Turbopump Operating Principles

Turbomolecular pumps consist of a series of bladed impellers rotating at high speed and fixed bladed stators. These impellers and stators are alternately spaced and are inclined in opposite directions.
The pumping action is based on momentum transfer from the fast moving impeller surface to the gas molecules.

The speed of the moving surface must be as high as possible to achieve optimum pumping efficiency in terms of pumping speed and compression ratio.
When this mechanism takes place several times in a pump a pumping action is created. The sequence of alternating rotors and stators typical of a conventional turbomolecular pump develops the compression ratio.

Turbomolecular drag pumps operate according to the same principle, but with a different geometry in the pumping stages. Gas molecules collide against a fast moving wall and are dragged into a channel toward the high pressure region.

Conventional turbomolecular pumps have high pumping speed but low compression ratio at foreline pressures higher than 10^{-1} mbar. Molecular drag pumps have low pumping speed but high compression ratios up to foreline pressures of more than 20 mbar.

When the two types of stages are combined together in one pump, as in the Varian MacroTorr® pumps, extended operational pressure ranges can be achieved. (See page 195 for further description of the MacroTorr® principle).

Pump Selection

How to Select a Turbo-V Pump

The right choice of a turbomolecular pump depends on the application; as a general rule we can reduce the choice to two types of use:

UHV (no gas flow) operations and Process Gas flow operations.

- UHV (no gas flow) operations.
  The former case includes most cases in which the turbomolecular pump is employed to create vacuum in systems where the gas load is mainly produced by outgassing. In this application the choice is typically based on the desired base pressure within a desired time as a function of the foreseen outgassing rate, i.e.

  $$S_{eff} = Q / p$$

  where:
  - p is the desired base pressure (mbar)
  - Q is the total outgassing rate at the desired time (mbar l/s)
  - S_{eff} is the effective pumping speed

- Process Gas flow operations.
  The second case relates to all operations where process gases must be used. The main parameters are therefore the desired operation pressure and the process gas flow

  $$S_{eff} = Q' / p'$$

  where Q' is the total gas flow and p' is the operating pressure.

How to Select the Backing Pump of a Turbomolecular Pump

The selection of a backing pump should be based analyzing two requirements of the vacuum system:
a. the roughing time
b. the minimum recommended backing pump of the turbo

a. Roughing: once the desired roughing time is established, the size of the forepump can be determined through the following formula:

$$S_{foreline} = (V / t) \ln (p_0 / p_1)$$

where
- $S_{foreline}$ is the pumping speed of the roughing pump (l/min)
- V is the volume of the chamber to be evacuated (l)
- t is the desired roughing time (min)
- p_0 is the starting pressure (mbar)
- p_1 is the end pressure (mbar)

When using a foreline pump much larger than the recommended size, a by-pass line might be necessary to achieve calculated roughing time.

b. Backing: the backing pump must be big enough to achieve an effective pumping speed as close as possible to the nominal speed.

$$p_{foreline} = Q / S_{foreline}$$

where
- $S_{foreline}$ is the pumping speed of the foreline pump
- Q is the gas load
- p is the operating foreline pressure

It should be noted that Q is the total gas load on the pump and includes process gases and turbo purge gases when used.

The size of the backing pump can be calculated according to the following rule:

$$S_{foreline} \geq 20S / K$$

where
- S is the pumping speed of the turbopump
- $S_{foreline}$ is the pumping speed of the backing pump
- K is the maximum compression ratio of the turbopump for a given gas (i.e.: process gas) at the operating foreline pressure.

The pumping speed of the backing pump should be the higher of the two values calculated as above (roughing and backing).

Finally, it is possible to use a dry pump (scroll or diaphragm) for hydrocarbon-free operation when pumps of the MacroTorr® type are used.

Turbomolecular Pump Parameters and Definitions

Throughput

"Throughput" is the flow rate of pumped gas through the turbomolecular pump (and foreline pump).
Throughput (Q) is measured in mbar l/s ≅ 1/60 standard cm^3/min.
The maximum throughput a pumping system can handle is, in general, dependent upon the size of its foreline pump rather than the turbomolecular pump.

