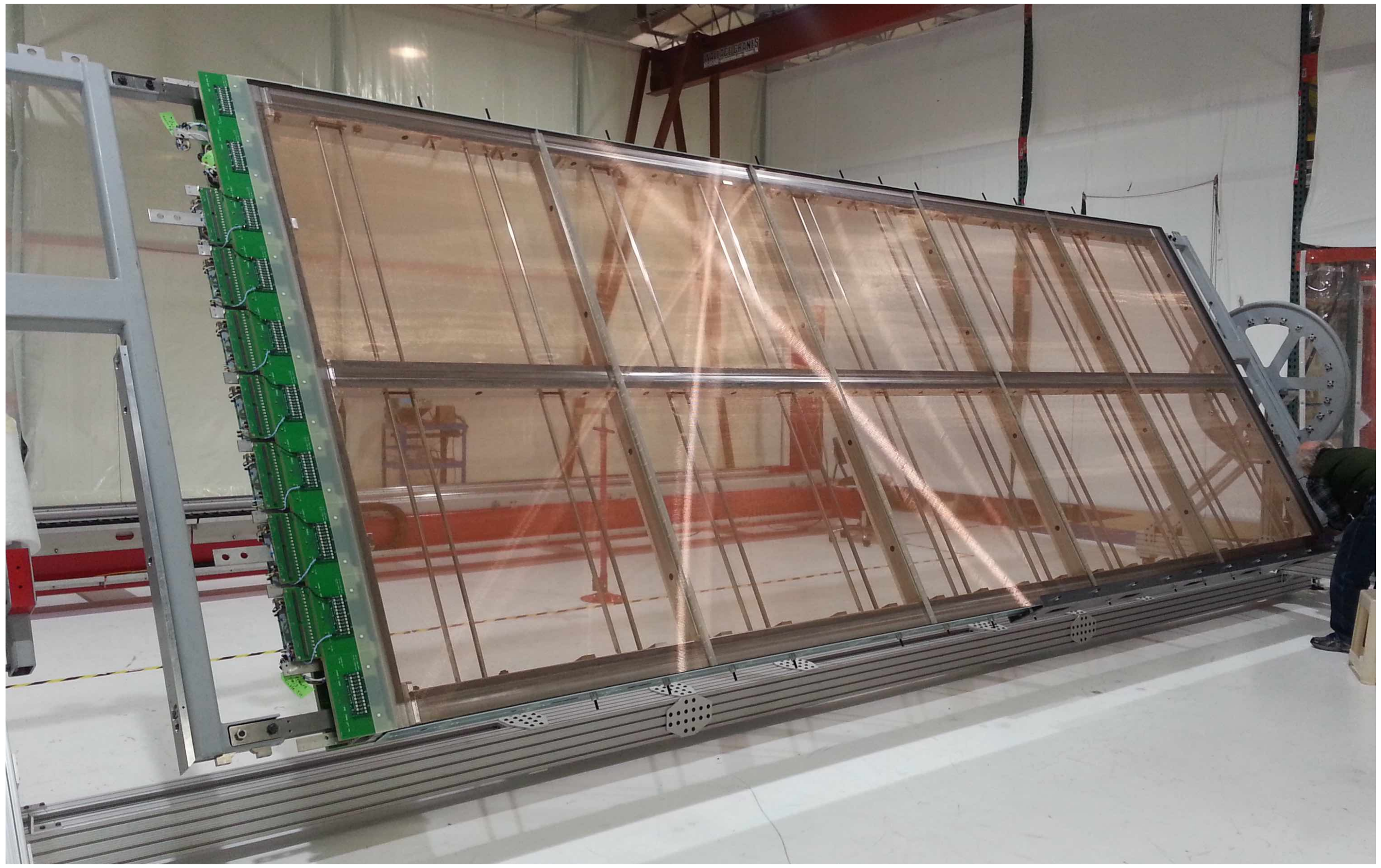


Quality Assurance and Quality Control protocols for DUNE APAs

Roxanne Guenette (for the APA team)
Harvard University

APA Review 27 March 2019

APA key requirements

- Number of working channels > 99% (continuity, isolation, tension)
- Wire pitch (frame flatness, tension) ± 0.5 mm
- Plane spacing (frame flatness, tension) ± 0.5 mm

Label	Name	Specification (Goal)	Rationale	Validation
SP-FD-9	APA wire spacing	4.669 mm for U,V; 4.790 mm for X,G	Enables 100% efficient MIP detection, 1.5 cm yz vertex resolution.	Simulation
SP-FD-10	APA wire position tolerance	± 0.5 mm	Interplane electron transparency; dE/dx, range, and MCS calibration.	ProtoDUNE and simulation
SP-APA-5	Frame planarity (twist limit)	<5 mm	APA transparency. Ensures wire plane spacing change of <0.5 mm.	ProtoDUNE-SP
SP-APA-6	Missing/ unreadable channels	<1%, with a goal of <0.5%	Reconstruction efficiency	ProtoDUNE-SP

from TDR

Outline

- **Quality Assurance**:

  Detailed description of what we have learned from protoDUNE, as this gives us confidence (QA) for DUNE

- **Quality Control**:

  Detailed description of the protocols for DUNE and what we are planning to improve before production

  Still trying to understand some tolerances in order to have strong justifications to reject an APA

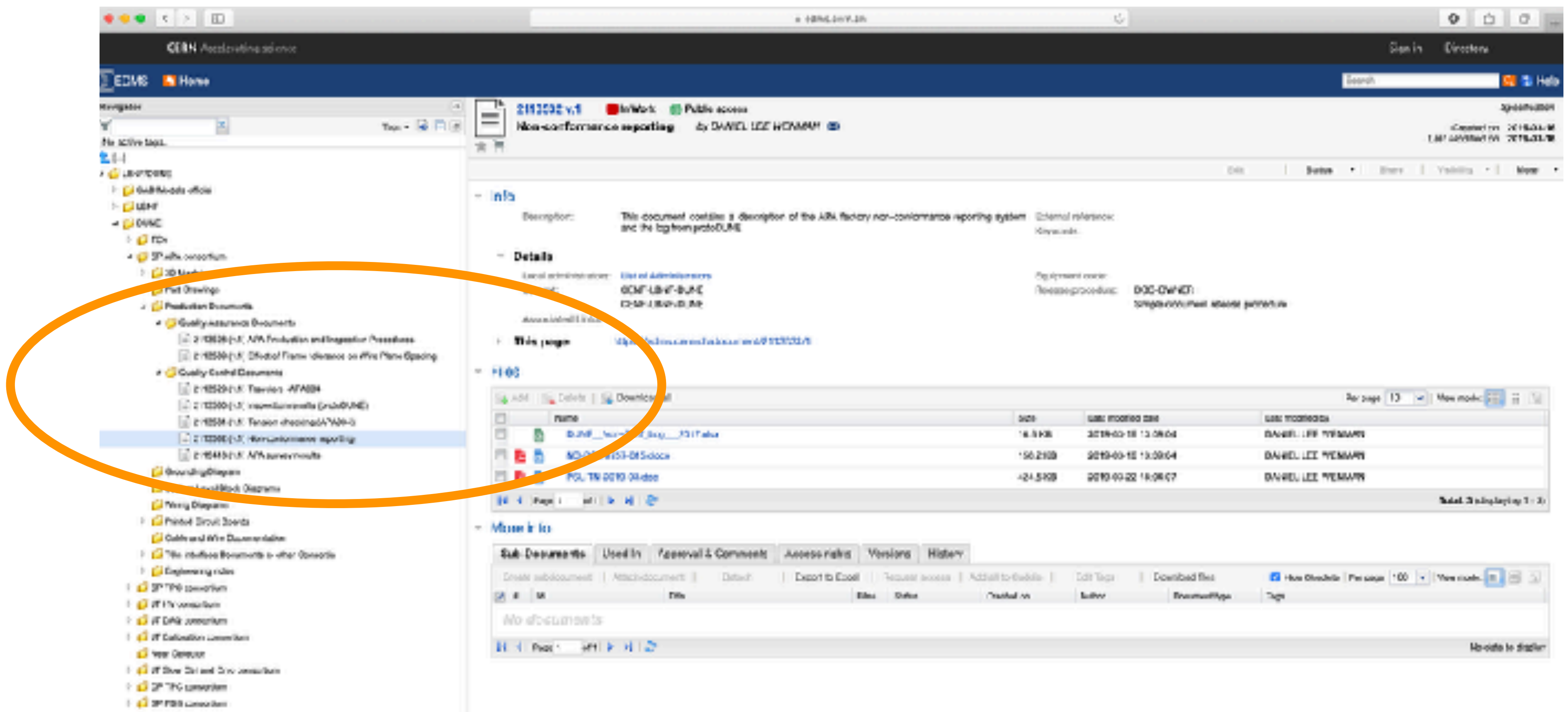
Quality Assurance

- Long history of wire plane construction (MicroBooNE, 35t, **protoDUNE**, SBND)
- Two Production Sites (PSL and Daresbury) have extensive experience with APA construction from protoDUNE (6+1 APAs)
- Robust construction process developed and tested

- Plans to construct 3 more APAs to test any modifications:
  - ➡ Larger size frames
  - ➡ New wire geometry boards
  - ➡ Final tuning of wire-winding machines

Quality Assurance (protoDUNE)

- Extensive information and documentation available from protoDUNE APA construction



- Results presented here are based on the 6 constructed APAs and on the tests at CERN during integration

