The US Particle Accelerator School
Materials, Fabrication Techniques, and Joint Designs

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Stainless Steel

- High strength, moderate formability, excellent weldability.
- Can be extruded in simple shapes
- 304 SS, least expensive
  304L SS, most commonly used in vacuum, a little more expensive
  316 SS, most expensive, resistant to chemical attack, welds are non-magnetic
- Wide variety of circular tubes and pipes available (seamless & welded)
- Outgassing rates can be decreased by employing good machining techniques, chemical cleaning and baking (up to 900^{o}C)
- Thermal and electrical conductivity is poor

Typical Physical Properties for Stainless Steels

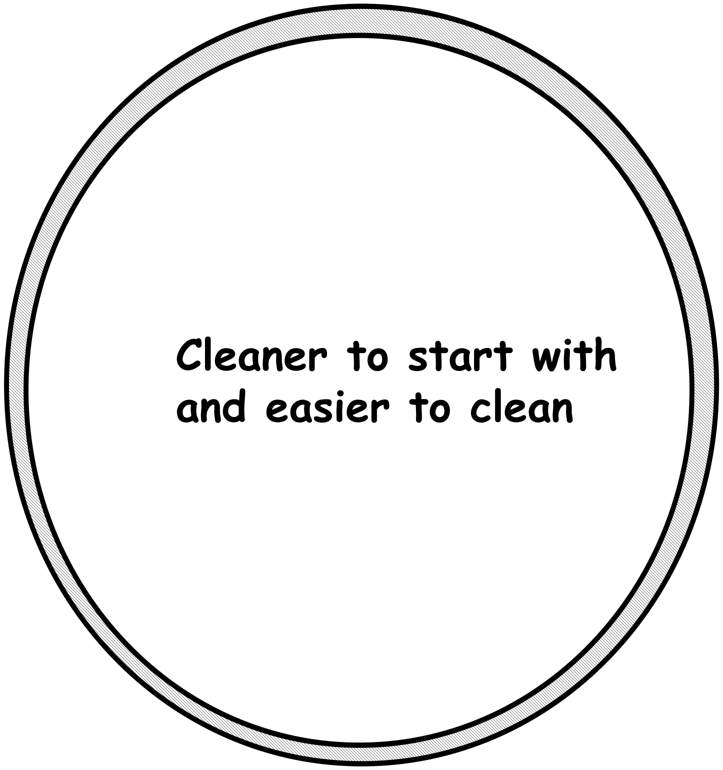
Property	304	304L	316	OFE Cu
Composition:	C 0.08% Cr 18-20% Mn 2% Fe 66-74% Ni 8-10.5% P 0.045% S 0.03% Si 1%	C 0.03% Cr 18-20% Mn 2% Fe 66-74% Ni 8-12% P 0.045% S 0.03% Si 1%	C 0.08% Cr 17% Mn 2% Mo 2.5% Fe 65% Ni 12% P 0.045% S 0.03% Si 1%	Cu 100%
Melting Point (°C)	1427	1425	1385	1083
Density (g/cc)	8.0	8.0	8.0	8.92
Electrical Resistivity (W-cm)	7.2×10^{-5}	7.2×10^{-5}	7.4×10^{-5}	1.71×10^{-6}
Elect. Conduct. (% IACS*)				101
Therm. Conduct. (W/m-K)	16.2	16.2	16.3	391
Coeff. Of Therm. Exp. ($^{o}C^{-1}$)	$17.2x10^{-6}$	$17.2x10^{-6}$	$16.0x10^{-6}$	$17.5x10^{-6}$
Mod. Of Elasticity (psi)	$28.6x10^{6}$	$28.5x10^{6}$	$28x10^{6}$	$17x10^{6}$

Typical Mechanical Properties for Stainless Steels

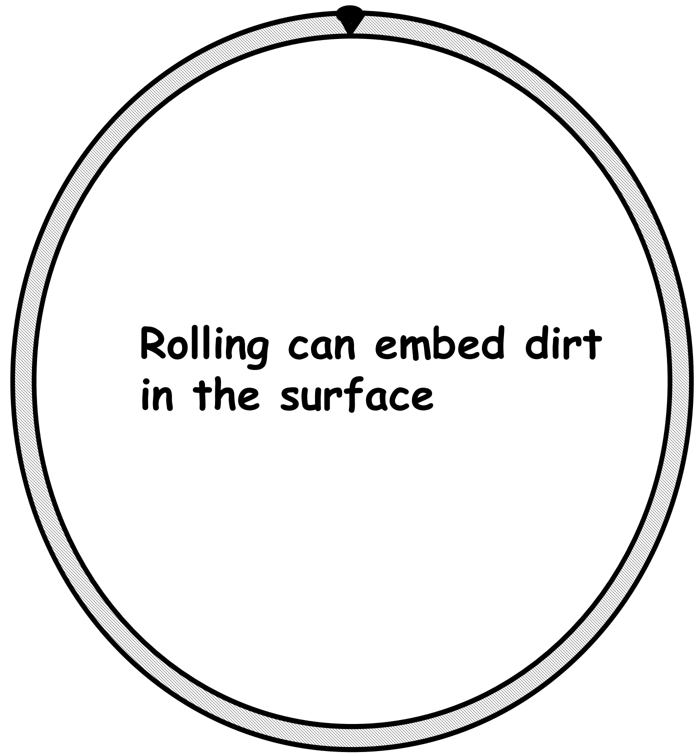
Property	304	304L	316	OFE Cu
Tensile Strength (MPa)	505	564	565	338
Tensile Strength (ksi)	73.2	81.8	81.9	49.0
Yield Strength (Mpa)	215	210	250	217
Yield Strength (ksi)	31.2	30.5	36.3	31.5
Elongation (%)	70	58	55	55
Modulus of Elasticity (Mpa)	197	197	193	115
Modulus of Elasticity (ksi)	28.6	28.6	28.0	16.7

Ref. www.matls.com

Tubing - Seamless and Welded

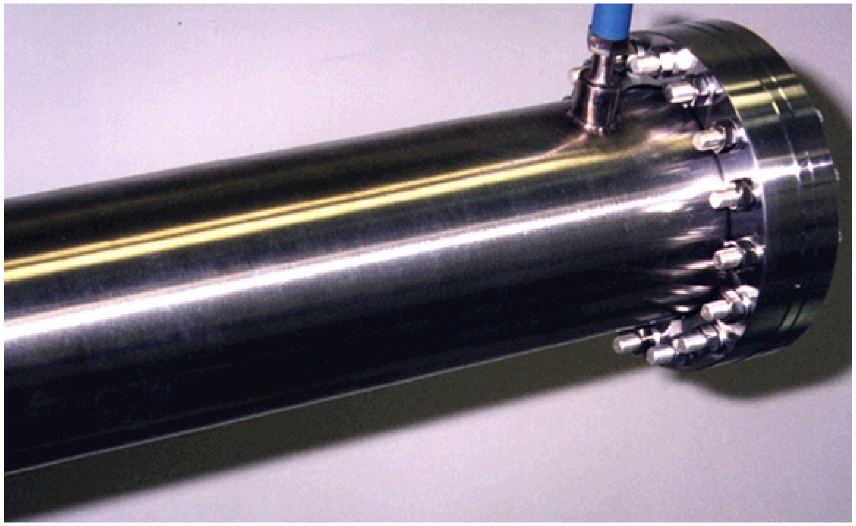


Seamless (extruded)



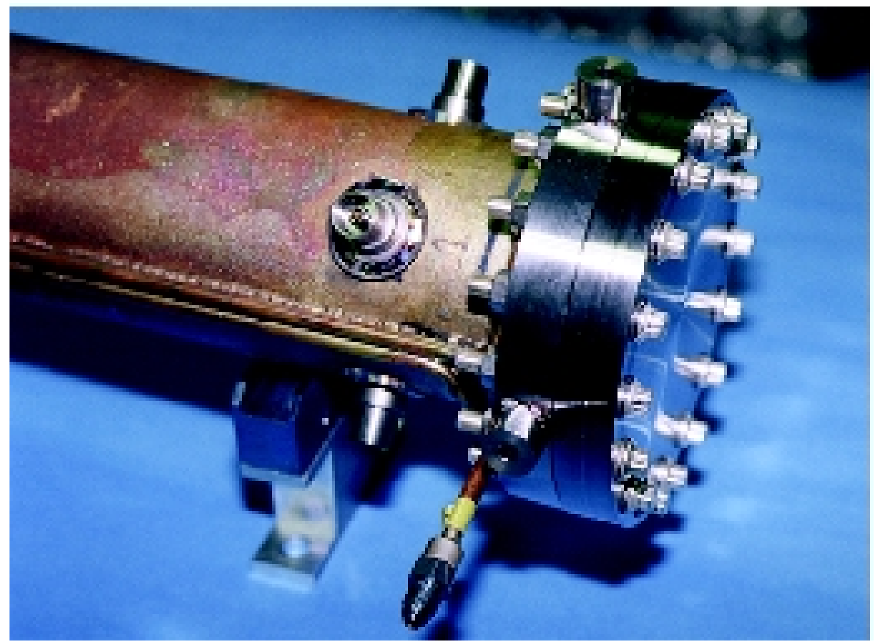
Welded (rolled & welded)

