

Vacuum Science and Technology for Particle Accelerators

Yulin Li

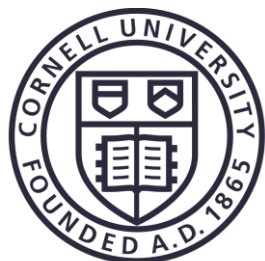
Cornell University, Ithaca, NY

Xianghong Liu

SLAC National Accelerator Laboratory



*Albuquerque, New Mexico
June 17-28, 2019*



Cornell Laboratory
for Accelerator-based Sciences
and Education (CLASSE)



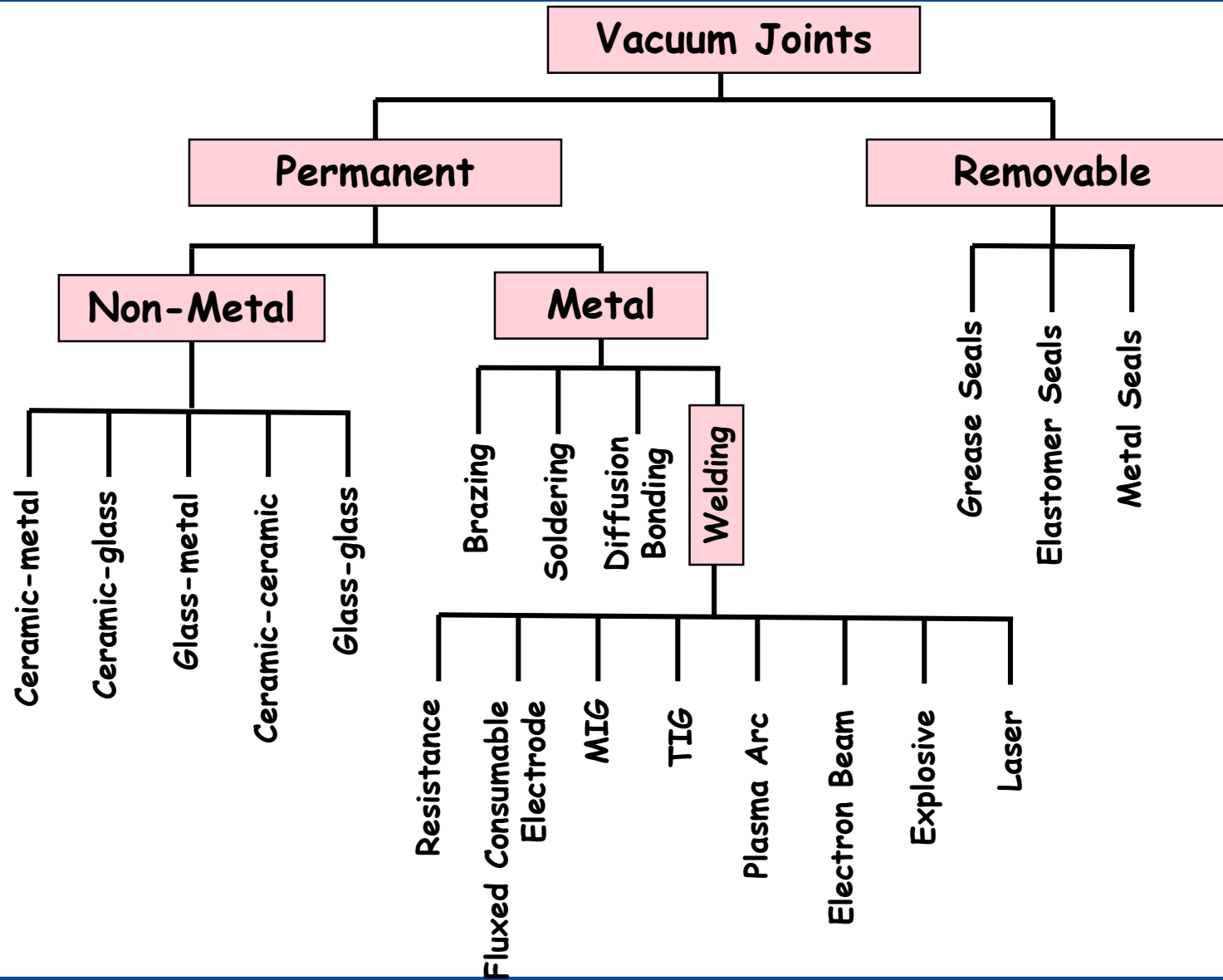
Table of Contents

- Vacuum Fundamentals
- Sources of Gases
- Vacuum Instrumentation
- Vacuum Pumps
- **Vacuum Components/Hardware**
- Vacuum Systems Engineering
- Accelerator Vacuum Considerations, etc.
- Beam-vacuum interactions

SESSION 5.2: *VACUUM JOINTS*

- Permanent Joints
 - Welding
 - Brazing and Soldering
 - Bonding
 -
- Removable Joints
 - All-metal flanges
 - Elastomer flanges
 - Dynamic joints

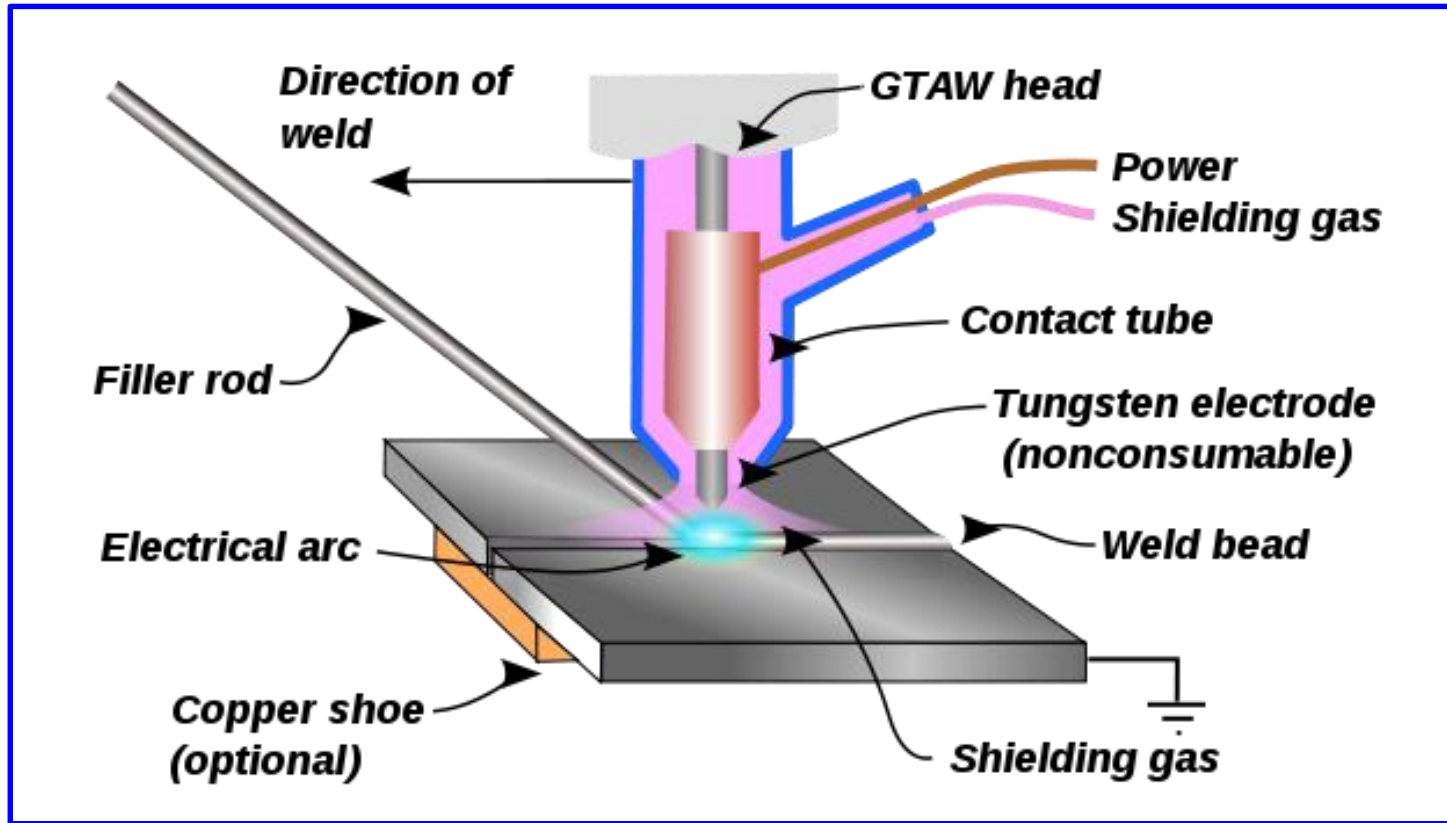
Methods of Making Vacuum Joints



Welding is the process where two materials are joined by fusion

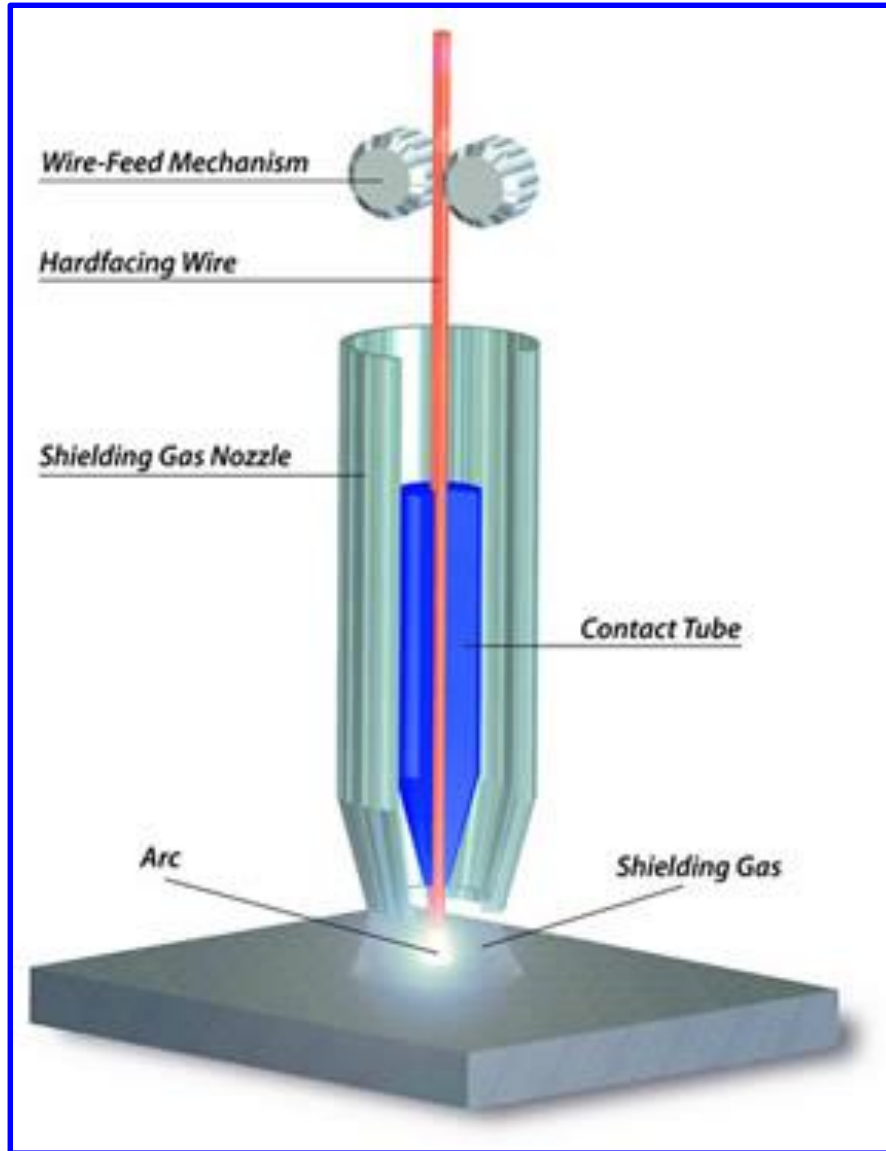
- Welding is the most common method for joining metals in vacuum systems.
- Inert gas welding is the most common type of welding (TIG, MIG).
- Joint design is critical from vacuum, metallurgical and distortion standpoints.
- Cleanliness is essential.
- Other welding processes to consider are electron beam and laser welding.

TIG – Tungsten Inert Gas Welding



- ❑ TIG welding is one of most difficult welding, when operating manually.
- ❑ Inert gas mixture (Ar and He) form a shield to protect the hot-zone from oxidization. The composition of the gas mixture vary with metal and mass.
- ❑ Arc power may be direct current or alternate current
- ❑ Filler rod is often used, but not needed for some fusion welds.

MIG – Metal Inert Gas Welding

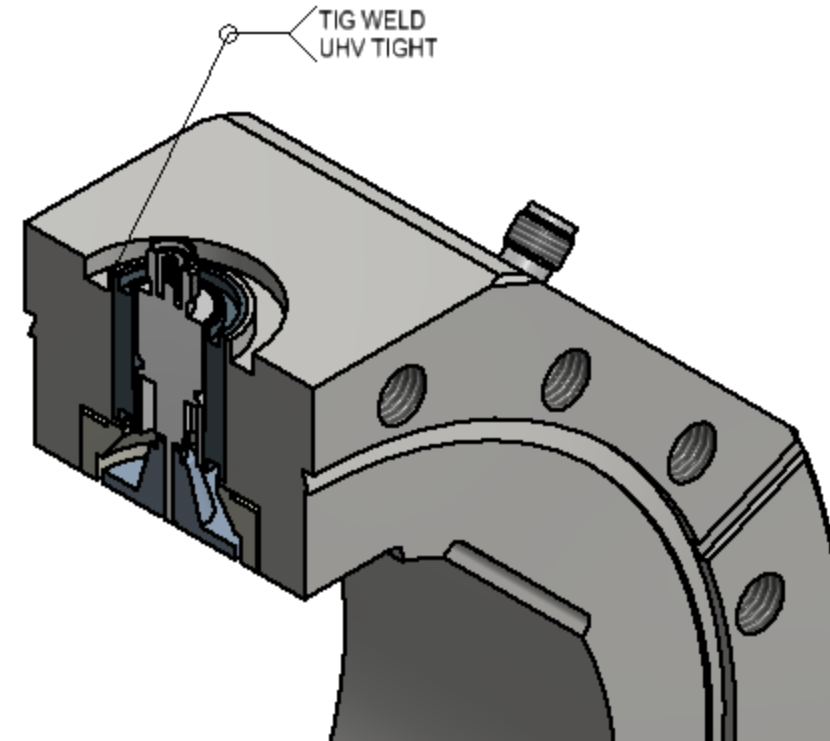
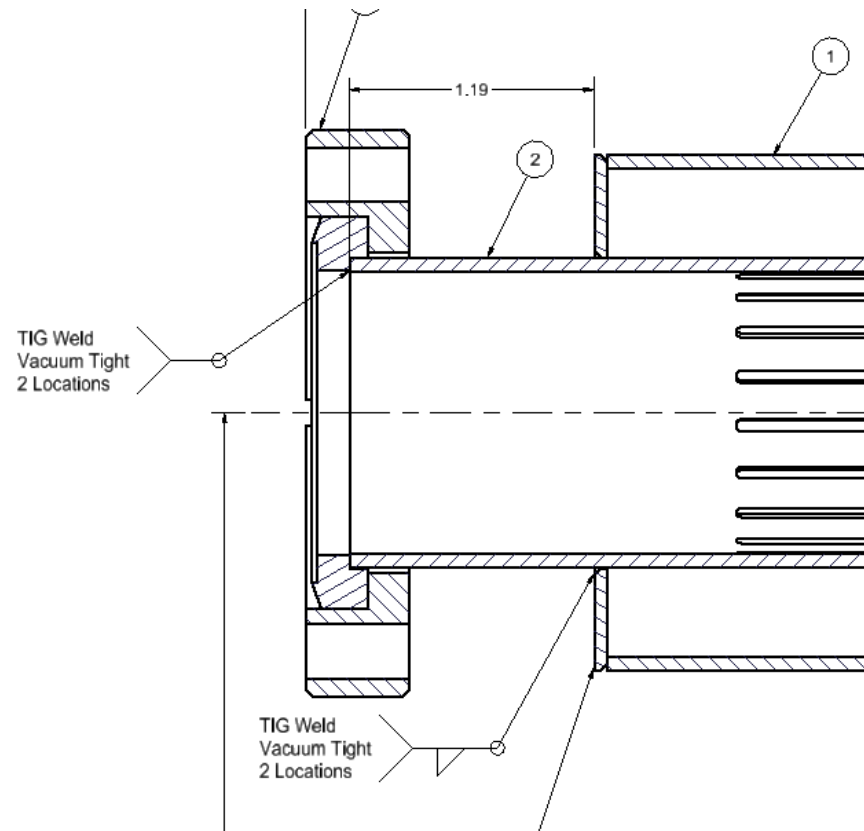


- ❑ Unlike TIG welding, the filler metal is a part of welding circuit.
- ❑ MIG welding is much easier, cheaper and faster
- ❑ But MIG welds are not as reliable and not nearly as clean as TIG.
- ❑ So MIG welding is generally not a choice for vacuum welds

Welding Stainless Steel



- ❑ TIG welding of stainless steels is among easiest, and heat-affected zone (HAZ) is very small.
- ❑ In most cases, filler is not needed. However, reinforce stitch welds with filler are added for strengthening the welded joint.





