High-Level Electrical Review

DUNE APA Final Design Review

September 2021

Electrical Topics Covered

- Grounding
- Geometry Boards
- CR and G-Bias Boards
- Component Selection and Qualification
- Bias Voltage Distribution
- APA Wire Electrical Tests

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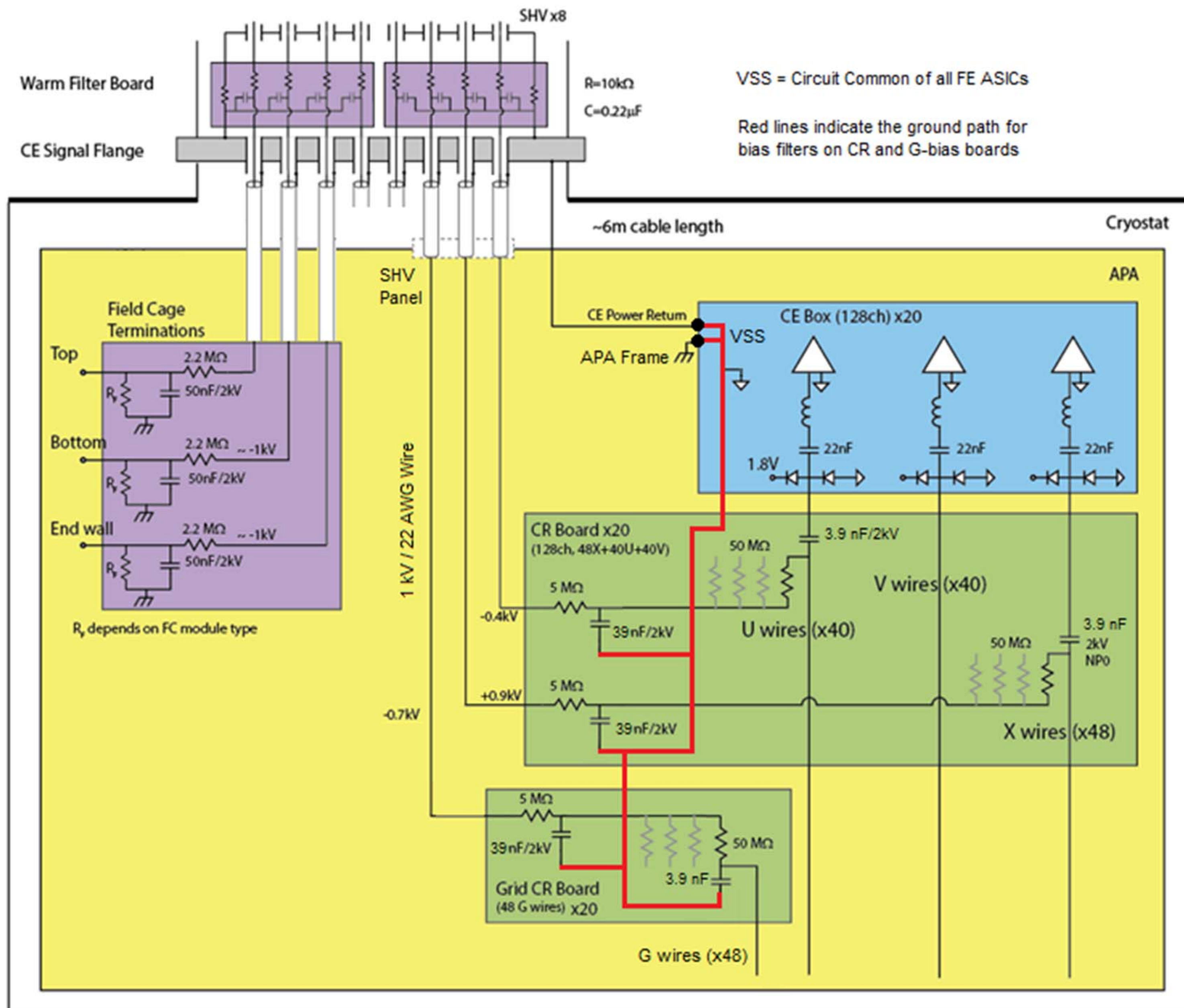
APA Grounding and Shielding

- EDMS 2095958 “Dune Grounding and Shielding Guidelines”
  - Circuit common [VSS] of the front-end ASICs and the Common plane of the cold readout PC board shall be connected to the enclosure of the CE module → **VSS = V(CE Enclosure)**
  - The APA frame shall be connected to the circuit common of all FE ASICs → **VSS = V(APA Frame)**
  - The last stage of the sense wire bias filters and grid bias filters shall be connected to the frame → **V(Filter Commons) = V(Frame)**
- Connecting Filter Commons to VSS satisfies these requirements



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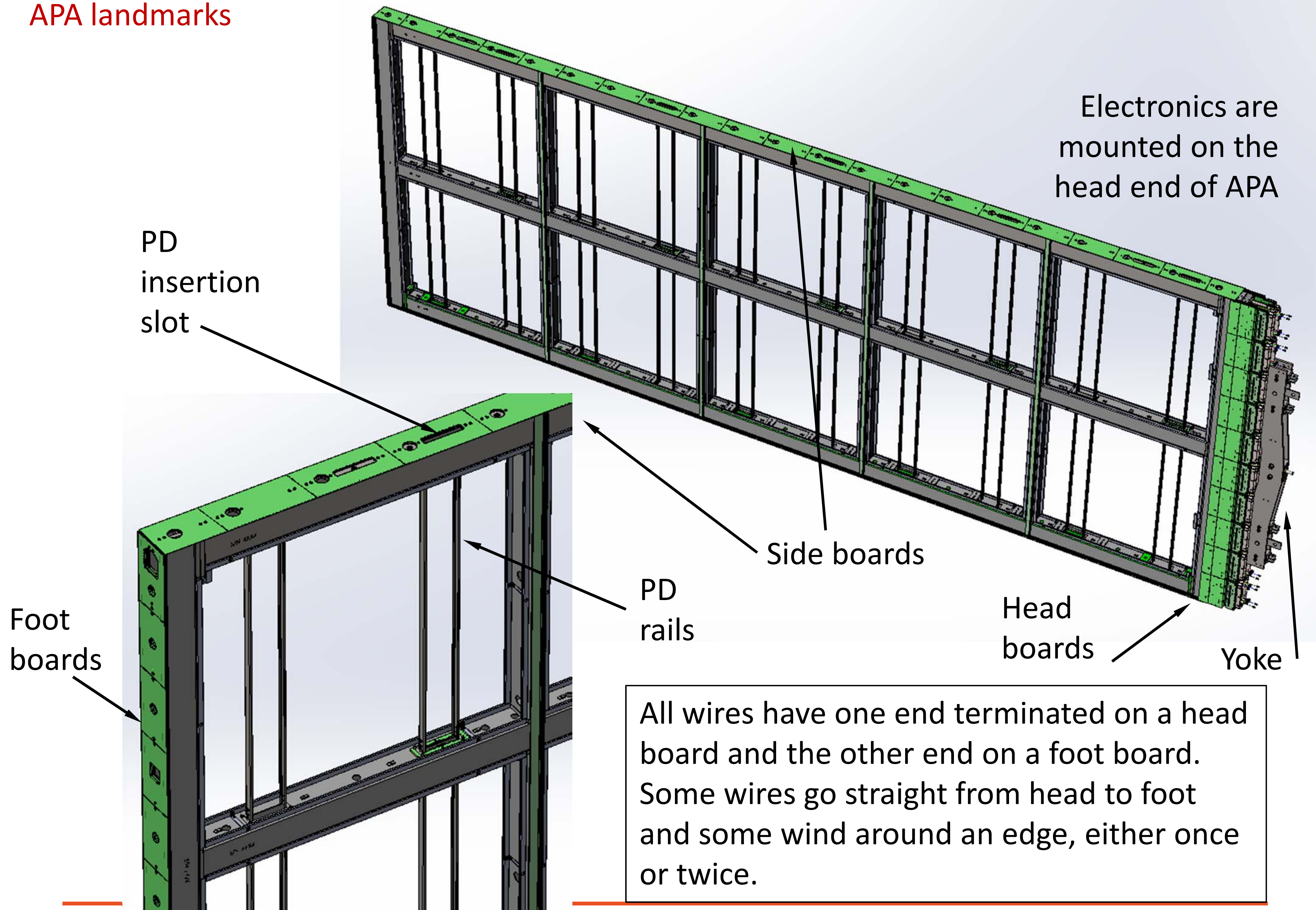
Geometry Boards

- Orientation and board count
- Design considerations
- Wire Mapping


APA landmarks
Electronics are mounted on the head end of APA
PD insertion slot
Side boards
PD rails
Head boards
Yoke
Foot boards
All wires have one end terminated on a head board and the other end on a foot board. Some wires go straight from head to foot and some wind around an edge, either once or twice.

Board types

On each APA there are:

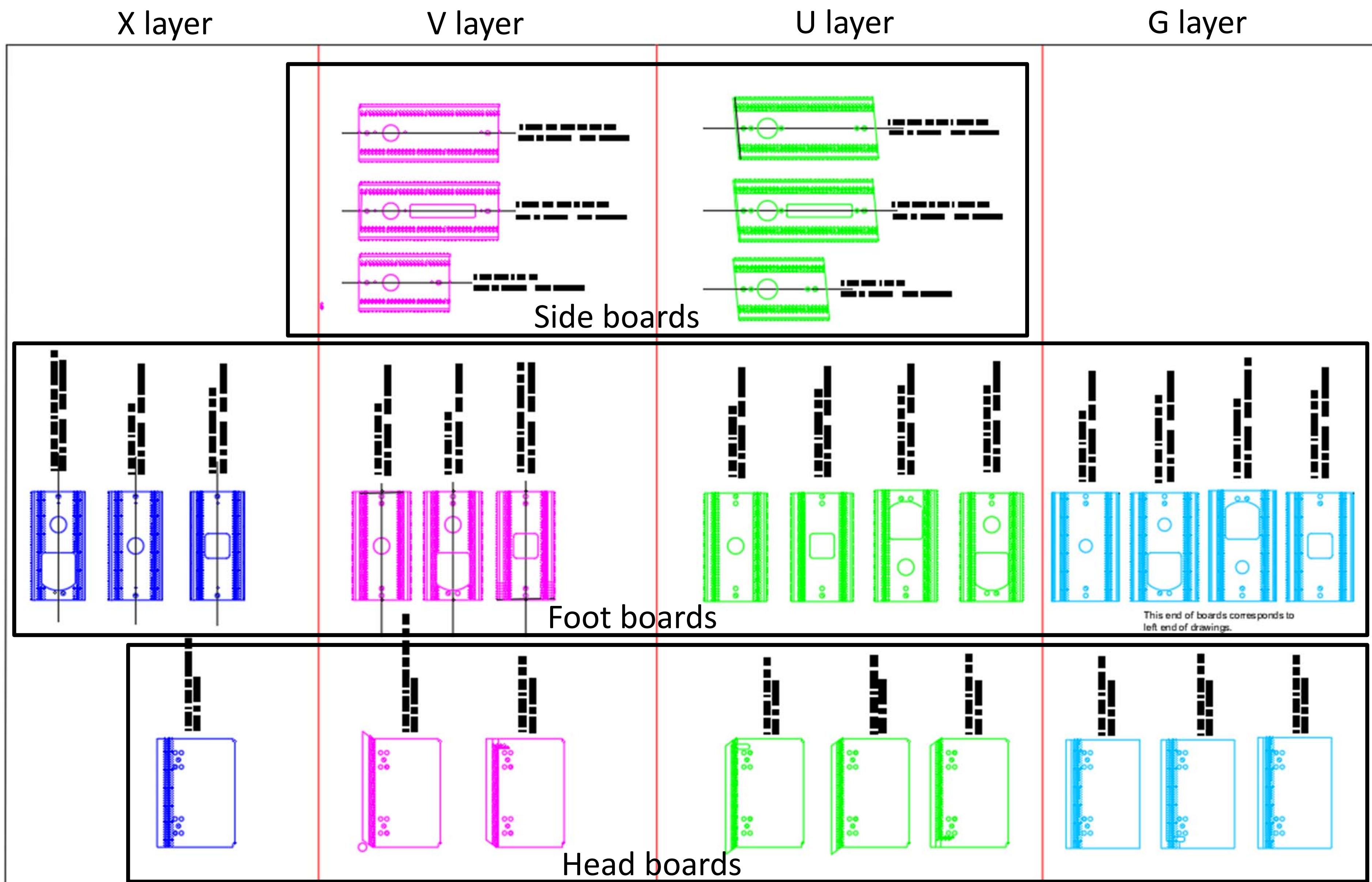
- 80 head boards
- 84 side boards
- 40 foot boards
- **A total of 204 boards in one APA**