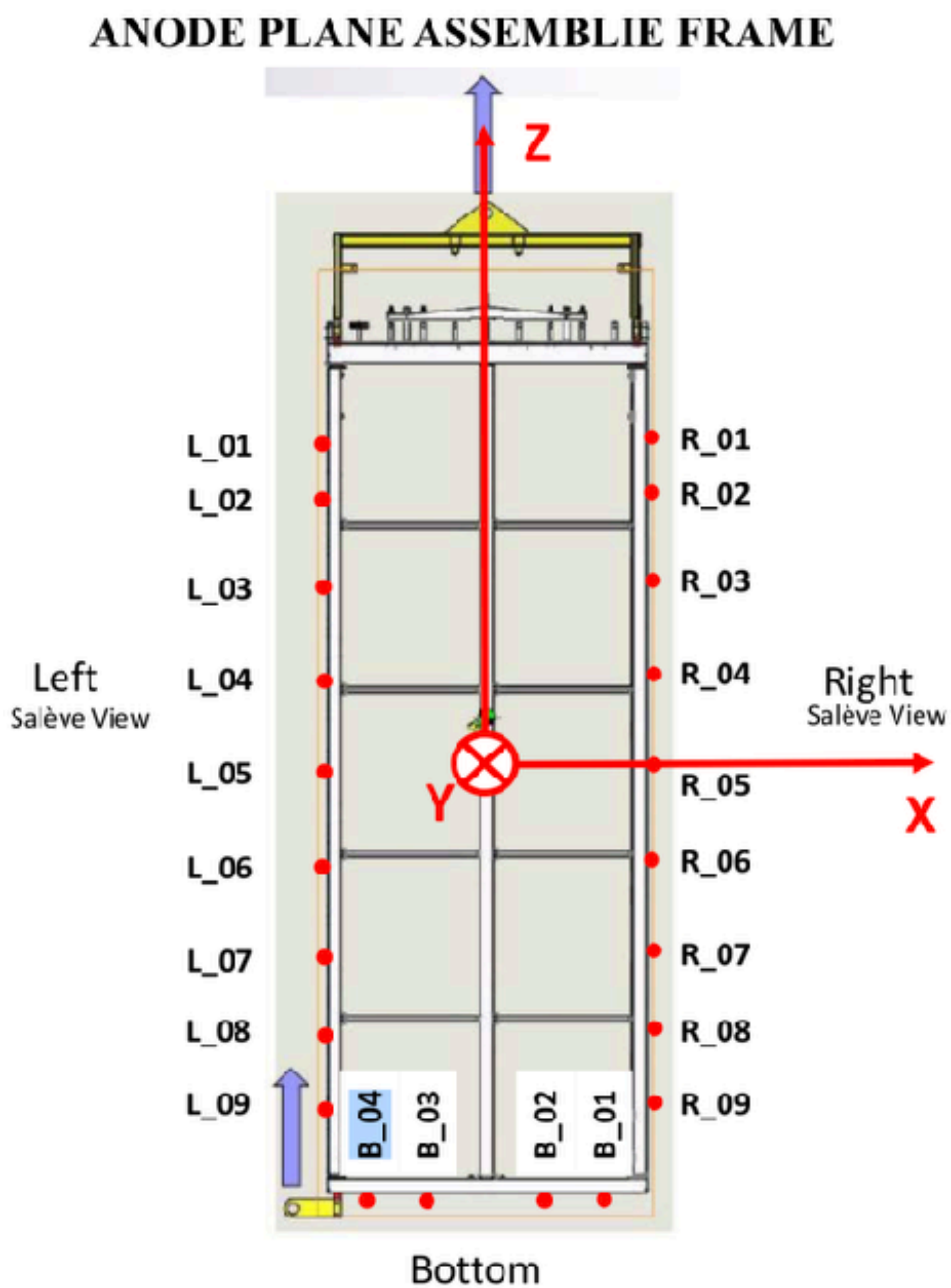
Number of disconnected channels

Total Channels	U-plane dead	V-plane dead	X-plane dead	Rate
15,360	17	13	12	0.27%

Channels / APA	APA 1	APA 2	APA 3	APA 4	APA 5	APA 6
2,560	11	6	8	3	4	10

All well below 1%!
Below 0.5%

APA Frame Flatness



APA flatness

APA flatness data from survey of rivnuts on the perimeter of the APA

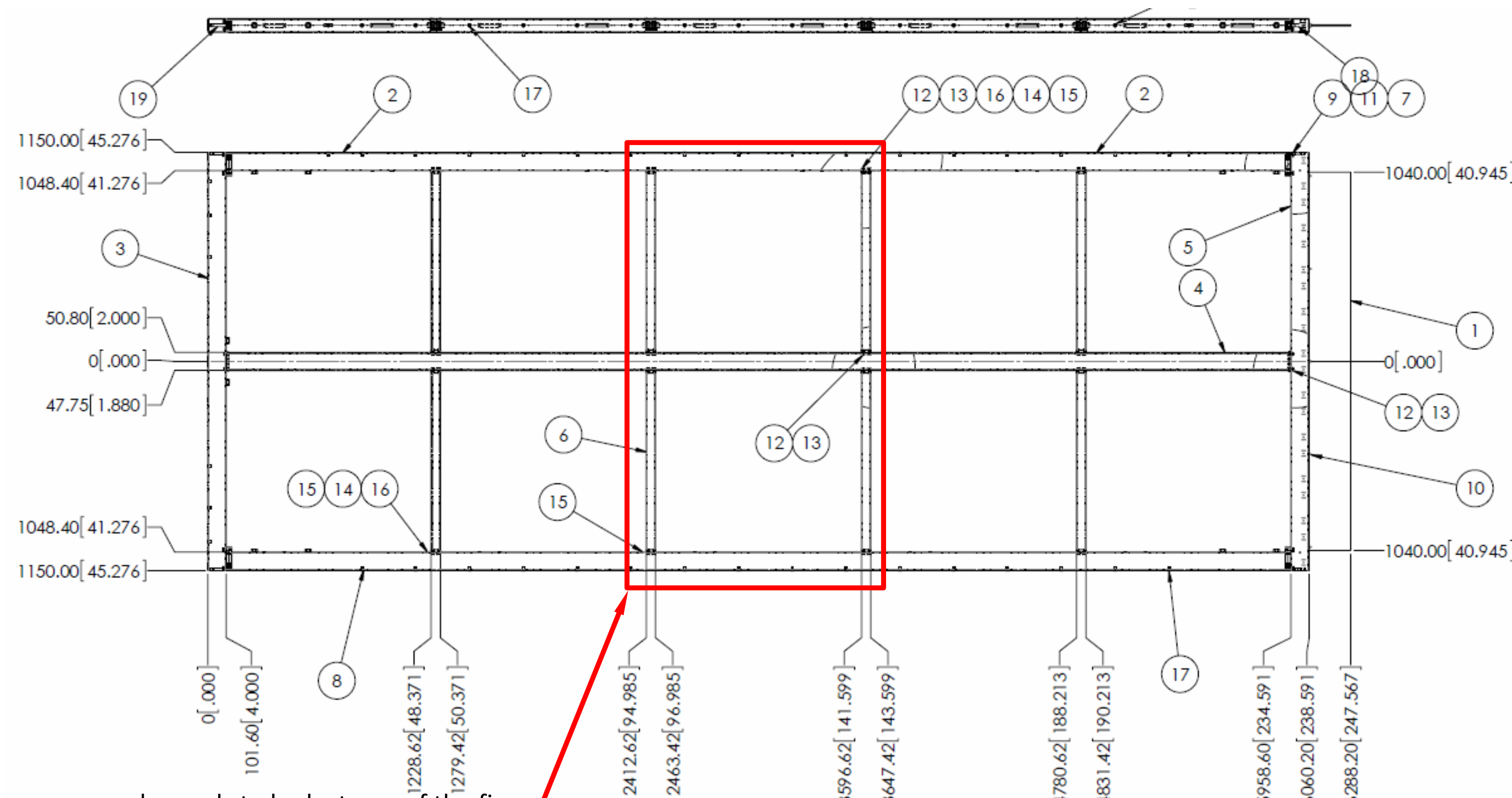
APA	Factory	CERN
USAPA1	1.5	1.2
USAPA2	3.0	1.9
UKAPA1	no data	+1.6/-2.5
USAPA3	1.7	no data
UKAPA2	no data	no data
USAPA4	1.5	no data

Data is maximum distance from "fitted" plane in mm

Below 5mm requirement

Frame Flatness (and wire plane spacing)

- Wire plane spacing is very important to ensure transparency of the different layers. A tolerance on the wire plane spacing of ± 0.5mm is required.
- Detailed mechanical studies of frame distortions have been performed for different bending modes (twist, bow, fold)

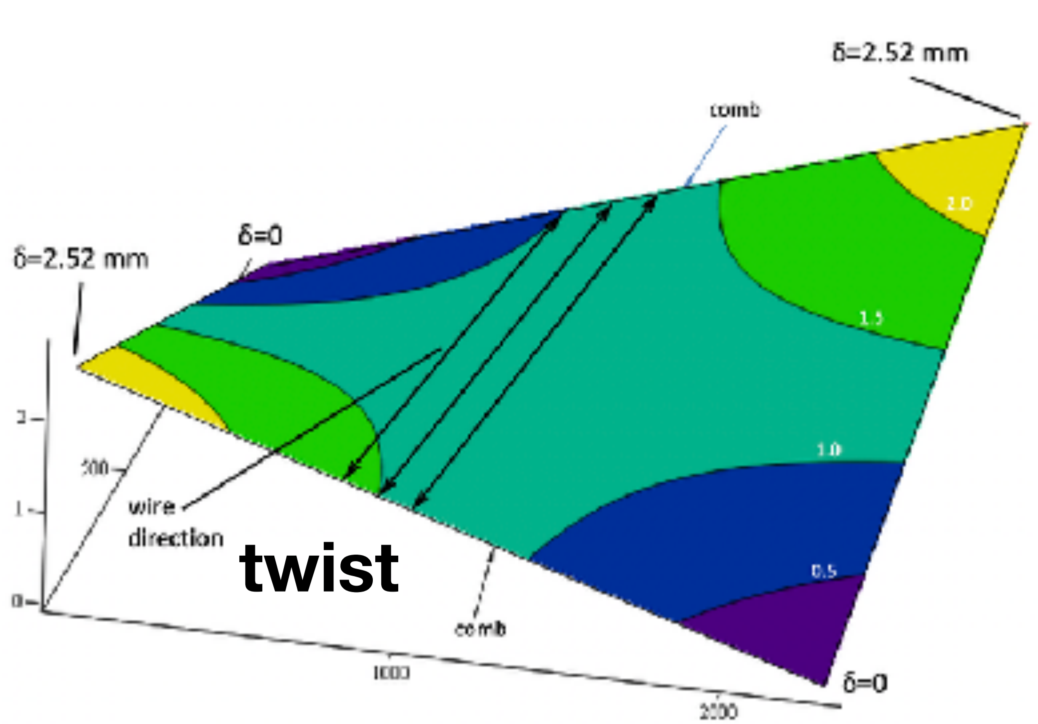


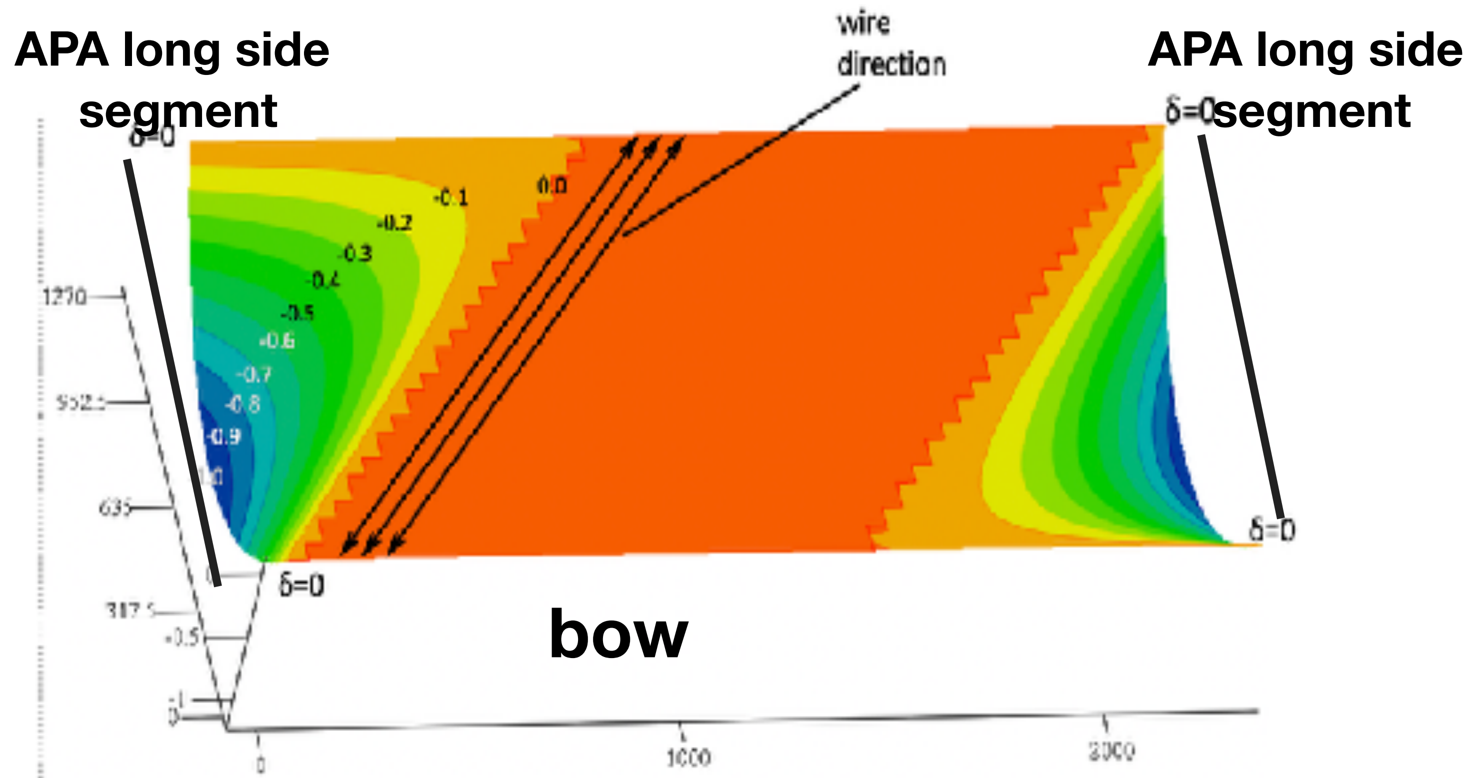
When considering a frame one only needs to look at one of the five "cells" of the frame.

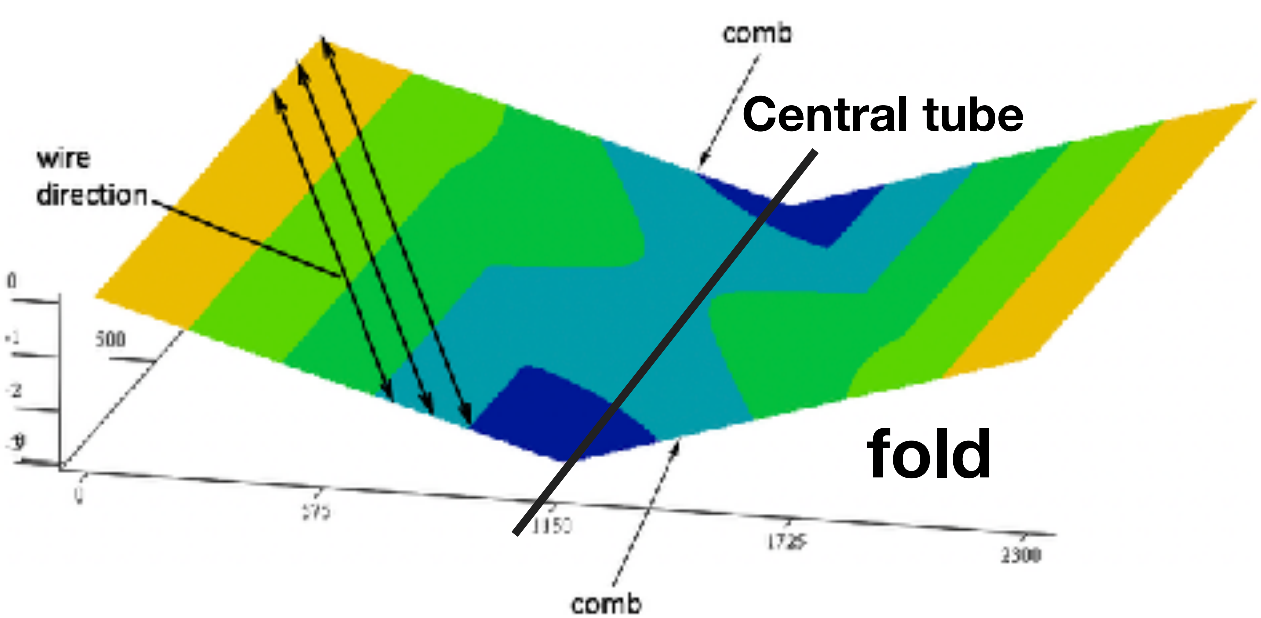
Each of these cells is separated from adjacent cells by combs that maintain correct wire spacing - so the wire movement in one cell is unaffected by movement in the others.

All cells are 2300mm across; the longest in the other direction is 1270mm.

Frame Flatness (and wire plane spacing)





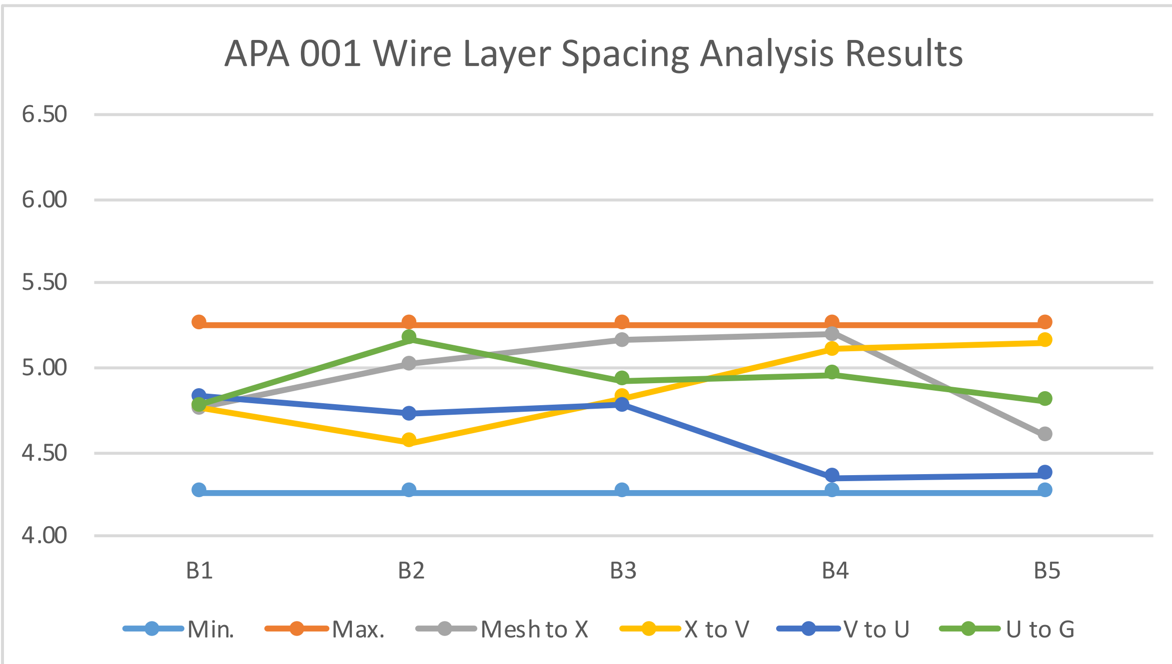


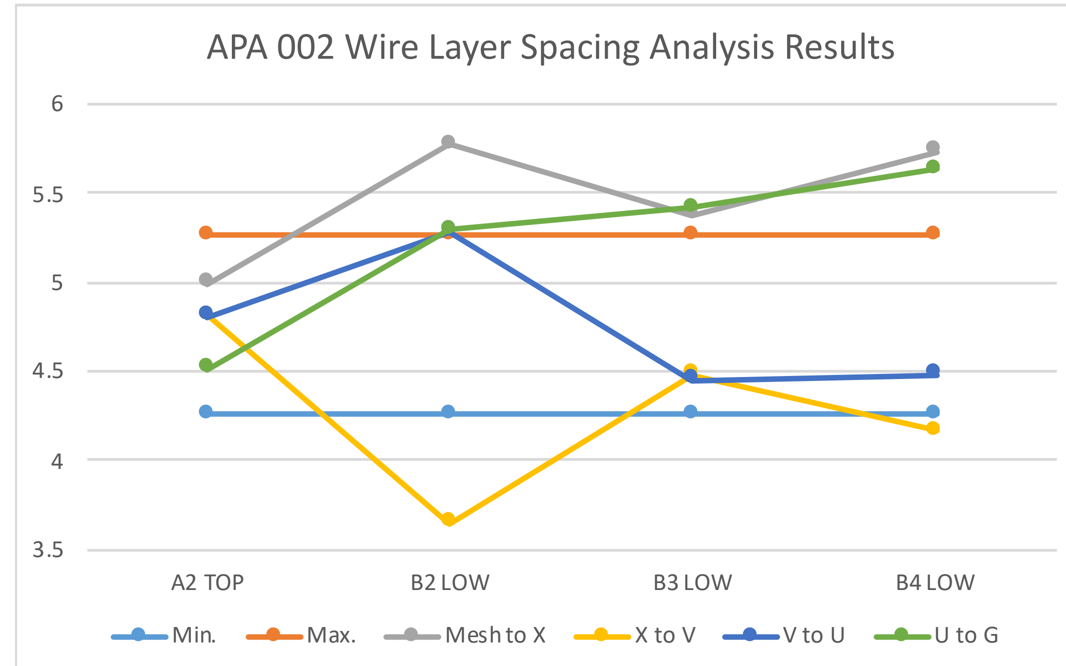
In summary, a **0.5 mm** change in wire plane spacing could come from:

