MAGNET LATTICES FOR THE PROPOSED TRIUMF KAON FACTORY

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Abstract

The magnet lattices of a chain of two proton synchrotron and three dc storage rings for the proposed TRIUMF KAON Factory are described. The KAON Factory will provide pulsed and dc proton beams of 30 GeV and 100 μA and will be fed from the existing TRIUMF cyclotron. The rapid cycling Booster (50 Hz) accelerates from 440 MeV to 3 GeV; the 10 Hz main ring is 5 times larger and brings the energy to 30 GeV. The lattices are all of the separated-function type. For avoiding serious beam losses at transition the transition energy is driven far above the top energy of the accelerators. This feature is obtained mainly by creating a superperiodic structure with missing magnet cells and by choosing the horizontal tune just below the number of superperiods. A special arrangement of the rf accelerating cavities is used to avoid synchro-betatron coupling. Fast extraction systems are described.

Introduction

A general account of the TRIUMF KAON Factory project is given elsewhere.[1] This paper describes the magnet lattices of the two proton synchrotron and three dc storage rings, termed A (Accumulator, 440 MeV), B (Booster, 440 MeV - 3 GeV), C (Collector, 3 GeV), D (Driver or main ring, 3 GeV - 30 GeV) and E (Extender or stretcher, 30 GeV).

The A and B rings have a circumference 4.5 times the circumference of the 440 MeV orbit in the TRIUMF cyclotron, and are installed in a common tunnel. The C, D and E rings have a circumference 5 times larger than A and B and also share a common tunnel. In each tunnel the rings have the same lattice structure and the same tunes. This allows the magnets to be conveniently mounted vertically above one another and makes for simple beam transfer from ring to ring, with automatic lattice function matching.

The lattice designs of the Booster and Driver accelerators are the most constrained, the major factors being:

- circumference optimization for cost minimization
- maximum dipole field levels consistent with the fast cycling rates (1.3 T for the 10 Hz Driver and 1.05 T for the 50 Hz Booster)
- transition energy γ_t above the operating range
- room for rf cavities where they will not excite synchro-betatron resonances
- room for injection and extraction systems and for correction elements.

The first factor excludes designs with long dispersion-free straight sections, requiring extra dispersion suppressor cells at each end. Our separated-function designs have a strictly periodic quadrupole structure with missing magnet cells for rf, extraction and injection. Thus systematic resonances induced by quadrupole errors are of high order.

The high γ_t ensures that instabilities and beam losses due to space charge defocusing forces at transition are completely avoided. It is realized by creating S superperiods and a tune ν_x just below S.[2,3]

Synchro-betatron coupling induced by rf cavities is of concern because of the non-zero dispersion in the missing magnet cells. It is avoided by grouping the cavities with superperiodicity K, such that $(k \cdot K - \nu_x) \gtrsim 0.5$ where k is an integer.[4]

Table 1 gives the lattice parameters of the five rings. For the lattice studies we have made extensive use of the code DIMAT[5] from R.V. Servranckx. Initial parameters of optical elements are found by a code developed at TRIUMF[6] which is based on the thin lens approximation of quadrupoles. This code also provides a DIMAT input file.

Booster

This separated-function lattice consists of 24 regular FODO focusing cells. The dipole bending magnets are arranged with a superperiodicity S = 6, each superperiod following the pattern OBOBBOBO. The layout is shown in Fig. 1. The choice of 24 cells

Table I

.		Accumulator	Booster	Collector	Driver	Extender	Unit
Energy	E	.44	.44-3	3	3-30	30	GeV
Average radius	R	34.11	34.11	170.55	170.55	170.55	m
Repetition rate	F	dc	50	dc	10	dc	Hz
Radio frequency	f	46.1	46.1-61.1	61.1	61.1-62.9	62.9	MHz
Number of cells	n	24	24	48	48	48	
Number of superperiods	N	6	6	12	12	12	
Tunes	ν_x/ν_y	5.23/6.22	5.23/6.22	11.22/12.18	11.22/12.18	11.22/12.18	
Chromaticities	ξ_x/ξ_y	-1.11/-1.20	-1.14/-1.13	-1.19/-1.26	-1.26/-1.25	-1.26/-1.25	
Max. hor. beta	β_x	14.7	15.8	37.7	38.1	38.1	m
Max. vert. beta	β_y	14.5	15.2	37.4	37.5	37.1	m
Max. dispersion	η	6.64	3.98	8.15	9.09	8.51	m
Transition gamma	γ_t	35.5	9.2	23.65	∞	∞	
Hor. emitt. (inj)	ϵ_x	92.9	139.35	36.8	36.8	4.6	π mmmrad
Vert. emitt. (inj)	ϵ_y	30.9	61.8	16.3	16.3	2.0	π mmmrad
Momentum spread	$\Delta p/p$	± 3.42	± 3.42	± 1.67	± 2.73	± 1.56	10^{-3}
Dipoles : Number	N_D	24	24	72	144	72	
Length	L_D	.88	3.18	1.13	3.46	5.63	m
Min. field	B_{min}	1.0	.28	1.0	.16	1.6	T
Max. field	B_{max}	1.0	1.05	1.0	1.30	1.6	T
Hor. apert.	w	9.3	11.8	9.1	12.9	8.8	cm
Vert. apert.	h	5.1	8.6	4.9	5.4	2.2	cm
Quads : Number	N_Q	48	48	96	96	96	
Length	L_Q	.2	.36	.15	.94	.46	m
Gradient	dB/dx	4.8	10.0	10.0	13.25	27.0	T/m
Long drifts : Number	N_d	24	24	24	24	24	
Length	L_d	4.3	4.1	11.0	10.2	10.7	m

