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# 1.0 Purpose

Describes the process of measuring the tension of the wires on the APA. After all wires have been verified to be within spec, proceed to 8760Doc041 V, U, and G layer wire comb installation to install the combs for the next layer.

# Scope

Applies to Anode Plane Assemblies made for ProtoDUNE2 (at CERN) or for the Far Detector in the Sandford Underground Research Facility (SURF) at Lead, South Dakota, USA.

# Reference Documents

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| **Document Number** | **Title** |
|  | DUNE APA Process Traveler |
| 8760Doc009 | Winding |
| 8760Doc011 | Soldering |
| 8760Doc041 | V, U, and G layer wire comb installation |

# Terms and Definitions

*High Slot Beam (HSB)*: The side beam of the APA that has a long slot in the first full-length side board position back from its attachment to the head beam.

*Low Slot Beam (LSB)*: The side beam of the APA that has a long slot in the first full-length board position from the foot beam.

*Side A*: The face of an APA when the HSB is on the right and the LSB is on the left, when viewed with the head end on top.

*Side B*: The face of an APA when the LSB is on the right and the HSB is on the left, when viewed with the head end on top.

*Left or right side of APA face*: This is from the perspective of someone standing near the foot beam, facing the head beam.

*Measurement zones 1-5*: Four comb assemblies span the APA and divide the wires or segments (see next entry) that cross them. The space between the head boards and the nearest comb assembly is called Zone 1; the space between that comb assembly and the next one footward is Zone 2, and so forth. Zone 5, the space between the footmost comb assembly and the foot boards, is used for measurement of tensions for all the x & g wires. The length of the wire (or segment) within a zone, its tension and mass per unit length determine the frequency at which it will vibrate if it is plucked within the zone. If the wire or segment is restrained snugly at the comb crossing, it will oscillate cleanly at a particular frequency; if not, its oscillation will be of varying frequency and will quickly decay. Note that combs don't end segments, as even if snug they do not restrain the wire sufficiently to create a difference in tension on opposite sides of the comb.

*Wires vs segments*: A "wire" is a single conductive path connecting one head board solder pad to a foot board solder pad, whereas a wire segment or "segment" is a piece of wire that is secured on both ends to a head, side, or foot board. A segment is assumed to have the same tension over its entire length, so that although it may run through several zones (crossing combs), it will need to be measured in only one of them. For the x & g layers, wires are each comprised of a single segment that runs parallel to the side beams from its origin to its termination; for the v & u layers, each wire is comprised of 2-3 connected segments, running from head board to side board, (in some cases) side board to opposite side board, and from side board to foot board.

*Capos*: Tools made from X or V/U combs to which a strip of self-adhesive soft rubber has been added to one side, covering the upper end of the comb’s wires slots. Capos are placed behind the APA’s combs with the edge of the rubber strips pressing the wires to the bottom of the combs, and are held in place with spring clips, in order to confine the vibration of plucked wires within a single measurement zone so that they will oscillate cleanly. Capos made from X combs are used on X & G wire layers; those made from V/U combs are used on V and U wire layers.

# Responsibilities

# Follow the most recent published procedure for the assembly operations contained herein.

* 1. Red laser light is emitted by the optical assembly’s laser diode when the laser power supply is connected and turned on; although the light is of low power, do not look directly into the beam.
  2. Use Personal Protective Equipment (PPE) whenever necessary, and specifically called out in documents.
  3. As operations and processes are completed, record the necessary related information in the associated traveler for the serial number of the APA being assembled.
  4. Exercise caution whenever reducing the Z axis setting of the winder arm, to avoid pushing the optical assembly into the wires. Setting a minimum z axis limit is recommended.
  5. Exercise caution while moving the winder arm along the X axis, particularly to ensure sufficient clearance of the optical assembly when crossing a line of installed capos.

