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Instruments That Advance The Art

User's Manual Differential Pump

Model DP-03

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1. Theory and Experimental Parameters

1.1. Background

Differential pumping is a vacuum technique for providing a transition between a high-pressure region and a lower pressure region via an alternating series of pumps and throttles (constrictions), see Figure 1.1. Its application to x-ray research lies in providing a windowless pressure isolation between experimental sections of low vacuum quality (e.g. 10^{-6} Torr) from those which must be ultra-high vacuum (UHV, $< 10^{-9}$ Torr) without using a physical barrier. Its advantage is that, having no physical barriers, it avoids all the issues which such barriers impose including excessive absorption losses in the soft x-ray and XUV regimes; mechanical problems associated with mounting and protecting such barriers against overpressures; and such thermal problems as arise on high power synchrotron radiation beamlines.

1.2. Potential Synchrotron Radiation applications

The following brief list is not meant to be exhaustive but merely to indicate some of the more obvious uses to which differential pumping could be immediately applied.

1. Studies of high vapor pressure or low melting point materials. These materials are inherently UHV incompatible, so their sample chamber therefore requires isolation from the rest of the UHV system. X-ray lithography resist studies are a major example of this class of experiments.
2. Rapid turnaround studies of systems which do not require clean surfaces. If one is not doing X-ray surface studies which require UHV conditions (eg spectroscopy, diffractometry or reflectivity) then there are major advantages in experimental simplicity to be gained by operating the sample chamber at 10^{-6} torr rather than 10^{-9} torr. For example, sample changing becomes a 30 minute rather than a 3 day process if system baking is eliminated.
3. Incorporation of non-UHV mechanisms into beamlines. It is generally recognized that designing mechanisms to operate at 10^{-6} torr is significantly easier and cheaper than ones which must operate at 10^{-9} torr. The elimination of baking and the relaxation on ultimate vacuum allows the use of a variety of lubricants, feedthroughs and materials which are otherwise unacceptable. In addition, the issues of crystal changes or replacements would be greatly simplified. Such devices would require isolation from at least the beamline and possibly the sample chamber as well if UHV experiments are contemplated. The latter case would require a differential pump on both the monochromator inlet and outlet, but this would be acceptable if they were inexpensive compared to the reduction in monochromator cost.

1.3. Differential pumping concept

Differential pumping has been known for many years and is readily described in the molecular flow regime. A two-stage differential pump (N=2) is shown in Figure 1.1. In the molecular flow regime the throughput q through the n^{th} throttle is given by $q_n = (P_n - P_{n+1})C_{n,n+1}$. The throughput of the n^{th} pump (speed S_n) is $P_n S_n$. In addition, residual desorption or virtual leaks may create a gas load L_n in chamber n . In equilibrium, conservation of mass in each chamber creates a set of N nodal equations in P_n :

$$(P_{n-1} - P_n)C_{n-1,n} - (P_n - P_{n+1})C_{n,n+1} - P_n S_n + L_n = 0 \quad (1.1)$$

Solving the N = 2 case for P_3 in terms of P_1 gives:

$$P_3 = \left(\frac{C_{23}}{C_{23} + S_3} \right) \left(\frac{C_{12}}{C_{12} + C_{23} + S_2} \right) + P_{30} \quad (1.2a)$$

where

$$P_{30} = \left(\frac{C_{23}}{C_{23} + S_3} \right) \left(\frac{L_2}{C_{12} + C_{23} + S_2} \right) + \left(\frac{L_3}{C_{23} + S_3} \right) \quad (1.2b)$$

is the background pressure P_3 measured in the case of negligible P_1 . We note that, unless the S 's or L 's are pressure dependent, P_3 the "output" or "upstream" pressure should be linear in P_1 , the "input" or "downstream" pressure. Here "upstream" and "downstream" are taken from the synchrotron radiation beamline vocabulary and refer to the direction of propagation of the x-ray beam in a beamline. "Upstream" is in the direction of the storage ring x-ray source, which is typically operated at 10^{-10} Torr.

