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CHROMATICITY CORRECTION FOR AN INTRINSIC DEPOLARIZING RESONANCE

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Abstract Chromaticity correction for the intrinsic resonance, $\gamma G=\nu_z$, in the booster was performed by a new correction sextupole magnet system. The features of the magnet system and the experimental results of correction are presented.

INTRODUCTION

At the KEK PS, development of polarized proton acceleration is in progress, and polarizations of 40% at 3.5GeV and approximately 25% at 5GeV were achieved in the main ring so far.[1,2,3]

Conventional resonance handling techniques such as the fast passage method (tune jump) and closed orbit control work well from 500MeV to 3.5GeV in the main ring, where depolarization was reduced to about 10% of the injected beam polarization.[1-3] On the contrary, depolarization in the booster has been about 25%.[1-5] This depolarization is thought to be due to the synchrotron oscillation effect at the spin flip intrinsic resonance $\gamma G=\nu_z$ which causes multiple resonance crossings.[4,5] Here γ is the Lorentz energy factor, G is the gyromagnetic anomaly and ν_z is the vertical betatron tune.

The strong depolarizing resonances in a proton synchrotron are classified into two resonances: the intrinsic resonance and the imperfection resonance. The intrinsic resonances are caused by mainly the horizontal fields of the focussing magnets. In these resonances each particle feels a resonant field proportional to its vertical betatron amplitude. Therefore the spin with a large vertical betatron amplitude is perturbed more. After crossing an intrinsic resonance by a spin flip the polarization of the beam center remains unchanged while the spin flip occurs near the beam boundary. The fraction of spin flipped particles increases as intrinsic resonance becomes stronger. The resonance crossing of intrinsic resonances with an adiabatic spin flip is a useful method for strong resonances which causes the complete spin flip of almost all particles in the beam.[1-3]

The $\gamma G=\nu_z$ resonance in the booster had been expected to be strong enough to cause almost complete spin flip by a first order calculation, contrary to measurements. But the acceleration rf voltage dependence of polarization was observed.[4-6] This indicated that synchrotron oscillation caused depolarization and that this was dominant depolarization effect in the booster.

THE SYNCHROTRON OSCILLATION EFFECT

The beam is a collection of particles bunched by the acceleration rf as well as confined transversely by focusing fields. Each particle oscillates in energy around the synchronous energy at the synchrotron oscillation frequency. This frequency is proportional to the square root of the rf voltage and the amplitude ranges between 0 and the maximum amplitude which is proportional to the square root of the rf voltage. This oscillation causes not only a modulation of the spin tune γG which is the precession frequency of spin in one revolution of the particle but also a modulation of the resonant frequency $nN \pm \nu_z$. Therefore spin tune modulation by synchrotron oscillation based on the resonant frequency is

$$\gamma G - (nN \pm \nu_z) = \alpha\theta + (\gamma_0 G\beta^2 \mp \xi_z)(\Delta p/p)\cos(\nu_s\theta + \phi)$$

for the resonance $\gamma G = nN \pm \nu_z$. This modulation leads to multiple resonance-crossing and consequently to depolarization. Here α is crossing speed for the resonance, the angle θ is the azimuthal variable which is the distance along the orbit s divided by the average radius of the orbit R, n is an integer, N is the super-period of the synchrotron, β is the normalized velocity, $(\Delta p/p)$, ν_s and ϕ are the amplitude, tune and phase of synchrotron oscillation, respectively, and ξ_z is the vertical chromaticity ($\Delta\nu_z/(\Delta p/p)$).

The amplitude and tune of synchrotron oscillation, $(\Delta p/p)$ and ν_s, respectively, depend on the rf voltage. Therefore one method for elimination of the synchrotron oscillation effect is to reduce the rf voltage. But this is limited by the longitudinal acceptance of the machine. A more attractive method is to adjust the vertical chromaticity to satisfy the condition of $\xi_z = \pm\gamma_0 G\beta^2$. The qualitative agreement between the measurement and the numerical calculation on the rf voltage dependence at the $\gamma G = \nu_z$ resonance of the booster[1-5] and the vertical chromaticity dependence at the $\gamma G = \nu_z$ resonance of the main ring (Figure 1) seemed to support the above model.

THE CORRECTION OF THE SYNCHROTRON OSCILLATION EFFECT

At the $\gamma G = \nu_z$ resonance in the booster, numerical calculation predicted that spin tune modulation will be cancelled out and an almost complete spin flip will occur, if the vertical chromaticity is changed from -6.8[7], which is the normal vertical chromaticity assumed by field measurements,[7] to ~1.0.[4,5] For this purpose a pulsed sextupole magnet system was constructed and the polarization dependence on the chromaticity was measured.

