An RF Resonance Polarimeter Phase 1 Proof-of-Principle Experiment

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Abstract

In this note we present a proof-of-principle experiment for an RF Resonance Polarimeter in the electron storage synchrotron at MIT-Bates. We give a brief description of the polarimeter, along with expressions for the expected signal-to-noise and signal-to-background ratios. The primary source of noise is thermal. Under the most favorable circumstances, for room temperature detector and electronics we expect the polarization signal to be about 50dB above the noise. The primary source of background is the beam current spectrum. The magnitude of this background is dependent on the relative position and orientation of the detector and beam. Under the most favorable circumstances, it may be possible to measure the polarization signal in the direct presence of this background. Otherwise, the polarization signal may be shifted in the frequency domain relative to the beam background by moving the polarization away from the stable spin direction to establish coherent free precession. Procedures of absolute calibration are also presented. In addition to providing a feasibility test, this experiment should provide an answer to the theoretically unresolved problem of the relativistic transformation properties of the magnetic dipole moment. Given a favorable outcome of this resolution the resulting polarimeter, which would look like beam instrumentation rather than a scattering experiment, would be less expensive, more accurate, faster, and applicable over a broader range of energies and particle species than existing polarimeters.

1 Introduction

Despite recent proposals[1,2] to enhance the performance of the RF Resonance Polarimeter[3], there remain compelling reasons to proceed with the implementation of the most basic version of the polarimeter. Perhaps the most important motivation is to resolve uncertainties regarding the relativistic transformation properties of the magnetic dipole moment[4]. This resolution will have a major effect on the future course of RF Polarimetry. A second impetus is to provide improved and cost-effective polarimetry at existing accelerators, which might be accomplished by the unenhanced RF Polarimeter in a few special circumstances. Finally, the success of future enhanced polarimeters must rest upon a foundation of experience with the basic device.

The storage ring at MIT-Bates provides an excellent environment for a Phase 1 Proof-of-Principle Experiment, which would employ the most basic version of the RF Polarimeter to determine the relativistic transformation properties of the magnetic dipole moment, and perhaps provide a useful working polarimeter. This could lead directly to a Phase 2 Experiment, which might permit the incorporation of some or all of the proposed enhancements. In addition, by reciprocity[5] the Stern-Gerlach spin splitter[6] is the kicker version of the RF Polarimeter pickup, so that these experiments might lead into further exploration of Stern-Gerlach splitting.

The particular suitability of the MIT-Bates ring[7] derives from the combination of several factors. The RF Resonance technique, which requires a periodic beam, benefits from the precise periodicity and stability to be found in a storage ring. The beam current is reasonably high (40 to 80 ma), as is the polarization (about 40 percent now, and twice that when a strained crystal source becomes available). The energy range (0.1 to 1 GeV) makes possible exploration of a significant span of the relativistic gamma factor (from $\gamma = 200$ to 2000). Unlike other polarized electron synchrotrons, where the polarization grows from a spin-dependent asymmetry in the synchrotron radiation cross section[8] and therefore results in vertical polarization, the beam is injected into the Bates storage ring with longitudinal polarization. With the presence of a single Siberian snake[9] the stable spin direction is in the horizontal plane, so that either longitudinal or transverse polarization can be achieved by the proper selection of energy and location in the lattice. With the snake off, the stable spin direction is the usual vertical direction, so that injection of a beam having longitudinal polarization results in coherent free precession of the polarization about the stable spin direction, without the need for kicking the beam to move the polarization away from the stable spin direction. For instance, if the fractional spin tune is 1/2, then the polarization direction at a given location in the ring will alternate from turn to turn. This will place the polarization lines in the frequency domain midway between the revolution harmonics, at a location in the beam spectrum where there is no background due to the beam current. And finally, a fast, accurate, and economical polarimeter might be useful to the Nuclear Physics experimental program at MIT-Bates.