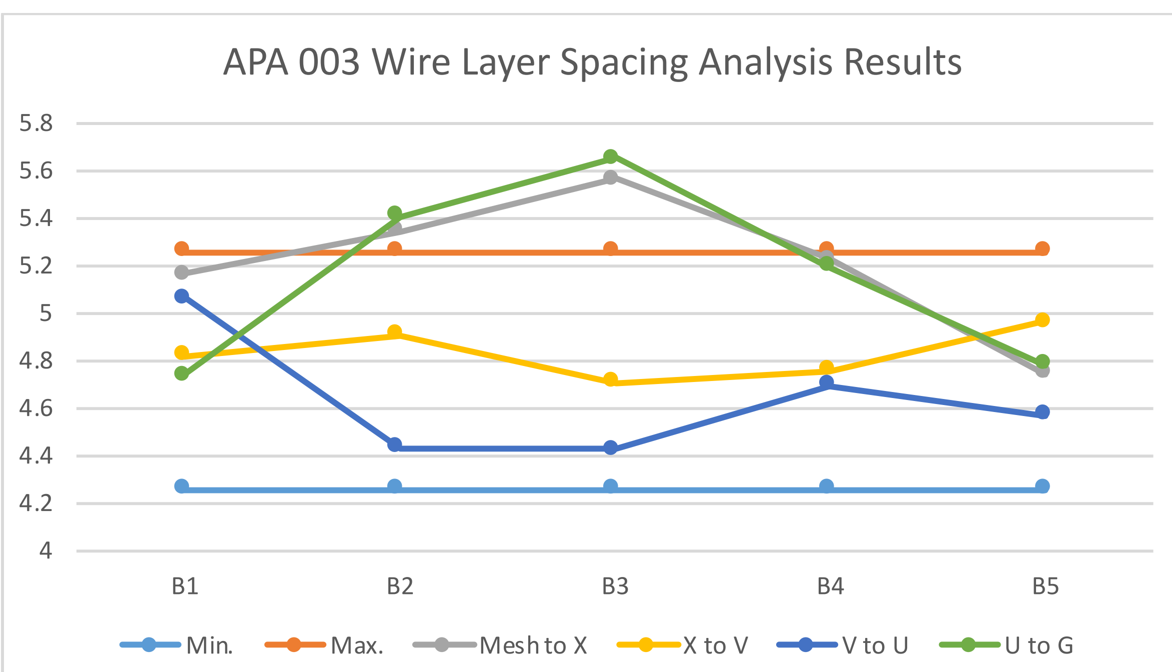
- 6mm overall out-of-flatness in the frame due to twist
- 11 mm out-of-flatness due to bow
- 1.2 mm out-of-flatness due to a “fold” down the center

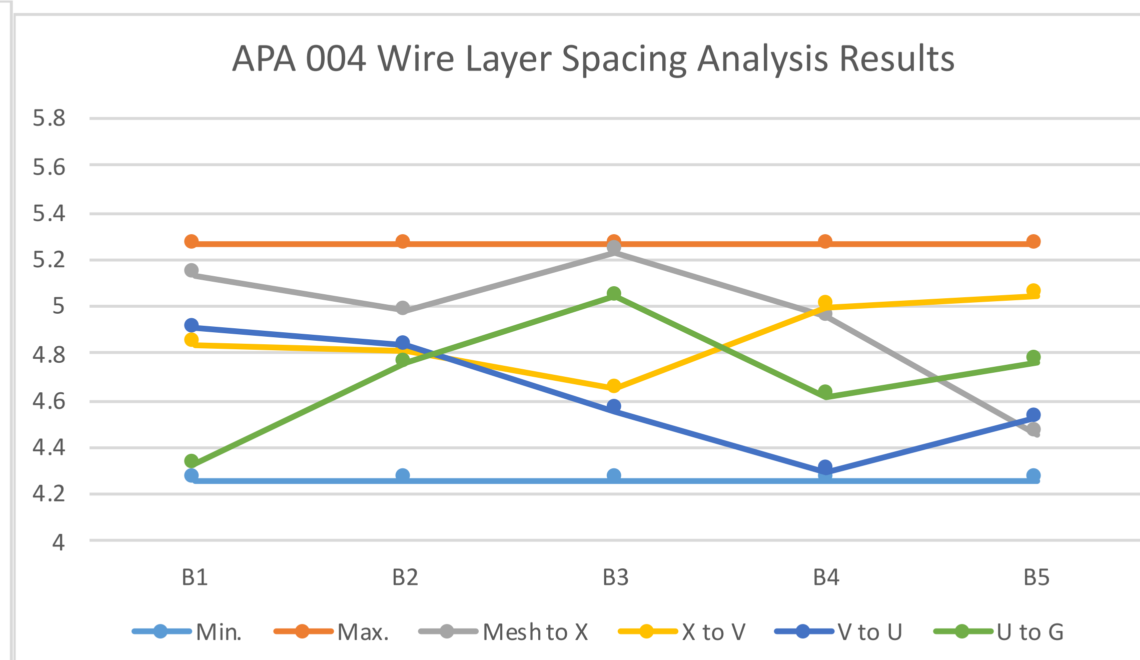
Actual plane spacing measurements (protoDUNE)

Plane spacing



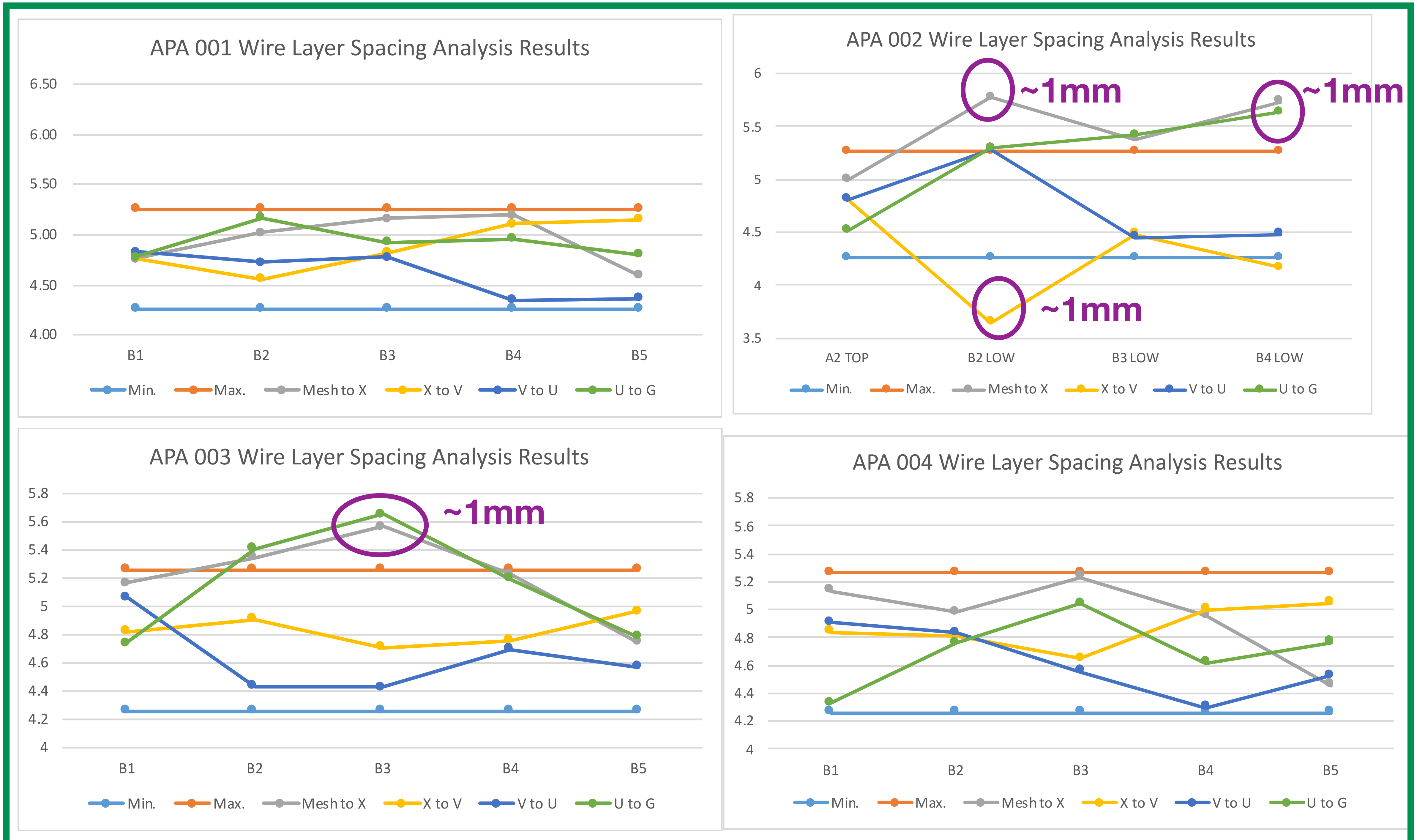






Actual plane spacing measurements (protoDUNE)

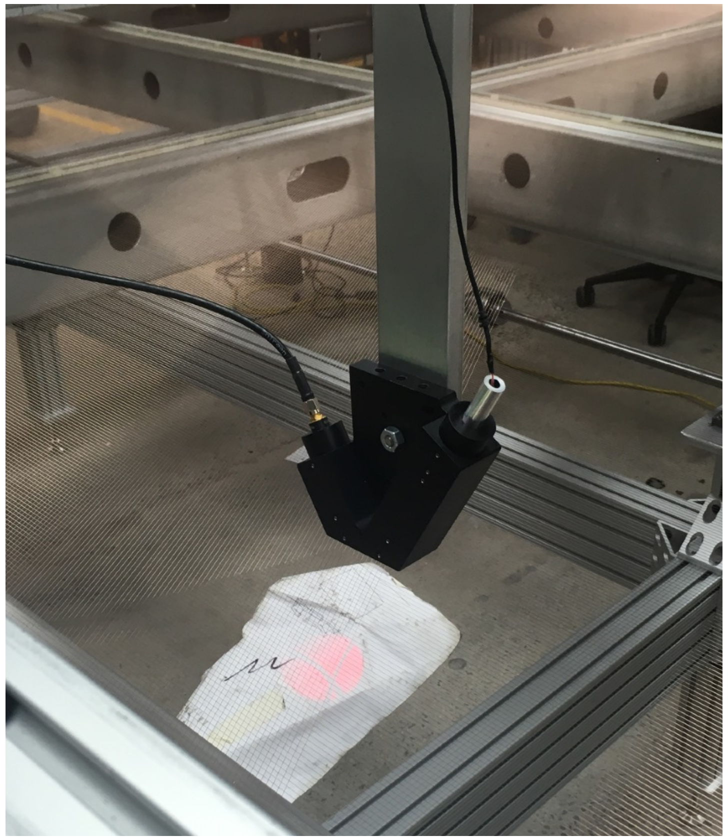
Plane spacing

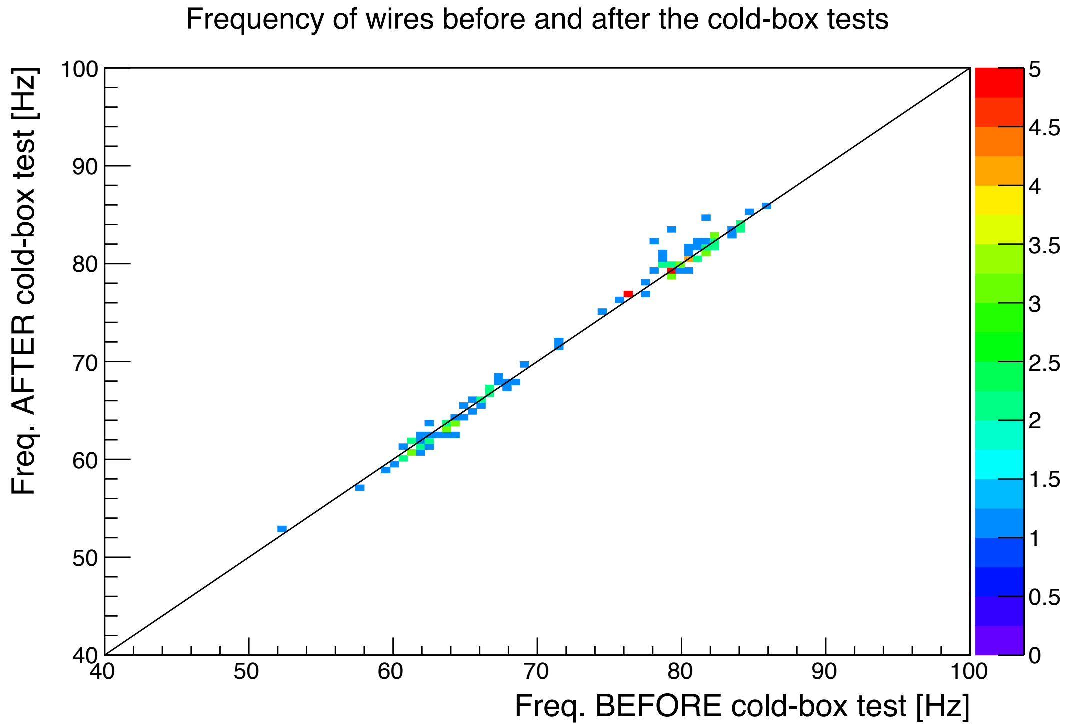


All points outside tolerances are between mesh or G plane. Exact tolerance for rejection currently under study (2D field simulations show that G-U tolerance may be relaxed a bit)
One exception (APA2 B2 low due to known issues with the combs pre-wiring. Solution has been implemented already to avoid it in the future.

