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Beam Dynamics Problems of the Muon Collaboration: ν-Factories and μ^+-μ^- Colliders

David Neuffer
Fermilab, Batavia IL 60510

Abstract. We present some of the outstanding beam dynamics problems that are being explored by the muon collaboration, which is studying potential uses of cooled muons in neutrino factories and muon colliders. These problems include the search for more efficient muon capture and cooling methods, improved acceleration options, and more affordable neutrino factory scenarios. Recent progress in ring coolers enables longitudinal cooling and may extend cooling performance to the level needed for μ^+-μ^- colliders.

1. Introduction

The relatively long lifetimes of muons, coupled with their properties as high-mass leptons, make them a candidate for collection, acceleration and storage scenarios in high-energy physics facilities. The Muon collaboration is studying these possibilities, initially for a future μ^+-μ^- collider [1,2], and more recently for a ν-factory. The collider concept is displayed in fig. 1, and the ν-factory concept [3,4] is displayed in fig. 2.

The ν-Factory feasibility studies [3,4] have established that a high-intensity ν-Factory could be built within present technological capabilities, but that its expected cost would be a bit larger than the currently limited resources of US high-energy physics. The key high-cost systems are the μ-capture and rf rotation systems, the beam cooling, and the acceleration components. The present R&D efforts are focussed on developing more affordable alternatives and improvements to these systems; improved performance with reduced cost would make the facility a leading candidate for the next world high-energy physics facility.

This R&D requires extensive use of computational accelerator physics (CAP). These efforts are focussed on improving the $\pi \to \mu$ collection scenarios, and the cooling concepts, as well as developing acceleration scenarios. Promising approaches in each of these areas are developing; for example, ring cooler approaches have demonstrated "emittance exchange" required for simultaneous longitudinal and transverse cooling. These are discussed below. Initial experiments on possible target systems and on initial cooling systems are in progress and also require CAP support.

2. Muon production and capture problems

An R&D priority is the development of an optimal μ production and capture system. Fig. 1 shows the current muon collaboration baseline design. It requires a high intensity proton source (up to 10^{14} ~20 GeV protons per pulse, operating at ~15Hz). Intense proton bunches from this source are sent onto a liquid-metal target, producing a large number of π's which are captured within a strong-focussing (~20T) solenoidal field. The captured π's decay in the following transport. This design has been developed through extensive use of CAP studies, most notably using the particle interaction and production code MARS of N. Mokhov et al., but also using magnet design and target material response codes. Variations on this scenario continue to be studied, searching for lower cost and/or higher performance. Variations in the driver p-beam, different targets (solid Cu or C or …), varying capture optics (Li lens, magnetic horns, quads, etc.), and differing following μ-transport systems can be considered and studied, using CAP.

2.1 μ-bunching and phase-energy rotation options

Following initial capture, the muon beams must be matched into the following cooling and/or acceleration systems. The initial step is to reduce the energy spread. In the collider studies [1, 2] this is done by phase-energy rotation using low-frequency rf (~30 MHz), which is matched into a low-frequency initial cooling system. For the ν-factory scenarios, [3,4] an induction linac is used to to decelerate the high-energy "head" and accelerate the low-energy "tail" of a muon bunch, obtaining a long bunch (~30-100m) with small energy spread (~10MeV). This is trapped into a train of 200 MHz bunches, which is then injected into a 200 MHz cooling system. (~200 MHz rf systems may be an optimum in cost/acceptance for cooling.) Both of these methods require development and construction of large and expensive novel acceleration systems, with gradients and total voltages substantially larger than currently available.

More recently, a variant capture and phase/energy rotation system using only ~200MHz rf has been proposed.[6] In this variant, the muons first drift, lengthening into a long bunch with a high-energy "head" and a low-energy "tail". Then, the beam is transported though an "adiabatic buncher", a section of rf cavities that gradually increase in gradient and decrease in frequency (from ~300 to ~200MHz). The rf wavelength is fixed by requiring that reference particles at fixed energies remain separated by an integer number of wavelengths. This forms the beam into a string of bunches of differing energies (see fig. 4). Following the buncher, the beam is transported through a high-gradient fixed-frequency (or slightly varying) rf section that aligns the bunches to (nearly) equal central energies, suitable for injection into a fixed-frequency ~200 MHz cooling system.

