A HIGH QUALITY POLARIZED CYCLOTRON BEAM FOR THE TRIUMF PARITY VIOLATION EXPERIMENT

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An experiment (E497) is underway at the TRIUMF cyclotron to measure the parity violating longitudinal analyzing power in elastic scattering of a 221 MeV polarized proton beam in a liquid hydrogen target, to a precision of $\pm 0.2 \times 10^{-7}$. Obtaining such accuracy imposes very stringent limitations on the cyclotron beam quality. The contributions of random and spin-correlated beam modulations to the experimental error will be discussed. The required beam quality is obtained by combining efforts at every stage: reduction of modulations in the source, minimization of transfer coefficients in the injection line and cyclotron, feedback systems for injected and accelerated beam stabilization, precision measurements of the beam energy, position and intensity modulations and reduction of the experimental apparatus sensitivities to these modulations.

1 INTRODUCTION

In the parity violation experiment the quantity measured is longitudinally-polarized proton current changes after scattering in a liquid hydrogen target, correlated with spin-reversal /1/. The magnitude of change caused by weak interactions of the protons is expected to be less than 3×10^{-9} and accurate measurements of this effect push to the limit the requirements for cyclotron beam quality and experimental apparatus. In the last 25 years, parity violation studies were attempted at 15 MeV tandem and 800 MeV linac accelerators at LANL, at 6 GeV energy at the AGS, at 45 MeV at the PSI injector cyclotron, at the 13.8 MeV cyclotron at Bonn, and at 221 MeV beam energy at TRIUMF/1/. So far, the experiment at PSI sets the benchmark of precision for parity violating analyzing power $Az=(-1.57\pm0.23) \times 10^{-7}$ /2/.

The cyclotron current fluctuations at ac line frequency and its harmonics can be as large as a few percent. Mechanical vibrations in the injector or cyclotron contribute to fluctuations in a low (5-30 Hz) frequency domain. The only way to measure current modulation of 10^{-9} magnitude is synchronous detection technique, when proton polarization is reversed in the source at some regular time pattern and current in the detectors is measured synchronously with the spin reversal. Ideally, only the direction of longitudinal polarization at the target should change at spin-reversal. In practice, all beam parameters (current, energy, position, size, polarization) change slightly too. Primary modulations of the beam parameters originate in the source. Beam transport in the injection line, acceleration in the cyclotron, extraction and high energy beam transport can mix, amplify or produce new modulations. Furthermore, the amplification and mixing can vary in time. The general layout of the TRIUMF parity experiment is presented in Fig.1. The optically pumped polarized H^- ion source (OPPIS), beamlines and cyclotron are considered as the parts of the common experimental setup. Their parameters are included in the data stream of the parity data acquisition system together with the detector signals.

2 POLARIZED BEAM QUALITY

There are two types of beam property which affect the experimental accuracy. Modulations correlated with spin reversal are most dangerous, since they contribute to systematic errors; in contrast, random fluctuations contribute to RMS noise in the measurements and increase the running time of the experiment. The TRIUMF high current polarized source produces 30 uA of H^- ion beam current in its low current parity mode of operation/3/. The optimum beam current at the parity apparatus is only 200 nA, therefore most of the source intensity can be sacrificed to improve beam quality. For example, the RF bunchers in the injection beamline, which enhance the cyclotron transmission by a factor of five, also amplify the correlated energy modulations by two orders of magnitude, and cannot be used during the parity experiment.

(2a) Beam position stabilization at injection:
The beam position fluctuations at the injection point to the cyclotron are caused by instabilities in the source, beamline power supplies and mechanical vibrations of the whole injector building structure, and are converted to energy and current modulations of accelerated beam. They are significantly reduced by a position stabilization feedback system installed in the vertical section of the injection beamline. The system is based on two N-S, E-W split plate beam position monitors, with correction voltages applied to the electrostatic steering plates. About 50% of the beam intensity is scraped by the split-plates, but the result is a significant improvement of the beam position stability and noise reduction, as shown in Fig.2. Similar noise suppression was observed for the current fluctuations in the parity detectors. The sampling rate of the integrated current feedback amplifier is 1 kHz, and therefore, spin-flip correlated position modulations produced in the source at a 40 Hz rate are also reduced by

