ON THE FEASIBILITY OF POLARIZED HEAVY IONS IN RHIC*

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Abstract

Heavy nonspherical ions such as uranium have been proposed for collisions in RHIC[1]. When two such ions collide with their long axes aligned parallel to the beams (large helicities), then the plasma density might be as much as 60% higher. Since the collisions might have any orientation of the two nuclei, the alignment of the nuclei must be inferred from a complicated unfolding of multiplicity distributions. Instead, if it would be possible to polarize the ions and control the orientation in RHIC, then a much better sensitivity might be obtained. This paper investigates the manipulation of such polarized ions with highly distorted shapes in RHIC. A number of ion species are considered as possibilities with either full or partial Siberian snakes in RHIC.

INTRODUCTION

"Why on earth would anyone consider polarized heavy ions in RHIC?" you ask. It turns out that some of the nuclei of the heaviest ions are quite oblong in shape. Head-on collisions with the long axes aligned parallel to the velocities could produce a considerably higher quark-gluon plasma density than when the long axes are perpendicular to the velocity. While collisions of all orientations would occur with unpolarized beams, manipulation of the spins could significantly enhance this effect.

To achieve collisions with polarized heavy ions several topics need to be considered:

1. A polarized source must be developed.
2. Polarimeters need to be developed to verify the polarization at various stages (source, injectors, RHIC).
3. During acceleration, depolarizing resonances must be eliminated or crossed to maintain polarization.
4. These oblong ions are radioactive and are not "politically correct" with names like U-235, and plutonium.

Additionally since the ions at lower energies will still have some bound electrons there could be some unexpected depolarization during the stages of stripping.

Developing an optically pumped ion source may be possible[2]. These ions have rather high spin values of spin ($I \geq \frac{5}{2}\hbar$). Relative to the quantization axis, the desired states would have a magnetic quantum number with maximal value $m = \pm I/\hbar$.

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Polarimetry for heavy ions beams is pretty much an unknown for this application and could be a serious problem at least for the low energy beams. With the high spin value, the spin density tensor will have quite a few terms to consider; however, the desired state with maximal helicity could perhaps simplify the requirements. At high energies, the best polarimetry might come from differences in the distributions of particles from the colliding beams.

In this paper I set aside the worries of sources and polarimetry, and only consider the dynamics of the spins in the RHIC. In particular, would it be possible to build Siberian snakes to completely flip the spin of one of these ions?

MAGNETIC MOMENTS OF HEAVY IONS

In the rest frame of the ion, the spin will precess according to

$$\frac{d\vec{I}}{dt} = \vec{\mu}^* \times \vec{B}^* = \frac{gZe}{2m}\vec{I} \times \vec{B}^* \qquad (1)$$

in a classical sense, Since the spin occurs on both sides when we scale the usual Thomas-BMT equation from a spin-½ to a higher spin particle, the highest helicity states $m = I/\hbar$ will precess in the usual way as a proton, except for the different value of $G = (g-2)/2$. The behavior of states with smaller magnetic quantum numbers will be somewhat more complicated and not be considered in this paper. One should realize that all the spin information of a particle is in the spinor, and we need only consider the tensor description when measuring the polarization of the ensemble of spins via some scattering process at the polarimeter.

Ref.[3] lists magnetic moments and spins for whole host of nuclei. The magnetic moment for an ion may be written as[4]

$$\mu = g\frac{Ze}{2M}I \simeq g\frac{Z}{A}\frac{I}{\hbar}\mu_{\rm N}, \quad \text{so} \quad g \quad \simeq \frac{\mu}{\mu_{\rm N}}\frac{A}{Z}\frac{\hbar}{I}, \qquad (2)$$

where the nuclear magneton is given as

$$\mu_{\rm N} = \frac{e\hbar}{2m_{\rm p}} = 3.15245 \times 10^{-8}\ {\rm eV/T}. \qquad (3)$$

Table 1 lists the spin and $G = (g-2)/2$ for a few of these oblong nuclei[3]; the proton is included for comparison. To build a full snake, the larger magnitude $|G|$ of the plutonium ion is most attractive since it would require lower magnetic fields in spin rotators and snakes for the same angular precession. At high energies, solenoids are too weak and not really practical for spin manipulation, so magnets with transverse fields are necessary. Keeping the lengths

Table 1: Spin and anomalous G-factor of various ions

Ion	$I/\hbar$	G	$B_{\rm ion}/B_{\rm p}$
p	1/2	1.7928474	1
$^{235}_{92}$U	$7/2$	-0.34	-4.5
$^{237}_{93}$Np	$5/2$	0.5	7
$^{241}_{94}$Pu	$5/2$	-1.35	-3.7

