Reply to the Report of 2015 SoLID Director's Review

The SoLID Collaboration

March 30, 2017

Contents

1 Overview

A Jefferson Lab Directors Review for the Solenoidal Large Intensity Device (SoLID) was held in February 2015. The review committee felt that SoLID was in a good state to move forward, but also identified a number of areas where additional work would be needed. Thirty-six recommendations were made in total (summarized in the Appendix of this document), with some aiming at longer term efforts of the type requisite to any project of this magnitude, and others more specifically relevant for the nearer term. After discussions with the Physics Division and Jefferson Lab management, the collaboration aimed as a first step to address those recommendations that were necessary to proceed with a Science Review as required for a DOE Critical Decision CD-0. While continuing to also address the longer term recommendations to the extent possible, the collaboration has completed this first step.

This document summarizes the preparatory work to reach this milestone. It includes the experiment-specific recommendations related to the three core measurements (SIDIS, PVDIS and J/ψ production), as well as the ones related to the general performance of the instrumentation to reach the scientific goals. For PVDIS, the viability of the calibration procedure to determine Q^2 was studied including realistic misalignments. The design of the baffles was re-examined, including the choice of materials. For SIDIS, careful studies were performed to show the impact of SoLID compared to the world data, including comparisons to Jefferson Lab 12 GeV era projected data from the CLAS12 and SBS programs. Examples of physics reach, such as the transversity/tensor charge, were simulated and are presented. For J/ψ, bin migration effects and the trigger rate were simulated. Studies of promising additional science reach facilitated by SoLID, such as Generalized Parton Distributions and kaon identification, were also recommended and considered.

Realistic simulations, as well as tracking and data acquisition development, have shown that the performance of the instrumentation will allow realization of the SoLID scientific goals with the proposed instrumentation. The acceptances, efficiencies and systematic uncertainties were simulated in detail for each of the three core measurements. Meticulous magnet field modeling confirmed that the forces are tolerable and the fringe field at the polarized target location can be controlled to the desired level. The effects of possible radiation damage were carefully evaluated. Significant progress has also been made in the development of a full analysis simulation and software framework.

Beyond the above, which were deemed critical to the near term path to a Science Review, continuing work on the many recommended fronts is discussed in the Appendix of this document as well. The coils and cryostat of the CLEO-II magnet have arrived at JLab and the exterior steel is being shipped. Other activities include the development of GEM foil production in China and the risk factor, communication with expert groups in calorimeter design and R&D, and stability testing of the conductivity of MRPC glass. An initial study of the slow control system has been performed. A pre-R&D plan was developed with input from Jefferson Lab management, and has been submitted to the DOE. Pre-R&D activities are continuing with some detector pre-R&D activities supported by the international collaboration (China and Canada).

As a whole, the collaboration considers the progress on SoLID to be adequately substantive and positive to enable the next phase to begin, in particular a DOE Science Review. We therefore submit this document as a first formal response to the 2015 Director's Review, and look forward to the committee's evaluation and subsequent guidance from the laboratory.

2 Physics Program

2.1 SIDIS Production of Charged Pions

The SoLID SIDIS program includes three approved experiments, using transversely and longitudinally polarized ^{3}He targets and a transversely polarized proton (NH_3) target. With the combination of high luminosities and large acceptance including a full azimuthal coverage, the SoLID SIDIS experiments will allow measurements in 4-dimensional bins with high statistics and well controlled systematics. Compared to CLAS12 and SBS SIDIS programs, SoLID has better FOM, corresponding to higher statistics, in the region $x = (0.05, 0.55)$, as shown in Figure 1. To demonstrate the physics impact of SoLID SIDIS program, we perform the transversity extractions

