SPIN DYNAMICS AND POLARIZED ION SOURCES ON ISOCHRONOUS CYCLOTRON U-240

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ABSTRACT

A matrix method approach to treat spin dynamics in electromagnetic fields of a beam line is developed and some results of calculation for Kiev's isochronous cyclotron U-240 are presented. Spin depolarization resonance conditions of various polarized ion acceleration at this cyclotron are analyzed. Polarized light and heavy ion sources for the cyclotron are discussed shortly.

1. INTRODUCTION

A great progress in development of isochronous cyclotrons, external injection systems and polarized ion sources caused applications of these accelerators for the mean energy polarized beam production to investigate various polarization phenomena in the field of nuclear physics. Contemporary high requirements to a precision of such investigations, particularly at symmetry laws studying, a necessity to have different spin states of the beam on a target, and perspectives to use isochronous cyclotron as first stage of facilities producing intermediate and high energy polarized beams, stimulate to study ion beam spin dynamics and depolarization from a source to a target. In present work the results of investigations and elaborations for production, acceleration and transportation of various polarized beams (p, $^{1}H^{-}$, d, $^{2}H^{-}$, t, $^{3}H^{-}$, $^{3}He^{2+}$, $^{6,7}Li^{3+}$, $^{14}N^{5+,7+}$, $^{23}Na^{9+}$) with energy 120 q^2/A^2 MeV/u at the isochronous cyclotron U-240 of Institute for Nuclear Research in Kiev are discussed.

2. SPIN DYNAMICS IN BEAM TRANSPORT LINE

A spin precession of polarized ions at passing through electromagnetic fields results on final spin orientation. Because of different ion trajectories and different magnetic field component directions, the movement through such fields affects an absolute value of the beam polarization, and during acceleration the beam may be fully depolarized if corresponding resonance conditions take place. For spin dynamics calculation of the ions passing through transportation system units a matrix method was used with following expression of a rotation matrix (α,β,γ are Euler's angles)

$$R=\begin{vmatrix} \cos\alpha\cos\beta\cos\gamma-\sin\alpha\sin\gamma & -(\cos\alpha\cos\beta\sin\gamma+\sin\alpha\cos\gamma) & \cos\alpha\sin\gamma \\ \sin\alpha\cos\beta\cos\gamma+\cos\alpha\sin\gamma & -\sin\alpha\cos\beta\sin\gamma+\cos\alpha\cos\gamma & \sin\alpha\sin\beta \\ -\sin\beta\cos\gamma & \sin\beta\sin\gamma & \cos\beta \end{vmatrix} \quad (1)$$

The matrix elements are essentially simplified at decreasing of the Euler's angle number. Such simplifications are accomplished for consideration of spin dynamics in right-hand frame with $z \parallel \bar{k}$ and vertical axis y, what is convenient for an accelerator and transport line with horizontal symmetry plane.

A final spin state $\bar{S}_n(S_x, S_y, S_z)$ is a result of successive actions of the type (1) matrices R_i, inherent to each of transport line units:

$$\bar{S}(S_x,S_y,S_z)=R_nR_{n-1}\cdots R_2R_1\bar{S}(S_{x_o}S_{y_o}S_{z_o}) \qquad (2)$$

One unit may be represented by several matrices in accordance with peculiarities of the magnetic field (for example, input, central and output parts of a dipole magnet). There are among R_i matrices free path matrices and matrices needed at a plane change of the initial beam line. Thus one has opportunity to calculate spin dynamics in the transport line with any number of units and any trajectory in accordance with a specially developed TRANSPIN program. The angular (x', y') and spatial (x,y) trajectory parameters one takes from corresponding transport line calculations on the base of TRANSPORT program. A knowledge of the angles of spin axis orientations permits to determine ion polarization component values t_{kg} what is realized in TRANSPIN using appropriate formulas of work [1] for spins 1/2 and 1. The expression of Euler's angles for some typical magnetic units of a transport line as the functions of ion properties (g,A,q,v), unit parameters (B,L,ε,ρ) and trajectory parameters (x,y,θ_o,θ) are demonstrated in Table 1. Formulas for other possible units and their detailed treatment are considered in references [2,3]. Analysis of the Table 1 expressions shows that edge fields of transport line units do not affect on ion polarization values only for the central trajectory $(\theta_o=\theta=0,\ x=y=0)$. The ions moving on side trajectories get spin precession around field components which do not coincide with main field direction. The difference in precession angles finally causes the beam depolarization. Calculation data for different transport lines always show decreasing of the depolarization effects at even crossovers independently on a unit set. The same takes place at decreasing of the beam emittance.

