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Abstract

The outline of the polarized proton acceleration project at KEK and the results of the first acceleration test are described. Depolarization in the 500 MeV booster synchrotron was investigated as the first step of this program. The beam polarization was measured in the 20 MeV beam transport line from the linac to the booster and in the main ring at the injection energy. About 40 % of the linac beam polarization was kept in the main ring. This acceleration test encouraged us to proceed with this program.

KEYWORDS: polarization, spin, polarized beam, accelerator, depolarizing resonance, depolarization

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I. Introduction

The project of polarized proton acceleration in the KEK 12 GeV proton synchrotron began in the fiscal year 1980. After the construction of 750 keV pre-accelerator and the 750 keV beam transport line for the polarized proton beam, the first acceleration test in the KEK PS was performed in October 1983.

We developed a high current polarized H^- ion source. The polarized H^- beam is produced by the charge-exchange reaction with Na vapor which is optically pumped by dye lasers[1]. The polarized H^- beam is injected into the booster synchrotron by a charge-exchange injection through a thin carbon target of $\sim$ 120 $\mu g/cm^2$ for the electron stripping[2]. The polarized proton is accelerated up to 500 MeV in the booster and then injected to the main ring.

One of the most serious problems is the beam monitoring in the accelerator and the beam transport lines since the intensity of the polarized beam is very low, less than 10^{-3} times the usual proton beam. In order to transport the beam from the booster to the main ring and to accelerate the polarized beam passing through the phase transition of the main ring ($\sim$ 5.4 GeV) stably, the frequency and the phase of the accelerating RF have to be controlled with the beam signal. High sensitive beam position and beam-to-RF phase monitors were developed. The accelerating RF can be controlled by the beam signal if the intensity of the polarized beam is more than 1×10^9 p/bunch in the main ring.

II. Depolarizing resonances in the booster and the main ring

Both the booster and the main ring of KEK PS are strong focusing synchrotrons and therefore strong depolarizing resonances are expected during acceleration. Such depolarizing resonances occur at the resonance conditions of $\gamma G = nN \pm \nu_z$ for intrinsic resonance and $\gamma G = n$ for imperfection resonance. γ is the Lorentz factor, ν_z is a vertical betatron oscillation frequency, N is the superperiodicity of the machine, n is an integer and $G = g/2-1$. The polarization of the beam after crossing a depolarizing resonance is given by[3)]

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

where P_0 is the initial polarization before crossing the resonance, ϵ is the resonance strength and α is the crossing speed for the resonance.

$$\alpha = (\dot{\gamma}G \pm \dot{\nu}_z)/\omega_0 : \text{ for intrinsic resonance} \quad ,$$

$$\alpha = \dot{\gamma}G/\omega_0 \quad : \text{ for imperfection resonance} \quad .$$

ω_0 is the revolution frequency of the beam. The resonance strength ϵ is proportional to the betatron oscillation amplitude for intrinsic resonance and is proportional to the vertical closed orbit distortion (COD) for imperfection resonance. The depolarization is small for small ϵ^2/α. On the other hand the polarization flips for large ϵ^2/α ($P \sim -P_0$ for $\epsilon^2/\alpha >> 1$)[4)9)].

In the booster of KEK PS there are one intrinsic resonance at about 260 MeV and one imperfection resonance at 108 MeV. Figure 1 shows the calculated resonance strength ε of the strong depolarizing resonances[5] for the maximum amplitude of vertical betatron oscillation which corresponds to the vertical maximum acceptance of 49π mm·mrad at 20 MeV. The strength of the intrinsic resonance is so strong that the spin flips almost completely in passing through the resonance. The imperfection resonance is calculated for the vertical COD of 1 mm (rms) and 5 mm (rms), respectively. The large depolarization is expected even if the COD is corrected to less than 1 mm. On the other hand spin-flip seems to be feasible if COD is larger than 5 mm.

The strength of strong depolarizing resonances in the main ring is shown in Fig. 2 for the vertical emittance of 19π mm·mrad at 500 MeV[5][6]. The accelerated proton has to pass through 10 intrinsic resonances for ν_z = 6.25 and 22 imperfection ones during acceleration from 500 MeV to 12 GeV. It is expected that 7 resonances can be passed through with spin-flip in the normal operating condition ($d\gamma/dt$ = 26 - 35 sec^{-1}). On the other hand there is significant depolarization in passing through 3 "weak" resonances. The depolarization can be reduced by the standard method of rapidly changing ν_z (tune jump). Four pulsed quadrupole magnets are installed in the main ring for tune jump.

