Description of the Test Facility

The *first test station or Stage 1* is a microscope equipped with a digital camera, as well as a separate camera which is used in conjunction with a traveler interface to enter information digitally into a global database. At this station the operator records high-resolution images of each MPPC, inspects for mechanical defects, and estimates parameters such as the active area of the device.

The *second test station or Stage 2* is for room-temperature measurements of the Photon Detection Efficiency (PDE), the pulse rise time, and the pulse width. While the pulse characteristics are measured for all cells, the PDE measurement is slower and thus we measure PDE directly for 3 out of 32 MPPCs at this station, then perform a relative PDE measurement for the remaining 29 MPPCs, using the first 3 as a calibration, in the dark box station. Information from this station is entered digitally into a global database.

The *third test station or Stage 3* is a large temperature-controlled “dark box” capable of measuring properties of all 32 MPPCs at a time, including measurement of each of the 16 cells of each MPPC, for a total of 512 individual measurements. In this dark box, the current-vs-voltage characteristics are be recorded, as well as responses to fast light pulses. The darkbox is equipped with a temperature control system based on a water chiller, and temperatures are monitored at a variety of locations inside and outside of the box. This system allows temperature control over a much wider range of temperatures than is required for this project. This system is used in conjunction with a traveler interface to enter information digitally into a global database.

Specifications

The specifications of the MPPC are shown in Table 1. In Table 2 is a summary listing of what is measured in the USM Test Facility, mapped line-by-line to the entries in Table 1.

Table 1. Technical requirements for silicon photomultiplier arrays for the Hall D BCAL. All requirements must be met at the nominal operating voltage and at a specified temperature in the range between 5 and 30° C.

Property	Specification
Gain at nominal operating voltage	$(0.5–2)\times10^6$
Photo-sensitive area	>140 mm^2
Macroscopic active area coverage	> 75%
Number of micro-pixels	> 56000
Sensitivity to magnetic field	< 1% gain change at 2 T independent of orientation
PDE at 490 nm [Note 1]	> 19 % [Note 2]
Dark rate	< 100 MHz [Note 2]
Dark current	< 40 μA
Sensitivity to temperature	< 10% charge amplitude change/deg C
Maximum output difference of any cell within one array from the array's average	<+/- 7.5%
Variation between average output of arrays under uniform illumination at their nominal operating voltage	<+/- 5%
Nominal operating voltage	25-80 V
Nominal operating voltage above breakdown voltage	0.9–3.0 V
Fraction of multiple photoelectrons in dark noise	< 5%
Package dimensions	See Drawing D00000-01-07-3000
Package substrate	Al_2O_3
Inputs	Positive bias voltage
Outputs	16 individual outputs
Output connector	Cu alloy pins on 0.05" centers
Rise time 10%–90%	< 16 ns [Note 3]
Pulse width 10%–10%	< 100 ns
Sensitivity of signal-to-noise to radiation	< 1%/Gy

[Note 1] The PDE measurement is made in pulsed mode.
[Note 2] There is a tradeoff between specific values of PDE and dark current to obtain a fixed detector resolution. The tradeoff is made explicit in the following equation: PDE > $0.0518 + \sqrt{(0.002685 + 0.01629 \bullet DR(MHz)/100)}$, where the dark rate DR is given in MHz;
[Note 3] Measured with a light input pulse of less than 7 ns.

#	Property	Testing plan
1	Gain at nominal operating voltage	All cells at 2 temperatures
2	Photo-sensitive area > 144 mm^2	Microscope inspection, all arrays
3	Macroscopic active area coverage > 75%	Microscope inspection, all arrays
4	Number of micro-pixels > 56000	Estimate lower limit from linearity measurement
5	Sensitivity to magnetic field	Unmeasured, Hamamatsu exception
6	PDE at 490 nm	3 MPPCs of 32 measured directly, estimate for the remainder
7	Dark rate	All cells at 2 temperatures
8	Dark current	All arrays at 2 temperatures
9	Sensitivity to temperature	All cells at operating voltage and 5°C
10	Maximum output difference of any cell within one array from the array's average	All arrays, operating voltage and 5°C
11	Variation of the average output of arrays under uniform illumination at their nominal operating voltage	All arrays at 5°C
12	Nominal operating voltage	All arrays at 5°C
13	Nominal operating voltage is above breakdown voltage by 0.9-3.0V	All arrays at 5°C
14	Fraction of multiple photoelectrons in dark noise < 5%	All cells at 2 temperatures
15	Package dimensions	Microscope inspection, all arrays
16	Package substrate	Reference to HAMAMATSU model #
17	Inputs (sign of bias voltage)	All arrays
18	Outputs (16 individual outputs)	All arrays
19	Output connector	Reference to HAMAMATSU model # and microscope inspection, all arrays
20	Rise time 10%-90%	All cells
21	Pulse width 10%-10%	All cells
22	Sensitivity of signal-to-noise to radiation	Unmeasured, Hamamatsu exception

