Neutrino Beamline Prototype Horn A Final Design Review

Prototyping

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Outline

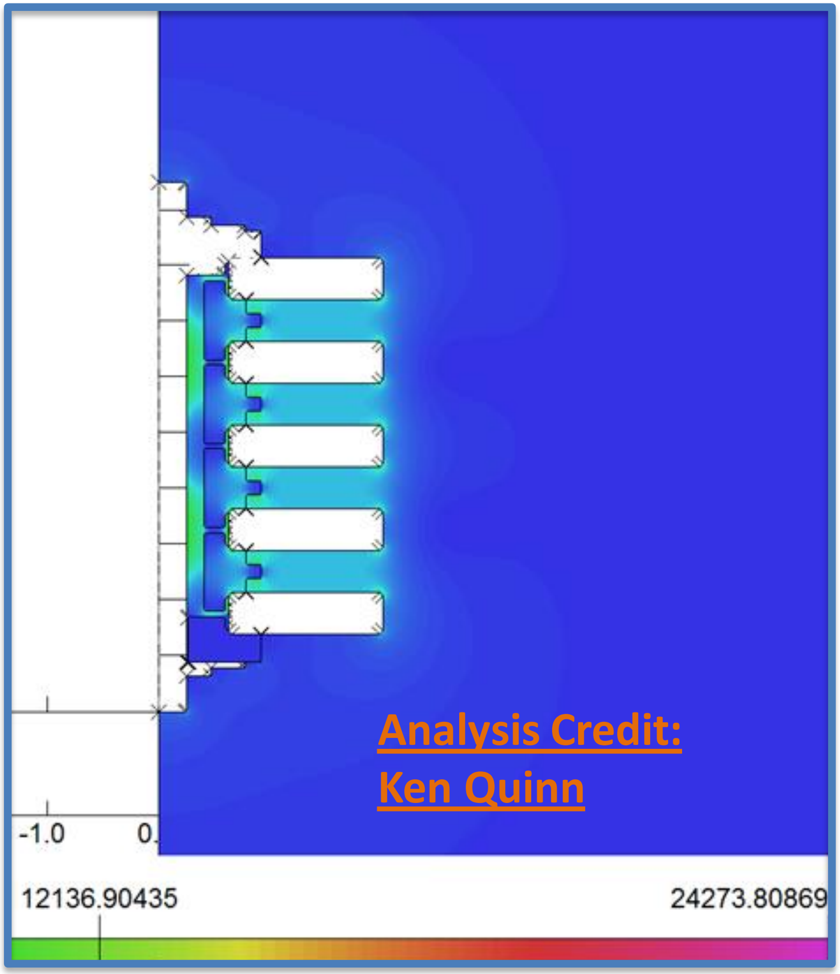
- Prototyping Approach
- Stripline
- Water Ports
- Instrumentation Connections
- Spider Supports
- Summary

Prototyping Approach

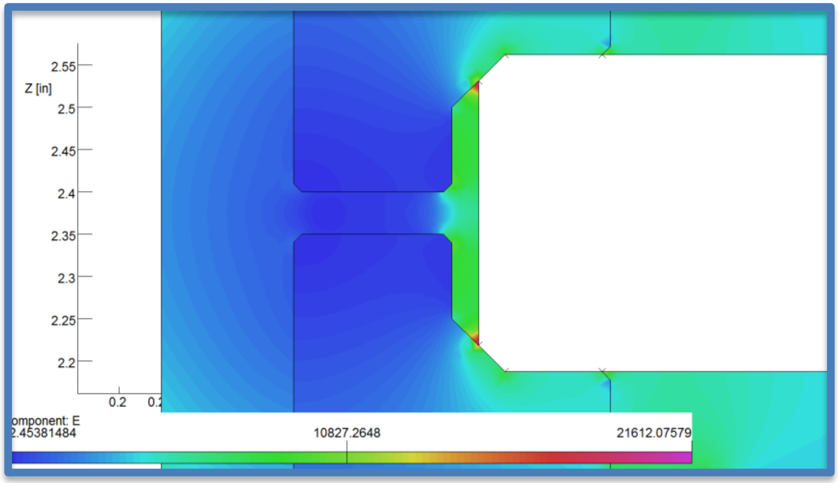
- Focus on high value, high risk elements that carry across all horn designs.
- Approach is graded in order of magnitudes.
  - Test 10K in ceramics before testing 100K+
  - Test 4 water ports before testing 40+
  - Test 1 assembly process & document before testing 10+ more…
- Horn A prototype will test all features at next order of magnitude.
- Results of that effort will provide guidance for 10M+ production horn & stripline block designs. Likely ~50M+ throughout entire operational lifetime of facility.

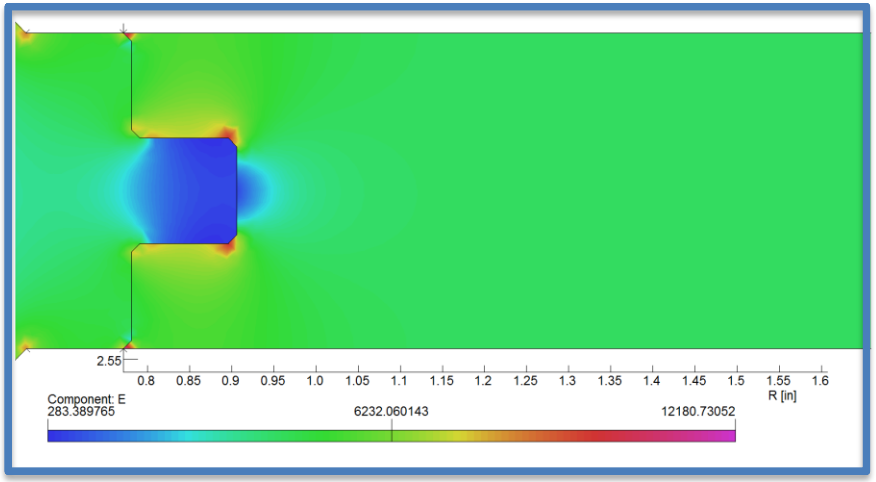
Stripline Prototyping – PDR Refresh

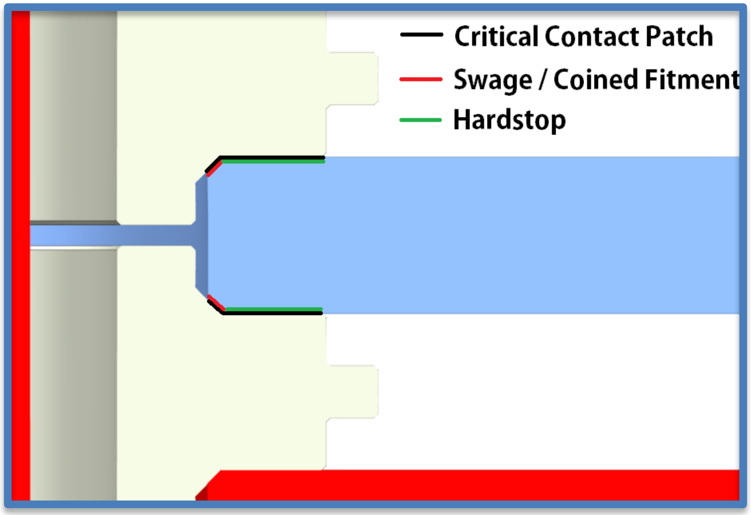
- NuMI design unusable for 5kV.
- Had to switch to self-centering ceramics but stuck with PSZ-MGO for resilience.
- Bolt upsized to ½-13 to guarantee "swaging" of tapered ceramic interface concept to bus before face-to-face hard stop.
- External ceramic provides centering of bolt group.
- Metallic spacer on opposite side ties hardware to voltage potential.
- No electrically floating hardware.



