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20% Partial Siberian Snake in the AGS[1]

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Abstract. An 11.4% partial Siberian snake was used to successfully accelerate polarized protons through a strong intrinsic depolarizing spin resonance in the AGS. No noticeable depolarization was observed. This opens up the possibility of using a 20% to 30% partial Siberian snake in the AGS to overcome all weak and strong depolarizing spin resonances. Some design and operation issues of the new partial Siberian snake are discussed.

AGS POLARIZED PROTON RUNS SINCE 1990'S

Polarized protons have been accelerated in the Brookhaven Alternating Gradient Synchrotron (AGS) since 1980s. In 1980s, it was used for fixed target high P_T proton-proton elastic scattering experiment[1]-[2]. Since 1990s, AGS polarized proton program has been running to develop the AGS as injector for spin physics program in RHIC[3]. The goal for the AGS is to deliver 2×10^{11} proton/bunch with 70% polarization at 24GeV/c.

Acceleration of polarized proton beams to high energy in circular accelerators is difficult due to numerous depolarizing resonances. During acceleration, a depolarizing resonance is crossed whenever the spin precession frequency equals the frequency with which spin-perturbing magnetic fields are encountered. In the presence of the vertical dipole guide field in an accelerator, the spin precesses $G\gamma$ times per orbit revolution [4], where $G=(g-2)/2=1.7928$ is the coefficient of the gyromagnetic anomaly of the proton, and γ is the Lorentz factor. The number of precessions per revolution is called the spin tune ν_{sp} and is equal to $G\gamma$ in this case.

There are three main types of depolarizing resonances in the AGS: imperfection resonances, which are driven by magnet misalignments; intrinsic resonances, driven by the vertical betatron motion through quadrupoles; and coupling resonances, caused by the vertical motion with horizontal betatron frequency due to linear coupling [5]. The resonance condition for an imperfection resonance is $\nu_{sp}=n$, where n is an integer. The resonance condition for an intrinsic resonance is $\nu_{sp}=nP\pm\nu_y$, where n is an integer, $P=12$ is the superperiodicity of the AGS, and ν_y is the vertical betatron tune. The resonance condition for a coupling spin resonance is $\nu_{sp}=n\pm\nu_x$, where ν_x is

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the horizontal betatron tune; it is only important if ν_{sp} is close to a strong intrinsic resonance condition. The spin resonance strength ε_k is defined as the Fourier amplitude of the spin perturbing field. In general, the intrinsic resonance strength is proportional to $\sqrt{\gamma\varepsilon_N}$, where ε_N is the normalized vertical emittance of the beam; and the imperfection resonance strength is proportional to γ for a given closed orbit error. When a polarized beam is uniformly accelerated through an isolated spin resonance, the final polarization P_f is related to the initial polarization P_i by the Froissart-Stora formula[6]

$$P_f = (2e^{-\pi|\varepsilon_k|^2/2\alpha} - 1)P_i, \tag{1}$$

where α is the resonance crossing rate given by $\alpha = \frac{d(G\gamma)}{d\theta}$, and θ is the orbital bend angle in the synchrotron.

In the early days, the polarization was preserved by non-adiabatic techniques, tune-jump for intrinsic resonances and harmonic orbit correction for imperfection resonances[1]-[2]. Over the years, the adiabatic techniques have prevailed. Several novel schemes have been developed to overcome these resonances in the AGS. A 5% partial solenoidal Siberian snake [7] has been used successfully to overcome imperfection resonances [8].

For a ring with a partial Siberian snake of strength s, the spin tune ν_{sp} is given by [9]

$$\cos \pi\nu_{sp} = \cos\frac{s\pi}{2}\cos G\gamma\pi, \tag{2}$$

where $s = 1$ corresponds to a full Siberian snake which rotates the spin by 180°. When s is small, the spin tune is nearly equal to $G\gamma$ except when $G\gamma$ equals an integer n, where the spin tune ν_{sp} is shifted away from the integer by $\pm s/2$. Since the spin tune never equals an integer, the imperfection resonance condition is never satisfied. Thus the partial Siberian snake can overcome all imperfection resonances, provided that the resonance strengths are much smaller than the spin tune gap created by the partial Siberian snake. For the AGS, nominally $\alpha = 4.8 \times 10^{-5}$, resonance strength $|\varepsilon_k| < 0.01$ for all imperfection resonances from experience of earlier runs [1]-[2], a 5% partial Siberian snake is enough to overcome all imperfection resonances.