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makes the drift space between quadrupoles 4.1 m, providing a comfortable allowance for installation of dipole magnets (3.2 m), rf cavities (2.5 m), and injection and extraction magnets.

High transition energy is achieved by arranging the horizontal tune $\nu_x \approx 5$ to be just below the number of superperiods. The vertical tune ν_y is taken one unit higher than ν_x to avoid the zero-harmonic coupling resonance $\nu_y = \nu_x$ and to raise the space charge limit at injection. The exact choice of working point (5.23, 6.22) allows sufficient room for the space charge tune spread ($\Delta\nu_x = -0.08$, $\Delta\nu_y = -0.15$) — see Fig. 2. The nearest systematic resonances of low order are octopole ($\nu_x + 3\nu_y = 24$) and sextupole ($\nu_x + 2\nu_y = 18$). The one-unit difference between ν_x and ν_y is obtained by making the D quadrupoles slightly longer than the F quadrupoles. With 4 cells in each superperiod, the phase advances per cell are 78.3° horizontally and 92.7° vertically, close to the optimum value for minimizing peak betafunctions and apertures. All quadrupoles have the same aperture.

Figure 1 also shows the lattice functions for one superperiod. There are 4 dipole magnets in each superperiod occupying 4 half-cells and leaving the other 4 empty. The 6-fold superperiodicity is obtained by reversing a regular BOBO arrangement in every other pair of cells. This brings two dipoles together to make a full cell and two straight sections together to make an empty cell, creating an oscillation in the dispersion η, lowering the average value $\overline{\eta}$, and raising the transition energy $\gamma_t \approx 1/\sqrt{\overline{\eta}}$.

For ease of construction, the dipoles have parallel entrance and exit faces. The associated focusing action introduces a small modulation in the vertical betafunction. In order to provide a transition energy sufficiently far above the top energy of the booster, the modulation in the bending power in each superperiod has to be accompanied by a small extra modulation in the horizontal betafunction. This requires very small ($\approx$0.5%) adjustments in the strengths of the focusing quadrupoles. The value $\gamma_t = 9.2$ is chosen[7]; this is associated with a maximum dispersion of $\eta_x = 4$ m in the empty cell.

The empty cells are used for the fast extraction, fast abort and injection systems. The quadrupole in the middle of the empty cell is defocusing in the horizontal plane, allowing the entire fast extraction system to be accommodated in that cell.

The 12 rf cavities are located in the 12 single empty half-cells. The dispersion function η crosses zero at these locations, aiding the suppression of synchrobetatron resonances, although its gradient η' is non-zero.

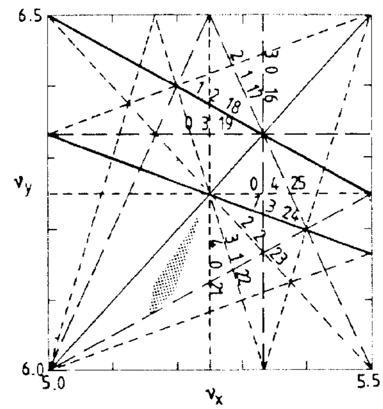

Fig. 2. Tune diagram for the Booster.

The arrangement chosen allows small correction dipoles to be placed near the defocusing quadrupoles for correction of any vertical closed orbit distortion. The horizontal closed orbit distortion will be minimized with backleg windings on the dipoles, and with horizontal correction bends.

