FURTHER STUDIES ON THE PROSPECTS FOR MANY-TEV MUON COLLIDERS *

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Abstract

New self-consistent parameter sets are presented and discussed for muon collider rings at center-of-mass energies of 10, 30 and 100 TeV. All three parameter sets attain luminosities of $\mathcal{L} = 3 \times 10^{35}\ \mathrm{cm}^{-2}.\mathrm{s}^{-1}$. The parameter sets benefit from new insights gained at the HEMC'99 workshop [3] that considered the feasibility of many-TeV muon colliders.

1 INTRODUCTION

Table 1 of this paper presents self-consistent parameter sets for muon collider storage rings at center-of-mass energies of $\mathrm{E}_{\mathrm{CoM}} = 10$, 30 and 100 TeV. The parameter sets have benefitted and evolved from previous attempts at defining plausible parameter sets for many-TeV muon colliders. It is helpful to begin by reviewing these previous studies and their motivation in order to provide a context for the discussion of the current parameters.

Parameter sets for muon collider rings at energies up to $\mathrm{E}_{\mathrm{CoM}} = 100$ TeV were presented in 1998 [1] and 1999 [2]. Following this, a much improved level of understanding was then obtained from the first substantial dedicated study of such many-TeV muon colliders, which took place at the week-long HEMC'99 workshop [3]. The majority of the studies at HEMC'99 either assumed or critiqued straw-man parameter sets [4], one at $\mathrm{E}_{\mathrm{CoM}} = 10$ and two at 100 TeV, that were provided expressly for this purpose.

Besides presenting an overview of the HEMC'99 parameter sets, reference [4] also reviewed the feed-back on the parameters that was provided by the workshop. This paper should be referred to for many discussions that remain relevant for the current parameter sets of table 1.

The 48 participants at HEMC'99 considered side-by-side the accelerator challenges and the high energy physics (HEP) potential of many-TeV muon colliders. The HEP motivation for the workshop was very strong because experimental discoveries in HEP normally come from advances in energy reach, as has been emphasized and discussed in, for example, references [5] and [6]. HEP discussions specific to many-TeV muon colliders can be found in [7] and, mainly, in the HEMC'99 Proceedings [3].

Of the three many-TeV parameter sets in table 1, those at 10 TeV and 100 TeV evolved directly from the corresponding 10 TeV and (the first of the) 100 TeV parameter sets for HEMC'99, taking into account the constructive criticisms that emerged from the workshop. A mid-point energy was considered valuable for examining parameter trends with increasing energy, and the 30 TeV parameter set provides such an interpolation between the lower and higher energy sets.

Invaluable benchmarks for all of these many-TeV studies were provided by lower energy parameters that have been studied and evaluated [8, 9] by the Muon Collider Collaboration (MCC). The first column of table one shows, for comparison, the range of parameters for the muon colliders in the range $\mathrm{E}_{\mathrm{CoM}} = 0.1$, 3 TeV from the MCC's status report [9].

2 DISCUSSION ON PARAMETER SETS

The energy scale and some other parameter choices in table 1 were strongly influenced by considerations of synchrotron radiation. This imposes a natural cut-off scale for circular muon storage rings in the range $\mathrm{E}_{\mathrm{CoM}} \sim 100$ TeV since the synchrotron radiation loss at such energies has risen rapidly to become comparable to the beam power. At HEMC'99, Telnov made the additional observation [10] that the quantum nature of the sychrotron radiation could lead to beam heating, rather than cooling, for sufficiently high beam energies and small emittances. This observation effectively invalidated the more aggressive of the two HEMC'99 parameter sets at 100 TeV – which therefore won't be discussed further in this paper – and also cast some doubt on the 100 TeV parameter set with the larger emittance.

The synchrotron radiation concerns were addressed in the 100 TeV parameter set in table 1 by:

1. raising the emittance in each of the transverse coordinates by the large factor of 90. This should comfortably address Telnov's concern and result in net synchrotron cooling by raising the horizontal emittance to well above the quantum break-even value
2. increasing the collider ring circumference by a factor of two and, correspondingly, reducing the average bending magnetic field by a factor of two, to 5.3 Tesla
3. reducing the average beam current by nearly a factor of 2, to 4 mA.

