Polarized Drell-Yan Proposal: Questions & Answers

(Fermilab Proposal: P-1027)

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1 Introduction

This document presents the answers to the questions on the Polarized Drell-Yan proposal P-1027 posed by the Physics Advisory Committee following their June 2012 meeting in Aspen. Each question from **Q 1** to **Q 5** is repeated in italics and followed by an answer in roman starting with **A:**".

We will first give a brief summary of the physics motivation and a brief discussion of the substantial redesign of the polarization scheme and our decision to go with one Siberian Snake. The document will conclude with the answers to the five questions asked by the PAC.

2 Physics Motivation

Polarized Drell-Yan scattering has become a major milestone in the hadronic physics community, motivated by a fundamental prediction of QCD that postulates that a time-reversal-odd distribution function (*e.g.* the Sivers function [1]) measured in Drell-Yan must change sign [2, 3] if measured in semi-inclusive deep inelastic scattering (DIS). The Sivers function is described by a transverse-momentum dependent distribution function that captures non-perturbative spin-orbit effects inside a polarized proton. The experimental verification of the sign change goes to the heart of the gauge formulation of QCD and would be crucial to confirm the validity of our present conceptual framework for analyzing hard hadronic reactions.

The HERMES experiment [4] at DESY and the COMPASS experiment [5] at CERN have measured single transverse spin asymmetries to high precision, and global fits to the Sivers function have been performed [6]. In order to make a meaningful comparison of sign and shape, comparable measurements are needed for single spin asymmetries in the Drell-Yan process. While many experiments around the globe aim to measure polarized Drell-Yan either with a polarized beam or a polarized target, none of them is optimized for Drell-Yan, except for the SeaQuest dimuon spectrometer at the Fermilab Main Injector. At present, only the COMPASS experiment is scheduled to run in the near future. COMPASS is scheduled to take data in 2014 for one year and expects to measure the sign of the Sivers function in the same kinematics as semi-inclusive DIS* with a statistical precision of $\delta A_N/A_N$ of 1%–2%. A polarized Drell-Yan experiment such as E-906/SeaQuest is needed, however, to measure the sign, the magnitude, and possibly the shape of the Sivers function with sufficiently high precision.

There is a great opportunity at Fermilab, at a relatively modest cost ($10 Million) and with minimal impact on the neutrino program (10% of beam time), to set up the best polarized Drell-Yan experiment to perform this fundamental test of the gauge structure of QCD. The big attraction for a polarized Drell-Yan program at the Fermilab Main Injector is the high luminosity in combination with a spectrometer and a hydrogen target that are well-understood, fully functioning, and optimized for Drell-Yan at the end of data collection for the E-906/SeaQuest experiment (estimated to be in early 2015). Furthermore, the E-906/SeaQuest spectrometer accommodates a large coverage in parton momentum fraction x, *i.e.* $x_b = 0.35 - 0.85$ covering the valence quark region, and $x_t = 0.1 - 0.45$ covering the sea quark region. Although the Sivers function can be measured for both the valence quarks or the sea quarks, valence quarks constrain the SIDIS data from HERMES and COMPASS much more than the sea quarks [6, 7]. Thus, using a polarized beam promises to

*Note, COMPASS will measure A_N in one x_f-bin centered at $x_f = 0.2$ in the invariant mass region $4 < M < 9$ GeV.

be a substantial advantage over a polarized target.

Based on the study submitted to the Fermilab directors in August 2011 [8], and experience gained from current polarized ion sources, it is expected that an ion source that produces 1 mA at the source can deliver up to 150 nA (9.5×10^{11} p/s) average beam current to the experiment, using 30 two-second cycles and slip stacking in the Main Injector. Since the liquid targets are designed for average beam currents of about 80 nA, *i.e.* three times the beam current foreseen for SeaQuest, a luminosity of $1 \times 10^{36}/\mathrm{cm}^2/\mathrm{s}$ could be obtained if 50% of the total beam time was allocated to the experiment. However, a polarized Drell-Yan program at Fermilab seems only feasible if not more than 10% of the available beam time is diverted from the neutrino program. Thus, assuming 10% of the available beam time was allocated to the experiment, which corresponds to a luminosity of $2.0 \times 10^{35}/\mathrm{cm}^2/\mathrm{s}$, and further assuming a beam polarization of 70%, a running efficiency of 50% and a running period of 2 years, not only the sign, but also the size and shape of the Sivers function could be measured. This is illustrated in Fig. 1, where the red line indicates the prediction for the Sivers asymmetry, and the gray shaded area represents the $\sqrt{20}$-sigma error band.[†]

