STATUS REPORT ON THE SIX-MONTH STUDY ON HIGH ENERGY MUON COLLIDERS [*]

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Abstract

A progress report is given at one month from completion of the “Six-Month Study on High Energy Muon Colliders: Oct’00–Apr’01”. The structure and parameters of the study are reviewed and the areas of significant progress and results so far are reported.

1 INTRODUCTION

Muon colliders are a potential option for exploring and extending the energy frontier of experimental high energy physics (HEP). Research on muon colliders is at the stage of feasibility studies and this paper reports on the ongoing “Six-Month Study on High Energy Muon Colliders: Oct’00–Apr’01” [1].

Muons are leptons with a mass 206 times larger than the electron. It follows that their collisions are expected to display similar physics to that of electrons at the same energy but, in contrast to electrons, the natural energy limitation for *circular* muon storage rings due to synchrotron radiation is not reached until center-of-mass energies $\mathrm{E_{CoM}} \sim 100$ TeV, where the synchrotron radiation energy loss has finally risen to become comparable to the beam power. On the negative side, muons are unstable, decaying with a rest-frame lifetime of 2.2 microseconds into an electron and two neutrinos. To cope with these decays, the muon bunches must be frequently replenished and then quickly cooled, accelerated and collided, and allowance must be made for dealing with the decay products.

Historically, most of the dedicated research on muon colliders was performed from 1996-9 by the then-named Muon Collider Collaboration, including the publication of two fairly substantial reports [2, 3]. Now named the “Neutrino Factory and Muon Collider Collaboration” (MC) their main focus [4] has shifted to the related technology of neutrino factories.

The above-mentioned studies by the Muon Collider Collaboration considered “straw-man” parameter sets at center-of-mass energies ($\mathrm{E_{CoM}}$) up to 4 TeV. Energies above this have been considered previously at the week-long HEMC’99 workshop [5] “Colliders and Collider Physics at the Highest Energies: Muon Colliders at 10 TeV to 100 TeV” and elsewhere [6]. The majority of the studies at HEMC’99 either assumed or critiqued straw-man parameter sets [7] at $\mathrm{E_{CoM}} = 10$ TeV and 100 TeV. Additionally, Zimmermann [8] raised the speculative possibility of reaching even higher energies using *linear* muon colliders, even presenting a parameter set with $\mathrm{E_{CoM}} = 1000$ TeV!

Building on these previous studies, the current Study is open to all interested participants, with a mailing list currently consisting of the MC (156 names automatically included) as well as 144 interested people from outside the MC. Its proceedings [1] will consist of an overall summary report as well as individual write-ups on topics relevant to energy frontier muon colliders.

2 STUDY TOPICS AND CHALLENGES

The preparation of bunched muon beams suitable for acceleration to collision and, in particular, the ionization cooling channel [9], is the biggest technical challenge common to all muon colliders. The Study concentrates on complementary aspects of this “front-end” to those addressed in MC studies, namely, on a broader survey of targetry technologies and on the longer-term possibilities for cooling beyond the final beam emittances anticipated using ionization cooling. “Exotic” cooling options include non-relativistic muon production or cooling schemes as well as an optical stochastic cooling [10] “after-burner” for the ionization cooling channel.

The major technical issues that are relatively specific to energy frontier muon colliders are 1) affordable acceleration to the TeV energy scale and above, 2) collider rings with very large beam demagnifications at the final focus, 3) more serious backgrounds from muons in the experiment’s detector and 4) restrictions imposed by neutrino radiation [11], which rises sharply with beam energy.

Table 1 presents the straw-man muon collider parameter sets used for the Study, at $\mathrm{E_{CoM}} = 400$ GeV, 4 TeV and 30 TeV (2 parameter sets) and with respective luminosities of $\mathcal{L} = 3.0 \times 10^{33}, 5.0 \times 10^{33}, 3.0 \times 10^{35}$ and $3 \times 10^{35}\ \mathrm{cm^{-2}.s^{-1}}$.