1. **Materials and Tools**
   1. APA with at least some wires wound on one or more layers, mounted in:
   2. APA Winder Assembly
   3. Remote operation device for winder
   4. Tensometer optical assembly
   5. Power supply for laser in optical assembly
   6. Small bar clamp, ~15cm (6 inch) span
   7. Tektronix 2465 (or similar) oscilloscope
   8. Laptop computer, equipped with Excel software and the appropriate tension measurement spreadsheet
   9. Cell phone, running Pano Tuner or similar app
   10. Amplifier / speaker assembly
   11. 50 ohm coaxial cable, SMA connector on one end, BNC on other, at least 305cm (10 ft) long
   12. Capos of appropriate type for layer (X/G with 4.79mm pitch or V/U with 5.75mm pitch), qty 5
   13. Clips to secure capos to combs, qty 25+
   14. Head capo and attachment M4 screws, studs, nuts & washers
   15. 3mm ball-end hex wrench
   16. 7 mm combination wrench (for M4 nuts)
   17. 2.5mm ball-end wrench
   18. Torque-limiting driver with 2.5mm hex bit
   19. Cart to hold equipment for tension testing
   20. Cable tie or other suitable object used to pluck the wires
   21. Rolling ladder(s) to reach wires on upper edge of APA

# Requirements / Additional Information

* 1. For all following processes lint free, non-fiber gloves (e.g. vinyl, nitrile, latex, or neoprene gloves) should be worn by all personnel to minimize any epoxy debris or hand oils being transferred to the APA assembly.
  2. At least two operators will be needed for this process: one to sit near cart with good view of oscilloscope and cellphone, and enter the frequencies displayed by the cellphone app into a spreadsheet running on the laptop; the other to pluck the wires lit by the optical head’s laser, and occasionally to check position of measured wire by counting boards and wires. One of these operators (or a third) will also need to run the winder’s head motion controls, preferably using a remote device.
  3. The rivnuts are sized to supply adequate hold to the side of the frame but are not designed to resist direct twisting torque.  **Do not tighten a single bolt directly to a rivnut.**  Most connections to the rivnuts are made with a M10 stud and an insert spacer. **Failure to follow this instruction could cause the rivnut to loosen and result in scrapping the APA.**

# Preparation / Setup

* 1. Position the APA in a vertical orientation, with the side containing the first wires to be measured facing the winder side with the Z-axis adjustment. Note whether APA side A or B is in this position. (Check definitions in Section 4 if you’re not sure how to tell!)
  2. Inspect the wires on the surface of the APA where wire tensions will be measured. Every comb slot must have exactly one wire it in before any capos are installed(*see figures 1 and 2)*. Misrouted wires can usually be resolved by gently pinching, with gloved fingers, the improperly-cohabitating wires at the comb slot, pulling them back a cm or two, then letting go.

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***Figure 1. Wires not properly positioned in the comb.***



***Figure 2. Wires routed correctly through comb.***

* 1. Put the winding arm in parked position, with the Z-axis retracted. Detach the winding head from the winder by pushing down the latch on the ramp side of the winding head, then carefully pulling the head towards the ramp. Store the winding head in a safe location.
  2. Place the winder z axis control near its maximum setting.
  3. Move the winding arm to proper zone to begin desired wire tension measurement; for full layer measurements, this will usually be zone 5, near the foot end of the APA.

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***Figure 3. Capos clipped onto combs in measurement zone 5.***

* 1. Attach caps of the proper type for the wire layer (X or V/U) to the combs that border the measurement zone. The capos should be placed on the outer surfaces of the combs that define the zone borders. Slide the first capo down so its first groove engages the first wire on one side of the APA, pressing it down gently while installing a spring clip to hold it in place. Repeat the pressing and clipping on the other end, then in the middle, then between the middle and end clips on each side. Place another capo starting on the first wire beyond the capo just installed. Five capos will span the APA. Each capo should be well-secured with five spring clips.
  2. Latch the tensometer’s optical assembly into the winder arm’s head mount.

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***Figure 4. Tensometer optical assembly showing signal and power connectors.***

* 1. Attach the SMA connector of the long coaxial cable to the optical assembly’s photo diode; attach BNC connector on the other end of the cable to the Channel 2 input on the oscilloscope.
  2. Use the bar clamp to attach the laser power supply to one of the winder frame’s diagonal struts; connect the power supply’s output plug to the mating jack on the laser diode in the optical assembly, and connect the power supply’s AC mains jack to power. Switch on the power supply and make sure the laser emits light.
  3. To the “Channel 2 signal out” jack on the rear panel of the oscilloscope, connect the amplifier/speaker’s BNC cable input; connect the amplifier’s power cable to AC power. Switch on the amplifier.
  4. Run the Pano Tuner app on a cell phone set near the speaker.
  5. Turn on the oscilloscope and set it to display Channel 2. Set Channel 2 input for DC coupling, 50mV per division, inverted. Set time base (sweep rate) to 5 msec/ div, auto triggering, DC coupled to Channel 2. Check that everything’s properly connected by having one operator move a finger with a couple cm of the optical assembly’s laser output, while the other operator watches the scope display: the display should show an increase in DC level (signal trace moves up at least a couple of divisions) when the finger approaches the sensor and is lit by the laser.