The natural chromaticity is −1.14 for horizontal and −1.13 for vertical motion. In these designs, where transition is never crossed, it is no longer essential to make the chromaticity zero. (At its largest the chromatic tune spread only amounts to ±0.02.) Indeed, for controlling transverse coupled-bunch instabilities, the natural negative chromaticity is advantageous. With these considerations in mind, it is proposed to retain the natural chromaticity with its attendant advantages of linearity, stability and elimination of sextupoles.

The fast extraction and fast abort systems for horizontal single turn extraction each consist of a kicker magnet K, two septum magnets (S_1,S_2) and two bump magnets (B_1,B_2) (Fig. 3). The kicker magnet gives a deflection of 10 mrad. The defocusing quadrupole downstream of the kickers enhances the deflection. At the septum a separation of 1 cm between the circulating and the extracted beam is induced. The kicker magnet has a length of 3.5 m and a magnetic induction of 0.035 T. The septum magnets, each 1 m long and with a septum < 1 cm thick, provide 1 T and 1.7 T fields and 100 mrad and 130 mrad deflections respectively, in order to clear the next quadrupole and dipole. The bump magnets shift the equilibrium orbit in the extraction region towards the septum during acceleration, and leave it undisturbed outside the extraction area. The septum lies just outside the area occupied by the beam at injection, i.e. about 5 cm from the optical axis. Bump magnets 15 cm long providing up to 0.55 T give a displacement at the septum of 5 cm for the 3 GeV beam.

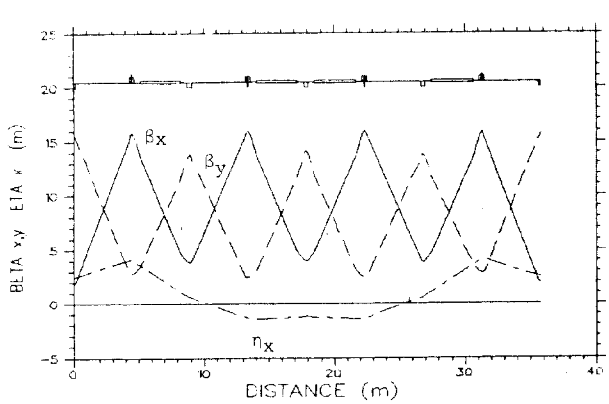

Fig. 1. Lattice functions for the Booster.

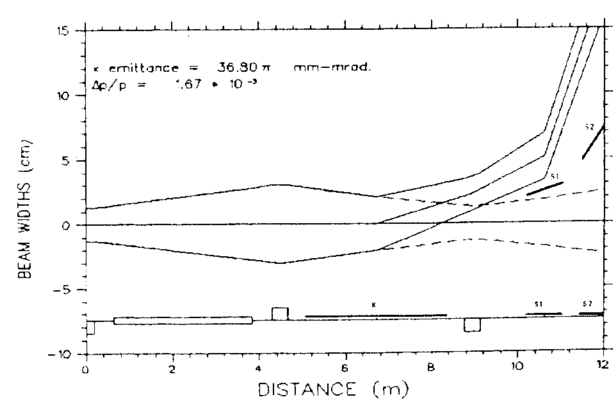

Fig. 3. Fast extraction from the Booster.

Accumulator

The Accumulator ring collects the 440 MeV cw H^- beam from TRIUMF during the 20 ms cycle time of the Booster. Injection into this machine is via charge exchange employing a stripper foil.[8] The machine lies 1 m above the Booster and has the same circumference and the same lattice structure as the Booster. Moreover the tunes have been chosen equal. This implies that the lattice functions are almost the same as those of the Booster, and simplifies beam transfer between the A and B rings.

The foil lifetime benefits from a high value of the quantity $\eta_x/\sqrt{\beta_x}$ and from an overall maximum of β_x at the stripper foil location, where η_x and β_x are the horizontal dispersion and betafunction.[8] Therefore the stripper foil is placed in the middle of the focusing quadrupole in the empty cell of one superperiod.

The dipoles perturb the regular horizontal focusing structure of the quadrupoles. The modulations thereby induced in β_x are largely removed by adjusting the quadrupole strengths at the centre and at the beginning of each superperiod, giving the additional benefit of an increased maximum dispersion of 6.6 m.

Driver

The Driver accelerates the proton beam from 3 GeV to 30 GeV. This machine is fast cycling, 10 Hz, and has an average radius of 170.55 m. i.e. 5 times the Booster.