Presuming that a TeV-scale linear electron-positron collider is built then the 400 GeV parameter set may not be considered to be truly at the energy frontier for lepton colliders. It is included partly to illustrate the progression of parameters with collider energy.

Much of the 4 TeV parameter set is similar or identical to that presented at Snowmass’96 [2] by the Muon Collider Collaboration. The most significant difference is a substantial reduction in the muon bunch repetition rate, to only 1 Hz, in order to reduce the maximum off-site neutrino radiation dose to a tiny fraction of regulated legal limits (e.g. 1 mSv/year in the U.S.). The unavoidable consequence is a reduction in luminosity; compensations are a relaxation of component specifications in the areas of the proton driver, the pion production target, radiation shielding and radiation damage to magnets etc., and of pulsed devices such as kicker magnets and lithium lenses.

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Progress in the design of FFAG magnet lattices for acceleration [3, 12] has provided the most significant recent advances in potential cost reduction for energy frontier muon colliders. As the acceleration energy increases, the relatively expensive SC rf cavities can become more and more efficiently utilized for recirculating acceleration: the Study considers as many as 100–200 passes through the same rf linac through use of several recirculating arcs of multi-pass FFAG lattices. Design improvements [14] in the average bending field of FFAG lattices for the Study's 4 TeV parameter set may allow the final acceleration arcs to fit in the collider ring, presumably resulting in a significant cost reduction.

The two 30 TeV parameter sets obtain very impressive luminosities by assuming beam currents limited only by beam power. This assumption could be met only at an isolated or elevated laboratory site that either greatly minimizes or totally eliminates any human exposure to the neutrino radiation disk. Beam currents would need to be orders of magnitude lower for many-TeV muon colliders at an existing laboratory (e.g. in the LHC tunnel). This would imply a large luminosity reduction and would strongly motivate a push towards higher specific luminosities. Lower beam emittances could help, although, for large gains in specific luminosities, cooler beams would probably need to be accompanied by a tuneshift compensation scheme (e.g. as is being developed [15] for the Fermilab Tevatron) in order to evade unacceptable beam-beam tuneshift limits.

Two straw-man parameter sets at 30 TeV in were included due to uncertainties in the difficulty of final focus designs at such high energies. Encouragingly, an attractive lattice design now exists [16] that appears to meet the more difficult of the two final focus specifications (i.e. 30 TeV set A).

3 SUMMARY

The structure, study topics, straw-man muon collider parameter sets and technical challenges for "Six-Month Study on High Energy Muon Colliders: Oct'00–Apr'01" have been summarized at one month from completion of the study. The extremely high constituent particle energies and luminosities of the parameter sets presented in table 1 continue to suggest that muon colliders could play a central role in exploring and extending the HEP energy frontier. The study has already resulted in encouraging progress in areas such as the final focus lattice design and cost-efficient acceleration.

4 REFERENCES

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Table 1: **The self-consistent "straw-man" collider ring parameter sets used for the Study.**

