CLAS12 Upgrade for High Luminosity Operations

Task Force Report

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Improving the performance of CLAS12 in terms of $L \times \eta$ (luminosity times the reconstruction efficiency) will significantly enhance the physics reach of experiments in Hall B. In the proposal stage, experiments assumed operations at a luminosity of $L = 10^{35}$ cm^{-2}s^{-1} (the design luminosity of CLAS12) with a particle reconstruction efficiency of $\eta \simeq 1$. As it turns out, the reconstruction efficiency of charged particles (both in the Forward Detector and in the Central Detector) have a strong dependence on the luminosity and at the design luminosity is presently $\sim 75\% - 80\%$. This amounts to $> 35\%$ loss of the reconstructed events for two-prong final states. This higher than expected inefficiency has limited the operating luminosity on the LH$_2$ target, for example, to $\sim 0.6 \times 10^{35}$ cm^{-2}s^{-1}. It was also realized that with improved tracking detectors and track reconstruction algorithms, this inefficiency can be reduced significantly. Below is a report of the task force dedicated to study various options for improving the response of the CLAS12 detector for efficient operation at much higher luminosity than was originally proposed.

Contents

I. Introduction

The design luminosity of CLAS12, $L = 10^{35}$ cm^{-2}s^{-1}, has been achieved, but with somewhat lower than expected single-particle reconstruction efficiency, $\sim 75\% - 80\%$. Based on the analysis of data acquired during RG-A/B/K, CLAS12 achieved its design performance goals [1]. Detailed studies showed that a high occupancy in the DC R1 is largely responsible for the low reconstruction efficiency in the Forward Detector. The reconstruction inefficiency in the Central Detector is not fully understood yet. CVT tracking is not at the level to pinpoint the exact root cause of the problem, but all indications are that the high occupancy in the tracking detectors could be the major part of it.

A task force (TF) has been organized to study options for CLAS12 to run at higher luminosity. The goals of the group were, as a first stage, to develop a path to achieve a luminosity of $L = 2 \times 10^{35}$ cm^{-2}s^{-1} for normal running with charged particle reconstruction efficiencies of $> 85\%$. This will allow to expedite execution of the already approved physics program. For the second stage of upgrades, the TF will study options for CLAS12 to operate with up to two orders of magnitude higher luminosity ($L > 10^{37}$ cm^{-2}s^{-1}). Such high luminosities will open-up new physics opportunities for Hall-B.

The charge for the task force is:

1. Assess the current CLAS12 luminosity and identify the limiting factors (tracker granularity, integration time, readout, ...)

2. Assess existing tracking technologies identifying the most suitable to upgrade or augment the CLAS12 trackers

3. Quantify the expected improvement (luminosity, acceptance, resolution, efficiency) by mean

of realistic MC simulations and using data collected in the current configuration

4. Define a work plan to test the proposed solution with a time chart and milestones for in-beam tests in the current configuration;
    - required R&D (if any)
    - prototyping
    - full implementation
5. Estimate costs and identify resources needed in the different phases of the project
6. Evaluate synergies with other projects at the lab providing a list of shared resources and common goals

The TF activities are documented on the associated TF wikipage [2]. The results of the studies and discussions are in the bi-weekly meeting minutes. The TF concludes that the CLAS12 upgrades to higher luminosity are possible. The first stage, achieving ×2 higher luminosity with acceptable performance, will be a tremendous help to the currently running physics program and should be done within the next 2 to 3 years. The possibility of going to much higher luminosity, $> 10^{36}$ cm^{-2}s^{-1} will need more studies, thorough simulations of various shielding/detector configurations, and more R&D of detector technologies. Such an upgrade will significantly enhance the physics potential of Hall B and can be done in a time frame of 7 to 10 years.

II. Current Performance Based on RG-A/B/K

The Hall B runs, *e.g.* RG-A and RG-B, which were not limited by the DAQ lifetime, took data at luminosities of $L = 0.6 \times 10^{35}$ cm^{-2}s^{-1} and $L = 1.3 \times 10^{35}$ cm^{-2}s^{-1}, respectively. These are luminosities on the physics targets only. In addition to the target, $\sim 20\%$ of the particle rate comes from other materials along the beam, 60 cm air gap downstream of the scattering chamber, foils of the target cell windows, and the exit window of the scattering chamber (all of these amount to 30% r.l. of LH_2).

The above mentioned operating luminosities were defined by the figure-of-merit (*fom*) for three-prong events, between the efficiency loss and the rate increase as a function of the beam current. Extensive studies of the reconstruction efficiency in the Forward Detector found that the main reason for the efficiency loss for the charged particle reconstruction is high occupancy in region-1 drift chambers (DC-R1)[1]. Moreover, a correct accounting of the occupancy in the detectors reproduces the inefficiency of the reconstruction. More on the effect of the beam background merging on the reconstruction efficiency can be found in the report of the task force on background merging and reconstruction efficiency studies [3]. With the current level of the reconstruction software that has been used for the pass-1 processing of data, the efficiency loss is 0.35% per nA of beam current.

III. Stage-1 Upgrade - 2 to 3 Years

To achieve the goal of operations at a luminosity of $L = 2 \times 10^{35}$ cm^{-2}s^{-1} ($\sim$150 nA on a 5 cm LH_2 target and $\sim$ 70 nA on LD_2) with a single track reconstruction efficiency $> 85\%$, the rate of the efficiency loss must be $< 0.1\%$ per nA of beam current. An assessment was made for the performance of the detectors, DAQ, and the beamline, and the conclusion is that except the forward tracker (DC), all CLAS12 systems are capable of handling a factor of two increase of luminosity without loss of performance. The details of this assessment and the options for improving the forward tracking system are presented below.

A. PMT Detectors

FTOF system: The FTOF is expected to maintain its timing response and resolution at or close to the performance achieved for the RG-A and RG-B data for up to 2 MHz of sustained PMT count rates. Based on the rates recorded during the runs on the 5-cm-long LH_2 and LD_2 targets, this limit will correspond to beam currents of 350 nA and 200 nA on these targets, respectively. These currents are far above those required for ×2 higher luminosity operations.

CTOF system: The CTOF has a limited range for the linear response of its PMTs. Based on the data collected during the “nuclear target test run”, the rate limit is $\sim$ 0.5 MHz. This corresponds to beam currents of 200 nA and 100 nA on the 5-cm-long LH_2 and LD_2 targets, respectively. Still, about 30% higher than is required for a factor two luminosity increase.

The details of the TOF system performance expectations at higher luminosities can be found

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[1] The average occupancy of DC-R1 for the RG-A/B datasets is $\sim$4% – 5%.

in an associated task force report [4], This note includes, among other details, reduction of the operating lifetime of the PMTs at increased operating luminosities and the cost of replacing the PMTs. One, however, should note that the lifetime is defined by the charge drawn from the photocathode and depends on the total integrated luminosity over the life of the device. With higher instantaneous luminosity this time will be shorter but so will the collection time of the physics data.

ECAL system (PCAL and EC): The ECAL is expected to maintain its energy and timing responses, as well as its resolution at or close to the performance achieved currently at ×2 higher luminosity.

HTCC and LTCC systems: The Cherenkov systems are generally low rate detectors and will operate and perform as expected at ×2 higher luminosity.

RICH: There are no issues foreseen for high luminosity operations of the RICH detector and it is expected that it will achieve the required performance at $L = 2 \times 10^{35}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

B. CVT

The performance of the CVT is not yet fully understood due to software/alignment issues that are presently being worked on. The "nuclear target test" run showed that the SVT can withstand high luminosities. The radiation damage and occupancies in the SVT and MVT systems will be within operational limits with ×2 higher luminosity running of CLAS12. The performance of the detector will largely depend on the software and calibration.

C. Forward Tagger

While there is no need for any changes to operate the Forward Tagger at ×2 higher luminosity, it is expected that there will be a degradation of the FT-Cal crystal light yield due to radiation effects. The radiation damage is recoverable, but will make calibrations a bit more difficult.

D. DAQ

The expected CLAS12 event rate at ×2 higher luminosity will be ~ 85 kHz. The current DAQ/trigger system can run reliably with acceptable livetimes at up to 30 kHz event rate. Several systems will have to be upgraded to be able to support a 100 kHz event rate. The major bottleneck is the CAEN TDCs. The upgrade of the TDCs and the installation of new VXS crates has already started. The readout of the MVT and SVT can be improved for high rate operations, but the detector performance must be studied. Improvements of the CODA software (EB and ER) may be needed for high rate data processing, and a Level-3 trigger will be useful. The other systems (FADC250, DCRB, VSCM, SSP, and VTP boards) are capable of supporting high rate DAQ operations.

E. Beamline

The existing beamline with beam position and current monitors, wire harps, targets, shields, and the dump will support operations at up to 450 nA at 11 GeV. This limit comes from the present beam dump, rated at 5 kW. For completion of the approved physics program, the upgrade of the dump to 100 kW is in progress.

F. Forward Tracking

The Forward Detector efficiency depends on the tracking system's ability to find tracks with 4% – 6% average occupancies in DC-R1. While it is possible to improve the track reconstruction efficiency with more advanced software algorithms (discussed elsewhere), significant upgrades of the first region of the tracker to handle higher occupancies are needed to achieve the desired performance at a luminosity of $L = 2{\times}10^{35}$ cm^{-2}s^{-1}. Options for the upgrade include improvements in the response of the existing DCs, the addition of faster tracking layers to complement DC-R1, or replacing DC-R1 with a different tracking detector system altogether. Below are proposals for each of the above options.

Upgrade of the HV system for the entire DC is also needed. The old DC HV system is limited in current and cannot support much higher than the design luminosity for channels with a large number of wires. The new HV system has been purchased and will be installed during the 2021 downtime.

DC improvements: currently, for each DC channel, only the time of the leading edge of the first signal in the readout window above the discriminator threshold is recorded. The signals from real tracks have a unique time characteristic - tracks passing the cell close to the sense wire will be early in the time window but will have a longer duration, while signals from tracks passing close to the edge will be late in the time window and have a shorter time. These characteristics can help to reject out-of-time accidentals. It requires measurements of the signal duration over the threshold. Such a readout can be set up with a firmware change and tested during the ongoing runs.

A similar objective, with more information on the signal shape, can be achieved with the readout of full FADC waveforms. Such an upgrade will require new FADC-type readout boards.

