



HIGH-FREQUENCY BUNCHING AND ϕ - δE ROTATION FOR A MUON SOURCE

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Abstract

A scenario for capture, bunching and rf rotation of μ 's from a proton source is presented. It consists of a drift section, a variable frequency $\sim 300 \rightarrow 180$ MHz bunching section, and a fixed (or variable) frequency (~ 180 MHz) ϕ - δE rotation section. In 1-D and 3-D simulations (SIMUCOOL and ICOOL), the overall capture performance of the system is similar to that of induction linac + buncher scenarios developed for the neutrino factory.[1] The total rf required for the system is quite modest. Optimisation procedures are described.

1 INTRODUCTION

In scenarios for a $\mu^+\mu^-$ Collider or a ν -Factory a phase-energy (ϕ - δE) rotation is performed on the beam exiting the decay channel.[1, 2, 3] In that rotation the beam is allowed to lengthen and an acceleration system (which decelerates the high-energy "head" of the bunch and accelerates the low energy "tail") is used to reduce the energy spread. The resulting beam, which is a long bunch with smaller energy spread, has an energy spread reduced to a level where the bulk of the μ -beam is captured by a downstream bunching and/or cooling system. The difficulty with previously proposed ϕ -E rotation systems is that they require either very-low-frequency rf, or an induction linac, matched to the elongated bunch length of the ϕ -E rotated system. This long-wavelength (or long rise-time) acceleration system requires new technology development and considerable expense.

We are thus interested in alternatives which avoid such new acceleration systems. We present an approach which uses high frequency rf systems for bunching the beam, and then reduces the bunch-to-bunch energy difference, obtaining a beam distribution similar to that obtained from the ν -Factory ϕ -E rotation + initial buncher system. Various examples with these properties are presented. The rf systems are chosen with frequencies in the ~ 200 – 300 MHz frequency regime, which is a frequency range where rf systems can be readily developed.

2 SIMPLE EXAMPLE

The first example is adapted from the Fermilab neutrino factory scenario parameters [1]. An initial beam with a small phase spread, but large energy spread (similar to beam from a $\pi \rightarrow \mu$ production target) was generated and drifted for 100m. This is followed by an "adiabatic buncher" section, in which an rf system is gradually increased in gradient, "adiabatically" capturing the beam

into a string of bunches. In a usual rf system the central energy of each bunch would be the same, corresponding to the synchronous energy of the fixed frequency rf system. In our case the rf frequency decreases along the length of the buncher, following the constraint that the phase difference between two reference energies remains a fixed number N_W of wavelengths, as the beam propagates down the buncher. Thus the reference energies remain at zero phase in their respective bunches, and stable phases and energies are obtained for $N_W - 1$ evenly spaced intermediate points, and at locations before and after the reference energies. For this first example the central kinetic energy is at 125 MeV kinetic energy and the reference energies are at +50 MeV and -50 MeV from that value, with N_W set at 15. With these numbers the matched rf frequency at the beginning of the buncher section is ~ 300 MHz, and at the end of the 60m buncher it is reduced to ~ 180 MHz.

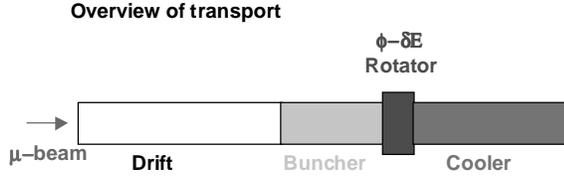
In the bunching system the bunching gradient is gradually increased from zero to a value of 4.8 MV/m over the length of the buncher (with a quadratic ramp in this example). The goal is an "adiabatic capture", in which the beam within each bunch is compressed in phase so as to be concentrated near the zero phase for each bunch. Note that, since each of the bunches is centered at different energies, they have different longitudinal oscillation frequencies, and a simultaneously matched compression for all bunches is not possible. Instead a quasi-adiabatic capture with an approximate bunch length minimization in each bunch is attempted. (A buncher – similar up to this point - was also proposed by Johnson and Scrivens.[5])

Following the buncher the rf frequency is fixed to the matched value at the end of the buncher and the rf gradient is increased to a larger value. In this example this matched frequency is ~ 183 MHz, while the rf gradient is 10 MV/m. In this system, the centers of the low-energy bunches increase in energy, while the centers of the high-energy bunches decrease in energy, similar to the particle motion in a fixed frequency system with a large energy spread and zero initial phase spread. After $\sim 1/4$ -synchrotron oscillation (~ 10 m), the energy spread is minimized.

At that point the beam is in a string of similar-energy bunches, and can be captured into a ~ 180 -MHz muon cooling system matched to the central beam energy. In initial 1-D simulations, the following cooling system was approximated as a longitudinal buncher, with an acceptance corresponding to the net bunching voltage available in prototype cooling designs (~ 4 MV/m). These 1-D

simulations indicated that acceptance similar to induction linac based scenarios was possible.

