

# Ultra-High Vacuum Chambers

K. M. Birnbaum and The Quantum Optics Group  
*Norman Bridge Laboratory of Physics 12-33*  
*California Institute of Technology, Pasadena, CA 91125*  
(Dated: September 30, 2005)

## I. OVERVIEW

These are notes containing general information about UHV systems. Some of this comes from my own experiences in building the Lab 1 chamber, but most of it is from the collective wisdom and experience of the entire group (because the plural of “anecdote” is “data”). Some of the people I talked to are Theresa Lynn, Cristoph Nägerl, Dave Boozer, Hideo Mabuchi, Ben Lev, Sergey Polyakov, Russ Miller, and Liz Wilcut. Of course, much of what they know they were taught by their elders, in a fine oral tradition which I will refer to as The Lore That Has Been Passed Down Lo These Many Years. I have attempted to write down as much of this as possible together with what I learned from talking to technical support staff at various companies, reading catalogs, surfing the web [1, 2], and perusing a few books on vacuum technology [3, 4]. These notes are by no means complete, and quite probably not entirely accurate. I hope that this will be a living document which will evolve and grow with the group’s experiences.

Here are the major steps in creating a vacuum system: designing the system, ordering the parts, cleaning and preparing them for use, assembling the system, pumping it down, baking it, and loading the Cesium.

## II. DESIGN CONSIDERATIONS

It’s a good idea to put a lot of thought and planning into any vacuum system. Getting a vacuum system working can be a slow process, and discovering problems along the way can make it a lot slower. With careful planning you can catch a lot of the problems and design around them. You’ll probably still find a few things you didn’t think of or didn’t expect, so try to leave some room for flexibility in the plan. Before you design your system, read through this entire set of notes and think about the whole process. You probably will also want to read the books in the bibliography, and look through the catalogs. When designing your vacuum chamber, here are some of the major considerations:

### Good Conductance

There will always be some residual outgassing from all surfaces in your vacuum chamber. To achieve a low pressure, you need good conductance to the pumps. In the molecular flow regime (mean free path much larger than

the size of the chamber), the conductance of a pipe (in units of liters/second) is about  $(12.4D^3/(L + 1.33D))$  for nitrogen ( $N_2$ ) at 295 K, where  $D$  and  $L$  are the diameter and length of the pipe in cm. This formula is supposed to be accurate to about the 10% level. Conductance scales as  $(T/M)^{(1/2)}$  where  $T$  is the absolute temperature and  $M$  is the mass of the molecule. For greater accuracy or more sophisticated shapes see Refs. [3, 4].

### Materials

Parts that will be inside the chamber should be made of low outgassing materials, and should be cleanable and bakeable. Stainless steel is the preferred material; 304L and 316LN are the most commonly used alloys for vacuum systems; 304LN and 316L are also OK. Christoph has used 303 steel (a magnetic alloy). Be aware that you cannot screw one piece of clean steel into another without it seizing. You can use gold as a lubricant (gold plate one part); the gold will rub off when you screw it together, so if you want to re-use a part you will need to re-plate it. OFHC copper is vacuum safe and nonmagnetic (the stainless steel alloys are labeled “nonmagnetic,” but anything with iron should be used with care if you are sensitive to magnetic fields). Copper is difficult to clean (see Section V), so we now prefer to gold plate our copper for vacuum use. If you get a copper piece gold plated, be sure to specify that you do *not* want them to use nickel in the plating process (by default they will first plate the copper with nickel, then with gold, which will make the piece ferromagnetic). Teflon (PTFE) and Mica/Macor are recommended for nonconductive materials. Glass is acceptable, but be careful not to allow thermal gradients or sudden cooling as this can cause it to crack. Most organic materials (e.g., plastic and rubber) have high outgassing rates and are not useable. Some exceptions are viton and RTV, which we have used in the vibration isolation stack inside our chambers. We have also used optical fibers which have acrylate coatings. Still, it is recommended to keep such materials to a minimum. Most epoxies are also not vacuum compatible. TorrSeal is a specially designed epoxy for use in high vacuum, but should still be used sparingly. We have also used small quantities of Dynaloy Inc 325 electrically conductive epoxy and MasterBond EP30LTEND (for matching the thermal expansion coefficient of glass). Other materials we have used include: EBL 3 shear mode PZTs, kapton insulated wire from MWS (36HML, DN-15376-1, 67429-03, PO#PP212167-77, Class 220 Type M2, J-W-

1177/15), Kester Sn62 .015 solder with “44” rosin core, 100% Tin solder without rosin. All materials should have a smooth finish to reduce the effective surface area to as little as possible. Where dissimilar materials meet, remember that the system will be baked, so take into account the different coefficients of thermal expansion. In addition to low-outgassing, cleanability and bakeability, you should also consider what mechanical, electrical, thermal, optical, acoustic, and chemical properties you need for materials in your system.

### Virtual leaks

Take care not to have any trapped volumes inside your chamber. Any region that cannot be effectively pumped will act like a “virtual leak,” loading your chamber with gas. For example, if you must screw something into a blind hole, make sure that there will be some access from the hole to the pump (e.g., use vented screws, which have a hole through their center along their length).

The term “virtual leak” can also refer to dirty objects that have high outgassing rates. You can avoid this problem by choosing materials carefully and following a good cleaning procedure.

### Assembly/Flanges

ConFlat (CF) is the standard for UHV flanges. It is good to the lowest pressures and at temperatures up to 400 C. There are two types of flanges: rotatable and non-rotatable. Be aware that if you attach two non-rotatable flanges to each other then your choice of orientations is limited. You can attach two rotatable flanges to each other, but it can be a pain (especially if you have to attach them in a vertical orientation; see Section VI). One rotatable attached to one non-rotatable is usually most convenient. For very large sizes, ConFlat is replaced with wire seal (which is much the same, except that instead of a pre-formed copper gasket, you use a piece of copper wire). When you only need pressures down to  $10^{-7}$  Torr, you can use QuickFlange (also called KwikFlange, KleinFlange, QF, KF, or, inexplicably, NW). It is good up to 200 C, depending on what materials are used in the clamp and the O-ring. QuickFlange is convenient because it can be quickly assembled and disassembled (hence the name) and the elastomer O-rings are re-used. However, it is not good for UHV, so it should only be used in situations with higher pressures (e.g., between a turbopump and its backing pump). ISO and ASA flanges are similar to QF. For more information on flanges and O-rings, see the Kurt J. Lesker catalog.

There is another type of seal we have used in our vacuum systems: the large (6”) windows on the Lab 1 chamber used to be held on with a double viton O-ring connection. The chamber had ConFlat ports, but instead of using a copper gasket, there was a viton O-ring in the tri-

angular cross section groove next to the knife edge. This formed a seal between the chamber and the glass. The glass was held in place with a metal ring that had bolt holes that aligned with the ConFlat port. Between the glass and the metal ring was another viton O-ring. Bolts held the metal ring against the chamber and compressed both O-rings. This was a pain to assemble because the O-rings would slip out of position. It was also a pain to leak detect the system because viton is permeable to helium (see troubleshooting section). The vacuum system with these windows pumped down to a pressure of  $10^{-8}$  Torr.

### Access

You should consider how your vacuum system will interface to the rest of your experiment. This means, for example, providing optical access for beams and cameras. You should consider how many windows you will need and whether they will require antireflective coatings. AR coated windows are more delicate, so windows should not be coated unless it is necessary. If you need electrical access to your chamber, you should consider how many pins you need and how much noise is allowable. If you need low noise then you may want to use coaxial feedthroughs, but if you need many pins on a small flange then this will not be possible. Anecdote: we once had an electrical feedthrough that had long metal pins that went through a piece of ceramic. Electrical connection was made to the pins on the outside by soldering. The feedthrough developed a leak, which was attributed to mechanical stress on the pins causing a leak in the ceramic. Since then, we have had success using feedthroughs that end in BNC jacks. Liz Wilcut has successfully used fiber optic feedthroughs based on a Swagelock fitting with a Teflon ferrule (following Ref. [5]) in chambers achieving  $10^{-9}$  Torr.

Finally, you should consider how your chamber is mechanically connected to the outside world. For experiments with cavities that are very sensitive to vibration, the vibration isolation stack inside the chamber is supplemented by the support system of the chamber itself. The chamber is held by aluminum clamps that grip the flanges. Between the flange and the clamp are layers of damping materials. The clamps are attached to New Focus pedestals which rest on more damping materials, and are held down by a fork which is also padded with damping material (see Figure 1). The idea is to avoid metal to metal contact since this transmits high frequency acoustic noise.

