Overview of the proposed Solenoidal Large Intensity Device (SoLID) and its physics programs at Jefferson Lab

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On behalf of the SoLID Collaboration

JLab Hall A/C Collaboration Meeting
July 8-9, 2021
Outline

• Introduction

• The three pillars of the SoLID program
  • Nucleon 3-D momentum tomography with SIDIS
  • QCD with PVDIS
  • Quantum anomalous energy with J/Ψ

• SoLID run-group proposals

• The SoLID device

• Summary
SoLID will maximize the science return of the 12-GeV CEBAF upgrade by combining...

**High Luminosity**

$10^{37-39}/\text{cm}^2/\text{s}$

[$>100\times \text{CLAS12}$][$>1000\times \text{EIC}$]

**Large Acceptance**

Full azimuthal $\phi$ coverage

Research at SoLID will have a unique capability to explore the QCD landscape while complementing the research of other key facilities.
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- Pushing the phase space in the search of new physics and of hadronic physics
- 3D momentum imaging of a relativistic strongly interacting confined system (*nucleon spin*)
- Superior sensitivity to the differential electro- and photo-production cross section of $J/\psi$ near threshold (*proton mass*)
SoLID@12-GeV JLab: QCD at the intensity frontier

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**Synergizing with the pillars of EIC science**

(proton spin and mass) through high-luminosity valence quark tomography and precision \(J/\psi\) production near threshold
Nucleon Structure from 1D to 3D – orbital motion

5-D Wigner distribution

Image from J. Dudek et al., EPJA 48,187 (2012)

Generalized parton distribution (GPD)
Transverse momentum dependent parton distribution (TMD)

X.D. Ji, PRL91, 062001 (2003);
Belitsky, Ji, Yuan, PRD69,074014 (2004)
## TMDs – confined motion inside the nucleon

**Leading twist: 8 TMDs**

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Quark polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-Polarized</td>
<td>Longitudinally Polarized</td>
</tr>
<tr>
<td>$f_1$</td>
<td>$g_1$</td>
</tr>
<tr>
<td>$f_{1T}$</td>
<td>$g_{1T}$</td>
</tr>
</tbody>
</table>

- $f_1$ = \( \text{Boer-Mulder} \)
- $g_1$ = \( \text{Helicity} \)
- $g_{1T}$ = \( \text{Transversity} \)
- $h_1 = \text{Pretzelosity}$

→ Nucleon Spin
→ Quark Spin
**TMDs – confined motion inside the nucleon**

**Transversity**

Transversely Polarized Nucleon TMDs

- **Nucleon Spin**
- **Quark Spin**

\[ h_{1T} = S_T \cdot s_q \]

**Relevant Vectors**

- **S\(_T\):** Nucleon Spin
- **s\(_q\):** Quark Spin
- **k\(_\perp\):** Quark Transverse Momentum
- **P:** Virtual photon 3-momentum (defines z-direction)

- \( h_{1T} (h_1) = g_1 \) (no relativity)
- \( h_{1T} \) tensor charge (lattice QCD calculations)
- Connected to nucleon beta decay and EDM

**Sivers**

\[ f_{1T}^\perp = S_T \cdot k_\perp \times P \]

- Nucleon spin - quark orbital angular momentum (OAM) correlation – zero if no OAM (model dependence)

**Pretzelosity**

\[ h_{1T}^\perp = S_T \cdot [k_\perp k_\perp] \cdot s_{qT} \]

- Interference between components with OAM difference of 2 units (i.e., s-d, p-p) (model dependence)
- Signature for relativistic effect
SIDIS SSAs depend on 4-D variables \((x, Q^2, z, P_T)\) and small asymmetries demand **large acceptance + high luminosity** allowing for measuring asymmetries in 4-D binning with precision!

\[
A_{UT}(\phi_h, \phi_S) = \frac{1}{P_{t,pot}} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}
\]

Leading twist formulism
(higher-twist terms can be included)

\[
= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)
\]
Separation of Collins, Sivers and Pretzelosity through angular dependence

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\[
A_{UT}(\phi_h, \phi_S) = \frac{1}{P_{t,pol}} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}
\]

Leading twist formulism
(higher-twist terms can be included)

\[
A_{UT} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp
\]

