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POLARIZED PROTONS IN THE TRIUMF KAON FACTORY

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ABSTRACT

In the following paper, methods for acceleration of polarized protons in the proposed TRIUMF-KAON Factory without too much depolarization are examined. Two ways of improving polarization transfer will be treated: passing through depolarizing resonances using either fast tune shifts or slow adiabatic spin flip, and reducing the strength of depolarizing resonances by redesigning the lattice using spin matching. It is shown that a combination of the two methods can result in about 70% polarization transfer through the accelerators, providing about 55% polarization of 30 GeV protons.

INTRODUCTION

Depolarizing resonances occur in cyclic particle accelerators when the rotation frequency of the spin about the (vertical) guide field equals any harmonic frequency present in the (horizontal) focusing fields or error fields. The two major components are the radial fields in the vertically focusing quadrupoles due to betatron oscillation, whose frequency spectrum is determined by interference between the betatron tune and the frequency of the field, and the horizontal fields seen by the particle in the quadrupoles and other magnets due to closed orbit excursions, which are unrelated to betatron oscillation. The first component leads to the intrinsic resonances given by the condition

$$\gamma G = k \pm \nu, \quad (1)$$

the second one to the imperfection resonances given by

$$\gamma G = k, \quad (2)$$

where $G=1.7928$ is the magnetic anomaly of the proton and γ is the relativistic energy. γG is the number of spin revolutions per turn.

The effect of crossing a depolarizing resonance in the course of acceleration is given in the asymptotic limit by the formula

$$P/P_0 = 2 e^{-\pi \epsilon^2 / (2\alpha)} - 1, \quad (3)$$

where ϵ is the resonance width, $\alpha = G d\gamma/d\theta$ is the crossing speed in units of spin tune per azimuthal radian.

Position and strength of the depolarizing resonances in the KAON Factory accelerators have been calculated numerically using the program DEPOL3. In the 3-GeV Booster (Fig. 1a), two intrinsic and five imperfection resonances have to be crossed; in the 30-GeV Driver (Fig. 1b) there are 9 intrinsic resonances and 53 imperfection

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resonances. In each case, the resonances reflect the superperiodicity of the machine ($S=6$ for the Booster, $S=12$ for the Driver). The invariant emittance used for calculation of the intrinsic resonances was 10 mm-mrad, consistent with the space-charge limit for 10-20 μA of polarized protons in the machines. Current in this range is expected from the optically-pumped ion source under development at TRIUMF. The figures show the resonance strength normalized by the crossing speed to take into account the sinusoidal magnet variation.

Fig. 1. Depolarizing resonances in the (a) Booster and (b) Driver. The horizontal lines represent 1% depolarization and 99% spin flip.

As is evident from the figures, the resonance strengths are large, leading to depolarization and even spin flip for most of the resonances. While imperfection resonances will be made weak using programmed orbit correctors, intrinsic resonances are more difficult to deal with. In the following, techniques are investigated to reduce depolarization crossing the resonances and to reduce the resonance strengths by themselves.

CROSSING AN INTRINSIC DEPOLARIZING RESONANCE

In order to reduce depolarization on crossing an intrinsic resonance of a given strength, one has to either increase the crossing speed to preserve polarization or reduce the crossing speed to make spin flip more efficient. This is done by pulsing the tune with a fast leading ramp downwards and recovery on a slower trailing ramp. Crossing on the fast ramp leads to fast crossing, while crossing on the slow trailing ramp leads to a reduction of crossing speed, since the machine tune follows the spin tune for a while. For a fast, finite tune step, the resulting depolarization differs from the value given by the above formula because the

asymptotic condition is not valid anymore. Depolarization is given by

$$\frac{P}{P_0} = \frac{\delta^2 - \epsilon^2}{\delta^2 + \epsilon^2} - \frac{2\epsilon^2\delta^2}{3\alpha^2} - \frac{\delta^2}{\delta^2 + \epsilon^2} \quad (4)$$

with δ being one half of the tune-step size. The tune-jump method is limited by the amount of tune shift that can be accommodated in the tune diagram and by emittance growth caused by the nonadiabatic change in the betatron function.

For slow adiabatic crossing on the trailing ramp of the tune shift, the reduction in crossing speed achievable is determined by the asymptotic condition, which we derive from Ref. 4 to be

$$\Theta_A \geq 10 \frac{\epsilon}{2\alpha} \coth \sqrt{\frac{\epsilon^2}{\pi \delta \alpha}} \quad (5)$$

This leads to the following expression for the reduced crossing speed,

$$\alpha_r = \alpha \frac{\epsilon}{0.2\delta + \epsilon}, \quad (6)$$

which shows that unless δ can be made very large compared to ϵ the reduction achievable is small, 0.5 to 0.9 in our cases.

For the purpose of this investigation a tune step 2δ of 0.2 is assumed, thus avoiding to cross betatron resonances of order <3 . A value of 0.06/rad has been assumed for the speed of the fast ramp, the value achieved in the AGS setup. Using these parameters and slow or fast resonance crossing, whichever results in better polarization transfer for each resonance, polarization transfer can be as high as 95% for the Booster intrinsic resonances, but only about 36% for crossing the nine intrinsic resonances in the Driver, integrated over the beam distribution.

REDUCING THE STRENGTH OF DEPOLARIZING RESONANCES

An obvious way to reduce the strength of resonances is to lower the vertical tune, thus reducing the vertically focusing fields. While this does have some effect, it was found insufficient for the Driver.

