DISTRIBUTED MODULATING BUNCHER

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Abstract

So-called phase rotation scheme can reduce a large energy spread of muon beams. It, however, requires rather low frequency or long slope in the RF waveform with rather high gradient field against the short muon lifetime. Because such a low frequency high gradient RF cavity tends to become huge, use of a high frequency RF is desired. A long muon bunch has to be rebunched for the high frequency operation. The bunching system has to handle a time dependent central energy and to change its amplitude rapidly. Such a rapid amplitude change can be achieved by a superposition of a few frequency components. The bunching system located after 100m from a production target can bunch a muon beam of 100MeV ±50% with 200MHz RF, and a 100MHz bunched muon beam is obtained at 200m position.

1 INTRODUCTION

Muons are obtained as decay products from pions that are generated by high-energy protons hitting on a production target. Because the muons are tertiary products, muon beams have very bad quality. A long drift makes a good correlation between the TOF (time of flight) and its energy, where the bunch becomes as long as 20m. The large energy spread can be reduced by so-called phase rotation, which decelerates early coming fast muons and accelerates late slow muons. This operation has to be completed well less than the muon lifetime ~2.2μs, which requires rather high gradient such as 0.5MV/m.

The high gradient makes a use of magnetic material as an inductive load in a cavity difficult. An air core cavity, however, will have a radius of more than a few meters. In order to eliminate such huge low frequency cavities and to make use of high frequency cavities such as 100MHz, a high frequency bunching system was proposed[1,2], while the resulted bunching factor was not sufficient. The scheme is improved[3] after an introduction of High-Frequency "Adiabatic" Buncher[4].

2 MODULATING BUNCHER

Figure 1 shows the muon phase space distribution (energy as a function of TOF) at the 100m downstream of production target with its original phase space whose full width of the time spread is 3ns. By applying a kick with a sawtooth waveform after the 100m drift (Drift-1), the phase space can be flipped, where the amount of the kick depends on the energy of the slice. After the same drift length (Drift-2), the trapezoidal area rotates to upright position. Noting that the center energy for each slice does not change, the time distances between the slices develop twice.

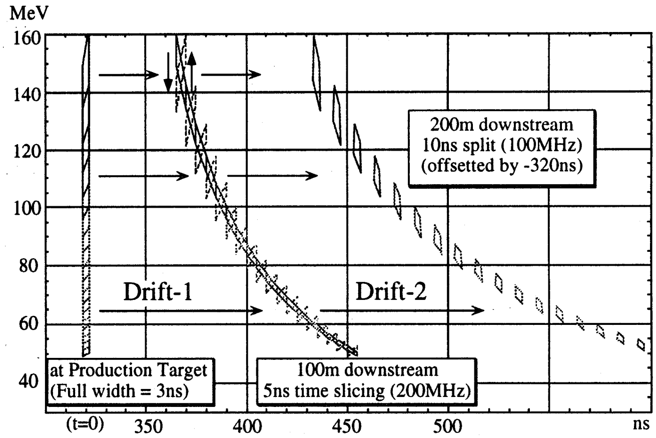

Fig. 1 Muon energy as a function of TOF at 100m from the production target(left t=0). Each time slice at 100m is kicked to flip the local phase space distribution (middle). The flipped slice becomes upright after 100m more drift and forms the well-bunched structure with small emittance increase.

2.1 Rough Simulation

The buncher period has to be large enough compared with the initial time spread to keep good bunching factor. Assuming that an initial time spread is 3ns, 200Mhz should be a reasonable choice as a buncher frequency. The resulted bunch frequency at 200m becomes 100MHz. Use of single sine wave instead of the sawtooth waveform makes the buncher system less complex with some bunching loss. We can add higher order components later to recover it, if needed. The required waveform for the buncher system is as follows:

$$V(t) = 2\frac{\sin(\omega_b t)}{\omega_b}\frac{dW_\mu(t)}{dt}, W_\mu(t) = m_\mu\left(\frac{ct}{\sqrt{c^2t^2 - L^2}} - 1\right)$$

