no severe constraints on beam intensities. It was also shown that the proposed scheme has some advantages with respect to other possible lepton-hadron colliders, such as LEP+LHC and TESLA+HERA. The muon-proton collider at FNAL seems to be also a perfect candidate as the first stage of high-energy $\mu^+ \mu^-$ facility.

5 ACKNOWLEDGMENTS

I acknowledge valuable comments and corrections done by Dan Green and David Neuffer. Discussions with Reinhard Brinkmann, Joerg Rossbach, Gus Voss (DESY), and Pat Colestock encouraged me to pursue the topic.

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