USE OF HELICAL TRANSPORT CHANNELS FOR BUNCH RECOMBINATION*

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Abstract

Cooling scenarios for a high-luminosity Muon Collider require bunch recombination for optimal luminosity. In this paper we describe a new method for bunch recombination. We combine the high-chronicity of a helical transport channel (HTC) with the high-frequency bunching and phase-energy rotation concept (time-reversed) to obtain a compact bunch recombination system adapted to a muon collider scenario. We first present an idealized 1-D system with multiple chronicity transports. We then implement the concept in a single-chronicity channel, obtaining bunch recombination of 13 200MHz-spaced bunches to a single collider-ready bunch within a compact transport with modest rf requirements. That example is demonstrated within G4BL 3-D simulations. Variations and adaptations for different recombination requirements are discussed.

INTRODUCTION

For a μ^+-μ^- collider, muons from a high intensity production system must be cooled into short, intense bunches for maximal luminosity [1, 2]. The muons are produced within a very large phase space that must be compressed and cooled to obtain high-luminosity parameters. Ref. [3] presents a scenario for this capture and cooling process. Longitudinally, the muons are initially captured into a string of rf bunches, and kept within those bunches until cooled, both longitudinally and transversely. At that point is desirable to recombine the bunches, recapturing into a single bunch with large longitudinal acceptance. That single bunch would then receive further cooling toward collider densities.

Figure 1 shows the progression of transverse and longitudinal emittances through the muon cooling system [3]. The muons are produced with initial emittances of ~0.02m transverse and ~0.4m longitudinally (~0.03/bunch) and are captured in ~12 bunches (200MHz). The bunches are cooled to ~0.0015m transverse and ~0.001m/bunch longitudinally, where they are then merged into a single bunch (step 5 of Fig. 2). The merged bunch is further cooled and emittance exchanged to collider emittances. The merger into a single bunch was imagined to require a very long rf and transport section, with losses of ~50% from μ decay alone. In this report we note that the large chronicity that is possible in a helical transport channel enables performing this bunch combination in a much more compact system that should be much more efficient. An HTC transport segment is shown in Fig. 2.

*Work supported by US DOE under contract DE-AC02-07CH11359 and DOE SBIR grant DE-SC00002739.

HTC BEAM DYNAMICS

In Ref. [4], Derbenev and Johnson proposed the use of helical transport channels (HTC) for cooling of muon beams to small emittances.

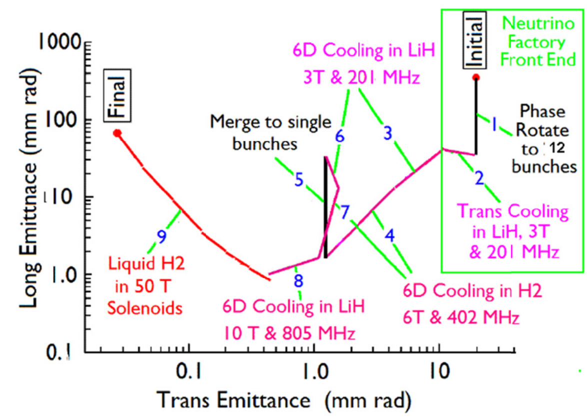

Figure 1: Cooling scenario overview.

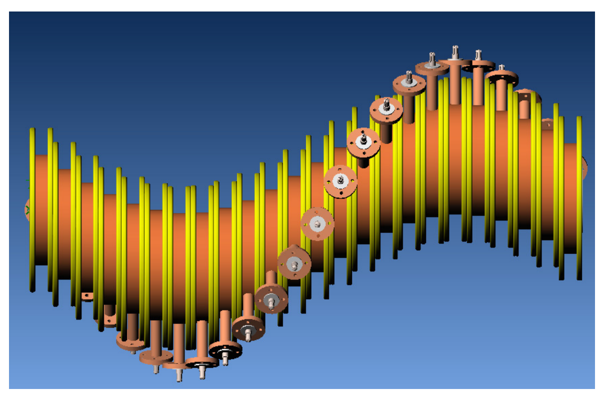

Figure 2: A cell of an HTC as designed for muon cooling.