Since the resonances arise from a coherent contribution from the superperiods, spin matching has been used to design a superperiod that reduces the effect on the spin. Because of other constraints like fixed circumference and imaginary transition energy, the superperiodicity was not to be changed and also the basic FODO structure of the focusing elements was considered fixed, leaving the distribution of the bending magnets in the cells as the major parameter to be varied.

Only radial fields in the defocusing quadrupoles (D-quads) are considered. In the coordinate system used, x denotes the radial, y

the longitudinal and z the axial direction of the machine. The strength of the radial fields in the i -th D-quad are

$$b_{z,i} = g_i \cdot b_{z,i} \cdot \cos(\nu_z \Theta_i + \phi_i), \quad (7)$$

where g_i is the focusing strength, ϕ_i is the initial betatron phase and Θ_i is the azimuthal position of the quadrupole.

The change in the polar angle of the polarization vector with respect to the y axis in this field is given to first order by

$$\Delta\alpha_i \propto b_{z,i} \cdot \cos \beta \quad (8)$$

with β being the azimuthal angle of the polarization vector around the y axis, given by

$$\beta_i = 2\pi f_G (N_{b,i}/N_{b,tot}) + \beta_0 \quad (9)$$

for an initial angle β_0 , where $N_{b,i}$ is the number of bending magnets up to the i -th cell and $N_{b,tot}$ is the total number of bending magnets in the ring.

Inserting this into Eq. 7, summing over all four D-quads in a superperiod and using the fact that in our case the phase advance per cell is close to 90° , we get for the deflection of the polarization vector passing through one superperiod,

$$\begin{aligned} \Delta\alpha_{sp} &\propto \cos\phi_0 \cdot [\cos \beta_0 \\ &[\sin(\pi f_G (N_{b2}-N_{b0})/N_{b,tot}) \cdot \sin(\pi f_G (N_{b2}+N_{b0})/N_{b,tot}) \\ &+ \sin(\pi f_G (N_{b3}-N_{b1})/N_{b,tot}) \cdot \sin(\pi f_G (N_{b3}+N_{b1})/N_{b,tot}) \cdot \cos(2\pi\nu/N_c)] \\ &+ \sin \beta_0 \cdot [\text{same as above}]] \\ &+ \sin \phi_0 \cdot [\text{other terms}]. \end{aligned} \quad (10)$$

A factor of the form

$$\sin \pi f_G [(N_{b1}-N_{b1-2})/N_{b,tot}]$$

is common to all terms including those multiplied by $\sin \phi_0$ and determines the contribution of one superperiod to depolarization. It only involves the number of bending magnets between two D-quads 180° apart from each other. We will therefore classify the lattices according to this number, i.e. a $(m-n)$ lattice has m bending magnets between the first pair of D-quads and n magnets between the other pair.

Table I lists the values of the strength factor for 2, 3, and 4 bending magnets between a pair of D-quads.

The Driver lattice of the reference design in the KAON Factory proposal is a (2-3) lattice in the above notation, which has a large value of the strength factor for one or the other pair of D-quads for

all but the $36\pm\nu$ resonances. This indicates more or less even distribution of resonance strength over the full energy range of the ring, consistent with the DEPOL calculation.

According to Table I, a (4-4) lattice should have less strength in all resonances except the $36\pm\nu$ resonances. The result of the DEPOL calculation for such a lattice is given in Fig. 3 and is in good qualitative agreement with the prediction. The layout and lattice functions are given in Fig. 4.

Table I. Resonance-strength factor for a Driver-type superperiod.

Res.	γG	$\sin \pi \gamma G (\Delta N_{b1}=2)$	b_3/N_b	$\text{to } \frac{1}{4}$
$0+\nu$	10.18	0.77	0.97	0.97
$24-\nu$	13.82	0.93	0.97	0.86
$12+\nu$	22.18	0.93	0.23	-0.66
$36-\nu$	25.82	0.77	-0.23	-0.97
$24+\nu$	34.18	0.16	0.97	-0.31
$48-\nu$	37.82	-0.16	-0.97	0.31
$36+\nu$	46.18	-0.78	-0.23	0.97
$60-\nu$	49.82	-0.93	0.45	0.66
$48+\nu$	58.18	-0.93	0.97	-0.67

$N_{b \text{ tot}}=72$ is the number of bending magnets in the Driver.

The resonance strength is now concentrated in the $36\pm\nu$ resonances, increasing their strength and making spin flip crossing them quite efficient. Using tune jump and spin flip as described in the preceding section, 75% polarization transfer through the nine intrinsic resonances in the Driver with a vertical tune of 10.18 rather than 13.18 can be achieved, integrated over the beam distribution.

The same procedure can be carried out for the Booster, where it was found that reversing the polarity of all quadrupoles from that in the reference design reduces the resonance strength considerably.

Together with a reduction of the vertical tune from 7.22 to 4.22, only one weak intrinsic resonance ($0+\nu$) remains in the acceleration range. This resonance can be jumped with more than 99% polarization preservation

SUMMARY

It is shown that by a slight modification of the lattices and applying proven techniques of fast and slow crossing of resonances, about 75% of the polarization can be preserved crossing the intrinsic resonances in the KAON Factory accelerators.

If we assume 5% residual depolarization from imperfection resonances in the Driver and 1% depolarization in the Booster (which should be achievable applying computer-assisted dynamic orbit correction), and 81% polarization of the beam delivered from the TRIUMF cyclotron, a polarization of about 55% appears to be achievable at 30 GeV. Improving on this value, however, calls for more drastic measures in the form of "Siberian Snakes" that will be the subject of another contribution to this conference.

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Fig. 2. Depolarizing resonances in the modified Driver lattice.

Fig. 3. Modified Driver lattice.

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