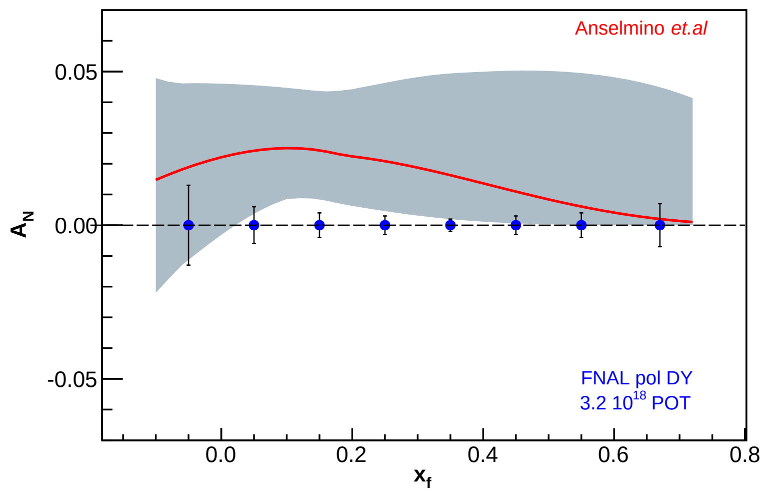

Figure 1: Single spin asymmetry A_N as a function of x_f. The expected statistical uncertainties (blue solid circles) for a 70% polarized beam on an unpolarized target and 3.2×10^{18} protons on target are (arbitrarily) plotted on the zeroline. The red line indicates the prediction for the Sivers SSA [9] based on the SIDIS results of HERMES and COMPASS, and the gray shaded area represents the $\sqrt{20}$-sigma error band.

The combination of high luminosity, large x-coverage and a high-intensity polarized beam makes Fermilab arguably the best place to measure single-spin asymmetries in polarized Drell-Yan scattering with high precision. It would allow for the first time to perform a measurement of the sign, the magnitude, and the shape of the Sivers function with sufficient precision to verify this fundamental prediction of QCD conclusively.

[†]The χ^2 analysis and the statistical uncertainty bands are discussed in the Appendix of Ref. [6]. The error band corresponds to a $\Delta\chi^2 = 20$.

3 Main Injector Polarization Scheme - 1-Snake Solution

Since two Siberian Snakes in the Main Injector would impact the Fermilab neutrino program at unacceptable levels, Derbenev, Kontratenko, Courant and Krisch, some of the world experts in Siberian Snake design and their younger colleagues, made a concerted effort over the past two month to find a 1-snake solution for the Main Injector. They found that the depolarizing effect of the spin perturbations in the Main Injector can be suppressed equally by either 1 or 2 snakes. A single snake seems preferable in an accelerator of about 120 GeV, since its spin resonances are not strong enough to need 6 snakes (as at the Tevatron and perhaps soon at RHIC) and the spin precession axis can lie anywhere in the horizontal orbit plane. This allows one to substantially reduce the snake's total length compared to the originally proposed 2 snakes with horizontal perpendicular axes, which must be at $\pm 45°$ with respect to the beam direction.

The consequence of this fortunate finding is that 1 snake is as strong as 2 snakes in the Main Injector, with equally little loss in polarization. Fig. 2 shows a workable solution that consists of a 5-T snake that has a 3.31-m-long double-twist superconducting helical dipole, surrounded by two 0.222-m long 5 T superconducting conventional dipoles each separated by a 0.20-m gap.

