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Beam optics for electron scattering parity-violation experiments

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Abstract. Parity-violating electron scattering experiments at intermediate energies measure asymmetries in the $10^{-6} - 10^{-5}$ range and therefore require stringent control of false asymmetries. One of the primary sources of such asymmetries is the combined effect of helicity-correlated changes in a certain beam property, accompanied by a change in the detector response. Careful control of the beam, including the optical properties of the acceleration and transport system, is required in order to reduce these false asymmetries to a manageable level. Developments in beam optics associated with the HAPPEX and G0 experiments at Jefferson Lab are presented.

PACS. 29.27.Hj Polarized beams – 13.60.-r Photon and charged-lepton interactions with hadrons – 25.30.-c Elastic electron scattering

1 Introduction

Parity-violating electron scattering experiments measure the interference between the electromagnetic and neutral weak interactions with the target. As such, the experimental asymmetries are of order 10^{-5} with nucleon/nuclear targets at intermediate energies. The counting rates required to accumulate 10^{12} or more events are achieved with the combination of high intensity beams, thick targets and detectors with large solid angle acceptance as discussed extensively at this conference. Control of false asymmetries is achieved by careful control of the beam, starting on the laser Table [1] and extending throughout the accelerator to the target.

The most important aspect of beam control is maintaining a constant current independent of the beam helicity. This is achieved by measuring the electron beam current for each helicity state and feeding the resulting error signal back to control the laser intensity. Such systems have become fairly standard. The emphasis here is instead on the control of helicity-correlated position and angle differences to which the present and future experiments have a significant sensitivity. To set the scale, suppose the response of the detector yield (Y) to a change in beam position x is $(1/Y)(dY/dx) = 0.1\%/\text{mm}$. In order for the asymmetry induced by such a sensitivity to be $A_f \leq 10^{-7}$, the helicity-correlated beam motion must be $\Delta x \leq 10^{-4}$ mm, or 100 nm. Control of beam position and angle at these scales is non-trivial. Helicity-correlated motion of the polarized laser beam in the electron source (used to produce electrons by the photoelectric effect) can easily be 1000 nm without careful attention.

Two different approaches were used by the G0 and HAPPEX experiments to reduce the helicity-correlated beam position and angle differences. In the G0 experiment, the position of the laser beam on the cathode was actively controlled to reduce beam position differences at the target with an automatic feedback system. To date, the HAPPEX experiment has essentially relied on careful setup of the optical polarization and transport system for the laser beam, together with "damping" of the position differences inherent in the acceleration of the beam. They have also recently introduced careful control of the optics near the target ("phase trombone"). The status of both techniques is discussed below.

2 General beam optics

Beams which are launched off the axis ("central orbit") of an optical system will oscillate about the axis with a motion known as betatron oscillation. The formalism of linear beam optics can be used to determine the transverse motion of beam particles in the vicinity of the nominal beam trajectory. The particle orbit is described by the quantities $[x, x', y, y']$ which are a function of the distance s along the central orbit. Here, x and y are the transverse displacements from the central orbit, while $x' \equiv dx/ds$ and $y' \equiv dy/ds$ are the inclination angles of the particle orbit relative to the central orbit. Under the assumptions of linear beam optics (small inclination angles and only constant or linearly increasing magnetic restoring forces) the solution of the equations of motion for the transverse

