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ACCELERATION OF POLARIZED BEAMS USING MULTIPLE STRONG PARTIAL SIBERIAN SNAKES *

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Acceleration of polarized protons in the energy range of 5 to 25 GeV is particularly difficult since depolarizing spin resonances are strong enough to cause significant depolarization but full Siberian snakes cause intolerably large orbit excursions. Using a 20 - 30 % partial Siberian snake both imperfection and intrinsic resonances can be overcome. Such a strong partial Siberian snake was designed for the Brookhaven AGS using a dual pitch helical superconducting dipole. Multiple strong partial snakes are also discussed for spin matching at beam injection and extraction.

1. INTRODUCTION

Accelerating polarized beams requires the control of both the orbital motion and spin motion. The evolution of the spin direction of a beam of polarized protons in external magnetic fields, such as those existing in a circular accelerator, is governed by the Thomas-BMT equation[1],

$$\frac{d\overrightarrow{P}}{dt} = -\left(\frac{e}{\gamma m}\right)\left[G\gamma\overrightarrow{B_\perp} + (1+G)\overrightarrow{B_\parallel}\right] \times \overrightarrow{P}$$

where the polarization vector P is expressed in the frame that rotates with the particle's velocity. Comparison with the Lorentz force equation shows that, in a purely vertical field, the spin rotates $G\gamma$ times faster than the orbital motion. Here G=1.7928 is the anomalous magnetic moment of the

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proton and $\gamma = E/m$. Gγ gives the number of full spin precessions for every revolution and is also called the spin tune ν_{sp}.

During acceleration, a depolarizing spin resonance is crossed whenever the spin precession frequency equals the frequency with which spin-perturbing magnetic fields are encountered. The resonance condition for imperfection depolarizing resonances, driven by magnet errors and misalignments, arise when $\nu_{sp} = G\gamma = n$, where n is an integer. Imperfection resonances are separated by only 523 MeV energy steps. The condition for intrinsic resonances, driven by the focusing fields, is $\nu_{sp} = kP \pm \nu_y$, where k is an integer, ν_y is the vertical betatron tune and P is the super-periodicity of the machine lattice.

All imperfection resonances can be overcome by introducing a local spin rotator ("partial Siberian snake")[2] that effectively increases the strength of all imperfection resonances to the point that they all introduce complete spin flip. The resonance strength ϵ_{ps} caused by a spin rotator that rotates the polarization by δ around a horizontal direction is $\delta/2\pi$. Note that with a partial Siberian snake the closest approach of the spin tune to an integer value is equal to ϵ_{ps}. This is a special case of the formula for the spin tune of a ring with a partial Siberian snake:

$$\nu_{sp} = \frac{1}{\pi} \cos^{-1} \left[\cos\left(\frac{\delta}{2}\right) \cos(\pi G\gamma) \right]$$

2. STRONG PARTIAL SIBERIAN SNAKE

With a strong enough partial snake it is possible to increase the gap between the spin tune and an integer enough that it becomes possible to place the fractional part of the betatron tune and therefore the intrinsic resonance inside this gap as has been demonstrated at the Brookhaven AGS[3]. Tracking calculations revealed that for strong intrinsic resonances this betatron tune window is reduced further by higher order depolarizing resonances that are similar to snake resonances. The strongest higher order resonance is located in the middle of the gap but sufficient room is still available for placing the betatron tune.

If it is possible to build such a strong partial Siberian snake a single device would eliminate depolarization from all spin resonances and allow for polarized proton acceleration in medium energy accelerators. For the AGS the challenge amounts to building a 36° spin rotator with a maximum length of 2.6 m and internal orbit excursion of less than about 4 cm. The most compact solution consists of a 3 Tesla helical dipole with a helical pitch that is double at the ends than at the center. This field profile allows for a compact matching of the outside orbit to the helical orbit inside the magnet.