### Pumps and Gauges

Any vacuum system will need an ion pump to achieve and maintain low pressures. You should choose an ion pump such that your pumping rate will be limited by

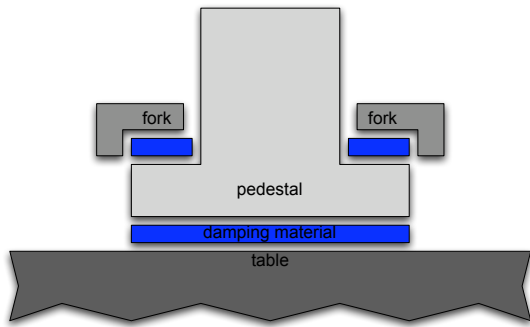


FIG. 1: How to sandwich vibration isolation material between a fork, a pedestal, and the table. The body of the fork is behind the pedestal in this view.

the conductance to the pump, and not by the pump itself. This means choosing a pump with a pumping speed (in liters/sec) higher than the conductance of the chamber (also in liters/sec). You should take into account the dependence of the pumping speed on pressure, the type of gas being pumped, and the saturation of the pump. In this lab, we have always used Varian ion pumps with StarCell elements (which are supposed to pump a wider range of gasses and work better at  $10^{-8}$  and above than the Diode elements) with one exception: a Perkin-Elmer ion pump was once used. Ion pumps can also be used in combination with titanium sublimation pumps (TSPs) (as in the lab 2 chamber) or non-evaporable getter pumps (NEGs) for greater pumping speed at lower pressures. However, TSPs and NEGs do not work on inert gasses and cannot be used alone. In principle, some turbo pumps could be used to very low pressures, but they lead to a lot of mechanical vibrations.

You will also need an ion gauge to monitor the pressure. Although you can use the ion pump current to give you some indication of the pressure, it is not that accurate so you probably don't want to rely on it. We have always used Bayard-Alpert type ion gauges from Varian. In the past, we have mostly used the standard glass enclosed gauges (the 571 for example). For very low pressures we used "extended range" nude gauges (e.g., the UHV-24p). For future chambers, I would discourage the use of glass encapsulated gauges since it is preferable to eliminate glass to metal seals whenever possible, and we have had no problems with nude gauges.

It should be noted that gauges are not necessarily accurate over the entire range for which they give a reading; the response can be grossly distorted, especially at very low pressures ( $10^{-9}$  for ordinary gauges,  $10^{-10}$  for extended range gauges). They tend to read higher than the actual pressure. Also, they depend on the nature of the gas; according to the Lesker catalog, they will typically read 28 times higher for acetone than for an equal pressure of helium. The displayed pressure usually assumes the gas is  $N_2$ . For very low pressures, it may also be possible to use inverted magnetron gauges, but we

have never used them. It should also be possible to use residual gas analyzers (RGAs), which give not only the pressure, but will also use mass spectrometry to tell you the composition of the gas. We have not used RGAs in this lab before, but Russ Miller used them at Michigan and recommends them.

## Valves

Finding good valves has been a real problem. So far the only valve we have found that we trust for UHV is the VAT all metal right angle valve. Before we have used: Varian and MDC linear gate valves (not reliable against air pressure; have elastomer seals, which are not very good for vacuum and degrade in the presence of Cs), Varian right angle elastomer valves (more reliable, but still has elastomer), MDC right angle all metal valves (unreliable), and a Swagelock valve (this was just a bad idea).

## Cesium Reservoir

There is no consensus at this point on the best design of a Cesium reservoir. Some points that should be taken into consideration are the loading technique, the separation of the reservoir from the main chamber, and the ease with which the Cesium can be monitored. Of the two techniques that have been used for loading Cesium ingots (see Section IX), the breaking-in-a-bellows method is now preferred for its relative simplicity and cleanliness, but it is not without its problems. If you use this technique, be sure to use a bellows with a  $3/4$ " outer diameter, such as that sold by Varian. It is easy to accidentally use  $3/4$ " inner diameter, such as that sold by Lesker, which then makes it very hard to break the ampule.

There is more debate over whether the reservoir should be separated from the main chamber by one valve or two. The idea of a two valve system is to make a Cesium "airlock"; that is, some Cesium is transferred from the reservoir to an intermediate space, then from there to the chamber. If there is always one valve closed at any time, then it should reduce the chance of accidentally flooding the chamber with too much Cesium. However, more valves means more complication, more parts to fail, a bigger system to pump, more cost, etc., and in practice it can be hard to use the "airlock" transfer technique effectively.

Another design point which is still under debate is the use of windows in the Cesium section. The advantage of a window is it makes it a lot easier to tell what is happening with the Cesium. You can see if it becomes oxidized, whether it is solid or liquid, and where most of it is. On the other hand, windows are much more likely to fail than steel parts, so there is a desire to keep the number of windows to a minimum. A window on

the reservoir may be particularly vulnerable because the reservoir may be heated and cooled often. More than one system has been killed by failure of a window on a reservoir. Anecdote: the window on the Cesium reservoir of the Lab 2 chamber started to leak in December 2000 for no apparent reason. The Cesium was oxidized. The leak was located by spraying methanol and appeared to come from one region of the glass to metal seal on the window (made by MDC).

A new technique for introducing Cesium to the chamber is the use of Cesium-rich “getter wires.” These are designed to sublime Cs (among other elements) into a vacuum chamber when a high current is run through them (using an electrical feedthrough). They have been successfully used in the second chamber of the atomic ensemble experiment and the microtoroid chamber.

Cesium getters present a different set of design constraints and trade-offs. The advantage of using them is that they release very little Cesium and are easier to control. When the current to the wires is off, there is very little free Cs loose in the chamber. The major disadvantage is that they have a limited life span. After they have expelled all of their Cs, the chamber must be opened and they must be replaced. At this time, we do not know how long they last. According to the manufacturer, the total amount of Cs they carry is about 4.3-4.4 mg per centimeter of active length (although they have plots which show the yield asymptote near 2.2 mg/cm at 6.5 Amps and 3.9 mg/cm at 7.5 Amps). The second atomic ensemble chamber, which uses 1/2” getters, has been running for more than a year, with the getters on all day (but turned off at night) about 5 days a week.

Another design constraint when using getters is that they require line of sight from the wire to the target (where the MOT will form). This is because they do not have enough Cs to plate the walls of the chamber, so any Cs that comes off of them will fly in a straight line until it hits a surface, where it will stick permanently due to chemical reactions.

### Bellows

In addition to their use in the Cesium reservoir, bellows can also be used to make two parts of a vacuum system meet even if they aren’t perfectly aligned. This can be very useful. However, it’s generally best to keep the number of bellows to a minimum, since they are harder to clean and have a greater risk of failure than ordinary steel parts. Bellows should be hydroformed (not edge-welded) for greater robustness. It is good to have rigid mounts at both ends of a bellows so that it does not move as the system is evacuated (an inevitable exception is the Cesium reservoir). Air pressure can compress a bellows beyond its minimum length (20% less than its natural length; maximum length is 15% longer than the natural length).

### III. ORDERING PARTS

Most vacuum parts can be ordered from Varian Vacuum Technologies or Kurt J. Lesker Company. You can also get general accessories from Huntington. Specialty items: We get our valves from VAT. We buy windows from Larson Electronic Glass with coatings by Guernsey. Larson has been slow and expensive, however, so one could also investigate buying the windows and sending them out to be coated independently. Sergey has tested windows from Huntington and found them acceptable. We have gotten small spherical hex chambers and larger octagonal chambers from Kimball Physics. The large chambers in lab 1 and lab 11 were custom made by Nor-Cal. We have gotten electrical feedthroughs from ISI. GCG Corp (in Glendale) does gold plating. We have had bad experiences when buying from MDC (in particular, problems with valves and windows) so we don’t buy from them anymore. We bought Cesium getters (listed under “alkali metal dispensers with terminals”) from SAES Getters. Order plenty of getters, and try to use as many as possible from different lots (since there are rumors that different lots can be very different in quality, and you want to minimize the chance of having all low-quality getters).

