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Absolute Calibration and Beam Background of the Squid Polarimeter

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ABSTRACT

The problem of beam background in Squid Polarimetry is not without residual benefits. We may deliberately generate beam background by gently kicking the beam at the spin tune frequency. This signal may be used to accomplish a simple and accurate absolute calibration of the polarimeter. We present details of beam background calculations and their application to polarimeter calibration, and suggest a simple proof-of-principle accelerator experiment.

INTRODUCTION

The possibility of a RF-Resonance Polarimeter for fast non-destructive measurement of beam polarization is enhanced by the use of the Superconducting Quantum Interference Device, or squid, which is about five orders of magnitude more sensitive than any other magnetic field measuring transducer. The method makes use of the fact that, in synchrotrons with polarized beams, it is possible to introduce a component of the polarization of a given bunch perpendicular to the stable spin direction, for instance by perturbing the beam with a fast kicker magnet. By using snakes, or in a machine without snakes by adjusting the machine energy, the spin tune can be set to a fractional value, typically 1/2, so that the direction of this component alternates at a frequency which is a subharmonic of the rotation frequency. This results in the presence of lines in the beam spectrum which are due only to the magnetic moment of the beam, and which are well removed from the various lines, primarily the revolution and betatron lines and their synchrotron satellites, due to the charge of the beam.

The magnitude of the polarization lines can be calculated from first principles. They are many orders of magnitude weaker than the Schottky signals. Absolute calibration of their magnitude can be accomplished in a simple and straightforward manner, by gently kicking the beam at the spin tune with a known kick. Measurement of the intensity of any one of these lines would then yield an absolute measurement of beam polarization. Using a squid, along with the proper combination of shielding, pickup loop design, and narrow band filtering, we believe it is possible to successfully make such a polarization measurement. The resulting instrument would be fast, capable of making an absolute polarization measurement to the few percent level in less than a second, and comparatively inexpensive.

Details of the method have been presented in previous papers [1-4]. Recent effort has been concentrated upon design of the pickup loop and filter, and upon the calibration technique. Major progress has been realized in both areas, and the balance of this paper will be devoted to discussion of this progress.

THE PICKUP LOOP

As a practical consideration, narrow-band filtering of the pickup output is necessary so that the squid flux-locked loop sees only the polarization signal. In fact, it is advantageous to combine the pickup loop and filter into a single integrated device. The quality factor of the pickup loop and filter are then the same. Because the pickup loop is then resonant, its shunt impedance is increased by the quality factor, as is the power of the signal generated in the loop by the beam at the resonant frequency. With a superconducting filter, the quality factor is limited by the line width of the polarization signal. With a revolution frequency of 78 KHz in RHIC, and assuming that the spin is maintained in coherent free precession for about 2000 turns, the line width is about 40 Hz. If the filter frequency is about 1 MHz, then a 3 dB filter bandwidth of 100 Hz would seem reasonable to permit encompassing the polarization line, and would result in a Q of 10,000.

Let us define the beam direction along the z axis and the stable spin direction along the y axis. With a loop length $L = 1m$ long in the z direction and a loop half height $y = 10\sigma_y$, where σ_y is the vertical beam size at injection, then the amount of flux per turn due to magnetic moment which might be captured by the loop if all the polarization were kicked into the x direction can be found by integrating the vector potential over the perimeter.[5]

$$\Phi_{signal} = \frac{G}{G+1}\frac{\mu_0}{4\pi}\frac{\mu_p n_p n_b n_f PQLy\gamma}{C}\int_{\frac{-L}{2}}^{\frac{L}{2}}\frac{2}{(x^2+y^2+\gamma^2 z^2)^{\frac{3}{2}}}dz$$

Performing the integration, for $x = 0$ we have

$$\Phi_{signal} = \frac{G}{G+1}\frac{\mu_0}{4\pi}\frac{\mu_p n_p n_b n_f PQL^2\gamma}{yC}\frac{2}{\sqrt{y^2+\frac{\gamma^2 L^2}{4}}}$$

which, for large γ, can be approximated by

$$\Phi_{signal} \approx \frac{G}{G+1}\frac{\mu_0}{4\pi}\frac{4\mu_p n_p n_b n_f PQL}{yC}$$