3. MULTIPLE PARTIAL SIBERIAN SNAKES

With a partial Siberian snake the stable spin direction reverses direction at all imperfection resonances but is very close to the vertical direction at half-integer values of $G\gamma$ as long as the partial snake is relatively weak. It is therefore possible to inject and extract vertically polarized beam at these energy values without much loss of polarization. The AGS injection and extraction is set to occur at $G\gamma = 4.5$ and 46.5, respectively.

For a strong partial snake, however, polarization loss at injection and extraction is no longer negligible. A 20% snake will lead to a 10% polarization loss due to this spin direction mismatch. This could be solved with appropriate spin rotators in the injection and extraction beam lines. However, a single additional partial snake located in the AGS can provide the spin direction matching at injection and extraction and also increase the effective partial snake strength if its position is chosen properly.

The location and the precession axis direction of multiple partial Siberian snakes has to be chosen very carefully to maintain control of the spin tune in a similar way as is necessary for multiple full Siberian snakes. For practical partial Siberian snakes the precession axis direction is always very close to longitudinal, which leaves only the location and strength of the partial snakes as free parameters.

The spin tune for two partial Siberian snakes with rotation angle δ_1 and δ_2 and separated by 1/m of the ring is given by:

$$\nu_{sp} = \frac{1}{\pi}\cos^{-1}\left[\cos\left(\frac{\delta_1}{2}\right)\cos\left(\frac{\delta_2}{2}\right)\cos(\pi G\gamma) - \sin\left(\frac{\delta_1}{2}\right)\sin\left(\frac{\delta_2}{2}\right)\cos\left(\frac{\pi(m-2)}{m}G\gamma\right)\right]$$

The maximum effective strength of $\delta_1 + \delta_2$ occurs at mn where n is an integer. The minimum effective strength of $|\delta_1 - \delta_2|$ and also the maximum vertical component of the stable spin direction occurs at $G\gamma = mn + m/2$. For the maximum strength to occur at the strong intrinsic resonances m has to be a common factor of both the vertical betatron tune and the machine super-periodicity. In addition, in order to avoid having the minimum strength occur at an imperfection resonance m needs to be an odd integer.

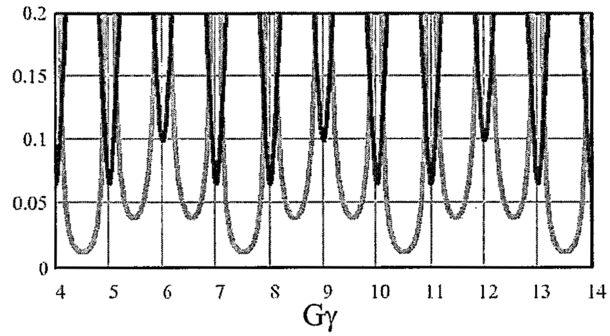

Figure 1. Deviation from an integer for the spin tune (blue, dark) and vertical component of the stable spin direction (red, light) for 5% and 15% partial Siberian snakes separated by 120° orbital deflection angle as a function of $G\gamma$.

At the AGS the vertical betatron tune is about 9 and the the superperiodicity is 12. All the above conditions can therefore be fulfilled for m=3. With both snakes at equal strength δ, $\nu_{sp} = \delta/\pi$ effectively doubling the strength of the partial snakes. At the injection and extraction energies, for which $G\gamma = 3n + 1.5$, the two snakes cancel. The polarization direction is therefore exactly vertical and no polarization is lost due to spin direction mismatch.

Even using the presently installed normal-conducting helical partial Siberian snake[4] with a rotation angle of 9° a very substantial reduction of the injection and extraction spin mismatch can be achieved. At the same time the effective strength of the partial snakes at the intrinsic resonances is significantly increased. Figure 1 shows the spin tune and the vertical component of the spin direction in the AGS with two partial snakes with rotation angles of 9° (5% partial snake) and 27° (15% partial snake), respectively. The injection and extraction regions have to be located both in between the two partial Siberian snakes. In this case the polarization loss due to injection and extraction mismatch is only 2.4%.

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