As shown in Fig. 1, the measured asymmetry changed sign at every $G\gamma$= integer because of the partial Siberian snake. The polarization loss at $G\gamma = 42.3$ is caused by a hybrid resonance [10]. The additional structure between integers is due to the numerous weak resonances at $G\gamma = k \pm \nu_y$ where integer k is not an integer multiple of superperiodicity of AGS. Since these resonance strength are very weak, it would not cause noticeable polarization loss at nominal resonance crossing rate. However, the asymmetry for each energy of Fig. 1 was measured by coasting beam at that energy. Therefore, the resonance crossing rate was very low and the depolarizing effect at these resonances was enhanced. More importantly, within error bars, the polarization measured at half integers agrees with the expected values, except $G\gamma = 39.5$, where intrinsic resonance $G\gamma = 48 - \nu_y$ located. This confirmed that a 5% partial Siberian snake is strong enough to overcome imperfection resonances up to high energy in the AGS and full spin flip was achieved at all imperfection resonances.

By adiabatically exciting a vertical coherent betatron oscillation using a single ac dipole magnet, an artificial spin resonance is excited. If the resonance location is chosen

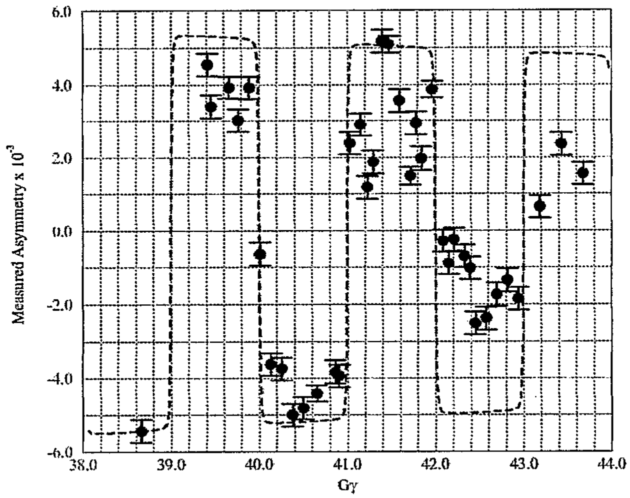

FIGURE 1. The measured asymmetry for different beam energies or $G\gamma$ values. The dashed line shows the asymmetry expected from a 5% partial Siberian snake. It is scaled based on the assumption that the analyzing power is inversely proportional to the beam momentum.

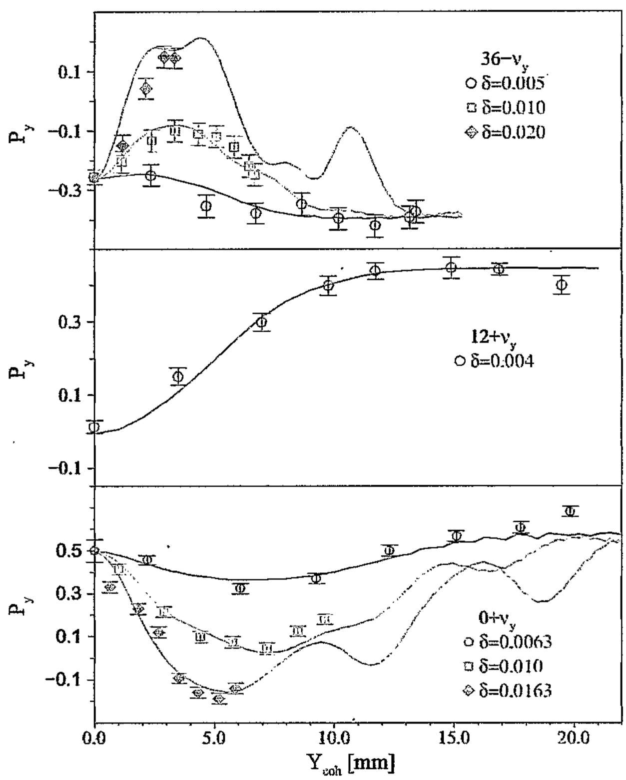

FIGURE 2. Measured polarization as function of generated coherent betatron motion amplitude Y_{coh} for various tune separations with an ac dipole. Note that when driving amplitude is large enough, all curves reach plateaus, which indicate full spin-flip is achieved.