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***Figure 5. Laptop, oscilloscope, and speaker/phone ready for tension testing.***

* 1. Turn on the laptop and open the appropriate wire tension measurement template file for the layer being measured. Insert the proper APA serial number in cell B9 and save the spreadsheet into the tension measurement folder with an appropriate name including APA s/n and wire layer, such as “PSL002, X pre-solder”.
  2. Starting and ending wires for measurements in each zone are given in Section 9
  3. For each wire to be measured, the operator standing near the APA will gently pluck (with the pointy end of a small cable tie) the wire illuminated by the laser (*see figure 6)*. The vibration of the wire will be detected by the optical assembly, and amplified to produce a steady pitch from the speaker. The cellphone app (Pano Tuner) will read out the frequency of the sound, which the 2nd operator (seated by the equipment cart) will enter into the spreadsheet on the row corresponding to the wire or segment number being measured. The column adjacent to the entered frequency will display the calculated tension of the wire, based on its vibration frequency and expected length (the latter is constant for X & G wires in zone 5, but varies by segment number for V & U). The operator controlling winder movement can then step the laser’s focus to the next wire or segment to repeat the process.

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***Figure 6. Plucking the wire with the cable tie.***

* 1. X and G wires can all be measured in zone 5, between the foot boards and the footmost comb base of both sides. Measurement of the V and U layers is more complicated, as the numerous diagonally-wound wire segments are not all accessible in a single zone (per side); instead, measurement in four zones per side will be needed: 5, 4, 2, & 1. Measurement in zones other than 5 requires installation of two capo sets on the footward and headward borders of the zone. In zone 1, a special head capo must be used to restrain the wires’ vibration to the part below the head boards’ footward edge, while a set of ordinary capos are used along combs on the headmost comb base.
  2. The X & G layers’ wires are numbered across the APA from left to right. V & U wire segments are a bit more complicated. V segment #1 runs from the headmost pad of the first (headmost) left side board to the leftmost pad on the left head board, and the next 750 segments start on wire pads of the 21 left side boards. Segment 752 begins on the 1st pad of leftmost foot board, and the last 400 segments (for a total of 1151 per side) are numbered left to right on pads of the ten foot boards, each ending on the right side boards. The U layer is the mirror image of the V layer, and is numbered as such, with segment 1 starting at the headmost pad of the first (headmost) right side board, with successive segments continuing all the way down the 21 side boards to segment 752 which begins at the rightmost foot board’s 1st pad, then continuing **right to left** along the foot boards to the final segment (1151, again) in the leftmost foot corner. Not all the V & U segment’s tensions can be measured; this system is capable of measuring only segments at least 5 cm (~2”) in length; on the V layer, that means only segments 8 through 1146 are measured. (On the U layer, it’s segments 9 through 1143.)
  3. On entering the vibration frequency of the wire or segment into the tension spreadsheet, the spreadsheet will (as previously mentioned) automatically calculate and display the tension of the wire. The target tension is 6.5N ± 1N, and tensions within that range are displayed with a green background, while under-tensioned wires are shown with pink or red highlighting, and over-tensioned, with blue. The disposition of wires or segments that fall outside the 2N tolerance range will be evaluated after a layer’s tension measurement is completed on both sides of the APA. In some cases, wires outside the official tolerance range may be accepted; in others, a badly-tensioned wire may need to be retensioned by means of a weight temporarily connected to it via a hemostat clamp over a low-friction roller while it is soldered to one of its terminal circuit board pads.