The strength of imperfection resonance in the main ring is also shown in Fig. 2 for the vertical COD of 1 mm (rms). It seems that we have no serious problem of the depolarization up to 10 GeV (γG = 22) for imperfection resonance. The depolarization at γG = 14,18,22 can be suppressed by reducing the sixth harmonic of COD using 28 correction dipole magnets installed in the main ring. These correction magnets are controlled by the computer control system in order to reduce the vertical COD to less than 1 mm (rms) during acceleration[7].

III. Polarimeters

The polarization of the linac beam is measured by the 20 MeV polarimeter. The polarimeter is placed in the scattering chamber of 655 mm in diameter installed in the 20 MeV beam line from the linac to the booster. The left-right asymmetry of elastic scattering events at a laboratory angle of 90° from proton-carbon scattering is measured by using a carbon fiber target of 100 μm in diameter. The detector consists of a pair of 1500 μm surface barrier SSD and a double slit with 5 mm diameter hole. The distance between the target and SSD is 235 mm. The schematic of the 20 MeV polarimeter is shown in Fig. 3.

An internal polarimeter is installed in the long straight section II-2F of the main ring to measure the absolute polarization of circulating beam from 500 MeV to about 7 GeV. Hereafter we call it the main ring polarimeter. It is necessary to measure the beam polarization in a short period at various energies during acceleration for the machine tuning to pass through the depolarizing resonances. For this purpose, an internal polarimeter is quite useful. The polarization is measured from the asymmetry of proton-proton elastic scattering. The main ring polarimeter consists of a polyethylene string target and the forward and backward scintillation counter telescopes. Figure 4 is the schematic of the main ring polarimeter. The scattered events are detected by two forward counter telescopes of 3 m in maximum length and two backward telescopes of 55 cm in maximum length. The elastic event is identified by the coincidence of the forward scattered proton and the backward one. The detection angle and the distance between scintillators and the target are adjusted to measure the asymmetry at the momentum transfer of $t = -0.15\ (\mathrm{GeV}/c)^2$ for the various energies. Each forward telescope has two scintillation counters and each backward one has three scintillation counters. The aluminum absorbers (A1, A2) and the veto counter (B3) reject pions and other high energy particles.

The coplanarity of scattered and recoil protons is checked to separate the proton-proton elastic scattering from proton-carbon reactions in the polyethylene target. The coincidence count is used to calculate the beam polarization as follows:

$$P = \frac{1}{A_y}\left(\frac{L - R}{L + R}\right) \quad .$$

L(R) denotes the coincidence count corresponding to the left (right) forward scattered proton and right (left) backward scattered proton. The analyzing power A_y of proton-proton elastic scattering is 0.42 ± 0.025 at 500 MeV and $t = -0.15\ (\mathrm{GeV}/c)^2$.[8]

Two targets are mounted in the scattering chamber, one is a polyethylene string of 150 μm in diameter and another is a carbon fiber of 220 μm equivalent diameter. Each target can be flipped into the beam in- dependently. The carbon target is used for the subtraction of the background events from the carbon in the polyethylene.

We measured the polarization at 500 MeV in the main ring with a coasting beam. The typical data of coplanarity shown in Fig. 5 shows that the elastic events are clearly observed and the background rate is less than a few percents at 500 MeV. The beam polarization in the main ring is measured in a few minutes with the statistical accuracy of $\leqq 2$ %. The asymmetry of the polarimeter measured by the unpolarized beam is less than 0.2 %. The details of the main ring polarimeter will be reported elsewhere[10].

IV. Beam scraper and vertical deflector in the booster

In order to investigate the strength of the intrinsic resonance in the booster, the polarization was measured by varying the vertical beam size at about 170 MeV with the beam scraper. Figure 6 shows the schematic of the beam scraper installed in the straight section S-5 of the booster. The fast rotating aluminum rod of 3 mm in diameter and 80 mm in length scrapes the circulating beam in the booster within 1 msec. The rotation of the aluminum rod is synchronized with the booster acceleration cycle (20 Hz) and the inserting timing of the rotating rod into the beam is controlled by the phase-locked loop (PLL) system. The vertical beam size can be varied by adjusting the insertion of the rotating rod into the beam. As mentioned in section II, the resonance strength of the intrinsic resonance is proportional to the amplitude of vertical betatron oscillation. Thus we can get the information about the resonance strength by varying the vertical beam size.