Table 2. Mapping between specification document and unit testing plan. Each row matches a row in Table 1. ***In the table, "all arrays" means 2800 MPPC arrays, and "all cells" means 2800x16 MPPC array cells.***

Quality Assurance and Acceptance Test Plan

Last revision: December 9, 2011.

Component Inspection Plan

Upon receipt of shipments, there is an initial visual inspection of each MPPC array as detailed under “Shipping and Receiving Procedures,” and a much more thorough inspection as detailed under “MPPC Microscope Inspection Procedures” below.

Process Quality Plan

Database and Traveler System

We keep all relevant information in a MySQL database, including digital photographs, recorded visual observations, and digital measurements. We have interfaces for the three measurement stations that structure the information entered into the database, capturing all information that needs to be archived. The database is backed up using a RAID strategy on a local disk. We have a traveler for each MPPC, as well as a traveler for each batch of 32 measured MPPCs that are tested with the dark box as explained below. Export of information from this database can be performed flexibly, thus, customized reports can be developed as required.

Shipping and Receiving Procedures

1) Received shipping packages shall be inspected for damage before opening and the result noted on Received Shipment record, along with date and name of inspecting person.
2) Initial visual inspection of individual MPPCs for damage shall be noted on Received Shipment record, along with date and name of inspecting person. MPPCs suspected of being damaged shall be noted by identification number and a description of the observed evidence of damage.
3) Following initial visual inspection, the shipment package shall be permanently labelled with shipment number and date, and stored in secure, fire-resistant safe in the UTFSM SiLab.
4) Copies of paper documents accompanying the incoming shipment shall be scanned into the Batch Traveler system and shall subsequently be archived and stored within the MPPC safe.
5) For outgoing shipments to JLab, the packages shall be supplied with a packing list that shows the identification numbers of the included MPPCs, and all necessary import/export documentation. For outgoing shipments to Hamamatsu, the packages shall be supplied with a packing list that shows the identification numbers of the included MPPCs, all necessary import/export documentation, and all documentation associated with return of products. Electronic copies of the packing list and all other documentation shall be archived in the Outgoing Shipment record, and paper copies shall be archived

and stored within the MPPC safe. Documentation from the carrier for this shipment shall be archived in the same way, once it is available. The person performing the shipping shall verify each item in the package is listed accurately on the packing list and in all other documentation, and shall note this in the Outgoing Shipment record, together with the date and his or her name. If any item in the package appears to be damaged, the Production Manager or his designee shall be notified and no further action shall be taken until the Production Manager or his designee resolves the situation appropriately.

MPPC Measurement Procedures
There are three MPPC Measurement procedures that are carried out in the order listed:
(i) MPPC Microscope Inspection Procedure - Stage 1
(ii) MPPC PDE and Pulse Shape Measurement Procedure - Stage 2
(iii) MPPC Dark Box Procedure - Stage 3