There are different variations of boards in each layer

- Ends
- Middles
- Special openings for photon detectors and cables

There are 29 different geometry board designs

Board types (https://edms.cern.ch/file/2619625/1/Pictorial_guide_to_DUNE_boards_2019Aug15.pdf)



Foot boards: Used by all wire layers, all are 3.2 mm thick

- Include solder pads for wires and test pads for electrical probes
- Single-sided with machined features, some with large cut-outs
- No wire traces connecting solder pads

Side boards: V and U layers only, all are 3.2 mm thick

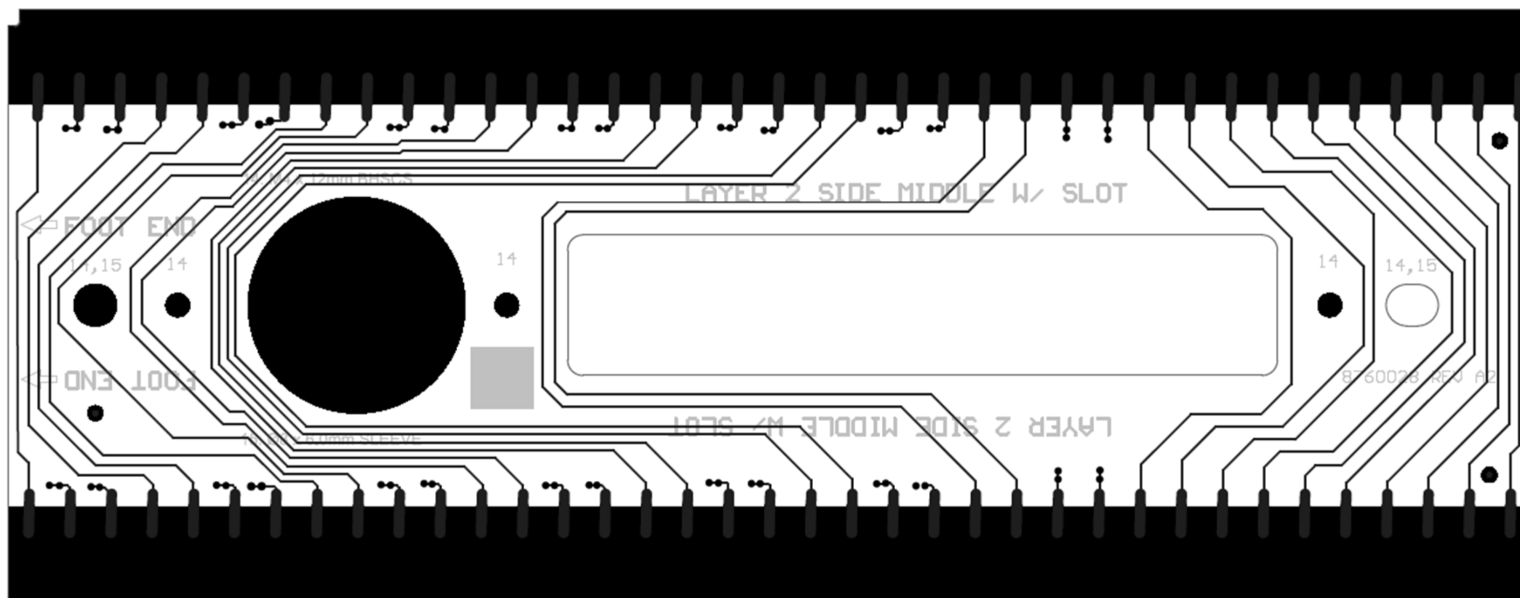
- Solder pads for wires
- Machined features and large cut-outs on some boards
- Wire traces connect pads along two edges of the boards
- A few boards are multi-layered to enable densely packed traces

Head boards: Used by all wire layers, all are 4.8 mm thick)

- Solder pads for wires and test pads for electrical probes
- Double-sided, with machined features and plated through-holes
- Wire traces connect solder pads to plated through-holes
- Mill-Max pins and receptacles are pressed into plated through-holes
- The pins and receptacles provide board-to-board connectivity

Layout goals for conductor traces

- Meet or exceed IPC-2221 for the spacing of embedded & coated traces
- IPC-2221 is a guideline for trace spacing verses voltage differentials
- The IPC standard is met for voltages expected during APA operation and during electronic tension testing
- For crowded layouts, traces were strategically assigned to different layers to minimize voltage differentials between traces on the same layer



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Other Design Goals

- Maximize trace spacing to minimize the capacitance between traces
- Widen traces near solder pads to tolerate small nicks when wires are trimmed during winding operations
- Avoid routing traces too close to board edges
- Factor in board manufacturing tolerances
- Adhere to component manufacturer guidelines

Design documentation status

- Mechanical drawings are managed in SW PDM and copied to EDMS
- Computer-Aided Manufacturing files including Gerbers, NCM drill files, and board manufacturing instructions are also copied to EDMS
- Sharing of PCB designs is through the Altium 365 portal

PCB Layout and Manufacturing Information in EDMS

- / SP APA consortium / Printed Circuit Boards / PCB – Vendor Specs
- Download: PartNo_RevNo.zip (contains all manufacturing info)
- Navigate to: / Fabrication / Fabrication.pdf (Altium-generated plots)
- Navigate to: / Assembly / Schematic Prints.pdf
- Navigate to: / Assembly / BOM / Bill of Materials PartNo.xls

PCB Mechanical Drawings in EDMS

- / SP APA consortium / Printed Circuit Boards / PCB – Assembled Boards

Wire segment to channel mapping

There are 6,526 wire segments in an APA

Of these 5,565 are assigned to CE channels

The geometrical coordinates of the start and end points for each wire segment, and a cross-reference between channel numbering and wire segment numbering, can be found in EDMS

An explanation of nomenclature is included.

/ SP APA consortium / Wiring Diagrams /

Wire segment to channel mapping

For every wire segment in each layer, the XY coordinates of the wire's end points are given, as well as the corresponding board number (1 through 20) and the solder pad (1 through 40 or 48)

			Start		Finish			
Board	Pad	Segment position on wire	X	Y	X	Y	Seg. number	Front/Back
1	1	A	-1132.031	5984.271	1153.350	2804.610	400	Front
1	2	A	-1126.281	5984.271	1153.350	2812.610	399	Front
1	3	A	-1120.531	5984.271	1153.350	2820.610	398	Front
1	4	A	-1114.781	5984.271	1153.350	2828.610	397	Front
1	5	A	-1109.031	5984.271	1153.350	2836.610	396	Front
1	6	A	-1103.281	5984.271	1153.350	2844.610	395	Front
1	7	A	-1097.531	5984.271	1153.350	2852.610	394	Front
1	8	A	-1091.781	5984.271	1153.350	2860.610	393	Front
1	9	A	-1086.031	5984.271	1153.350	2868.610	392	Front
1	10	A	-1080.281	5984.271	1153.350	2876.610	391	Front
1	11	A	-1074.531	5984.271	1153.350	2884.610	390	Front
1	12	A	-1068.781	5984.271	1153.350	2892.610	389	Front
1	13	A	-1063.031	5984.271	1153.350	2900.610	388	Front
1	14	A	-1057.281	5984.271	1153.350	2908.610	387	Front
1	15	A	-1051.531	5984.271	1153.350	2916.610	386	Front
1	16	A	-1045.781	5984.271	1153.350	2924.610	385	Front
1	17	A	-1040.031	5984.271	1153.350	2932.610	384	Front
1	18	A	-1034.281	5984.271	1153.350	2940.610	383	Front
1	19	A	-1028.531	5984.271	1153.350	2948.610	382	Front

The numbering used here assumes a front and back have been defined. The origin of the coordinate system used is located on the foot end of the APA - at the center of the foot tube. It is at interface between the steel surface of the foot tube and the first foot wire boards. When standing at the foot of an APA face, the X axis is to the right and the Y axis runs from the foot towards the head. The X axis is to the right for looking at either the front or back face of the APA.

The **head board numbering** starts with 1 at the left end of the front face and ends with 10 at the right end. It continues with 11 at the left end of the back face (as seen when looking at the back face) and extends to 20 at the right end of the back face.

The total number of pads is 480 on each face of the X layer (481 on each face of the G layer) and 400 on each face of each of the U and V layers. Total # pads = 2[480+400+400+481]=3522. Each full length, head-to-foot wire connects to one pad.

Segment # starts at the left end (except at right end of U layer only) and counts upward. In the case of the diagonal layers the count extends down the adjacent side after reaching the end of the top. This give 480

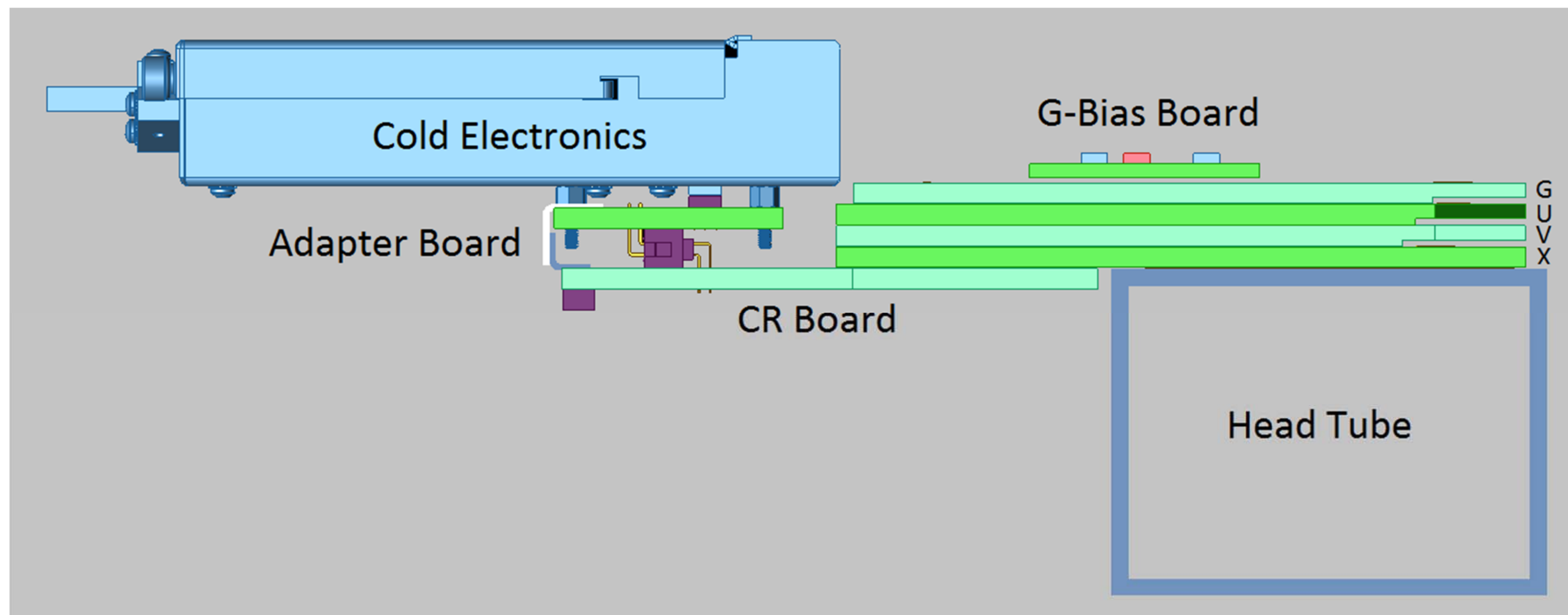
For every solder pad in a board stack, the Cold Electronics Front-End ASIC channel is known