On the other hand the depolarization by the imperfection resonance depends on the vertical COD. We installed the pulsed dipole magnet (vertical deflector) in the straight section S-2 of the booster to generate the vertical COD at the resonance energy. It is excited with the pulsed current of 8 msec width. The vertical COD generated by the vertical deflector is shown in Fig. 7. The maximum peak current of 250 A can generate the COD of 7 mm in rms.

V. Acceleration test of polarized proton beam

The depolarization in the booster synchrotron was studied as the first step of polarized proton acceleration in KEK. The study time was so short, about three weeks, that we had no time to accelerate the polarized proton in the main ring.

The intensities of polarized beam at the various stages of the accelerator were

ION SOURCE	($H^-\uparrow$, 750 keV)	5 - 10 μA (pulse duration 75 μsec) ,
LINAC	($H^-\uparrow$, 20 MeV)	0.5 - 1 μA (pulse duration 75 μsec) ,
BOOSTER	($p\uparrow$, 500 MeV)	1 - 3 x 10^8 p/bunch ,
MAIN RING	($p\uparrow$, 500 MeV)	1 - 2 x 10^8 p/bunch .

Since the study was just after the summer long shutdown, we had many troubles in the machine operation. The beam intensity after the linac was remarkably lower than expected because of the troubles in the 750 keV beam line, which was newly constructed for the polarized proton, and in the quadrupole magnets in the linac.

The main purpose of this study was to investigate the depolarization in the booster. We have not installed any equipment to reduce the depolarization in the booster because spin-flip is expected for the two strong resonances. The polarizations of the polarized beam were

LINAC	P(LINAC, 20 MeV)	= 47 ± 6 - 56 ± 8 % ,
MR	P(MR, 500 MeV)	= 12 ± 2 - 15 ± 2 % .

Thus about 25 % of the linac beam polarization was kept in the main ring:

$$P(\mathrm{MR},\ 500\ \mathrm{MeV})/P(\mathrm{LINAC},\ 20\ \mathrm{MeV}) \sim 25\ \% .$$

In order to investigate the resonance strengths, the dependences of the beam polarization on the beam size and on the vertical COD in the booster were measured. Figure 8 is the vertical beam size dependence of the polarization measured by inserting the beam scraper before crossing the intrinsic resonance $\gamma G = \nu_z$. This result shows that spin is flipped by crossing this resonance in the booster until the vertical beam emittance decreases to about 1/100 of the usual one. Thus the strength of the intrinsic spin resonance is strong enough for the resonance crossing by spin flip. If the vertical beam size is blowed up to 1.5 - 2 times by the RF-knock out method or so, the spin-flip becomes more complete near the beam center.

Figure 9 shows the measured polarization vs. the excitation current of the vertical deflector. When the excitation current was negative, polarization was flipped by crossing the imperfection resonance. On the other hand the polarization was kept without spin-flip in passing through this resonance at the excitation current of about 169 A. (The measured polarization in the main ring became negative because spin is flipped by the intrinsic resonance only.) This result shows that the vertical COD in the booster is large enough to pass through the imperfection resonance by spin-flip without the excitation of the vertical deflector. At the excitation current of 169 A, the depolarization is small since the second harmonic of the vertical COD is reduced by the deflector.

An important problem has been left. The measurement shows that spin was almost completely flipped by the two strong resonances ($\gamma G = 2$, $\gamma G = \nu_z$) as expected from the calculation. What is the other cause of depolarization in the booster ? We aimed to investigate the $\gamma G = 5-\nu_z$ resonance at about 450 MeV due to the symmetry breaking of the machine. This resonance is the same kind of the resonance as the $\gamma G = 7-\nu_z$ resonance in SATURNE II of Saclay[9]. Toward the top energy the crossing speed α decreases since the magnetic field of the booster varies sinusoidally. Thus in order to increase the crossing speed for the $\gamma G = 5-\nu_z$ resonance, the resonance energy was decreased by the excitation of a correction quadrupole magnet. Figure 10 shows the dependence of the polarization on the excitation of the correction quadrupole magnet. The polarization of about 1.5 times was obtained at the excitation current of 60 A.

