DETERMINATION OF PROTON BEAM POLARIZATION AT HIGH ENERGIES BY MEASUREMENTS AFTER DECELERATION

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Résumé Nous étudions à SATURNE II une nouvelle méthode pour déterminer la polarisation d'un faisceau de protons à haute énergie après décélération à une énergie plus basse où il est possible d'utiliser des techniques simples et précises qui font appel au pouvoir analyseur important et bien connu de la diffusion élastique proton-proton. Cette méthode exige de bien connaître la dépolarisation du faisceau pendant la décélération. Une première mesure a montré que la dépolarisation lors du passage de la résonance $\gamma G = 3$ à 631 MeV en décélération était la même qu'en accélération. Une deuxième mesure a montré que l'égalité des dépolarisations en montée et en descente était réalisée avec une bonne approximation également lors du passage successif des deux résonances $\gamma G = \nu_z$ à ≈ 900 MeV et $\gamma G = 4$ à 1145 MeV.

Abstract We are investigating a new method to determine the polarization of proton beams accelerated to high energies by measurements after deceleration to low energies where simple and precise techniques can be used based on the large and well known analyzing power of pp elastic scattering. The polarized proton beam of SATURNE II was accelerated to 520 MeV and its polarization was measured by extracting the beam onto the N-N beam line polarimeter. The beam was then accelerated to 800 MeV, decelerated to 520 MeV and again extracted. The loss in polarization is due to crossing twice the intrinsic depolarizing resonance $\gamma G = 3$ at 631 MeV with adiabatic spin flip, once during acceleration and once during deceleration. The depolarization was intentionally increased by partially correcting the resonance, thus making the adiabatic flip less complete. The correction was introduced either at the rise or at the descent. The final polarization was the same in both cases showing that the depolarization, as expected, was the same during acceleration and deceleration. Another measurement was performed between 880 and 1200 MeV crossing successively two intrinsic resonances $\gamma G = \nu_z$ at ≈ 900 MeV and $\gamma G = 4$ at 1145 MeV. Here the polarization at 1200 MeV was measured directly and is compared to the value calculated from the measurements at 880 MeV before accelerating to 1200 MeV and after decelerating from 1200 MeV, assuming symmetric depolarization. The measured and the calculated values agree within $\Delta P_B = 0.03$ at $P_B \approx 0.75$.

I - INTRODUCTION

Deceleration of the unpolarized beam had been used at SATURNE II. The Figure 1 shows the absence of beam loss during acceleration and deceleration and the reproducibility of the beam phase space when returning to the same energy. This suggested that also the depolarizing mechanisms encountered during acceleration should reproduce during deceleration. The theory of depolarizing resonances shows in fact that the depolarization depends on the rate of change dB/dt of the magnetic field B but not on the sign of dB/dt . This permits to envisage a method to determine the beam polarization at a high energy E_1 by two polarization measurements at a low energy E_0 , once before accelerating up to E_1 and once after returning from E_1 to E_0 by deceleration.

The interest of this method for experiments at SATURNE II resides in the fact that the standard technique for absolute measurement of beam polarization by elastic pp scattering in a polarimeter begins to lose its precision at energies above 800 MeV. The polarimeter [1]

Fig.1 Acceleration of 2×10^{11} protons to > 2 GeV followed by deceleration. Upper trace: magnetic cycle 450 msec rise, 100 msec flat-top, 450 msec descent. Lower trace: pick-up electrodes. The baseline shows the intensity, the envelop of the RF peaks shows the decrease of bunch length and the symmetric increase during deceleration.

