SHV coaxial feed-through two stage RC filter with pulse line

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August 9, 2022

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Abstract

This filter is intended for use biasing germanium detectors for the LEGEND experiment, where the load current is expected to be < 1 nA and a large series resistance is acceptable. The final filter is a two stage RC filter with 100 MΩ resistances and 11.3 nF capacitance to ground. The expected capacitance between input and output is around 0.01 pF. The filter is constructed to minimize radiation power transfer by keeping the input on the same axis as the output and keeping the capacitors symmetric about the output axis so capacitor radiation is emitted perpendicular to the output axis and cancels. A pulse line connects to the final capacitor to allow applying a test pulse through the HV line and provide source termination to noise on the HV line. The entire filter is contained in a sealed tube that can be filled with oil and mounts with front-side nut bulkhead jacks.

1 Parts:

1.1 Filter components

- SHV bulkhead jack, TE Connectivity AMP Connectors 5225059-3
- BNC bulkhead isolated jack, Amphenol RF 112252
- 3/4 inch OD 0.032 inch wall copper 101 tube
- 6x 3.3 nF 5 kV ceramic capacitors, Vishay Vitramon HV2225Y332KXMATHV
- 6x 0.47 nF 6 kV ceramic capacitors, Vishay Vitramon HV2225Y471KX6ATHV
- 11/16 inch OD 1/4 inch ID copper washer. Hillman 44142
- M4 brass standoff in 6 mm hex, 5-6 mm length
- 2x 100 MΩ 7.5 kV axial lead resistors, Ohmite MOX1125231006FE
- 1 MΩ resistor for ground isolation
- 51 Ω resistor for pulse line ground
- 2x M2 brass nuts
- Pulser PCB
- High voltage cable for the output, FTAPP094-10-48
- Ground break insulator, printed part
- End cap, printed part

1.2 Jigs and other multi use components

1.2.1 M2 bolt to use for attaching nuts to tube fill ports

1.2.2 Guard ring positioning jig

- M4 flat head bolt
- 3x M4
- 11/16 inch OD washer, Hillman 44142 will work but a stainless steel one would be better
- M4 washer

1.2.3 Capacitor array jig

- Capacitor jig, machined from aluminum or stainless steel
- 6x 4-40 nylon bolts
- Capacitor jig removal tool, printed part

1.2.4 Positioning jigs

- 2x Resistor positioning jig, printed part
- Resistor jig stand, printed part.
- PCB positioning jig, printed part.
- Short pin positioning jig, printed part.
- Long pin positioning jig, printed part.

1.3 Consumables

- Isopropyl Alcohol (IPA)
- Tray for cleaning parts in IPA
- Epoxy, Loctite Hysol EA 0151
- Electrical tape
- ~1/8" wide Polymide tape
- Conductive Epoxy, MG Chemicals 8330S (optional)
- Double shielded coaxial cable for pulse line, LMR-100
- Wire braid to shield the output cable
- Heat shrink to cover shield braid. (optional)
- Solder flux
- High temperature solder [1]
- Low temperature solder[2]

[1] SAC 305 was used for the high temperature solder. SAC 305 melts at 217-220 C solidus-liquidus (not a eutectic alloy). Spreading solder in the plastic stage, where it had a consistency similar to acrylic paint, was found to be helpful in controlling temperature to a local area without melting off other components while distributing solder. This was followed by a reapplication of flux with a flux pen and a brief heating to above full melting temperature to ensure the solder made a good joint. This method was used to ensure a good seal around the M2 nuts on the tube fill ports, where solder had to be spread over a large area without melting the solder joint for the guard ring washer.

[2] 60/40 Sn-Pb was used, which melts at 183-190 C and is not a eutectic alloy. 63/37 Sn-Pb, a eutectic alloy which melts completely from solid to liquid at 183 C, would likely work just as well as no spreading of solder around difficult components is necessary.

Assembly

2 Assembly the Tube

2.1 Cut and drill tube

1. Measure a 61 mm section of tube with the jig and cut with a tube cutter.

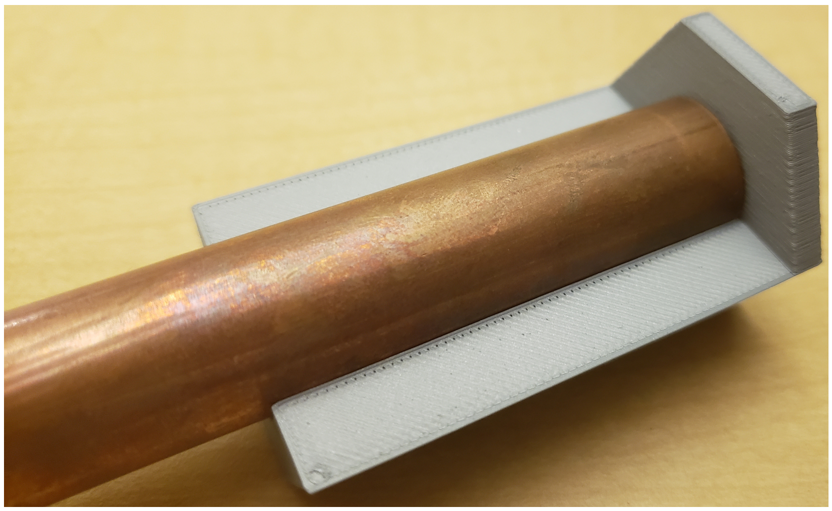

Figure 1: Tube jig used to measure the proper length of tube.

2. Use the jig to drill the smaller, 1/16 inch, holes in the tube.

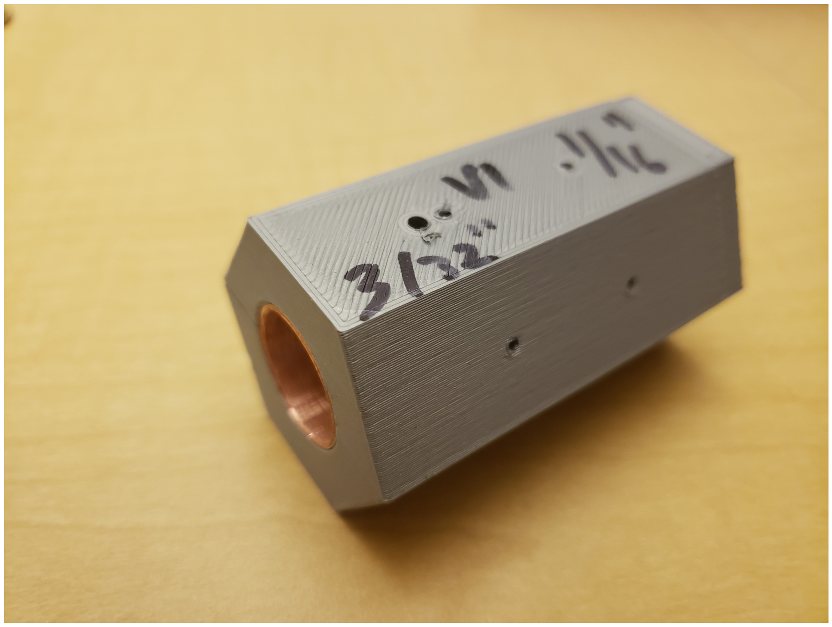

Figure 2: Tube in jig for drilled hole placement.