The change of ν_z is about 0.01 at 60 A and the crossing speed α for this resonance increases about 10 %. The polarization in this figure is low because the Na vapor was trapped in the polarized ion source by sudden stop of electric power with earthquake. If we had no such happening, the polarization would reach 20 - 25 %. This result shows that about 40 % of the linac beam polarization is kept in the main ring by this small change of ν_z. That is,

$$P(MR, 500MeV)/P(LINAC, 20\ MeV) \sim 40\ \%$$

The depolarizations by other weak spin resonances are not so large because the sextupole field, which was applied by a small correction sextupole magnet, was not effective for the depolarization. The depolarizations by the strong resonances in the booster are small and the weak resonance due to the symmetry breaking of the machine causes more than 35 % depolarization.

This preliminary result encouraged us to proceed with the acceleration program of the polarized proton at KEK. The large depolarization in the booster will be solved by tune jump using a small pulsed quadrupole magnet. We are planning to install it in 1984.

Acknowledgments

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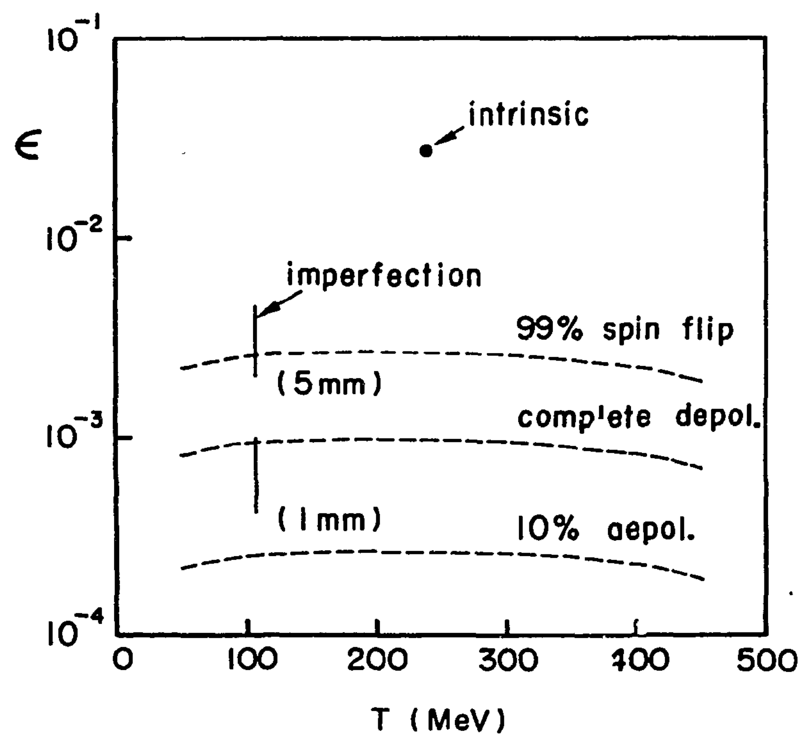


Fig. 1 Depolarizing resonances in the booster.

