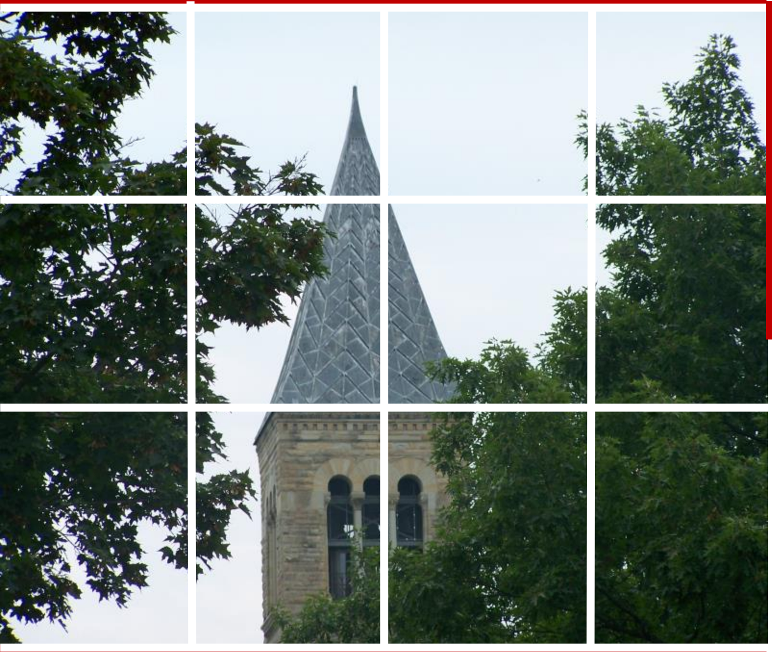

Vacuum Science and Technology for Particle Accelerators

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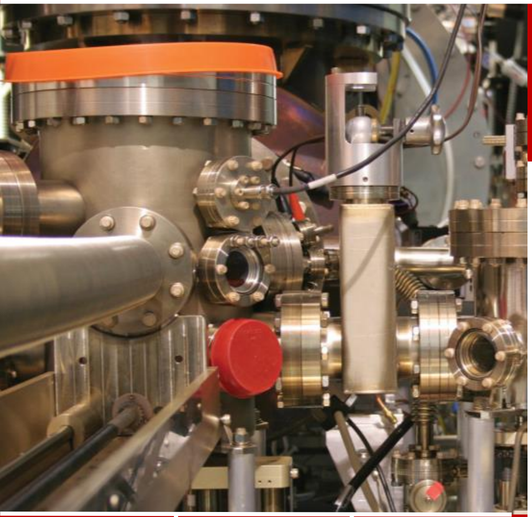


Table of Contents

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

SESSION 4: VACUUM PUMPS

- Category of Vacuum Pumps
- Displacement Pumps (Sec. 4.1)
- Capture Pumps (Sec. 4.2-4.4)
- Accelerator Pumping Considerations

Two Major Categories of Vacuum Pumps

Based on how the gases are removed from gas phase

Displacement Pumps

- Pumping by displacing gas to outside of the vacuum envelope, via ***volume exchange***, or ***momentum transfer*** to compress and to convey gaseous molecules to the exhaust
- Primary pumps can start from atm. Pressure.
- No capacity limit
- Moving parts may fail in continuous operations. Potential contamination.

Capture Pumps

- Pumping by storing, or capturing gas molecules through ***chemi***- or/and ***physi***-sorption onto the pumping elements
- No moving parts, clean
- Can't (effectively) operate at high pressure
- Limited pumping capacity

Fundamental Pump Parameters

Pumping Speed

- Pumping speed of a pump is the volumetric rate at which gas is transported across the pump inlet port.
- It has a dimension of volume per unit time. Commonly used are: m^3/s, CFM, m^3/h, L/s
- Pumping speed is usually pressure dependent, and gas dependent.

Working Pressure Range and Ultimate Pressure

- Every pump has a finite range of pressure in which it performs effectively in removing gases.
- Ultimate pressure is the lowest pressure a pump can achieve with inlet blanked off.

Pumping Capacity

- Most capture pumps have finite pumping capacity, which measures the amount of gases it can capture either (1) before a regeneration is needed, or (2) a pump has to be replaced

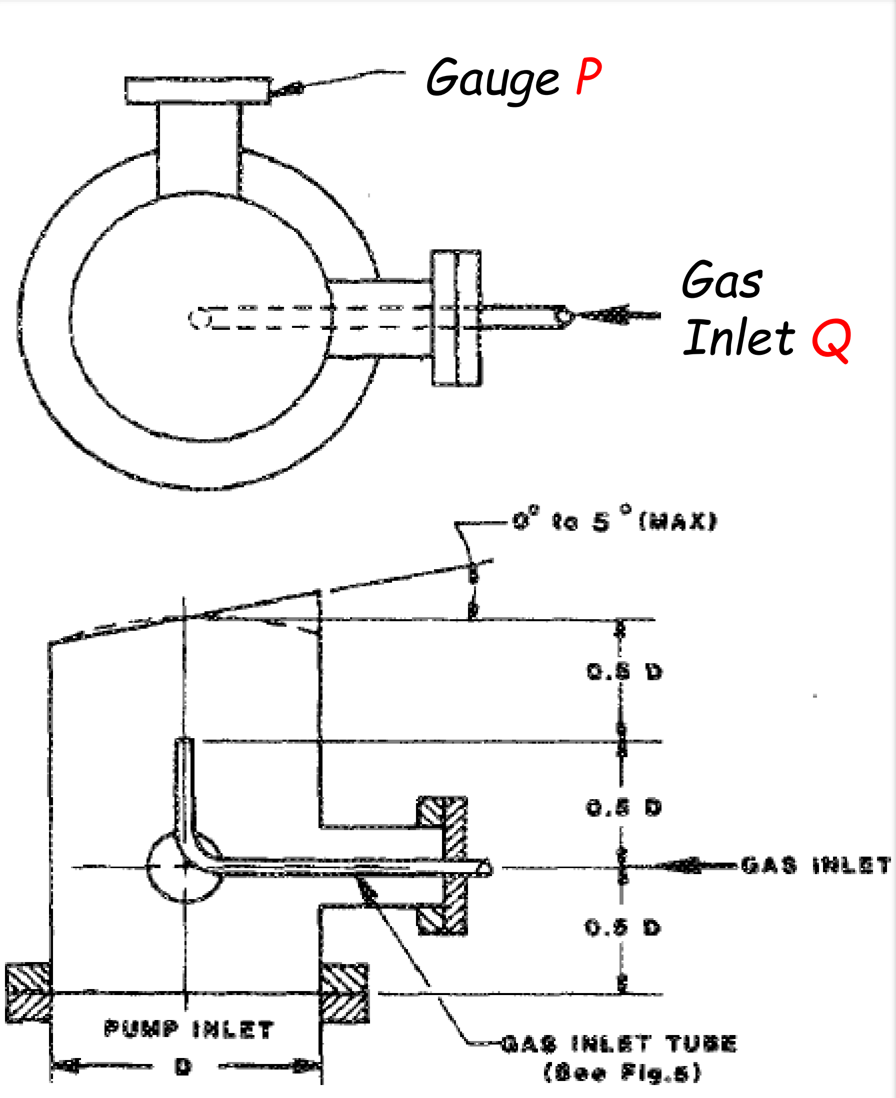
Measuring Pumping Speed

Pumping Speed Measurement

- *In most applications, the pumping speed information supplied by the pump manufacturers is sufficient.*
- *However, there may be needs for measuring pumping speed of a pump for reasons such as:*
  → *To verify pumping performance, after a pump rebuild or recondition.*
  → *To measure pumping speed for a specific gas*
  → *To measure pumping speed at specific conditions (different operation voltages, temperature, magnetic environment, etc.)*
- *Pumping speed is defined as: $S = Q/P_{inlet}$. So both the throughput (Q) and pump inlet pressure (P_{inlet}) need to be independently measured in pumping speed measurements.*
- *There are two AVS recommended methods of pumping speed measurement: the flow-meter method and the conductance (orifice) method.*

