# POLARIZED PROTON ACCELERATION AT THE KEK PS

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## Abstract

The KEK PS consists of a 750 KeV Cockcroft-Walton pre-injector, a 40 MeV injector linac, a 500 MeV booster synchrotron and a 12 GeV main ring synchrotron. Both the booster and the main ring of the KEK PS are strong focusing synchrotrons and therefore strong depolarizing resonances are expected during acceleration. Research and development of polarized proton beam acceleration is being carried out at the KEK PS, and approximately 40% and 25% polarization has been obtained at 3.5 GeV and 5.0 GeV, respectively, in the main ring.[1,2,3]

In this article, the performance of the polarized proton beam acceleration and the origin of the depolarization in the booster will be described.

## Introduction

Since there are generally many depolarizing resonances in a strong-focusing synchrotron, a polarized beam can not be accelerated without using several correction methods to reduce the depolarization. There are basically two types of depolarizing resonances. One is an intrinsic resonance which is excited by the periodical focusing structure of the machine. The other is an imperfection resonance which is due to the magnet misalignment leading to vertical closed orbit distortion (COD).

At the KEK PS, several weak and intermediate intrinsic depolarizing resonances are passed through by the fast-crossing method. Although the other strong depolarizing resonances are expected to be passed through with a natural adiabatic spin-flip. The synchrotron oscillation effects were observed, especially in the booster synchrotron.

## Equipment for polarized beam acceleration

The equipment designed for polarized beam acceleration is shown in Fig.1. Polarized $H^-$ ions which are produced by an optically pumped polarized ion source[4] are accelerated by the 750 KeV Cockcroft-Walton pre-injector and the 40 MeV linac, and then injected into the booster synchrotron by a charge-exchange method[5] through a thin carbon foil to strip the electrons. The polarized proton beam is accelerated up to 500 MeV in the booster and then injected into the 12 GeV main ring.

In the booster ring, two pulsed dipole magnets are installed to correct the $\gamma G=2$ imperfection resonance. For the investigation of weak resonances such as $\gamma G=\nu_x$ and $\gamma G=5-\nu_z$, two pulsed quadrupole magnets are also installed. In the main ring four pulsed quadrupole magnets with a rise time of 40μsec to 200μsec are installed to pass through some of the intrinsic depolarizing resonances. The rise time was designed close to the critical speed in considering the calculated resonance strength to save magnet and pulsed power supply costs. The harmonic correction of the vertical COD to manipulate the imperfection resonances has been done using twenty eight correction dipole magnets which are equally distributed around the machine.

Three polarimeters are installed in the accelerator to measure the beam polarization at different stages of the acceleration. One is situated between the two linac tanks to measure the polarization at 20 MeV by detecting an asymmetry of proton-carbon elastic scattering using a fine carbon-fiber as a target. The others are installed in the main ring for the exclusive use at 500 MeV (called the injection polarimeter) and for the accelerated beam (called the main ring polarimeter). The injection polarimeter is used for tuning and monitoring the depolarization in the booster, and the main ring polarimeter is used for the acceleration tuning of the polarized beam

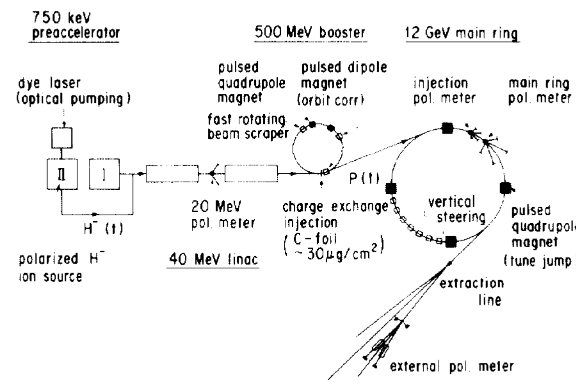


Fig. 1. Equipment designed for the polarized beam acceleration.

in the main ring.[6] The asymmetry in a pair of fixed-angle backward counter telescopes of the main ring polarimeter is also continuously measured during acceleration. Typical example shown in Fig. 2 indicates a very useful for identifying the location of depolarization. An external polarimeter installed in the extracted beam line was used to monitor the polarization during the physics experiment. [7]

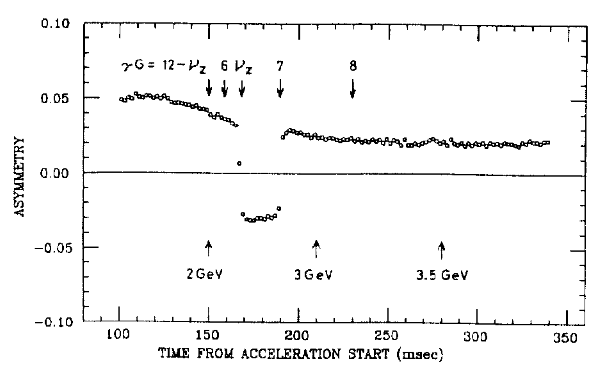


Fig. 2. The asymmetry continuously measured during acceleration.

