# Run Group H Jeopardy Update Document
# CLAS12 Experiments with a Transversely Polarized Target

The RGH Team
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This document provides an update on the physics case and preparatory work for the C1 conditionally approved CLAS12 deep-inelastic scattering (DIS) experiments with a transversely polarized target, identified as run-group H.

## I. INTRODUCTION

**The CLAS12 run-group H (RGH) comprises 3 experiments approved with rating A by PAC39 to run for a total of 110 days with a 11 GeV beam scattering off a transversely polarized target.**

- **C12-11-111** contact: M. Contalbrigo, *Transverse spin effects in SIDIS at 11 GeV with a transversely polarized target using CLAS12*: a multi-dimensional analysis of the semi-inclusive (SIDIS) reactions to access transversity and tensor charge, and the Sivers and Collins functions (among others) connected with the spin-orbit phenomena of the strong-force dynamics [1];
- **C12-12-009** contact: H. Avakian, *Measurement of transversity with dihadron production in SIDIS with transversely polarized target*: a multi-dimensional analysis of the SIDIS reactions exploiting the dynamics of the di-hadron final state to access transversity in the benchmark collinear limit and investigate novel parton correlations inaccessible on the single hadron case [2].
- **C12-12-010** contact: L. Elouadrhiri, *Deeply Virtual Compton Scattering at 11 GeV with transversely polarized target using the CLAS12 Detector*: a multi-dimensional analysis of the exclusive reactions to access the most elusive parton distributions entering the orbital momentum sum rule (Ji sum rule) [3].

The experiments where approved with the C1 condition to address the technical issues related to the target performance with the laboratory management before scheduling [4]: "One has to achieve at least within a factor 2 the figure-of-merit determined by the target design value (I=1 nA and 60% polarization) and a spin relaxation time of 50 days at 1 nA before the experiments with the transversally polarized target are approved."

**All the three experiments were selected among the high-impact JLab measurements by PAC42 [5].**

RGH experiments are precursor of EIC in one of the pillars of its physics program [6]. Distinctive features in common of all the three experiments are the precise measurement of novel parton distributions and phenomena in an unexplored valence region where their magnitude could be maximal, a luminosity at least on order of magnitude higher than the precursor experiments, a large acceptance detector for the disentanglement of the various correlations and kinematic regimes, an excellent particle identification capability to access flavor sensitivity, the development of innovative solutions for the transversely polarized target to reach the best factor of merit and kinematic coverage.

## II. PHYSICS HIGHLIGHTS

In the recent years, new parton distributions (PDFs) and fragmentation functions (FFs) have been introduced to describe the rich complexity of the hadron structure, focusing on the parton transverse degrees of freedom at the scale of confinement and moving toward the achievement of a 3D description of the parton dynamics. Relevant examples are transverse momentum dependent (TMD) and generalized (GPD) parton distributions, relating the intrinsic partonic transverse momentum and position, respectively, with the longitudinal (referred to the direction of the hard probe) momentum fraction. Their detailed investigation requires a novel level of sophistication in the deep-inelastic scattering (DIS) experiments that should conjugate precision, in discriminating semi-inclusive and exclusive reaction details, and power, in collecting large amount of data to allow multidimensional analyses.

**The CLAS12 run-group H program comprises several fundamental measurements that provide access to elusive quantities and are only possible with the use of a transversely polarized target in conjunction with a large acceptance high-precision spectrometer.**

The **Transversity** PDF describes the parton transverse polarization inside a transversely polarized nucleon, reflects the relativistic nature of the parton confinement and exhibits peculiar evolution properties. It is the less known PDF that does not vanish when integrated in the transverse momentum $k_\perp$, and can thus be studied over the collinear limit. Although essential for the nucleon description, due to its chirally-odd nature transversity has only recently been accessed in a limited kinematic range and with a large uncertainty that still prevents a reliable flavor decomposition [7]. Its first moment in Bjorken $x$, the tensor charge, is a fundamental quantity in quantum chromodynamics (QCD) connected to searches of beyond Standard Model phenomena such as the Electric Dipole Moment (EDM) of particles [8] and the tensor interaction [9]. CLAS12 data will extend in the unexplored valence interval of Bjorken-x, provide unprecedented constraints to the tensor charge and allow precise comparison with lattice QCD, which has made remarkable progresses in the past decades [10].

The **Sivers** PDF is a genuine TMD function which vanishes with $k_\perp$ integration. Among the most intriguing parton distributions, it requires a non-zero parton orbital angular momentum and a correlation with the nucleon spin. As a consequence of its non-trivial gauge-invariant definition, the Sivers function probes QCD at the amplitude level: it is naively T-odd (does not violate T-invariance due to the interaction phase) and exhibits a peculiar process dependence. A sign change is expected moving from SIDIS to Drell-Yan processes, whose verification is one of the most urgent goals of the present experimental activity [7]. It is among the few TMDs that, while describing the non-perturbative nature when $k_\perp \ll Q^2$, should in principle match the perturbative regime with increasing transverse momentum, providing a formal bridge between the two QCD descriptions [11]. CLAS12 data will allow an extended coverage and a disentanglement of the Sivers kinematic dependences, a crucial information for the study of these phenomena and the connections among different QCD regimes.