Fig.2 On-line measurements of the magnetic field. Several cycles are superposed. The dispersion is less than the size of the points.

measures the left-right asymmetry ϵ_{pp} of the elastic cross section in the plane perpendicular to the beam polarization at a center of mass angle θ^* where the analyzing power A_{00n0} is largest. The beam polarization P_B is given by the product of asymmetry and analyzing power $P_B = \epsilon_{pp} A_{00n0}$. Up to 800 MeV the large number of data on pp elastic scattering yield a unique solution for an energy dependent phase shift analysis [2] from which $A_{00n0}(E, \theta^*)$ is known with a precision of $\pm 3 \times 10^{-2}$ and which describes very well the direct measurements of A_{00n0} entering the analysis. In the region from 800 MeV to 1 GeV the analyzing power is still known with a precision better than 10^{-2} , but above 1 GeV where no phase shift analysis is presently possible, the sparse direct measurements of A_{00n0} with polarized proton targets have statistical errors of $(5 \text{ to } 10) \times 10^{-2}$ and systematic uncertainties which may be as large as $(10 \text{ to } 15) \times 10^{-2}$.

In principle it is possible to determine the beam polarization at SATURNE II in the region from 1 to 3 GeV with precision of the order of 10^{-2} by comparing the asymmetry with polarized beam to the asymmetry with polarized target after absolute calibration of the target polarization at an energy below 800 MeV. This, however, would require a long experiment at each beam energy, with off-line analysis of the data recorded in the two-arm MWPC spectrometer with magnetic analysis detecting scatterings from the polarized target. The method of deceleration would be considerably faster and more convenient, taking advantage of the higher analyzing power at low energies and of the simplicity and on-line response of the polarimeter.

At higher energies this method may become even more interesting since the factor of merit of elastic pp scattering, the analyzing power squared times the differential cross section, continues to decrease at all scattering angles. One estimates that methods others than pp elastic scattering are needed to measure beam polarizations above 50 or 100 GeV.

II - EXPERIMENTAL CONDITIONS AT SATURNE II

Deceleration without extraction had been used previously (Figure 1). The magnet power supply does not allow flat-top during descent and the beam had to be extracted on a short spill. The pulse-to-pulse reproducibility of the magnetic cycle is shown in Figure 2 where the on-line measurements for several cycles are superposed. These measurements provide the local slope dB/dt at any point of the cycle. The Figure 3 shows the depolarizing resonances of SATURNE II. Closed orbit imperfection resonances $\gamma_G = n$ ($n = 3, \dots, 7$) occur at fixed energies. The precise energy of the systematic quadrupole resonances depend on the vertical wave number ν_z and can be changed within certain limits.

To study passing of resonances during acceleration and the symmetric process during deceleration we have chosen two energy regions: Between 520 and 800 MeV where we cross the uncorrected resonance $\gamma_G = 3$, and between 880 and 1200 MeV where we cross both $\gamma_G = \nu_z$ and $\gamma_G = 4$.

During descent we use dynamic resonant extraction with the horizontal wave number ν_x tuned to the desired energy. The corresponding values of the F- and D-quadrupole currents are registered and displayed. The external beam channel is set at the nominal energy and the exact beam energy is obtained by fine-tuning of ν_x until the beam is on the center line up to the polarimeter. The extraction hexapoles must satisfy the condition $x = d\nu_x / (dp/p) = 0$ in order to bring the entire beam to resonance. The Figures 4a and 4b show the spill during descent as seen by the extracted beam monitor and by the polarimeter, respectively. The Figure 4b shows the superposition of six consecutive bursts. The leading edge jitter is of the order of 200 μsec corresponding to $\Delta B/B = \Delta p/p \approx 10^{-3}$. Pulse-to-pulse intensity fluctuations are the same as for flat-top extraction. The only serious inconvenient is the short spill which obliges us to reduce the number of protons per burst. Otherwise the operating conditions of the polarimeter such as background, empty target effect etc. are the same as on flat-top.

Fig. 3 Diagram of the depolarizing resonances at SATURNE II.

Figure 4a

Figure 4b

Fig.4 Short spill at dynamic extraction during descent.
 (a) External beam monitor and (b) integrated
 counter signal from the polarimeter. Six bursts
 are superposed. Scope sweep 2.5 msec/division.

