MAP Cavity Status Review

SLAC National Accelerator Laboratory

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May 2014

Summary of Review

- Cavity Fabrication Overview
- Initial RF Testing
- Problem Diagnosis
  - Mechanical Inspection
  - Mechanical Simulation
  - Diagnostic RF Testing
  - Diagnostic summary, interpretation
- Solution
  - Requirements/constraints
  - Review of some options
  - Proposed solution
- Recovery Schedule and Cost Estimate

Some Acknowledgements

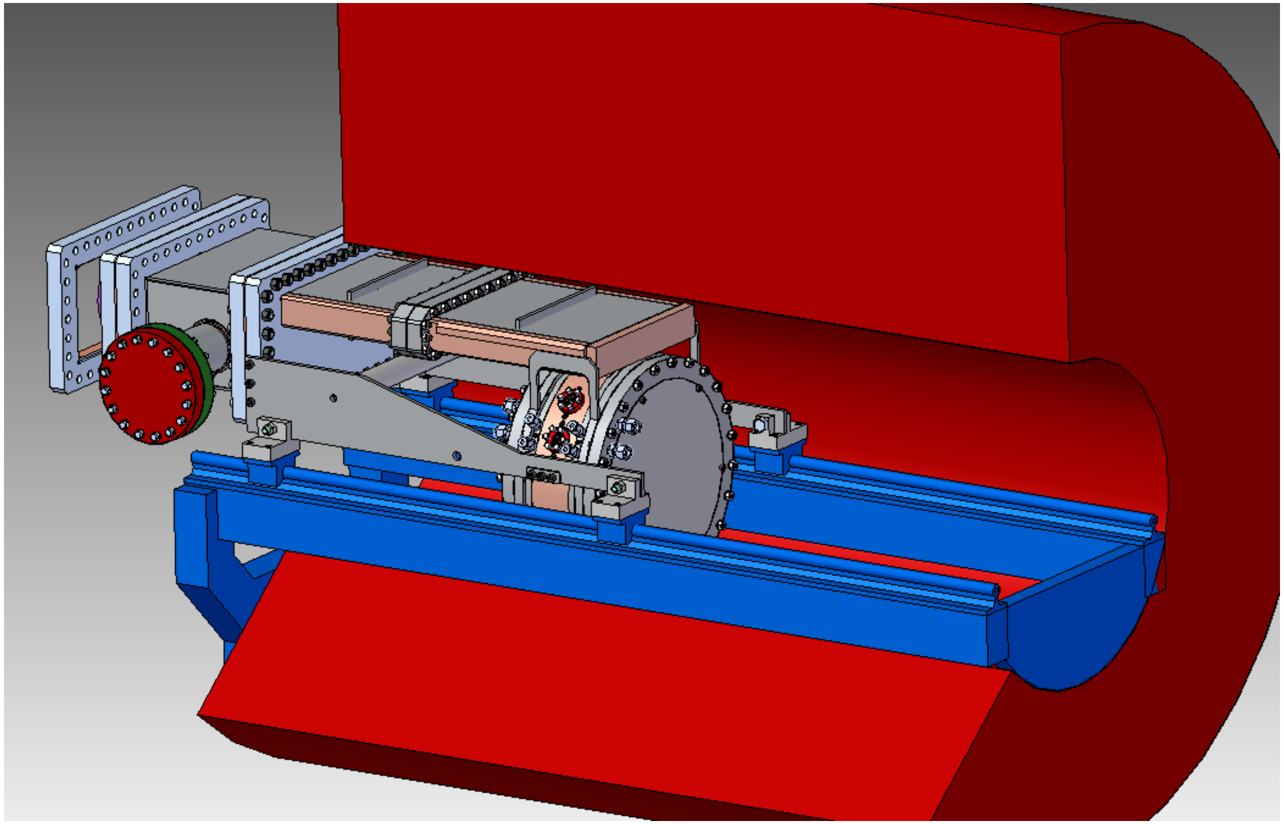
- Considerable support in collaboration provided by staff from LBNL, FNAL, and SLAC
- Special thanks to
  - Daniel Bowring
  - Tianhuan Luo
  - Erik Jongewaard
  - Chris Pearson
  - David Martin
  - Chris Adolphsen
  - Derun Li
  - Mark Palmer

Cavity Fabrication Overview

- Collaboration between FNAL, LBNL, and SLAC to fabricate a test cavity and waveguide assembly for exploring cavity operation in high magnetic fields
- Key characteristics
  - Designed for lower off axis surface electric fields
  - All metal seals
  - High temperature processed and vacuum fired
  - Titanium Nitride coated in select areas
  - Field replaceable end plates
- Pictures and drawings of some of the key features and sub-assemblies are shown in the following slides

Top Assembly Overview

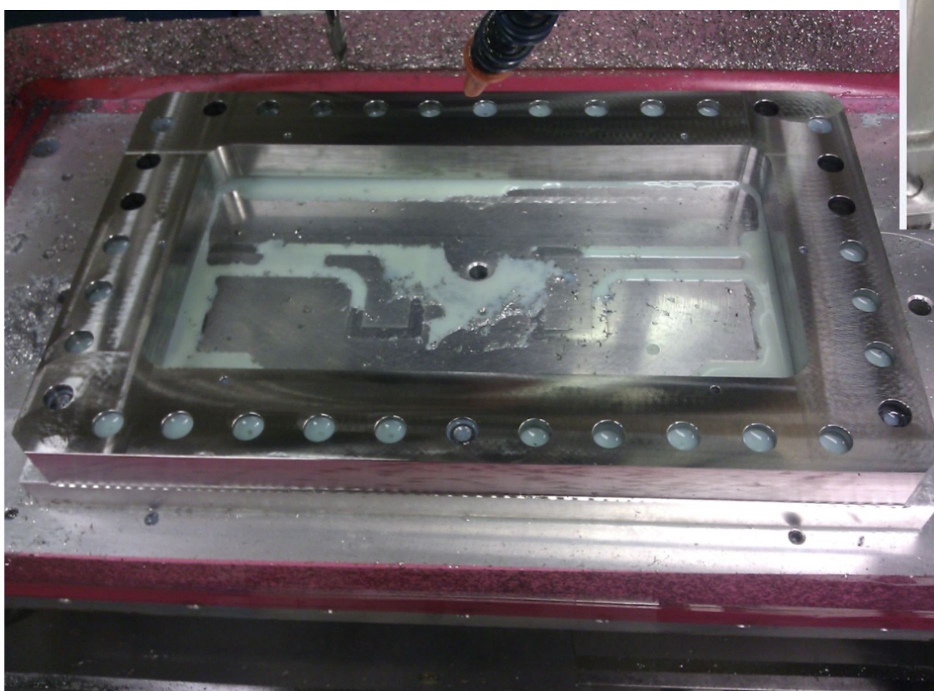
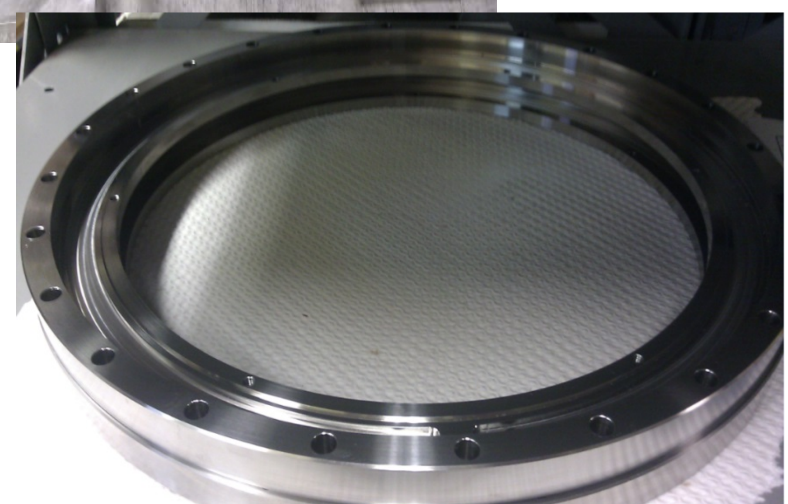
- Cavity and waveguide assembly shown installed in the test Magnet
- Window/feed and vacuum components not shown



