m^+-m^- COLLIDER: m^+-m^- GENERATION, CAPTURE AND COOLING

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ABSTRACT

A μ^+-μ^- collider requires a high-intensity proton source for π-production, a high-acceptance π-μ decay channel, a μ-cooling system, a rapid acceleration system, and a high-luminosity collider ring for the collision of short, intense μ^+-μ^- bunches. Critical problems exist in developing and compressing high-energy proton bunches for producing π's, in capturing π's and their decay μ's, and in cooling μ's into a compressed phase-space at which high luminosity collisions are possible. These problems and some possible solutions are discussed; the current μ^+-μ^- collider research program is described

1. INTRODUCTION

Considerable interest has developed in the possibility of a high-energy high-luminosity μ^+-μ^- collider,[1,2,3,4] and a multi-laboratory collaboration has been formed to study this concept.[4] Initially the concept of a 4 TeV collider with a luminosity of L = 10^{35}cm^{-2}s^{-1} was developed.[1] Recently the research has concentrated on developing a design concept for a lower-energy first μ^+-μ^- collider at ~100GeV, and in developing the new technologies needed for that and any μ^+-μ^- collider. [5]

Particle physics has identified some clear physics goals for μ^+-μ^- collider technology. Recent LEP and SLC results imply that the Higgs mass is in the 100—170 GeV range. A small energy spread μ^+-μ^- Collider at that energy would be uniquely capable of precise Higgs studies.[6] Also, ν-oscillations have been recently reported. These could be checked by ν-beams that are produced through μ^+-μ^- collider methods of intense π production, μ collection and cooling, with the ν-beams produced by μ-decay in a storage ring.[7,8]

The first μ^+-μ^- collider would be a low-energy machine (possibly at 50×50 to 70×70 GeV), designed both to test the basic concepts as well as to provide significant physics at the Higgs mass, and may be at somewhat lower intensity. This machine would be particularly valuable if it could deliver high luminosity at very small energy spreads, matched to the expected Higgs width of δE ~ 1.5 KeV. Later, higher-energy machines could probe energy frontiers beyond that accessible to existing technology.

Table 1 shows parameters of possible μ^+-μ^- colliders, including a ~100GeV Higgs factory, a 400 GeV and a 4 TeV machine, and Fig. 1 shows a layout view of a 100-GeVcollider facility. The collider requires a high-intensity proton source for π-production, a high-intensity π-production target with a high-acceptance π-μ decay channel, a μ-cooling system to cool the beams to collider requirements, a rapid acceleration system, and a high-luminosity collider ring for the collision of short, intense μ^+-μ^- bunches.

In Table 1, nearly identical proton source parameters are shown for each collider case. This is based on an assumption that a single new high-intensity source is developed and is used to drive different colliders. Also in developing parameters for different energy colliders, we have assumed that the cooling system can cool in 6-D normalized phase space to a fixed emittance, which can then be distributed betweeen transverse and longitudinal for differing collider requirements. (Lower-energy colliders require smaller longitudinal phase-space, and a Higgs Collider shoud have very small energy spread.) Greater variations in p-source and cooling scenarios are possible.

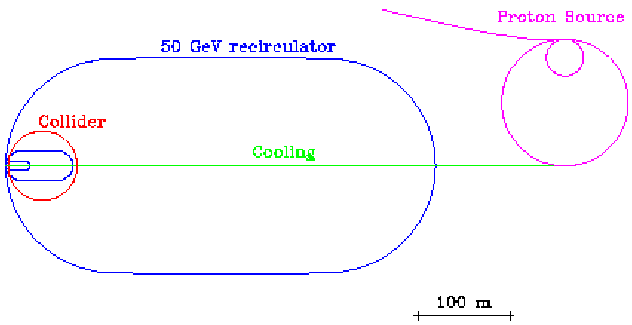
The critical property of muons in a collider is that the muons decay, with a lifetime of τ_μ = 2.2 (E_μ/m_μ) μs. This is sufficient for multiturn acceleration and storage, but only a few hundred turns can be allotted to the μ^+-μ^- collection, cooling, and acceleration, which means that obtaining high luminosity requires frequent production of high-intensity μ-bunches and compressing and cooling the bunches to high densities.