Pumping Speed

"Pumping speed" (S) (volumetric flow rate) of a turbomolecular pump is the ratio between throughput and inlet pressure (foreline pump size must be the recommended one as a minimum).

$$S = Q / p$$

The pumping speed of a turbomolecular pump is constant over a wide pressure range and depends upon geometric factors such as diameter and rotational speed. For most turbomolecular pumps, pumping speed is nearly independent from gas species (molecular weight).

Compression Ratio

"Compression Ratio" is the ratio between foreline (partial) pressure and inlet (partial) pressure for a given process gas, measured in "zero flow" conditions (performed by injecting the process gas in the pump foreline while the high vacuum port is blanked off).
Compression ratio is generally indicated with the letter "K".

In technical specifications of turbomolecular pumps, it is the maximum attainable value of K (at low foreline pressure).
Compression ratio is, in fact, a function of the foreline pressure as shown in Figure 1.
Compression ratio decays at high pressure depending on turbomolecular pump configuration (the number of molecular stages) and/or power limitations that slow down the rotor (gas friction increases with pressure).
The maximum compression ratio is strongly influenced by gas species: it is an exponential function of the molecular weight of the pumped gas (compression ratio is considerably lower for light gases).

Pumping Speed and Pressure Ratio

The pressure ratio between foreline and inlet pressures in each operational situation is indicated by "R_p". This is, in general, equal to pumping speed ratio

$$R_p = p_{foreline} / p_{inlet} = S_{eff} / S_{foreline}$$

where S_{eff} is the effective pumping speed, and $S_{foreline}$ is the pumping speed of the foreline pump.
In fact

$$Q = S_{eff}\, p_{inlet} = S_{foreline}\, p_{foreline}$$

therefore

$$S_{eff} / S_{foreline} = p_{foreline} / p_{inlet}$$

The pumping speed of a turbomolecular pump is minimally affected by pressure ratio (and foreline pump size) in most common operational conditions (when pressure ratio is much smaller than K).
Generally, however, the effective pumping speed "S_{eff}" is a linear function of the pressure ratio "R_p" as shown in Figure 2 (and therefore is also dependent upon the size of the backing pump).

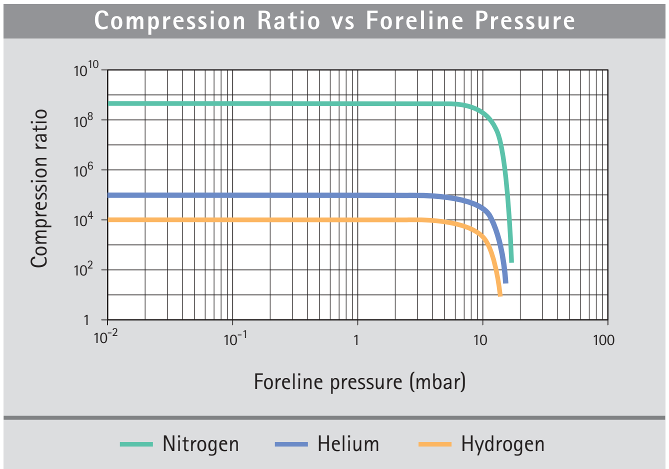


Figure 1

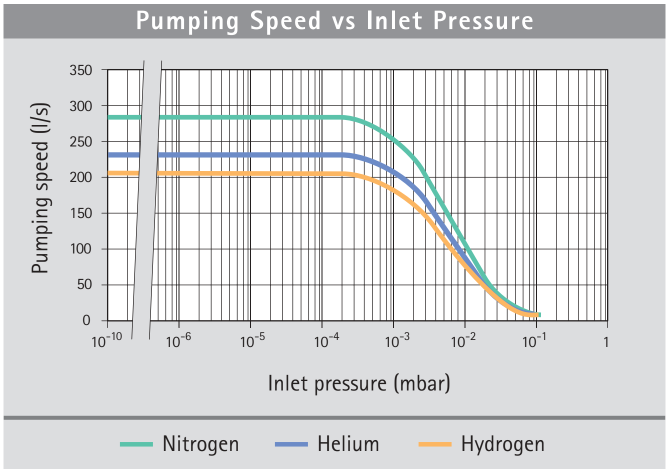


Figure 2

S_{eff} reaches its maximun value "S" (nominal pumping speed) when "R_p" equals unity, and it is zero when the pressure ratio R_p has reached its maximum value "K".
This linear dependence can be expressed by the following relationship:

$$S_{eff} = S / (1 - 1 / K + S / S_{foreline}K) \qquad (1)$$

As it can be seen:
when
$K >> S / Sforeline$
and
$K >> 1$
then
$S_{eff} \cong S$

when
$K \cong 1$
then
$S_{eff} = S_{foreline}$

The above formula (1) must be used to evaluate pumping speed when operating at high pressure, especially with light gases (low K).