The core feature of the HTC is the helical magnetic field, which consists of a constant solenoid plus a periodic component: $\vec{B} = B_o\, \vec{e}_z + \vec{b}(\rho, \psi)$, where $\psi = \varphi - kz$ with $k = 2\pi/\lambda$. λ is the helical period and (ρ, φ, z) are cylindrical coordinates for the HTC. In the helical fields there will be periodic orbits with radius a depending on the momentum p. The relationship between p and a is:

$$p(a) = \frac{\sqrt{1+(ka)^2}}{k}\left[B_0 - \frac{1+(ka)^2}{ka} b(a)\right].$$

A critical function is the dispersion factor:

$$\widehat{D} = \frac{p}{a}\frac{da}{dp}$$

ISBN 978-3-95450-115-1

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which can be calculated from inverting the above expression, obtaining:

$$\hat{D}^{-1} = \frac{a}{p}\frac{dp}{da} = \frac{\kappa^2}{1+\kappa^2} + \frac{(1-\kappa^2)(1+\kappa^2)^{1/2}}{pk^2 a} b - \frac{(1+\kappa^2)^{3/2}}{pk^2}\frac{\partial b}{\partial a}$$

where κ=*ka*. The time slip factor that appears in the longitudinal motion equations (Δ(ct) /Δ(z)) is $\sqrt{1+\kappa^2}/\beta$. and its dependence on energy is:

$$\frac{\partial \frac{\sqrt{1+\kappa^2}}{\beta}}{\partial E} = \frac{\eta_{HTC}}{mc^2} = \frac{\sqrt{1+\kappa^2}}{mc^2\gamma\beta^3}\left(\frac{\kappa^2}{1+\kappa^2}\hat{D} - \frac{1}{\gamma^2}\right)$$

The factor $\eta_T = \frac{\kappa^2}{1+\kappa^2}\hat{D}$ is analogous to the $1/(\gamma_T)^2$ factor that appears in synchrotron motion.

In Fig. 3 we display time of flight τ as a function of momentum for various HTC transport channels. At ~200MeV/c the beam is nearly isochrnous, enabling quasiisochronous transport [5, 6]. But at p ≈ 300MeV/c (kinetic energy ~ 200 MeV) there is a strongly anisochronic dependence, which is also very linear in δE. (η_{HTC} ≈ 0.4). Those characteristics are very important in developing bunch combination over a large momentum spread with minimal phase-space dilution and distortion.
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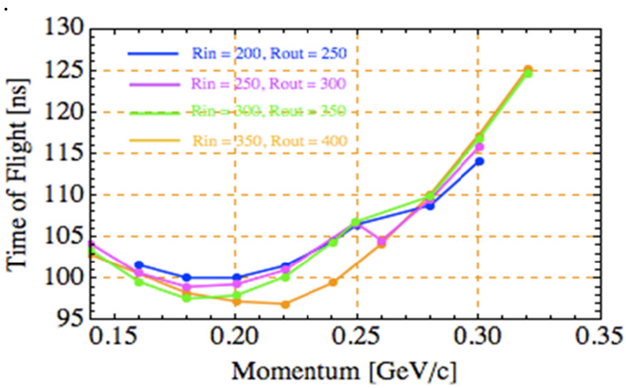

Figure 3: Time of flight as a function of muon momentum for various HTC transport channels.

BUNCH RECOMBINER-INITIAL EXAMPLE

In an initial example, we start with beam at the end of the baseline cooling channel. The bunches have relatively small longitudinal emittances (0.002m with σ_z=0.6cm, σ_E = 33MeV) The bunches have a mean kinetic energy of ~200MeV, and are spaced at ~200MHz.

