POLARIZED DEUTERONS AT THE NUCLOTRON*

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Abstract

Started at the beginning of the 80^{th}, the spin physics programme at the JINR Synchrophasotron is being continued succesfully. The next step of this programme is to accelerate of polarized beams at the Nuclotron. The first test run of polarized deuteron injection and acceleration has been carried out. The status and development of the polarized deuteron source, analysis of the depolarized effects in the linac, Nuclotron ring and beam injection/extraction transport lines are presented. Computer simulation of charge exchange injection into the accelerator is also considered.

1 INTRODUCTION

Polarized deuterons as the simplest nuclei with the well known spin structure are the best tool to study the inner nucleon structure at a distance of r < 0.5 fm, where quark-gluon degrees of freedom should manifest themselves. First spin experiments at the JINR synchrophasotron were carried out to study inclusive and binary reactions with vector and tensor polarized deuterons in 1981. After installing the Saclay-ANL proton polarized target on 1995, the spin program was supplemented by correlation experiments.

The scheme for acceleration of polarized deuterons at the Nuclotron accelerator facility [1] includes a cryogenic polarized deuteron source Polaris, a 5 MeV/u linac, a superconducting heavy ion synchrotron of a 6 GeV/u energy with 10 second spill slow extraction (under construction now), thin internal targets and a wide net of external beam lines. This scheme also allows one to generate high energy polarized neutron beams with well-determined characteristics.

Two principal problems of polarized particle acceleration are discussed in this paper. The first of them is to keep spin orientation during beam acceleration and transportation, the second one is to produce a high intensity of polarized ions sufficient for data taking in physics experiments..

2 DEPOLARIZATION OF THE BEAM

The spin vector of the every particle and beam polarization change during deuteron acceleration and transportation. Let us denote Π as a beam polarization vector and $\mathbf{S}$ a unit vector, which shows the particle spin direction, then

$$\Pi = \langle \mathbf{S} \rangle,$$

angular brackets mean the average value of a particle distribution in the beam. If the $\mathbf{S}$ direction does not differ much from the one, determined by unit vector $\mathbf{n}$ ($\mathbf{S} = \mathbf{n} + \Delta\mathbf{S}$), the depolarization degree D is determined by the dispersion of spin vector components transversal to $\mathbf{n}$:

$$D \approx 1/2[\langle(\Delta\mathbf{S}_{tr})^2\rangle - \langle\Delta\mathbf{S}_{tr}\rangle^2];$$

where

$$\Delta\mathbf{S}_{tr} = \Delta\mathbf{S} - \mathbf{n}(\Delta\mathbf{S}\mathbf{n})$$

The dynamics of unit polarization 3-vector during its motion in external electric and magnetic fields is described by the Thomas quasi-classical equation:

$$d\mathbf{S}/dz = \Omega \times \mathbf{S}$$

where the derivative $d\mathbf{S}/dz$ goes with respect to the z-coordinate along the equilibrium particle trajectory, Ω is the rotation vector, which modulus is the Larmor frequency determined by the electromagnetic field structure. The analytical and numerical computation of this equation [2] allowed one to get the following results of beam depolarization in the linac, beam transport lines, beam acceleration and slow extraction.

In the injector of the Nuclotron, a 5 MeV/u Alvarez type linac, for equal transverse emmitances $\varepsilon_x = \varepsilon_y = 45\pi$ mm mrad and longitudinal motion equilibrium phase $\varphi = 31.5^0$ the depolarization factor does not exceed 0.13%. The value $D \leq 0.25\%$ for the same beam parameters in the the injection beam line. The injected beam is rotated in the vertical plane at angle 13^0 during beam transportation from linac to the Nuclotron. For polarization matching, it is necessary to turn polarization vector through the same angle in the channel entrance. A 13^0 rotation can be realized by the longitudinal field in the ion source solenoid. Otherwise, additional beam depolarization, due to coherent polarization rotation in the injection line, appears. Its value $D \approx \theta/2 \approx 2.5\%$.