Base Pressure
The base pressure of a turbomolecular pump is the equilibrium pressure between outgassing of pump surfaces exposed to high vacuum, including test dome, and the pumping speed of the pump.

$$p_{base} = Q_{outgas} / S_{eff}$$

In the case of ultimate operational pressure, as specified by norms, the pressure is measured after 48 hours bakeout of pump and dome (provided with metal gasket); therefore the prevailing outgassing product is H_2 and equilibrium is reached with hydrogen pumping speed.

$$p_{base} = Q_{H2} / S_{effH_2}$$

When foreline pumps with relatively high base pressures are used, base pressure is sometimes limited by the compression ratio for H_2O (or N_2).

$$p_{base} = p_{forelineH_2O} / K_{H_2O}$$

Vibration Level

Thanks to low vibration, focused design, and computer assisted balancing tools, today turbomolecular pumps generate very low levels of mechanical vibration. This is mainly a result of the numerical modeling of the pump rotodynamics (see Figure 3) and a specific vibration damping system already built into the pump structure. Thanks to

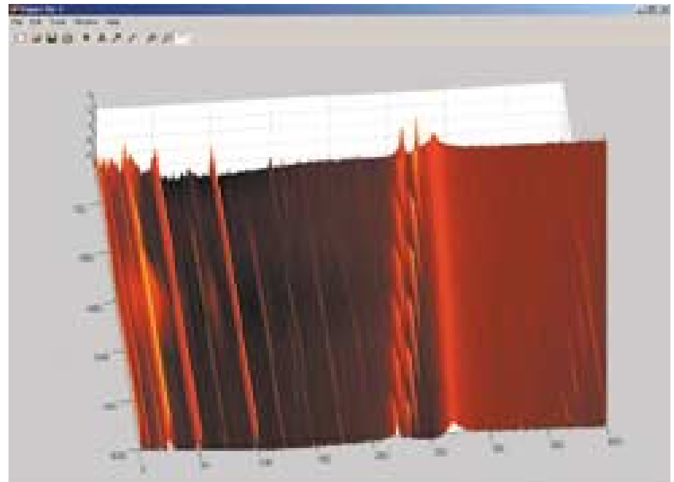


Figure 3

both design features, today ceramic ball bearings pumps are standard even in very high vibration applications like SEM and Metrology Tools.
A typical vibration spectrum of a turbomolecular pump can be seen in Figure 4:

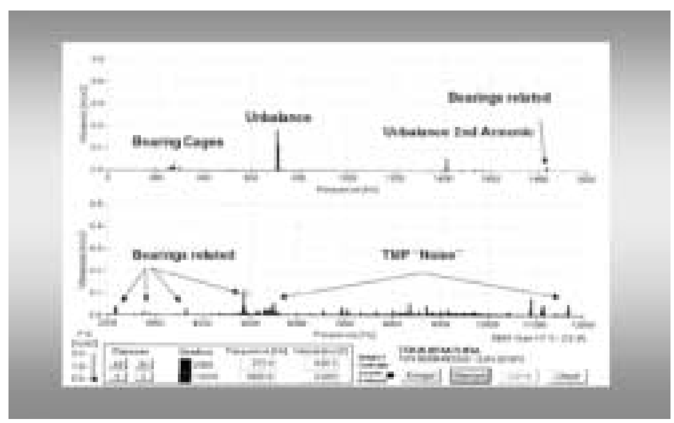


Figure 4

Possible sources of vibration in a turbomolecular pump are unbalanced rotor, high frequency motor or bearings. Rotor unbalance can be reduced to a very low level through dynamic balancing, which minimizes forces caused by a nonsymmetric distribution of masses in relation to the rotational axis. As an order of magnitude, the radial displacement on the pump HV flange after balancing can be as low as 0.001 µm.