2 Relativistic Transformation of the Dipole Moment

In the pursuit of RF polarimetry, an unexpected question with a long and interesting history[4] has come to our attention. This question regards the relativistic transformation properties of the longitudinal magnetic moment. The longitudinal moment is useful for the RF polarimeter for two reasons. First, it permits TE cavity modes to couple to the beam magnetic moment. TE modes are desirable, as they have no longitudinal electric field, and therefore have neither longitudinal nor, by the Panofsky-Wenzel theorem[10], transverse coupling to the beam charge. Second, if the longitudinal moment transforms as γ, the magnitude of the polarization signal is increased by many orders of magnitude in ultra-relativistic accelerators. The question is simply this: Does the moment transform as γ or $1/\gamma$?

The commonly accepted answer, as given for example by Hagedorn[11] and Jackson[12] and used by Conte[6], is that the moment transforms as γ. This approach derives the transformation property by defining a spin four-vector in the particle rest frame, and then applying the usual Lorentz tranformation to the four-vector.

Alternatively, application of quasi-classical Hamiltonian methods[1,3] to the experimentally proven BMT equation[13] gives the result that the longitudinal moment transforms as $1/\gamma$, and further that for transverse polarization the anomalous portion of the moment has no γ dependence, whereas the Bohr magneton portion goes as $1/\gamma$. This has particular significance at electron machines, where the anomalous moment is only a small part of the total moment. The Hamiltonian is a sum of the conventional spinless Hamiltonian and a spin term defined to reproduce the Thomas-BMT equations for spin. It coincides with the Hamiltonian that can be derived from the Dirac equation for a particle with an anomalous magnetic moment, when splitting the Dirac equation into two branches with positive and negative energies according to Foldi-Wouthuysen[14]. This approach has been used earlier[15] to reproduce the Sokolov-Ternov polarization effect.

Discussion has been ongoing but inconclusive regarding the root cause of the contradiction between these two approaches. Since the review by Heinemann[4] various aspects of the problem have received further treatment[14,16,17,18] in the literature, and informal discussions have ranged considerably beyond that which has been published. It remains that, to the best knowledge of the authors of this paper, a clear and unambiguous resolution has not yet been achieved. The resolution is of utmost importance for RF polarimetry and for longitudinal Stern-Gerlach splitting, and may have significant impact beyond accelerator spin physics. In view of the complexity of the question and the straightforward nature of the proposed experiment, the obvious solution is simply to make the measurement. The assumption that the moment varies as γ is used in the formulas in this paper.

3 The Basic RF Polarimeter

In its most simple form, the RF Polarimeter consists of a passive resonant cavity which extracts and accumulates spin-dependent energy from the beam via the Stern-Gerlach interaction between the beam and field in the cavity. The field in the cavity is that which was left by the beam in previous transits. The cavity is designed to interact maximally with the dipole and minimally with the charge by careful selection of the cavity mode. Figure 1 shows a side view of a rectangular cavity excited in the TE201 mode. In the top panel of the figure, a longitudinally polarized bunch is shown entering the left end of the cavity. The cavity phase is such that at that instant the stored energy resides in the magnetic field, which is longitudinal and has its maximum value on the beam axis. As the polarized bunch passes through the gradient region it experiences a retarding Stern-Gerlach force, and leaves energy in the cavity. In the middle panel, the bunch has reached the middle of the cavity. At that time the stored energy is in the electric field, which is transverse and has its minimum value on the beam axis. As mentioned above, a charged beam will interact only with a pickup mode that has longitudinal electric field. Interaction of the beam current with the cavity is minimized to first order by the absence of longitudinal electric field throughout the cavity, and to second order by the absence of even transverse field on the beam axis. In the bottom panel the magnetic field in the cavity is again at its maximum value, but now with the opposite sign, so that the bunch is again retarded while traversing the gradient region, and again leaves energy in the cavity. The stored energy in the cavity increases until equilibrium is attained, where the power supplied by the beam equals the power dissipated as a result of the finite cavity Q. We can write this as

$$Q \equiv \frac{stored\ energy}{loss} = \frac{\omega U}{\frac{dU}{dt}} \tag{1}$$