Adding fast tracking layer(s) to DC-R1: will help to reject out-of-time accidentals and isolate the correct hits for tracking (*i.e.* those associated with the charged trackers of interest coming from the target). One should note that due to space constraints between the HTCC and DC-R1, the HTCC, Central Detector, and the target have to go further upstream to open a space for the new tracker. Such dislocation of the target will change the acceptance of the Forward Detector to some degree. Simulations are needed to quantify the acceptance change. For both options below, R%D, and prototyping will be needed before full implementation.

- a new drift chamber layer with a smaller cell size and a shorter drift time (readout window), prototyping will be needed to build a full scale detector
- 1 or 2 MPGD modules with 2-D readout, about $20 - 30$-mm-thick with $\sim 1\%$ r.l. material budget. Prototyping for a large area triple-GEM configuration and R&D for light weight and low channel count readout will be needed (see below). After R&D work, a full scale detector can be built and tested in one sector.

Replacing R1 with an MPGD tracker: is a costly solution but will be an important step for future higher luminosity upgrade. Studies of the forward tracking resolution with 2% radiation length MPGD's show no degradation of momentum resolution (see III H).

G. MPGDs for High-Luminosity CLAS12 Forward Tracking

Two MPGD technologies have been considered for the CLAS12 forward tracking upgrade, a triple-GEM design, see Appendix V A, and a Resistive Micro Well (µRWELL), Appendix V B. Below are specific design proposals for CLAS12, needed R&D, and the cost estimates for various options.

1. Large MPGDs for High-Luminosity CLAS12 Forward Trackers

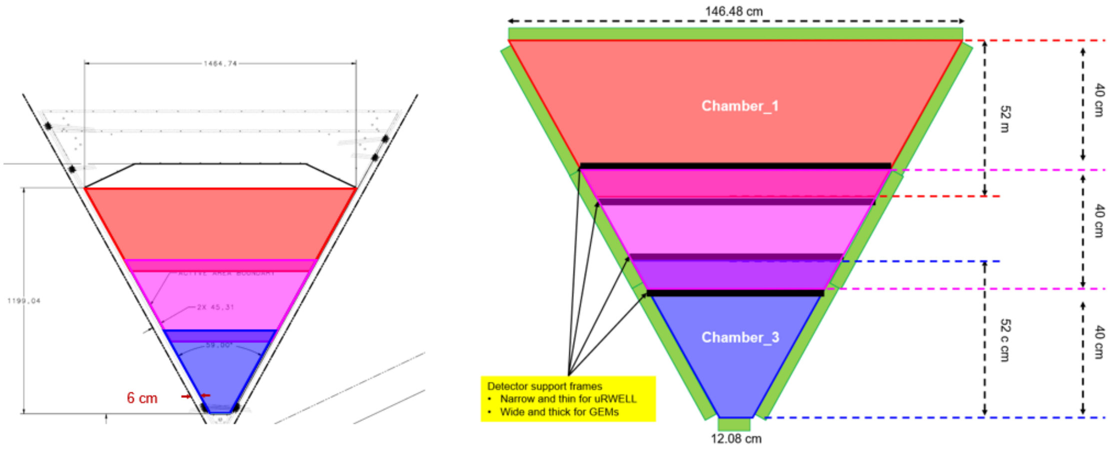

FIG. 1. Left: Cross section view of a triple GEM; right: Large GEMs in PRad setup in Hall B at JLab

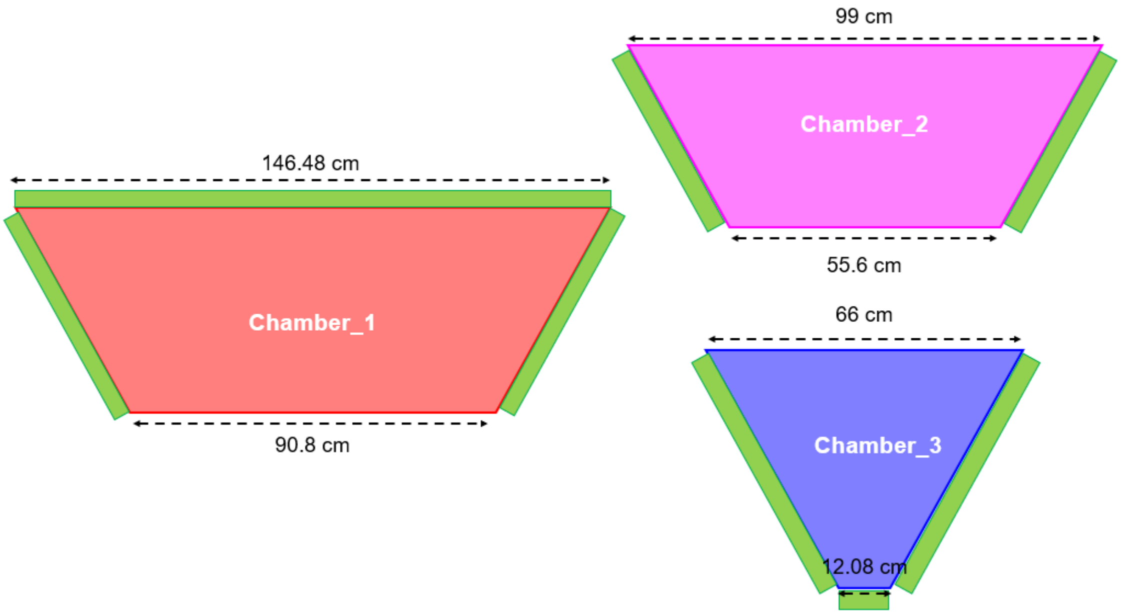

FIG. 2. Left: Cross-sectional view of a triple GEM; right: Large GEMs in PRad setup in Hall B at JLab

For the initial phase of the high-luminosity CLAS12 upgrade, only the inner layer of the forward tracker drift chamber (DC), *i.e.* region 1 (R1) is expected to be upgraded to MPGD trackers. The R1 tracker consists of six large DC sectors, with each sector covering an active area defined by a trapezoid with a height of 1199 mm and a base of 1464 mm. The amplification device (GEM foils or µRWELL foils) used in both GEM µRWELL detector technologies, as well as the low-mass readout structure (*X*-*Y* strips, *U*-*V* strips, or pad readout) are all manufactured from the same base material, the double-sided copper clad polyimide commonly referred to as Kapton foil commercially available as a 62-cm-wide roll product. The width of the base Kapton roll defines the upper limit in the maximum size possible for the active area for both the GEM and µRWELL in one dimension. Therefore, it will not be possible to have a single GEM or µRWELL detector module to replace the DC sector of R1. Each R1 sector will be split into 3 MPGD modules as shown in the sketches of Fig. 1 and Fig. 2. The largest module (red) will be a trapezoid with an approximate width of the larger base of 1470 mm and height of 520 mm. The front-end (FE) electronics (green bars on the cartoons) will be located on the two lateral (non-parallel) sides and on the large base. For the medium-size module (magenta), the FE cards will be located only on the lateral sides to avoid the material of these electronics in the active area and to limit exposure to radiation. For the smallest module, the FE cards will be installed on the lateral sides and on the shorter base. The height of the modules will be selected to allow maximum overlap of the modules. The overlap will provide an additional space point and a powerful tool for the alignment of the modules relative to each other.

2. R&D and Prototyping

A dedicated R&D program, albeit limited in scope and timeline, is required for both the GEM and µRWELL technologies for the high-luminosity CLAS12 forward trackers. The competing requirements of large area, low mass, and high performance poses a certain numbers of challenges that would need to be addressed with detector R&D and prototyping. Here are the key areas of R&D that will be needed for the CLAS12 MPGD forward tracker

- Comparing GEM and µRWELL technology options for the CLAS12 forward tracker R1 (see V A & V B)

- Development of high performance and low channel count readout electronics (see V C 3 & V C 4)

- Investigation of new material and structure for low-mass MPGDs (see V D)

3. Timeline for the R&D and prototyping

We antcipate that the R&D and prototyping program described above could be successfully carried out in a 2 years time frame. The development of low channel count capacitive-sharing readout with low mass chromium pad layers will be performed on small size GEM and µRWELL prototypes and completed within a year. The main performances studies and tests will be performed in the MPGD detector lab at UVa and at any opportunity for beam test. In parallel, during this first year we will collaborate with CERN for the design of large prototypes as described in section III G 1. In the second year, we will procure the parts for both GEM and µRWELL, built the prototypes and test with cosmic and radioactive source at UVa. Ideally, we would also want to test the chambers in realistic beam environment such as in Hall B.

4. Cost Estimate

The cost estimate of a large area triple-GEM detector relies on the experience gained from the Hall-A SBS project (under construction). To estimate the cost of the µRWELL based module, quotes obtained for a small detector are used. For electronics, the currently used per-channel cost was doubled as the old chip (APV25) is not an available option for CLAS12. The new generation of chips will cost more and will require new developments of front-end readout electronics. Details of the cost breakdown of various options can be found in section V E. In Table I, a summary of the cost estimates for the R&D, prototyping, and for one full-scale R1 module is presented. For the option of adding one module on R1 DCs, the total cost will be ~ 600 k$ (including R&D and prototyping). To replace the whole R1 DCs will cost about 2 M$.

TABLE I. default

Item	Triple-GEM (k$)	µRWELL (k$)	Electronics (k$)
R&D and Prototype	38.6	28	20
R1 detector module	50	40	40

For the option of adding one module on R1 DCs, the total cost will be ~ 600 k$ (including R&D and prototyping). To replace the whole R1 DCs will cost about 2M$.

H. CLAS12 FD performance with GEM Type Region-1 Tracking

Simulations to determine the impact of the material thickness of the R1 GEM tracker on the FD tracking resolutions were performed using the standard GEMC setup. To keep the digitization in GEANT and the tracking algorithm the same, the DC-R1 gas density was altered in GEMC. The gas used in the DC is 90% Ar with 10% CO_2 with a density of 1.8 mg/cm^3. The thickness of the DC R1 gas volume is 18.2 cm, making the gas thickness 0.16% in radiation lengths (r.l.). The 2D readout GEM module is 0.5% r.l. (see above), and with the proposed 4-layer tracker for R1, the total thickness will be 2% r.l.. So, to introduce this material thickness of the R1 GEM tracker without changing the GEMC setup, the DC-R1 gas density was increased by ×13.