This high-frequency bunching and phase-energy rotation uses present technology and should be much more affordable than low frequency options. Much more simulation and optimization study is needed to determine whether it traps sufficient useable muons for cooling and acceleration.[7] Complete, realistic simulations for a neutrino factory have not yet been performed.

3. Muon Cooling challenges

The muon bunches must then be compressed in size to fit within the neutrino factory acceleration and storage systems. This requires beam cooling, and the cooling and acceleration must occur within a fraction of a muon lifetime. (More cooling would be required for a high-luminosity μ^+-μ^- Collider.) The cooling method that can be fast enough is "ionization cooling."[8,9] In ionization cooling the muons pass through a material medium, losing both transverse and longitudinal momentum, followed by reacceleration in rf cavities, regaining longitudinal momentum. The net effect is loss of transverse momentum, obtaining transverse cooling. (Energy loss in wedges at nonzero dispersion can add longitudinal cooling.) Configurations for cooling have been developed by the muon collaboration; they require high-gradient rf as well as strong focussing. A particular configuration that has been developed is a "FOFO" cell which relies on high-field solenoids for focusing, and places the cell tune between resonances to obtain focusing over a broad energy range.[10]

3.1 Simulation tools for muon cooling

Detailed simulation is required for the verification and optimization of possible cooling systems, and these systems present many novel features for simulation codes. The optimum μ cooling energy is ~200 MeV ($\gamma \cong 2$—3) so the dynamics is neither nonrelativistic nor fully relativistic. Also the μ's have large transverse momenta, and nonparaxial motion must be considered. Ionization cooling requires energy loss in materials; simulation codes must include the full complexities of particle-material interactions (multiple scattering, energy-loss straggling, correlations, etc.). Strong focussing to small beam sizes and high-gradient reacceleration are required; simulations must include all nonlinear field effects due to realistic rf cavities, solenoidal fields, quad, dipole and fringe fields, etc. All kinematic effects must be included, including x-y coupling and angular momentum effects of solenoidal fields, and chromatic effects from large-momentum spreads.

New simulation codes have been developed, and other codes have been adapted to simulate ionization cooling. These include:

a. ICOOL, a new simulation code developed by R. Fernow and collaborators.[11]
b. Geant4, based on particle in matter and fields simulations for particle physics detectors.[12]
c. COSY, a general purpose beam dynamics code that can use its flexible framework to encompass cooling problems.[13]

Other single user simulations have also been used, as well as analytical models.[14]

A critical need is for simulations that can vary parameters within the cooling systems to develop optima; COSY, in particular, has significant capabilities for this application.

3.2 Ring Coolers

An important problem for cooling is the development of systems that can obtain longitudinal as well as transverse cooling. These systems require dispersion with wedge absorbers to cause higher energy particles to lose more energy than lower energy particles, and effectively combining this with the transverse cooling has been a challenge.

Recently, a number of approaches using a "ring cooler" type of design[15-20] have been developed and studied in CAP simulations. Fig. 5 shows a particular ring cooler[17] and simulation results from another case[19]. The ring coolers are designed for multiturn cooling and can cool both transversely and longitudinally by up to a factor of ten in each of the 3 dimensions. Detailed simulations, including accurate modelling of dipoles, fringe fields and wedge absorbers are needed to confirm these designs.

These designs are a large step toward the goal of achieving the cooling needed for a collider.[20] The multiturn cooling systems could also be much more affordable than the single pass systems used in the ν-factory feasibility studies.