Early Fabrication

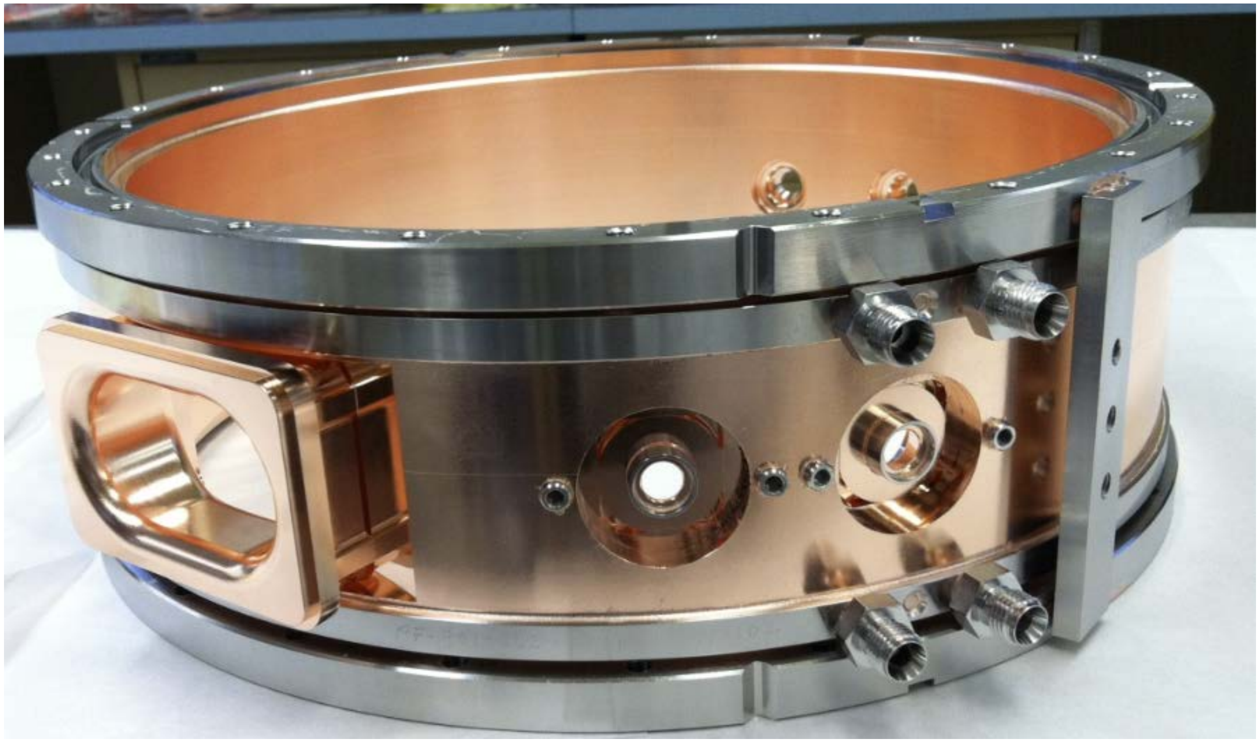
- Manufacturing began early 2013



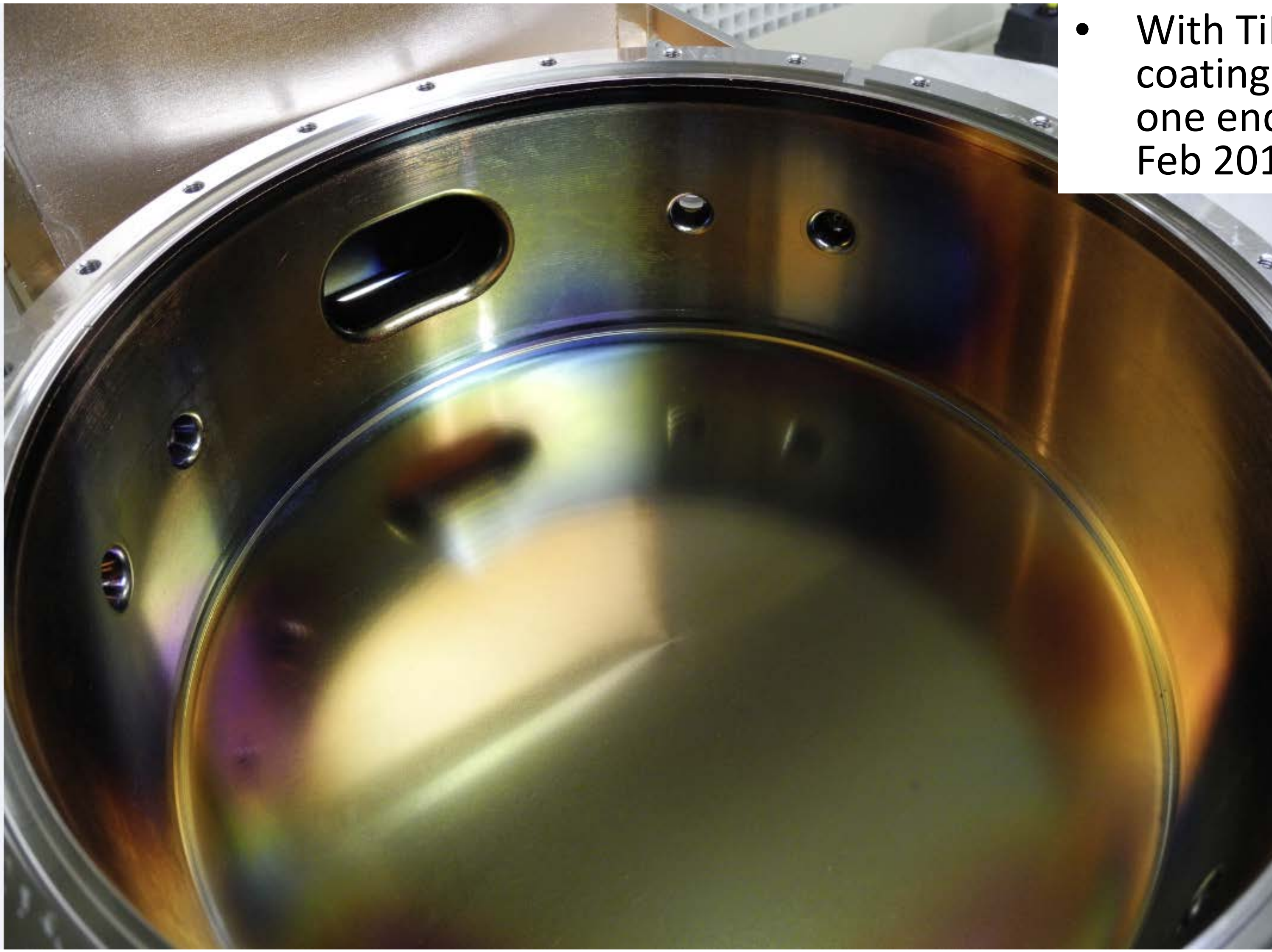



Cavity Body Braze

- Cavity final braze prior to cutting ID Fall 2013

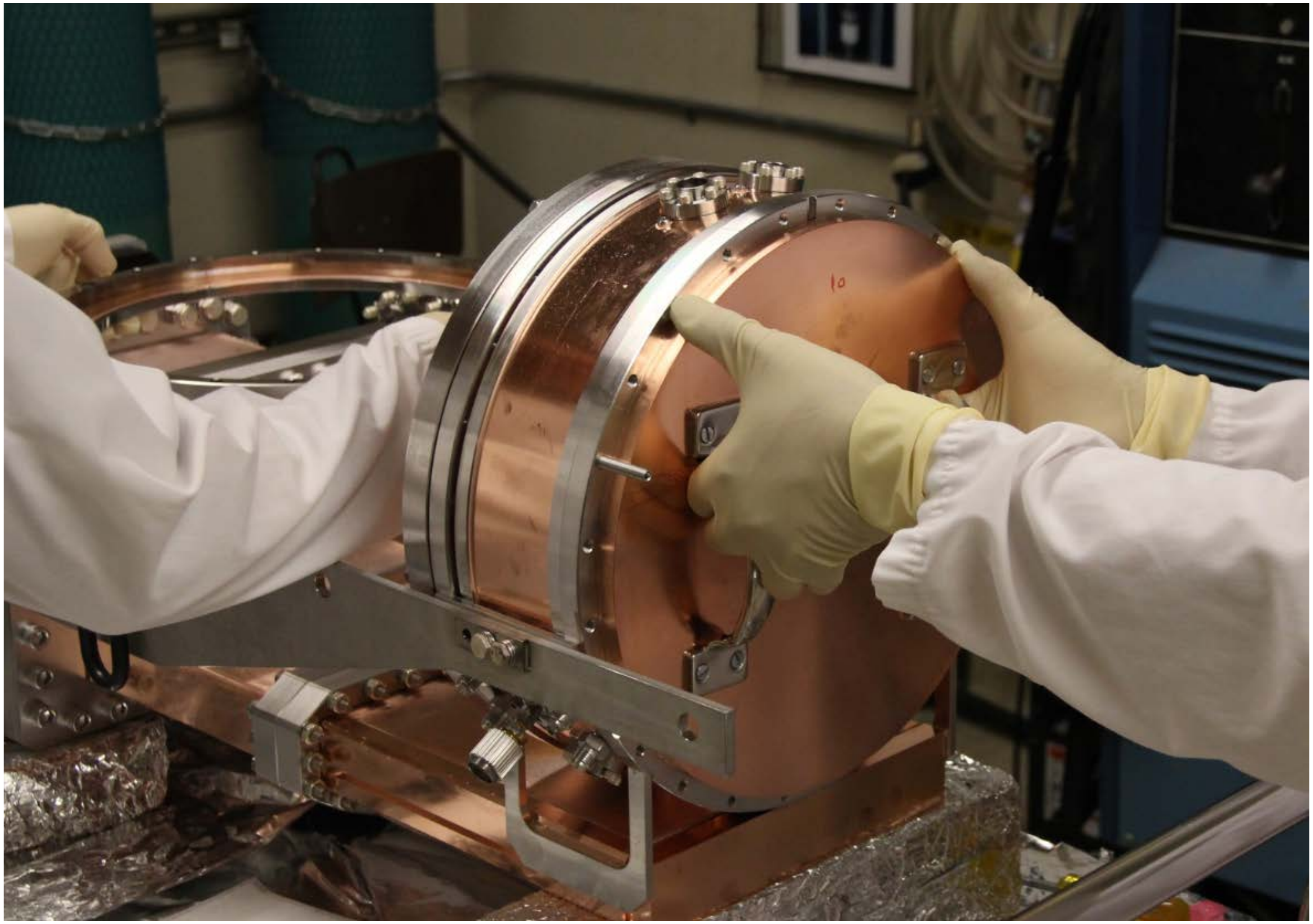


Cavity Assy



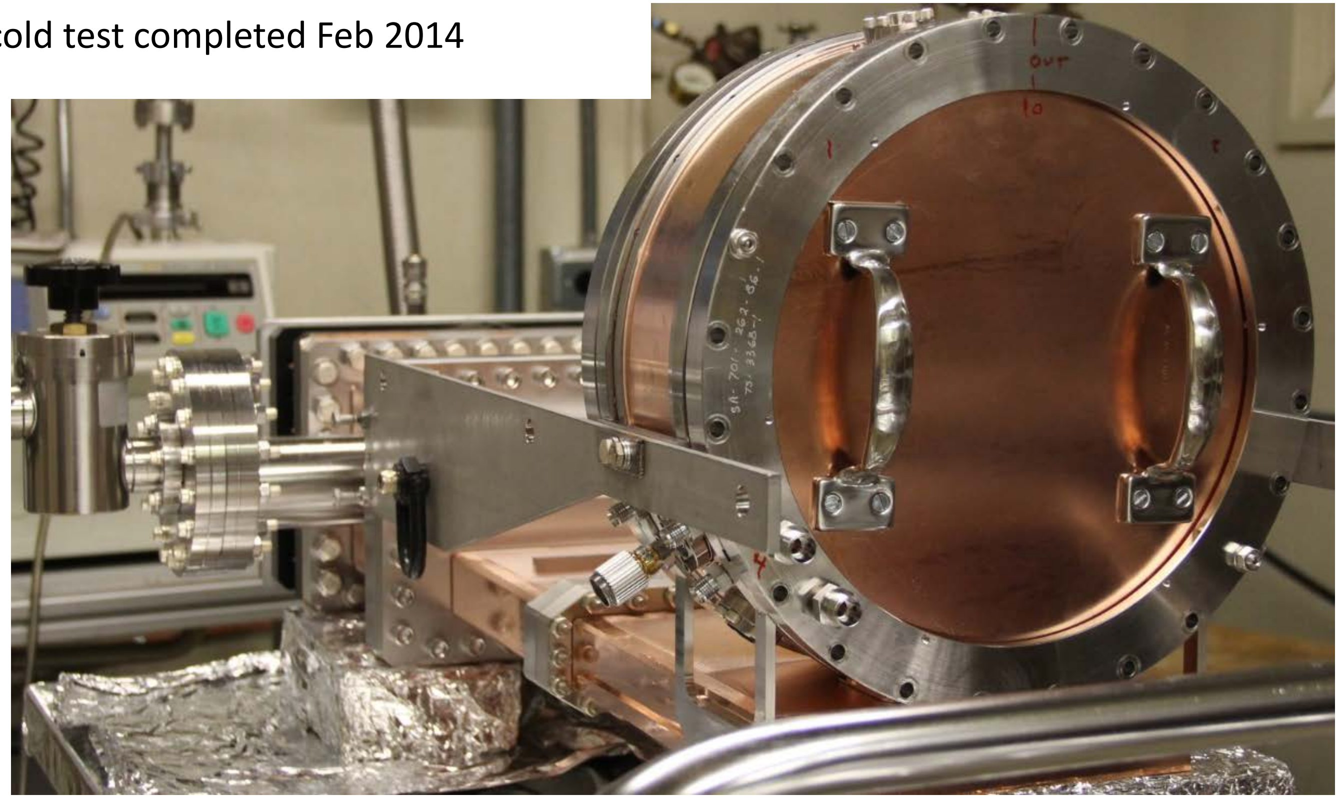
- With TiN coating and one end plate Feb 2014

System Assembly



Build Complete

- Unplanned work delayed final assy ~5 Months
  - Design issues
  - Parts fabrication
  - Cu plating
  - Process error
- Final assembly and cold test completed Feb 2014

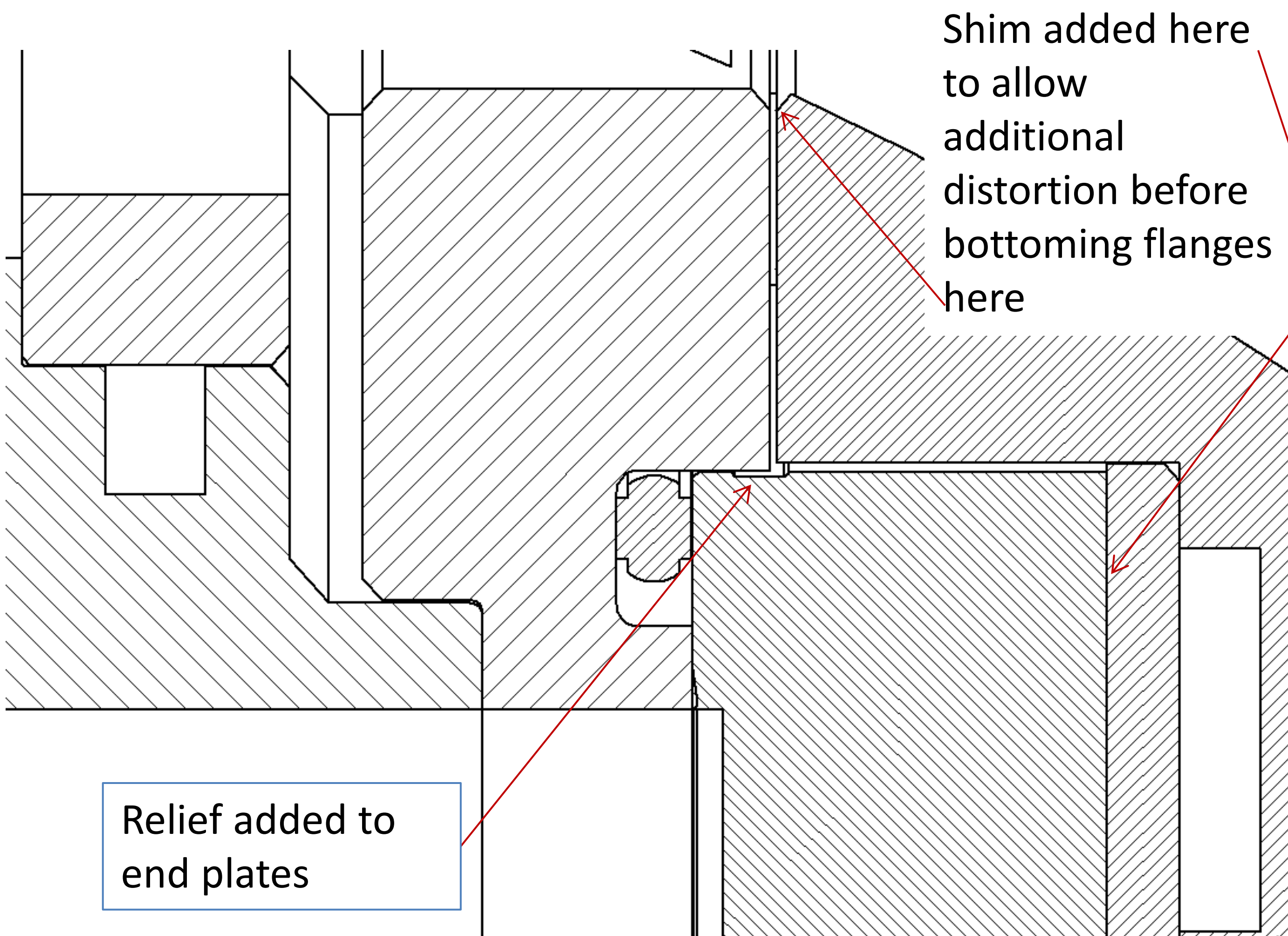


Initial RF Testing

- First RF testing at the end of February
- The results indicated significantly lower cavity Q_0 and coupling than expected/required
- Initial observations
  - Significant flange distortion
  - One of the end plates had hung up on the cavity flange and was not properly seated
  - It was decided to modify the end plates to reduce the potential for binding and add a clamp spacer to allow for additional flange load

Flange Relief Modification

- Close-up cross section showing relief added to end plates to help prevent flange rolling from grabbing the end plate OD
- Axis is horizontal and below the image
- Cavity is on the left, clamp flange is on the right
- Original flange gap and cooling plate thickness is shown
- Gap with completely rigid components, as shown is .009”
- Fit tight to maintain alignment



Post Corner Relief Cold Tests "The Problem"

- Once the end plates were modified two additional rounds of RF testing were completed by 3/14
- Observations from these tests were summarized by Daniel Bowring as:
  - The cavity is significantly under-coupled.
    - The measured Qext = 21540 at full clamping strength is higher than the simulated Qext = 15141 (assuming Cu end plates).
    - The measured Q0 is unstable and depends strongly on flange bolt torque. We have observed 8500 < Q0 < 14000. Compare this with the design Q0 = 25600.
  - The cavity design is intentionally over-coupled.
    - Experience in the MTA suggest clamping losses may lower the Q0 by roughly 30%. For Cu end walls, the design $\beta = 1.7$ might then result in measured $\beta = 1.1$.
- During the tests it was noted that the RF measurements did not stabilize at any level of end plate fastener torque applied
  - After approaching the design targets the performance began to degrade with additional fastener torque above ~100 in-lbs
- Significant flange distortion was noted by unaided eye.

Diagnostic Work

- RF results could result from
  - external components
    - Window
    - Adapter
  - Waveguide geometry
  - Cavity/coupling iris geometry
  - End plate contact (most suspect)
- Work to verify that end plate contact was the sole or very dominant contributor to the RF performance problems involved:
  - RF simulations , review of sensitivities and nominal mechanical design dimensions
  - Mechanical measurement
    - Quantify the observed distortions
    - Validate simulations
    - Verify “built to spec”
  - Mechanical simulation
    - Simulate existing design, evaluate for possible root cause
    - Simulate possible design changes
  - Additional RF test
    - Assemble with RF contact gasket and w/o the vacuum seal to measure RF performance with good contact assured

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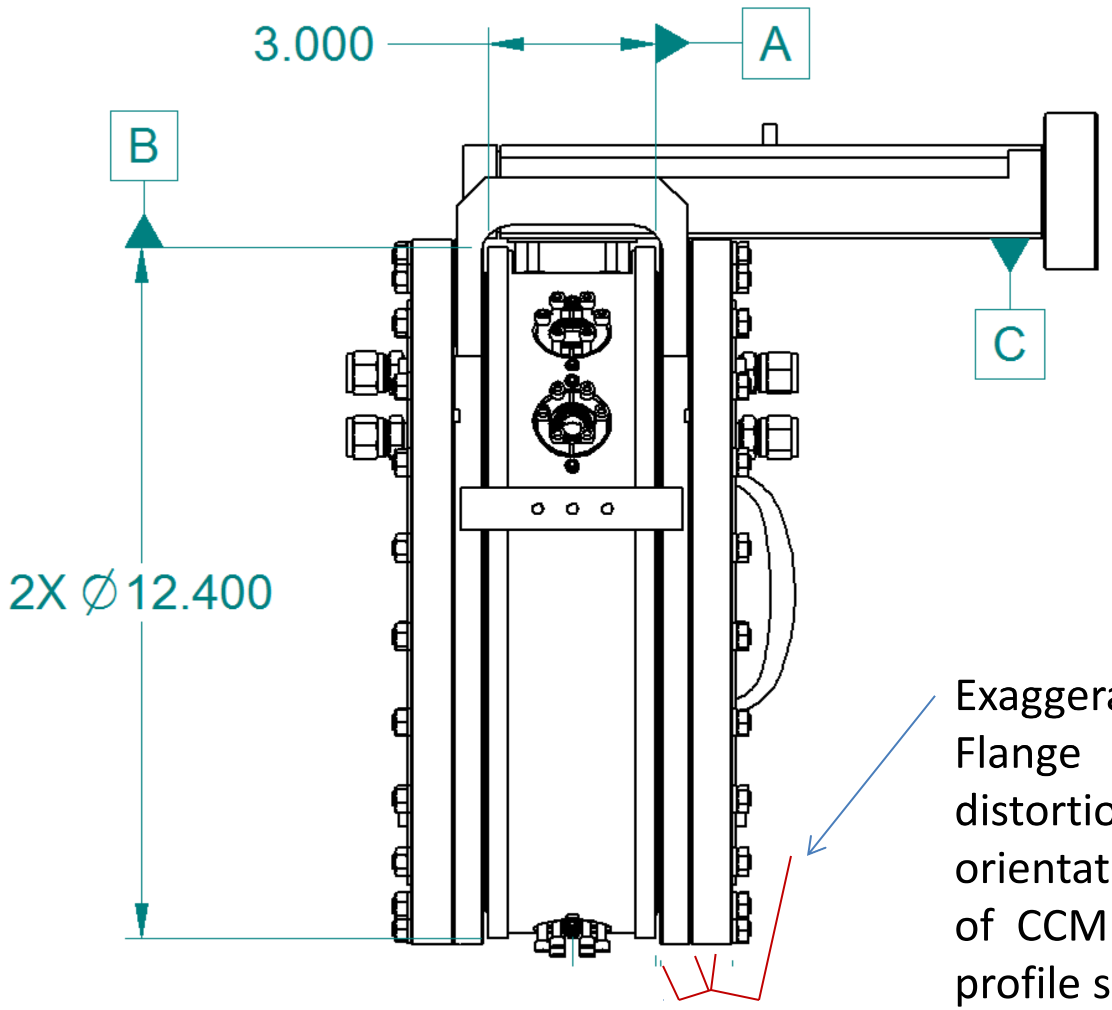
Measurements of Clamped Assembly

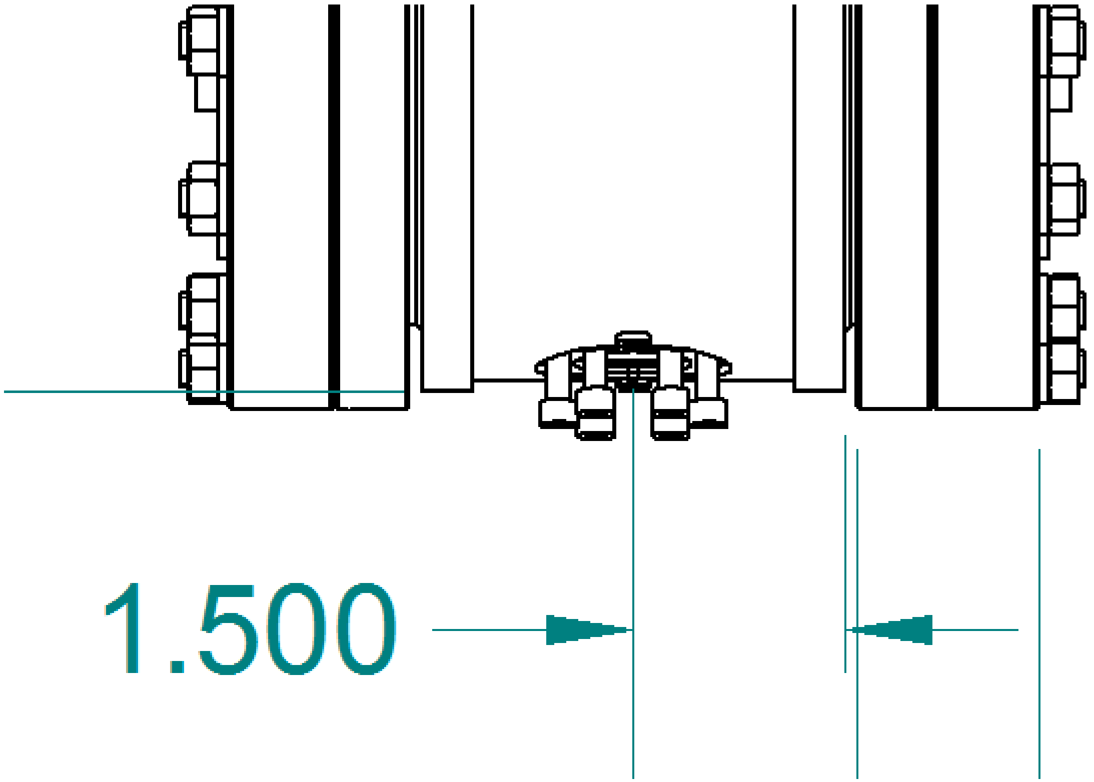
- Datum Structure established as shown



Exaggerated Flange distortion, orientation of CCM profile scans

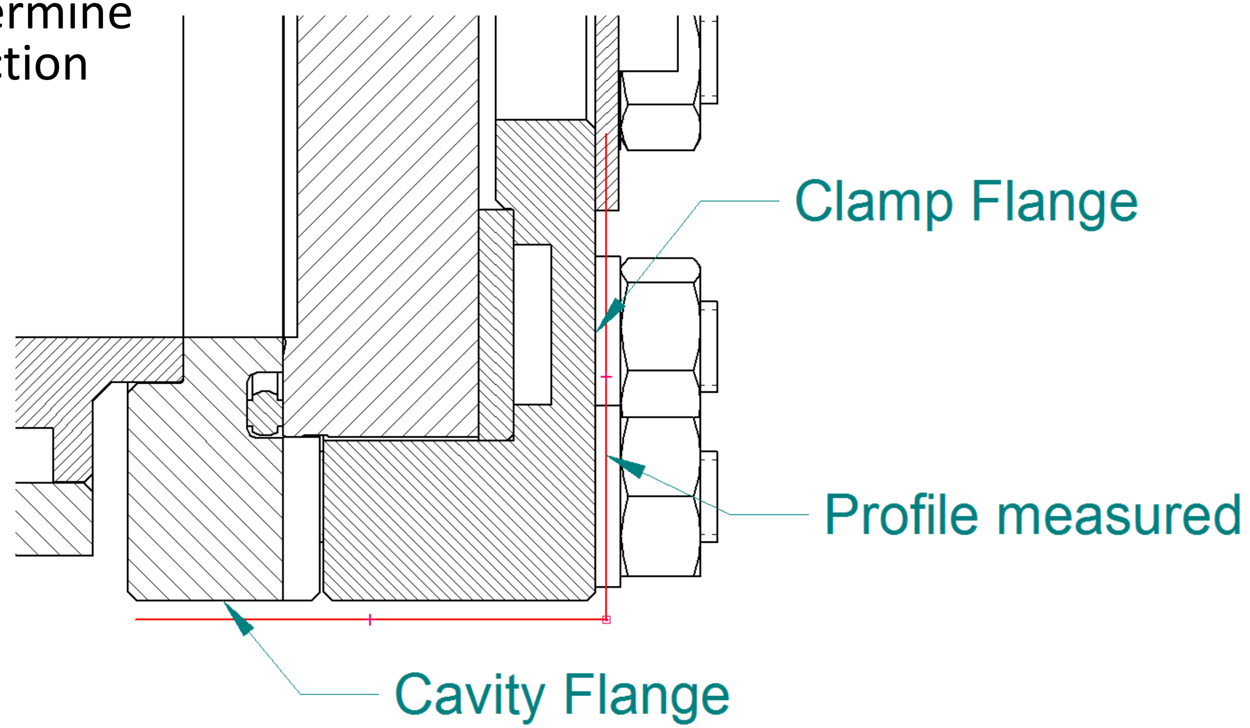
Distance to Face of Water Rings

- Nominal 1.5” spacing measures 1.501 flat w/in .007 on one end and 1.502 flat w/in .003” on the other