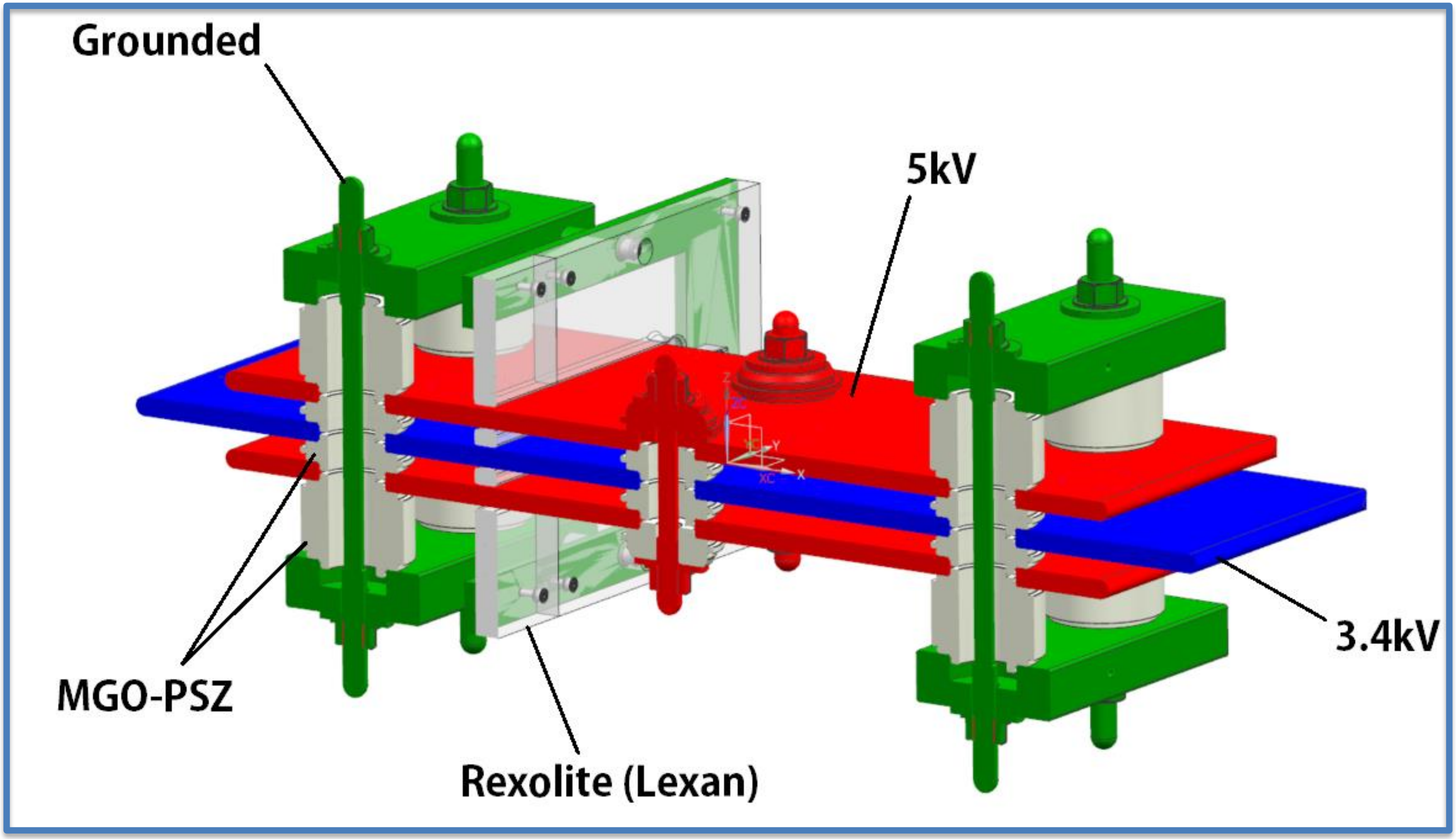
Initial Concept: E-Fields & Fitment





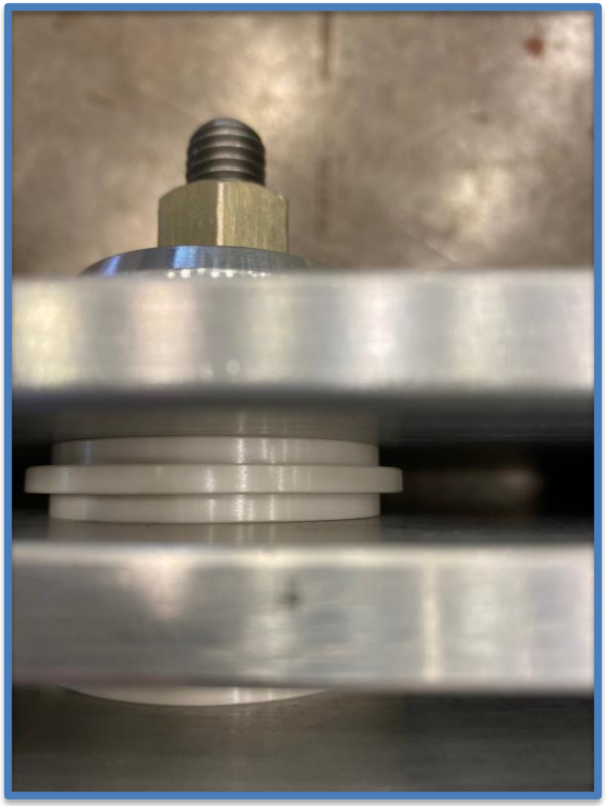


Prototyping Plan at PDR



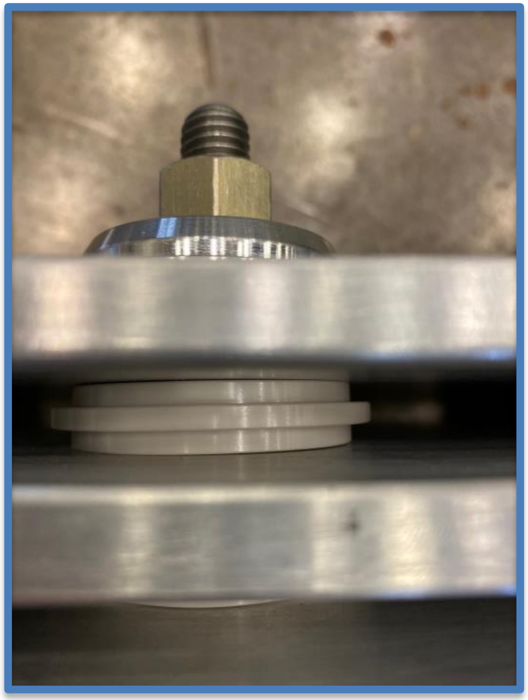
Started Assembling!

- All parts arrived at specifications.
- Started checking fitment.
- Looking good…
- Parts swaging…



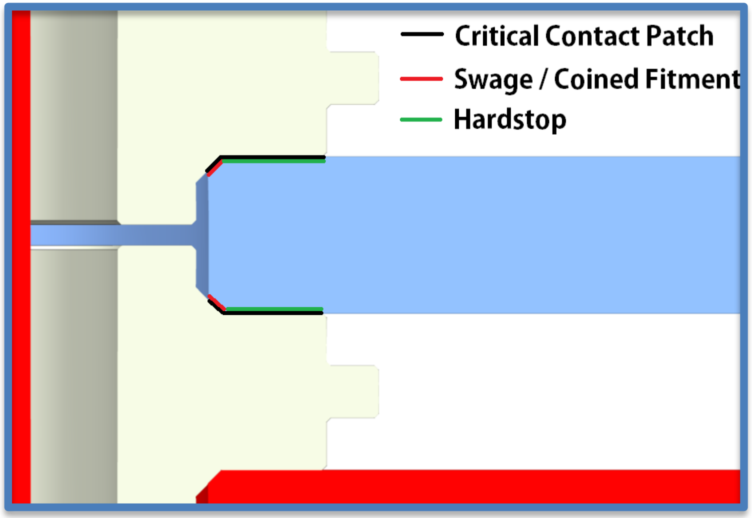
Started to Fail…

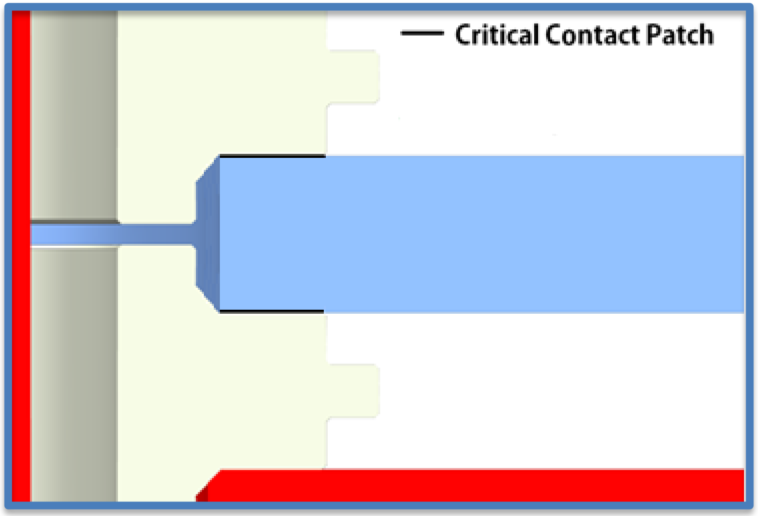
- Some swaging stacks did work.
  - Took every bit of bolt preload to close-up.
- Most were failures
  - Crooked seating when starting swage process / never re-aligned.
  - Major gaps present.
  - Yielded bolts…
- If unable to work with 100% parts in test environment, will never work in field with 100X connections to make & greater variability.
- Did not proceed to electrical testing.



