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ACCUMULATOR LATTICE DESIGN FOR SPL BEAM

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Abstract

In this note, a design study of an accumulator ring, which is a component of proton driver in the neutrino factory, is described. Proton beam accelerated with the SPL (Superconducting Proton Linac) is accumulated in the ring for several tens of μs, and is transported to a compressor ring. The proton bunches are then compressed and are finally sent to the target.

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1. Introduction

In this note, a design study of an accumulator ring, which is a component of proton driver in the neutrino factory, is described. Proton beam accelerated with the SPL (Superconducting Proton Linac) is accumulated in the ring for several tens of μs, and is transported to a compressor ring. The proton bunches are then compressed and are finally sent to the target.

2. Basic choices

The radius of ring has been determined so as to meet the strategy of accumulation and compression [1]. The maximum number of bunches in the accumulator and the compressor are six and three, respectively. The accumulated bunches are transported to the compressor ring bunch by bunch, every 1/3 period of bunch compression. The bunch transported to the compressor ring should be allocated to a different longitudinal position, for instance 1/3 circumference behind of the previous bunch. When the number of turns for bunch compression is 36 turns, the radiuses of accumulator Ra and compressor Rc should satisfy

$$2\pi R_a(12+1/6) = 2\pi R_c(12+1/6+1/6)\,. \qquad (1)$$

This equation means that the bunch in the accumulator revolves 12 turns during the previous bunch in the compressor revolves 12+1/6 turns. Note that the additional 1/6 turn is necessary for the present bunch to reach the extraction kicker. When the radius of compressor is assumed to be 50m, the radius of the accumulator is $R_a = \frac{74}{73} R_c = 50.685$m.

The most important parameter of the accumulator ring is the slippage factor. It is expected to be zero (isochronous) so that the proton bunches are frozen longitudinally during accumulation. The rf cavities are not necessary, and the momentum spread from SPL will be preserved during accumulation. The kinetic energy of proton beam from SPL is assumed to be 5GeV [1]. The transition gamma should then be $\gamma_{tr} = \gamma = 6.329$. When the basic FODO cell is employed, the transition gamma is approximately [2]

$$\gamma_{tr} \approx Q_H \left[\frac{\mu_H/2}{\sin(\mu_H/2)} \right], \quad (2)$$

where Q_H is the horizontal tune, μ_H is the horizontal betatron phase advance per cell. Generally, the horizontal phase advance is preferred to be nearly 90degrees for beam injection and extraction. When this condition is fulfilled, the number of cells is about 25. Since the circumference is about 320m, the cell number of 25 results in the cell length of about 13m when we assume there are regular cells only. A ring composed of regular cells only is preferred from the transverse resonance point of view because of large super-periodicity. The total length of dipole magnets is about 80m when the dipole field of about 1.6T is assumed. The length of dipole is about 1.6m when two magnets are assigned in a FODO cell, in other words 50 dipole magnets for 25 cells. The sagitta in the 1.6m dipole magnet is about 26mm. It would be accepted. The number of cells, the number of dipole magnets and the cell length estimated above seem reasonable. With this consideration, basic parameters are determined, and are summarized in Table 1.

Table 1. Basic parameters

Parameters	Values
Kinetic energy (GeV)	5
Machine radius (m)	50.685
Transition gamma	6.329
Number of cells	24
Number of dipoles	48

3. FODO and triplet lattices

Linear lattice parameters with FODO cell are obtained based on the basic parameters in Table 1, after several runs of MAD program. They are shown in Fig. 1.