where $\omega = 2\pi f$, $f = 2.856$ GHz is the bunching frequency, and U is the stored energy. The rate at which polarization leaves energy in the cavity, or the signal power, is

$$\frac{dU}{dt} = 2\mu B \tau_\mu b_\mu n f \gamma P \tag{2}$$

where the factor of 2 results from energy being left by the bunch both upon entering and exiting the cavity, μ is the magnetic dipole moment of the electron, B is the field in the cavity at equilibrium, $\tau_\mu \approx 0.7$ is the transit time factor[5], $b_\mu \approx 0.7$ is a bunch length factor resulting from the head and tail of the bunch being out of phase with the field in the cavity, $n = 10^8$ is the number of electrons per bunch for all buckets filled and 50 ma beam current, $\gamma = 2000$ is the relativistic gamma factor at 1 GeV, and

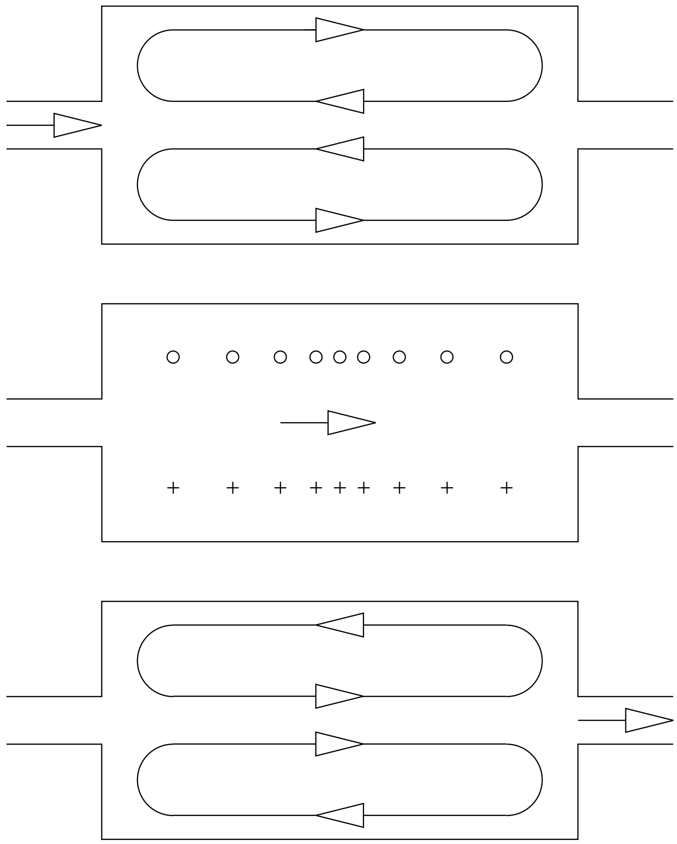

Figure 1: Stern-Gerlach Pickup

$P \approx 0.4$ is the beam polarization. Rearranging equation (1), we can write

$$U = \frac{Q}{\omega}\frac{dU}{dt} = \frac{\epsilon_0}{4}(Bc)^2 V \tag{3}$$

Substituting (2) into (3) and solving for the equilibrium field B,

$$B = \frac{4Q\mu\tau_\mu b_\mu n\gamma P}{\pi\epsilon_0 c^2 V} \approx 4 \cdot 10^{-12} Tesla$$

where $Q = 10^4$, ϵ_0 is the permittivity of free space, c is the speed of light, and $V \approx 1000cm^3$ is the cavity volume. The equivalent electric field $E = Bc$ is then about 1 millivolt per meter. Substituting the value found for the equilibrium field into (2), the signal power is

$$\frac{dU}{dt} = \frac{2fQ(2\mu\tau_\mu b_\mu n\gamma P)^2}{\pi\epsilon_0 V c^2} \approx 10^{-14} watt \tag{4}$$

or about -110 dBm. In the world of small signal instrumentation, this is a good strong[19] signal. If it cannot be observed, the implication would be that the moment transforms as $\frac{1}{\gamma}$. Measurement at $\gamma = 200$ would then give, because of the resulting $\frac{1}{\gamma^2}$ power dependence, a signal power of about -220 dBm. It is interesting to note that the power varies as f^4, because of the $\frac{1}{f^3}$ dependence in the cavity volume, so that there might be some advantage to operating the cavity at higher frequencies, and accepting the penalty in the bunch length factor.