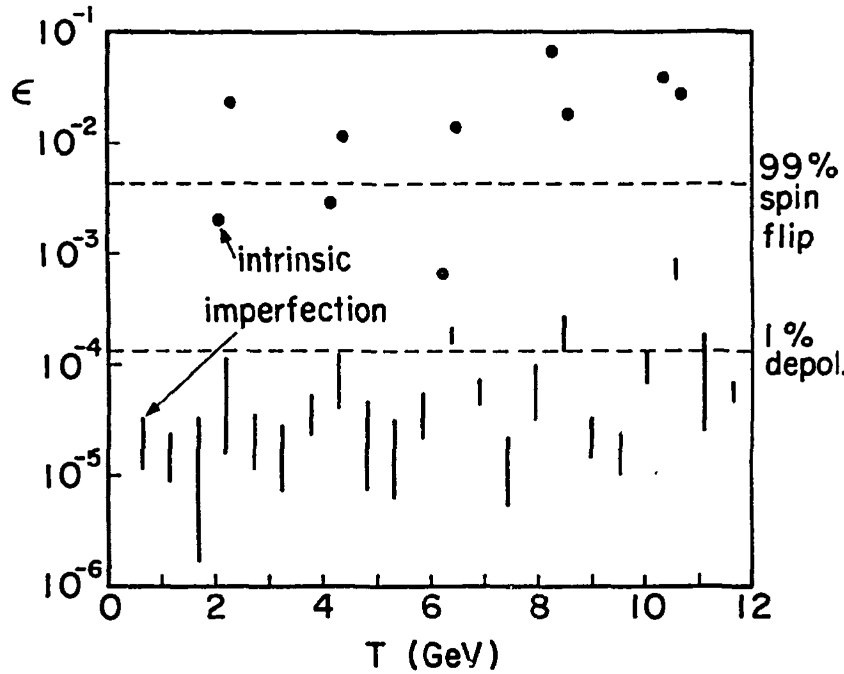


Fig. 2 Depolarizing resonances in the main ring.

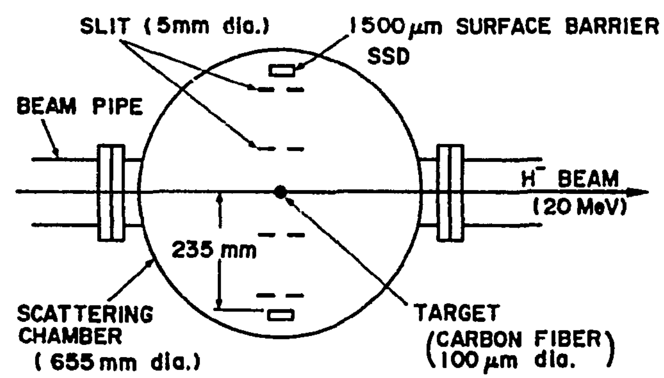


Fig. 3 Schematic of the 20 MeV polarimeter.

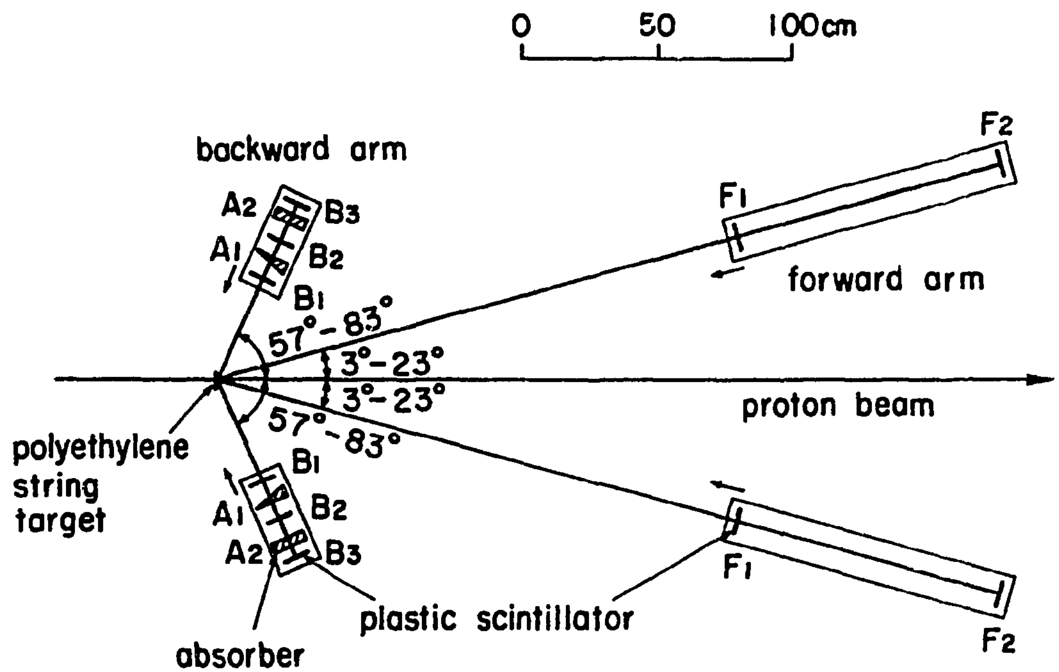
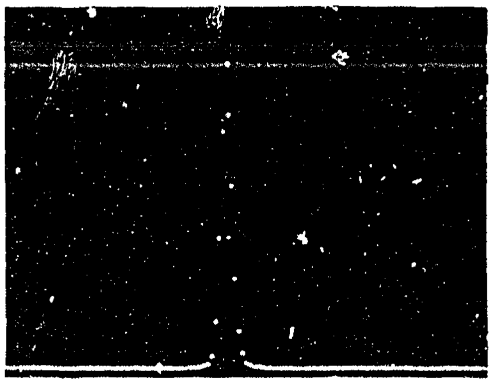


Fig. 4 Schematic of the main ring polarimeter.