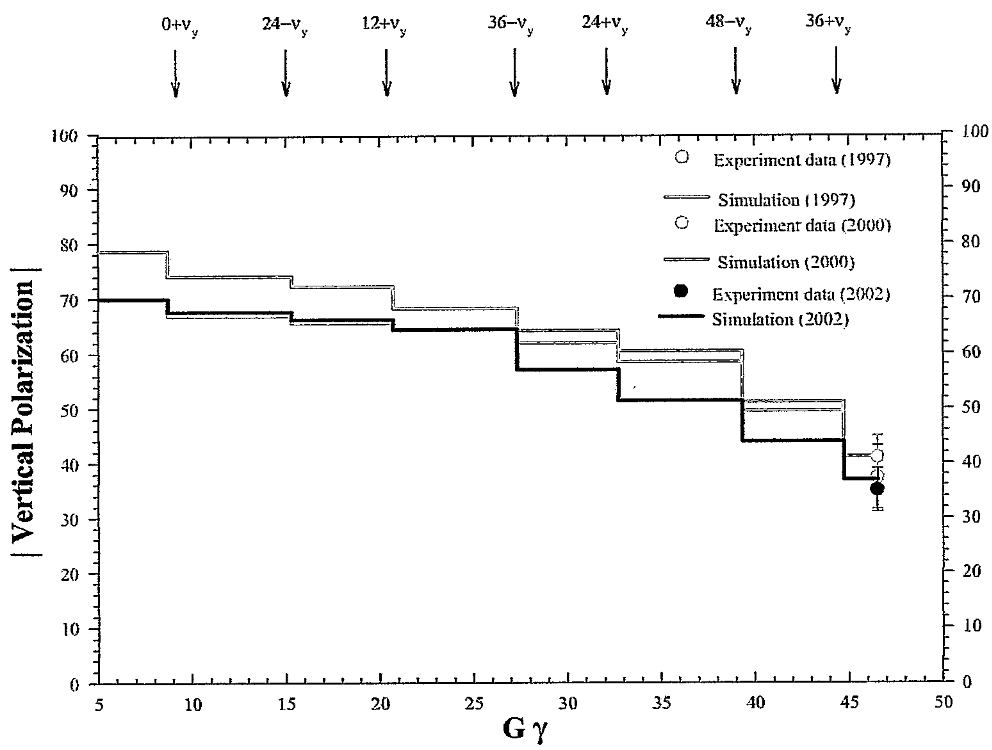

FIGURE 3. Summary of polarization in the AGS. The solid lines are the SPINK simulation results.

near an intrinsic spin resonance, the spin motion will be dominated by the ac dipole resonance, and full spin-flip can be achieved without significant emittance growth [11]. Fig. 2 shows the measured polarization as function of ac dipole driving amplitude and tune separation δ (difference between the modulation tune and the vertical betatron tune). It reveals that we have achieved full spin-flip at $0+\nu_y$, $12+\nu_y$ and $36-\nu_y$ within the uncertainty of the AGS internal polarimeter. It should be noted that no such data exists for $36+\nu_y$. At high energies, the existing polarimeter has small analyzing power and polarization level is lower, so it is very difficult to make such a plot for $36+\nu_y$.

Due to the linear coupling induced by the solenoidal field of the partial snake, coupling depolarizing resonances are enhanced. The two betatron tunes have to be well separated to reduce the coupling effect[5]. The typical betatron tune separation is 0.15.

In summary, the proton polarization in the AGS is shown in Fig. 3. Simulations done with SPINK [5] are also included in Fig. 3. Full spin-flip is achieved at all imperfection resonances using the 5% partial Siberian snake, and at all strong intrinsic resonances using an ac dipole. The remaining polarization loss comes from coupling and weak intrinsic resonances. The steps in the polarization levels are the polarization losses due to coupling resonances and weak intrinsic resonances.