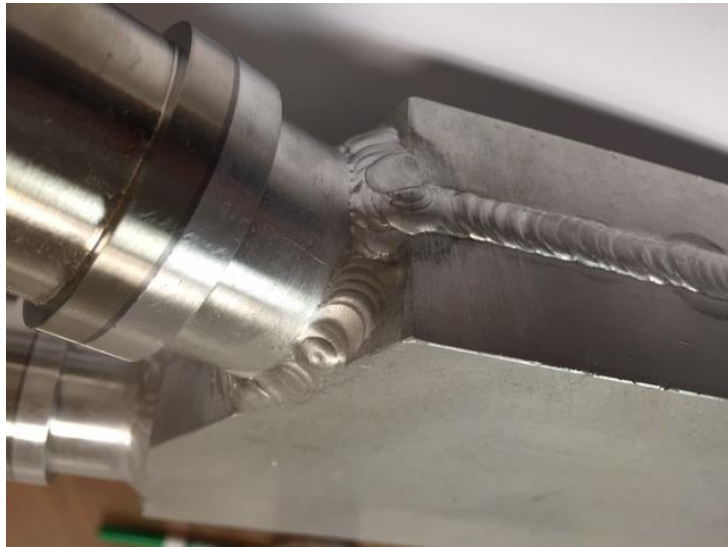
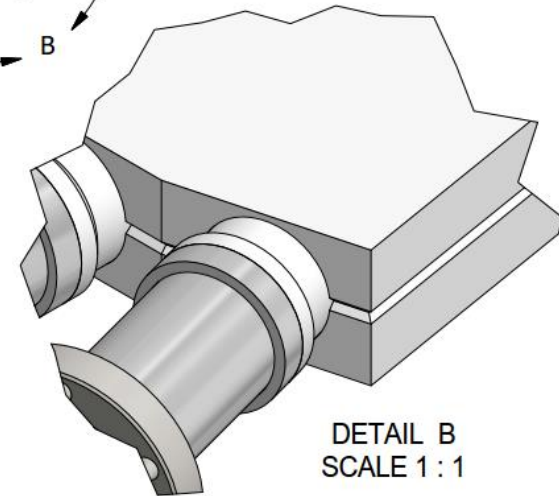
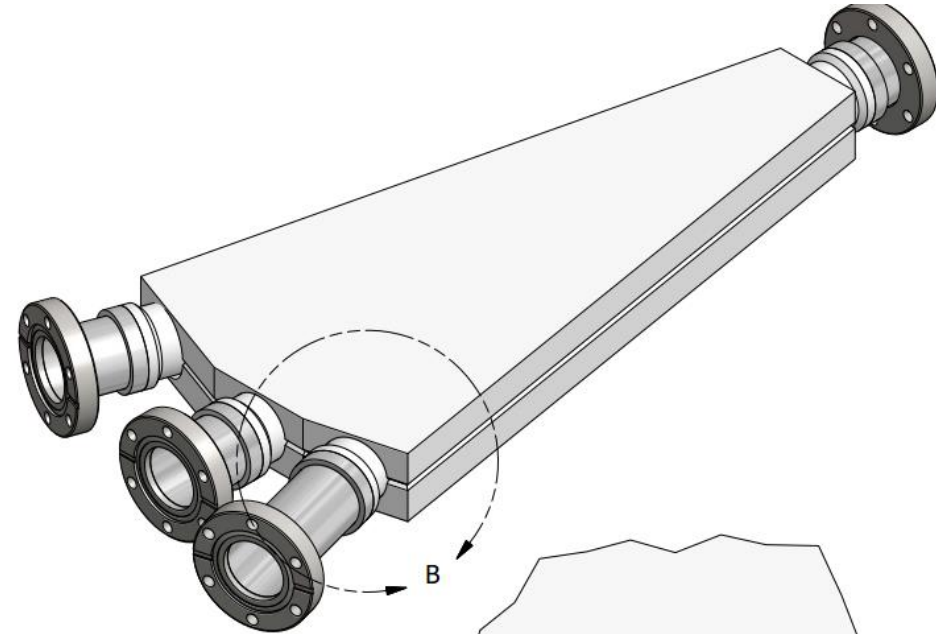
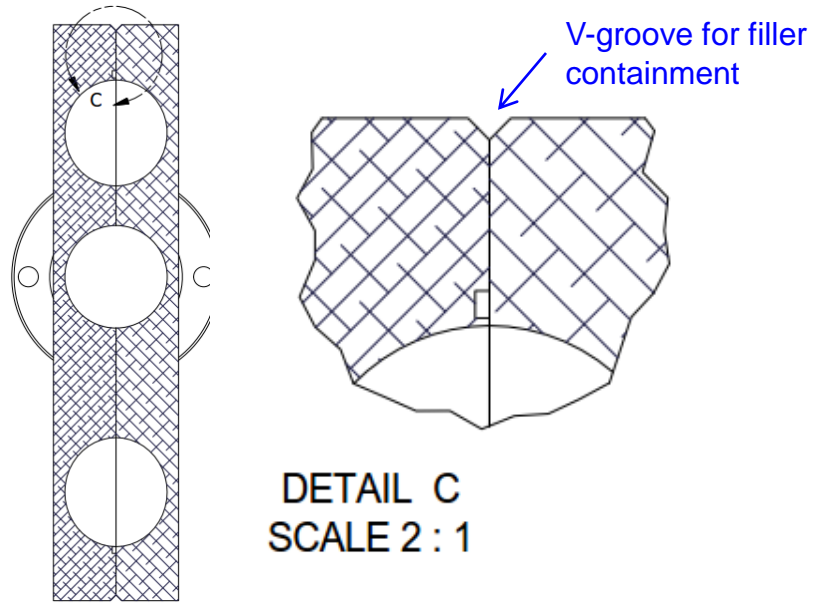
- The high thermal conductivity of copper makes welding difficult. Heating causes the copper to re-crystallize forming large grain size and annealing. Distortion is also a big problem.
- Copper weldment can be fused via TIG with or without fillers.
- Braze copper to copper, or copper to stainless steel is also done with TIG technique, using CuSil (72%Ag-28%Cu) alloy fillers. (At Cornell, we call this BT-weld, or Braze-TIG.)



- Copper requires:
 1. Very high welding speeds
 2. Excellent material purity (OFE copper) and cleanliness.
 3. Good joint design
 4. Welding coppers must be done in an inert glove-box, or at least purging in-vacuum surfaces.
- Electron beam welding is an excellent process for welding copper.
- Vacuum furnace braze is also a good option for coppers.

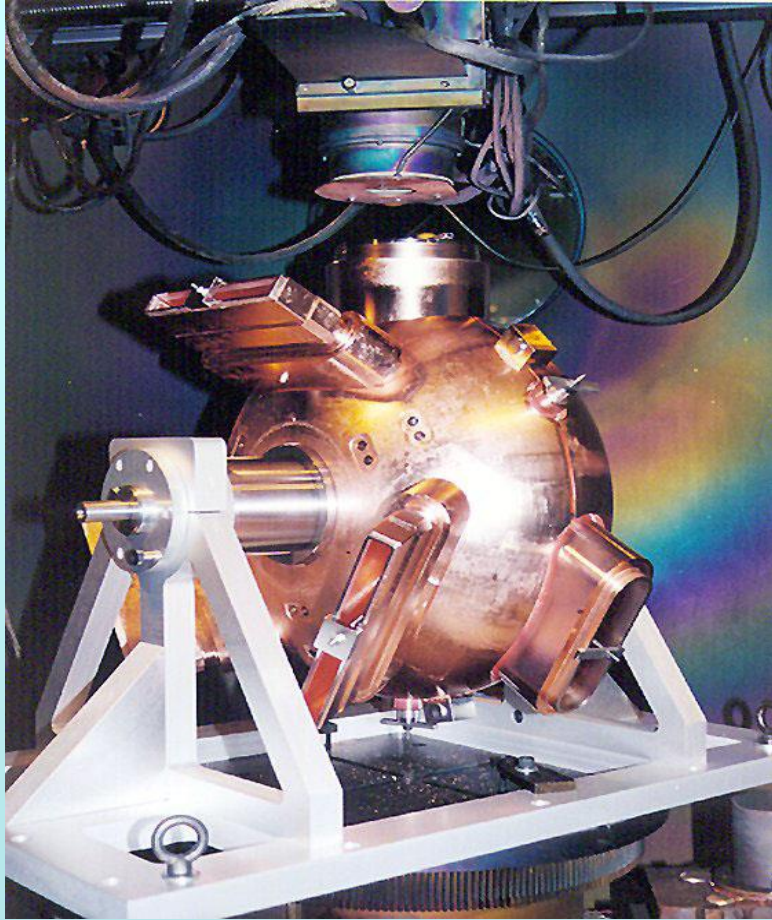
- ❑ *Low melting point, relatively high thermal conductivity, and high rate of thermal expansion make welding aluminum more problematic than stainless steel.*
- ❑ *Aluminum requires:*
 - *High welding speeds (higher current densities)*
 - *Good material purity and cleanliness*
 - *Good joint design*
- ❑ *Aluminum welds have a tendency to crack from excessive shrinkage stresses due to their high rate of thermal contraction. Filler rods (usually 4043 or similar alloys) always needed.*
- ❑ *Due to relatively large weld-beads, out-side welding seams are very common for aluminum welds*
- ❑ *To keep the aluminum weldment clean from oxidization, AC power is usually used during TIG, with characteristic popping noises.*

Welding Aluminum – Examples



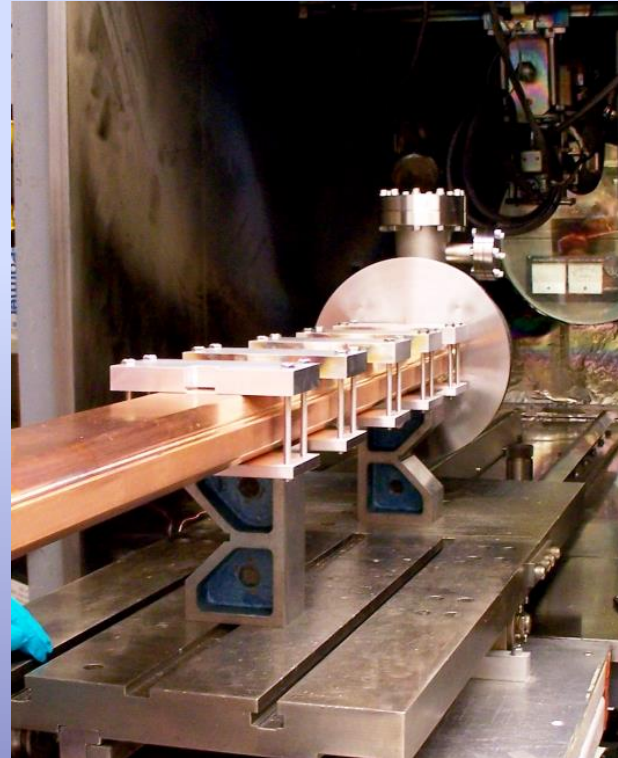


- EBW provides extremely high energy density in its focused beam producing deep, narrow welds.
- This rapid welding process minimizes distortion and the heat affected zone.
- Very good control and reproducibility in weld penetration.
- A disadvantage of EBW is that the process takes place under vacuum ($P = 10^{-5}$ Torr):
 - Extensive fixturing required
 - High initial cost
 - Weld preps are extremely critical, as no filler used.
 - Complexity
 - Welds are not cleanable

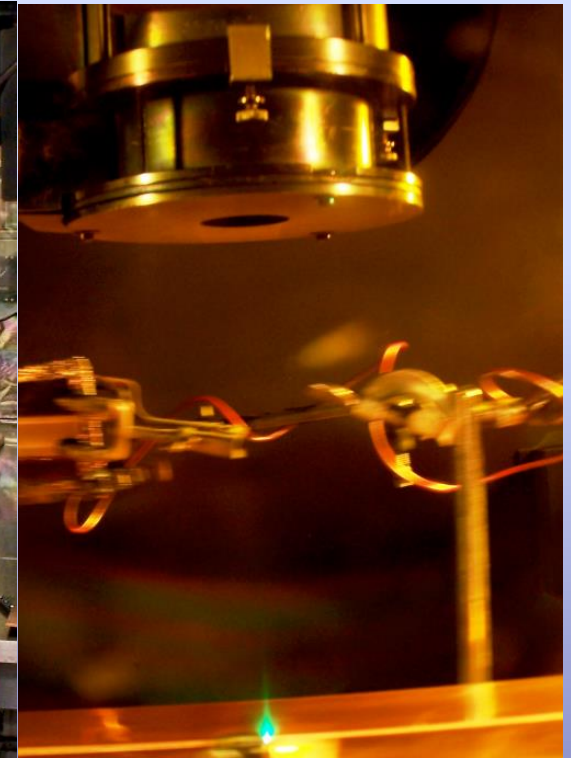


RF Cavity

**Welding 1-mm thick Copper Cover
on CesrTA EC Detector Chamber**



Load into EBW Chamber



E-beam welding

SLAC Electron Beam Welder



Soldering is the process where materials are joined together by the flow of a “filler metal” through capillary action.

- ❑ *Soldering is differentiated from brazing primarily by the melting temperature of the filler metals. Solder alloys melt below 450°C.*
- ❑ *Because of lower working temperature, usually corrosive flux is needed to ensure proper 'wetting' of the surfaces.*
- ❑ *All soft solders are unacceptable for UHV systems because:*
 - ❖ *They contain Pb, Sn, Bi, Zn (vapor pressures are too high)*
 - ❖ *System bake-out temperatures typically exceed alloy melting points.*
 - ❖ *Residuals of corrosive flux left on the joints, a long-term reliability issue.*
- ❑ *Most silver solders are unacceptable.*

Brazing is the process where two dissimilar materials are joined together by the flow of a “filler metal” through capillary action.

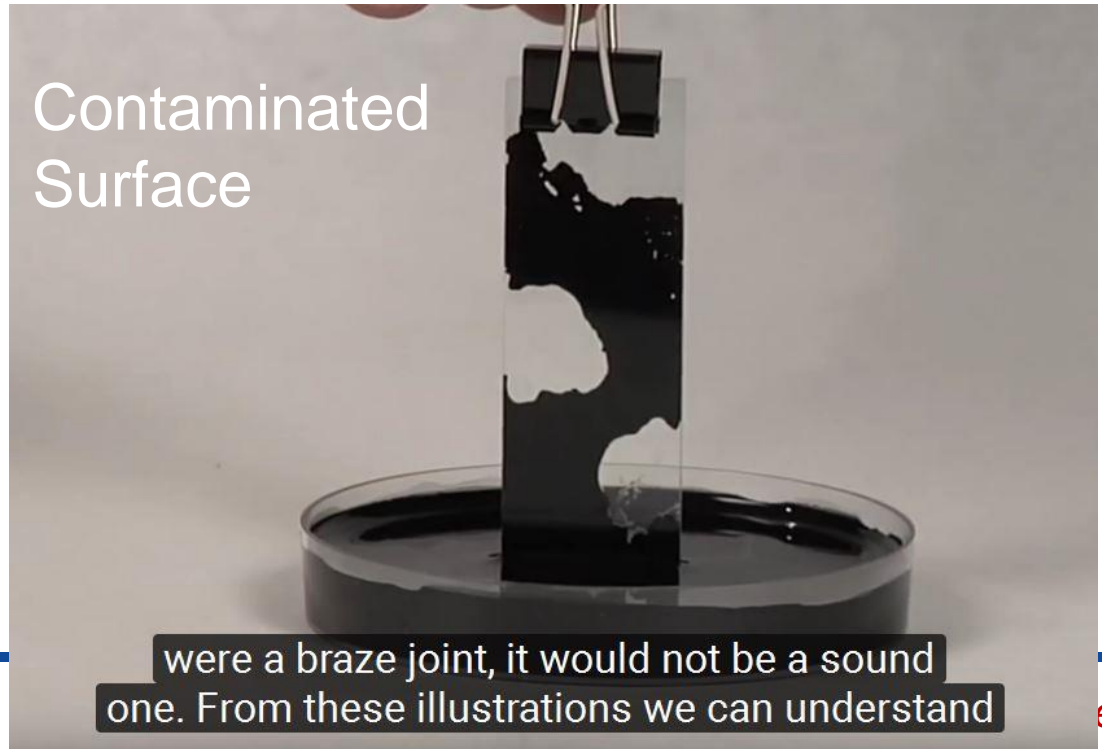
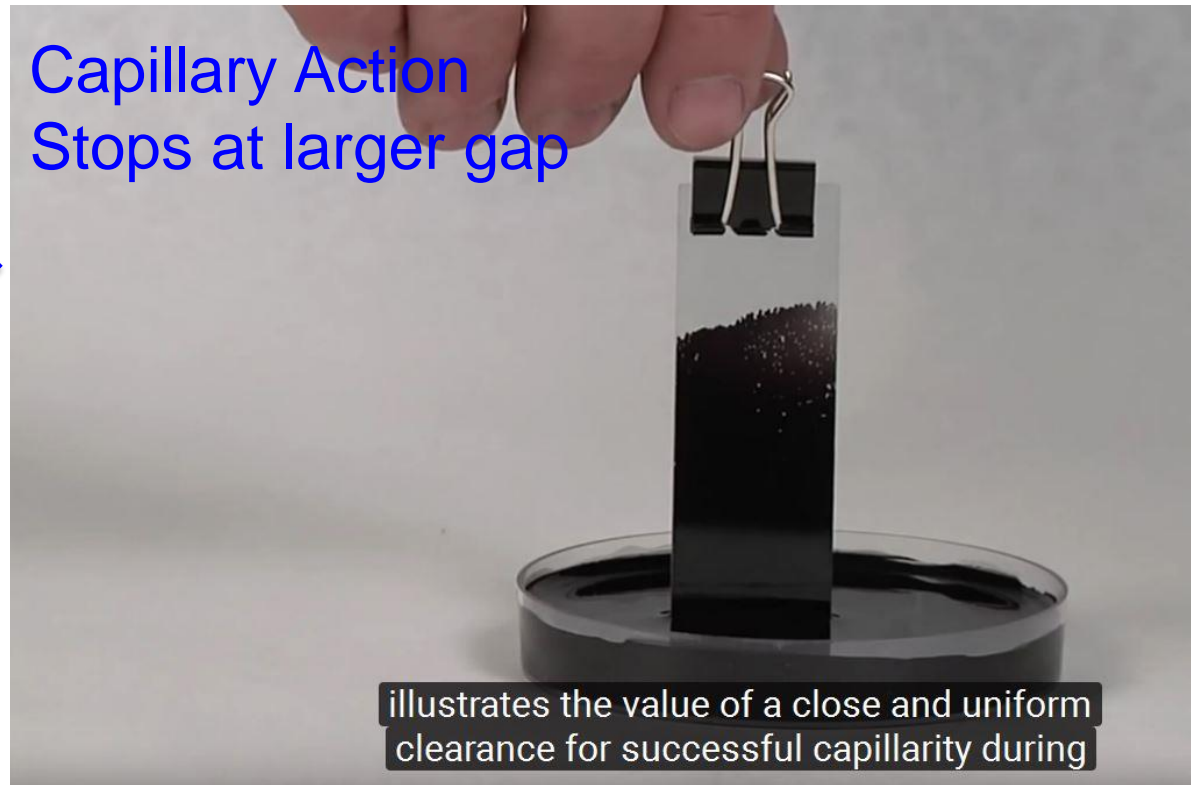
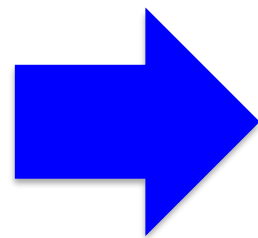
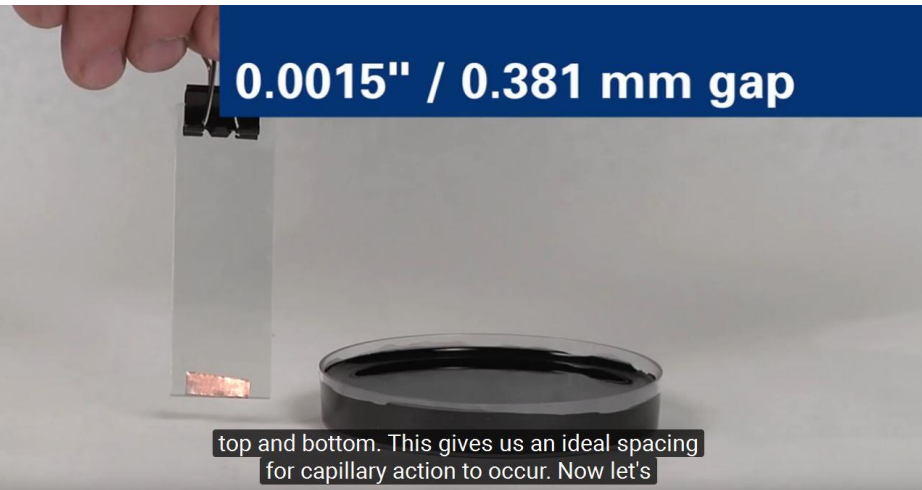
- ❑ *There are several different brazing processes:*
 1. *Torch*
 2. *Furnace*
 3. *Induction*
 4. *Dip*
 5. *Resistance*