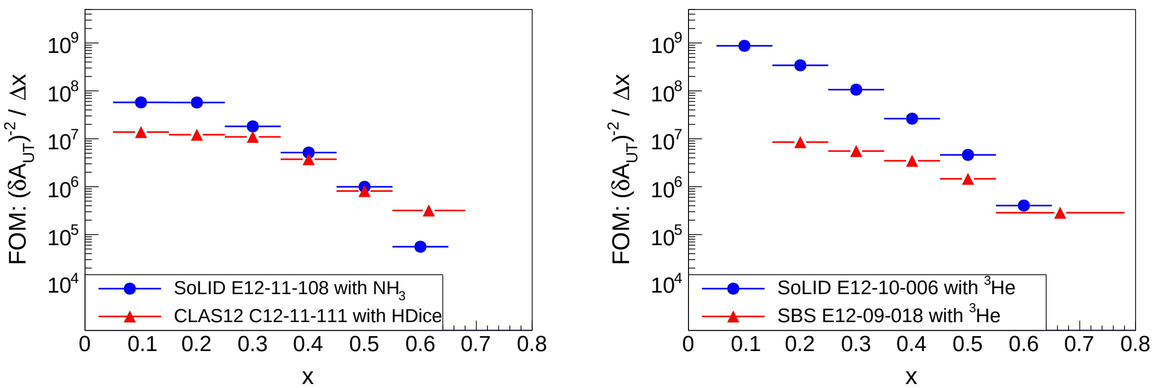

Figure 1: Comparisons of the FOM, defined as the sum of the inverse square of the statistical uncertainties of the single spin asymmetry (roughly proportional to statistics). The SoLID SIDIS experiment with the NH_3 target is compared with CLAS12 experiment in the left panel. The SoLID SIDIS experiments with the ^{3}He target are compared with the SBS experiment in the right panel. In both comparisons, the kinematic cuts of $W > 2.3\,\mathrm{GeV}$ and $0.3 < z < 0.7$ are applied.

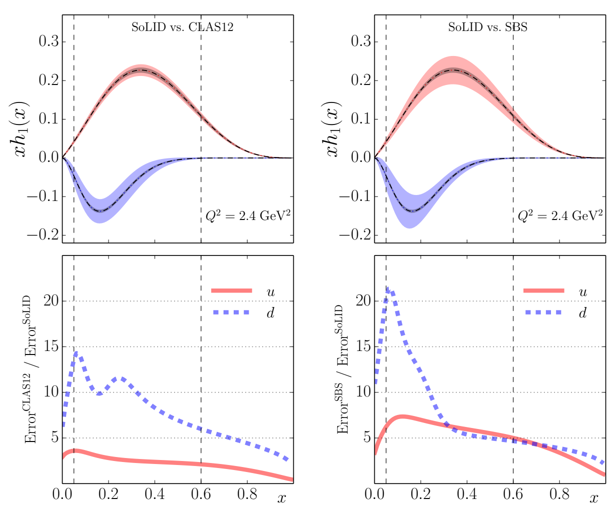

Figure 2: Comparisons of the impact on transversity extractions, as the extension of published works [5, 6]. The left column shows the comparison between SoLID and CLAS12, and the right column shows the comparison between SoLID and SBS. In the upper panels, the light shade bands show the uncertainties after SBS/CLAS12, and the dark shade bands show the uncertainties after SoLID. Curves in the lower panels show their ratios. Both u and d quark results are presented. All results are plotted at a typical JLab12 scale $Q^2 = 2.4\,\mathrm{GeV}^2$.

based on the works of [5, 6] with simulated data of CLAS12, SBS and SoLID, and then compare them in Figure 2. SoLID can improve the error of the transversity for u (d) quark by a factor of 3 (7) more than CLAS12, and by a factor of 5 (10) more than SBS. The tensor charge determination will have similar improvements which together with nEDM measurements will provide constraints on quark EDMs and thus new physics models. It is clear that the projected high precision results from SoLID will provide powerful tests of Lattice QCD, and much more quantitative information about TMDs and quark OAMs inside the nucleon.