# Procedure

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***Figure 7. APA in vertical orientation.***

* 1. **X Layer:**
     1. All X wires should be measured in zone 5, which requires application of only a single set of five X/G capos, across the headward side of the X combs on the footmost comb base.
     2. Adjust the X-axis position to bring the optical assembly about 30 cm (12”) away the foot boards, making it easy to count wires from a foot board edge to check the wire number being measured.
     3. X wires are numbered 1 to 480 from left to right across the APA, 48 wires on each head and foot board. Reduce the Z axis setting to within a couple centimeters of the wires and adjust the Y axis to focus on wire #1 at the left edge of the APA. Home in on this wire with the Z and V axis controls to maximize the signal level shown on the oscilloscope. Gently pluck the first wire; you should hear the sound of its amplified vibration coming out of the speaker, and the Pano Tuner app should display the frequency of the note produced. Step the optical assembly in 4.792mm increments across the X layer to measure all wires.
     4. The X layer tension spreadsheet has the wire numbers 1 through 480 in column 1, running down the left side of the spreadsheet. The corresponding head and foot board pad numbers for each wire are in adjacent columns. Record frequencies of side A’s wires in one of the columns labeled “Measured F, side A”. When you’re measuring side B’s wires, the wire numbers and corresponding head & foot board numbers for that side start on the spreadsheet’s column Q, with measurement columns beginning at column V.
     5. When you complete the tension measurement on one APA side’s wires, dock the winder arm behind the APA head, rotate the APA in the winder, and repeat zone 5 capo installation and tension measurement on the opposite side.
  2. **V Layer:**
     1. Begin measurement on each side in zone 5 after placing a set of **three** V/U comb capos on the headward side of the V combs of the footmost comb base: the first is to be placed adjacent to the right side board and the next two contiguous to the first. 395 of the 1151 segments on each side may be measured in this zone.
     2. In the V measurement spreadsheet’s cell G12 (labeled “Measure Zone”), click the box with the downward arrow, then click the “Select All” box to deselect everything, then click the box by “5”, then “OK”, to select just zone 5.
     3. A good place to start zone 5 is at the shortest measurable segment, the sixth one from the corner between the right side beam and the foot beam. Adjust the X and Y axis positions to focus the optical assembly’s laser on the approximate center of this roughly 5cm segment. V segments are spaced 5.75mm apart across the foot and head boards, and 8mm apart along the side boards. Upon plucking the first wire (segment #1146) and recording its frequency, step the winder ½ of both kinds of wire pitch toward the opposite corner of the APA; that is, 2.875mm to the left and 4mm headward, This diagonal step, repeated for the next 150 segments or so (while you back your way upwards through the spreadsheet’s zone 4 segment list), will keep the laser focus near the centers of the shorter corner segments, so that their vibration amplitude is maximized. After that point (near segment #1000, which is 149 cm in length), one can adopt a solely leftward step of 5.75mm across zone 5, all the way to segment 752, which originates on the first solder pad of the leftmost foot board. Then it’s time to move up to zone 4.

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***Figure 8. Capos clipped onto combs in measurement zone 4.***