The **Collins** and **Di-hadron** FFs originate from spin-orbit effects connecting the spin of a fragmenting quark with the final observed hadron or di-hadron transverse momentum, respectively. Convincing evidences have been found for the existence of these mechanisms [7]. These peculiar FFs act as a polarimeter and allow one to access the elusive chirally-odd distribution functions in SIDIS reactions. In particular the Di-hadron FF, sensitive to the hadron pair *relative* transverse momentum, can be studied in the collinear limit providing a complementary access to transversity that does not depend on the TMD formalism, and can be reliably extended to the hadron-hadron scattering case [12]. High precision data from CLAS12 can complement present and future information gathered at the much higher center-of-mass energy of experiments at the $e^+e^-$ colliders, like BELLE-II [13], and at hadron-hadron colliders, like PHENIX and STAR [14].

The **GPD E** describes asymmetries in the parton spatial distribution that imprint the underlying confinement dynamics. It it the least known GPD that enters the Ji sum rule quantifying the parton orbital momentum [15]. Its measurement in the golden deeply-virtual Compton scattering (DVCS) channel requires a transversely polarized proton target as a complementary approach to the beam spin asymmetry off an unpolarized neutron target [16]. As the latter is among the goals of RGB experiments that already begun to take data, both measurements can be accomplished at CLAS12 providing an unprecedented level of information.

## III. THE CLAS12 SPECTROMETER

The CLAS12 spectrometer has been designed to run at high luminosity, up to about 3 orders of magnitude higher than the precursor experiments like HERMES and COMPASS, and bring the 3D nucleon structure study into the precision phase. CLAS12 started the data-taking with unpolarized hydrogen targets in spring 2018 and has so far successfully run with different targets and detector configurations. Detailed calibration procedures and event reconstruction algorithms have been developed to reach a performance close to, or in same case superior of, the design specifications.

With respect to the goals of run-group H, the spectrometer has specifically demonstrated to be able to achieve the following performance.

**Luminosity:** CLAS12 run with hydrogen and deuterium targets, and reached the design luminosity of $10^{35}$ cm$^{-2}$s$^{-1}$ with a deuterium target and 45 nA electron beam current. This is much higher than the luminosity L $= 5{\cdot}10^{33}$ cm$^{-2}$s$^{-1}$ assumed for the RGH experiments as being sustainable by the transverse target.

**Detector Occupancy:** CLAS12 has measured the hit occupancy levels in the Drift Chambers (DC), the most sensitive detectors, as a function of the beam intensity and solenoid current, see left panel of Fig. 1. As the hit occupancy is observed to increase linearly with the beam current [17], the value extrapolated at the anticipated transverse target working point, (40% solenoid current and few nA beam current), is below 2% in accordance with the proposal. This estimate takes into account that RGH experiments will run with no Forward Tagger (FT-OFF) and additional shielding elements installed, and that the compact target holding field has been shown to cause only a modest increase of the Moeller background.

