PHASE ROTATED INTENSE SLOW MUONS WITH LINAC

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Abstract

In PRISM(Phase Rotated Intense Slow Muons) project, a large energy spread of muons (20MeV+-50%) will be reduced by manipulations of the muon phase space. They are decay products from pions generated by short-bunched energetic protons. The bad quality of the muons requires rather low RF frequency as low as 6MHz. Because of the short life time of muons(~2µs), the phase space manipulation by RF cavities has to be finished as quickly as possible. Thus, we need very high field gradient of ~0.5MV/m at 6MHz.

1 INTRODUCTION

In order to make use of a lot of muons that can be produced by the coming high intensity proton driver, one can reduce the large energy spread of muons (20MeV+-50%) by manipulations of the muon phase space [1,2]. In PRISM (Phase Rotated Intense Slow Muons) project [3], short-bunched (<10ns) energetic protons hitting on a production target will produce muons as decay products from pions with large energy spread and fairly short time duration. Thus, muon beams have very bad quality except the initial time structure. A long drift after the production target makes a good correlation between the TOF (time of flight) and its velocity, where the early arriving muons have larger energy than the late ones. So-called phase rotation can reduce the large energy spread by decelerating the early coming fast muons and accelerating the late slow muons (see Fig. 1). The bunch length grows as long as 20 m and thus the corresponding RF frequency is as low as 6MHz. Because of the short lifetime of muons (~2.2µs), the phase space manipulation by the RF field has to be finished as quickly as possible, which requires rather high gradient such as 0.5MV/m. Although, magnetic materials are usually used in such low frequency cavities for inductive loads, the high gradient requirement makes it difficult.

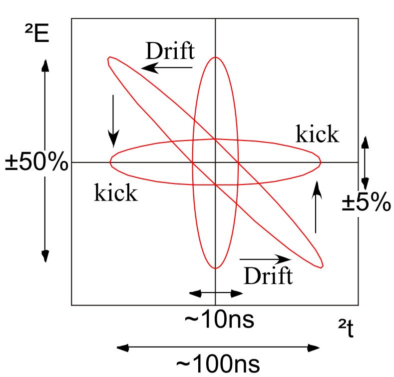


Fig. 1 Phase rotation technique.

2 PRISM/L

While the baseline design of PRISM uses FFAG as the phase rotator, linac based one (PRISM/L) is discussed here, because of the simplicity of muon transport system. Current configuration of field distribution in PRISM/L is shown in Fig. 2. In this configuration, the continuous solenoid field holds the pions from the beginning to the end.

2.1 Target and π Capture/Decay Section

Carbon target is immersed in 6T solenoidal field. Although higher field is preferable to capture as many pions as possible, practical reasons in fabrication and operation of a superconducting solenoid magnet enforce the field level up to 6T for the time being[4].

Only pions emitted backwards will be handled because of less radiation compared with the forward area and isotropic distribution of the low energy pions. The maximum energy of a pion that can produce a muon with energy of 30MeV (=20MeV+50%) is about 75MeV (see Fig. 3). The required bore radius is twice the pion's radius (see Fig. 4).

Because the pion velocity is around a half of the speed of light, it takes about 20ns for a pion to travel 3m downstream and thus more than half of the pions decay to muons. Thus the radius of the major source region for the muons is considered to be the first 3 m region.

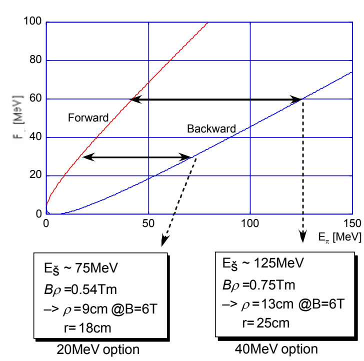


Fig. 3 Muon energy as functions of pion energy.

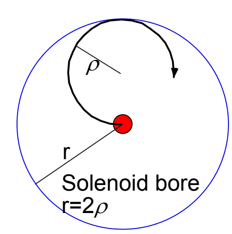


Fig. 4 Motion in a solenoid field and required bore.

