SoLID subsystem R&D, integration and commissioning

Electromagnetic Calorimeter and Scintillator Pad Detector

The Electromagnetic Calorimeter (EC), in combination with other detectors, provides the main trigger and the particle identification for the SoLID experiments. The EC consists of a Preshower and a Shower portion. The technologies that we chose for the EC: WLS-fiber-embedded scintillator for the Preshower, and the Shashlyk-type modules for the Shower, have both been used in collider experiments. The main goal of the R&D is thus to ensure the physics requirement of the SoLID program can be met with the EC design. The Scintillator Pad Detector (SPD) is only needed by the SIDIS program of SoLID. It is divided into a large-angle (LASPD) and a forward-angle (FASPD) section. Both LASPD and FASPD provide photon rejection, while LASPD also provide time-of-flight information. The main challenges of the SPD is to minimize photon conversion (false positives) while keeping a reasonable signal-to-noise (S/N) ratio, and for LASPD to ensure the timing resolution meet the requirement of SIDIS.

In the following we will describe the objectives and the tasks to be completed during the pre-R&D and the R&D stages of each subsystem – FASPD and LASPD, Preshower, and Shower, and divide them into the following priorities:

- Priority A – design-related tasks: must be completed in the pre-R&D stage because they may affect the basic design of the subsystem;
- Priority B – performance evaluation: preferrablly to be completed in the pre-R&D but can also be completed in the R&D stage. These tasks are usually related to the fine-tuning of the subsystem design.
- Priority C – final design work: preferrably to be completed by the end of the R&D stage but can also be completed in the early (few) months of the construction stage. These tasks are usually related to the mass production or evaluation of the subsystem.

We will also describe the basic procedure of integrating these subsystems to the whole SoLID package and propose an outline for the calibration methods.

1 R&D Plan

1.1 R&D Plan for Preshower

The preshower module is made of 2-cm thick, 6.25-cm-side hexagon-shape scintillators. Light is guided out using WLS fibers, then connected to clear fibers for readout outside the solenoid field region by multi-anode PMTs (MAPMT). We have already carried out preliminary cosmic tests on the Preshower light yield and optimized the WLS fiber embedding. The highest photo-electron yield can be achieved using two WLS fibers per module, each embedded 2.5 turns in a 9-cm diameter groove. The preshower scintillator is wrapped in aluminized mylar to improve light reflectivity and then wrapped in black tape. The total light yield is about 80 photoelectrons per MIP, readout directly at the end of the WLS fiber which extend about 20 cm beyond the edge of the scintillator. Tests have been performed on scintillators from three vendors: IHEP (Russia), Kedi (China) and CNCS (China). It was found all scintillators gave similar light yield, while the quotes from both Chinese companies are less than IHEP. We have thus determined that either Chinese vendor can be contracted to produce the preshower scintillators for SoLID. We have also worked together with Shandong University (SDU, China) to ensure that we can obtain the same light yield results under similar test conditions. For the preshower detector the remaining R&D includes:

1. Priority A: studying the light loss in the fiber connector and clear fibers;
2. Priority A: design and testing the MAPMT base with an integrated ×50 preamplifier, to design and test the connector between clear fibers and the MAPMT;
3. Priority A: support design for both Preshower and Shower modules;
4. Priority A: design and developing an LED testing system;

5. Priority B: testing the MAPMT performance, such as gain uniformity, cross-talk, etc;
6. Priority B: radiation resistance test for the Preshower module;
7. Priority C: developing test systems at both SDU and UVa for testing the preshower modules at the production scale.

The Preshower R&D work will be carried out parallel at UVa and SDU.