PEP-II Straight Section Stainless Steel Beampipes



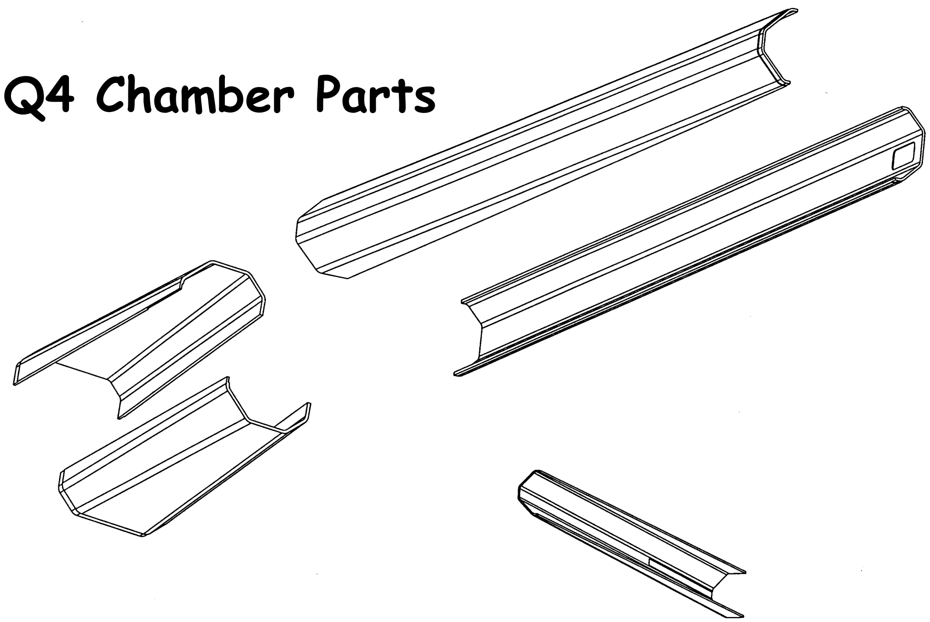
Stainless Steel Double-wall Tube

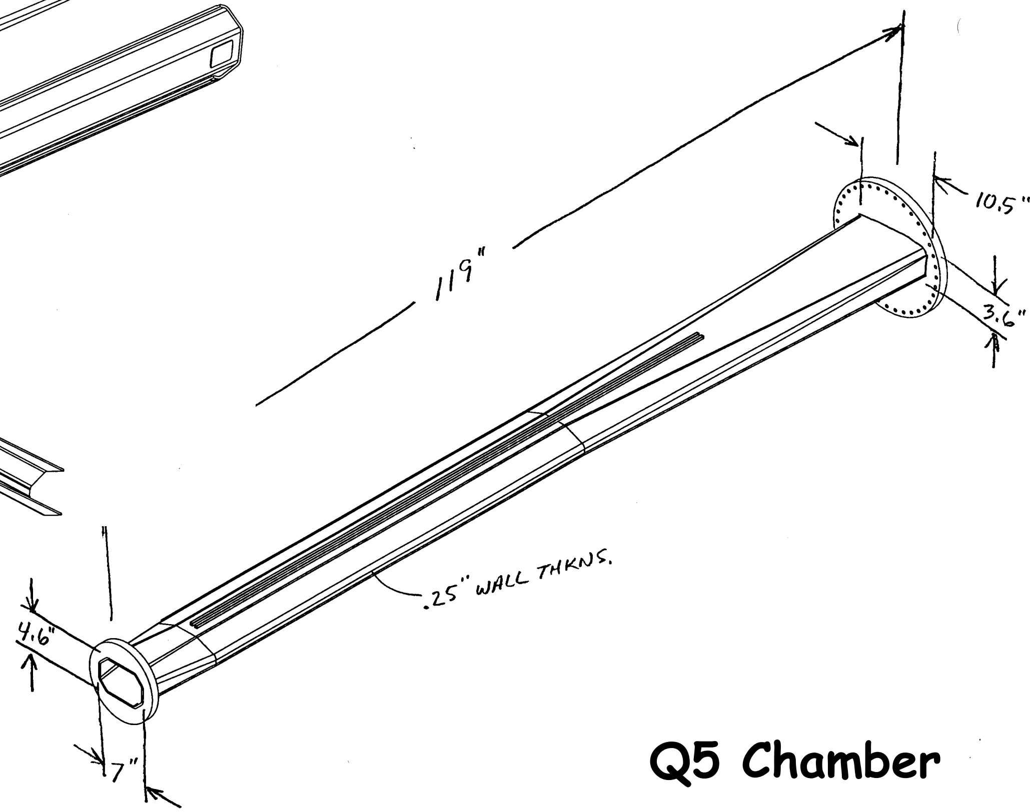
Copper-plated Seamless Stainless Steel Tube



Formed and Welded Stainless Steel Chamber - Manpower Intensive

Q4 Chamber Parts





Q5 Chamber

Aluminum

- Moderate strength, good formability, easy to machine
- Can be extruded in complicated shapes
- 6061-T6 is the most common aluminum alloy for vacuum components
- 5083 is a good alloy for welding
- Aluminum is much cheaper to machine than stainless steel
  (2x to 3x cheaper)
- Special care must be taken in the design of welds and the techniques used due to higher thermal conductivity and thermal expansion (30% > SS)
- Surface anodizing degrades outgassing characteristics, but improves chemical resistance

Typical Mechanical Properties for Aluminum

Property	1100-0	5083-H34	6061-T6	OFE Cu
Tensile Strength (MPa)	165	345	310	338
Tensile Strength (ksi)	23.9	50.0	45.0	49.0
Yield Strength (Mpa)	150	280	275	217
Yield Strength (ksi)	21.8	40.6	39.9	31.5
Elongation (%)	5	9	12	55
Modulus of Elasticity (Mpa)	69	70.3	69	115
Modulus of Elasticity (ksi)	10.0	10.2	10.0	16.7

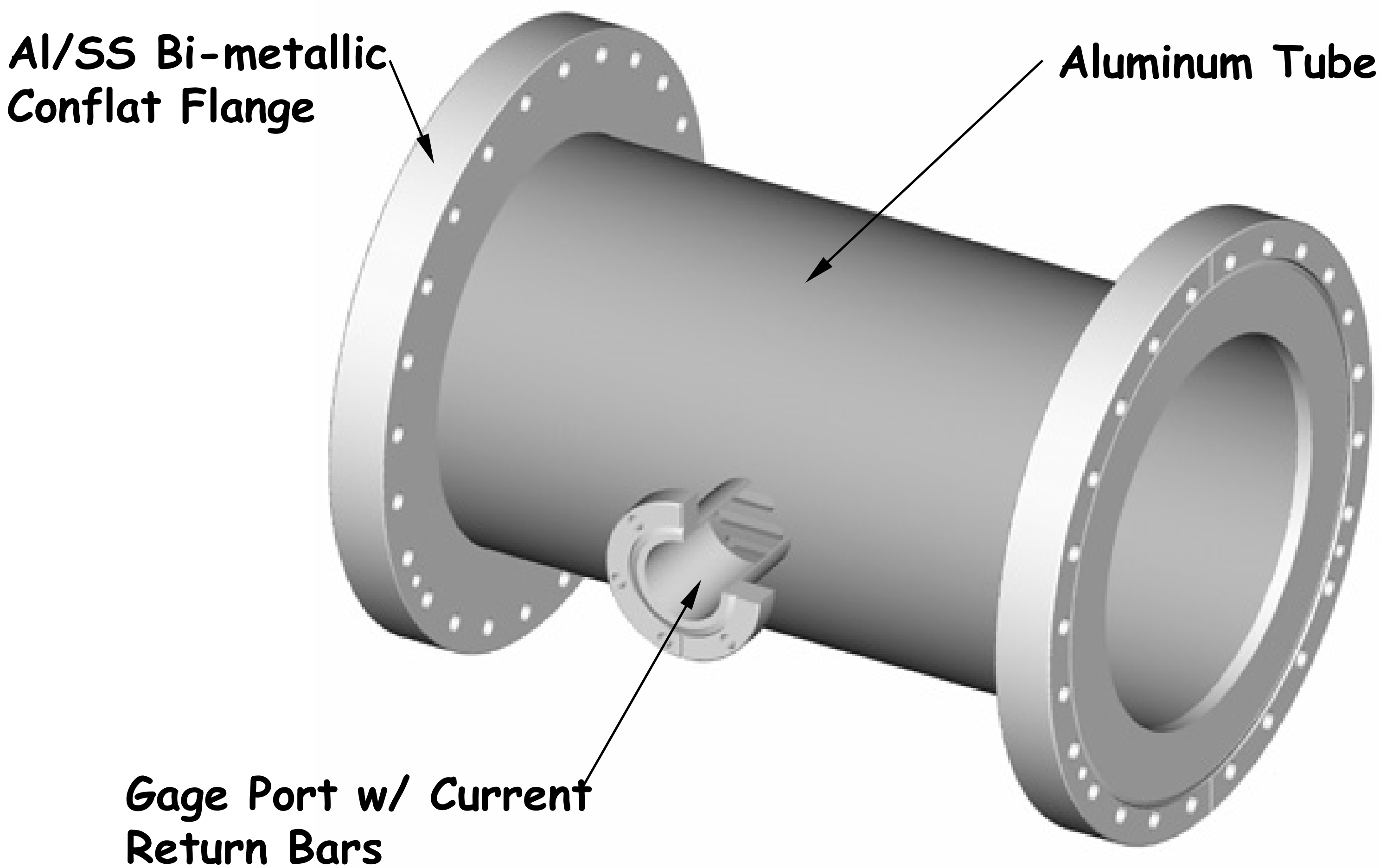
Ref. www.matls.com

Typical Physical Properties for Aluminum

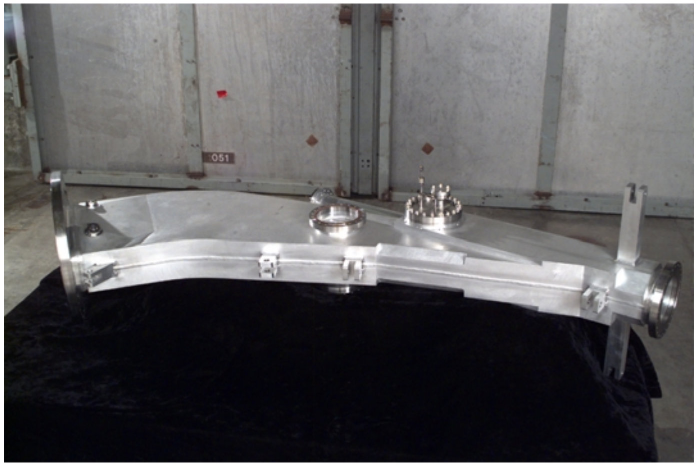
Property	1100-0	5083-H34	6061-T6	OFE Cu
Composition:	Al 99% Cu 0.05-0.2% Mn 0.05% Si+Fe 0.95% Zn 0.1%	Al 94.8% Cu 0.1% Cr 0.05-0.25% Mg 4-4.9% Mn 0.4-1% Fe 0.4% Si 0.4% Ti 0.15% Zn 0.25%	Al 98% Cu 0.15-0.4% Cr 0.04-0.35% Mg 0.8-1.2% Mn 0.15% Fe 0.7% Si 0.4-0.8% Ti 0.15% Zn 0.25%	Cu 100%
Melting Point (°C)	643	591	582	1083
Density (g/cc)	2.71	2.66	2.7	8.92
Electrical Resistivity (W-cm)	3×10^{-6}	5.9×10^{-6}	3×10^{-6}	1.7×10^{-6}
Heat Capacity (J/g-°C)	0.904	0.9	0.896	0.385
Therm. Conduct. (W/m-K)	218	117	167	391
Coeff. Of Therm. Exp. ($°C^{-1}$)	25.5×10^{-6}	26×10^{-6}	25.2×10^{-6}	17.5×10^{-6}