Pumping Speed Measurement – Flow-Meter Dome

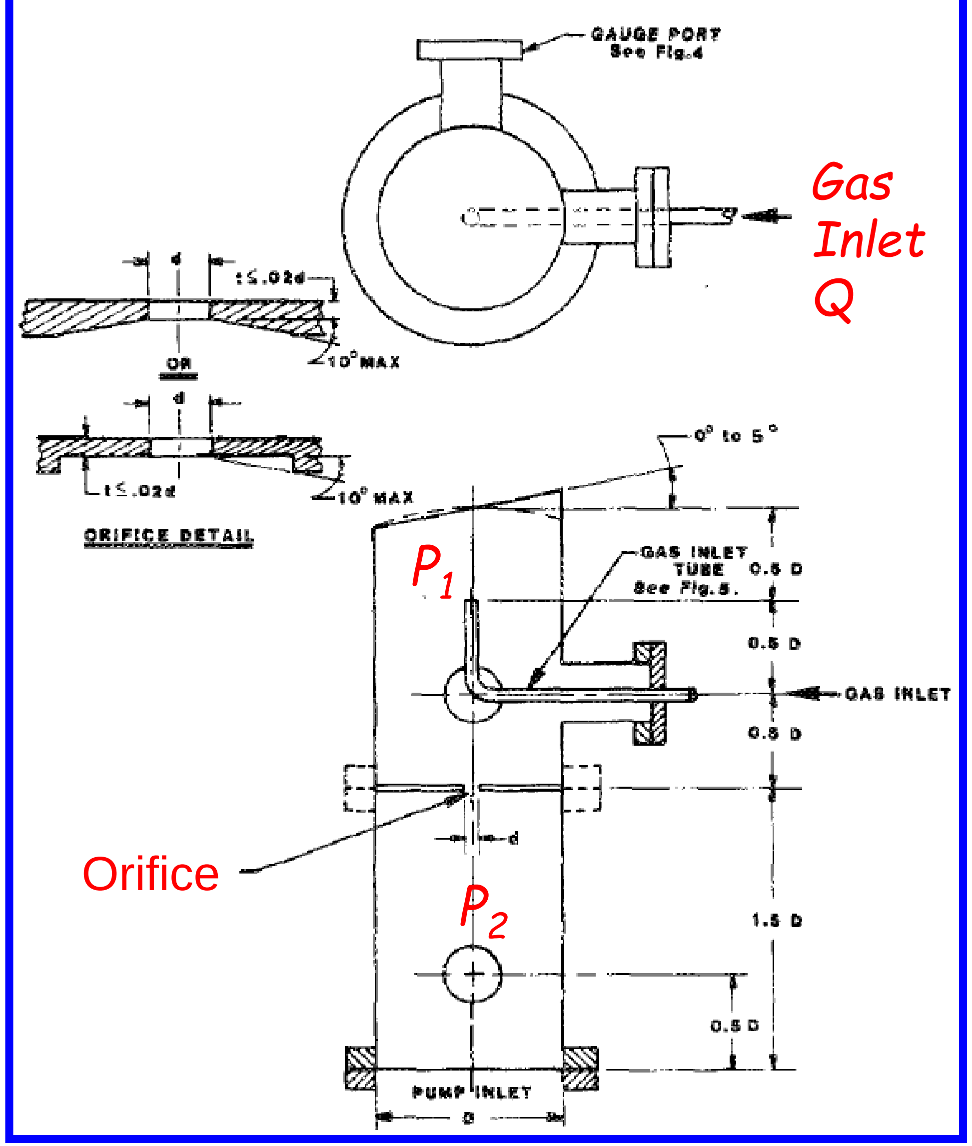
- *Gas is introduced into the test dome with a known rate, Q*
- *Q is controlled either with a flow-meter (at high loads), or using a calibrated leak.*
- *$S = Q / (P-P_0)$, P_0 is the base pressure.*
- *This is mostly used for primary pumps*



From: M. H. Hablanian, J. Vac. Sci. Technol. **A5**, 1987, p.2552

Pumping Speed Measurement – Orifice Dome

- *An orifice with defined geometry defines the flow rate.*
- $Q = C_{orifice} \times (\Delta P_1 - \Delta P_2)$
- $S = Q / \Delta P_2$
- *This is mostly used for HV and UHV pumps. No need for calibrated flow rate control.*



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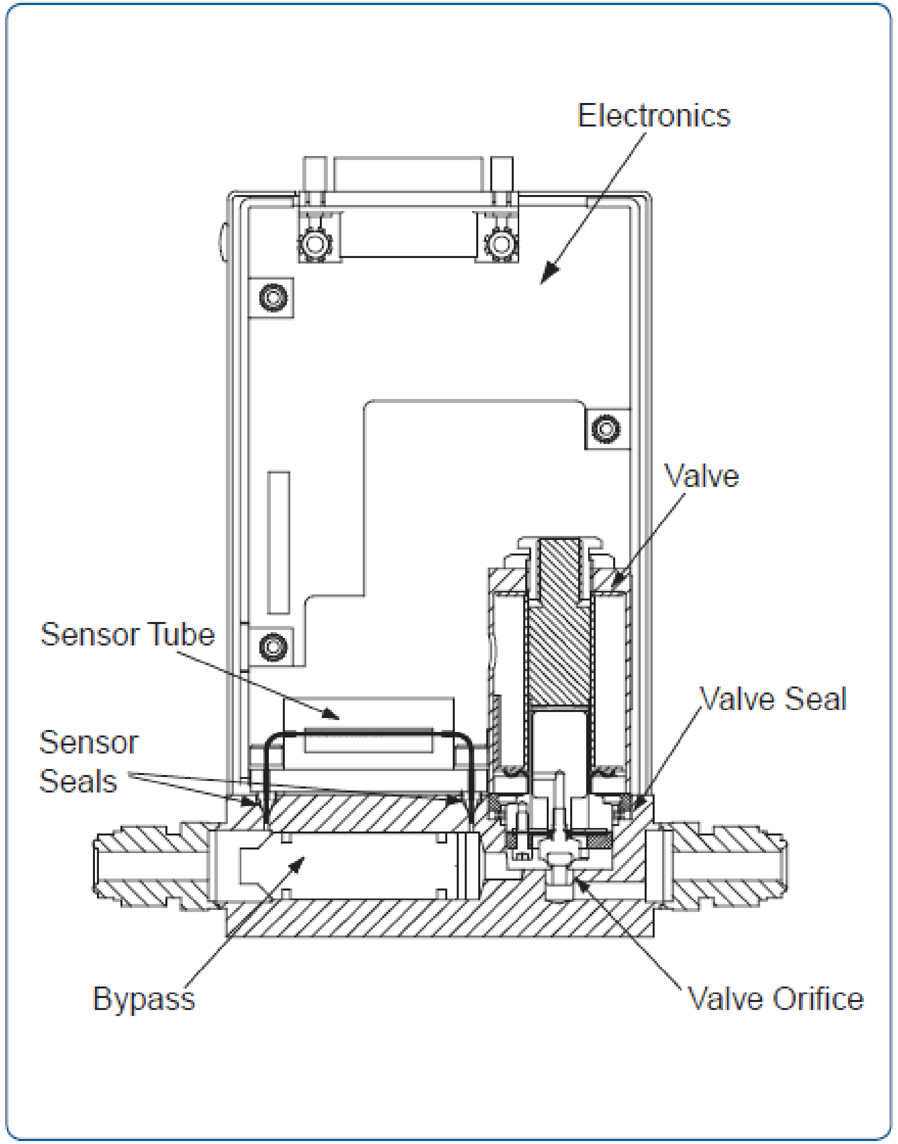
Flow Control – Flow meters

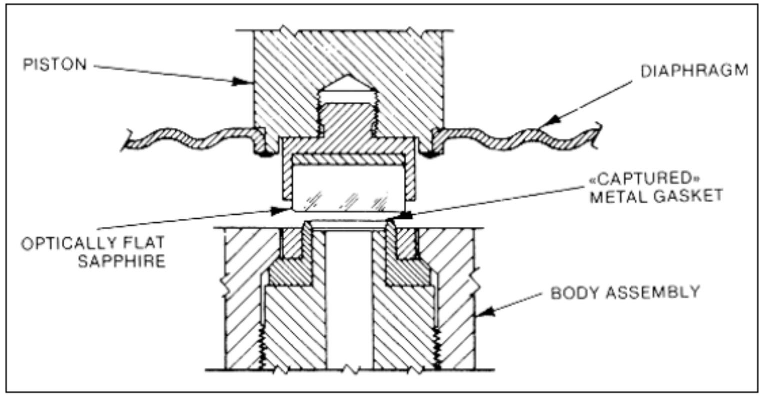


- Flow rates: 5 sccm ~ 10 slm (N_2 equivalent)
- Precision: 0.1% ~ 1% F.S.