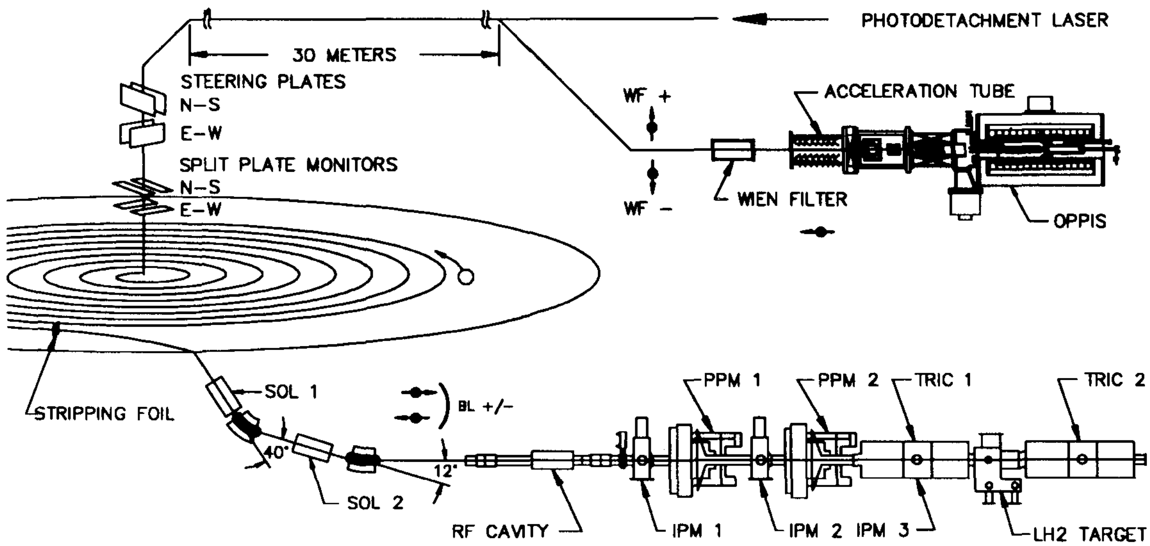

Figure 1: Parity experimental layout.

the position stabilization system.

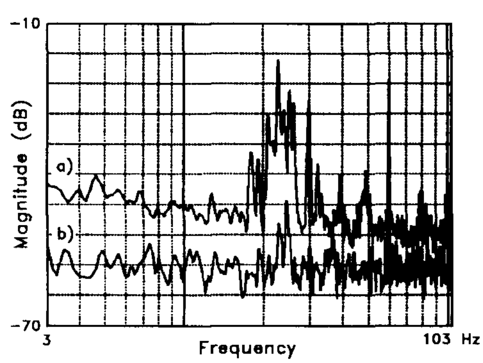

Figure 2: FFT spectrum of the beam position signal at injection. a) loop "off"; b) loop "on".

(2b) Beam current stabilization:
Spin-flip correlated current modulations introduce a systematic error via nonlinearity of the ionization chambers. The parity apparatus achieves minimal sensitivity to this type of modulation by precision analog subtraction of current signals from two identical ionization chambers upstream and downstream of the liquid hydrogen target. An enhanced "spin-correlated" current modulation is required for tuning the precision subtractor circuitry for minimum current modulation sensitivity. This modulation of about 0.4% is provided by laser photostripping of H^- ion beam in the 30 m long horizontal section of the injection beamline /4/,(see Fig.1). The balance point of the analog subtractor, where the sensitivity to current modulations is minimal, depends on beam current, which implies that the absolute current must be restricted to 200±2 nA. Current fluctuations and drift caused by injection beamline and cyclotron instabilities are typically about ±5%. A current stabilization system was implemented, which takes a current signal from the parity ionization chamber and produces a feedback correction voltage to the last set of four quadrupole lenses upstream of the slits. Again, an excess of current is required to set the initial setpoint, where about 10% of the beam intensity is skimmed at the slits. The current stabilization system operation is presented in Fig.3. Careful tuning is required to minimize the steering effect of the quadrupoles. To exclude coupling of current modulation to position and energy modulations, sampling rate is slow (0.5 Hz) , i.e. much slower than the spin-flip rate of 40 Hz. The active range of the current stabilization loop is quite narrow (±10%), to avoid correcting drift caused by large excursions of the cyclotron tune. The current loop operation is a sensitive indicator of cyclotron stability and operators make fine adjustment of the cyclotron tune if necessary.

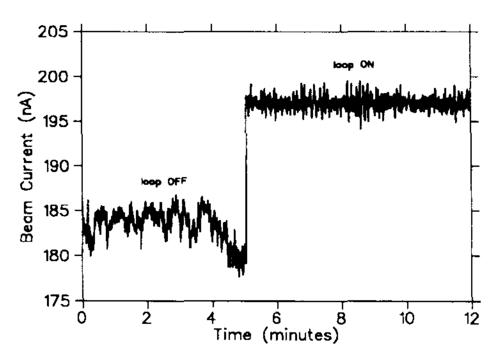

Figure 3: Current stabilization system operation.