In this paper we discuss the key technologies which are needed to develop these high intensity μ^+-μ^- beams, identify the critical difficulties, and describe the current and planned research program on these topics. We also discuss the remaining unsolved problems and challenges.

Table 1: Parameter lists for m^+-m^- Colliders

Parameter	Higgs Factory (Small—Large δE)	Top Source	4TeV
Collision Energy($2E_\mu$)	100	400	4000 GeV
Energy per beam(E_μ)	50	200	2000 GeV
Luminosity($L=f_0 n_s n_b N_\mu^2/4\pi\sigma^2$)	10^{31}—10^{32}	10^{33}	10^{35} cm^{-2}s^{-1}
Source Parameters (4 MW p-beam)			
Proton energy(E_p)	16	16	30 GeV
Protons/pulse(N_p)	4×2.5×10^{13}	4×2.5×10^{13}	4×3×10^{13}
Pulse rate(f_0)	15	15	15Hz
μ acceptance(μ/p)	0.2	0.2	.2
μ-survival (N_μ/N_{source})	0.4	0.4	.4
Collider Parameters			
Collider mean radius(R)	50	150	1200m
μ /bunch ($N_{\mu\pm}$)	4×10^{12}	2×10^{12}	2.5×10^{12}
Number of bunches(n_B)	1	2	2
Storage turns($2n_s$)	1000	1500	1800
Norm. emittance(ε_N)	0.028– 0.01	10^{-2}	5×10^{-3}cm-rad
μ-beam emittance($\varepsilon_t=\varepsilon_N/\gamma$)	(5.6– 2)×10^{-5}	5.3×10^{-6}	2.5×10^{-7}cm-rad
Interaction focus β_o	13– 4	1	0.3 cm
IR Beam size $\sigma=(\varepsilon\beta_o)^{1/2}$	270– 90	23	2.1μm
δE/E at collisions	0.003– 0.12	0.12	0.12%

Figure 1 Overview of a 100 GeV μ^+-μ^- Collider facility showing p-source, μ-Cooling, recirculating-linac acceleration (RLA) and collider.



2. PROTON SOURCE

The collider requires an intense source of protons for $\pi \Rightarrow \mu$ production. Present studies indicate that a proton beam at energies of 16—30 GeV at a beam power of ~4 MW is optimal. This is an intensity comparable to that proposed for a KAON factory[9] or a spallation neutron source,[10] but with the significant difference that the beam is extracted in short bunches to set up rf rotation (i. e., bunches of 2.5×10^{13}p of ~1 ns). Strategies to reach this intensity are being developed[5], and considerable variation is possible, as long as the high beam power in a bunch structure suitable for development of intense μ-bunches is obtained.

Table 2 shows parameters of a possible proton driver, which consists of a 1 GeV linac, a 3 GeV prebooster and a 16 GeV booster. The parameters are from a Fermilab-based plan for a multipurpose proton source upgrade (K-ν factory/μ-collider/Tevatron, etc.), which would replace the existing Fermilab booster.[11] A new booster tunnel would be required, and the linac would be either extended from its current location or moved.

The 1 GeV Linac is based on the Fermilab 400MeV linac, which consists of a 18 kV magnetron ion source which feeds a 0.75 MV Cockroft-Walton column, followed by a 100 MeV 201 MHz linac, and a 300 MeV 805 MHz side coupled linac. The upgrade requires a magnetron source which can provide 100 mA of beam in 250μs pulses (~1.2×10^{14} H^- ions). The additional 600 MeV structure is an extension of the 805 MHz linac, using 11½ additional modules (131.3m).