FWHM 540 psec

Fig. 5 Coplanarity plot of elastic proton-proton scattering events.

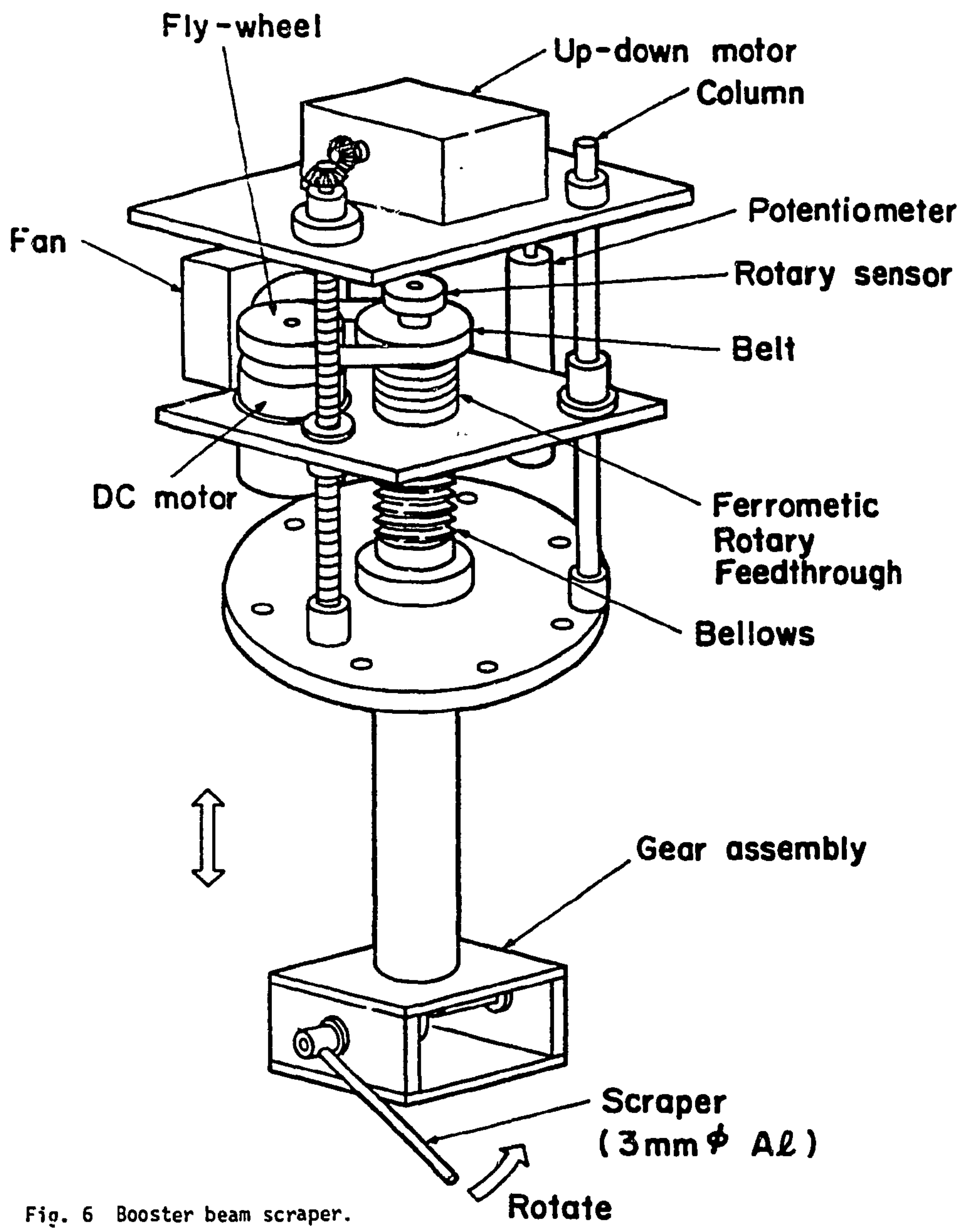


Fig. 6 Booster beam scraper.