4 Thermal Noise and Beam Background

The thermal noise power is $p_{noise} = kTW$, where k is Boltzmann's constant, T is the temperature in Kelvins, $kT = -170\frac{dBm}{Hz}$ is the noise power density at room temperature, and W is the bandwidth. With good technique the reasonable maximum sensitivity for spectrum analyzer measurements is in the range of $-160\frac{dBm}{Hz}$. Spin tune spread affects the amplitude of the spin line, but not the arrival time of the particle at the detector, so the spin line will be extremely narrow, on the order of a few Hz or less. For fast measurements, the minimum measurement bandwidth will be set by the measurement time. With a signal of -110 dBm in a 1 Hz bandwidth and a noise background of $-160\frac{dBm}{Hz}$ at a frequency of $f = 2.856$ GHz, the signal will emerge above the noise in a measurement time of about $40\mu sec$. In the world of polarimeters, this is very fast. It is not yet a turn-by-turn measurement, but it's getting close.

If μ goes as $\frac{1}{\gamma}$ the situation is much more difficult, and significant further effort (for instance, using a superconducting cavity to increase Q and the power level by perhaps 40dB and reduce thermal noise by perhaps 20dB) would be required to accomplish a marginal quality measurement whose main value might be to confirm what would be, from the view of RF polarimetry and Stern-Gerlach splitting, an unfortunate resolution of the question of the relativistic transformation properties of the dipole.

The beam background can be found by a method similar to that followed above to find the signal power. The rate at which the beam current leaves energy in the TE201 mode, or the beam background power, can be found by writing the charge equivalent of equation (2)

$$\frac{dU}{dt} = qE\tau_q b_q n f l \sin\theta \sin\phi \tag{5}$$

where q is the fundamental charge, $\tau_q \approx 0.7$ is the transit time factor for charge in the cavity (which may differ from τ_μ because the magnetic dipole interacts with the gradient of the magnetic field at the ends of the cavity, whereas the electric monopole interacts with the electric field in the center of the cavity), $b_q \approx 0.7$ is the bunch length factor for charge (which similarly may differ from b_μ), and E is the field in the cavity at equilibrium. As previously mentioned, since TE modes have no longitudinal electric field, the beam charge can leave energy in the TE201 mode only if the beam axis is not perfectly aligned with the longitudinal magnetic field. We take θ as the angular misalignment of the beam, and l as the cavity length, so that $l\sin\theta$ is the length of electric field traversed by the beam. Similarly, since the transverse electric field of this mode vanishes for $x = 0$, the beam charge can leave energy in the cavity only if the beam is offset from the center of the cavity. We take

$$\phi = 2\pi\frac{x}{a}$$

where x is the beam offset and a is the cavity dimension in the direction of offset. The equilibrium beam background field can then be written as

$$E = \frac{2Qq\tau_q b_q n l \sin\theta \sin\phi}{\epsilon_0 \pi V}$$

Substituting this value for the equilibrium field into (5), the beam background power is given by the charge equivalent of equation (4),

$$\frac{dU}{dt} = \frac{2fQ(q\tau_q b_q n l \sin\theta \sin\phi)^2}{\pi\epsilon_0 V}$$

Figure 2 shows signal and background power levels as a function of beam offset for a 1 GeV electron beam with polarization $P \approx 0.4$, under the assumption that μ transforms as γ. Background power levels are shown for angular misalignments of 10^{-5} and 10^{-6} radians. The figure suggests that it might be possible to measure polarization *at the revolution harmonic*, without displacing the frequency of the polarization