A SIDIS event generator was used to run particles through GEMC and reconstruct was done with the standard CLAS12 reconstruction code. There have been two sets of simulations done, one with the standard setting of the CLAS12 DCs, another with an increased gas density in the volume of the DC-R1 detectors. In Fig. 3 the momentum, angle, and vertex resolutions for negatively (mostly e^-s) and positively (mostly π^+s) charged tracks are shown for the nominal settings. No beam background is included. The same quantities for simulations with denser DC-R1 gas are shown in Fig. 4. Not much difference is seen in the momentum and angle resolutions, but somewhat worse resolution is seen in the vertex reconstruction. Similarly, no degradations of the missing resolutions for the $e\pi^+$ and $e\pi^+\pi^-$ reactions are apparent as can be seen from the fits to the missing neutron and proton peaks in Fig. 5 and Fig. 6, respectively. These results show that a thicker GEM tracker with the same position resolution as DC-R1 will not diminish the FD performance. Further studies with a realistic GEM tracker simulation in GEMC will be needed to determine the number of GEM modules and the readout granularity necessary to achieve the luminosity and performance goals.

I. Conclusions for Stage-1

Achieving a luminosity of $\sim 2\times10^{35}$ cm^{-2}s^{-1} for CLAS12 in a normal running conditions (e.g. on LH_2/LD_2 targets) with charged particle reconstruction efficiencies of $> 85\%$ is feasible. This can be done with modest upgrades within 2-3 years. Most of the CLAS12 subsystems, beamline, the target system, shielding, magnets, forward tagger, and PMT detectors will operate and perform without any upgrades. At this point, it is hard to evaluate the performance of the central vertex tracking, but operationally it is capable of handling such luminosities. Updates and upgrades

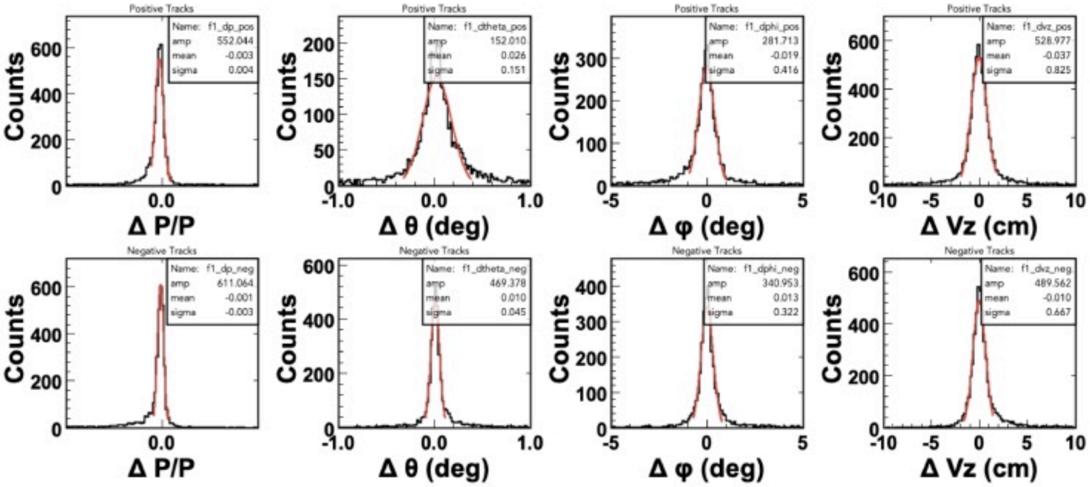

FIG. 3. The momentum, angle, and vertex resolutions of the CLAS12 FD for positively and negatively charged particles.

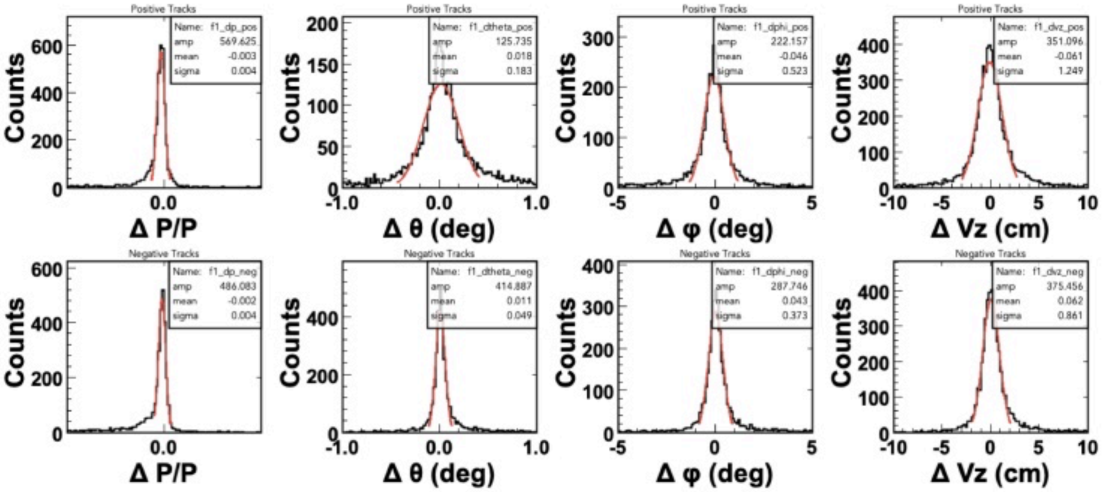

FIG. 4. The same resolutions with a "denser" DC-R1 gas.

that are currently in progress (e.g. DC HV, beamline upgrades, and ongoing updates of DAQ system[2]) will further aid stable operations of CLAS12 higher than designed luminosity. The main upgrade necessary to achieve the luminosity goal is for the forward tracking system. A faster and finer granularity tracking detector is needed to mitigate high occupancies in R1 drift chambers. A promising avenue in this regard is to use MPGD tracking detectors. The minimal upgrade is to add an MPDG layer(s) to the existing DC R1 system. The ultimate goal is to replace DC R1 with

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[2] Some upgrades to CODA software and the implementation of a Level-3 trigger will be needed as well.

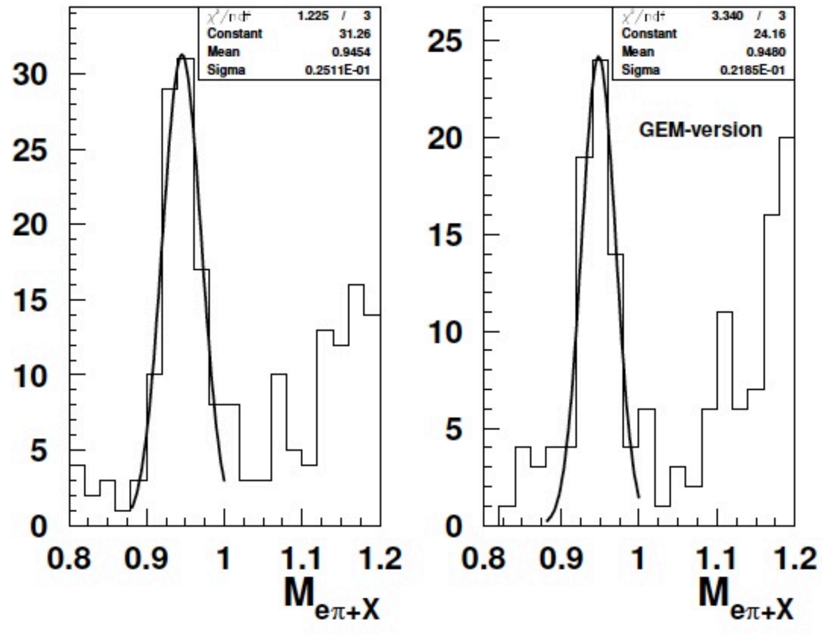

FIG. 5. The missing mass distributions of the reaction $ep \rightarrow e'\pi^+X$ with the normal DC-R1 gas density (left) and with a "denser" gas in DC-R1 (right).

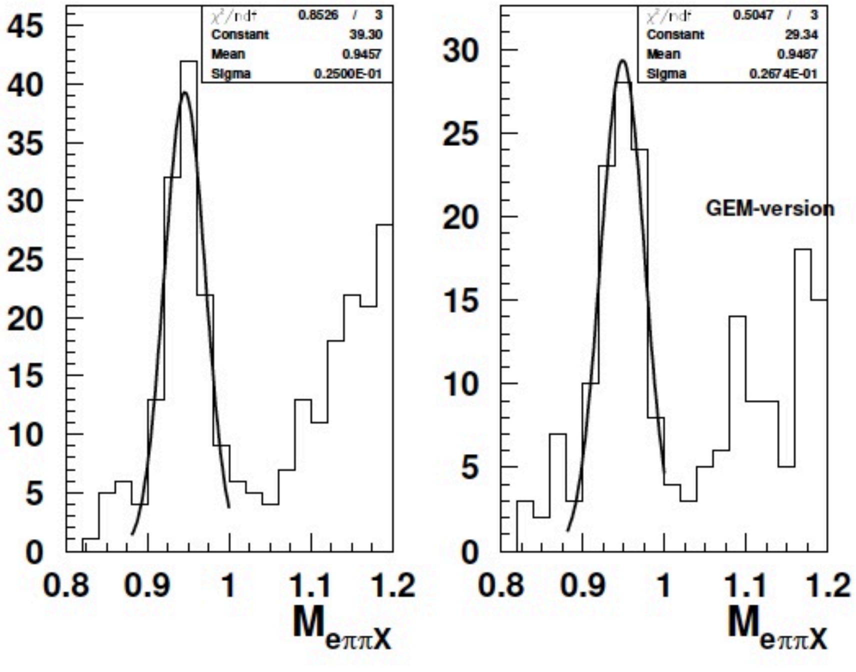

FIG. 6. The missing mass distributions of the reaction $ep \rightarrow e'\pi^+\pi^-X$ with the normal DC-R1 gas density (left) and with a "denser" gas in (right).

such trackers. To implement a large area MPGD tracking system, about two years of R&D and prototyping will be needed and will cost about 100k$. The minimal version of the FD tracking upgrade will cost 540k$ to 600k$. The cost for the full replacement of DC R1 is about 2M$.