There are also a lot of general supplies that you will need. You should have large quantities of oil-free aluminum foil (from All-Foils), lint-free cloth (clean room polyester cloth from McMaster-Carr), powder free gloves (latex or nitrile aka N-Dex are OK and can be found at the Bio stock room), lens paper, solvents, and Fel-Pro C-100 Hi-Temp molybdenum disulfide anti-seize lubricant (from Varian).

Other miscellaneous stuff you may need: glove bags (from I-squared R, Instruments for Industry and Research), epoxies (TorrSeal from Varian or equivalents (e.g., Huntington Bond\*Seal\*Repair, or any other name for Dexter Hysol-1C) for general use in vacuum, Master-Bond EP30LTEND for attaching mirrors to substrates, Dynaloy 325 electrically conductive silver epoxy from Lesker), EBL 3 shear mode PZT’s (1.0” sq. 020 thick PO#PV292756 EL24460 from Staveley Sensors Inc, East Hartford CT). You can get wire from MWS wire industries. You can get vented screws, hardware made of different alloys, raw materials, rosin-free solder, etc. from McMaster-Carr. Selco is the distributor for Watlow heating bands. Cole-Parmer has heater tapes. Mindrum Precision will machine glass parts. You can order Cesium ingots from Aldrich. You can get ultrasound accessories from Process Equipment and Supply Inc.

For each ConFlat joint, you will need nuts, bolts, and gaskets. Nuts come in two types: hex and plate. Plate nuts have two threaded holes in them side by side. They are convenient to use since they cannot turn once both screws have been started, so you don’t need to hold them with a wrench while tightening the bolt. Bolts come with different heads, lengths, and finishes. For size 8-32 screws we have always used socket heads. For sizes 1/4-28 and

TABLE I: Appropriate type of screw for common sizes of ConFlat flanges.

flange OD [in.]	screw	length [in.] (tapped flange)	length [in.] (untapped flange)
1 1/3	8-32	1/2	3/4
2 3/4	1/4-28	7/8	1 1/4 (plate nut) 1 3/8 (hex nut)
4 1/2	5/16-24	1 1/4	2
6	5/16-24	1 1/4	2 1/4

5/16-24 you have the choice of hex or 12-point cap head. If you are attaching a window you will have to use a cap head since the hex head is too large and will cover part of the glass. The cap screws are usually more convenient to use, but the hex heads are good in some spaces where you can't fit a ratchet, but you can slide in a wrench from the side. You probably will want to use washers with hex head screws.

The length of the screw you need depends on how it is being used. If one of the flanges has a tapped hole (you are not using a nut), then you will use a shorter screw than if you were attaching two flanges with clear holes (using a nut). Table I has a list of what screws go with what flanges, from the Lesker catalog. I don't know why they have a different length of screw for plate nuts vs. hex nuts on the 2 3/4" flange. You also have the choice of getting either regular stainless steel screws or silver-plated steel screws. The silver is supposed to act as a dry lubricant preventing seizing. I haven't used them, so I don't know if it works or not. You should order a lot more (1.5x as many) screws and nuts than you need since some of them will have defects in the threads. You will also need to get gaskets for each ConFlat joint. For most joints you can use regular copper gaskets. For situations where you want the piece to have as little stress as possible during assembly, you should use fully annealed copper gaskets (which are softer than the regular kind). If you are worried about chemical reactions involving the copper then you can get gaskets which have been plated with silver or gold (note that Cs, however, reacts even with gold). Buy lots of extra gaskets (see Section VI).

#### IV. GENERAL CLEANING PROCEDURES

This covers most structural components of a UHV system, including flanges, blanks, nipples, bellows, elbows, T's, crosses, 5-ways, 6-ways, multi-port chambers, and anything else made of stainless steel. It should be noted that the amount of effort spent on cleaning the components depends on how low a pressure is desired for the system. The microtoroid chamber was assembled from components which were solvent cleaned but never baked, and that chamber achieved pressures of  $\sim 10^{-9}$  Torr. In order to get the lowest pressures, however, we have used

the following procedures.

Parts should first be inspected for obvious contaminants, e.g., chunks of dirt or Cesium oxide. If there are large quantities of gunk, these should be removed first by hand using lens paper and solvent. Also, this is a good time to check that the knife-edges are in good condition. If they are notched, scratched, bent, or blunted then there's no point cleaning it – you're going to need a new one. If the part has been exposed to oil (e.g., it has been machined) then it should be ultrasounded in soapy water (tap water + Alconox) for ten minutes and then ultrasounded in clean water (tap water OK) for ten minutes to remove the soap. One exception is bellows: the Red Book vacuum specification CS/05/95 [2] says bellows should *not* be cleaned with alkalines (soap) because it can leave precipitates in the grooves. Once a piece has had the oil removed and is visibly clean (swiping with lens paper and solvent does not make the paper dirty), then it is ready for vacuum cleaning.

Varian tech support recommends cleaning such components with a solvent like acetone or isopropanol, then storing in lint-free cloth.

The Lore suggests the following:

1. Ultrasound the parts for 15 minutes in acetone. Place parts in the solid basket (make sure this is clean first!) and pour in acetone to completely submerge all parts. There should be some water under the basket for good acoustic contact between the ultrasound generator and the acetone-filled basket. Afterwards, acetone should be poured into empty acetone bottles and marked WASTE. From this point on, you should not touch the parts with your bare hands. Wear gloves and only set parts down on clean foil.
2. Rinse the parts with isopropanol. Hold the part by an external surface and spray with isopropanol from a squirt bottle. This is just to eliminate any residue from the acetone. Allow the parts to dry in air. If you are in a hurry you can use a blast of nitrogen.
3. Bake the parts in the small vacuum oven. To do this, place the piece or pieces on a sheet of foil, place in the small vacuum oven along with a thermometer, close the door, and start the pump. Make sure that the valve to the pump is open and the valve to air is closed. Getting the door to make a good enough seal for the oven to pump down can be tricky – if the pressure does not rapidly decrease, stop the pump, open the door, pull off the orange rubber door seal, rotate it 90 or 180 degrees, and try again. Also, you can try pushing on the glass part of the door while the pump is going. Once it makes a good seal, then you quickly get 15 pounds/sq.inch helping you, so you can let go. Notice that the vacuum gauge is in strange units where “zero” means atmosphere and evacuated is

around 30. Once the oven is *completely* evacuated (wait 1 hour), turn on the oven and increase the temperature. For steel, you don't have to worry about the temperature too much, so just turn it all the way up. Bake for about 48 hrs. Turn off the heat, and allow parts to cool. You should be able to see the temperature on the thermometer, but be aware that the temperature is not uniform within the oven and the thermometer may not be at the temperature of the vacuum parts. When the parts have cooled to room temperature, valve off the pump and shut it off. Then carefully open the valve to air. If you have small parts that may blow away (e.g., screws), then you should open this valve slowly.

4. Wrap the parts in foil for safe storage. If you have a heavy piece which must be rested on a knife edge (e.g., a big multiport chamber), then you might rest it on a piece of soft material (with many layers of foil between for safety, since the knife edge can cut through the foil).

Alternative cleaning procedures have been used with similar results. For example, ultrasounding in isopropanol and skipping the rinse step can be appropriate for parts that aren't very dirty. The pre-bake step may not be important if the chamber will be baked anyway. Here's the general rule for solvents: Acetone is an aggressive solvent that works for a range of contaminants, but may leave a residue. The alcohols do not dissolve as many substances, but evaporate without leaving residue. Methanol is the most aggressive and quickest to evaporate and is good for swabbing at visible dirt. Isopropyl is the gentlest and safest to use when you are worried about damaging a material. It also evaporates more slowly, so it's convenient to use in large quantities, such as when ultrasounding. Ethanol is in between. If you are going to ultrasound with a solvent that evaporates quickly, or if you choose to ultrasound for a long period of time, you may want to cover the ultrasound basket with clean foil to reduce the amount of vapor in the room.

In general, according to Roth [3] you actually want to use solvents first followed by an alkaline (soap) step. This is also the order used by the Red Book [2] standard. However, since we have access to pure solvents, but not to clean (distilled and/or deionized) water, we prefer to use the water based steps earlier.

## V. SPECIAL CLEANING PROCEDURES

More complicated or delicate parts should be cleaned separately, each following a procedure appropriate for that part. It is best to check with the manufacturer of the item before doing anything to it... even things printed here.