The H^- ions are multiturn injected through a foil stripper into the 3 GeV prebooster (500 turns), where they are captured in 6.64 MHz buckets and accelerated as 4 bunches of 2.5×10^{13} protons to 3 GeV in 33ms. The four bunches are then transferred into matched buckets in the 16 GeV booster for acceleration to full energy. At full energy, the bunches are compressed to minimal lengths (σ_z ~ 0.3m) and extracted to the π-production target. The 16 GeV ring circumference is matched to that of the existing Fermilab booster for compatibility with existing Fermilab accelerators.

A key limitation is transverse space charge and the design goal is to keep the space-charge tune-shift $\delta\nu = r_p N/(4\varepsilon_n\beta\gamma^2 B)$ less than ~0.25—0.4 throughout the cycle, where r_p is the classical proton radius, N the number of protons, B the bunching factor(average/peak current), and ε_n is the normalized rms emittance. This is minimized by higher injection energies, and large emittances, and larger B. ε_n is increased to ~ 33 mm-mrad (rms) by painting the beam across the foil in multiturn injection. B is conservatively set at 0.25 at injection into the prebooster, which is initially filled with 4 bunches (large B). The beam bunches as it accelerates, and is transferred to the larger ring at 3 GeV, at $\delta\nu \cong 0.25$ (small B but larger γ), with minimal bunch lengths at the extraction bunch rotation.

The beam transports of both rings consist of rapid-cycling separated-function magnets. The peak dipole field is set at 1.3 T in both lattices, and the transition energy ($\gamma_t m_p c^2$) is set above extraction so that the beams are always below transition, which avoids instabilities due to "negative mass" and at transition crossing, and maintains a stable natural chromaticity. The high-γ_t is obtained by use of a "flexible-momentum-compaction" lattice, which gives a tuneable γ_t..[12] The large emittances imply large apertures (13cm for the 3 GeV ring and 10cm for the 16 GeV ring). To minimize eddy currents from rapid-cycling, a high-impedance beam pipe using Inconel or ceramic with conducting wires/strips is needed.

Griffin has developed an acceleration scenario with rf system designs for each ring. [13] The rf cavities are 1m long units with ceramic accelerating gaps and metal-alloy tape-wound cores, with outboard inductive tuners containing NiZn ferrite rings with bias current windings for tuning from 6.6 to 7.4 MHz during the acceleration. Power amplifiers for cavity excitation and transient beam loading compensation are coupled directly to the accelerating gaps. 10 such cavities can generate up to 200 kV in the prebooster, and 40 cavites can produce 1.5 MV in the booster. Bunches injected with ~100ns full-width in the prebooster are compressed to ~20ns after booster acceleration, and rotated to ~6ns ($\sigma_{rms} \cong$ 1ns and $\delta E = \pm200$ MeV) at booster extraction. An inductive insert to cancel space charge is helpful in the final compression. Simulations of this acceleration and bunching have been performed.[14]

Some critical experiments testing elements of the proton source design have been performed. A set of inductive ferrite modules was placed in the LANL Proton Storage Ring. Longitudinal space charge effects were reduced without generating instability, and the results supported the use of inductive inserts to cancel space charge.[15] At the BNL AGS experiments in bunching the beam near transition were performed, at parameters similar to the post-acceleration bunching of the proton source. The rms bunch length of the 3 MHz, 8 GeV bunches was reduced from 6.7 to 2.1 ns.[16] The results support the proposition that initially long proton bunches can be accelerated and compressed to ns lengths, as is required for the μ^+-μ^- collider.