Flow Control – Calibrated Leaks

- *Crimped capillary leaks are widely used*
- *Flow (leak) rates: 10^{-9} to 10^{-4} torr·l/sec for most stable gases (single and mixtures)*
- *Very reproducible gas sources (with periodic calibrations)*
- *NIST-traceable calibrations*

Flow Control – Variable Leak Valves



Sealing detail

Variable leak valve specifications

Minimum leak rate	1 x 10^{-9} Torr-litres/sec. in normal operation; 1 x 10^{-10} Torr-litres/sec. with condensable vapours eliminated from leak gas
Rate of change of leak	The valve provides an increasing rate of change as the size of the leak increases giving precise control in proportion to the size of the leak
Vacuum range	From atmospheric pressure to below 10^{-11} Torr
Temperature range	Up to 450 C in either open or closed position
Inlet gas pressure	*500* psi maximum
Gasket life	For unbaked systems, approximately 300 closures; For baked systems, 20 to 30 closures Gasket assemblies are replaceable
Material	300 series stainless steel; sapphire; OFHC copper and copper alloy
Weight	1.8 Kg (4 lbs)

Pumping Speed Measurement – No Dome

- Pumping speed may be estimated without a test dome, and without calibrated gas load (but need a load!)
- Assume that the speed of a pump does not change over a pressure range (1~2 orders of magnitude):

$$S = \frac{Q_{load} - Q_{base}}{P_2 - P_1} = V \frac{dP_{load}/dt - dP_{base}/dt}{P_2 - P_1}$$

- First pump down the system to a base pressure P_1, then turning the pump off to measure rate-of-rise dP_{base}/dt .
- Then introduce a gas load to raise system pressure to P_2, with the pump on. Re-measure rate-of-rise dP_{load}/dt by turning the pump off.