The combined effect of the second and third changes was to reduce the synchrotron radiation to 50 MW, down from the previous, somewhat problematic level of 195 MW in the HEMC'99 parameter set. Although still a factor of 2.5 larger than the synchrotron power at LEP II, this reduced level was considered very appropriate for a far future collider at the energy frontier.

These changes should also help to address reservations expressed by Harrison [11] at HEMC'99 about the feasi-

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bility of 10 Tesla cosine theta dipoles in the presence of large amounts of synchrotron radiation. Besides lowering the average required magnetic field by a factor of two, it is noted that the synchrotron radiation power deposited per unit length around the collider ring has fallen by almost a factor of 8 from the HEMC'99 parameter set at 100 TeV.

In addition to the adjustments just mentioned that were specific to the 100 TeV parameter set, all three many-TeV parameter sets in table 1 were made more conservative than the HEMC'99 parameter sets in several areas:

- in recognition of the difficulty and novelty of ionization cooling, the phase space densities in table 1 were all scaled back to coincide with the upper end of the parameter choices from reference [9] for lower energy muon colliders, i.e. $2.4 \times 10^{22}\ \mathrm{m}^{-3}$.

- the final focus parameters are perhaps the most difficult of all for a non-specialist to evaluate. As has been discussed in references [1, 2, 4], the final focus difficulty can be usefully benchmarked to other muon collider and $\mathrm{e}^+\mathrm{e}^-$ collider parameter sets according to the value of 3 parameters in particular: the β^* in the x and y coordinates and of two other defined parameters, the so-called "demagnification factor" and "chromaticity quality factor". All three benchmark parameters have been somewhat relaxed in response to feed-back [4] from the studies by final focus lattice experts at HEMC'99. Further explicit magnet lattice designs, now for each of the three parameter sets in table 1, would be invaluable for assessing whether the new, more relaxed parameters have reached an acceptable level of plausibility

- the average beam currents and resulting beam powers were reduced so that the worst case, at 100 TeV, had a summed beam plus synchrotron power of 180 MW, i.e. comparable to the 170 MW beam power that has been under consideration for the Accelerator Production of Tritium project [12]

- the beam-beam tune disruption parameter was lowered slightly for all three sets to a value, in the worst case, of $\Delta\nu = 0.091$. This is not far above the impressive new LEP II record of $\Delta\nu = 0.083$ that was reported in this conference [13]

The unavoidable cost of these relaxed machine parameters was to lower the luminosity to $\mathcal{L} = 3 \times 10^{35}\ \mathrm{cm}^{-2}.\mathrm{s}^{-1}$ for each of the 10, 30 and 100 TeV parameters. This is a reduction to 30% of the luminosities, $\mathcal{L} = 1 \times 10^{36}\ \mathrm{cm}^{-2}.\mathrm{s}^{-1}$, of the corresponding HEMC'99 parameter sets for 10 TeV and 100 TeV. To put this in perspective, the new luminosities are still orders of magnitude higher than at any existing colliders and are also higher than any speculated parameters the author is aware of for plausible future machines other than muon colliders.

3 SUMMARY

The extremely high constituent particle energies and luminosities of the parameter sets presented in table 1 continue to emphasize the impressive potential of muon colliders for exploring the energy frontier of elementary particle physics. Therefore, further paper studies and simulations for many-TeV muon colliders should continue to play a valuable role in our field. More specifically, the parameter sets presented in this paper would certainly benefit from feed-back and constructive criticism by experts in areas such as the design of final focus lattices.

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Table 1: Self-consistent collider ring parameter sets for many-TeV muon colliders. For comparison, the first column displays the range of parameters for the lower energy muon colliders discussed in reference [9].