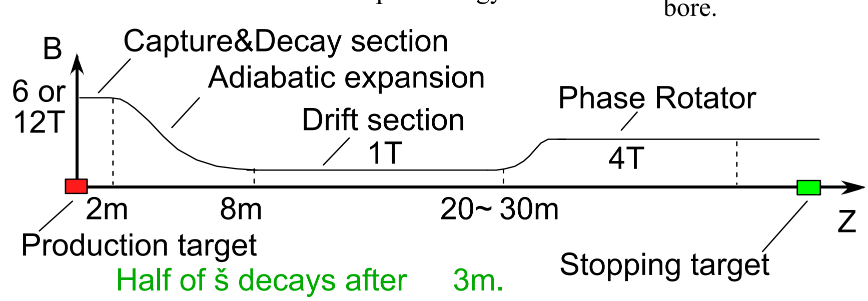
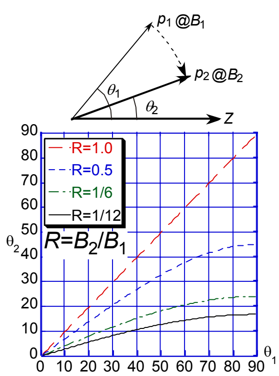


Fig. 2 Magnetic field distribution for PRISM/L

2.2 Adiabatic Expansion and Drift Section

Because the momentum transfer from transverse phase space to longitudinal phase space are expected in the decreasing field B, while the beam size expands in proportion to $B^{-0.5}$, field level of 6 T will be adiabatically decreased to 1 T in the drift section (see Fig. 5). The bore diameter of the drift section becomes 0.6m. Because the time of flight (ToF) develops not as a function of its total momentum but that of longitudinal one (see Fig. 6), the magnetic field level of the drift section has to be as small as possible. This decreases the stored energy in the solenoid coils and may reduce its cost.

A rough simulation result of the muon energy as a function of ToF is shown in Fig. 7. Because of the low energy region (~20MeV), decay process of $\pi \rightarrow \mu + \nu$ introduces rather large disturbance in the correlation (Fig. 7 top). The bottom figure shows the project to the ToF axis. The yield does not increase much even if the central energy increases for the backward region. Both options have late components. These are coming from the trapped pions in the high magnetic field region around the target, which have small longitudinal momentum and stay until their decay. The number of such pions is not small because the solid angle of such pion component is large compared with that directing backward at the birth .



p_t decreases, while ρ increases.

$\rho_2 = \rho_1 (B_1/B_2)^{1/2}$ B_1=6T
-> ρ_2 = 9x6$^{0.5}$=22cm@B_2=1T
ρ_2 = 13x6$^{0.5}$=32cm@B_2=1T
r = 64cm (1m)

Fig. 5 Adiabatic expansion

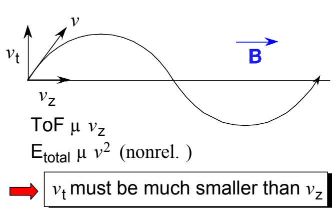


Fig. 6 ToF develops as a function of its longitudinal momentum.

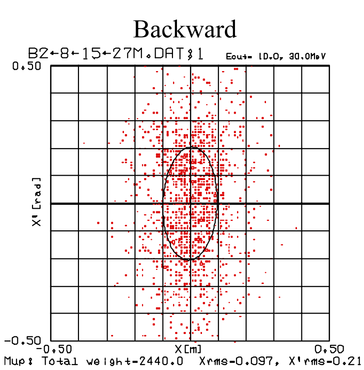


Fig. 8 Phase space at 27m.