Wire tension (protoDUNE)

- Wire tension measured with laser-diode system
- **All wires** were measured at Production Sites (horizontal APA)
- Requirement: 5 +/- 1 N
- ~10% of wires were measured for tension at CERN before integration (vertical APA)
- Small sample of wires were measured before and after a cold test

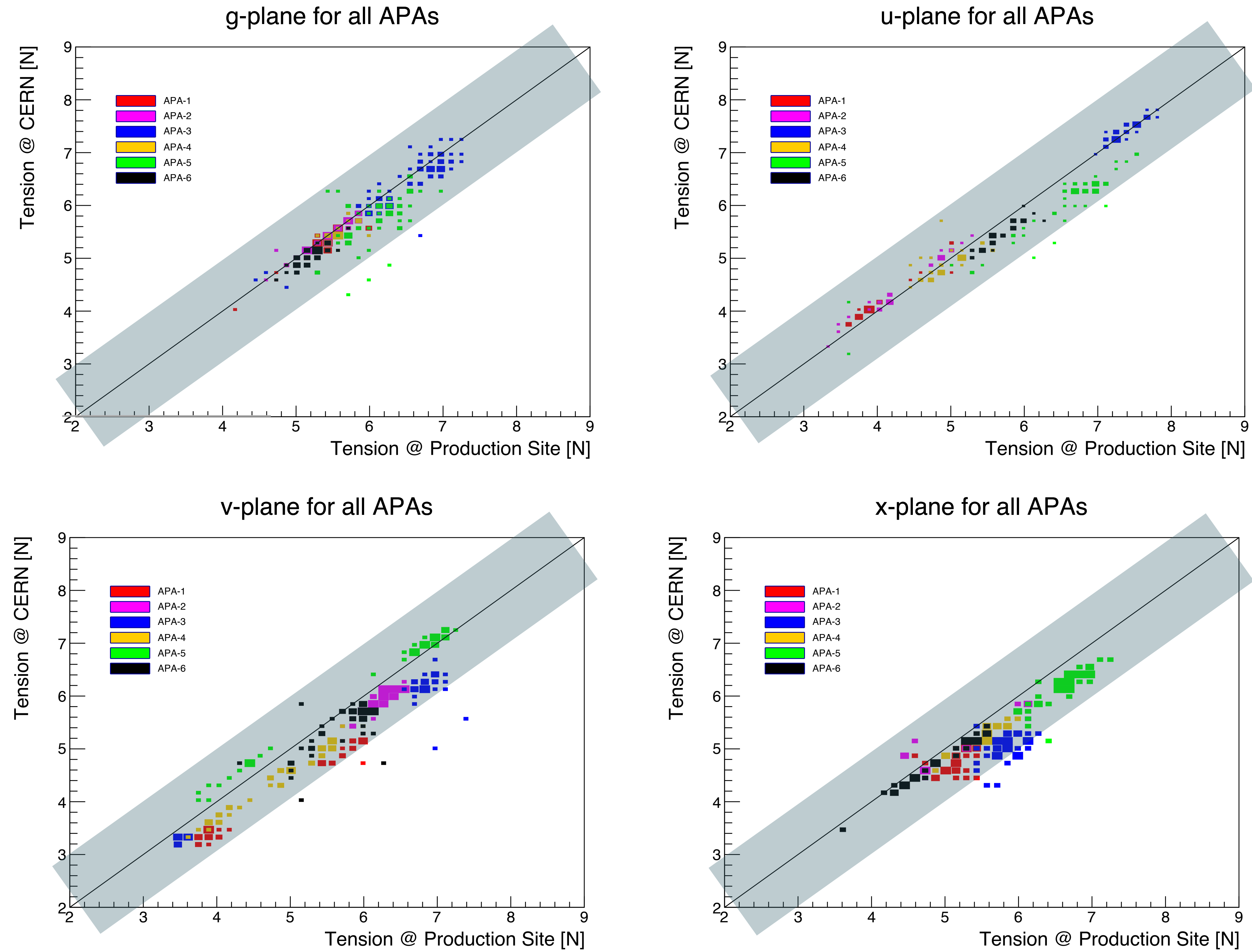




Only few % difference in Hz for handful of wires

Wire tension (protoDUNE)

Wire tension (on ~10% of wires)



± 1N

At production = Horizontal APA

At CERN = Vertical APA

Lessons learned from wire tension at protoDUNE

- Tension measurement is extremely time consuming and new method need to be developed if all wires will be measured (current plan with the laser method is only 10% of wires measured at ITF)

- A new winding head with a more precise control of the tension during Production will be highly beneficial

- Tension was increased from 5N to 6N to decrease the risk due to tension relaxation

- Tolerance of ±1 N may be too tight. This is currently under investigation with protoDUNE data

Quality Control procedures at Production Site

1. (bare) Frame flatness. Use precise survey measurements to assess the flatness. Bolted frames allow for some adjustments (+ shims)

2. Wire boards are inspected, measured and tested (see Andrew's talk)

3. Wire winding:
   ➡New winding head will allow for better precision of tension
   ➡After each layer, visual inspection, full wire tension measurement of **all** wires and continuity/isolation tests (can re-tension at this stage)

4. Survey APA flatness and measure wire plane spacing after the completion of the wiring

5. **Fully functional (>99% channels) APA shipped with "traveller document"**

Note on Frame Flatness QC (and wire plane spacing)

- We have concrete tolerance values for each of the possible deformation (twist, bow, fold) to keep the wire plane spacing within 0.5mm
  - 6mm overall out-of-flatness in the frame due to twist
  - 11 mm out-of-flatness due to bow
  - 1.2 mm out-of-flatness due to a "fold" down the center
- Exact tolerance on multiple frame distortions is harder to quantify, but we know that they are not directly additive
- We also can measure directly the plane spacing post-construction
- If there are small deviation outside the tolerance, we still have a mitigation strategy to use higher bias voltage to ensure transparency. This will be studied in detail with dedicated protoDUNE data soon

Quality Control procedures at Integration location

1. Unpack the APA and visual inspection
2. Survey APA flatness and measure wire plane spacing
3. Measure wire tension and wire continuity/isolation to ensure > 99% channels
    - ➡ Current plan with laser method: 10% of wires have tension measurement
    - ➡ Alternative plan with electrical method: 100% of wires are measured (preferred and currently under investigation)
4. After integration with cold electronics and photon detectors, the APA is inserted in a cold box

Quality Control procedures post-integration

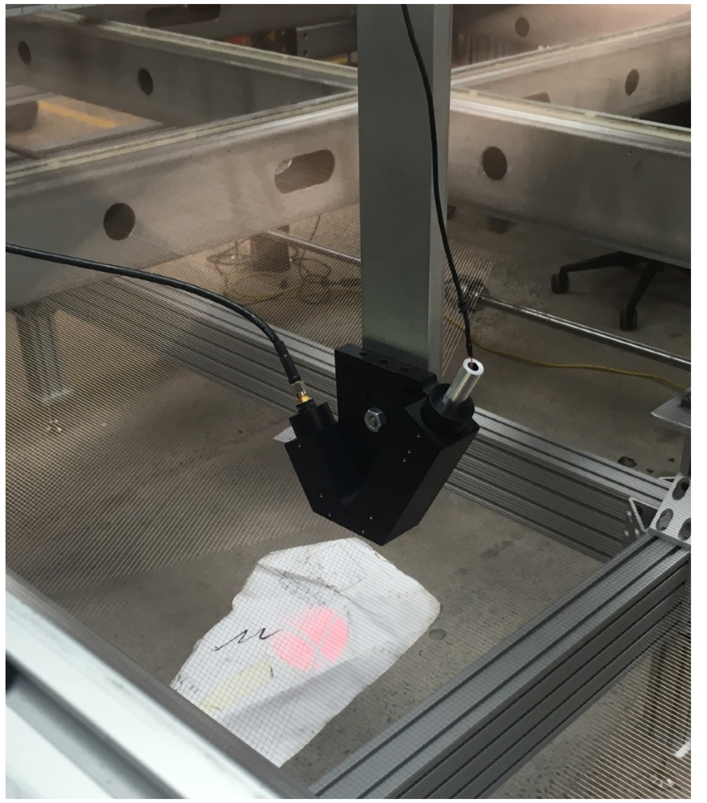
- Once the cold electronics and cables have been installed, we cannot really assess the quality of the wires alone anymore (e.g. cannot measure tension with the electrical method)

- Cold tests of the electronics inform the state of wires

- Noise measurement in cold could inform on wire tension. Studies are currently undergoing about using cold electronics output to correlate to tension. Nothing concrete yet, but since integration happens underground, re-measuring wire tension is less critical and may not be relevant.

Wire tension measurement methods

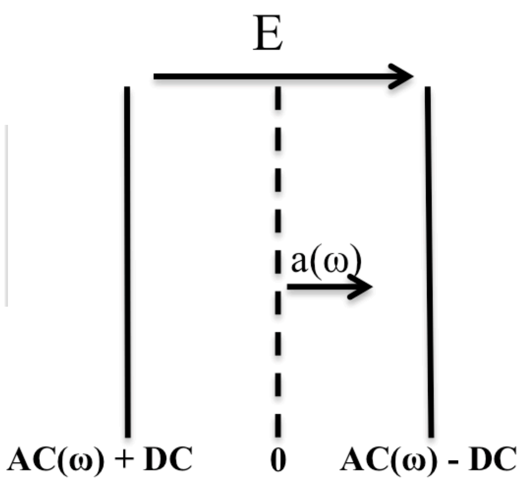
- Default: Laser method
  - ➡ Extremely tedious and time consuming (same as whole wiring time)
  - ➡ Schedule allows only ~10% of wires to be measured at ITF
- Alternative: Electrical method
  - ➡ Could significantly reduce measuring time (exact time under investigation)
  - ➡ Would allow for 100% of the wires to be measured at all sites
  - ➡ Potentially provide continuity and isolation tests for free (under investigation)



Details on the electrical method (proof of principle)

- Use DC + AC voltages on adjacent wires to induce motion in sensed wire (motion frequency ∝ tension)

$$T = 4\mu L^2 f_0^2$$



- Principle demonstrated by Manchester on 3mm wire pitch

- Voltages required for 5mm seemed high

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Volume 915, 21 January 2019, Pages 75-81

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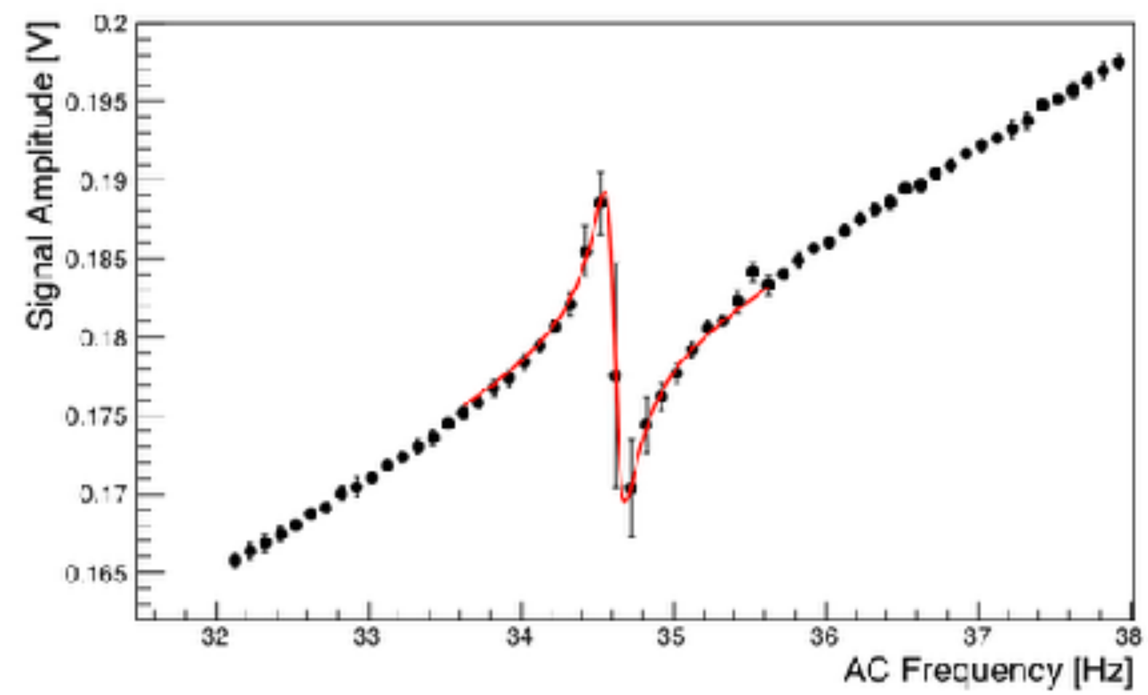
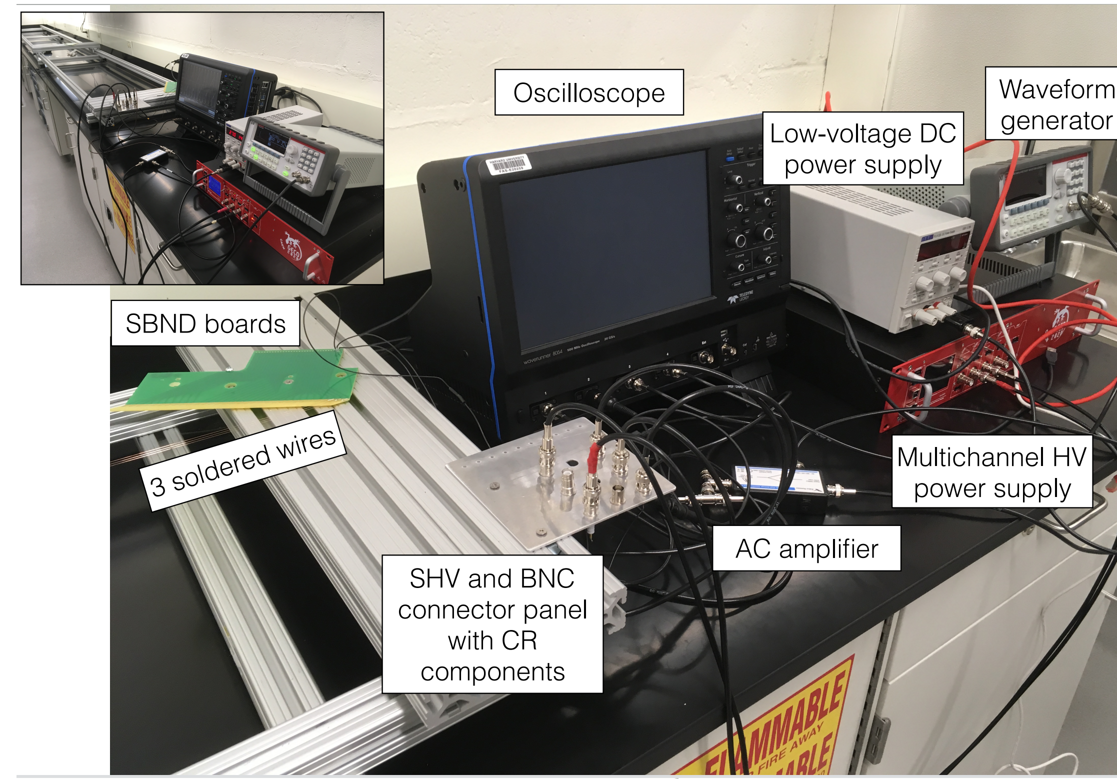
https://doi.org/10.1016/j.nima.2018.09.031