From the Ashes…

- Rely on ceramic chamfer to self-center.
- Lightly broke edge for no cuts.
- Eliminated swage fit & custom tooling needs described in PDR.
- Maintain:
  - 45 degree fitment with ceramic for field stress concerns.
  - No possibility of small gap & no use of radii.
  - They fail entirely in supporting analysis.
- We understand stress riser increases on the hole edge.
- The stress riser at the end of ceramic circumference compressive pre-load is what highly dominates fatigue safety factor.

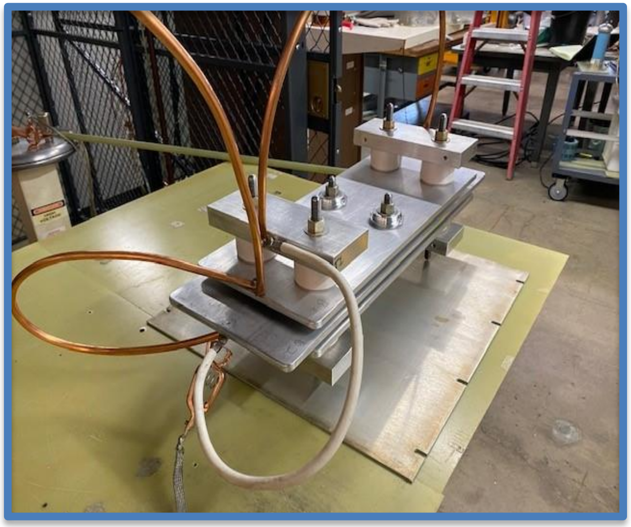
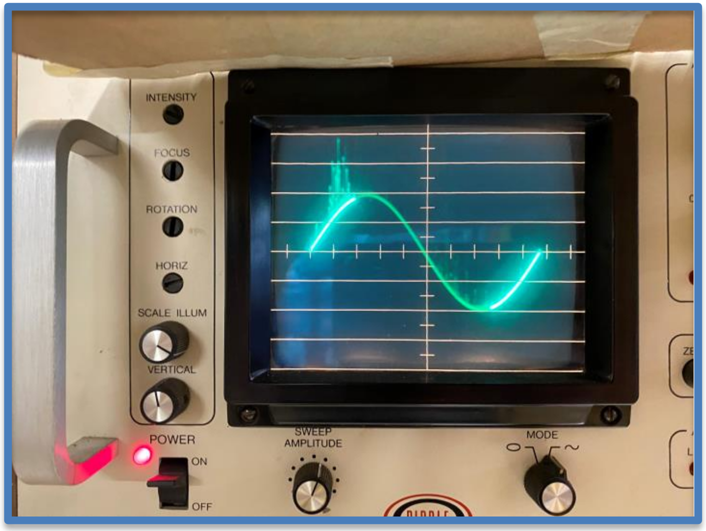




Initial Test Setup & Readout

- Reassembly of modified components was successful.
- Attempted a few different combinations & always pulled together with little preload.
- Transferred to corona testing cage & hooked up to equipment per EE support direction.
- EE support completed test process & scope interpretation.

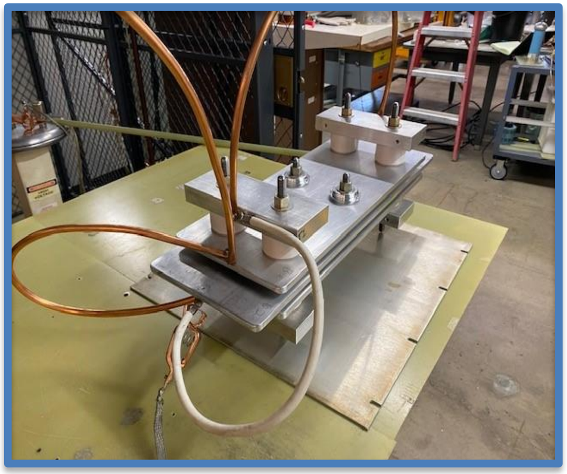
Credit:
EE Support

High Voltage Testing – High Voltage Bolt Groups

- Trial 1: Test voltage drop (1.6kV) with grounded support blocks & HV bolt groups in place.
- Required: 4.8kV, Results: 6.5kV / Passed

Trial	Background Discharge [uC]	Inception Voltage [kV-rms]	Inception Voltage [kV-peak]	Inception Discharge [uC]	Extinction Voltage [kV]	Extinction Voltage [kV-peak]	Extinction Discharge [uC]
1	10	4.5	6.4	110	4.0	5.7	10
2	10	4.6	6.5	110	4.1	5.8	10



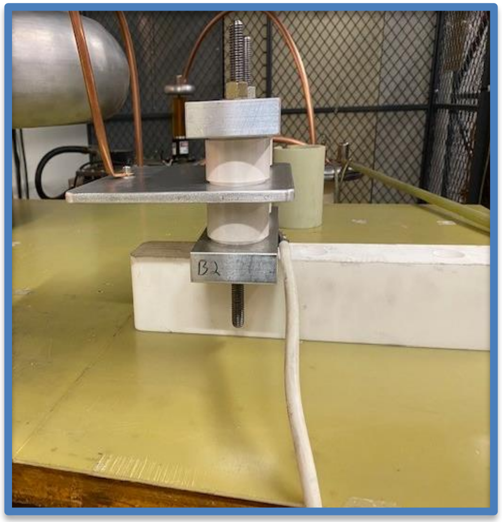
- Trial 2: Test voltage drop (1.6kV) with support blocks at HV & HV bolt groups in place.
- Required: 4.8kV, Results: 6.5kV / Passed

Trial	Background Discharge [uC]	Inception Voltage [kV]	Inception Voltage [kV-peak]	Inception Discharge [uC]	Extinction Voltage [kV]	Extinction Voltage [kV-peak]	Extinction Discharge [uC]
3	10	4.6	6.5	110	4.2	5.9	10
4	10	4.6	6.5	110	4.2	5.9	10

High Voltage Testing – Grounded Bolt Groups

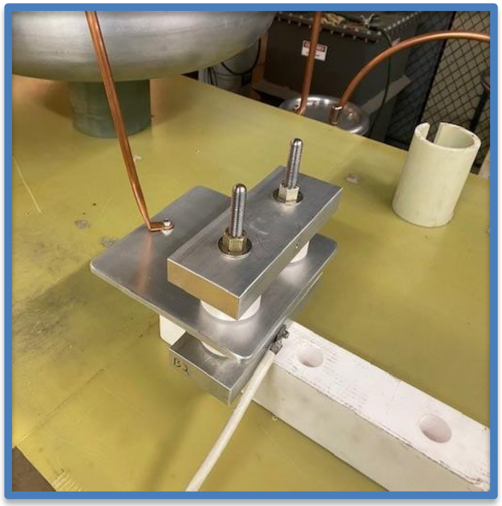
- Trial 1: Test HV conductor (5kV) with grounded support blocks.
- Required: 15kV, Results: 19.9kV / Passed

Trial	Background Discharge [uC]	Max Voltage [kV-rms]	Max Voltage [kV-peak]	Discharge [pC]	Inception	OC Trip
1	3	11.2	15.8	250	x	
2	3	13.8	19.5	70		x
3	3	12.8	18.1	20-30		x
4	3	14.1	19.9	60		



- Trial 2: Swap out isolators to verify repeatability.
- Required: 15kV, Results: 20.1kV / Passed

Trial	Background Discharge [uC]	Max Voltage [kV-rms]	Max Voltage [kV-peak]	Discharge [pC]	Inception	OC Trip
1	3	12.1	17.1	20		x
2	3	14.0	19.8	20		
3	3	14.2	20.1	20		



- Results improved over time; burn-in???