## Windows

1. Clean by hand with lens paper and methanol. Clean entire glass face, glass-metal seal (there may be a lot of dirt here), and metal that will be in vacuum.
2. Ultrasound in methanol. Place windows (inside surface facing down) in a wire mesh basket inside the solid basket in ultrasound. Be careful not to trap air bubbles under the glass.
3. Rinse with isopropanol. Let dry in air on clean foil.
4. Bake in vacuum oven. Turn up temperature slowly – try to keep rate of temperature change below 20 C/hr (you can do this by going from room to max temperature in about 3 steps). Keep at max temp for 48 hrs. It is OK to turn off heat all at once since it takes more than 8 hrs for the oven to cool to room temp. Window temperature should never exceed 250 C (this temperature should not be possible in the vacuum oven anyway, but it's worth checking). Excessive temperature can damage coatings.
5. Place "lint free" clean room polyester cloth on *outer* face of window to prevent it from being scratched (inner face should be recessed anyway). Be aware that "lint free" cloth is not, in fact, free of lint. Wrap in clean foil for storage.

## Glass Ion Gauges (and Guages)

1. Clean accessible parts (basically, the steel) by hand with lens paper and methanol, very carefully. Pay special attention to the grooves.
2. Bake in small oven. Do not immerse gauges in solvent.

## Ion Pumps

If the ion pump has been used before, then it should just be cleaned by hand with lens paper and methanol around the steel flange (but not the functional parts). If it has not been used before, then it has a pinched copper tube bolted to the front and is evacuated inside. Leave it alone until you are ready to assemble your chamber.

According to Jun Ye (as reported by Theresa Lynn), an ion pump that is very dirty can be cleaned by removing the pump body from the case and vapor degreasing it with acetone, "occasionally banging it against the table to knock stuff loose." Theresa has vapor degreased an ion pump once without hitting it, and found that it was not improved (it started out "marginal" and remained so).

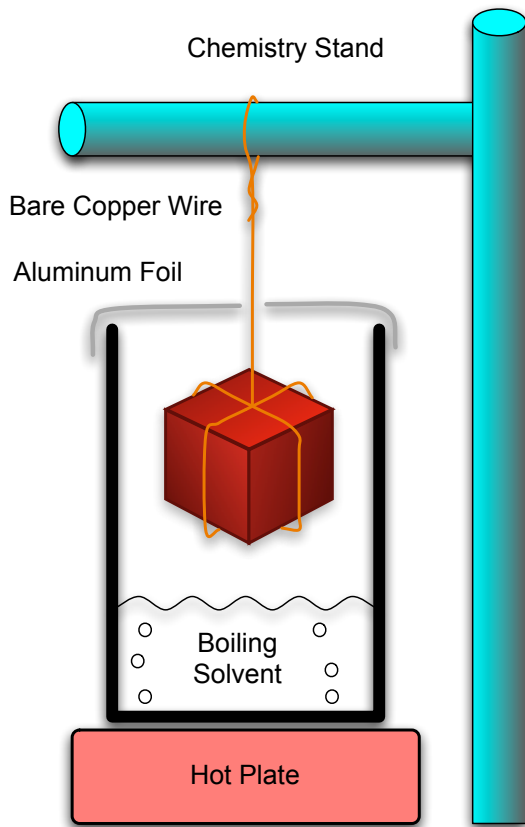


FIG. 2: Diagram of how to vapor degrease an object.

### Viton Parts

Viton should be cleaned by swiping with lens paper and isopropanol. Acetone makes viton brittle and should not be used (also, viton dissolves in acetone). Viton should be baked in the vacuum oven. The first time viton is baked it emits a large quantity of gas, so viton which has not been previously used/baked should not be put into a chamber.

### Vapor degreasing

This is a technique we use occasionally. The part to be cleaned is held by a piece of bare copper wire over a bath of boiling solvent (usually acetone). The vapor condenses on the part and drips back into the bath. This way the solvent that touches the part is always clean. The amount of solvent that escapes can be minimized by using a tall beaker and covering the top in clean foil (see Figure 2). Vapor degreasing should always be done in the fume hood. Be extremely careful, since there is a risk of setting the solvent on fire.

### PZTs

According to The Lore, PZTs should be wiped with solvent, ultrasounded for a maximum of 5 minutes, rinsed with alcohol, and left to dry in air. It is now preferred to bake them after they have been glued in place. Check the maximum temperature allowed for PZTs before baking them. The Curie temperature is 190 C for the shear mode PZTs we use (raising a PZT above its Curie temperature will depolarize it completely).

### Electrical Feedthroughs

The Lore recommends solvent cleaning by hand, then baking in the small oven. Check the maximum bake temperature for the part. The feedthrough on the Lab 1 chamber has a maximum temperature of 200 C.

### Copper

This procedure was obtained from Ali Farvid, the supervisor of the SLAC metal finishing shop. He can be reached at farvid@slac.stanford.edu or (650)926-2580. We have modified it slightly. Note that this procedure involves strong acids and presents serious safety risks. Never try this alone.

1. Vapor degrease in acetone.
2. Soak in Enbond Q527 for 5 minutes at 180 F (0.5 lb/gallon = 60 g/L). Enbond is made by Enthone Inc. New Haven, CT.
3. Rinse in cold tap water for 2 minutes.

Prepare the fume hood for the next few steps. You will need a large bin filled with clean water for the rinse steps. From this point forward you need to perform rinse steps *immediately* with as little exposure of the piece to air as possible. For a rinse step, you will first dump the piece into the bin, give it a once-over with your gloves to get the acid off the surface, then transfer to a bucket in the sink with water constantly running in it. Keep wiping all the surfaces with your gloves, paying special attention to corners and hard to reach places. Try to keep to the timing as well as you can. You will have to prepare your solutions in advance. You should use teflon coated tongs to remove pieces from acid solutions.

4. Immerse in 50% hydrochloric acid at room temperature for 1 minute.
5. Rinse for 2 minutes.
6. Immerse in the following solution (at room temperature) for 1 minute:

Phosphoric Acid, 75%	697 mL
Nitric Acid, 42° Baumé (68%)	232 mL
Acetic Acid, glacial	66 mL
Hydrochloric Acid, analytical grade	5 mL

7. Rinse for 2 minutes

8. Immerse in the following solution until the part is covered with white film (do *not* immerse part for more than 5 seconds):

Sulfuric Acid, 66° Baumé (94%)	431 mL
Nitric Acid, 43° Baumé	232 mL
Water	332 mL
Hydrochloric Acid, 20° Baumé (31%)	3.9 mL

9. Rinse for 2 minutes.

10. Immerse in solution of Oxyban 60 (1% by volume) for 2-5 minutes. Thiokol/Dynachem Oxyban 60 can be ordered from Triteck Circuit Products, (714)279-1060.

11. Rinse for 1 minute.

12. Immerse in room temperature deionized water for 1 minute (minimum resistivity 1Mohm-cm).

13. Immerse in hot deionized water for 1 minute (minimum resistivity 1Mohm-cm).

14. Immerse in analytical reagent grade isopropyl alcohol at 115 F for 30 seconds.

15. Blow dry with nitrogen. Do *not* touch with gloves!

16. Place on clean foil in small vacuum oven. Pump down for 1 hour, bake for 48 hours. Do *not* expose to air while hot.

### Cesium Getters

Sergey says Cesium getters should not be pre-cleaned or baked prior to vacuum chamber assembly.

## VI. ASSEMBLY

Before you begin assembly, you should check the following:

- Have all the vacuum parts been cleaned and pre-baked (if possible)?
- Do you have all the necessary copper gaskets, nuts, and bolts?
- Do you have plenty of gloves, foil, lens paper, solvents, and anti-seize compound?

- Do you have all the structural supports you need to hold your chamber?
- Have you installed the heating elements on your ion pumps?

To install the heating element in an ion pump, follow the directions in the manual. If you have to open the pump case, be very careful. There are strong permanent magnets inside that can come dislodged, fly together, and damage themselves (or objects in the nearby vicinity). If you remove the pump body from the case, it's a good idea to put a wooden spacer in its place to hold the magnets apart.

