POLARIZED PROTONS ACCELERATION AT U-70

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A possibility to accelerate polarized proton at the synchrotron U-70 is considered. Estimations of the spin resonances are given in the energy range 2.5…70 GeV. To suppress depolarizing effects of spin resonances, a scheme of three partial Siberian snakes is suggested. Each snake consists from helical magnets with 4.5 T magnetic field. The scheme provides the adiabatic spin flip at imperfection resonances and suppresses all intrinsic resonances by quite realistic beam emittance and magnets misalignments ±5 mm.

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1. INTRODUCTION

At present moment there is a reach experience in an acceleration of polarized protons in synchrotrons. But in each concrete case one have to choose more appropriate equipment and to solve problems how to implement these parts in the existing machine lattice. First attempt to consider this problem for U-70 have been done in 1984 year. However, proposed measures have demanded big enough efforts to enlarge one straight section by displacements of a number of dipole magnets.

First of all, let's remind main approach to description of spin motion in accelerators. Quantum mechanical average of spin operator $\sigma? = \left(\sigma_x;\sigma_y;\sigma_z\right)$ – spin vector **S**=$\langle\psi^* |\sigma?|\psi\rangle$ is moving in magnetic **B** and electric **E** fields along the generalized azimuth accelerator θ according to the BMT equation: [1]

$$\frac{dS}{d\theta} = S' = [W\times S];$$
$$-W = \left(\frac{q_0}{\gamma} + q'\right)B_\perp + \frac{q}{\gamma}B_P + \left(\frac{q_0}{\gamma+1} + q'\right)[E\times V], \tag{1}$$

where magnetic field **B** is decomposed along particle velocity **V** and transversely; q', q_0 are anomalous and normal parts of the gyro-magnetic ratio $q = q_0 + q'$.

Similar to the orbital motion a periodical part $\mathbf{W_0}$ of the precession frequency ($\mathbf{W}=\mathbf{W_0} + \mathbf{w}$) in (1) leads us to a periodical solution – "spin closed orbit" $\mathbf{n_0}$ and spin tune $\nu = W_0/\omega$, [2] where

$$-\omega = \frac{q_0}{\gamma}B_\perp + \frac{\gamma q_0}{\gamma^2 - 1}[E\times V] \tag{2}$$

is the Larmor frequency.

In usual case of a machine with the vertical guiding field $\mathbf{B}=B\cdot\mathbf{e_z}$ the spin precession axis $\mathbf{n_0}$ coincides with the unit vector $\mathbf{e_z}$ and spin tune in the accelerator frame ($\mathbf{e_x};\mathbf{e_y};\mathbf{e_z}$) is equal to $\nu=\gamma a=\gamma q'/q_0$. Linear dependence of the spin tune on particle energy creates many troubles while acceleration, Multi periodical part **w** of the precession frequency is connected with particle deviations from the CO due to some imperfections of magnetic systems the same as betatron and synchrotron oscillations. How it's seen from (1), first of all, radial magnetic fields tilts $\mathbf{n_0}$ from the vertical direction. More dangerous situations happened when spin tune is equal to one of a harmonic number of the radial field: $\nu=\nu_k=k$ (k – integer). In this case spin deflections are accumulated in time. Finally, it can lead to a beam depolarization. These imperfection spin resonances take place in each 440.652 MeV for electrons and 523.342 MeV for protons and their strengths increase with beam energy.

It's clear, that resonances $\nu=k=P$, where P is machine periodicity, are strongest between others. Thus for acceleration of polarized particles one has to take a care about a quality of the guiding magnetic field.

Moreover, due to the vertical betatron oscillations of the particle its spin is deflected also by radial magnetic fields, intrinsic for a beam focusing system (B_x~z). In this case intrinsic spin resonances arise by a condition: $\nu = \nu_k = k \pm \nu_z$; ($\nu_z$ is vertical betatron tune). So, even in the first linear approximation the acceleration of polarized particles up to high energy looks very complicate issue.

2. SPIN RESONANCE CROSSING

Let's consider the case of a separate spin resonance crossing. According to the paper [3] a change of polarization is described by the formulae:

$$\delta S = S_f - S_i = 2S_i\left(e^{-\chi} - 1\right), \tag{3}$$

where $\chi = \pi w_k^2 / 2\dot{\delta}$ is a spin phase advance in a resonance zone $\delta : w_k$: (w_k – resonance strength; $\delta = \nu - \nu_k$ – resonance tuning).

There are two practically interesting cases. By a fast crossing ($\dot{\delta} ? w_k^2$) the polarization change is small: $(\delta S \approx \chi = 1)$. In opposite case slow (adiabatic) tuning rate $\dot{\delta} = w_k^2$ we have a spin flip: $S_f \; ; \; -S_i$ with exponentially small polarization losses. Based on this understanding of the resonance passing process a number of practical approach have been developed for the polarized particles acceleration. Compensations of CO harmonics by correctors at imperfection resonances and pulse quadrupoles at intrinsic are successfully applied for the fast resonances crossing by the polarized proton acceleration up to few GeV [4].