- ❑ *Brazing can be used to join many dissimilar metals. The notable exceptions are **aluminum** and **magnesium**.*

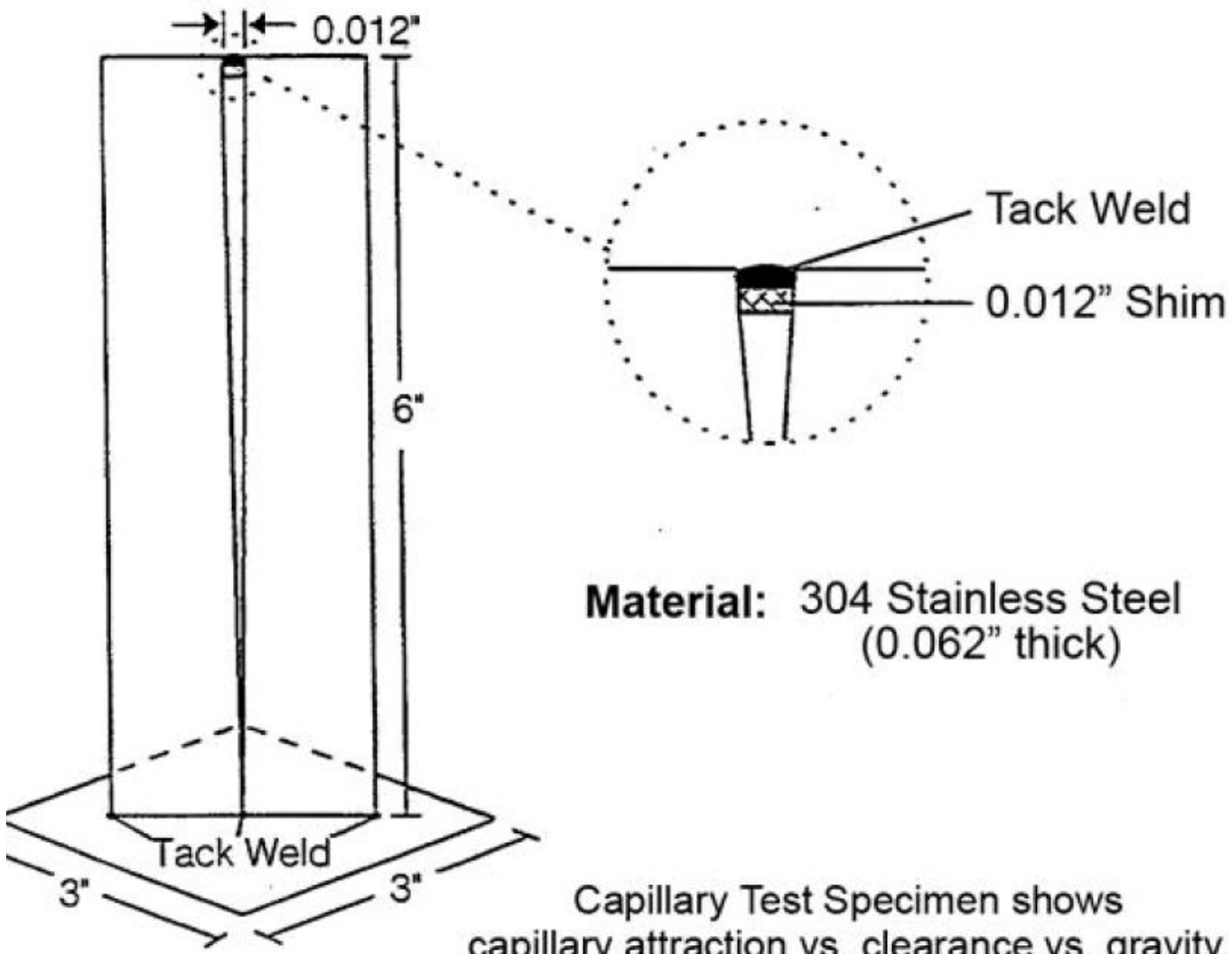
- ❑ *Cleanliness is important in brazing. Cleanliness is maintained by use of a flux or by controlling the atmosphere (vacuum or H_2).*

- ❑ *For vacuum furnace brazing, flux is NOT used.*

Capillary 'Wetting' Rely on Uniform and Clean Narrow Gap



Vertical Capillary Test Specimen



Material: 304 Stainless Steel
(0.062" thick)

Capillary Test Specimen shows capillary attraction vs. clearance vs. gravity.



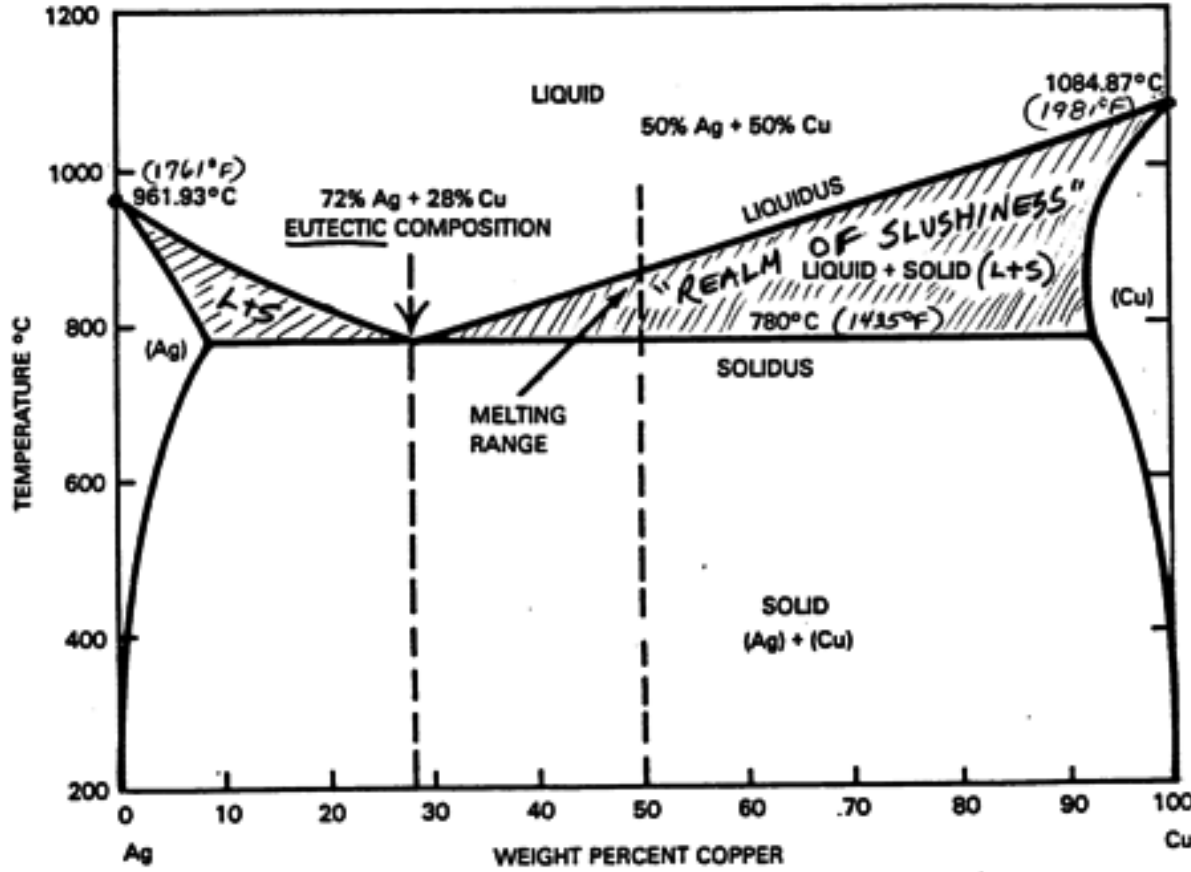
- *Filler metals (brazing alloys) come in the form of wire, foils, or paste.*
- *Brazing alloys are selected to have melting points below that of the base metal. The brazing alloys must be able to 'wet' the base metal(s).*
- *Generally, brazing alloys can be categorized into eutectic or non-eutectic. For eutectic alloy, the transitions between solidus and liquids occur at a very narrow band (within a degree). Eutectic alloys are usually preferable.*
- *Multiple braze steps are possible by choosing alloys of differing melting points and proceeding sequentially from highest to lowest temperature.*
- *Braze joints require tight tolerances for a good fit (0.002" to 0.004") to ensure capillary flow.*

Some Braze Alloys for UHV Components



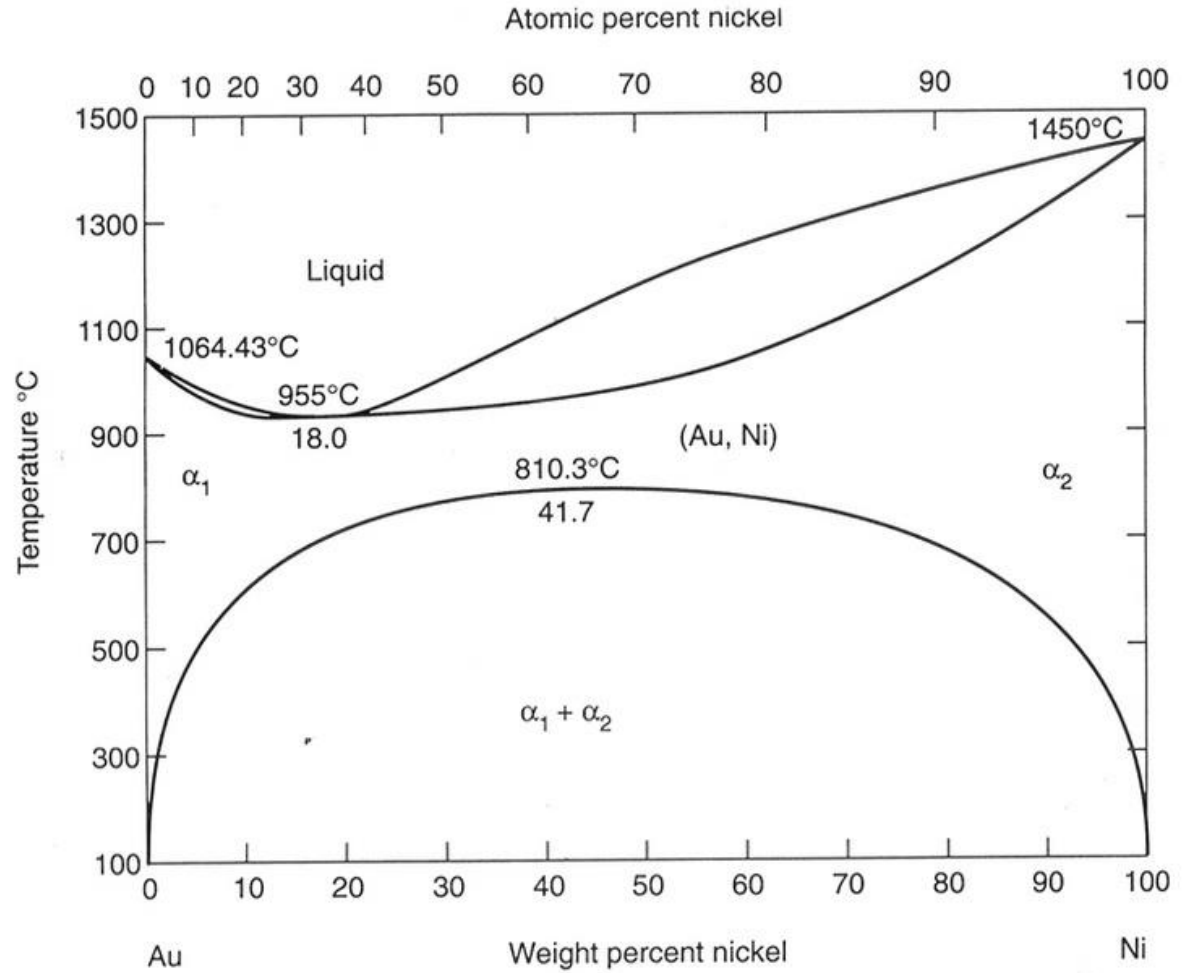
Alloy	Brazing Temperature	Composition
Georo™	361°C	88% Au, 12% Ge
CuSil™	780°C	72% Ag, 28% Cu
BAu -2	890°C	80% Au, 20% Cu
Au-Cu-Ni	925°C	81.5% Au, 16.5% Cu, 2% Ni
BAu -4	950°C	82% Au, 18% Ni
50/50 Au-Cu	970°C	50% Au, 50% Cu
35/65 Au-Cu	1010°C	35% Au, 65% Cu

Braze Alloy Phase Diagram Examples

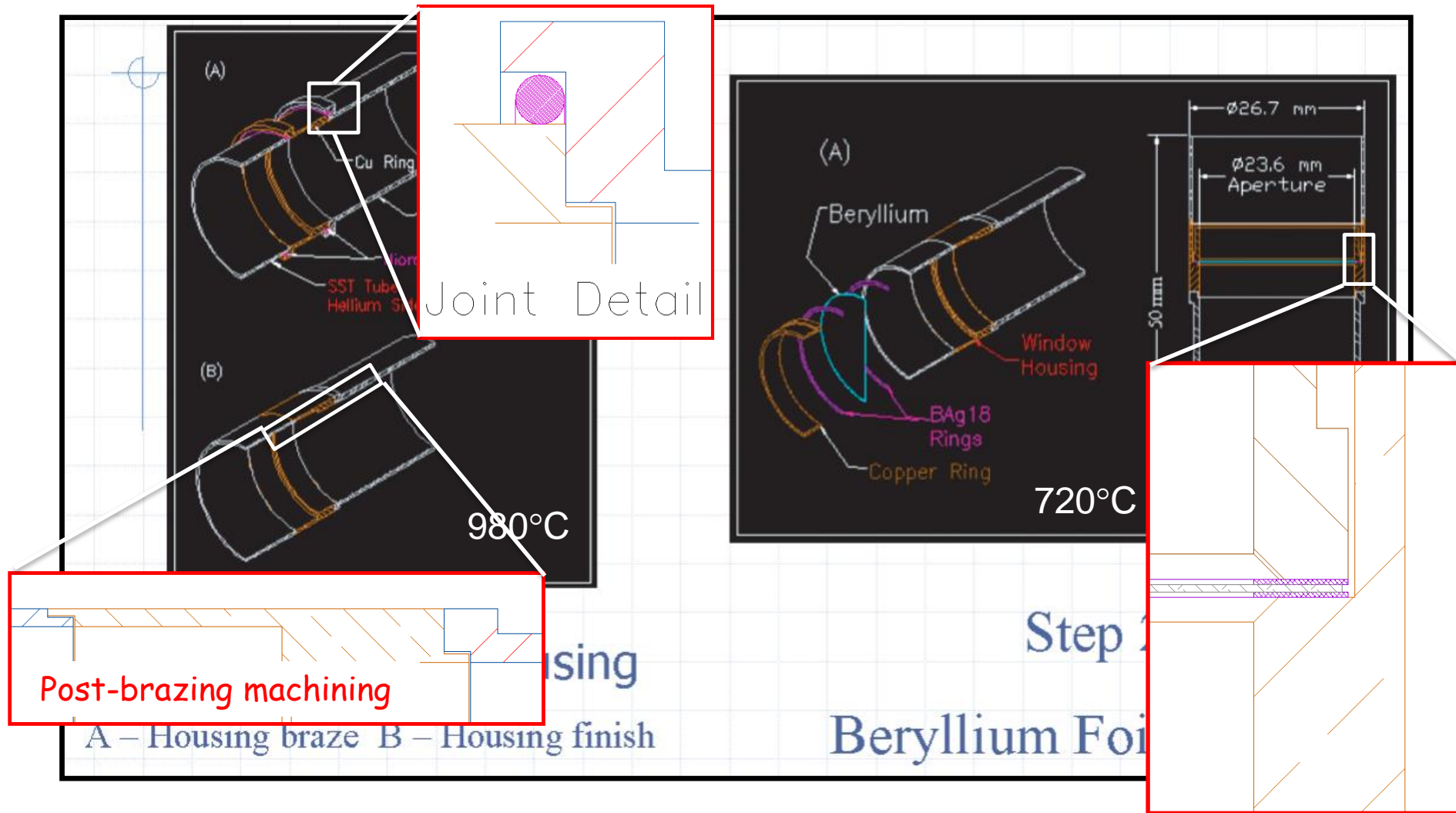


— Ag-Cu Phase Diagram.