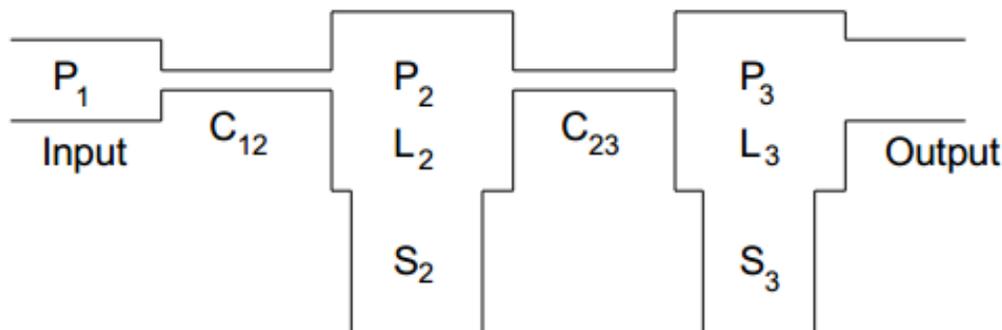


Figure 1.1: Schematic diagram of 2-stage differential pump, showing pressures (P), conductances (C), pumping speeds (S), and gas loads (L).

1.4. The XIA Differential Pump

The design concept employed in XIA Differential Pumps differs from the classical description above in two major ways:

1. Providing large line of sight clearances through the pump while keeping the overall pump length short.
2. By incorporating a pumping mechanism for the "straight-through" molecules which might otherwise pass directly from region 1 to region 3.

Both are accomplished by placing distributed pumping along the line of sight through the differential pump, principally by passing the line of sight directly through the active pumping region (Figure 1.2). This design has three important characteristics:

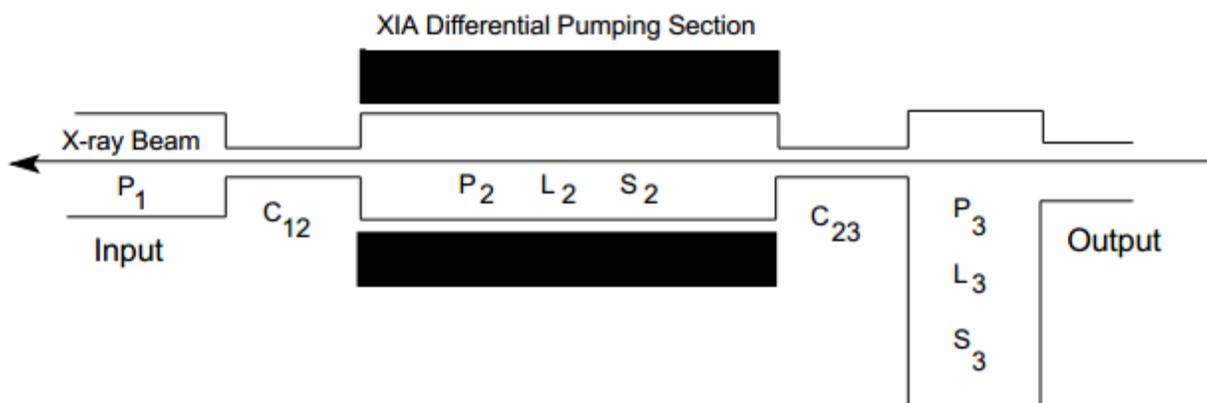


Figure 1.2: Schematic diagram of 2-stage differential pump using one XIA Differential Pumping Section and one conventional pump section. The x-ray beam passes through the active region of the XIA pumping section.

1. The Penning electrons trapped by the magnetic field in the ion pump's active pumping region have a substantial cross section for the straight through molecules and are able to remove many of them.

2. When the details of the design are optimized, the differential pump's effective pumping speed can be greatly enhanced, which allows much larger throttle dimensions for a given overall pump length.
3. Because of the distributed pumping, the relation between input and output pressures can no longer be described by the classical model, Equation 1.2.