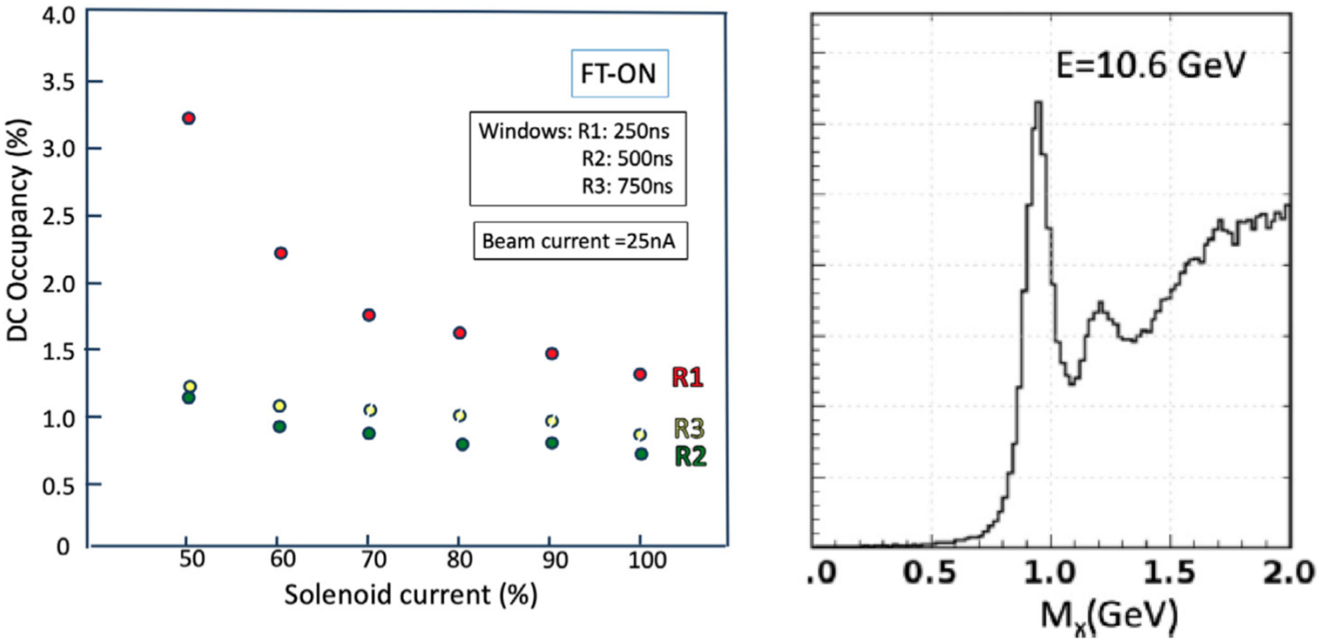


FIG. 1. Left panel: The measured DC hit occupancy as a function of the current in the solenoid magnet at 25 nA beam current [17]. Right panel: Missing mass distribution for the reaction $ep \to e'pX$ with sharp peaks at the neutron and $\Delta(1232)$ mass [17].

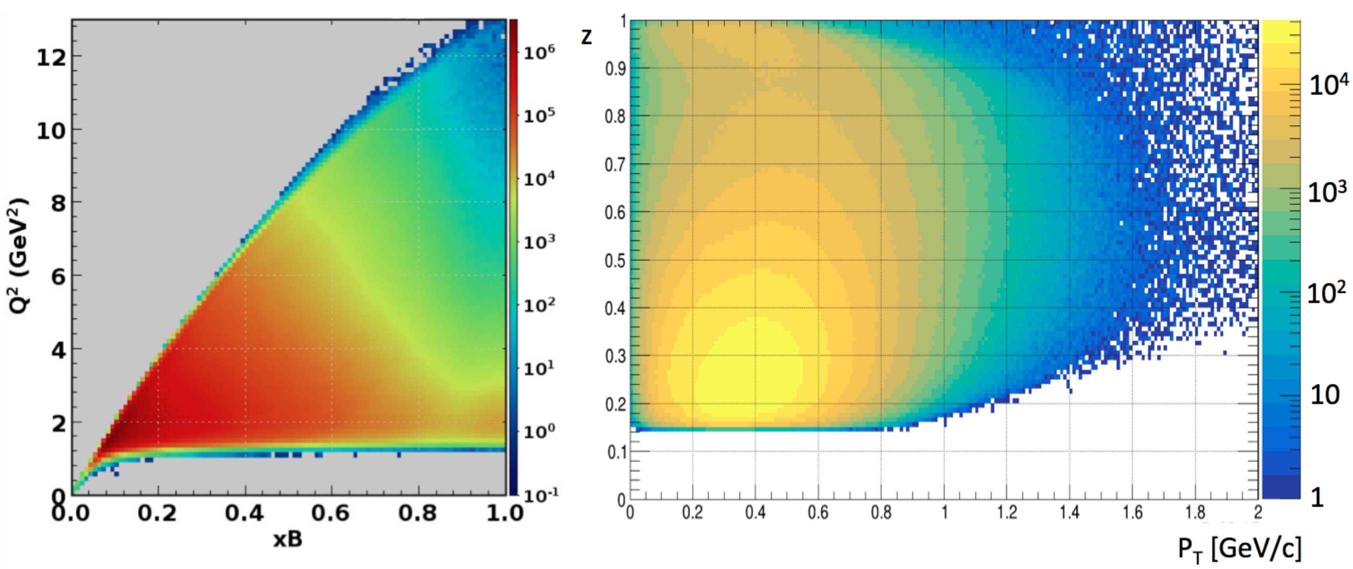


FIG. 2. The CLAS12 reach in the relevant kinematic variables at a beam energy of 10.6 GeV. Left panel: Inclusive electron coverage in the hard scale $Q^2$ versus Bjorken $x$ [17]. Right panel: Charged hadrons coverage in the fractional energy $z$ versus the transverse momentum $P_T$. An excess of exclusive $e'n\pi^+$ events is visible at large values of $z$.