Board stack wire mapping to CE ASIC channels

WIRE NUMBER	WIRE PLANE	CE ASIC Channel	CE ASIC	WIRE NUMBER	WIRE PLANE	CE ASIC Channel	CE ASIC	WIRE NUMBER	WIRE PLANE	CE ASIC Channel	CE ASIC	WIRE NUMBER	WIRE PLANE	CE ASIC Channel	CE ASIC
19	U	0	1	20	U	15	3	26	X	0	7	25	X	15	5
17	U	1	1	18	U	14	3	28	X	1	7	27	X	14	5
15	U	2	1	16	U	13	3	30	X	2	7	29	X	13	5
13	U	3	1	14	U	12	3	32	X	3	7	31	X	12	5
11	U	4	1	12	U	11	3	34	X	4	7	33	X	11	5
19	V	5	1	20	V	10	3	36	X	5	7	35	X	10	5
17	V	6	1	18	V	9	3	22	V	6	7	21	V	9	5
15	V	7	1	16	V	8	3	24	V	7	7	23	V	8	5
13	V	8	1	14	V	7	3	26	V	8	7	25	V	7	5
11	V	9	1	12	V	6	3	28	V	9	7	27	V	6	5
23	X	10	1	24	X	5	3	30	V	10	7	29	V	5	5
21	X	11	1	22	X	4	3	22	U	11	7	21	U	4	5
19	X	12	1	20	X	3	3	24	U	12	7	23	U	3	5
17	X	13	1	18	X	2	3	26	U	13	7	25	U	2	5
15	X	14	1	16	X	1	3	28	U	14	7	27	U	1	5
13	X	15	1	14	X	0	3	30	U	15	7	29	U	0	5
9	U	0	2	10	U	15	4	38	X	0	8	37	X	15	6
7	U	1	2	8	U	14	4	40	X	1	8	39	X	14	6
5	U	2	2	6	U	13	4	42	X	2	8	41	X	13	6
3	U	3	2	4	U	12	4	44	X	3	8	43	X	12	6
1	U	4	2	2	U	11	4	46	X	4	8	45	X	11	6
9	V	5	2	10	V	10	4	48	X	5	8	47	X	10	6
7	V	6	2	8	V	9	4	32	V	6	8	31	V	9	6
5	V	7	2	6	V	8	4	34	V	7	8	33	V	8	6
3	V	8	2	4	V	7	4	36	V	8	8	35	V	7	6
1	V	9	2	2	V	6	4	38	V	9	8	37	V	6	6
11	X	10	2	12	X	5	4	40	V	10	8	39	V	5	6
9	X	11	2	10	X	4	4	32	U	11	8	31	U	4	6
7	X	12	2	8	X	3	4	34	U	12	8	33	U	3	6
5	X	13	2	6	X	2	4	36	U	13	8	35	U	2	6
3	X	14	2	4	X	1	4	38	U	14	8	37	U	1	6
1	X	15	2	2	X	0	4	40	U	15	8	39	U	0	6

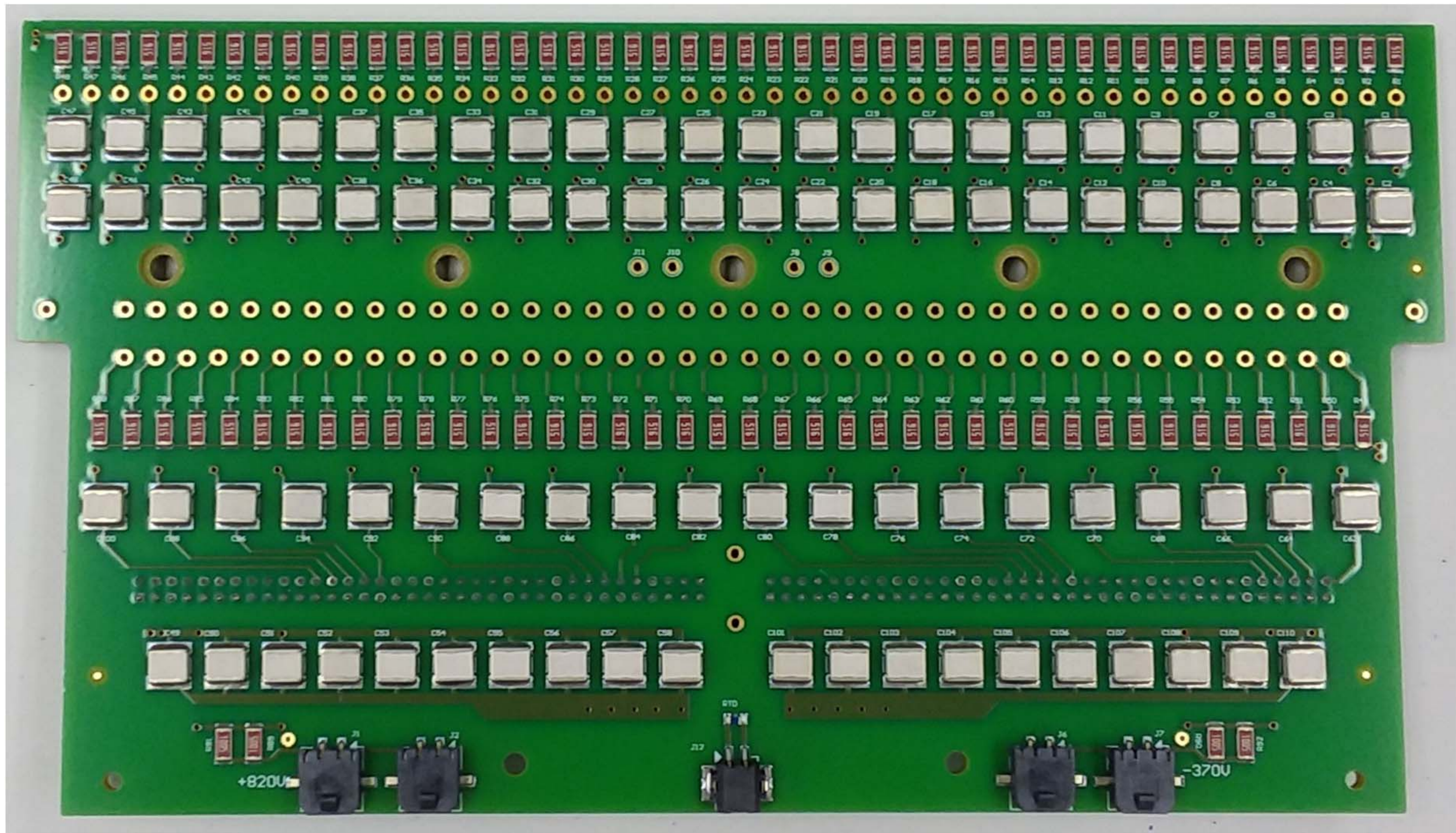
CR and G-Bias Boards

CR Boards Provide Bias to X and U Wires, and Route Signals from X, V and U wires to CE Modules

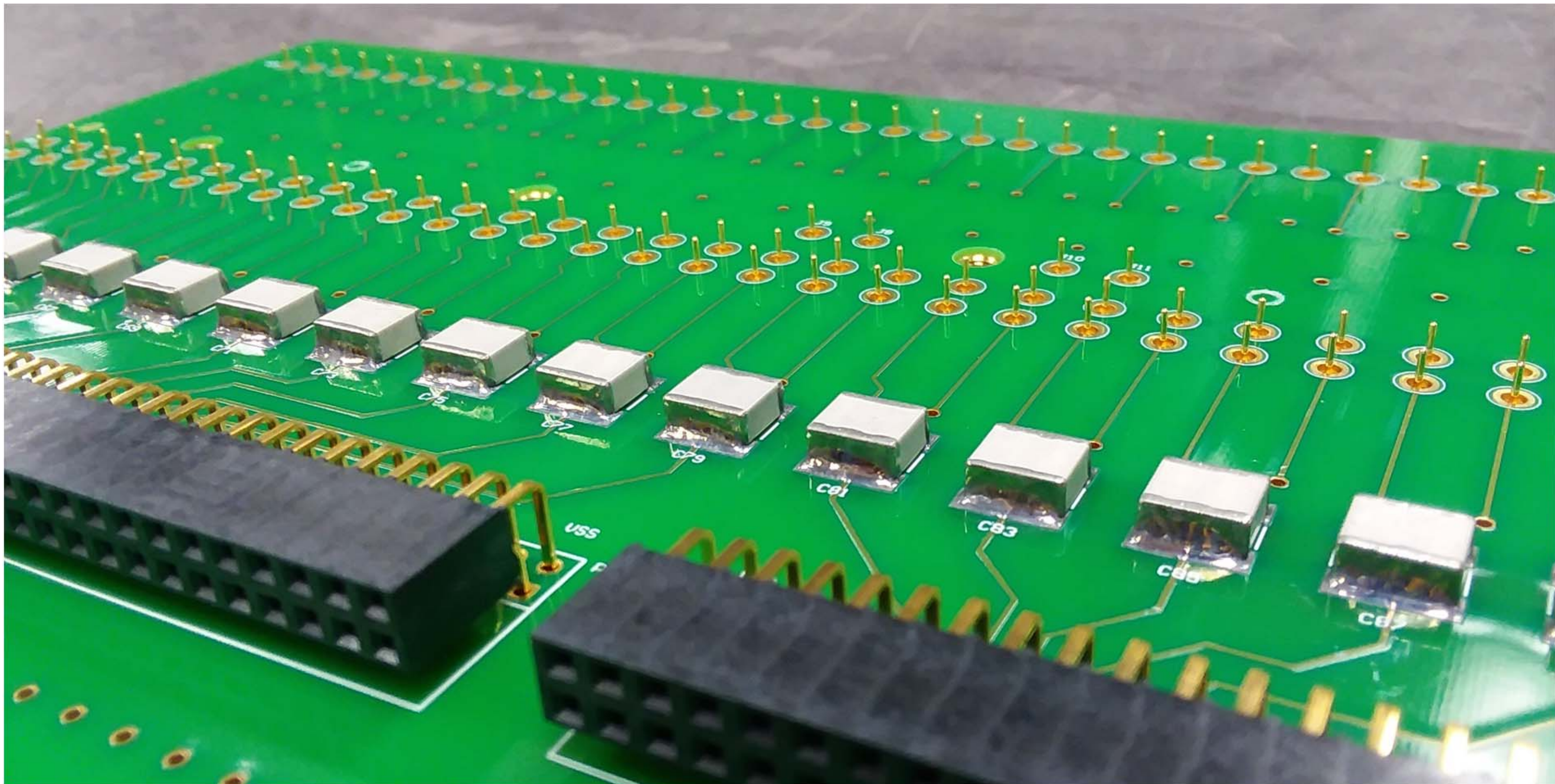


CR boards plug into X-layer head boards. Five screws are gradually tightened to mate pins with receptacles. The mating force has been reduced by a factor of 4 using improved Mill-Max pins and receptacles.

The CR board “bottom” side carries most of the electrical components. The six-layer board has 48 coupling capacitors for the X layer and 40 for the U layer. Ten capacitors are used for each of the X and U bias filters. Half of the U-layer coupling capacitors are on the top side.



The CR board's top side carries two right-angle connectors that are mounted 2.0 mm above the board surface. Mill-Max pins mate with receptacles in the X-layer head board to provide connectivity with all wires terminating on the board stack.