1.5. Projected performance

Extensive measurements on the new design established that, for many common applications, the new pump was sufficiently efficient that only a single stage was required when combined with an output pump of conventional design (ion or turbomolecular) as shown in Figure 1.2. In this configuration the output pressure P_3 for N_2 gas can be well described ($\pm 50\%$) over 5 orders of magnitude in input pressure P_1 (10^{-10} – 10^{-5} Torr) by

$$P_3 = 5.0 \times 10^{-5} \times P_1^{0.78} \times \sqrt{\frac{C_{12} \times C_{23}}{S_3}} + P_{30} \quad (1.3)$$

where P_{30} is the output pressure for negligible input pressure P_1 . S_3 is the pumping speed in liters/sec (l/s) of the conventional output pump and the throttle conductances may be computed for N_2 from the molecular flow formula

$$C_{N_2} = \frac{29 h^2 w^2}{(h + w) L} \quad (1.4)$$

in l/s, where h and w are the height and width (in cm) of the throttle cross section and L is its length (in cm).

Note that these performance estimates apply only to pumps with standard throttle dimensions (less than 15mm by 10mm). Increasing throttle sizes beyond these dimensions may result in performance that doesn't obey Equation 1.3, as the pumping behavior at these dimensions has not been experimentally verified by XIA.

2. Installation

Installation, whether directly into final location or into a bench setup for testing, consists of the following procedures: Support Equipment Acquisition, Prealignment Measurements, Assembly and Bakeout, and Acceptance Pressure Tests. Installation into final location requires the additional step of Alignment.

IMPORTANT NOTE: This manual provides some generic advice on how to align your new DP during installation and how to bake it out prior to first use. You should read these sections carefully to understand the general issues, including XIA's general experience with baking out the DPs and the DP features provided to assist with alignment. HOWEVER, because of the large variety of different environments in which DPs may be employed, XIA cannot provide reliable case-by-case advice on how best to carry out these alignment and bakeout procedures at your specific installation. Our best advice, therefore, is that, as part of your design and planning activities, you consult with your facility Alignment Team to develop plans for carrying out installation and alignment and similarly consult with your Vacuum Group about local best practices to develop an appropriate bakeout procedure.

2.1. Support Equipment Acquisition

The following additional pieces of equipment are required to produce a minimal completed differential pumping assembly: 1: Mounting support; 2: Output Pump; 3: Power Supply and High Voltage Cable. For acceptance pressure tests both and upstream and downstream ion gauges and controllers are required. For best results these should be calibrated and capable of measuring changes in the 10^{-10} Torr range with a stability and resolution of 1×10^{-11} Torr. A source of oil-free N_2 is also required, preferably boil-off from a supply of LN_2 and a precision leak valve such as the Varian 951-5106.

2.1.1. Mounting Support

The XIA Differential Pump DP-03 is designed to be bolted directly to the end user's support frame using the provided blocks at either end (see Figure 2.1). The support structure, obviously, should be designed to possess sufficient freedom of motion to allow the pump's through clearance path to be aligned with the x-ray beam and to possess sufficient rigidity to prevent motions caused by changing vacuum loads on pump body.

2.1.2. Output Pump

An output pump (S_3) is required for the XIA Differential Pump to achieve its design performance. This pump is not normally supplied by XIA with the differential pumping unit, but should be acquired by the user. Its pumping speed, S_3 , should be at least the value which was specified to XIA at the time of order. Increases or decreases of S_3 from the design value will enhance or degrade performance according to Eqn 1.3. Typically a value of 50 to 60 liters/sec has been found to function effectively.

2.1.3. Power Supply and High Voltage Cable

The XIA Differential Pump requires an ion pump power supply which is not normally supplied by XIA, as well as a high voltage connector cable to attach it to the pump. The supply must be capable of supplying between 5.0 and 5.5 kV, **negative** voltage and meeting startup current needs equivalent to those found in operating a Varian 110 l/s triode ion pump. The DP-03 can accept any controller that meets those specifications and has available for purchase a mating HV Feedthrough mounted on a 1.33" Conflat flange. The Gamma Vacuum SHV10 Safecon Style is a common choice, as is the Varian classic-style HVFT-5143. But we can support any controller that meets the previous requirements.

