Proceedings of the 9th International Conference on Cyclotrons and their Applications
September 1981, Caen, France

POLARIZATION PROGRAMME AT THE UNIVERSITY OF MANITOBA CYCLOTRON FACILITY - PROGRESS REPORT*

S. Oh, J. Birchall, M. de Jong**, I. Gusdal, A. McIlwain, R. Pogson and J.S.C. McKee

Cyclotron Laboratory, University of Manitoba, Winnipeg, Manitoba, R3T 2N2

Abstract.- A Lamb-shift source is now operational at the University of Manitoba Cyclotron Laboratory. Polarized D^- beam has been successfully accelerated. Polarized H^- beam was, however, severely depolarized during acceleration. Studies on the depolarization[1] are described.

Polarization Project.- A nuclear spin filter type Lamb-shift source is now operational at the University of Manitoba Cyclotron Laboratory. This produces up to 250 nA of polarized H^- beam at 11 keV and 120 nA of polarized (vector and tensor) D^- beam at 5.5 keV. The duoplasmatron used in the source is a modified version of the one used in LASL. With its 0.3mm aperture (0.4mm for D^+) anode disc we extract 700μA of hydrogen (400μA of deuterum) ions from it at 600 eV (1.2 keV). Most of the beam reaches the cesium canal. The elimination of the unpolarized direct H^- (D^-) beam component is achieved by biasing the Cs canal to +50 V (+100V) and the argon canal to -50V (-100V) with respect to the main body of the source. Such a bias produces 100 eV (200 eV) difference in energy between the polarized and the direct component of the H^- (D^-) beam. In the subsequent velocity filter region the direct component is turned back by deceleration. This method works reliably in this laboratory. the source is provided with a 15 cm high speed diffusion pump in the Cs canal compartment and a 20 cm cryogenic pump in the Ar canal compartment. As is usual with this type of source it takes ∿ 24 hours to reach the optimum performance (both in current and stability) after which it will remain steady for 2 to 3 weeks until the cryopump has to be outgassed. Unlike other techniques we do not incorporate a collimator downstream of the argon canal to cut down the unpolarized component originating from the ground state atoms.

For H^- beam the polarization was deduced from the beam quench ratio[2]. This indicates that the polarization is between 0.75 and 0.93 depending on the thickness of argon gas and cesium vapor etc. We notice that the quench ratio improves significantly as the beam moves downstream along the 10m long beam transport system. This system consists of two 90^0 electrostatic (E.S.) deflection channels, an E.S. quadrupole doublet, 8 E.S. quadrupole triplets and a beam buncher. We also notice that the beam buncher improves the polarization by as much as 10% when tuned properly. Some of these beneficial effects have been studied with some success in understanding. As will be described later we have a serious depolarization[3,4] of polarized H^- beam during acceleration inside the cyclotron and therefore polarized H^- beam has been used mainly for depolarization studies.

For D^- beam the polarization was deduced from an elastic scattering of a 12.6 MeV polarized deuteron beam from the University of Manitoba cyclotron on ^4He[5]. The measurement showed that Py was between 0.75 to 0.83 when the $m_I=1$ state was selected. This was then compared with the values deduced from the quench ratio. The two methods consistently agreed with each other within 2%, the statistical error of each measurement. We observed improvement in polarization when the beam buncher was turned on for polarized D^- beam. However the degree of improvement was significantly less than the case with the polarized H^- beam. At the same time we had persistently poor buncher efficiency (factor of only ∿ 2) compared to a factor of 5 with the polarized H^- beam.

The University of Manitoba cyclotron was originally designed for acceleration of H^- beam. Acceleration of D^- beam was later achieved by adjustment of available cyclotron and beam injection parameters only[6]. The quality of the deuteron beam from the cyclotron is therefore considerably inferior to that of the proton beam. To correct the situation a 5 year upgrading project was started in 1980. This includes a cyclotron field mapping, a new dees and central region, a modified coupling to the dees etc. We expect that the beam quality (energy resolution in particular) will improve significantly as well as the beam transmission efficiency of the cyclotron.

Polarized H^- Beam and Its Depolarization.- When we switched to the acceleration of polarized H^- beam we found that the beam is much less polarized. Furthermore the degree of polarization had a range of values ∿ + 30% down to 0 and even the wrong sense of polarization (down to -60%). It was quite often found that readjustment of the cyclotron or beam parameters (such as the phase of the buncher) can change the polarization by a large amount. The polarization deduced from the beam quench ratio however, indicated that it is highly polarized (75-93%) throughout the operation. The poor polarization was, in fact, largely caused by the resonant depolarization of H^- beam during acceleration in the four sectored cyclotron of the University of Manitoba. Thus the condition for resonance crossing[1].

$$\gamma\left[\frac{g}{2}\left(\frac{m_e}{m_p}\frac{p}{e}\right)-1\right] = \pm n \pm l_z\nu_z \pm l_r\nu_r \qquad (1)$$

is satisfied at r ∿ 23 cm (9 MeV) radius inside the cyclotron. The parameters in eq (1) at this radius is

* Research supported in part by the Natural Sciences and Engineering Research Council of Canada

** Now at the Atomic Energy of Canada Ltd. Chalk River, Ontario.

n=4 sector, $l_z=1$, ν_z (the vertical betatron oscillation frequency) = 0.18, $l_r=0$ and $\gamma=1/\sqrt{1-\beta^2} \sim 1.01$.