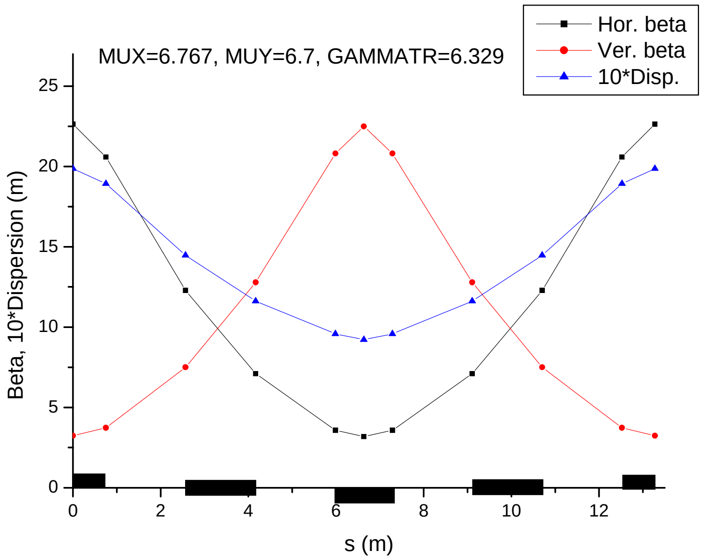

Figure 1. Linear lattice parameters (one cell)

From Fig. 1, we found that the isochronous lattice with reasonable beta functions and dispersion function is realized. Since it is assumed that the ring is composed of regular cells only, long straight section in cell should be secured for injection and extraction. This could be realized with triplet lattice. The lattice parameters are again obtained with MAD as shown in Fig. 2.

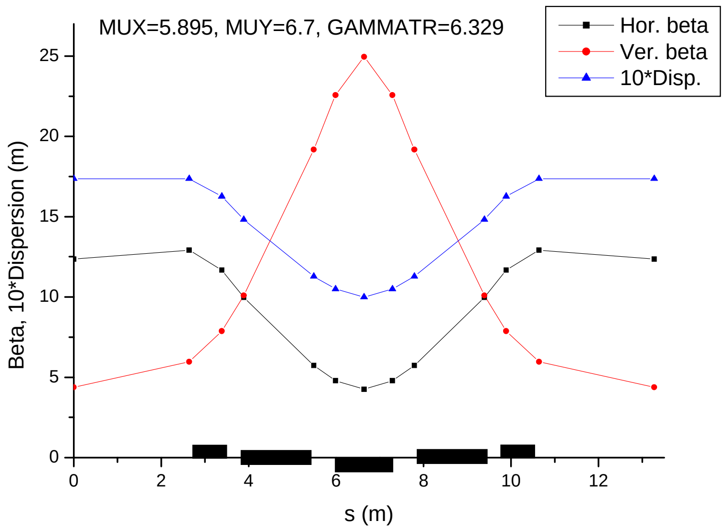

Figure 2. Linear lattice parameters with long straight section (one cell)

In Fig.2, the straight section is more than 5m. It would be long enough for the injection and extraction of 5GeV beam. And the horizontal phase advance is about 88 degrees, as expected. In practical operation, the transition gamma can be adjusted by changing the horizontal tune.

4. Beam emittance and magnet aperture

In order to estimate the required magnet apertures, the beam emittance should be determined. The relevant factors to determine the beam emittance are collective effects because the beam intensity of proton driver is very high. We assume the intensity is 10^{14} (per ring). As an index quickly obtained, the Laslett tune shift in free space (Eq. (3)) is calculated for various beam emittance as shown in Fig.3.

$$\Delta \nu = -\frac{n_t r_p}{4\pi\varepsilon\beta^2\gamma^3}\frac{1}{B_f}, \qquad (3)$$

where n_t is the beam intensity (particles per ring), r_p is the classical proton radius, ε is the beam emittance (physical emittance, Gaussian, r.m.s.), β and γ are the relativistic factors, and B_f is the bunching factor (average/peak).

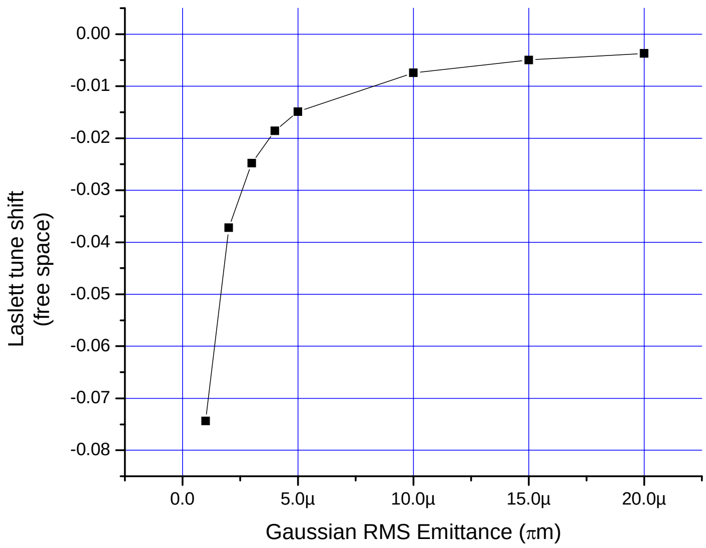

Figure 3. Laslett tune shift as a function of beam emittance

$n_t=10^{14}$, $B_f=0.667$ are assumed.