III - RESULTS

1. Depolarization between 520 and 800 MeV ($\gamma G=3$ at 631 MeV)

The beam was extracted on flat-top at 520 MeV onto the polarimeter [1] in the Nucleon-Nucleon beam line. The slow spill of 200 msec duration allowed to use $(2 \text{ to } 5) \times 10^8$ particles per burst. The accidental rates measured between conjugate arms of the polarimeter were $\leq 2 \times 10^{-3}$. Under these conditions the results corrected for accidental coincidences are independent of beam rate. The measured beam polarization was $|P_1| = 0.8665 \pm 0.0043$.

The accelerator cycle was then modified for a 50 msec flat-top at 800 MeV without extraction, followed by deceleration and dynamic extraction at 520 MeV with a spill of 2 msec (Figure 4). The intensity was reduced by detuning the RF capture after injection to achieve an accidental rate of $\leq 3 \times 10^{-2}$ between two counters in the same polarimeter arm. This corresponds to the upper limit of instantaneous beam rate compatible with reliable measurements. The beam polarization was found to be $|P_2| = 0.8317 \pm 0.0015$. The difference $|P_1| - |P_2|$ represents the combined loss due to crossing twice the uncorrected intrinsic depolarizing resonance $\gamma G = 3$ at 631 MeV with adiabatic spin flip, once during acceleration and once during deceleration.

The following procedure was used to check if passing the resonance during acceleration produces the same depolarization as crossing it during deceleration: First, the resonance was partially corrected both at the rise and at the descent. Reducing the strength of the resonance reduces the amount of adiabatic flip, thus increases the depolarization. By progressively increasing the correction, the polarization was found to decrease from $|P| = 0.83$ to $|P| = 0.77$. Then, the same fixed correction of the resonance was introduced either only at the rise (R) or only at the descent (D). The measured beam polarizations were $|P|_R = 0.818 \pm 0.014$ and $|P|_D = 0.819 \pm 0.019$, respectively. This result is consistent with perfectly symmetric behaviour of the beam polarization when passing the same resonance during acceleration or deceleration. The conclusion is independent of A_{0000} since all measurements are performed at the same energy and center of mass angle. The relatively large statistical errors in these two measurements are due to the fact that the SATURNE magnet power supply does not allow a flat-top during descent.

2. Depolarization between 880 and 1200 MeV ($\gamma G = \nu_z$ at ≈ 900 MeV and $\gamma G=4$ at 1145 MeV)

This measurement studied the depolarization when crossing two consecutive intrinsic depolarizing resonances $\gamma G = \nu_z$ at about 900 MeV and $\gamma G = 4$ at 1145 MeV. The beam polarization (Table 1 and Figure 5) was measured by slow extraction on flat-top at (a) 880 MeV and (b) 1200 MeV, and (c) by dynamic extraction at 880 MeV during deceleration from 1200 MeV. The initial polarization at 880 MeV was $|P_a| = 0.8938$, the polarization at 1200 MeV was $|P_b| = 0.7277$ MeV and the polarization at 880 MeV after deceleration was $|P_c| = 0.6798$.

The absolute value of the rate of change of the magnetic field was not exactly the same during rise and descent. The measured values are $(dB/dt)_R = + 3.013 \text{ Tesla} \times \text{sec}^{-1}$ and $(dB/dt)_D = - 2.50 \text{ Tesla} \times \text{sec}^{-1}$. A simple interpolation between the two low energy measurements (a) and (c) taking into account this difference in slope but assuming otherwise exactly symmetric depolarization predicts a polarization $|P_b|(\text{calc.}) = 0.760 \pm 0.005$. The calculated value and the direct measurement agree within $\Delta P = 0.032$, i.e. within 4 percent.

At the upper end of the SATURNE energy range a determination of beam polarization with an relative error of 4 percent would already be a substantial improvement over the direct measurement affected by larger errors due to the uncertainty on A_{0000} at high energies.