Typical Phase (Constitution) Diagram



Vacuum Braze Joints – Examples



CESR Beryllium Injection Windows

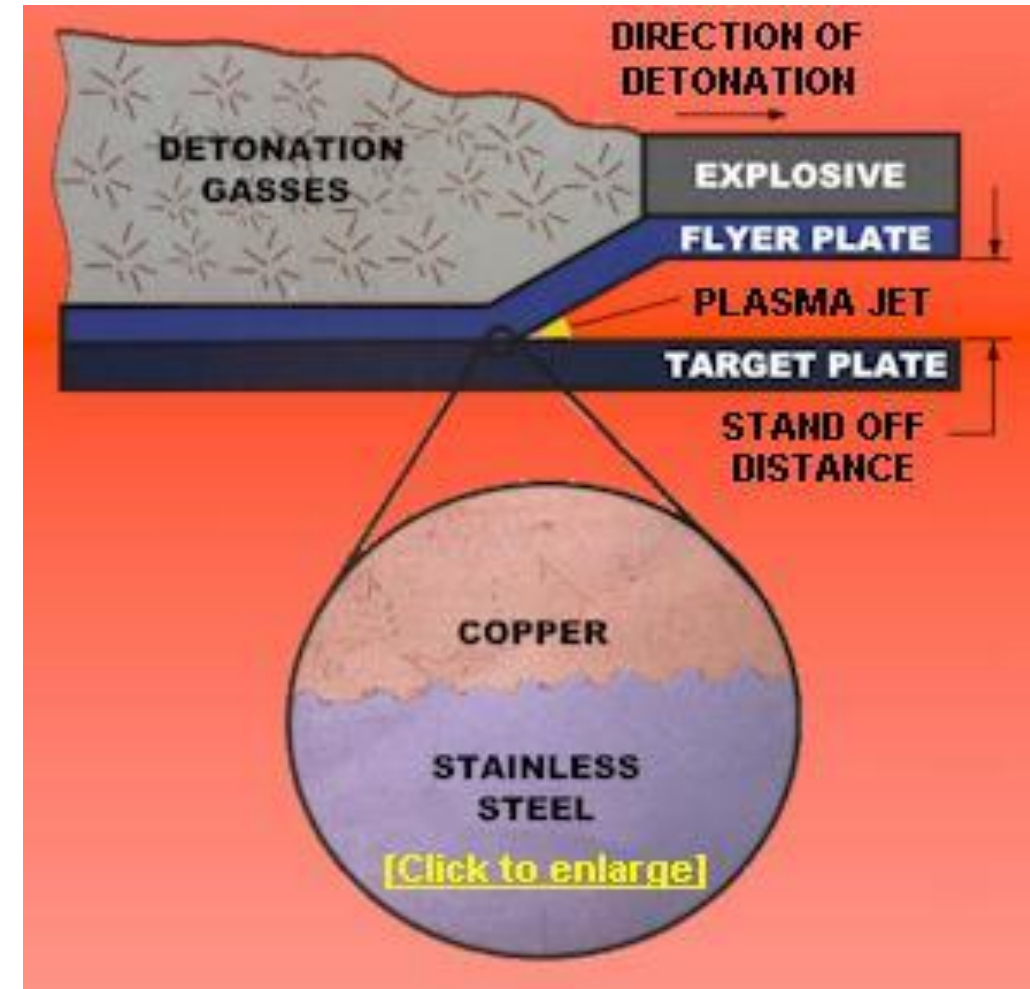


- Compatibility between materials to be jointed (welding, brazing etc.)*
- Weld (joint) preps - Consult with your welder(s)*
- Seam accessibility - Consult with your welder(s)*
- Leak checking procedures and fixtures - Consult with your vacuum technicians*
- Weld fixability - Any joint may be leaky*
- All parts MUST be UHV cleaned before any welding*

Explosion Bonding (Welding)



- The explosion bonding (EXB, or EXW) process is a solid-state joining process used to join a wide variety of materials that cannot be joined by traditional fusion welding processes.
- The basic components consist of a base metal, a clad metal above the base metal (with a small uniform gap) and the explosive charge on top of the clad metal. However, ductile metal interlayer(s) is needed to facilitate reliable bonding between the base and the clad metals, such as aluminum alloys to stainless steels.
- A controlled explosive detonation accelerates the clad metal into the base metal at a sufficient speed and causes the metals to fuse together.
- The force of the explosion sets up an angular collision, producing a plasma jet that removes impurity, leaving clean metal surfaces for joining.
- The pressure at the collision point (700~4000 MPa) causes the metals to behavior like viscous fluids, as evident by the wave-pattern at the bonding zone.



EXB components made to drawings:

- Atlas Technologies
(<https://www.atlasuhv.com/>)
- Thermionic Vacuum Products
(<https://thermionics.com/products/>)
- High Energy Metals, Inc.



EXB plates available from:

- PA&E (<http://pacaero.com/products/explosive-bonded-metals/>)
- High Energy Metals, Inc.
(<http://highenergymetals.com/>)

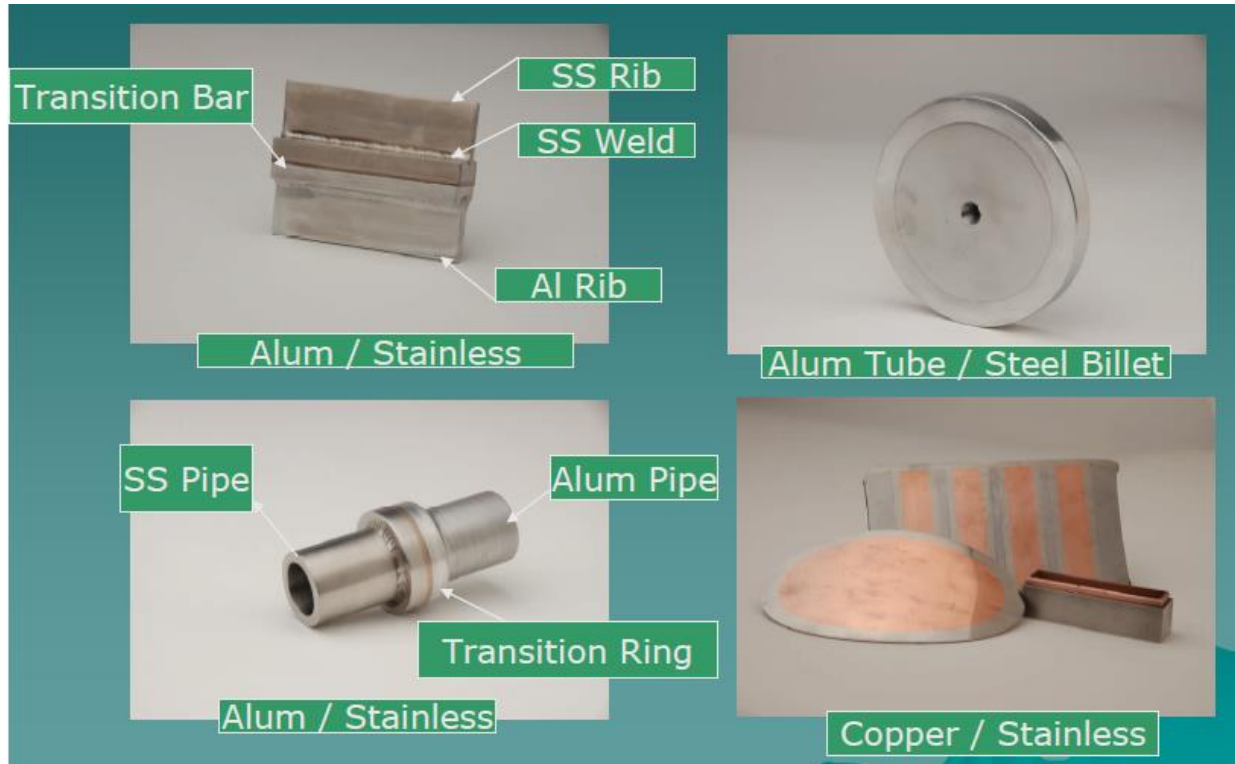
Explosive Forming

A Claim – All Metal Combinations can be bonded



Atlas Technologies Bonding Matrix																			Copy Right Atlas Technologies January 1998											
	Aluminum	AL. Alloy	Chromium	Copper	CU Alloy	GlidCop	Gold	Hafnium	Indium	Iron	Lead	Magnesium	Molybdenum	Moly. Alloy	Nickel, (Invar)	Niobium	Platinum	Rhenium	Silver	Steel, & Alloys	Steel, Mild	Stainless Steel	Tantalum	Tin	Titanium	Tungsten	Vanadium	Zinc	Zirconium	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
Aluminum	1																													
AL. Alloy	2																													
Chromium	3																													
Copper	4																													
CU Alloy	5																													
Gold	6																													
GlidCop	7																													
Hafnium	8																													
Indium	9																													
Iron	10																													
Lead	11																													
Magnesium	12																													
Molybdenum	13																													
Moly. Alloy	14																													
Nickel, (Invar)	15																													
Niobium	16																													
Platinum	17																													
Rhenium	18																													
Silver	19																													
Steel, & Alloys	20																													
Steel, Mild	21																													
Stainless Steel	22																													
Tantalum	23																													
Tin	24																													
Titanium	25																													
Tungsten	26																													
Vanadium	27																													
Zinc	28																													
Zirconium	29																													
Bonding Capability																														
Flange Metal Standards																														
Beam Stop, Absorber Materials																														
Super-conducting Flange Materials																														

Explosion Bonding – Examples



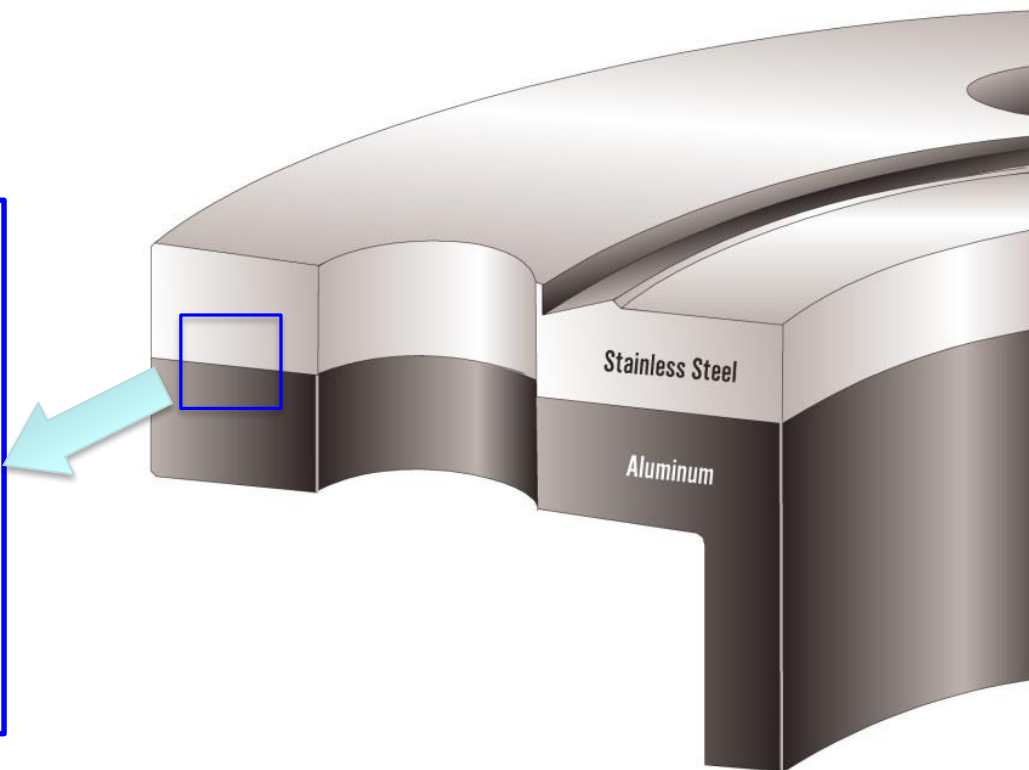
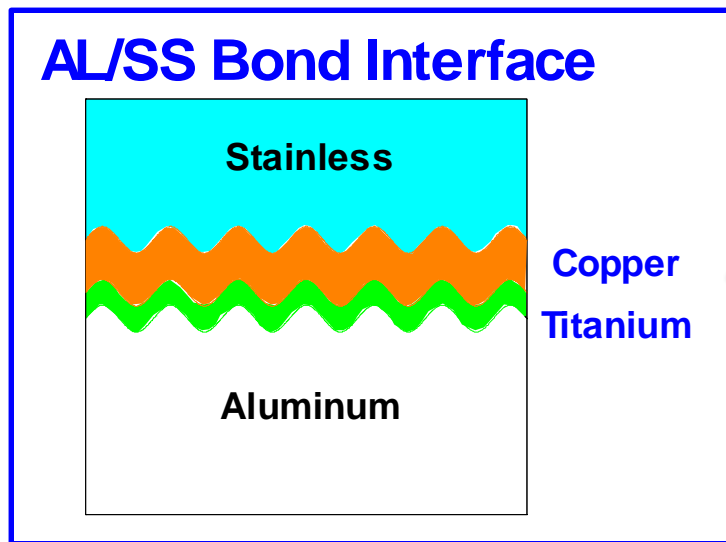
Ref: PA&E Bonded Metals Division



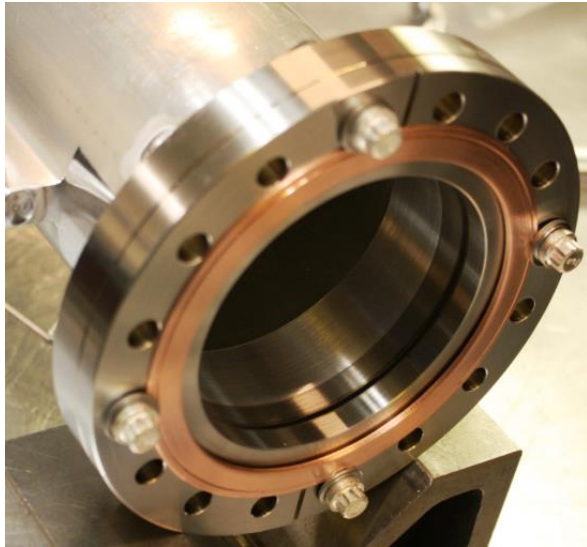
SS/AL Bond Interface

- Diffusion Inhibiting Layers: Copper and Titanium Interlayer enables Bonding AL/SS
- Vacuum: $<1 \times 10^{-10}$ cc He/Sec
- Thermal: Peak 500°C at weld up 0-250°C Operational
- Mechanical: Tensile 38,000 psi; Shear 30,000 psi