MPPC Microscope Inspection Procedures - Stage 1
1)The MPPC handling and mounting process may only be carried out by trained and qualified personnel who are identified by the Production Manager or his designee. A list of trained and qualified personnel shall be maintained in a notebook kept with the MPPC Test Stand Dark Box. The person(s) performing the measurement shall heretofore be referred to as the Operator.
2) Mount the MPPC face up onto the microscope specimen holder, and enter its number into the MPPC Traveler system.
3) Focus the image and take a photograph of the sensor surface of the MPPC using the microscope camera, store the digital image in the MPPC Traveler system, and make a hardcopy printout.
4) Compare the hardcopy printout to the transparent calibrated template overlay. Determine whether the photo-sensitive area is greater than 140 mm^2. Enter the result into the MPPC Traveler system. Verify that the photo-sensitive area is in the correct location with respect to the chip border, and if it is not, call the Production Manager.
5) Compare the hardcopy printout to the transparent calibrated template overlay. Determine whether the macroscopic active area coverage is greater than 75%. Enter the result in the MPPC Traveler system.
6) Remove and re-mount the MPPC face down onto the microscope specimen holder.
7) Focus the image and take a photograph of the connector side of the MPPC using the microscope camera, store the digital image in the MPPC Traveler system, and make a hardcopy printout.
8) Compare the hardcopy printout to the transparent calibrated template overlay. Determine whether the output connector pins have the correct spacing and are placed in the correct location. Enter the result in the MPPC Traveler system.
9) Based on the hardcopy printout and visual inspection through the microscope, evaluate whether there is or is not visible mechanical damage or an abnormal mechanical condition. Enter the result in the MPPC Traveler system.

MPPC PDE and Pulse Shape Measurement Procedure - Stage 2
1) The MPPC handling and mounting process may only be carried out by trained and qualified personnel who are identified by the Production Manager or his designee. A list

of trained and qualified personnel shall be maintained in a notebook kept with the MPPC Test Stand Dark Box. The person(s) performing the measurement shall heretofore be referred to as the Operator.
2) Choose an MPPC which passed the previous (MPPC Microscope Inspection) procedure.
3) Initialize the automated pulse shape measurement procedure on the computer.
4) Turn off all electronics associated with this station, and verify this in the MPPC Traveler.
5) Mount the MPPC in the PDE and Pulse Shape Measurement fixture. When inserting the MPPC pins into the connector, note that the pin spacing and placement is correct and does not produce stresses on the MPPC; if the fit is not perfectly correct, stop the process and call the Production Manager. If the pin fit is correct, record MPPC identification number, Operator name, and time and date, and ambient temperature.
6) Execute the automated pulse shape measurement procedure on the computer.
7) Record the results in the MPPC Traveler.
8) If the MPPC does not pass the pulse shape measurement, return to step 1), otherwise continue.

Note: out of every 32 MPPCs which pass the Pulse Shape Measurement procedure, at least 3 MPPCs for which the PDE was measured (and passed) are needed, and 29 MPPCs do not need to have this PDE measurement.

9) If the PDE measurement not desired, turn off all measurement electronics associated with this station, carefully remove the MPPC, and replace it in its storage container, otherwise, continue.
10) Initialize the automated PDE measurement procedure on the computer.
11) Record MPPC identification number, Operator name, time and date, and ambient temperature.
12) Execute the automated PDE measurement procedure on the computer.
13) Record the results in the MPPC Traveler.
14) Turn off all measurement electronics associated with this station, carefully remove the MPPC, and replace it in its storage container.

MPPC Dark Box Procedures - Stage 3

1) The MPPC handling and mounting process may only be carried out by trained and qualified personnel who are identified by the Production Manager or his designee. A list of trained and qualified personnel shall be maintained in a notebook kept with the MPPC Test Stand Dark Box. The person(s) performing the measurement shall heretofore be referred to as the Operator.
2) Choose up to 32 MPPCs which passed the Pulse Shape Measurement procedure, including at least 3 that also passed the PDE measurement.
3) Initialize the Dark Box automated procedure.
4) The beginning of the Dark Box procedure shall be recorded in the Batch Traveler, include date, name of the Operator, and any comments needed for a complete characterization of the measurement.