Displacement Pumps

Displacement Pumps

Based on working pressure ranges

Primary Pumps

<u>Oil-sealed or "Wet" Pumps</u>

- Rotary vane pumps
- Piston pumps
- Roots pumps

<u>Dry Pumps</u>

- Diaphragm pumps
- Scroll pumps
- Screw pumps

HV-UHV Pumps

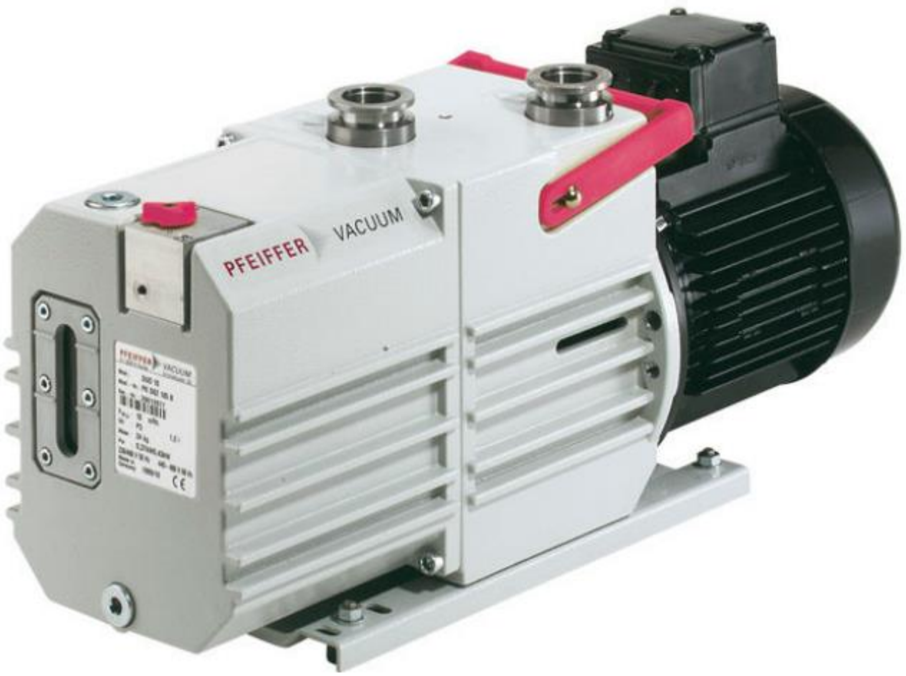
<u>Diffusion Pumps</u>

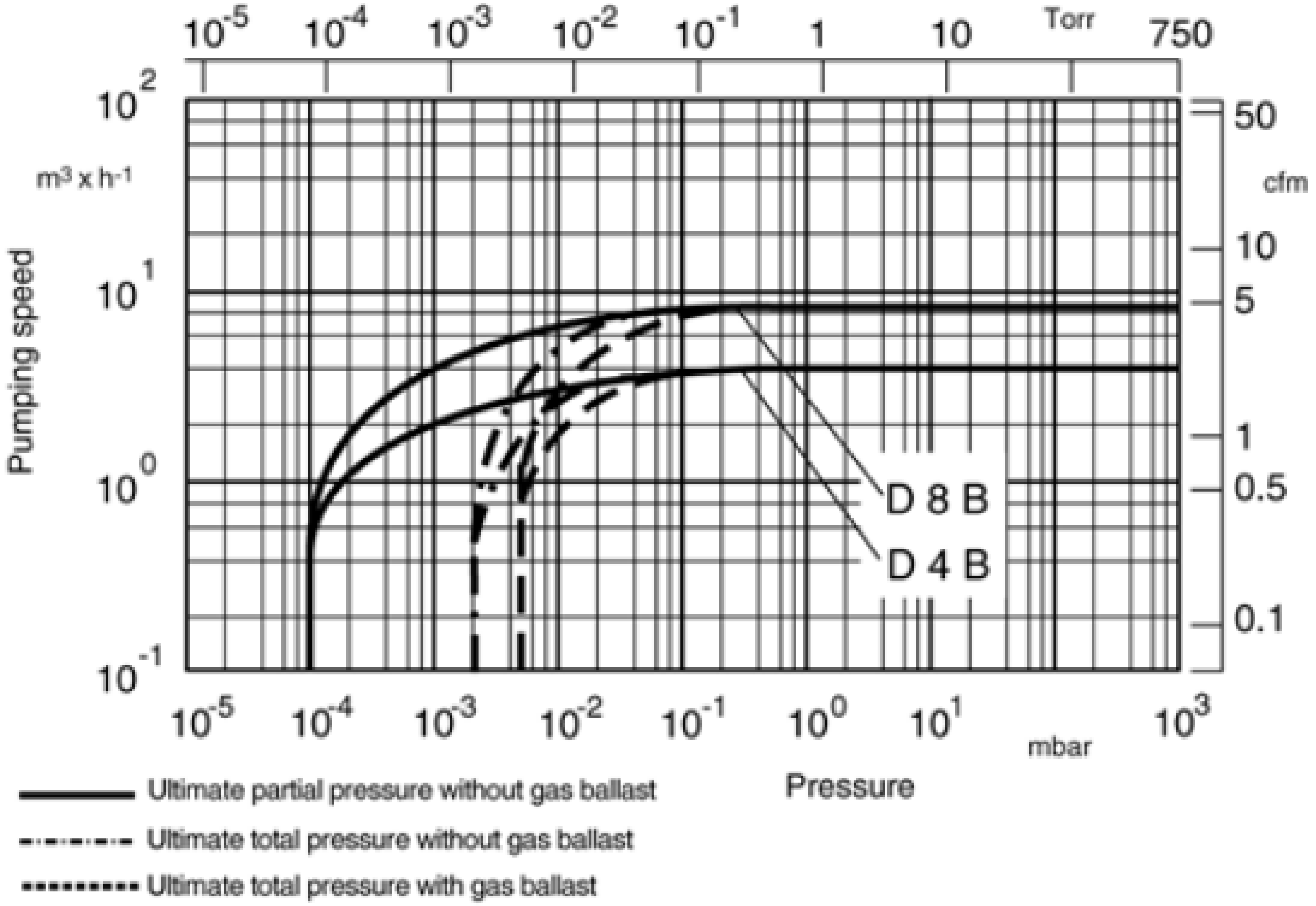
<u>Turbo-molecular pumps</u>

Primary Pumps

Type	Advantages	Disadvantages
Rotary Vane	Low Ultimate Pressure Low Cost Reliable	Source of Backstreaming Oil & Hazardous Waste
Rotary Piston	High Pumping Speed Low Cost	Noisy Source of Vibration
Scroll	Clean Low "clean" Ultimate Pressure	Permeable to light gases Clean applications only
Diaphragm	Quiet Easy to work on	Low Pumping Speed High Ultimate Pressure Requires frequent servicing
Roots Blower	No (Low) Backstreaming Low Ultimate Pressure	Expensive Requires frequent servicing Requires purge gas
Screw Pump	Handle high displacement rate Work with condensable gases/vapors Quiet operation	Expensive Heavy