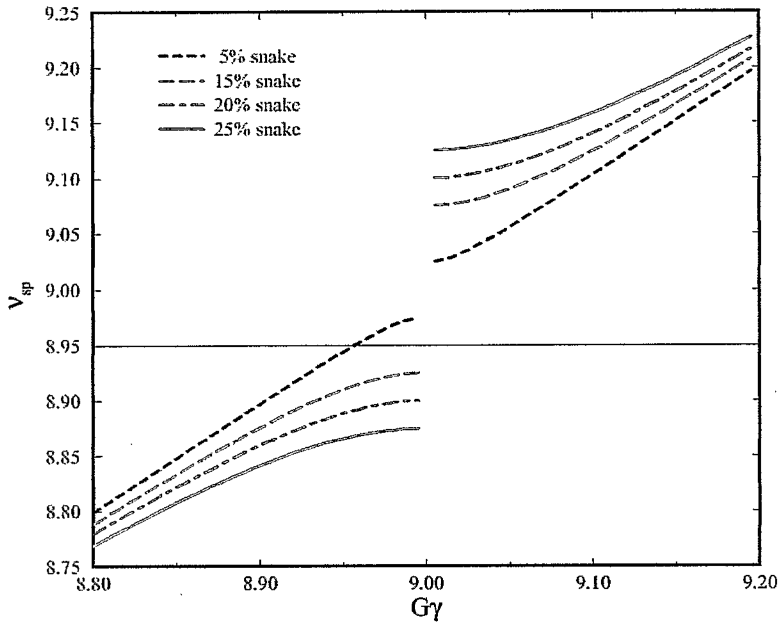

FIGURE 4. Spin tune for various partial Siberian snake strengths. The straight line indicates a possible value for the vertical betatron tune.

WHY STRONG PARTIAL SNAKE?

As shown in Fig. 3, the remaining depolarization in the AGS is due to the weak intrinsic resonances and coupling resonances which are enhanced by the presence of the solenoidal partial Siberian snake. To reduce coupling resonance strength, a new snake with less coupling is needed. The ac dipole technique only works for strong intrinsic resonances, since it relies on the strength of the intrinsic resonances to induce a strong enough artificial resonance. In addition, ac dipole operation need precise control of betatron tunes to the level of 0.0005 and need to be constantly monitored for polarized proton operation. Currently, there is no scheme to overcome the weak intrinsic resonances. It should be noted that two other techniques presented in this workshop may also work for the weak intrinsic resonances: tune-jump [12] and spin harmonic matching [13].

As can be seen from Fig. 4, with a strong enough partial Siberian snake, the spin tune gap can be increased to allow placing the betatron tune inside the gap so that the intrinsic resonance conditions can also be avoided. This idea has been proposed previously in Refs. [14] and [15]. Simulations showed that for the first intrinsic resonance at $0+\nu_y$, a 10% partial Siberian snake would be strong enough. In a recent experiment at the AGS this was successfully demonstrated.

For the AGS, this method has several advantages. First, it works for both strong and weak intrinsic resonances. Currently, there is no effective way to overcome the weak intrinsic resonances in the AGS. Second, if the coupling of a new Siberian snake could be reduced, the strength of coupling resonances could also be reduced. Or, if both horizontal and vertical betatron tunes could be put into the spin tune gap, both intrinsic and coupling resonances could be avoided.

STRONG SNAKE EXPERIMENT

The polarized H^- beam from the optically pumped polarized ion source [16] was accelerated through a radio frequency quadrupole and the 200 MeV LINAC. The beam polarization at 200 MeV was measured with elastic scattering from a carbon fiber target. A fast switching magnet assured the polarization can be measured on subsequent pulses at the end of the LINAC and in the AGS. During the study, the polarization measured by the 200 MeV polarimeter was (66±0.5)%. The beam was then strip-injected and accelerated in the AGS Booster up to 1.5 GeV kinetic energy ($G\gamma = 4.7$). The vertical betatron tune of the AGS Booster was chosen to be 4.9 in order to avoid crossing the intrinsic resonance at $G\gamma = 0 + \nu_y$ in the Booster. The imperfection resonances at $G\gamma$=3, 4 in the Booster were corrected by harmonic orbit correctors.