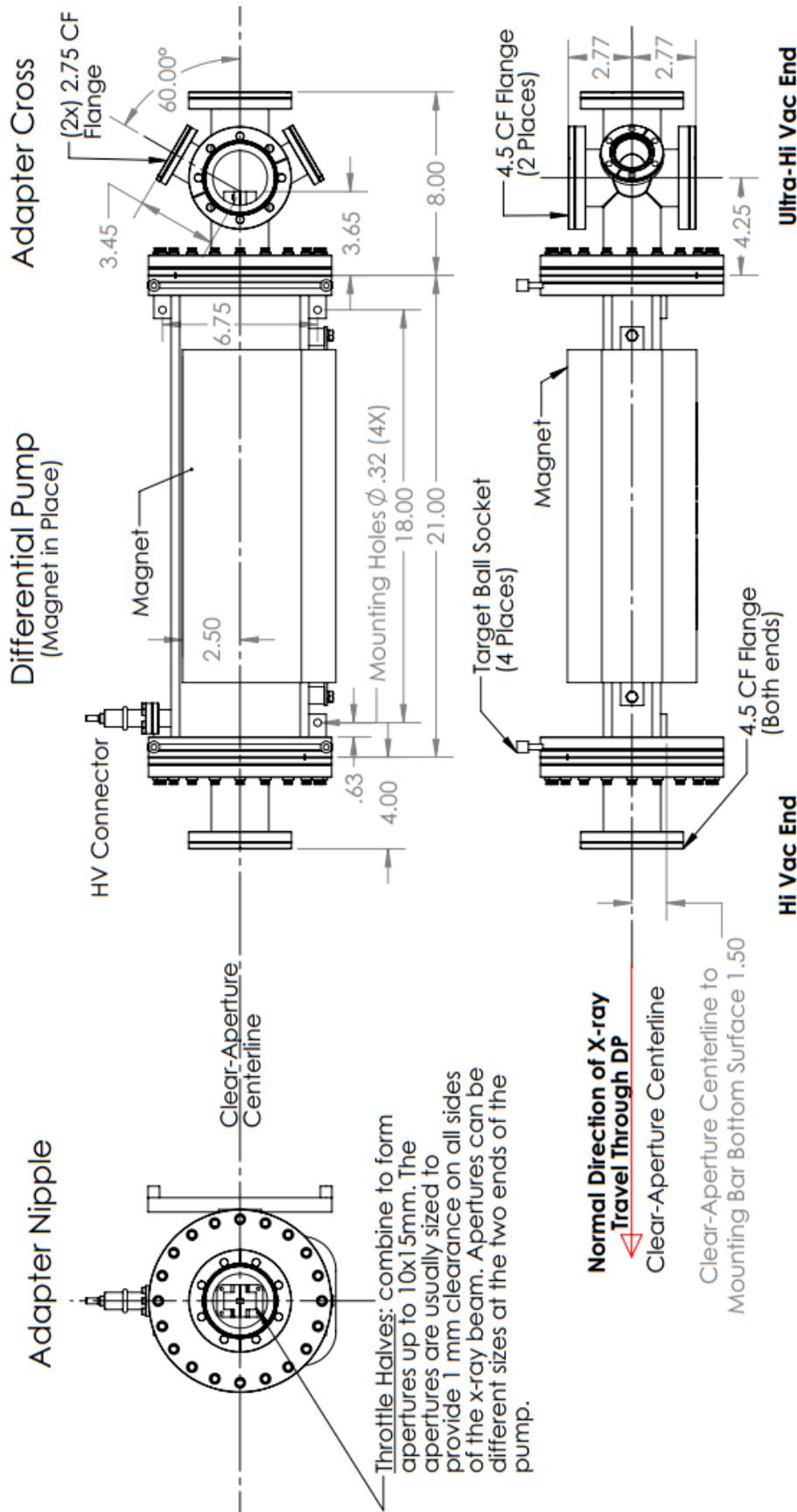


Figure 2.1: DP-03 outline drawing showing dimensions and mounting holes.

2.2. Pre-alignment Measurements

Two steps are required in order to be able to pass an x-ray beam through the XIA Differential Pump. First, the two throttles must be aligned to be co-linear; second, the throttle axis so defined must be aligned with respect to the x-ray beam. The first step is carried out by XIA during final assembly of the pumping unit with the result that both the throttle tubes and their inserts are parallel to better than 0.25 mm at all points.