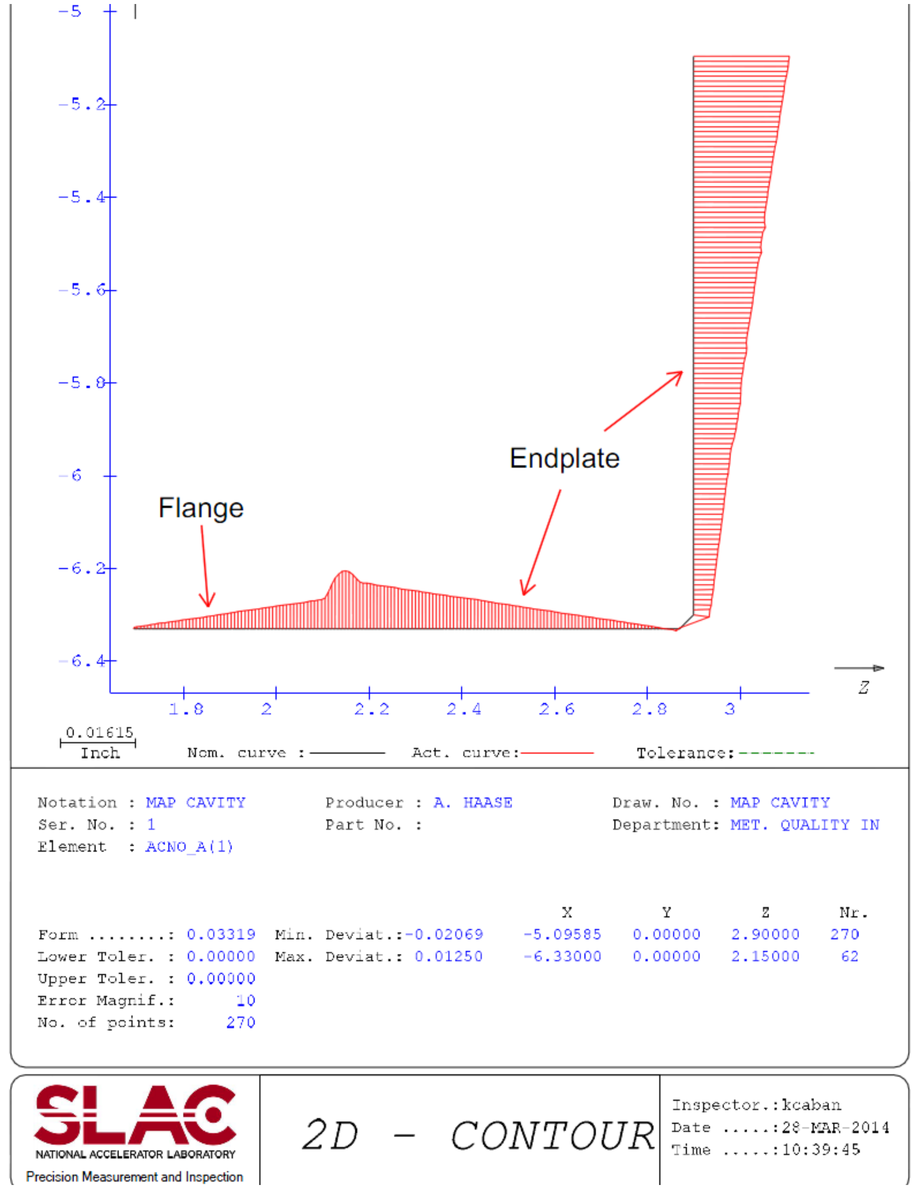
Flange Distortion

- The exposed surfaces of the cavity and clamp flange were measured at several locations to determine the profile in section as shown



Profile Along Outside of Clamped Flanges

- CMM measurements confirm significant flange distortion
- Image shows OD of cavity “flange” on the lower left and the OD and end face of the clamp ring (called “endplate”)
- The red lines show deviation from a perfect cylinder with perpendicular end face (shown in black)
- The ~.02” of flex over ~1” of end plate indicates ~1° of flex

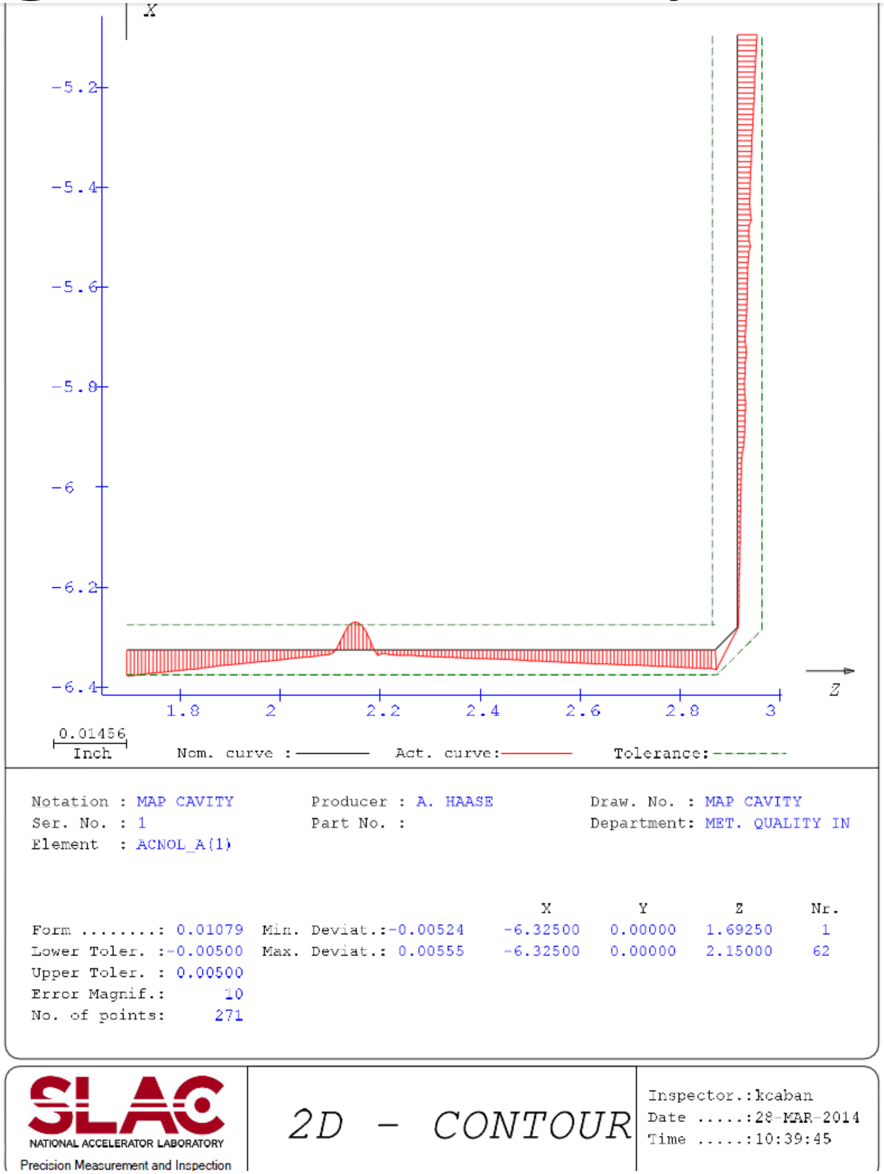


Residual Flange Distortion

- Once the clamp rings and end plates were removed the cavity flange was measured in a free state.
  - Measurements show plastic deformation of the flange in “rolling”
  - Little permanent deformation of the RF contact features
  - A key feature is localized distortion resulting from the two support bar “ties”
- Following slides document key findings

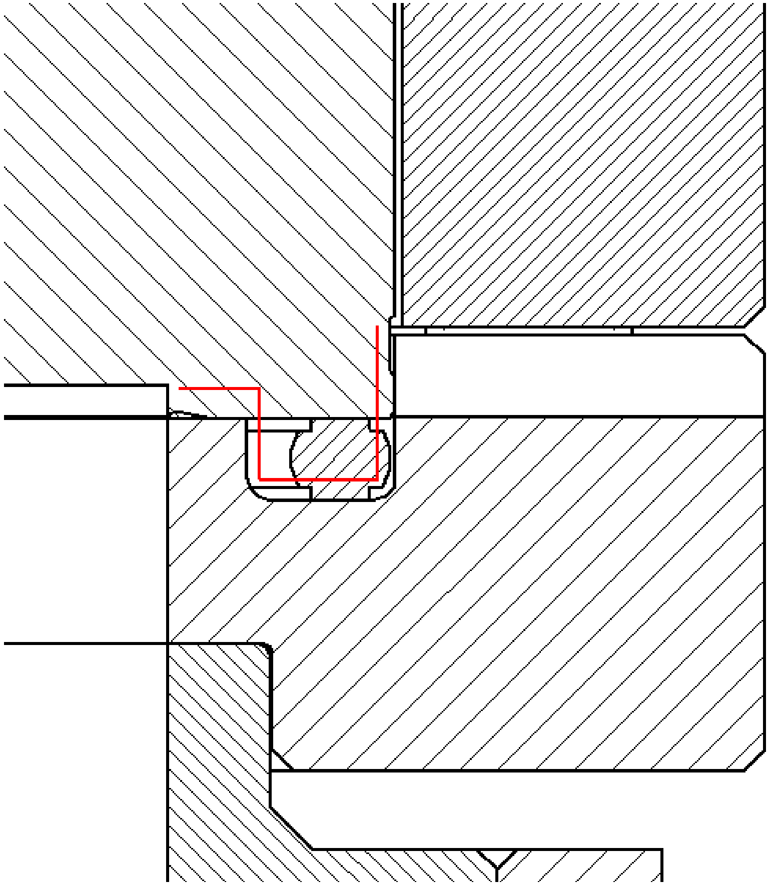
Profile of Flanges Post Clamped

- Flange measurements confirm plastic distortion
- Image shows OD of cavity "flange" on the lower left and the OD and end face of the clamp ring on the right
- The red lines show deviation from a perfect cylinder with perpendicular end face (shown in black)
- The roughly .005" over 1" on the end plane indicates ~.3° residual flex



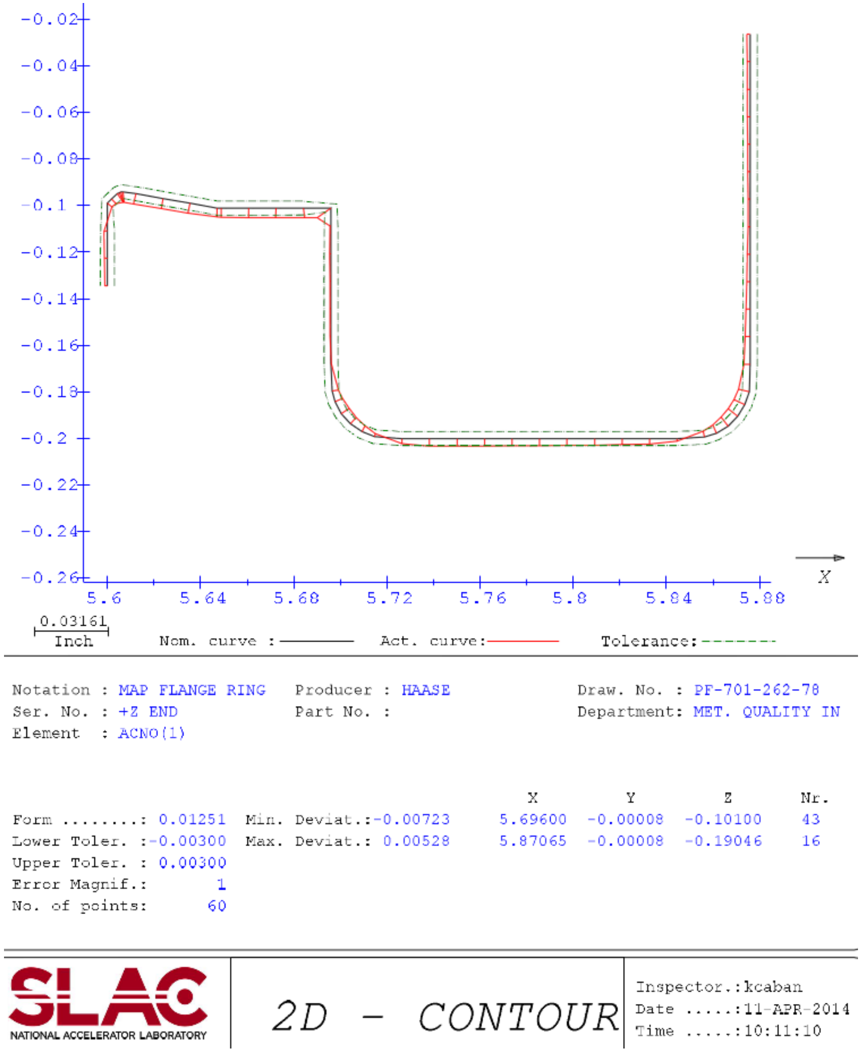
Cavity Flange Profile

- Once the end plates were removed the vacuum and RF contact surfaces were checked for conformance with design



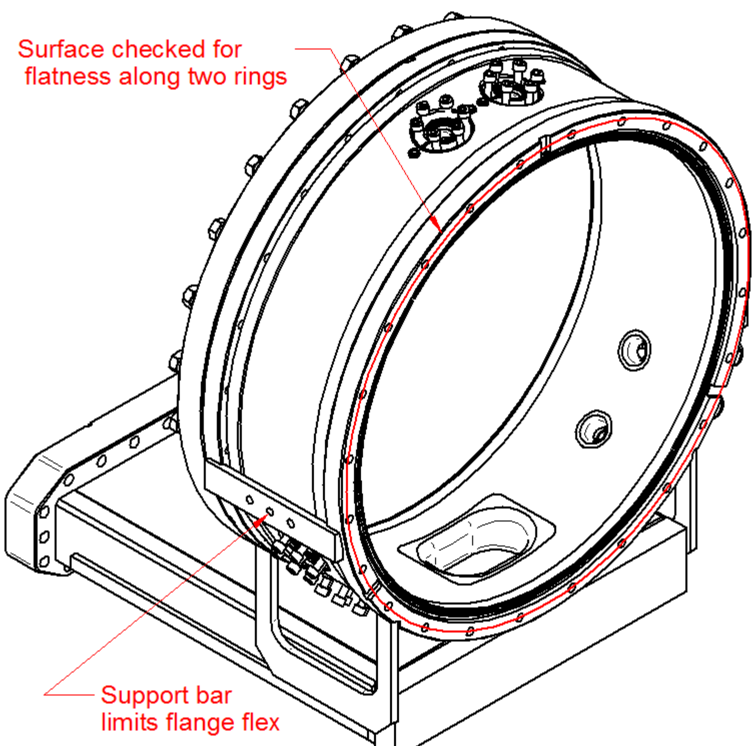
Flange Contact Feature Measurement

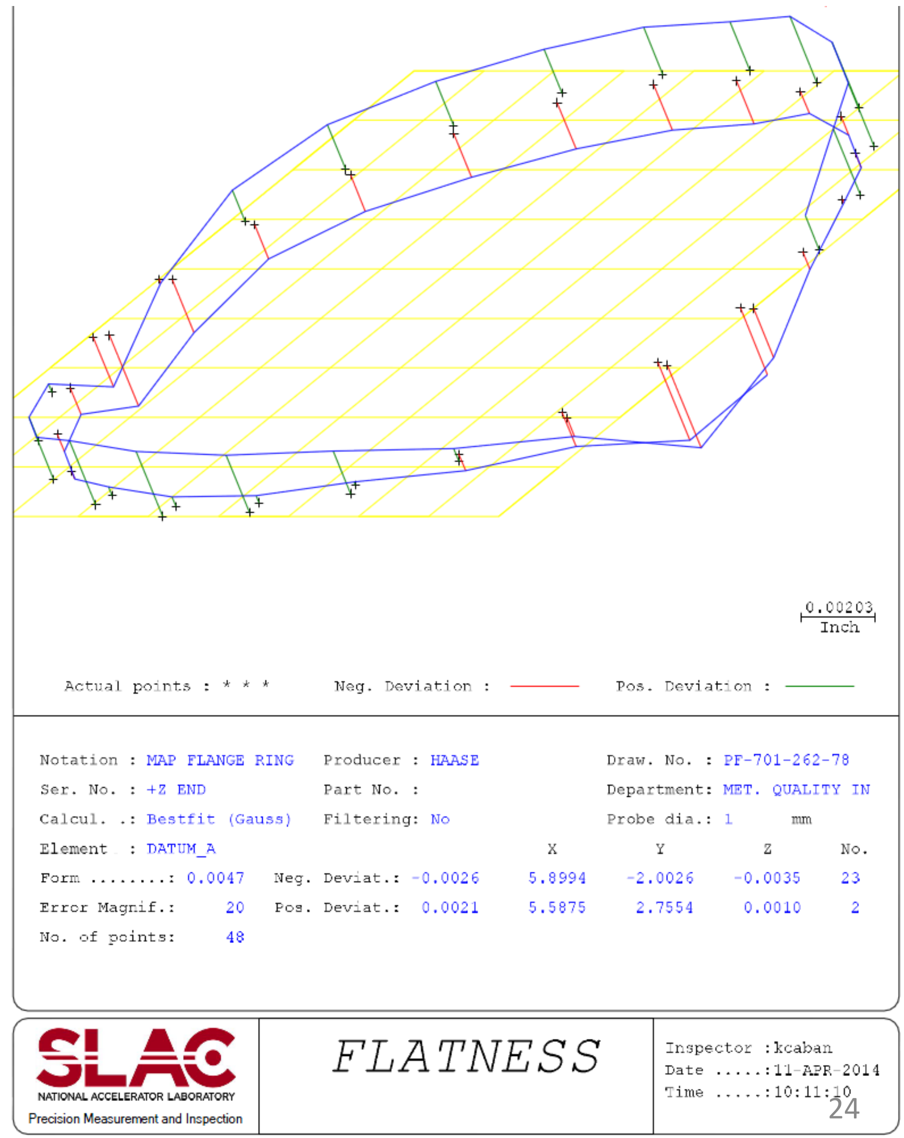
- The profile of the cavity flange at the vacuum and RF contact surfaces was measured at several points around the circumference
- Measurements indicate little localized distortion to the seal and contact surfaces