High Voltage Testing – Grounded Bolt Groups

- Trial 3: Test full assembly with grounded through bolts only.
- Required: 15kV
- Results: 19.7kV / Passed

Credit: EE Support

Trial	Background Discharge [uC]	Max Voltage [kV-rms]	Max Voltage [kV-peak]	Discharge [pC]	Inception	OC Trip
1	3	12.7	18.0	60		x
2	3	13.7	19.4	60		x
3	3	13.9	19.7	60		x

High Voltage Testing – Grounded Bolt Groups

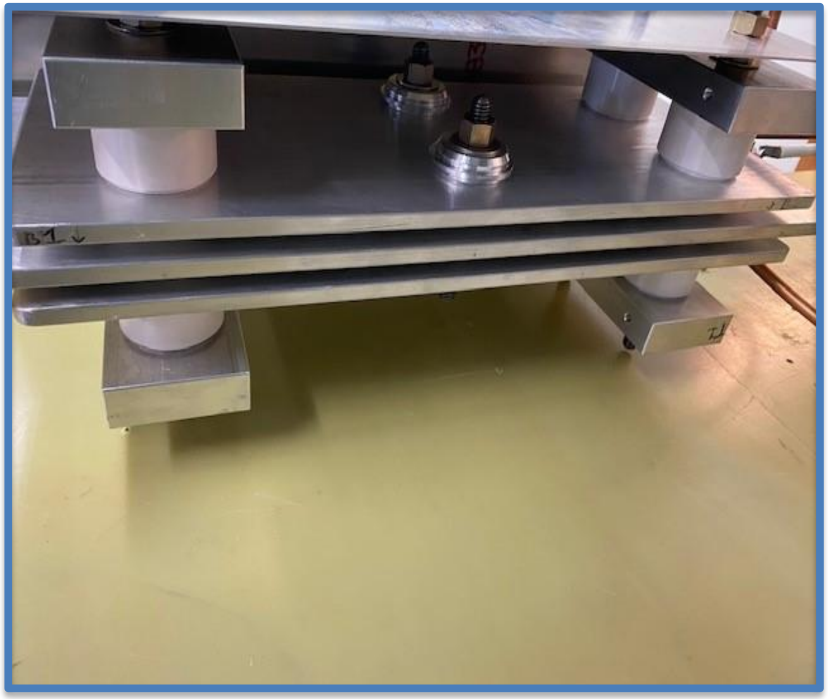
- Trial 4: Test outer conductors to grounded component (Stripline pull-up block / Stripline shield block.
- Required: 15kV
- Results: 20.2kV / Passed

Credit: EE Support

Trial	Background Discharge [uC]	Max Voltage [kV-rms]	Max Voltage [kV-peak]	Discharge [pC]	Inception	OC Trip
1	3	14.3	20.2	64		x
2	3	14.3	20.2	60		

High Voltage Testing – Grounded Bolt Groups

- Trial 5: Replicate grounded exterior shield with high voltage bolt groups & isolators in place.
- Required: 15kV
- Results: 20.1kV / Passed

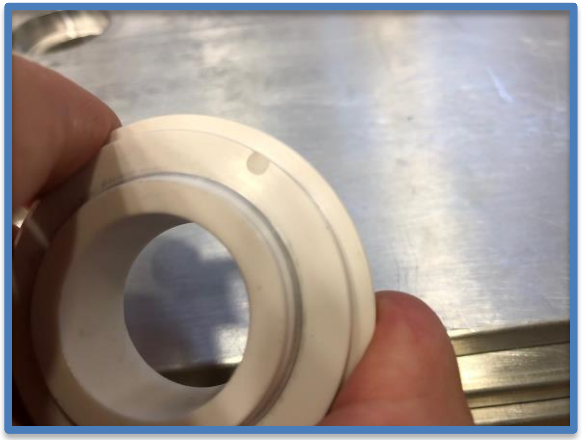


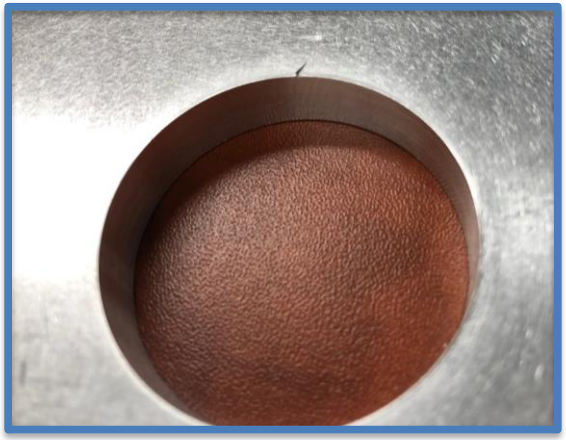
Credit: EE Support

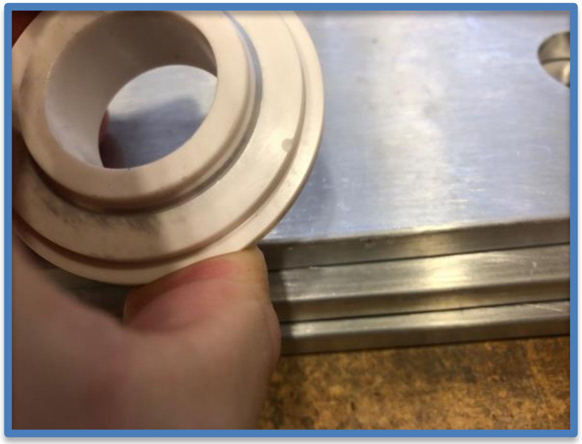
Trial	Background Discharge [uC]	Max Voltage [kV-rms]	Max Voltage [kV-peak]	Discharge [pC]	Inception	OC Trip
1	3	14.2	20.1	60		

Findings Throughout Testing

- All parts started out 100% to specification.
- Tests required reconfiguring 10+ times due to number of variables to test. Many assembly / re-assembly steps, transport, handling…
- Noticed ceramics started to chip, bore edges started to get nicks / scratches.
- Still passed all tests, including deformation test on next slide.
- Shows design is not overly sensitive to material imperfections.



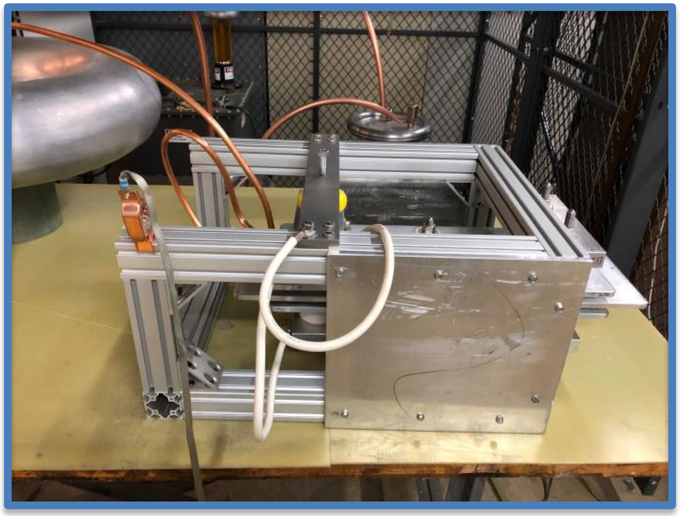


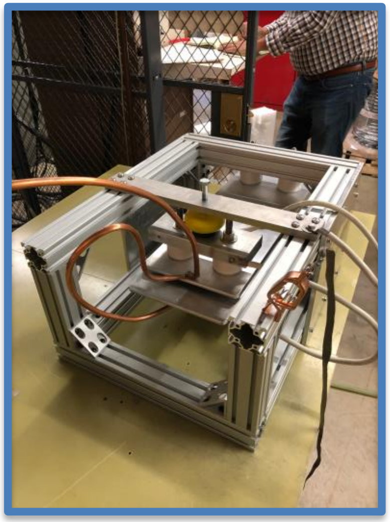


High Voltage Testing – Combined Mechanical / Electrical

- PDR recommendation: Complete mechanical testing of stripline isolation scheme to replicate real movement.
- We could accommodate building a deformation rig. No resources / time to accommodate full vibration testing & we believe best suited for full structure testing when on test stand. Full scale experimental data is highest value data.
- Tested with “GO” gauge (shim) to confirm .0625” deflection per 9” of stripline & repeated corona test; passed.