IV. Stage-II Upgrade

A longer-term goal for the upgrade is to reach high enough luminosities to study very low-rate reactions such as Double Deeply Virtual Compton Scattering (DDVCS). The major part of the physics program of JLab12 is the description of the partonic structure of hadronic matter via the GPDs. Several experiments have been approved and have already taken data for studying GPDs using spin (beam/target) observables and cross sections in exclusive electro- and photoproduction reactions such as DVCS, Deeply Virtual Meson Production (DVMP), and Time-like Compton Scattering (TCS). Compton scattering is the golden reaction for mapping GPDs in the longitudinal and transverse momentum space. However, both DVCS and TCS can measure GPDs integrated over the internal quark momenta, due to the loop in the "handbag" diagrams, or can access GPDs at a specific kinematic point ($x = \pm\xi$) in the spin asymmetries. This limits unambiguous interpretation outside of specific correlation lines. The DDVCS process, when both the incoming and outgoing photons have large virtualities, allows for mapping the GPDs along each of the three axes (x, ξ, and t), as the three variables can now be varied independently. DDVCS is a challenging reaction to study experimentally. The cross section of DDVCS is significantly smaller (more than two orders of magnitude) than that of DVCS, and it is preferable to reconstruct the outgoing time-like photons through their di-muon decays to eliminate ambiguity and anti-symmetrization issues. There have been LOIs to the JLab PAC [5, 6] for measuring DDVCS using specialized setups with the SoLID and CLAS12 detectors. Both proposals aim to run at luminosities of $L > 10^{37}$ cm^{-2}s^{-1}.

Such luminosities require up to 10 μA beam currents in Hall B. The Hall-B beamline and the beam dump after the upgrade[3] are adequate for such high current beams. Some upgrades for instrumentation will be needed, *e.g.* for beam current measurements. A continuous vacuum beamline will be critical to keep the overall background low (currently the vacuum beamline is discontinued at the target with an air gap between the upstream and downstream beamlines). The readout electronics of CLAS12 are all located in the hall, and keeping radiation low is important for reliable operations.

The task force finds that such a luminosity upgrade will possible in a 7 to 10 year time frame. Some studies have been done for $\mu-$CLAS12 at a luminosity of 10^{37} cm^{-2}s^{-1}. Currently more simulations are underway and will continue with more realistic detector options to find optimum solutions for shielding and detector configurations.

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[3] The upgrade of the beam dump is planned for approved experiments with gaseous targets.

A. μ–CLAS12 for $L > 10^{37}$ cm^{-2}s^{-1} Operations

A detector concept that converts the CLAS12 Forward Detector into a muon detector (μ–CLAS12) has been presented in LOI12-16-004 [6] to PAC44. The proposed setup will use the CLAS12 FD for muon detection and a lead-tungsten calorimeter for the detection of scattered electrons. The calorimeter will replace the high threshold Cherenkov counter, see Fig. 7. There will be a tungsten shield/absorber downstream of the calorimeter that will play a dual role as a shield for the CLAS12 FD from large electromagnetic and hadronic backgrounds produced in the target, and as an absorber for charged hadrons (mostly pions) in front of the muon detector. There will be GEM vertex tracker in front of the calorimeter-shield to track the electron and muons to the production vertex. The setup in the LOI does not use the CLAS12 CD. One addition to the setup that was discussed by the task force is a radiation hard, high-rate recoil detector based on, for example, a tracker using μRWELL technology to detect recoil protons.

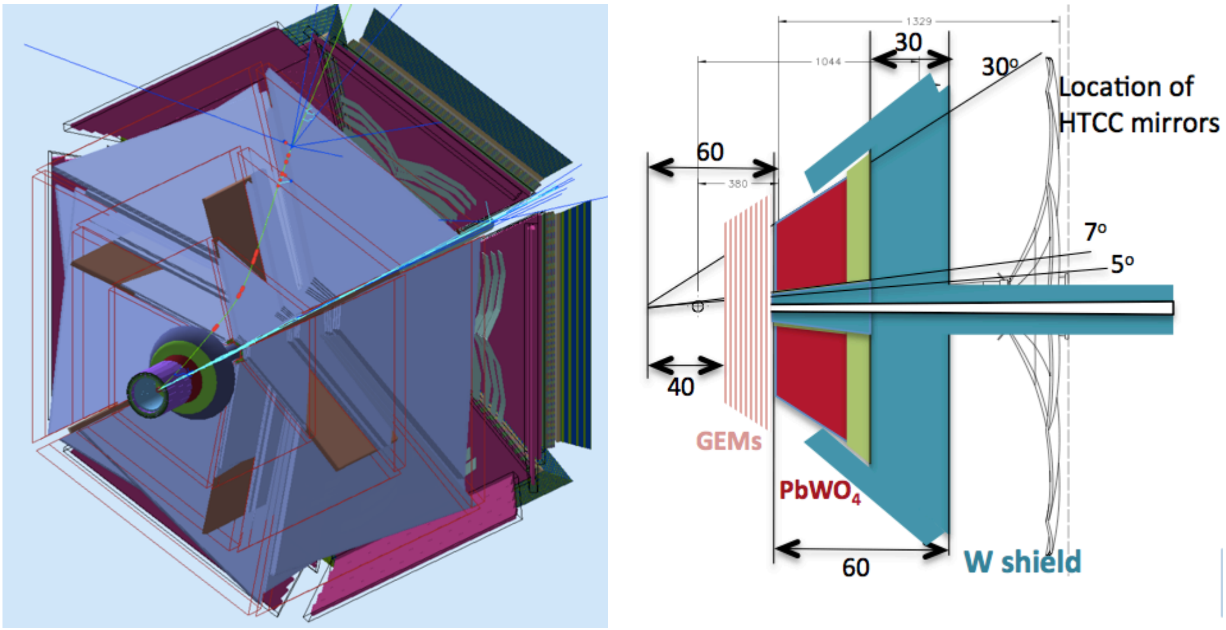


FIG. 7. The concept of the proposed $PbWO_4$ calorimeter and the tungsten shield in place of the HTCC.

The initial simulations done for the LOI were promising. The obtained occupancies and detector rates for the CLAS12 FD were reasonable. The simulations for the LOI used the drift chambers, and to retain $< 4\%$ occupancy in the R3 DCs, the 16 wires closest to the beamline had to be discarded. With the possible upgrade of the tracking system with GEMs, this loss of the acceptance will not be needed. The details of the background simulations as well as the trigger rates and particle reconstruction can be found in Ref. [6].

To fully develop this idea of the high luminosity μ-CLAS12, more MC studies for the detector and shield configurations with new tracking detectors, including a recoil detector, must be done. More studies will be needed for the rates in the PMT-based detectors (FTOF, ECAL) and possible radiation to the electronics using data from the future high current running in Hall B. There will be a need for detector R&D and beam tests for the high-rate vertex tracker and the recoil detector.

B. Upgrade to $L \simeq 10^{36}$ cm^{-2}s^{-1}

Taking advantage of the proposed upgrade to a few $\times 10^{35}$ cm^{-2}s^{-1} luminosity, when the forward DC-R1 will be replaced by GEM detectors, and continuing with the further upgrade of the remaining part of the forward tracking for μ-CLAS12, one can explore the possibility of running the CLAS12 FD and a radiation-hard, high-rate recoil detector at luminosities of $\sim 10^{36}$ cm^{-2}s^{-1}. While this is an intriguing possibility and will be important for detailed, high statistics studies of exclusive (DVCS, DVMP, TCS) and semi-inclusive (tagged-nuclear DIS) reactions, J/ψ photoproduction, etc., running the open acceptance CLAS12 with such high luminosity will be challenging. Simulations are in progress to understand the rates and occupancies in the detectors, and to come up with shielding solutions. Simulations are performed using the CLAS12 GEMC setup with drift chambers. In Fig. 8, the DC occupancies and rates in the FTOFs with a 1 MeV energy cut for a luminosity of $\sim 10^{36}$ cm^{-2}s^{-1} with a hydrogen target are shown. The shielding configuration is almost the same as for the nominal CLAS12 configuration for the so-called "FT-OFF" mode with one change, the tungsten Møller cone extends up to 8° of the FD acceptance. The occupancies in the tracking detectors are reasonable considering that high-rate GEM detectors can be used. The rates in FTOFs are much higher than what can be tolerated by this system for reasonable performance [4]. More studies will be needed to find the optimal shielding options. Besides the FTOF, the performance of the Cherenkov counters at such high luminosities must be understood (has not been studied in detail yet). Of course data rate will be huge and triggered DAQ will not be an option, streaming readout must be considered. This open acceptance options will have significant radiation to the electronics in the hall, some kind of shielding or relocation of racks may be needed.

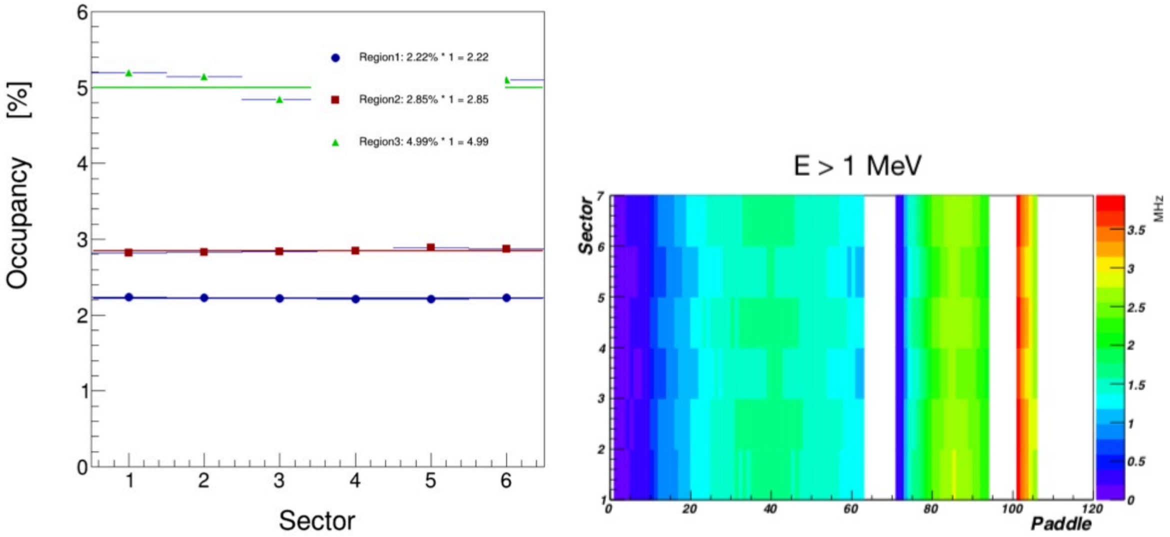


FIG. 8. Occupancies in the DCs and rates in the FTOF at luminosity of ∼ 10^{36} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the Møller shield cone covering up to 8° of the FD acceptance.