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It is known, that difficulties of beam polarization keeping in the accelerator ring are due to the crossing of spin resonances. Their perturbation conditions are determined by the relationship:

$$\nu = k_\theta + k_x Q_x + k_y Q_y ,$$

where /ν/ is the number of spin precession per orbit revolution, k_θ, k_x, k_y - integer numbers and Q_x, Q_y - betatron tunes.

Table 1 shows possible spin resonances up to second order ($/k_x/ + /k_y/ \leq 2$) over a beam energy range from 5 MeV/u to 6 GeV/u and betatron tunes $Q_x \approx 6.8$, $Q_y \approx 6.85$. The results of computer simulations of resonance depolarization at a guide magnetic field velocity of dB/dt = 1 T/sec are shown in Table 1. The high lattice periodicity (32 cells and 8 superperiods) allowed to avoid an excitation of the most dangerous lattice resonances. The influences of magnetic field imperfections and correcting fields (normal and skew dipole, quadrupole, sextupole and octupole) are taken into account. Among non-perfection resonances in the Nuclotron, the most powerful one is ν = -1 at an energy of 5.6 GeV/u. Its crossing is dangerous without taking special measures.

Table 1.Spin resonances at the acceleration

k_θ	k_x	k_y	ν	W_{kin},GeV/u	D, %
-7	0	1	-0.15	0.005	8
-7	1	0	-0.20	0.37	8
-14	0	2	-0.30	1.02	0.5
-14	1	1	-0.35	1.35	0.5
-14	2	0	-0.40	1.68	0.3
13	-2	0	-0.60	2.99	0.1
13	-1	-1	-0.65	3.32	0.1
13	0	-2	-0.70	3.65	0.1
6	-1	0	-0.80	4.30	0.3
6	0	-1	-0.85	4.63	0.73
-1	01	1	-0.95	5.29	0.06
-1	**0**	**0**	**-1.00**	**5.62**	**40**

The task of beam polarization keeping under stationary conditions is appeared, when the spin and betatron tunes do not change much arises from a 10 second slow extraction. The beam depolarization degree under stationary conditions depends on closeness to spin resonance. A maximum effect appears when the particles are in the resonance band. In a real accelerator, it is very difficult to realize these resonance conditions exactly because of synchrotron modulation and betatron tune spread.

The data on beam depolarization for a 10 second spill duration of slow extraction are presented in Table 2.

The resonance ν = -1 is dangerous for all the regimes.

The same situation occurs for experiments with an internal target.

Table 2. Spin resonances at the slow extraction

k_θ	k_x	k_y	ν	W_{kin}, GeV/u	D
-7	1	0	-0.20	0.37	16
-14	1	1	-0.35	1.35	0.7
6	-1	0	-0.80	4.30	4
6	0	-1	-0.85	4.63	1.5
-1	**0**	**0**	**-1.00**	**5.62**	**100**

3 CRYOGENIC ION SOURCE POLARIS

About 20 years the Polaris [3] has been used to produce polarized deuterons at the Synchrophasotron. The source is based on the Stern-Gerlach atomic beam method and has the following features:

- magnetic fields are set by superconducting magnets operating in a persistent current state,
- cooling the dissociator, nozzle and skimmer is produced by a thermal contact with the cryostats,
- the source is very compact and requires power only for RF and control systems,

It is installed on a 700 kV terminal, and information exchange is performed by a fibre glass lines. Polarized deuterons are produced by exchange between polarized deuterium atoms and ions of hydrogen plasma $D^0\uparrow + H^+ = D^+\uparrow + H^0$ and ionization $D^0\uparrow$ by plasma electrons. The beam current at the source entrance is equal to 200 μA, the energy 15 KeV and the emittance 2.0π mm·mrad.

A magnetic filter and cesium converter ($H^+ \rightarrow H^-$) is planed to install for $D^-\uparrow$ beam production at the charge exchange reaction $D^0\uparrow + H^- = D^-\uparrow + H^0$.

Polaris operates either in the vector or tensor polarization modes. The polarization sign can change pulse by pulse. To measure the beam polarization after acceleration in the 5 MeV/u linac, two types of low energy polarimeters with semiconductor detectors are used.