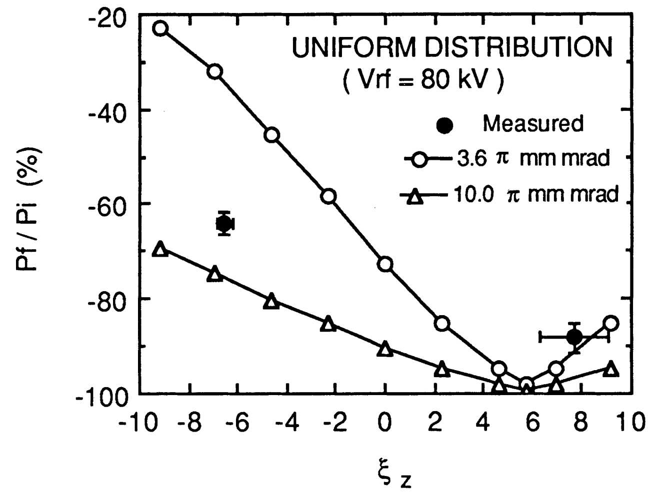

FIGURE 1 Dependence of the polarization ratios on the vertical chromaticity before and after crossing the $\gamma G=\nu_z$ resonance in the main ring.

<u>The pulsed sextupole magnets</u>

The pulsed sextupole magnets are required to have enough power to change the chromaticity: $\Delta\xi_z$~7.8. The required sextupole strength is 160 T/m^2. Another requirement is a fast enough response to avoid the crossing of neighboring resonances. The nearest neighboring resonances are $\gamma G=\nu_x$, lying at a lower energy, and $\gamma G=\nu_x+\nu_z-2$ or $7-\nu_x-\nu_z$, lying at a higher energy. Therefore the excitation period had to be less than 5.6msec. A half sign wave form using a resonant discharging circuit with the magnet inductance and the internal capacitance was chosen for simplicity.

As only two straight sections, S4 and S5, are available in the booster for installation of correction sextupoles, two magnets were designed to fit in these spaces. The iron core of the magnet was made of 0.35mm thick non-directional silicon steel insulated with inorganic material. The pole shape was designed with the aid of the magnetostatic program (POISSON) so that the sextupole field is uniform in the useful aperture. The coil has a cross section of 9×4mm^2 and is air-cooled.

Parameters of the correction sextupoles are summarized in TABLE I. The measured field strength was 0.52 I T/m^2, corresponding to $\Delta\xi_z$=0.024 I, where I is a current in amperes. The effective length was 277mm.

TABLE I. Parameters of the sextupoles.

Mechanical		
	Core length	250 mm
	Bore radius	70 mm
Electrical		
	Turn number	21 turns/pole
	Resistance	50 mΩ
	Inductance	8.5 mH
	Maximum current	390 A
	Maximum voltage	1.9 kV

The Results of The Experiment

There are two strong depolarizing resonances in the booster during acceleration from 40 MeV to 500 MeV. One of them is the imperfection resonance, $\gamma G = 2$, at 108 MeV and another is the intrinsic resonance, $\gamma G = \nu_z$, at about 280 MeV.

At first the $\gamma G = 2$ resonance was optimized by adjusting the vertical closed orbit distortion using a vertical pulsed dipole magnet (deflector). Additional closed orbit distortion which corresponds to the deflector current of 80 A was made in order to confirm a stable spin flip, because there was a little depolarization without any additional closed orbit distortion as shown in Figure 2.

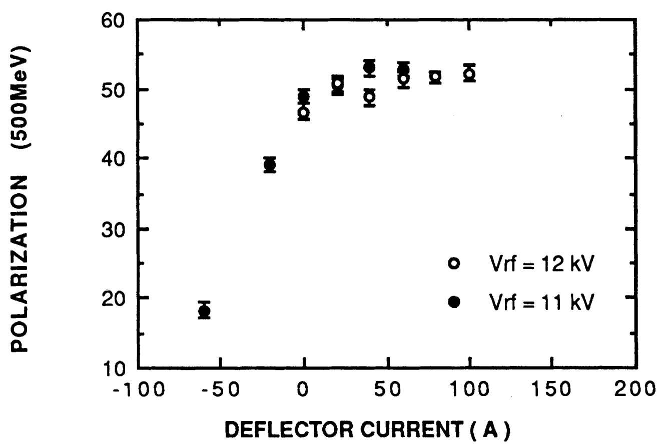

FIGURE 2 Deflector current dependence of the $\gamma G=2$ resonance.

The sextupole trigger timing was set at 11.7 msec from acceleration start in order to make the peak current just at the resonance. This is calculated from the vertical tune data, $\nu_z=2.33$. The sextupole excitation was performed at two different rf voltages, 12kV and 9kV. The result is shown in Figure 3. The polarization has a peak around a sextupole current of 50 A. The sextupole trigger timing was varied around the timing, 11.7msec. The polarization was almost flat at 12 ± 1 msec.