When you have all the components prepared, you are ready to assemble the chamber. Follow these steps for each ConFlat joint:

1. Prepare the screws and nuts. Select out how many you will need and put them on a tray or in a convenient place where they can be easily reached. Be sure to have extra in case some are defective (having 1.5x as many as you need is very safe). If you are using anti-seize, carefully apply it to the end of the screw and smear it into the grooves using your gloved fingers. Make sure that the part of the screw which will eventually be in the nut or the tapped flange is thoroughly coated, but do not leave large amounts of excess since you do not want to smear it all over your chamber. Be very careful not to get it on the head of the screw, and leave enough of the screw clean that you can pick it up without getting your gloves dirty. *You don't want to get any anti-seize in your chamber.* Set the screws down on a clean piece of foil in such a way that you can pick them up without getting your gloves dirty. One way is to use a rectangular tray and put the screws with the ends in the corner and the heads fanning out towards the center of the tray. You might need to change pieces of foil in the tray between doing flanges because the anti-seize can get all over the place. Taking these precautions is not always necessary but it can make it a lot easier because you will not have to be as concerned about what your gloves are touching.
2. Inspect the knife edges and clean them with methanol. Put on clean gloves, unwrap the foil off of the flanges that you will join, and carefully inspect the knife edges. If they are damaged, you need a new part. Remember when working on a part that has multiple flanges not to get the other flanges dirty (keep them wrapped in foil) or damage them (do not let a knife edge rest or press against a hard surface). Swipe the knife edge with lens paper and methanol. Look for any bits of lint on the accessible surfaces. It's OK if you see some as long as you can remove them with lens paper and methanol or a blast of nitrogen. If you are attaching a window, carefully inspect the inside surface.

It may help to have a flashlight or a strong light source nearby. Do not hold the window inner face upwards for a long period of time since dust will settle on it. There will be a substantial amount of lint on the outer face from the “lint free” cloth – don’t worry about this since it can be cleaned later. Try to get the inside face as clean as possible using methanol and lens paper. Using a blast of nitrogen is acceptable, but be very careful. It may help to move the window onto a fresh piece of foil since the foil it was wrapped in may have lots of lint from the “lint free” cloth.

3. Carefully place the gasket between the knife edges. Only touch a gasket with clean gloves, and try to touch it only around the outer edge (where it will not be in the vacuum). If it touches a dirty surface (i.e., anything that is not a fresh sheet of clean foil), throw it away and get a new one. It may be difficult to keep the gasket in place while assembling the joint, especially if the gasket has to remain vertical. It may help if the chamber has a slight tilt so that the gasket will remain in its seat without falling out. It helps if you can put it in the non-rotateable flange first. Also it sometimes helps to hold the top edge of the gasket in place by sliding a poky tool (inoculating needle) down the groove in the flange (some, but not all, flanges have grooves that go between the screw holes) and using the tip to hold the gasket from falling forwards. Carefully put the flanges together and make sure the copper gasket is properly seated. You may drop a lot of gaskets while putting together vertical joints – don’t worry about it. It may help to have two people so that one person can hold the gasket and the other can bring up one of the flanges, and then one person can hold the flange together while the other puts in the screws.
4. Put the bolts in place and tighten them. Put them all in and get them finger tight before tightening any of them with a wrench. If getting the screw finger tight is difficult or if it feels like the threads are bad, throw away the nut or screw responsible and use your spares. If the gasket falls out while you are putting the screws in, be aware that you may have smeared anti-seize on the flanges. If the gasket falls out, you will have to go back to step 3 with a new gasket, and it will require great care and much checking of your gloves when you try to put the joint back together. When the joint is held together by the screws and nuts, with the gasket properly seated and in place, you are ready to tighten. You want to make sure that the seal is even all the way around, so you will go around the flange many times tightening each screw by a small amount. It is advisable to use a “star-shaped” pattern for tightening, where the next screw you tighten is as far away as possible from the screws

TABLE II: Recommended torque for ConFlat flanges.

1 1/3"	51in.lb.
2 3/4"	96in.lb.
4 1/2" or greater	192 in.lb.

you just tightened. See Figure 3 for flanges with 6, 8, and 16 screws.

If you are using annealed gaskets, the Lesker catalog recommends no more than 1/16th of a turn on each screw per round. Varian tech support has a recommended torque for each size of ConFlat flange (see Table II). Be careful not to damage the heads on any of the screws. It is especially easy to damage the heads of the 8-32 screws (used on 1 1/3" ConFlat joints).

Christoph says that there should always be some room between the steel edges of the flange (that is, you should always be able to see some of the gasket from the outside). It’s OK if this room isn’t very much (e.g., just enough to slide a sheet of paper or foil between the edges) as long as it isn’t zero. The reason is that if the steel parts are touching each other, then a torque on the joint will have more leverage to separate the knife edge off of the copper. Also, it will be impossible to further tighten the joint if a minor leak occurs some time later.

#### Unsealing an Ion Pump

1. Check the manual for special instructions for your model.
2. Clean off the end of the pinched copper tube with lens paper and methanol.
3. Slowly crush the end of the tube between the jaws of a machinist’s vise. Crush along the long dimension of the pinch. You should hear a hissing sound when the copper springs a leak. You want to use a vise and not a cutter or saw because air is going to rush in and you don’t want metal shavings or other junk to fly into the pump body.
4. When the hissing stops it is safe to undo the ConFlat fitting holding the copper piece on. It may be very difficult to undo the bolts.
5. Clean off steel flange with methanol and lens paper. Now it’s ready to be attached to your system.

#### Preparing Cesium Getters

The Cesium getters that we buy have a cross section which is roughly square (about 1 mm on a side), have a variable length (usually about 1-2 cm), and end in flat tabs. These getters must be connected to an electrical

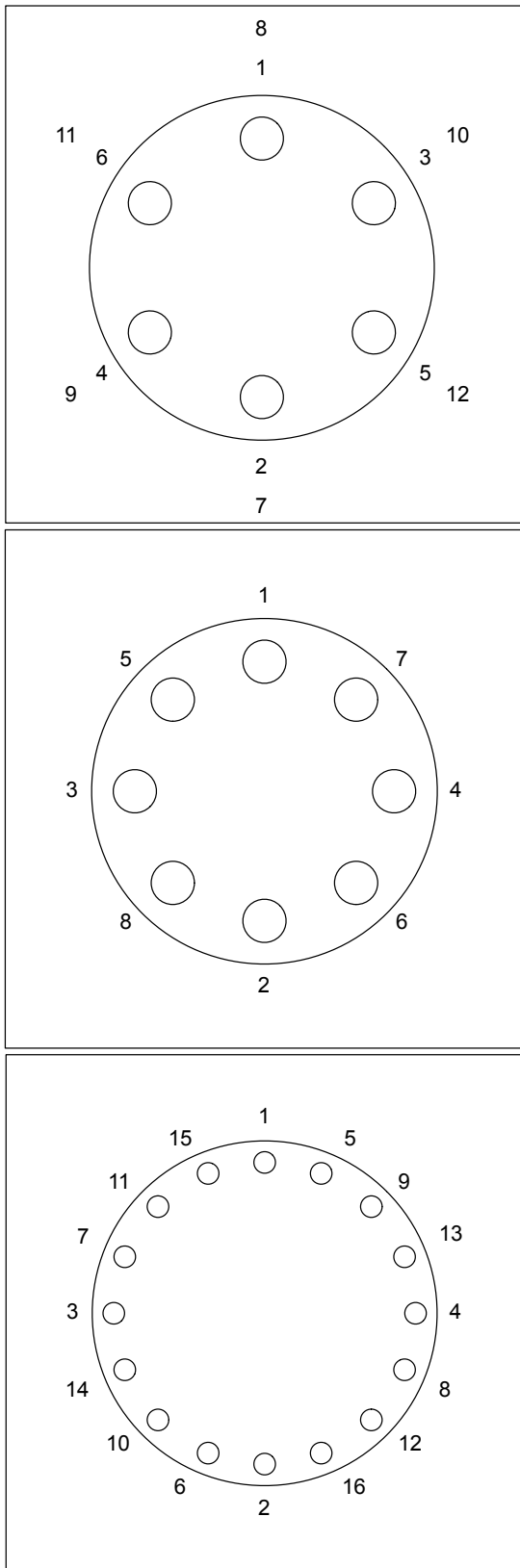


FIG. 3: The order in which to tighten bolts on ConFlat flanges with 6, 8, and 16 screws.

feedthrough in order to use them. This has been done using crimp connectors which come with the feedthrough. The crimp connectors are metal sleeves (hollow cylinders) which slide over the pins on the feedthrough. The tabs at the end of the getters are bent and inserted into the sleeves, which are then crushed with pliers in order to hold the tabs and make electrical contact. Note that the getters have a preferred direction; one side should have a groove which will emit the Cs. Be sure that this points toward the target region of the chamber where you will form the MOT. We do not have much data on the reliability of the crimping technique but it has worked so far. Be careful not to damage the feedthroughs. The manufacturers say not to bend or cut the pins, since any stress on them can cause leaks.