For $n_p = 2 \times 10^{11}$, $n_b = 120$, $P = 0.7$, $\sigma_y = 1mm$, a RHIC circumference of $C = 3834m$, the flux quantum $\Phi_0 = 2 \times 10^{15} Tm^2$, a Q of 10^4, $n_f = 2$ (due to the appearance in the frequency domain of both negative and positive frequencies), and the anomalous portion [6] of the gyromagnetic ratio of the proton $G = 1.793$, the flux captured by the pickup loop per turn is about $\Phi_{signal} = 0.015\Phi_0$. Typical squid flux noise levels are between 10^{-5} and $10^{-6}\frac{\Phi_0}{Hz^{\frac{1}{2}}}$, so that with a filter bandwidth of 100 Hz the signal would be about 40 dB above the intrinsic noise floor of the squid.

BACKGROUND DUE TO PICKUP OFFSET

Alignment of the pickup loop relative to the beam may be accomplished by beam steering, by moving the loop, or by a combination of the two. The flux captured by the loop as the result of a small vertical misalignment δ is

$$\Phi_{background} = \frac{\mu_0}{4\pi}\frac{n_p n_b n_f \gamma v q}{C}\int_{\frac{-L}{2}}^{\frac{L}{2}}\int_{10\sigma_y-\delta}^{10\sigma_y+\delta}\frac{1}{(x^2+y^2+\gamma^2 z^2)^{\frac{1}{2}}}dydz$$

where q is the charge and v the velocity of the proton. For a displacement δ=10 microns, this background is about 125 dB, or slightly more than 6 orders of magnitude, greater than the polarization signal. However, the former will appear at integer multiples of the revolution frequency, whereas the latter (due to the spin tune of $\frac{1}{2}$) will appear at half-integer multiples. They are distinguishable in the frequency domain.

BACKGROUND DUE TO COHERENT MOTION AND SCHOTTKY NOISE

The deflection of the beam due to the kick which moves the spin away from the stable spin direction is about 50 microns. Because the betatron and spin tunes need not be harmonically related, it is possible to simultaneously kick the beam to flip the spin and damp the coherent motion due to the spin-flip kicks. Despite this, during spin-flip kicking coherent motion resulting in a background signal of large magnitude will appear at the spin-tune frequency. Like the polarization signal, this signal will be enhanced by the Q of the pickup loop. It is desireable to place the pickup loop at a multiple of 180 degrees of betatron phase away from the kicker to minimize these displacements, as to first order the pickup loop is not sensitive to the angle at which the beam passes. In addition, it will be necessary to shunt the pickup loop during spin-flip kicking. After coherent free precession is established, the coherent betatron motion of the beam can be reduced to a few microns or less through a combination of damping and decoherence. For a coherent betatron amplitude of 1 micron, the signal is about 105 dB, or slightly more than 5 orders of magnitude, down from this background, which will appear at the betatron harmonics.

Another source of background is Schottky noise within the beam. The signal is about 45 dB, or slightly more than 2 orders of magnitude, down from the Schottky noise, and to first order this is independent of beam position. This background will appear as satellites of the revolution lines and the betatron lines, separated by the synchrotron frequency.

THE FILTER

The polarization signal shows up as AM sidebands of revolution harmonics. As previously mentioned, the minimum filter bandwidth is about 100 Hz. Raising the passband frequency for a given bandwidth raises the Q, and hence the shunt impedance and both the absolute magnitude of the signal at the filter output, and the magnitude relative to the beam background. It is desirable to look at the highest frequency sideband possible to maximize signal-to-background ratio.The maximum practical frequency is limited by squid flux-locked loop bandwidth, and also by practical component sizes in the filter. The bandwidth of flux locked loops is typically a few hundred KHz, although recent development has raised the upper limit to about 5 MHz, and further extension to 20 MHz is predicted.[7] It is also possible to lock the loop at a lower bandwidth, and pick off the amplified high frequency signal at the squid output. The more serious limitation is component size in the filter, specifically the minimum practical inductor size. Parasitic lead inductance of the interconnect wiring and filter capacitors will limit the maximum passband frequency. A conservative estimate is that a passband frequency of 1 MHz is feasible.