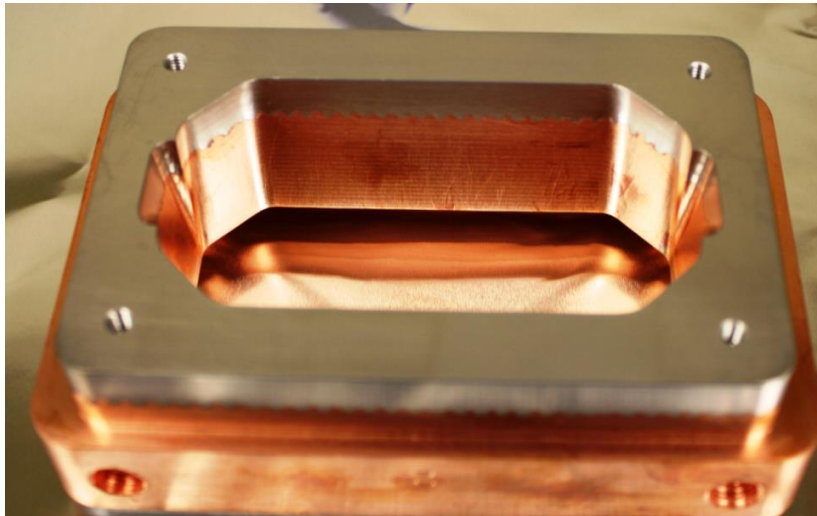
Ref: Atlas Technologies



Applications for bi-metallic joints



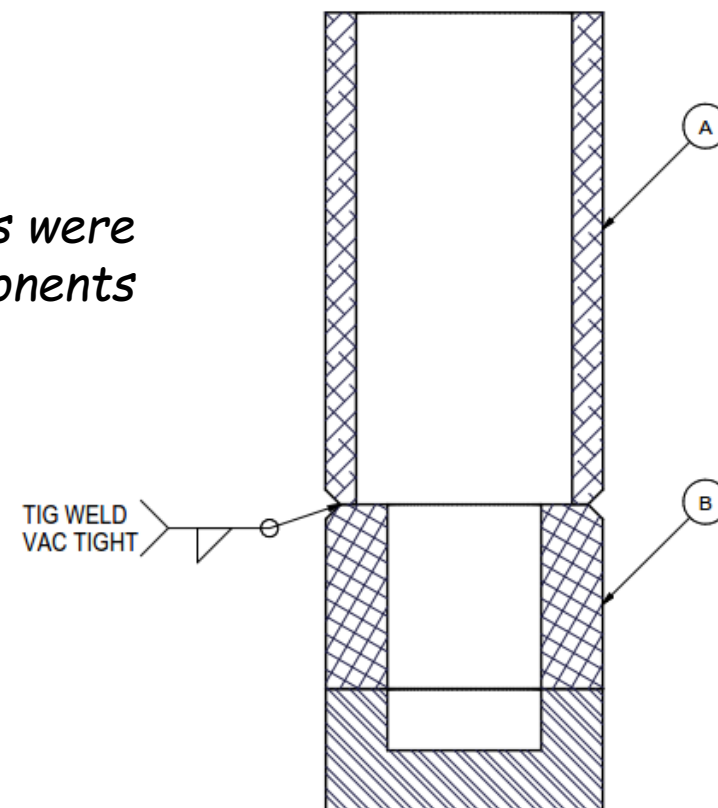
Alum/SST transition enable welding instrument feedthroughs to aluminum beam pipe



Cu/SST transition used on Cestr-C damping wiggler beam pipes

SS/AL Bonding - Tests and QCs

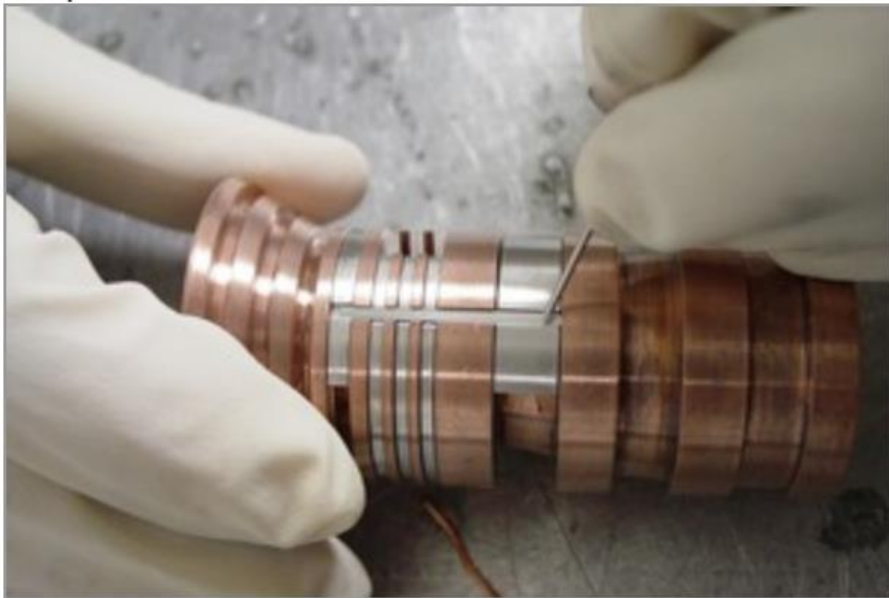
- ❑ *SST/AL transition is most commonly used on accelerator UHV systems. However, the SST/AL bonding is among most difficult combination. The bonding usually involve one or more interlayer materials, such as Cu, Ti, Nb, just to name a few.*
- ❑ *Some tests are specified in testing the bonding quality during procurement of SST/AL materials and components, including:*
 - *Tensile strength test of the bond - e.g. Ram-tensile test*
 - *Bonding void inspection - such as ultrasonic test*
 - *Leak test - Sample specimen leak checks or component leak check*
- ❑ *Some recent difficulties experienced by Cornell and NSLS II projects were occurred when leaks (often very large) were only detected after components completion of welding of the SST/AL to the final assembly (!!), the worst scenario.*
 - *The failed material usually involve the entire bonded plate. The possible causes of failure including (1) the interlayer(s) material(s) too thin; (2) the bonded plate is too large*
 - *At Cornell, we have included a welding test as a part of procurement specification, as shown to the left.*



Diffusion Bonding

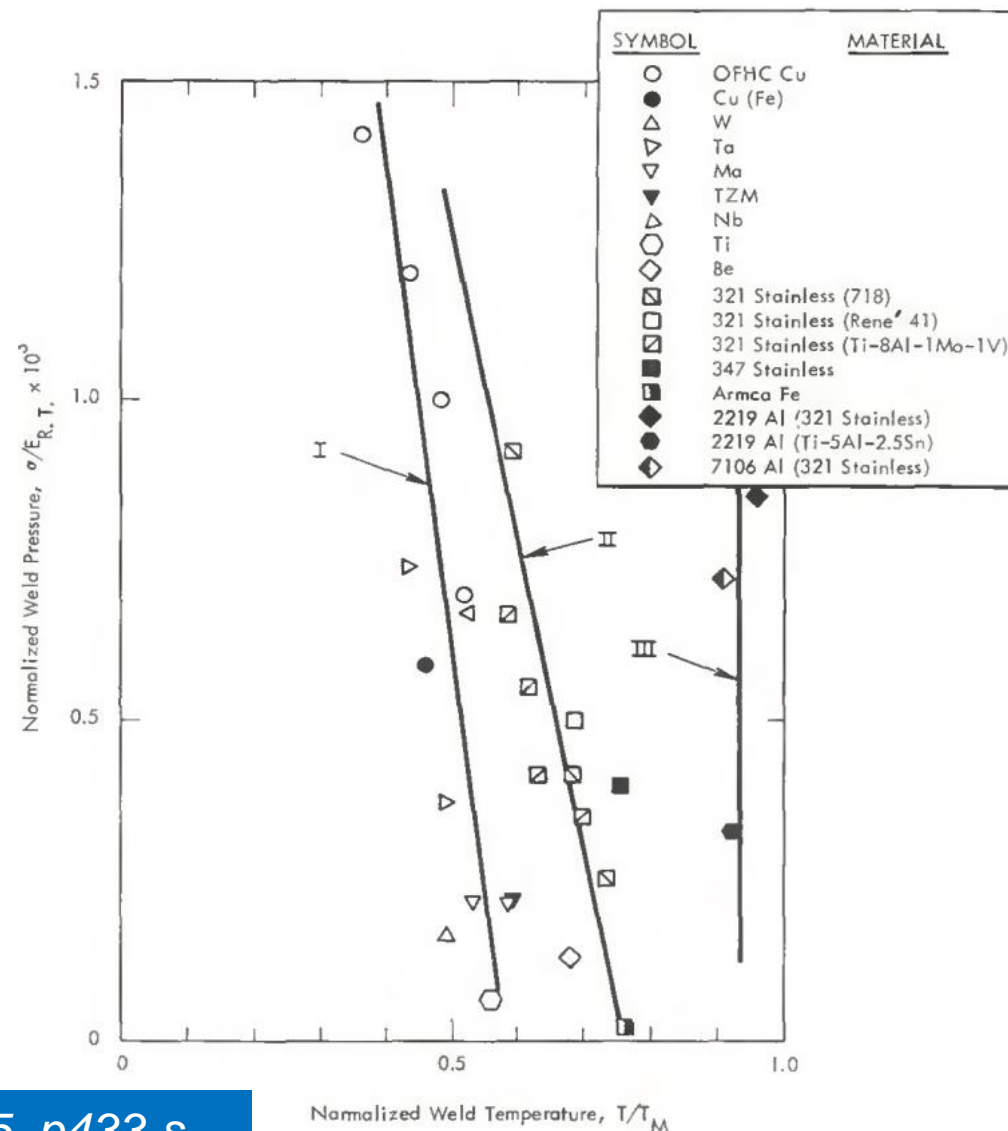


- Diffusion bonding is a joining technique where pre-machined components are held together under modest loads at elevated temperatures.
 - The loads are usually well below those producing deformation.
 - Bonding temperatures typically range from 50-80% of melting temperatures of the metals.
 - Processing times vary from 1 minute to over an hour.
 - Most diffusion bonding operations are conducted in vacuum or in an inert gas atmosphere
- Diffusion bonding requires very clean components with excellent surface finishes.
- Diffusion bonding can also bond dissimilar materials

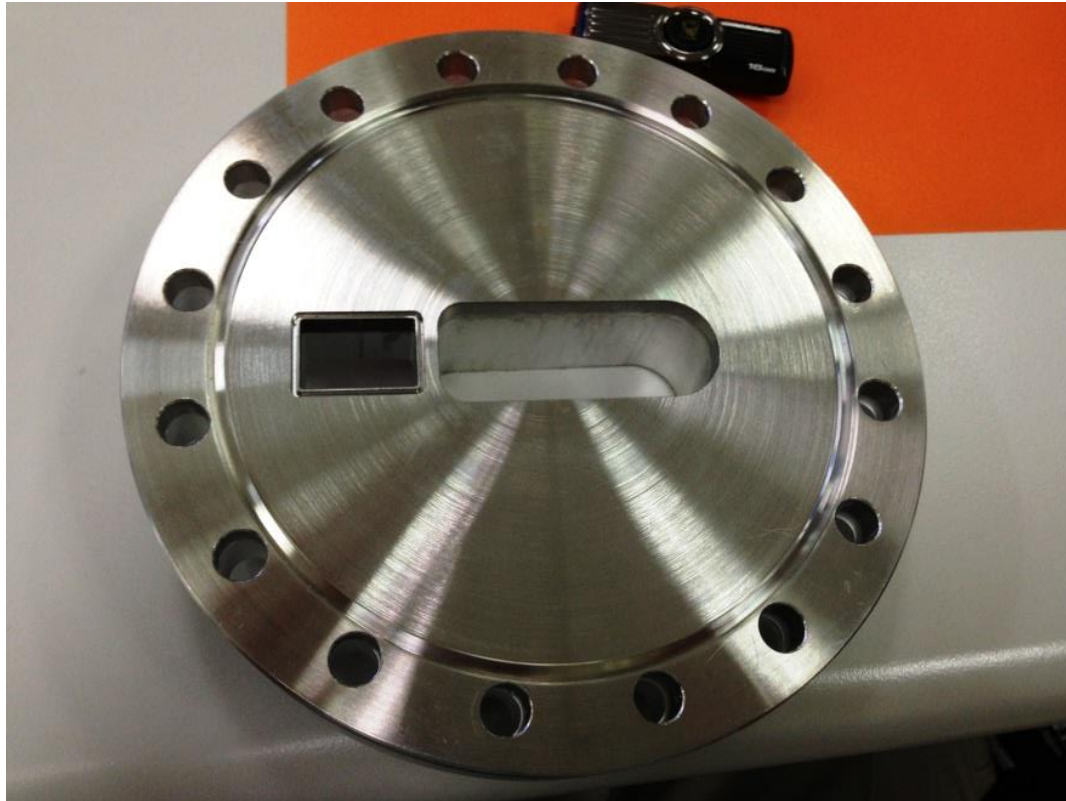


Hot Isostatic Press – Metal Transitions

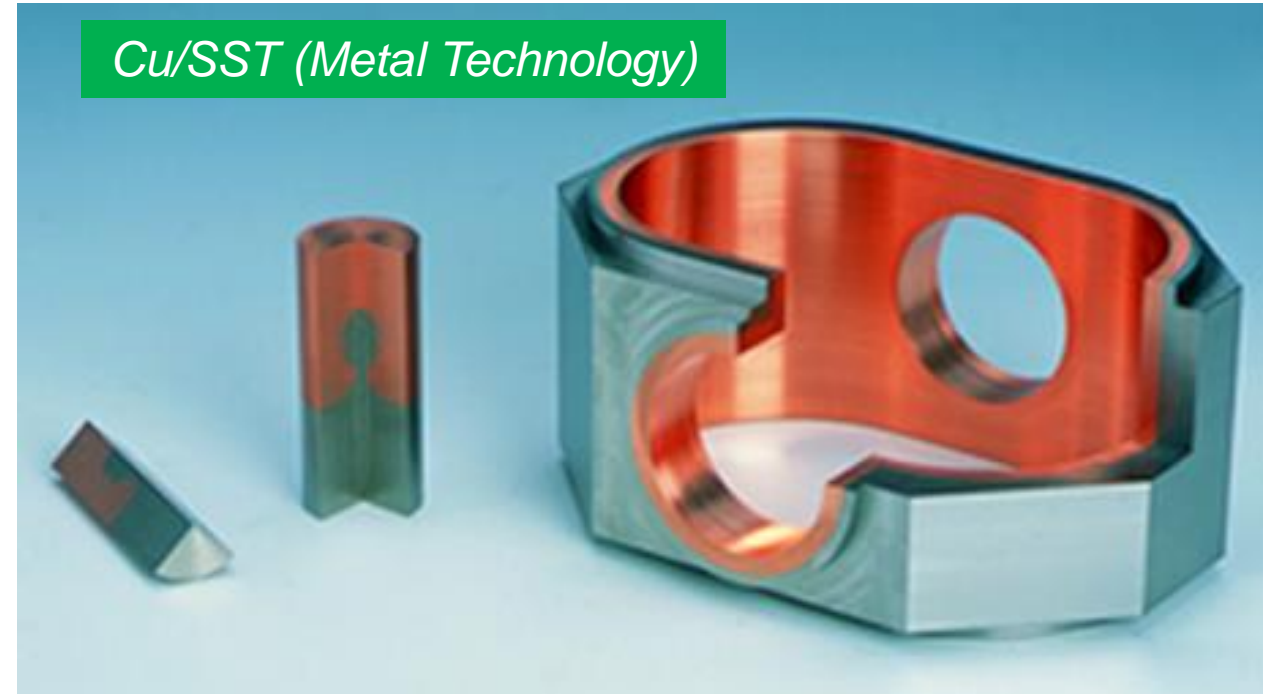
- ❑ Hot Isostatic Press, HIP, is a solid-phase process that involves the application of a high-temperature, high pressure gas (typically Argon) to components. Unlike diffusion-bonding, HIP allows the welding of more complex geometries. HIP relaxes surface finish requirements on the mating facets.
- ❑ Typical HIP process takes 6 to 16 h, but many components can be fitted into one furnace.
- ❑ Comparing Alum/SST, price is similar to ExB material, ~\$30/sq.in.
- ❑ TPS and Super-KEKB vacuum system used extensively of HIP bi-metal material, without failure, but they had problem with ExB bi-metal flanges.
- ❑ [Metal Technology Co.](#) is one of company in Japan perform HIP services.