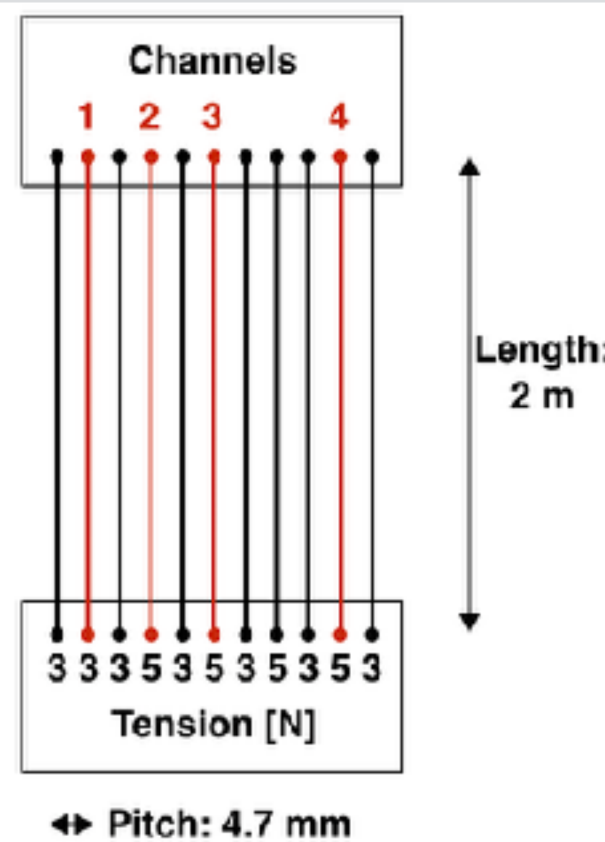


Plans and progress towards the electrical method

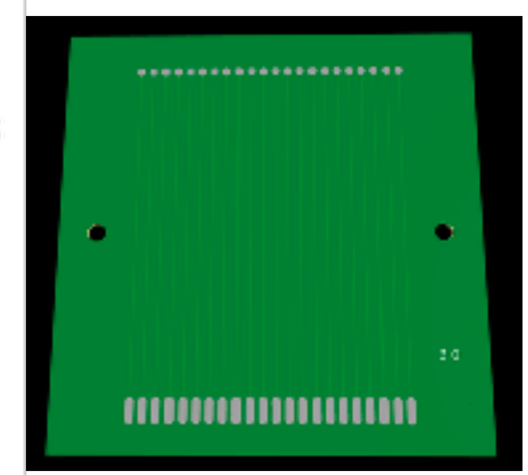
- Harvard team has been working on optimizing the method for DUNE

- Using test bench, results from Manchester were reproduced with 5mm pitch with DC of 200V and 400V





Home-made test-boards



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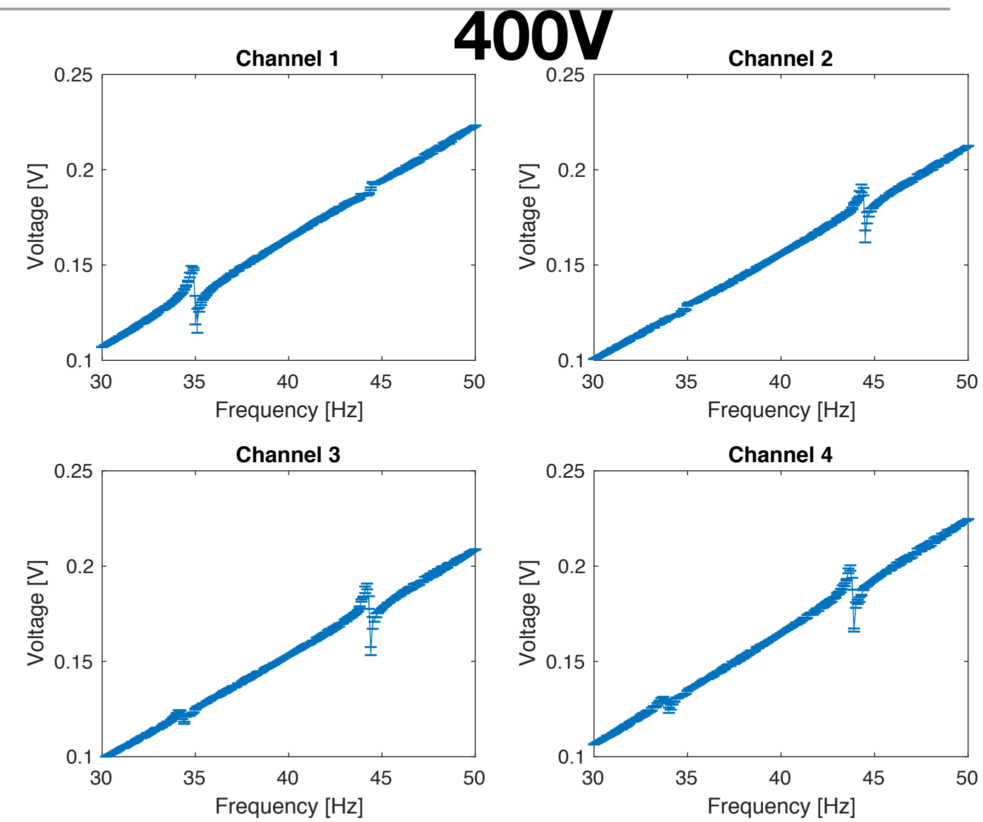
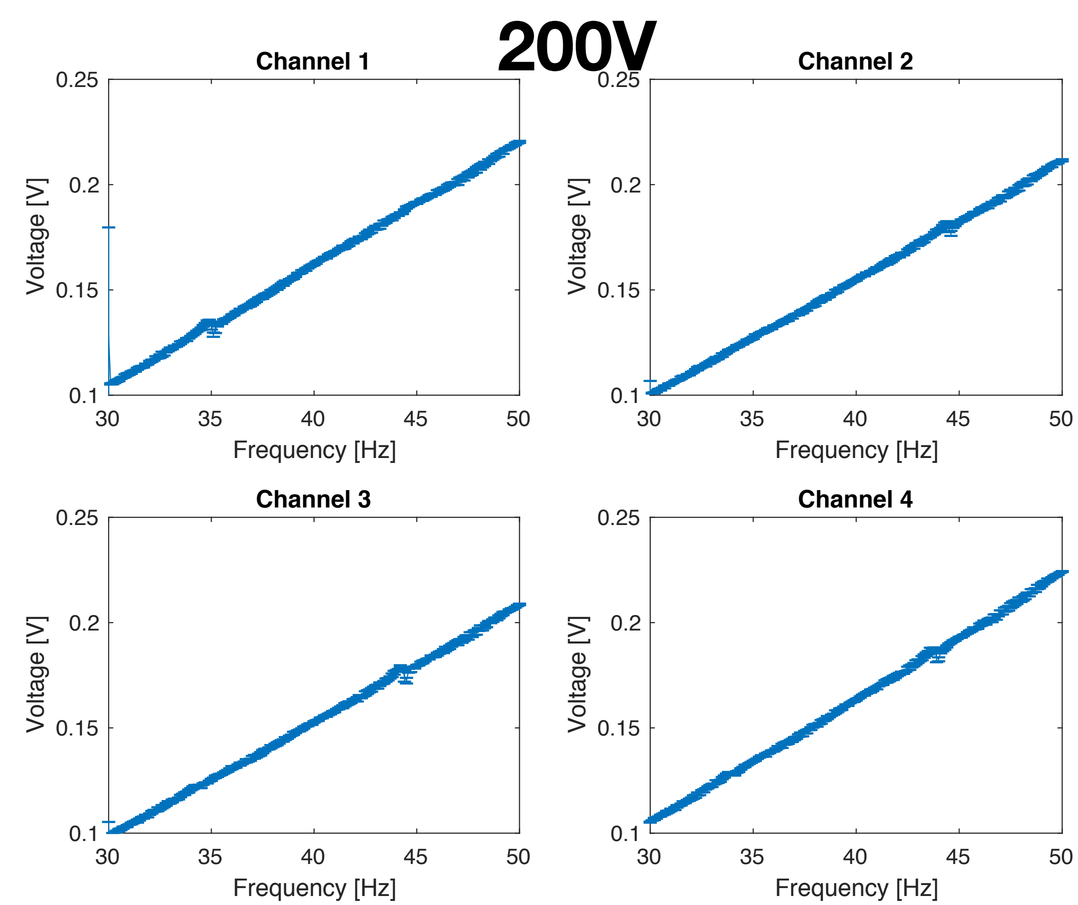
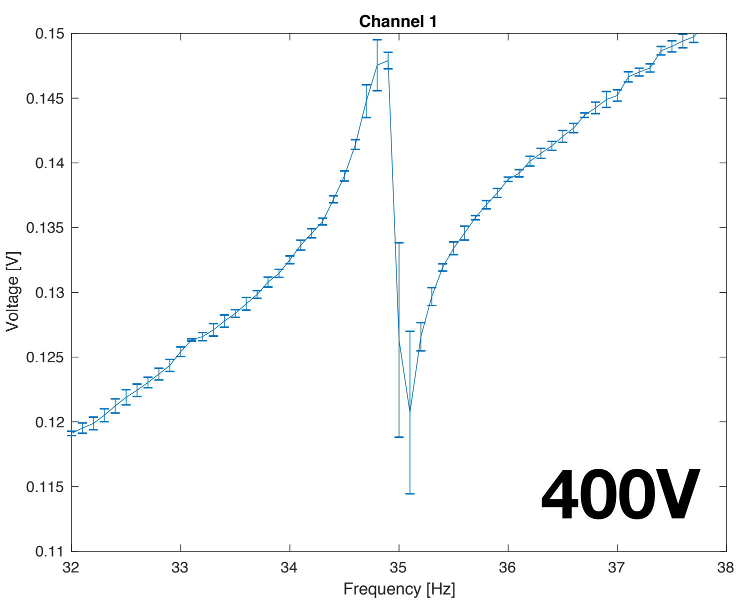
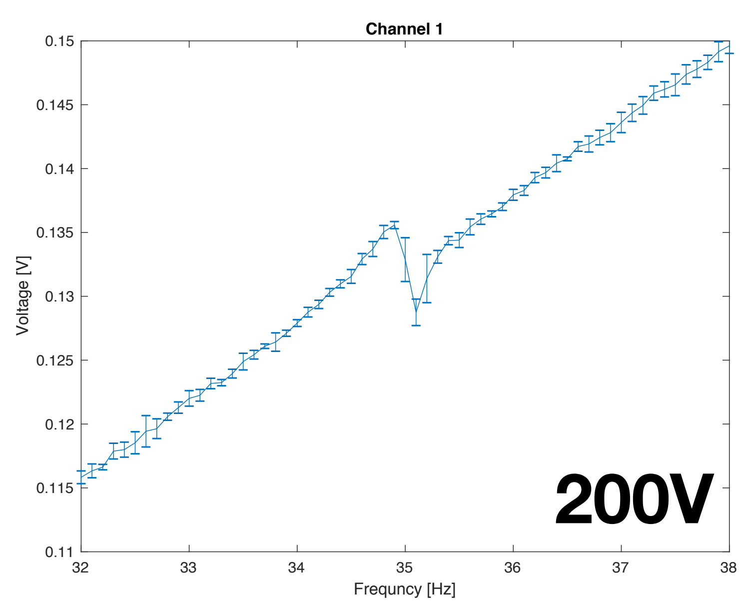


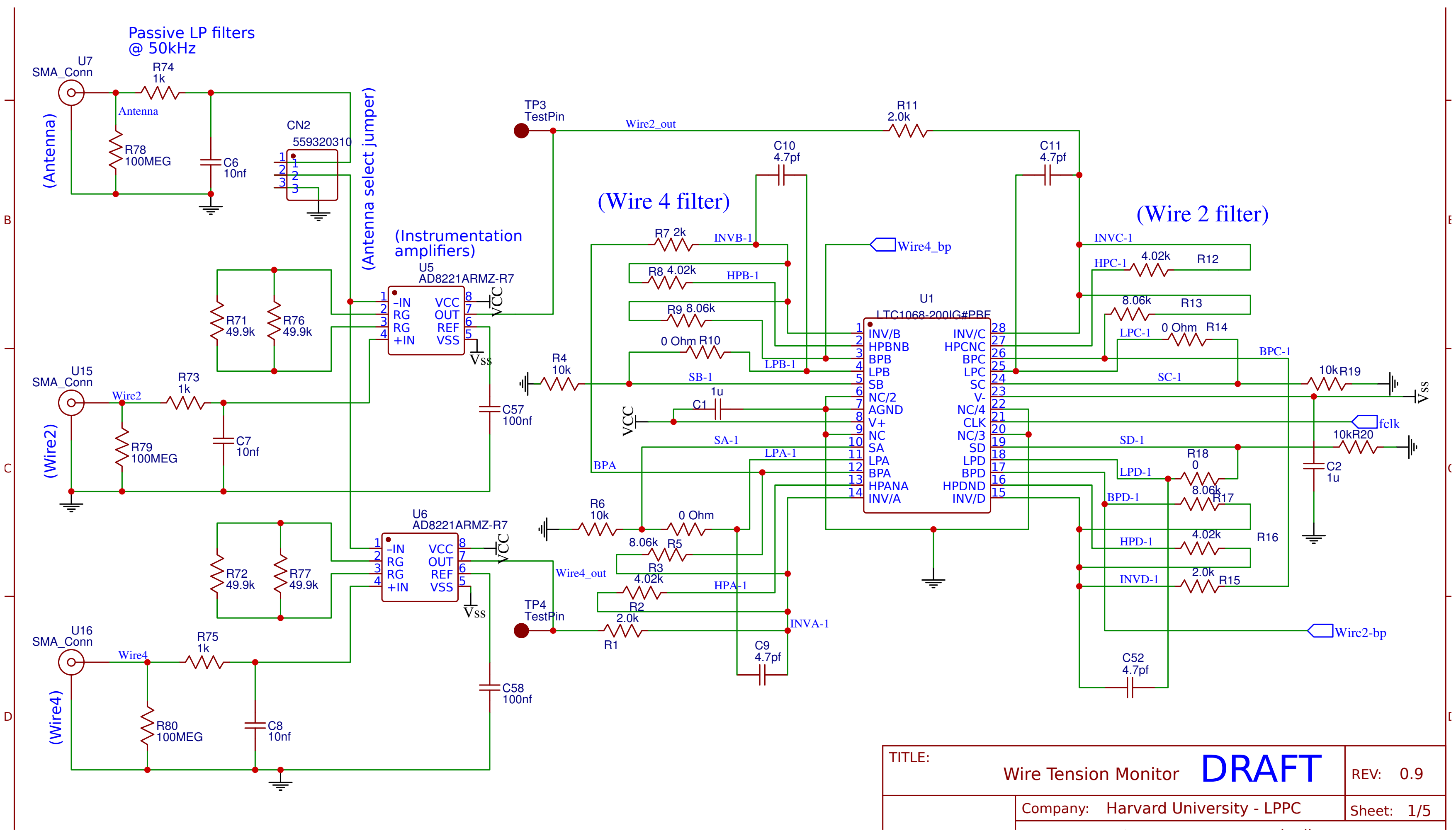






Plans and progress towards the electrical method

- Idea is to use an analog board mounted on FPGA to input known wave form and allowing to read out the same frequencies, to reduce the noise and speed up the frequency scan. Still under development.