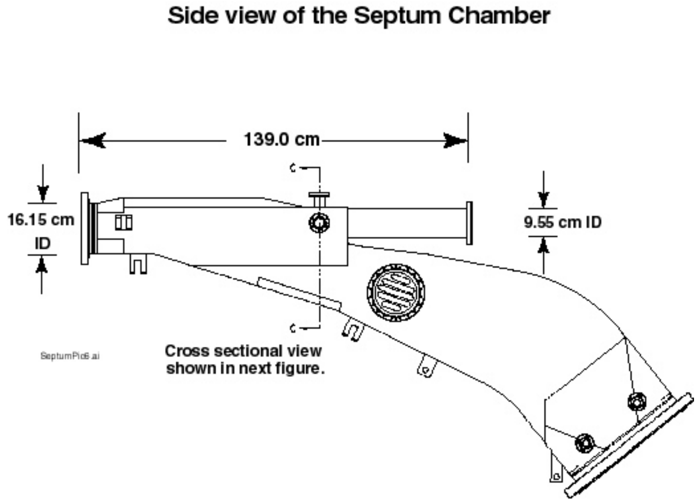
Ref. www.matls.com

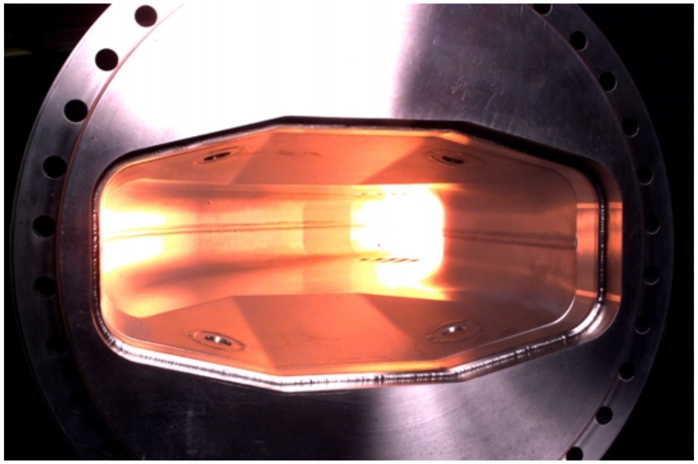
Aluminum Beam Pipe Spool

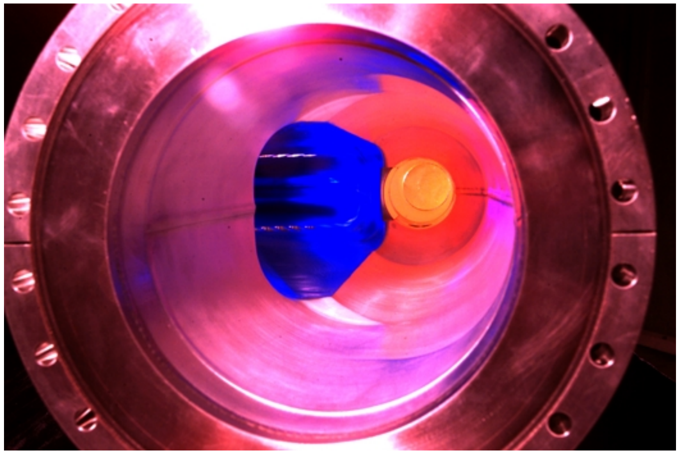


Machined Aluminum Vacuum Chamber

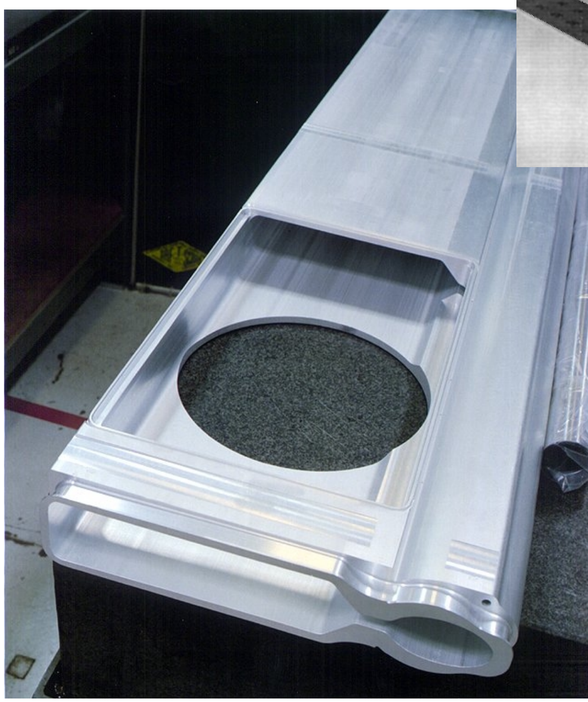


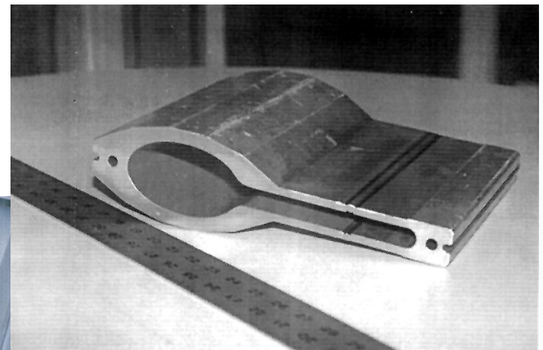


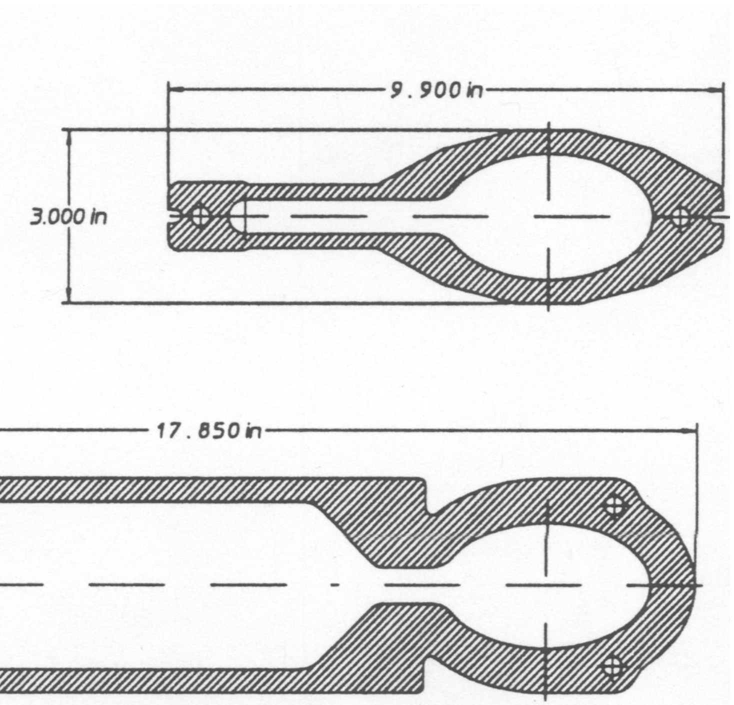




Aluminum Extrusions



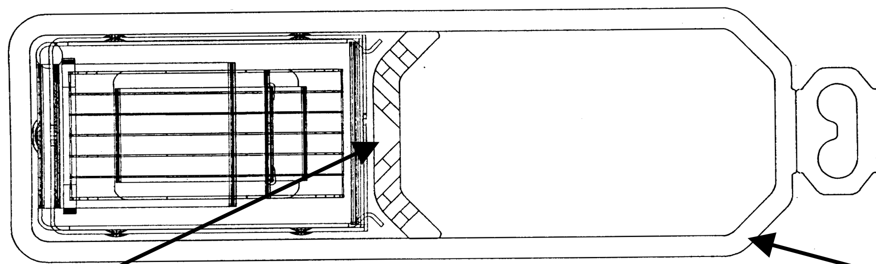




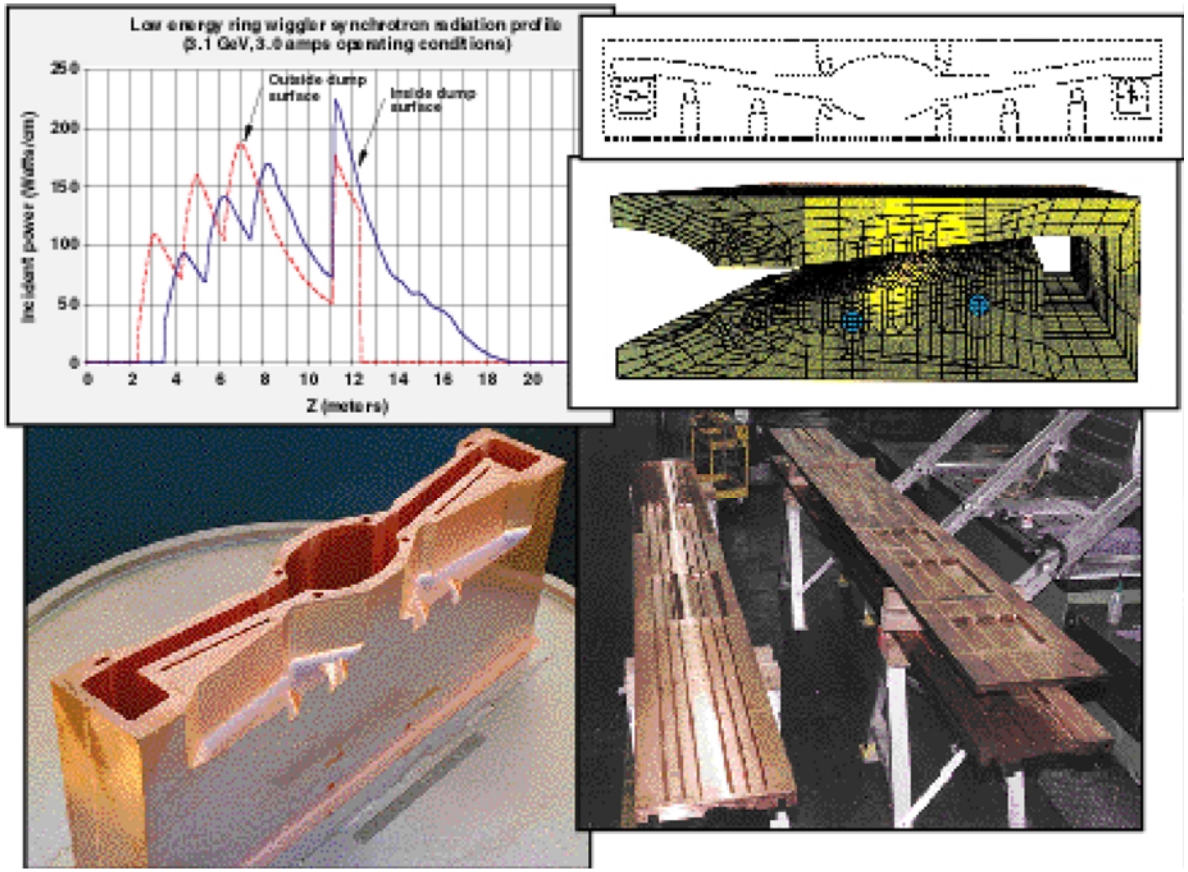
Copper

- Typical copper alloys are C10100, C26800, C61400, C17200
- Low-to-moderate strength, good formability
- Excellent electrical and thermal characteristics
- Difficult to weld (e-beam welding is best)
- May be joined by welding, brazing, and soldering
- Good outgassing characteristics, rates can be decreased by following good machining techniques, chemical and baking (~200°C)

Copper Extrusions

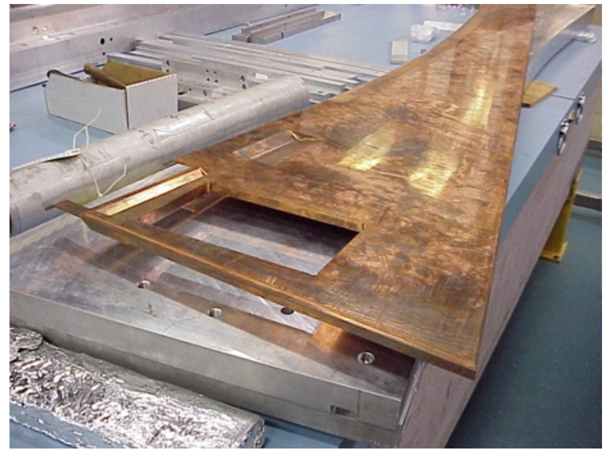


Machined Copper Chamber (PEP-II Wiggler Vacuum Chamber)



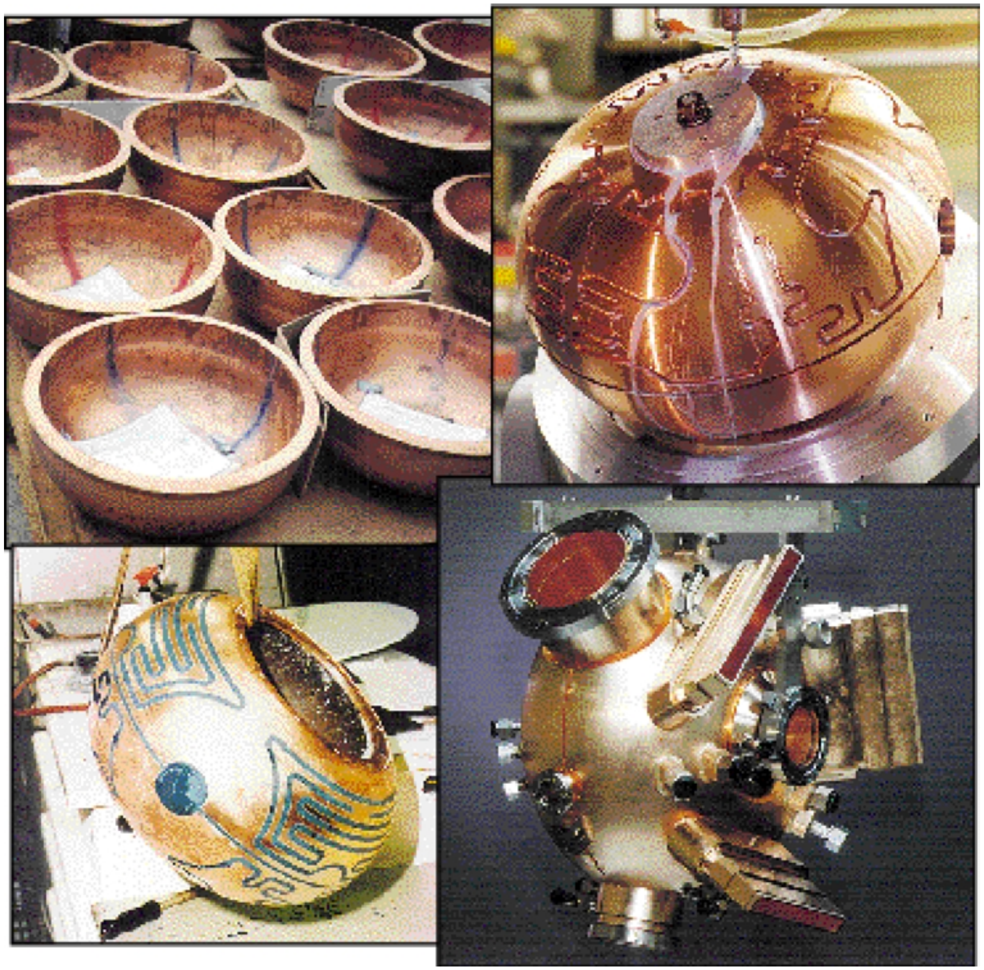
- 25 meters of machined copper chamber (5 – 5 meter sections)
- 410 kWatts of synchrotron radiation power absorbed
- Water cooling passages are externally machined and e-beam welded closed
- 1-1/2 years to fabricate

Machined Copper Chamber (SPEAR3)



PEP-II HER High Power Synchrotron Radiation Dump Chamber

Machined Copper Chamber (PEP-II RF Cavities)



- 26 cavities
- $4M total fabrication cost
- Integral cooling channels with electroformed cover
- 5 axis machining
- e-beam welded
- 17 separate manufacturing steps

Glidcop

Glidcop is pure copper with Al_2O_3 dispersed throughout.

- High strength, moderate formability, poor weldability.