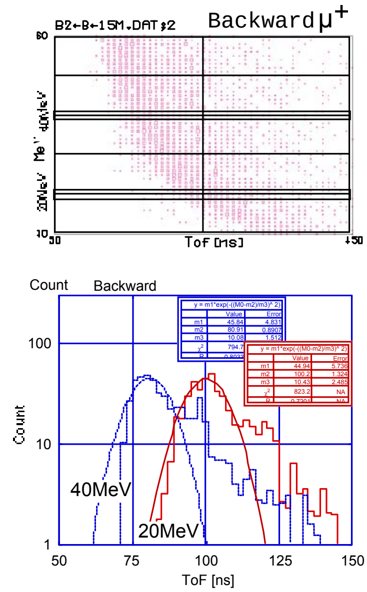


Fig. 7 Energy and longitudinal momentum as a function of TOF after the drift section (25m). Time is measured from the target.

The phase space distribution at 27m (just before the phase rotator) is shown in Fig. 8. The emittance of the ellipse in the figure shows 2000 πmm.mrad.

2.3 Phase Rotator

The voltage generated by the phase rotator has to change very slowly; the duration from peak to peak is as long as 100 ns. Thus the cavity frequency becomes about 6 MHz. Assuming that the total voltage of 10MV is generated within 20 m, the average field gradient becomes 0.5 MV/m, which is not an easy demand in this frequency rage.

Two types of cavities are possible. Fig. 9 shows single-gap cavities, which have rather large diameters; more than 6m. They have thick drift tubes that can hold superconducting solenoids for muon transport. Left two cavities have large gaps and can generate field gradient of 1 MV/m, which corresponds up to 1.4 times of Kilpatrick

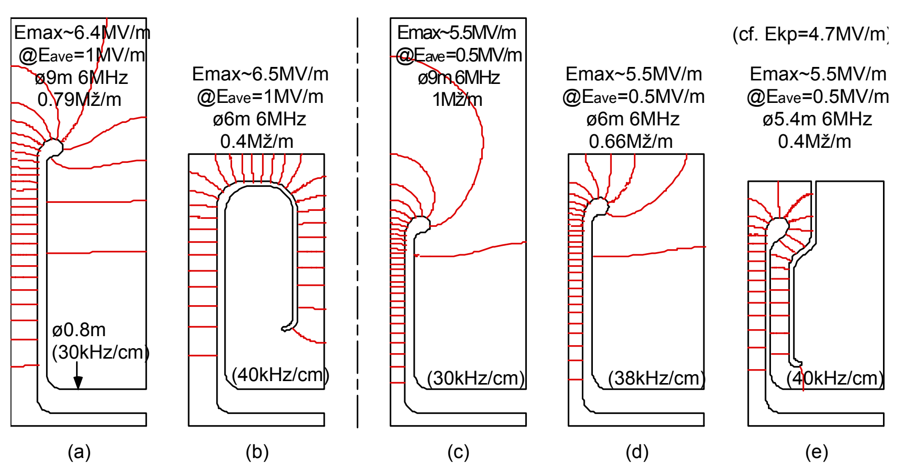


Fig. 9 Phase Rotation Cavity (Single Gap)

criterion E_{Kp}. Right three cavities are good for 0.5 MV/m. The right most one is an extension from the CERN AD cavity [5]. The smaller gap distance has an advantage in reducing the magnetic field dip at the gap, while the maximum surface field increases. The sensitivity on the resonant frequency is large for the drift tube diameter, because its inductance has an important role to decrease the resonant frequency.

Another option is a two-gap cavity as shown in Fig. 10. Although this type can be smaller in its diameter, the length of one cavity is much longer than the single gap one. For a muon with ß=0.5, the length becomes ßλ/2=12m. Three of these units can generate 10MV in 36m length. It requires 3 MW RF power and the total peak power is 9 MW. Because of the small duty factor (~<1%), the average RF power is not significant.

A layout of the total system using above described components is shown in Fig. 11. It include second order higher harmonic cavity and the total length from the target is more than 70 m. The longer the distance, the smaller the pion contamination at the end.

