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ON THE FEASIBILITY OF A PULSED 14 TeV C.M.E. MUON COLLIDER IN THE LHC TUNNEL*

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Abstract

We discuss the technical feasibility, key machine parameters and major challenges of a 14 TeV c.m.e. muon-muon collider in the LHC tunnel [1]. The luminosity of the collider is evaluated for three alternative muon sources – the PS synchrotron, one of a type developed by the US Muon Accelerator Program (MAP) and a low-emittance option based on resonant μ-pair production.

INTRODUCTION

A next generation energy-frontier particle physics facility must provide an energy reach beyond that of the LHC, with the potential for the discovery of new physics, and still be affordable within future available budgets [2,3,4]. The proposed pulsed 14 TeV c.m.e. muon-muon collider in the CERN's 27 km tunnel – see Fig.1 - will have a significant (factor of 6-10) advantage in energy reach compared to the existing proton-proton LHC and, therefore, outstanding discovery potential despite somewhat lower luminosity [5]. The 0.146s lifetime of a 7 TeV muon enables storage and collisions for thousands of turns; that is a great advantage over the single turn of useful collisions possible in a light lepton (e^+-e^-) collider [6]. The collider cost is expected to be feasible because of the re-use of existing tunnels and the CERN injection complex, as well as the use of cost-efficient magnets and a very limited use of expensive SRF acceleration [7, 8]. The other expected advantages of this proposal are a narrow c.m. energy spread in collisions and an outstanding energy efficiency (luminosity per MW ofwall-plug electric power) [9, 10, 11].

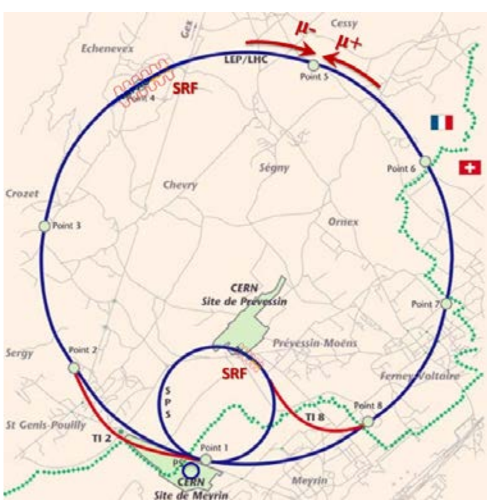

Figure 1: Schematic layout of a pulsed 14 TeV c.m.e. muon collider in the LHC tunnel.

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ACCELERATION

Due to their limited lifetime $\tau=\gamma\times 2.2\mu s$, the acceleration of muons must be fast, so that the number of surviving muons $N_f = N_0 (\gamma_0/\gamma_f)^k$, where $k=(0.105\text{GeV}/\Delta E)(C/660\text{m})$ will be acceptable. That requires a high energy gain ΔE per revolution C and a correspondingly fast change in the average magnetic field $\langle B\rangle = 2\pi E/(0.3C)$. We assume that the ring is filled with a combination of short and very high field SC magnets with DC fields of B_{SC} and longer and weaker pulsed magnets that change their fields from $-B_{pls}$ to $+B_{pls}$ (see Fig.2). For the ratio of the fields $f = B_{SC}/B_{pls}$ and the required range of acceleration $R= E_{max}/E_{inj}$, the ratio of the lengths of these magnets is $L_{pls}/L_{SC}=f(R-1)/(R+1)$ and the maximum attainable beam energy is equal to $E_{max} = B_{SC}\times(\Pi C/\pi)\times 0.3/(1+f+(1-f)/R)$, where $\Pi<1$ is the magnet packing factor.

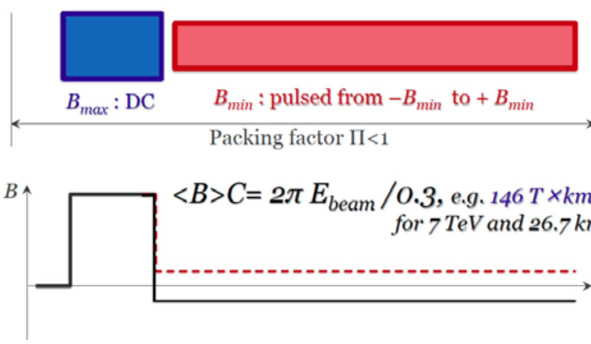

Figure 2: Arrangement (top) and field strengths (bottom) in the SC and pulsed magnets of the pulsed muon RCS.