1.2 R&D Plan for SPD

1.2.1 FASPD

The FASPD consists of 240 segments (60 radial times 4 azimuthal). Scintillating light is guided out by the embedded WLS fibers, then connected to clear fiber for readout by MAPMTs outside the solenoid field region. To minimize photon conversion (false positives), the thickness of the FASPD will be between 5 and 6 mm, with 4.5-mm deep by 1.1-mm wide grooves for WLS fiber embedding (the thickness of the FASPD must ensure enough material beneath the 4.5-mm deep groove). The shape of 4 FASPD radial segments is shown in Fig. 1. We have compared 4 scintillator vendors – Eljen, Saint-Gobain, Kedi (China) and CNCS (China). The current choice is to contract Eljen for both FA- and LASPDs because their scintillator light yield is expected to be 50% higher than both Chinese vendors, and the estimated cost is much lower than Saint-Gobain whose scintillator has similar light yields. We have carried out preliminary cosmic test on two Eljen 5mm-thick FASPD modules, one for the 266.3 cm^2 and one for the 966.2 cm^2 size. The light yield at the WLS fiber output (about 20 cm outside the module) is about 11 and 9 photoelectrons per MIP for the smallest and the largest size, respectively. These results are consistent with the simulation. On the other hand, the light yield after the use of fiber connector and clear fibers is estimated to be 6 photoelectrons per MIP and is marginal. In addition, the cosmic test result is the averaged light yield. The uniformity of the light yield should be characterized due to the large surface area of the module. The R&D for the FASPD thus includes:

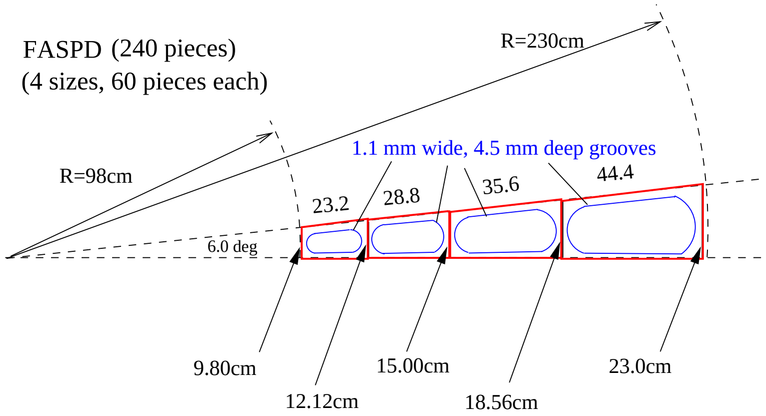

Figure 1: FASPD segments. The surface area is (from inner to outer): 266.3, 409.0, 625.6, and 966.2 cm^2.

1. Priority A: testing FASPD prototypes from the Chinese vendor to confirm the lower light yield.
2. Priority A: design and test the MAPMT base with an integrated ×50 preamplifier, to design and test the connector between clear fibers and the MAPMT. This is the same as for the Preshower.
3. Priority A: designing and testing connectors between the clear fiber and the MAPMT. This is the same as for the Preshower.
4. Priority A: testing the MAPMT performance. The MAPMT performance test for the FASPD is more important than for the Preshower because of the lower light yield, and thus lower S/N ratio and higher anode current load, of the FASPD compared to Preshower.

5. Priority B: characterizing the uniformity of the light yield using a radiative source, and adjust the fiber-embedding route accordingly;
6. Priority B: maximizing the light yield by adjusting fiber-embedding routes.

These R&D work will be carried out primarily at UVa, with MAPMT base design carried out by the JLab detector group and MAPMT performance tests can be done at UVa, or W&M, or JLab.

1.2.2 LASPD

The LASPD serves as both a photon rejector and a TOF counter for SIDIS. To ensure enough light yield for the TOF, the LASPD will be 20-mm thick and the signal must be readout immediately by attaching phototubes directly to the scintillator. Our current design for the LASPD module and readout is shown in Fig. 2. We have carried out preliminary TOF test for the LASPD using comics and the "3-bar" method, and found the timing resolution obtained by reading out both the inner and the outer edge of the LASPD to be between 100 and 115 ps. For the SIDIS running condition, only the outer edge will be readout and one must use data from a tracking detector to remove the timing uncertainty due to position. Without knowing the exact hit position of comic rays in the LASPD, we can only extrapolate from the comic results to the running condition and we found the extrapolated timing resolution, using only readout from the outer edge of the LASPD, to be about 140-160 ps and is marginal for SIDIS.