3. DEPOLARIZING RESONANCES IN THE CYCLOTRON

The second cause affecting on the ion beam depolarization is the horizontal component of magnetic field in the acceleration region. A periodical

Table 1.

№	Unit	α	β
1	Dipole magnet(DM)	–	$\beta_q(gA/2q-1)\pm(\theta-\theta_o)gA/2q$
2	Input of DM	$ygA\cos(\varepsilon)/2\rho q$	$ygA\sin(\varepsilon)2\rho q$
3	Output of DM	$ygA\cos(\varepsilon)/2\rho q$	$ygA\sin(\varepsilon)2\rho q$
4	Quadrupole lens (F)	–	$\pm(\theta-\theta_o)gA/2q$
5	Quadrupole lens (D)	–	$\pm(\theta-\theta_o)gA/2q$
6	Wien filter (WF)	–	$g\mu_oBL/hv+(\theta-\theta_o)gA/2q$
7	Input of WF	$yg\mu_oB/hv$	–
8	Output of WF	$yg\mu_oB/hv$	–

Notes: g-factor, atomic weight (A), charge (q), velocity (v) of ion; magnetic induction (B), length of unit (L), angle between normal to magnet edge and system axis (ε), trajectory radius (ρ); trajectory coordinates (x,y), input and output angles between central and treated trajectory, correspondingly (θ_o,θ).

structure of the isochronous cyclotron U-240 magnetic field (3 sectors) is a rotating field in particle bound frame. Such field may induce transition between spin substates m and m' with probability $P_{mm'}$, which is described by Majorana's formula [4]. It gives opportunity to determine a transition probability for the particles of any spin value taking into account the probability for spin I=1/2 particles $P_{1/2-1/2}$ at the same gyromagnetic ratio. Unhomogeneous magnetic field of the cyclotron in the right-hand frame (z is vertical, y∥k) has components B_x and B_y in horizontal plane. They deviate ion spins from vertical direction because of precession around horizontal components.

Owing to distortion of ion orbits depolarization resonance conditions may appear which in general relativistic case are determined by an equation

$$\gamma G = \pm k \pm m\nu_z \pm n\nu_r \qquad (3)$$

where k, m, n - are integers including 0, ν_z, ν_r are numbers of horizontal and vertical vibrations per one turn, correspondingly, $\gamma = E_t/E_o = 1 + E_k/E_o$ with $E_o = mc^2$, G is Larmor to cyclotron frequency ratio $G = \nu_L/\nu_c = gA/2q - 1$.

An application of the equation (3) to the isochronous cyclotron U-240 shows existence of several resonance conditions at acceleration of each of the above mentioned polarized ion types. The most important cases are shown in the Fig.1 where full lines represent solutions of the equation (3) for ν_z; points are experimental data for different field levels of the cyclotron U-240 as the functions of orbit radius (ion energy).