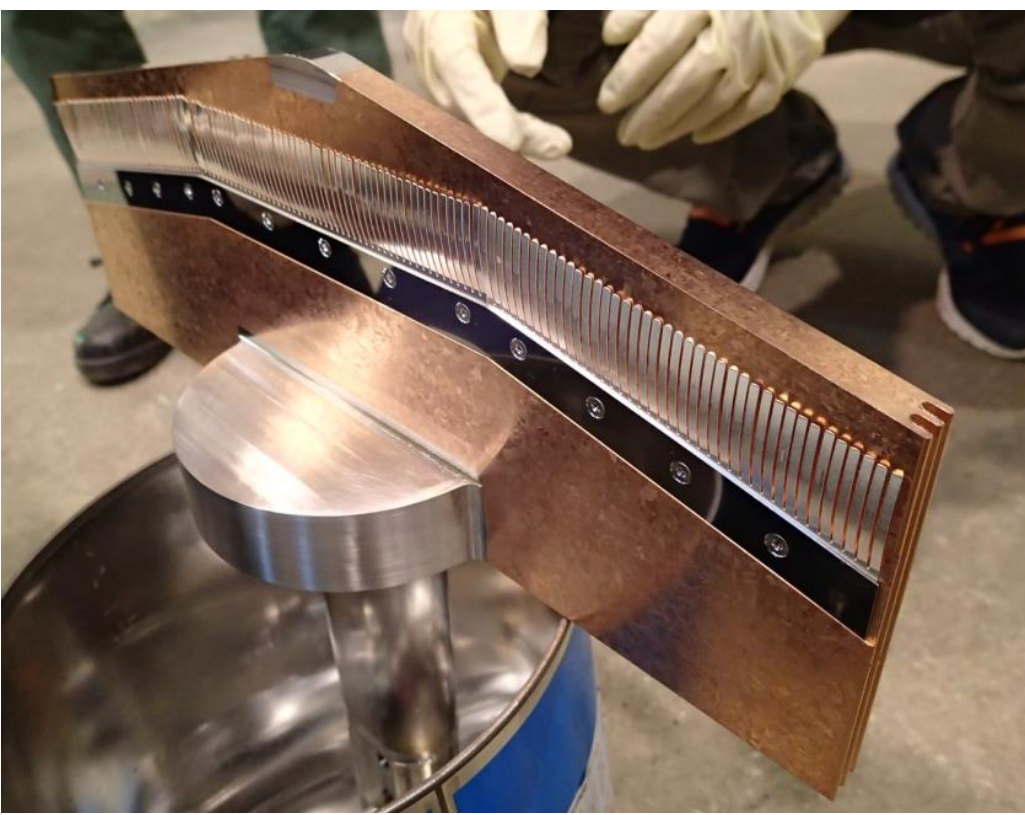
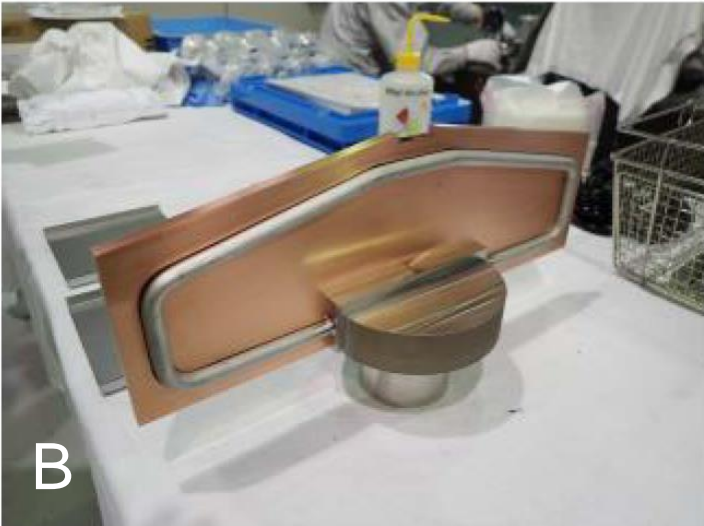
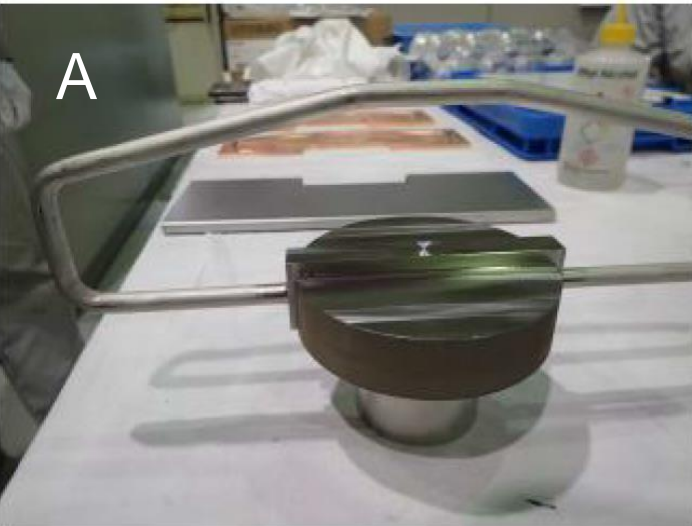
W. A. Bryant, *Welding J.*, Dec 1975, p433-s



*Alum/SST (Injection Flanges)
(Taiwan Photon Source)*



One HIP Example – SuperKEKB's Collimator



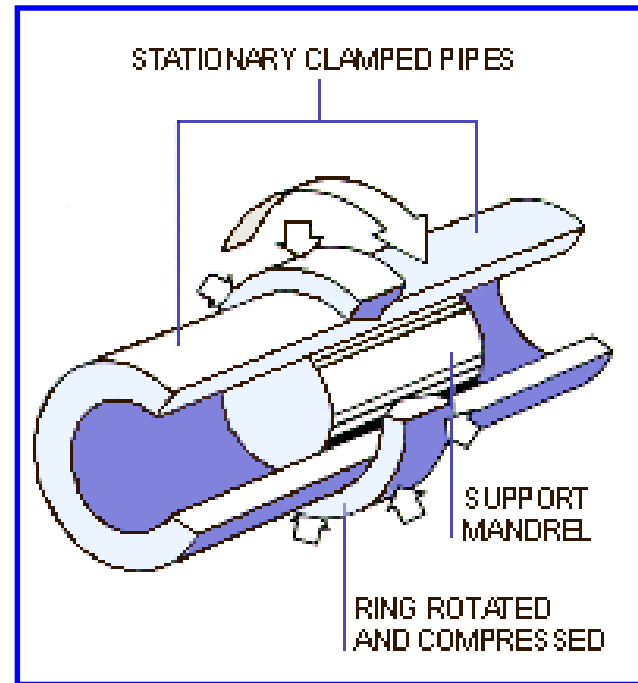
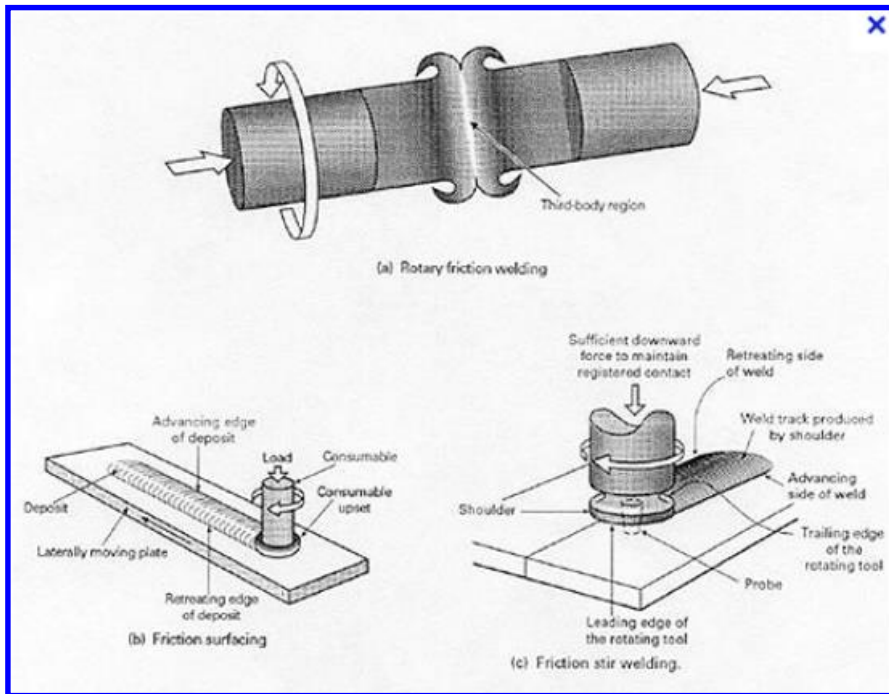
A: Inner cooling loop welded
B&C: Two Cu blades and W tip clamped

The entire collimator blade was formed by HIP

Friction Bonding/Welding



- Friction welding (FW) is a class of solid-state welding processes that generates heat through mechanical friction between a moving work piece and a stationary component, with the addition of a lateral force called "upset" to plastically displace and fuse the materials.
- FW is useful to bond dissimilar materials, such as aluminum to stainless steel, which otherwise difficult to joint.



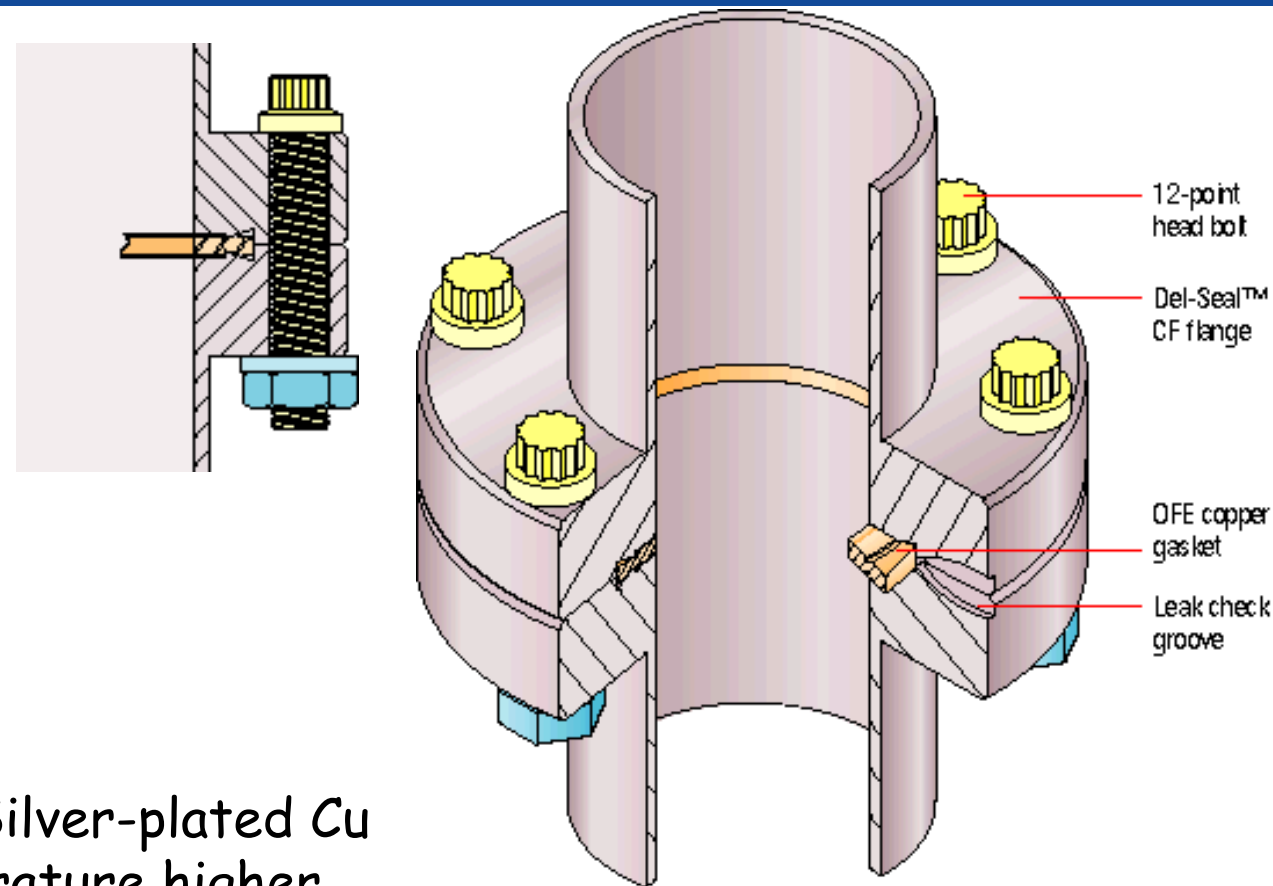
There are a variety of metal seals available for vacuum systems, including:

- ConFlat® flanges: for flanges OD <26"*
- Helicoflex® seals: for customer designed flanges*
- Metal wire seal flanges: for large flanges*
- VATSEAL® flanges: good RF properties*

Metal seals are used for UHV systems, where permeation, as well as radiation damages, are not acceptable.

Conflat® Flanges

- Conflat® style metal seal flanges are the most widely used for UHV vacuum systems.
- During sealing, knife-edges of a pairing stainless steel flanges plastically deform a copper gasket to form a reliable seal.
- The close match of C.T.E. of stainless steel and copper ensure proper sealing force through temperature cycles, up to 450°C.
- Gaskets are usually made of ½-hard OFHC. Silver-plated Cu gaskets are used for system baked at temperature higher than 250°C.
- Standard sizes range from 1-1/3" to 16" OD, with fixed and rotatable styles.

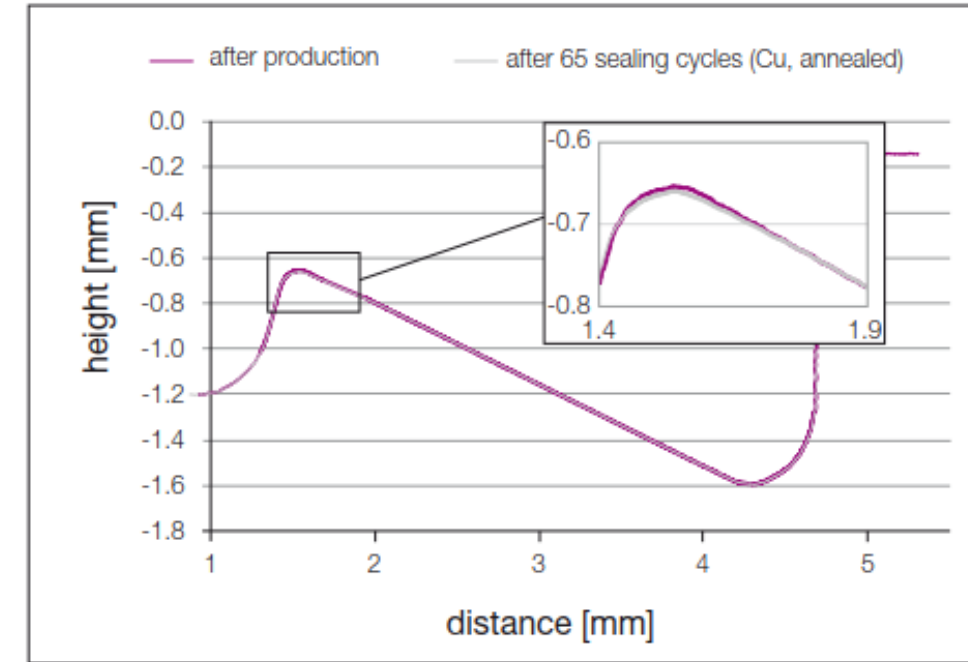


❑ To avoid transition to stainless steel, CF flanges made of aluminum alloys may be directly welded to aluminum chambers. At least two styles are available commercially.

1. Base material in A2219 alloy with CrN hardening coating on knife-edge. Need to use aluminum gaskets for seal, and knife-edge cannot be repaired.
2. 6xxx-T6 alloy without hard coating (AluVac), using Al or annealed Cu gaskets.

[Knife Edge Stability of CF Components made of Lightweight Aluminum](https://www.vacom.de/en/downloads/white-papers)

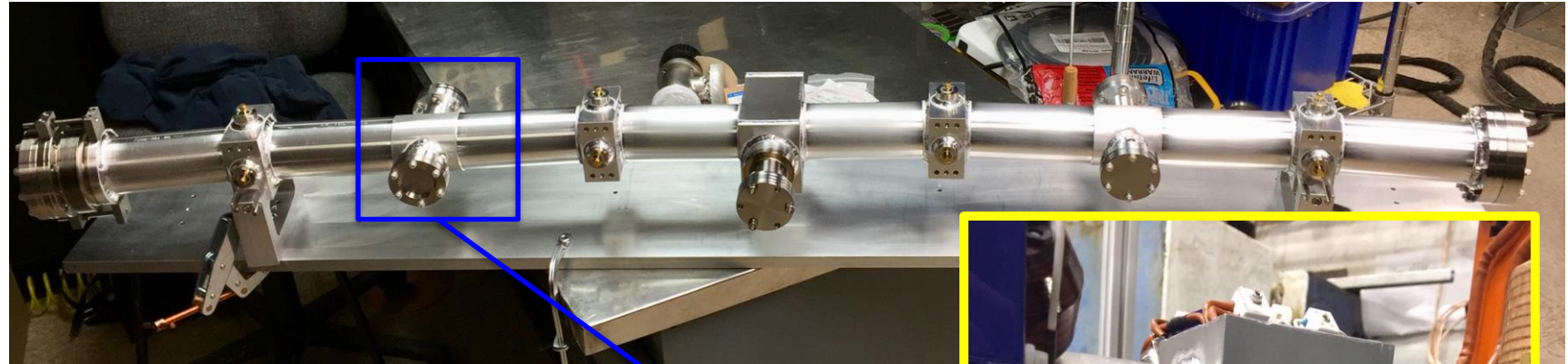
<https://www.vacom.de/en/downloads/white-papers>



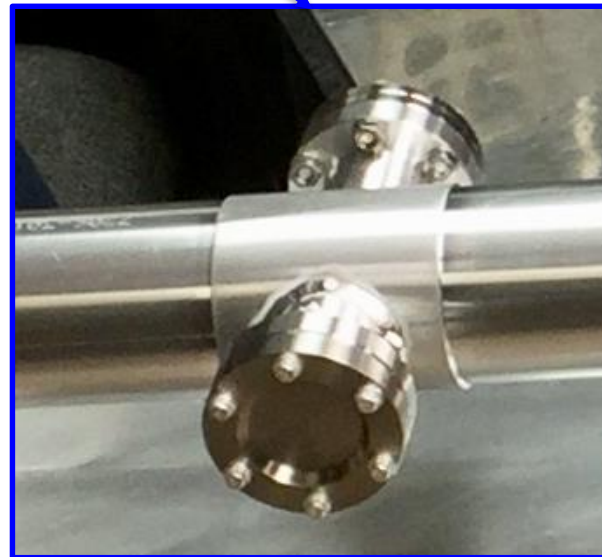
❑ CF flanges could also be made of Cu alloys, such as ZrCrCu, for better thermal design for applications dealing with high power density (such as photon-absorbers.)