CR Board Manufacturing Challenges

- Leakage current across coupling capacitors must be less than 0.5 nA
- Solder flux residues trapped beneath capacitors can be difficult to clean and may result in excessive leakage currents
- All capacitors must have leakage current tested to ensure successful cleaning

CR Board Lessons Learned

- Solder flux residues are easier to clean when pre-heat and solder reflow temperatures are lower, and are sustained for shorter periods
- Thicker boards and larger components can require higher pre-heat temperatures, longer pre-heat periods, and longer exposures to reflow temperatures (equipment-dependent)
- Competing requirements for levels of heat complicate the development of successful soldering and cleaning methods

Soldering Process Goals

- Use a process that raises and lowers the temperature of the board surface quickly
- Limit the maximum temperature of the PC board and electronic components
- Provide enough copper thickness to yield adequate clearances for washing below components
- Select compatible solder products and cleaning processes

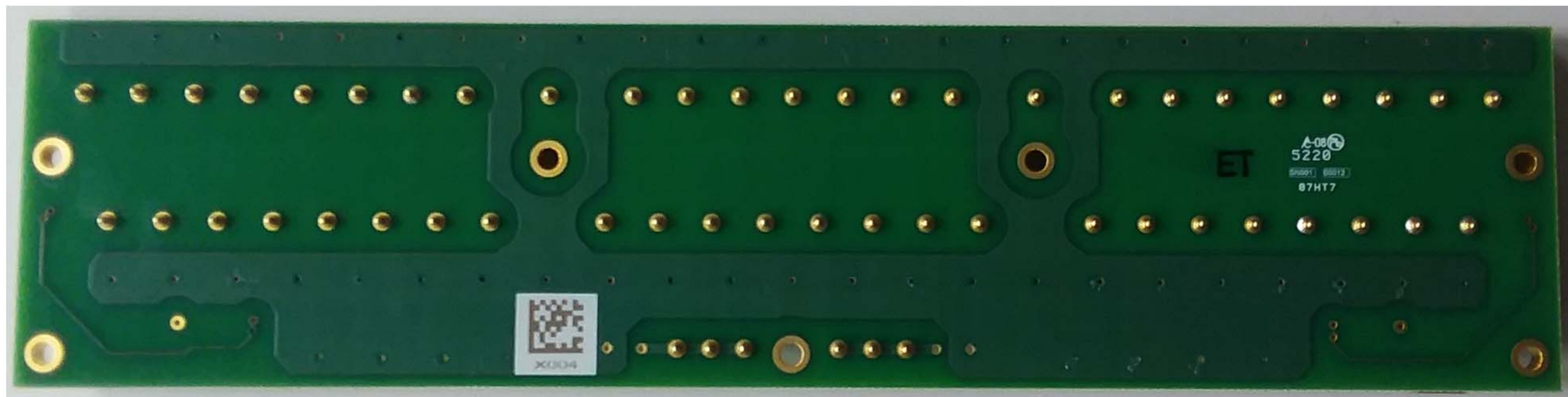
CR Board Manufacturing Approach

- Solder top-side capacitors using a Vapor-Phase reflow oven, tin/lead solder paste, and water-soluble flux
- Solder bottom-side capacitors, resistors, and bias connectors using the same process
- Hand-solder or wave-solder through-hole connectors
- Wash boards using a high-flow cleaning system
- Test all coupling capacitors for leakage current
- Replace capacitors as needed, re-clean and test
- Press Mill-Max pins into boards after final cleaning
- Functionally test all components

G-Bias Boards

- Same resistors, capacitors, and bias input connectors as used in CR boards
- Spring-loaded pins mate with contact pads on G head boards
- Same basic design as ProtoDUNE except each wire is biased individually
- Larger G-bias boards now span the width of head boards

G-Bias Boards

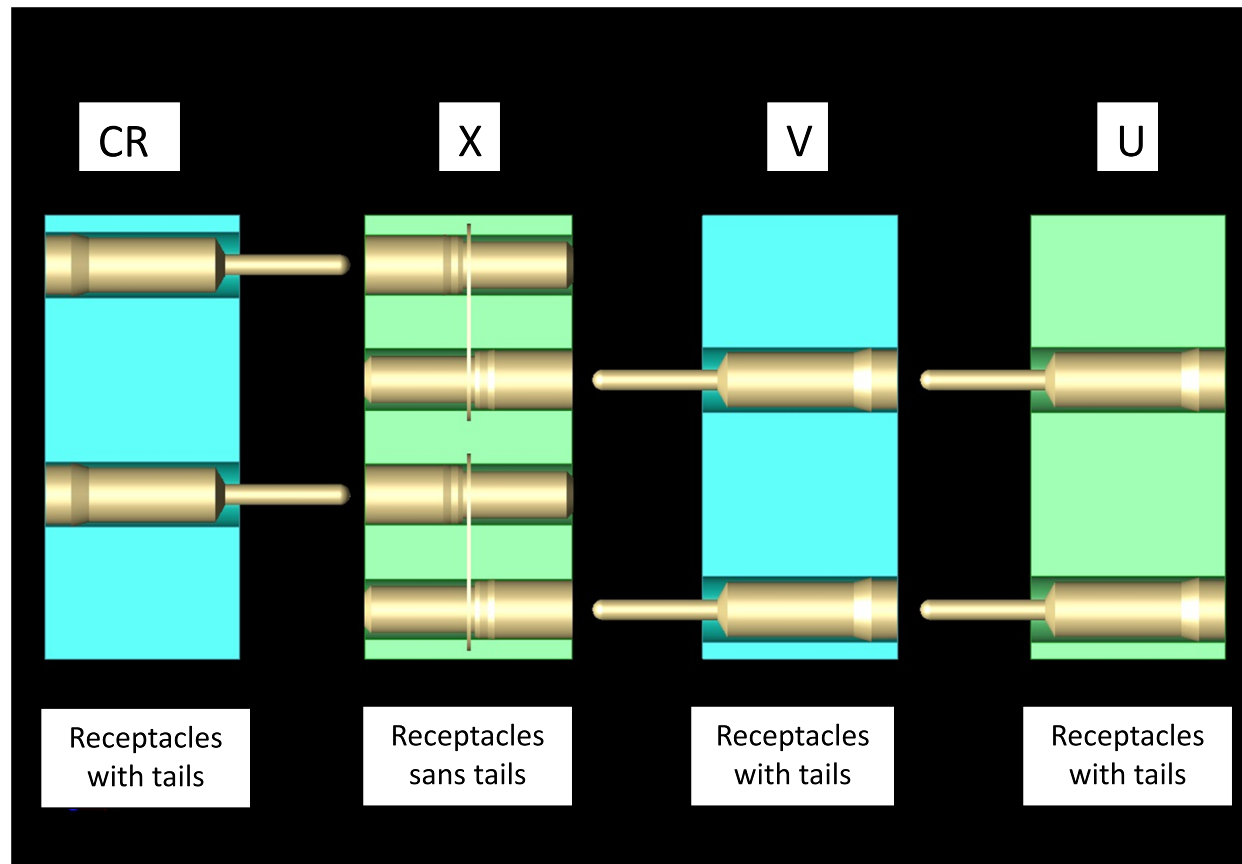


G-Bias Boards

- A soldering process similar to that used for CR boards is recommended
- Leakage current tests are less stringent (50 nA would cause a 2.5 V bias drop)
- Boards are 3.2 mm thick, and easier to solder and clean successfully compared to CR boards

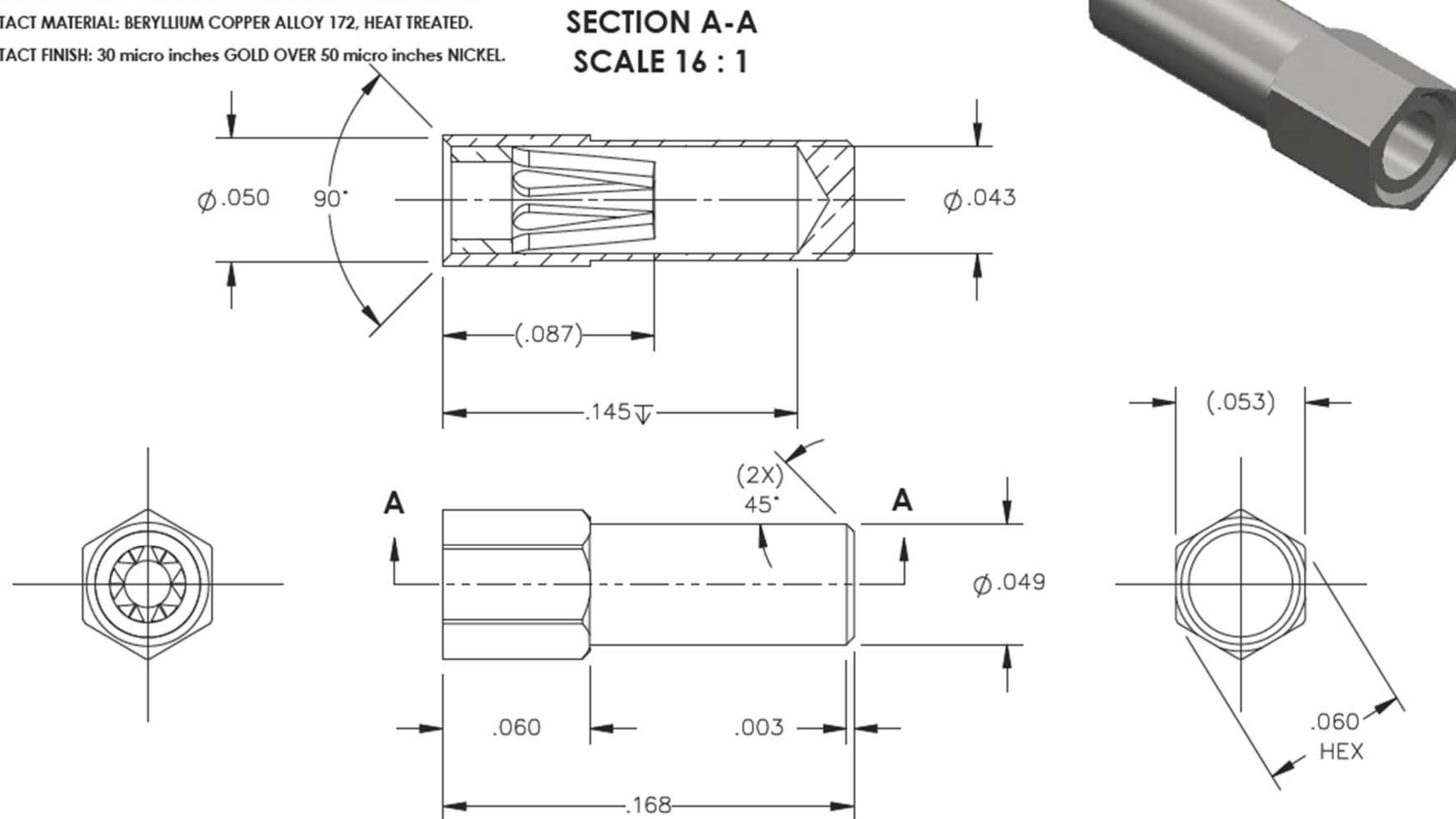
Component Qualification

Board Interconnects (Mill-Max)



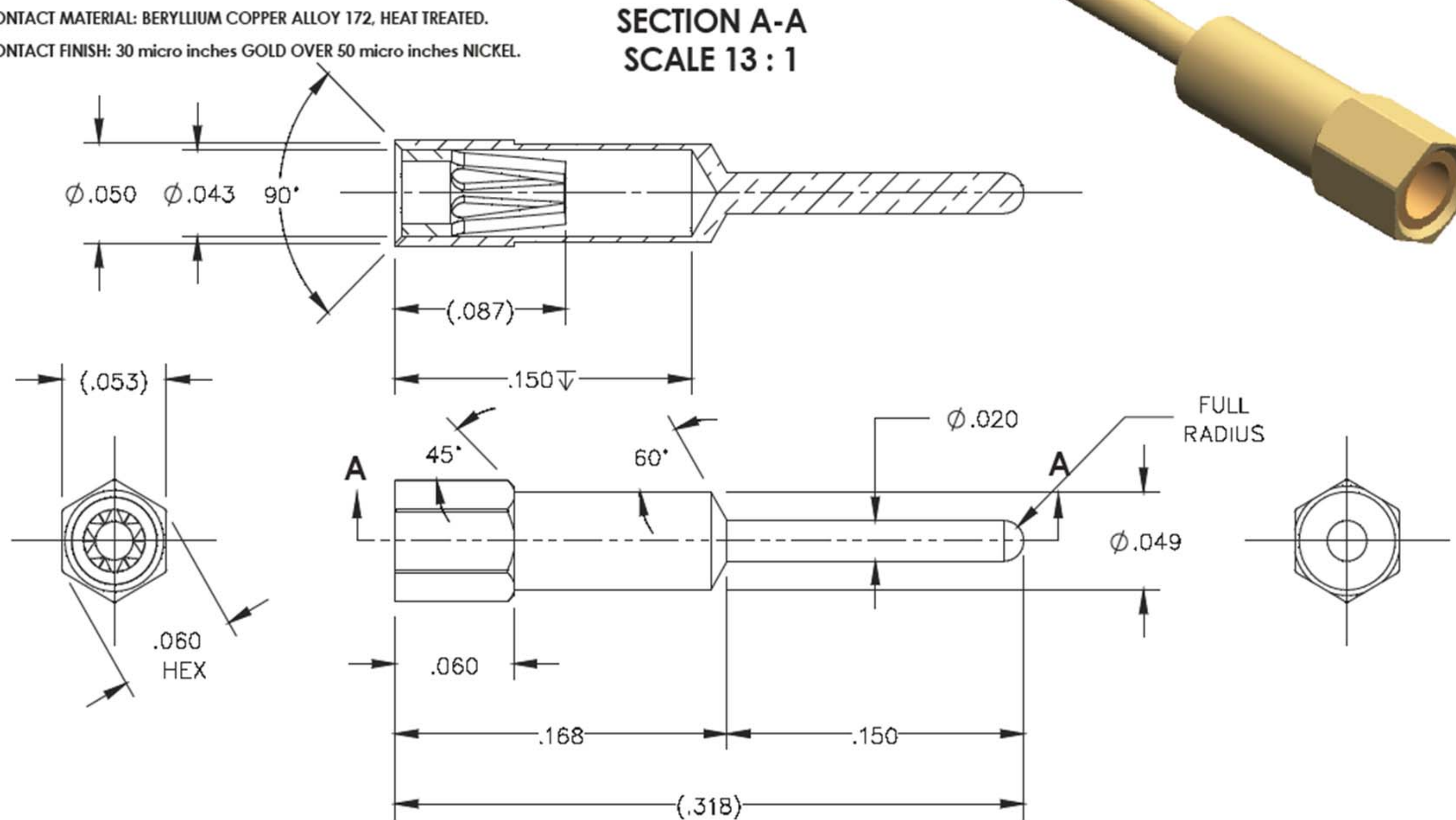
Mill-Max receptacles, with and without “tails”, form a network of pins and sockets to electrically connect head boards and CR boards. All pins point toward X head boards.