The vibrations from a high frequency motor are caused by electromagnetic interactions between the motor stator and rotor: their characteristic frequencies are multiples of the motor driving frequency. Also, the rotor supports generate both white noise and vibrations at specific frequencies of the bearings' moving parts (cage, balls and rotating ring, usually the inner one).

In general, the vibrations caused by an electric motor or bearing are even lower than those caused by unbalance. They may be relevant in the case of bearing damage or because of excitation of a natural resonant frequency of the system connected to the pump. In the second case, the system structure should be modified by adding mass, changing the stiffness and/or inserting a vibration damper between pump and system.

Operation in Presence of Magnetic Fields

Magnetic fields induce eddy currents in the turbomolecular pump rotor that tend to oppose its rotation. As a consequence the power delivered to the electrical motor is increased. Since the pump rotor is not in contact with the stator, all the heat generated by the eddy currents must be dissipated by radiation, so the rotor can be overheated even if the static parts remain cool.
According to our tests, the maximum magnetic field that our pumps can tolerate is:

- 50 Gauss in the transversal direction
- 100 Gauss in the axial direction

In these cases, a power increase to the motor can be expected.
If the magnetic field is greater than the above values a shield must be used in order to have a residual magnetic field around the pump below the value specified.
Please contact Varian for more details.

Electrical Interfacing

The input/output of our controllers have been designed to give maximum flexibility to operate the pump remotely. Two types of interface are offered for the following two controller families:

- Rack controllers (including V 81, V 301, V 550, V 700HT, V 1000HT)
- Navigator controllers (including V 301, V 551, V 701, V 1001)

Please contact Varian for more details.

Turbomolecular Pump Bearings and Lubrication System

The Turbo-V pumps incorporate Varian's innovative ceramic bearing design with a proprietary ultra-low vapor pressure solid lubricant, which enables these pumps to provide a long service life and a high degree of cleanliness under most operating conditions. This lubrication system is a superior feature of Varian Technology and guarantees no contamination of the vacuum system, especially when compared to other oil-lubricated turbomolecular pumps (See figures 5-6).
The ceramic bearings utilize balls made of silicon nitride, a polycrystalline material with an amorphous intergranular binder base that offers the following advantages:

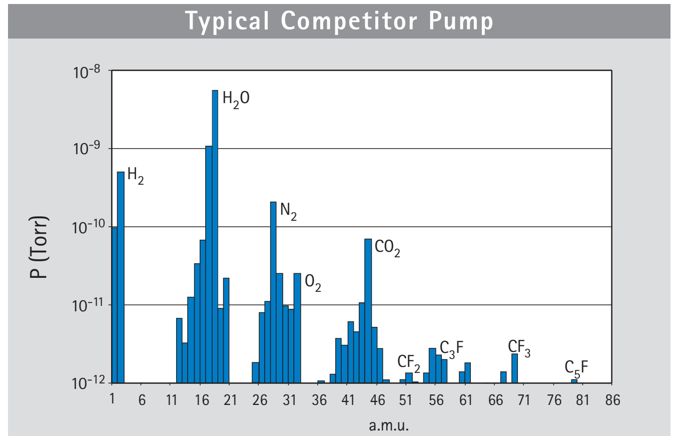


Figure 5

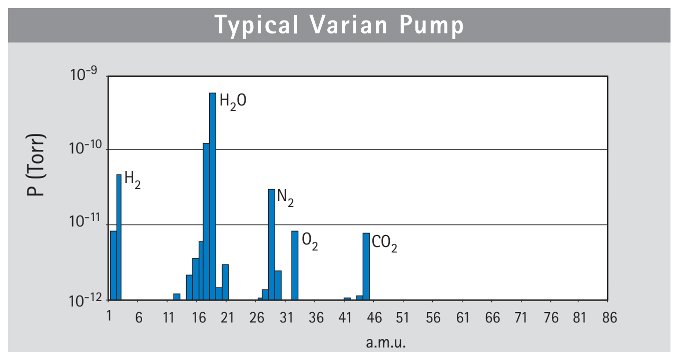


Figure 6

Hardness
This is a critical aspect of bearing design, and it closely relates to bearing performance and reliability. The silicon nitride material used in Varian's Turbo-V bearing system is twice as hard as conventional steel providing dramatic improvement in wear resistance while minimizing the effects of surface contact and stress.