5) If the internal copper cooling plate is cold, adjust cooler to bring it to room temperature, and wait until it is fully equilibrated. Record the final temperature in the Batch traveler for the Batch that has just been warmed up.
6) Turn off all electronic power supplies, and the chiller, and the dry nitrogen purge gas, and certify this in the Batch Traveler.
7) The main body of the Dark Box shall be detached and rolled back.
8) Remove the plastic housing protecting the MPPCs.
9) A soft, clean, thick cloth shall be spread on the table to reduce the probability of damage to the MPPC in case of droppage. Certify this condition in the Batch Traveler.
10) If the previous batch of MPPCs are still in place, remove them starting from the bottom row, on the side closest to the Operator. Check that the identification number of the MPPC matches the MPPC location in the Batch Traveler for the appropriate batch. Replace the MPPC into its Batch Case.
11) Repeat this procedure, working from the point closest to the operator across a row, and working from the lowest rows upward.
12) Remove first MPPC to be tested from its storage case. Record MPPC identification number in the next Batch Traveler. Starting from the top row and the furthest point away from the Operator, insert MPPC into socket. Record MPPC location in Batch Traveler.
13) Repeat procedure across the top row, working in the direction toward the Operator.
14) Repeat procedure for subsequent rows, starting with the socket furthest from the Operator; note that the three SiPMs that passed the PDE test must be placed in the marked locations, to be used as calibration devices for the batch.
15) Once all MPPCs have been inserted, remove the protective drop cloth, replace the plastic housing and the body of the dark box, and start the dry nitrogen purge gas flow.
16) Perform the light leak test and record the results in the Batch Traveler.
17) Turn on the chiller and adjust the temperature to 20°C. Once temperature equilibrium has been achieved, enter the temperature readback into the Batch Traveler.
18) Begin the automated testing and documentation sequence on the computer. Observe that the test procedure is working properly; if not, call the Production Manager.
19) Once the automated testing and documentation sequence has finished, adjust the temperature to 5°C. Once temperature equilibrium has been achieved, enter the temperature readback into the Batch Traveler.
20) Begin the automated testing and documentation sequence on the computer. Observe that the test procedure is working properly; if not, call the Production Manager.
21) Once the automated testing and documentation sequence has finished, adjust the temperature to 6°C. Once temperature equilibrium has been achieved, enter the temperature readback into the Batch Traveler.
22) Begin the automated testing and documentation sequence on the computer. Observe that the test procedure is working properly; if not, call the Production Manager.

MPPC Handling and Mounting Training

1) The MPPC Handling and Mounting Training shall be carried out by the Production Manager or his designee.
2) The training shall cover the following elements at a minimum:

- the fragility of the MPPC devices
- the need to protect the pins from stress

• the need to keep the front surface clean
• an in-situ demonstration of how to mount the devices in each station
• the need to wash hands before and after the process, including informing of the possible exposure to lead solder, and the elements of the MSDS for lead solder
• a reminder of the basic elements of electrical safety, and instruction in where exposure to the ~80 VDC for the MPPCs could take place if proper procedures are not followed
• pointing out sharp edges and pinch points in the mechanical assemblies at each station
• instruction in hazards concerning repetitive stress disorders and its relationship to handling the MPPCs
• provision for at least two “shadow shifts” together with a more experienced worker

Final Acceptance Test Plan

Tables 1 and 2 summarize the specifications against which the MPPCs are evaluated, and the planned method of measurement, respectively. In the following are provided more descriptions of the measurements, numbered according to the entries in Table 2. In the following, “all arrays” means 2800 MPPC arrays, and “all cells” means 16x2800 MPPC array cells. MPPCs which do not conform to the specifications are returned unless Jefferson Lab requests a different procedure.

1) Gain at nominal operating voltage is measured for all cells at a minimum of 2 well-separated temperatures, e.g. 5°C and 20°C for all cells. This measurement is performed in the dark box. The I-V curve for each cell of MPPC array at room temperature (20°C) is measured with the SourceMeter Keithley 2400 in the voltage range from -0.5 V (direct voltage on MPPC) to +70 V (inverse voltage on MPPC). This procedure gives the first look at the MPPC quality. The MPPC array is put in the dark box and each cell is tested by the Keithley 2400 as the voltage source on the MPPC cells with dark current measurements of a few nA accuracy. During the test at different temperatures the MPPC array is supplied with CAEN A3501 Power Supply. This module allows to measure the I-V curve for MPPC array in the region from 0V to the maximal operation voltage with 100 mV voltage and 100 nA current resolution. We use a CAEN A1510 power supply board in a CAEN A3501 mainframe. According to the CAEN specifications, the A1510 has a voltage ripple smaller than 15 mV pp. To suppress the ripple down to 1-3 mV pp we use additional filters. In order to achieve the 10 mV voltage specification we use a 6-1/2 Digit Keithley 2000 multimeter with Keithley analog switches in a Keithley 7001 main frame to measure the bias voltage after the filter. Providing 10 nS low intensity light pulses on MPPC and measuring the charge of the MPPC cell response, the photoelectron peak position (or one pixel charge) is determined as the pedestal-to-first peak distance at amplitudes distribution of the MPPC cell response for the light pulse and for measurements without the light pulse. This distribution is obtained with 12 bit, 0-400 pC dynamic range QDC (CAEN V792) with a 120 nS gate. The first electron peak position is an averaged pixel charge over all pixels of the MPPC cell and the gain is the pixel charge divided by electron charge.