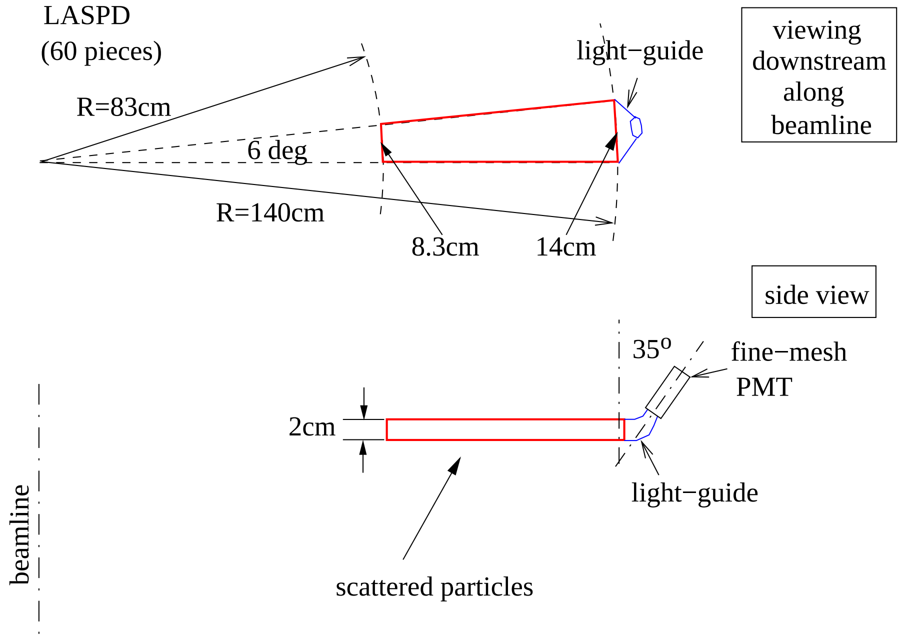

Figure 2: LASPD segments, both viewing along beamline (top) and viewing from the top (bottom). Existing data show that FMPMTs can be used if they are aligned at an angle between 30 and 40 degrees with respect to the external field. Therefore we will use a 55-degree bending light-guide between the LASPD module and the FMPMT readout.

The LASPD readout must be both high-field and high-neutron-background (SIDIS neutron fluence is up to $(6-10)\times 10^{13}$ cm^{-}2 1-MeV-equivalent). Our current choice is fine-mesh PMTs, which have been shown to work under 1-T fields if the PMT's axis is aligned at an angle less than 40 degrees w.r.t. the field. We will carry out tests of the FMPMT's gain and timing resolution for fields up to 2 T (since the SoLID field is about 1.5T) and for a wider angle range. Meanwhile, development in the SiPM readout indicates that the radiation resistance of SiPM has improved over the past decade. For example the LHCb tracker upgrade plans to use SiPM at -40 $^{\circ}C$ with an expected neutron fluence of 10^{12} cm^{-2}, which is a much higher fluence than what was commonly perceived for SiPM. However, the LHCb neutron fluence is still about $6-8$ times smaller than for SoLID, and using SiPM for SoLID will require excessive cooling. We will keep following the development in SiPM radiation resistance and should it exceeds the requirement of SoLID, we may use SiPM for the LASPD readout.

The prioritized R&D for the SPD thus include the following:

1. Priority A: test of FMPMT performance under high fields. We plan to use the FROST magnet at JLab;
2. Priority A: test of LASPD timing resolution under SoLID running conditions. This will require the use of a tracking detector and thus will be an in-beam test. We may carry out this test at JLab.
3. Priority B: radiation test of LASPD and FMPMT under a high neutron background. This may be done at a neutron source at either LANL or ORNL. Note that Hamamatsu already agreed to produce custom FMPMT H6614-70 with synthetic silica or alternatively UV glass windows instead of the usual boron-silicate window.
4. Priority N/A: Continue investigating SiPM radiation resistance.

We expect the majority of the LASPD R&D to be done at UVa, the in-beam timing resolution test to be done at JLab, and the neutron radiation test may be done with help from the LANL group.