**Tracking** The single track reconstruction efficiency is well above 90% at the RGH foreseen luminosity. The measured resolutions in the relevant kinematic quantities at the much higher 60 nA beam current are $\Delta p/p = 0.67\%$, $\Delta\theta = 0.85$ mrad and $\Delta v_z = 4.6$ mm, in line with the design specifications of a resolution better than 1% in momentum and 1 mrad in azimuthal angle [17].

**Scattering Electron** The efficiency of the CLAS12 trigger for DIS events, with the electron scattered inside the acceptance at an energy above 1.5 GeV, is greater than 99% [18]. Electrons are identified by a combination of signals in the Cherenkov counters and calorimeters. Thanks to the large acceptance of CLAS12, scattering electrons are detected in a wide kinematic range from elastic events, see right panel of Fig. 1, to DIS with an extended reach at large values of $Q^2$, Bjorken $x$, and forward hadron kinematics, see Fig. 2.

**Recoil Particle** Whilst the reconstruction algorithm is still in evolution, the central detector has proven to be able to correlate the recoil particle with the event in the forward detector, to identify charged hadrons and to distinguish neutron from photons, see Fig. 3. These features are instrumental for the selection of specific exclusive events originating from the scattering off a given target nucleon.

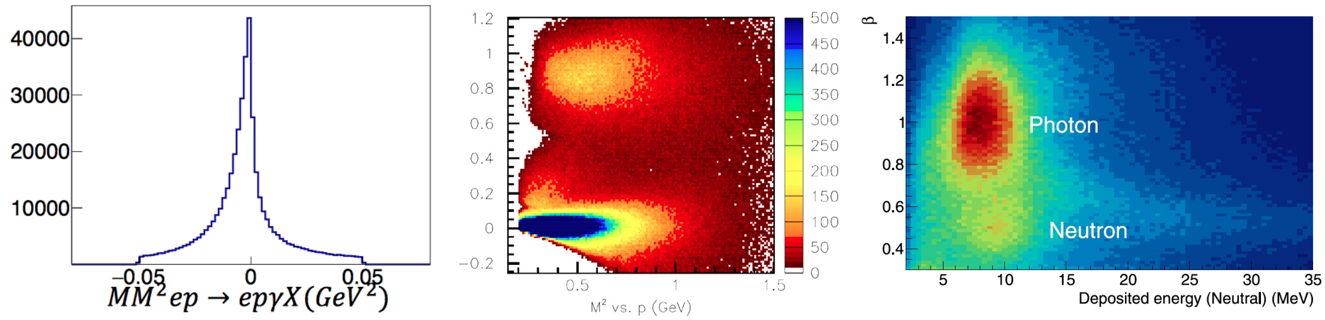


FIG. 3. Left panel: Missing mass distribution for DVCS candidates presented at DNP19. Central panel: Hadron identification in the central time-of-flight system [17]. Right panel: Neutron and photon separation in the central neutron detector [17].

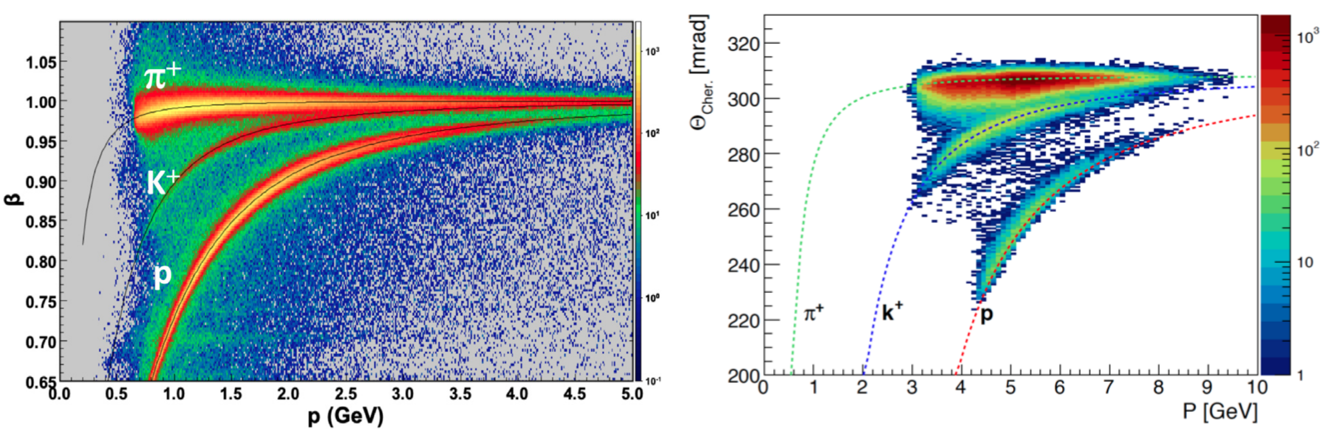


FIG. 4. Left panel: The hadron separation provided by the Forward time-of-flight system [17]. Right panel: The hadron separation obtained by the RICH detector [19].