The optimum choice of the accelerator magnet parameters depends on the technology limits for the SC and pulsed magnets. Table 1 presents major parameters for the accelerators under the assumptions of Π=0.85, 50% muon survival per stage N_f/N_0=0.5 and availability of 16 T Nb_3Sn SC magnets in the LHC tunnel and 8 T NbNi SC magnets in the SPS tunnels.

Table 1: Muon RCS Accelerator Parameters

	"LHC-S"	"LHC-D"		"SPS"
C, km	26.7	26.7	26.7	6.9
E_{max}, TeV	7	7	4	0.45
E_{inj}, TeV	0.45	4	0.45	0.03
f_{rep}, Hz	5	4	4	20
ΔE/turn, GeV	14.0	3.5	9.2	3.7
B_{SC}, T	16	16	16	8
L_{SC}, km	4.8	7.1	2.9	0.63
B_{pls}, T	3.8	2.0	1.9	0.8
τ_{ramp}, ms	42	76	34	2.6
dB_{pls}/dt, T/s	180	52	112	615

Beam acceleration from 0.45 TeV to 7 TeV can be done either in a single stage using 3.8T pulsed magnets, or – if the maximum pulsed field is limited to 2 T – in two stages (see options "LHC-S" and "LHC-D" in Table 1). Note, that 16 T SC magnets are actively and successfully being developed for the FCC project [12]. The required pulsed magnets could either be normal-conducting - up to 5T peak fields have been demonstrated in ~2ms pulsed prototypes [13-16], or superconducting. The latter are more economical. In spite of a number of specific issues, such as AC loss, cooling, quench detection and protection, field quality and material fatigue [17], ramping rates of ~1000 T/s are believed to be achievable in HTS-conductor based super ferric magnets [18-20].

Alternative acceleration scheme is a RLA, in which the arcs could be composed of multipass (5-20 turns) nonscaling FFAG lines [21], similar to those proposed for eRHIC in 2014 [22] and being constructed for the CBETA test accelerator [23]. These would be non-ramping fixed-field magnets, e.g. upto 8T NbTi SC magnets. Non-scaling or recently proposed scaling FFAG arcs [24] could also be considered in multipass synchrotron scenarios (100-1000 turns) which would require ramped frequency RF acceleration system.

COOLING AND LUMINOSITY

The collider performance is determined by the intensity and brightness of the muon source. Table 2 summarizes key parameters of three options offor a 14 TeV muon collider in the LHC tunnel (i.e., circumference of 26.7 km, beam energy of 7 TeV and beam lifetime of 0.146 s): the first one adapts the existing 24 GeV CERN PS source, the second requires a new 8 GeV linac plus storage ring while the third is based on a threshold μ^+-μ^- low-emittance muon collider (LEMC) source [25, 26].

Table 2: Options for a 14 TeV μ^+-μ^- Collider

Parameter	"PS"	"MAP"	"LEMC"
Avg. luminosity	$1.2{\cdot}10^{33}$	$3.3{\cdot}10^{35}$	$2.4{\cdot}10^{32}$
Beam $\delta E/E$	0.1%	0.1%	0.2%
Rep rate, Hz	5	5	2200
N_μ/bunch	$1.2{\cdot}10^{11}$	$2{\cdot}10^{12}$	$4.5{\times}10^7$
n_b	1	1	1
$\varepsilon_{t,N}$ mm-mrad	25	25	0.04
β^* , mm	1	1	0.2
σ^*(IR), µm	0.6	0.6	0.011
Bunch length, mm	0.001	0.001	0.0002
μ production source	24 GeV p	8 GeV p	45 GeV e^+
p or e/pulse	$6{\cdot}10^{12}$	$2{\cdot}10^{14}$	$3{\cdot}10^{13}$
Driver beam power	0.17MW	1.6MW	40 MW
Acceleration, GeV	1-3.5, 3.5-7 RCS	1-3.5, 3.5-7 RCS	40 GV, RLA 20 turn
ν radiation, mSv/yr	0.08	1.5	0.015

PS and MAP Options

The first two scenarios are extensions of the US Muon Accelerator Program (MAP) work which explored the feasibility of a muon collider, and developed detailed scenarios for 1.5, 3.0 and 6.0 TeV colliders [27, 11].