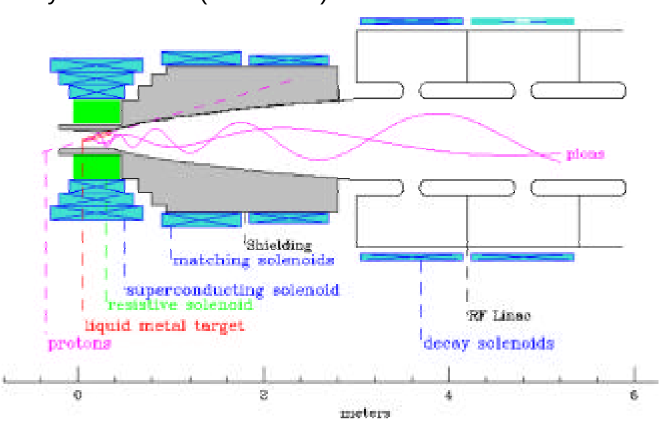
3. p-PRODUCTION AND m-COLLECTION

The purpose of the production target and subsequent transport is to produce the maximum number of muons which can be subsequently accepted and cooled into collider bunches. From recent studies, maximal capture is obtained by immersing the production target in a high-field solenoid, with sufficient aperture such that most π's are trapped (a 20T solenoid with 7.5cm radius is proposed). This is followed by a solenoid transport which accepts most of the low energy μ's (100—600 MeV/c) produced by π-decay. (see fig. 2) An rf system within that decay transport reduces the energy spread by "rf rotation", in which the faster particles decelerate while slower ones accelerate. This transforms the short-bunch beam on target producing a large momentum spread in μ's to a longer μ-bunch with reduced δp/p.

Table 2: Parameters of 16 GeV Proton Source

Parameter	Linac	PreBooster	Booster
Final Kinetic Energy (E_p)	1	3	16 GeV
Pulse rate(f_0)	15	15	15Hz
Protons/pulse($n_B \times N_p$)	40000×3 10^9	4×2.5 10^{13}	4×2.5 10^{13}
Length/circumference	+134	158	474 m
Emittance (95%, 6×rms)	6	200	240πmm-mrad
Dipole packing factor (1.3 T peak field)		0.39	0.575
aperture		13	10cm
tunes(ν_x,ν_y)		3.9,2.4	9.4,4.9
transition γ (γ_T)		7	25
rf Parameters			
rf frequency(f_{RF})	201→805	6.6–7.4	7.4–7.5MHz
rf harmonic	-	4	12
rf voltage /turn		0.2	1.2 MV
rf length		10	40 m

Figure 2: Capture solenoid and match to transport for π→μ decay + rf rotation (from ref. 5).



Extensive simulations on π-production as a function of proton energy, target material and geometry within a capture geometry have been performed, using Monte Carlo codes such as MARS[17] (and DPMJET[18] and ARC[19])and these codes have been verified by comparison with experiments, particularly the recent pion production experiment 910 at BNL.[20] They show that the target should be ~2—3 interaction lengths of a high-density, relatively high-Z material. Optimal proton energy was in the 10-30 GeV range. A target radius of ~1cm appears optimal, maximizing secondary production while minimizing absorption. Tilting the target by 100—150mrad was found to minimize absorption of low-energy π's, which follow helical trajectories through the magnetic region. π-yield is maximal for longitudinal momenta of the same order as the rms transverse momentum (~200 MeV/c). The magnetic field (20T, r=7.5cm) is designed to capture these momenta in helical orbits.[21]

About 400 kW of energy is deposited in the target and handling that is a serious problem. Cooling with a thermal bath would lead to large π-absorption and thermal radiation is insufficient. Moving solid metal and flowing liquid jet targets are under consideration. Conducting liquid jets may be distorted by the magnetic fields; however, nonconducting jets are considered. A moving cable or "band-saw" target is possible.

Following the target, the magnetic field is adiabatically decreased and the beam size is increased, following Br^2 = constant to B=5—1.25T (r=15—30cm). The magnetically confined transport continues through a sufficient length for π-decay. This transport also contains a multiharmonic ~30—150MHz rf system embedded in a short-period solenoid transport In studies rf rotation section solutions with lengths of 40—80m containg a total of 200—500 MV of rf cavities. In simulations ~0.35 μ's (of one sign)/proton are captured from 16—30 GeV protons within an acceptance window of a bunch length of ~6m and δE ~±100 MeV. This is roughly half the number of initially produced π's.[1,22,23] Energy selection in the μ-decay can be used to select a relatively high polarization in the μ-beams [24]

Significant problems exists in designing the rf + focusing system, since it requires combining large low-frequency, relatively high-gradient cavities with relatively high-field superconducting solenoids. Several design iterations have been considered; a recent one (see fig.2) uses low-field 1.25T msgnets completely outside the cavities; a previous one uses 5T magnets placed in the cavity irises.

