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Accelerator Scenario and Parameters for the First Muon Collider and Front-End of a Muon Collider

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Abstract. In November 1997 a workshop was held at Fermilab to explore the physics potential of the first muon collider, and the physics potential of the accelerator complex at the "front–end" of the collider. This paper describes the configuration of the muon collider accelerator complex, including the major accelerator parameters, and the particle fluxes and luminosities that would result from such a facility.

INTRODUCTION

The Workshop on Physics at the First Muon Collider and Front–end of a Muon Collider was held at Fermilab from 6–9 November 1997. The goal of the workshop was to explore the physics potential of each of the various options for the first muon collider (FMC), including the physics that could be pursued at the accelerator complex at the "front–end" of the collider. The accelerator parameters assumed for the workshop are based on recent studies of how the facilities at Fermilab might evolve with two goals in mind: to enhance the existing Fermilab physics program based on proton beams, and to provide what is needed for a high-energy muon collider. A summary of these parameters can be found in Tables 1–3. Figure 1 shows in a schematic way how the FMC might fit within the existing accelerator complex at Fermilab.

FRONT–END PARAMETERS

The "Front-End" of a muon collider consists of:

TABLE 1. Operational parameters of an upgraded Fermilab proton source for a Muon Collider. The right–most column shows parameters for the fully upgraded source, and the other columns for possible intermediate steps in the upgrade.

	Step 1	Step 1	Step 2	Step 3
Linac (operating at 15 Hz)	Scenario 1	Scenario 2		
Kinetic Energy (MeV)	400	1000	1000	1000
Pulse Length (μs)	0.75	0.75	0.75	0.75
H^- per pulse	1×10^{13}	1.5×10^{13}	2.5×10^{13}	1×10^{14}
Pre–Booster (operating at 15 Hz)				
Extraction Kinetic Energy (GeV)				4.5
Momentum Spread (95% FW)				0.5%
Circumference (m)				180.6
Protons per bunch				5×10^{13}
Number of bunches				2
Extracted bunch length (ns)				21
Transverse Emittance (mm–mr)				200π
Longitudinal Emittance (eV-sec)				1.8
Booster (operating at 15 Hz)				
Extraction Kinetic Energy (GeV)	16	8	16	16
Momentum Spread (95% FW)	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$	1.2%
Circumference (m)	474.2	474.2	474.2	474.2
Protons per bunch	1.2×10^{11}	1.8×10^{11}	3×10^{11}	5×10^{13}
Number of bunches	84	84	84	2
Extracted bunch length (ns)	4.9	4.9	4.9	2.3
Transverse Emittance (mm–mr)	50π	30π	50π	240π
Longitudinal Emittance (eV-sec)	2.2	1.8	1.8	4.0

TABLE 2. Parameters of muon bunches downstream of the ionization cooling channel.

	Narrow σ_p	Broad σ_p
muons per bunch	5×10^{12}	5×10^{12}
μ^+ bunches per cycle	1	1
μ^- bunches per cycle	1	1
Momentum (MeV/c)	200	200
σ_p/p	5%	10%
Bunch length (cm)	1.5	10
Normalized $\epsilon_\perp$ (mm–mr)	200π	60π
Repetition rate (Hz)	15	15
μ^+ per year (10^7 secs)	7.5×10^{20}	7.5×10^{20}