Board Interconnects (Mill-Max)



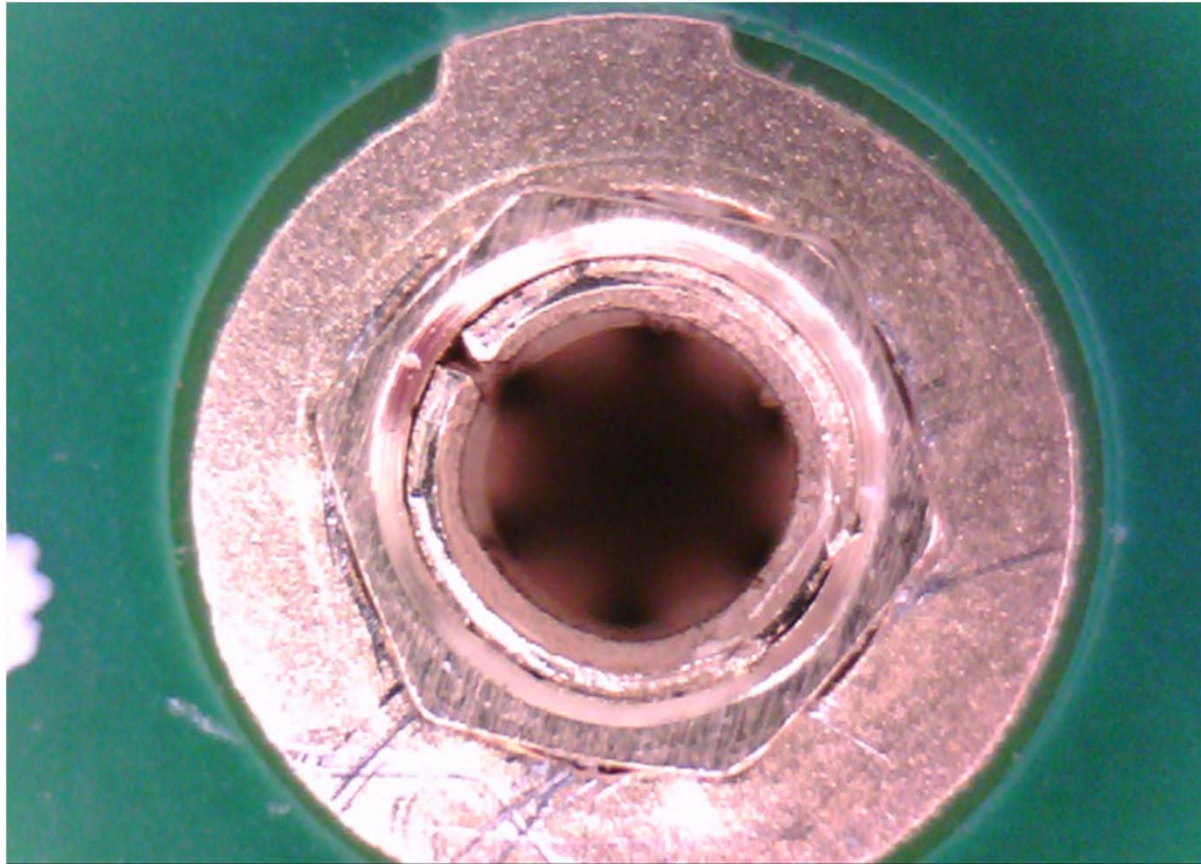
Mill-Max receptacles without tails are used exclusively in X head boards. The custom design was developed with the help of Mill-Max engineers.

Board Interconnects (Mill-Max)



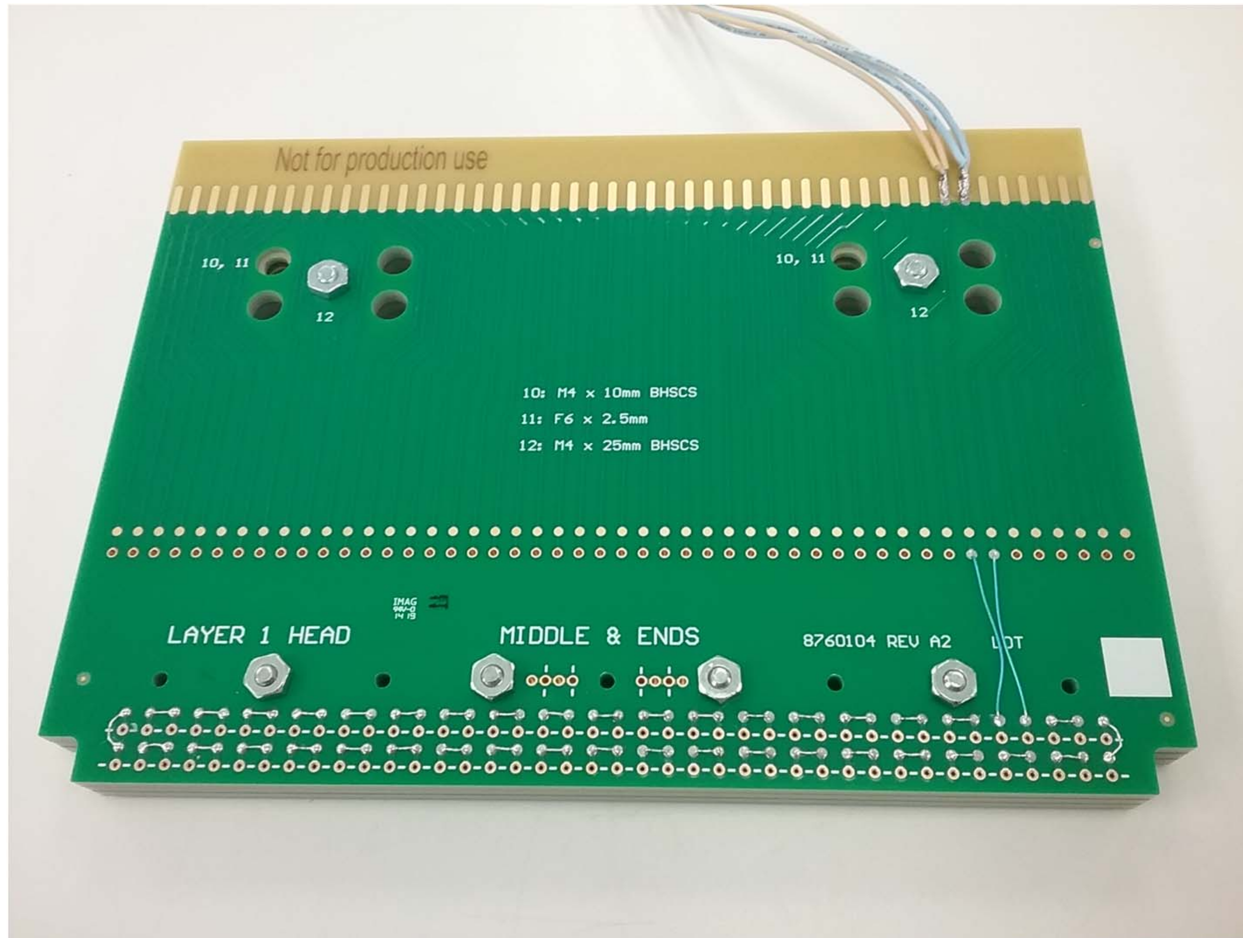
Receptacles with tails are also a custom design. Existing designs were not compatible with the thickness of DUNE PC boards. New design were developed by elongating existing designs.

Board Interconnects (Mill-Max)



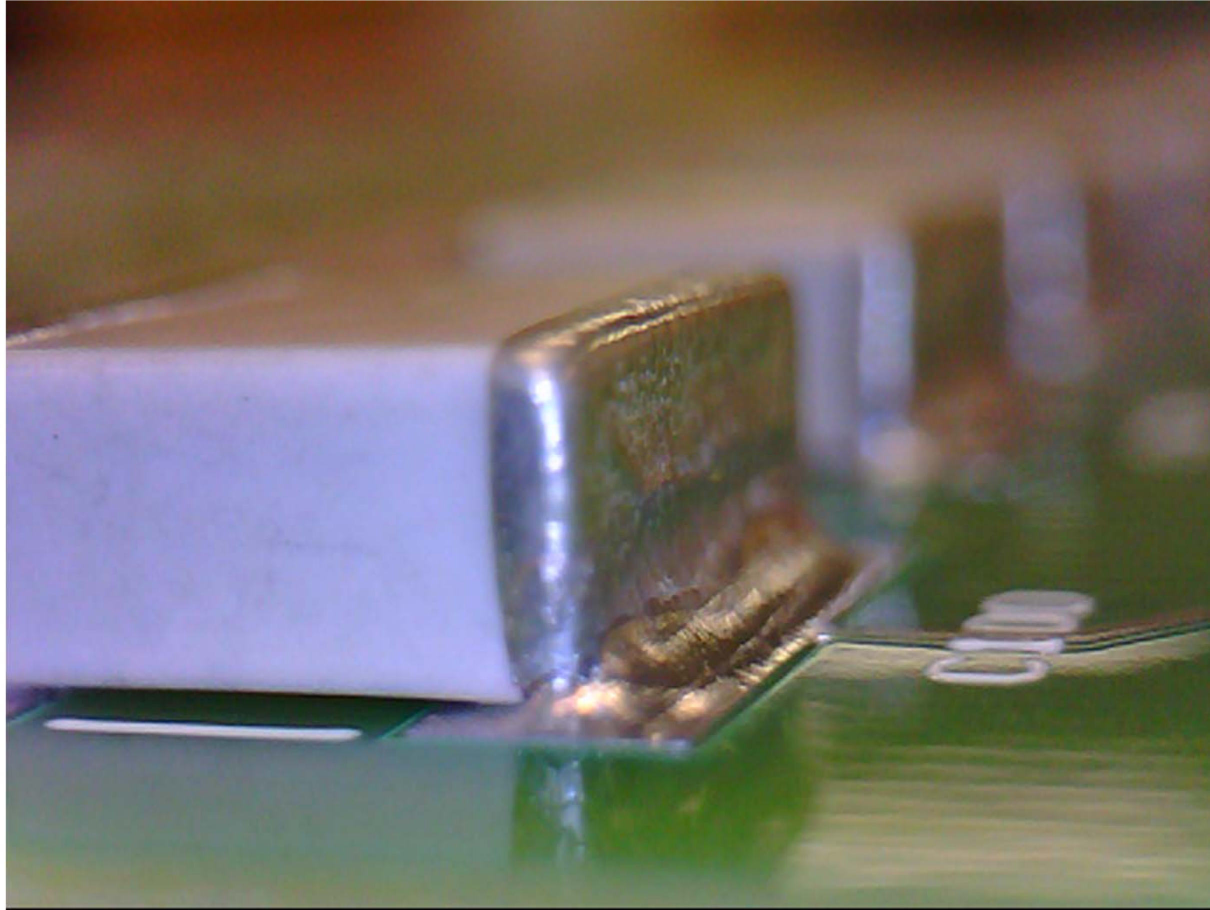
Mill-Max components are pressed into plated through-holes. Points on the hexagonal profile displace hole plating longitudinally to retain connectivity between board layers.