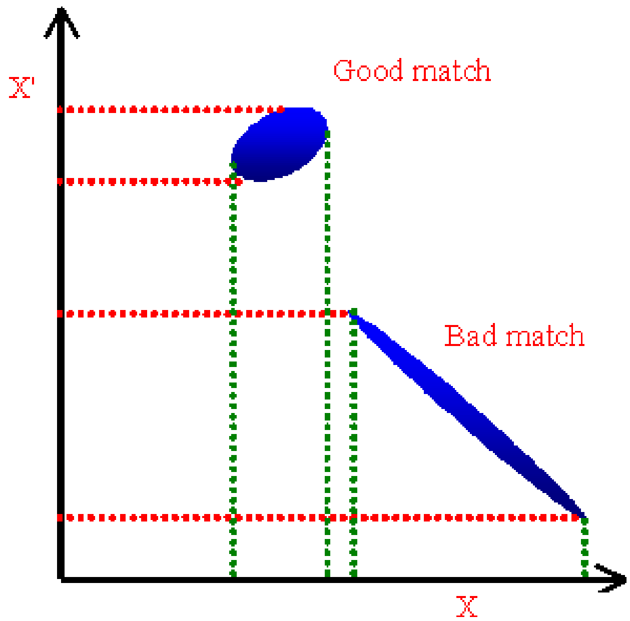

Fig. 1. A schematic illustration of the phase-space ellipses at the end of a well-matched and poorly-matched optical transport system. In the case of the badly matched system, the phase-space ellipse area is preserved, but the ellipse is distorted leading to a larger betatron amplitude than expected from the adiabatic damping factor

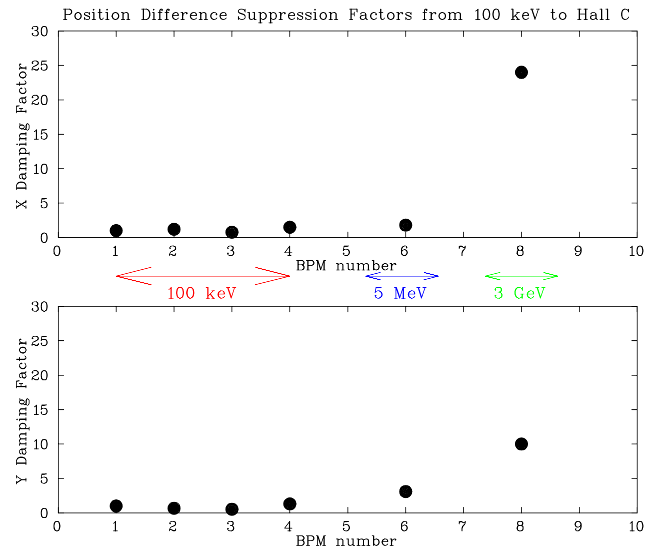

Fig. 2. Measured damping factors in the G0 experiment. The arrows below the graph show the kinetic energy of the electron beam at the various beam position monitors where the measurement are made. The damping factor is defined to be the helicity-correlated position difference observed at the first BPM (BPM number 1) divided by the helicity-correlated position difference observed at the BPM of interest. The expected damping in the injector (from 100 keV to 5 MeV kinetic energy) is not observed because of optics mismatches. Damping is observed in the accelerator (from 5 MeV to 3 GeV kinetic energy)

displacement in the case of no acceleration is given by [3]:

$$x(s) = \sqrt{\epsilon}\sqrt{\beta(s)}\,\cos\{\psi(s) + \phi\} \tag{1}$$

where

$$\psi(s) = \int_0^s \frac{ds'}{\beta(s')} \tag{2}$$

is the accumulated betatron phase, ϕ is the initial phase, ϵ is the emittance, and $\beta(s)$ is referred to as the beta function or amplitude function. So, the transverse position of the beam at a given point along the central orbit (e.g. at the target) depends on the initial position and angle of the beam as well as on the intervening optics (the integrated beta function along the orbit).

The solutions for x and x' can be combined in the form

$$\gamma(s)\; x^2(s) + 2\;\alpha(s)\; x(s)\; x'(s) + \beta(s)\; x'^2(s) = \epsilon \tag{3}$$

which defines a phase-space ellipse in the $x - x'$ plane. The three parameters that characterize this ellipse (α, β and γ) are referred to as the "Twiss parameters". Note that these parameters are functions of the path length s along the central trajectory, so the phase-space ellipse can change shape as the particle moves along its orbit. The area of this phase-space ellipse is simply $\pi\epsilon$, where ϵ is the emittance. For the case of no acceleration, Liouville's theorem states that the area of the phase-space ellipse (and therefore the emittance) remains constant.

When there is acceleration, and the relative momentum changes are small over the scale of the optical element spacing, the expression for the transverse position is modified in a simple way

$$x(s) = \sqrt{\epsilon}\sqrt{\beta(s)}\sqrt{\frac{p_0}{p}}\,\cos\{\psi(s) + \phi\}\,, \tag{4}$$

where p_0 and p are the initial and final beam particle momenta, respectively. This reduction in the amplitude of the betatron motion as the beam momentum is adiabatically increased is referred to as adiabatic damping. Therefore the acceleration of the machine gradually reduces the amplitude of the betatron oscillation, and the transverse displacement from the central orbit can be reduced further at a given point by controlling the overall accumulated betatron phase.