where ω_b is the angular frequency of the buncher (200MHz) and m_μ is the muon mass in electron volt (see Fig.2). $W_\mu(t)$ is the muon energy at the buncher position L and the time t. The voltage of $V(t)$ flips the time slice of the beam after 100m drift. The slope of $V(t)$ is similar to that of an exponential function but steeper, which corresponds to a very low Q value for a cavity. Because rather high voltage (±10MV at the beginning) is required, such a cavity is not practical. Figure 3 shows the envelop of $V(t)$ $(= V_{envelop}(t) = V(t)/sin(\omega_b t))$ and a fitted result with a sine wave and its harmonics, where the function $V_{envelop}(t)$ is approximated by

$$V_{envelop}(t) = 20(\sin(\omega_e t + \varphi_1) + A\sin(2\omega_e t + \varphi_2))\ [\text{MV}].$$

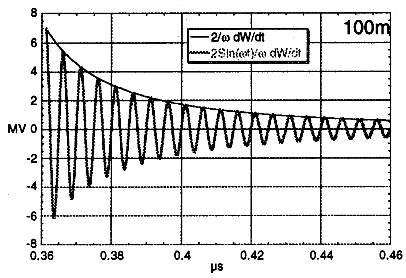

Fig. 2 Waveform for a modulating buncher.

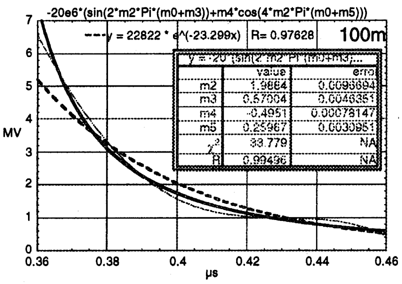

Fig. 3 Envelope for a modulating buncher.

Thus $V(t)$ can be written in a form:

$$V(t) = 20\sin(\omega_b t)\left(\sin(\omega_e t + \varphi_1) + A\sin(2\omega_e t + \varphi_2)\right),$$

where ω_e correspond to about 2MHz. With use of the trigonometric reduction, $V(t)$ can be reduced to a sum of four sine functions:

$$V(t) = 10\left\{\cos((\omega_e - \omega_b)t + \varphi_1) - \cos((\omega_e + \omega_b)t + \varphi_1)\right\}$$
$$+ 10A\left\{\cos((2\omega_e - \omega_b)t + \varphi_2) - \cos((2\omega_e + \omega_b)t + \varphi_2)\right\}.$$

These can be generated by four cavities with the frequencies of 196, 204, 198 and 202MHz, which generate the low frequency components as the beat. Figure 4 shows a simulation result of the modulating buncher. In the simulation, all the cavities are located at the same position and only drifts and kicks are assumed (no transit time factor included). About 79% of the muons are collected within 5ns and 69% within 3.5ns at the 200m point with 50% more voltage. Because the real cavity has finite length, the frequency f_n of the cavity has to be modified as the location changes :

$$f_n' = f_n L_0 / L_n \quad \text{(to the first order approximation)},$$

where L_0 is the buncher location (100m) and L_n is the location of the n-th cavity. Assuming that all the cavities have length of 1m, about 73% of the muons are still collected within 5ns (60% within 3.5ns). Because of the strong nonlinearity in the phase space motion, further numerical improvements have to be performed iteratively.

2.2 Dual Frequency Cavity (DFC)

It is possible to construct a cavity with two close resonant frequencies (see Fig. 5) with an extra resonator (i.e. λ/4 resonator) that has a resonance close to the central frequency. The central frequency is determined by the cavity size and the frequency difference can be adjusted by the coupling between the main cavity and the perturbator. The two modes appear as 0- and π-modes. More than ±10% split was obtained in the MAFIA calculation for the example with >7MΩ/m at 100MHz.

