PROTON BUNCHING OPTIONS *

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Muon Colliders [1] need intense, very short, proton bunches. The requirements are presented and a number of possible bunching systems discussed. The best solution uses a small super-conducting buncher ring with 6 bunches that are taken though separate transports and combined on the target.

Keywords: Muon Collider; proton driver; space charge tune shift

1. Introduction

Because a muon collider luminosity depends on the square of the bunch charges, intense bunches of 2 10^{12} muons are required. To generate such bunches needs intense proton bunches. Fig.1 shows the relative muon fluxes vs. the proton energy used to make them. Pi production was from MARS 15 [2]. Muons were from an ICOOL [3] simulation [4] of the front end of a neutrino factory including pion decay, muon phase rotation, 80 m of transverse cooling, and accelerator acceptances of 30 mm transverse, 150 mm longitudinal. Since a muon collider is assumed to have a similar front end, this is a good measure of relative efficiency. This efficiency is maximum at around 8 GeV. At this relatively low energy, the required number of protons is very large ($\approx 200\ 10^{12}$), and the space charge tune shift with the required 2 ns bunch length, can be a problem.

Space Charge Tune Shift [5] is given by

$$\Delta\nu \;=\; F_{dist}\;\left(\frac{2\pi R}{\sqrt{2\pi}\;\sigma_z}\right)\;\frac{N_p\;r_o}{2\pi\;\epsilon_N\;\beta_v\gamma^2}$$

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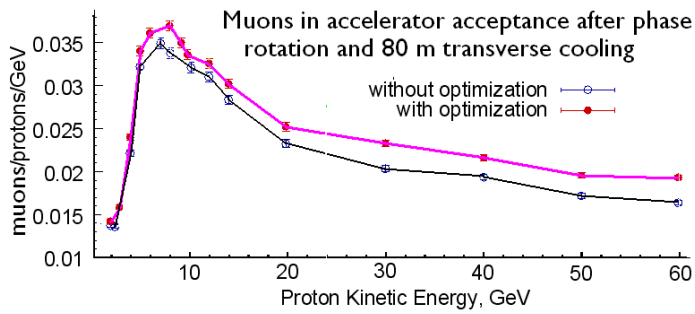

Fig. 1. Relative pion production vs. proton energy.

For Gaussian beams $F_{dist} = 3$, ϵ_N is the normalized (95%) emittance as used for protons at FNAL. The rms normalized emittance $\epsilon_\perp = \epsilon_N/6$.

2. Six buncher cases considered

The above formula is applied to the following numbered cases with parameters given in Tb.1.

Table 1. Parameters of bunchers

		1 Booster at inj	2 Booster at 8 GeV	3 SC	4 24 GeV	5 FFAG	6 6 bunch
E	GeV	0.4	8	8	24	8	8
Circ	m	474	474	200	561	339	200
N_p	10^{12}	0.06	200	200	96	200	200/6
σ_z	m	1.2	.66	.66	.66	.66	.66
σ_θ	mrad	1.2	1.2	2.5	0.83	25	2.5
ϵ_N	μm	12	112	200	200	2000	200
$\epsilon_\perp$	μm	2	19	33	33	330	33
nb		84	1	1	1	1	6
$\Delta\nu$		0.4	4.0	0.95	0.17	0.17	0.16

(1) To check the formula we consider the FNAL Booster at its 400 MeV injection energy. It gives a tune shift of 0.4, as published [6].
(2) This Booster, bunching 200 10^{12} protons to 2 ns at 8 GeV, assuming the full geometrical emittance as used at injection (normalized 95% emittance at 8 GeV of 112 μm), gives a space charge tune shift of 4: far above the value of 0.2 considered maximum for such an intense beam.

(3) A ring using super-conducting magnets would have a smaller circumference e.g. ≈ 200 m (instead of 474 m) and could have a larger acceptance: e.g. a 95% emittance of 200 μm (instead of 112 μm). But it's tune shift would still be an unacceptable 0.95.