parameter set		A	B	C
center of mass energy, $\mathrm{E_{CoM}}$	0.1 to 3 TeV	10 TeV	30 TeV	100 TeV
collider physics parameters:				
luminosity, $\mathcal{L}$ [10^{35} cm^{-2}.s^{-1}]	8×10^{-5}→0.5	3.0	3.0	3.0
$\int \mathcal{L}$dt [fb^{-1}/year]	0.08→540	3000	3000	3000
No. of $\mu\mu \to$ ee events/det/year	650→10 000	2600	290	26
No. of 100 GeV SM Higgs/year	4000→600 000	4×10^6	5×10^6	6×10^6
CoM energy spread, $\sigma_{\mathrm{E}}/\mathrm{E}$ [10^{-3}]	0.02→1.1	0.42	0.080	0.071
collider ring parameters:				
circumference, C [km]	0.35→6.0	15	39	200
ave. bending B field [T]	3.0→5.2	7.0	8.1	5.2
beam parameters:				
(μ^- or) μ^+/bunch, $\mathrm{N_0}[10^{12}]$	2.0→4.0	2.9	2.0	1.6
(μ^- or) μ^+ bunch rep. rate, $\mathrm{f_b}$ [Hz]	15→30	15	7.5	5
6-dim. norm. emit., $\epsilon_{6N}[10^{-12}\mathrm{m}^3]$	170→170	125	85	70
$\epsilon_{6N}[10^{-4}\mathrm{m}^3.\mathrm{MeV/c}^3]$	2.0→2.0	1.5	1.0	0.83
P.S. density, $\mathrm{N_0}/\epsilon_{6N}[10^{22}\mathrm{m}^{-3}]$	1.2→2.4	2.3	2.4	2.3
x,y emit. (unnorm.) [$\pi.\mu$m.mrad]	3.5→620	0.84	0.19	0.040
x,y normalized emit. [π.mm.mrad]	50→290	40	27	19
long. emittance [10^{-3}eV.s]	$0.81 \to 24$	28	40	68
fract. mom. spread, δ [10^{-3}]	0.030→1.6	0.50	0.20	0.075
relativistic γ factor, $\mathrm{E}_\mu/\mathrm{m}_\mu$	473→14 200	47 300	142 000	473 000
time to beam dump, $\mathrm{t_D}[\gamma\tau_\mu]$	no dump	no dump	no dump	no dump
effective turns/bunch	450→780	1040	1200	780
ave. current [mA]	17→30	29	12	4.0
beam power [MW]	1.0→29	70	72	128
synch. rad. critical E [MeV]	$5\times10^{-7}\to 8\times10^{-4}$	0.012	0.12	1.75
synch. rad. E loss/turn [GeV]	$7\times10^{-9}\to 3\times10^{-4}$	0.017	0.52	25
synch. rad. power [MW]	1×10^{-7} →0.010	0.48	6.0	50
beam + synch. power [MW]	1.0→29	70	78	180
power density into magnet liner [kW/m]	1.0→1.7	2.0	0.84	0.48
interaction point parameters:				
spot size, $\sigma_{x,y}$ [μm]	3.3→290	1.7	0.88	0.47
bunch length, σ_z [mm]	3.0→140	3.4	4.0	5.4
$\beta^*_{x,y}$ [mm]	3.0→140	3.4	4.0	5.4
ang. divergence, σ_θ [mrad]	1.1→2.1	0.50	0.22	0.086
beam-beam tune disruption, $\Delta\nu$	0.015→0.051	0.079	0.79	0.091
pinch enhancement factor, $\mathrm{H_B}$	1.00→1.01	1.06	1.06	1.09
beamstrahlung frac. E loss/collision	negligible	2.3×10^{-8}	1.0×10^{-7}	5.5×10^{-7}
final focus lattice parameters:				
max. poletip field of quads., $\mathrm{B}_{5\sigma}$ [T]	6→12	12	12	12
max. full aper. of quad., $\mathrm{A}_{\pm5\sigma}$[cm]	14→24	21	25	31
quad. gradient, $2\mathrm{B}_{5\sigma}/\mathrm{A}_{\pm5\sigma}$[T/m]	50→90	120	97	77
$\beta_{\max}$[km]	1.5→150	520	3200	24 000
ff demag., $M \equiv \sqrt{\beta_{\max}/\beta^*}$	220→7100	12 000	28 000	67 000
chrom. quality factor, $Q \equiv M\cdot\delta$	0.007→11	6.2	5.7	5.0
neutrino radiation parameters:				
collider reference depth, D[m]	10→300	100	100	100
ave. rad. dose in plane [mSv/yr]	2×10^{-5}→0.02	1.2	4.8	20
str. sec. len. for 10x ave. rad. [m]	1.3→2.2	0.95	1.6	8.4
ν beam distance to surface [km]	11→62	36	36	36
ν beam radius at surface [m]	4.4→24	0.75	0.25	0.075