SOME CONTINUOUSLY VARIABLE PARTIAL SNAKES OF TYPE I AND TYPE II*

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ABSTRACT

In order to obtain polarized beam in proton accelerators, Siberian snakes of two types may be needed in order to establish a spin tune independent of energy. We have done a numerical study to find a type II partial snake and to find more exact solutions for the type I partial snakes previously proposed. We find a type II partial snake. We find that the unequal field integrals needed to modify approximate type I snakes to exactly type I snakes with horizontal and vertical bends result in unacceptably large orbit excursions. We find a new type I snake with smaller field integrals at small overall rotation. An 8 magnet type II snake works from 0 to π but more magnets might be used to reduce the excursion at small angle. Also, no type I partial snake with as few as 8 magnets has been found which will work continuously from 0 to π . It appears that horizontal and vertical bends cannot provide solutions for pure type I or type II that allow the field integrals to approach zero as the rotation goes to zero. Versions of both the new type I and type II partial snakes are presently used as rotators in the external polarized beamline at Fermilab.

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1. Introduction

Siberian snakes consisting of strings of dipole magnets with fields perpendicular to the beam direction have been studied in some detail as a way of avoiding depolarizing resonances in proton accelerators. Extensive new results of computer studies were presented at the Snake Workshop held in conjunction with the VII International Spin Symposium held in Minneapolis in September 1988 [1-7]. The most straightforward schemes utilize two snakes known as type I and type II which rotate the spin by π about two different axes perpendicular to the machine guide field. These axes are parallel and perpendicular to the beam, respectively. This allows the polarization eigenvector to be either aligned or anti-aligned with the guide field, which is thought to be a stable and simple solution. If only a single snake of type I is used which rotates about the beam axis, the eigenvector is in the plane of the machine and rotates around the vertical.

The number of snakes required to avoid certain kinds of resonances is a function of energy of the machine and appears to increase approximately linearly with energy [1,2]. T. Roser has proposed that partial snakes with precession less than π could be used in machines of energy less than perhaps 30 GeV [3]. Machines in this range are the Brookhaven AGS, the KEK proton machine, and a proposed kaon factory machine at TRIUMF. The effect of turning on a partially excited snake has also been studied [4]. As pointed out by L. C. Teng, [5] another use might be in an accelerator such as the Fermilab main ring where small orbit excursions below 50 GeV could be obtained. This is also being studied for RHIC and the 70 GeV injector for the SSC [1].

A computer program to search for snake solutions was written several years ago by the present author. It was only used to find net rotations of $\pi/2$ or π . Solutions were published in Nucl. Instrum. Meth. [6]. Upon examination it

has now been found that some of the solutions were in fact partial snakes, some of type II and some of type I, with net rotation delta equal to $\pi/2$. It was not known whether these solutions could be made to work at other values of delta.

2. The Present Study

There are many snake configurations such as three magnet ones, helical ones, octagonal approximations to a helix, etc. We have restricted ourselves so far to studying 4 bends in each plane and in the detailed study of partial snakes to orthogonal planes, although not just horizontal and vertical. Snakes which act as a drift space and use bends in orthogonal planes and equal bend point spacing fundamentally involve 8 units of bend or multiples thereof. In each plane including the beam there must be at least 3 units of bend to compensate any given unit bend to restore the beam. As an example, the ten magnet type I snake proposed by Steffan [7] (Fig. 1) which has 4 bends of 90° and 6 bends of 45° is basically two 8 magnet snakes of 45° in series, with the center two magnets eliminated by symmetry and some others combined. In our present numerical study and a previous one [2] we examine only 8 magnet snakes with the intention of combining or simplifying them for specific applications.

We have considered three really different arrangements of two strings of four magnets. The various cases studied are obtained from these three by rotations and reflections. Rotations are not a trivial change. A 90° rotation of a snake with horizontal and vertical bends changes the ordering of horizontal and vertical, and determines whether vertical spin encounters horizontal or vertical bending first. Also, all of the best partial snake solutions found have all the magnets at $\pm 45^\circ$ from the vertical.

The first arrangement could be called a single shift. For chains A and B the ordering is ABABABAB. The second could be called a double shift and the ordering is AOBAAABBAOB. The O is a gap with no magnet. The third is a span and the ordering is ABABBABA. One can make a triple shift etc. but this has not been considered to be useful.

We use two computer programs. The first is a search program to find solutions which are pure type I or type II. The accuracy is presently limited to about one degree due to computer time requirements. The second is a demonstration to show the size of spin components for a given tune of a snake. The second is to some extent a check of the first program, although some subroutines are identical. The second program is useful for studying approximate solutions and for checking that we agree with published solutions.