**Hadron PID** Identification of hadron particles is essential to gather flavor information in SIDIS observables. The CLAS12 forward time-of-flight system (FTOF) provides an excellent pion separation from kaons and protons at momenta up to about 3 GeV/c and 5 GeV/c, respectively, see left panel of Fig. 4. To complement such CLAS12 baseline configuration and provide hadron separation in the whole range of interest for SIDIS physics, up to momenta of 8 GeV/c, a ring-imaging Cherenkov detector (RICH) has been anticipated at the time of the proposal. The RICH has been designed as composed by two modules in a left-right symmetric configuration, to reduce the systematic effects in observables dependent on the target transverse polarization. The peculiar geometry of CLAS12 suggested an innovative hybrid-optics solution to limit the active area to about 1 m$^2$ per sector, with part of the light directly imaged and part of the light detected after reflection from mirrors. In order to limit the material inside the acceptance and realize a light but stiff structure, composite materials derived from aeronautic applications have been employed.

Improvements have been pursued in all the components, achieving the world leading aerogel radiator clarity of 0.0050 $\mu m^4\, cm^{-1}$ at high refractive index (n=1.05), a 20% reduction of the aerial density of spherical mirrors in carbon fiber composite polymer with respect to the LHCb realization, the first use of glass-skin planar mirrors in a nuclear physics experiment, the first use of the flat-panel multianode H12700 photomultiplier with a dynode structure dedicated to the single photon detection. The first module has been completed and installed before the start of CLAS12 data taking. A preliminary data analysis shows that the CLAS12 RICH is able to match the required time and Cherenkov angle resolutions, and provides hadron separation in the wanted momentum range, see right panel of Fig. 4. The second module is in construction and expected to be ready in 2021, in advance of the RGH experiment schedule.

**Physics Observables** Physics analyses are in progress based on the 12 GeV data. Preliminary results for both the SIDIS and exclusive channels have been release by the Collaboration and presented at the conferences. As an example, the beam spin asymmetry of SIDIS $\pi^+$ and DVCS events, based on a few percent of the recorder statistic, are shown in Fig. 5. Data confirm that CLAS12 allows a much extended reach inside the DIS regime (large $Q^2$) and a significant increase in statistics with respect to CLAS. With the improved knowledge of the instrumental effects, and the refinement of the calibration procedures and reconstruction algorithms, further progresses on the CLAS12 performance are expected before the start of RGH experiments.

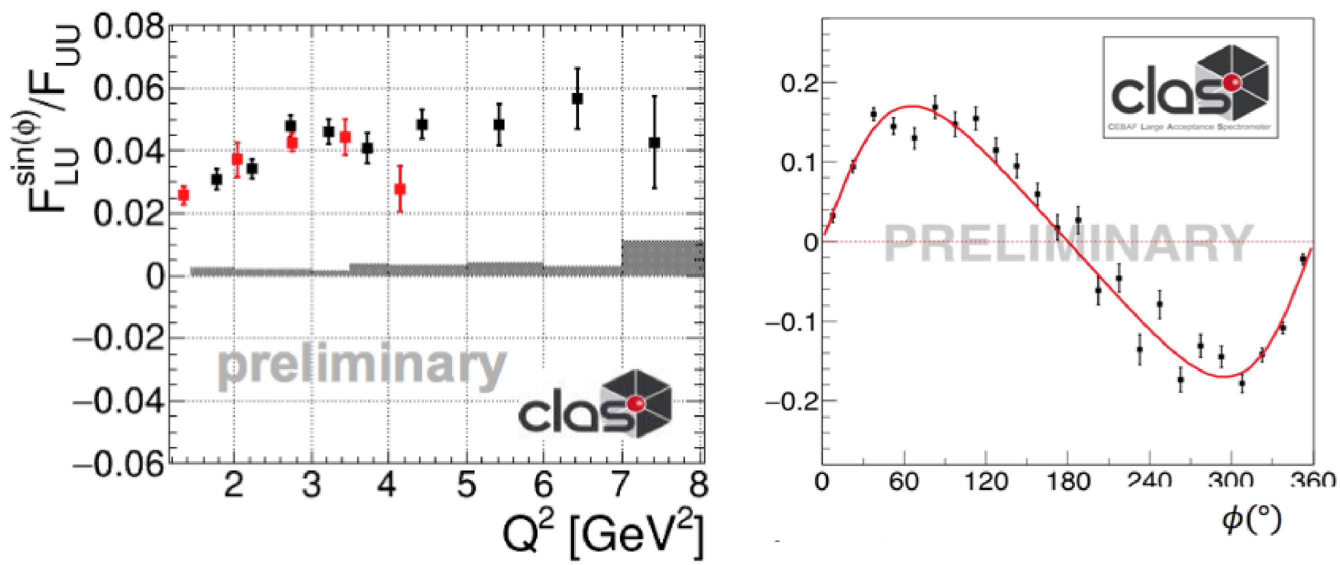


FIG. 5. CLAS12 preliminary results on beam spin asymmetry observables based on a few percent of the recorded statistics. Left panel: SIDIS $\pi^+$ asymmetry as a function of $Q^2$ with in red the previous CLAS published result presented at DNP19. Right panel: DVCS asymmetry as a function of the azimuthal angle $\phi$ presented to the JLab User Group Meeting 2019.