An experiment is proposed at the AGS on targetry related issues, which will test some of these systems.[25] It would include tests of liquid jet and other targets, placed within magnets, and then with beam, measuring π-production. An rf cavity with solenoid would be added to test rf rotation components.

4. m-COOLING

After rf rotation the beam still has both a large momentum spread (δp/p ≅ 10%) and transverse phase space (ε_T ≅ 0.015 m-rad). The μ^+-μ^- collider concept relies on ionization cooling to compress the beam phase-space volume to obtain high luminosity. In ionization cooling,[2,3] the beam loses transverse and longitudinal momentum while passing through a material medium, and regains only longitudinal momentum in acceleration cavities. Cooling by large factors requires successive stages of energy loss and reacceleration (20 to 50 stages).[1] Since ionization cooling does not directly cool the beam longitudinally, these stages must include wedge absorbers at non-zero dispersion to exchange longitudinal and (cooled) transverse phase-space.

The differential equation for rms transverse cooling is:

$$\frac{d\varepsilon_T}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_T + \frac{\beta_\perp E_s^2}{2\beta^3 m_\mu c^2 L_R E}$$

where the first term is the frictional cooling effect and the second is the multiple scattering heating term. Minimal heating requires that $\beta_\perp$, the betatron focusing amplitude at the absorber, be small, and that L_R, the absorber radiation length, be large (light elements; i.e. Li or Be or H). The energy loss mechanism also causes energy-loss straggling, which naturally sets rms δp/p at the ~4% level, even with longitudinal cooling.

The beam dynamics problems in μ-cooling include the beam-material interactions intrinsic to the cooling process, the single-particle beam transport problems associated with obtaining strong foci at the absorbers, the chromatic effects of ~4% δp/p, dispersion and transverse matching at wedge absorbers, as well as longitudinal motion control with rf reacceleration, and the multiparticle constraints imposed by space-charge and wake-fields in the short intense bunches, where the beam intensifies as it is cooled.

Lattices for cooling have been developed and a favored design includes sequences of solenoid cells with rf cavities and LiH or H absorbers at low-β of the lattice.[26] Another desirable focusing situation is obtained by confining the cooling beam within a high-current Li rod which both focuses and cools the beam.[27] The transport must include arc segments with wedges for cooling longitudinally; obtaining large δp/p acceptance configurations with cooling and transport stability is nontrivial.

An outline design scenario for μ-cooling has been developed, and critical sections of the cooling section have been simulated.[28,29] Figure 3 displays transverse phase space before and after a cooling section which cools transverse phase space by $10^4\times$. However an integrated design including the full complexity of the beam transports, reacceleration and bunching, and including nonlinear beam dynamics coupled with the ionization interactions, has not yet been fully developed. Initial cooling experiments verifying cooling efficiency must also be developed. Because effective μ-cooling has not yet been demonstrated and because of its importance in establishing the feasibility of a μ^+-μ^- collider, an extensive R&D program has been established.

Simulation efforts have been intensified, by developing the codes ICOOL[30] and DPGeant[31] and extending their capabilities to include a complete description of μ-material interactions and beam optics. These tools will be used to develop and optimize complete cooling systems.

An experimental collaboration called MUCOOL has been formed in order to establish and demonstrate the technologies needed for effective μ-cooling.[32] In MUCOOL, a muon beam line will be built which would include equipment for precision measurement of muon trajectories entering and leaving a cooling system test channel. Beam cooling sections will be inserted into the test channel, and measurement of muon beams entering and leaving the channel will determine the degree of cooling effectiveness. The cooling sections consist of arrays of absorbers within focusing systems with reacceleration rf. As an initial example a cooling system which includes H_2 cooling elements within strong (15T) solenoids and 800MHz rf cavities has been designed. Detailed designs of rf systems, solenoids and detector components have been developed, and construction of a prototype rf cavity with Be windows has begun.[33] MUCOOL will also include development of Li lenses for cooling, with construction and testing of a 1m long, 1cm radius, 10 T lens.