4 CHARGE-EXCHANGE INJECTION

The intensity of polarized deuterons at the Synchrophasotron is now equal to $5\ 10^9$ particles per cycle due to multiturn injection. Without a special procedure, the intensity at the Nuclotron is approximately by an order lower because of single-turn injection into the latter. To increase the intensity of a polarized deuteron beam, three ways are considered at the Laboratory of High Energies:

- the formation of a particle short pulse comparable to the one revolution time in the new POLARIS ionizer,
- charge exchange ($D\uparrow^- \rightarrow D\uparrow^+$) injection into the Nuclotron
- construction of a booster used to store and preaccelerate ions up to 200 MeV/u [4].

The last one is most effective and very useful for other ions, but it is the most expensive, of course. Below the second possibility of increasing the intensity, the charge exchange injection of polarized deuterons into the Nuclotron, is studied by computer simulations.

Injected beam parameters:

deuteron energy 5 MeV/u,

emittance: ε_x = 45.0π mm·mrad, ε_y = 45.0π mm·mrad, relative momentum spread: $\Delta p/p = \pm 5.10^{-3}$.

To estimate the injection efficiency, a simple model of particle passage through matter was chosen. It includes elastic Coulomb scattering, ionization energy losses and energy struggling. We suppose to change the charge of every negative ion having passed through the stripper to the opposite one ($D\uparrow^- \rightarrow D\uparrow^+$) for the first passage only, positive charge deuterons do not change their charge.

There are no perturbations and imperfections of the magnetic and electrical fields.

The following steps were undertaken using the computer program to simulate stripping injection into the Nuclotron:

1) to generate an injected beam - particles at transverse deviation-angle (x,x‘), (y,y‘) and relative momentum spread Δp/p, Gaussian distributed,

2) to add to the circulating beam,

3) Monte Carlo simulations of the processes in foil,

4) to compute particle emittances $\varepsilon_{x,y}$ and to remove particles with

$$\varepsilon_x > A_x,\ \varepsilon_y > A_y \text{ and } \Delta p/p > (\Delta p/p)_{mach},$$

$A_{x,y}$ =45π mm·mrad is the acceptance for particle with $\Delta p/p = 5\ 10^{-3}$.

Carbon was chosen as a stripping foil material.

All the calculations were carried out with the specially designed computer simulation code SINSIM - Monte Carlo object-oriented C++ program for Windows[5].

The growth of emittance and relative momentum spread was simulated by 100 macroparticle during 100-turn stripping injection. The intensity gain (I/I_0) during 100 turn stripping injection with the Nuclotron acceptance restriction is shown in Figure below.

This work is based on the preceding results for simulations of heavy ion stripping injection into synchrotrons [6], where. advantages to store ions with a small atom mass unit (up to carbon) by this method were shown.

5 CONCLUSION

The analytical and numerical simulations of the deuteron depolatization in the Linac, beam transport lines and Nuclotron showed the most resonanses not to be dangerous. The exception is the resonanse ν = -1at the energy of 5.62 GeV/u. Its crossing during acceleration time and and slow extraction near this energy are impossible without taking of special measures

We consider the possibility to get sufficient quantity of the polarized D^- in improved Polaris with optimism.

At the charge exchange injection of $D^-\uparrow$ into the Nuclotron, it is possible to gain at least a factor of more than 10 for augmentation of the polarized deuteron intensity.

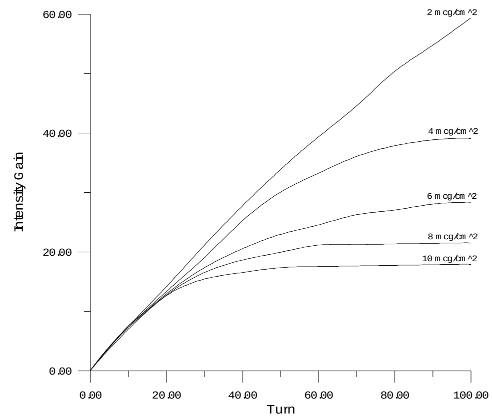

Figure. The intensity gain (I/I_0) during 100 turn stripping injection with the Nuclotron acceptance restriction.

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