The polarization at 20 MeV before injection into the booster measured by the 20MeV polarimeter[8] was 63.66 ± 5.91 %. The polarization was improved by a relative 7.8±0.7% at Vrf =12kV and 3.3±1.1% at Vrf=9kV compared to the value at sextupole off. The maximum polarization was 54.2±0.6%.

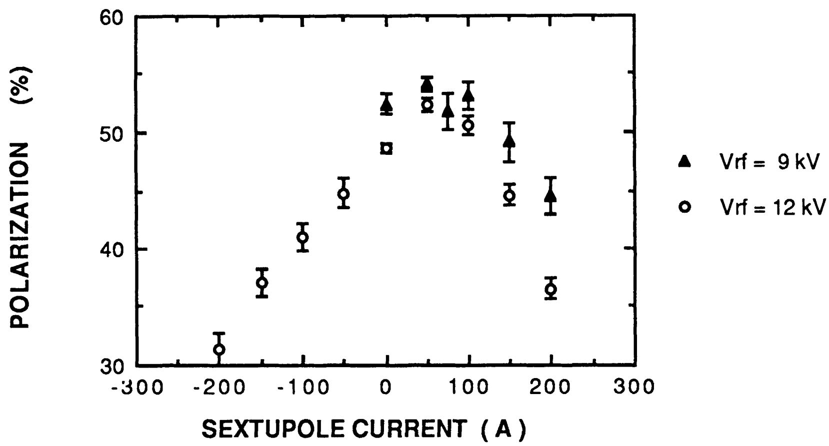

FIGURE 3 Sextupole current dependence of the $\gamma G=\nu_z$ resonance.

Discussion

The expected feature of the chromaticity dependence of the polarization is: polarization goes to maximum at $\xi_z = \pm \gamma_0 G \beta^2$ for $\gamma G = nN \pm \nu_z$. In the measurement the polarization had a peak around the sextupole current of 50 A, corresponding to a vertical chromaticity change of 1.2. The value of chromaticity is calculated from the field strength because at present it is impossible to measure the vertical chromaticity in the booster. For stability of the normal beam, another sextupole is exited and this causes another chromaticity change of −0.3. Therefore, the total chromaticity change was 0.9 at the peak polarization. If this is the optimum point, the normal vertical chromaticity will be ~0.1. This value does not agree with the value of ~−6.8.[7] In Figure 4 the dashed line was calculated by assuming the above chromaticity and a vertical emittance of 9.8 πmmmrad. The upper and lower lines correspond to the uniform and quadratic distributions in phase space, respectively.

Beam loss was observed for sextupole currents greater than 100 A by the intensity monitor (current transformer). The sextupole magnets may excite the orbital resonance and this might have caused the beam loss. There remains a possibility that the orbital resonance changed the particle distribution in the transverse phase space and caused polarization loss.

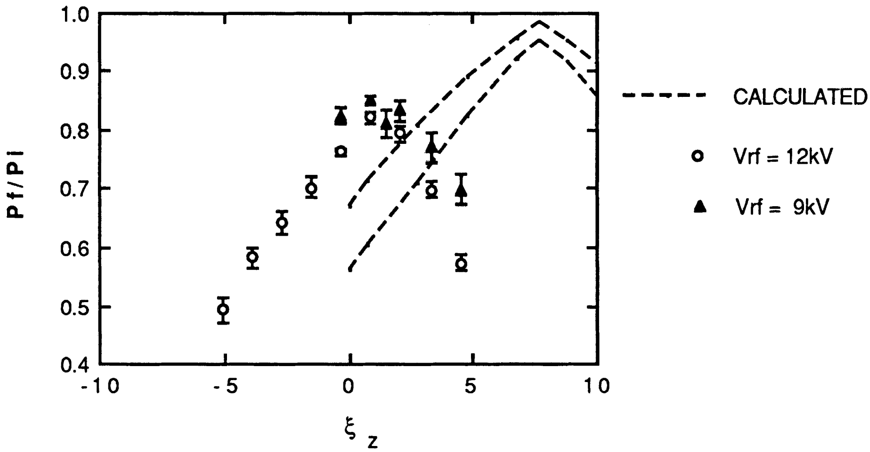

FIGURE 4 Dependence of polarization ratios on the vertical chromaticity before and after crossing the $\gamma G = \nu_z$ resonance in the booster.

In the normal accelerating condition for the booster, i.e. at the acceleration rf voltage of 12 kV, polarization survival was improved from about 75% to about 82% by the sextupole correction at the $\gamma G = \nu_z$ resonance. At least the sextupole field works well up to a current of 50 A. Therefore, the measurements of the vertical chromaticity and the transverse emittance at the $\gamma G = \nu_z$ resonance are the next experiment.

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