Cavity Flange Plastic Deformation

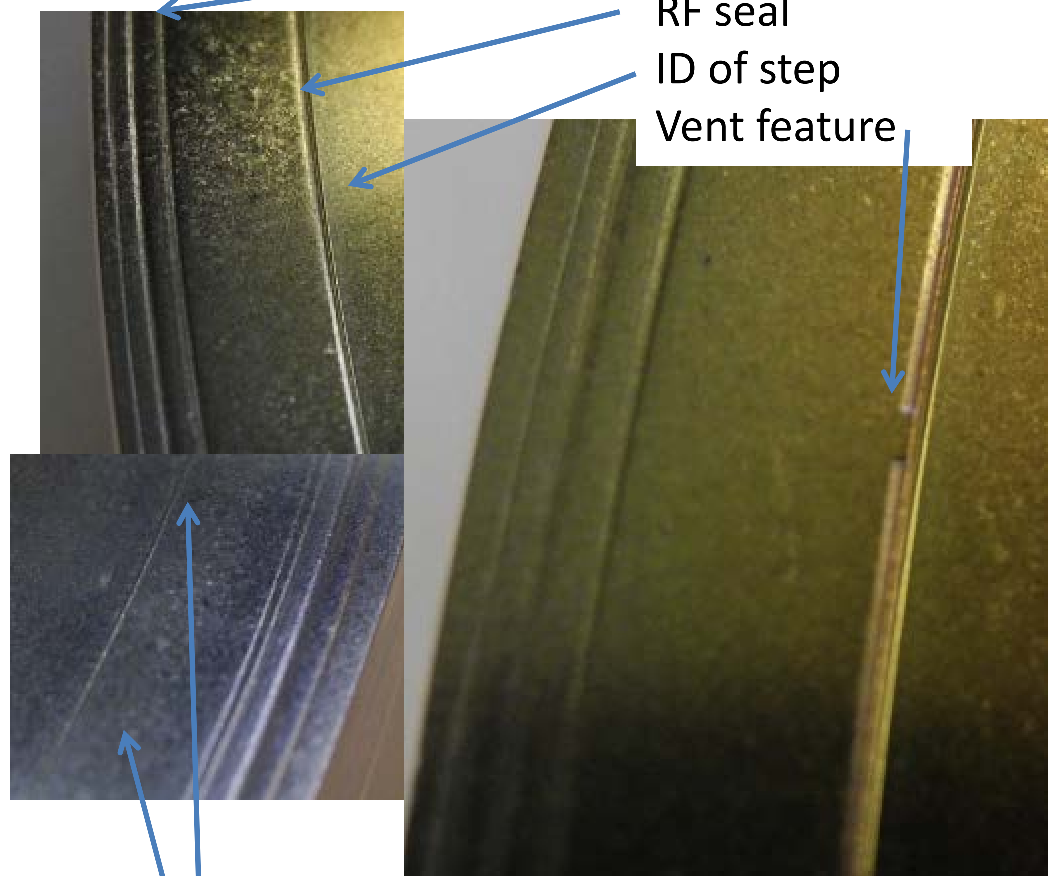
- After disassembly the flange face was measured
- The Nominally flat end face of cavity flange was sampled at two diameters (best fit grid)
- Measurements show residual “roll” of ~.004” (between inner and outer circular samples spaced ~.3” apart)
- The flange distortion is constrained at the two support arm attachment points resulting in “problematic” local distortion





End Plate Contact Impressions

- Inspection by loupe reveals variation and areas of little/no? marking
- The clear discontinuity at one of the pump-out slots (shown at the right) indicates good contact in that region
- Additional contact detail provided later
- At the time of these inspections the significance of the support ties was not recognized and so not specifically studied



Mechanical Simulation

- Mechanical models of the clamp ring and contact features were prepared
  - To better understand observations and measurements
  - To prepare for evaluating possible solutions
  - Several iterations and refinements were made
  - Progressed from simplified axisymmetric approximations to 3D with contact elements and bolt loads
- Next slides highlight some key results of the simulations

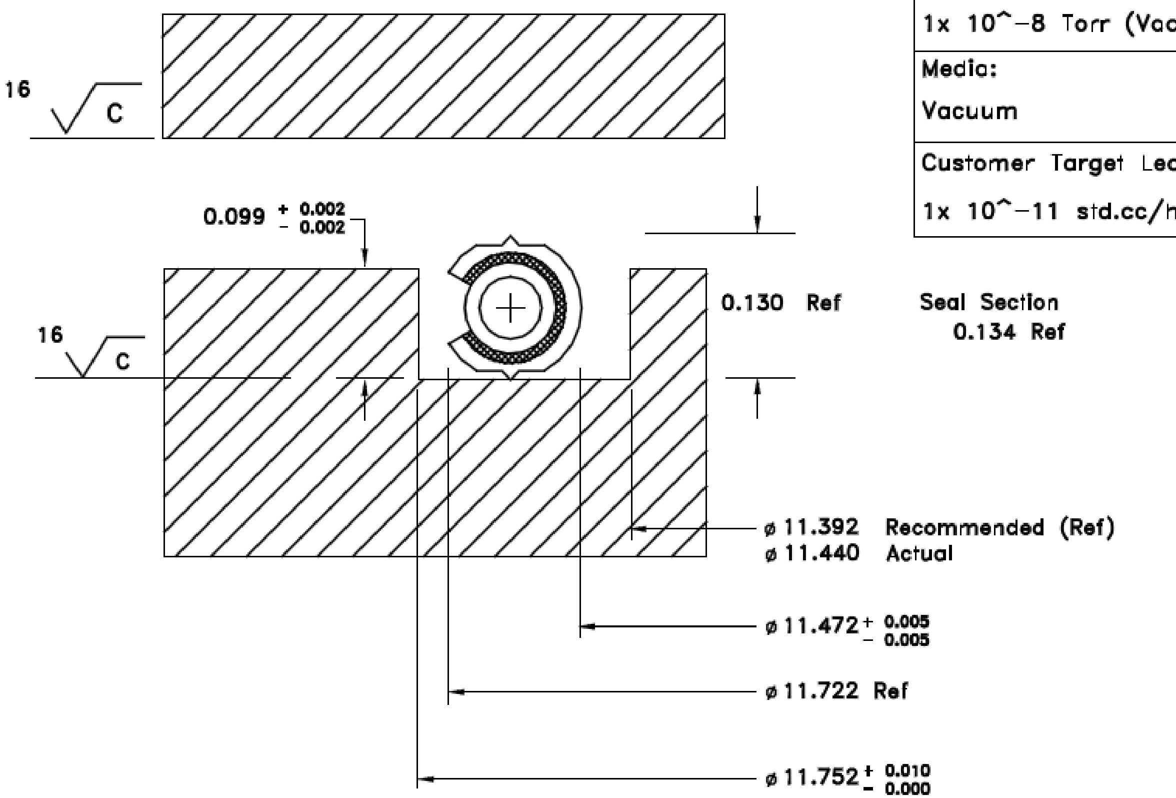
Review Mechanical Design

- Helico-flex “metal O-ring” vacuum seal
  - Aluminum jacket for most compliance to reduce damage to the SST cavity flange
  - Manufacturer specification is 800 Lbs/in to close the seal
- RF contact via contact feature shown earlier
  - Excellent RF contact in previous structures, with annealed copper and geometry has been achieved at ~250Lbs/in
  - Design intent is plastic deformation of the end plate as needed to conform to the cavity flange
  - The raised pad on the end plate can be resurfaced a few time to support repeated assembly
- Gaskets were not used to reduce the number of contact interfaces, improve alignment, and reduce vacuum traps
- Clamp bolts and clamp ring to load the end plate against the cavity flange seals

Details of Vacuum Seal

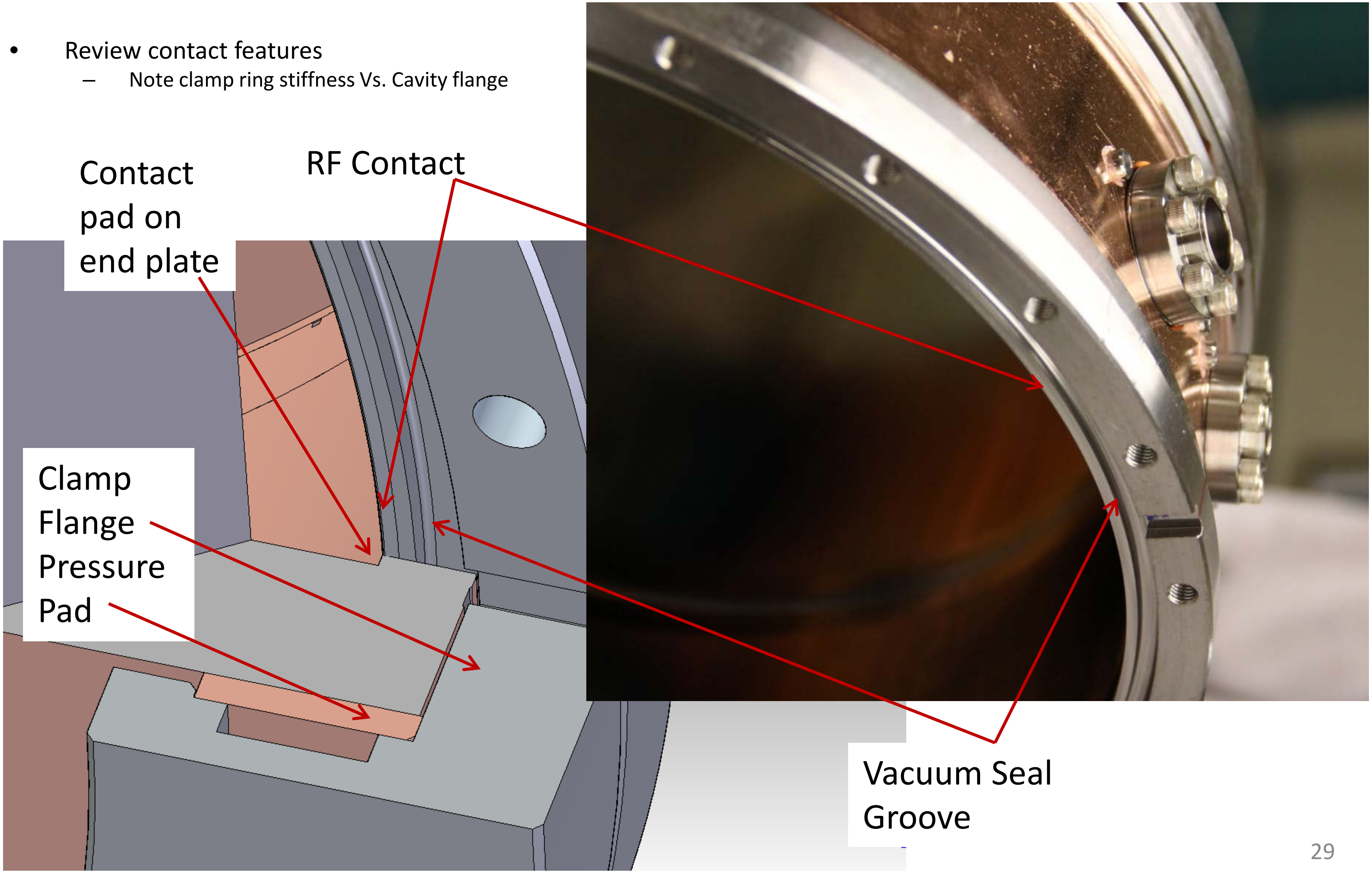
- Notice clearance on diameter allowing additional load/distortion asymmetry

Seal Type HNV 200	Part Number: H-312361	Jacket Material: ALUMINUM
Working Temperature: 122°F (50°C)		Seating Load: Y2 (lbs.in) 800 lbs/in TOTAL: ~ 29,154 lbf
Working/Proof Pressure 1x 10^-8 Torr (Vacuum)		Compression: e2 .031
Media: Vacuum		Min. Flange Hardness: (Vickers) 65
Customer Target Leak Rate: 1x 10^-11 std.cc/he		Scale: none Dimensions: inches Finish: microinches



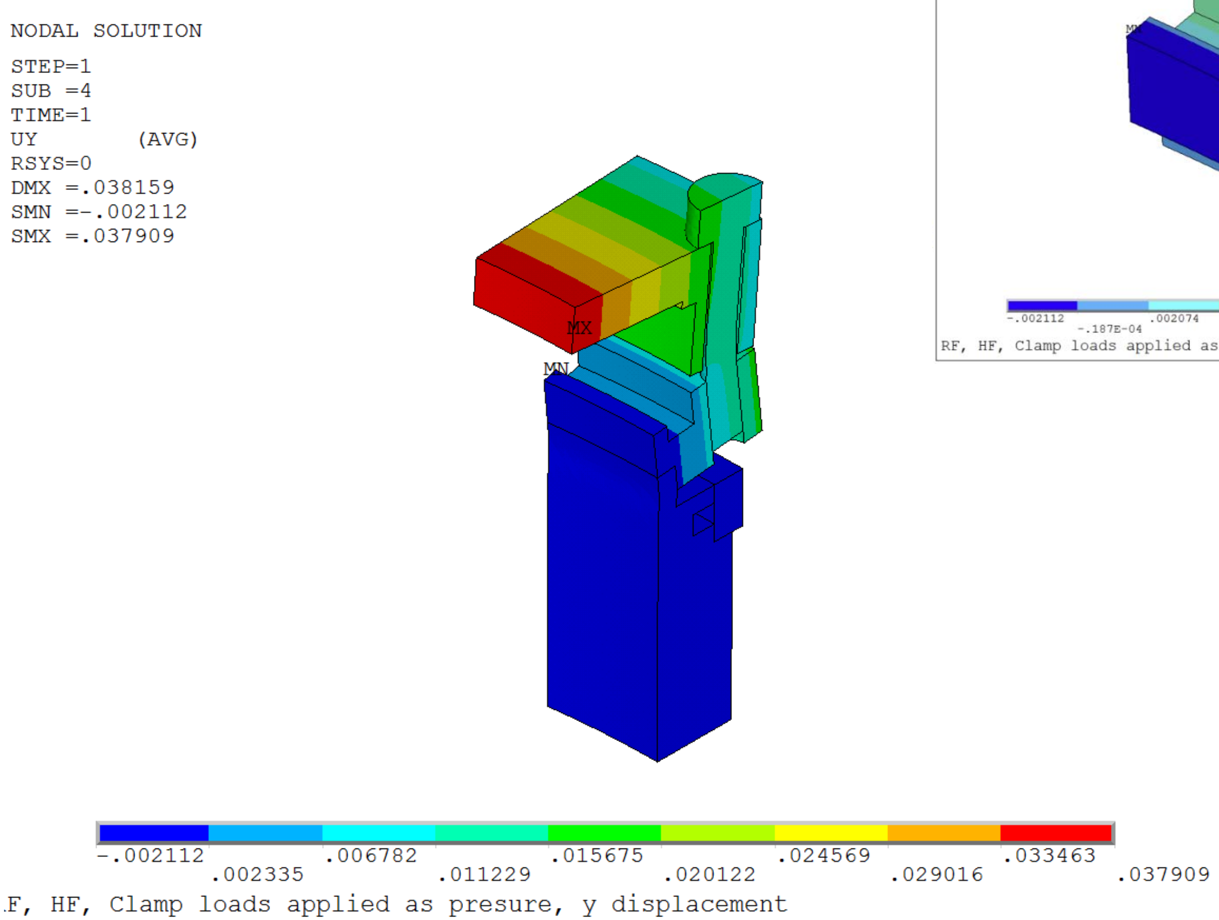
Cavity Flange

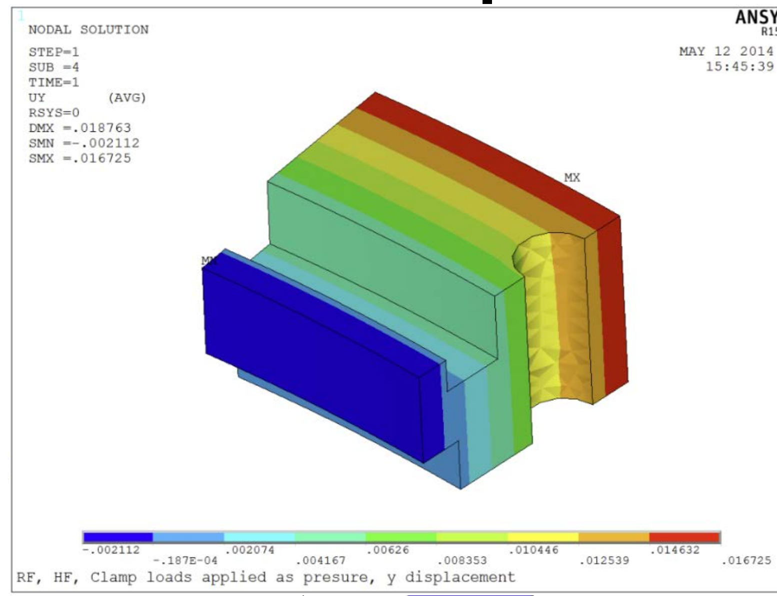
- Review contact features
  - Note clamp ring stiffness Vs. Cavity flange