The key components of a MAP collider system are displayed in block diagram form in Figure 3(a): a high-intensity proton source, a multi-MW target and transport system for π capture, a front-end system for bunching, energy compression and initial cooling of μ's from π decay, muon cooling systems to obtain intense μ^+ and μ^- bunches, acceleration up to multi TeV energies, and a collider ring with detectors for high luminosity collisions. The parameters in Table I are scaled from the 6 TeV collider scenario presented in [11]. In the PS case, the ring cycles at 1.2 Hz, accelerating 8 bunches of $6{\cdot}10^{12}$ protons ($4.8{\cdot}10^{13}$ total), which is a modest extrapolation of achieved parameters. A fixed energy storage ring could place 1 compressed bunch at a time (5 Hz) onto a target for μ production and cooling following the baseline MAP scenario. This low-cost scenario would be an order of magnitude lower power than the MAP case, with consequently lower luminosity. It could be a first-stage scenario, to be upgraded later by a new high-power proton source.

The baseline MAP proton source produces pulses of $2{\cdot}10^{14}$ 8 GeV protons at 15 Hz. This is scaled back to 5 Hz to match the 7 TeV beam lifetime and the above-considered RCS cycle time. The MAP scenario also requires a km-scale cooling system with high-field magnets and RF, and still obtains a relatively large emittance beam for the collider.

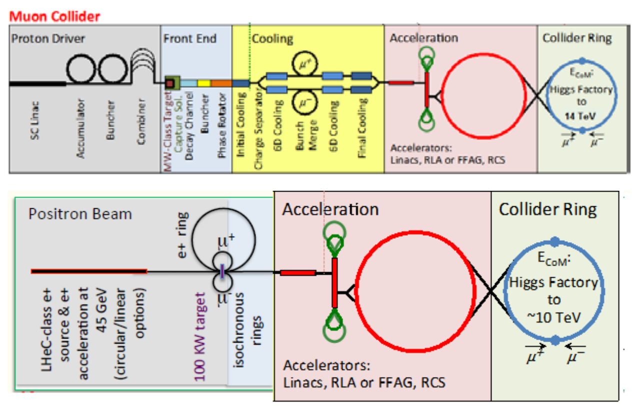

Figure 3: (a) Top- block diagram of a muon collider facility, as studied under MAP [11]; (b) bottom – same for the LEMC option.

LEMC Option

Recently, a scenario that uses resonant production of μ^+-μ^- pairs at threshold from e^+-e^- collisions has been developed [25, 26]. This has the advantage of producing μ^+-μ^- with very small emittances; it has the disadvantage of low production rate. Fig. 3(b) shows an overview of the scenario. The primary engine for this source is a ~45 GeV positron storage ring. Bunches of positrons collide with an electron target (within a material slab) producing μ^+ and μ^- at threshold, each with ~22 GeV/c momentum. A small transverse-momentum at threshold production and small spot creates µ beams with small emittance. With a slab target of 0.3mm Be, ~10^{-7} muon pairs per e^+ bunch pass are obtained. A 6.3km circumference ring with 100 bunches of $3{\times}10^{11}$ e^+ feeds 63m circumference 22 GeV μ rings, which accumulate μ's for ~ 2500 turns, obtaining bunches of ~4.5×10^7 μ's at ~2200Hz (10^{11} μ/s) [27]. The e^+ storage ring in this scenario is quite challenging. At $3\cdot10^{13}$ e^+ stored, it produces ~140MW of synchrotron radiation. An e^+ lifetime of ~250 turns implies a beam source of 40 MW of 45 GeV e^+ is required and ~$5\cdot10^{15}$ e^+ /s, much larger than that readily available from modern day positron sources. Beam dynamics simulation [27] showed lifetimes of only ~40 turns in a model lattice; this would then require ~$3\cdot10^{16}$ e^+ /s (250 MW).

The scenario accumulates μ's at 22 GeV, and therefore has a natural cycle time of ~0.45 ms (~2.2kHz). A special type of fast RLA accelerator will be required, e.g. 40 GeV/turn in the LHC tunnel providing 7 TeV of energy gain in 170 turns (15 ms). CW SRF RLA system should be capable accelerating simultaneously 15 ms/ 0.45 ms=34 bunches. Then the bunches are delivered to a 26.7 km 7 TeV DC collider ring at 2200 Hz, where each bunch collides at the detector for the muon lifetime of 1600 turns. At any given time ~200 bunches would be colliding, though with relatively low average luminosity as indicated in Table 2. The luminosity could be increased if the bunches could be superimposed, however, phase space conservation implies that bunch combination will increase emittance, reducing luminosity. A scenario that increases net luminosity must be identified.