3. Rotate the tube 1/16 turn so two of the small holes line up with the seam on the jig on each side. Place the cover so the large holes are on opposite ends of the jig and drill out the large, 3/32", holes. This positioning of the holes allows cleaning fluid to flow through the filter and if bolts are used to seal an oil filled filter this keeps the ends of the bolts further from the capacitors.

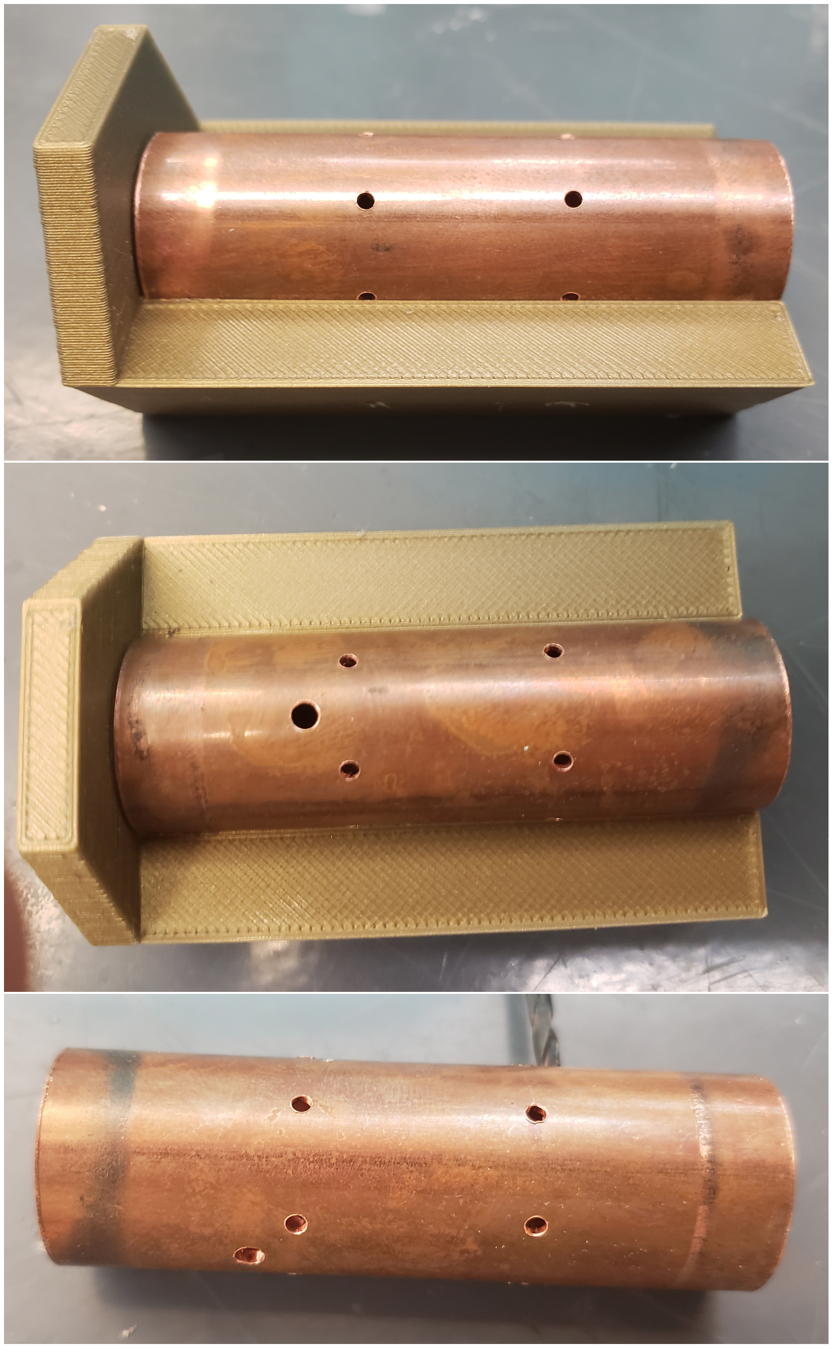

Figure 3: Large hole positions of tube.
Top: Tube rotated in jig to position large holes.
Middle: Large holes drilled, second large hole is under tube on right.
Bottom: Large hole positions, drill bit inserted in hole shows position of large hole hidden from view.

4. Bore out the inside of the tube on a lathe to fit the pulser PCB. It should be bored 1 mm (0.039 inches) deep so the PCB protrudes slightly from the end of the tube. The end cap has a 0.4 mm high lip around the edge that will engage with the protruding PCB. Ensure the bored hole is wide enough the PCB easily slides in. The capacitors are very brittle and can easily get damaged if forcing the PCB into a tight fitting hole.

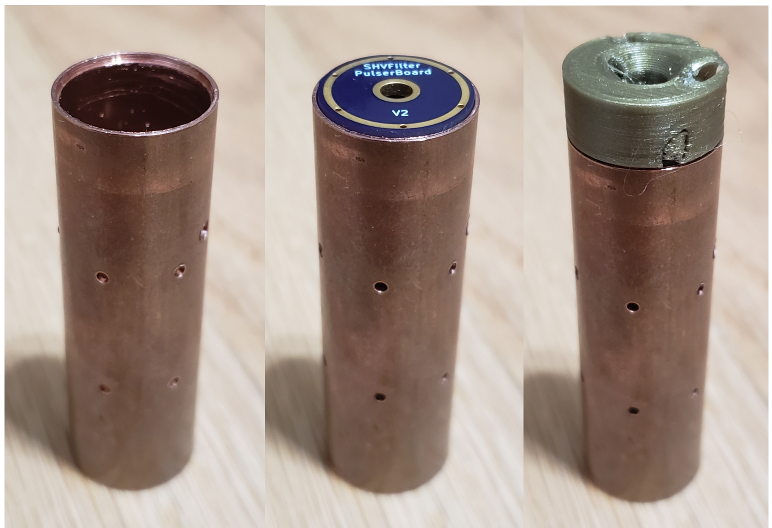

Figure 4: Test fitting the PCB in a bored out tube.

5. Deburr the inside of the tube with a rat-tail file or a flap wheel. If there are any burs the capacitors may catch later.

2.2 Install guard ring washer in tube

Warning: be careful handling the tube after first application of heat. It will remain hot for quite some time.

1. Place a copper washer on a flat head M4 bolt and tighten it against the head with a nut. Use a drill and file to turn the washer down until it slides into the tube.

2. File a notch in the edge of the washer to allow cleaning fluid to flow past the washer along the wall of the tube.

3. Put another washer on the end of the bolt sandwiched between two nuts. Position the washer so when it is inserted in the bored out portion of the tube the turned down washer is centered on the holes in the tube.

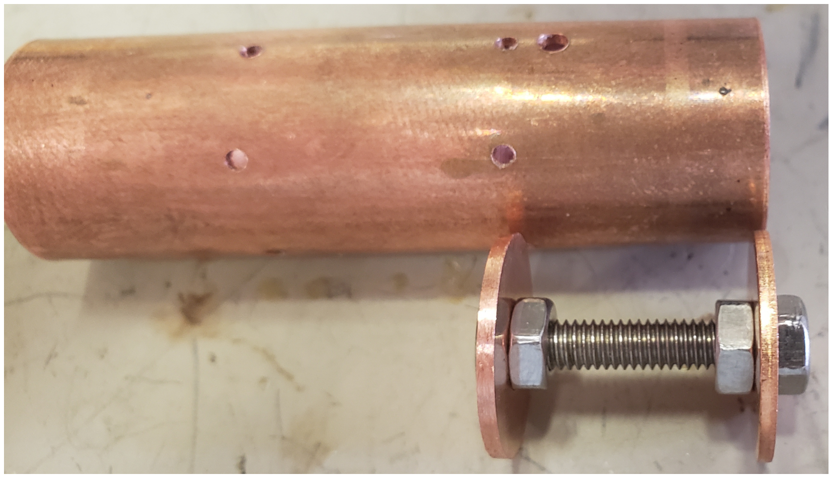

Figure 5: Copper washer and M4 nuts and bolt used as washer position jig.