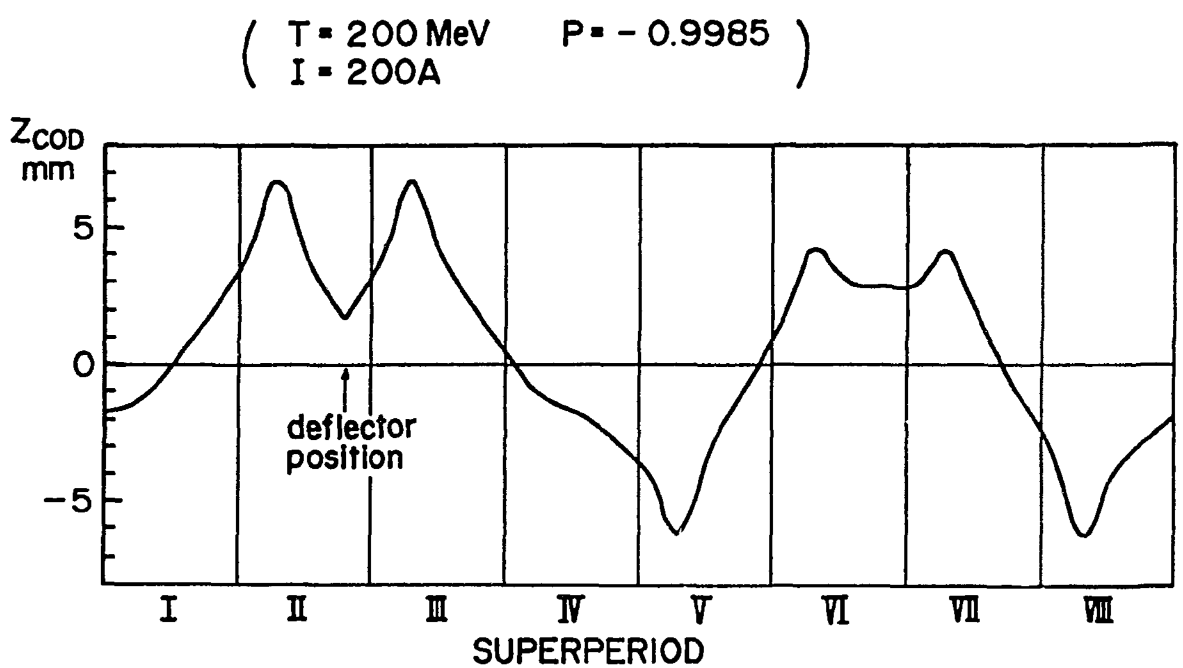
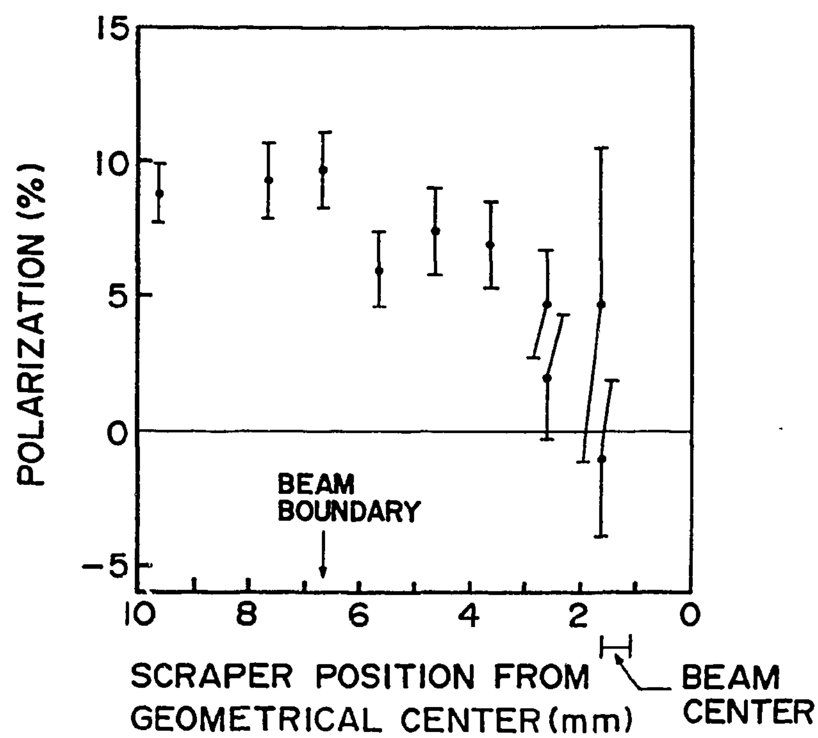


Fig. 7 Vertical COD generated by the deflector.



