MUON BUNCH COALESCING*

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Abstract

The idea of coalescing multiple muon bunches at high energy to enhance the luminosity of a muon collider provides many advantages. It circumvents space-charge, beam loading, and wakefield problems of intense low-energy bunches while restoring the synergy between muon colliders and neutrino factories based on muon storage rings. A sampling of initial conceptual design work for a coalescing ring is presented here.

INTRODUCTION

A major conceptual improvement to the plans for cooling muon beams for collider use is the idea of recombining smaller bunches at higher energy in coalescing rings such as those shown schematically in Fig. 1, a plan for a low-emittance muon collider [1,2].

One difficulty with collider plans of a decade ago was that the muon bunch intensities were assumed to be large in order to obtain the required luminosity, since the luminosity in general depends on the square of the bunch intensities. Accelerating bunches with such large intensities in modern linacs would create problematic beam-loading and wake field effects.

Furthermore, in two new techniques to achieve extreme muon beam cooling, parametric-resonance ionization cooling and reverse emittance exchange, space charge detuning can have serious detrimental effects. In both of these techniques the beam is required to be tightly focused on relatively small wedge absorbers. Space charge tune spreads for large bunch intensities spread out the particle focal points in a way that is not easily compensated, leading to a loss of efficiency for the desired process and additional beam heating.

A third argument for combining bunches at high energy involves the synergy of plans for neutrino factories and plans for muon colliders. Neutrino factories based on a muon storage ring must have as large a number of muons in the ring as possible in order to maximize the neutrino flux. To the extent that this can be achieved by accelerating beams in large aperture devices such that muon cooling is minimal or even unnecessary, most plans for neutrino factories can no longer really be considered as intermediate steps for muon colliders, which require extensive cooling of the muon beams. If, on the other hand, one wants to make a powerful neutrino factory based on the concept of excellent muon cooling, efficient acceleration, and high duty factor operation [3], the neutrino factory and the muon collider can be the same up to the coalescing ring discussed here.

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These three separate reasons, namely limitations on linac charge per bunch, space-charge tune spread, and muon collider-neutrino factory synergy, have led us to consider ways to cool and accelerate muon bunches of smaller intensity with the idea that the bunches can be combined at higher energy for collider use. Thus the initial stages of a muon collider cooling and acceleration facility can be almost the same as those used by a neutrino factory.

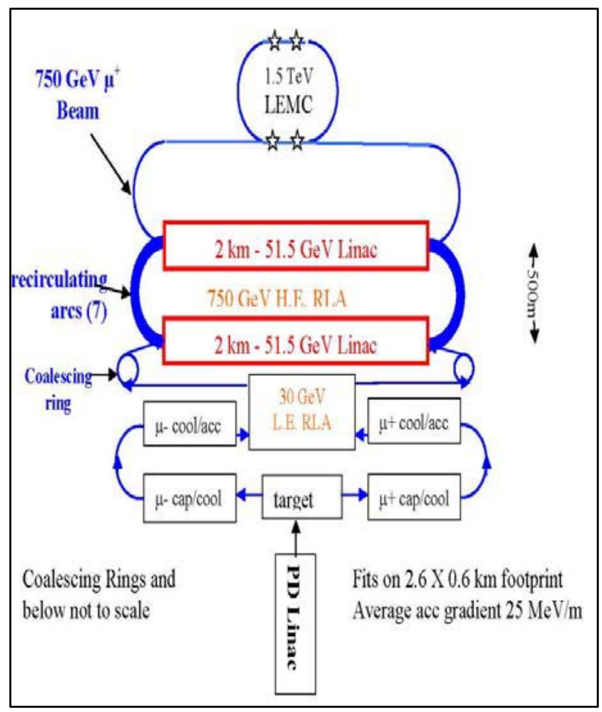

Fig. 1: Schematic layout of a low-emittance muon collider based on a low energy and a high energy recirculating linear accelerator (RLA), showing coalescing rings.

There are two reasons we can consider coalescing after the muon beams have been cooled and accelerated to an energy high enough to avoid space charge, beam loading and wake field effects. The first is that Lorentz time dilation of the muon lifetime at higher energy allows the necessary beam manipulations. The second reason is that when accelerated the fractional momentum spread or unnormalized longitudinal phase space of muon beams in a high energy collider becomes smaller than is required for a collider ring interaction point (IP). At the IP s in a collider, the maximum luminosity is achieved when the bunch length is about the size of the beta function at the IP. For a 1.5 TeV center of mass energy collider, adiabatic damping relative to the cooling energy reduces the longitudinal emittance by 0.1/750 =1/7500. Thus if we coalesce in momentum space while maintaining the cooled transverse emittances, the luminosity will not be degraded as long as the bunch length is less than the beta function at the IP.