## IV. THE TRANSVERSE TARGET

The use of a polarized target is a challenge for any experiment. In case of solid targets, a compromise has to be found with the dilution due to the presence of unpolarized material in the target, that limits the factor of merit of the measurement, and the constraints on the acceptance and effects on the beam path and synchrotron radiation generated by the target magnet. The RGH experiments pursue an innovative solution based on a polarized Hydrogen Deuteride (HD) frozen spin target. After polarizing at 15 T and 12 mK and reaching a frozen spin mode, a HD target can be installed in the experiment and the polarization preserved with moderate magnetic field, of about 1 T, and temperature, of about 0.2 K. Clear advantages are the possibility to independently polarize hydrogen and deuterium atoms with minimal dilution, and the modest requirements of temperature and magnetic field strength and homogeneity, that will reduced impact on the spectrometer acceptance and resolution.

### A. The HD frozen spin target

Molecular HD in the solid phase had been successfully used as a frozen-spin target (HDice) with photons during the E06-101 experiment in 2011-2012 (the g14 run in CLAS), where polarization relaxation times of years were measured [20, 21]. Opportunistic tests with electrons during the g14 period, under far less than optimal conditions, suggested that the target might retain its frozen-spin state with electron beams for sufficient lengths of time to make electron experiments practical. To explore this option, the Laboratory began an Upgrade to the Injector Test Facility (UITF) in 2014, to create a 10 MeV testbed for HDice. Although the energy lost by electrons is much higher at 10 GeV, most of this is carried away in bremsstrahlung which has no effect on the target. In fact, the energy deposited at 10 MeV is only 30% less than that at 10 GeV.

When exposed to charged-particle beams, polarization-loss mechanisms are very dependent on the target material. Three potential loss mechanisms have been identified with HDice, and these have been addressed by an optimized target configuration and operation mode.

**Temperature:** Molecular HD has two paired electrons in a 1s state that have no effect on the nuclear polarizations. A charged-beam particle can either dissociate the HD molecule or unpair and knock out one of the molecular electrons (typically by Møller scattering), leaving single 1s electrons as paramagnetic centers. If those electrons are unpolarized, the frequent flips of their spins have Fourier components at the Larmor frequencies of H (and D) that can depolarize the nuclei. However, if the target remains sufficiently cold in the magnetic field of the cryostat, then such electrons are essentially 100% polarized and spin flips no longer take place. The HD target cell has been redesigned to enhance cooling, reaching a thermal response time of about 2 milli-seconds. and a 1 kHz high-speed raster has been constructed for the UITF, both of which should guarantee temperatures at which the HD remains sufficiently cold under bombardment to guarantee complete polarization of any unpaired target electrons.

**Hyperfine interactions:** The magnetic moment of the electron is opposite in sign to that of the proton (or D), so that even when an unpaired target electron is 100% polarized, its spin will mix and dilute the spin of the polarized target-H (or D) through hyperfine interactions. An RF process of Adiabatic Fast Passage (AFP) has been developed that inverts the sub-state population and orients, with 98% efficiency, the spin of the polarized H antiparallel to the cryostat's holding field, so that it will be parallel to any polarized paramagnetic electrons. This will completely eliminate hyperfine dilution.

**Radiation Damage:** Through dissociation and ionization the electron beam can create different chemical species. Their mobility through the solid HD lattice is strongly temperature dependent. In fact, to enhance healing through recombination higher temperatures are preferred. In a worse-case scenario, chemical reactions might increase the concentration of ortho-H2 which could bring the HD out of its frozen-spin state. An analysis of gas used in the 2012 studies showed no evidence for this potential effect. Further tests will be conducted during extended exposures at the UITF.

The UITF experiments are designed to match both energy deposition density and target temperature to the RGH conditions, and validate the HD target working point prior to the actual run. The C1 technical condition benchmarks the performance against a 1 nA beam current on a 50 mm long HD target. Better control of the target temperature, with the same luminosity, would be achieved by using 2 nA on 25 mm long HD targets. Without additional R&D, this is assumed to be the current goal.