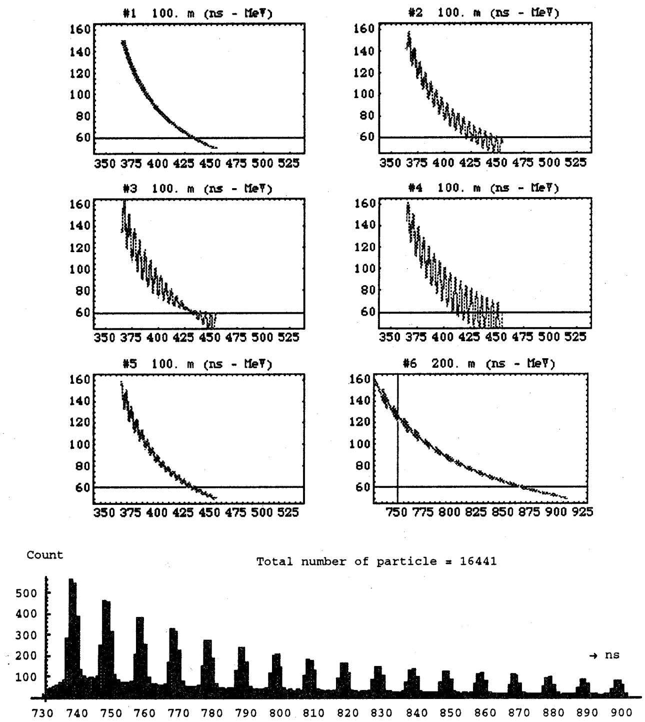

Fig. 4 Simple simulation results of the modulating buncher with no cavity length. #1: after 100m drift, #2: after 196MHz kick, #3 after 204MHz kick, #4: after 198MHz kick, #5: after 202MHz kick, #6: at 200m point. The bottom figure shows the bunched structure.

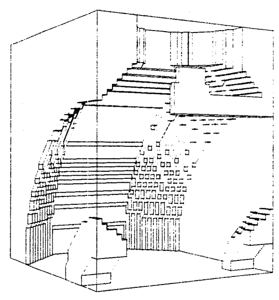

Fig. 5 Dual Frequency Cavity. The extra resonator splits the resonant frequency.

The shorter cavity length reduces the discrepancy between the first and second simulation results, and 74% muons are collected within 5ns and 64% within 3.5ns with 40% more voltage.

3 DISTRIBUTED MODULATING BUNCHER

'Adiabatic' buncher [3] can improve the bunching factor, which distributes the RF cavities along the beam line and change the apmlitude adiabatically. As a preliminary study, two modulating bunching stations are situated at 80m and 120m position. Because of the locations, each cavity has different function $V(t)$. A rough simulation showed that 83% of the muons are collected within 5ns and 73% within 3.5ns(see Fig.6). The voltages and the frequencies are listed in the caption. Use of more stations will increase the bunching efficiency.