Board Interconnects (Mill-Max)



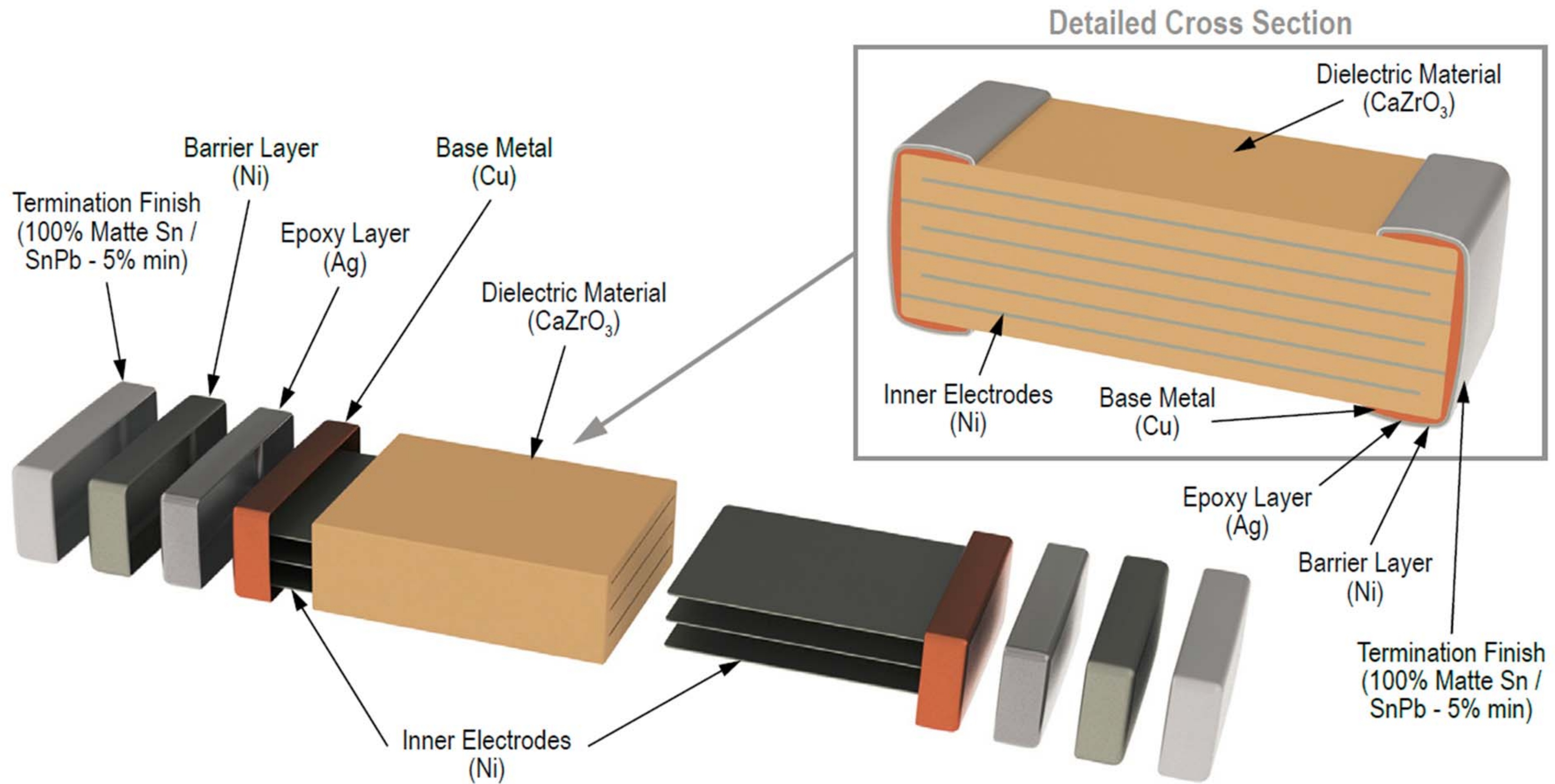
Daisy-chained arrays of mated Mill-Max components were temperature cycled to liquid argon temperatures multiple times. No measureable changes in resistance were observed.

Surface-Mount Capacitors



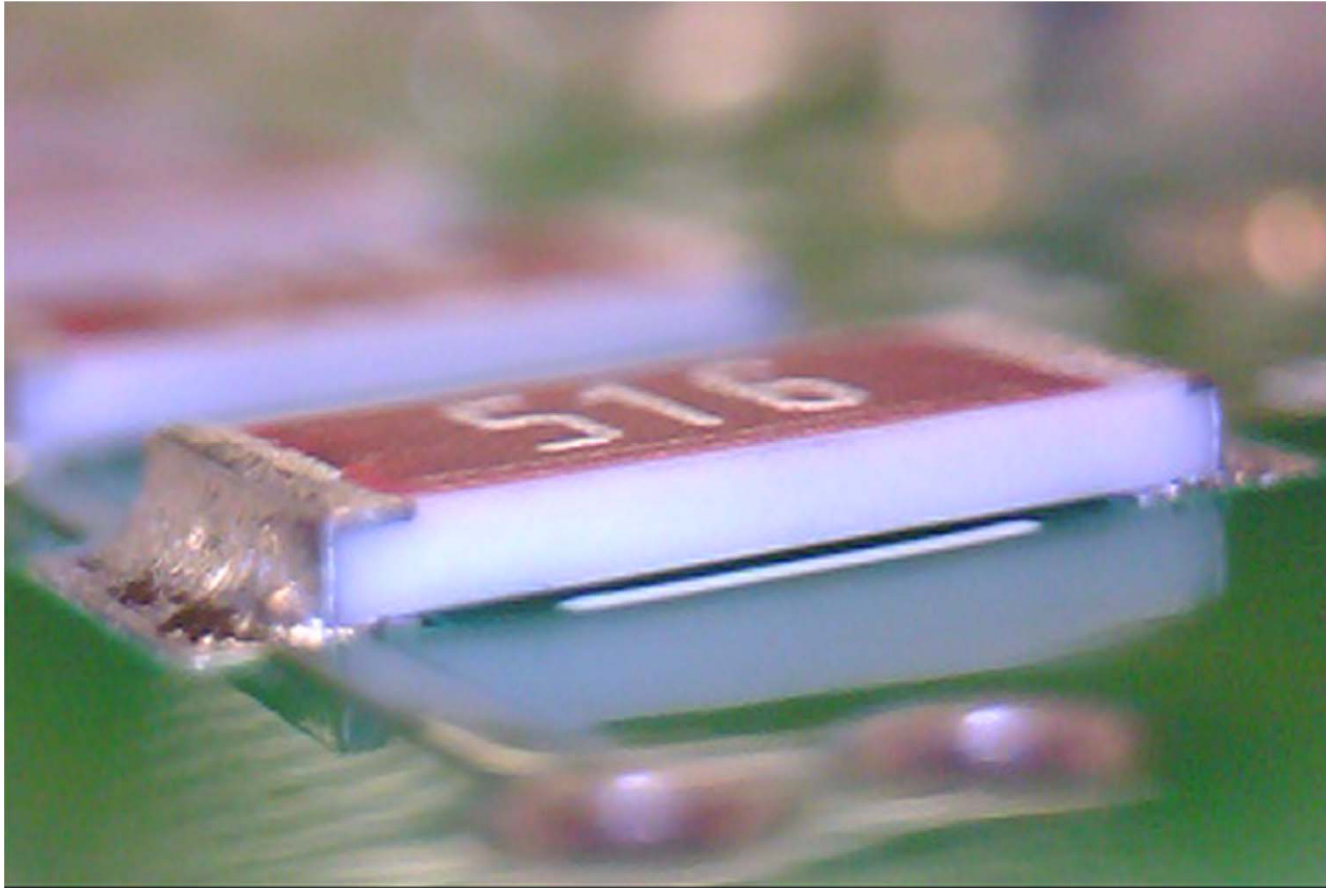
Ceramic surface-mount capacitors are used to AC-couple X and U wires to the front-end detector inputs. The components are designed to withstand temperature extremes.

Surface-Mount Capacitors



Mechanical stresses caused by extreme temperature excursions are greatly reduced by terminals that include a compliant epoxy layer. Cyrogenic tests of more than 10,000 capacitors during ProtoDUNE CR board manufacturing did not yield any failures.

Surface-Mount Resistors



Thick-film resistors perform bias filtering and apply bias voltages to wires. Cyrogenic tests of more than 10,000 resistors during ProtoDUNE CR board manufacturing did not yield any failures.

Summary

- All electronic components are evaluated for expected performance when subjected to cryogenic temperatures
- Initial tests include repeated temperature cycling to liquid argon temperatures with electrical and mechanical performance evaluated at high and low temperature extremes
- Electronic assemblies built with new component types or with modified manufacturing procedures should be subjected to full functional tests at room temperature and at liquid argon temperature
- Testing can be relaxed when statistics support it

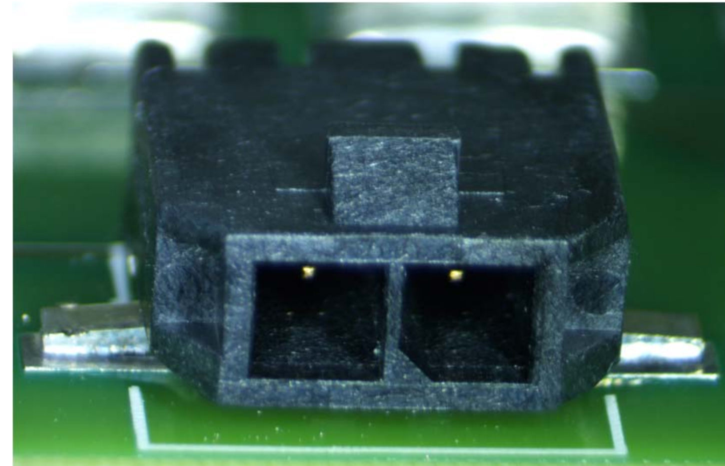
Bias Distribution Assembly

Bias Distribution System

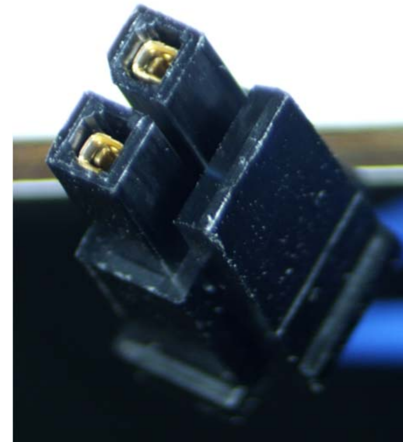
- Supplies bias voltages to CR boards and G-bias filter boards on the APA
- Redundancy tolerates single-point failures
- Three coax cables feed bias to the SHV panel
- New for DUNE:
  - Connectors more securely lock when mated
  - Wire bundles are supported by the CR boards
  - Wire bundles plug into the SHV panel
- Schematics: EDMS/ SP APA consortium / Wiring Diagrams

Bias Connectors

Surface-mount bias connectors on CR and G-bias boards are compact and mount securely to circuit boards. The insulation material is Nylon.
Molex part number: 43650-0212



Wire bundle connectors have locking clips to prevent separation. A lever must be pressed to pull connectors away from the circuit board.
Molex part number: 43645-0208