Operational voltage for each cell is found for (0.2 - 4.0) x 10-1 pC output charge pulse corresponding to (0.125 - 2.5) $x10^6$ gain. The MPPC cell signal is amplified by a current amplifier with gain 40. It corresponds to 8-160 channels of the QCD. The breakdown voltage is calculated from the one-pixel charge and bias voltage curve. We measure the gain with a precision of 5%.

2) The photo-sensitive area is estimated by comparing a microscope photograph of each array to a calibrated template overlay.

3) The macroscopic active area is estimated by comparing a microscope photograph of each array to a calibrated template overlay.

4) Number of micro-pixels - a lower limit of the number of micropixels is estimated from the nonlinearity of the curve of pulsed light intensity vs. measured charge. The linearity is measured for a low gain (0.125 $x10^6$) and large LED light pulses. The LED light intensity is adjusted by getting from a few to 500 photoelectrons from each cell. For each LED intensity, about 10000 events are accumulated, and the mean amplitude and the RMS are obtained. The average number of photons are estimated as (mean amplitude/RMS)^2. The mean amplitude vs. estimated photon number curve is obtained. The difference between the curve and the linear dependence manifests the nonlinearity of the cell response which depends on the number of pixels in a cell. This measurement gives an approximate estimation of the number of good pixels in the cell as well as capturing an important performance parameter for the device.

5) Sensitivity to magnetic field is not measured under this contract, since Hamamatsu took exception to this.

6) PDE at 490 nm is measured directly for at least 3 out of each batch of 32 MPPCs. The MPPCs that are directly measured are used to calibrate the PDE for the rest of the batch. We believe this procedure is accurate enough for the acceptance tests, since we can cross-check it in several ways. As a practical implementation, we interpret “490 nm” as being equivalent to “the light from a short green Kuraray fiber” and we have implemented this test using fibers that correspond to this interpretation. In the dark box measurement of the 32 MPPCs, the LED light source and the MPPC array positions is fixed; the distance between the light source and the MPPC is ~1.5 m when the light source size and MPPC size are less than 25 mm, and this allows the measurement of the PDE of each cell of MPPC array in arbitrary units, which can thus be inter-calibrated using the 3 MPPCs that were calibrated in the dedicated PDE measurement. We believe we attain a 4-5% measurement of the PDE (e.g., 20% PDE with a 1% uncertainty). The precision is higher for the subset of MPPCs for which PDE is measured directly, but should still be within 5% for those that are cross-calibrated within the dark box setup.

7) Dark rate is measured for all cells for at least 2 well-separated temperatures, e.g., 5°C and 20°C. One of the test setup operation modes is measuring MPPC cell pulses in a 120 nS gate without the light injection. The output charge distribution has 3 or more peaks. The first peak is the pedestal, the second peak is the single photoelectron (or single pixel) peak, the third is the two-photoelectron peak, etc. The number of events with amplitude equal to the pedestal after the normalization gives the probability not to

have any signal from the cell. The dark rate is calculated from this probability. We measure the dark rate with a precision of 2% at a given temperature.

8) Dark current is measured for all arrays for at least 2 well-separated temperatures, e.g., 5°C and 20°C.

9) Sensitivity to temperature is measured for all cells at operating voltage and in the neighborhood of 5°C. We make one measurement at 5°C and another at, e.g., 6°C, to minimize the temperature equilibration time. We believe the best choice of a second temperature can be made after gaining more operating experience with the dark box device.