(4) Since $\Delta\nu \propto 1/\gamma^2$, the tune shift can be lowered to a reasonable value by raising the proton energy to 24 GeV. From Fig.1 the needed proton bunch intensity is now 96 10^{12}. Assuming the same buncher ring normalized acceptance and average bending field as case # 3, then the tune shift for is a reasonable 0.17. But because pion production per GeV is now less, the required proton power is a factor of $\approx$1.7 higher: Not a good solution.

(5) Instead of raising the energy, one can try using a very large acceptance ring, such as the 5-10 GeV FFAG designed for muon acceleration in Study 2a [8]. That ring has a 339 m circumference and a normalized muon acceptance of 30 mm. With a 95% emittance one half this, the normalized proton emittance $\epsilon_N = \ 30,000/2 \times 106/970 \approx 2000 \ \ \mu m$. The tune shift is now a reasonable 0.17. But when this huge emittance is focused down to one third of the 5 mm target radius ($\sigma_r = r_{\rm target}/3 \approx 1660 \ \ \mu$m) then three times the rms angular spread is:

$$3\sigma_\theta = 3\ \frac{\epsilon_\perp}{\beta\gamma\ \sigma_r}\ =\ 3\ \frac{330}{8\ 1660}\ =\ 75 \quad \text{mrad}$$

over twice the crossing angle between the beam and jet, which is not viable.

(6) But if one can have multiple bunches in the ring and bring them simultaneously onto the target, then there appears to be a good solution. Consider the same ring as case #3 but with 6 bunches. The tune shift is now an acceptable 0.16. The bunches can be extracted into transports of differing lengths (trombones) [7] to bring them all onto the target at the same time: see Fig.2a. Since it is assumed that the beam intersects the mercury jet target from the side at an angle $\approx$ 33 mrad, it should be possible to bring multiple beams in from multiple azimuths, all at the same angle to the jet, see Fig.2b. The three sigma angular spreads are now 7.5 mrad, small enough to keep the transports for the beams well separated from the jet and one another.

3. Conclusion

Pion, and thus muon, production is predicted to have a maximum for 8 GeV protons. The muon collider then requires 200 10^{12} protons/bunch with $\sigma_t \approx$

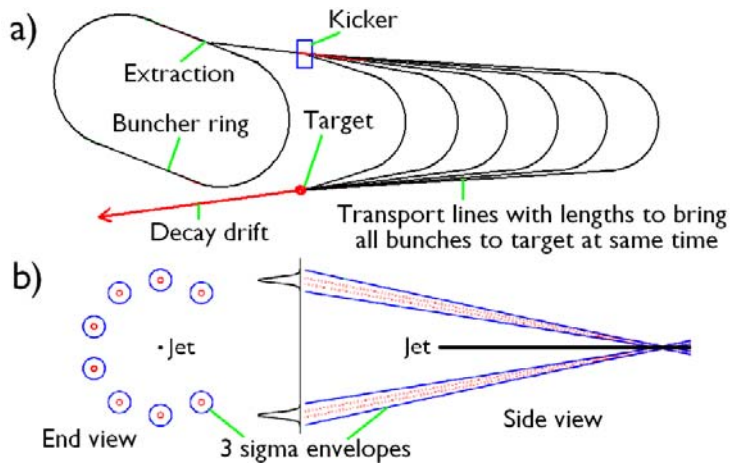

Fig. 2. a) Trombone transport lines to bring all bunches to the target at the same time; b) Multiple beam target geometry

2 ns. The space charge tune shifts of such bunches in an FNAL Booster-like ring is excessive.

The space charge is reduced if higher bending fields allow a smaller circumference ring (474→200 m), and if the acceptance is increased $\approx 1.8\times$, but this is not enough unless the proton energy is increased to 24 GeV, with a resulting increase in required power of 1.7. The best solution is to use multiple bunches in the ring, extracted into different transports that bring them all to the target at the same time.

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