In practice, one works to achieve the minimum possible helicity-correlated position and angle differences in the beam in the injector by proper alignment and configuration of elements in the polarized injector laser path as described in reference [1]. One then expects additional reduction in the position and angle differences observed at the experimental target by the adiabatic damping factor - $\sqrt{p_0/p}$. The full expected adiabatic damping factor is often not achieved due to an optically mismatched beam transport system. In a perfectly matched system, the Twiss parameters after passing through each beamline element match the design parameters. As discussed in the next section, various types of imperfections in the transport system lead to a deviation from this ideal case.

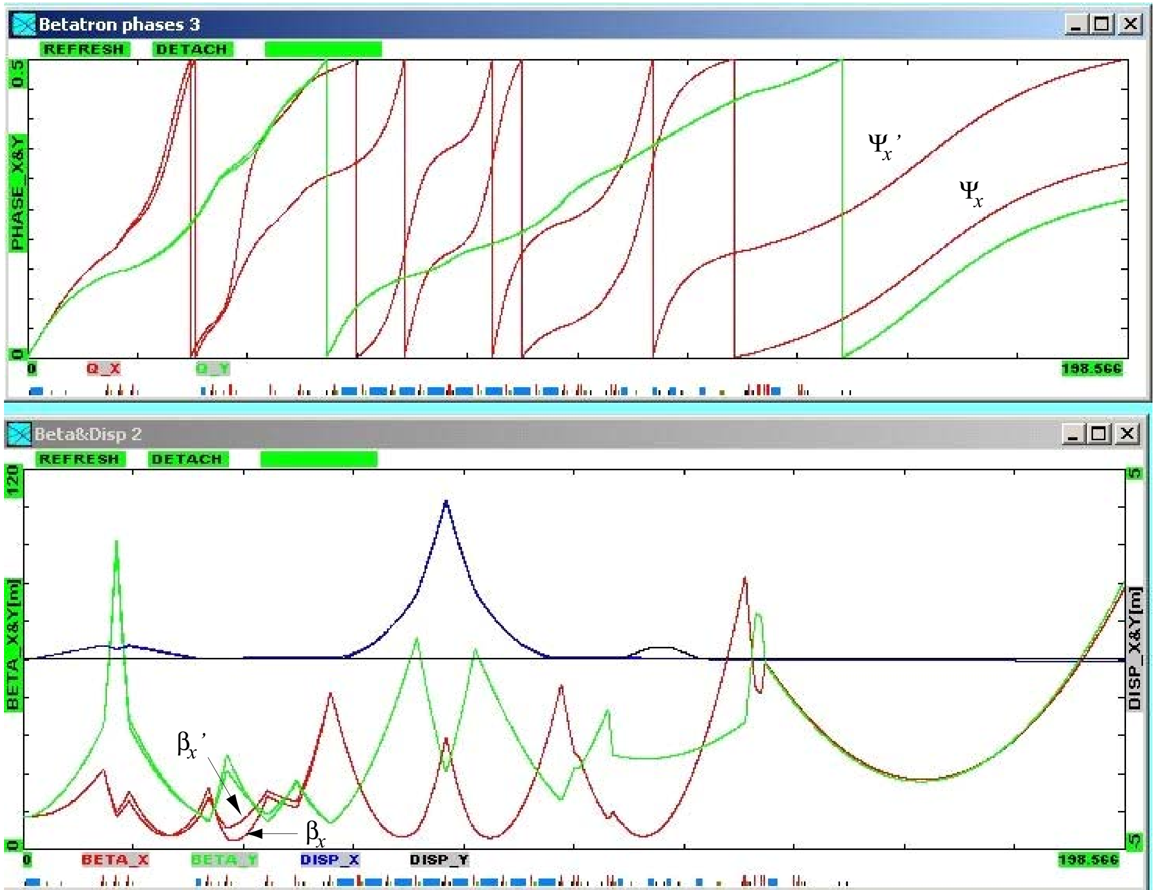

Fig. 3. Calculated effects of the phase trombone in the Hall A beam line at Jefferson Lab. The *upper panel* shows a difference in the phase of the β_x function of 60° (*upper curves at right:* Ψ_x *and* Ψ'_x) for slightly different tunings. The small difference in the tuning can be seen in the *lower panel* where the nearly identical pair of curves show β_x, β'_x for the two cases. The y functions are unaffected

The result of a mismatched transport setup are shown schematically in Fig. 1. At a given location, the phase-space ellipse preserves its area, but in a badly matched system the ellipse becomes distorted leading to a larger betatron amplitude ("orbit blow-up") than ideal adiabatic damping would predict.