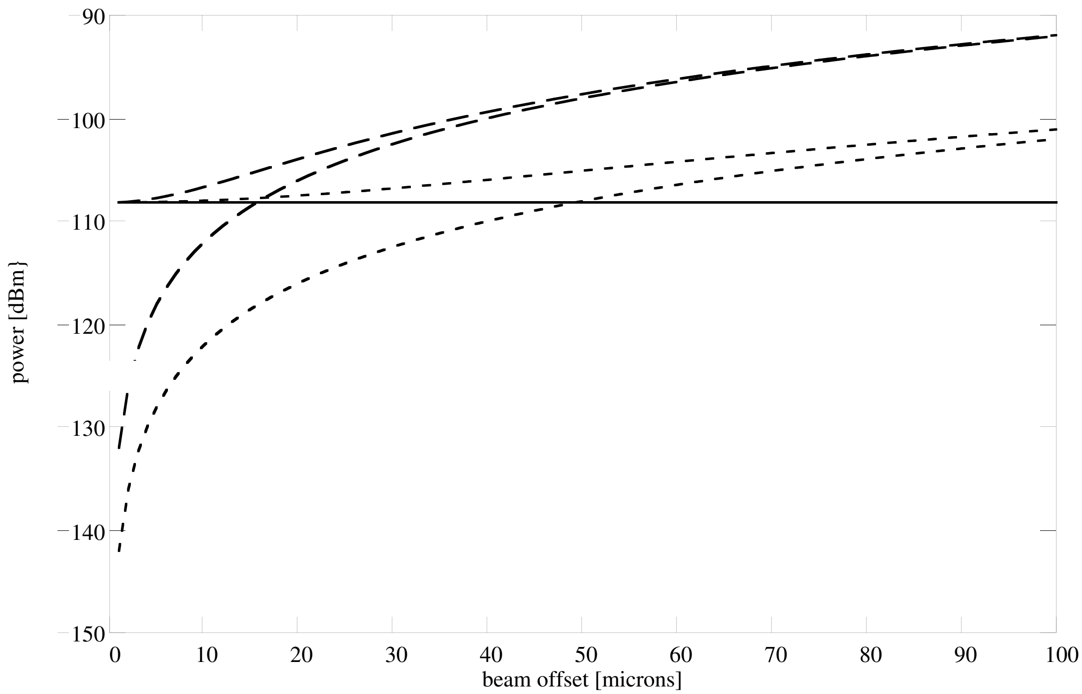

Figure 2: Signal and Background Power Levels for a 1 GeV electron beam with polarization $P \approx 0.4$, under the assumption that μ transforms as γ (see text). The solid line shows the signal power level. The dotted lines show the beam background and signal plus background for $\theta = 10^{-6}$radians, and the dashed lines show the same quantities for $\theta = 10^{-5}$radians.

signal away from that of the beam background by moving the spin away from the stable spin direction. The result would essentially be a completely non-perturbative polarization measurement. Beam position stability of better than 50 microns on a time scale of milliseconds to seconds will be required if the angular stability is around 1 micro-radian. A perspective[20] on the required stability might be gained by defining an equivalent emittance for the allowable orbit error

$$\epsilon_{equiv} = 6\pi\beta\gamma x\theta = 6\pi \cdot 2000 \cdot 5 \cdot 10^{-5} \cdot 10^{-6} = 0.6\pi \; mm \; mrad$$

This is to be compared with the 0.1π mm mrad typical beam emittance at MIT-Bates, which suggests that beam stability on reasonably long time scales might not be a problem. However, if this level of stability is not possible, it remains that the polarization measurement can be accomplished by establishing coherent free precession to move the signal to a clean part of the beam spectrum.

In addition to beam stability on a time scale of milliseconds to seconds, there are at least three additional possible sources of beam background that should be considered; transverse coherent motion, coherent beam size effects, and Schottky signals. Transverse coherent motion whose amplitude is much larger than the 50 microns mentioned above can be tolerated during polarization measurement, as it will show up in the frequency domain not at the spin tune, but rather at the betatron tune. To first order beam size effects on background power levels are neglegible, particularly if the beam is centered, as the gradient of the electric field is symmetrical about the cavity center and very nearly linear over the transverse dimension of the beam. It can be shown that the Schottky signal is tens of dB below the background calculated above.