2.2 PVDIS

The unique feature of SoLID, combining high luminosity and large acceptance, makes it possible to reach the high precision needed to have a high impact by using PVDIS to probe physics beyond the Standard Model. A measurement of PVDIS in deuterium will determine the fundamental coupling constant $2C_{2u} - C_{2d}$ that is inaccessible with other means. PVDIS measurements can also access a number of topics in QCD physics, including searching for charge symmetry violation in the parton distribution functions, determining the d/u ratio in the proton without nuclear effects, and a clean extraction of higher-twist effects due to quark-quark correlations. The 6-GeV PVDIS collaboration [1] has recently published in Nature a new experimental result $2C_{2u} - C_{2d} = -0.145 \pm 0.068$,

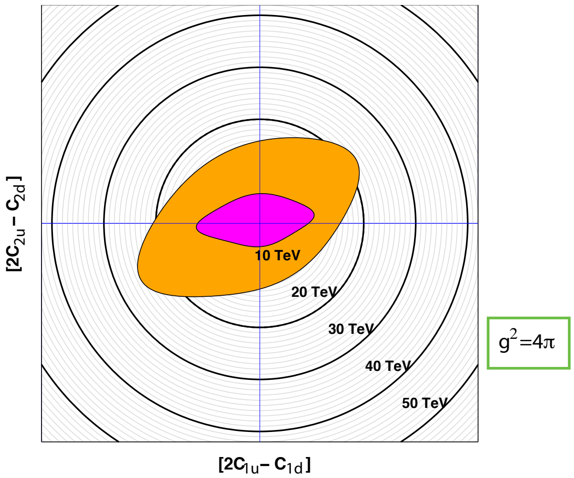

Figure 3: Projected mass limits for composite models. Purple region is excluded by published data and the orange region is the projected reach with SoLID and final Qweak result.

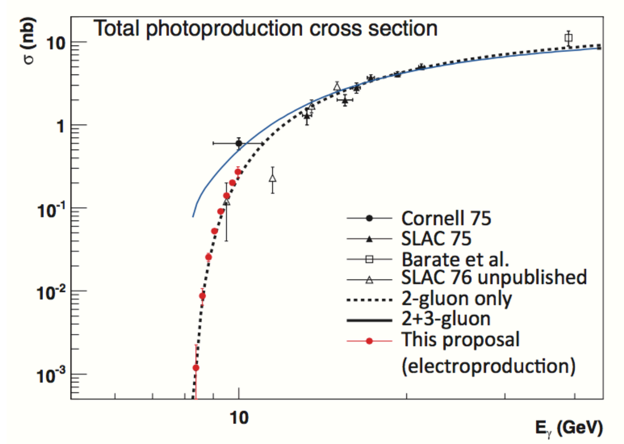

Figure 4: Projected uncertainties on total J/ψ electroproduction cross section. Our projections are based on the 2-gluon exchange model.

the first measurement sufficiently sensitive to show that the C_{2q} are non-zero as predicted by the SM. One way to quantify the reach of various experiments is to quote mass limits suitable for composite models [2], where the couplings are on the order of $4\pi/\Lambda^2$ where Λ is the compositeness mass scale. Such limits for the 6-GeV PVDIS collaboration and the SoLID PVDIS experiment [3] are shown in Figure 3. The sensitivity to be reached by SoLID is at the same level as LHC's for non-parity-violating couplings.

2.3 J/ψ

The impressive luminosity offered by SoLID combined with large acceptance detection opens new opportunities for the measurement of rare processes with unprecedented precision impacting directly our understanding of QCD. In particular the measurement of the elastic production of J/ψ on the proton near threshold could provide the unique and much needed information on the pure gluonic component of the QCD interaction, as well as the verification of the nature of the recently observed charmed "pentaquark" states at the LHC. A measurement very close to the threshold (Figure 4) where the cross section drops rapidly can provide important information on the trace anomaly, a key component responsible for the mass of the nucleon. Hadrons, the emergent phenomena of QCD, are in the realm of the strong interaction regime where much of its dynamics remains to be understood. While significant progress has been achieved in exploring QCD in its asymptotically free regime, the theory in the strong coupling regime is hardly tractable without numerical techniques. For example, an impressive success was achieved with the recent lattice QCD determination of the low-lying levels of the baryon spectrum [4] but there is a long road ahead to fully grasp the implications of QCD in this regime. One aspect is the decomposition of the mass of the nucleon in terms of its constituents quarks and gluons. The threshold region of electro- and photo-production of J/ψ could very well shed light on the anomaly responsible for a large fraction of the proton mass.