- Available in sheets, plate, wire, and extruded rounds.
- Maintains good mechanical strength after brazing.
- Outgassng rates are similar to pure copper.
- Thermal and electrical properties are good.

Grade Designations		Copper		Al_2O_3	
UNS	SCM Metal Prod.	Wt %	Vol %	Wt %	Vol %
C15715	Glidcop AL-15	99.7	99.3	0.3	0.7
C15725	Glidcop AL-25	9.5	98.8	0.5	1.2
C15760	Glidcop AL-60	98.9	97.3	1.1	2.7

Glidcop Physical Properties

Property	C15715	C15725	C15760	OFE Cu
Melting Point (°C)	1083	1083	1083	1083
Density (lb/in^3)	0.321	0.320	0.318	0.323
Electrical Resistivity (W)	11.19	11.91	13.29	10.20
Elect. Conduct. (% IACS*)	92	87	78	101
Therm. Conduct. (W/m-K)	365	344	322	391
Coeff. Of Therm. Exp. ($^{o}C^{-1}$)	$16.6x10^{-6}$	$16.6x10^{-6}$	$16.6x10^{-6}$	$17.7x10^{-6}$
Mod. Of Elasticity (psi)	$19x10^{6}$	$19x10^{6}$	$19x10^{6}$	$19x10^{6}$

* International Annealed copper Standard

Welding

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.

Welding Aluminum

- Low melting point, relatively high thermal conductivity, and high rate of thermal expansion make welding aluminum more problematic than stainless steel.

- Aluminum requires:
  1. High welding speeds (higher current densities)
  2. Good material purity and cleanliness
  3. Good joint design

- Aluminum welds have a tendency to crack from excessive shrinkage stresses due to their high rate of thermal contraction.

Welding Copper

- The high thermal conductivity of copper makes welding difficult. Heating causes the copper to recrystalize forming large grain size and annealing. Distortion is also a big problem.