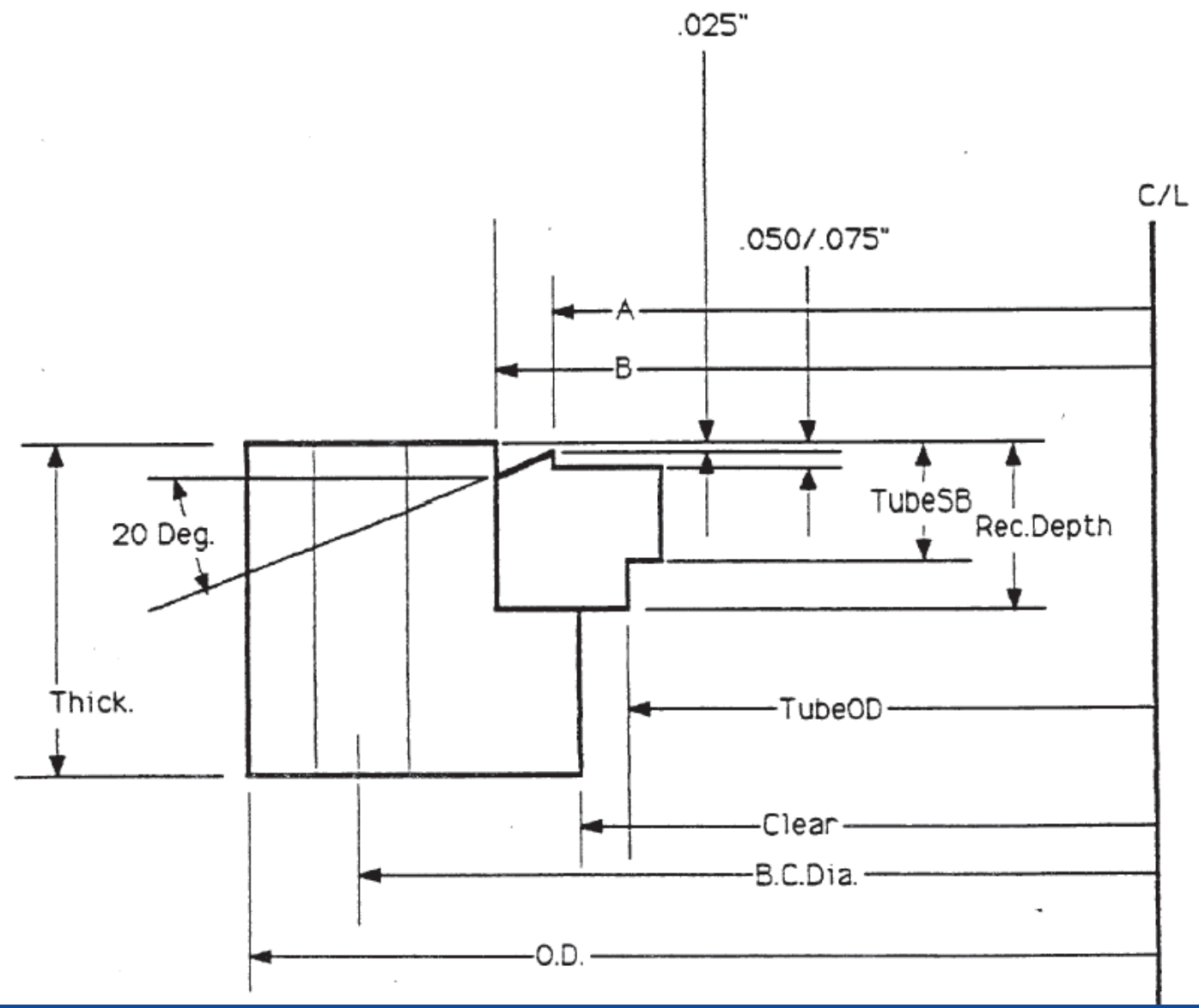
Aluminum Conflat® Flanges @ CBETA

Over 100 2-3/4" CF flanges, made of 6013-T8 alloy, were used on the vacuum system of CBETA (Cornell Brookhaven ERL Test Accelerator)



- Use commercially available 1100-H14 gaskets.
- Tested with repeated sealing cycles and bakeouts (150°C)





Conflat® Flanges Cont.

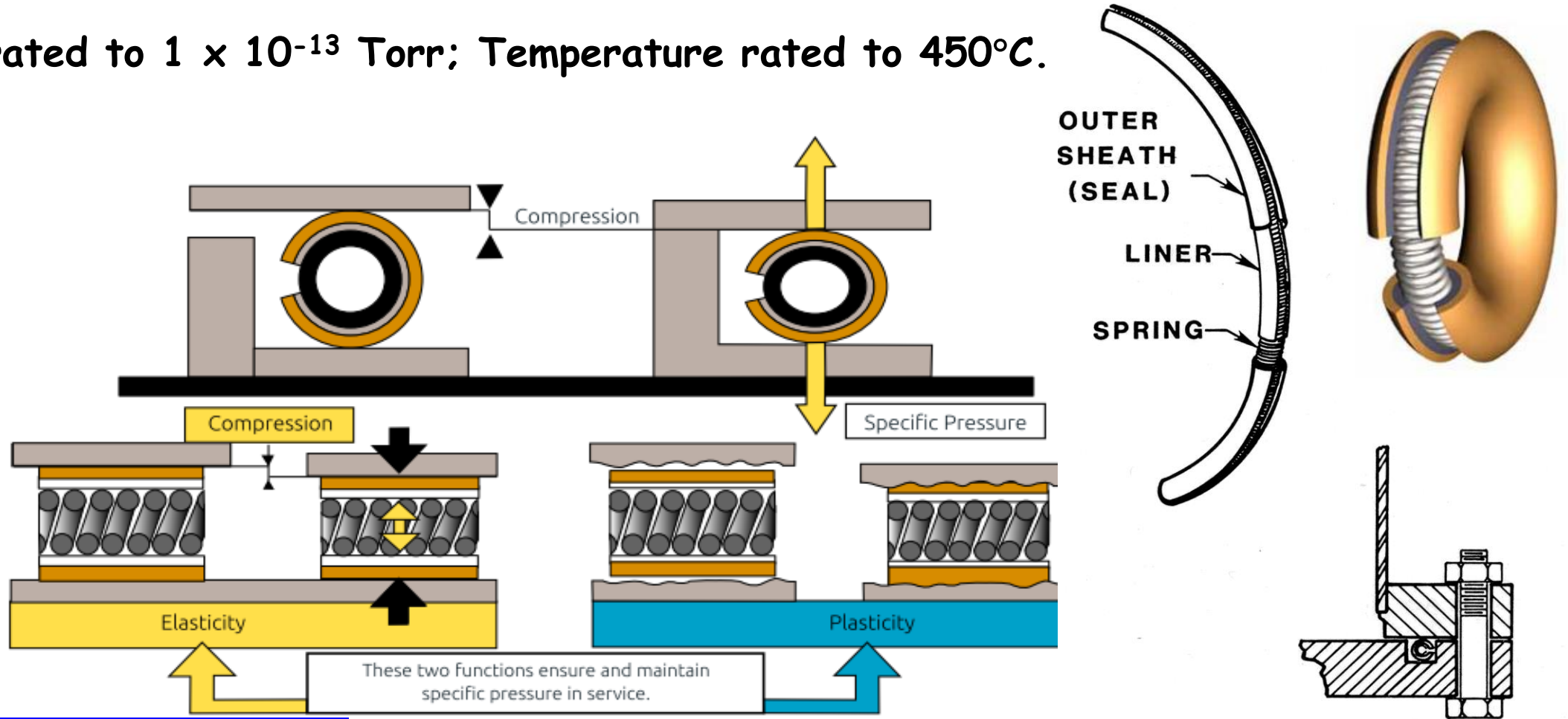


O.D.	Config.	Bolts	B.C.Dia.	Gas.OD	Gas.ID	Thick.	TubeSB	TubeOD		Clear	RecDepth	A-Dia.	B-Dia.
1.33" 133	fixed rot	6 8-32	1.060	0.834	0.640	0.280	0.500	0.75				0.718	0.841
2 1/8" 218	fixed rot	4 1/4-28	1.625	1.290	1.010	0.470	0.170	1.00		0.750	0.280	1.086	1.297
2 3/4" 275	fixed rot	6 1/4-28	2.312	1.895	1.451	0.500	0.209	1.50		1.075	0.236	1.650	1.902 1.906
3 3/8" 338	fixed rot	8 5/16-24	2.850	2.425	2.010	0.625	0.225	2.00		1.560	0.300	2.188 2.200	✓ 2.432
4 1/2" 450	fixed rot	8 5/16-24	3.628	3.243	2.506	0.687 0.750	0.375	2.50		2.030	0.318	3.040	3.250
4 5/8" 458	fixed rot	10 5/16-24	4.030	3.598	3.010	0.750 0.810	0.375	3.00		2.625	0.500	3.395 3.347	3.605
6" 600	fixed rot	16 5/16-24	5.128	4.743	4.006	0.781 0.843	0.438	4.00		3.100	0.505	4.540	4.750
6 3/4" 675	fixed rot	18 5/16-24	5.969	5.567	5.010	0.840	0.460	5.00		4.125	0.563	5.364	5.574
8" 800	fixed rot	20 5/16-24	7.128	6.743	6.007	0.875 0.937	0.500	6.00		5.125	0.563	6.540	6.750
10" 1000	fixed rot	24 5/16-24	9.128	8.743	8.007	0.968	0.500	8.00		6.125	0.624	8.540	8.750
13 1/4" 1325	fixed rot	30 3/8-24	12.060	11.587	10.810	1.120	0.500	10.75		8.125	0.675	11.350	11.595
14" 1400	fixed rot	30 3/8-24	12.810			1.120	0.875	12.00		10.875	0.775		
16 1/2" 1650	fixed rot	36 3/8-24	15.310			1.120	0.875	14.00		12.250	0.775		
										14.290	0.775		

Helicoflex® Flanges



- Metal O-ring using an internal spring to maintain the seal force, while outer layer of the gasket deforms to make seal.
- Vacuum rated to 1×10^{-13} Torr; Temperature rated to 450°C.
- Typical :



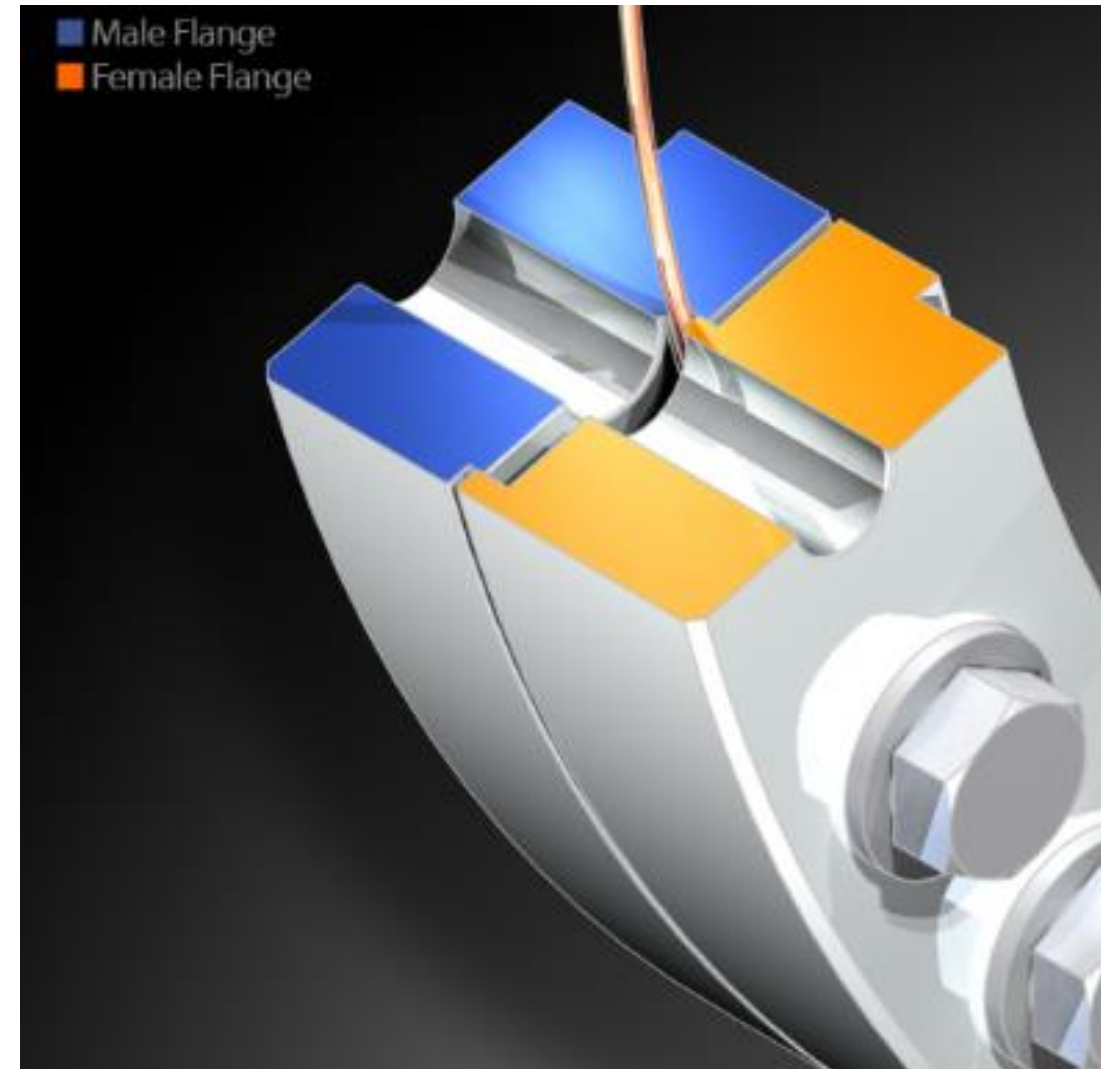
Ref: <http://www.techneticsgroup.com>



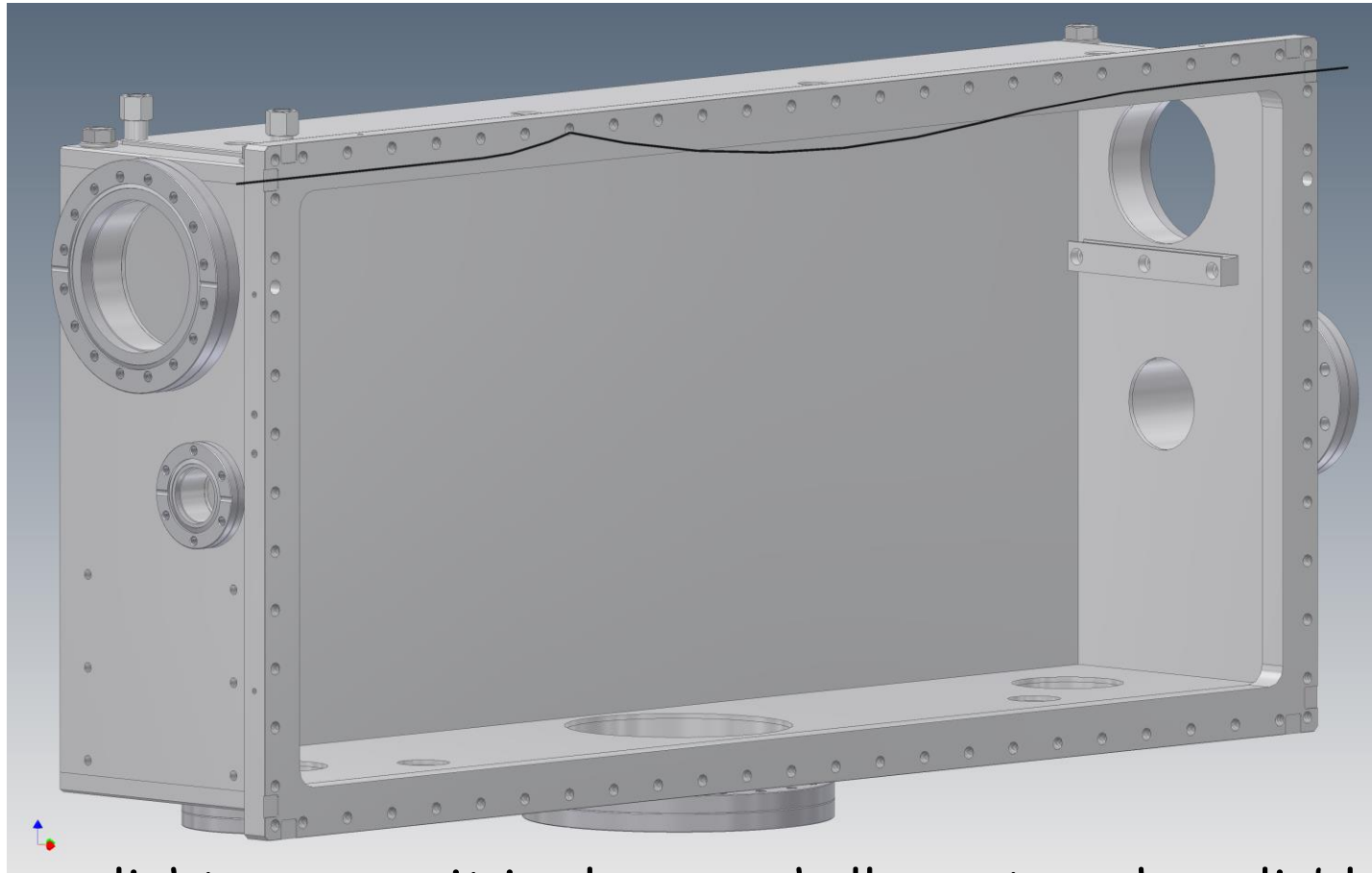
Commercial Wire Seal Flanges



- Vacuum rated to 1×10^{-13} Torr, Temperature rated to 450°C with copper wire gasket.
- Typical size range: 20" - 27" od with >30" possible
- **Warning** - male and female flanges