Weight
Silicon nitride is 40% less dense than conventional steels, which helps to reduce centrifugal loading and stress levels at high rotational speeds, especially in the bearing race area.

Friction
Silicon nitride's low coefficient of friction enhances wear resistance and adds to the bearing's operational life.

Thermal Stability
With its low thermal expansion coefficient, the silicon nitride bearing material ensures that tight tolerances and mating component fit will be maintained over an extremely wide temperature range. In addition, silicon nitride has an outstanding resistance to fracture by thermal shock.

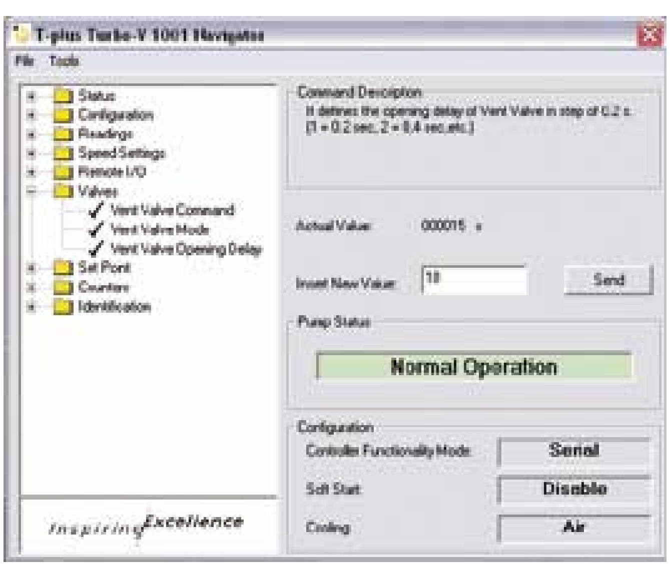
Chemical Stability
Silicon nitride is virtually inert.

Another feature of the Turbo-V bearing system is its proprietary lubricant which has an extremely low vapor pressure and is virtually hydrocarbon free. The use of this lubricant in the permanently sealed bearing system ensures clean, reliable operation without the need for any maintenance whatsoever.

Varian T-plus

Varian T-plus (**T**urbo **P**umps **L**inked **U**ser **S**oftware) is the new communication, control and monitoring software for Varian Turbomolecular Pumps and all other Varian products featuring the Varian Window Serial Protocol.
With T-plus, you can simultaneously drive and control one or more Turbo Pumps, connected to a PC through an RS232 or an RS485 serial communication.
Automatic identification of the connected Pumps, description of each command always on screen, and User Interface adaptable to the Pump Status are only some of the new features developed to make the approach to pump settings easy and to reduce the number of steps during pump configuration.
Moreover, special care is given to the GUI (Graphical User Interface), to reproduce the environment of well-known User Interfaces (such as Microsoft® Windows® applications), to obtain a real User Friendly tool, and to reduce the user learning time.
T-plus software features several options like Data Logging, Chart Representation and Network Configuration, to help you configure your Vacuum devices quickly, and to check your vacuum system status at any time.
Exhaustive online Help is also included, providing the user with a complete, easy to learn system, tailored to customer requirements.

The previous software release Navigator 2.2 is included in the T-plus CD.