4. Insert the washer into the tube and rotate the washer so the notch aligns with the large hole in the tube. Solder the washer into the tube using a high temperature solder. Be careful to handle the tube with a hot pad or some other thermal insulator — it will get very hot. Make sure there are no gaps in the holes in case it is later decided to fill the filter with oil. When soldering apply heat next to the hole with a bit of solder on the tip to improve heat transfer to the tube. Once the tube is hot enough to solder blob will wet to the tube instead of pool on the tip. At this point solder can be fed into the hole and it will wet to the washer inside the tube. Be careful to keep the washer properly inserted as once the tube it heated it will easily melt all the solder joints, not just the one being worked on.

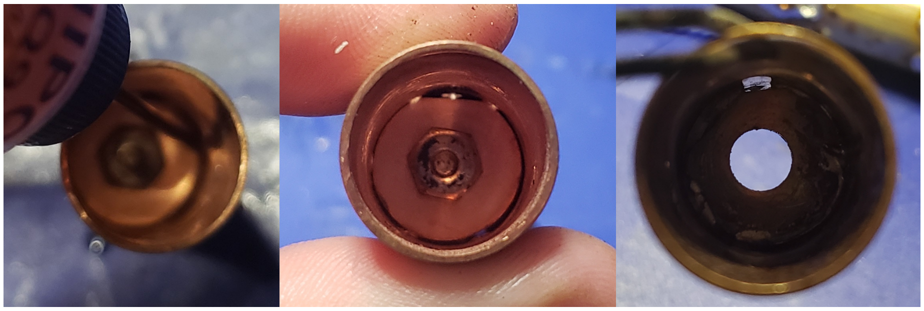

Figure 6: Left: Applying flux to washer inside tube.
Center: position of washer with notch towards fill port.
Right: gap after soldering washer. This particular washer was soldered with the gap down and too much solder for the final joints and excess solder flowed down and filled in the gap. It had to be reworked to remove excess solder and open the gap.

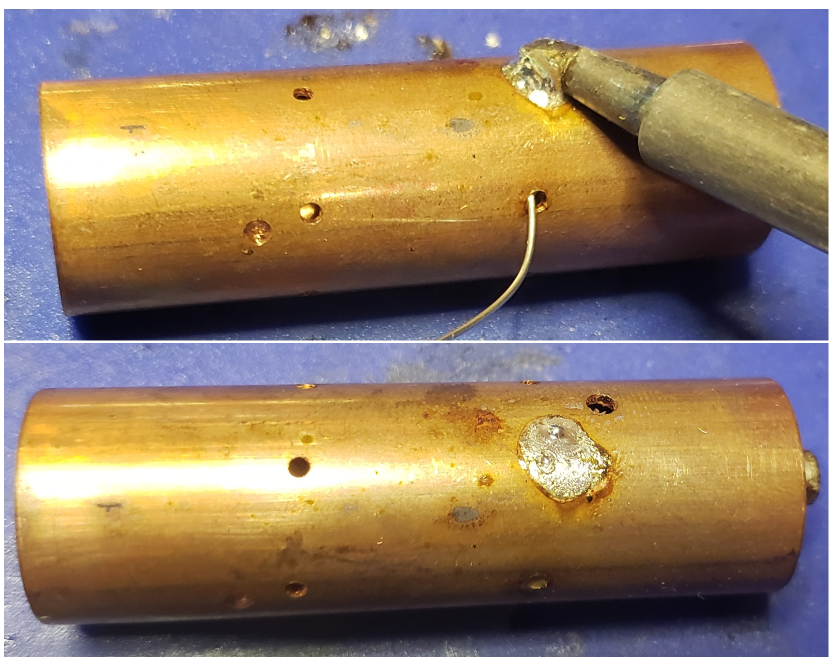

Figure 7: Top: solder being fed into a hole while the tube is heated from an adjacent hole.
Bottom: after heat removed and tube cooled the lower hole is plugged with solder.

5. Put a brass M2 nut on a stainless steel bolt and use it to solder a brass

M2 nut to the fill port. Brass can be difficult to solder to, be sure to use aggressive flux. Do this for both fill ports and use high temperature solder. See 1.

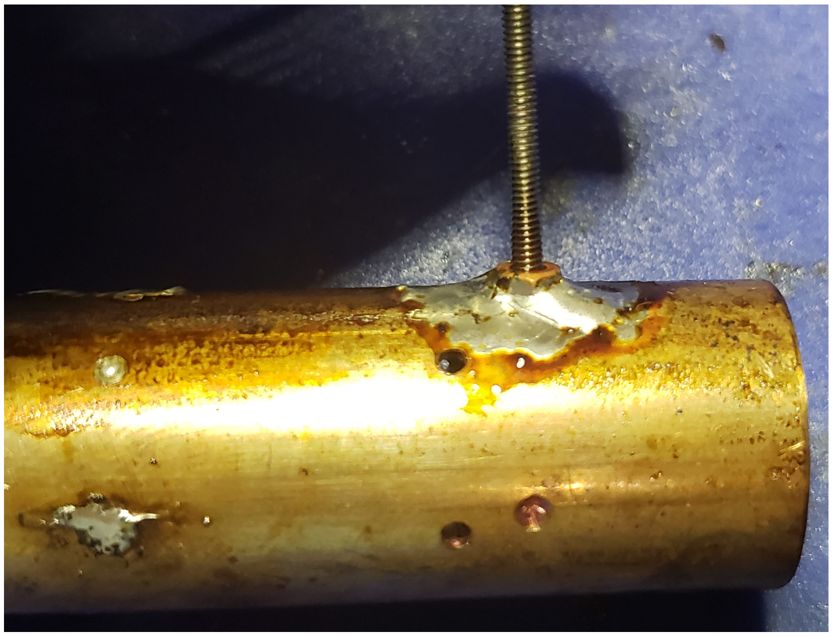

Figure 8: Brass nut soldered to tube using stainless steel bolt as aid.

3 Assemble the filter internals

3.1 Assembly the first stage capacitor array

Warning: the ceramic capacitors are very brittle and will not hold high voltage if cracked or chipped. Be very careful handling the capacitors and do not attempt to use any capacitors that are cracked or chipped.