Suppose that we look at the AM sideband which is 39 KHz away from the 1.014 MHz revolution harmonic. If we build a third order Butterworth superconducting bandpass filter with a Q of 10^4 and a center frequency of 1.014 MHz, the 3 dB passband will be about 100 Hz wide. With an ideal third order Butterworth filter the background at the betatron lines 25 KHz away would be attenuated by about 145 dB, and the background at the revolution harmonics 39 KHz away would be attenuated by about 155 dB, so that at the filter output the signal would be about 30 to 40 dB above the background due to the beam current.[8] In addition, the background will remain separated from the polarization signal in the frequency domain, so it can be removed by additional digital filtering of the squid output. Such a filter would have a characteristic time of about 10 msec, corresponding to about 800 revolutions in RHIC. During this time the envelope of the output of the filter would rise as $e^{-\frac{t}{10ms}}$, so that ideally after 800 revolutions the flux applied to the squid would be about 0.63 of the flux at the filter input from a single revolution. In reality the flux reaching the squid will be less than that, both because of mismatch between the pickup loop inductance and the small squid inductance, and because of flux lost to inductance in intermediate stages of the filter. A reasonable estimate [9] is that about one tenth of the flux applied to the pickup loop will arrive at the squid, so that the signal would be about 20 dB above the intrinsic noise floor of the squid.

In practical filter construction, there exist inevitable holes in the tails of the filter response due to resonances resulting from parasitic inductance and capacitance. High frequency bleeding through the filter will be a problem. We are now building filter/pickup loop prototypes to measure the higher frequency resonances. These resonances must eventually be removed by limiting and adjusting the parasitic capacitances and inductances, by adding material which is lossy at high frequencies, and by additional lowpass/stopband filtering. While the final filter must be superconducting to achieve the desired quality factor and shunt impedance, the change from warm to superconducting will primarily affect only the width of the passband and resonances, and other details of the filter can be worked out with warm prototypes.

ABSOLUTE CALIBRATION AND PROOF-OF-PRINCIPLE

In the section on Background Due to Coherent Motion, it was pointed out that the spin-flip kick generates a signal at the spin tune frequency. A very gentle kick at this frequency can be used to calibrate the polarimeter. This signal will be enhanced by the Q, so that for a vertical displacement of one nanometer at the resonant frequency, the signal at the pickup loop will be about one flux quantum. Locating the calibration kicker and pickup loop at opposite ends of a warm straight section in RHIC, without intervening magnetic elements, eliminates any dependence on uncertainties in the local lattice functions. At full RHIC energy, a 10 cm long stripline kicker would require about 5 volts of excitation to accomplish this kick. Because this calibration signal is at the pickup loop, and at the spin tune frequency, uncertainties in the response of the rest of the polarimeter are removed. The magnitude of a small low-frequency kick can be controlled to the one percent level without undue effort, and somewhat beyond that with greater effort. Therefore, it does not seem unreasonable to think of absolute calibration approaching the one percent level.

This raises the possibility of a simple proof-of principle experiment, perhaps at an accelerator like the Brookhaven AGS. The experiment would use an unpolarized beam detected by a short version of the pickup loop, perhaps 10 cm long. An acceptable Q might be obtained with a warm copper pickup loop, with the balance of the filter superconducting. The vertical correction dipoles could be used to minimize background due to beam displacement. Using a very small kick at the spin tune to simulate the presence of beam polarization, the opportunity would exist to demonstrate the capability of separating the signal from the background, and measuring its magnitude.

CONCLUSION

There is a good possibility that the technique described here could be used to accomplish fast and accurate absolute polarization measurement at RHIC. There is precedent for using squids in the magnetically noisy accelerator environment.[10] However, the beam spectrum has never been explored at this level of sensitivity, and there is concern that unexpected noise or signals might exist. Because of the large dynamic range of the squid, the narrow filter bandwidth, and the possibility of background subtraction, a good measurement can be accomplished in the presence of significant noise and background. A next step would be to build and install a prototype at a working accelerator.

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