1.3 R&D Plan for Shower

The current design for the Shashlyk module is to use 194 layers each of 1.5-mm scintillator and 0.5-mm lead. WLS fibers will be inserted at a density of one per cm^2. The upstream end of the fiber will be reflected by mirrors and the downstream end will be connected to clear fibers for reading out outside the solenoid field by conventional PMTs. So far the most promising choice for the Shashlyk Shower module production is by IHEP (Russia), who have the capacity for manufacturing all modules within two years. On the other hand, the calorimeter technique, in particular shashlyk module production, is signficantly more advanced in Europe than in the US. In light of the future EIC, it is highly desired for the MEP community in the US to master the production of Shashlyk modules. We therefore propose to carry out R&D for producing Shashlyk modules in the US.

After production, individual Shashlyk modules can be shipped to our collaboration groups at other laboratories and universities for testing. This includes UVa, WM, and Los Alamos National Laboratory (LANL). After initial testing, pre-assembling of Shower, Preshower, and SPD modules can be done at WM, which has a high-bay area for assembling large detectors. The support system of EC and SPD will be designed by the engineering group of Argonne National Lab (ANL), with help from the JLab engineering group. Testing of all readout PMTs can be performed at SDU because of the large-scale PMT testing setup they have.

The R&D plan for the Shower detector is as follows:

1. Priority A: carry out full-scale module simulations, focusing on particle identification, characterizing the requirement on the layer uniformity, effect of the supporting stainless steel rods and endcaps;
2. Priority A: investigate the feasiblity of Shashlyk module production in the US. This includes investigating possible vendors for the scintillator and the lead layers, and for attaching mirrors to the fiber ends; learning from the Wayne State U. and the Iowa U. groups who had experience producing shashlyk modules for LHC; and design of the assembly stand and development of the assembly procedure;
3. Priority A: support design for both Preshower and Shower modules;
4. Priority A: design and testing different techniques for connecting 100 WLS to 100 clear fibers;
5. Priority A: design and develop the LED testing system;
6. Priority A: design of a quality-control system and screening procedure;
7. Priority B: testing radiation hardness of the scintillator material and the WLS fiber. Performance can be evaluated using an LED or a beta source for the WLS fiber. The scintillator material alone can be evaluated using comics.

8. Priority B: procuring shashlyk prototype modules, ideally 8 modules from IHEP and 8 modules constructed by ourselves, and carry out in-beam test to charaterize their energy, position, and timing resolutions and PID performance. Tests may be carried out with the incident particles perpendicular to the module front-face and with an angle similar to the running condition of SIDIS or PVDIS.
9. Priority C: constructing multiple assembly stands for mass production.
10. Priority C: Further design of the quality control system and screening procedure and apply them to mass production.

2 Integrating into SoLID and Calibration Procedure for EC and SPD

In developing the calibration procedure for EC and SPD, we focus on the following different scenarios: 1) the "worst case" scenario where only the subsystem being calibration is working, in which case we focus on a procedure with the goal of both a basic checkout and a crude calibration of the single subsystem and to provide useful information for bringing other subsystems online; and 2) the "best case" scenario where a number of subsystems are working which allows a full, final calibration of the subsystem; and 3) any possible intermediate step(s) between the worst and the best scenarios.

2.1 Calibration procedure for SPD

The calibration and commissioning procedure for SPD is straightforward because of the simplicity of the system. Once the SPDs are working, they can be used to provide triggering for checking out other subsystems.

1. Cosmic test, without beam, can be done with only SPD working. Will rely on the MIP, slow. Identification of the single photoelectron peak will require very high statistics. The goal is to characterize the MIP and making sure it is above the noise.
2. Calibration with beam, can be done with only SPD working, fast. The goal is similar to cosmic test,
3. Characterizing photon rejection performance, must be done with beam and the Cherenkov detector (to help identifying photons). with the additional goal of characterizing photon rejection performance.
4. Testing LASPD timing resolution with beam, must be done with tracking.

2.2 Calibration procedure for EC

We propose below several methods for calibrating and commissioning the EC. For SIDIS, the LASPD and FASPD, if working, can be used in all methods. Once EC is working, it will provide triggering, position, and PID information for bringing other subsystems online.