1. Place Kapton take on the sides of capacitors to protect them from the aluminum capacitor jig.

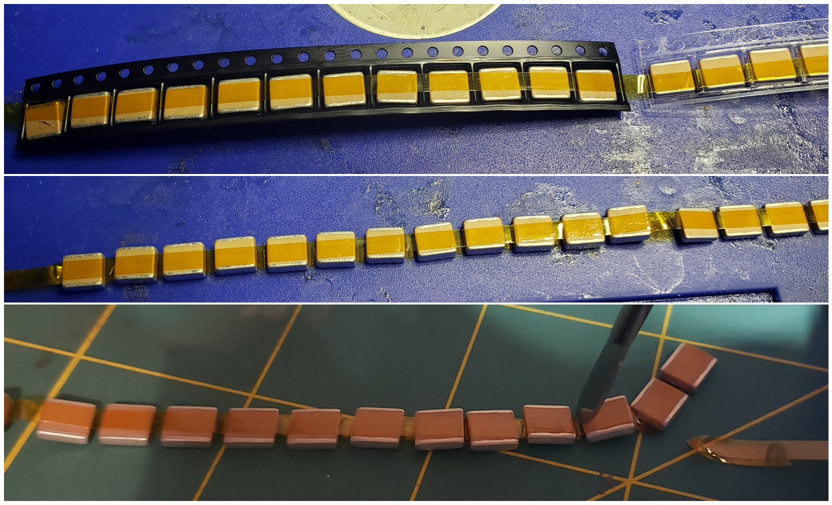

Figure 9: Top: Taping capacitors while still in strip.
Middle: Taping second side of capacitors once removed from strip.
Bottom: *Carefully* separating capacitors with scalpel.

2. Place three 3.3 nF and 3 470 pF capacitors and M4 standoff in the jig. Ensure there are no jagged edges on the standoff before installing, inspect under a microscope. Evenly distribute the capacitors so the values are alternating around the array, the slots in the jig are of different size for the different capacitors. Gently tighten the bolts to press the capacitors firmly against the standoff.

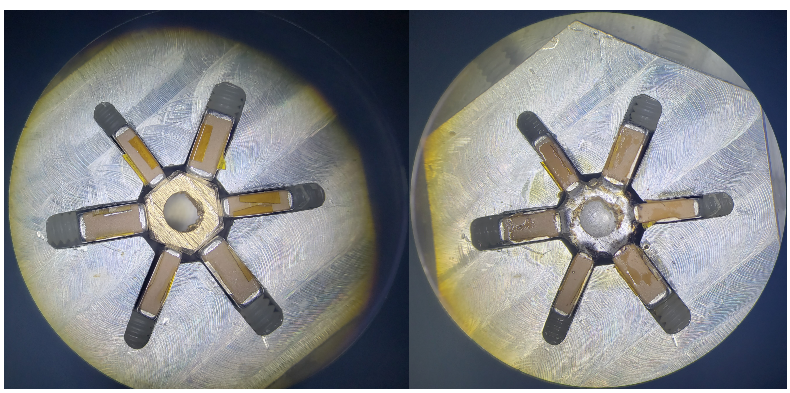

Figure 10: Capacitors in jig around an M4 standoff. Left: before soldering. Right: after soldering. Note that some of the capacitors are not well centered in their slots. This capacitor array was difficult to remove.

3. Press the capacitors and standoff down on a flat surface to get one side of

the capacitors flush with the standoff. Press on the jig so the capacitors stick out of both sides slightly.

4. Center the capacitors in their slots such that they aren't touching the sides of the jig on either side, this will allow them to be easily removed after soldering.

5. Solder the capacitors to the standoff.

   (a) Recommend starting on the side flush.

   (b) Apply some liquid flux so it flows across the face of the standoff and down the sides.

   (c) Heat the nut and apply solder to all the capacitor to standoff joints, allowing solder to flow down the sides of the standoff.

   (d) Flip the jig over and if done properly enough solder will have flowed along the capacitor to standoff joint that the joint is already soldered on the other end as well.

3.2 Install SHV pin on resistor

This can be done before or after attaching the resistors to the capacitor array. Doing it before is recommended.

1. Select an input resistor and test fit the resistor to ensure it can easily slide into the SHV jack bulkhead connector. Due to manufacturing tolerances on the epoxy coating not all resistors will fit in the connector. If a resistor doesn't fit try the other end or use it for the output resistor instead.

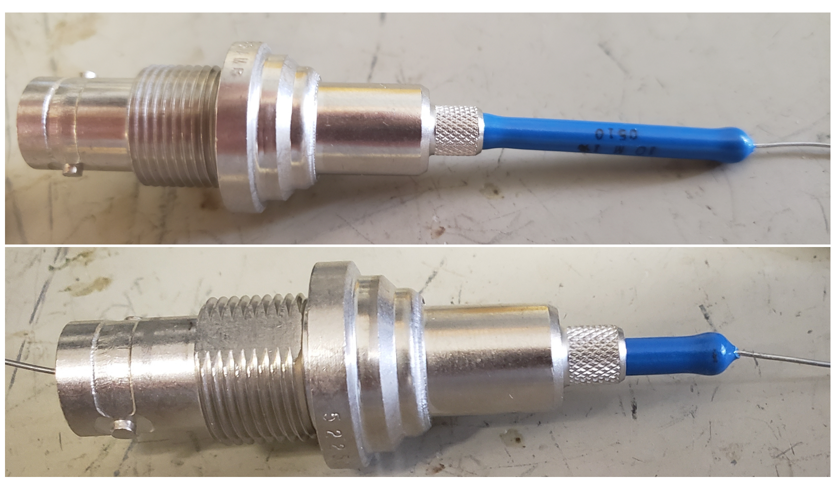

Figure 11: Resistor fit test.
Top: Resistor doesn't fit into connector.
Bottom: Resistor slides into connector.

2. Cut the fit tested lead of the resistor down to 6 mm, trim length for TE Connectivity AMP Connectors 5225059-3.

3. Put some solder flux on the resistor lead with the flux pen and solder a blob of solder to the resistor lead.

4. Gently pushing the pin onto the resistor lead, heat the pin until the solder melts and the pin slides fully onto the resistor lead. Make sure no solder protrudes from the side of the pin further than the widest feature of the pin.

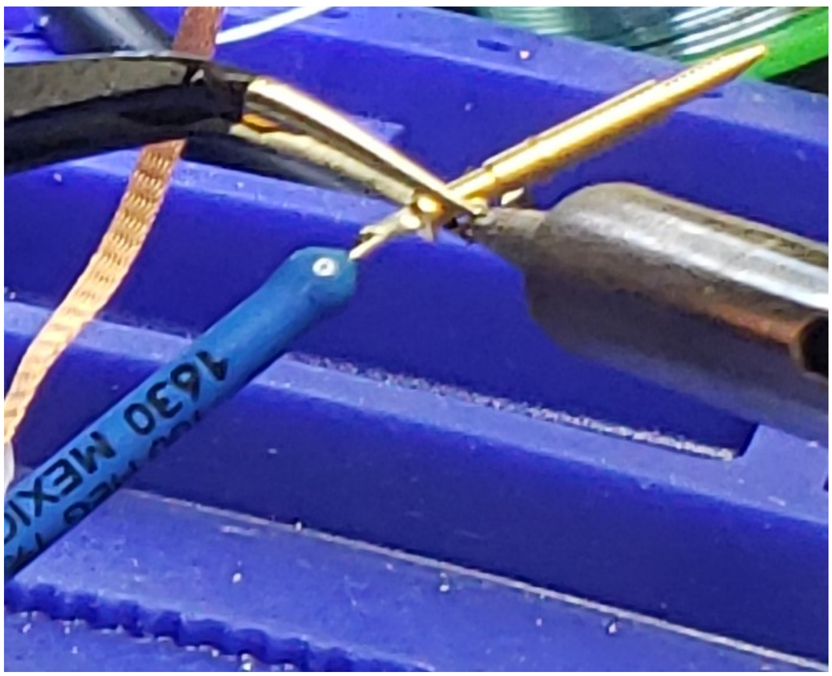

Figure 12: Soldering pin to input resistor.