3 Plan for Possible Expansion in Physics Reach

3.1 GPD

The unique features of SoLID's large acceptance and high luminosity make it an attractive device for the experimental study of GPDs. A number of groups have been working on developing a SoLID-GPD program. There are several GPD experiments in different stages of study/approval. A run-group proposal of Time-like Compton

Scattering (TCS) from an unpolarized LH2 target has been approved to test the universality of GPD, explore the underlying principles of factorization and quantify the importance of higher twist effects. Double Deeply Virtual Compton Scattering (DDVCS) in the di-lepton channel on an unpolarized LH2 target was reviewed by the JLab PAC as a Letter-Of-Intent and the collaboration was encouraged to develop it into a two-stage program with an initial focus to have a first significant DDVCS measurement (over a limited kinematic region) using the baseline SoLID setup. Measurements of DVCS and Deep Exclusive Meson Production (DEMP) with the transversely polarized ^{3}He target are under development and the DEMP run-group proposal was reviewed by the SoLID Collaboration and received a strong encouragement. These measurements, together with the planned CLAS12 and Hall A/C GPD experiments, will make a significant contributions in disentangling different GPDs in the JLab 12-GeV kinematic region.

3.2 SIDIS Production of Charged Kaons

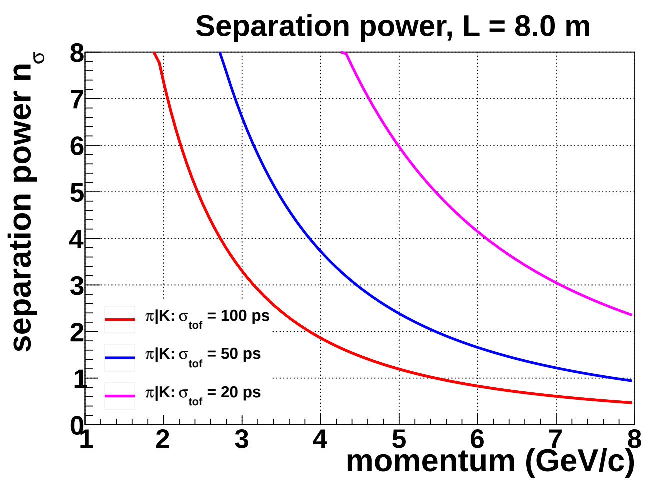

Figure 5: Kaon identification by TOF.

We have studied kaon identification for SoLID to potentially extend its physics programs. A full RICH detector for kaon detection is likely to be too costly to consider. High resolution TOF is a more practical solution. SoLID needs kaon identification over a momentum range of 1 GeV/c to 7 GeV/c. Given the $\sim$ 8 meter flight distance, a TOF time resolution of 20 ps is required to obtain a 3 sigma separation between pions and kaons as shown in Figure 5. A promising avenue is to improve the timing of the planned SoLID TOF-MRPC detector. The baseline MRPC is designed to reach 80 ps time resolution in the SoLID high-rate environment. Bench testings of thin-gap MRPC prototype detectors demonstrated the potential to reach a resolution of sub-20 ps [9, 10]. A planned R&D effort by a Chinese collaboration (Tsinghua University, USTC and CCNU) on the next generation MRPC jointly for SoLID, sPHENIX and EIC is being pursued, aiming for 20 ps resolution in a high-rate environment. The plan is to develop a prototype and readout electronics system next year. Beam test and finalization of the detector and electronics will be done in the following year.

4 Experimental Design, Simulation and Feasibility

4.1 Solenoidal Magnet

The CLEO II magnet was removed from the CESR beamline by Cornell University and JLAB personnel during the 2016 summer down. All ancillary power, cryogenic and control services were disconnected from the magnet in preparation for iron removal. The iron was removed layer by layer and stored at the Cornells laydown yard until

2017 when it will be shipped to JLAB. With the cryostat exposed, the axial transport brackets were installed and the cryostat moved to the transport frame. The service turret and neck were removed to reduce the height of the cryostat for safe highway transit. The entire unit was wrapped in marine grade shrink wrap to provide a weather barrier for the trip to JLAB. Three-axis accelerometers were mounted to the cryostat to monitor loads during the road trip. All loads remained under allowable thresholds specified in the Oxford CLEO II Operating Manual. Upon arrival at JLAB in November 2016, the magnet was rolled into the Test Lab for climate controlled storage, as shown in Figure 6. We are making plans of testing the magnet with a new power supply and in-situ mapping.