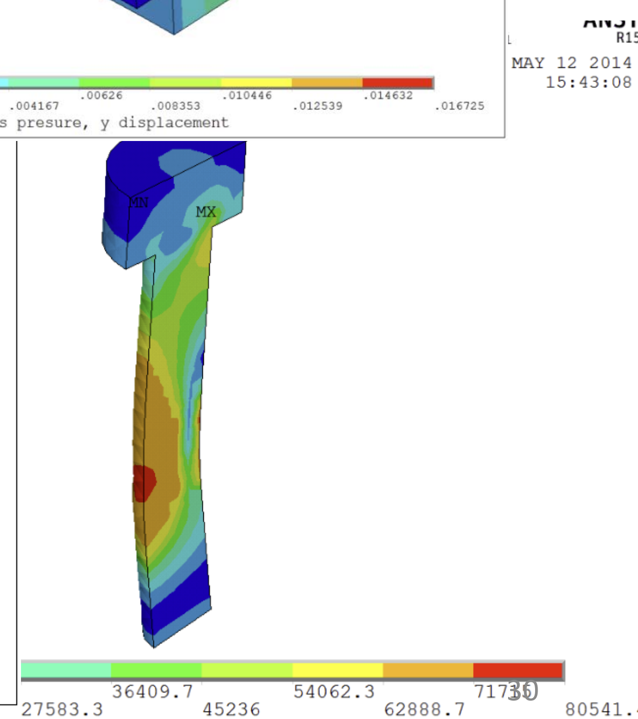


Existing Conditions Clamped

- Design pressure loads (9 and 30 k-lbs) and contact reaction
- Compares well with measurements, see slide 18

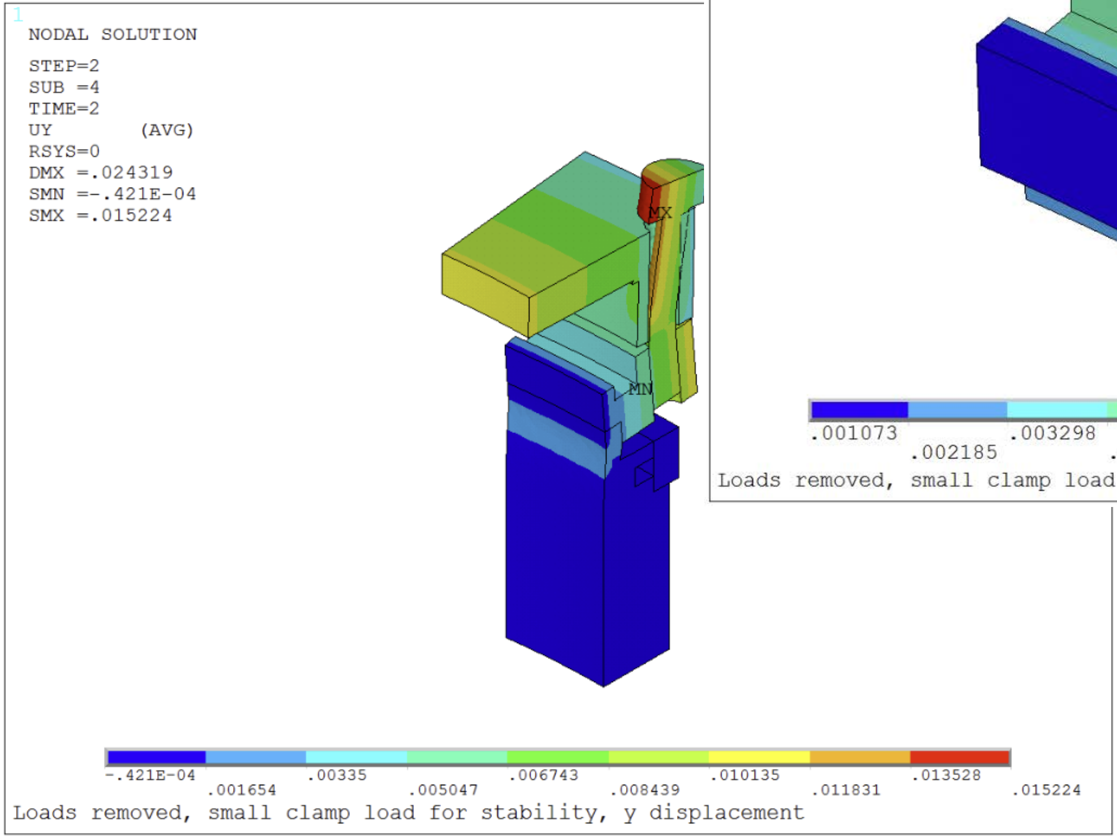


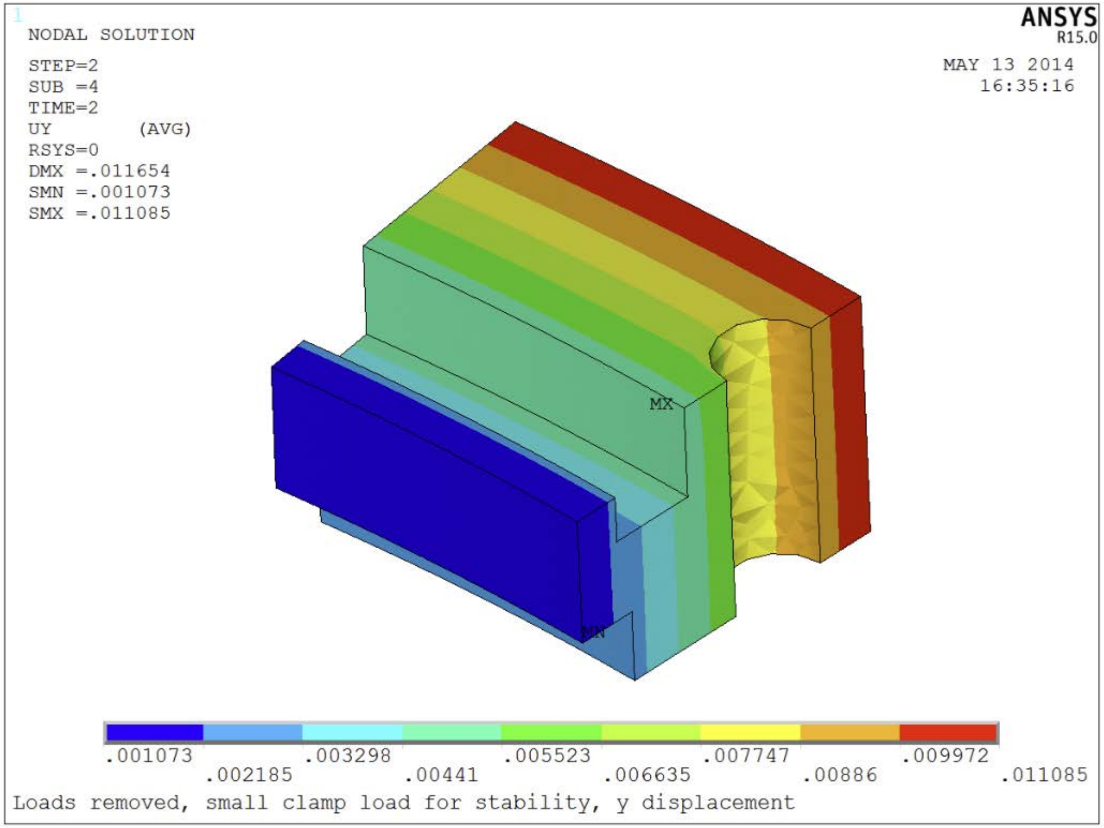




Existing Plastic Distortions

- Plastic deformation also compares well to measurements see (slides 20, 23)

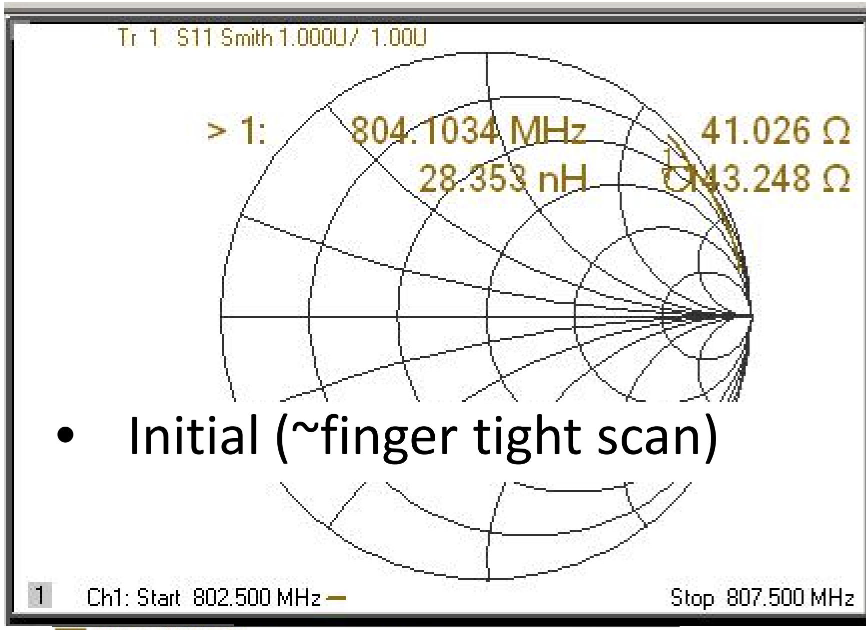




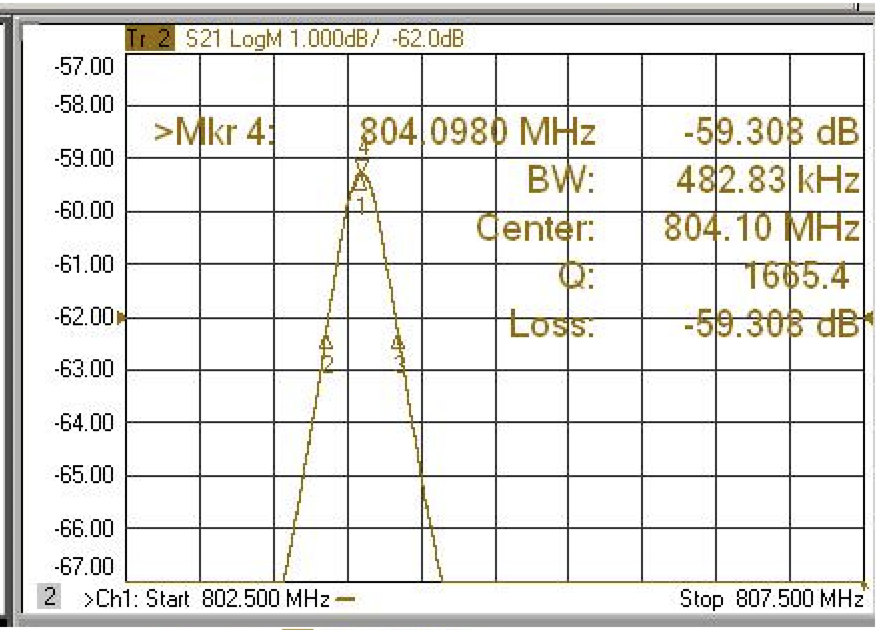
Additional Diagnostic RF Testing

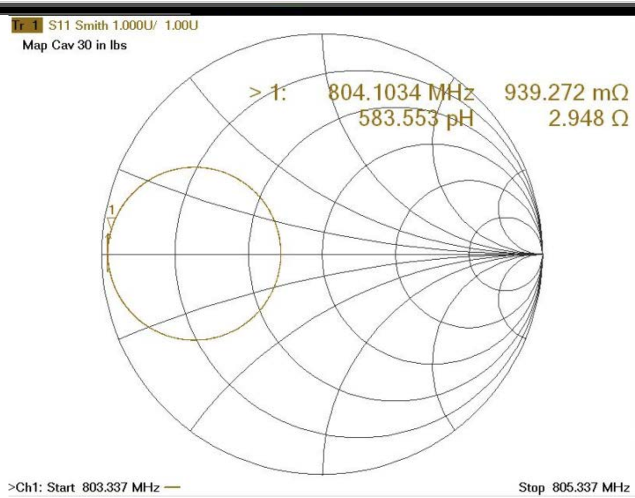
- Annealed copper gasket with pre-crushed Helico-flex ~4/17
  - The results were very informative
  - Design values approached but were unstable and dropped with additional fastener torque before reaching target
- Previously used copper gasket with helico-flex seals removed 5/12
  - The measurements were taken between 80 and 100 in-lbs
  - Results were quite close to design targets and were stable over a considerable range torque
  - See 5/12/14 report by Tianhuan Luo
- Fresh copper gasket without helico-flex seals 5/15, details follow

Diagnostic RF Gasket Test Results

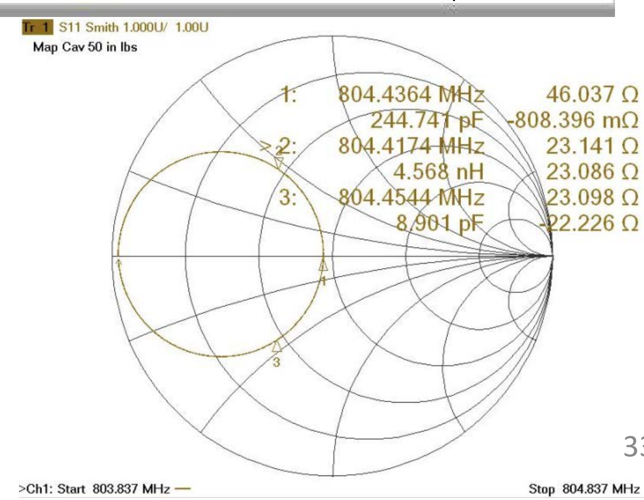


- Initial (~finger tight scan)