The NIST and GEANT codes both predict energy deposition rates that are 1.32 times higher at 10 GeV than at 10 MeV. With the existing in-beam cryostat, the Hall B beam would be rastered to an outside diameter (OD) of 24 mm (incident on 25 mm OD HD target) that is larger than the 18 mm OD (incident on a 19 mm OD HD target) possible at UITF. As a consequence, in Hall B the energy deposition density is reduced by 1.78 times. Taking into account both factors, RGH conditions would be best simulated by a rescaled UITF current of 1.5 nA. The expected energy deposition in the target by 2 nA electron beams at 10 GeV is 2.90 mW, a power that would raise the HD temperature to 208 mK. At UITF, the transport and focusing of the low energy beams limit the target to half the length. By applying 4.1 mW to a heater anchored to the IBC mixing chamber, tests with 1.5 nA electron beams at 10 MeV are expected to create HD thermal conditions that mimic what will be encountered in Hall B with a double length target.

With the completion of the beam line, see Fig. 6, and the HDice in-beam test setup, see left panel of Fig. 7, the program of HDice tests at the UITF has undergone an extensive Experimental Readiness Review. Following a period devoted to the commissioning of the UITF accelerator in cave-1 (Run 0), three HDice runs are planned that culminate in an extended test of polarized HD with electrons [22]. As of early March 2020, the UITF accelerator commissioning Run 0 was scheduled for the beginning of April, and the three HDice runs were expected to be completed in August 2020. While the Lab transition to MEDCON-6 status put an abrupt halt to this, a revised schedule is now under discussion with the goal of completing the HDice runs in the fall of 2020.

FIG. 6. Left panel: MeV section of the UITF beam line. Right panel: elevated UITF beam line serving the HDice test area.

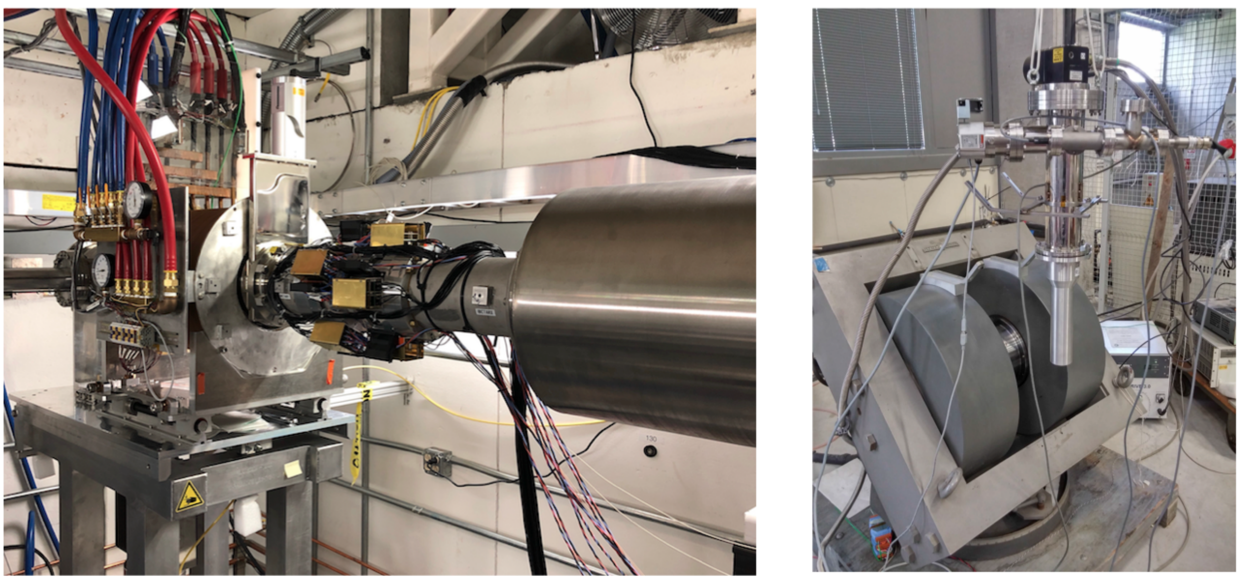

FIG. 7. Left panel: HD-ice in-beam cryostat at UITF. Visible are the beam-halo readout units (copper boxes) surrounding the target location and the active beam dump downstream. Right panel: $MgB_2$ test setup composed by a conventional 1 T dipole magnet and a cryostat housing the superconducting cylinder cooled down to 14 K by means of a cool head.