## VII. PUMPING

When your system is fully assembled, you are ready to pump it down. You can use a turbo pumping system to get from room pressure to high vacuum.

A turbomolecular (or turbo) pump is a stack of rapidly spinning blades. It works by transferring momentum from the blades to gas particles, sending them to the output port. Turbo pumps may have greased bearings in them, but are designed to minimize the flow of oil molecules back into the system. Some turbo pumps use magnetically levitated bearings to eliminate lubricants altogether, but these pumps may be easily damaged by bumping them and displacing the rotors (according to Hideo). Turbo pumps may be rated with a compression ratio (max value of (pressure at the exhaust port / pressure at the intake port), usually for  $N_2$ ). Note, however, that they are designed only to work in a certain pressure range, so this compression ratio is a function of pressure. Also, the compression ratio is better for heavy molecules than for light molecules since it depends on the thermal velocity of the molecule relative to the speed of the blade. Be aware that turbo pumps can be damaged by being suddenly exposed to high pressure, or by large particles (e.g., flakes of dust) entering the pump during operation.

Turbo pumps do not work with the exhaust port at air pressure so they must be backed by another pump. There are two kinds of pumps commonly used for this purpose: rotary vane pumps and diaphragm pumps. Each has its advantages. Rotary vane pumps are generally more powerful and will usually give the system a better pumping speed and a better ultimate pressure. However, they are extremely dirty. Diaphragm pumps are usually not as powerful but are oil-free which makes them more convenient and safer to use.

If you have a turbo backed by a rotary pump then there are a few things to consider. One is that there must be a trap between the pumps to prevent oil molecules from the rotary pump from contaminating the turbo and eventually the vacuum chamber. The trap is basically just a volume filled with densely packed metal fibers which

makes the diffusion time very long for the oil. According to Varian, traps are maintenance-free, but the Lesker catalog recommends baking and pumping on traps frequently to prevent them from getting saturated with oil. The Lesker catalog has a lot of information on how oil can get into your system and how to prevent it in its technical notes on traps and traps and filters. As far as I know, we have never cleaned the traps on our system. Another thing to consider is that you never want to have a pressure imbalance in the system that will suck air/oil from the rotary pump into the trap/turbopump. This means, for example, that the system must be vented upstream of the trap before the rotary pump can be turned off. Since the order of operations for starting and stopping the pumping system, and the timing of the venting that will quickly bring the turbo to rest without damaging the blades, is tricky and very important, it is best to have a system with a master controller that performs these functions automatically.

Around the labs we have two pumping stations on carts, each with a turbo pump, a rotary pump, a trap, an automatic valve for venting, and a controller (Hideo also has a turbo/diaphragm combined unit). The controller should take care of most situations so as to prevent oil backstreaming, but be aware that if the power is suddenly cut then there will be problems: (1) the valve will automatically vent, so everything, including whatever the pump is attached to, will be filled with air; (2) the valve has a built-in delay, so for a few seconds the rotary pump will not be pumping but the system will still be at low pressure, meaning oil will be sucked through the trap and into the turbo pump and whatever it is attached to (e.g., your chamber). This is very bad.

Here are the basic steps to pumping down your chamber:

1. Check the oil in the rotary pump. If it is dark then you should probably replace it. Check the manual for instructions on changing the oil. Basically, you unscrew plugs on the top and on the front and let the oil drain out, tipping it forward to get the last bit out. Then you put the front plug back in and fill from the top until you see the level in the sight glass is between the notches. The oil usually needs to be replaced after about 3 weeks of pumping.
2. Clean the bellows. As a precaution, we usually pump and bake on everything attached to the pump (e.g., a long bellows, an ion gauge, a T or cross, maybe an elbow or a valve, etc.) before exposing the chamber to it. This can be done either by blanking the bellows where it would be attached to the chamber or by attaching to the chamber but having the valve separating them be closed. For more information on baking, see the next section. The turbo unit can be baked to 120 C (check manual first), but we don't usually bake the turbo itself at all (though it might be a good idea). As you bake and pump, you can monitor the pressure on the ion

gauge, which you can turn on after the system has been pumping at "normal operation 70kRPM" for an hour. The gauge will probably need frequent degassing. We usually start the pumping, then start baking the next day, then watch the pressure until it stops falling, turn off the bake, then wait for everything to come back to room temperature before moving to the next step. If you were going to clean the trap (which we have never done as far as I know, but might be a good idea), you should probably do it before pumping and baking the bellows or turbo. You would clean the trap by disconnecting it from the turbo, blanking the end, and pumping on it with the rotary pump while baking it.

3. Pump on the chamber. If you cleaned the bellows with a blank, then shut off the pump, take off the blank, attach the bellows to the chamber with the valve open, and start the pump. If the bellows is already attached to the chamber but the valve is closed, then you need to slowly and carefully open the valve. You don't want to hit the turbo pump with too much gas too quickly. You can watch the pumping speed on the front of the controller to give you some indication of how much stress the pump is under. You cannot use the ion gauge at this time because the pressure will be too high; turn off the gauge before you start to open the valve.

## VIII. BAKING

In order to achieve low pressure you must bake your system as it is pumped. Baking increases the outgassing rates, and in general the hotter you bake the faster you get your chamber clean.

In this lab there have been two basic approaches to baking. One is to cover the chamber with heating elements over every part and adjust the power to each element to achieve the desired temperature. The other is to put the entire chamber inside a large oven (or build a large oven around the entire chamber). There are problems with both approaches. If you use lots of heating elements, then you need lots of controls and lots of sensors. Getting a uniform temperature that changes at a specified rate is very difficult and requires a lot of attention and adjustments. High temperatures may not be accessible at all. On the other hand, building a big oven requires enormous amounts of power, lots of irritating fiberglass insulation, a spare room (which will be uninhabitable due to heat, baking smells, fiberglass particles, possibly exposed high voltage... Don't even think of doing this in your lab) and a chamber which has been designed (with its mounts) to be transported without stressing the joints.

Here are some tips and caveats for the many-heater method. If you are baking your chamber on an optical table, be careful not to get the table too hot. Accord-

ing to Newport, optical tables have damping materials inside that degrade at 50 C (check for your table – Ben’s is good to 80 C). Use heating bands where you can, and remember to put a thermocouple under each one so you can monitor the temperature. Use tapes on pipes and irregular shapes. If you have tape over glass (e.g., on a glass ion gauge), you might want to put a layer of aluminum foil underneath the tape to help distribute the heat (though this can make it harder to get high temps due to reflection). It’s better to avoid having a heating element directly on a piece of glass if you can avoid it. Remember that steel is a poor thermal conductor and glass is worse. Be careful not to heat glass unevenly because you can crack it. Cooling it quickly is also very dangerous. Steel is less sensitive, but remember that if you leave a cold spot, the stuff that comes off as you bake will condense or stick to the cold region; a bake is only as hot as the coldest point. Cover the face of every window with foil to distribute the heat across the surface, but do *not* allow the foil to touch the glass anywhere (if the foil touches the face of the window at one point, it will rapidly conduct heat to/away from that point and will lead to thermal stress). For windows we have used a heating band around the outside of the steel with foil wrapped over the face, stretched between the bolts so as to not touch the glass. Cover everything over with layers of aluminum foil (with some air between the layers) to give as good an insulating layer as you can. Fiberglass insulation should be used with caution. It can be very effective, but it can leave a real mess of nasty irritating dust and fibers. Heating elements can be powered by variacs (variable autotransformers) or dimmer switches (solid state power controls). Mostly we have used variacs, but they are expensive and are really more than you need. You can get dimmer switches for lamps from Home Depot that work up to 500 watts, but the slider controls are not linear and they can be a pain to adjust. You can also order just the components from electronic catalogs and wire up a knob and a power cord, but it takes longer to make the boxes and do the soldering. When ramping the temperature, go slowly and watch all your sensors. Try to keep everything at about the same temperature. You should have at least one sensor for every heating element, with extras for long tapes or for locations without direct contact from a heater.