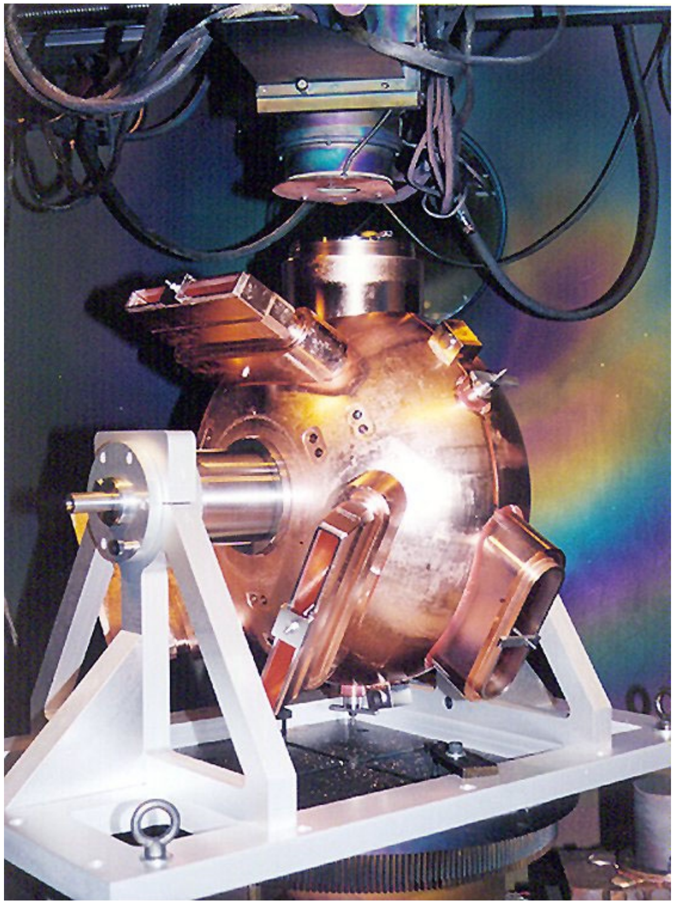
- Copper requires:
  1. Very high welding speeds
  2. Excellent material purity (OFE copper) and cleanliness.
  3. Good joint design

- Electron beam welding is an excellent process for welding copper.

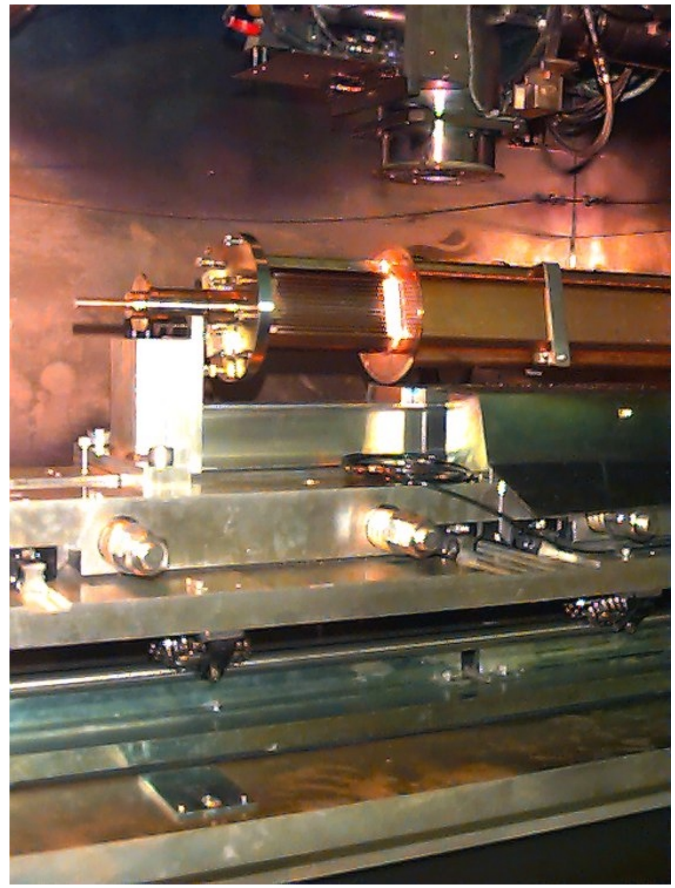
Electron Beam Welding (EBW)

- 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.
- A disadvantage of EBW is that the process takes place under vacuum ($P = 10^{-4}$ Torr):
  - Extensive fixturing required
  - High cost
  - Complexity
  - Welds are not cleanable

Copper chambers ready for electron beam welding



RF Cavity



HER Quadrupole Chamber

SLAC Electron Beam Welder

Soldering

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.
- All soft solders are unacceptable for UHV systems because:
  - They contain Pb, Sn, Zr, Bi, Zn (vapor pressures are too high)
  - System bake-out temperatures typically exceed alloy melting points.
- Most silver solders are unacceptable.

Brazing

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).

Brazing (cont.)

- Filler metals come in the form of wire, foils, or paste.
- Filler metals are selected to have melting points below that of the base metal.
- 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”).

Typical Braze Alloys for UHV Components

Alloy	Brazing Temperature	Composition
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

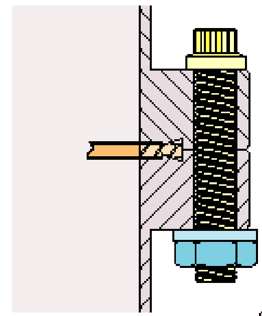
Time @ Temperature: 2-20 minutes

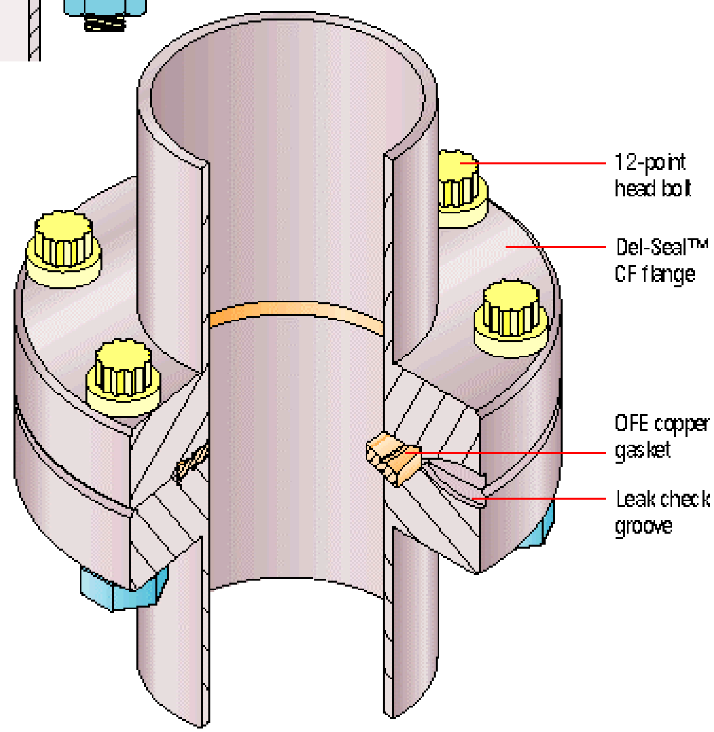
There are a variety of metal seals available for vacuum systems

- Copper (Conflats, wire, VATSEALS)
- Indium Foil or Wire
- Aluminum Wire
- Tin Wire or Foil
- Gold/Silver Wire

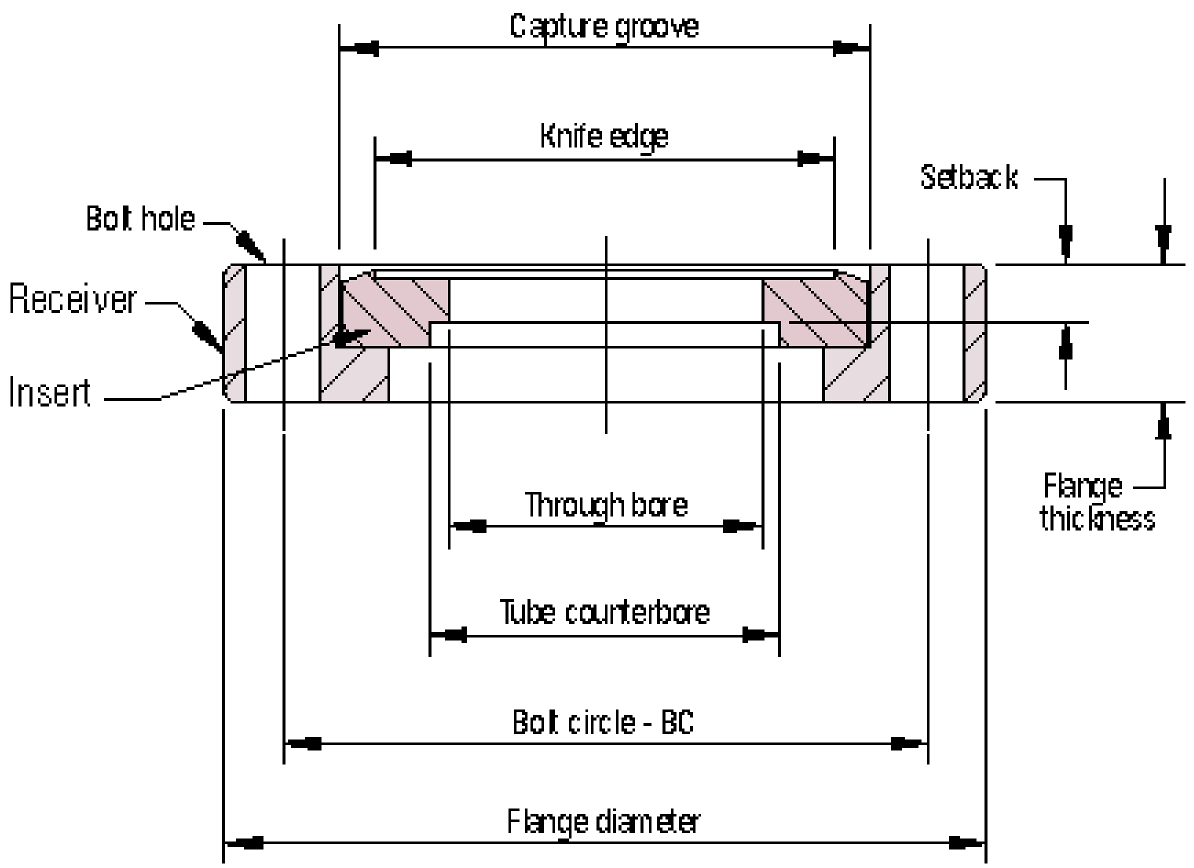
Conflat Flanges

- Vacuum rated to 1 x 10^{-13} Torr
- Temperature rated to 450°C
- Typical size range: 1-1/3”-16-1/2” od
- Flanges come in a variety of configurations
  - rotatable
  - non-rotatable
  - tapped or clearance bolt holes
  - double-sided
- Flanges are genderless