ROTATION IN A LINEARIZED BUCKET

The idea in high energy muon bunch coalescing is to first partially rotate the entire ensemble of bunches in energy-time space with a linear low frequency RF bucket and then let the bunches drift in an appropriate ring until they merge and can be captured in a high frequency RF bucket. Figures 1a, 1b, and 1c show the results of initial ESME simulations of beam manipulations in longitudinal phase space. In this example, the coalescing takes 55 μs with a 21 GeV beam energy where the muon lifetime is about 430 μs. About 13% of the muons decay.

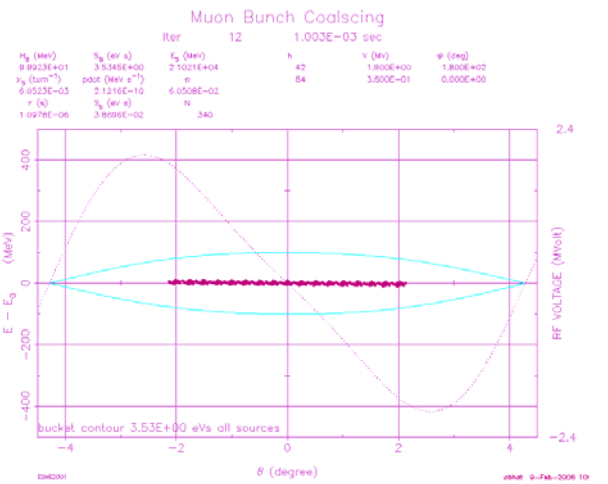

Figure 1a: the distribution of bunches after injection into the coalescing ring

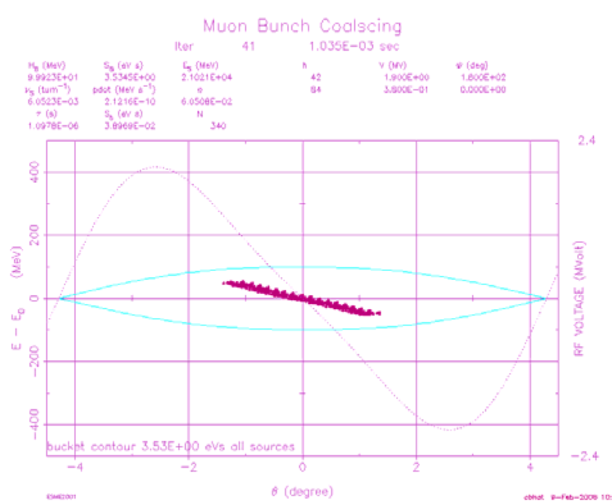

Figure 1b: after 32 μs of bunch rotation.

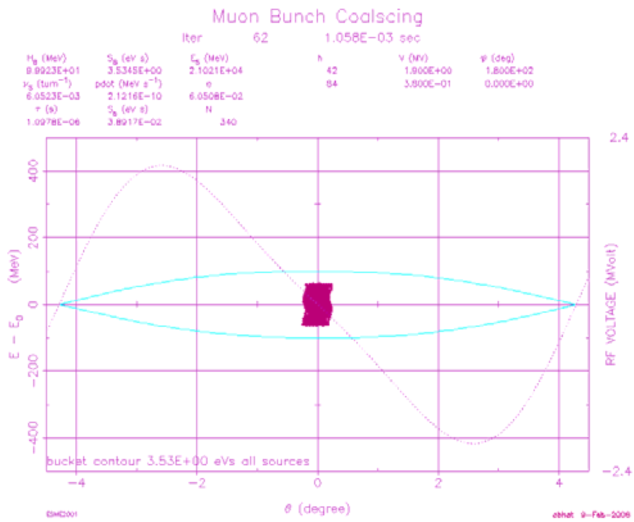

Figure 1c: After drifting 23 μs in the coalescing ring, before recapture.

Reverse emittance exchange (REMEX) [4] is scheme for achieving small transverse emittance to enhance collider luminosity by increasing longitudinal emittance using wedge absorbers. The available longitudinal emittance will have to be partitioned between REMEX and coalescing to maximize the integrated luminosity.

COALESCING RING LATTICE

In order to facilitate rapid merging and thereby avoid intolerable muon decay losses, the lattice for a bunch coalescing ring should have a large momentum compaction, M_{56}, while maintaining small betas, in order to achieve the required low transition gamma and large radial aperture.