Figure 6: CLEO II magnet at JLab.

4.2 Acceptance, Efficiency and Systematics

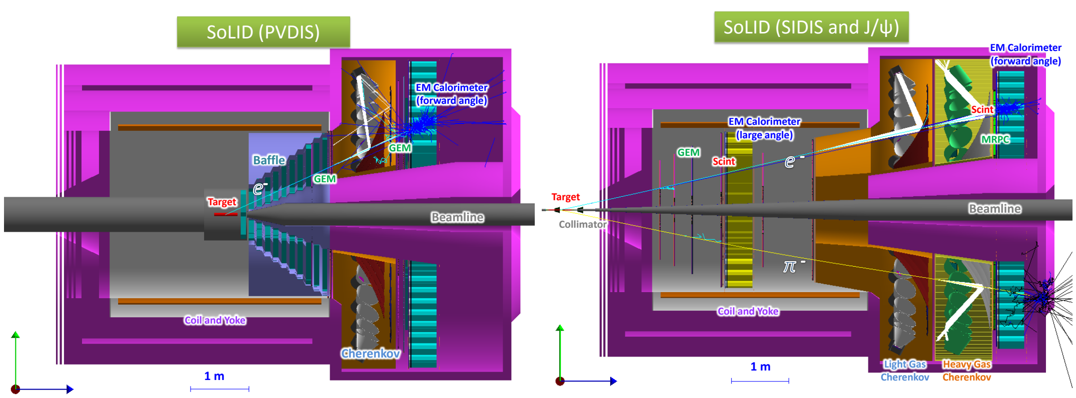

Figure 7: Left: SoLID PVDIS setup. Right: SoLID SIDIS and J/ψ setup.

The SoLID setups [8] for the PVDIS and the SIDIS and J/ψ configurations are shown in Figure 7. Substantial progress has been made in developing a SoLID simulation package with realistic subsystem responses that includes all elements of the apparatus, EM shower in the electromagnetic calorimeter, optical process in the two Cherenkov detectors, energy deposition in GEM and MRPC and their digitizations. A new event generator has been used for the estimation of hadron background rates. The simulation package allowed detailed simulations of the performance and feasibility of all core measurements, namely the PVDIS, SIDIS and J/ψ measurements.

A Kalman Filter based track finding and fitting algorithm is being developed and tested with digitized GEM simulation data. Tracking resolution from the simulated tracking fitting results including all material effects was studied. With background taken into account, tracking efficiency was obtained with the simulation. We have good