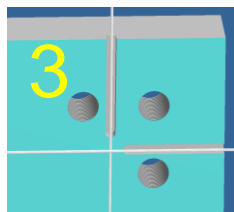
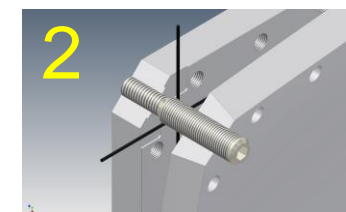
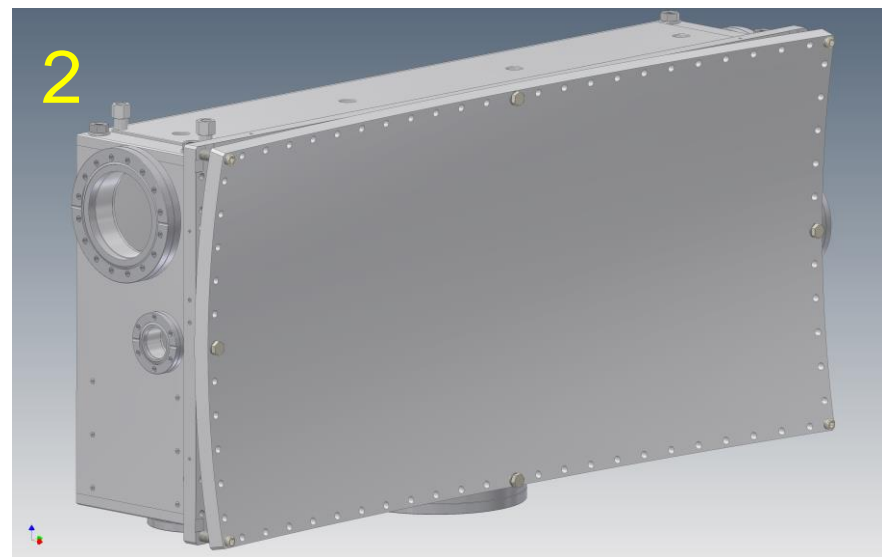
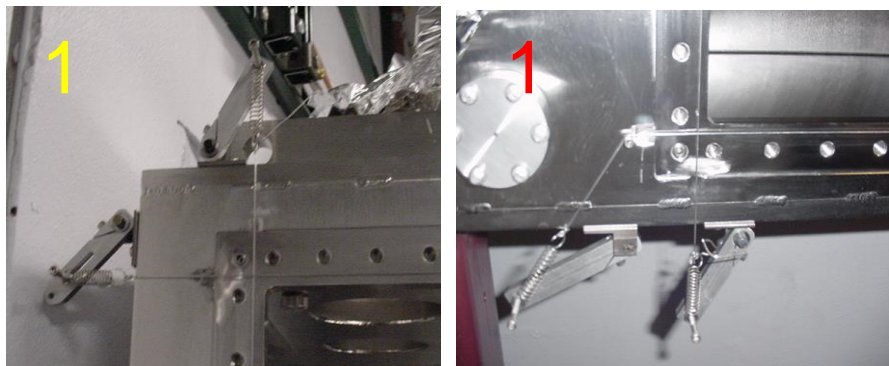


Large Wire Seal Flanges at CHESS



- ❑ As with many X-ray light sources, it is always a challenge to make reliable UHV-compatible seal on a very large lid (often in vertical position) for X-ray optics, as elastomer seal is not acceptable.
- ❑ A reliable, inexpensive and very scalable aluminum wire seal scheme was developed at CHESS, and also adapted by NSLS II.

Large Wire Seal Flanges at CHESS Cont.



How the seal is made:

1. Four aluminum wires are stretched across sealing surfaces, and tensioned with springs.
2. The large lid is placed (with exaggerated bending) over the wires. Tightening from center towards to the corners, to ensure that the wires kept stretched .
3. Under cuts at corners may improved sealing reliability.

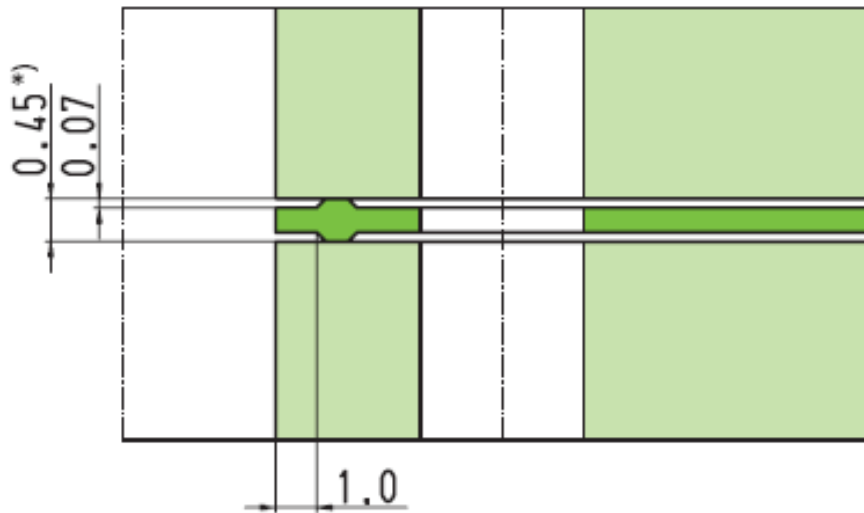
Features of the seals:

1. No 'upper-size' limit.
2. Reproducible and reliable seals
3. Relatively relax seal surface finish, but need to be flat.
4. Only work on flanges with straight sealing edges

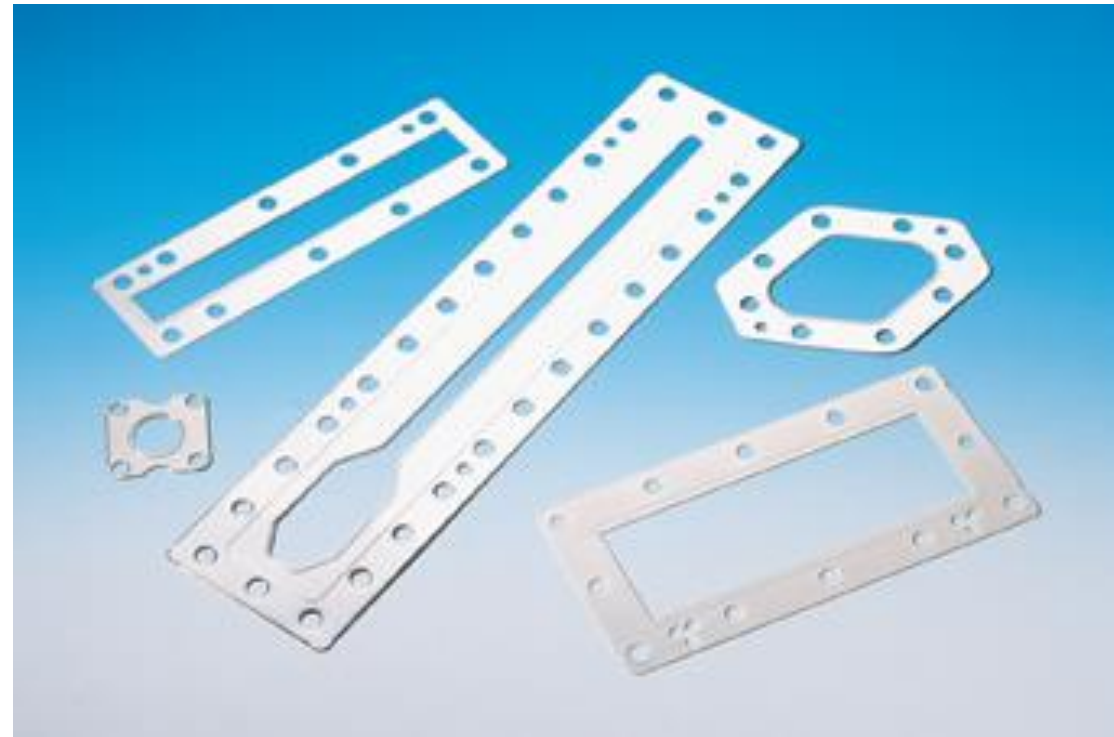
VATSEAL® Flanges



- ❑ A style of metal seal for vacuum, cryogenics and high temperature applications.
- ❑ silver-plated or gold-plated copper gaskets
- ❑ VATSEAL metal seals make a leak-tight seal and at the same time a reliable, low resistance RF contact



*) 0.6 uncompressed

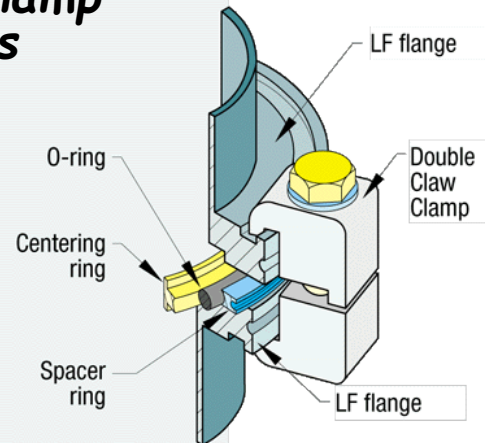


Elastomer (O-ring) sealed flanges found their uses in accelerators mostly in high-vacuum, or insulation vacuum for cryo-genic systems (such as superconducting magnet).

ISO Flanges

Flanges come in a variety of fastening styles:

- Kwik-flange
- Rotatable & Non-rotatable
- Double claw clamp
- Banded clamps



ASA Flanges



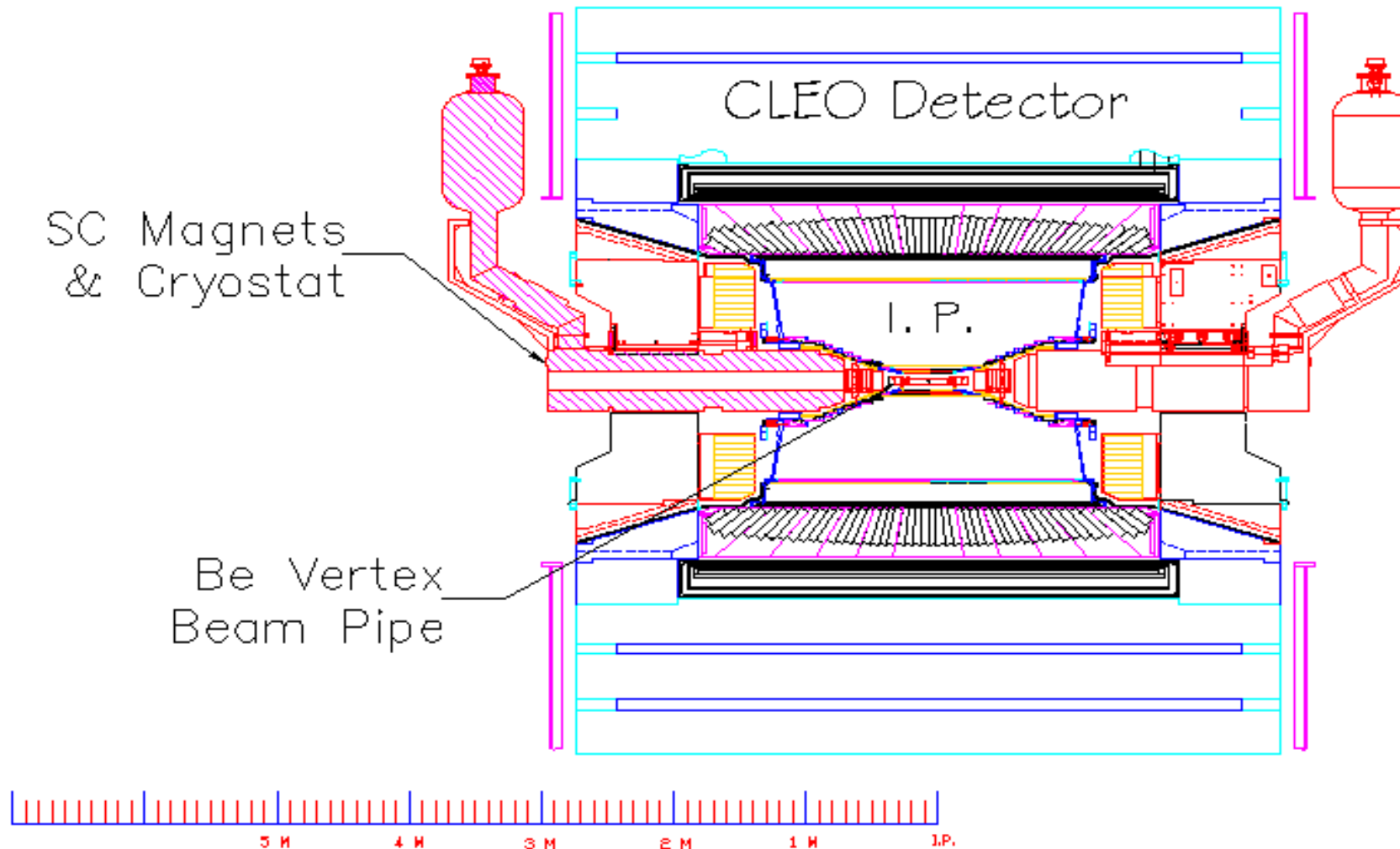
Typical size range:
1" to 12" dia.

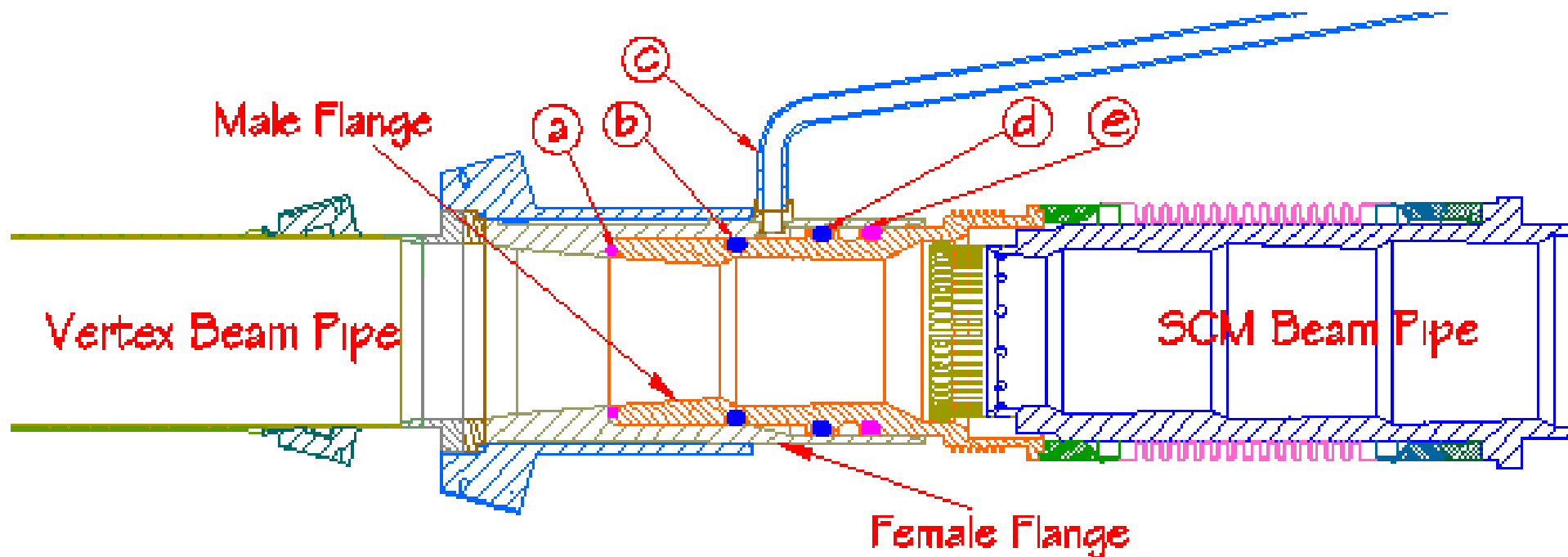
Elastomer Seals for UHV Systems

- ❑ In general, elastomer seals are not suitable for accelerator UHV systems for the following reasons:
 - Permeation through O-ring seals can be significant in humid environment ('seasonal-effect' was very visible at CESR in early days, with our old home-made GVs using O-ring bonnet seals.
 - Radiation hardening of elastomer seals will result in leaks.

- ❑ However, elastomer seals have been used with successes, in following CESR examples:
 - Use O-ring as gate through seals for CESR's RF-shielded gate valves with oval beam apertures. ~30 GVs in use in CESR for more than 20 years, no O-ring leak due to radiation hardening. This resulted in a very significant saving as compared to all-metal special RF-shielded GVs.
 - Differentially pumped O-ring seals for (decommissioned) CLEO beryllium beampipe remote flange joints, aka the 'magic' flanges.

The Challenge: Making an UHV joint 3-m in-the-hole





Differentially pumped double O-ring sealed 'magic' flange

- (a) Be-Cu spring for RF contact;
- (b) Primary Viton O-ring;
- (c) Differential pumping;
- (d) Outer Viton O-ring;
- (e) Electrically conductive elastomer (**EcE**) O-ring for RF shield