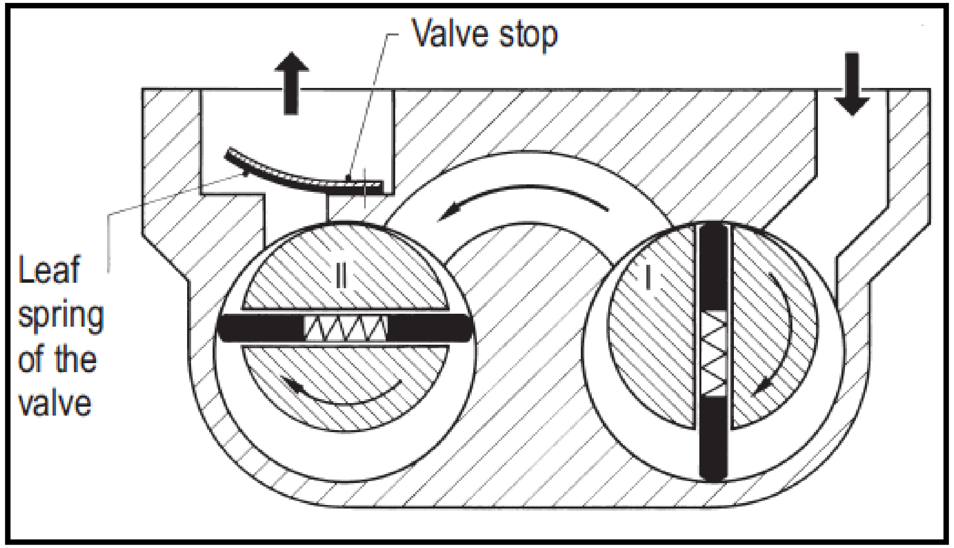
Rotary Vane Mechanical Pumps

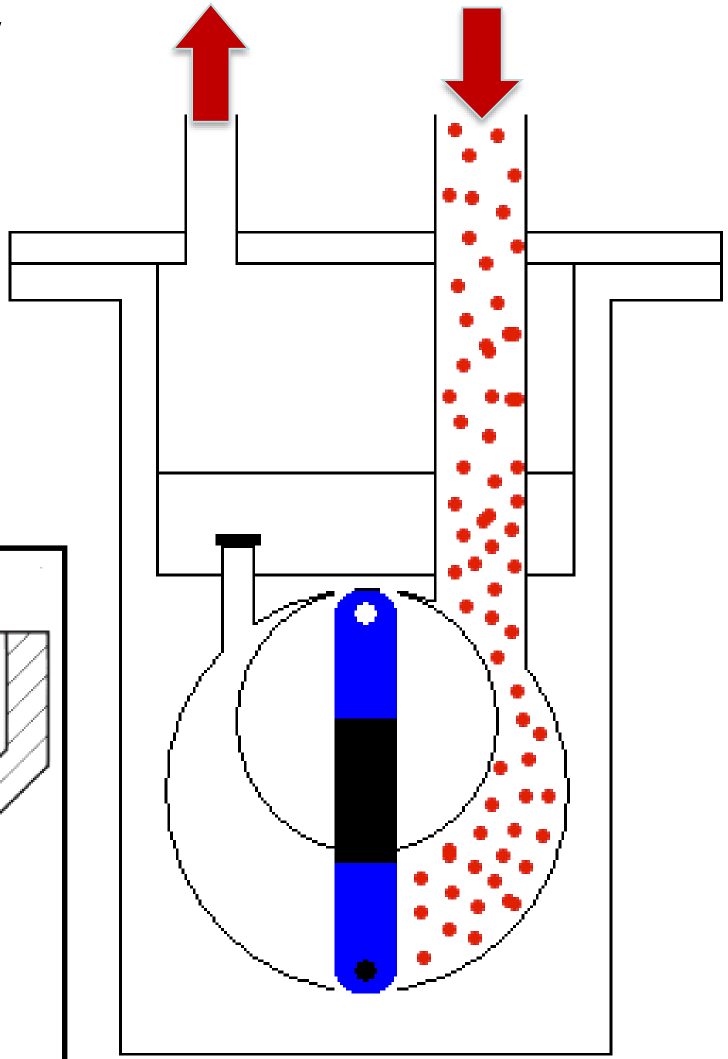




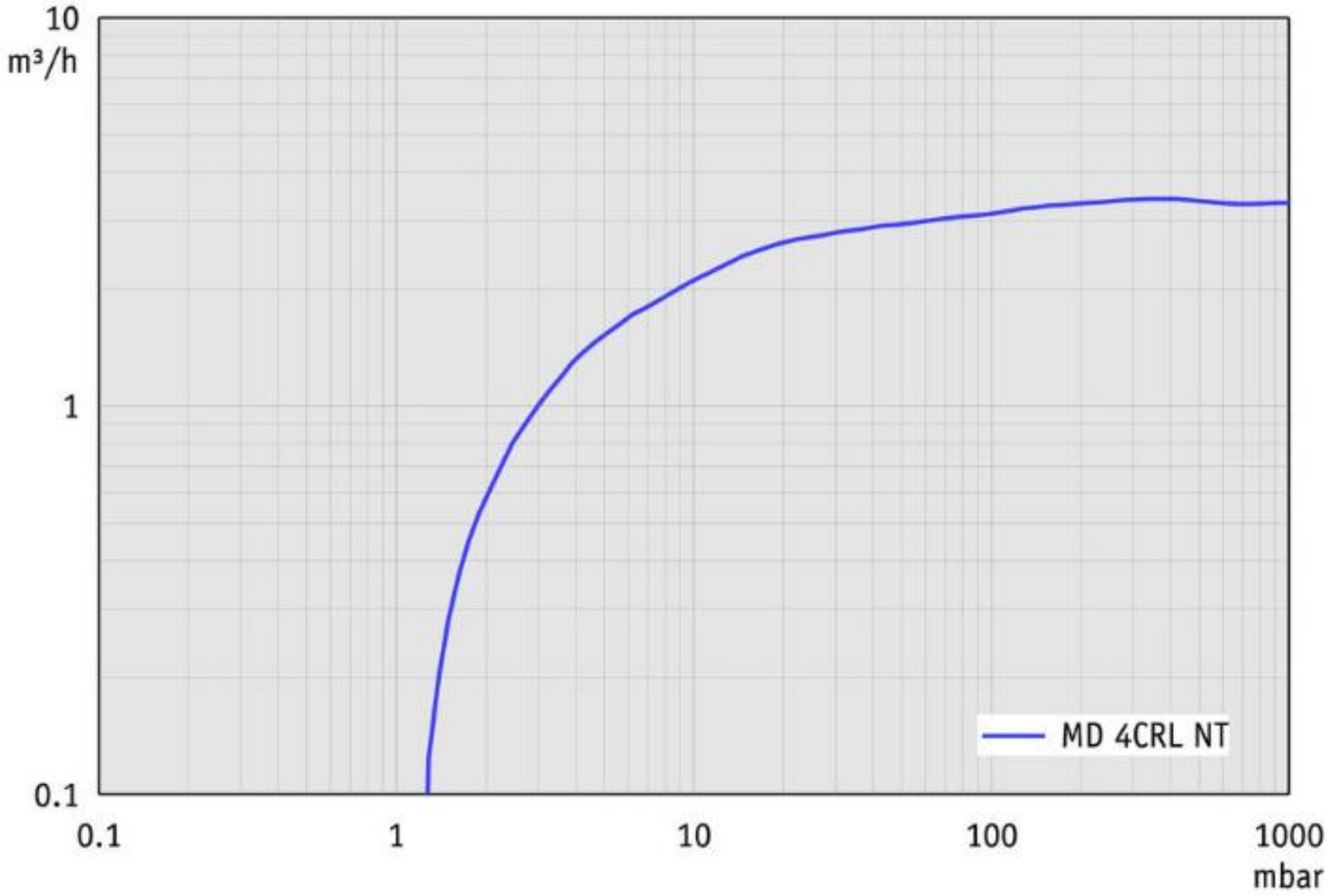
Rotary Vane Mechanical Pumps

- *Spring loaded on eccentric rotors compress gas from inlet to exhaust*
- *Single-stage and two-stage versions are available*
- *Gas displacement speed up to 100 m^3/h*
- *Ultimate pressure for two-stage pumps <10^{-3} torr. Limited by leak through oil-seals and 'dead' volume*
- *Rugged, long-term continuous operations. Suitable for LV systems, and backing for HV pumps.*
- *Most pumps equipped with anti-suck-back valves*
- *Main drawback:*
  oil back-stream