The second step must be carried out by the user. To assist in this process 4 target sockets are attached to the XIA Differential Pump into which standard tooling balls with ¼" stems can be inserted (custom target sockets can be substituted upon request). Then, using mechanical or optical measurements, the user should establish and record the location of the beam axis with reference to the tooling balls using whatever alignment procedures are locally favored. The best place to record these reference dimensions may be on the pump itself. The Adapter Cross and Adapter Nipple, if present, need to be removed prior to this procedure. Due to this fact they are installed using only enough bolts to ensure no movement during shipment, so as to not require increased effort for disassembly. They should be replaced with all bolts fully screwed down prior to the bakeout procedure in §2.3. It should not be necessary to replace the copper gaskets due to the non-vacuum-tight attachment method described above, but they should be inspected to ensure they will be satisfactory and replaced if not.

2.3. Assembly and Bakeout

The XIA Differential Pump should have its output pump mounted and then be attached to whatever additional components are required. Normal UHV procedures should be followed here for roughing the system and turning on the various pumps. Following successful establishment of pumping and leak testing, the system should be prepared for baking and baked using standard local practice. If acceptance tests are planned, don't forget to attach the N₂ supply line to the variable leak valve and purge it prior to rough pumping.

Two important points should be noted here:

1. The differential pump is unable to pump either input or output volumes during the bake (or any other time, for that matter). This is because of the extremely small conductances of the two throttles, which are typically less than 0.5 l/s. The output pump can be used to pump the output volume during the bake, but an input side pump should be explicitly provided to pump the input side. If such a pump is not provided, the input side will probably not achieve better than high 9's pressures after the bake. This may be perfectly acceptable, since the XIA Differential Pump will completely isolate such pressures from the output side, but the range of pressures tested to meet acceptance criteria will have to be modified accordingly.
2. Because of the relatively close fits of the Throttle Assemblies into the pump, the clearance spaces show a tendency to act like virtual leaks and pump down slowly. As a result, somewhat longer baking times (or slightly higher temperatures) than normal are required to achieve the lowest background pressures. This is normal behavior for the design and causes no particular operational difficulties once it is recognized.

2.4. Acceptance Pressure Tests

Acceptance pressure tests should be performed immediately following the bake and attainment of acceptable background pressures. While differential pumping performance is guaranteed only at a single pressure (typically $P_1 = 1.0 \times 10^{-6}$ Torr) the careful user will wish to determine performance across the pump's entire operating range.

This is easily done. All that is required is to measure P_3 for a series of P_1 values from background up to the highest input pressure which can be accommodated without exceeding safe pump operating current limits. This limit will neither overload the pump power supply nor produce excessive pump heating. The latter condition can be recognized by P_3 values which rise fairly rapidly in time for a fixed P_1 . Such behavior will not typically be seen unless the pressure inside the differential pump is in the low 5's or higher. It is important to

start with P_1 at background and work up in pressure, since desorption from the pump surfaces plus virtual leaking of the type mentioned above cause the time constant for dropping output pressures to be much longer than for rising output pressures.

Also, if one of the ion gauge controllers is more stable or accurate than the other, use the better one to measure P_3 . This is because P_1 will be varied over at least 5 orders of magnitude (10^{-10} 's to 10^{-5} 's or higher) while P_3 should stay in the 10^{-10} 's or low 10^{-9} 's the whole time.

We recommend that a sequence of pressures on a logarithmic scale be collected for each pressure decade, particularly for pressures above 1×10^{-7} . A good coarse sequence of values is 1.0, 2.0, and 4.0 in each decade. A fine sequence is 1.0, 1.5, 2.0, 3.0, 4.0, 6.0, and 8.0 in each decade. We recommend the fine sequence, particularly at higher pressures. Each point only takes a minute or two to collect and then you know exactly what the pump is doing. Included at the end of this manual is a curve of the projected performance of this pump. Plotting this data on the same figure will not only allow a direct comparison between predicted and attained performance but will also record the data in a place where they will be easy to find later in pump's life when you want to determine whether it need cleaning or rebuilding.

2.5. Alignment

The XIA Differential Pump's through clearance path is typically only a few milliradians in solid angle and requires careful alignment to fully pass the x-ray beam. This task is complicated by the fact that the throttles are not readily visible from outside the pump body. In preparation for this task, however, the pre-alignment measurements of §2.2 should have been made to establish the location of the clearance path with respect to tooling balls located on the exterior of the pump. Measurements to the tooling balls may now be used to establish the location of the clearance path in space as well as to adjust its roll, pitch and yaw. We will not attempt here to lay out an alignment procedure to be followed since any such procedure will typically have to be custom designed for each installation. We strongly recommend, in fact, that such a procedure be designed at the same time as the pump support is being designed to assure that the support and procedure are compatible with each other.