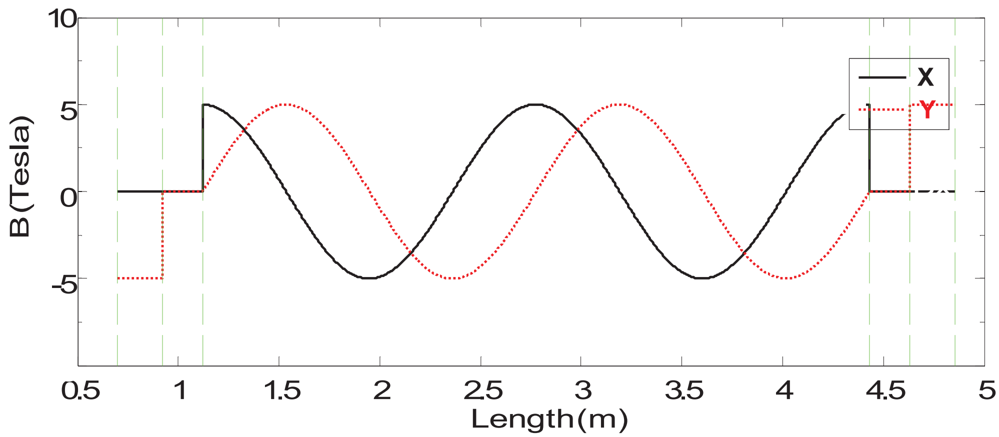

Figure 2: Siberian Snake B-field strengths.

Figure 3 shows the beam excursions in the x and y directions. Note that this single snake is less than 5 m long and can comfortably fit into the Main Injector's MI-30 straight section.

Only a single superconducting helical dipole is needed for this snake design, compared to two times 4, i.e. 8, superconducting helical dipoles in the original 2-snake design. Thus, the cost of the snakes, as well as the total project cost have dropped dramatically, as discussed in the answer to Q 3.

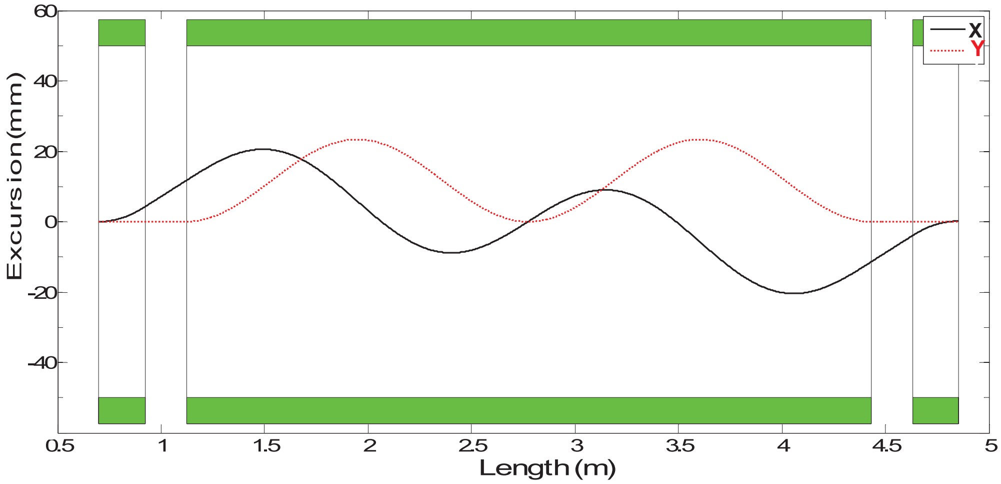

Figure 3: Siberian Snake beam excursions.

4 Questions and Concerns raised by PAC

Q 1: *Running with two Siberian Snakes in the Main Injector would impact the core Fermilab program as one of them would require removal of the NOvA extraction kickers. What would the reduction in polarization be with one MI snake and what would be the quantitative effect on the goals of the experiment?*

A: As described in Section 3, it was fortunate that there was a problem with the 2-snake design. This forced the Siberian Snake experts to find a better solution, which uses less real estate in the accelerator complex, at a substantially lower cost (see **Q 3**), and with no additional loss in polarization. Thus, there is no change to the physics goals of the experiment.