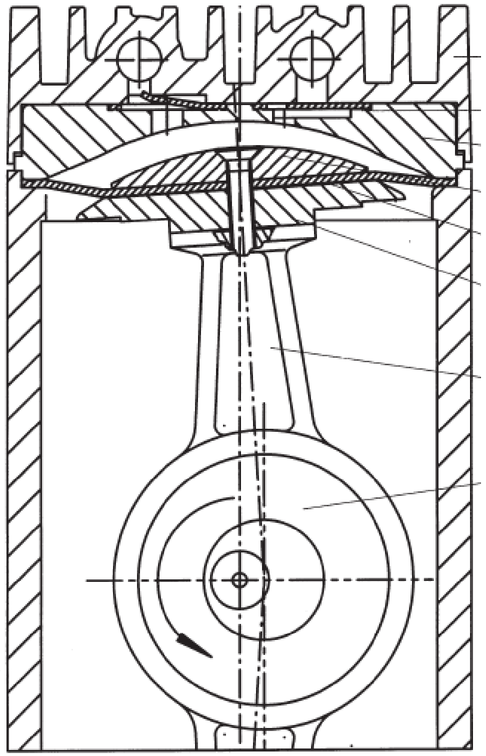


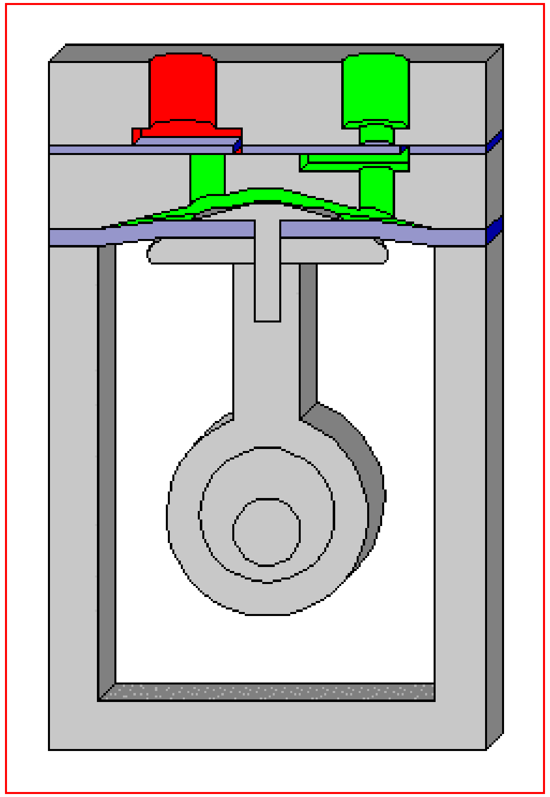
Diaphragm Pumps

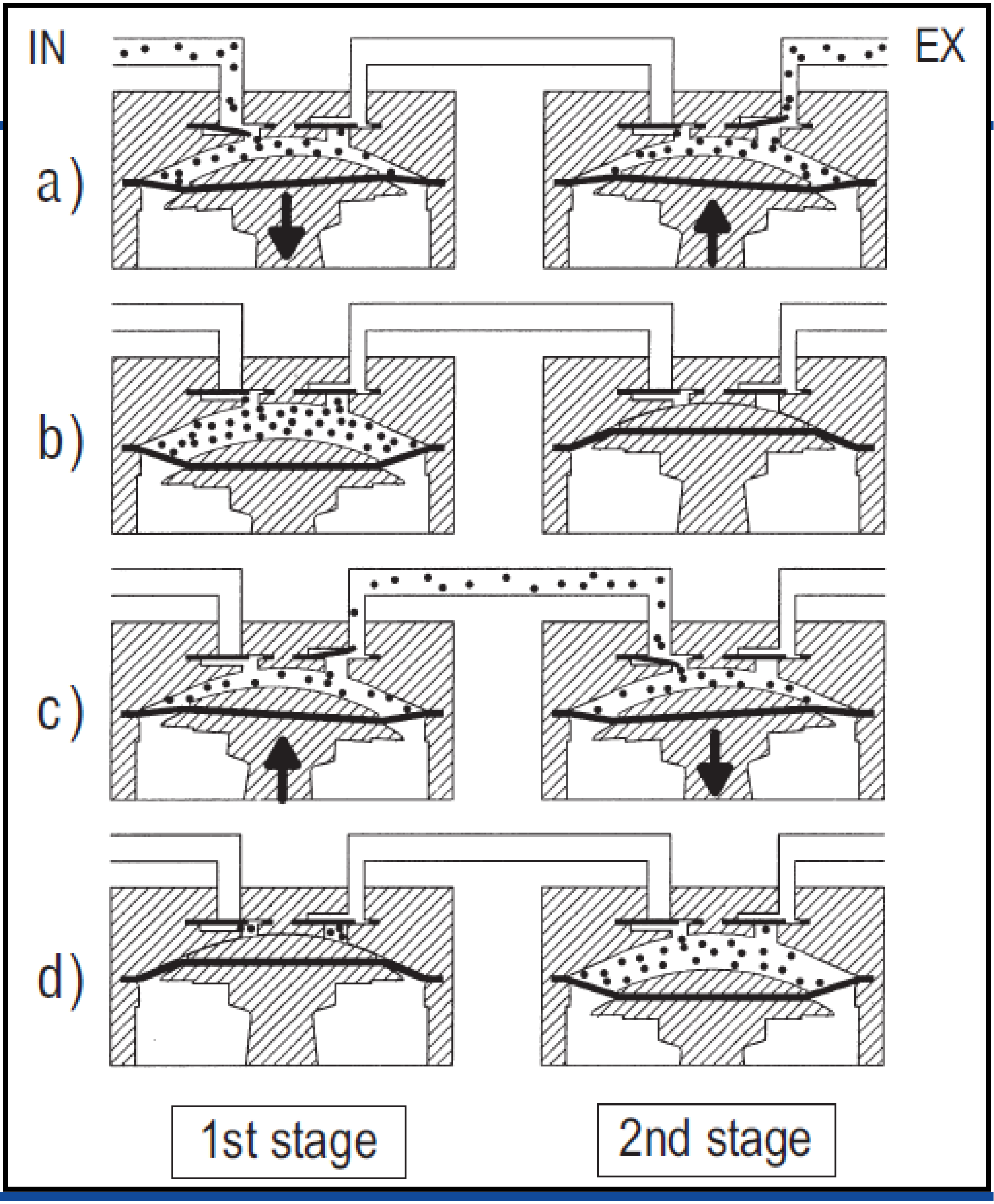


Diaphragm Pumps

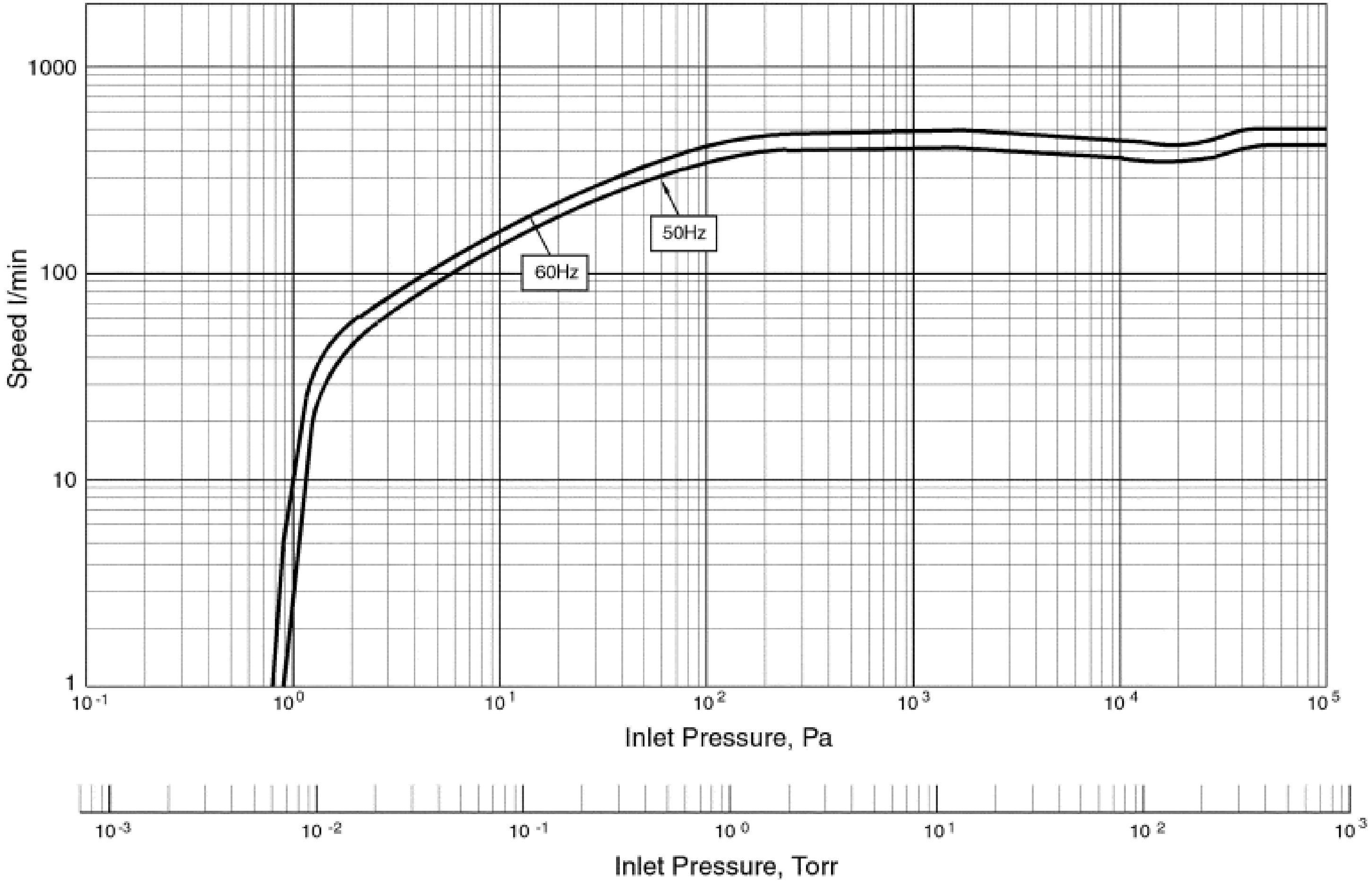
- Dry primary pumps. Usually available in multiple stages (up to 8 stages)
- Quiet operations
- Ultimate pressure ~ 1 torr
- Require more frequent maintenances