Only one bunch of the twelve rf buckets in the AGS was filled, and the beam intensity varied between 1.3 -1.7×10^{11} protons per fill. The polarized proton beam was accelerated up to 5.6 GeV kinetic energy ($G\gamma = 12.5$) passing through just one intrinsic resonance located at $G\gamma = 0 + \nu_y$. The resonance crossing rate α was 2.4×10^{-5}. Polarization was measured at $G\gamma = 12.5$ during an approximately one second flattop after the partial Siberian snake was ramped to zero. The spin rotation angle ϕ in the solenoid is given by

$$\phi = e(1+G)\mu_0 NI/cp, \tag{3}$$

where p is the momentum of the proton beam, μ_0 is the permeability of vacuum, and NI is the current in ampere turns. The effective Siberian snake strength s of the partial Siberian snake is $s = \phi/\pi$. The solenoidal partial Siberian snake in the AGS is capable of achieving a 5% Siberian snake strength at 24.2 GeV kinetic energy ($G\gamma = 48$). At $G\gamma = 0 + \nu_y$, the solenoid can in principle generate a 25% partial Siberian snake. However, the solenoidal field will also generate significant coupling, which will cause sizeable depolarization. In addition, such a strong Siberian snake will tilt the stable spin direction away from vertical by 12.5°, reducing the measurable vertical polarization component. For this experiment an 11.4% partial Siberian snake was chosen as a compromise between obtaining a large enough spin tune gap and minimizing the coupling effects. The AGS partial Siberian snake was turned on to 6% before beam injection into the AGS and then ramped up to 11.4% before the first intrinsic resonance crossing at $0 + \nu_y$. The orbit was carefully corrected to maintain beam stability as the vertical betatron tune was moved as high as 8.98. During the experiment, the horizontal betatron tune was kept at 8.54, while the beam polarization was measured as a function of the vertical betatron tune.

RESULTS AND DISCUSSION

The experimental data and simulation results are plotted in Fig.5. The polarization was measured with the AGS internal polarimeter [17]. Measured vertical betatron tunes were

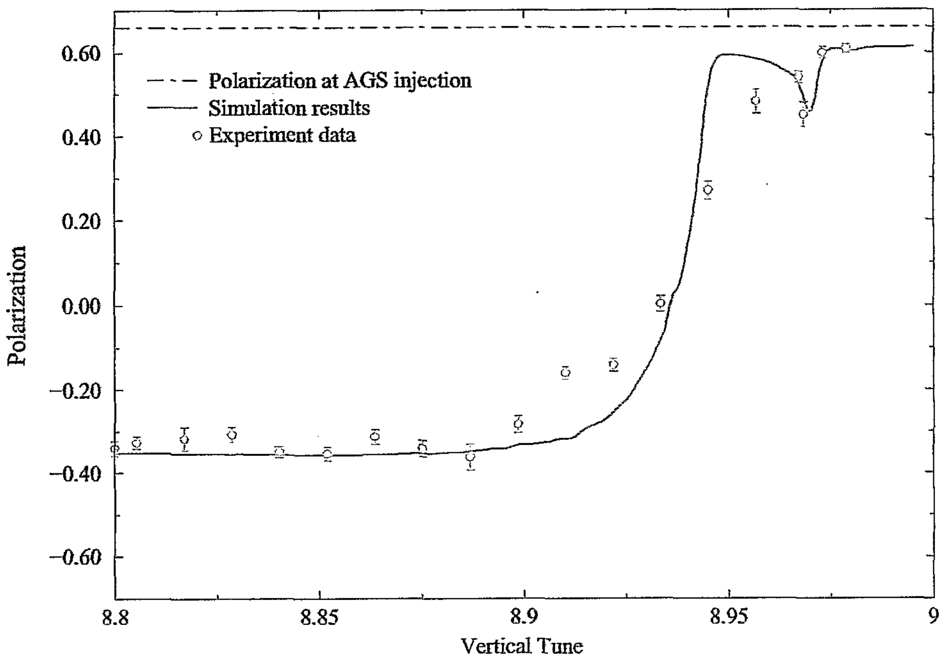

FIGURE 5. The measured vertical polarization as a function of the vertical betatron tune for an 11.4% partial Siberian snake. The dots are measured polarizations, and the error bars represent the statistical errors only. The dashed straight line indicates the polarization level measured at the end of the LINAC. Since the two imperfection resonances in the Booster have been corrected by harmonic orbit correctors, this is also the beam polarization at AGS injection. The solid curve shows the simulation results.

not available in the tune window $\nu_y = 8.90$ to 8.96. A fit of set tunes to measured tunes outside this window was used to derive the vertical betatron tunes from the set values inside this window. To estimate the depolarizing resonance strength, both vertical and horizontal beam emittance were measured using the AGS ionization profile monitor(IPM) except for the data points in the tune window $\nu_y = 8.90$ to 8.96. As can be seen from Fig.5, the measured polarization reached a plateau when the vertical betatron tune was very close to nine. The polarization loss in this region was only about 6% and can be completely explained by spin mismatch at AGS injection and depolarization from coupling resonances as discussed below.