3 POLARIZATION AND SPATIAL POLARIZATION DISTRIBUTION

Beam in the OPPIS is produced longitudinally polarized. The Wien filter rotates spin in such a way that after precession in the cyclotron residual field during transport in the injection line, beam polarization is exactly vertical in the cyclotron. Since all optical elements in the beamline are electrostatic, they do not affect spin direction. After extraction the polarization is aligned longitudinally by a combination of two superconducting solenoids and two bending magnets in the parity beamline (see Fig.1). The residual transverse components of polarization and the spatial distribution of polarization across the beam might produce significant false asymmetries in the parity apparatus. The propagation of transverse polarization of the injected beam was studied for different cyclotron tunes. For these purposes, the Wien filter was mistuned to produce large transverse polarization at injection, and polarization components of the extracted beam were measured at 230 MeV in the parity polarimeters. Despite thousands of revolutions, the spin precession remains coherent and some residual transverse polarization was observed in the extracted beam. Usually, the particle orbits are not separated at 230 MeV in the TRIUMF cyclotron and 10-20 turns are extracted simultaneously by the stripping foil. Since proton precession is about 2.8 times faster than momentum circulation, the spin direction is different for different orbits and averaging of several turns at extraction should reduce the transverse polarization of the extracted beam. The coherence and turn separation can be enhanced by phase-restricted tunes of the cyclotron, which improves the survival of injected transverse polarization, but this is an unwanted effect. On the contrary, a broadband tune, with RF detuned from the optimal synchronous condition increases the number of extracted turns and reduces the transverse polarization. Experimentally, a reduction factor of about 20 was measured under these conditions (see Fig.4).

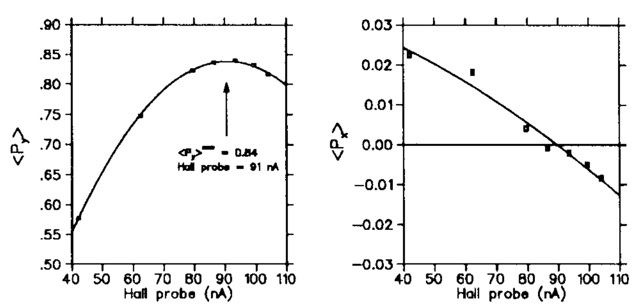

Figure 4: Wien Filter Tuning. At a magnetic field corresponding to a Hall probe reading of 40 uA, transverse polarization of the injected beam is about 60%, and of extracted beam 2.5%.

The polarization distribution across the extraction foil surface is a source of polarization moments, which were identified as a major systematic error contribution to the parity experiment. It is affected by the betatron amplitudes and number of turns. This distribution had been measured by scanning a short (6 mm height) "hockey stick" foil across the beam. Up to 2-3% transverse polarization difference was observed across the beam. Since the polarization moments are products of polarization and beam size, extracting only the central part of the beam by the short stripping foil, or vertical "shadowing" of the long foil, helps to keep moments within the tolerable range (less than 10 um).

4 STRIPPING FOILS

Three types of stripping foils were used for the parity experiment. Initially, a 32 mm long, 5.0 mg/cm^2 thick, pyrolytic graphite foil suspended at one end was tested (see Fig.5a). The foil width was 2.5 mm and it extracted about 60-70% of the circulating beam. The vertical beam size is quite large at 220 MeV beam energy and use of a long foil helps to reduce the beam current fluctuations caused by vertical beam position oscillations. As discussed above, the short "hockey stick" foil was used for polarization distribution measurements. To avoid beam extraction by the holder's thick stainless parts, one of the cyclotron diagnostics probes situated opposite the foil was used to shadow the holder and to reduce the effective foil width to about 2-3 mm. Polarized beam scattering in the carbon foil produces an asymmetry in the beam halo distribution, which can cause systematic errors in the parity detectors. The scattering effect is proportional to the foil thickness, which can be reduced significantly.

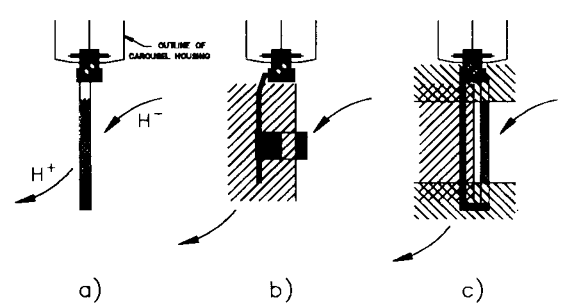

Figure 5: Stripping foils.