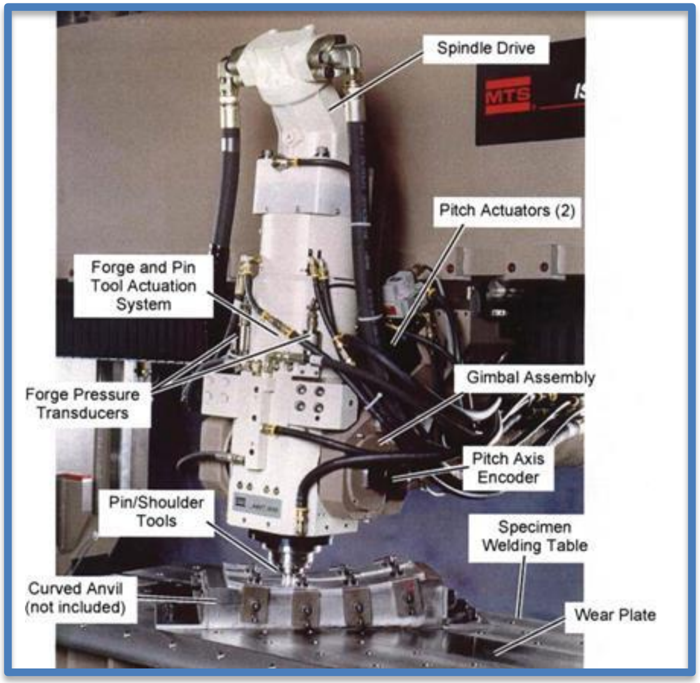
Credit: Quinn Peterson & EE Support





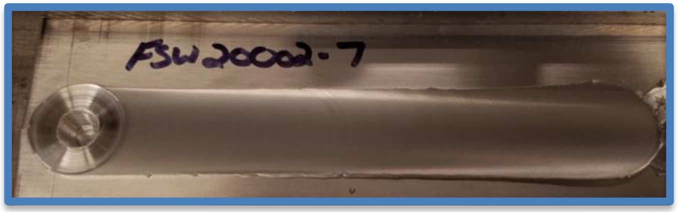
Vendor Prototypes

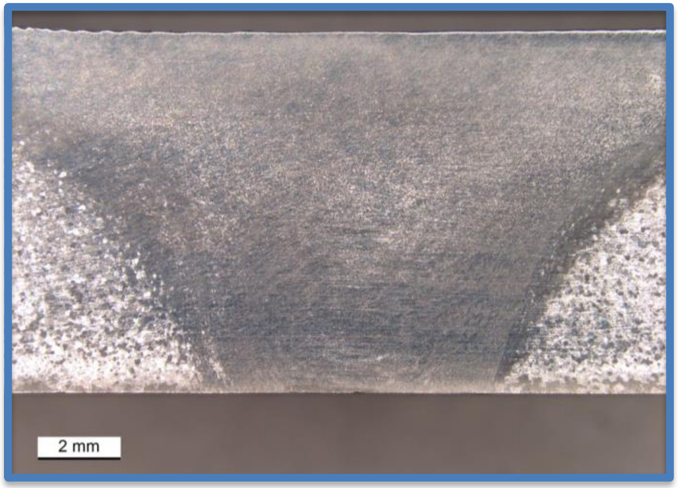
- SDSMT is LBNF partner institution & has advanced friction stir-welding lab (AMP Lab).
- Completed major prototyping & testing exercise to confirm capabilities.
- They have “bid” the work & provide the foundation for our welding cost. Estimates.
- SOW in process.
- Vendor spec. developed.



Vendor Prototypes

- Completed comprehensive testing & evaluation that exceeded expectations.

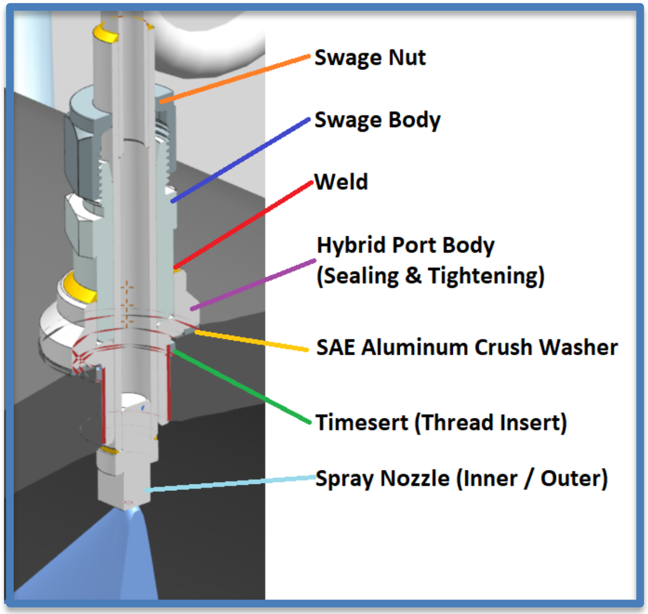


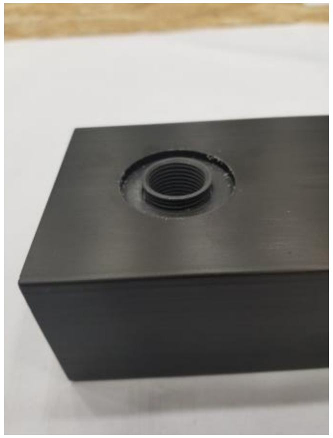


Sample	Yield (KSI)	UTS (KSI)	%EL	Weld Efficiency
6101-T61 Longitudinal	17.9 ± 0.1	23.9 ± 0.1	22.3 ± 0.2	NA
6101-T61 Transverse	17.1 ± 0.0	22.9 ± 0.1	22.9 ± 0.1	NA
FSW20002-6 (Transverse)	11.9 ± 0.3	19.5 ± 0.2	17.4 ± 0.2	85%
FSW20002-7 (Transverse)	11.9 ± 0.1	20.0 ± 0.1	17.7 ± 0.7	87%

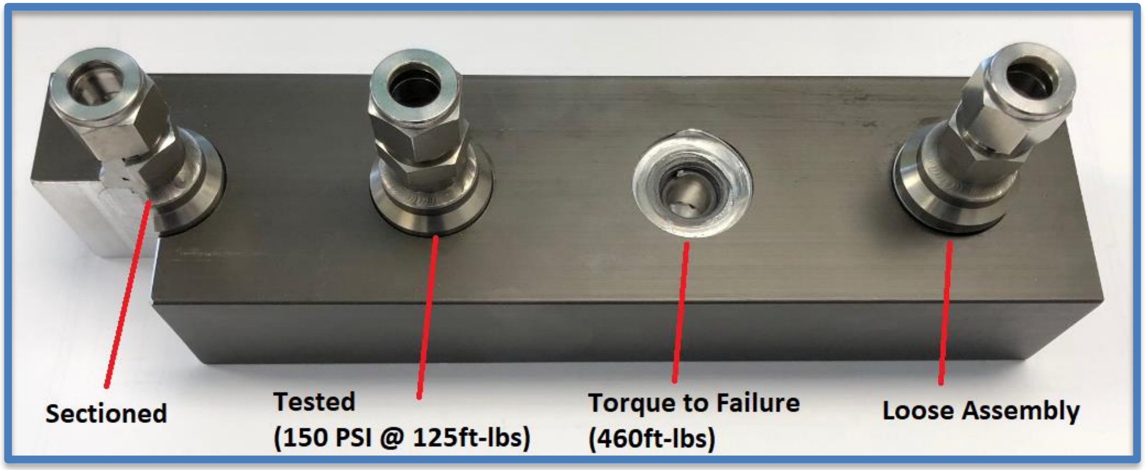
Horn A Design Prototypes – Water Ports

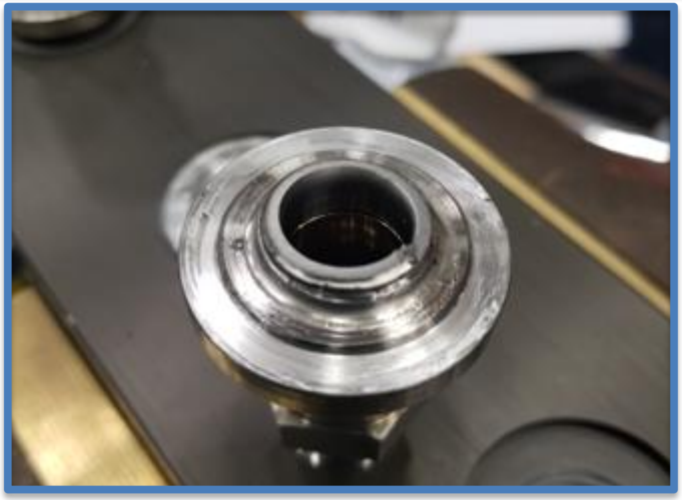
- LBNF Horns pursue a revision of port design as compared to NuMI / BNB. Different from T2K as well.
- Small footprint, inexpensive, immediate assembly, high pressure rating, & reduced component count.
- Required prototype testing in preparation for design review & to verify resilience of concept.