These observations agree well with spin dynamics calculations. With a partial Siberian snake inserted, there are two strong resonances in this energy region: one located at $G\gamma = 9$ generated by the partial Siberian snake and the intrinsic resonance at $G\gamma = 0 + \nu_y$. When the intrinsic and imperfection resonances do not overlap ($\nu_y \leq 8.85$), the resonance at $G\gamma = 9$ should flip the spin completely while the intrinsic resonance at $G\gamma = 0 + \nu_y$ causes some depolarization. When the two resonances are very close, such as for $\nu_y = 8.98$, the intrinsic resonance is overpowered by the resonance at $G\gamma = 9$. The particles essentially just experience one resonance at $G\gamma = 9$, and full spin-flip is observed. When the two resonances are at intermediate separations, such as for $\nu_y \approx 8.90$ to 8.95, the two resonances interfere with each other.

A simulation was performed to better understand the polarization behavior in this experiment. The simulation is a combination of a DEPOL [18] calculation and a tracking model with two overlapping resonances: one located at $G\gamma = 9$ generated by the partial Siberian snake and the intrinsic resonance at $G\gamma = 0 + \nu_y$. The strength of the intrinsic resonance was determined from beam size measurements. A ±0.004 vertical tune spread was included in the simulation.

The strengths of the coupling resonances located at $G\gamma = 17 - \nu_x, 0 + \nu_x, 18 - \nu_x$, and $1 + \nu_x$ were calculated using an extended DEPOL that was modified to include coupling [19]. Since these coupling resonances are well separated from the other two resonances, they can be treated independently. The total polarization loss from the coupling resonances was calculated, using the Froissart-Stora formula, to be 5% out of the total 6% polarization loss shown in Fig. 5. The remaining 1% loss is due to spin mismatch at injection with a 6% partial Siberian snake.

In general, the simulation agrees well with most data points. The remaining discrepancies for data points between $\nu_y = 8.90$ to 8.96 could be due to a different beam size or vertical betatron tune, since there were no beam size and tune measurements performed for these data points.

The simulation shows a polarization dip close to ν_y=8.97, which may also be seen in the experimental data. This is caused by a snake resonance [20] as predicted in Refs. [15] and [21]. Even when the intrinsic resonance condition can not be met for $\nu_y > 8.943$, depolarization can occur from resonance conditions extended over many turns if the intrinsic resonance is very strong. This happens when the following condition is met

$$\Delta\nu_y = \frac{k \pm \nu_{sp}}{n}, \tag{4}$$

where $\Delta\nu_y$ is the fractional part of vertical betatron tune, n and k are integers, and n is called the snake resonance order. With an 11.4% partial Siberian snake, the spin tune is close to 0.057 for $G\gamma \sim 9$. The polarization dip then corresponds to the second order snake resonance ($n = 2$). With the given resonance crossing rate and intrinsic resonance strength, snake resonances higher than second order do not show a significant effect. The existence of this snake resonance reduces the usable betatron tune space where depolarization is avoided.

At the vertical betatron tune of 8.98, the difference between the beam polarization at injection and the polarization measured after $0 + \nu_y$ is due to spin mismatch at injection and depolarization from coupling resonances. If spin matching were achieved at the AGS injection and the linear coupling were eliminated, this scheme could provide full spin-flip through the intrinsic resonance. It would also work for weak intrinsic resonances, such as $G\gamma = 24 \pm \nu_y$, and $48 - \nu_y$. In addition, if the horizontal betatron tune were also in the gap, the coupling resonance could also be avoided.