With these values eq (1) new becomes

$$\gamma[\frac{g'}{2} - 1] \equiv \gamma[\frac{g}{2}(\frac{m\, e_p}{m_p\, e}) - 1] = -4 + \nu_z \qquad (2)$$

In the above $m_p = 1.6724\times10^{-27}$ kg and $m=1.6742\times10^{-27}$kg are the protons rest mass and the rest mass of H^- ions, e_p and $e=-e_p$ are the electronic charge of protons and the H^- ions, $\frac{1}{2}g=2.793$ is the proton magnetic moment (in terms of the nuclear magnetic moment). In the early state of the investigation doubts were raised as to whether g is significantly different from that of protons. We now believe that the effect of Lorentz force upon g can be neglected unless it is so strong that the electromagnetic stripping of H^- ions becomes significant (above 42 MeV for the University of Manitoba cyclotron).

Eq (2) now becomes

$$-3.796\gamma = -4 + \nu_z \qquad (3)$$

or

$$4-3.796\gamma = \nu_z \qquad (4)$$

Fig. 1 shows the ν_z and $4-3.796\gamma$ with respect to the beam energy.

To study the depolarization in detail it is essential to trace the beam from injection to extraction. Such studies[1] were carried out as follows:-

a) Three dimensional relaxation calculations for the cyclotron central region to determine the r.f. and static bias electric field. This and the magnetic field data from a cyclotron field mapping done in 1976 were fed into a beam orbit dynamic code, TRIWHEEL and ions were traced from injection to near 2 MeV.

b) To trace the beam from ∿ 2 MeV to extraction (∿ 20-50 MeV) another orbit dynamic code, GOBLIN, was modified to describe the accelerating dees of the University of Manitoba cyclotron and to include the integration of spin motion equation

$$\frac{d\bar{S}}{dt} = \frac{e}{m}\, \bar{S} \times [(\frac{g'}{2} - 1 + \frac{1}{\gamma})\, \bar{B} - (\frac{g'}{2} - 1)\frac{\gamma}{\gamma+1}(\bar{\beta}.\bar{B})\bar{\beta}] \qquad (5)$$

for polarized H^- ions. Here the direction of the cyclotron magnetic field is taken to be along z-axis.

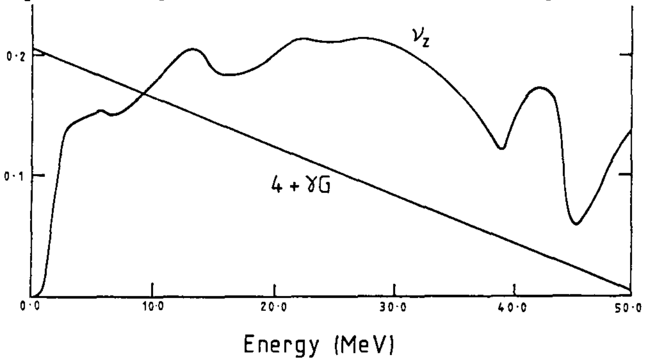

Fig. 1 "The Resonance Crossing". The line $4+\gamma G \equiv 4 - \gamma\{\frac{g}{2}(\frac{me}{m_p e_p}) - 1\}$, crosses ν_z at 9 MeV.

Fig. 2 shows the temporal progress of the spin z-component, S_z, of an H^- ion. The flutter field starts at around 2 MeV and therefore the spin was set to be vertical at this energy. The curves 1, 2 and 3 are for the vertical betatron ocillation amplitude of 0.7, 1.4 and 2.1 mm at the resonance crossing. To obtain the above GOBLIN was set so that the vertical motion does not affect the r-θ motion and the horizontal field components are derived from the linear approximation. The starting conditions are the same for the three cases except the vertical displacement. Studies were made for other starting conditions but the essential features are contained in these three examples. It is noticed that the depolarization resonance width with the University of Manitoba cyclotron is ∿ 2 MeV (this width depends only on the energy gain per turn) and that there is a large fluctuation in S_z with the energy for a long time. For instance, with the example 2 in fig. 2 the polarization will vary between 14 and 27% when the beam is extracted between 19.9 and 20.16 MeV (the width of the fluctuation is ∿ 520 keV at this energy). This fluctuation, however, is not expected to be observed unless a single turn extraction is possible. In fact, with an expected ± 3 mm centre spread at this energy this alone can smear out the fluctuation ($\nu_r \sim 1.03$ at this energy and therefore of the order of 10 turn ∿ 0.4 MeV energy spread is expected) to a large extent. The degree of smearing out may however be rather sensitive to the coherent centre spread of the beam and in turn to the change in the cyclotron parameters etc. This interpretation is consistent with our observation mentioned earlier.