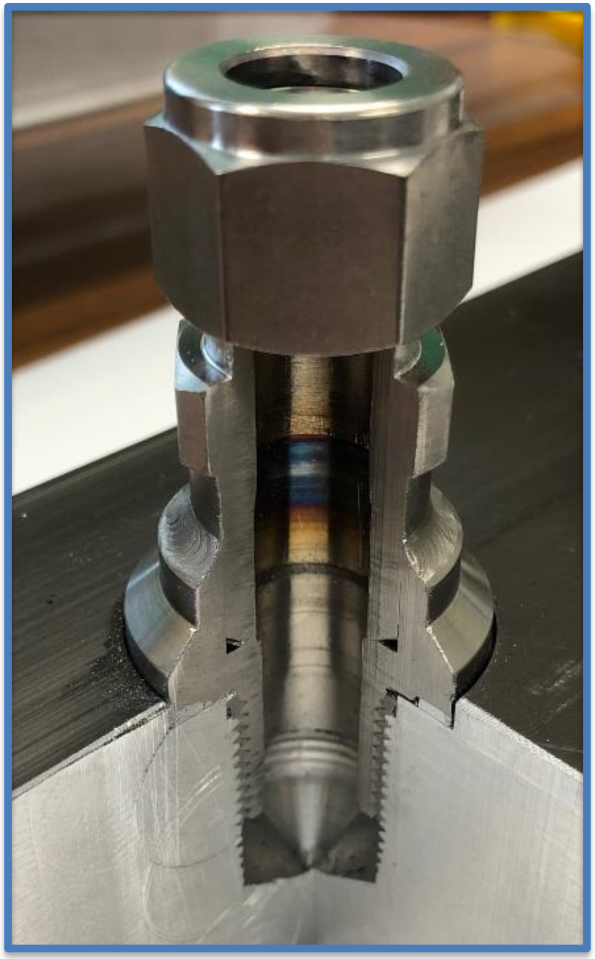




Horn A Design Prototypes – Water Port Testing

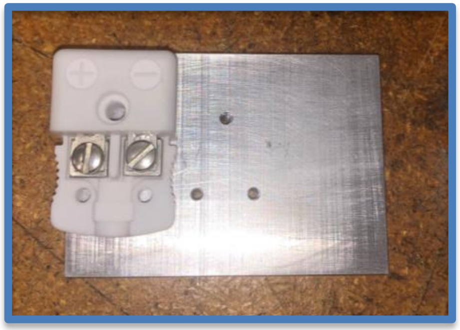


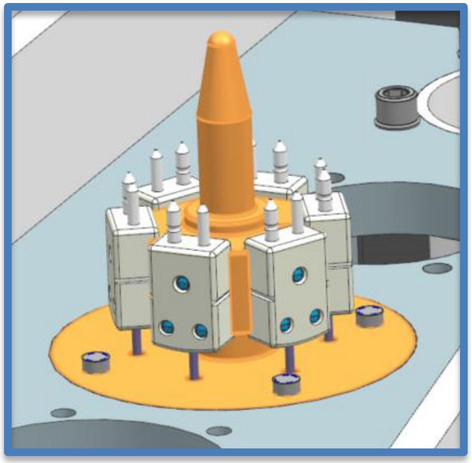


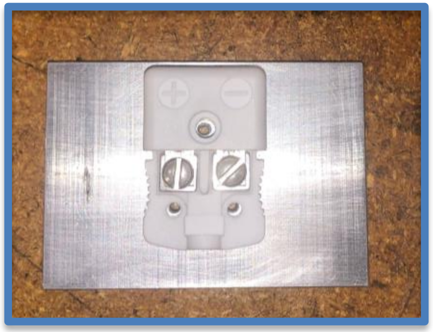


New Instrumentation Connection

- Thermocouple vendor (Omega) changed die-sets on ceramic connectors few years ago.
- NuMI stock out, changeover period from old mounts to new connector required drilling out ceramic holes & eventually plug welding & re-drilling mounts.
- We must not repeat.
- RAL likely to use some version of this.





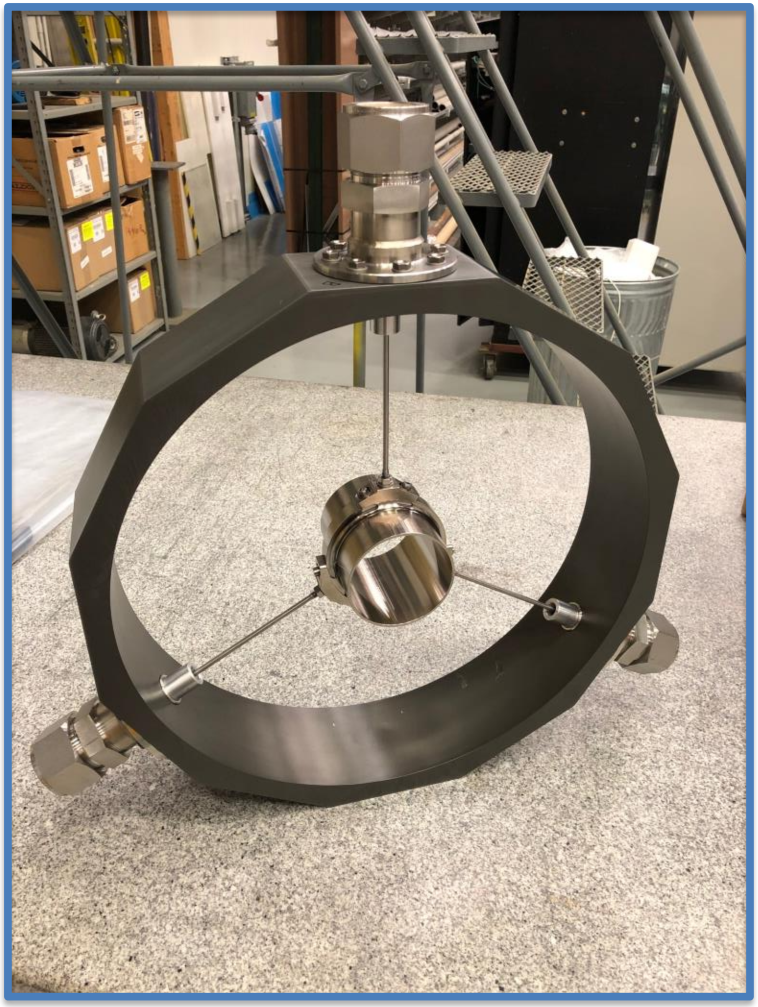


Spider Supports

- PDR recommendation:
- Turn plastic into metal. Done!