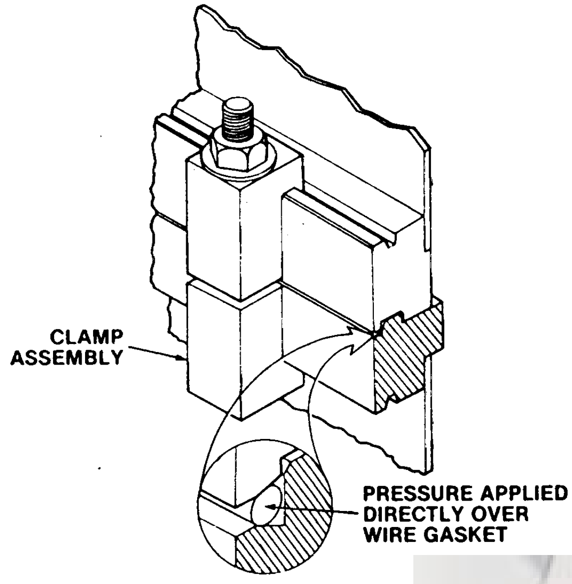


Conflat Flange Designations

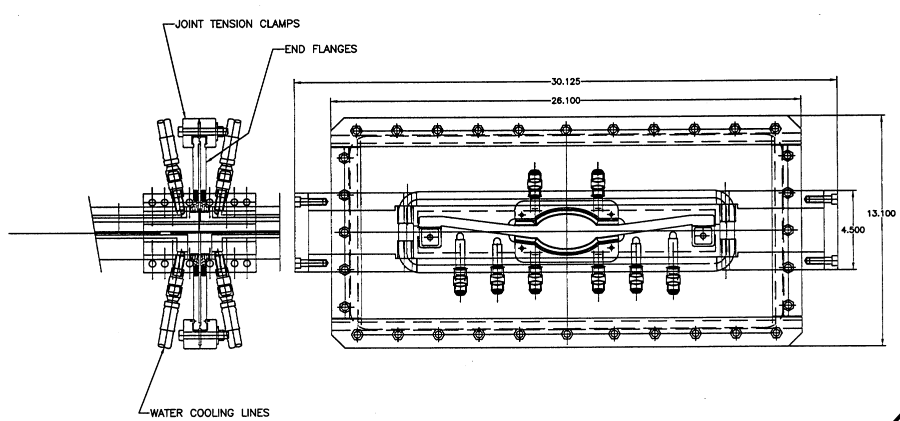


Wire Seal Flanges

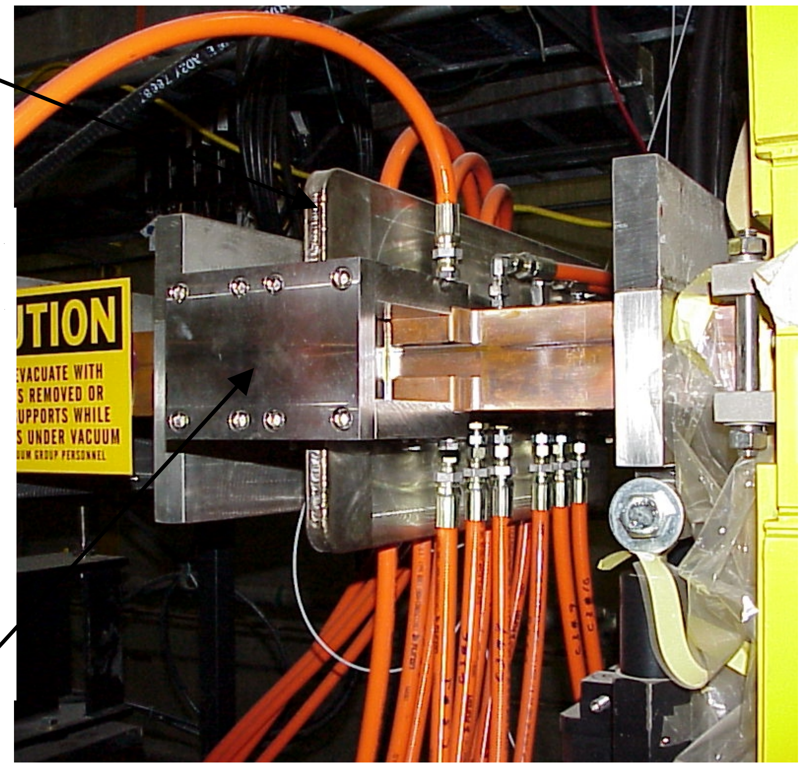
- Vacuum rated to 1 x 10^{-13} Torr
- Temperature rated to 450°C
- Typical size range: 10” - 20” od
- Warning – male and female flanges