Fig. 1. Overview of a μ -capture system, which includes a 100m drift, a 60m buncher, a 8.4m. ϕ - δE rotator, and a 100m cooling system.



The scenario was simulated in ICOOL, a 3-D particle tracking code which incorporates the complexity of muon beam motion in magnetic fields, rf cavities, and cooling absorbers.[6] In the ICOOL simulations the initial beam was obtained from a simulation of π production at a target within a 20T solenoid, as used for the ν -factory studies.[4] The initial field is adiabatically reduced over ~ 15 m to 1.25 T (or 3 T), and is then kept constant until the end of the buncher. Initial simulations show capture within potential cooling acceptance of $\sim 0.25 \mu$ /initial proton, which is competitive with ν -study scenarios (see fig. 2).

3 OPTIMIZATION AND “VERNIER” BUNCH ROTATION

The buncher-rotation system has been simulated and reoptimized using SIMUCOOL,[7] which can track large statistics. The large statistics was used to determine the centroids of the beam bunches developed by the adiabatic buncher, and enables further optimisation. The initial beams were obtained from a MARS simulation of π -production by 16 GeV protons on a mercury target, provided by N. Mokhov. [8] Fig. 3A shows beam at the end of the buncher and fig. 3B shows beam at the end of a fixed frequency ϕ - δE rotator. Reference energies in this and the next example are 64 and 186 MeV with $N_w=20$ which improves acceptance somewhat.

Acceptance can be improved by changing fixed-frequency rotation to “vernier bunch rotation.” The matching frequency is slightly decreased to provide more net deceleration to the leading higher energy bunch and acceleration to the low energy bunch. The central bunch remains at stable phase. Maximal effect occurs when the frequency is increased by $(N_w + \frac{1}{2})/N_w$, that is, by a half wave-length over the capture region. In the vernier optimisation the rf wavelength initially increases as the reference bunches continue to spread apart. It was found that this could be further optimized by interspersing the vernier cavities with cavities providing either fixed frequency or one matched to the beam. In the optimisation vernier bunching alternates with fixed-

frequency bunching to maximize the yield within an energy acceptance window of 80 MeV at the end of the ϕ - δE rotation. Figure 4 shows some simulation results from vernier bunching, that show an increase in beam in the 80 MeV acceptance window to $0.337 \mu/p$, from $0.28 \mu/p$ obtained with a fixed-frequency rotator. The buncher and ϕ - δE rotator were also simulated using ICOOL, and the programs obtain the same results within statistics.

5 FUTURE STUDIES

Even if the basic structure of the capture, buncher and ϕ - δE rotation is maintained, the system has a large number of interrelated parameters. The key parameters are:

1. *Drift:* The key parameter is the length of the section, which was arbitrarily set initially to 100m. Increasing that length should decrease the energy spread of the final beam, enabling somewhat better acceptance. The focusing field strength (1.25—3 T) could also be significant.
2. *Buncher:* The length of the section, the bunching voltage, the voltage increase program and the reference particles and spacing can all be explored. In these example, the length of the buncher was 60 m, the final bunching voltage was 4.8 MV/m, increasing following $(V'_{rf} = V'_{final} (z/L_{buncher})^2)$. (Reference particles at $E = 175$ MeV and $E = 75$ MeV, with $N_w = 15$ wavelengths apart, and reference particles at 64 and 186MeV with $N_w = 20$ have been tried.)
3. *ϕ - δE rotation:* The length and rf voltage of the phase rotation section ($L_{RFR} = 8.4$ m and $V' = 10$ MV/m in the initial example) are the key parameters. In general, more gradient would be better and the length should be $\sim 1/4$ synchrotron oscillation for the beam. Acceptance is improved if the rf frequency and phase can be changed along the section as is done in the “vernier” algorithm discussed above, and higher harmonic rf could also be included.
3. *Cooling System:* the rf frequency, rf voltage plus absorber energy loss rate set the longitudinal dynamics while the transverse focusing sets the actual cooling effectiveness. Larger rf voltage is desirable; rf frequency is set by the bunch spacing at the end of the buncher. The next major step in studies will be to match into actual cooling sections and optimise the parameters for acceptance of captured and cooled μ -beams.

6 CONCLUSIONS

This initial study shows that this approach can be used as an initial μ -capture system for a neutrino factory. Our evaluations show that it may have similar performance to that of the BNL Feasibility Study[4] double induction linac capture and phase rotation system, with $\sim 2/3$ to $\sim 1 \times$ the acceptance in captured muons. It avoids the very large expense of development and construction of the induction linac acceleration system, or any other low-frequency rf system. It also has the significant advantage that the same system would obtain strings of both μ^+ and