For the present measurement we have estimated an upper limit for the ratio of the analyzing powers at 880 and 1200 MeV, respectively, with the conclusion that the difference $\Delta P = 0.032$ is probably significant. This would mean that depolarization symmetry is a useful approximation but that it was not exactly realized in this experiment.

Although the evidence for asymmetry is very weak in this measurement we further discuss the point in view of its interest for detailed understanding of depolarizing mechanisms. During the measurements we made the following observation: For the initial measurement at 880 MeV

Fig.5 Depolarization between 880 and 1200 MeV. Comparison of the direct measurement at 1200 MeV with the value calculated from the measurements at 880 MeV before acceleration and after deceleration.

	Energy MeV	Extraction	Beam Polarization		
			Statist.	System.	
$ P_a $	880	Flat-top	0.89385	± 0.00296	± 0.0055
$ P_b $	1200	Flat-top	0.72772	± 0.00866	± 0.0180
$ P_c $	880	Descent	0.67982	± 0.00417	± 0.0103
$ P_d ^*$	1200	Flat-top	0.58045	± 0.00916	± 0.0144

* With cut-off in vertical betatron oscillation amplitude.

Table 1 Beam polarization measurements at 880 and 1200 MeV. The systematic errors correspond to upper limits for uncertainties of the analyzing power used to calculate the polarizations from the measured asymmetries.

the pulse-to-pulse intensity fluctuations had been stabilized by a standard procedure which at this energy had no effect on beam polarization. When changing to 1200 MeV we first found an unusually low polarization of only $|P| = 0.5805$. We discovered that removing the stabilizer increased the polarization to $|P| = 0.7277$. The procedure limits the intensity fluctuations by a cut-off in the vertical betatron oscillations shortly after injection. No change in polarization was observed when producing the same reduction in intensity by an alternate method, detuning the RF capture. A systematic study of this effect was subsequently carried out [3] by accelerating through two successive quadrupole resonances $\gamma G = \nu_z$ and $\gamma G = 8 - \nu_z$ with precise polarization measurements on flat-top only. The results are suggesting the following mechanism. A cut-off on the vertical betatron oscillations leaves the core unchanged but reduces the peripheral part. On the other hand, when crossing the quadrupole resonance with adiabatic flip it is reasonable to expect that only the peripheral part experiences a strong resonance while the core sees a very weak resonance and does not flip. The intermediate phase space sees a resonance too weak for adiabatic flip but strong enough to depolarize. The observed depolarization when passing an odd number of quadrupole resonances with adiabatic flip is actually composed of a true loss corresponding to statistical disorder and an apparent loss since different phase space regions have opposite polarizations. The polarimeter in the extracted beam measures the average polarization of all particles.

In our case, after crossing the resonances again during deceleration, the losses due to $\gamma G = 4$ and the true losses due to $\gamma G = \nu_z$ cumulate, but not the apparent losses since the second adiabatic flip restores the same ν_z sign for core and halo. The expected depolarization asymmetry is very small since we worked at full betatron amplitude. The effect becomes appreciable only when severely limiting the vertical phase space [3].

IV - CONCLUSIONS

Determination of the polarization of proton beams accelerated to high energies by measurements at lower energies before acceleration and after deceleration requires detailed study of resonant depolarization. We have used well known resonances of SATURNE II as test cases. The study concerns strong resonances inducing adiabatic spin flip. The depolarizations are the same during acceleration and deceleration for the closed orbit imperfection resonances $\gamma G = n$ ($n = 3, \dots, 7$). For the systematic quadrupole resonances we observe almost symmetric behaviour. However, this case especially requires additional studies and computer simulation to achieve the understanding necessary for precise calculation of the polarization at high energy from the measurements at low energy. The present results confirm that this is a very promising method which becomes very simple and fast in the case of an accelerator capable of flat-top on descent. Other methods for direct beam polarization measurements at high energy are being developed. We feel that reducing the problem to an already solved problem at low energy gives the method of deceleration an obvious competitive advantage.

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