3.3 Attach resistors to capacitor array

Warning: Be careful handling the capacitor array after the first application of heat, it will remain hot for quite some time. Be carefuly handling the assembled capacitors and resistors, too much stress on the resistors can easily break the leads once attached with a zero length solder joint.

1. Trim the lead on the resistors that will connect to the capacitor array down to $\sim$ 6 mm. Bend a loop into the trimmed lead so it easily holds a solder ball. Make sure the resistor that will be used for the SHV connector end can fit in the connector. See figure 11.

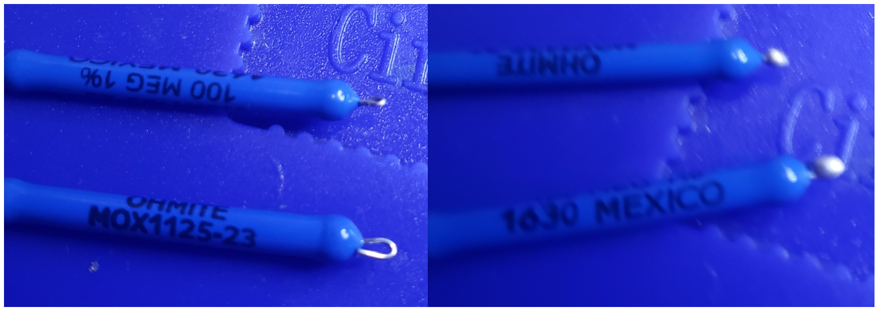

Figure 13: Left: loop on resistor lead to easily hold a ball of solder.
Right: solder ball on resistor ends prepared for installing on capacitor array.

2. *Optional:* Wrap Kapton tape around the mid section of the input resistor to provide additional insulation when inserted into the connector. Do not wrap around the bulge at the end of the resistor or it won't fit into the connector. The resistor epoxy should be sufficient to prevent discharges without this additional tape.

3. Solder one resistor to the capacitor array, gently push the resistor down so it is almost flush with the standoff in the center of the array, leaving a little bit of room so it can be tilted. Put the flush end up towards the input resistor. Use the resistor jig to ensure it can be centered. It is possible to solder the resistor to the capacitors array while installed in the jig, just more difficult and if the resistor is installed carefully it should be well enough centered without the jig. Bend the other lead into a spring, this keep the resistor pushed against the standoff when the jig is inverted. If the input resistor already has a pin installed then the output resistor must be done first so the spring can be formed.

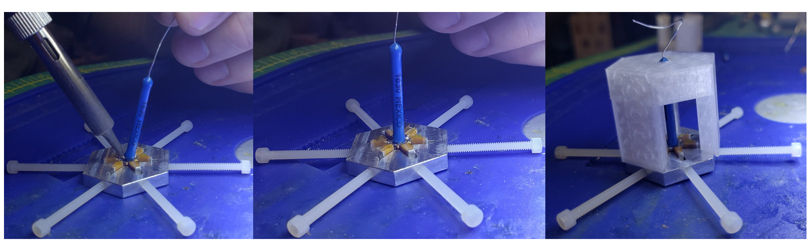

Figure 14: Installing input resistor on capacitor array.

4. Turn the jig over and place it on the resistor jig stand. Solder the second resistor to the capacitor array and check that it is centered afterwards with the jig. There are two jig versions, one with a 4.0 mm hole and one with a 4.4 mm hole. The 4.4 mm hole may be required depending on the epoxy coating shape on the resistor.

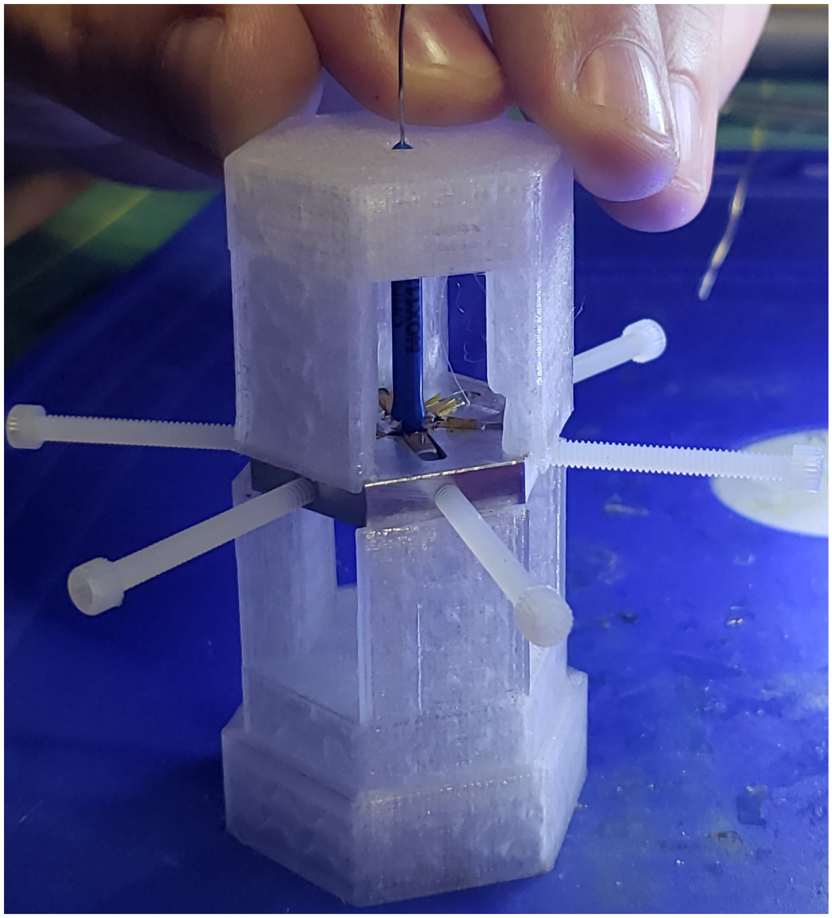

Figure 15: Checking the alignment of the second resistor with the resistor jig. The entire resistor jig assembly with two resistor jigs and a resistor jig stand is shown.

5. Loosen the nylon bolts. If the capacitor array doesn't easily come out of the jig do not attempt to apply significant force with the resistors or they will break. Use the capacitor array removal tool to gently push the capacitor array out of the aluminum jig. The jig has narrow and wide portions to match the narrow and wide resistors. Push from the side flush with the capacitors so if the capacitors are crooked they are assured to fit through the jig. Use both resistor jigs to get enough height to remove the resistors without hitting the table.

6. Remove the nylon bolts and place the jig and bolts in IPA to remove solder flux. The bolts will start to stick in the jig if it is not cleaned after every use.