center of mass energy, $\mathrm{E}_{\mathrm{CoM}}$	400 GeV	4 TeV	30 TeV A	30 TeV B
description	top threshold	frontier	many-TeV	many-TeV
collider physics parameters:				
luminosity, $\mathcal{L}$ [$\mathrm{cm}^{-2}.\mathrm{s}^{-1}$]	3.0×10^{33}	5.0×10^{33}	3.0×10^{35}	2.0×10^{35}
$\int \mathcal{L}$dt [$\mathrm{fb}^{-1}/\mathrm{year}$]	30	50	3000	2000
No. of $\mu\mu \rightarrow \mathrm{ee}$ events/det/year	16 000	270	290	190
No. of (115 GeV) SM Higgs/year	14 000	55 000	5.1×10^{6}	3.4×10^{6}
CoM energy spread, $\sigma_{\mathrm{E}}/\mathrm{E}$ [10^{-3}]	1.4	1.0	0.14	0.07
collider ring parameters:				
circumference, C [km]	1.0	8.7	45	45
ave. bending B field [T]	4.2	4.8	7.0	7.0
beam parameters:				
(μ^{-} or) μ^{+}/bunch, $\mathrm{N}_0[10^{12}]$	4.0	3.5	2.3	2.2
(μ^{-} or) μ^{+} bunch rep. rate, f_{b} [Hz]	15	1.0	7.5	10
6-dim. norm. emit., $\epsilon_{6N}[10^{-12}\mathrm{m}^{3}]$	170	170	100	82
$\epsilon_{6N}[10^{-4}\mathrm{m}^{3}.\mathrm{MeV}/\mathrm{c}^{3}]$	2.0	2.0	1.2	1.0
P.S. density, $\mathrm{N}_0/\epsilon_{6N}[10^{22}\mathrm{m}^{-3}]$	2.4	2.2	2.3	2.7
x,y emit. (unnorm.) [$\pi.\mu\mathrm{m.mrad}$]	41	2.4	0.19	0.17
x,y normalized emit. [$\pi.\mathrm{mm.mrad}$]	77	46	27	24
long. emittance [$10^{-3}\mathrm{eV.s}$]	10	28	48	50
fract. mom. spread, δ [10^{-3}]	2.0	1.4	0.20	0.10
relativistic γ factor, $\mathrm{E}_{\mu}/\mathrm{m}_{\mu}$	1890	18 900	142 000	142 000
time to beam dump, $\mathrm{t}_{\mathrm{D}}[\gamma\tau_{\mu}]$	no dump	0.5	no dump	no dump
effective turns/bunch	620	450	1040	1040
ave. current [mA]	24	0.63	12	15
beam power [MW]	3.8	2.2	83	106
synch. rad. critical E [MeV]	1.1×10^{-5}	0.0013	0.11	0.11
synch. rad. E loss/turn	0.6 keV	700 keV	450 MeV	450 MeV
synch. rad. power	15 W	470 W	5.2 MW	6.6 MW
beam + synch. power [MW]	3.8	2.2	88	113
decay power into beam pipe [kW/m]	2.1	0.06	0.8	1.0
interaction point parameters:				
rms spot size, $\sigma_{x,y}$ [μm]	18	2.7	1.0	1.3
rms bunch length, σ_z [mm]	7.5	3.0	4.8	10
$\beta^{*}_{x,y}$ [mm]	7.5	3.0	4.8	10
rms ang. divergence, σ_θ [mrad]	2.3	0.90	0.20	0.13
beam-beam tune disruption, $\Delta\nu$	0.056	0.083	0.092	0.100
pinch enhancement factor, H_{B}	1.02	1.08	1.09	1.11
beamstrahlung frac. E loss/collision	negligible	6×10^{-9}	9×10^{-8}	2×10^{-7}
final focus lattice parameters:				
max. poletip field of quads., $\mathrm{B}_{5\sigma}$ [T]	10	12	15	15
max. full aper. of quad., $\mathrm{A}_{\pm 5\sigma}$[cm]	18	18	18	12
quad. gradient, $2\mathrm{B}_{5\sigma}/\mathrm{A}_{\pm 5\sigma}$[T/m]	110	130	160	250
approx. $\beta_{\max}$[km]	8	140	1800	800
ff demag., $M \equiv \sqrt{\beta_{\max}/\beta^{*}}$	100	7000	19 000	9000
chrom. quality factor, $Q \equiv M \cdot \delta$	0.003	10	4	1
neutrino radiation parameters:				
collider reference depth, D[m]	20	300	100	100
ave. rad. dose in plane [mSv/yr]	7×10^{-4}	9×10^{-4}	6	7
str. sec. len. for 10x ave. rad. [m]	1.6	1.1	1.9	1.9
ν beam distance to surface [km]	16	62	36	36
ν beam radius at surface [m]	8.4	3.3	0.25	0.25