### B. The Target Magnet

To maintain a transverse target holding field inside the CLAS12 central solenoid longitudinal field is a formidable challenge. With respect the proposal based on conventional superconducting wiring technology, an innovative solution has been pursued based on a bulk superconducting $MgB_2$ magnet. A hollow bulk superconductor is able to provide a transverse holding field inside, while adjusting its internal currents to shield any outside field without the need of a current supply [23, 24]. The latter feature is an important improvement with respect to a conventional coil-based magnetic solution. Distinctive advantages include minimal space needed to fit within the target cryostat, maximal field compactness to reduce electron beam deflection in the transverse field, the absence of cryogenic load from current leads and the ability to operate without a copper stabilizer, which reduces the energy–loss of particles traversing the material. The choice of magnesium diboride ($MgB_2$) as the superconductor is motivated by its high critical current, critical field and transition temperature (39 K), by its availability in suitable shapes, as well as by its low density and low average-Z that minimize the energy-loss in the path of the reaction products [25, 26]. Polarized targets inherently require low temperatures, and as a result, the cooling of an $MgB_2$ cylinder to 4 K can be readily incorporated within the target cryostat.

In order to trap the wanted magnetic configuration, the bulk $MgB_2$ superconductor should be cooled down below the transition temperature in a given external field. After the transition to superconductor, the $MgB_2$ material will be able to generate the currents needed to compensate any change of the external field without spending energy, and no internal field alteration will occur as long as temperature or current do not exceed their critical limits. For the planned set of experiments with transversely polarized HD in the CLAS12 detector, the necessary field manipulation is straightforward to accommodate within the installation procedure of the HDice frozen-spin polarized target [27, 28]. A $MgB_2$ cylinder inside the target cryostat is conditioned within an external dipole before being inserted into the CLAS12 central detector, and the solenoid activated. At that point, any HD target could be inserted without experiencing depolarization effects in low field transitions.

A setup has been realized to verify the capability to generate a dipole field with a $MgB_2$ cylinder [29], see right panel of Fig. 7. After cooling down the $MgB_2$ cylinder inside a dipole field of about 1 T, the external field is zeroed and the dipole field at the center of the cylinder measured. With the decrease of the temperature below the transition point, an increasing fraction of the original field is trapped, see left panel of Fig. 8. At the minimum temperature of 12.8 K reachable by the setup, a field of about 940 mT is preserved for days, without any significant degradation except for small effects ascribed to the not-perfect temperature stability, see right panel of Fig. 8.

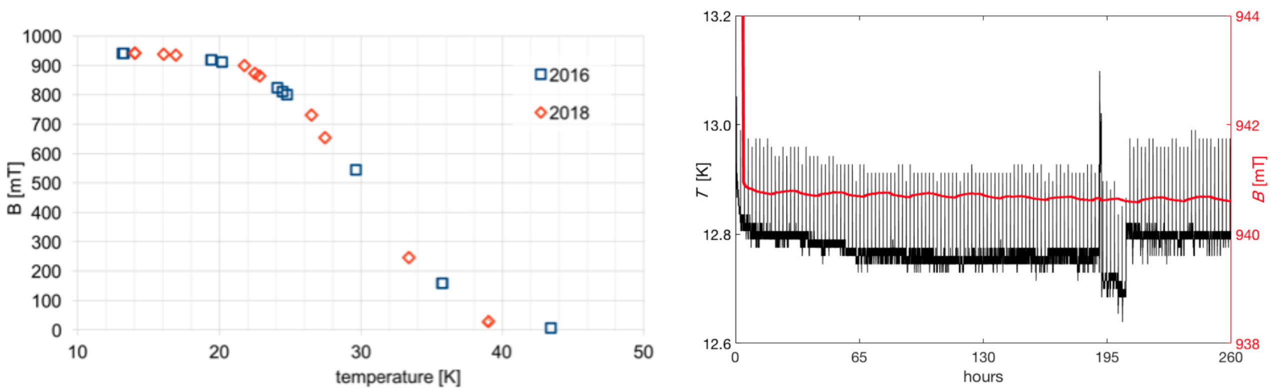


FIG. 8. Left panel: Results of the measurements of trapped dipole field versus temperature performed in two different years with the same $MgB_2$ cylinder. Right panel: Trapped field long-term stability measurement: the $MgB_2$ temperature and central field are shown as black and red curves, with scales on the left and right axis, respectively.

## V. CONCLUSIONS

RGH experiments at CLAS12 offer a compelling physics program that has the potential to provide unprecedented information on the peculiar parton dynamics within the nucleon and during fragmentation. Since the approval in 2012, the interest in this field of research has worldwide grown and culminated with the recent EIC CD0 announcement, the theoretical understanding and lattice calculations have made important progresses and consolidated the interest in new experimental results. At the same time, a comprehensive program has been pursued at JLab to overcome the technical challenges connected with running a transversely polarized target inside CLAS12, and only external conditions have temporarily delayed its accomplishment.

**We request the PAC to confirm the conditionally approved beam time for the experiments with transversely polarized target (110 days), and allow the RGH team to complete the preparatory work for the best running conditions with the polarized target in order to address the C1 condition with the laboratory management before scheduling.**

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