3 Active feedback of beam position difference

In the G0 experiment, the relatively large bunch charge (running at 31 MHz pulse rate, necessitated by time-of-flight measurements, see [2]) required a non-standard tuning of the injector which made reduction of the helicity-correlated beam position differences with the standard damping difficult to achieve. Nominally, with 3 GeV incident energy, the damping from the injector to the target would be

$$\sqrt{\frac{3\ \mathrm{GeV}}{355\ \mathrm{keV}}} = 95 \qquad (5)$$

However the damping factors measured in the x and y directions were typically 25 and 10, respectively as shown in Fig. 2.

The precise cause of the reduced damping is not clear; however, there are several likely contributors. In order for the damping to be realized, the beam, characterized by its Twiss parameters, must have the envelope to which the subsequent optical elements are matched. In practice, correction elements are used to restore the envelope after sections of the beamline (e.g. linac, arc, etc.). Matching is particularly important in the injector where the relative acceleration is large, but is particularly difficult because of the focusing effects of the accelerating sections. The impact of this focusing is larger in the injector because of the lower energy of the beam; it is further complicated by the focusing components that mix the x and y phase spaces. Work continues to make improvements in this difficult tuning problem [4].

During the G0 experiment, the lack of damping was overcome with active feedback on the beam position at the target [5]. Helicity-correlated beam position difference measurements were made near the target and used to move the polarized source laser beam (using a piezo-electric actuator to move a reflecting mirror) in a helicity-correlated manner to null the error signal. In practice, this feedback was somewhat more difficult as the beam current and motions in the x and y directions were fully coupled, e.g. changing the y position of the laser beam at the source changed the x and y positions at the target, as well as the beam current. Successful operation of the feedback system required periodic calibration of this "response" matrix, as well as some optical adjustments to insure that the matrix was non-singular.

4 Phase trombone

In the most recent run of the HAPPEX experiments [6], beam position differences were mitigated using different techniques. As HAPPEX ran with the standard bunch charge (499 MHz pulse rate), the tuning of the injector was more standard and larger damping factors (though not the theoretical values) were routinely obtained. The position differences of the laser beam on the polarized source crystal were also reduced through a combination of a new, larger diameter Pockels cell (the electro-optic $\lambda/4$ plate that sets the laser beam polarization) and more careful optical alignment.

In the current run, a newly developed technique was also initiated. Starting with reduced position differences at the target, the HAPPEX group, in collaboration with the JLab Accelerator Division used a group of eight quadrupole magnets in the arc to adjust the beta function phase advance at the target (hence the name phase trombone) to trade off helicity-correlated position and angle differences (see Fig. 3). The basic idea is to change the phase advance periodically during the experiment to trade, e.g., a large position difference for a large angle difference or even to reverse the sign of a position difference to cancel the effect in an earlier part of the run. Technically, this amounts to rotating the phase space ellipse that describes the beam envelope. Development of this tool is also continuing.

5 Conclusion

Because the asymmetries in parity-violating experiments are small, careful control of the beam is required to reduce false asymmetries to acceptable levels. Therefore, in a real sense, the apparatus for these experiments involves the entire accelerator as an integral part. Among other accelerator challenges, controlling helicity-correlated beam positions and angles at the target at a level of a few nm and a few nrad, respectively, requires sophisticated control mechanisms. Achieving the natural (due to acceleration) damping of motion in the transverse planes is becoming easier as new sources of optical mismatches are identified. In the G0 experiment, active feedback was used with some success to reduce the position and angle differences, although changing beam conditions required periodic adjustments. The present HAPPEX run has seen the beginning of development of a new optical tool to allow position and angle differences to be traded off, reducing the overall effect on the experiment. Continued development of these techniques will be important to the success of future measurements of even smaller asymmetries.

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