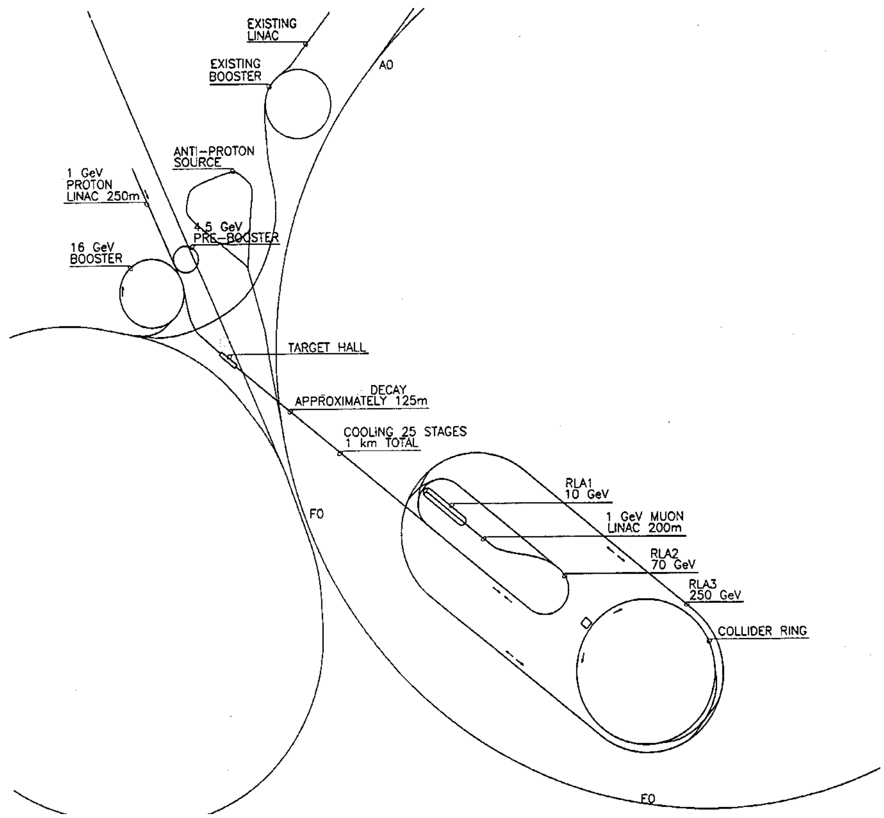

FIGURE 1. Schematic showing a plausible location for the First Muon Collider at Fermilab.

(a) A high-intensity proton source. We will assume that the proton source accelerates protons to 16 GeV/c, is cycling at 15 Hz, and produces 2 proton bunches per cycle, each containing 5×10^{13} particles. These parameters are based on the Fermilab summer study summarized in Ref. [1]. This upgrade to the existing proton source at Fermilab would require upgrading the 400 MeV Linac to a 1 GeV Linac, moving the 8 GeV Booster to a new location to overcome radiation limitations, upgrading the Booster energy to 16 GeV, and finally, adding a 4.5 GeV Pre-Booster to enable the protons to be compressed into short ($\sim$ 2 ns) long bunches. The upgrade can in principle be staged. Plausible staging steps and the associated proton source parameters are summarized in Table 1.

(b) A pion production and collection system, followed by a pion decay channel. Each incident proton bunch interacts in a target to produce $\sim 3\times10^{13}$

TABLE 3. Recirculating linear accelerator parameters.

	RLA 1	RLA 2	RLA 3
Input Energy (GeV)	1.0	9.6	70
Output Energy (GeV)	9.6	70	250
No. of turns	9	11	12
Linac Length (m)	100	300	533.3
Arc Length (cm)	30	175	520
Bunch Length (ps)	158	43	19
Revolution Time (μs)	0.9	3.1	7.0
Decay Losses	9.0%	5.2%	2.4%
Initial muons per bunch	5×10^{12}	4.6×10^{12}	4.3×10^{12}
μ^+ bunches per sec	15	15	15

charged pions of each sign. The $\pi^\pm$ are confined within a high field solenoid co-axial with the beam direction. At the end of a 20 m long decay channel consisting of a 7 Tesla solenoid with a radius of 25 cm each incident proton results in about 0.2 muons of each charge. If in each accelerator cycle the first incident proton bunch is used to make and collect μ^+s, and the second bunch used for μ^-s, there will be about 10^{13} muons of each charge available at the end of the decay channel per cycle.