10) Maximum output charge difference of any cell within one array from the array's average is measured for all arrays at operating voltage and 5°C. We note parenthetically that Hamamatsu can meet the specification at a higher temperature, and the behavior at 5°C may or may not fall within this specification due to differing temperature characteristics of different cells.

11) The variation of the average charge output of arrays under uniform illumination at their nominal operating voltage is measured for all arrays at 5°C. We note parenthetically that Hamamatsu can meet the specification at a higher temperature, and the behavior at 5°C may or may not fall within this specification due to differing temperature characteristics of different cells.

12) The nominal operating voltage is identified at 5°C for all arrays.

13) We check whether the nominal operating voltage is above the breakdown voltage by an amount that is between 0.9 and 3.0 V at 5°C. We note parenthetically that Hamamatsu can meet the specification at a higher temperature, and the behavior at 5°C may or may not fall within this specification due to differing temperature characteristics of different cells.

14) We check the fraction of multiple photoelectrons in the dark noise for all cells at two temperatures. The procedure is the same as in 7), but including both 0-photoelectron and 1-photoelectron events. The precision of measurement of the "cross talk" or two-photoelectron signal depends on how big the cross talk is, and whether it is well-represented by the expected statistical distributions of photostatistics or not. It can also be discussed whether the cross talk is the same with a signal as it is without a signal, particularly considering the effect of a possible dependence of this effect on the position of illumination. If the cross talk in the absence of a light signal is 5%, and the distributions are, e.g., Poisson-distributed, we believe we determine it to a precision of 30% (e.g., 5% cross talk with a 1.5% uncertainty). With further studies, this number can probably be improved if necessary.

15) We check the package dimensions for all arrays using a photograph taken through a microscope compared to a calibrated template.

16) We do not directly verify that the package substrate is aluminum oxide, but rather refer to the Hamamatsu model number as evidence that the correct substrate is being used.

17) We verify that the MPPCs operate with a positive bias voltage for all cells in all arrays.

18) We verify that the MPPCs are equipped with 16 individual outputs for all arrays.

19) We verify the output connector type by reference to the Hamamatsu model number for all arrays for pin diameter, coating, and length. We verify the pin spacing and location using the microscope inspection procedure.

20) We check the rise time for all cells at room temperature. For this purpose a fast LED pulse is used.

21) We check the pulse width for all cells at room temperature. For this purpose a fast LED pulse is used.

22) We do not check the sensitivity of signal-to-noise to radiation, since this was a Hamamatsu exception.

Additional Comments and Discussion

The MPPC test strategy is based on following facts and parameters:
For evaluations with MPPC it is necessary to know the MPPC parameters: PDE, breakdown voltage, and gain at the operational voltage, which is slightly above the breakdown voltage. For selecting the optimal working point, the dark current, the dark rate, and the fraction of two and more photoelectrons in the dark rate (the appearance of the noise excess factor) are important.

PDE has little or no temperature dependence at practical operational temperatures. The breakdown voltage depends on the temperature. The gain depends on over-voltage only. The operating voltage at fixed gain depends on the temperature only due to break-down voltage temperature dependence. The dark current depends on the temperature and on the over-voltage.

The PDE and Pulse Shape station consists of a light-proof housing for one MPPC, the light injection LED system, the bias voltage source SourceMeter Keithley 2400 and readout with 16 fast amplifiers and digital oscilloscope.

The dark box setup consists of the thermo-isolated dark box, the thermo stabilization system including a chiller connected to the heat exchanger, integrated into the dark box via the copper cooling plate, and a system of sockets for 32 MPPCs in the dark box with a patchthrough for the connection of readout electronics. The readout electronics is placed outside the dark box and consists of 8 large motherboards with amplifiers and analog switches to connect 512 readout channels from each MPPC cell to 64 channels of CAEN QDC (model V792, 32 channel multi-event QDC). Each MPPC has an individual bias voltage power supply with bias current monitoring. The temperature inside and outside of the dark box is controlled by a slow controls system. The light injection is provided by 4 LEDs with 4 LED drivers, and 2 PIN diodes are used for monitoring. This setup allows rapid measurement of the characteristics of 32 MPPC arrays at once for a given temperature, and to vary the temperature from 5°C to 25°C with an accuracy of 0.1 °C.