C. R&D and prototyping

The new tracking detectors will require some R&D, prototyping, and beam tests. We assume that the high-rate vertex tracker and the recoil detector will use MPGD technologies. The developments that are necessary for Stage-1 will be an important first step for Stage-2. There is not much to be done for the calorimeter. A $\mathrm{PbWO_4}$ calorimeter is a well-developed technology, some small scale prototyping can be done as part of the construction for performance studies.

D. Cost Estimate

A precise cost estimate for the upgrade is hard to make without defining the final configuration of the detector for each proposed option. Nevertheless, using experience with the ongoing construction of various similar detectors in other experimental halls and the EIC R&D project, a crude estimate is given below. We did not consider the cost for PMT detectors as rates are modest for μ-CLAS12 case and also not much of performance is needed from FTOF, for example. There is no cost estimate for the readout electronics as we assume electronics from CLAs12 can be reused.

Calorimeter and the shield for μ-CLAS12: The first choice for the calorimeter for electron detection for μ-CLAS12 option is a $\mathrm{PbW0_4}$ calorimeter. Such calorimeters are now under construction in Hall-C for Neutral Particle Spectrometer (NPS) and in Hall-D for the Jlab Eta Factory (JEF) program [7]. Based on the quotes received, cost per module will cost $\sim$ 2500$ (1800$ for $2 \times 2 \times 30$ cm^3 crystals, photodetectors 500$ and on-board electronics and cables 200$). Based on studies in LOI-16-004[6], the calorimeter will consist of 1200 modules, which makes the total cost of the calorimeter $\sim$ 3M$. The shield was estimated to be 0.3M$, bringing the total cost of the calorimeter-shied to 3.3M$.

There are other, less expensive options for the calorimeter. Some are in the development stage for EIC, e.g. SciGlass calorimeter (see the latest report at the EIC detector R&D meeting [8]). All the available options will be considered at the time of the project development.

Tracking systems: Assuming that the R1 tracking of the forward detector will up to snuff for high luminosity operations after Stage-1 upgrade, the only tracking systems that will be needed are R3 addition, vertex tracker, and the recoil detector. Scaling up from the R1 estimate for Stage-1 upgrade to add one module in from of R3 DC in all sectors will cost 3.2M$. The vertex tracker was estimated in LOI to coset $\sim$ 1M$, and we assume a similar cost for the recoil detector. So the overall cost of tracking devices will round up to $\sim$ 5.2M$.

Note that the simulations for LOI-16-004 were done with drift chambers and deemed to be a workable solution for μ-CLAS12. The additional tracking for R3 is needed only for the open acceptance CLAS12.

With these, the total cost of such upgrade, detectors only is about 8.5M$.

E. Conclusions for Stage-2

The motivation for high luminosity CLAS12 is well in line with the JLAB12 physics program. The μ-CLAS12 can be a key device to measure DDVCS and J/ψ electroproduction with 12 GeV CEBAF. The initial studies of backgrounds, detector, and DAQ rates at high luminosities are promising. TF finds that such upgrades can be done in a 7 to 10 years time frame, under 10M$ budget. However, to fully develop these ideas more studies using realistic simulations are needed. Radiation to the electronics can be an issue and must be considered carefully.

V. Appendix

A. GEM Detectors

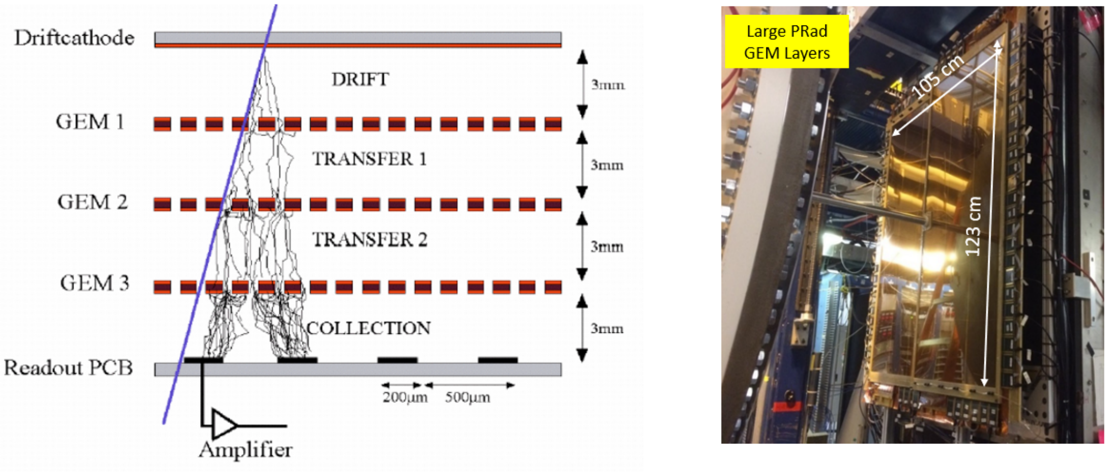


FIG. 9. Left: Cross-section view of a triple GEM; right: Large GEMs in the PRad setup in Hall B at JLab

Gas Electron Multiplier (GEM) detectors [9] are now a well-established technology for particle tracking in high-rate, high-radiation environments with high-spatial resolution for the instrumentation of high- and medium-energy particle physics experiments. Major breakthroughs such as the single mask technique [10] related to the fabrication of the GEM foils, have opened the field for large-area and cost-effective tracking detectors with space-point resolution performance better than 70 μm, a rate capability that far exceeds 1 MHz/cm^2, and high tolerance to radiation in high-background environments. A cross-sectional view of the standard COMPASS triple-GEM design [11] is shown on the left of Fig. 9 with the stack of the 3 GEM foils providing the high-gain electron amplification. Several high-luminosity experiments of the CEBAF 12 GeV upgrade in Hall A [12–14] have adopted GEMs for their spectrometer tracking detector subsystem. The proton radius experiment [15] in Hall B successfully operated the largest GEM trackers as shown on the right of Fig. 9 at the time when the experiment ran in summer 2016. In parallel, there is an intense ongoing effort within the future Electron Ion Collider (EIC) [16] detector R&D effort to develop large-area and ultra-low-mass GEM trackers of radiation length $\leq 0.4\%$ X/X$_0$ with fine granularity *U-V* strip layers as an anode readout option [17] to provide excellent 2D spatial resolution.

B. µRWELL Detectors

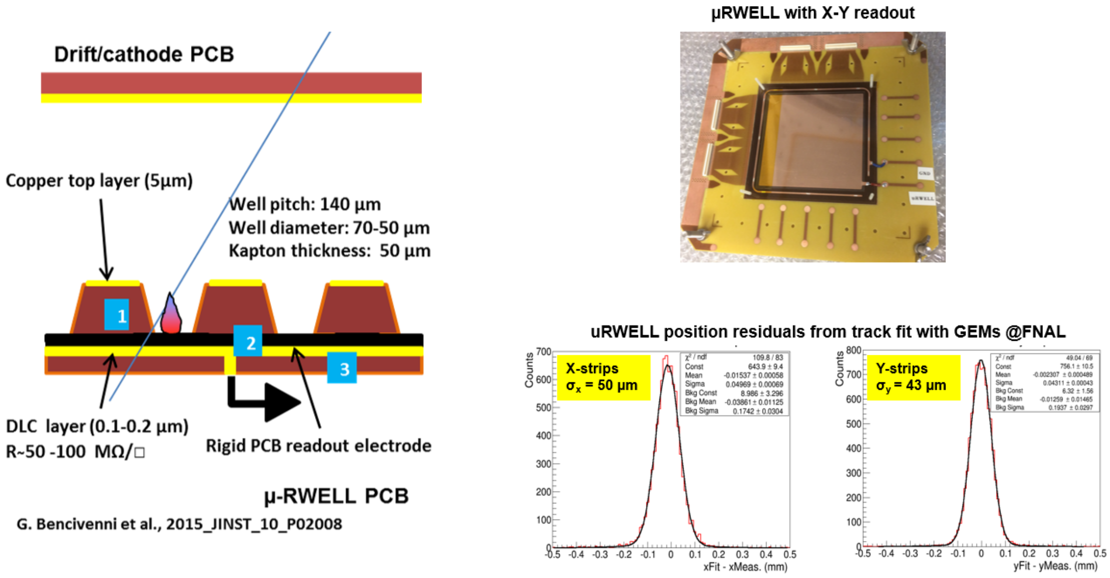


FIG. 10. Left: Cross-section view of a µRWELL detector; Top right: small 10 cm × 10 cm µRWELL prototype under test at UVa; bottom right: spatial resolution for the *X* and *Y* strip readout µRWELL prototype from Fermilab beam test data.

A new MPGD technology known as a Resistive Micro Well (µRWELL) [18] detector has emerged as a viable alternative to the more established GEM or Micromegas [19] detectors for tracking applications in high energy and nuclear physics experiments. The key electron amplification feature of a µRWELL detector is based on the same technology used for GEM foils in a GEM detector. However, unlike a GEM detector that requires a stack of a few GEM foils to provide electron amplification gain in the range of 10^4 as described above in Fig. 9, a (µRWELL) detector is a single-stage amplification detector similar to Micromegas technology. Compared to a triple-GEM detector, a µRWELL offers intrinsic low mass due to a single amplification stage, simpler mechanical construction, and low production costs especially for large-area tracking devices, while providing similar performances in term of spatial and timing resolution to triple-GEMs detectors. A cross-sectional view of a (µRWELL) detector is shown on the left of Fig. 10 and on the top right is shown a small prototype with *X*-*Y* strip readout developed by the MPGD-Detector group at University of Virginia. The test beam results of the prototype are shown on the two residual plots of the bottom left of Fig. 10, which demonstrates a spatial resolution performance better than 50 µm in both the *X* and *Y* directions. Because a µRWELL is part of the resistive MPGD family such as Micromegas, it has a rate capability typically one order of magnitude lower than standard triple-GEMs, but could still operate in stable gain conditions at a rate above 100 kHz/cm^2, which exceeds by a few orders of magnitude the particle rates expected even after the high luminosity upgrade of the CLAS12 spectrometer. This makes μRWELL technology a better suited option for the large-area and high-performance tracking system to equip the CLAS12 spectrometer.