(c) A muon cooling channel. The muons exiting the decay channel populate a very diffuse 6–dimensional phase–space. The diffuse muon cloud must be cooled using a new fast cooling technique to form an intense beam before most of the muons have decayed. The cooling method proposed for the muon collider is ionization cooling [2]. Table 2 summarizes the properties of the muons at the end of the cooling channel. Note that the phase–space occupied by the muons can be optimized either to maximize the luminosity of the collider, or alternatively to minimize the beam energy spread at the expense of luminosity. At the end of the cooling channel each muon bunch is expected to contain about 5×10^{12} muons with a momentum of order 200 MeV/c.

(d) A muon acceleration system. A series of recirculating linear accelerators (RLAs) to accelerate the muons up to the colliding beam energy. Each RLA consists of two Linacs connected together by two arcs. Three RLAs with the operational parameters summarized in Table 3 would be able to accelerate the muons up to 250 GeV.

The front–end accelerator complex could be used for a variety of fixed target type physics experiments. Note first that the new Fermilab Main Injector can probably accept a factor of ~ 5 more protons per cycle than can be provided by the existing Fermilab proton source. Hence, an upgraded proton source of the type required for a muon collider would directly benefit the foreseen FNAL MI program. In addition, a muon collider front–end offers many other possibilities, some of them quite unique. Four working groups

TABLE 4. Neutrino beam pulses from the straight sections of the Recirculating Linacs.

	1	2	3	4	5	6	7	8	9	10	11	12
RLA 1												
E_μ(start) (GeV)	1.0	1.96	2.92	3.88	4.84	5.8	6.76	7.72	8.68	9.64		
E_μ(end) (GeV)	1.48	2.44	3.4	4.36	5.32	6.28	7.24	8.2	9.16			
$< E_\mu >$ (GeV)	1.24	2.2	3.16	4.12	5.08	6.04	7.0	7.96	8.92			
$\gamma c\tau$ (km)	7.72	13.7	19.7	25.7	31.7	37.8	43.8	49.6	55.7			
$f_{decay} = 100m/\gamma c\tau(\%)$	1.3	0.73	0.51	0.39	0.32	0.26	0.23	0.20	0.18			
N_{decay}/bunch ($\times 10^{10}$)	6.5	3.7	2.6	2.0	1.6	1.3	1.2	1.0	0.9			
N_{decay}/year ($\times 10^{18}$)	9.8	5.5	3.8	2.9	2.4	2.0	1.7	1.5	1.4			
RLA 2												
E_μ(start) (GeV)	9.6	15.1	20.6	26.1	31.6	37.1	42.6	48.1	53.6	59.1	64.6	70.1
E_μ(end) (GeV)	12.4	17.9	29.4	28.9	34.4	39.9	45.4	50.9	56.4	61.9	67.4	
$< E_\mu >$ (GeV)	11.0	16.5	22.0	27.5	33.0	38.5	44.0	49.5	55.0	60.5	66.0	
$\gamma c\tau$ (km)	68.7	100	140	170	210	240	270	310	340	380	410	
$\gamma c\tau$ (km)	68.7	100	140	170	210	240	270	310	340	380	410	
$f_{decay} = 300m/\gamma c\tau(\%)$	0.44	0.30	0.21	0.18	0.14	0.13	0.11	0.097	0.088	0.079	0.073	
N_{decay}/bunch ($\times 10^{10}$)	2.0	1.4	0.97	0.83	0.64	0.60	0.51	0.45	0.40	0.36	0.34	
N_{decay}/year ($\times 10^{18}$)	3.0	2.1	1.5	1.2	0.96	0.90	0.77	0.68	0.60	0.5 4	0.51	
RLA 3												
E_μ(start) (GeV)	70	85	100	115	130	145	160	175	190	205	220	235
E_μ(end) (GeV)	77.5	92.5	108	123	138	153	168	183	198	213	228	243
$< E_\mu >$ (GeV)	73.8	88.8	104	119	134	149	164	179	194	209	224	239
$\gamma c\tau$ (km)	460	550	650	740	840	930	1000	1100	1200	1300	1400	1500
$f_{decay} = 533m/\gamma c\tau(\%)$	0.12	0.10	0.08	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.04	0.04
N_{decay}/bunch ($\times 10^{10}$)	0.52	0.42	0.35	0.31	0.27	0.25	0.23	0.21	0.1 9	0.18	0.16	0.15
N_{decay}/year ($\times 10^{18}$)	0.78	0.63	0.53	0.46	0.41	0.37	0.34	0.31	0.28	0.26	0.25	0.23