PEP-II Wiggler Vacuum Chamber
Welded Flanges

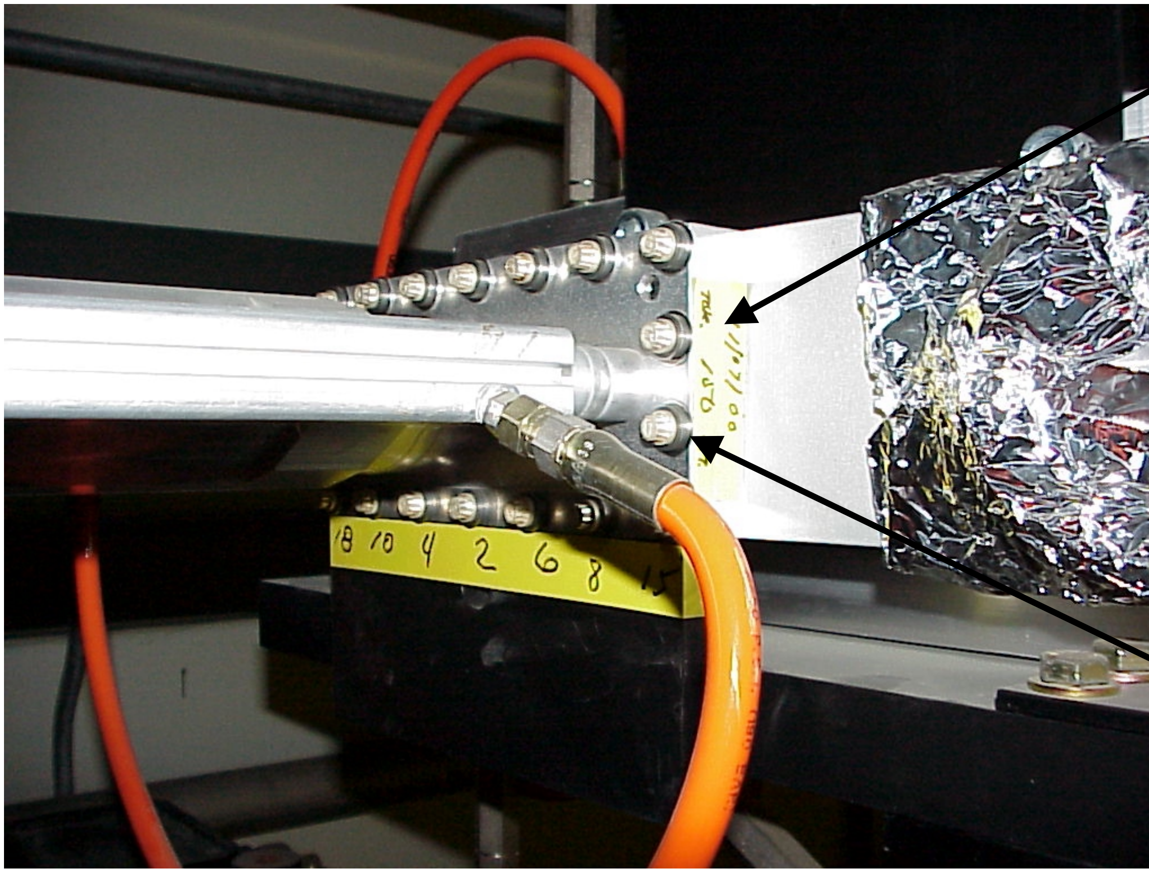


Weld Joint



Structural Joint

PEP-II LER Arc Magnet Chamber Tin-Seal Flanges



Aluminum Raised-Face Flange with 0.010” thick Tin-Seal

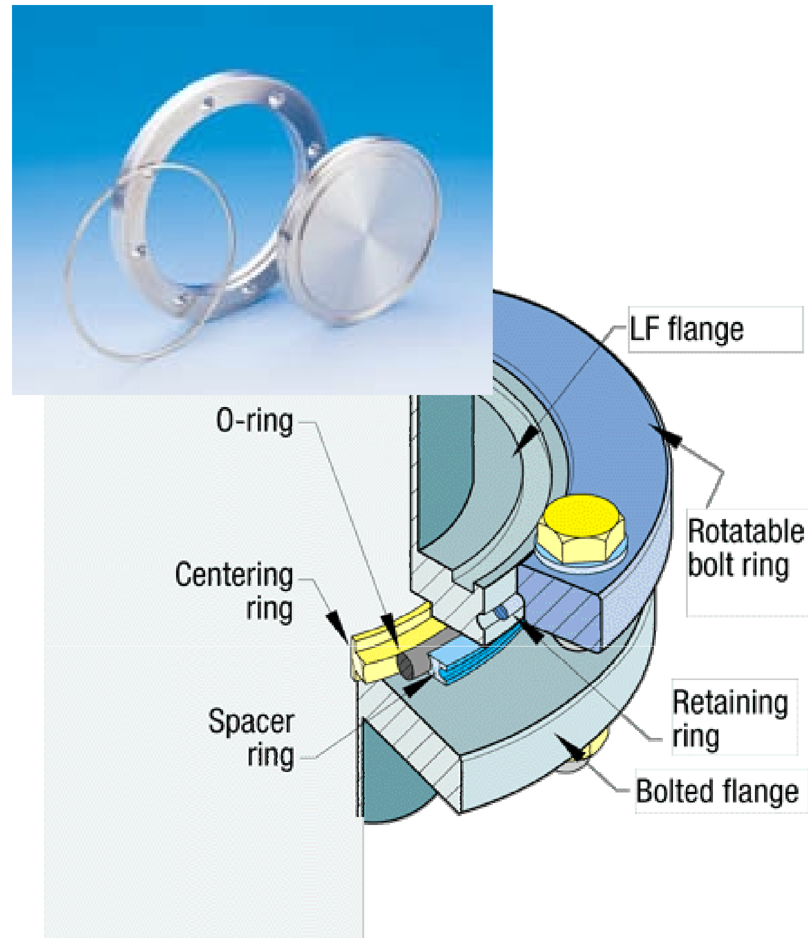
Bellville Washers

ANSI ASA Flanges

- Flanges come with either a flat-face or with an o-ring groove.
- Vacuum rated to 1×10^{-8} Torr (better suited to 1×10^{-6} Torr)
- Temperature rating is dependent on which elastomer o-ring is used (usually 150°C)
- Typical size range: 1" to 12" dia.

ISO Flanges

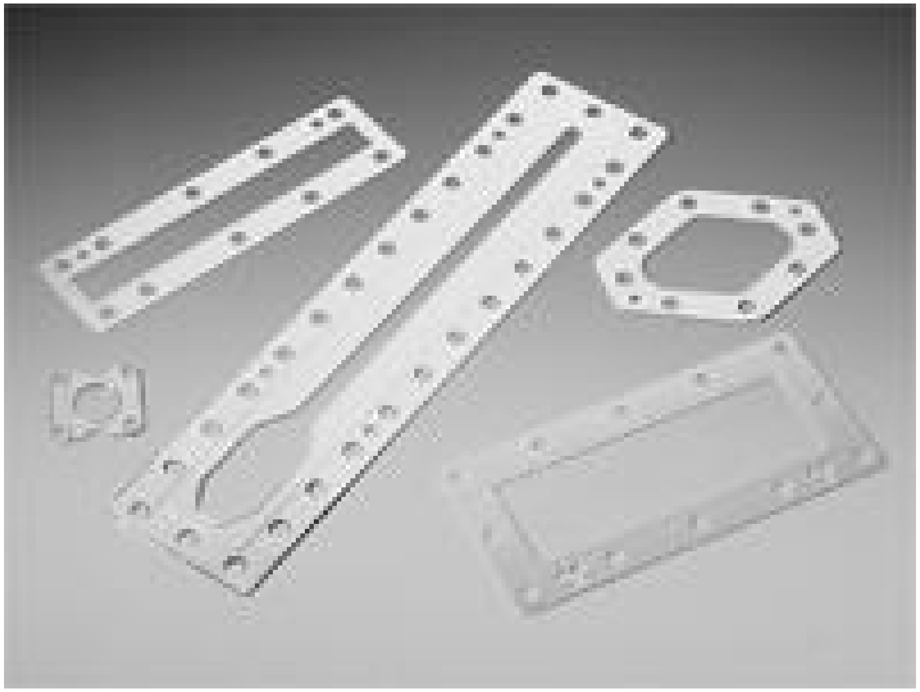
- Vacuum rated to 1 x 10^{-8} Torr (better suited to 1 x 10^{-6} Torr)
- Economical, re-usable flanges
- Elastomer gasket seal
- Temperature rated to 150°C
- Flanges come in a variety of fastening styles:
  - Kwik-flange
  - Rotatable
  - Non-rotatable
  - Double claw clamp
  - Banded clamps



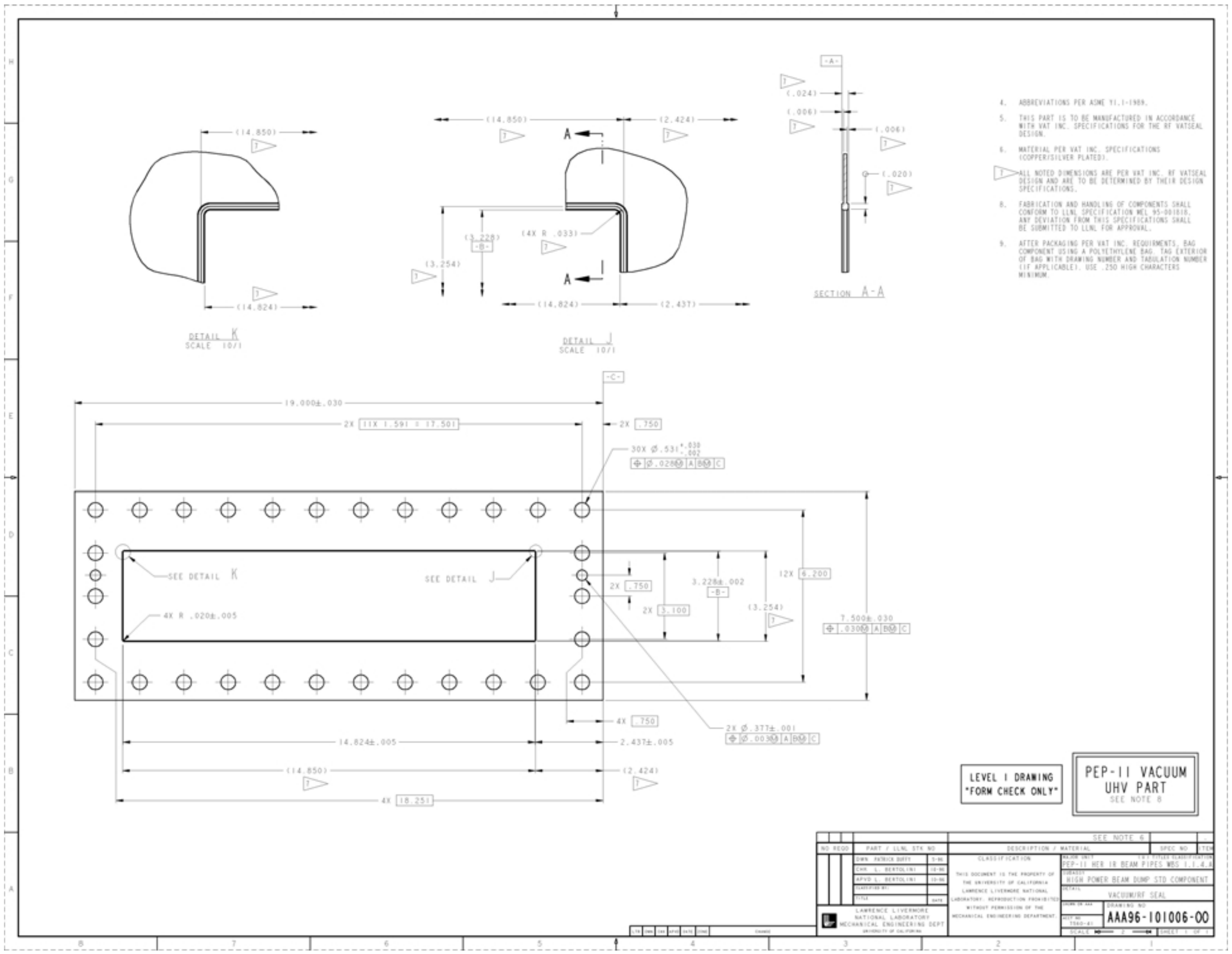
VATSEAL Flanges

Silverplated copper

- Metal seal, bakeable to 300°C
- Custom sizes and shapes
- Radiation resistant
- UHV compatible
- Accelerator option - RF contact between flanges