Scroll Pumps

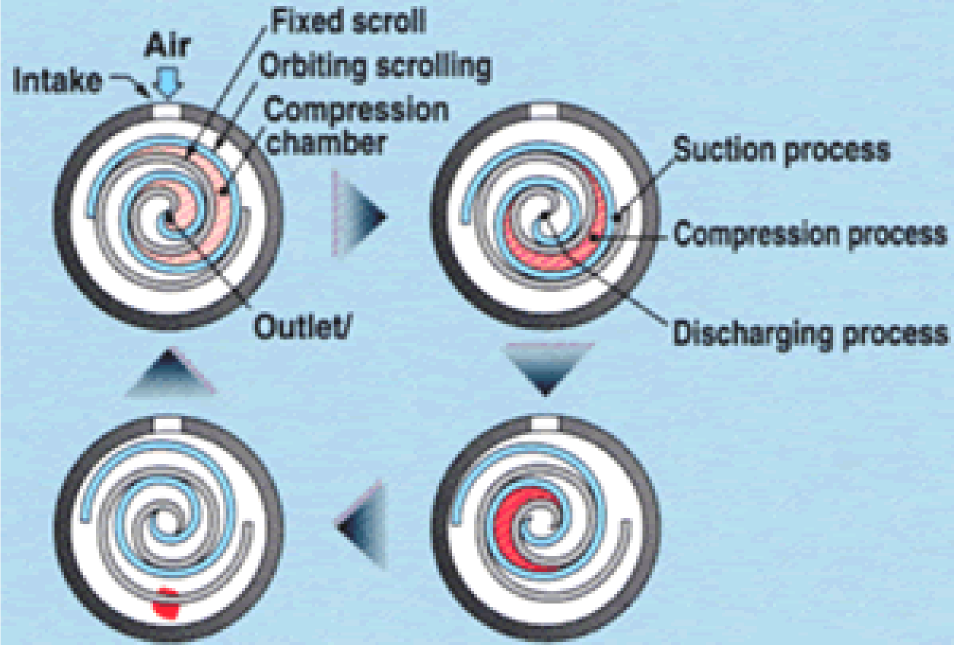


Scroll Pumps

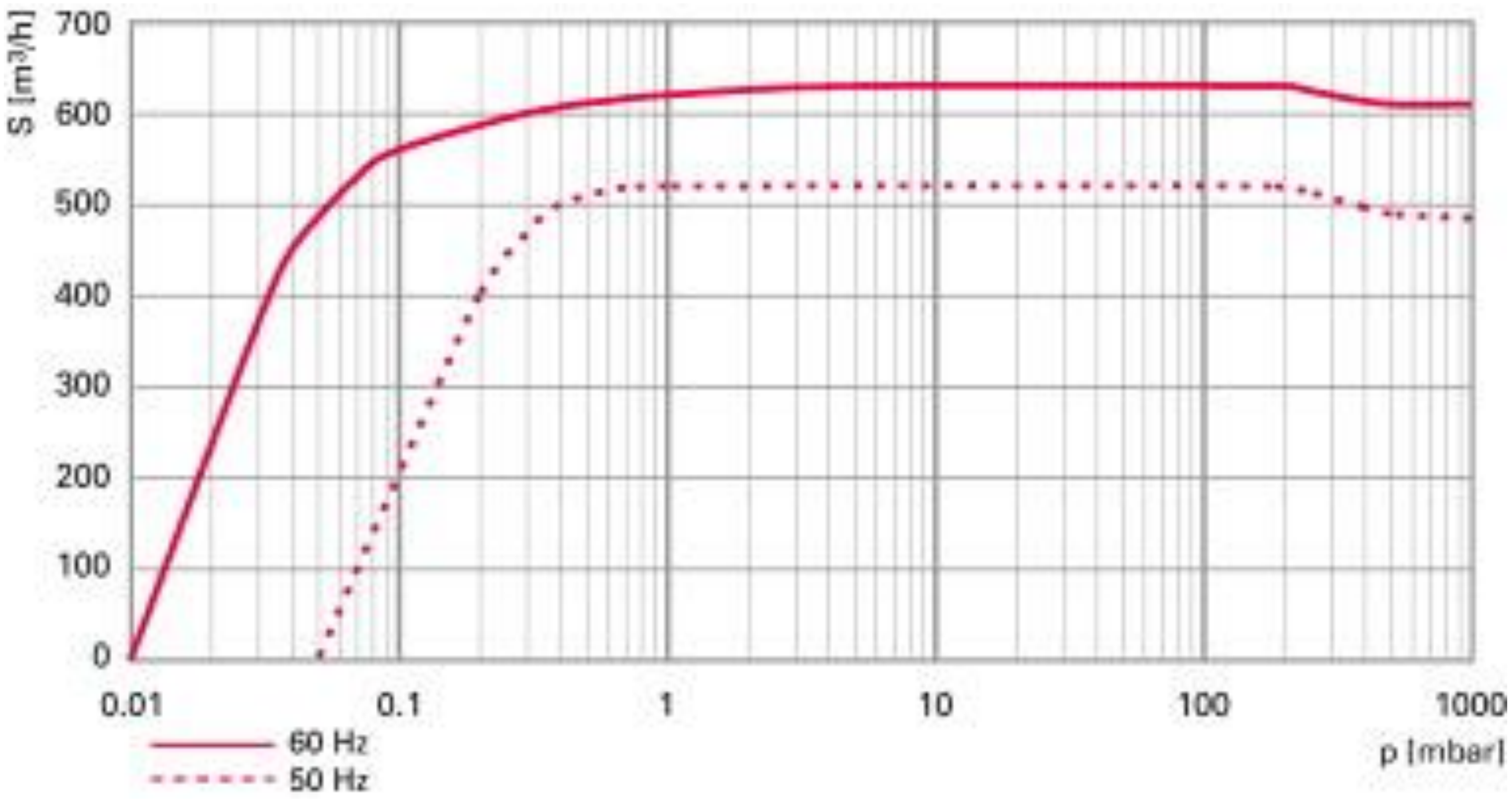
- The scroll pump is a relative simple dry compressor, with two spiral surfaces, one fixed, on orbiting. Teflon tip seals are commonly used, and easy to replace.
- Pump sizes: 15-40 m^3/h; ultimate pressure ~10^{-2} torr.
- Moving scroll may create dust at exhaust. Moisture may shorten scroll lifetime

Stator Scroll

Orbiting Scroll

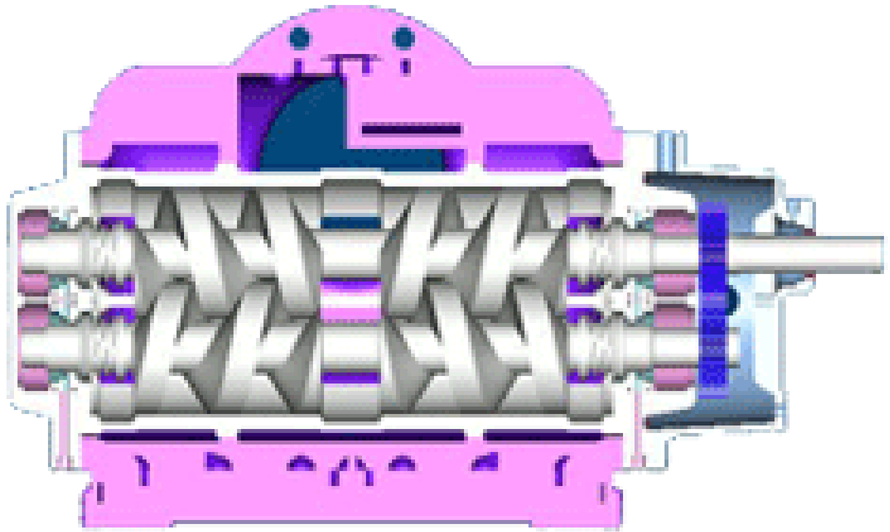


Screw Pumps – Moving/Compress Gases

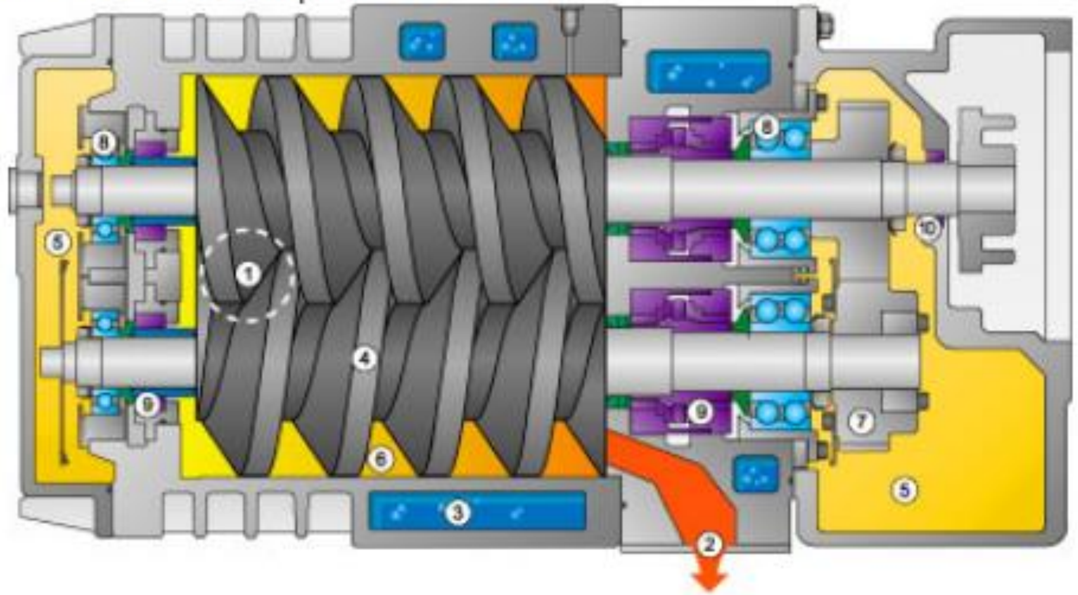


Screw Pumps

- Screw pumps are dry compressor, consisting of a pair of counter-rotating shafts.
- Screws pumps can have very high pumping speed (up to 2500 m^3/h), and lower ultimate pressure ($5x10^{-3}$ torr)
- Screw pumps can handle corrosive, abrasive and condensable gases/vapors (with ballast valve).
- Relatively high cost