Print Credit: Quinn Peterson

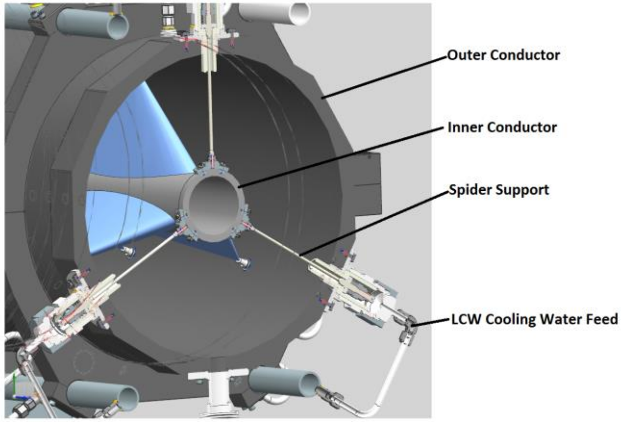
Build Credit: Meredith Lee & Clay Leonard



Overview

- Spider support installation and measurement procedure was developed to systematically set preloads and ensure concentricity of conductors
- Procedure is used in conjunction with measurement spreadsheet
- Prototype assembled using procedure and spreadsheet
- Specialized sockets developed and tested during the build

Sockets for spider support installation



Spider support assembly

Measurement Spreadsheet

- Centralized document for all measurements made during spider support installation
- Provides tracking for adjustments
- Calculates key quantities including total displacement and preload

	Initial Depth Measurement (in.)			
Spider Support	h_1	h_2	h_3	h_4
C	0.589	0.309	0.89	1.788
A	0.6	0.3	0.89	1.79
B	0.571	0.309	0.89	1.761

A

Quantity	Measurement Iteration															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
h_4 (in)	1.792	1.8	1.89	1.86	1.818	1.859										
IC Distance (in)																
Preload (lb)	8.3	41.5	414.8	290.4	116.1	286.2										

B

Quantity	Measurement Iteration															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
h_4 (in)	1.764	1.77	1.781	1.79	1.798	1.809	1.83									
IC Distance (in)																
Preload (lb)	12.4	37.3	83.0	120.3	153.5	199.1	286.2									

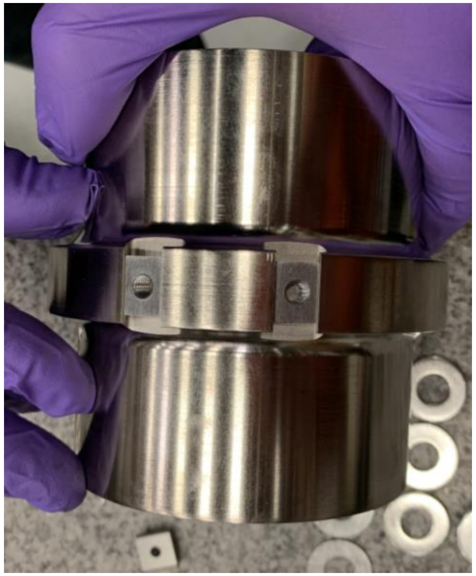
C

Quantity	Measurement Iteration															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
h_4 (in)	1.786	1.794	1.83	1.815	1.821	1.857										
IC Distance (in)																
Preload (lb)	-8.3	24.9	174.2	112.0	136.9	286.2										

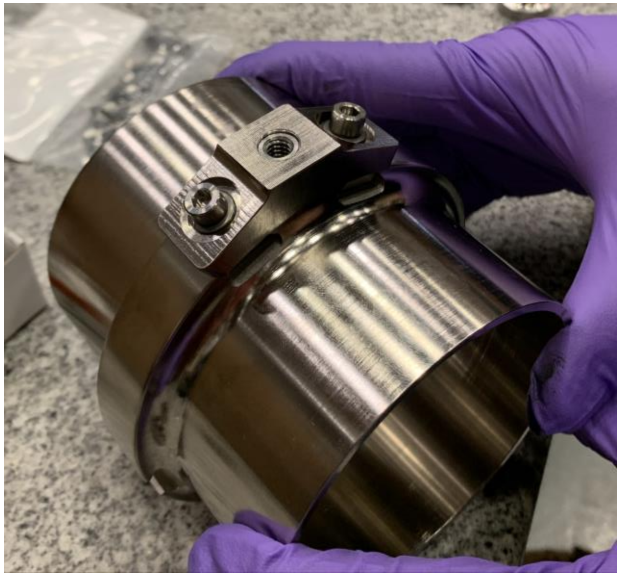
		Belleville Washer Stackup			Spoke					
Horn	Spider Support	Number of Belleville Washers	Single Belleville Washer Spring Rate (lb/in)	Belleville Washer Stack Spring Rate (lb/in)	Elastic Modulus (lb/in^2)	Minimum Diameter (in)	Length (in)	Cross-sectional Area (in^2)	Spoke spring rate (lb/in)	Total Spring Rate (lb/in)
A	A	6	27750	4625	1.60E+07	0.18	10.125	0.0254	4.02E+04	4148
	B	6	27750	4625	1.60E+07	0.18	10.125	0.0254	4.02E+04	4148
	C	6	27750	4625	1.60E+07	0.18	10.125	0.0254	4.02E+04	4148

Spoke Base Hardware Installation

- Slide the spoke base nuts into the corresponding grooves on the inner conductor
- Position the spoke base over the nuts and torque socket head screws to 51 in-lb each
- Repeat for the remaining 2 spoke bases



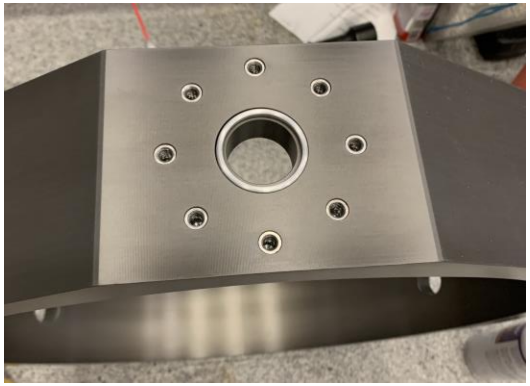
Spoke base nuts in position



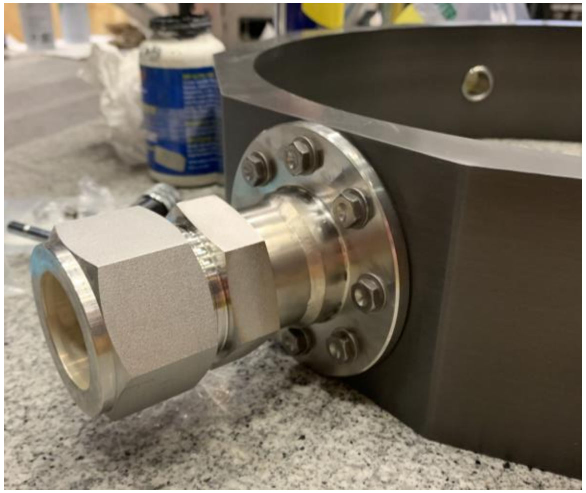
Spoke base installed

Timeserts and Flange Installation

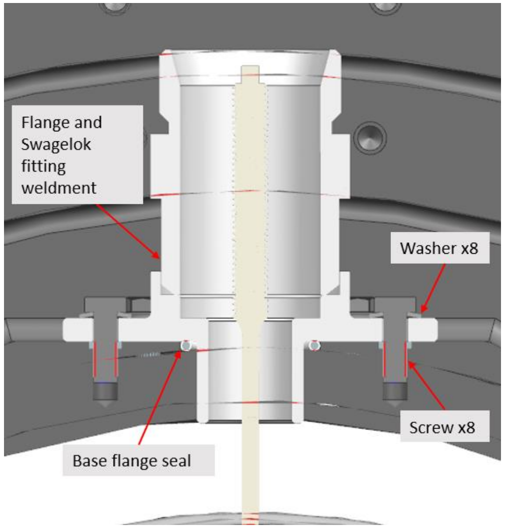
- Install Time-Serts in outer conductor
- Apply light film of WD-40 to flange seal and insert in groove
- Fasten flange and Swagelok fitting weldment for each support
  - Torque screws in alternating star pattern in 25 in-lbs increments
    - Final torque on each screw is 125 in-lbs
  - Tested both titanium & SS screws. Titanium screws also compressed remaining .004" flange warp from welding step



Timeserts and seal installed



Flange and hardware installed



Cross section of flange assembly

Findings from Weld Process

- Socket weld was anticipated to create some level of flange warpage.
- Warpage measured to ~.009". Flange essentially becomes Belleville washer.
- Fastening with all preload from SS bolts, seal compresses 100% & flange pulls in .005". Edge measured .004" gap.
- Fastening with all preload from Ti bolts, seal compresses 100% & flange pulls in before final torque spec is achieved.
- Will use Ti bolts so all surfaces are fully seated.
- No plans to change process. Belleville direction is in our favor & adds to fastener elasticity.