In the initial section of the BR, rf voltages place the bunches at different energies, with the head bunches at a higher energy than the trailing bunches, while the individual bunch momentum spreads are reduced. An rf system with a frequency near 200 MHz. The difference between that frequency and the baseline is used to place the centers of the bunches at different phases such that head bunches are accelerated and tail bunches are decelerated. Setting the BR parameters such that internal synchrotron oscillation compresses the beam (~1/4 synchrotron oscillation) enables a solution where the high frequency rf naturally bunches the beam into the longer-bunch smaller-δE format needed for the BR drift. For the BR buncher we choose an rf wavelength of (λ_{RF}=1.5-0.03) meters, obtaining an rf frequency of ~204.08 MHz. The rf system is 9.6m long, with V_{rf} = 15MV/m gradient and a transport chronicity of η_{HTC}=0.05. At these parameters, we find the bunches formed into a string of compact bunches with linear energy spacing. (σ_z=~10cm, σ_E = ~2.5MeV, with ~10 MeV spacing.). (See Fig. 3)The HTC transport would then be modified to obtain high η_{HTC} ,(~0.43) (i. e., λ=1.6m, *κ* = 1, and HTC fields of *B* = 4.2T b_d= 0.75, and b_q=-0.45) Drift over ~40m within a large-η_{HTC} transport superimposes the bunchlet areas, at which a modest 200 MHz system forms the beam into a single bunch. (see Fig. 4)

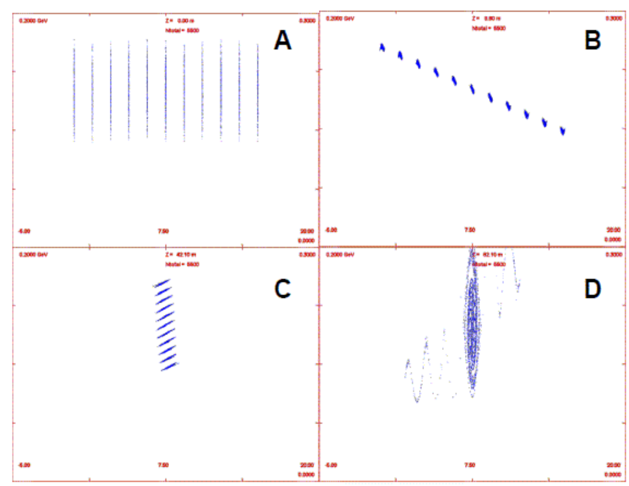

Figure 4: Overview of bunch recombiner with initial quasi-isochronous bunch formation.

3-D HTC BUNCH RECOMBINER

After establishing the principle of bunch combination in 1-D motion, we present a first example within a complete 3-D G4Beamline simulation [7]. To eliminate matching complications and simplify design, this initial 3-D study will use an existing HTC design, with a constant slip factor of η_{HTC}= 0.43 throughout the BR, matched to an upstream HCC cooling channel.

Values of the helical channel parameters are:
λ = 1m, a_{ref} = 16 cm, $\kappa = p_T/p_z = 2\pi a_{ref}/\lambda$ = 1 = (tangent of the pitch angle of the reference trajectory), B_0 = 5.7 T, $B_z(a)$ = 5.0 T, $b_\varphi(r)|_{\text{on reference}}$ = 0.72 T and $\delta b_\varphi/\delta\rho(\text{ref})$= -1.2 T/m.

We start the BR with a train of 13 bunches at the central energy of 200MeV/c, and emittances as would be cooled in an HCC. Bunching and energy rotation at large η_{HTC} requires an adiabatic solution, with a weak rf

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gradient (~1MV/m). and rf frequencies that vary along the channel. The frequency set is by the time difference between the center reference bunch that is not being accelerated and the fourth bunch ahead of it that is being accelerated with a phase of 30º; hence, there are $4^1/_{12}$ rf wavelengths between these four bunches. (The 4^{th} bunch behind is then decelerated at phase = -30º.) From an initial 200 MHz spacing, this places the initial rf frequency at 204.17MHz.