As I am writing this, Tracy Northup and Russ Miller are looking into large commercial ovens that could be used for baking vacuum chambers. This seems highly preferable over our previous methods. Our attempt at using a homemade oven (for baking the first Lab 2 chamber) was very unpleasant.

General points: Check the maximum temperature of all your components. You may want to assemble your chamber in stages so that you can bake different parts to different temps. For example, the lab 2 chamber was first baked with steel blanks where the windows go. Then they replaced the blanks with windows (while keeping the chamber overpressured with dry nitrogen) and baked

TABLE III: Maximum bake temperatures.

Steel	450 C
Uncoated windows	400 C
Coated windows	200-250 C
All-metal valves	450 C open, 350 C closed
Nude ion gauges	450 C
Ion pumps	350 C
Viton	150-200 C, depends on type
ISI feedthrough with 4 BNCs	200 C
Kapton insulated wire	220 C
Cesium getters	500 C

again to a lesser temperature. Windows should not be ramped faster than 20 C/hr (check with your manufacturer); valves no more than 60 C/hr. Dave Boozer once had a valve get stuck in the open position after a bake, so he now recommends leaving valves almost, but not completely open while baking.

If possible, you want to bake to at least 200 C since around 180-190 C is supposedly a “magic temperature” at which water in thin films on surfaces evaporates (as told by Christoph, and as sort of confirmed by Varian tech support, though they were pretty vague). Table III lists some maximum temperatures for various components. You should check with the manufacturers to find the maximum temperature of all of your components before you bake.

This would also be the time to do a special bake of the Cs getters. The second atomic ensemble chamber was the first test of using getters as a Cs source. This chamber was not baked because it was not necessary in order to get to the desired pressure range ( $10^{-8}$ - $10^{-9}$  Torr). However, the getters needed a special bake before they could be used. That is because they operate at very high temperatures (the manufacturers say 550-850 C) and they give off a lot of other substances before they get hot enough to release their Cs. Sergey’s technique for baking off these unwanted substances was

1. With the turbopump pumping on the chamber, run 1 amp through the getter. This raised the pressure of his system to  $10^{-4}$  Torr. Wait until the pressure falls back to what it was without current (around  $10^{-7}$ - $10^{-8}$  Torr for his chamber when hooked up to the turbopump). This took about 24 hours for him.
2. Increase the current to 2 amps. Again the pressure will greatly increase at first and then return to a low pressure, this time over several hours.
3. Again increase the current to 3 amps. It took his chamber about an hour for the pressure to come back down.
4. Turn off the current to the getter. It is now ready

for operation. Repeat this process for each getter in the chamber. For the second atomic ensemble chamber, there were 3 getters so this process was done twice. The third getter was left alone in case there was a problem with this method.

At the end of this procedure he switched over to the ion pump and was ready to use his chamber.

If doing a full chamber bake, continue to bake (while turbopumping) until the pressure is not falling (usually about a week). After it cools down, you can close off the valves, and turn on the gauges and pumps. With the turbo pump still pumping on the chamber, turn on the chamber ion gauge. Make sure that it is working and giving a reasonable reading (typically somewhat higher than the reading of the gauge on the turbopump, depending on your chamber geometry). Then turn on the ion pump. According to The Lore (from Jun Ye via Theresa), we “burp” ion pumps when we first turn them on. This means that we turn them on and off a few times. The reason for this is that when you first turn on an ion pump after a bake it has a high pump current and it seems to increase the pressure of nearby gauges. So we turn it on and off at first to get the stuff out of it (and hopefully have it removed from the system by the turbopump). Then when the pump current is lower, at a level corresponding to the ion gauge readings, we leave it on. You should now be able to see the pressure on the ion gauge falling due to the action of the ion pump. When you have confirmed that the ion pump is working, close off the valve to the turbopump. Congratulations, you have yourself a vacuum system!

## IX. LOADING CESIUM

Now that you have a beautiful clean vacuum system, the first thing you get to do is contaminate it with some nasty Cesium. There are three techniques we have used to add Cesium to a vacuum system: pouring the Cesium into the chamber inside a glove bag (not recommended), breaking an ampule of Cesium in a bellows, and running current through a Cesium getter.

### Pouring Inside a Glove Bag

Starting state: chamber is evacuated, pumps and gauges are off, nitrogen line (which has been flushed) is connected to closed valve. This takes at least two people (one with their hands inside the bag and one outside) and preferably three (one to monitor/adjust the flow of nitrogen or pressure of the bag).

1. Attach glove bag to chamber. You will have to cut open the narrow end to attach it. We have used electrical tape to make a seal from the glove bag to the chamber and it seems to work fine.
2. Put needed items in the glove bag. These include wrenches to open and close the chamber, plenty of gloves (you need to wear disposable gloves inside the glove bag to prevent the built-in gloves from getting dirty or punctured), fresh gaskets, the Cs ampule, etc. Make sure the nitrogen hose is securely in place inside the bag. You can close off the wide end of the bag with a twist tie or the Ziploc style plastic things that come with the bag. It’s good to have something that is easily adjustable so that you can maintain the pressure in the bag without having it deflate or explode.
3. Fill and flush the bag with nitrogen. Let it fill and then compress it, expelling the gas through the wide end of the bag. Repeat about 4 times so that the oxygen/water content of the bag is very little.
4. Open the chamber. Slowly open the valve to the nitrogen line (which should be overpressured). You want the chamber pressure to be greater than room pressure, but not so large that you risk damaging delicate components (e.g., glass ion gauges or cells). A few kPa above room pressure is OK. For added safety, you can use a “blowout” valve on the nitrogen line to prevent the pressure from getting too high. When the chamber is filled with nitrogen, unbolt the accessible flange of the vacuum chamber. If you are using a right angle valve with an elastomer seal on the moving part of the valve, be careful not to blow the elastomer out of its seat as you open the valve. Keep the nitrogen line at a modest pressure until just after the valve has started to open, then crank up the pressure. Once the chamber is open (a flange is unbolted) you don’t have to worry about overpressuring any components, so you can turn up the nitrogen to get a good flow rate (so the bag isn’t deflating nor inflating so fast it’s in danger of popping).
5. Break the ampule. Make sure all Cesium is at the bottom of the ampule – you can warm it with your fingers to get it to flow. Hold the ampule against a hard vertical surface (e.g., the chamber). Hit the top of the ampule (above the notch) with a small wrench. It should snap off.
6. Pour the Cs into the chamber. Use the warmth of your fingers to keep the Cesium liquid. Try to get as much of it out as you can. Carefully tape (electrical tape is OK) the ampule in an upright position to a disposable item (e.g., a small cardboard box) inside the bag, taking care not to let Cesium touch anything.
7. Close the chamber. See Section VI for details. After the chamber is sealed, close the valve to the nitrogen.
8. Dispose of the remaining Cesium. Quickly but carefully detach the bag from the chamber, keeping

it filled with nitrogen. Take the bag and contents outside, dump it in a bucket (metal trash can), and pour water over it. Try not to get close since as the water hits the Cesium it might splatter Cesium hydroxide which is a strong base. Also, the reaction will release hydrogen gas, which may ignite. Poke it with a long stick and make sure all the Cesium has reacted before you approach it. Dilute it with lots of water before disposing of it.

9. Pump on the chamber. Keep the Cesium reservoir cold so you don't overly contaminate your pumps. Start with the turbo then switch to the ion pumps when the pressure is low enough.

### Breaking Ampule Inside a Bellows

Starting state: chamber is clean and evacuated, pumps and gauges are off, nitrogen line is connected to valve (which is closed).