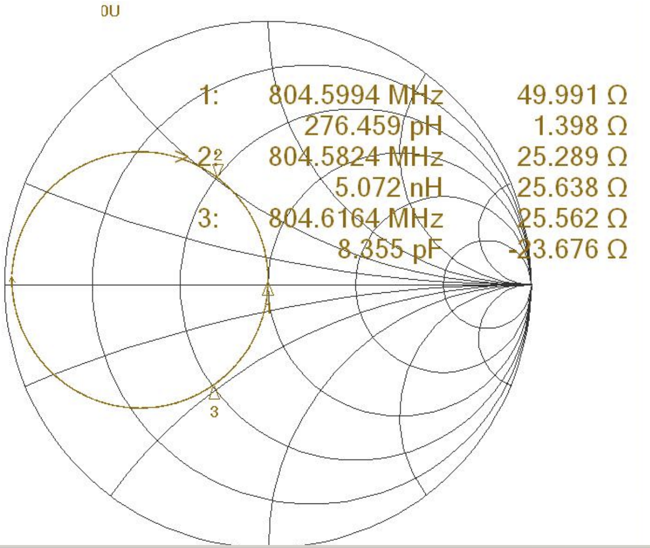


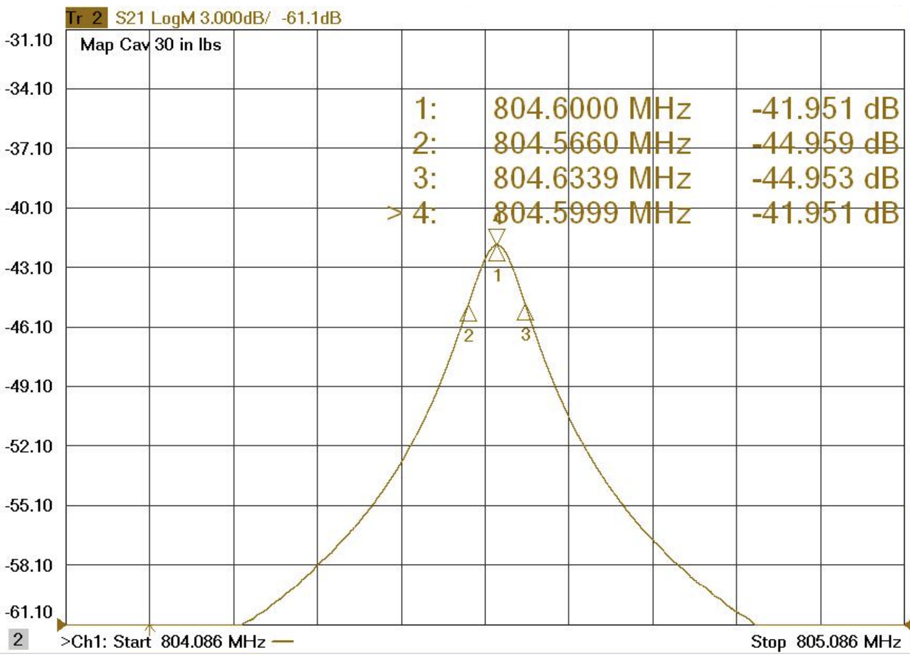
30 in-lbs on left
50 in-lbs on right

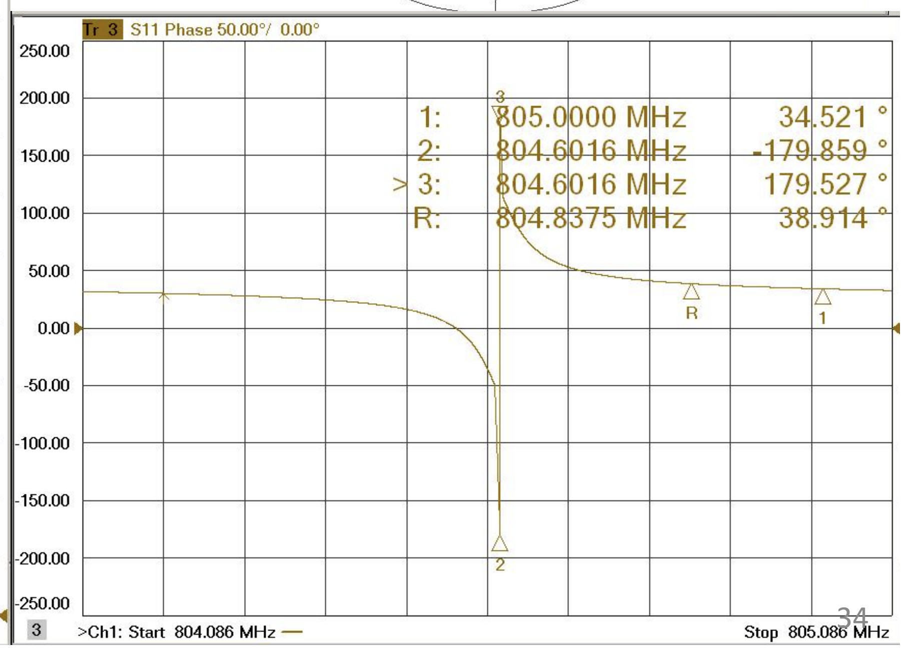


RF Gasket Test Results

- 80 in-lbs
- Q_0=23665
- Q_l=11850
- Beta=.997

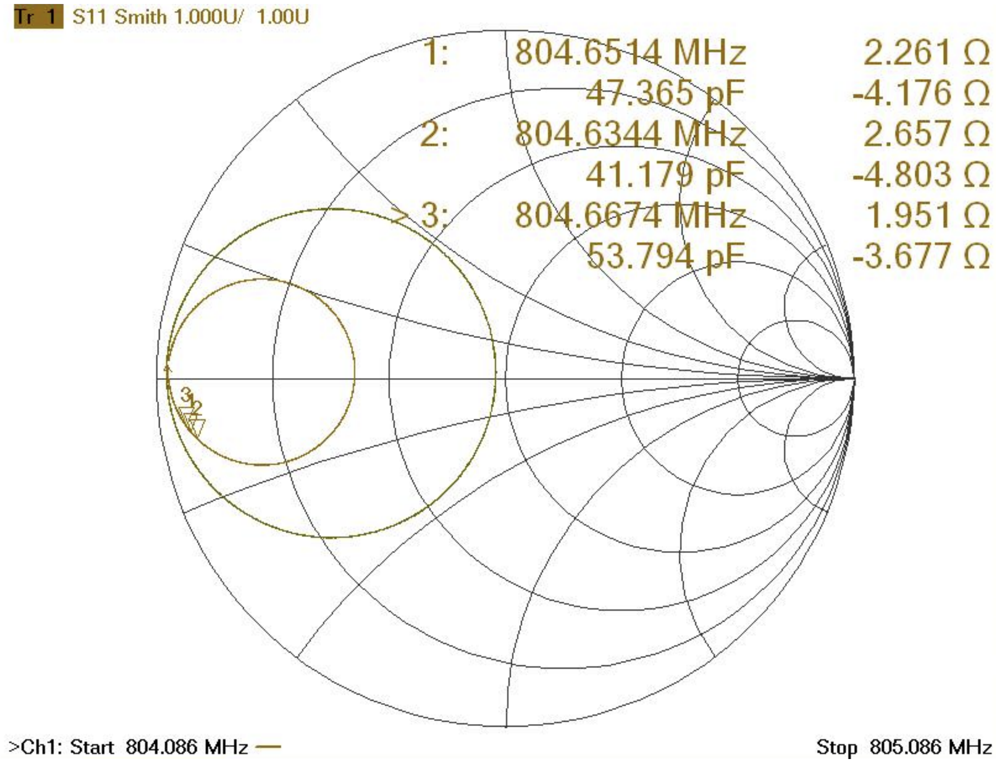






RF Gasket Test Results

- Trace and memory with loosened bolts
- Recovery is nearly complete with just ~1/16 of a turn on one bolt
- Full recovery at 40 in-lbs



Diagnostic Summary/Interpretation

- Summary:
  - Limited measurements of existing features to verify as built, dimensions checked were OK
  - Both mechanical measurement and simulation indicate large flange distortions with RF and vacuum seal contact loads
  - Reviewing the initial tests it was noted that the performance would drop most significantly as bolts in the vicinity of the cavity support bars were tightened
  - RF tests with an RF gasket and pre-crushed vacuum seal indicated little/no range of stability
  - RF tests with soft RF gasket indicate that performance is ~as expected when complete/design end plate contact is achieved
  - RF tests additionally show that performance is altered dramatically with even a very localized region reduced contact
  - RF tests also show that if the contact surfaces are “conformal” little pressure is needed to achieve nominal cold test performance
- Problem verified as poor contact between the cavity and end plates
- Root Cause:
  - A. Flange Flex, non-uniformly
    - As the clamp hardware is tightened the cavity flange is distorted significantly and , due to the support “ties” non-uniformly around its circumference, resulting in a non-flat cavity RF contact surface
  - B. Clamp system too rigid to force end plate into conformance with distorted cavity flange.
  - C. The contact interface has insufficient compliance to “absorb” the mismatch between cavity flange and clamp plate

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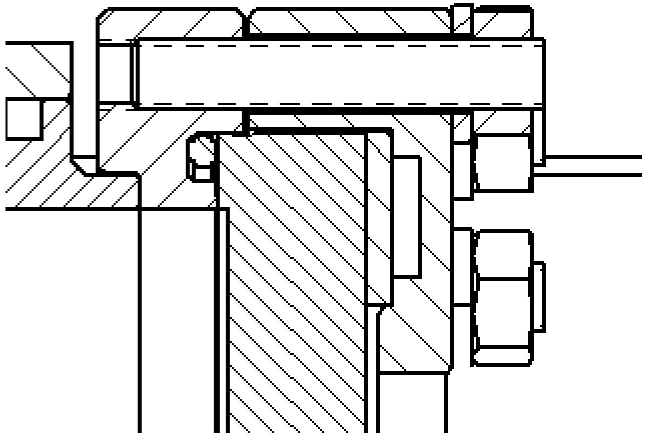
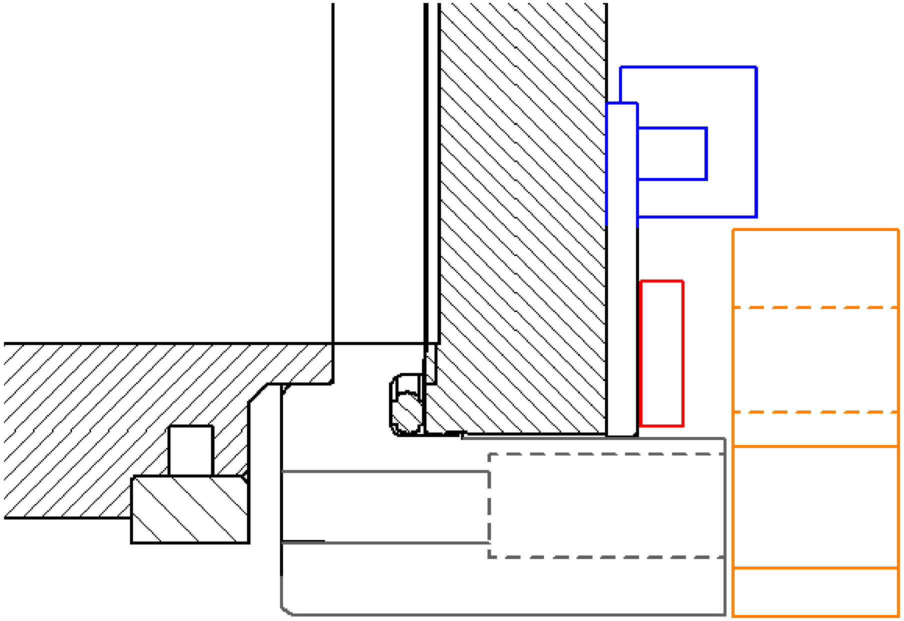
Design Revision

- Based on diagnostic work, and review of other successful designs, the suggested “green field” design changes required to eliminate this performance deficiency are fairly straight forward
  - Increase rigidity of the cavity flange and contact surfaces via new flange geometry
  - Use distributed clamp loading to allow conformance to variation from flat
  - Improve uniformity of flange distortion by eliminating support “ties”
  - Use additional/larger fasteners to provide required clamp loads
  - If changes in anticipated use require repeated test of individual end plates consider incorporating an RF gasket

What Should Have Been

- Existing Vs. Improved





Recovery Solution Space

- Requirements
  - Maintain UHV standards
    - Low gas permeability
    - Minimize virtual leaks
  - Maintain reasonable field replacement protocol
  - Accommodate a minimum of 10-20 test and replace cycles
  - As quick and low cost as possible
    - This suggests using as much of the existing design as possible
  - Achieve acceptable RF performance
    - Proper alignment, prevent exposed corners etc.
    - Complete RF contact
      - As previously noted, the components must provide enough load along the contact interface to generate conforming surfaces
      - Perfectly flat and rigid components would require little force to make adequate RF contact
      - Unless the cavity flange contact is flat, the clamping system must be able to force some combination interface yielding and/or end plate bending to achieve conformance

Critical Elements of an Effective Solution

- Existing design is deficient because of a combination of 3 factors
  A. Cavity flange RF contact is insufficiently flat
  B. Clamp system is too stiff to apply a conformal load
  C. The specification of “A insufficiently” and “B too stiff” is established by the compliance of the RF contact interface
- The factors are interrelated
  - Proven results with flatter contact surfaces
  - Gasket and vacuum seal limitations are uncharted
    - To avoid a development effort prefer to duplicate previously successful results rather than explore alternatives

Potential Corrective Actions

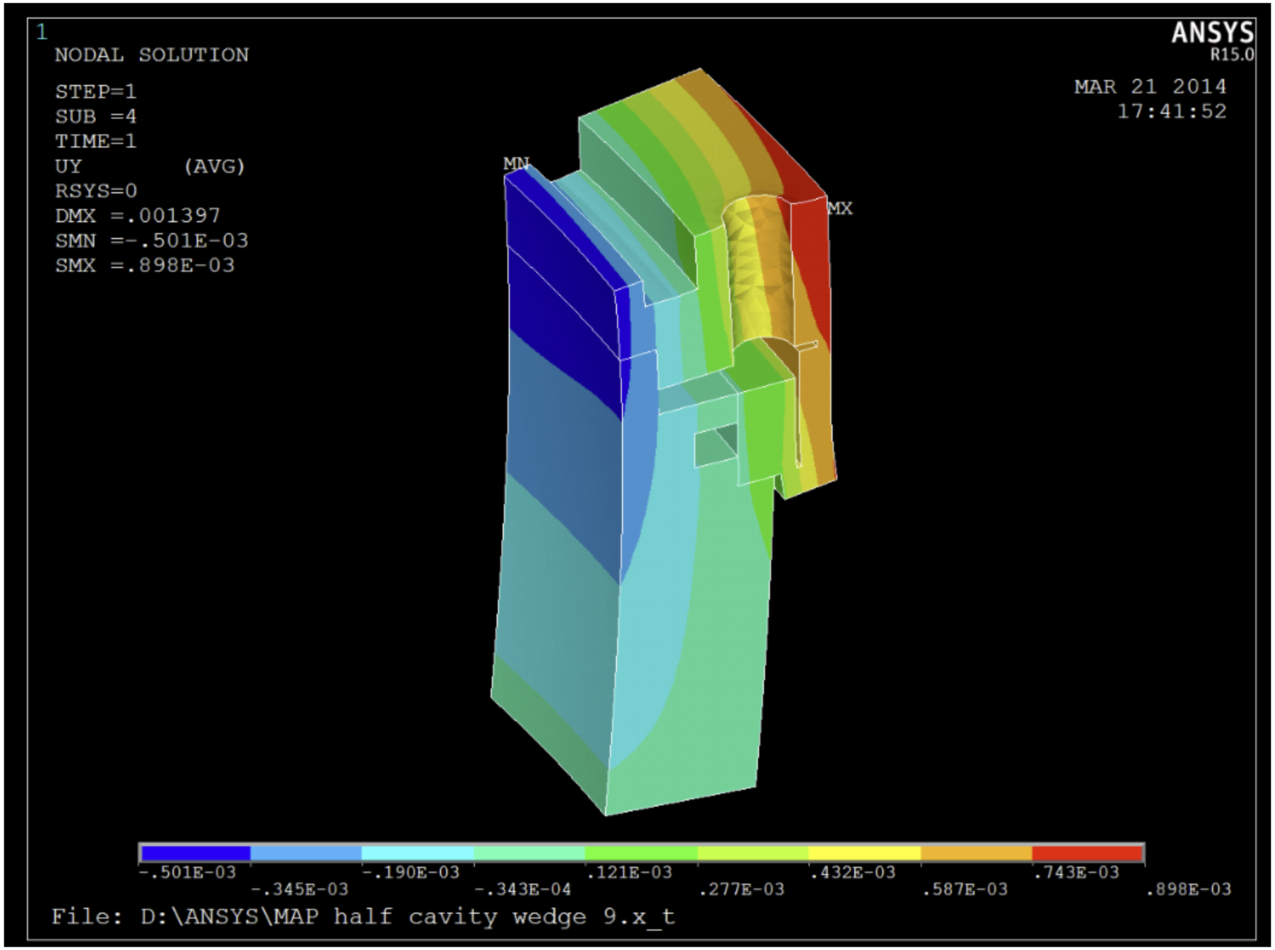
- Simple: Various combinations of reduced compression/loading at the helico-flex and softer/more compliant RF contacts and/or stronger bolts
  - Increase “A” and “B” tolerance by adding compliance “C” via an RF gasket
    - Does not significantly reduce flange/fastener distortion yielding.
    - Need considerable compliance to conform to large azimuthal variation resulting from support bar ties and flexible cavity flange
      - Insufficient information to properly design at this time
      - No precedent for successful contact against such a warped cavity surface
    - Located across vacuum seal
      - Uncharted vacuum seal performance, certainly limits thickness
      - Adds complexity to avoid creating significant virtual leaks
    - If a gasket it added it can/should be located inside vacuum seal
      - Can be “thick” by adding step to end plate
      - Improved alignment , sealing, and virtual leak characteristics
  - Reduce flange flex “A” by reducing vacuum seal load
    - Retain Helicoflex but squeeze less or squeeze through an additional gasket
      - Uncharted territory related to vacuum seal performance
    - Switch to a more compliant seal like a Viton O-ring
      - Higher permeability may contribute to test results
  - Above combined with stronger bolts (Magnetic OK?, use “316Mo”?)
    - Not enough strength to address “B”
    - Using bolt load to address “B” and “C” worsens “A”

More Possible Solutions

- Complex
    - Can extend to cavity assembly replacement…
    - no need to review the far out ideas at this time!
- Intermediate solutions include
    - **Directly and completely address "A" and "B" using a bolted on, pressure bolt flange (PBF)**
        - Excellent performance In 48 hole machined cavity version
        - May work well in a 24 hole version if combined with other changes
        - When well done reduces "C" and provides a more stable solution
    - Address "A" by removing existing ties to reduce localized distortion
        - Could consider but significant flange roll and plastic deformation expected to prove unreliable
        - Without addressing "B" unlikely to succeed
    - Address "A" by adding welded "ties" added to reduce flange roll
        - Tough to locate uniformly and in all critical areas
    - Ties added or removed in combination with gasket/seal changes
        - Unless significant load reduction is realized the 24 ¼-28 are still limiting
        - Circumferential stiffness of existing clamp flange "B" expected to limit contact pressure uniformity
    - **Completely address "B" and partially "A" by using a PBF with only the existing bolts. If needed address "A" and "C" via gasket and or changing tie backs**
        - Lower risk than adding bolts to the cavity
        - Addresses all three issues (incrementally if needed).
- Some details of possible solutions are presented on the next few slides