Collins fragmentation
function from \( e^+e^- \) collisions

\[
A_{UT} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp
\]

Unpolarized fragmentation function

\[
A_{UT} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1
\]
QCD intensity frontier with SoLID: large-acceptance & high luminosity

**Quantum leap: 4-D binning for the first time!**

SoLID-SIDIS program: Large acceptance, Full azimuthal coverage + High luminosity
- 4-D mapping of asymmetries with precision
  $$\Delta z = 0.05, \Delta P_T = 0.2 \text{ GeV}, \Delta Q^2 = 1 \text{ GeV}^2,$$  
  $x$ bin sizes vary with median bin size 0.02 (statistical uncertainty for each bin: $\delta A \leq 0.02$)
- Constrain models and forms of TMDs, Tensor charge, …
- Lattice QCD, QCD dynamics, models

- More than 1400 bins in $x$, $Q^2$, $P_T$ and $z$ for 11/8.8 GeV beam.
SIDIS with polarized “neutron” and “proton” @ SoLID

E12-10-006: Single Spin Asymmetries on Transversely Polarized $^3$He @ 90 days
Rating A
Spokespersons: J.P. Chen, H. Gao (contact), J.C. Peng, X. Qian

E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized $^3$He @ 35 days
Rating A
Spokespersons: J.P. Chen (contact), J. Huang, W.B. Yan

E12-11-108: Single Spin Asymmetries on Transversely Polarized Proton @ 120 days
Rating A
Spokespersons: J.P. Chen, H. Gao (contact), X.M. Li, Z.-E. Meziani

Run group experiments approved for TMDs, GPDs, and spin
- Coincidence detection of electrons and charged pions: good PID for electrons (LGC+EC); moderate PID for pions (HGC)
- $^3$He target: transverse and longitudinal in-beam polarizations of $\sim 60\%$; NH$_3$ target: in-beam transverse polarization $\sim 70\%$
- Large acceptance with full azimuthal coverage @ pol. Lumi. $10^{36}$ cm$^2$ s$^{-1}$ ($^3$He), $10^{35}$ cm$^2$ s$^{-1}$ (NH$_3$); 4-d kinematic binning requires good momentum and angular resolutions – GEMs offer excellent tracking capability
- DAQ rate: up to 100 KHz (unpol. Lumi $10^{37}$ cm$^2$ s$^{-1}$ ($^3$He))

**MRPC:** enhanced configuration for kaon and improved pion detection

**HGC performance at 2.5-3.0GeV, 8-9deg**

- $\pi$ efficiency ($\sim 0.9$)
- $K_{\text{rej}} \sim 10$

**SIDIS & J/$\Psi$**:

- 4xGEMs
- LASPD
- LAEC
- 2xGEMs
- LGC
- HGC
- FASPD (MRPC)
- FAEC

Combined light gas Cherenkov and Calorimeter detector performance

$\pi/e^-$ ratio (%) after $\pi^-$ rejection

MRPC: enhanced configuration for kaon and improved pion detection
• Fit Collins and Sivers asymmetries in SIDIS and $e^+e^-$ annihilation
• World data from HERMES, COMPASS
• $e^+e^-$ data from BELLE, BABAR, and BESIII
• Monte Carlo method is applied
• Including both systematic and statistical uncertainties

SoLID baseline used

Anselmino et al., JHEP 04 (2017) 046
Off the simplest isoscalar nucleus and at high Bjorken $x$

\[ A_{PV} = \frac{G_F Q^2}{2\sqrt{2} \pi \alpha} \left[ g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y) F_3^{\gamma Z}}{2 F_1^{\gamma}} \right] \]

\[ Q^2 >> 1 \text{ GeV}^2, \ W^2 >> 4 \text{ GeV}^2 \]

\[ A_{PV} = \frac{G_F Q^2}{\sqrt{2}} \left[ a(x) + f(y) b(x) \right] \]

$y \equiv 1 - E'/E$

$R(x, Q^2) = \sigma^l/\sigma^r \approx 0.2$

At high $x$, $A_{iso}$ becomes independent of pdfs, $x$ & $W$, with well-defined SM prediction for $Q^2$ and $y$
12 GeV CEBAF: Extraordinary opportunity to do the ultimate PVDIS measurement