An influence of resonance conditions on the ion polarization depends on resonance width Γ and a strength ω. It may be shown following the works [5,6], that after passing of resonance the ion polarization P_z will be

$$P'_z = P_z\left[2\exp\left(-\frac{\pi\omega^2}{2\Gamma}\right) - 1\right] = P_z(1 - 2P_{1/2-1/2}), \qquad (4)$$

$$P_{1/2-1/2} = 1 - \exp\left(-\frac{\pi\omega^2}{2\Gamma}\right).$$

As it is obvious from (4), at $\omega^2/\Gamma \ll 1$ resonance is weak and $P'_z = P_z$, at $\omega^2/\Gamma \gg 1$ it is strong and $P'_z = -P_z$, at intermediate conditions the depolarization takes place. As in general form

$$\omega^2/\Gamma = \frac{(1+G\gamma)^2}{G\,d\gamma/d\theta}(B_r/B_o)^2 \qquad (5)$$

besides the individual properties of the ion type G, acceleration rate dγ/dθ and magnetic field level B_o, the resonance strength depends on horizontal component

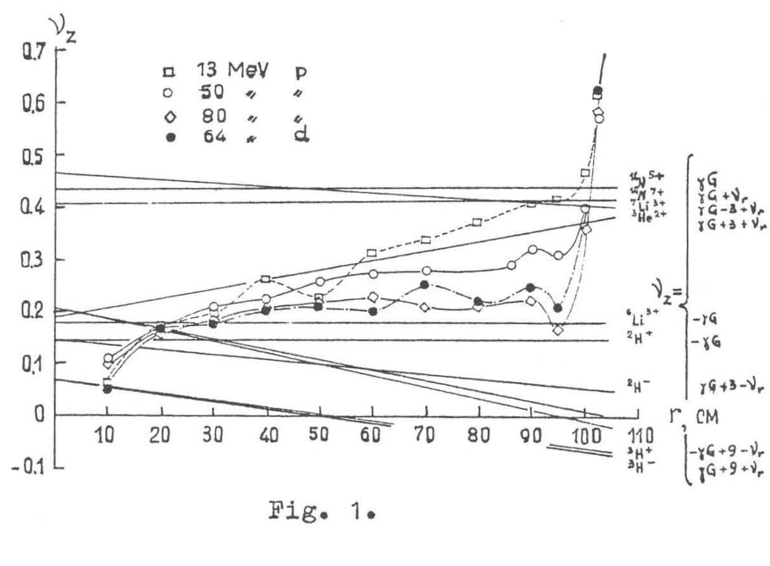

Fig. 1.

of the field in the resonance B_r

$$B_r=(B_x^2+B_y^2)^{1/2}, \quad |B_x|,|B_y|\le B_r\le|B_x|+|B_y| \quad (6)$$

To determine B_r values in different resonances, the harmonic analysis of the magnetic field was carried out like reference [6], taking into account experimental data of the magnetic measurements for cyclotron U-240 and radial dependence of the field harmonics (details will be published elsewhere).

Upper and lower limits of B_r/B_o were determined from expression (5) for all ion types at the assumption that the resonances did not affect polarization if $\omega^2/\Gamma<1/3$ or $\omega^2/\Gamma>3$. Although values of these limits depending from G and γ can differ by an order for various ion types, at $B_r/B_o<0.43\ 10^{-3}$ the resonance is weak and at $B_r/B_o>1.25\cdot10^{-2}$ it is strong for all mentioned ions. The field expansion coefficients, their derivatives and the B_r/B_o limits permit to neglect all resonances of the $\gamma G=\pm\nu_z\pm\nu_r$ type, B_x components for k=6, 9 resonances, and all k=1, 2, 4, 5 resonances due to small contributions of these harmonics in the real magnetic field of the accelerator. This approach proves the absence of dangerous resonances for $^{23}Na^{9+}$. Comparisons of real field B_r/B_o ratios and their limits for every ion type in details testify that, excluding $^3He^{2+}$ ions, resonances shown in Fig.1 are also not dangerous. Therefore it is possible to produce almost all polarized ion beams without resonance depolarization at the accelerator.

4. POLARIZED ION SOURCES

To accelerate polarized ions at cyclotron U-240, ion sources of stable hydrogen isotopes and ^6Li were elaborated, using classical method of polarization [7,8]. Last years a new atomic beam unit including two sextupole magnets and a cooled nozzle for the polarized proton source, a new alkali atom source and diagnostic devices are developed.

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