* + 1. First, remove the three capos you placed on the *headward* side of the 4th comb base in step 9.2.1, and install two of those capos against the *footward* side of the V combs on that 4th comb base, starting adjacent to the left side board and heading right. Against the headward side of the V combs on the 3rd comb base (the next one toward the head), center a first capo over the APA center beam, and then install another capo contiguously to both ends of that first capo.
    2. Making sure to have clearance under the optical assembly when crossing the footmost comb base, move the winding arm with the optical assembly into zone 4.
    3. In the V measurement spreadsheet’s cell labeled “Measure Zone” (G12), click the box with the downward arrow, then click the checked box by “5” to deselect it, then click the box by “4”, then “OK”, to select zone 4.
    4. Unlike zones 5 and 1, where you can easily count a few wires out from a corner, it’s a bit more challenging on zone 4 to find your starting point. The 200 segments to measure in zone 4 span segment numbers 552 through 751. Segment 552 begins on the 10th solder pad from the headmost end of left side board #16 (counting from the head), which is also the fifth side board from the foot end. So, count up five boards along the left side beam from the foot end, then down 10 solder pads from the head-end of that board, and you’ll have your starting segment. Your best bet for starting out is to do the board and segment counting described, then place on the side board a piece of masking tape with an arrow on it pointing to the proper segment. Count segments again to be sure you’ve marked the right one, then focus the optical assembly’s laser on that wire 15 cm (6”) or so from the side board, and have the other operator strum the marked segment while watching the scope display to make sure you’ve got it, then record its vibration frequency in the Segment 552 row of the same column you used for the zone 5 segments. The hard part is over: you can find the remaining 199 segments in zone 4 just by stepping the winder to the right in 5.75mm increments. Before you head for zone 2, remove the five capos you installed for zone 4 along comb bases 3 & 4.
    5. Against the footward side of the V combs on the 2nd comb base from the head, center a first capo over the APA center beam, and then install another capo contiguously to both ends of that first capo. Install a capo on the heardward side of the first comb base from the head, then add a 2nd one to its left.
    6. Carefully drive the optics assembly from zone 4 into zone 2, ensuring you have sufficient clearance under the optics when crossing the 2nd comb base with its three capos.
    7. Set the V measurement spreadsheet’s G12 cell to zone 2, deselecting zone 4.
    8. There are 150 segments to measure in zone 2, spanning the range 402 to 552, The last of these segments ends on the 16th solder pad of the fifth side board (counting both from the head) on the right side beam, and is just four pads footward of the 1st comb base’s V comb. Compared to zone 4, this should be a fairly easy segment to locate. Record its vibration frequency, then step the winder left in 5.75mm increments 149 times to go backwards through the zone 2 list of segments. When complete, remove the five capos you used in the zone.
    9. To set up for zone 1, we’ll need the head capo installed over the V head boards: remove the 20 M4x25 blue-dyed steel BHSCSs from the hold-down screw positions at the centers of the two five-hole patterns per board. The boards are held on sufficiently by two board layers’ locating screws so that they will not loosen when you remove the hold-down screws. Into the first hold down screw hole nearest each side beam, insert a 5cm (~2”) M4 stud (length of M4 threaded rod) and screw it in a cm or so; these studs will serve to hold the head capo in place while you install the rest of its mounting screws. Working from a ladder, place the head capo against the head board stack, positioning its outermost holes over the M4 studs you just installed. Place M4 nuts and washers onto the studs over the head capo and lightly snug them against it. Into the other head capo screw holes, gently insert M4x25 blue-dyed steel socket-head fixturing screws, wiggling them as necessary to get past the wires that may cross their holes; tighten these (and the two nuts on the studs) evenly in small increments (a couple turns at a time) as the foam edge on the capo compresses under the screws’ clamping force. (Snug is good enough here -- there’s no need to torque the head capo’s mounting screws!) In addition to the head capo, install three V/U comb capos on the footward side of the V combs of the comb base assembly nearest the head. The first of these should start at the left side board, with the other two mounted contiguously.
    10. Select zone 1 on the V tension spreadsheet, deselecting zone 2 at the same time.
    11. There are 394 segments to measure in zone 1. Similar to the approach in zone 5, start with the first corner wire that’s long enough to measure: this would be the approximately 5 cm length wire coming from the eighth solder pad of the headmost left side board. Focus the laser on near the center of this wire, then (as you did after the first measurement in zone 5) move the optical assembly diagonally away from the corner, using a combined 4mm x-axis and 2.875mm y-axis motion, to focus the center of each of the next 80 or so wire segments in turn. At that point, you can resume use of a solely y-axis step to access the remaining segments to the right. On completion, remove the three comb capos and the head capo (leave the two M4 studs in place until you lift the capo away from the head boards), then replace the 20 original blue-dyed M4x25 SHCSs in the head board hold-down holes and retorque them with the torque wrench and 3mm hex bit to 200 N-cm (18 lb-in).