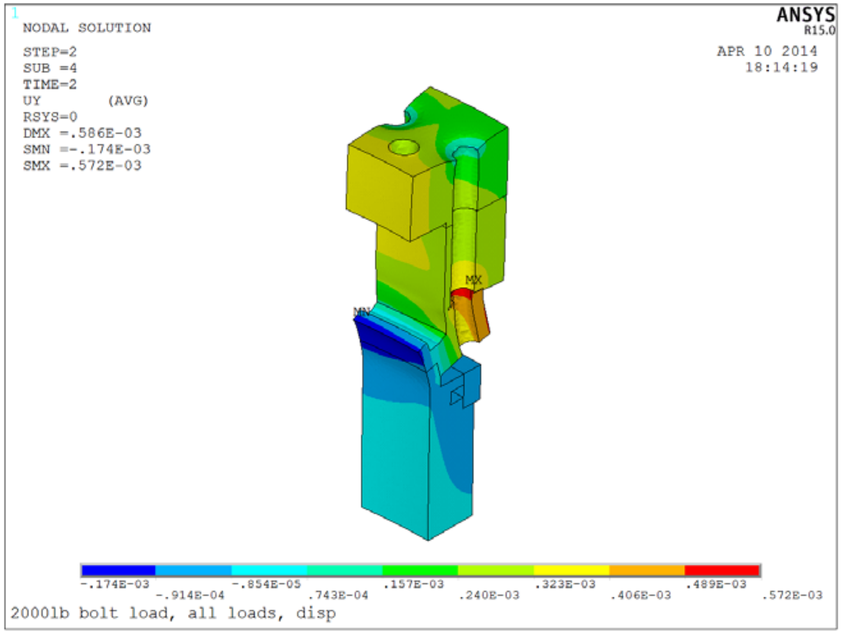
Reducing “A” Flange Distortion uniform “ties”

- Tie bars from flange to flange provide “cross talk” and are not needed, tie back to the water cooling rings dramatically reduces distortion (~.0015 Vs .019”)
- Trouble is avoiding weld distortions and accessing under the waveguide
- Unless completely effective does not address “B” and “C”



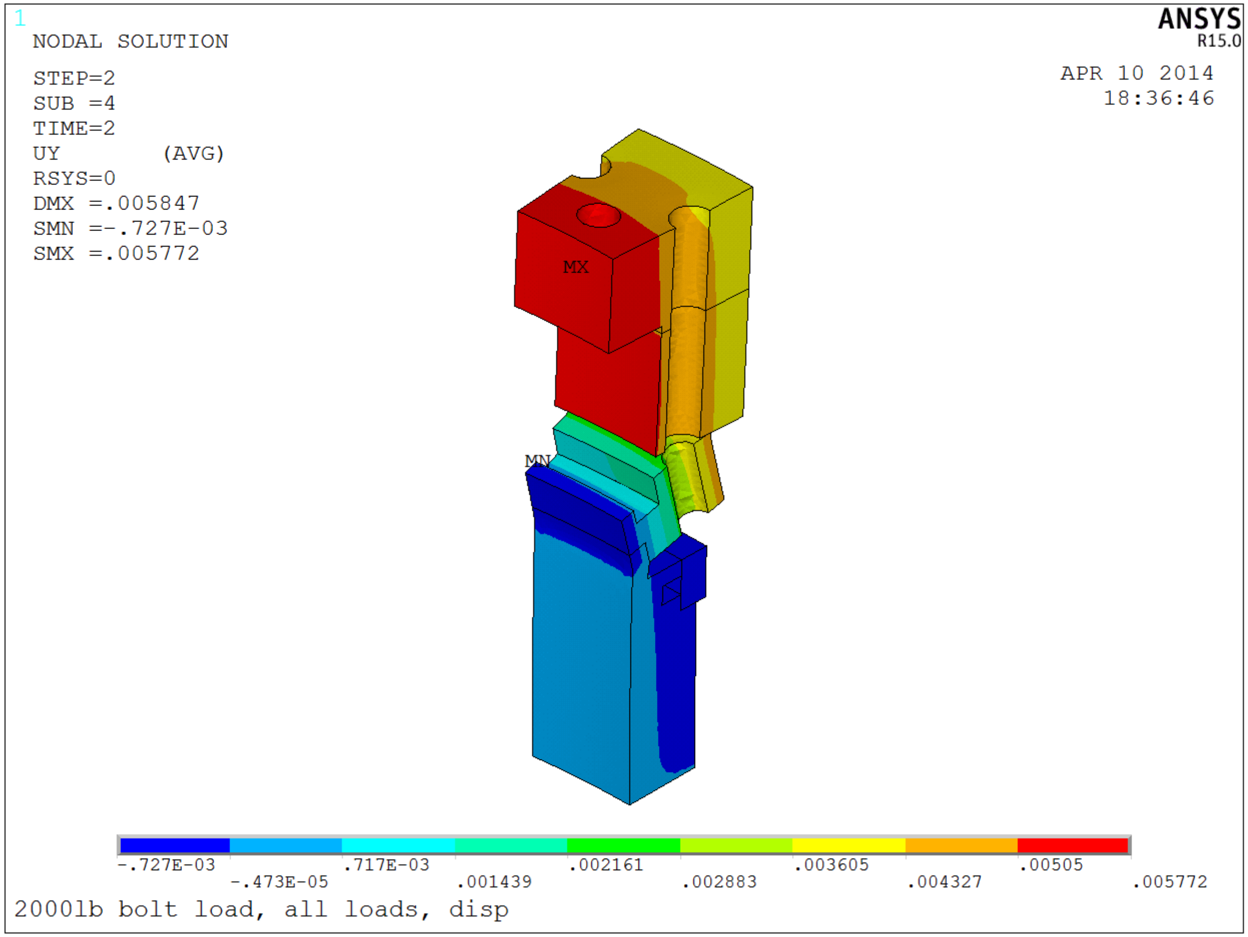
Welded Extension

- An extension cylinder welded to cavity flange ID results in very rigid joints with considerable reserve strength
  - Clamp flange bolted through extension cylinder to cavity flange with 24 existing bolts
  - Clamp flange bolted to extension cylinder with 24 additional bolts
  - 48 pressure bolts used through the clamp flange to load the end plate
  - OD of removable clamp flange increased for improved performance
- Thoroughly addresses "A" and "B" ensuring "C" behavior per previous success
- Primary concern is risk associated with welding the extension ring to the cavity



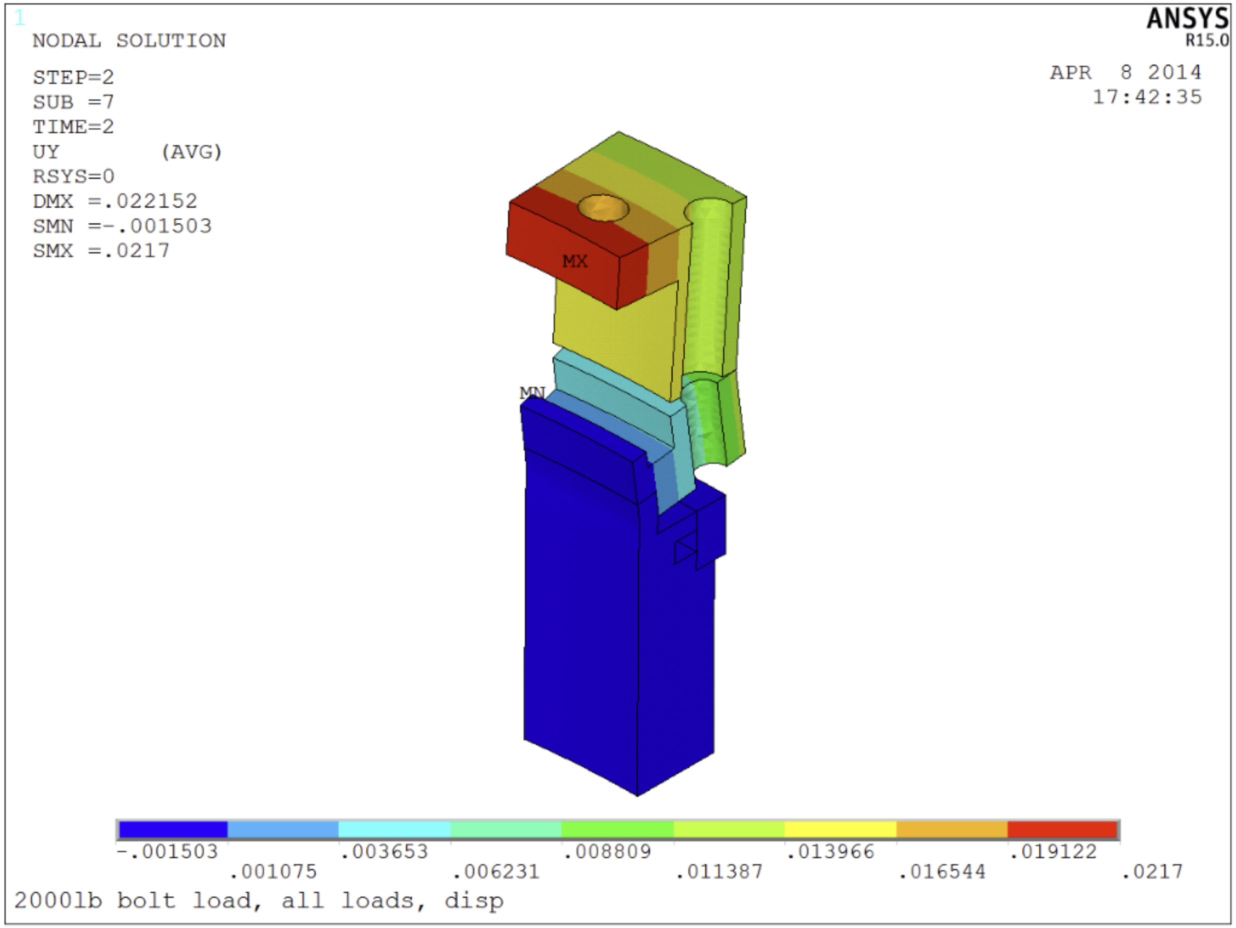
Bolted Extension

- Bolting the extension/clamp flange to the cavity flange with the existing bolts but w/o welding is a considerable improvement over the existing case
  - ~.005" cavity flange roll Vs. ~.019"
- Partial "A"
- Effective "B"
- "C" is independent
- Bolts yield, may require stronger bolts

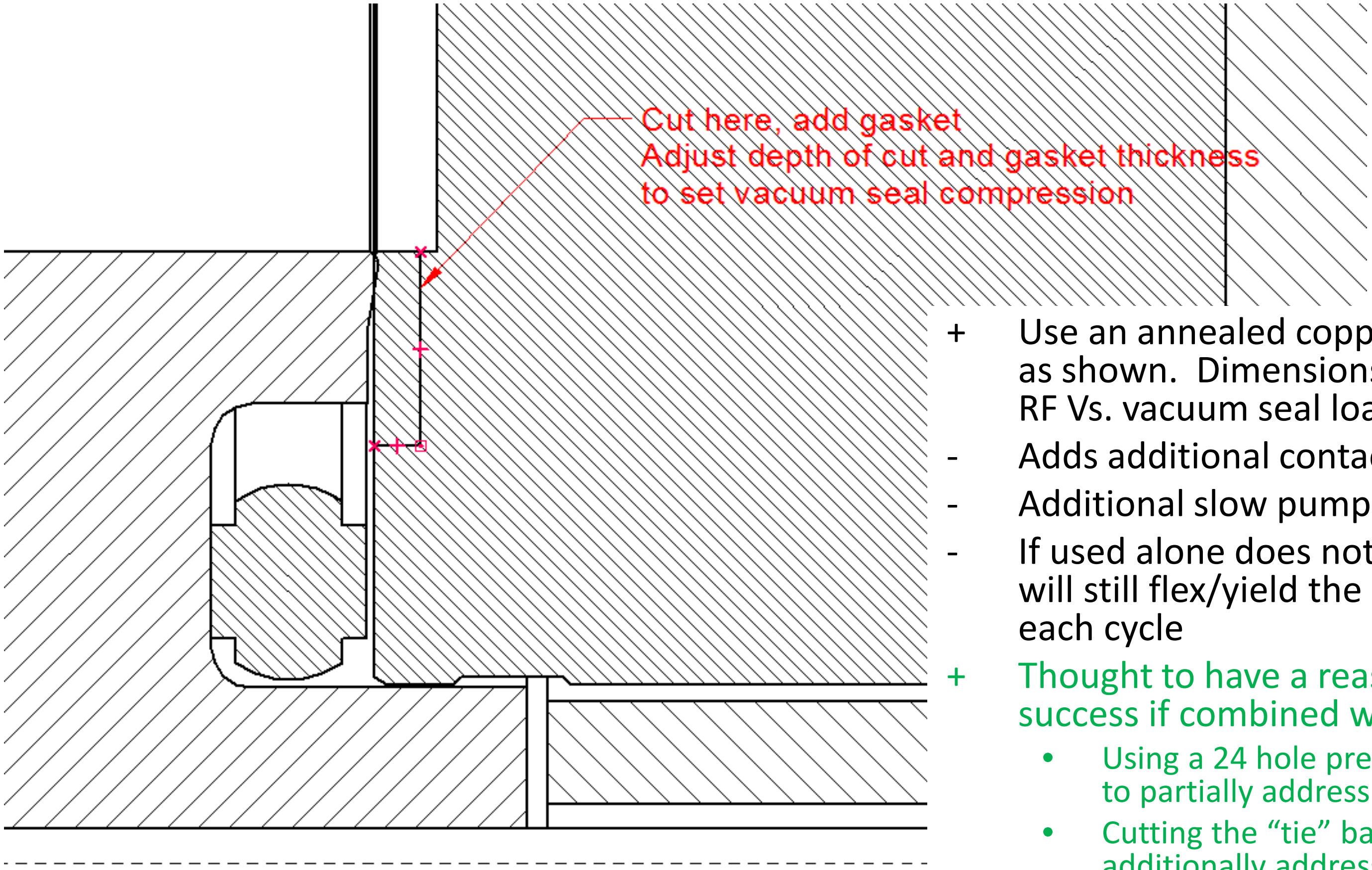


Smaller Bolted flange

- If the extension flange is not welded, it can be one piece and smaller
- With existing bolts only partially addresses “A” (flatness)
- Addresses “B” clamp conformability
- Is simple and can be combined with gaskets to address “C”



Possible Gasket Solution



- \+ Use an annealed copper gasket positioned as shown. Dimensions allow adjustment of RF Vs. vacuum seal load balance.
- \- Adds additional contact interface
- \- Additional slow pumping faying surfaces
- \- If used alone does not address “A”, flange will still flex/yield the cavity and bolts at each cycle
- \+ Thought to have a reasonable chance of success if combined with
  - Using a 24 hole pressure bolt clamp flange to partially address “A” and “B”
  - Cutting the “tie” bars if needed to additionally address “A”
  - Perhaps slightly unloading the Helicoflex seal

Helicoflex Notes

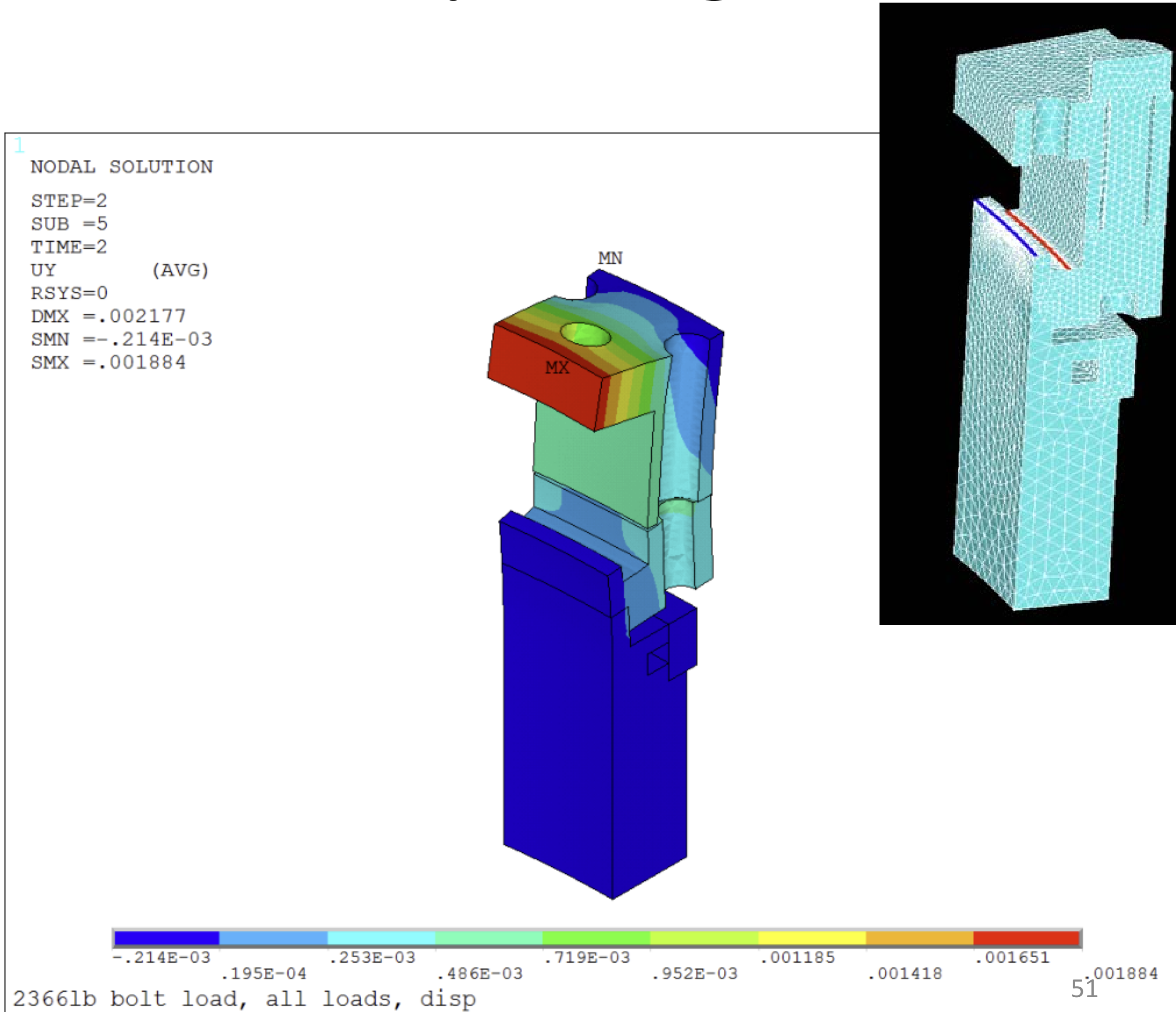
- The seal that has been designed for this application is a Delta seal made from an Aluminum jacket material. The seal requires at least 800 lbs/in of circumferential seating load in order to properly seal and create the leak rate desired for this application. Delta seals are the only product we offer that can achieve the leak rates you are trying to achieve. The “Aluminum” Delta seal is the only Delta product with the smallest amount of loads. It is not possible to reduce the spring rate of these seals, or else the sealing performance will be jeopardize. Please keep in mind also, that the flange hardness needs to be 65 vickers minimum – for both top and bottom flanges. All of these variables are critical for the Delta seal to work properly. The bolting configuration you currently have seems to be enough, especially since you are seeing coining.
- Also just as a note and precaution in case you aren’t currently doing so, these seals are a “ONE TIME” use only. Once the Delta is crushed it cannot be used again, and it must be replaced with a new part in order to work properly. Any unloading of the bolts jeopardizes the sealing contact, and we usually recommend replacing the unloaded seal with a new one.
- The recommended groove depth for this seal is .099” +/- .002. Sometimes seals perform beyond the recommended, but we have no data to show exactly where it starts dropping off. A seal that is compressed more than .030” - .031” (Recommended compression for this seal) will begin to over- compress where the Springs now have no function on the sealing performance. Last, the circumferential flatness of the groove is extremely important for these seals.
- Unfortunately, we don’t another alternative to a product that will perform as good as the Delta, and reducing spring rates for this seal will only make things worse. It will and can reduce the spring load, but the seal will perform unacceptable to your target of 1x10-11 std.cc/he sec. or Ultra High Vacuum.
- Is there a way for you to increase the thickness of the flanges? Also evaluate the number of bolts during installation?