C. Deails of the R&D and Prototyping

1. GEM vs. μRWELL: Technology Comparison

Unlike large GEM detectors, of size similar to the CLAS12 forward tracker GEMs, μRWELL have not, to our knowledge, been fully operated in nuclear physics (NP) and high energy physics (HEP) experiments. Small (10 cm × 10 cm) μRWELL prototypes have been studied (see Fig. 10) and performances in particle rate environments several orders of magnitude higher than the one expected for CLAS12 in Hall B have been demonstrated. However, additional detector R&D must be carried out for large-area μRWELL detectors. We propose to build two large (100 cm × 50 cm) prototypes of the size of the chamber2 design of Fig. 2, one based on μRWELL technology and the second a on standard triple GEM detector. We will compare the performance of the two prototypes with cosmics and x-rays at the MPGD Detector Lab at UVa and in a test beam. With these prototypes, we will be able to investigate most of the challenges associated with large-size detector, such as gain uniformity, rate capability, discharge rate, and aging and space point resolution. The prototypes will incorporate new ideas for low radiation length and narrow carbon fiber support frames.

2. High Performance & Low Channel Count Anode Readout for MPGDs

The MPGD detector group at UVa is also developing a new high-performance and low-channel count 2D anode readout technology for MPGDs that would perfectly match the requirements for large-area detectors such as the CLAS12 forward trackers. The principle of this new 2D readout concept is described in the appendix Section V C 3. The charge sharing concept based on capacitive coupling between pad layers ensures high spatial resolution performance (we expect typical space point resolution around 100 μm) similar to the performance of the standard COMPASS design of X-Y strip readout or triple GEMs but with a factor 2 to 4 reduction of the number of electronics channels. The development of this type of novel 2D MPGD anode readout layer has 3 important advantages for large-area MPGD detectors:

- Preserve the 2D space point spatial resolution performance in the range of 100 μm
- Factor of 2 to 4 reduction of the readout channel count (*i.e.* the electronic costs.)
- Allow all FE electronics cards to be located on the non-parallel sides as shown in Fig. 2.

Capacitive sharing of 2D (X-Y, U-V, or r-ϕ) strips as described in the appendix Section V C 4 is particularly suitable for large-area MPGD trackers. Such 2D strip readout layers require less pad layers for the charge sharing and therefore is a low radiation length version of the pad readout. The two large prototypes of Section V C 1 will be designed with capacitive sharing X-Y strip readout layers with the connectors on the side as shown in Fig. 2.

3. Capacitive-Sharing Large-Pad Anode Readout

The principle of capacitive sharing large pad readout is illustrated on the sketch of Fig. 11 and is based on a stack of Cu-pad layers, separated by 50-μm-thick Kapton foils as a dielectric to form a capacitor. The pad size doubles (and subsequently the area is multiplied by 4) from a one layer (layer[i]) to the layer[$i+1$] underneath it. Each pad of layer[i] is arranged is space so that its center is either always perfectly aligned with the center of a larger pad of layer[$i+1$] or with the boundary between of two adjacent pads of layer[$i+1$]. This space arrangement of the pads from one layer to the next ensures that the charges collected by two adjacent pads of layer[i] are always transferred to the two adjacent pads of layer[$i+1$] no matter the size of the pads of layer[$i+1$]. The charge is transferred between layers via capacitive coupling as two Cu-pad layers separated by the Kapton foil that acts effectively as a perfect capacitor. The pads of the bottom layer[n], which we name here the *charge-collection layer*, are connected to the front-end (FE) electronics readout, while all the other pad layers above, which we name here the *charge transfer layers* just serve to transfer and spread the original charges through capacitive coupling. With such a scheme, the area $a[n]$ of the pad of the *charge-collection layer* (layer[n]) in a n-layer-stack readout board is equal to $a[1] \times 2^n$ with $a[1]$ being the area of the pad of the top *charge transfer layer* (layer[1]) and the total number of pads of layer[n] is $1/2^n$ of the total number of pads of layer[1]. By design, the top layer pad size of this readout board basically defines the spatial resolution performance of the pad readout scheme and that is transferred via capacitive coupling to the bottom layer whose

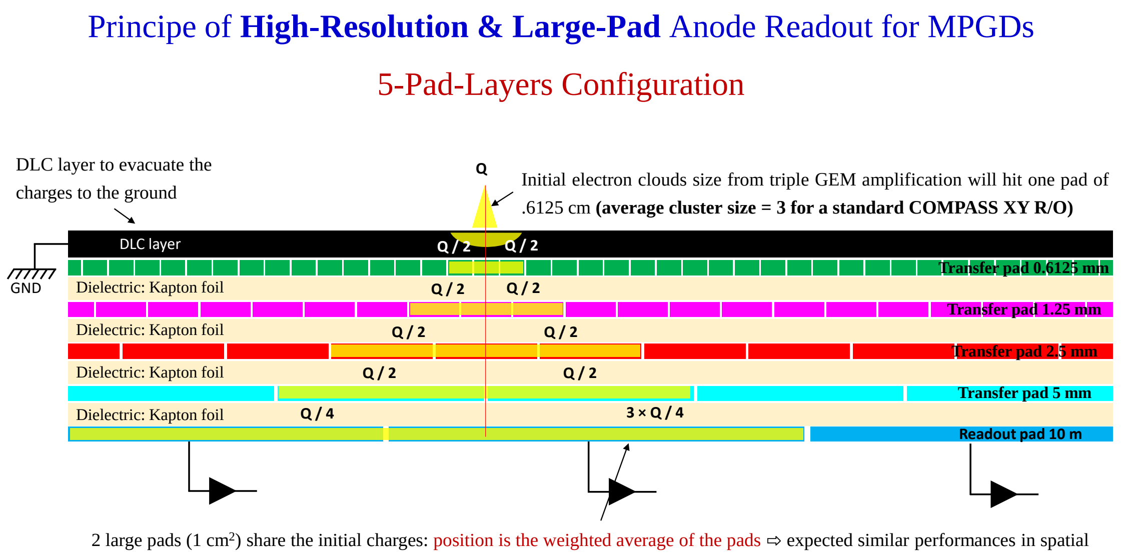


FIG. 11. Principle of charge sharing through capacitive coupling for large pads anode readout for MPGDs.

pad size defines the total number of channels to be read out. With this scheme, in first order, the spatial resolution performance is decoupled from the size of the readout layer pads connected to the front-end readout electronics. So, for example, a 5-layer large-pad readout PCB with a pad size of 0.06125 cm × 0.06125 cm for the top layer will have a pad size equal to 1 cm × 1 cm for the bottom layer for the charge collection that will only require 100 channels to be read out in a standard 10 cm × 10 cm triple-GEM detector configuration. This is **5 times less channels than the standard 2D X-Y COMPASS strip readout design** that requires 512 channels to achieve similar spatial resolution performance.

4. Extension of Capacitive-Sharing Concept to 2D Strip Readout

The concept of capacitive coupling readout could also be extended to 2D strip readout in order to reduce the number of readout strips. The scheme is described in Fig. 12. In this configuration, the stack pad layers are used for the charge sharing through capacitive coupling as described in Section V C 3, however, the readout layer that is on the bottom layer has a 2D strip pattern with straight strips in one direction (Y-strips) and pad-like strips (X-strips) in the other direction. Adding one more charge-sharing pad layer means a doubling of the 2D strip pitch and, therefore, a reduction by a factor 2 of the number of readout channels with limited impact on the spatial resolution.

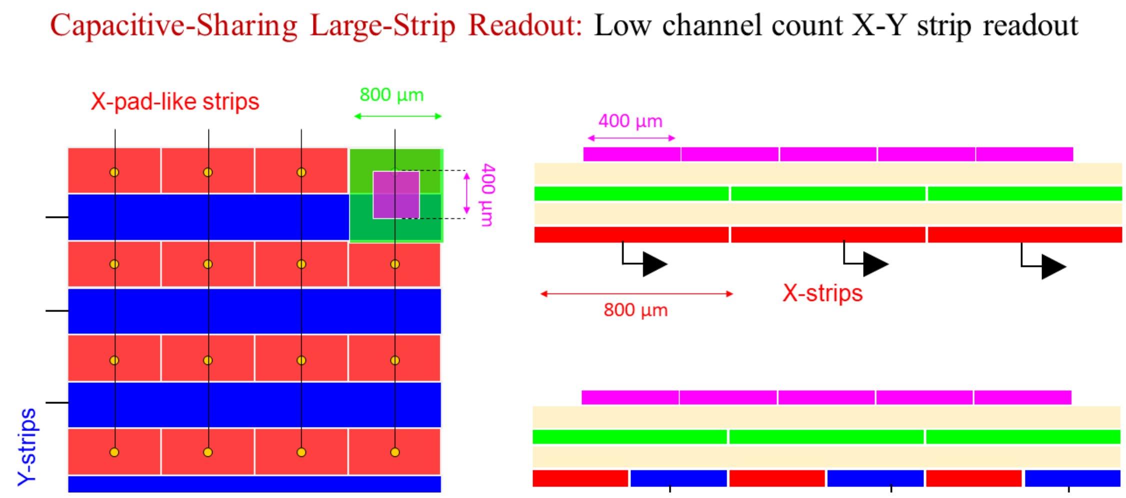


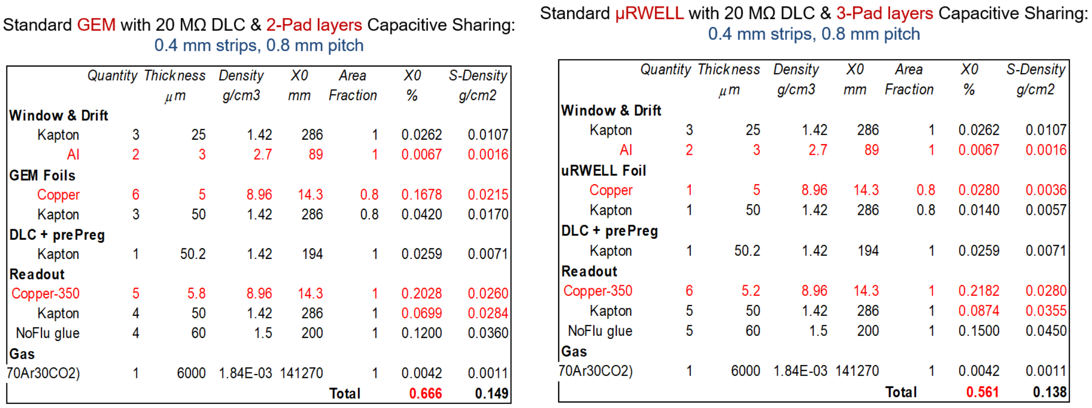
FIG. 12. Principle of charge sharing through capacitive coupling for wide X-Y strips 2D anode readout for MPGDs.