(Low Energy Hadron Physics, Neutrino Physics, Deep Inelastic Scattering, and Slow/Stopped Muon Physics) were convened in the workshop to consider the range of possibilities.

The neutrino beams would result from decays of circulating muons. A muon collider accelerator complex offers the very attractive possibility of making intense neutrino beams using muon decay channels consisting of straight sections in the RLAs or in the collider itself. The resulting beams would have precisely calculable fluxes [3] and, for μ^- decays, would be a mixture of 50% ν_μ and 50% $\bar{\nu}_e$. This would provide a uniquely "clean" tool for neutrino physics.

The characteristics of the neutrino pulses downstream of the RLAs are summarized in Table 4.

THE FIRST MUON COLLIDER

The workshop parameters for the First Muon Collider are shown in Table 5. Note that the assumptions that went into computing the luminosities were somewhat conservative. To obtain a more aggressive but still reasonable set of goals for the FMC these luminosities can be multiplied by a factor of three.

TABLE 5. Parameters for (going from left to right) a narrowband low–energy, broadband low–energy, medium–energy, top factory, and higher–energy FMC.

$\sqrt{s}$	100	100	200	350	500
σ_p/p	3×10^{-5}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
Muons per bunch	3×10^{12}	3×10^{12}	2×10^{12}	2×10^{12}	2×10^{12}
Number of bunches	1	1	2	2	2
Repetition rate (Hz)	15	15	15	15	15
Norm. $\epsilon_\perp$ (mm-mr)	297π	85π	67π	56π	50π
Collider circum. (m)	380	380	700	864	1000
f_{rev} (Hz)	7.9×10^5	7.9×10^5	4.3×10^5	3.5×10^5	3.0×10^5
turns/lifetime	820	820	890	1260	1560
$\beta^\star$ (cm)	13	4	3	2.6	2.3
σ_z (cm)	13	4	3	2.6	2.3
σ_r (μm)	286	85	47	30	22
L_{peak} $(cm^{-2}s^{-1})$	6×10^{32}	7×10^{33}	6×10^{33}	1×10^{34}	2×10^{34}
L_{av} $(cm^{-2}s^{-1})$	5×10^{30}	6×10^{31}	1×10^{32}	3×10^{32}	7×10^{32}

SUMMARY

The tables presented here contain the parameters, fluxes, and luminosities that were used by the working groups as they evaluated the physics potential of a First Muon Collider and of its front end. Summaries of the physics potential of a facility operating with these parameters can be found in references [4] and [5].

Acknowledgments

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REFERENCES

1. S. Holmes et al., "A Development Plan for the Fermilab Proton Source", FERMILAB-TM-2021, September 1997, unpublished.
2. A.N. Skrinsky and V.V. Parkhomchuk, Sov. J. Part. Nucl. **12**, 223 (1981).
3. S. Geer, "Neutrino Beams from Muon Storage Rings: Characteristics and Physics Potential", Fermilab-PUB-97/389 (hep-ph/9712290), submitted to Phys. Rev. D.
4. S. Geer, Workshop on Physics at the First Muon Collider and Front-End of a Muon Collider: A Brief Summary", Fermilab-Conf-98/063.
5. C. Quigg, "Physics with a Millimole of Muons", Fermilab-Conf-98/073-T.