This separated-function lattice consists of 48 regular FODO focusing cells. The dipole bending magnets are arranged with a superperiodicity S = 12, following the pattern BBBBBOBO within each superperiod. The layout is shown in Fig. 4. The choice of 48 cells makes the drift space between quadrupoles 10.2 m, providing a comfortable allowance for installation of dipole magnets (6.9 m), rf cavities (2.5 m), or injection and extraction magnets.

High transition energy is achieved by arranging the horizontal tune $\nu_x \simeq 11$ to be just below the number of superperiods. The vertical tune ν_y is taken one unit higher than ν_x to avoid the zero-harmonic non-linear coupling resonance $\nu_y = \nu_x$ and to raise the space charge limit at injection. The working point (11.22, 12.18) is chosen in a similar region to the Booster and allows sufficient room between nearby resonances for the space charge and chromatic tune spreads ($\Delta\nu_x = -0.01$, $\Delta\nu_y = -0.09$, $\Delta\nu_c = \pm 0.04$). The one-unit difference between ν_x and ν_y is obtained by making the D quadrupoles slightly longer than the F quadrupoles. With 4 cells in each superperiod the phase advances per cell are close to the optimum for minimizing peak betafunctions and apertures. All quadrupoles have the same aperture.

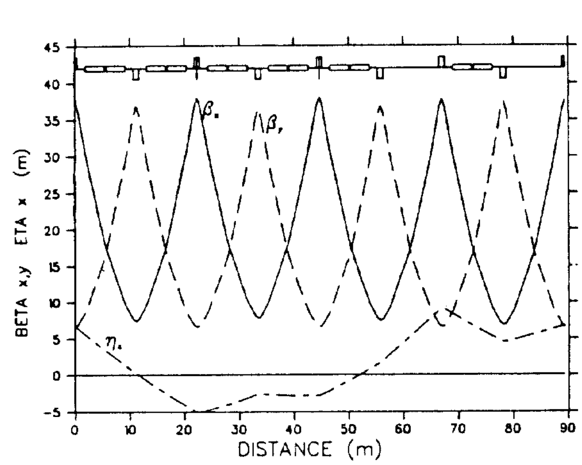

Fig. 4. Lattice functions for the Driver.

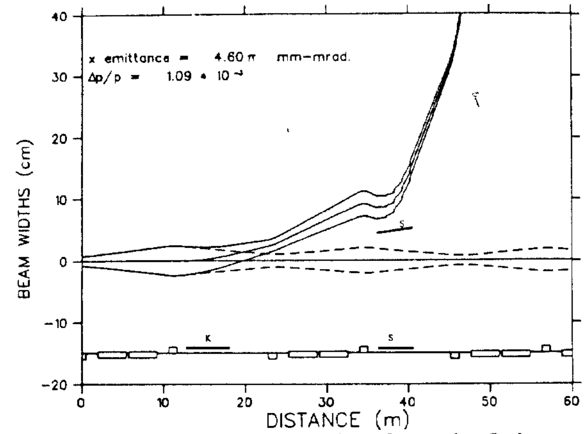

Fig. 5. Fast extraction from the Driver.

Figure 4 also shows the lattice functions for one superperiod. Except for a very slight modulation caused by the focusing action of the dipoles (which have parallel end faces) the betafunctions are completely regular. The oscillation in the dispersion function arises from the clustering of the dipole magnets. Out of the 8 half cells of the superperiod 6 contain dipoles - 5 together and one between the two straights. This arrangement is advantageous for fast extraction although the dispersion modulation produced does not drive the transition energy quite high enough. To achieve $\gamma_t \approx \infty$ a small (~3%) variation is introduced in the quadrupole strengths. The associated maximum dispersion is 9.1 m.

For ease of construction and handling the dipole magnets have been split in two parts each 3.46 m long (with a maximum field of 1.3 T). Drift spaces 1.5 m long remain between quadrupoles and dipoles, enough for placing correcting elements for closed orbit distortions, pumps, bellows and diagnostic equipment. Of the 12 pairs of empty half cells, 9 are allocated to the rf cavities and 3 to the injection, extraction and abort systems.

Horizontal fast extraction (Fig. 5) requires a space of three half-cells for placing kickers (6 m × 0.035 T) and septum magnets (40 mrad over 4.5 m). Two bump magnets (0.5 m × 0.41 T), 90° phase advance away from the septum, are used to shift the equilibrium orbit towards the septum during acceleration.

Collector and Extender

The C and E rings have the same lattice as the Driver, and the same tunes. The Collector has a high tune for a proton energy of 3 GeV, and $\gamma_t = 16.5$. The natural γ_t of the Extender is imaginary but quadrupole trimming windings will be provided to adjust it and change the bunch length to suit experimental requirements.

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