4. Acceleration scenarios and variations

4.1. Recirculating Linac Acceleration

The baseline schemes for the ν-factory and μ^+-μ^- colliders use recirculating linacs (RLAs) as the primary engines for muon acceleration. In a RLA, the beam is transported through a linac for multiple turns of acceleration, with a separate return transport for each turn. The simulation program OPTIM was used to develop the most recent ν-Factory scenario.[21] In the present ν-Factory scenarios, only ~4 turns of recirculating acceleration are included and each of the recirculating transports requires relatively large apertures to accept the very large μ-beams. While less expensive than a single linac, the acceleration is somewhat more expensive than desired; cost reduction is needed.

4.2. FFAG acceleration scenarios

Mori et al. have suggested using fixed-field alternating gradient (FFAG) accelerators for a ν-factory.[22] In an FFAG the beam is accelerated over the full energy gain within a single fixed magnetic field transport, avoiding the multiple return arcs of the RLA. A critical problem is to maintain synchronous acceleration over many turns; low-frequency or multiharmonic rf may be needed. Typical systems use ~10 turns of acceleration.

4.3. Very rapid cycling synchrotron scenarios

More recently, an accelerator scenario using a very-rapid-cycling synchrotron (VRCS) to accelerate muons from 4 to 20 GeV has been proposed.[23] In a VRCS the magnetic field is ramped as the μ-energy increases. The critical constraint here is that acceleration must be completed before μ decay. For the reference case, acceleration requires 35μs or 12 turns of a 900m circumference VRCS ring. Beam dynamic studies are needed to determine if particle stability is maintained (longitudinal and transverse) through the acceleration. Critical problems exist in developing the fast ramping magnets. The VRCS concept should be somewhat easier in higher-energy acceleration, since the acceleration time can be increased as the muon lifetime increases.

All of these acceleration alternatives require substantial computational physics for verification, optimization and development. Improved alternatives may result from these studies.

5. Experimental studies and support

The Muon collaboration has initiated experimental studies.[24] At BNL and CERN studies of liquid metal (Hg) jet targets have begun, and at BNL liquid jet target interactions with a high-intensity proton beam have been studied. At Fermilab, rf studies of high-gradient cavities for μ-cooling have proceeded. Design, construction and tests of liquid hydrogen cooling absorbers are in progress. Internationally, a collaboration for an international cooling experiment (MICE) based at the Rutherford Appleton Laboratories-ISIS μ beam line has been formed, with plans to transport and track beam through typical cooling segments (see Fig. 6) and to compare measured with predicted cooling performance.[25] These initiatives need substantial CAP support and development, both in component design and complete system optimization.

6. Discussion and future directions

We have presented some of the critical R&D challenges of the muon collaboration, particularly in muon targetry, capture, cooling, and acceleration. Many other challenges have not been described here; for example, the design of the μ-storage ring for the ν-factory and the collider ring for a μ^+-μ^- collider. Also, the best future applications for stored muons will depend on the currently developing status of particle physics. Many opportunities for computational accelerator physics applications exist within the present R&D, and computational physics initiatives can lead to dramatic changes and improvements in this program. Some of that research is presented in this conference in papers from M. Berz, D. Elvira, D. Errede, Y. Fukui, C. Johnstone, C. Maidano, K. Makino, P. Stoltz, and others [26].