D. Development of Low-Mass and Large-Area MPGDs

a. Low Mass in the Detector Active Area

GEM detectors such as the one being fabricated for the PRad experiment and for the SBS GEM trackers have a radiation length (r.l.) that is typically in the order of 0.8%. This includes a 3 mm honeycomb sandwiched between 2 × 100 μm G10 fiberglas material used as a base support structure for the chamber. A lighter design with no honeycomb support structure has been developed and successfully tested as part of the EIC detector R&D program. This reduces the detector thickness to 0.67% r.l. as shown in the left table of Fig. 13 of the appendix in Section. V D. The radiation length for a standard μRWELL detector will be comparatively smaller ~0.56% r.l. as shown in the right table of Fig. 13. These are the radiation lengths to be expected with the current state of the art of each of triple GEM technology. Large-area triple-GEM detectors of the size required for the CLAS12 R1 detector without a honeycomb support structure will present some serious construction challenges, as well as a certain number of risks during its operation under real experimental conditions. This is less of a concern when it comes to μRWELL detectors as there is no need for stretching foils or maintaining a uniform gap over a large area. Therefore, μRWELL technology presents, from this point of view a clear advantage over triple GEM for low mass and large area trackers. However, there are some new ideas to minimize even further the materual budget of these detectors. The tables of Fig. 14 of appendix Section V D show some of these R&D

ideas to reduce material budget of a triple-GEM further by 20% to 0.54 % r.l. and for a µRWELL by 33% to 0.4 % r.l. per layer. Achieving these goals, requires some dedicated but limited in scope R&D effort to explore the possibility of using 200 nm Chromium electrodes instead of 5 µm copper for the GEM foils electrodes and for the pad layers for the capacitive-sharing readout of both the triple-GEM and µRWELL options. The concept has been successfully tested in the past on low-mass GEM detectors but needs to be validated for large-area chambers. A way to reduce even further the material thickness by about 20 % of these chambers is to use a high-resistance DLC layer for these detector to help with the charge sharing at the cost of reducing the rate capability by about a factor of 10 with a slight degradation of the spatial resolution performance. This is illustrated in the tables of Fig. 15 of appendix Section V D with a radiation length of 0.45% for a triple GEM and 0.33% for a µRWELL. This R&D will be carried out on small size (10 cm × 10 cm) prototypes and will be completed within a year.



Standard GEM with 20 MΩ DLC & 2-Pad layers Capacitive Sharing:
0.4 mm strips, 0.8 mm pitch

	Quantity	Thickness µm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window & Drift							
Kapton	3	25	1.42	286	1	0.0262	0.0107
Al	2	3	2.7	89	1	0.0067	0.0016
GEM Foils							
Copper	6	5	8.96	14.3	0.8	0.1678	0.0215
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
DLC + prePreg							
Kapton	1	50.2	1.42	194	1	0.0259	0.0071
Readout							
Copper-350	5	5.8	8.96	14.3	1	0.2028	0.0260
Kapton	4	50	1.42	286	1	0.0699	0.0284
NoFlu glue	4	60	1.5	200	1	0.1200	0.0360
Gas							
70Ar30CO2)	1	6000	1.84E-03	141270	1	0.0042	0.0011
					Total	**0.666**	**0.149**

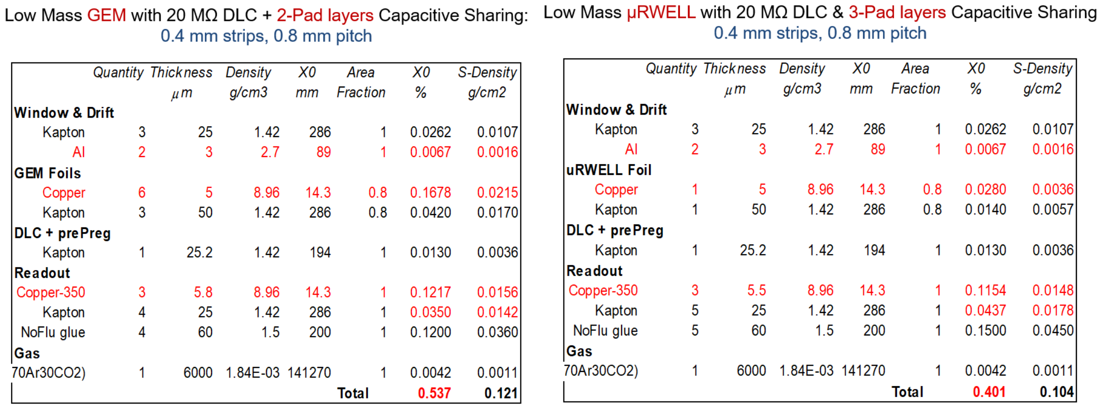
Standard µRWELL with 20 MΩ DLC & 3-Pad layers Capacitive Sharing:
0.4 mm strips, 0.8 mm pitch

	Quantity	Thickness µm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window & Drift							
Kapton	3	25	1.42	286	1	0.0262	0.0107
Al	2	3	2.7	89	1	0.0067	0.0016
uRWELL Foil							
Copper	1	5	8.96	14.3	0.8	0.0280	0.0036
Kapton	1	50	1.42	286	0.8	0.0140	0.0057
DLC + prePreg							
Kapton	1	50.2	1.42	194	1	0.0259	0.0071
Readout							
Copper-350	6	5.2	8.96	14.3	1	0.2182	0.0280
Kapton	5	50	1.42	286	1	0.0874	0.0355
NoFlu glue	5	60	1.5	200	1	0.1500	0.0450
Gas							
70Ar30CO2)	1	6000	1.84E-03	141270	1	0.0042	0.0011
					Total	**0.561**	**0.138**

FIG. 13. Material budget breakdown for triple-GEM (*left*) and µRWELL (*right*) with standard material (50 μm Kapton foil and 5 µm Copper pads) for capacitive charge sharing 2D readout layer.

b. Light-Weight Support Structures Materials

The limitation in size from the base material used for GEM foils, as well as a µRWELL device imposed to split the CLAS12 R1 forward tracker sector into 3 detector modules as shown in the sketches of Fig. 1 and Fig. 2, and as aconsequence, detector frames in the active area of the trackers could not be avoided. It is critical to explore new thin, narrow, and light-weight materials for the support frames of these trackers to minimize the acceptance. At the same time, one should make sure that the frames remain strong enough especially regarding holding the tension of the 3 GEM foils for the GEM detectors. The radiation length requirement for a µRWELL frames is expected to be about 4 times smaller than for a triple-GEM, which is another strong argument in favor of a µRWELL option. We will investigate the use of carbon fiber frames to replace of the standard



Low Mass GEM with 20 MΩ DLC + 2-Pad layers Capacitive Sharing:
0.4 mm strips, 0.8 mm pitch

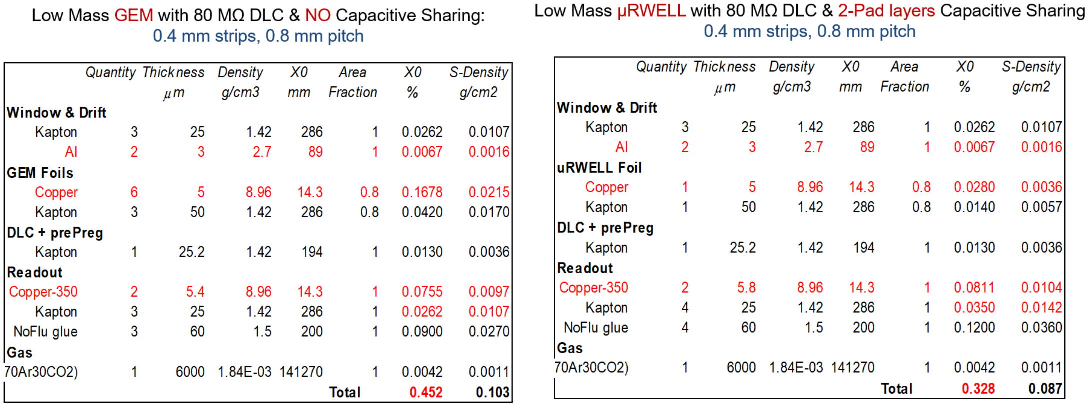
	Quantity	Thickness	Density	X0	Area	X0	S-Density
		μm	g/cm3	mm	Fraction	%	g/cm2
Window & Drift							
Kapton	3	25	1.42	286	1	0.0262	0.0107
Al	2	3	2.7	89	1	0.0067	0.0016
GEM Foils							
Copper	6	5	8.96	14.3	0.8	0.1678	0.0215
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
DLC + prePreg							
Kapton	1	25.2	1.42	194	1	0.0130	0.0036
Readout							
Copper-350	3	5.8	8.96	14.3	1	0.1217	0.0156
Kapton	4	25	1.42	286	1	0.0350	0.0142
NoFlu glue	4	60	1.5	200	1	0.1200	0.0360
Gas							
70Ar30CO2)	1	6000	1.84E-03	141270	1	0.0042	0.0011
					Total	**0.537**	**0.121**

Low Mass µRWELL with 20 MΩ DLC & 3-Pad layers Capacitive Sharing
0.4 mm strips, 0.8 mm pitch

	Quantity	Thickness	Density	X0	Area	X0	S-Density
		μm	g/cm3	mm	Fraction	%	g/cm2
Window & Drift							
Kapton	3	25	1.42	286	1	0.0262	0.0107
Al	2	3	2.7	89	1	0.0067	0.0016
uRWELL Foil							
Copper	1	5	8.96	14.3	0.8	0.0280	0.0036
Kapton	1	50	1.42	286	0.8	0.0140	0.0057
DLC + prePreg							
Kapton	1	25.2	1.42	194	1	0.0130	0.0036
Readout							
Copper-350	3	5.5	8.96	14.3	1	0.1154	0.0148
Kapton	5	25	1.42	286	1	0.0437	0.0178
NoFlu glue	5	60	1.5	200	1	0.1500	0.0450
Gas							
70Ar30CO2)	1	6000	1.84E-03	141270	1	0.0042	0.0011
					Total	**0.401**	**0.104**

FIG. 14. Material budget breakdown for triple-GEM (*left*) and µRWELL (*right*) with light-weight material (25 μm Kapton foil and 200 nm Chromium pads) for capacitive charge sharing 2D readout layer.

fiberglas G10 frames used for triple-GEMs. Though the carbon fiber material thickness is just roughly 15% smaller than for G10, because of the strength of this material, we will use narrower and thinner frames where it is possible and this would represent a significant reduction of the total material budget in the active area of the detector. This R&D will be ultimately validated with on a prototype of the size of chamber3 of Fig. 2.