Fgi. 8 Polarization vs. the vertical beam size in the booster.

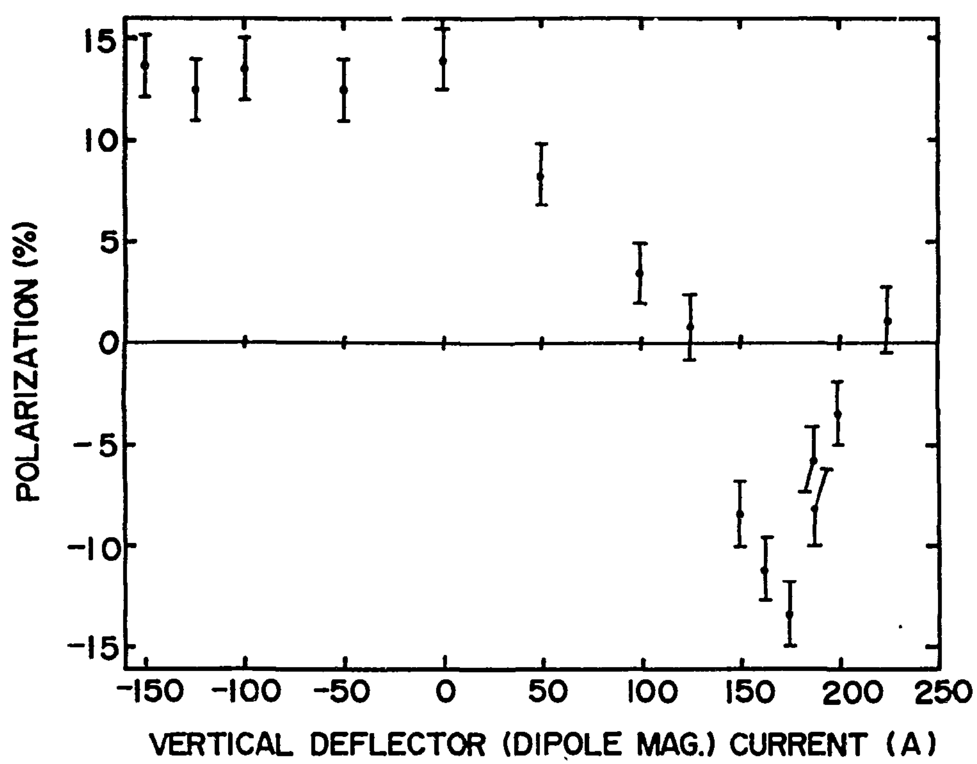


Fig. 9 Polarization vs. the excitation current of the vertical deflector.

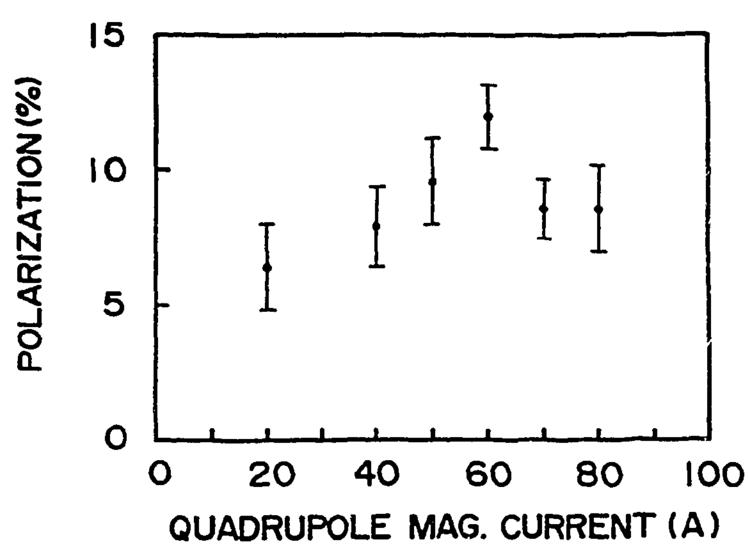


Fig. 10 Polarization vs. the excitation current of the correction quadrupole magnet.