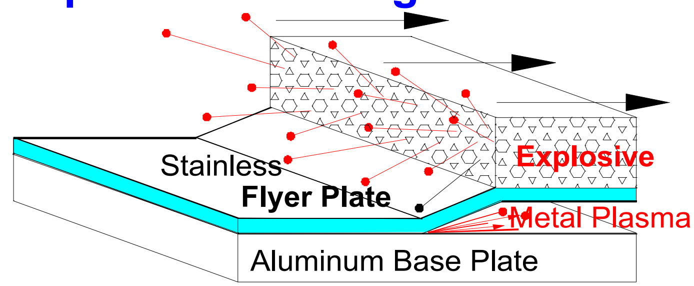


Example of a VATSEAL Flange Gasket



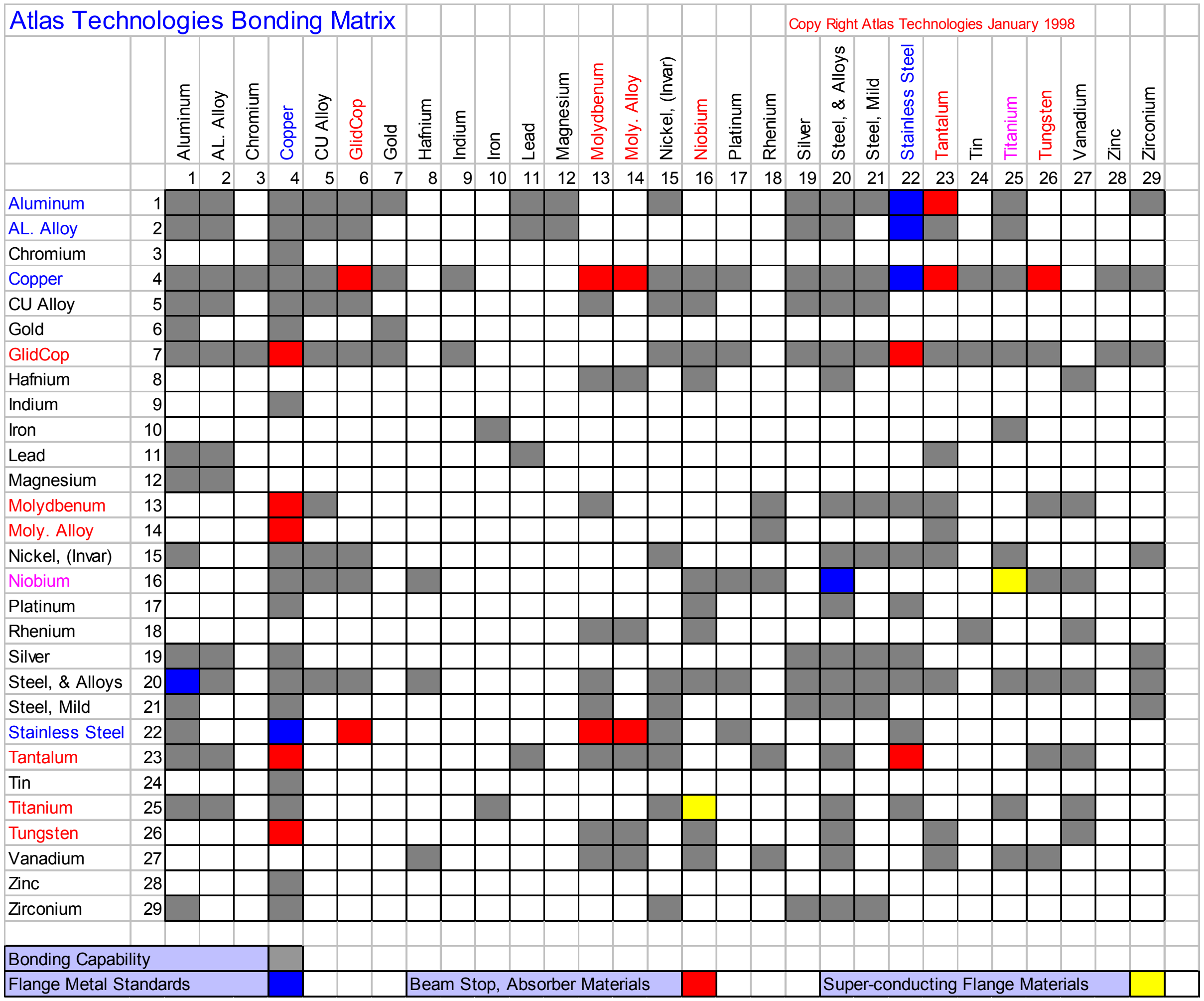
Explosion Bonding allows for joining a variety of metals

- Plates Are Spaced Above Each Other with Ammonium Nitrate Explosives Above
- A Point Source Progressive Charge is Detonated and the Plates Accelerated to Contact
- An Ion Plasma Jet is Formed at the Contact Point Stripping Oxides and Contaminates from the Metal Surfaces
- Extreme pressures at Impact and Ultra Clean Surfaces

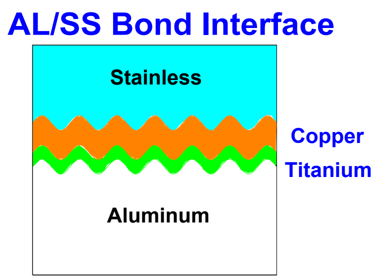


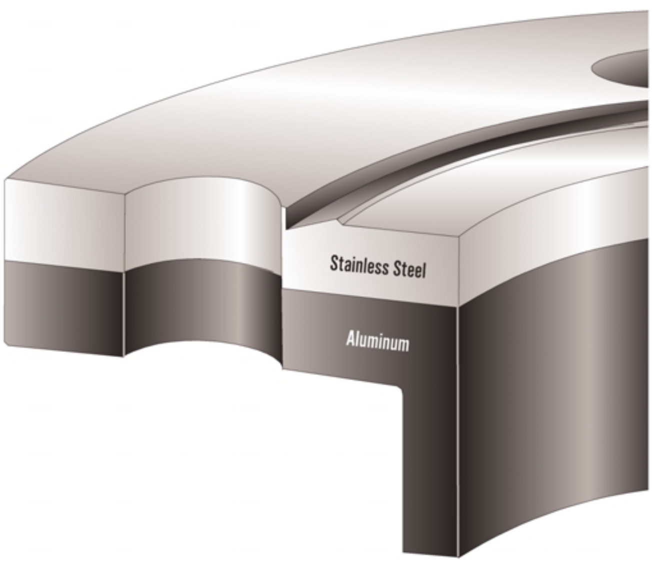
- Dissimilar Atoms Bonded Together
- Metallurgical Bond is made

Explosion Bonding Materials Matrix



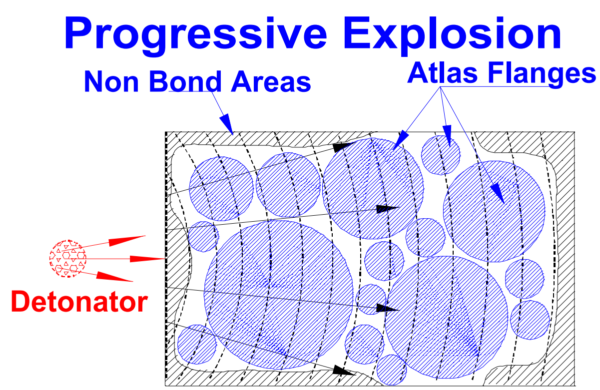
SS/AL Bond Interface
Patent# 5836623

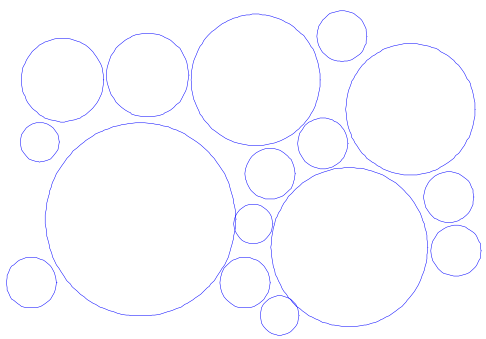




- Diffusion Inhibiting Layers
  - Copper and Titanium Interlayer
  - Enables Bonding AL/SS
- Vacuum:
  - $<1\times10^{-10}$cc He/Sec
- Thermal:
  - Peak 500C at weld up
  - 0-250C Operational
- Mechanical
  - Tensile 38,000 Psi,
  - Shear 30,000 Psi

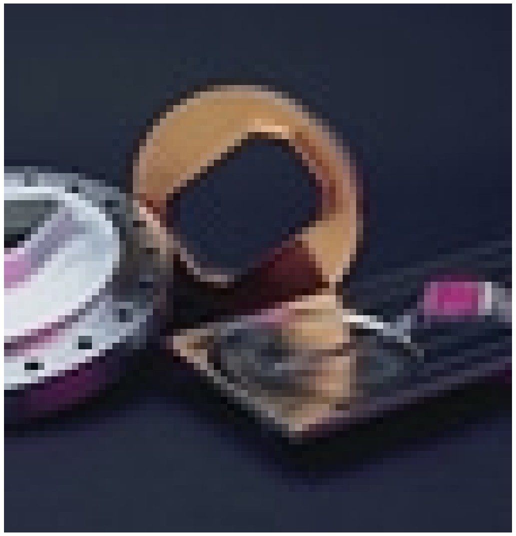
Flange Production Recipe
Patent # 5836623

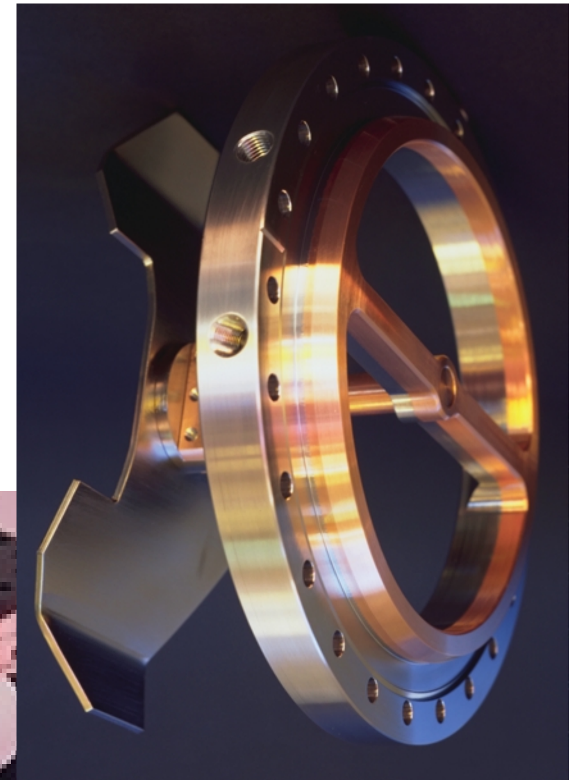




1. Bond AL Plate to Ti Sheet
   Bond SS Plate to Cu Sheet
2. Bond AL/Ti Plate to SS/Cu Plate
3. Determine Non-Bond Areas of the SS/Cu/Ti/Al Plate
4. Water Cut Discs From the Plate
5. Machine Flanges from Discs

Different applications for bi-metallic joints





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