- Mitigation: New wire board design allows for higher voltages (~400 V)

Summary

Quality assurance

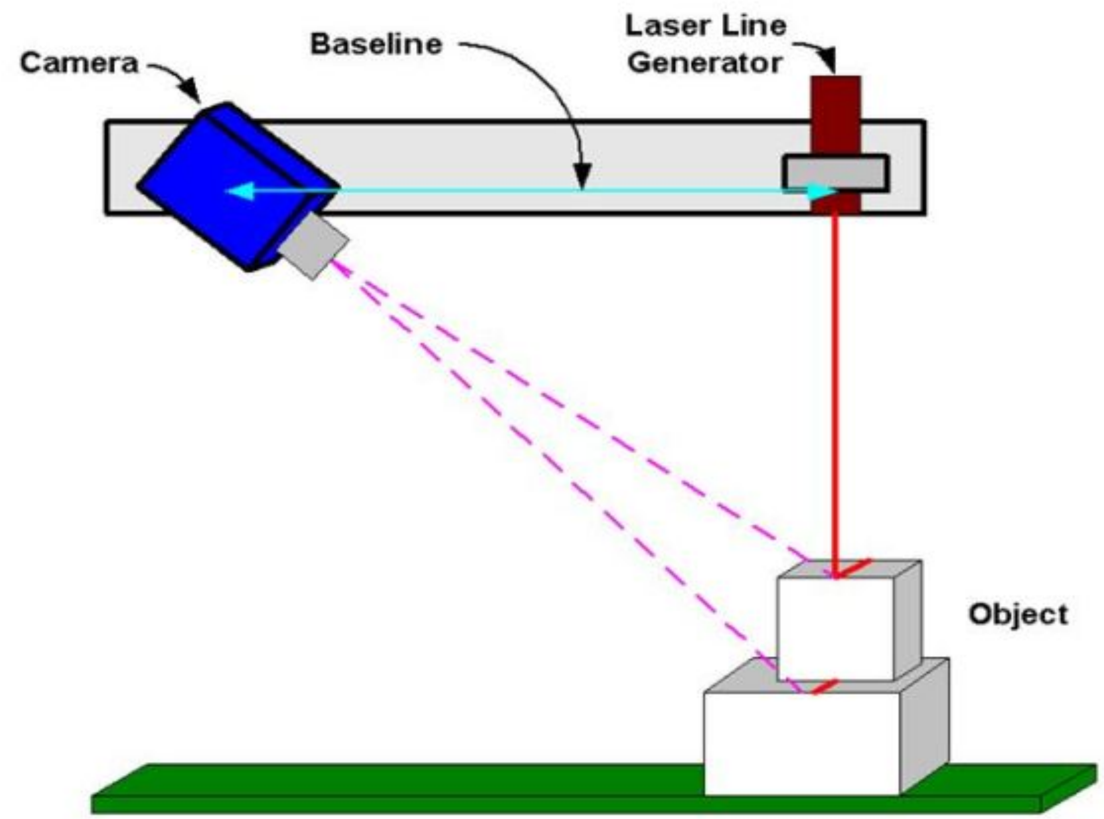
- QA has been developed over extensive experience with APA fabrication, especially during protoDUNE construction (7 APAs)
- Robust demonstration of the construction method
- Continued protoDUNE data analysis to ensure that APAs are fully functional and investigate any potential correlation to wires (e.g tension)
- 3 more APAs will be constructed before production starts to address any modifications or update from protoDUNE construction

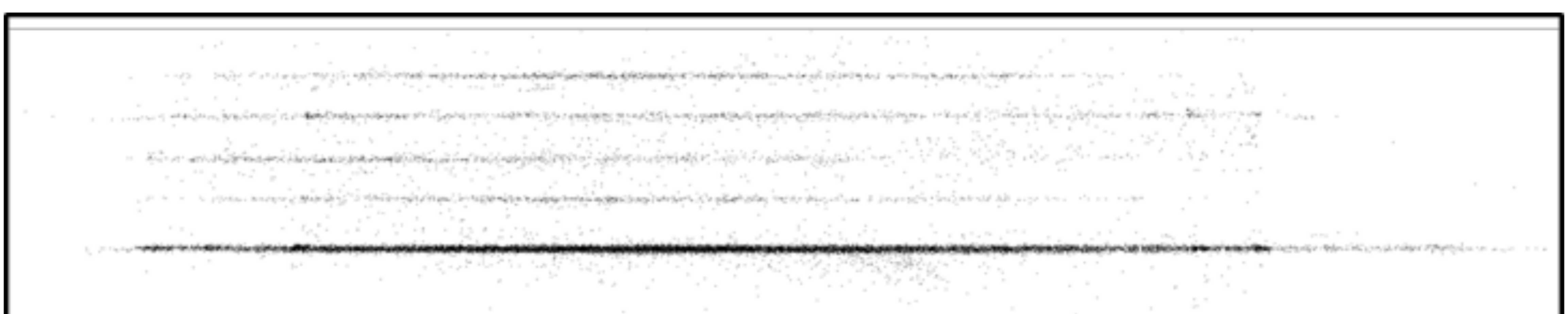
Quality Control

- Detailed QC protocols are in place
- ProtoDUNE data analysis will inform the exact tension tolerance (currently ±1N)
- Electrical tension method under development to increase our QC scope
- Mitigation strategies are also under investigation to allow robust decisions on APA acceptance

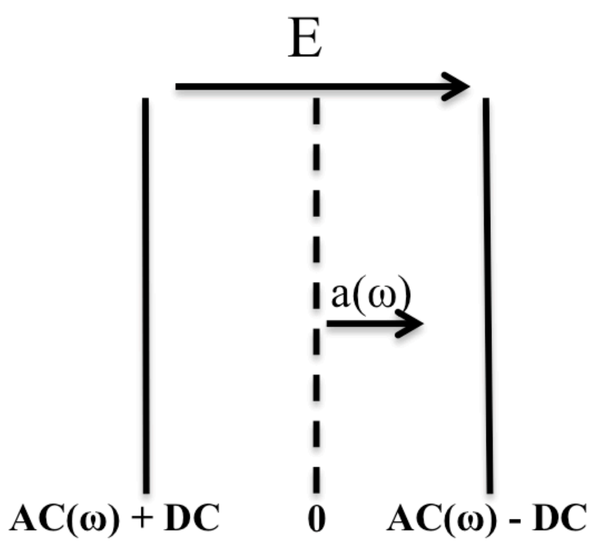
Backups

Plane spacing measurement





Electrical method



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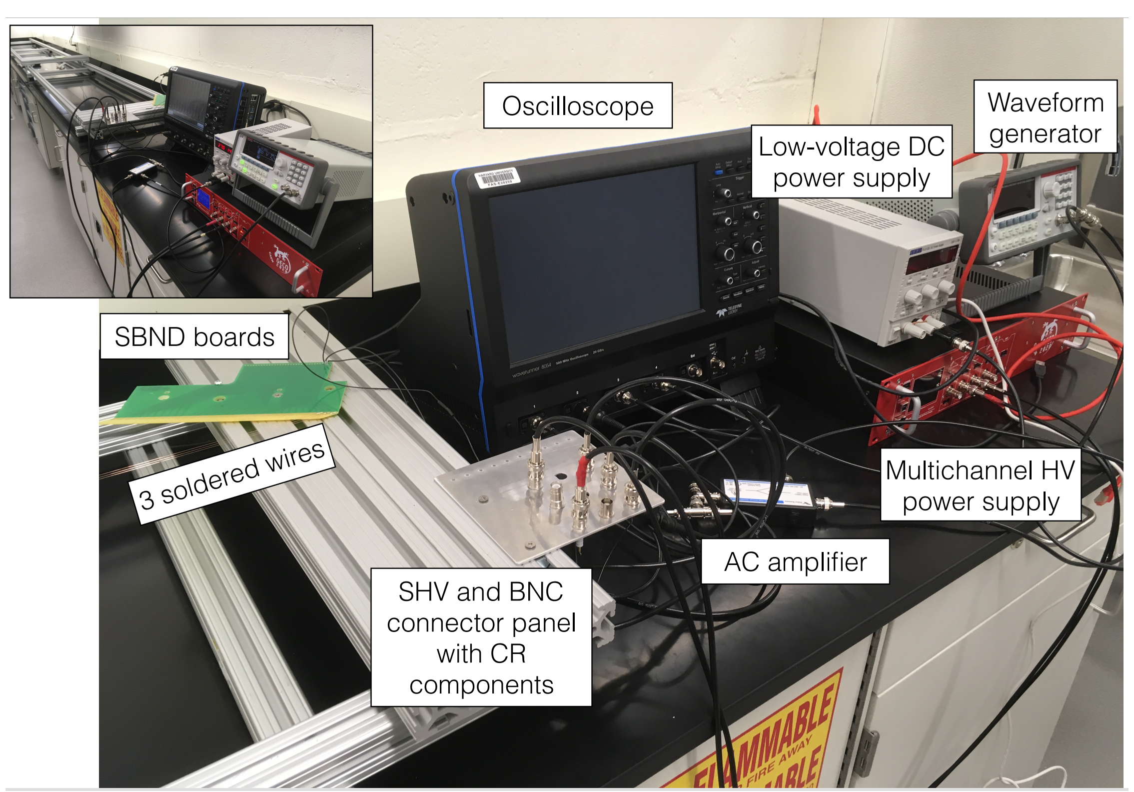
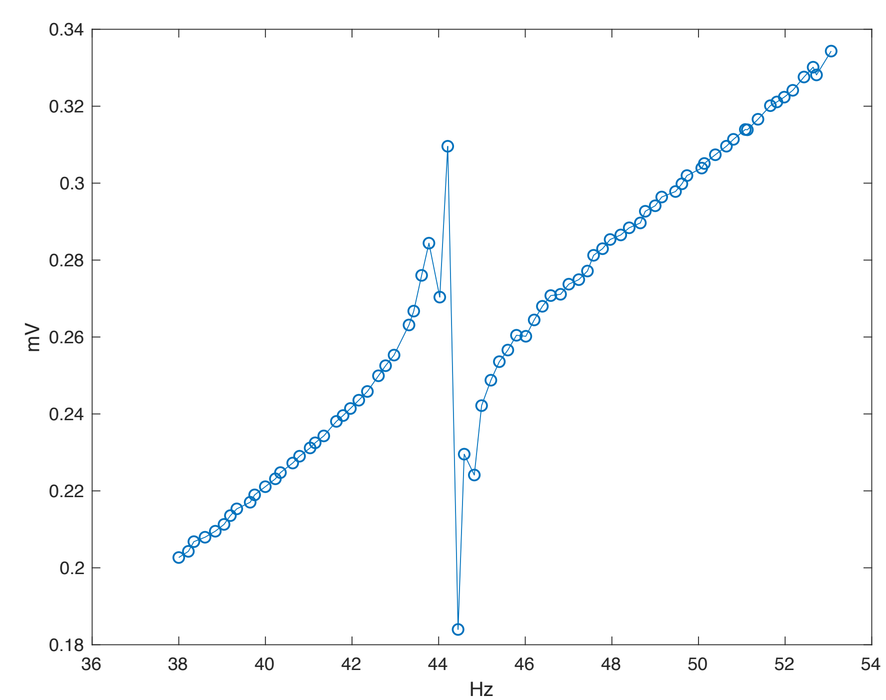
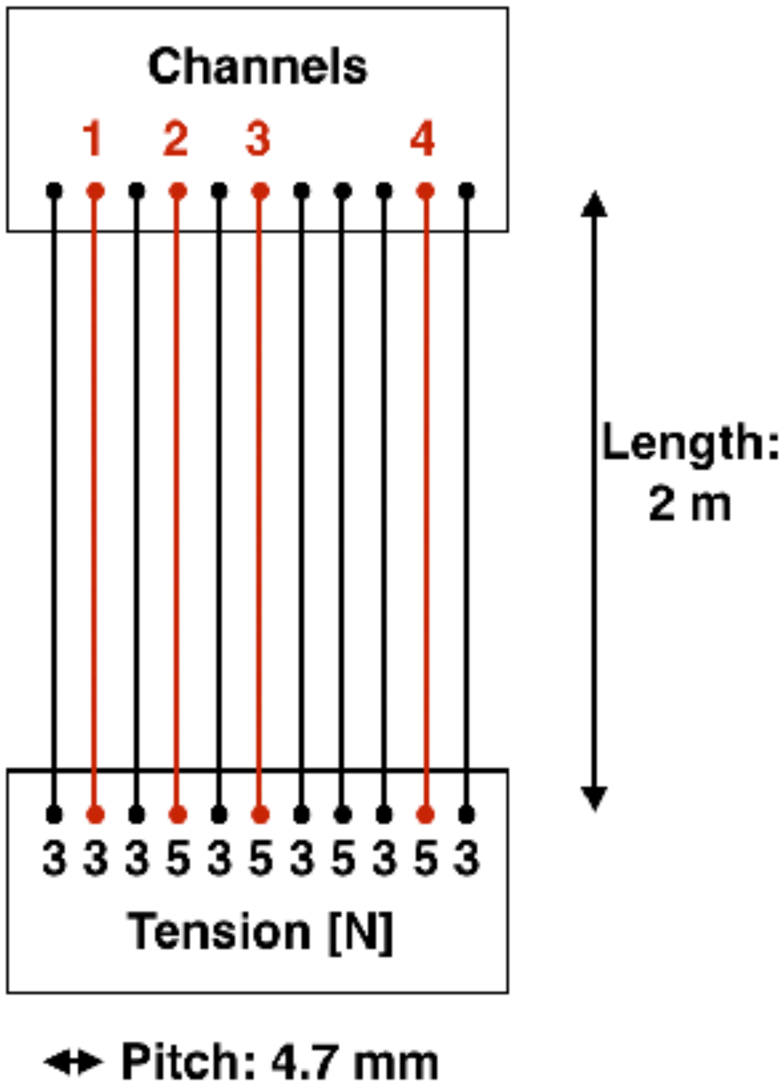
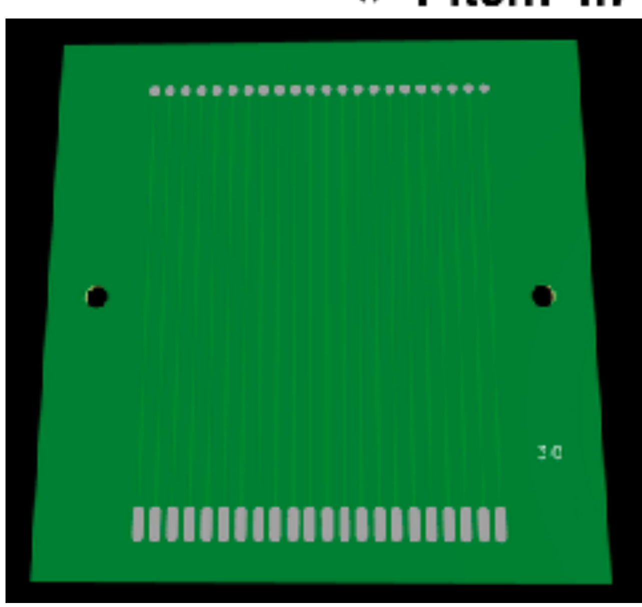