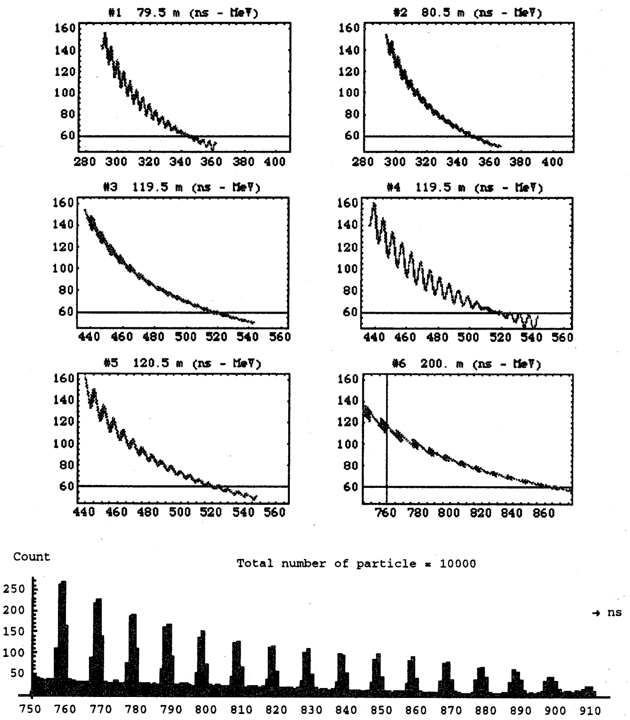

Fig. 6 Modulating buncher with two stations.
#1: 3.3MV DFC (246.1&257.0MHz)@79.5m,
#2: 6.6MV DFC (245.7&251.1MHz)@80.5m, #3: 119.5m,
#4: 7.5MV DFC (164.3&170.5MHz)@119.5m,
#5: 15MV DFC (164.4&167.5MHz)@120.5m, #6: 200m.
The bottom figure shows the bunched structure.

4 COMB PULSE ENERGY COMPRESSOR

The waveform V_{EC} needed for the energy compression or "phase rotation" again can be fitted by two components as follows:

$$V_{EC}(t) = 100 - 100\left(\sin(\omega_c t + \psi_1) + B\sin(2\omega_c t + \psi_2)\right) \text{ [MV]},$$

where ω_c corresponds to the low frequency. The offset 100MV can be changed to accelerate the center energy and exclude the deceleration, if limit of the cavity votage permits(see Fig.7). Because the modulating buncher does not break the global correlation between energy and TOF, we can still apply the "phase rotation" after it. Because the muons are now bunched, we do not need very low frequency RF such as a few MHz. Then the raw "phase rotation" waveform V_{EC} can be modulated by an approximated square wave V_{sq}:

$$V_{sq}(t) = 1.25\left(\cos(\omega_c t) - \cos(3\omega_c t)/4\right) \text{ and}$$

$$V_{CPEC}(t) = V_{sq}(t)V_{EC}(t),$$

where V_{CPEC} is the modulated waveform. The resulted waveform performs as a Comb Pulse Energy Compressor (CPEC). This also can be reduced to a sum of eight sine waves. With this function, about 40% muons can be compressed within 10% energy spread. When the CPEC is combined with the modulating buncher, the yield increases up to 68% (see Fig. 8).

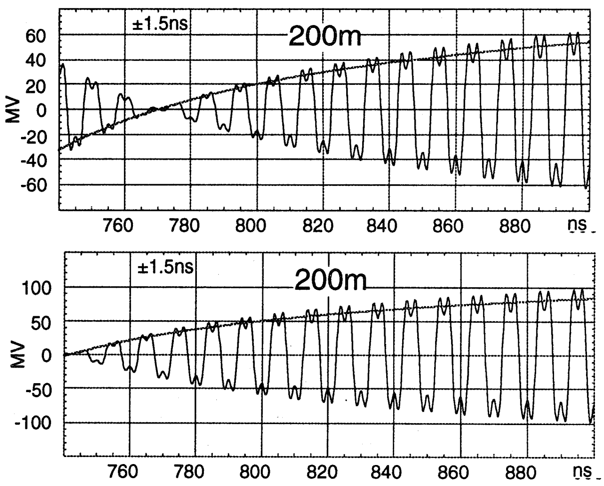

Fig. 7 "phase rotation" waveform modulated by approximated square waveform. Top:Center energy Ec=100MeV. Bottom: Ec=150MeV

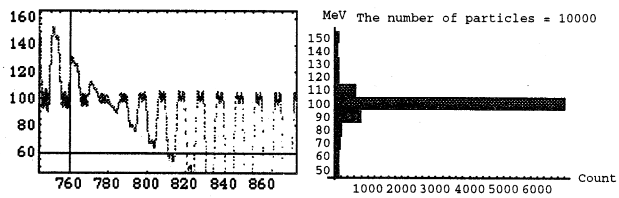

Fig. 8 Resulted phase space distribution with combination of the modulating buncher and the CPEC.

5 DISCUSSIONS

The distributed modulating buncher combined with the "Adiabatic" buncher will bunch the beam more efficiently. For a multi-bunch operation, the frequencies have to be multiples of the extraction cycle of the proton driver(~100kHz?). Sparking problem in a DFC is not clear, because of the complex waveform. A procedure to optimize the parameters has to be developed.

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