SNAKE DESIGN ISSUES

Simulation shows that a 20% partial Siberian snake is needed for the strongest intrinsic resonance at $36 + \nu_y$. This is beyond the capability of the existing solenoidal partial

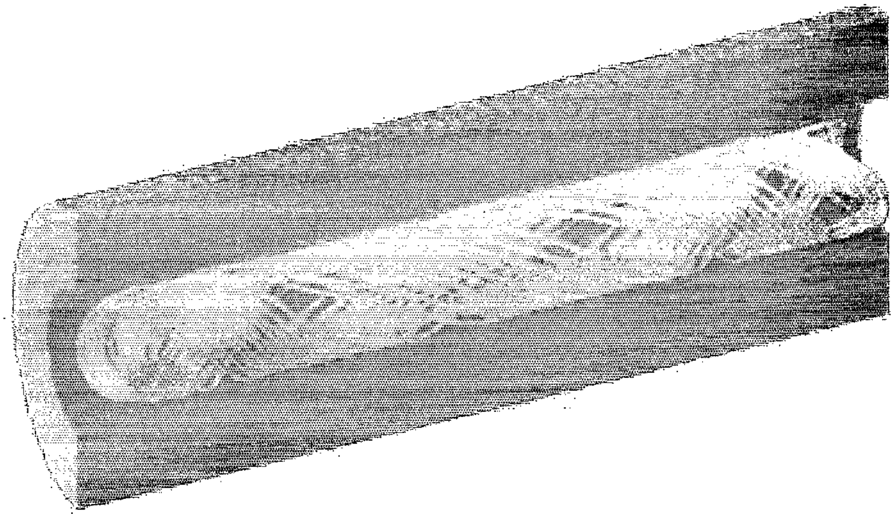

FIGURE 6. The design of superconducting snake magnet. It is 2.6 meters long and the diameter of the beam pipe is 15 cm.

snake. Furthermore, the solenoidal field is the main source of coupling, which causes coupling resonances in the vicinity of strong intrinsic resonances. The better choice would be a helical dipole magnet as has been used in RHIC polarized proton operation. With the constraint of 10-foot AGS straight section, the required field can only be achieved by a super-conducting magnet. With compensating coils, the coupling from the new snake can be greatly reduced. The drawback of a super-conducting magnet is the complicated cryogenic system, which needs special attention to cope with high intensity proton operation in the AGS. For high intensity proton operation, the magnet is power-off but stay cold. The radiation loss heat load at a quiet AGS straight section is estimated from beam loss monitor to be $1 \sim 2$ Watt for high intensity (7×10^{13} protons/spill), which is manageable. For polarized proton operation, the magnet stays power-on and the snake may be the limiting aperture. To prevent catastrophic beam loss in the snake magnet, a collimator upstream will be needed for the polarized proton operation as a protection device.

At injection energy, the maximum orbit excursion inside the helical snake is ± 3 cm in both horizontal and vertical planes. Given 15πmm-mrad normalized emittance at injection, the 15cm diameter beam pipe should be enough. For high intensity proton operation, the snake is off and there is no orbit excursion. No aperture problem exists for the 100πmm-mrad high intensity beam.

The design of a super-conducting helical AGS snake with strength on the order of 20% to replace the current solenoidal AGS partial snake has already begun. A sketch of the design is shown in Fig. 6. With the given field, the snake strength at AGS injection would be about 24%. At injection energy, the tune shifts are of the order of 0.2 units, and the beta functions fluctuate throughout the ring up to values around 100 m instead of the matched maximum of about 22 m. A solution has been found by E. Courant [22] to eliminate the coupling and beta function mismatch caused by the snake.

In addition, such a strong snake in the AGS will tilt the stable spin direction away from vertical significantly. Current design gives 24% partial snake at injection, which will tilt away the stable spin direction (SSD) at the AGS injection from vertical by 21.6°. A straightforward injection gives 7% polarization loss. One possible scheme to match the spin is to raise the injection energy to get $G\gamma$ from 4.7 to 5. Then the SSD is in horizontal plane in both Booster and the AGS. A proper choice of 5th harmonic corrector setting of the Booster can match the SSD in the Booster to the SSD in the AGS. To avoid $0+\nu_y$ intrinsic resonance in the Booster, the Booster vertical tune should be set at 5.1 (currently at 4.7), which is within the capability of Booster tune quadrupoles. Spin matching should also be done at AGS extraction and a scheme has been reported in Ref. [23].

CONCLUSION

In conclusion, we have demonstrated for the first time that an 11.4% partial Siberian snake can effectively overcome an intrinsic depolarizing resonance when the vertical betatron tune is put close to an integer. The critical element of this operation is to maintain beam stability under these conditions. The challenge will be spin matching at AGS injection and extraction, high order field compensation and cryogenic system operation.

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