3. Operation, Maintenance, Rebuilding and Modification

3.1. Operation

The operating characteristics of the XIA Differential Pump are identical to those of a Varian 110 l/s triode ion pump and the unit should be treated accordingly. In particular, the unit requires an appropriate power supply and high voltage cable. See §2.1.3 for suggestions. The power supply and high voltage cable are normally not supplied with the Differential Pumping unit and should be acquired separately by the user. Those who are unfamiliar with the operating characteristics of these pumps and supplies should consult the manuals which accompany their power supply and high voltage cable for further details.

3.2. Maintenance

In normal operation no periodic maintenance is required beyond assuring that the pump remains clean, dry and otherwise unexposed to environmental conditions which could lead to shorting of its high voltage supply.

3.3. Rebuilding

The normal lifetime of ion pumps is determined by the integrated pressures they see over time. At 10^{-6} torr **inside the pump** (as opposed to the downstream pressure, which is separated from the pump by throttle C1) lifetime will be approximately 50,000 hours and accordingly longer at lower pressures. When this lifetime is exceeded and the useful pumping rate has deteriorated an ion pump is typically rebuilt, which involves cleaning, removal of sputtered films from insulating surfaces, and replacement of its Ti cathode grid bars. In this regard the XIA Differential Pumping Element is identical to the Varian 110 l/s triode pump element and may be rebuilt by any company or facility which has experience rebuilding the latter or may be returned to XIA for rebuilding.

3.4. Modification

If, at some future point, the clearance apertures through the XIA Differential Pump need to be modified, the procedure is not difficult to accomplish. All that is required is to remove the throttle assembly (by loosening the two screws per assembly with a 1/8" hex key), removing them and replacing them with others of a more appropriate size. The projected new pump performance can be calculated using Equations 1.3 and 1.4.

The throttle assembly consists of the plate, which attaches the assembly to the pump, and two halves, which set the size of the aperture. New halves can either be ordered from XIA, made by machining the old ones to a new (larger) aperture size, or made by machining four entirely new halves. In the latter case, they can be made from 6061 Aluminum or essentially any other UHV compatible material using sulfur free cutting fluids, degreased, and prepared for vacuum according to accepted local UHV practice. Dimensions can be copied from the parts to be replaced.

4. QC Data

4.1. Weldment manufacture QC

The pump body, nipple, and cross weldments are produced for XIA by Nor-Cal products, an ISO-certified manufacturer located in California. Their specific QC procedures are available upon request. All weldments are leak tested to meet the following criteria:

1. Leak rate: $<1 \times 10^{-10}$ atm-cc / sec He
2. Vacuum reached during sealing: $<10 \times 10^{-9}$ Torr

Specific values for these measurements are not recorded and are not available.

Because XIA's installation of the ion pump does not modify the shell structure, the only source of leaks at the customer site will be through components attached to the DP's Conflat flanges by the customer. Therefore XIA does not conduct an additional leak check prior to shipping the DP as it would add no additional new information. Similarly, XIA does not bake pumps prior to shipment because the pump must be opened and its interior exposed to atmosphere during installation and alignment procedures at the customer site (see Chapter 2) and therefore requires a complete bakeout before it can be placed into service. Thus a bakeout at XIA would add nothing to final performance. XIA has been supplying DPs based on this paradigm for almost 30 years and not a single pump has had to be returned either for a detected leak or for failure to achieve specified vacuum levels after a proper bakeout at the customer site.

Assembly is performed at XIA where various QC steps including alignment data and short checks are recorded. These records are available upon request.

5. Warranty

5.1. Warranty

The XIA Differential Pump is guaranteed against defects in parts and workmanship for a period of 1 year from date of delivery. The pump is not guaranteed against damage resulting from abuse, carelessness, or operation using voltages or currents which are outside of the range of normally used parameters for 110 l/s triode ion pumps. In addition, on delivery and following an adequate bakeout cycle, the pump will achieve the performance levels indicated in the Customer Specifications document signed by the customer as per the terms of sale agreed to for this instrument.