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Figures

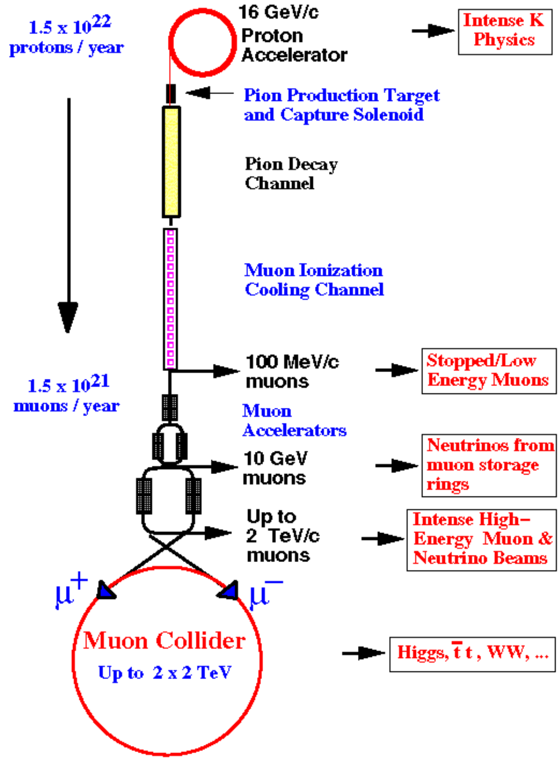

Figure 1. A schematic view of a μ^+-μ^- collider facility, showing a high-intensity proton source which would produce pions. π decay produces μ's which are cooled to collider intensities, and accelerated. Counterrotating μ^+ and μ^- bunches are inserted into a storage ring for high-luminosity collisions.

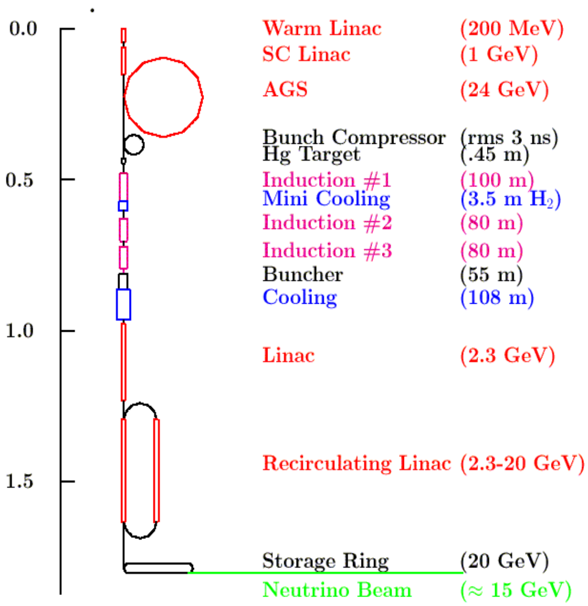

Figure 2. A schematic view of a μ-storage ring ν-factory. A proton driver produces μ's which are cooled and accelerated to 20 GeV and inserted in a storage ring. μ-decay ($\mu \to e + \nu_\mu + \nu_e^*$) in the storage ring straight section provides collimated electron and muon neutrino beams suitable for long baseline oscillation experiments.

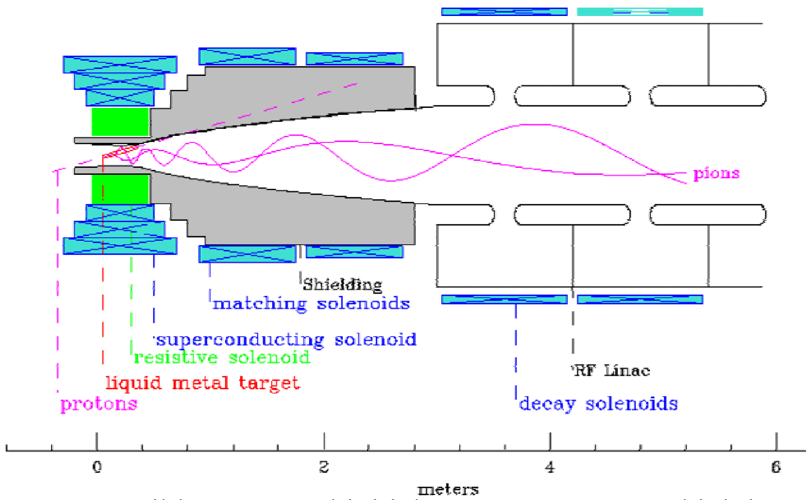

Figure 3: Possible target and initial capture system. A high intensity proton beam hits a liquid metal target inside a high-field solenoid, capturing π's which are focussed into a lower field solenoidal transport system for π→μ +ν decay; the μ's are captured and cooled.