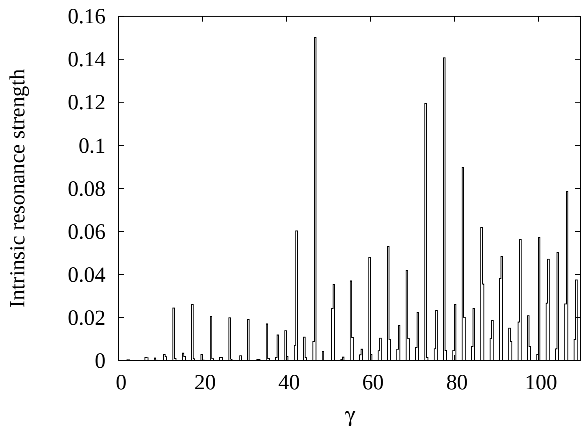

Figure 1: DEPOL calculation of vertical intrinsic resonance strengths for RHIC without snakes. This was for a $^{241}\mathrm{Pu}$ ion with vertical amplitude corresponding to a normalized 95% emittance of $10\pi \times 10^{-6}$ m.

and relative strengths of the magnets in a snake or spin rotator constant, we can consider scaling the fields by a constant ratio. In this case we should expect the required the fields to scale as

$$B_{\rm ion} = \frac{1 + G_{\rm p}\gamma_{\rm p}}{1 + G_{\rm ion}\gamma_{\rm ion}} B_{\rm p}, \tag{4}$$

for the same amount of spin precession at fixed rigidity.

Fig. 1 shows the strengths of the vertical intrinsic resonances as a function of γ calculated by DEPOL[5] for RHIC without snakes. There would be about 127 imperfection (integer resonances) between injection around 10 GeV/u ($p/q \simeq 80$ Tm) and top energy at 100 GeV/u ($p/q \simeq 833$ Tm). For comparison, Fig. 2 shows the same calculation for protons. Two advantages of $^{241}\mathrm{Pu}^{+94}$ is that the resonances are fewer and weaker. For $^{237}\mathrm{Np}^{+93}$ and $^{235}\mathrm{U}^{+92}$, $|G|$ is even smaller with even fewer and weaker resonances than the plutonium.

RHIC STYLE HELICAL SNAKES

In each ring of RHIC[1] there are two Siberian snakes each consisting of four identical right-hand-twisted helical dipole magnets which are each about 2.4 m in length. The twist angle is a full $360°$ for each helix. The snakes are located on opposite sides of the rings between quadrupoles in the free space of a dispersion suppressor half cell. In a given snake the inner pair of helices are connected in series

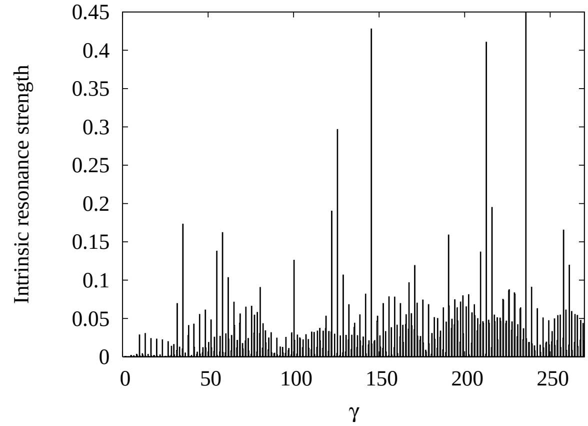

Figure 2: DEPOL calculation of vertical intrinsic resonance strengths for RHIC without snakes. This was for a proton corresponding to a normalized 95% emittance of $10\pi \times 10^{-6}$ m.

with opposite fields to a single power supply, and the outer pair of helices are connected similarly to a second supply. The opposite polarity of each helix in a pair ensures that the second helix cancels the vertical orbit shift from the first helix. For protons, the present snakes operate for protons with fields of around 1.2 T and 4 T in the outer and inner pairs of helices, respectively. This will give a snake rotation axis in the horizontal plane at $\pm 45°$ to the longitudinal axis depending on the overall polarity of the snake fields. By running one snake with polarities $+ - +-$ and the other with $- + -+$ the two snakes will have snake axes pointing at $90°$ to each other. In this case the spin tune $\nu_{\rm sp} = ½$ at all energies.

In principal one could change the length of a helix and readjust its field, but for a given spin rotation, the $\int |B_\perp| ds$ for the helix should remain constant. The overall integrated transverse field for these snakes is about

$$\int_0^{10.7} |B_\perp|\, ds = 25.5 \text{ Tm}. \tag{5}$$

To scale this overall integral to plutonium we expect from Eq. 4 a factor of 3.3 in peak field (>13 T) which is way beyond the short-sample limit for these superconducting magnets. RHIC however has some 30 m long straight sections nearer to the interaction regions.