## Depolarizing resonance correction in the booster

There are two strong depolarizing resonances in the booster. One is the intrinsic resonances at $\gamma G=\nu_z$ (280 MeV), and the other is the imperfection resonance at $\gamma G=2$ (108 MeV). The $\gamma G=2$ imperfection resonance could be corrected by adjusting the second harmonic component of the vertical COD, the main component in the booster, since the vertical betatron tune was 2.32 - 2.4. When the correction dipoles are not energized, this resonance is strong enough to flip the spin with no depolarization.[1]

Although almost complete spin flip was expected in passing through the $\gamma G=\nu_z$ intrinsic resonance from calculation, some depolarization was observed. Depolarization will occur due to the multiple resonance crossing by the synchrotron oscillation during the adiabatic spin flip. The simple method to avoid such depolarization is to decrease the accelerating rf voltage. Figure 3 shows the ratio of polarization P(500 MeV)/P(20MeV) as a function of the rf voltage. When the rf voltage is 8.9 kV, the polarization at 500 MeV is 50%, i.e. about 90% of the linac beam polarization is preserved in the booster. However, low rf voltage acceleration is a disadvantage to stable acceleration. For stable acceleration, a rf voltage of about 12 kV is needed and about 75% of the linac beam polarization is preserved in usual polarized beam operation.

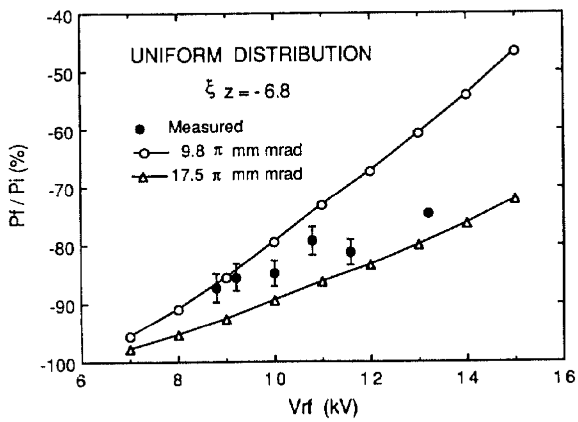


Fig. 3. Dependence of polarization ratios before and after crossing the $\gamma G=\nu_z$ resonance in the booster on the rf voltage.

The calculated ratio of polarization before and after passing through $\gamma G=\nu z$ intrinsic resonance is also shown in Fig.3 at the fixed chromaticity of $\xi_z$=-6.8, which is the normal chromaticity in the booster. The upper and lower curves are calculated using the vertical beam emittances of 9.8 $\pi$mm·mr and 17.5 $\pi$mm·mr, respectively. It shows that a significant depolarization of 20-40% for the rf voltage of about 12 kV. Since the synchrotron oscillation depends not only on the rf voltage but also on the chromaticity, this depolarization could be reduced by controlling the vertical chromaticity. This will be described later.

For the 5-$\nu_z$ resonance, the fast passage method was used to pass through this resonance, however, no sizable depolarization could be measured.[1] A small degree of depolarization depending on the skew quadrupole magnetic field was observed for the $\gamma G=\nu_x$ higher order resonance, however, definite experimental results have not been obtained so far.[8]

## Depolarizing resonance correction in the main ring

The resonance correction up to 5.0 GeV in the main ring has been investigated. There are four intrinsic resonances and nine imperfection resonances in the energy range from 500 MeV to 5.0 GeV. For two weak and intermediate intrinsic resonances, $\gamma G=12-\nu_z$ (2.1 GeV) and 16-$\nu_z$ (4.2 GeV), the depolarization can be reduced by the fast passage method (tune jump). Tune jump parameters are shown in Table 1.