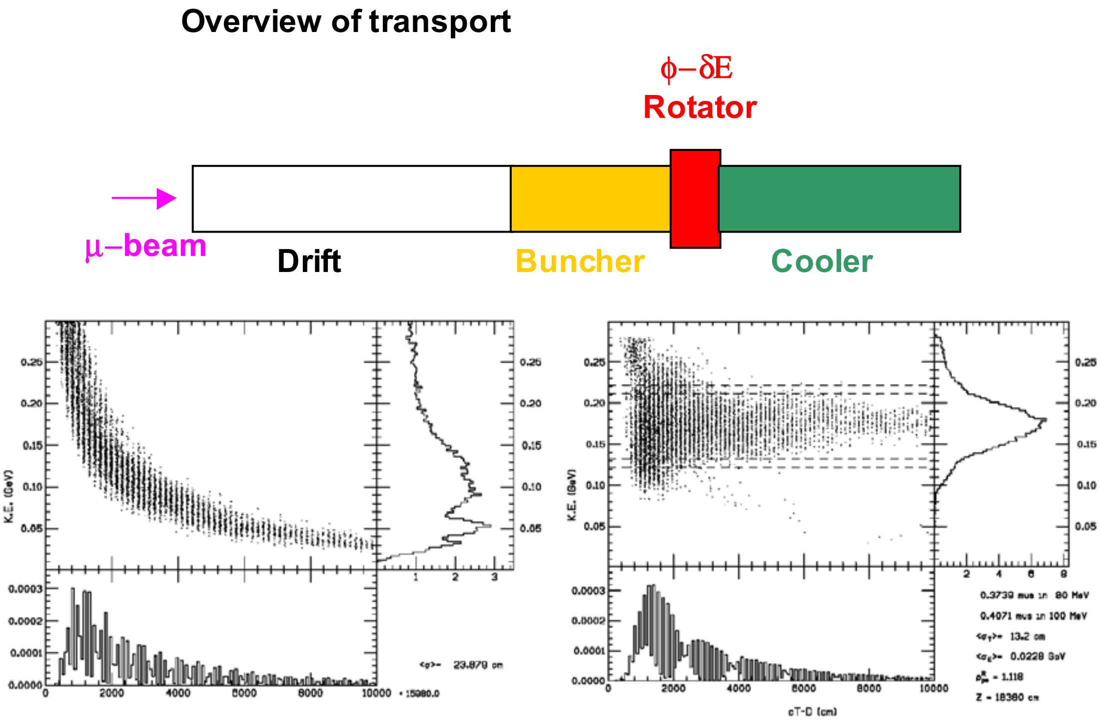

Figure 4: "High-frequency" buncher and phase rotation consisting of a ~100m drift followed by a ~ 60m "buncher" in which the beam is transported through a 300-200 MHz rf system which forms the beam into a string of bunches, which are then aligned in energy by a ~200 MHz high-gradient rf system (φ-δE rotator). The lower left figure shows simulation results of beam at the end of the buncher and the lower right shows beam at the end of the φ-δE rotator.