Q 2: *In-kind and M&O contributions from outside of Fermilab sufficient to mount and sustain the experiment would be necessary in order to recommend approval, and the budget model needs to be fleshed out in greater detail with DOE ONP, OHEP, and NSF. What arrangements can be made to secure outside funding?*

A: The collaboration does not expect to rely solely Fermilab resources to mount and sustain the experiment. We believe that participation from DOE/ONP and DOE/OHEP, as well as the NSF and foreign collaborators is necessary to successfully mount this experiment. In the E-906/SeaQuest experiment we were able to achieve such a balance with ONP providing most of the M&S contributions to mount the experiment and OHEP (through Fermilab) providing most of the effort. In the end, ONP and OHEP contributions were approximately the same. Additional in-kind contributions came from Taiwanese and Japanese collaborators. While it is too early for any of the financial considerations to be worked out, we are hopeful that a balance can also be arranged. To this end, we have been in contact with the Fermilab Directorate, ONP, NSF and foreign collaborators in Europe and Japan. At this time, naturally, there are no financial commitments from any organization. This late in the year, it is very unlikely that this can be included in the FY2014 budget, but with Phase I Approval, the spokespersons will undertake these discussions with both ONP, OHEP, NSF and the Fermilab Directorate.

Q 3: *There are two estimates for Snake fabrication and they vary widely. What are the anticipated costs for snake fabrication?*

A: There were indeed two cost estimates for Snake fabrication which varied by about a factor of eight. The initial estimate in the proposal was based on RHIC costs for 4 snakes and 8 rotators (which was $3.7 M in 1995 dollars). It did not contain the cryo-building costs, infrastructure changes including power, transformers, cooling and some personnel costs and escalation that were included in the estimate of the Accelerator Facility Impact Study Committee chaired by Herman B. White of June 5, 2012 [10].

Table 1 contains what we believe are realistic costs for the single snake discussed in the answers to **Q 1** above. These costs are based on the cost estimates presented by Herman B. White's committee [10] in June 2012 and on more recent discussions with Herman B. White, with three significant modifications: The complex 2-snake design, which contained a total of eight helical superconducting dipoles, was replaced with a simpler 1-snake design, which contains only one helical superconducting dipole; the two cryo-buildings are not needed for the 1-snake design; but a superconducting solenoid snake plus polarimeter is needed in the Recycler Ring.

Q 4: *What are the likely impacts on the Fermilab infrastructure and expert personnel in the installation and commissioning of the proposed polarized-proton beam in this system?*

A: With the 1-snake solution for the Main Injector, we see little impact on the present Fermilab infrastructure. In the previous plan, there were significant conflicts in terms of space, cooling and electrical requirements at MI60. All of these have been removed. At MI30, there is sufficient space for a snake. An additional building to house cryo compressors may be needed at MI30, as well as additional electrical power, but these appear to be quite feasible. (If needed, the budget shown in Table 1 will need to be increased by approximately $1.0 M [10] to include this building.)

The current skill set of Fermilab's expert personnel is sufficient for much of the installation and commissioning of the polarized proton beam. For the LINAC, Booster, Recycler, MI and transfer lines, these skills include the electrical and power supplies for the snakes and magnets; the cryogenic support for the cold snake; and beam line instrumentation. While Fermilab has never installed, commissioned or operated a polarized source, the expert personal needed for this can be found within the skill set required to operate the present accelerator complex. The polarimeters required in the LINAC, Booster, MI and transfer lines might be an exception to this, as the collaboration has yet to identify personnel within Fermilab who have worked on such units. In this case, the collaboration is willing to work with Fermilab and to identify people within the collaboration to work on these polarimeters.

Examining the effort listed in Table 1, the longest down times are of the order of 6 weeks. Assuming that much of the work in different areas can take place in parallel, this upgrade could likely take place as part of one of the (yet unscheduled) summer shutdowns that are likely to occur between 2014 and 2015. This, of course, assumes that the necessary personnel are available and not otherwise occupied during these shutdowns, so the exact choreography would need to be carefully planned and might result in a minor increase in duration of one of these shutdowns.