A sample racetrack lattice based on periodic FODO cells (72 deg. betatron phase advance) has been designed to provide tight focusing in both planes to open the transverse acceptance and relatively large average dispersion (~2.6 m) to get the right value of momentum compaction. The lattice's building block – the periodic cell – at 20 GeV is illustrated in Figure 2 in terms of Twiss functions (top) and the betatron phase advances (bottom).

For the above peak values of betas the beam envelopes are confined to 2.5 cm (sigma rms) assuming a normalized emittance of 0.001 m rad.

The bending achromat is configured as a super-period of 5 cells. Starting with zero dispersion and its derivative at the beginning of the achromat the betatron phase will advance by 2π (as given by a simple numerology: $5\times 2\pi/5 = 2\pi$). This in turn will create a periodic dispersion wave across the achromat (zero dispersion and its derivative at the achromat end). The super-period is naturally matched to individual 72 degree FODO cells with removed dipoles – the so called 'empty' cells. The empty cells will be used to construct the straight sections of the ring to provide room for injection, extraction, and

RF cavities. The resulting achromat super-period and adjacent empty cells are illustrated in Figure 3.

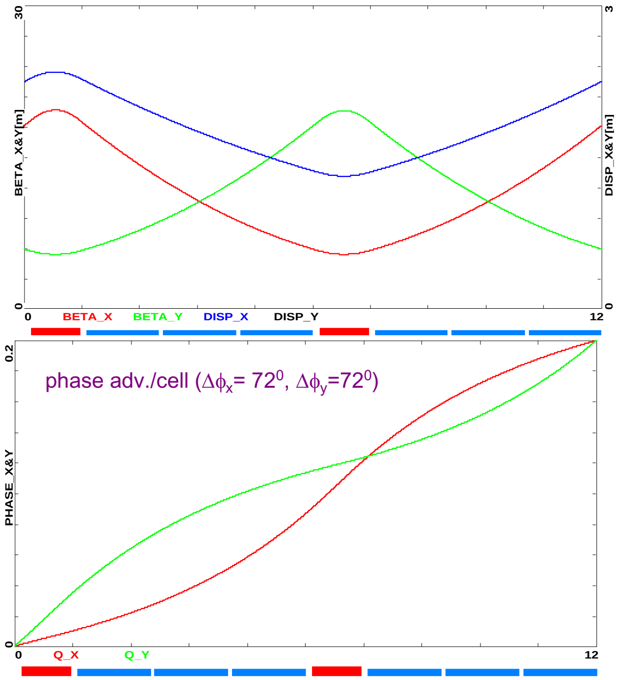

Figure 2: Periodic FODO cells with 72 deg. betatron phase advance in both planes (1.5 meter, 1.6 Tesla dipoles – blue: 1 meter, 14 Tesla/m quadrupoles – red)

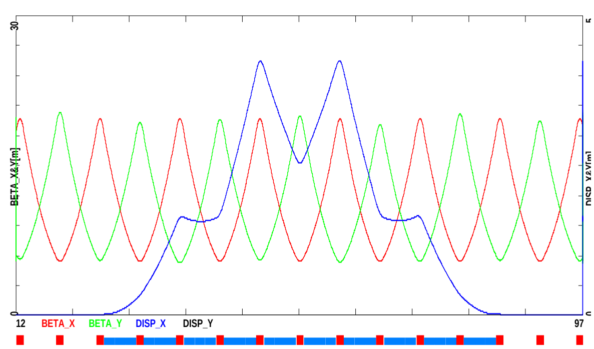

Figure 3: Achromatic Super-period matched to the empty cells (straights).

The final lattice for the ring consists of six consecutive lattice periods, each illustrated in Figure 4. The final lattice for the Racetrack configuration is illustrated in Figure 4.

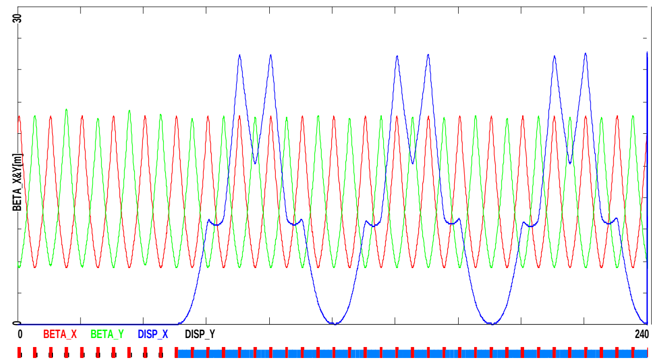

Figure 4: Half of the Racetrack lattice – 5 dispersion free empty cells and 3 Super-periods.

SUMMARY

The advantages of bunch coalescing as a valuable step on the path to a muon collider have been enumerated. Results of initial conceptual designs of the RF rotation system and the ring lattice have been presented.

REFERENCES

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