Fig. 3 shows the components of magnetic field in a scaled up version of the RHIC snakes with four identical helices of 6.72 m length. The inner helices have fields of 4.828 T, and the outer helix, 1.26 T. With these settings, an integration through a hard-edge model of helical fields shows that spin which is initially vertical ($+\hat{y}$) is rotated by $178°$ about an axis $47.9°$ from the longitudinal (not quite perfect, but good enough for estimation). The calculated rotation matrix was

$$\begin{pmatrix} 0.102629 & 0.019928 & 0.994520 \\ -0.026999 & -0.999375 & 0.022811 \\ 0.994353 & -0.029192 & -0.102027 \end{pmatrix}. \tag{6}$$

So far this does not sound too bad, but with the longer helices and smaller $|G|$ we have larger orbit excursions. For protons, the orbit in the middle of one of our present 10.7 m long snakes has a maximum transverse excursion of around 3.2 cm from the axis at injection. For plutonium, the longer snakes give a maximum excursion of 32 cm as shown in Fig. 5. Ouch! In fact examination of the trajectory through the snake shows that the vertical aperture would need to be around 50 cm.

Construction of such magnets could be possible although very expensive. Segmentation of the helices into smaller pieces could help with quench protection so that the individual segments would each have a smaller stored energy. If the individual segments were aligned along the trajectory, the aperture could be reduced, but we must remember that at high energy the transverse orbit excursions are reduced by a factor of ten. Since RHIC would spend a lot of time running other species with and without polarization, we should expect to require that the aperture be clear with the helices unpowered. Another wacko possibility one might consider would be to mechanically move helical segments with smaller apertures during ramps. Even with warm magnets, this could be a problem, but with superconducting magnets – Ay carumba!

So much for full snakes. Since there are many fewer resonances which are also weaker than for protons, it is more reasonable to consider using a partial snake.

CONCLUSIONS

While a full snake for an ion like plutonium-241 could be constructed, the ½-meter aperture would seem to make it too costly and impractical. Using one of the existing snakes with the same strength fields as for protons, we would have an 11% snake with ^{235}U ions. The aperture requirements would be the same as for protons, since the rigidity would be the same for both species. There are only about 33 integer resonances to cross, and the intrinsic resonances are weak so a partial snake for uranium looks good.

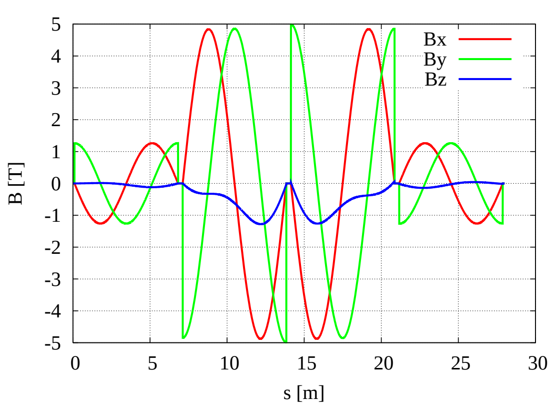

Figure 3: Magnetic field along the trajectory inside 100% helical snake for $^{241}\mathrm{Pu}^{+94}$ ions at injection ($\gamma = 10.25$) with $G\gamma = -13.8$.

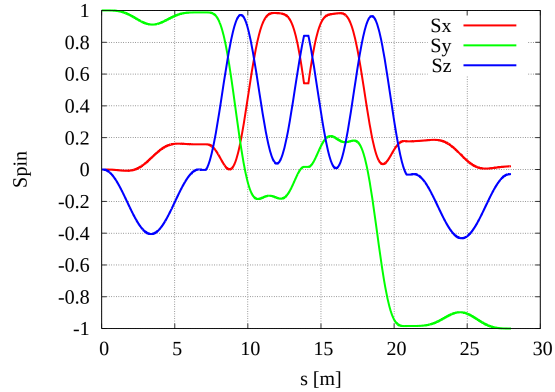

Figure 4: Spin inside 100% helical snake for $^{241}\mathrm{Pu}^{+94}$ ions at injection ($\gamma = 10.25$) with $G\gamma = -13.8$.

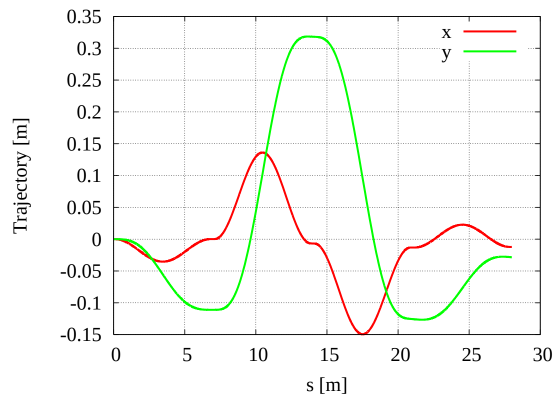

Figure 5: The trajectory inside a 100% helical snake for $^{241}\mathrm{Pu}^{+94}$ ions at injection ($\gamma = 10.25$) with $G\gamma = -13.8$. The offsets at the end of the snake are due to having such large excursions since the field components have a helical sextipole harmonic which increases away from the axis. There is also quite a sizable longitudinal component to the field along the trajectory through the inner two helices (see Fig. 3).

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