For the present study of partial snakes, the search program was applied to one magnet configuration at a time. The independent variable was the desired overall rotation angle δ . There were only two quantities which were varied in the search at each δ . These were the precession angles in the bends in each orthogonal string, or equivalently, the two field integral units. The signs of these precession angles turn out to be quite important.

3. Results

We have applied the demonstration program to two approximate solutions for type I partial snakes that were previously known. Steffan has shown the behavior of the particular type I, snake as shown in Fig. 1 as the magnet currents are reduced but kept equal to each other [6]. He finds that the snake is not pure type I for overall rotations less than π . Specifically, the unwanted component is about 6 percent for rotation near $\pi/2$. Our program also

finds this result. When we try to correct to a pure type I by using different currents in the two strings (using the search program) we find that a constant precession of 90° is needed in each magnet in one string, independent of overall rotation. This is shown in Fig. 2. We have modeled this snake as two 8 magnet snakes in series. This means running the magnets at twice the usual strength in one set. A similar but less severe problem is found for an approximate type I partial solution by Roser [3] shown in Fig. 3. The unwanted z component is almost 4 percent of the desired x component at an overall rotation of 20° . As shown in Fig. 4, when we try to make this a pure type I, one of the precession angles approaches 30° in the limit of zero overall rotation. This snake was proposed with 6 magnets and is the equivalent of 8 unit magnets. It will not work for overall rotations over $\pi/2$.

We have found more attractive solutions for both type I and type II with the magnets at $\pm 45^\circ$ from the vertical (see Figs. 5-7). In these cases the field integrals do approach zero in the limit of zero overall rotation. They do not do so in a particularly attractive way, approximately as the square root for type I and a combination of .23 power and .46 power for the type II.

Helical snakes of type I have been discussed by Courant [8]. On the issue of a helical type II snake, we make two observations. A plot of the bend vectors looking downstream makes two helical turns in opposite directions in our type II case as compared to two turns in the same direction in at least one type I case. Secondly, if long straight sections are available, one can add two partial snakes of this kind in series, each giving half the net required rotation, and smaller beam deflections. Since the fields go as a fractional power in angle, one does not win very much by doing this.

CONCLUSION

Two of the motivations for partial snakes were to reduce beam deflections at low energy and to reduce overall snake length. In the present type II snake these goals are not attained to quite the degree that appears possible with a type I snake, but at least solutions have been found. The good news is that there are both type I and type II partial snakes and furthermore these could be ramped with energy to maintain polarization and keep small orbit excursions over some range.

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Figure Captions

Figure 1 A type I snake by Steffan.

Figure 2 The approximate, with equal magnet strengths, and pure type I, with unequal magnet strengths, solutions for Steffan's snake as the overall rotation angle is reduced from π to 0. The magnet strengths in one plane do not approach zero in the pure type I solution.

Figure 3 A type I partial snake by Roser. This is equivalent to solution T in the Survey article.

Figure 4 The approximate, with equal magnet strengths, and pure type I, with unequal magnet strengths, solutions for Roser's snake as the overall rotation angle is reduced from $\pi/2$ to 0. The magnet strengths in one plane do not approach zero in the pure type I solution.

Figure 5 The pure type I solution for the snake SZ4 with magnets at $\pm 45^\circ$ from vertical and unequal strengths. The magnet strengths approach zero as the overall rotation of spin approaches zero.

Note 1 Solutions for negative δ exist with a different snake with u and v interchanged.

Note 2 Solid line is u string at high current and v string at low current. Dashed line is vice versa.

Figure 6 The solution for the continuously variable pure type II snake (rotation about an axis transverse to the beam). There are 8 magnets at $\pm 45^\circ$ to the vertical. The magnet strengths of the 4 magnets in each plane are different in each plane and the sign is critical.

Figure 6a) Plotted for overall rotation from $-\pi/6$ to $+\pi/2$.

Figure 6b) Plotted for overall rotation from 0 to π .

Figure 7 The type II solution as actually implemented in the Fermilab Polarized Beam. The overall rotation is $\pi/2$ around the vertical axis. We have not used the continuously variable feature. Some of the magnets requiring higher strength are physically made of two magnets and so 12 magnets appear in this diagram.

- a) the orbit and field directions.
- b) the field directions looking downstream.
- c) the spin direction looking from below on the right.
- d) the spin direction looking from above on the right.
- e) the spin after each magnet, looking downstream.
- f) the spin direction looking from directly above.

(spin rotation in braces)

Figure 1

Figure 2

01460

01482

Figure 3

Figure 4

Figure 5

Figure 6a

01459

Figure 6b

Field, Looking d.s.

Beam Centroid, 45 "side"

Beam Centroid, 45 "side"

Polar., looking d.s.

Polar. top view

Figure 7