**Strategy:** sub-1% precision over broad kinematic range: sensitive Standard Model test and detailed study of hadronic structure contributions

Spokesperson: Paul Souder
**SoLID Apparatus**

- **Kinematic Requirements**
  
  (x: 0.25-0.7: untangle physics
  \[ W^2 > 4 \text{ GeV}^2 \], isolate DIS
  \[ Q^2 \] range a factor of 2 for each x bin:
  
  Measure Higher Twist

- **Achieving High Luminosity**

  (target, beam current, GEMs, Baffles)

- **Requirements for Particle Identification and Trigger**

  (light gas Cherenkov,
  identify electrons for trigger;
  EMcal (coincident trigger, further pid,..)

- CLEO magnet with the LD\(2\) or LH\(2\) target in the center provides the desired acceptance.

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Baffle  5xGEMs  EC

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Vladimir Khachatryan
With this precision, SoLID makes a unique contribution to the SMEFT program.

Improvement in couplings

Improvement in energy reach for electron-nucleon couplings

Published data
Published data + P2
Published data + P2 + SoLID
PVDIS is complementary to the rest of the JLab d/u program.  
**PVDIS has no nuclear effects**

\[
A_{PV} = \frac{G_F Q^2}{\sqrt{2}} [a(x) + f(y)b(x)]
\]

\[
A_{PVDIS}^p(x) \approx \frac{u(x) + 0.91 d(x)}{u(x) + 0.25 d(x)}
\]

Proton Mass and Quantum Anomalous Energy

• Nucleon mass is the total QCD energy in the rest frame (QED contribution small)

\[ H_{QCD} = H_q + H_m + H_g + H_a \]

- \( H_q \) = Quark energy \[ \int d^3x \psi^\dagger (-i\mathbf{D} \cdot \mathbf{\alpha}) \psi \]
- \( H_m \) = Quark mass \[ \int d^3x \bar{\psi} m \psi \]
- \( H_g \) = Gluon energy \[ \int d^3x \frac{1}{2} (\mathbf{E}^2 + \mathbf{B}^2) \]
- \( H_a \) = Quantum Anomalous energy \[ \int d^3x \frac{9\alpha_s}{16\pi} (\mathbf{E}^2 - \mathbf{B}^2) \]

Sets the scale for the hadron mass!

X. Ji  PRL 74 1071 (1995),
X. Ji & Y. Liu, arXiv: 2101.04483

C. Alexandrou et al., (ETMC), PRL 119, 142002 (2017)
Y.-B. Yang et al., (χQCD), PRL 121, 212001 (2018)

• Measuring quantum anomalous energy contribution in experiments is an important goal in the future

Can be accessed through heavy quarkonium threshold (J/psi & Upsilon) production,
From Cross section to the Trace Anomaly

VMD relates photoproduction cross section to quarkonium-nucleon scattering amplitude

- **Imaginary part** is related to the total cross section through optical theorem
- **Real part** contains the conformal (trace) anomaly; Dominates the near threshold region and is constrained through dispersion relation

\[
\frac{d\sigma_{\gamma N \rightarrow \psi N}}{dt}(s, t = 0) = \frac{3\Gamma(\psi \rightarrow e^+e^-)}{\alpha m_\psi} \left( \frac{k_{\gamma N}}{k_{\gamma N}} \right)^2 \frac{d\sigma_{\psi N \rightarrow \psi N}}{dt}(s, t = 0)
\]

\[
\frac{d\sigma_{\psi N \rightarrow \psi N}}{dt}(s, t = 0) = \frac{1}{64\pi m_\psi^2 (\lambda^2 - m_N^2)} |M_{\psi N}(s, t = 0)|^2
\]

Heavy quark – dominated by two gluons

\[
\langle P | T_\alpha | P \rangle = 2P^\alpha P_\alpha = 2M_p^2
\]

A measurement near threshold could allow access to the trace anomaly

Y. Hatta et al., PRD 98 no. 7, 074003 (2018)
Y. Hatta et al., 1906.00894 (2019)
50 days of $3\mu A$ beam on a 15 cm long LH$_2$ target at 10 more days including calibration/background run
SoLID configuration overall compatible with SIDIS