Proposed Solution(s)

- The most robust approach, with highest assurance of success (if properly executed), consists of utilizing a new “Pressure Bolt Flange” attached to the existing cavity flange with the existing 24 fasteners and an additional 24 fasteners added between the existing holes
  - This “48 Hole PBF” has been shown to address “A” and “B” to the extent that the requirements of “C” are in line with previously successful assemblies
- A lower performance margin but also lower cost/risk alternative uses the same flange as above but uses only the existing cavity flange bolts.
  - This approach does not achieve the tolerance margins of previously successful designs
  - Margin can be improved by small low cost additions
    - Stronger (perhaps magnetic?) bolts
    - Use of RF gasket
    - Support tie modifications
- Next slides provide some details of these preferred solutions

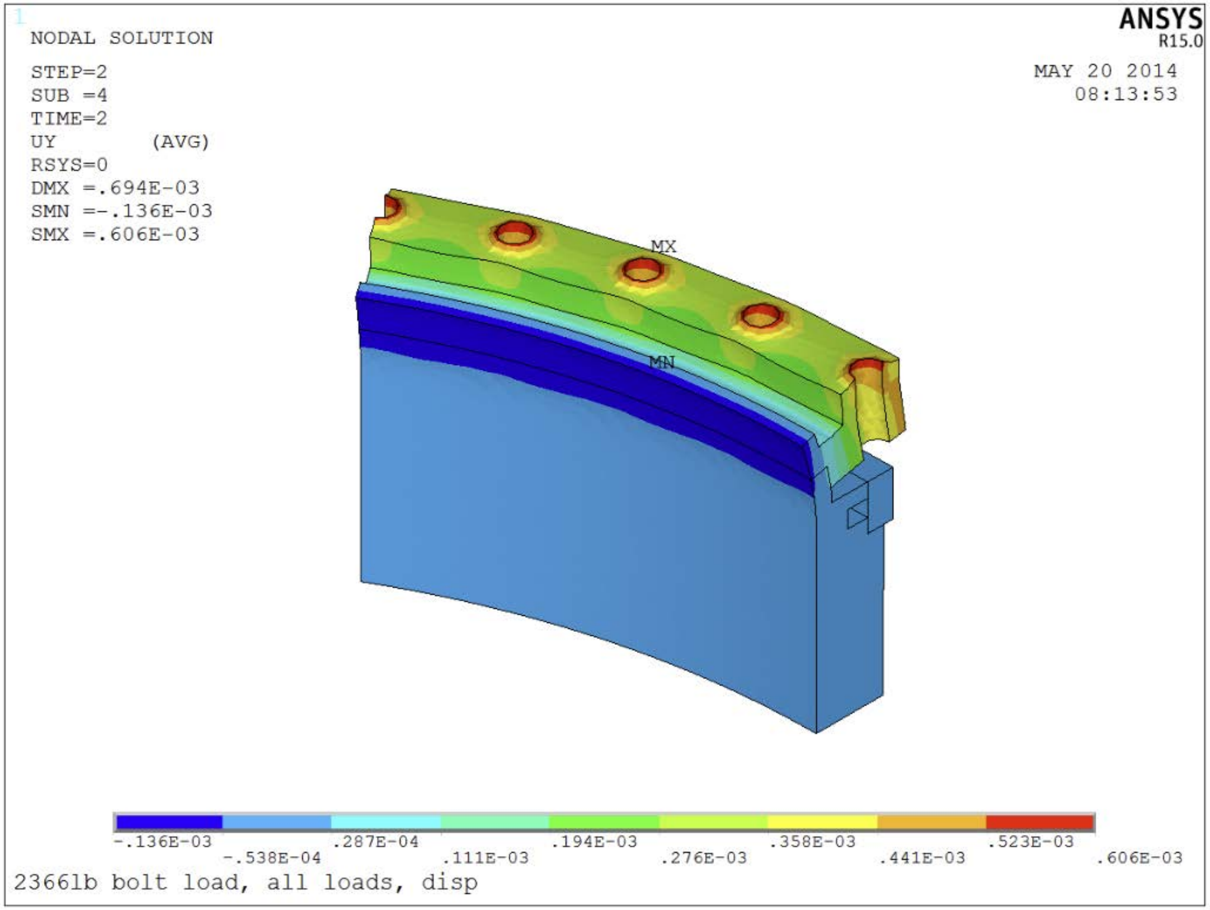
Bolted Clamp Flange

- 48 ¼-28 bolts to attach each clamp flange (24 existing plus 24 additional)
- 48 pressure bolts to load each end plate
- "A"chieves excellent cavity flange stability and flatness
- "B"y using pressure bolts addresses "B" to the fullest extent possible
- "C"onsiderably flatter interface make requirements for "C"ompliance similar to previous successful assemblies



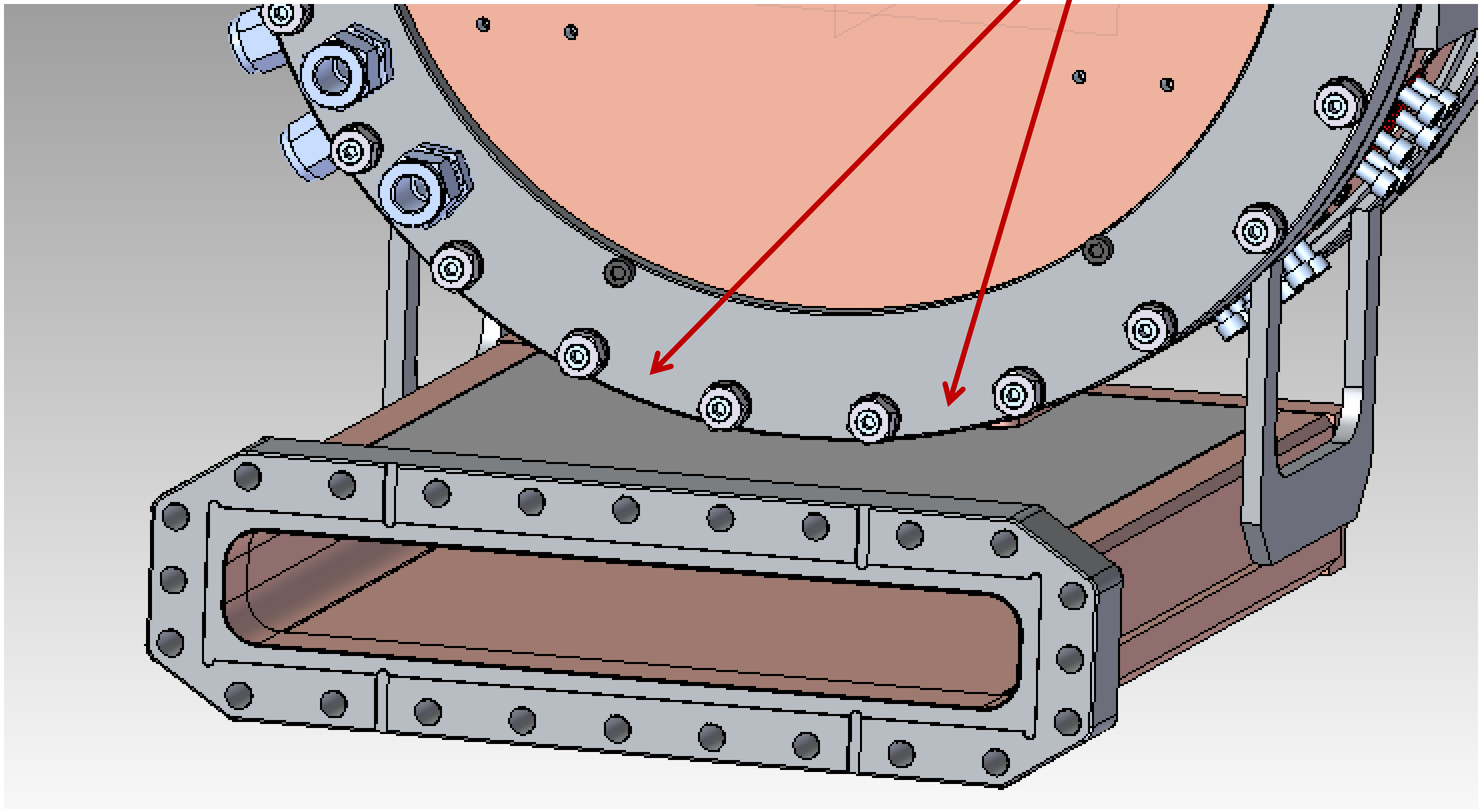
Bolted Flange Performance

- Flange roll reduced below <.001”
- Azimuthal variation at RF contact is less than .0001”
- Expect excellent RF and vacuum sealing performance



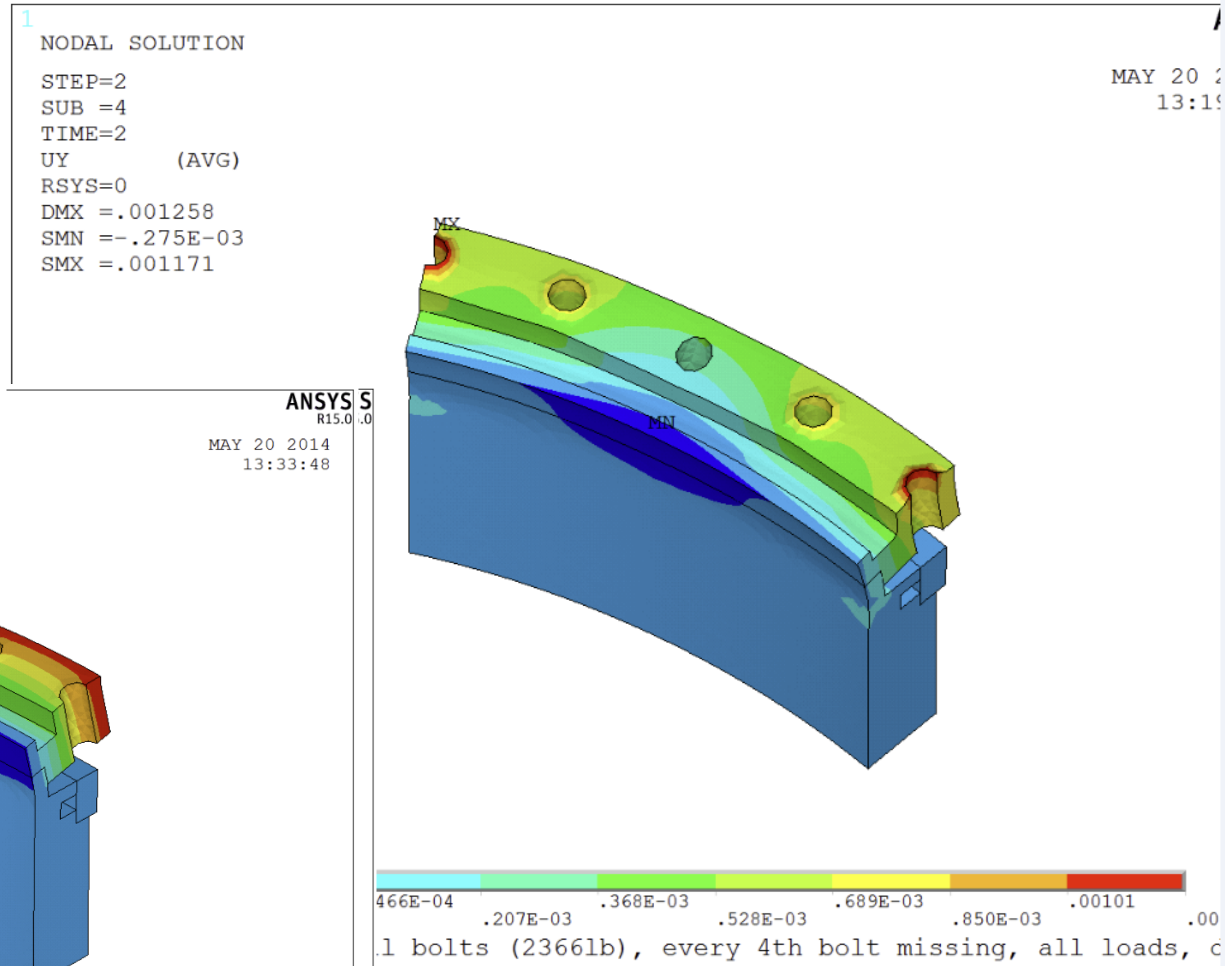
Difficult Bolts

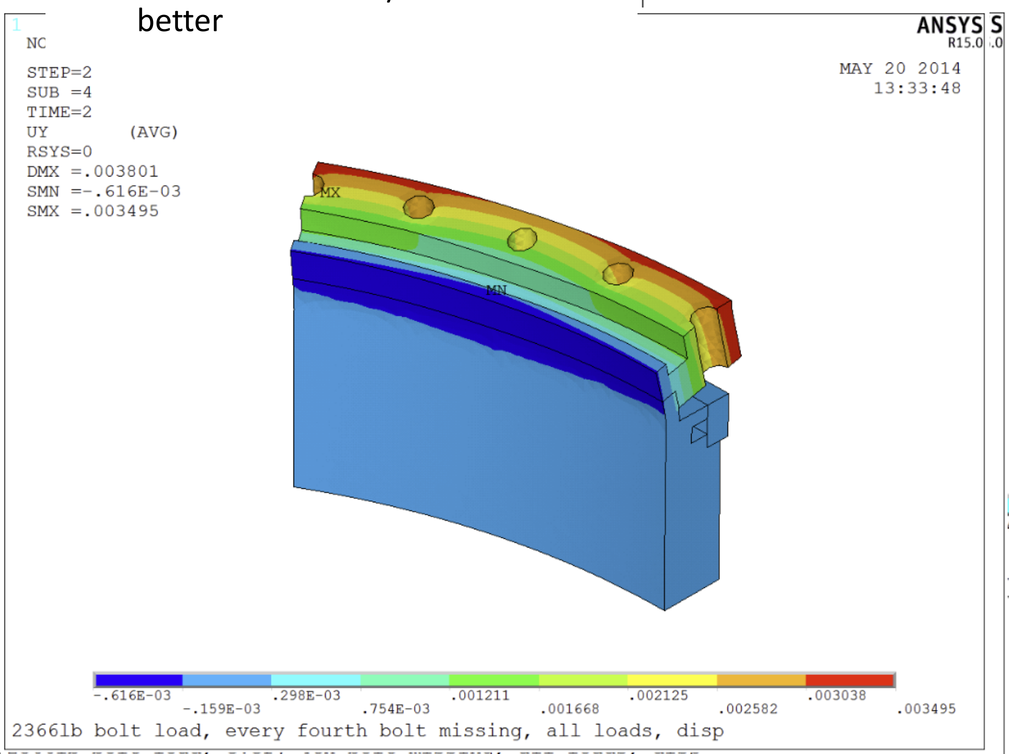
- Proximity to waveguide makes 2 positions difficult to add, can they be skipped?



Skip Difficult Bolts

- Two of the additional bolt holes will be quite difficult to drill and tap
- Checked impact of simply skipping these bolts
- Results are still quite good with less than .0005” of azimuthal variation in the RF contact position and <.0007” at the vacuum seal
- If new holes are 5/16 results are better





Solutions Compared

- "Misc" can include some combination of cutting the support ties, using stronger bolts, adding an RF gasket
- Have not detailed all options, numerical table is very approximate to assist in providing magnitude of options

Approach	Just gasket	24 Hole PBF	24 Hole PBF combined with misc	48 Hole PBF
Cost ($K)	15	25	30	45
Time (Weeks)	2	5	5	7
Risk	medium	low	low	medium
Flange Performance "A"	poor	marginal	fair	excellent
Clamp Performance "B"	poor	good	good	good
Contact Conformability required "C"	extreme	intermediate	slightly elevated	minimal
Overall Outcome	poor	marginal	good	excellent

Open Discussion

- Action Items:
  - Next steps