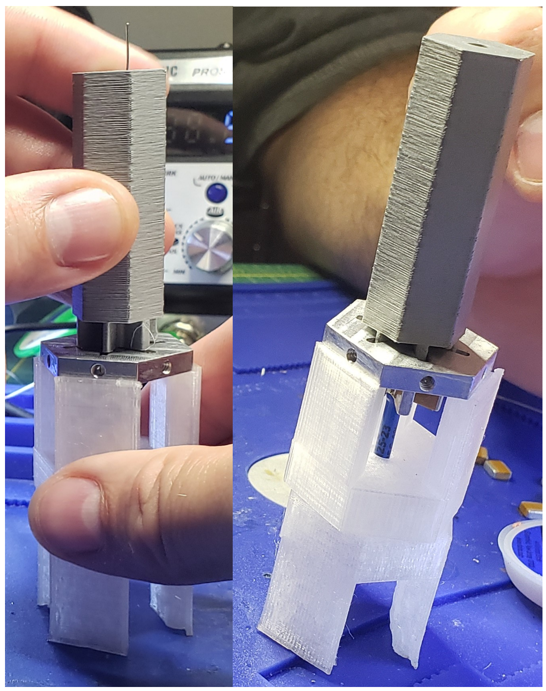

Figure 16: Removing capacitor array from jig using removal tool. Both resistor jigs were used to hold the assembly above the work table.

7. Remove the Kapton tape and inspect the capacitors for any signs of damage under a microscope.

4 Assemble the pulser PCB

1. Carefully solder three 470 pF and three 3.3 nF capacitors to the pulser PCB. Arrange the capacitors so they alternate values around the array. The capacitors shouldn't go over the hole in the center of the PCB, but can get arbitrarily close. The capacitors should be kept away from the sides so they just go on the pads, to keep as far from the tube wall as possible to avoid shorts. Use a high temperature solder so the joints don't melt when additional components are attached to the PCB later. Recommend doing one capacitors at a time and soldering outside pad to position capacitor then solder inside pad. Do all three large capacitors first so smaller capacitors are added when space is limited. Add fresh flux and clean up solder joints after all capacitors are placed.

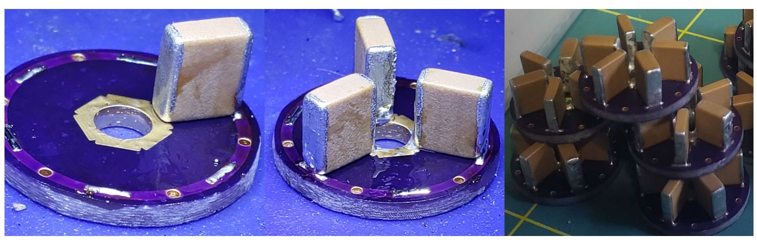

Figure 17: Capacitors soldered to pule PCBs.

2. Cut an 8 inch section of pulse line. Trim the cable down to the center conductor for ~2 mm on both ends, one end attached to the PCB the other is going to be used for continuity checks. Trim back the jacket and braid ~ 2 mm more. Trim off ~35 mm of jacket leaving either a bit of jacket at the end to hold the braid together or place a bit of heat shrink on the cable.

Figure 18: Trimmed cable with section of jacket removed from middle to expose shield, but portion left at end to keep shield braid in place. Markings are in inches.

3. Trim down and solder a lead of a 51 Ω resistor to the pulser PCB. Solder the pulse line to a hole on the opposite end of the PCB.

4. Feed the HV cable pigtail through the 3D printed end cap. Do not forget this as it can't be installed once the cable is soldered to the PCB.

Figure 19: HV cable fed through end cap prior to attaching cable to PCB.

5. Trim the HV cable end so the conductor goes through the hole in the PCB but not too far up along the capacitors, there needs to be room to the resistor lead later. Feed the cable through the hole and spread the conductor strands out so they will solder bridge to the capacitors. Solder the HV cable to the pulser PCB.

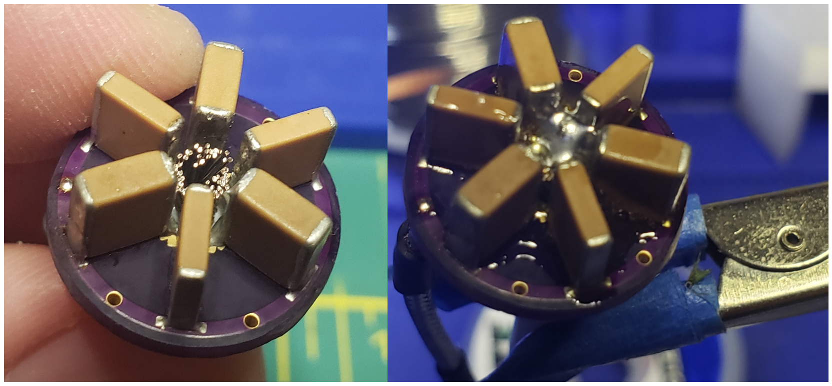

Figure 20: Soldering HV cable to PCB.

5 Install the ground on the SHV connector

1. File off a portion of the SHV connector body to reveal the brass underneath, this will make it much easier to solder to. Apply an aggressive flux to the revealed brass, it is still difficult to solder to brass.

2. Solder the end a 1 MΩ resistor to the SHV connector body. This needs to be positioned so that it can go through a hole in the ground isolation electric break and fit in a recess for the resistor. If the lead is too long it can be wrapped further around the SHV connector to take up slack, but if it's too short it needs to be removed and redone.

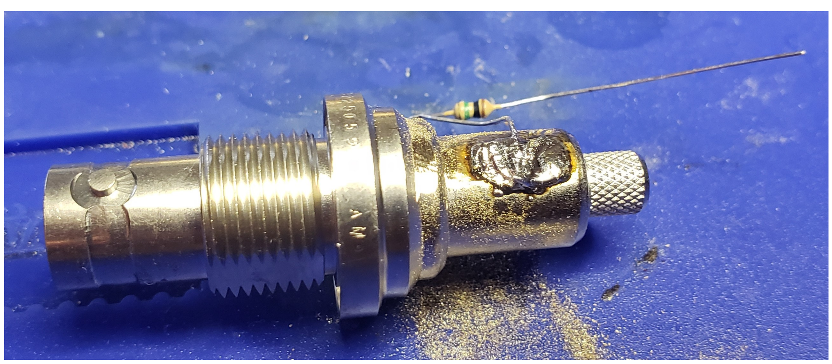

Figure 21: Soldering ground isolation resistor to SHV connector body. Note the nickel and brass residue from filing off some of the nickel plating to expose the brass connector body.

3. Allow the connector to cool then install the electric break on the SHV connector. Rotate so the resistor goes through one of the notches in the

connector side and is fully contained in one of the recesses. Ensure the electric break is fully installed on the connector.

6 Install the filter in the the tube

1. Use the short connector jig to position the pin 19.8 mm from the SHV connector end of the tube. The pin should protrude 1 mm from the end of the jig. This positions the pin 10 mm away from its final position and allows making a solder connection for the pulser PCB to the output resistor.

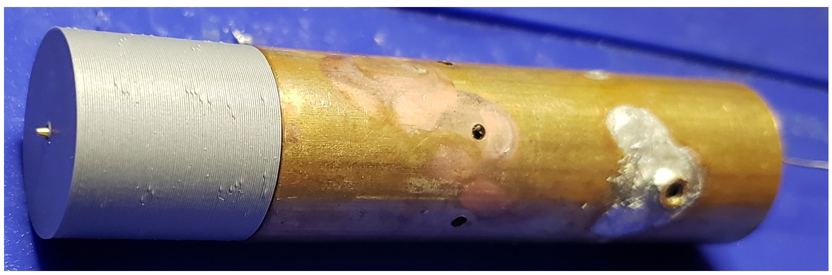

Figure 22: Short pin position jig installed on tube with pin sticking 1 mm through hole in jig.