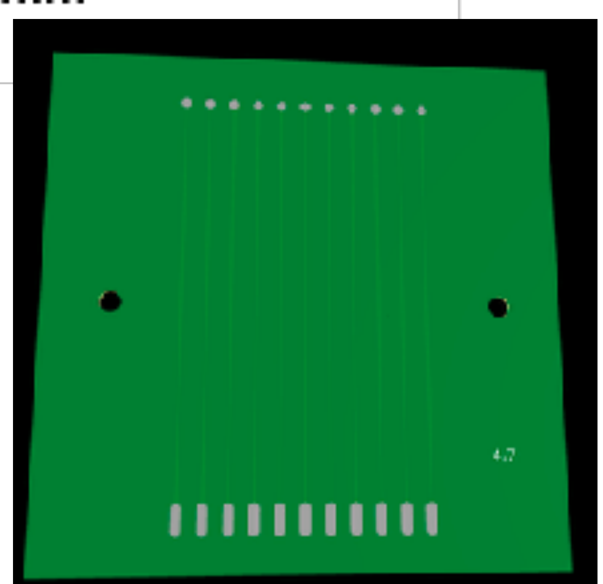
- Amplitude of fitted sinusoidal signal as function of frequency shown
  - 400 V DC, 80 V AC
- Resonance at 44.3 Hz, giving 4.96 N (wire tension at 5 N)