Low Mass GEM with 80 MΩ DLC & NO Capacitive Sharing:
0.4 mm strips, 0.8 mm pitch

	Quantity	Thickness	Density	X0	Area	X0	S-Density
		μm	g/cm3	mm	Fraction	%	g/cm2
Window & Drift							
Kapton	3	25	1.42	286	1	0.0262	0.0107
Al	2	3	2.7	89	1	0.0067	0.0016
GEM Foils							
Copper	6	5	8.96	14.3	0.8	0.1678	0.0215
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
DLC + prePreg							
Kapton	1	25.2	1.42	194	1	0.0130	0.0036
Readout							
Copper-350	2	5.4	8.96	14.3	1	0.0755	0.0097
Kapton	3	25	1.42	286	1	0.0262	0.0107
NoFlu glue	3	60	1.5	200	1	0.0900	0.0270
Gas							
70Ar30CO2)	1	6000	1.84E-03	141270	1	0.0042	0.0011
					Total	**0.452**	**0.103**

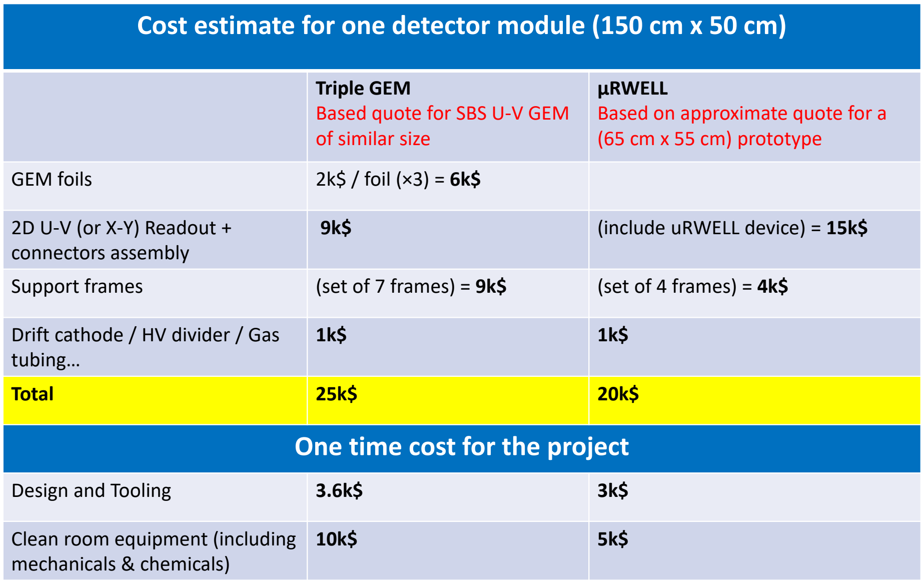
Low Mass µRWELL with 80 MΩ DLC & 2-Pad layers Capacitive Sharing
0.4 mm strips, 0.8 mm pitch

	Quantity	Thickness	Density	X0	Area	X0	S-Density
		μm	g/cm3	mm	Fraction	%	g/cm2
Window & Drift							
Kapton	3	25	1.42	286	1	0.0262	0.0107
Al	2	3	2.7	89	1	0.0067	0.0016
uRWELL Foil							
Copper	1	5	8.96	14.3	0.8	0.0280	0.0036
Kapton	1	50	1.42	286	0.8	0.0140	0.0057
DLC + prePreg							
Kapton	1	25.2	1.42	194	1	0.0130	0.0036
Readout							
Copper-350	2	5.8	8.96	14.3	1	0.0811	0.0104
Kapton	4	25	1.42	286	1	0.0350	0.0142
NoFlu glue	4	60	1.5	200	1	0.1200	0.0360
Gas							
70Ar30CO2)	1	6000	1.84E-03	141270	1	0.0042	0.0011
					Total	**0.328**	**0.087**

FIG. 15. Material budget breakdown for triple-GEM (*left*) and µRWELL (*right*) with light-weight material (25 μm Kapton foil and 200 nm Chromium pads) for hybrid capacitive & resistive sharing 2D readout layer.

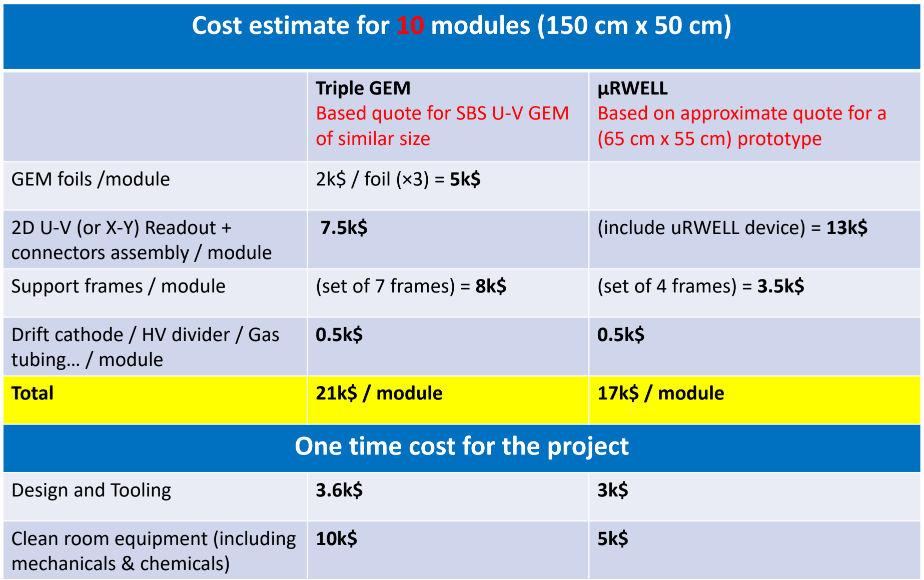
E. Cost Estimate

The discussion here on cost estimate for both the prototyping phase as well as the production module does not include labor or any overhead or contingency.



Cost estimate for one detector module (150 cm x 50 cm)		
	Triple GEM Based quote for SBS U-V GEM of similar size	**µRWELL** Based on approximate quote for a (65 cm x 55 cm) prototype
GEM foils	2k$ / foil (×3) = **6k$**	
2D U-V (or X-Y) Readout + connectors assembly	**9k$**	(include uRWELL device) = **15k$**
Support frames	(set of 7 frames) = **9k$**	(set of 4 frames) = **4k$**
Drift cathode / HV divider / Gas tubing…	**1k$**	**1k$**
Total	**25k$**	**20k$**
One time cost for the project		
Design and Tooling	**3.6k$**	**3k$**
Clean room equipment (including mechanicals & chemicals)	**10k$**	**5k$**

FIG. 16. Cost estimate for one CLAS12 large tracker R1 module prototype.



Cost estimate for 10 modules (150 cm x 50 cm)		
	Triple GEM Based quote for SBS U-V GEM of similar size	**µRWELL** Based on approximate quote for a (65 cm x 55 cm) prototype
GEM foils /module	2k$ / foil (×3) = **5k$**	
2D U-V (or X-Y) Readout + connectors assembly / module	**7.5k$**	(include uRWELL device) = **13k$**
Support frames / module	(set of 7 frames) = **8k$**	(set of 4 frames) = **3.5k$**
Drift cathode / HV divider / Gas tubing… / module	**0.5k$**	**0.5k$**
Total	**21k$ / module**	**17k$ / module**
One time cost for the project		
Design and Tooling	**3.6k$**	**3k$**
Clean room equipment (including mechanicals & chemicals)	**10k$**	**5k$**

FIG. 17. Extrapolation of the cost per module for a production chambers of 10 modules.

1. MPGD Detectors

In the table in Fig. 16, we provide our best cost estimate for the parts to assemble the largest size CLAS12 forward tracker R1 module (150 cm × 50 cm) for both a triple GEM and a µRWELL prototype. The cost estimates are based on quotes that we obtained for similar size detectors for other experiments. For the triple GEM, the cost of the parts was based on the actual cost of the large U-V strip triple GEMs currently under construction for the SBS in Hall A. This SBS U-V GEM chamber has an active area of 150 cm × 40 cm, very similar in size to that proposed for the CLAS12 forward tracker R1. For the µRWELL prototype, the cost estimate was based on a recent quote that we obtained for a smaller detector and we extrapolate the cost to the size of the CLAS12 R1 forward tracker. The table in Fig. 17 shows an extrapolation of the cost per module when we go from one single prototype to a production of 10 modules. Here again, based on previous experience with similar projects, we anticipate a cost reduction of about 15% per module unit for the production chambers.

2. Readout Electronics

With the ongoing low count 2D strip readout layer development, the total number of electronics readout channels for the largest module (see Fig. 2) for an X-Y strip readout is estimated to be in the range of 3k channels. The PRad GEM layers and the SBS GEM trackers are read out with APV25-based readout electronics with the cost per channel of \$3. However, the APV25 electronics will not be an available option for the CLAS12 forward GEM trackers. The cost per channel for alternative options to the APV25 for MPGDs such as VMM3, SAMPA, or DREAM electronics, is expected to be about double, so based on this, we estimate that the readout electronics cost for the largest module to be in the range of \$20k.

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