Figure 3. Transverse phase space (p_x-x) before and after a Li lens cooling channel which reduces ε_T from 0.01 to 0.00009 m-rad.

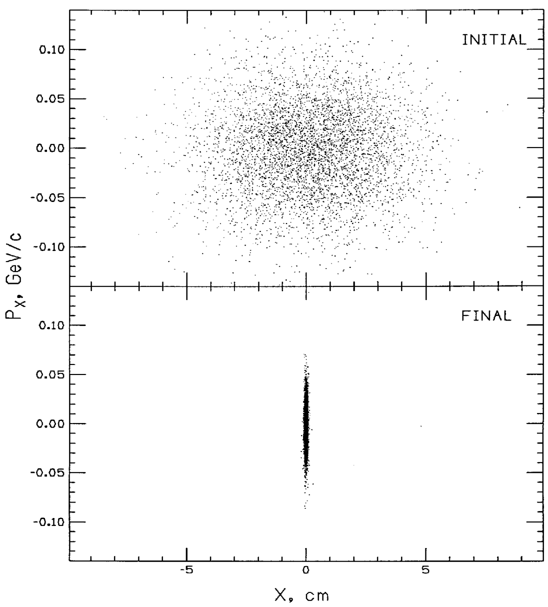
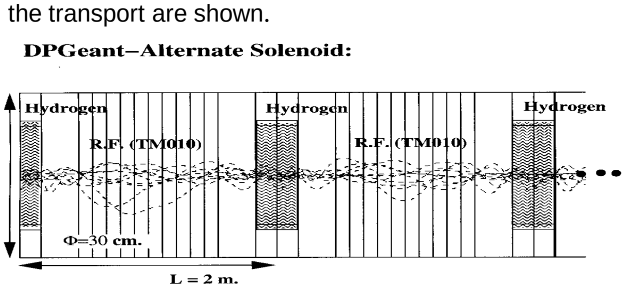


Figure4. schematic view of 2 cells of an alternate solenoid cooling system, with H_2 absorbers and 1.3m multicell Cu copper cavities with Be windows. Simulation tracks through the transport are shown.



5. m-ACCELERATION AND COLLISIONS

Acceleration must be completed before μ-decay. This constraint can be written as the equation:

$$eV_{rf}' >> \frac{m_\mu c^2}{L_\mu} \cong 0.16 \ \text{MeV/m},$$

where eV_{rf}' is the acceleration rate, and L_μ is the μ decay length (660m). Relatively fast acceleration is required, and two alternatives have been developed: recirculating linacs (RLAs) or very rapid-cycling synchrotrons (RCS). In both cases significant challenges exist in obtaining acceleration without phase-space dilution. Simulations show that longitudinal matching is relatively straightforward,[34] and transverse matching is possible. However precise matching in rapid-cycling systems may be difficult, and beam decay within the transport and acceleration must be tolerated.

After acceleration to full energy, the μ^+-μ^- beams are inserted into a storage ring for multiturn collisions at full energy until μ-decay. The number of storage turns before decay is ~300B, where B is the mean ring bending field in T, or ~2000 turns at B=6.7 T. High luminosity requires that the beams be focussed to small spots and short bunches at the interaction points (IPs). It also implies high beam densities and that could allow multiparticle instabilities. The small focus at the IP with the geometric and chromatic acceptance requirements is a significant design challenge.[35]

6. CURRENT R&D PROGRAM

Following initial studies presented at Snowmass, the high-energy physics advisory panel recommended expanded research including simulations and experiments to determine the feasibility of μ^+-μ^- colliders.[36] In response the μ^+-μ^- collaboration is expanding its efforts, including experiments on targetry/production at BNL and cooling at Fermilab. (discussed above) Much research and innovation is needed toward obtaining complete and optimal solutions to the difficult problems in developing a practical μ^+-μ^- collider.

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