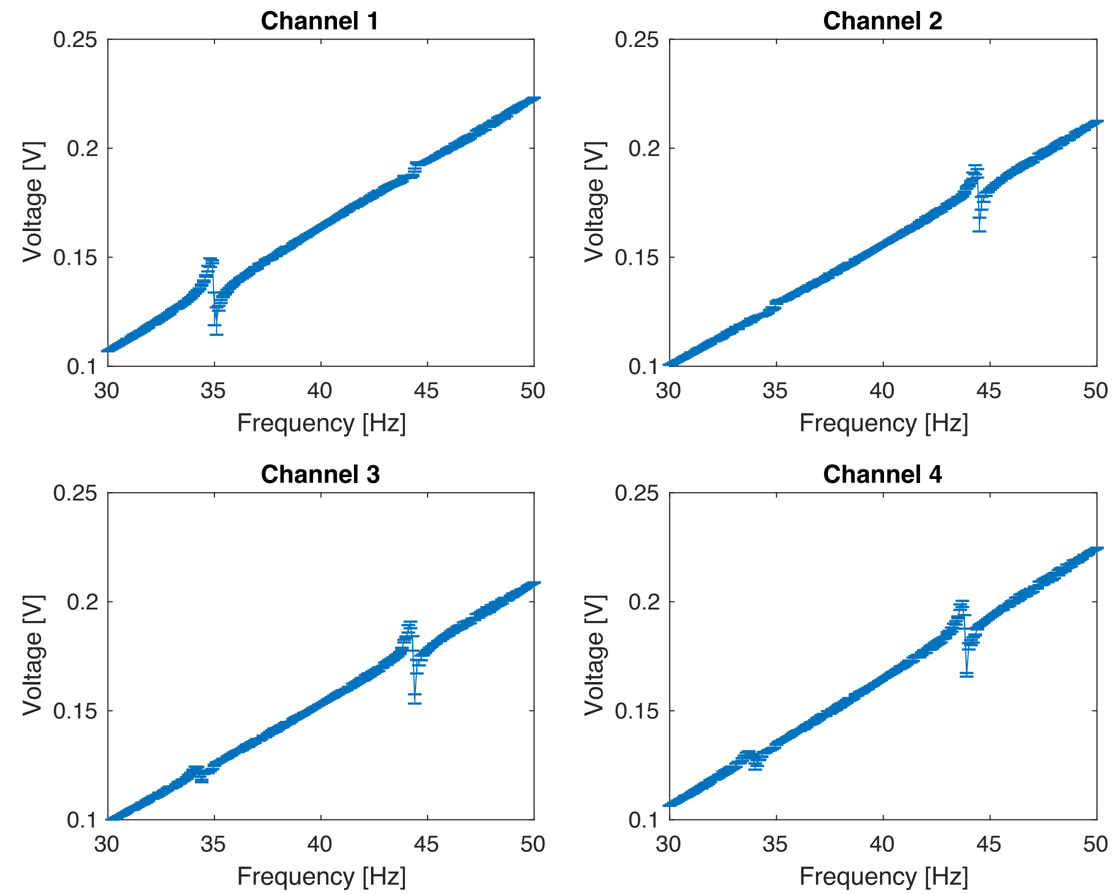


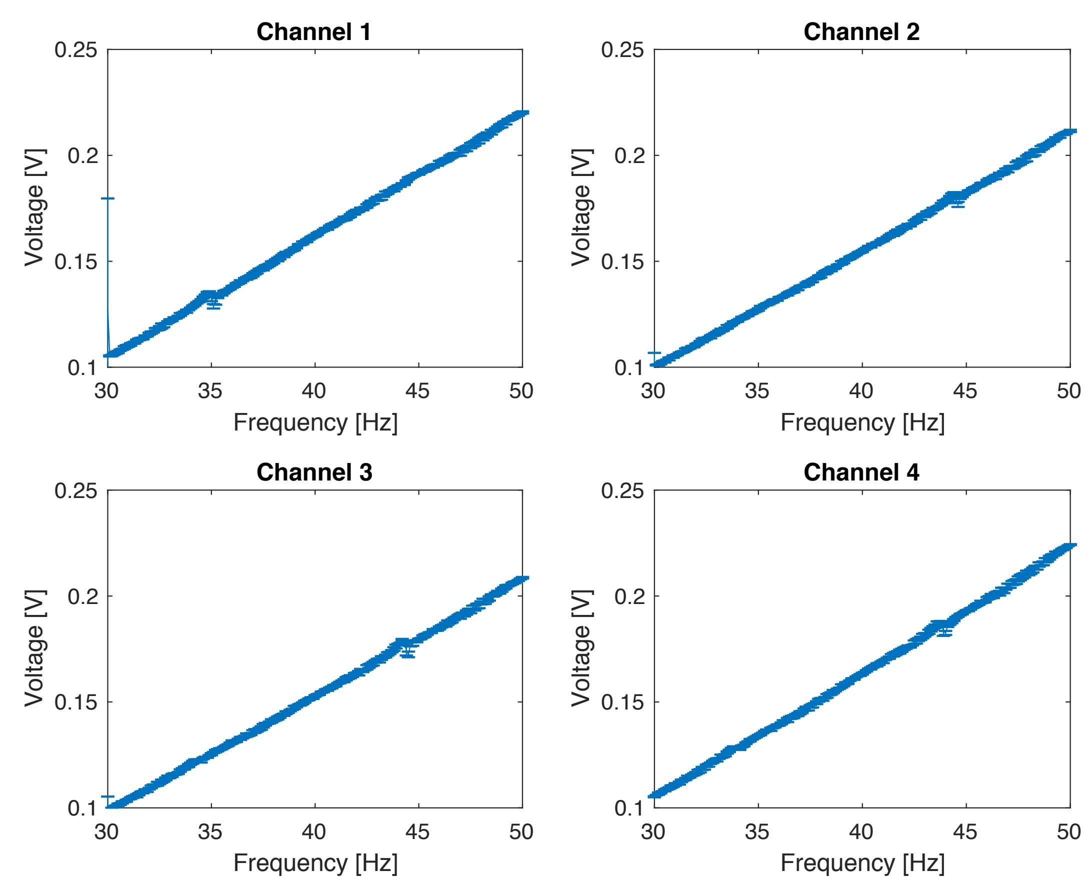
Electrical Method



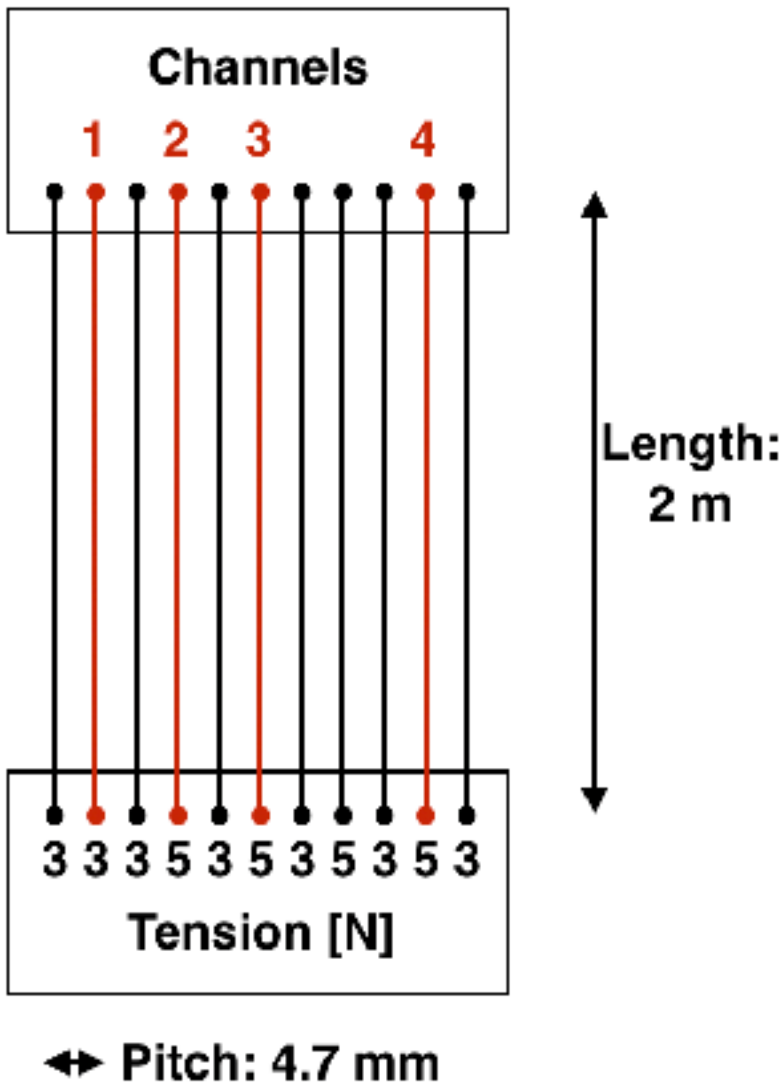


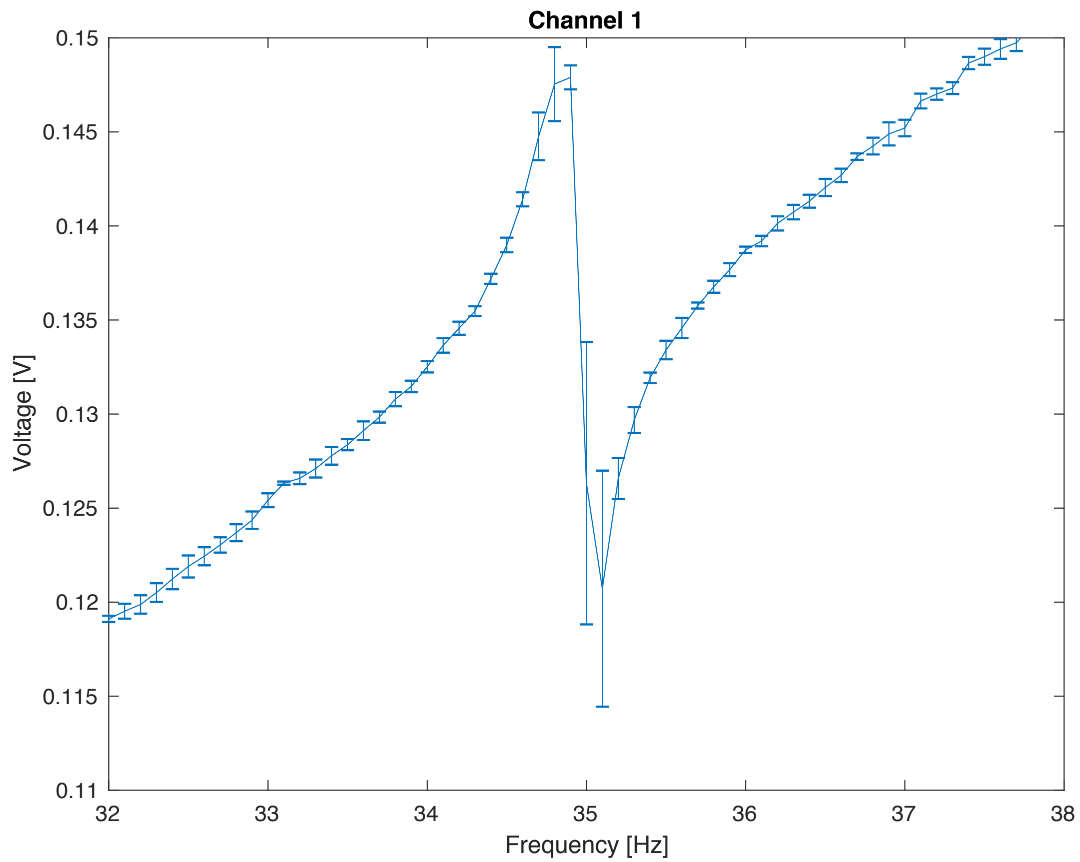


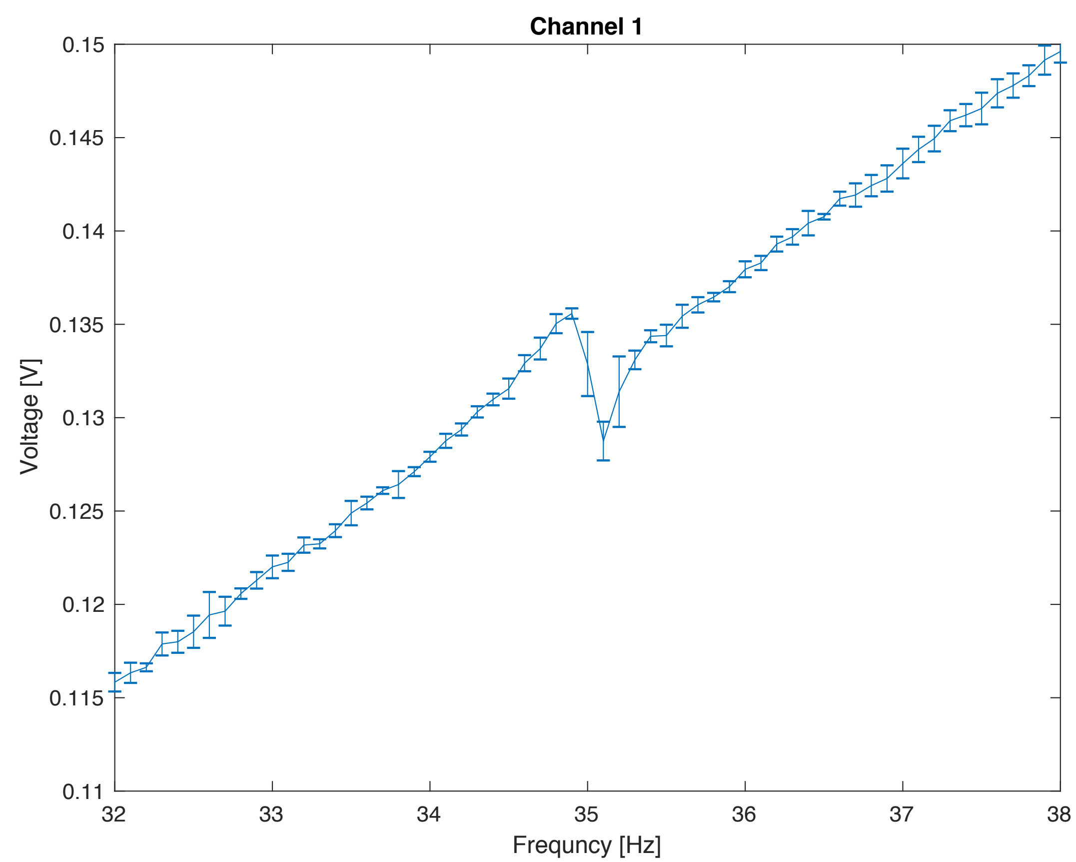




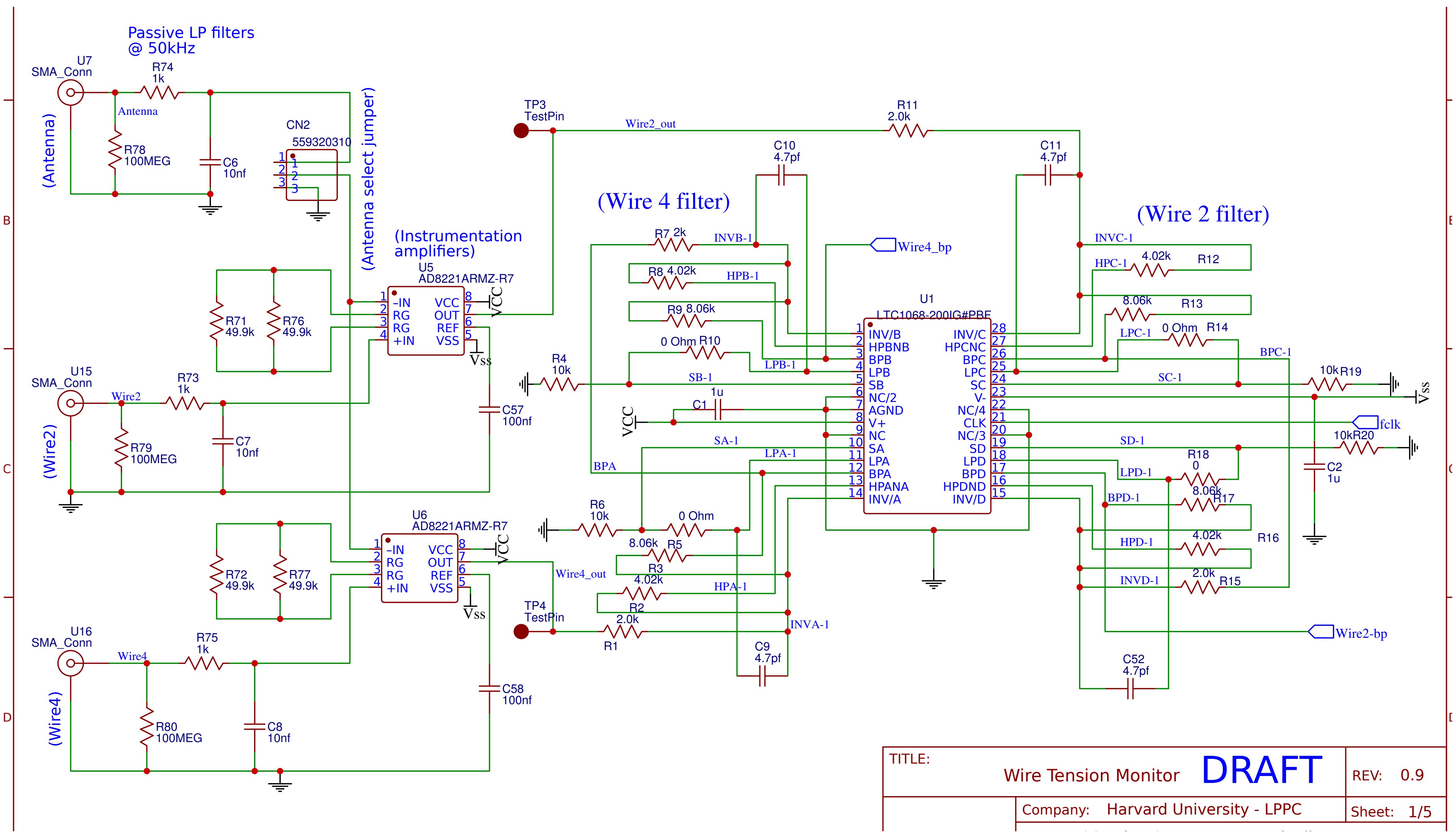
Electrical Method







Electrical method automatisation



Non-conformance documentation

Non-Conformance Log

Project: Proto - DUNE APA(s) **DATE:** 6/2/17

Issue	P/N of component	Found at Activity	Date Occurred	Reported By:	Description of Non-Conformance	Assigned To:	Qty	Disposition	Comments	Preventive Action	Status (Closed / Open)	Date Resolved	Suppporting Documentation
NC-PSL-8757-001	8752705 Rev B	Inc. Insp.	1/4/17	M. Sevenson/DH	Width measurement too wide.	A. Laundrie	22/22	Rework		Board House contacted. (3) holes to be added per board to facilitate locating boards on their milling equipment.	Closed	3/22/17	Incoming Inspection sheets available.
NC-PSL-8757-002	8752704 Rev B	Inc. Insp.	1/4/17	M. Sevenson/DH	Width measurement too wide.	A. Laundrie	10/10	Rework		Board House contacted. (3) holes to be added per board to facilitate locating boards on their milling equipment.	Closed	3/23/17	Incoming Inspection sheets available.
NC-PSL-8757-003	8752694 Rev A	In-process Insp	1/11/17	A. Laundrie	Plated through holes (that will accept sockets) have improper inner dimensions.	A. Laundrie	28/28	Use As Is	Modified a production process to use boards as is.	Test board was ordered with different sized holes to experiment.	Closed	4/20/17	Incoming Inspection sheets available.
		Inc. Insp.	3/2/17	M. Severson	Portion of Solder mask is scraped off a trace.	A. Laundrie	1/28	Reject / Re-purpose	Labelled as a 'practice' board for other processes.		Closed	3/2/17	Incoming Inspection sheets available.
NC-PSL-8757-004	8752686 Rev A	Inc. Insp.	1/30/17	M. Severson	Width measurement too wide.	A. Laundrie	3/80	Rework			OPEN		Incoming Inspection sheets available.
		Inc. Insp.	1/30/17	M. Severson	Overall Board thickness w/ solder mask too thin.	A. Laundrie	30/80	Use As Is	Modified a production process to use boards as is.		OPEN		Incoming Inspection sheets available.
NC-PSL-8757-005	8752685 Rev A	Inc. Insp.	2/16/17	M. Severson	Width measurement too wide.	A. Laundrie	7/55	Rework			OPEN		Incoming Inspection sheets available.
		Inc. Insp.	2/16/17	M. Severson	Overall Board thickness w/ solder mask too thin.	A. Laundrie	9/55	Use As Is	Modified a production process to use boards as is.		OPEN		Incoming Inspection sheets available.
		Inc. Insp.	2/16/17	M. Severson	Holes found in incorrect position on the board.	A. Laundrie	2/55	Reject / Re-purpose	Labelled as 'practice' boards for other processes.		OPEN		Incoming Inspection sheets available.
		Inc. Insp.	2/16/17	M. Severson	Overall (long length) too short.	L. Greenler	4/55	Use As Is	Engineering deemed OK for use.		OPEN		Incoming Inspection sheets available.
NC-PSL-8757-006	8752689 Rev A	Inc. Insp.	3/3/17	M. Severson	Width measurement too wide.	A. Laundrie	8/35	Rework		Supplier Notified.	OPEN		Incoming Inspection sheets available.
NC-PSL-8757-007	8752698 Rev A	Inc. Insp.	2/14/17	M. Severson	(1) set of 5 mounting holes found in incorrect position	A. Laundrie	1/18	Reject / Re-purpose	Board re-purposed for electrical hardware testing.	Supplier Notified.	CLOSED	4/3/17	Incoming Inspection sheets available.
NC-PSL-8757-008	8757 - 030 SN 001	In-Process Insp	2/28/17	KK / JH / RP	A few wires were found outside of Wire Tension Tolerance Requirement of +/- 1 N around 5 N nominal, on Layer V.	R. Paulos	APA-001	Rework	Out of Tension Wires were re-tensioned manually then rechecked.	2nd half of the V-winding layer of wires were wound with the Wire Spool Head tension set to 5.5N as a starting point.	CLOSED	3/16/17	Wire Tension Measurement Sheet and supporting email discussion forthe V-Layer.
	(APA-001)	In-process Insp		KK / JH / RP	A Few shorter length wires were left as is - out of tolerance, below 4N, or above 6N.	R. Paulos	APA-001	Use As Is	See Wire Tension Measurement Spreadsheet for **V-Layer**	Collaboration discussions ongoing.	CLOSED	3/16/17	Wire Tension Measurement Sheet and supporting email discussion forthe V-Layer.
	(APA-001)	In-process Insp	4/18/17	KK / JH /RP/Gina	Slightly < 100 of the shorter length wires were left as is - out of tolerance, below 4N, or above 6N.	R. Paulos	APA-001	Use As Is	See Wire Tension Measurement Spreadsheet for **U-Layer**	Collaboration discussions and an email exchange between PSL and FNAL confirmed the action to continue the APA-001 build activity w / o retensioning the shorter wires.	CLOSED	4/19/17	Wire Tension Measurement Sheet and supporting email discussion forthe U-Layer.
NC-PSL-8757-009	8752732 Rev A	Inc. Insp.	3/22/17	A. Laundrie	Counter sink feature missing on (2) 4.5 mm holes per board.	A. Laundrie	20/20	Rework	Machined in house.	Supplier Notified.	CLOSED	3/28/17	Incoming Inspection sheets available.
NC-PSL-8757-010	8752707 Rev B	Inc. Insp.	4/10/17	M. Severson	Width measurement too wide.	A. Laundrie	51/70	Rework		Supplier Notified.	OPEN		Incoming Inspection sheets available.
NC-PSL-8757-011	8757150 Rev A	In-process Insp	4/24/17	MS/JH/AA	Counter Bore feature only 1mm deep instead of 2.5mm.	A. Laundrie	20/20	Rework	Machined in house.	Supplier Notified.	CLOSED	5/10/17	Incoming Inspection sheets available.
		In-process Insp	4/24/17	MS/JH/AA	Silk screen incorrect on spacer dimension.	A. Laundrie	20/20	Use As Is	Drawing sent to boardhouse was incorrect.	Drawing will be modified before more boards are ordered.	CLOSED	5/19/17	Incoming Inspection sheets available.
NC-PSL-8757-012	8757043 Rev A	In-process Insp	4/26/17	M. Sevenson/KK	Maximum height of comb base is too high	A. Laundrie	20/36	Rework	Machined in house.	Supplier will be notified before more comb bases are ordered.	Closed	6/8/17	Measured heights available.
NC-PSL-8757-013	8752982	Inc. Insp.	5/2/17	M. Severson	Mounting holes on Comb Cap C are too small	A. Laundrie	19/50	Rework	Filed holes by hand.	Supplier Notified.	CLOSED	5/19/17	Incoming Inspection sheets available.
NC-PSL-8757-014	8752684 Rev B	Inc. Insp.	5/15/17	M. Severson	Overall Board thickness w/ solder mask too thin.	A. Laundrie	5/10	Use As Is	Modified a production process to use boards as is.		OPEN		Incoming Inspection sheets available.
NC-PSL-8757-015	8752706 Rev B	Inc. Insp.	5/22/17	M. Severson	Width measurement too wide.	A. Laundrie	2/24	Rework	Machined in house.	Supplier Notified.	CLOSED	5/22/17	Incoming Inspection sheets available.

Frame Flatness (and wire pitch)

- Wire spacing is controlled by the wire boards where they are soldered and support combs

- Mechanical studies on slide 6 incorporate the wire spacing requirements