    12. Having measured tensions on 1139 V wire segments, you’re halfway done with the V layer. Stow the winding arm beyond the APA, rotate the APA in the winder, and then repeat the capo installations and tension measurements in the four measurement zones on the opposite side.
  1. **U-Layer**:
     1. The U-layer is a mirror image of the V layer and its measurement procedure is quite similar. Begin measurement on each side in zone 5 after placing a set of **three** V/U comb capos on the headward side of the U combs of the footmost comb base: the first is to be placed adjacent to the left side board and the next two contiguous to the first. 394 of the 1151 segments on each side may be measured in this zone.
     2. In the U measurement spreadsheet’s cell U12 (labeled “Measure Zone”), click the box with the downward arrow, then click the “Select All” box to deselect everything, then click the box by “5”, then “OK”, to select just zone 5.
     3. A good place to start zone 5 is at the shortest measurable segment, the sixth one from the corner between the left side beam and the foot beam. Adjust the X and Y axis positions to focus the optical assembly’s laser on the approximate center of this roughly 5cm segment. U segments are spaced 5.75mm apart across the foot and head boards, and 8mm apart along the side boards. Upon plucking the first wire (segment #1146) and recording its frequency, step the winder ½ of both kinds of wire pitch toward the opposite corner of the APA; that is, 2.875mm to the left and 4mm headward, This diagonal step, repeated for the next 150 segments or so (while you back your way upwards through the spreadsheet’s zone 4 segment list), will keep the laser focus near the centers of the shorter corner segments, so that their vibration amplitude is maximized. After that point (near segment #1000, which is 151 cm in length), one can adopt a solely rightward step of 5.75mm across zone 5, all the way to segment 752, which originates on the first solder pad of the rightmost foot board. Then it’s time to move up to zone 4.
     4. First, remove the three capos you placed on the *headward* side of the 4th comb base in step 9.2.1, and install two of those capos against the *footward* side of the U combs on that comb base, starting adjacent to the right side board and heading left. Against the headward side of the U combs on the 3rd comb base (the next one toward the head), center a first capo over the APA center beam, and then install another capo contiguously to both ends of that first capo.
     5. Making sure to have clearance under the optical assembly when crossing the footmost comb base, move the winding arm with the optical assembly into zone 4.
     6. In the U measurement spreadsheet’s cell labeled “Measure Zone” (U12), click the box with the downward arrow, then click the checked box by “5” to deselect it, then click the box by “4”, then “OK”, to select zone 4.
     7. Unlike zones 5 and 1, where you can easily count a few wires out from a corner, it’s a bit more challenging on zone 4 to find your starting point. The 199 segments to measure in zone 4 span segment numbers 553 through 751. Segment 553 begins on the 11th solder pad from the headmost end of right side board #16 (counting from the head), which is also the fifth side board from the foot end. So, count up five boards along the left side beam from the foot end, then down 11 solder pads from the head-end of that board, and you’ll have your starting segment. Your best bet for starting out is to do the board and segment counting described, then place on the side board a piece of masking tape with an arrow on it pointing to the proper segment. Count segments again to be sure you’ve marked the right one, then focus the optical assembly’s laser on that wire 15 cm (6”) or so from the side board, and have the other operator strum the marked segment while watching the scope display to make sure you’ve got it, then record its vibration frequency in the Segment 553 row of the same column you used for the zone 5 segments. The hard part is over: you can find the remaining 198 segments in zone 4 just by stepping the winder to the left in 5.75mm increments. Before you head for zone 2, remove the five capos you installed for zone 4 along comb bases 3 & 4.
     8. Against the footward side of the U combs on the 2nd comb base from the head, center a first capo over the APA center beam, and then install another capo contiguously to both ends of that first capo. On the headward side of the first comb base from the head, install a capo with its end adjacent to the left side board, then add a 2nd one to its right.
     9. Carefully drive the optics assembly from zone 4 into zone 2, ensuring you have sufficient clearance under the optics when crossing the 2nd comb base with its three capos.
     10. Set the U measurement spreadsheet’s U12 cell to zone 2, deselecting zone 4.
     11. There are 151 segments to measure in zone 2, spanning the range 402 to 552. Seg 552 ends on the 17th solder pad of the fifth side board (counting both from the head) on the left side beam, and is just five pads footward of the 1st comb base’s U comb. Compared to zone 4, this should be a fairly easy segment to locate. Record its vibration frequency, then step the winder right in 5.75mm increments 150 times to go backwards through the zone 2 list of segments. When complete, remove the five capos you used in the zone.