Table 1. Tune jump parameters for the intrinsic resonance

| Resonance | Rise time | Fall time | Tune change |
|---|---|---|---|
| $\gamma G=12-\nu_z$ | 70$\mu$sec | 5msec | 0.15 |
| $\gamma G=16-\nu_z$ | 120$\mu$sec | 5msec | 0.17 |

Even though this is a rather slow rise time, however the rates of passage for these resonances are increased by about 40 or 50 times larger than those without tune jump. Figure 4 shows the correction curve for the $\gamma G=16-\nu_z$ resonance vs. the pulsed quadrupole timing counted in B-clock unit (a magnetic field generated number that is one clock count per gauss). We have successfully jumped the resonance in the region of (5380-5430) B-clock counts.

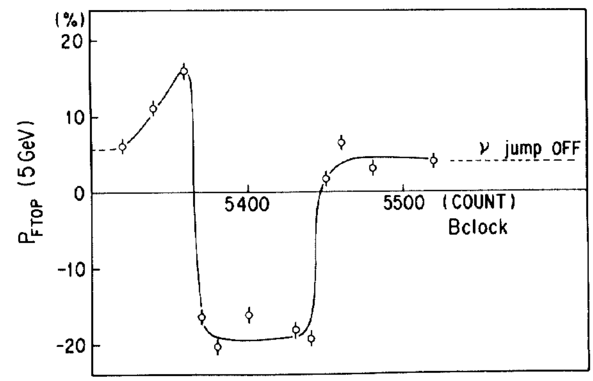


Fig. 4. Correction curve for the $\gamma G=16-\nu_z$ resonance by the fast passage method.

Other two strong intrinsic resonances, $\gamma G=\nu_z$ (2.3 GeV) and 4+$\nu_z$ (4.4 GeV), were passed through by the adiabatic spin flip. Since some degree of depolarization was expected for these resonances, it was planned to cross with the artificial slow passage method. That is, the falling tail of the pulsed quadrupole magnetic field was set to the gradient of $\gamma G$ by adjusting the voltage of the pulsed quadrupole magnet power supply. Sizable increase of the polarization by the slow passage method was obtained as shown in Fig. 5 for the $\gamma G=4+\nu_z$ resonance. In the normal intensity beam operation, the accelerating rf voltage is 80 kV. When the polarized beam was accelerated, the rf voltage was reduced to about 40 kV to avoid depolarization due to the synchrotron oscillation.

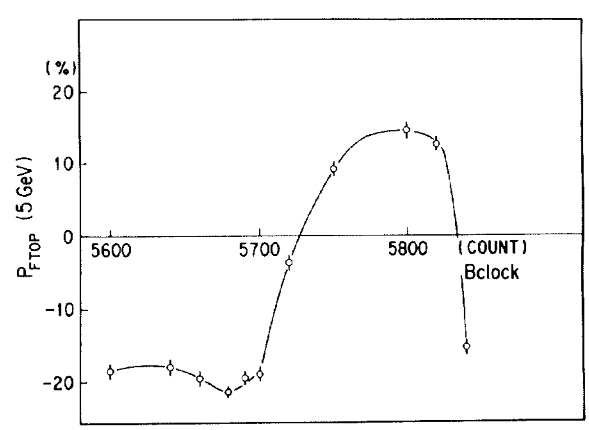


Fig. 5. Correction curve for the $\gamma G=4+\nu z$ resonance by the slow passage method.

There are nine imperfection resonances from 500 MeV to 5.0 GeV at $\gamma G=3,4,\ldots,11$. In the investigation of $\gamma G=3,4,5,7$ and 9 resonances, all these resonances were weak and no depolarization was observed without any correction. The large depolarization in crossing $\gamma G=6$ and 8 were avoided by the sixth and eighth harmonic correction of the vertical COD, respectively.[1,2] For the $\gamma G=10$ and 11 resonances are affected not only by the tenth and eleventh harmonic components but also the sixth and seventh harmonic components of the vertical COD, respectively.[2,3]