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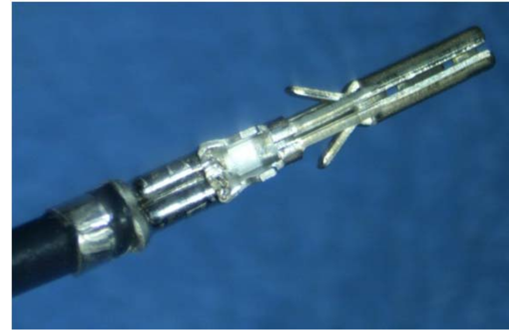
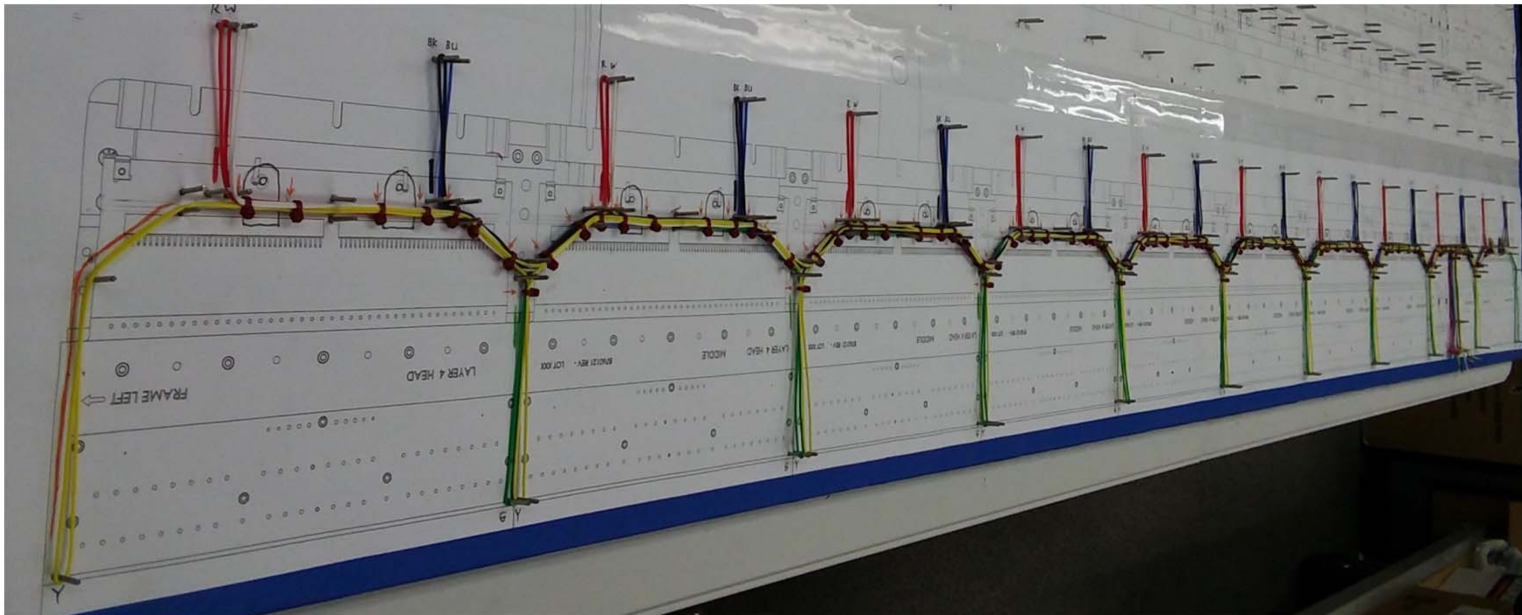
Bias Wire Assemblies

Connector terminals are securely crimped to bias wires.
Molex part number: 43030-0009



Wire assemblies are constructed using PEEK cable ties and cable clamps



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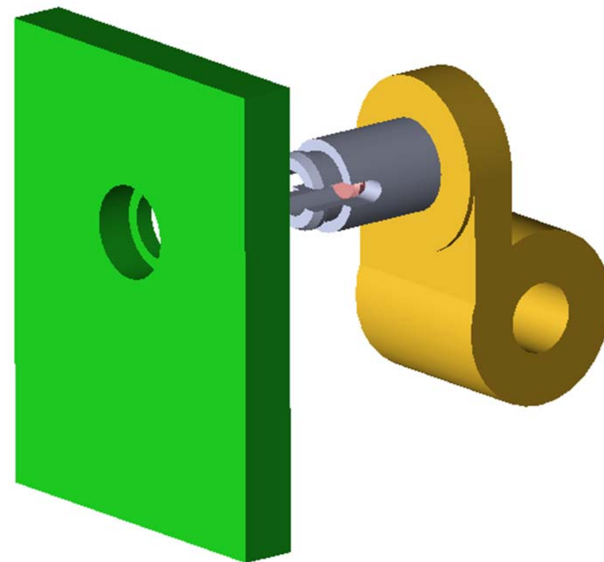
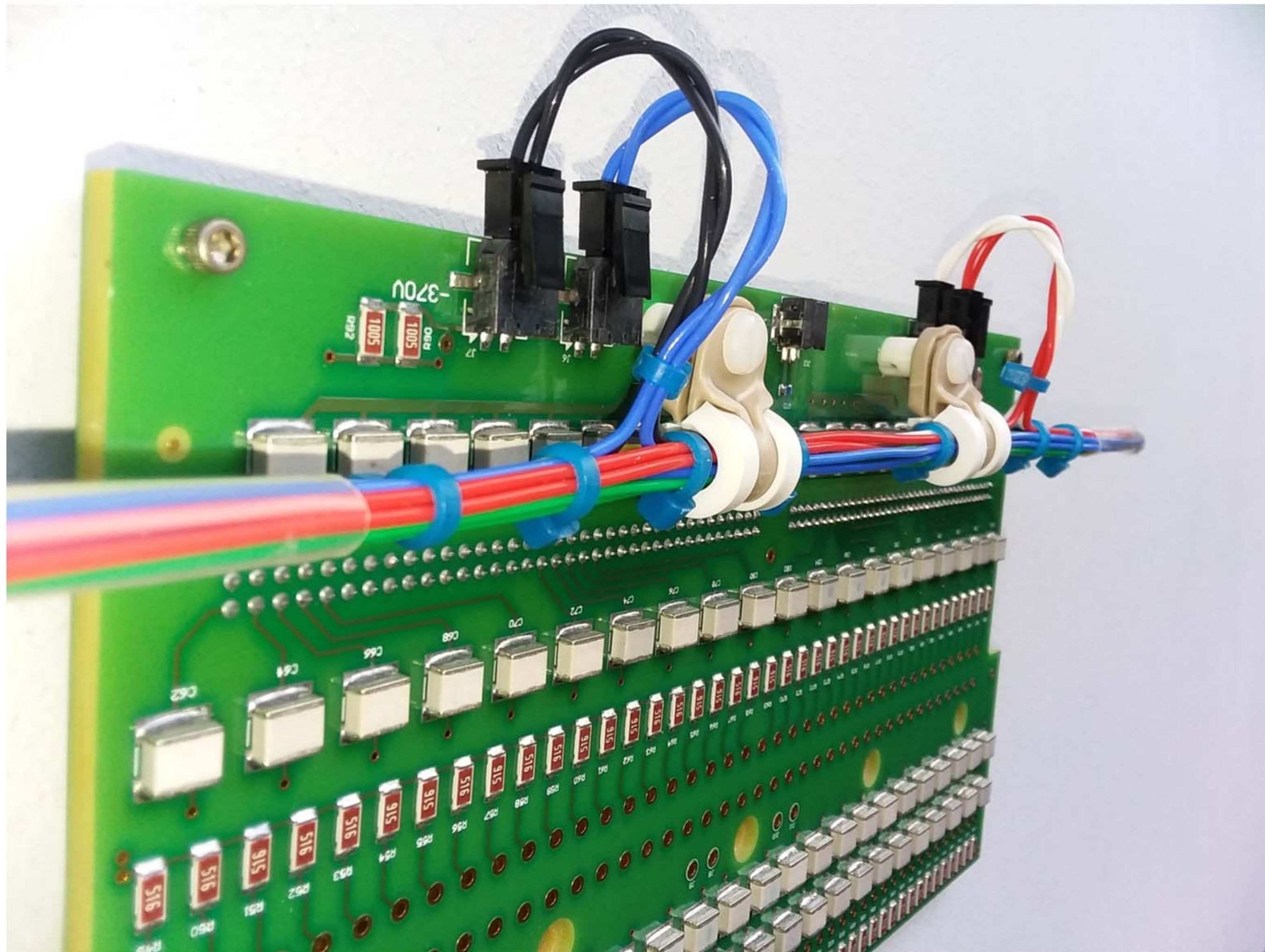
Wire assembly supports

- Cable clamps are installed when wire bundles are assembled.
- Snap-in standoffs are attached to the clamps.
- Clamp assemblies are snapped into mounting holes on CR boards

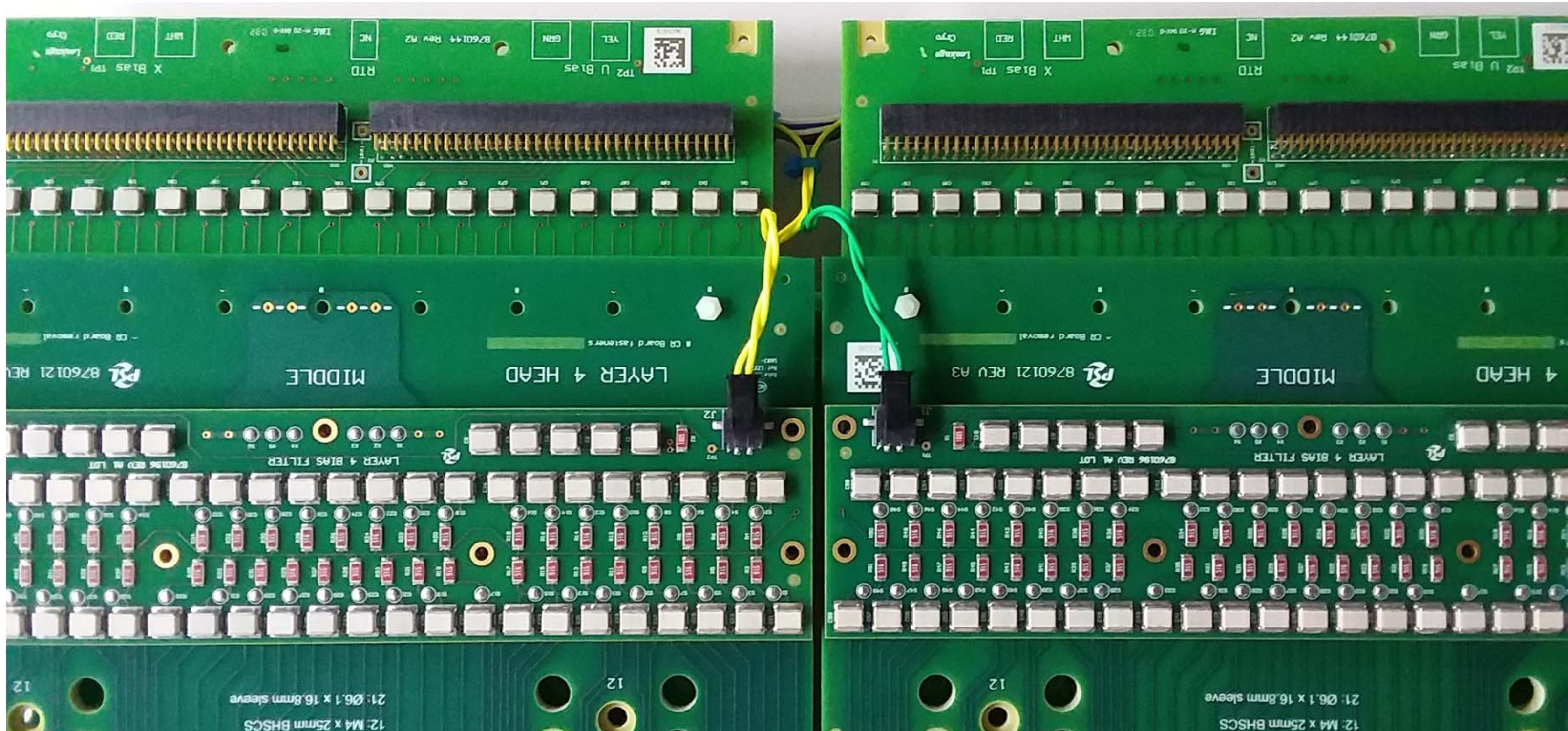
- CR boards have counter-bored mounting holes to prevent standoff heads from extending above the board surface