1. Cosmic test and LED test, without beam, can be done with only EC working. The calibration precision can be good to (10-20)%.
2. A rough fit. For Preshower we expect the signal to be dominated by MIP and thus independent of the position within the whole coverage of EC. For Shower the fit will be based on the fact that the energy deposit should be a smooth function of R and should be repetitive in phi. This step can be done relatively fast with a low-current beam and with only EC running.
3. Shower calibration with MIP, with beam, slow, can be done with only EC running, could be good to (2-5)%: If the electron signal is maxed at 1.5V, MIP peak (60 MeV) should be seen at around 40 mV with $(\Delta E/E)_{MIP} \approx \pm 20\%$ or ± 8 mV. The FADC range is 2 V with 12 bit, so the resolution is 2/4096=0.5mV which correspond to a MIP width of ± 16 bins, plenty for a clear identificiation of the MIP. Advantages of this method include: can be done continuously and non-intrusive, but precision can be limited.

4. Calibration with π^0's for Preshower and Shower combined, can be done at the same time as MIP calibration, can be done with only EC running. Need 2-cluster triggers. Advantages of this method include: can be done continuously and non-intrusive, can potentially reach high precision. (Ref: HERA-B note 00-103).

5. Using elastic electrons at low beam energies such as 2.2 GeV, for Preshower and Shower combined, can be done during commissioning or as needed, slow, coverage in momentum and angle may not be large, can be done with only EC running, but if tracking information is available this method can reach high calibration precision.

6. Using electrons with known tracking/momentum, with beam, can be done during commissioning or as needed, must be done with tracking, can reach high precision. This is another method (in addition to π^0) that can be done continuously and non-intrusive.

Once the whole SoLID is online, the PID performance of EC can be extracted using combined data from EC, Cherenkov, and tracking information.

2.2.1 Cost Estimate for R&D

We provide below cost estimate focusing on priority A and B. A cost of $10k per year for general material and lab supplies should be added in addition to the table.

Priority	Subsystem	Task	Material cost	Manpower cost (per year)
A	Preshower, FASPD, LASPD, Shower	simulation and design	N/A	0.5 postdoc
	Preshower, FASPD, Shower	fiber connector and clear fiber light loss study	$1k connectors, 400 meters BCF98 clear fiber $5k	0.5 postdoc, two half-time grad student
	Preshower, FASPD	MAPMT base design	3× MAPMT H12445-100MOD, $11k	
	Preshower, FASPD, LASPD, Shower	LED control system		
	FASPD	prototype testing	FASPD prototype $5.3k (3 sets, 4 sizes per set)	
	LASPD	fine-mesh PMT high field test		
	LASPD	in-beam test with tracking		
	Preshower, Shower	support design		0.1 physicist, 0.15 engineer
	Shower	prototyping at UVa	$3k for 10× R11102 PMTs, $55k for module parts, $3k for WLS fiber, $20k assembly stand, $4k HV, total $82k	0.2 engineer, 0.5 postdoc, part-time tech, 1 grad student, 3 undergrad
B	Preshower, FASPD	MAPMT test		0.5 postdoc, 0.5 grad student
	Preshower, FASPD, LASPD, Shower	radiation resistance test		
	FASPD	uniformity in light yield		
	Preshower, Shower	support design		0.33 physicist, 0.25 engineer
	Shower	procure prototypes from IHEP and test in-beam	$78k including 30% IHEP overhead ($4k HV)	N/A
C	Preshower, Shower	testing and assembly stands at the production scale		1 tech, 1 grad student
	Preshower, Shower	PMT testing at the production scale		0.5 tech, 1 grad student

2.2.2 Cost Estimate for Construction

Assuming 2 years of full-scale construction, estimate per year:

Material

- Material for a 6 testing array for Preshower and SPD testing (12 bars, 24 ch readouts): \$26k for 26x R9779 PMTs (24 for the hodoscope and 2 for the SPD), \$18k for 36x Preshower readout PMTs, \$8.4k for hodoscope scintillator bars (12 Eljen 5cm×100cm×15cm at \$700 each), \$25k for 62 channels HV, plus electronics.
- Material for Shower module construction: 10 assembly stands at \$20k each.

Manpower

- FASPD and LASPD: 0.25 postdoc/tech, 0.5 grad student
- Preshower module construction: 0.75 postdoc/tech, 0.5 grad student
- Shower module construction: 1 postdoc/tech, 1 tech, 8 full-time students (undergrad or graduate)
- PMT testing: 0.5 postdoc/tech, 1 grad student
- Support structure: ??