## The synchrotron oscillation effects and corrections

The beam is a collection of particles bunched by the acceleration rf. Since each particle oscillates in energy around the synchronous energy at the synchrotron oscillation frequency, the particles cross the resonance multiple times. This frequency and the maximum amplitude are proportional to the root of the rf voltage. This oscillation causes a modulation of the spin precession frequency and leads to depolarization. This effect was observed in the spin flip region of the $\gamma G=2$ imperfection resonance at SATUNE II[9] and well explained by computer simulation[10] and analytical methods.[11] In the case of the KEK PS booster, even if the estimation shows a little depolarization at the $\gamma G=2$ resonance, but it can be avoided by handling the vertical COD. On the other hand, for the $\gamma G=\nu_z$ resonance, sizable depolarization was expected by taking account the spin precession frequency modulation and the vertical betatron tune modulation as shown in Fig. 3. However, it is shown that if $\xi_z=\pm\gamma G\beta^2$, modulation of the spin precession frequency and of resonant frequency will cancel each other, so multiple resonance crossing will be avoided.[12,13] In the KEK PS booster, a relatively large vertical chromaticity, $\xi_z=-6.8$, causes the large depolarization at the $\gamma G=\nu_z$ resonance. Figure 6 shows the result of calculated depolarization. At $\xi_z=\gamma G\beta^2=1.0$, the depolarization is reduced to less than only a few percent. At present a sextupole magnet system is not available for cancellation of the synchrotron oscillation effect in the booster. Therefore, in order to confirm these effects, a test measurement was performed at the $\gamma G=\nu_z$ resonance in the main ring.

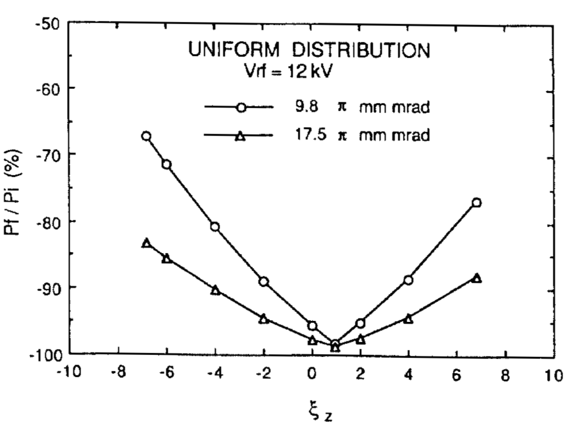


Fig. 6. Dependence of polarization ratios before and after crossing the $\gamma G=\nu_z$ resonance in the booster on the vertical chromaticity.

In normal operation of the polarized beam, the ramp (dB/dt) is 2.3T/sec and rf voltage is about 40 kV in the main ring. In order to clear the effect, rf voltage was increased to 80 kV and the ramp speed was to be slow as 0.94T/sec to get enough response for the sextupole magnet system. The result is shown in Fig. 7 with the estimated value. The polarization ratio is deduced from the continuous asymmetry measurement data during acceleration. A polarization ratio of about 64% at $\xi_z=-6.5$ is improved to about 88% at $\xi_z=7.8$. This result clearly proves that the depolarization due to the synchrotron oscillation at a spin flip intrinsic resonance can be corrected by adjusting the vertical chromaticity.

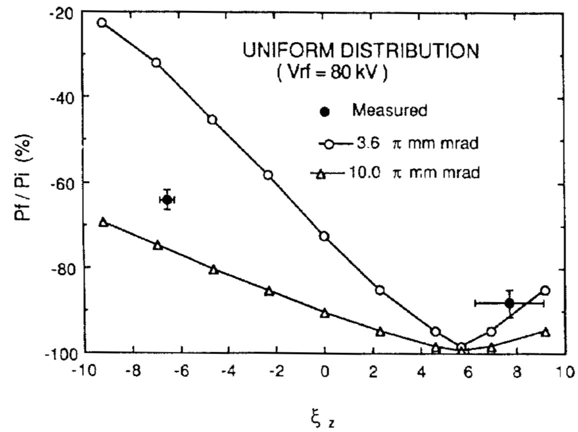


Fig. 7. Dependence of polarization ratios before and after crossing the $\gamma G=\nu_z$ resonance in the main ring on the vertical chromaticity.

## Summary

The KEK PS is the first cascade synchrotron with a booster which has demonstrated acceleration of a polarized proton beam.

For the booster, about 75% of the linac beam polarization has been preserved at 500 MeV during normal polarized beam operation. If the pulsed sextupole for manipulation of the chromaticity will be constructed, polarization at 500 MeV will expected to over than 90-95% of the linac beam polarization.

The polarization at various energies obtained so far in the accelerator are 60-65% at 20 MeV, 45-55% at 500 MeV, 34-40% at 3.5 GeV, and 25% at 5.0 GeV. As a preliminary result, about 8% polarization was obtained at 7.6 GeV. Accelerated beam intensity is $0.9\times10^{10}$ ppp at 3.5 GeV.

From May 1987, the KEK PS has delivered a polarized proton beam of 3.5 GeV to physics experiments. Two experiments were performed so far.[14,15]

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