Neutrino Radiation Considerations

A potential limitation in high energy muon colliders is the long-range radiation from the neutrinos produced from muons that decay in the Collider ring. Because of the high energy of the muons, the resulting neutrinos are emitted in a narrow plane along the ring orientation ($\theta \cong m_\mu/E_\mu$) and interact at a rate proportional to E_μ^2. While the interaction rate is low, it may accumulate into a radiologically significant dose where the beam reaches the earth's surface. A crude formula for that radiation dose in an idealized ring can be obtained from Refs. [28, 29]:

$$Dose \cong 0.57 \frac{N_\mu' E_\mu^3}{R_x^2} mSv/year$$

where N_μ' is the number of muons/second (in 10^{13}/s), E_μ is in TeV and R_x is the distance from the ring to surface exit in km. R_x is 36 km for a 100m deep ring in an idealized geometry.

This obtains the estimates shown in Table 2. The CERN external control limit is ~1.5 mSv/yr [30] and the MAP case is at this level. Some mitigation may be required. A more complete evaluation is needed. The radiation density can be reduced by ~ an order of magnitude by adding a vertical orbit variation of a few mm.

The lower luminosity PS and LEMC examples are relatively safe. The factor of 100 fewer muons used in the LEMC design provides a large margin of safety and is an important advantage of that scenario.

DISCUSSION

It is foreseeable that a 14 TeV lepton collider would have physics reach greater than a 100 TeV hadron collider. A critical difficulty toward the feasibility of performance is the muon beam cooling scenario. The MAP collaboration developed cooling scenarios that cool muons taken from a production target from ε_t ~0.02m-rad to ~25μm as well as adequate designs of very small β^* beam optics – see series of articles in a *JINST Special Issue* [31]. The first successful muon ionization cooling results are being reported by MICE collaboration [32]. The "no-cooling" (positron ring based) design needs very serious optimization to ease the facility power requirements.

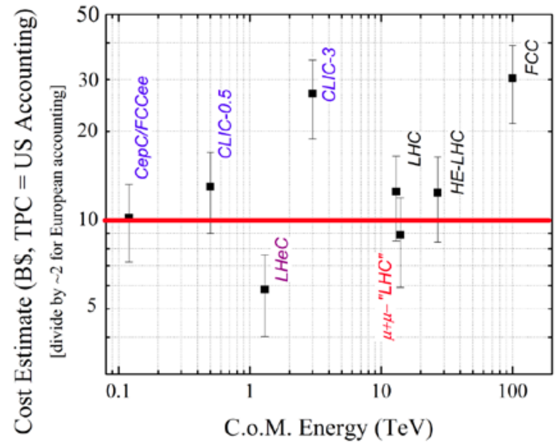

Figure 4: Cost estimates of various future colliders.

Acceleration based on pulsed and CW SRF should generally be considered feasible for gradients of about 30 MV/m (pulsed) and 20MV/m (CW). The required pulsed magnets exist only in prototypes and significant technology development is very much needed to prove technical feasibility.

The main attraction of the 14 TeV μ^+-μ^- collider discussed above is its cost feasibility – see Fig.4. The total project cost (TPC, a.k.a. "US accounting" and usually by factor of 2-2.4 greater than the "European accounting") of a future high-energy collider can be roughly estimated according to Eq. (2.1) in Ref. [7] which accounts for civil construction, technical components like NC and SC magnets and SRF, respectively, and for the total required site "wall-plug" power. In our proposal the civil construction costs can be reduced by reusing the existing 27 km LHC tunnel, the 7 km SPS tunnel and the accompanying CERN infrastructure. The incremental cost to build the proposed collider in its least expensive proton source configuration "PS" and combined system of SC and pulsed magnets to get to 7+7=14 TeV using upto 20 GeV of the SRF acceleration would be about 2B$ × sqrt(14TeV) +10 B$× sqrt(0.02TeV)=8.9±3 B$.

A high power proton driver (2 MW 8GeV beam, some 20MW of site power) is needed in the high-luminosity "MAP" configuration - see Table 2 – and will cost an extra ~10B$×sqrt(0.008)+ 2B$×sqrt(0.2)=1.8±0.6 B$.

The most expensive option is the "LEMC" – even if the SPS tunnel is reused, a new 45 GeV positron ring with 120 MW of SR power requiring 1 GV of SRF (some 250MW of total wall plug power) will cost additional ~1B$×sqrt(0.045)+ 10B$×sqrt(0.001)+2B$×sqrt(2.5)=3.6 ± 1.2 B$.

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