We should take into account the tune shift not only in the accumulator ring but also in the compressor ring. After bunch compression, the peak current in the compressor will be about 14 times larger than that of the accumulator. In order to avoid up to fourth order resonances, the Laslett tune shift should be smaller than 0.25. The beam emittance of 5π mm-mrad with 0.015 tune shift meets this condition. Some detailed studies of collective effects should finally be done to determine the beam emittance but we employ this value for the present estimation of the magnet apertures. Table 2 shows the estimation of required magnet apertures.

The quadrupole strengths are QF=4.43(T/m) and QD=4.60(T/m) in the triplet lattice (MAD result). The bore radius of 86.5mm results in about 0.4T field strength at pole tip. The apertures and field strength in Table 2 would be feasible. The lengths and strengths of quadrupoles could be further optimized, for example using the same length in QF and QD with different strengths.

Table 2. Estimation of the required magnet aperture

Emittance(πm) (i)	5.00E-06	
OD (~4.6T/m) (ii)		
Max beta (Ver.)	6sigma size (mm)	73.5
~30m(~120%)	COD (mm)	5
	Mechanical (mm)	3
	Chamber (mm)	5
	Sum=Bore radius (mm)	**86.5**
B (~1.6T)	**Horizontal**	
Max beta (Hor.)	6sigma size (mm)	46.5
~12m(~120%)	dx by disp. (mm)	3.6
Max beta (Ver.)	COD (mm)	5
~23m(~120%)	Mechanical (mm)	3
Max dispersion	Chamber (mm)	5
~1.8m(~120%)	Good field region ratio	0.5
	Saggita (mm)	26.2
dP/P~0.2%	**2*SUM/GFR=Pole width (mm)**	**304.7**
Bending angle 131mrad.		
	Vertical	
	6sigma size (mm)	64.3
	COD (mm)	5
	Mechanical (mm)	3
	Chamber (mm)	5
	2*SUM=Full gap (mm)	**154.7**

(i) Physical emittance, Gaussian, r.m.s.

(ii) The aperture of QF could be smaller than QD

5. Summary with parameters table

A possible lattice of the accumulator ring for the neutrino factory proton driver is designed. It is isochronous, and is triplet FDF cell. The ring could be composed of 24 regular cells only, with straight sections of more than 5m. The beam emittance is roughly determined to be 5πmm-mrad as taking into account the Laslett tune shift in free space. The specifications of dipoles and quadrupoles are estimated, and are feasible. The parameters are summarized in Table 3.

Table 3. Parameter table

Parameters	Values
Kinetic energy (GeV)	5
Machine radius (m)	50.685
Number of cells (FDF triplet)	24
Transition gamma	6.329
Betatron tunes H/V	5.90 / 6.70
Max. beta H/V (m)	13 / 25
Max. Dispersion (m)	1.8
RMS emittance (π mm-mrad) (i)	5
Straight sections (m)	~5 * 24cells
Quadrupole magnet (ii)	
Bore radius of Quad. (m)	0.087
Field gradient of Quad.(T/m)	4.6
Field strength at pole tip of Quad. (T)	0.4
Length of Quad. (m)	1.3
Dipole magnet	
Aperture of Dipole. (m*m)	0.305 * 0.155
Field strength of Dipole (T)	1.6
Bending angle per Dipole (mrad)	131
Length of Dipole (m)	1.6

(i): Physical emittance, Gaussian.

(ii): For defocus magnets

6. Acknowledgement

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his wide knowledge of MAD program and lattice design.

References

[1] R. Garoby, Presentation at NuFact'06,
https://edms.cern.ch/document/808094/1
[2] B. Autin et al., CERN-NUFACT Note 016 (2000)