A foil 0.2 mg/cm^2 thick is sufficient to strip 98% of a 220 MeV H$^-$ ion beam. In the tests, such a thin foil was supported along one side -the "hockey stick" geometry. The use of thin foil reduces significantly the extracted beam emittance due to reduction of multiple scattering and hence improves the beam transport conditions. The drawback of radial shadowing is an appearance of beam profile asymmetry caused by the fuzziness of the shadowing. This asymmetry is sensitive to the cyclotron tune and produces polarization moments. The solution is the use of a 0.2 mg/cm^2 foil strip, 2.5 mm wide, attached at both ends to a C-shaped holder (see Fig.5c). The holder shadowing doesn't affect the beam profile in this case, due to a 5.0 mm gap between the strip and holder. The end parts of the holder are shadowed by the second stripping foil, which is situated at smaller radius and therefore trims beam symmetrically at top and bottom. Narrow symmetrical beam profiles were obtained with the thin foil in the C-holder and this foil will be used for the next run.

5 SPIN-CORRELATED ENERGY MODULATIONS (CEM)

The parity detectors sensitivity to CEM of 2.8x10^{-8}/eV was measured with an RF post-accelerator in a parity beamline/5/. CEM of cyclotron beam is caused by coherent position modulations of the radial intensity distribution at the extraction foil; this converts radial position modulation of the injected beam to energy modulation of the extracted beam. The primary CEM produced in the source is converted to position modulation in the injection beamline and then back to energy modulation at the extraction foil. This process amplifies the primary CEM by a factor of approximately 100, as measured using a magnetic spectrometer at 220 MeV/5/. The sensitivity ΔAz=0.04x10^{-7} per meV of CEM at the source was measured by applying a square wave voltage of 0.5 V amplitude to the electrically isolated sodium ionizer cell in the OPPIS. Primary spin-correlated position modulation (CPM) produced in the OPPIS also contributes to the systematic error, with a sensitivity of about 0.01x10^{-7} per nm of CPM in the source. CEM and CPM produced in the OPPIS were studied by using an electrostatic beam energy analyzer and an intensity profile monitor with 16 collector strips 2.5 mm wide, and a 3.0 mm spacing (similar to the parity secondary emission monitors) to measure beam position modulations downstream of the steering analyzing plates. The monitor is mounted on a remotely controlled swinging lever arm. The two measurements of CPM for the right and left monitor positions allowed the separation of the energy and position modulation components of the OPPIS' beam. The very stable OPPIS beam, together with synchronous detection techniques allowed an excellent accuracy of about 2 nm in 10 minutes integration time for the spin-correlated position modulations. The sensitivity to energy modulations of about 10 nm/meV was measured in a calibration run, when a 50 meV pulsed square wave voltage was applied to the ionizer cell. This means that an accuracy of 0.2 meV in ten minutes integration time was achieved for CEM measurements. The results of the CEM measurements are presented in Fig.6. The modulation magnitudes are quite sensitive to the pumping laser asymmetry between the two polarization states; after careful laser tuning, the CEM was reduced to 1-2 meV, and CPM to the 20 nm level. These measurements are completely remotely controlled; the profile signals are transmitted from the 300 keV OPPIS terminal to ground through a 16 channel optolink and the measurement can be done in a short time without 300 keV interruption. The CEM and CPM measurements are interleaved with measurements in the parity beamline, and corrections to Az can be applied if necessary.

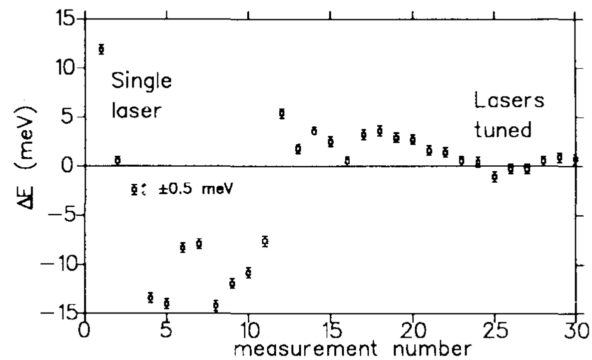

Figure 6: OPPIS spin-correlated energy modulations.

The achieved polarized beam quality and performance of the parity experimental apparatus have demonstrated that the design accuracy goal for the parity violating analyzing power Az of $\pm$0.2x10^{-7} is within reach.

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