3 PHASE SPACE AFTER PHASE ROTATION

In order to take advantage of the phase rotation, we have to apply a precise acceleration/deceleration voltage

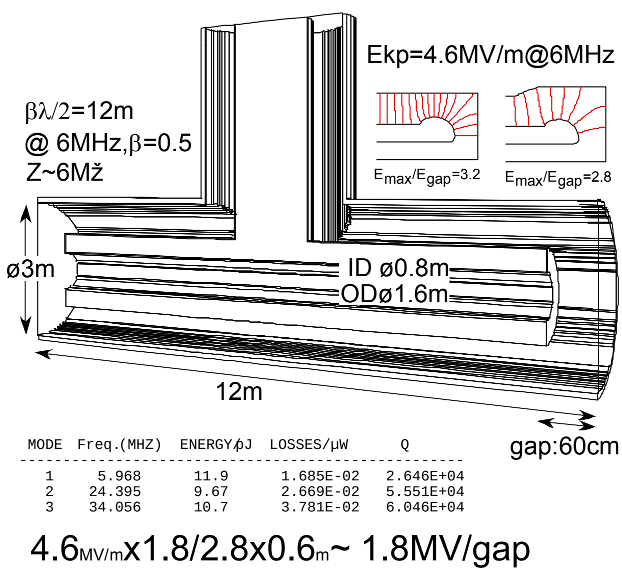


Fig. 10 Phase rotation cavity (Coax type)

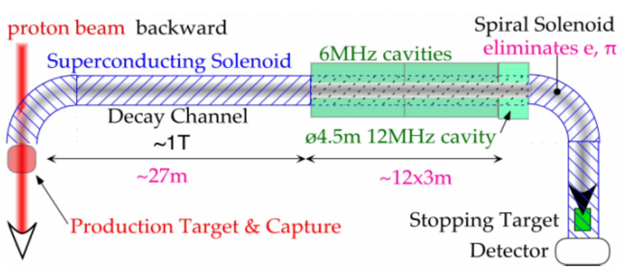


Fig. 11 PRISM/L system

according to the correlation between the muon energy and the ToF. Such a waveform can be synthesized from 6 MHz and 12 MHz components as shown in Fig. 12.

A simulation result after the phase rotation is shown in Fig. 13. The left figure shows only positive muons: they are well gathered around 20 MeV. Its energy histogram on the right shows that more than 400 muons are obtained within 20 MeV±5% from 10^5 protons. Because the solenoid channel can transport both charged muons, negative muons also reach to the end with less density in this energy range. Such contamination components including pions can be filtered by a spiral solenoid channel[6].

4 REFERENCES

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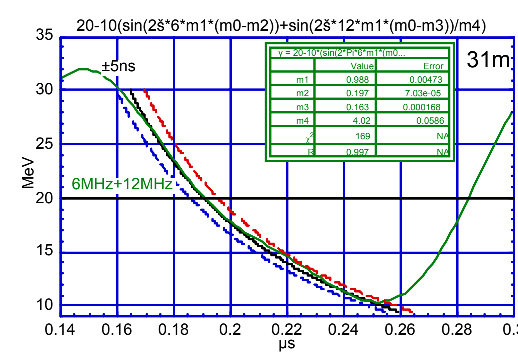

Fig. 12 Composed waveform for phase rotation.

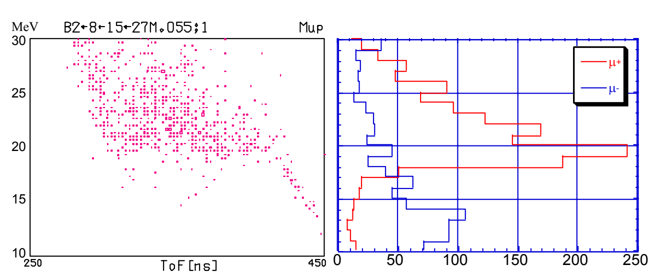

Fig. 13 Muon distributions. Left: energy as a function of ToF, right: projected histogram to the energy axis.