3. SIBERIAN SNAKES

Further progress required a different approach to the resonance crossing. In 1976 it was suggested [5] to introduce in machine lattice a special chain of magnets, which will rotate spin by 180 degrees by pass. How it easy to see, in this case the spin tune ν=1/2 *independently* on the beam energy and the resonance condition does not arise more totally. This approach was called as Siberian snake. It can be arranged in different magnet combinations, which rotates spin around any axis. At that the periodical precession axis $\mathbf{n_0}$ at opposite to the snake azimuth lies in the horizontal plane with the same angle to the CO as the snake axis.

The simplest snake is one solenoid with the longitudinal integral field $q\int B_y dl = \pi B_z \rho$; (37 Tm for 10 GeV protons). Some disadvantage of the solenoidal snake is a x-z coupling introduced by the longitudinal field. There are a number of schemes with combinations of solenoids and skew quads, that don't excite the coupling out side the insertion. But such schemes require, as rule, a long straight section.

More compact partial snakes can be designed from helical magnets /6/, because, how it's seen from (1), spin rotations by transverse fields don't depend on energy for high energy particles whereas the action on spin by longitudinal fields is inverse proportional to the energy. Orbit distortions from transverse fields can be minimized in the case of helical magnets by a special snake design a set of four full twist helixes with mirror symmetry and adjusted field levels. Such choice performs to rotate spin by 180 degrees around an arbitrary direction in the machine medium plane and compensate orbit distortions outside the snake taking them very moderate inside the insertion.

This advantage of helical snakes creates interesting possibilities for high energy machines with combinations of two Siberian snakes located at opposite azimuths with the snake axis perpendicular each other. In this case $\mathbf{n_0}$ is vertical in arcs ($\mathbf{n_0} = \pm \mathbf{e_z}$) and spin tune again is half integer (ν=1/2).

That is funny, that practically the same chain of helical magnets can work as spin rotator from vertical direction to horizontal plane.

The practical realization of these ideas have done at RHIC, where are installed two pairs Siberian snakes in each ring and eight spin rotators around two IP to deliver the longitudinal polarization for two detector STAR and PHENIX. Recently polarized protons in both rings were accelerated up to top energy 205 GeV with relatively small polarization losses.

4. PARTIAL SNAKE

But in the beginning so called a partial Siberian snakes found practical applications. Such snake rotates spin only by few degrees and thereby generates enough strong artificial imperfection resonances, which satisfy to the adiabatic condition. First test of this idea have been done in 1976 year at electron-positron collider VEPP-2M [6] and then routinely used to deliver e^+e^- beams, polarized at the energy 700 MeV, to the energy below main imperfection resonance ν=1 (E=440 MeV). Later the solenoidal partial snake was applied at AGS, where polarized protons are accelerated up to 25 GeV with some problems caused by mention above coupling [7].

Similar to full snakes the partial snakes from helical magnets look more promising [8]. The strength of such snake can be done big enough (up to 35% of the full one; $w_k = 0.175$). Partial snakes such strength or combinations of few of them open a possibility to suppress also intrinsic resonances. In a vicinity of each imperfection resonance ν=k there are two symmetric intrinsic resonances ($\nu = k_1 - \nu_z$ and $\nu = k_2 + \nu_z$). If these resonances lie inside the zone of the imperfection one, spin motion in such system is quite complicate, but computer simulations show that under condition $|w_{k1,2}|=1/3|w_k|$ modulations of the precession axis due to this adjacent resonances take adiabatic behavior and spin reverses in the same way as on a single imperfection resonance.

5. SYNCHROTRON U-70

The proton synchrotron U-70 is operating in Protvino since 1967 year. The synchrotron has 12 super-periods. The beam is injected from booster ring with the kinetic energy 1.5 GeV. The first attempt to modify U-70 to polarized proton acceleration have been taken yet at 1984./9/ However, proposed scheme have required big machine changes and it was not accepted. The present proposal suggests install three identical partial snakes in three super-periods of U-70, as it's shown in Fig.2. Each snake takes 3.5 m and consists of 4 periods helix (λ=70 cm; aperture 15 cm) with field up to 4.2 T. This combination rotates spin by 65 degrees. To compensate some CO distortions two dipole coils are wounded at the edges. Particle trajectories inside the snake are shown in Fig.2 for the energy 25 GeV. Spin rotation by the snake per pass is given in Fig.3. It's seen, that the snake axis is practically longitudinal and spin map is σ_y.