1. Gather the materials you will need. This includes gloves, ConFlat gaskets, etc. (see Section VI). The ampule should be prepared by scraping off the label, removing the glue using acetone, then following the procedure for cleaning glass for vacuum.
2. Open the chamber. Slowly open the valve to the overpressured, flushed nitrogen line. Be careful not to raise the pressure of the chamber too high (see step 4 of previous section). When the chamber is filled with nitrogen, carefully unbolt the access flange on the Cesium reservoir. This could be done in a glove bag but usually isn't for the sake of convenience.
3. Insert the ampule into the bellows.
4. Close the chamber and pump. Bolt the flange back together (see Section VI). Close the valve, switch from the nitrogen line to a turbopump, open the valve and start the pump.
5. Bake and pump the chamber. After the chamber has pumped down, bake it again to clean off anything on the outside of the ampule. When the pressure stops falling, allow the chamber to cool, while still pumping with the turbo pump.
6. Bend the bellows to break the ampule. You should feel the crunching of glass. Remember that there is buffer gas which must be pumped away, so turn off the ion gauges and don't be surprised to see a load on the turbopump. Keep the Cesium arm cool to reduce contamination of the pump.
7. Look for the Cesium. Turn on the ion gauge to monitor the pressure. Turn on the ion pump and close off the valve to the turbopump. You should

now look for Cesium vapor. You can adjust the vapor pressure by changing the temperature of the reservoir, while watching the ion gauge reading. You can see vapor using a resonant beam, or for greater sensitivity, forming a MOT. Be aware that it may take a while (possibly weeks at room temperature) for Cesium to migrate from the reservoir to the main part of your chamber, depending on the geometry.

This is because Cs atoms will react with pretty much anything, and will remain chemically bonded to any surface. The main exception to this is that Cs will come off of a Cs coated surface. Since Cs atoms travel in straight lines through the vacuum, in order to get Cesium to go around a corner you must wait for enough Cs to evaporate from the reservoir to essentially plate the interior of your chamber with Cs. Once a section has been plated, it acts as a source to coat more parts of the chamber. We used to "chase" the Cs from one section of the chamber to another with a heat gun, but this was far too uncontrollable. We once accidentally moved the entire mass of Cs from the reservoir to a little nook between two flanges. We didn't find it until we were disassembling the chamber. Now we leave the reservoir at room temperature or slightly above and wait patiently for the Cs to travel.

### Using Cesium Getters

If Cesium getters are installed, then you should be able to get Cesium vapor in your chamber by running the right amount of current through them to heat them to the correct temperature. The manufacturers state that the activation current (start of evaporation) is around  $4.7 \pm 0.2$  Amps and the operating current is 6.5-7.5 Amps. However, they envision dispensing all of the Cs in about 20 minutes, whereas we want these sources to last for years usually. You should therefore operate at a lower current. Sergey finds that 3.6-3.8 amps works for his chamber. You should not use more current than necessary, and you should turn off the current when you don't need it since there is a limited amount of Cs in the dispenser. Sergey finds that his MOT falls off in brightness within 5-10 minutes after shutting off the current to the getter, so this gives an estimate of how long it takes for the getter to cool off and stop emitting Cs.

## X. TROUBLESHOOTING

- *Something is wrong with the rotary pump.*

We once had a rotary pump that was leaking oil out of the casing. I took the thing apart and replaced all the gaskets and all the other plastic and rubber bits. It's a real mess but it's not that hard. You can

get a set of replacement parts by ordering a “maintenance kit” from Varian. There are instructions in the manual but they aren’t that helpful. After putting it back together it worked fine. I hope this helps.

- *The pressure of my chamber is way too high. I think my vacuum system is leaking. Help!*

If you think you have a leak in your chamber, the first thing to try is squirting methanol on various parts of the chamber and watching the pressure. If you have a large leak, the pressure should change when the methanol enters the leak. A more sophisticated method is to hook up the leak detector. The leak detector is a turbo pump with a mass spectrometer set to look for helium. Hook up the leak detector and let it pump down. When the pressure is low enough (you may need to bake the hose), open it to your chamber. Spray a small amount of helium around different parts of your chamber, waiting after each to see if the mass spectrometer lights up (read its instruction manual for details). Remember that it can take a while for the helium to migrate so you should spray a little helium in one place, wait a minute for the reading, then move on.

If you find that a ConFlat joint is leaky then you can try to tighten it, or decide to re-seal it (take it apart and put it back together). If you find that it is a bad glass-to-metal seal, or a bellows, then you will have to replace the part. These are the most common sources of leaks.

Liz Wilcut has also mentioned that Swagelock/Teflon fiber optic feedthroughs [5] develop a leak after a bake, but this can be fixed by tightening the Swagelock nut.

- *What happened to my Cesium?*

Sometimes it seems like you can’t see any Cesium vapor in your chamber – you don’t get any fluorescence from resonant beams and you can’t form a MOT. Here are some things to check: If you have optical access to the reservoir, then look at the Cesium. Does it look shiny or more like a flat grey? If it is grey then it has probably oxidized, likely because of a leak that allowed air to come into the chamber. You have to find and repair the leak and replace the Cesium. If you do not have optical access to the Cesium, then you might try warming it and watching the pressure and the MOT/fluorescence. It could just be that the Cesium is too cold to have an appreciable vapor pressure. Another thing to consider is the time it takes Cesium to get from the reservoir to the main chamber. This can be a long time, depending on the geometry of your chamber. It seems that the vapor pressure of Cesium is more temperature sensitive than that of Cesium oxide/hydroxide so if the Cesium is corrupted the pressure will not change as

rapidly under heating. There are anecdotes of a Cesium puddle with an oxidized crust, where tapping the chamber could disturb the crust and let fresh Cesium vapor out (increasing the pressure and showing up in the MOT).

- *I don’t think my ion pump is working.*

Ref. [6] has a lot of good information on troubleshooting ion pumps. One problem they mention is that after a long period of heavy use, the sputtering action of the pump can cause a metallic film to build up between the electrodes. This means that the current will flow through the film instead of through the vacuum, so there will be no pumping action. This problem can be diagnosed by measuring the resistance between the pump electrodes with an ohm-meter (with the pump controller disconnected). For low voltages, the pump should appear as an open circuit. Finite resistance means the pump needs to be replaced.

Another possible problem is field emission leakage. This is caused by fine metallic whiskers forming on the electrodes, which form regions of very high local electric fields where electrons can enter the vacuum. This does not actually impair the effectiveness of the pump, but it causes an anomalously high (and often noisy) pump current. It can be diagnosed by measuring current as a function of voltage in the kV range. Ion pump current should be roughly linear in applied voltage; field emission leakage will make it exponential. If you need to use the pump current to measure pressure, you can eliminate the metallic whiskers by banging on the pump to break them or applying 15-20 kV to melt them.

- *I need to do a bit of minor repair on my system, but it already has Cesium in it. Do I have to start over?*

We have done glove bag operations on a chamber with Cesium in it before. It can be done successfully without reacting all the Cesium if you are quick and careful. See Section IX on loading Cesium in a glove bag for more information.

## XI. DISASSEMBLY

Here are some tips for taking things apart: Loosen all the bolts on a flange slightly before loosening any of them all the way. This reduces stress on the part. If you are going to store the pieces, leave the copper gasket on one of the flanges. It will help protect the knife edge. Always wrap parts in clean foil for storage. You can write notes with a sharpie on the outside of the foil indicating what the piece is and any important information (e.g., “broken” “leaky” “OK” “removed MM/DD/YY” “Meow” etc.). If a gasket is stuck on a flange and you need to remove it, try sliding something under it along

the outer groove of the flange. If the flange doesn't have a groove along the outside, carefully grip the gasket in a machinist's vise and pull on the vacuum part. If this still doesn't work, you can crush the gasket in the vise,

which should free it from the flange without damaging the knife edge. Never touch the inside of a vacuum piece and always wear clean gloves.

- 
- [1] J. A. Venables, *UHV resources: Vacuum and materials*, available on the web at <http://venables.asu.edu/grad/appmat1.html>.
- [2] C. S. R. D. V. S. Group, Tech. Rep., Daresbury Laboratory (1996), available on the web at [http://srs.dl.ac.uk/vacsci/website%20now%20running%20from%20srdweb4/Documents/DL\\_Specifications/redbook/rbconts.html](http://srs.dl.ac.uk/vacsci/website%20now%20running%20from%20srdweb4/Documents/DL_Specifications/redbook/rbconts.html).
- [3] A. Roth, *Vacuum Technology* (Elsevier, Amsterdam, 1990).
- [4] A. Chambers, R. K. Fitch, and B. S. Halliday, *Basic Vacuum Technology* (Institute of Physics, Bristol, 1998).
- [5] E. R. Abraham and E. A. Cornell, *App. Opt.* **37**, 1762 (1998).
- [6] S. Rutherford, *Ion pump operation and trouble shooting guide*, available on the web at <http://www.duniway.com/images/pdf/pg/Ion-Pump-op-troubleshoot.pdf>.