2. Install the pulser PCB in the PCB assembly jig and attach to HV pigtail end of filter. The jig positions the PCB about 9 mm from the end of the tube which should allow it to insert 1 mm into the recess on the end of the tube later.

3. Check the position of the resistor for making the solder connection, then remove the jig and make a loop and add a solder ball to the end of the resistor. Position the loop so it can be soldered to the solder blob between the capacitors on the pulser PCB, which should be about in the middle of the capacitors.

4. *Optional:* Add a layer of Kapton film around the output resistor as added protection against discharges to the guard ring.

5. Reassemble the jigs and solder the output resistor to the pulser PCB. Use a lower temperature solder to avoid melting the solder joints of the capacitors on the PCB.

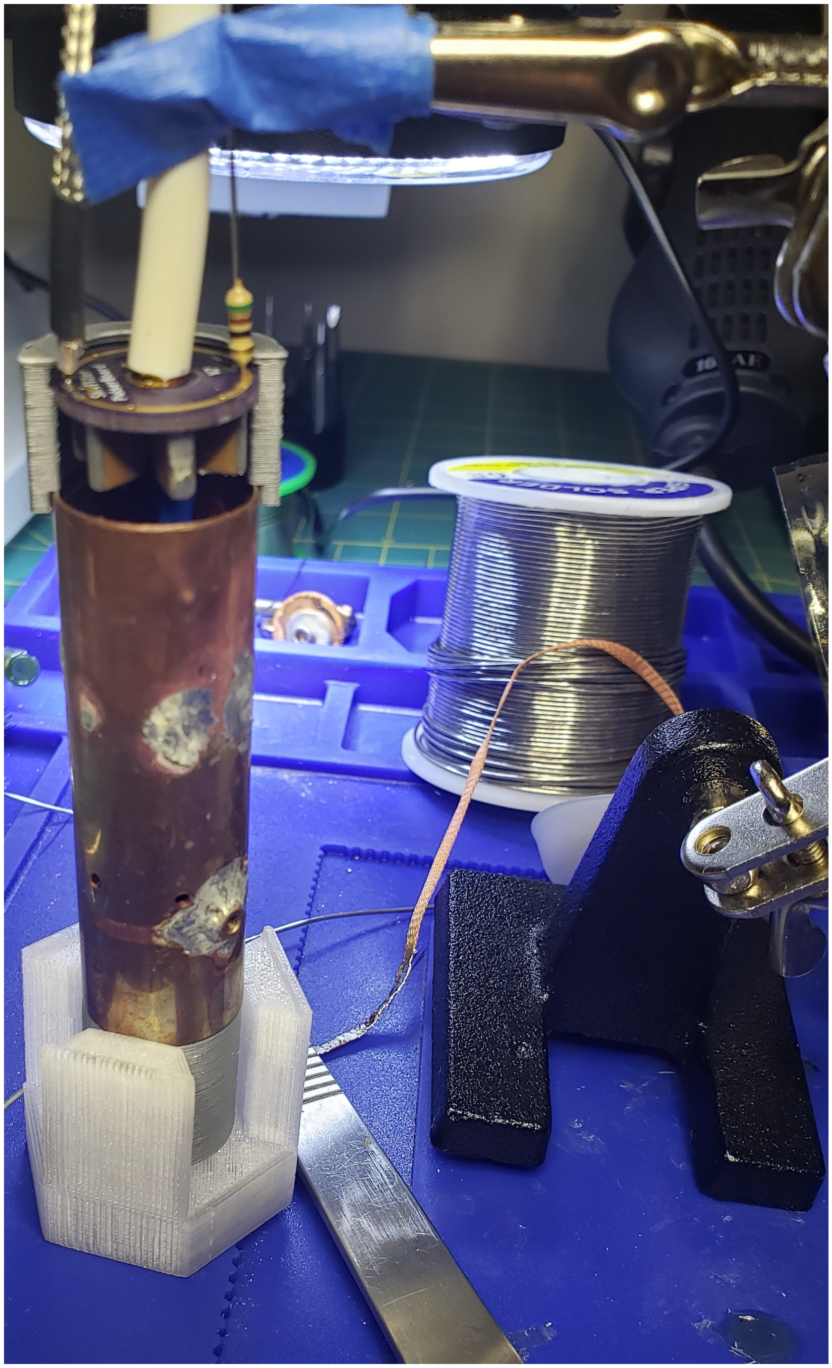

Figure 23: Soldering the output resistor to the pulser PCB.

6. Remove the jigs and carefully slide the filter components into the tube. The capacitors need to be rotated to align with the holes in the sides of the tube. Use the longer pin jig to ensure the tip of the pin is 29.8 mm from the end of the tube. The pin should protrude 1 mm through the hole in the jig. Tape the pulser PCB in place with electrical tape, this is to ensure the capacitors stay put as they are soldered to the tube. Do not try to install the end cap at this time, it will melt when soldering the capacitors in place. It is a good idea to check continuity on the pulser line and ground resistor, it will be difficult to correct problems once the capacitors are soldered to the middle of the tube. The center conductor of the pulse line should measure 51 ohms to the resistor lead and there should be an open between the pulse line or resistor to the tube wall.

Figure 24: Top: distance of pin from end of tube measured with calipers.
Middle: the position of the pin should be ensured using the jig. The rotation of the capacitors must be such that they can be soldered to the tube through the holes in tube, but the exact insertion of the capacitors in the tube isn't important and may vary slightly depending on the length of the capacitor array standoff and solder joints for the resistors.
Bottom: PCB taped in place to mitigate shifting of capacitor array.

7. Remove the jig and solder the capacitors to the tube. Be careful to handle the tube with a hot pad or some other thermal insulator — it will get very hot. Use low temperature solder to avoid melting other solder joints on the tube or the capacitors to the standoff at the center of the capacitor

array. Be careful not to shift the tube around while hot enough to melt solder to avoid moving the capacitors. Soldering capacitors on opposite sides first can help mitigate the likelihood of inadvertently shifting the capacitors.

7 Clean

1. Clean the SHV connector and filter with internals thoroughly with IPA. There is no more soldering after this and this is the perfect time to make sure everything is clean. If the endcap is made of PETG acetone can be used, but it will damage PLA. Short exposure to acetone will be fine and may help remove solder flux.

Figure 25: Filter taking an IPA bath before final assembly.

8 Install the end cap

1. Remove the electrical tape around the PCB and slide the end cap down on the PCB. Feed the resistor and pulse line through, folding the resistor over in its groove and the pulse line through its groove.

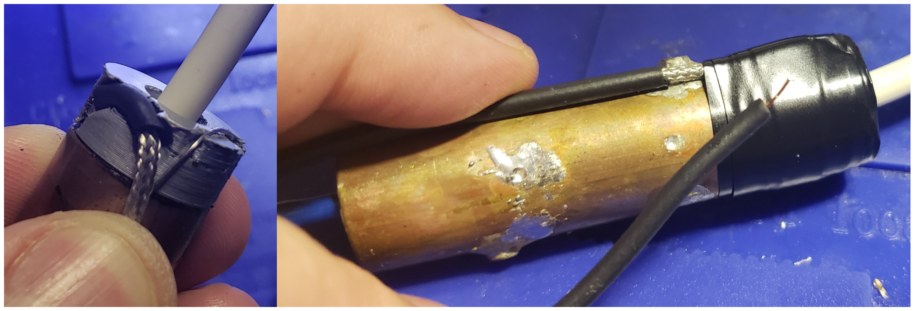

Figure 26: Left: end cap slid into position with resistor and pulse line fed through grooves.
Right: end cap taped in position, covering ground resistor and hold resistor lead and pulse line shield against tube.