     12. To set up for zone 1, we’ll need the head capo installed over the U head boards: remove the 20 M4x25 blue-dyed steel BHSCSs from the hold-down screw positions at the centers of the two five-hole patterns per board. The boards are held on sufficiently by two board layers’ locating screws so that they will not loosen when you remove the hold-down screws. Into the first hold down screw hole nearest each side beam, insert a 5cm (~2”) M4 stud (length of M4 threaded rod) and screw it in a cm or so; these studs will serve to hold the head capo in place while you install the rest of its mounting screws. Working from a ladder, place the head capo against the head board stack, positioning its outermost holes over the M4 studs you just installed. Place M4 nuts and washers onto the studs over the head capo and lightly snug them against it. Into the other head capo screw holes, gently insert M4x25 blue-dyed steel socket-head fixturing screws, wiggling them as necessary to get past the wires that may cross their holes; tighten these (and the two nuts on the studs) evenly in small increments (a couple turns at a time) as the foam edge on the capo compresses under the screws’ clamping force. (Snug is good enough here -- there’s no need to torque the head capo’s mounting screws!) In addition to the head capo, install three V/U comb capos on the footward side of the U combs of the comb base assembly nearest the head. The first of these should start at the right side board, with the other two mounted contiguously.
     13. Select zone 1 on the U tension spreadsheet, deselecting zone 2 at the same time.
     14. There are 394 segments to measure in zone 1. Similar to the approach in zone 5, start with the first corner wire that’s long enough to measure: this would be the approximately 5 cm length wire coming from the eighth solder pad of the headmost right side board. Focus the laser on the approximate center of this wire, then (as you did after the first measurement in zone 5) move the optical assembly diagonally away from the corner, using a combined 4mm x-axis and 2.875mm y-axis motion, to focus the center of each of the next 80 or so wire segments in turn. At that point, you can resume use of a solely y-axis step to access the remaining segments to the left. On completion, remove the three comb capos and the head capo (leave the two M4 studs in place until you lift the head capo away from the head boards), then replace the 20 original blue-dyed M4x25 BHSCSs in the head board hold-down holes and retorque them with the torque wrench and 2.5mm hex bit to 200 N-cm (18 lb-in).
     15. Having measured tensions on 1141 U wire segments, you’re halfway done with the U layer. Stow the winding arm beyond the APA, rotate the APA in the winder, and then repeat the capo installations and tension measurements in the four measurement zones on the opposite side.
  2. **G Layer**
     1. All G wires (as with the similar X layer) should be measured in zone 5, which requires application of only a single set of five X/G capos, across the headward side of the G combs on the footmost comb base.
     2. Adjust the X-axis position to bring the optical assembly about 30 cm (12”) away the foot boards, making it easy to count wires from a foot board edge to check the wire number being measured.
     3. G wires are numbered 1 to 481 from left to right across on each side of the APA, 48 wires on each head board except the first (leftmost), which has 49; similarly, the foot boards each have 48 wires save for the one at the HSB corner, which has 49. Reduce the Z axis setting to within a couple centimeters of the wires and adjust the Y axis to focus on wire #1 at the left edge of the APA. Home in on this wire with the Z and V axis controls to maximize the signal level shown on the oscilloscope. Gently pluck the first wire; you should hear the sound of its amplified vibration coming out of the speaker, and the Pano Tuner app should display the frequency of the note produced. Step the optical assembly in 4.792mm increments across the G layer to measure all wires. (As the X/G capos may all have been made from X combs, be aware that capo coverage may end with one wire yet to measure, which will require shifting a capo to cover the extra wire.)
     4. The G layer tension spreadsheet has the side A wire numbers 1 through 481 in column A, running down the left side of the spreadsheet. The corresponding head and foot board pad numbers for each wire are in adjacent columns. Record frequencies of side A’s wires in one of the columns labeled “Measured F, side A”. When you’re measuring side B’s wires, the wire numbers and corresponding head & foot board numbers for that side start on the spreadsheet’s column Q, with measurement columns beginning at column V.
     5. When you complete the tension measurement on one APA side’s wires, remove the capos you placed in 9.4.1, dock the winder arm behind the APA head, rotate the APA in the winder, and repeat zone 5 capo installation and tension measurement on the opposite side.
     6. Once all measurements on a specific layer (X, V, U, G) have been gathered, a chart will be created within the spreadsheet to visually demonstrate the tension results. Engineering will review the resultant Tension Chart and decisions made as to how many wires will neeed to be re-adjusted manually. If a subset of wires are re-tensioned, any wires that are adjusted will then be re-measured and a final Tension Chart will be posted for the results of this specific APA wire layer.