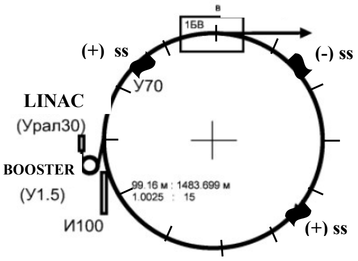

Fig.1. Layout synchrotron U-70

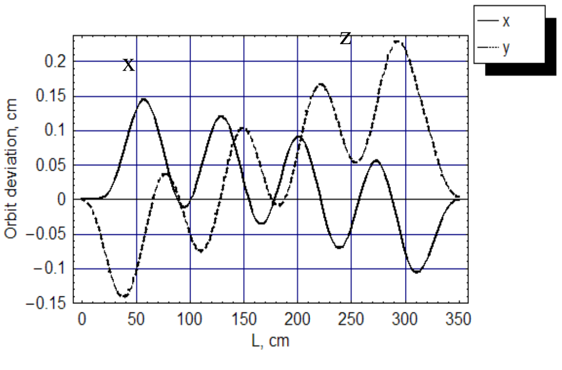

Fig.2. Orbit inside the snake

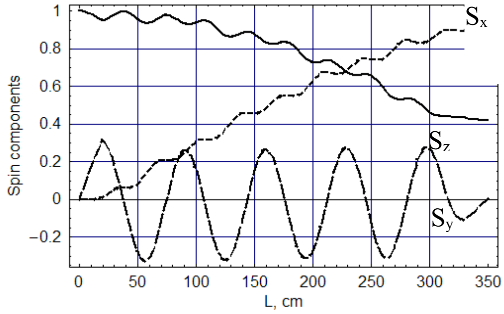

Fig.3. Spin rotation inside the snake

The spin rotations by all identical polarities snakes are added coherently at $\nu_0 = k = m \cdot P/4$ (m are integers) or at $\nu_0 = k = (m+1/2) \cdot P/4$ with one snake polarity reverse. The last option is appeared more suitable for U-70 (Fig.1).

A behavior the spin tune in this case is presented in Fig.4 for the energy range of more strong spin resonances. Their strengths $|w_k|$ are shown in the Fig.4 by triangles and boxes for imperfection resonances and by rounds for intrinsic resonances $\nu_0 = \nu_k = k \cdot P \pm \nu_z$. Estimations of the $|w_k|$ have been done with assumptions: dipoles vertical misalignments ±0.5 cm (in two different ways); normalized vertical emittance don't exceed $10^{-4} \cdot \pi$ cm.

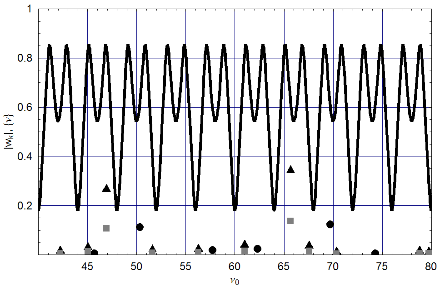

Fig.4. Spin tune with snakes and strongest resonances

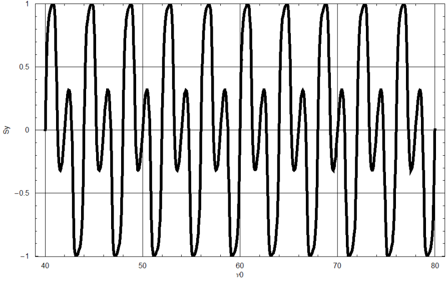

Fig.5. Vertical polarization by acceleration

This figure visually demonstrates, that intrinsic resonances are "absorbed" by imperfection resonances created by the snakes combination.

It's interesting to look at a motion of vertical component of polarization while acceleration with the snakes set (Fig.5).

Points with 100% vertical polarization are suitable for polarized beam extraction.

6. CONCLUSIONS

Proposed schemes of three helical partial snakes at U-70 can provide acceleration of polarized protons up to top energy E=70 GeV under conditions a conservation beam emittance from the booster ring during whole acceleration cycle and alignment requirements for machine magnets ± 5 mm.

A manufacturing of the superconducting helical magnet will demand some efforts. However, usual requirements of field qualities are not crucial in this case, because snakes take only short part of machine circumference. Some optics distortion (<5%) can be easy corrected by weak focusing coils at the edges of each snake.

We didn't discuss here possible problems with the beam acceleration at the booster ring. But according to international experience it can not be serious obstacle to cross few weak spin resonances on low energy.

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УСКОРЕНИЕ ПОЛЯРИЗОВАННЫХ ПРОТОНОВ В У-70

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В статье обсуждается возможность ускорения поляризованных протонов в синхротроне У-70. Дана оценка силы деполяризующих резонансов. Предлагается схема из трех спиральных частичных Сибирских змеек для подавления деполяризующего влияния, как целых, так и спин-бетатронных резонансов. Обсуждается конструкция спиральных магнитов и требования к качеству пучка и магнитной системы синхротрона У-70.

ПРИСКОРЕННЯ ПОЛЯРИЗОВАНИХ ПРОТОНІВ В У-70

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У статті обговорюється можливість прискорення поляризованих протонів у синхротроні У-70. Дана оцінка сили деполяризуючих резонансів. Пропонується схема із трьох спіральних часткових Сибірських змійок для придушення деполяризуючого впливу, як цілих, так і спин-бетатронних резонансів. Обговорюється конструкція спіральних магнітів і вимоги до якості пучка і магнітної системи синхротрона У-70.