**Electroproduction trigger:** 3-fold coincidence of $e, e^-e^+$

**Photoproduction trigger:** 3-fold coincidence of $p, e^-e^+$

**Additional trigger:** 4-fold coincidence of $ep, e^-e^+$
And (inclusive) 2-fold coincidence $e^+e^-$

\[
e^- + p \rightarrow e^- + p + J/\psi (e^+ + e^-)
\]

\[
\gamma p \rightarrow p' J/\psi (e^- e^+)
\]

Spokespersons: K. Hafidi, X. Qian, N. Sparveris, Z.-E. Meziani (contact), Z. Zhao

Haiyan Gao
Sensitivity at threshold at about $10^{-3}$ nb!
Impact on the Quantum Anomalous Energy Extraction and the EIC

Charm @ SoLID

S. Joosten, Z.E. Meziani, PoS 308 (2017) doi.org/10.22323/1.308.0017

Gryniuk, Joosten, Meziani, and Vanderhaeghen, PRD 102, 014016 (2020) (for update)

Beauty @ EIC

Following the 2015 Director’s Review recommendation “The SoLID Collaboration should investigate the feasibility of carrying out a competitive GPD program. Such a program would seem particularly well suited to their open geometry and high luminosity”, there are several GPD experiments in different stages of study/approval:

- **Deep Exclusive $\pi^-$ Production using Transversely Polarized $^3$He Target**
  - G.M. Huber, Z. Ahmed, Z. Ye
  - Approved as run group with Transverse Pol. $^3$He SIDIS (E12-10-006B)

- **Timelike Compton Scattering (TCS)** with circularly polarized beam and unpolarized LH$_2$ target
  - Z.W. Zhao, P. Nadel-Turonski, J. Zhang, M. Boer
  - Approved as run group with J/$\psi$ (E12-12-006A)

- **Double Deeply Virtual Compton Scattering (DDVCS)** in di–lepton channel on unpolarized LH$_2$ target
  - E. Voutier, M. Boer, A. Camsonne, K. Gnanvo, N. Sparveri, Z. Zhao
  - LOI12-12-005 reviewed by PAC43

- **DVCS** on polarized proton and 3He targets
  - Z.Y. Ye, N. Liyanage, W. Xiong, A. Cansomme and Z.H. Ye (under study)
Other approved SoLID run group experiments

- SIDIS Dihadron with Transversely Polarized $^3$He
  J.-P. Chen, A. Courtoy, H. Gao, A. W. Thomas, Z. Xiao, J. Zhang
  Approved as run group (E12-10-006A)

- SIDIS in Kaon Production with Transversely Polarized Proton and $^3$He
  T. Liu, S. Park, Z. Ye, Y. Wang, Z.W. Zhao
  Approved as run group (E12-11-108B/E12-10-006D)

- Ay with Transversely Polarized Proton and $^3$He
  T. Averett, A. Camsonne, N. Liyanage
  Approved as run group (E12-11-108A/E12-10-006A)

- g2n and d2n with Transversely and Longitudinally Polarized $^3$He
  C. Peng, Y. Tian
  Approved as run group (E12-11-007A/E12-10-006E)
Summary

• SoLID: A large acceptance device which can handle very high luminosity to allow full exploitation of JLab12 potential → pushing the limit of the luminosity frontier
• SoLID has rich and vibrant science programs complementary and synergistic to the proposed EIC science program
  Three pillars on SIDIS, PVDIS and J/ψ production
  A diverse set of approved run-group experiments including GPD program
• After a decade of hard work, we have a mature pre-conceptual design with expected performance to meet the challenging requirements for the three major science programs
• Recently completed the DOE science review (March 8-10, 2021)
• SoLID collaboration is active and international with many theory collaborators
• We welcome new collaborators!

Acknowledgement: Haiyan Gao, Jian-Ping Chen, Zein-Eddine Meziani, Paul Souder, Jianwei Qiu, Xiangdong Ji, Thia Keppel, Steve Wood, Rolf Ent and many others in the SoLID collaboration, supported in part by the U.S. Department of Energy under contract number DE-FG02-03ER41231

https://solid.jlab.org/