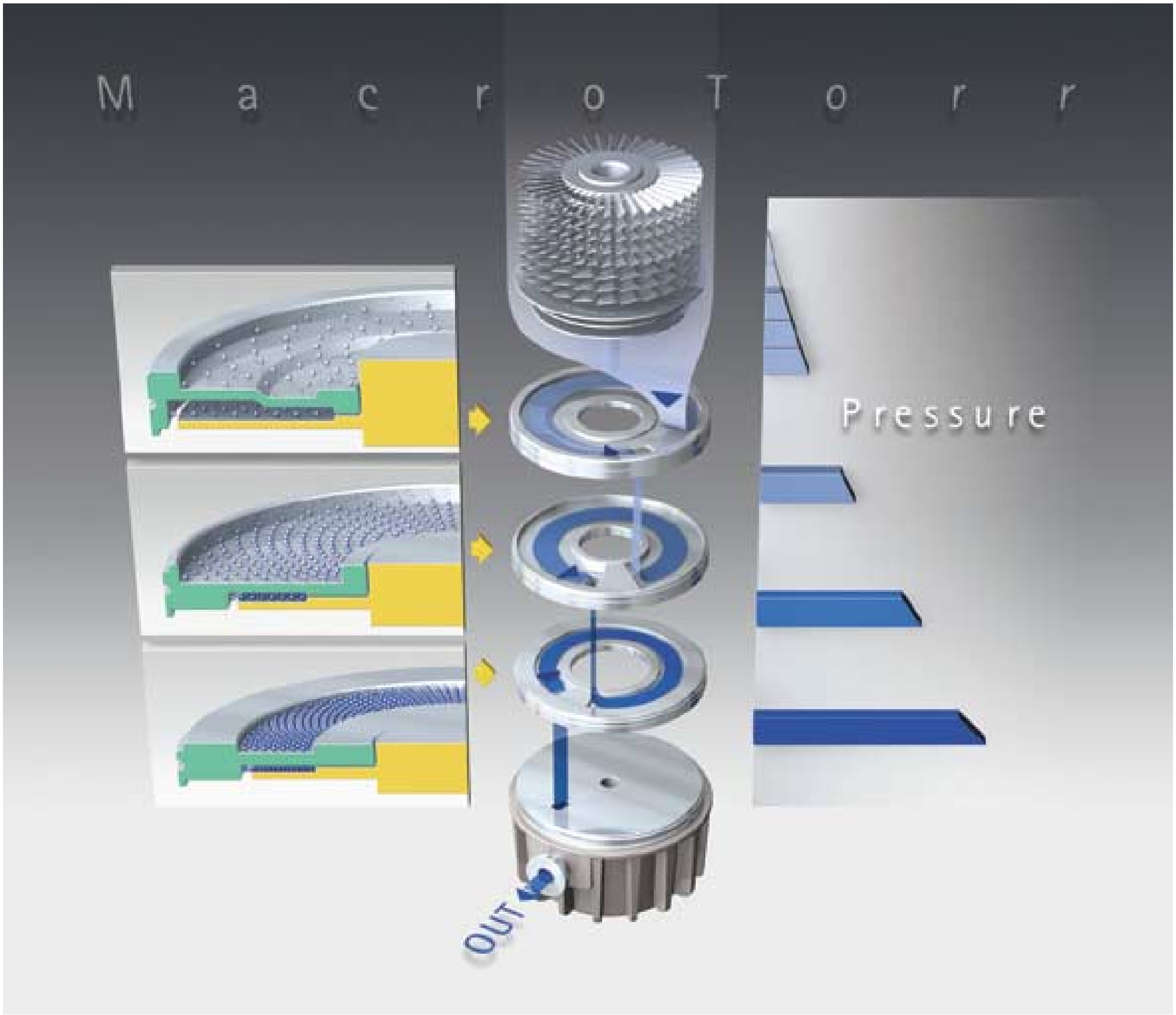
CE/CSA, EMC Electrical Specifications Compliance

Compliance to these norms guarantees that there are no limits on the use of the controllers and turbopumps in every type of ambient, and that their use doesn't create any kind of disturbance to electronic units connected to the same line.
Varian's new generation of Turbo controllers comply with the limits given by the following norms:

EN 55011 Class A group 1
EN 61000/3/2
EN 61000/3/3
EN 61000/4/2
EN 61000/4/3
EN 61000/4/4
EN 61010-1
UNI EN 291-1
UNI EN 292-2
EN 1012-2

The MacroTorr® Concept

The Varian award winning, patented MacroTorr® design, which was developed in 1991, is the result of the improvement of the original design of the Gaede molecular pump.
It is based on the idea of replacing (rather than adding) molecular impeller disks to some turbo bladed stages.
The molecular impellers consist of a disk rotating in a channel in which the inlet and outlet are divided by a wall.
The cross section of the channels decreases from the top to the bottom of the pump (from high vacuum to low vacuum or from the low pressure to the high pressure zone).
Gas molecules gain momentum after each collision with the moving surface of the impeller.
The gas is then forced to pass through a hole to the next stage due to the wall.
The result is a product that, with the same dimensions as a conventional turbopump, provides: high compression ratios for light gases and high compression ratios at high foreline pressure. This allows the use of a very small mechanical pump while maintaining a low inlet pressure, or the use of a dry pump, for an oil free environment, and high throughput capacity at inlet pressures greater than 10^{-3} mbar.


MacroTorr
Pressure
OUT