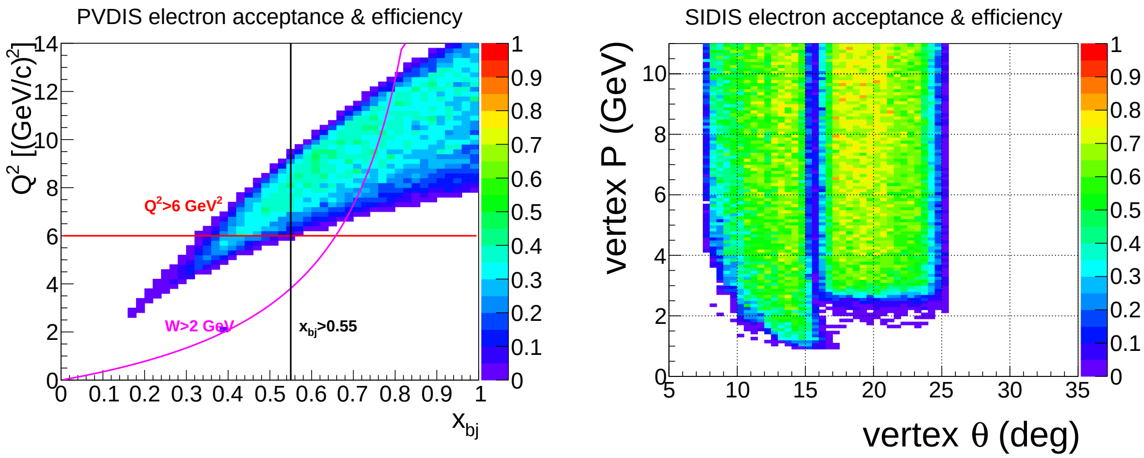

Figure 8: Left panel: electron acceptance and efficiency (except tracking) of SoLID PVDIS with the 40 cm LD2 target and baffle. Curves show bounds of the kinematic range with $Q^2 > 6$ GeV^2, $W > 2$ GeV, and $x_{bj} > 0.55$. Right panel: electron acceptance and efficiency (except tracking) of SoLID SIDIS with the 40 cm ^{3}He target and two target window collimators. The result for J/ψ has a similar shape, but higher values because it has a 15 cm long target and no collimator.

Table 1: Average electron detection efficiencies of all SoLID sub-detectors and the total SoLID efficiency.

Detector	EC	Cerenkov	Scintillator pad and MRPC	GEM tracking	Total
average efficiency	95%	95%	98%	90%	80%

electron detection efficiency from all sub-detectors. They vary slightly across the phase space and the average efficiency values are shown in Table 1. The PVDIS setup with its 40 cm long LD2 target has acceptance ~ 0.35 due to the baffle and the SIDIS setup with its 40 cm long ^{3}He target has acceptance ~ 0.7 due to the two target window collimators. Figure 8 shows the combined effect of acceptance and efficiency (except tracking) for the two configurations. Systematic uncertainties for PVDIS and SIDIS are summarized in Table 2. The total systematic uncertainty for J/ψ is about 11%, dominated by acceptance, and the bin-migration effect is expected to be small. These results were used as the inputs to the physics projections.

Table 2: The systematic uncertainties on the asymmetry measurements of PVDIS and SIDIS.

PVDIS Systematic (rel.)		SIDIS Systematic (abs.)		SIDIS Systematic (rel.)	
Polarimetry	0.4%	Raw asymmetry	0.0014	Target polarization	3%
Q^2	0.2%	Detector resolution	< 0.0001	Nuclear effect	$(4-5)\%$
Radiative corrections	0.2%			Random coincidence	0.2%
Reconstruction errors	0.2%			Radiative correction	$(2-3)\%$
				Diffractive meson	3%
Total	0.6%	Total	0.0014	Total	$(6-7)\%$

4.3 Rates and Data Acquisition

The trigger rates were simulated with the full background. (Table 3) The SIDIS configuration, with an expected trigger rate of 100 kHz and total data rate of over 3 GB/s represents the greatest challenge for SoLID data acquisition. Recent performance of the GlueX and HPS DAQs with extrapolations by the JLab data acquisition and fast electronics groups give confidence that trigger rates of 100 kHz and above are achievable. Data for each of the 30 sectors of SoLID will pass through two readout controllers (ROCs), a PC based ROC for GEM data, and a VME ROC for all other detectors. The portion of the total data rate for non-GEM detectors, about 400 MB/s, is less than 15 MB/s per VME crate, so will not limit the trigger rate at 100 kHz. GEM detector trigger rates of 50 kHz have been obtained by HPS using an APV25 sample size of six. With a planned sample size of one for SIDIS, the GEM readout will not be limited to 100 kHz. The overall data rate required by SIDIS, which exceeds the rate currently achieved by GlueX, can be recorded by multiplexing data from the readout controllers to multiple event building computers. Designing a DAQ system with 60 ROCs that can handle data rates of several GB/s will require some R&D, including firmware and software improvements, but is feasible using technology currently in use at JLab.

Table 3: Rates, run times and data total estimates for the PVDIS, SIDIS and J/Ψ experiments. For PVDIS, there are 30 sectors each of which has a separate DAQ.

Experiment	PVDIS	SIDIS ^{3}He	J/ψ
Trigger rate (expected) (kHz)	15×30	100	30
Data rate (GB/s)	0.2×30	3.2	2.5
Running time (days)	169	125	60
Total data (PB)	175	70	25

5 Summary

The strong and unique physics programs with PVDIS, SIDIS and J/ψ production are presented in the context of the worldwide effort. The science related recommendations from the Director's Review committee have been addressed. The science reach, unique strength and feasibility of the SoLID program demonstrate that we are ready for the next step: the anticipated Science Review by DOE.

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