Spider Support Spoke Insertion

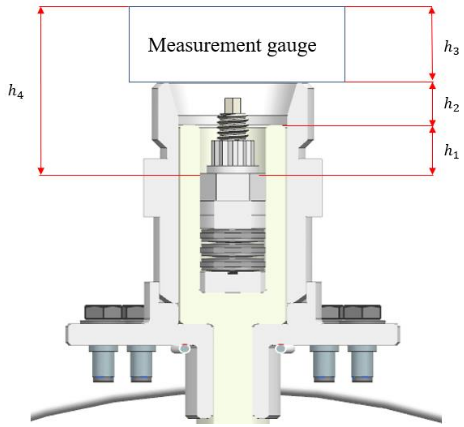
- Thread a Belleville washer and the base nut onto the spider support rod
- Screw the spider support rod into the spoke base
  - Tighten the nut at the base to 125 in-lb using the base nut socket
- Repeat for the remaining 2 spider supports

Using spoke socket to insert spoke

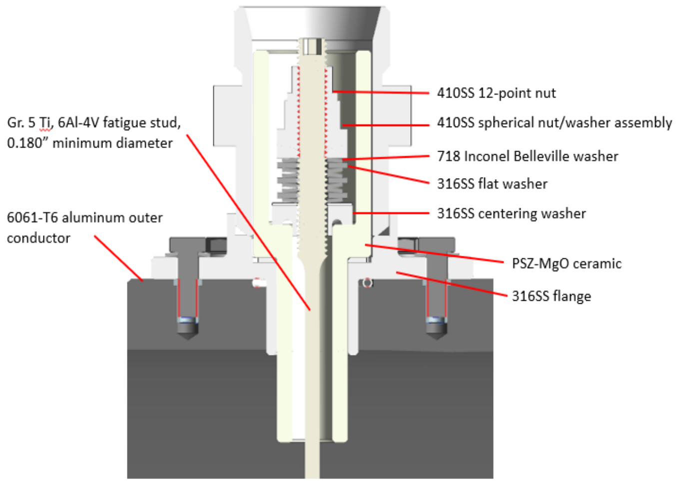
Using base nut socket to tighten nut

Hardware Stackup Assembly & Measurement

- Using a 3/8" threaded rod, insert the ceramic isolator and hardware stackup from the centering washer to the hex nut
- Use a vise to hold the assembly vertically
- Use a depth micrometer to measure from the top surface of the ceramic isolator to the top of the hex nut. Record as h_1.



Measurement diagram

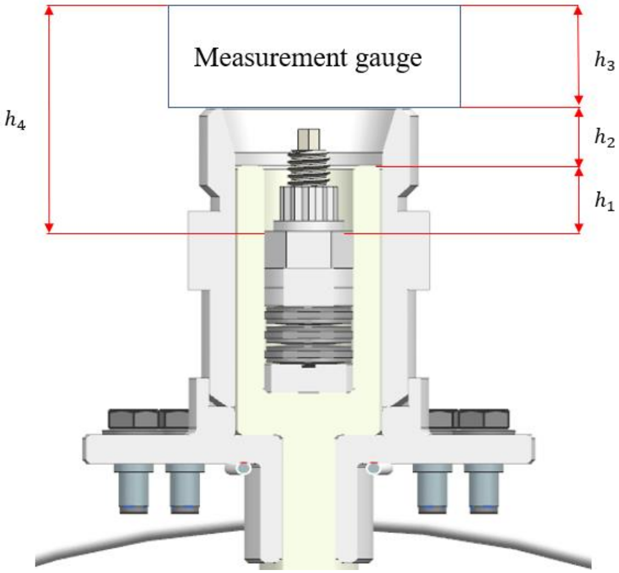


Hardware stackup

Measuring depth in vise

Hardware Stackup Install

- Install the isolator and hardware stackup onto the spider support
- Use a depth mic to measure from the top of the Swagelok fitting to the top of the ceramic isolator, and record as h_2
- Measure the height of the measurement gauge and record as h_3

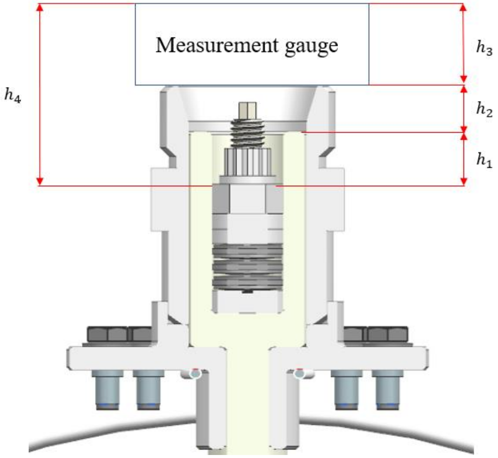


Measurement diagram

Measuring h_2

Setting Initial Hex Nut Position

- Install the measurement gauge
- Measure from the top of the measurement gauge to the hex nut
  - If the measurement does not match what the spreadsheet calculates for h_4, use the hex nut socket to adjust its position

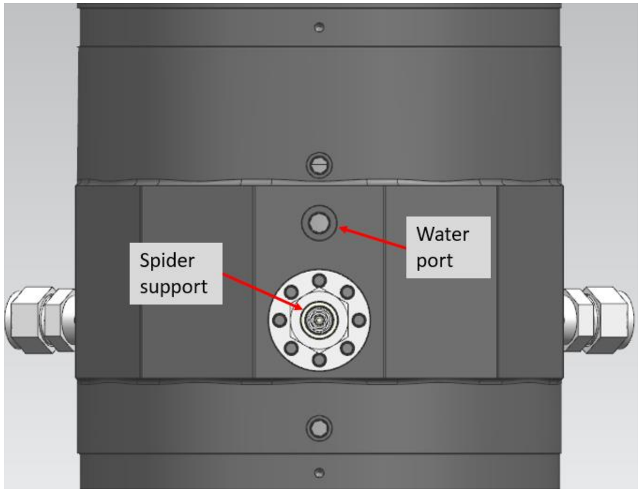


	Initial Depth Measurement (in.)			
Spider Support	h_1	h_2	h_3	h_4
C	0.589	0.309	0.89	1.788
A	0.6	0.3	0.89	1.79
B	0.571	0.309	0.89	1.761

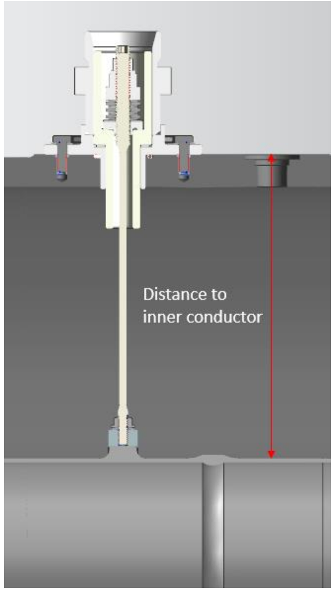
Measuring h_4

Measuring Inner Conductor Position

- Place a depth micrometer over the water port adjacent to the spider support to measure the initial distance to the inner conductor
  - Record its value in the spreadsheet
- Repeat slides 30-33 for the remaining 2 spider supports



Water port location



Distance measurement to inner conductor

Setting Preloads

- For one spider support, tighten the hex nut 1/8 turn (45°) using the hex nut socket while holding the spoke at the top with the spoke socket
  - Use a depth mic to measure h_4 and record
  - Use a depth mic to measure the inner conductor position and record
- Repeat for the other spider supports

Using the hex nut and spoke sockets to tighten hex nut

Setting Preloads

- Continue alternating between the spider supports, incrementally tightening the hex nut 45°
- Stop when the spreadsheet calculates that one spider support reaches a preload of 285 lbs
  - Maximum allowable preload

Final Hardware Assembly

- Insert and tighten 12 point nut to 66 ft-lbs on each spoke
  - Use the 12 point nut socket while holding the hex nut with its socket
- Screw on the top Swagelok fitting on each spider support

Completed spider support assembly

Summary

- Major electrical, mechanical, and process assembly steps that could undergo early-stage prototyping have been completed.
  - Corona tests remain for spider support assembly due to ceramic vendor delivery delay.
  - Ceramic puck design that separates striplines at remote clamp now mimic analyzed design for pucks on 12” wide PS bus. Prototyping expected this year.
  - Our stripline will have these features machined late, just before plating.
- Ceramic materials & design features that represent bulk of cost & complexity have passed all EE support tests & meet all EE support requirements for surface path length, voltage isolation, & electric field stress.
- Drawing packages are updated to reflect tested geometry.
- We are ready for full scale prototype production.

Questions?