Wire assembly supports



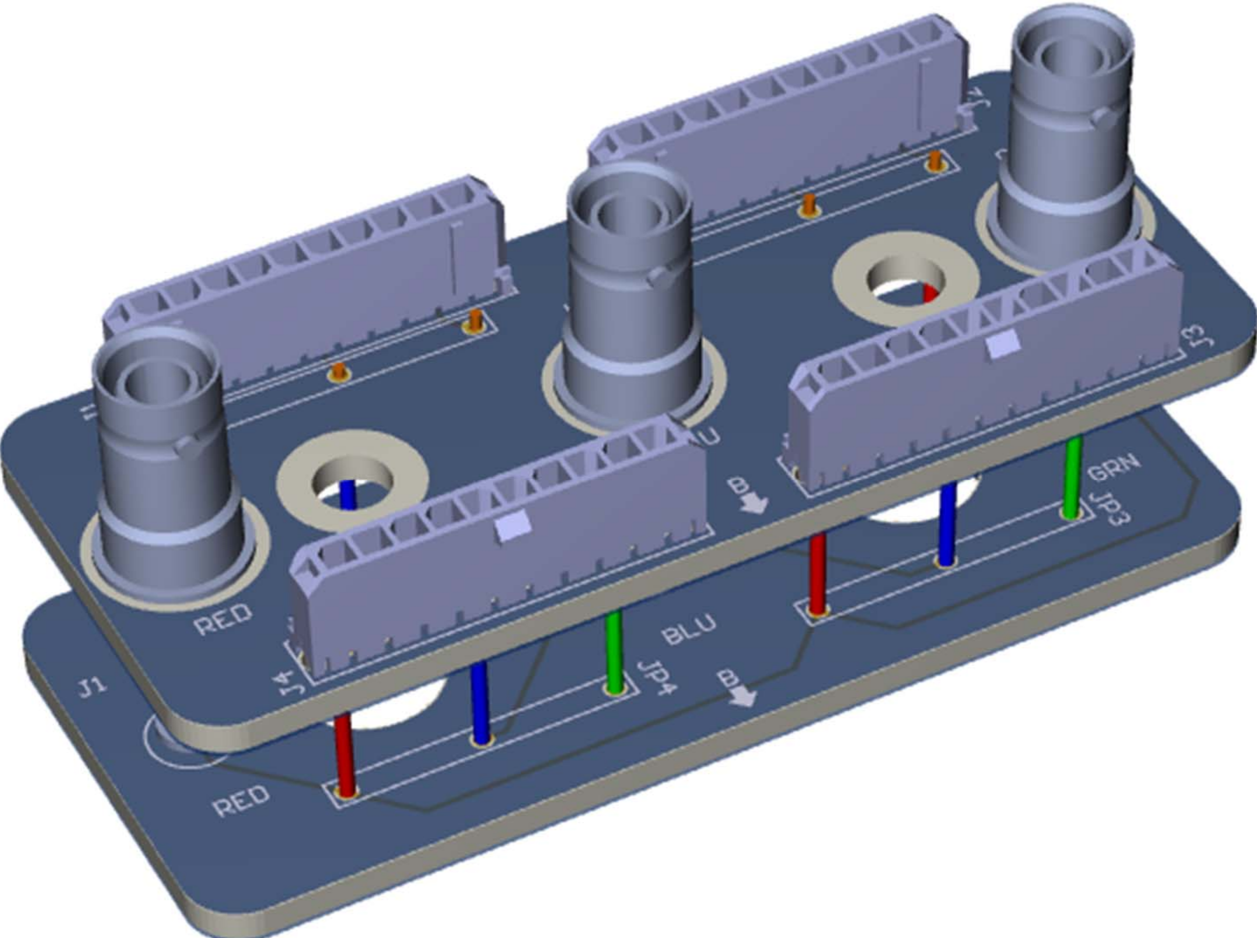
G bias pigtails are less likely to be pinched during CE installation



Wire Bundle Test Plans

- Visual inspection
- Pull tests of all connector wires
- Electrical continuity
- High-voltage leakage (Hi-Pot)

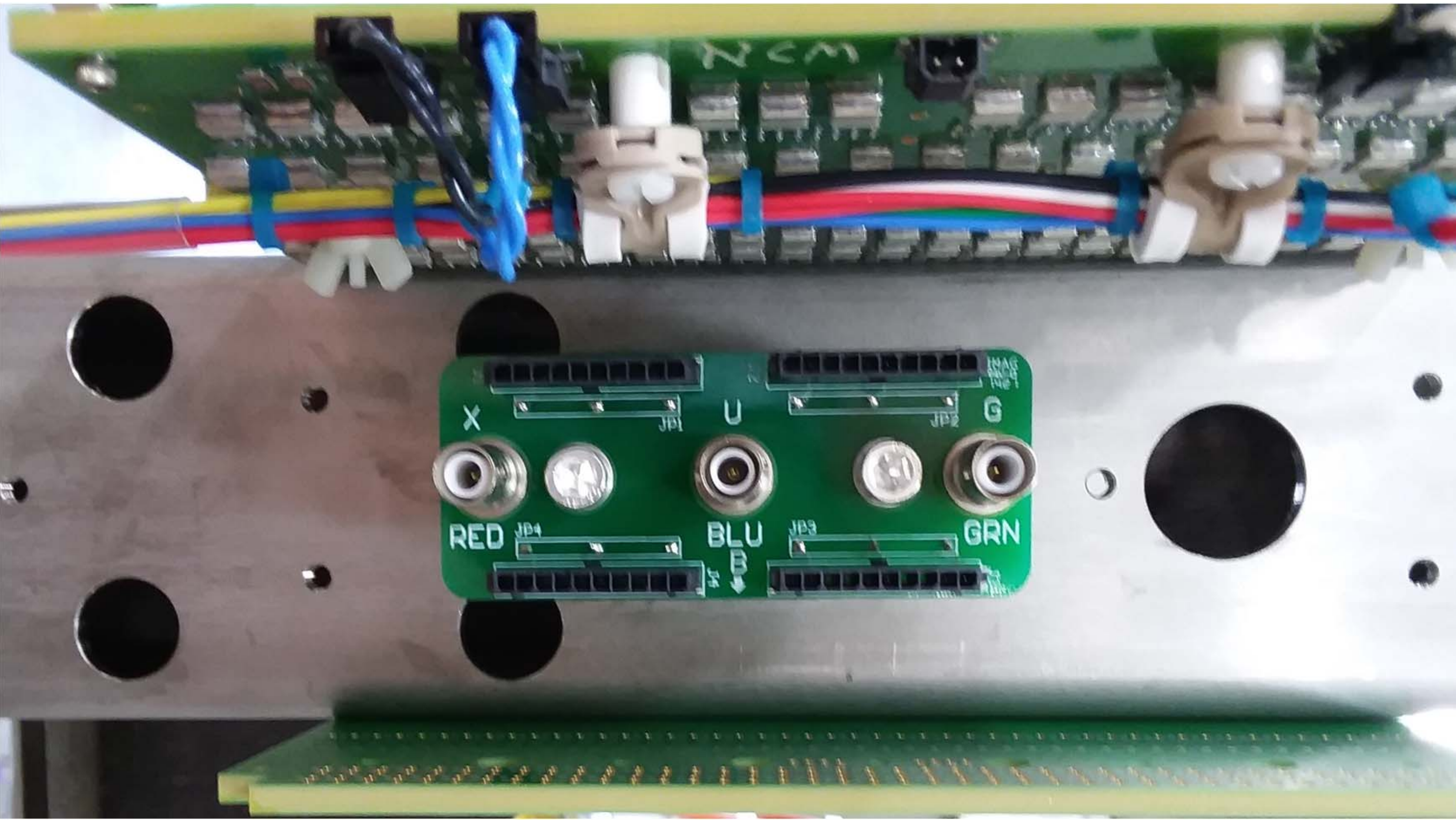
SHV Assembly



SHV Assembly

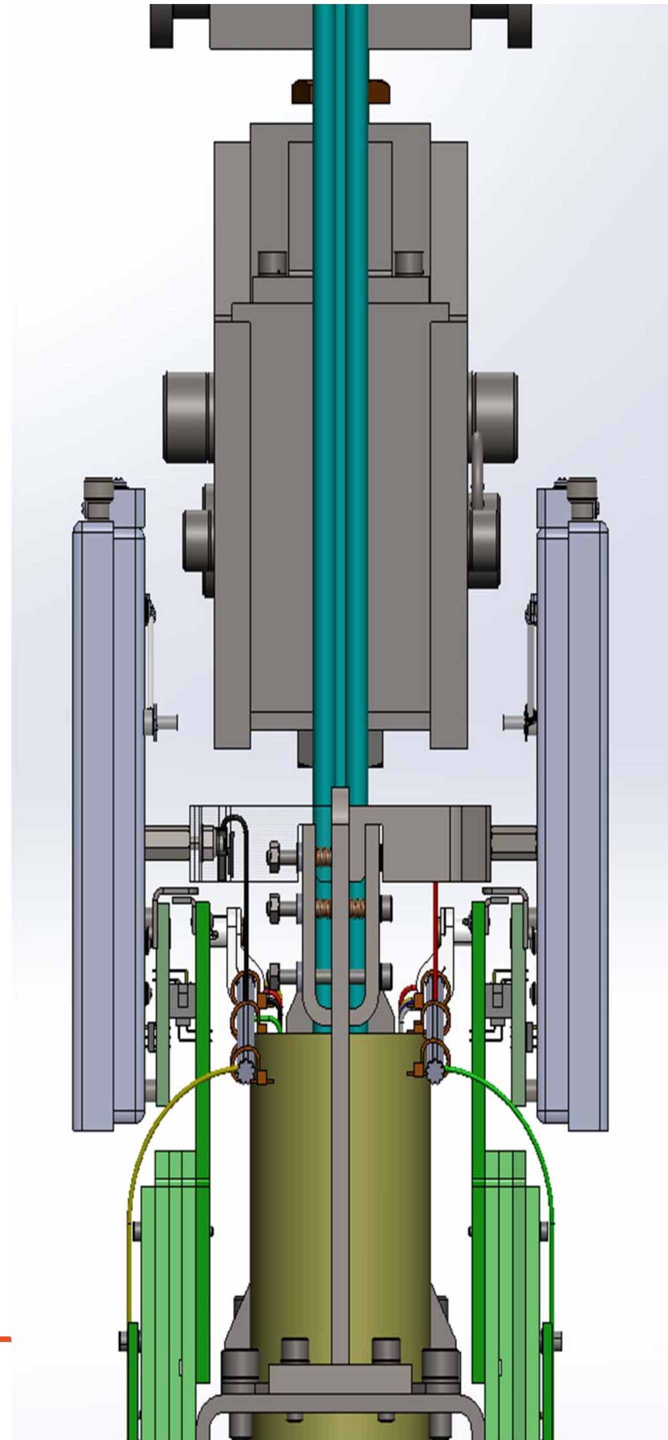
- Terminates X, U and G bias cables
- Two boards are stacked
- The top board holds SHV receptacles and is supported by two stainless steel standoffs attached to the head tube
- The bottom board distributes voltages and is supported by the SHV receptacle center pins
- Cable shields are isolated and ungrounded
- Each wire bundle has two connectors that plug into the top SHV board
- Connectors and wires are the same types used elsewhere in the bias distribution system

SHV Assembly



Side View, 8760075

- CE Cable Bundle Grip Support Hidden
- Half of CE brackets (8760085) transparent



DUNE

APA Wire Tests

- Electrical continuity through board stacks
  - Detect missing or damaged Mill-Max parts
- Electrical continuity from Head to Foot
  - Detect opens caused by broken PCB traces
- Electrical isolation of wires
  - Detect shorts to frame or to adjacent wires
- Wire tension, etc. using DWA

APA Wire Tests, sans DWA

- Probe cards similar to those developed for the DWA can be used to more efficiently apply signals to wires at the head end (replacing hand-held probes)
- Groups of wires can be tested simultaneously to speed up testing
- Failures at the group level can be further tested and analyzed to isolate problems to individual wires (failures are rare)

Backup Slides