Table 1: Cost Table for polarizing the MI based on the 1-snake design discussed in Section 3. These costs are based on the cost estimates presented by Herman B. White's committee [10] to the June 2012 PAC with three modifications: the complex 2-snake design (containing 8 helical dipoles) is replaced with a simpler 1-snake design (containing only 1 helical dipole), which lowers the cost dramatically; the two cryo-buildings are not needed for the 1-snake design, which lowers the cost significantly; but a superconducting solenoid snake plus polarimeter is needed in the Recycler Ring, which adds slightly to the cost.

Preaccelerator			\$1.9 M
	Polarized H^- ion source	\$0.6 M	
	35 keV polarimeter	\$0.2 M	
	RFQ and power supply (35 keV to 750 keV)	\$0.3 M	
	Beam lines, switching magnets & vacuum system	\$0.5 M	
	Building Modification	\$0.1 M	
	Installation (∼4wks)	\$0.2 M	
400 MeV LINAC			\$0.3 M
	400 MeV polarimeter	\$0.1 M	
	Installation (∼4wks)	\$0.2 M	
8.9 GeV/c Booster			\$1.1 M
	Solenoid and Partial Siberian snake (ramped warm)	\$0.4 M	
	Two 3 μsec pulsed quadrupoles with power supplies	\$0.1 M	
	8.9 GeV/c polarimeter	\$0.2 M	
	8.9 GeV/c transfer line spin rotator	\$0.1 M	
	Installation (∼6wks)	\$0.3 M	
Recycler Ring			\$0.4 M
	one superconducting solenoidal Siberian snake	\$0.1 M	
	8.9 GeV/c polarimeter	\$0.2 M	
	Installation (∼2wks)	\$0.1 M	
Main Injector			\$1.3 M
	One superconducting helical Siberian snake	\$0.5 M	
	Power supply for snake	\$0.1 M	
	120 GeV/c polarimeters (CNI & Inclusive)	\$0.4 M	
	Installation (∼6wks)	\$0.3 M	
120-150 GeV/c Transfer Line			\$0.5 M
	120-150 GeV/c polarimeters (CNI & Inclusive)	\$0.4 M	
	Installation (∼2wks)	\$0.1 M	
Miscellaneous			\$0.6 M
	Computers, control modules, cables, and interface	\$0.3 M	
	Transport, reconfiguration, technical (guess estimate)	\$0.3 M	
Subtotals			\$6.1 M
Project Management estimate		\$0.9 M	
Contingency (∼50%)		\$3.5 M	
PROJECT TOTAL			∼\$10.5 M

Q 5: *What are the likely resources and infrastructure implications for operating such a beam?*

A: With the 1-snake solution presented in Section 3, the impact on other experimental programs at Fermilab (*e.g.* NuMI-based experiments) is minimized and these programs can run in parallel with a polarized Drell-Yan experiment[‡]. Nevertheless, the addition of a polarized Drell-Yan program will have some impact on resources and infrastructure at Fermilab:

- **NuMI Luminoisty:** First, the experiment will be using a slow extraction beam from the MI. This will decrease the integrated luminosity available to NuMI. As with SeaQuest, we are limiting our beam request to 10% of the MI time. During the slow extraction, the beam is split and also sent to the Fermilab Test Beam Facility, so our running will have no impact on the test beam, and for the time that the test beam would be running anyway, we will not be causing any additional luminosity decrease to NuMI.
- **MCR Operations:** Once commissioned, operation of the beam line is likely to have a similar impact as running the present external beam to SeaQuest and to the test beam in terms of the personal needed in the Main Control Room.
- **Polarimeter Operations:** There are several polarimeters included in this project. The collaboration does not know if there is presently experience at Fermilab with the operation of these devices. Although such expertise may exist within Fermilab, the collaboration is willing to accept initial responsibility for the operation of these devices, and to work with AD to integrate them into whatever control or feedback systems are needed.
- **Maintenance:** Clearly, the installation of additional devices in the Fermilab accelerator complex will add to the maintenance responsibilities of AD. The additional elements being added are relatively "standard" devices with no unusual demands. We anticipate that the normal maintenance can be accomplished during the normally scheduled maintenance times, or with only minor extensions.

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[‡] This was always our intention. The conflict at MI60 with extraction to NuMI only became apparent shortly before the last PAC, at which point we were already looking for a solution.