As the train progresses down the channel, the bunch spacing decreases, and the rf frequency increases to maintain the bunch phases. The buncher is continued for 40m, which is an empirical optimum for energy rotation with minmal bunch distortion. The range of rf frequencies used is 204.17 to 271.84 MHz. Figure 5 shows the effect of this transport on a train of 13 bunches, where the extreme ± 6 bunches are at ±45º, displaying development of the longitudinal beam distributions.

After the buncher the beam continues to drift in the HTC until the bunches overlap, after ~60m. The distance L_z needed to align the bunches is determined by the ΔE/Δt slope of the bunch string and the slip factor of the channel. In particular,

$$L_z = \frac{1}{\eta_{HTC}} m_\mu c^2 \frac{c}{\left|\Delta E/_{\Delta t}\right|} = 60m$$

where ΔE/Δt is -1.23 MeV/nsec, obtained from the beam distribution at the end of the buncher. Figure 6a displays simulation of the resulting bunch recombination. The beam is then suitable for capture within a single bunch. To approximate beam capture, we place the beam within a 200 MHz rf system with V'=10 MV/m. After ~5m, the individual bunch structure is diluted and a single captured bunch appears in simulation, as displayed in Fig. 6b.

~94% of simulated particles in the 13 bunch system are captured, with most of the losses and mismatch from the leading/trailing bunches. The simulations presented here are 3-D simulations within the G4Beamline simulation code. The simulations included 3-D evaluations of the magnetic fields with a pillbox model for the accelerating cavities.

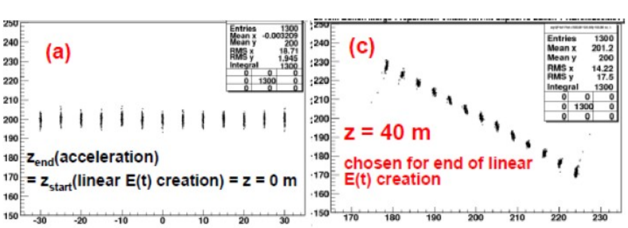

Figure 5: Creation of linear energy-time correlation from bunches at 200 MeV kinetic energy. The string of bunches injected into the HTC at 200 MeV is shown in (a); bunches after 40m are shown in (c) .

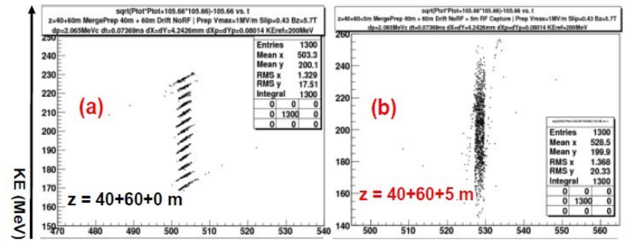

Figure 6: RF capture into a single bunch from 13 initial bunches. Bunches at the end of the drift section and start of the RF capture are shown in (a). Results of RF capture into a single bunch are shown in (b).

DISCUSSION

The simulation demonstrates an example of bunch recombination using a HTC. It is certainly not an optimum example. An HTC with η_{HTC} changing between buncher drift and rf section (as in the 1-D model) would be more compact, and a 3-D example should be developed.

We would also like to study an HTC with a larger acceptance to test the limits of the concept. A longer period HCC with weaker fields is likely to have a larger momentum aperture, with somewhat weaker focusing. A larger momentum aperture would increase the range of bunch compression.

The longitudinal bunch combiner can also be used with a transverse combiner for a more symmetric solution. This option is being explored by Palmer et al. [8].

The concept must also be integrated into a complete cooling scenario, with the pre- and post- merge cooling reoptimized following the 3-D beam dynamics. An optimum scenario is likely to have less transverse cooling before the merge and more transverse cooling after.

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ISBN 978-3-95450-115-1