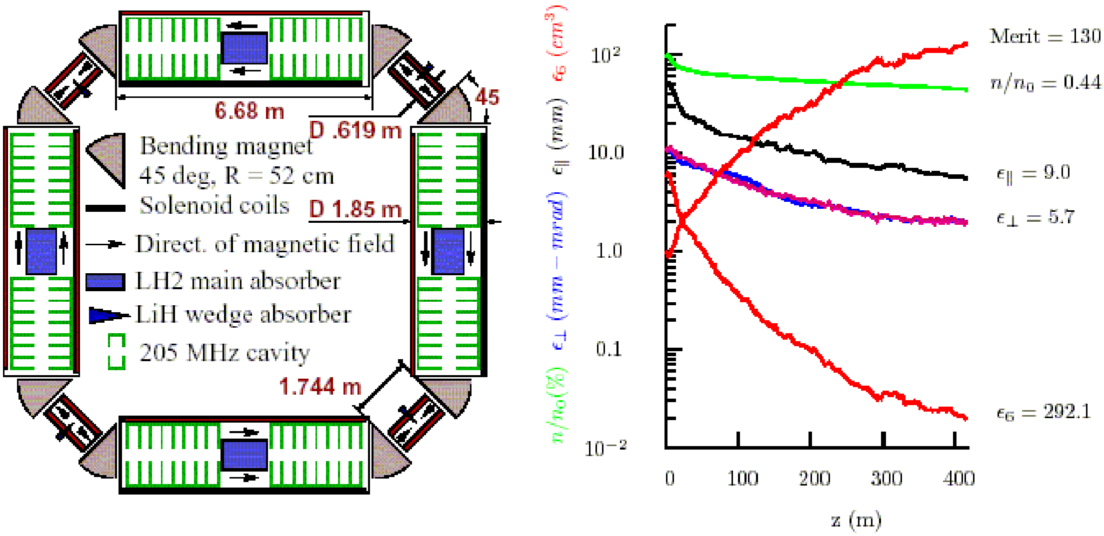

Figure 5: On the left a 4-sided "ring cooler" is displayed.[from ref. 17]. On the right simulation results from a (different) 12-sided ring cooler "[from ref. 19], are shown, with the simulations showing reduction of transverse emittances by a factor of 5.7 and of longitudinal emittance by a factor of 9 after ~10 turns.

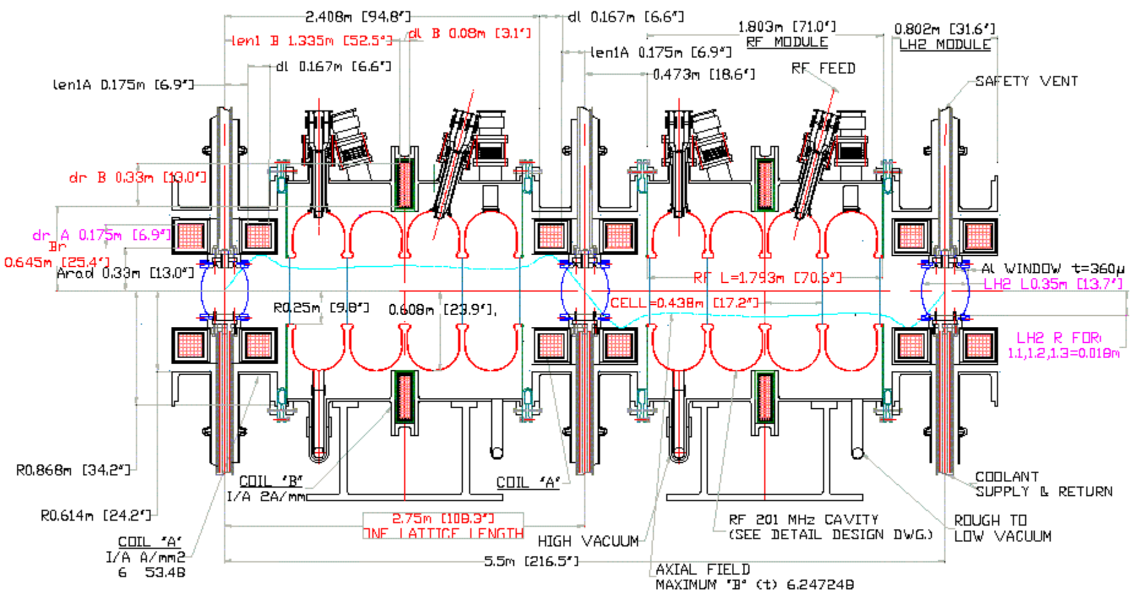

Figure 6: Overview of a cooling cell (engineering design), such as may be used in the MICE experiment as a prototype for a ν-Factory cooling system. The cell includes rf cavities, magnetic focusing coils, and hydrogen absorbers.