The study also indicates that the shape of ν_z in the energy region that is far away from the resonance contributes to the overall depolarization rather significantly. Thus the usual formula[1,7,8] for resonance depolarization

$$S_z = 2 \exp [-\frac{\pi}{2\gamma} (\frac{\omega}{\omega_c})^2] - 1 \qquad (6)$$

may be relied upon only when the slope of ν_z is constant over a wide range of energy. From the practical point of view it tells us that a localized shimming around the resonance crossing (to increase the slope) may not be as effective as one might have hoped for. Measurements were made to see if the polarization indeed varies as is indicated by fig. 2. The overall beam polarization is the weighed average of individual spin S_z over the beam phase space area. Studies using vertical slits at the resonance crossing yielded confusing results; it did not necessarily improve polarization. Until now we have not found a convincing explanation for this effect. We suspect that an imperfection field (such as hills tilted at an angle to the valleys) might be the cause of it. Depolarization under an imperfection field of this kind can be shown to behave quite differently from the resonance arising from a vertically symmetric field component.

Finally, the computer study indicated that there is a factor of ∿ 4 growth in the effective phase space area from injection to 9 MeV. The observed beam vertical height was, on the other hand, ±2.5 mm at the resonance crossing. This corresponds to ∿ 40 mm mrad MeV$^{1/2}$. The emittance of the polarized beam from the source was estimated from calculation and measurement which yielded 7 ∿ 15 mm mrad MeV$^{1/2}$. Thus the agreement between each other seems to be satisfactory.

With ± 2.5 mm beam vertical spread our best estimate based on the computer study is $S_z \sim 0.15$, the

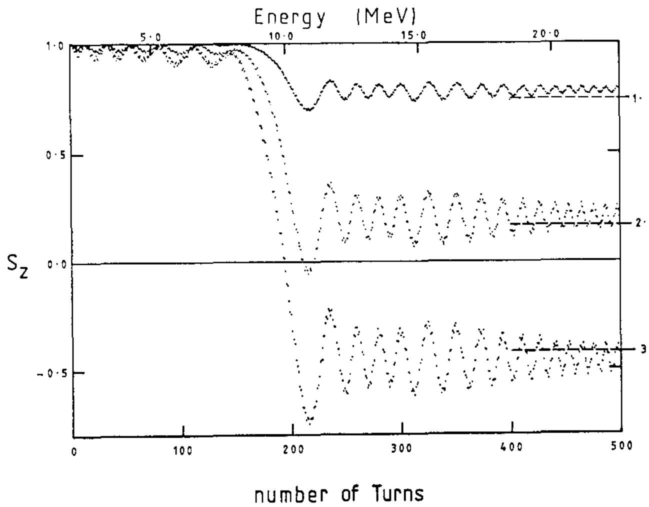

Fig. 2 "Evolution of S_z Inside the Cyclotron" for vertical betatron oscillation amplitudes of 0.7 (curve 1), 1.4 (curve 2) and 2.1 mm at the resonance crossing. The dashed lines on the right hand side of each curve represent S_z calculated from eq (6).

figure which is not far away from our observed long term average of $S_z \sim 0$.

An acceptable beam polarization for nuclear physics experiment would be ≤50%. To achieve this appears to be a hard task. The elimination of any vertically asymmetric imperfection field is a prerequisite. After this a possible direction would be a combination of

a) increasing the energy gain per turn by 50 to 60%.

b) magnetic shimming around the resonance cross in favor of rapid crossing.

c) vertical slit to remove the most severely depolarized beams.

Acknowledgement.- The computer codes, TRIWHEEL and GOBLIN, were obtained from TRIUMF in 1975. We are grateful for the help given to us by the orbit dynamic group, Drs. G.H. MacKenzie and P. Schmore in particular, in the early stage.

References.-

1. M. de Jong, Ph.D. Thesis, submitted to the University of Manitoba (1981).

2. G.G. Ohlsen, Los Alamos Scientific Lab. LA-4451 (1970) 9.

3. S. Oh, M. de Jong, J. Birchall, I. Gusdal, A. McIlwain and J.S.C. McKee, Annual Research Report, University of Manitoba Lab. (1979) 6.

4. M. de Jong, S. Oh, J. Birchall, I. Gusdal, A. McIlwain and J.S.C. McKee, 5th International Sumposium on Polarization Phenomena in Nuclear Physics, Santa Fe (1980) 973.

5. J. Birchall, N.T. Okumusōglu, M. de Jong, M.S.A.L. Al-Ghazi and J.S.C. McKee, 5th International Symposium on Polarization Phenomena in Nuclear Physics, Santa Fe (1980) 1290.

6. I. Gusdal, G. Knote, A. McIlwain, J.S.C. McKee, S. Oh and W.H. Uzat, Nucl. Instr. and Meth. 136 (1976) 393.

7. M. Froissart and R. Stora, Nucl. Instr. and Meth. 7 (1960) 297.

8. H.G. Kim and W.E. Burcham, Nucl. Instr. and Meth. 27 (1964) 211.