2. Tape the end cap to the tube. Ensure the pulse line shield and ground resistor lead make good contact with the tube before applying tape. Optionally with conductive epoxy.

9 Inspect

This is the last chance to make sure there are no problems before applying epoxy. Disassembly for repair will be difficult after application of epoxy.

1. Look in the end of the tube to ensure the capacitor solder joints to the tube are good.

2. Test the electrical connections.

   (a) Between pulse line center conductor and tube should be 51 ohms. This ensures the connection between pulse line to pulser PCB, pulser PCB to 51 ohm resistor, and resistor to tube.

   (b) Check the pulse line shield is shorted to the tube.

   (c) Check capacitance between output and tube is about 11.3 nF. To connect to the output do not force a multimeter probe into the connector or it may rip. Use a short piece of metal like a hex wrench.

   (d) Check capacitance between the standoff in the middle of the capacitor array and tube is about 11.3 nF. If the electrical connections are clearly good on visual inspection this isn't necessary.

   (e) Check resistance between SHV pin and output is 200 MΩ, many multimeters can't go up to this high a resistance.

10 Attach the SHV connector assembly to the filter

1. Apply epoxy to the SHV pin around the joint with the resistor. Make sure no epoxy gets on the contact area of the pin for mating with a socket connector. There is a small barb-like ring around the connector that keeps it from pulling out of the connector, no epoxy should go past that. Keep the pin, resistor, and capacitor assembly oriented pin up, until inserted into the connector, to prevent epoxy from flowing along the pin towards the contact portion.

2. Generously apply epoxy to the area between ground break insulator and connector. Coat the entire inner surface to add a second sealing layer in case the filter is filled with oil. Also apply epoxy to the top of the electric break where it will insert into the tube. This epoxy is not going to be exposed to high voltage and doesn't need to be free of bubbles.

3. Insert the ground break insulator with SHV connector into the filter tube. The SHV pin needs to be centered so it slides into the connector and fully inserts into the SHV connector housing.

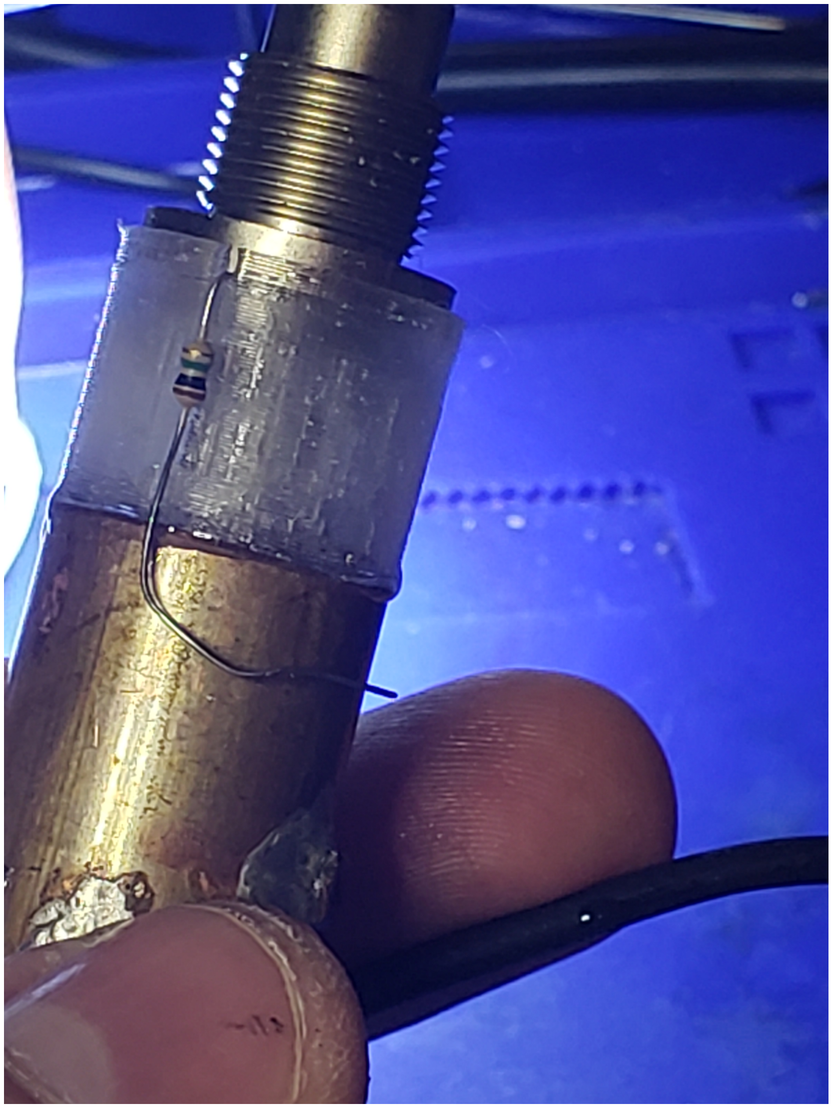

Figure 27: Epoxied SHV connector and ground isolation electric break installed on tube. Note the resistor lead is bent to wrap around the tube, this is to ensure good electrical contact when the joint is taped over with electrical tape.

4. Check the series resistance again from SHV pin to filter output, it should be 200 MΩ. This checks if something was broken when the connector was installed and gives a chance to take it apart before the epoxy cures.

5. *Optional:* Use conductive epoxy to ensure good electrical connection between ground isolation resistor and tube.

6. Tape over the joint with electrical tape and keep the assembly oriented connector end down while the epoxy cures. Make sure the ground isolation resistor makes good contact with the tube when taping it down.

11 Finishing touches

1. Install the BNC connector on the pulse line.
2. Pot the HV pigtail connection to the pulser PCB by filling the end cap with degassed epoxy through the end cap fill port. Keep the filter oriented with the SHV connector end down while the epoxy cures. This will also seal the tube so it can be filled with oil if desired.

Figure 28: Fill port for potting HV pigtail connection. Fill port is the small hole next to the cable.

3. Install copper foil around the HV pigtail. Foil can also be used to min-

imize the gap in the shielding at the ground break insulator and shield around the filter end cap. Kapton tape cover the resistor lead can prevent undesired shorts allowing the shield to be nearly complete.

4. Install shield braid around the HV pigtail covering the entire length of the cable, including the connector, and extend up around to filter end cap to contact the tube. The braid can be bunched up to go around the filter tube and stretched out to be snug around the cable. Conductive epoxy can be used to ensure a solid electrical connection to the tube for contact the shield braid around the HV connector pigtail. Do not attempt to solder connections to the tube or the 3D printed plastic parts will melt.

5. Solder the ground wire with connector to the HV pigtail connector end of the shield braid.

6. Label the filter and record any details. Is there Kapton tape around the input resistor? How about a film around the output resistor? Is it potted? What was the HV pigtail serial number?