Finally, in addition to the beam charge effects at the polarization signal frequency of the TE201 mode, minimization of the interaction of the beam with other cavity modes[21] must be given careful attention. The primary concern is excitation of coupled bunch instabilities. This will be discussed in detail in a forthcoming note.

5 Absolute Calibration

The problem of beam background is not without residual benefits. The beam charge and the beam magnetic moment are tied to the same elementary particle, and their ratio is known quite well. The beam charge can be used to calibrate the polarimeter, offering the possibility of eliminating errors due to beam intensity, bunch length, and frequency-dependent effects. Many calibration scenarios are possible. We present two here, one for the case in which the beam is stable enough to permit polarization measurement at the revolution harmonic, and a second for when polarization is measured during coherent free precession. In the first case, we move the cavity relative to the beam, and the time scale of the movement is on the order of a second. In the second case, we move the beam relative to the cavity, and the time scale is on the order of twice the revolution period.

To accomplish absolute calibration while measuring at the revolution harmonic (ie with the spin in the stable spin direction) we might take a series of measurements while scanning θ and x. The dependence of the beam background on position and angle is known, so that the polarization can be unfolded from the beam background, and polarization calculated from line shape analysis. This method could be occasionally checked (fiducialized?) by setting θ and x to minimize the cavity output, and then depolarizing the beam, say by turning off the snake. After observing the depolarization, another set of measurements would be taken while again scanning θ and x. The difference of the measured minimums would be the polarization signal power. Knowing the values of θ_{eq} and x_{eq} for which the measured unpolarized power is equal to the signal power, we can set equations (5) = (2), and solve for the polarization.

$$P = \frac{qc}{2\pi\mu\gamma}\frac{\tau_q b_q}{\tau_\mu b_\mu} l \tan\theta_{eq} \tan\phi_{eq}$$

With the exception of the transit time and bunch length factors, all of the factors on the right hand side of this equation are either fundamental constants or quantities which can be measured with good accuracy. The effects of transit time and bunch length factor can be dealt with both through measurements and simulations; a detailed description of the techniques will be presented in forthcoming notes.

If the measurement technique is to measure during coherent free precession, then the signal will appear offset from the revolution harmonic by the fractional spin tune. To perform an absolute calibration will require that the calibration signal also appear at that frequency. This can be accomplished by gently kicking the beam[22], say at half the revolution frequency if the fractional spin tune is $\frac{1}{2}$, generating beam current lines at a location in the beam spectrum where beam current background is normally absent. The magnitude of a small kick can be accurately controlled without undue effort, and the power delivered to the cavity as a result of the kick is easily and accurately calculated from first principles. Measuring this deliberately generated line while scanning θ and x would provide a simple and accurate calibration, which might also be useful to provide a cross check to the previously mentioned calibration technique. It should be pointed out that in either method the beam which is used to calibrate the polarimeter is the same beam which provides the polarization signal, the magnitude of the two signals being related by geometric factors and fundamental physical constants, so that intensity and frequency dependent effects are automatically compensated and will not reduce the accuracy of the calibration.

6 Conclusion

This experiment is clearly a win-win situation. Which win we end up with depends on how the magnetic moment transforms. If μ goes as γ, the experiment should result in a useful working polarimeter for the Nuclear Physics program at MIT-Bates, provide the instrumentation needed to open the door to an unprecedented series of spin accelerator physics experiments, and serve as the foundation for the development of the enhanced versions of the RF Polarimeter. If the less-expected result follows and μ goes as $\frac{1}{\gamma}$, the theoretical situation will become more intense, and we will all think and learn more about spin physics. Either way, the potential benefit is large, the experiment is reasonably simple and straightforward, and the cost is small, suggesting that the effort should proceed in the quickest manner reasonably possible.

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