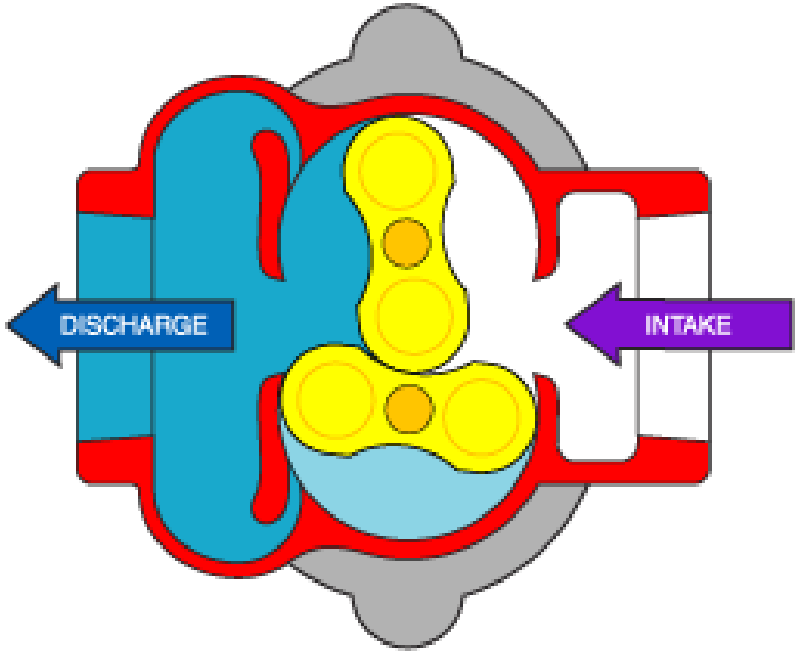
BUSCH Cobra description



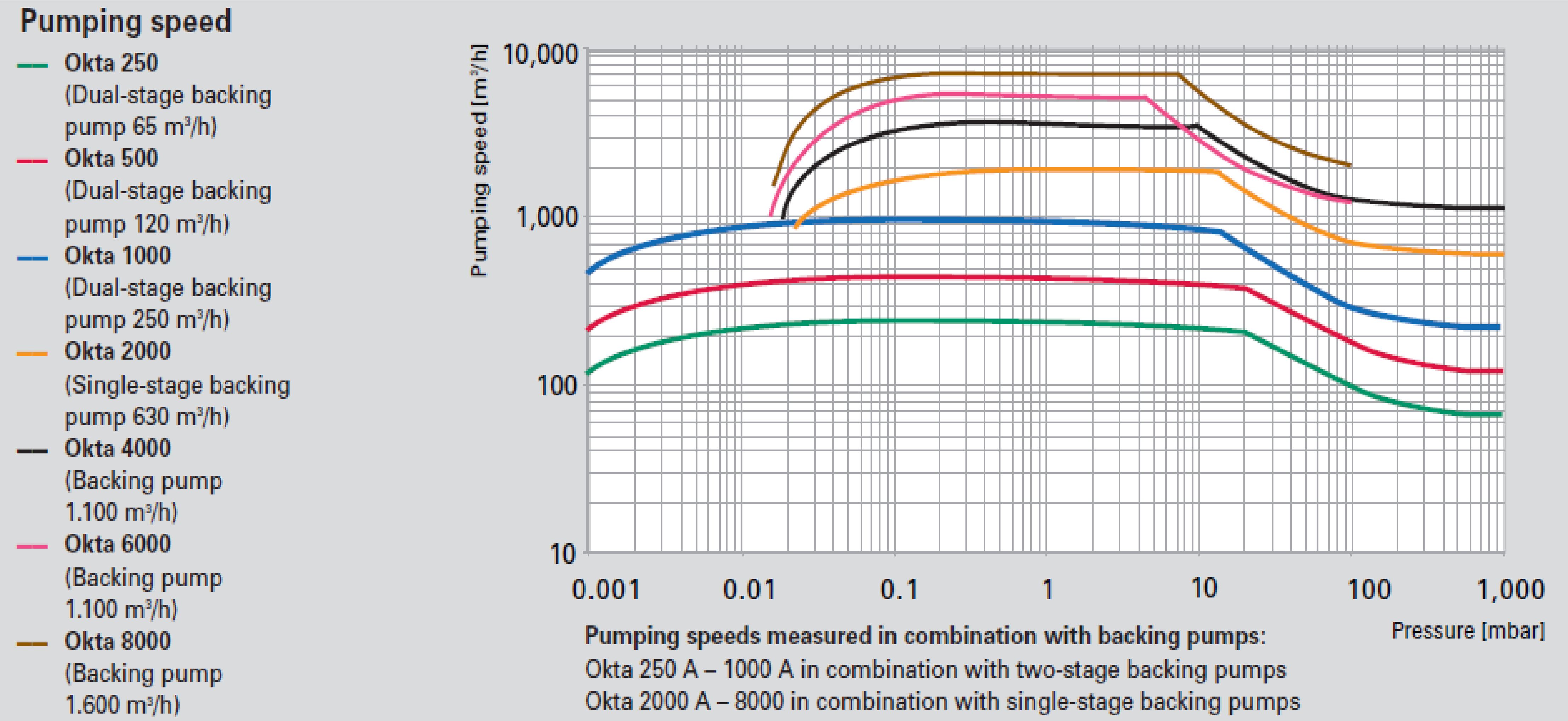
1.Inlet - 2.Exhaust - 3.Water Jacket - 4.Screw - 5.Oil - 6.Gas Path - 7.Timing Gears - 8.Bearings - 9.Shaft Seals - 10. Oil Seal

Lobe-type (Roots) Vacuum Pumps

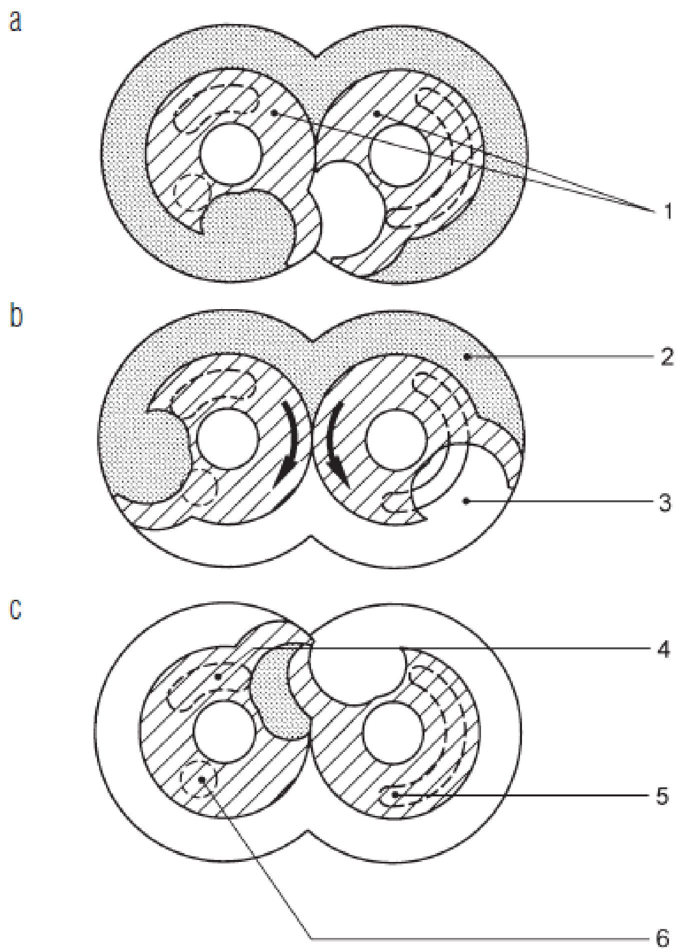
- Roots pumps have very high gas displacement speed. Sometime are called blowers.
- Roots pumps are generally considered as dry mechanical pumps, but their gear-box contain lubrication oil.
- Roots pump usually need a small backing pump.



Roots Vacuum Pumps – Examples

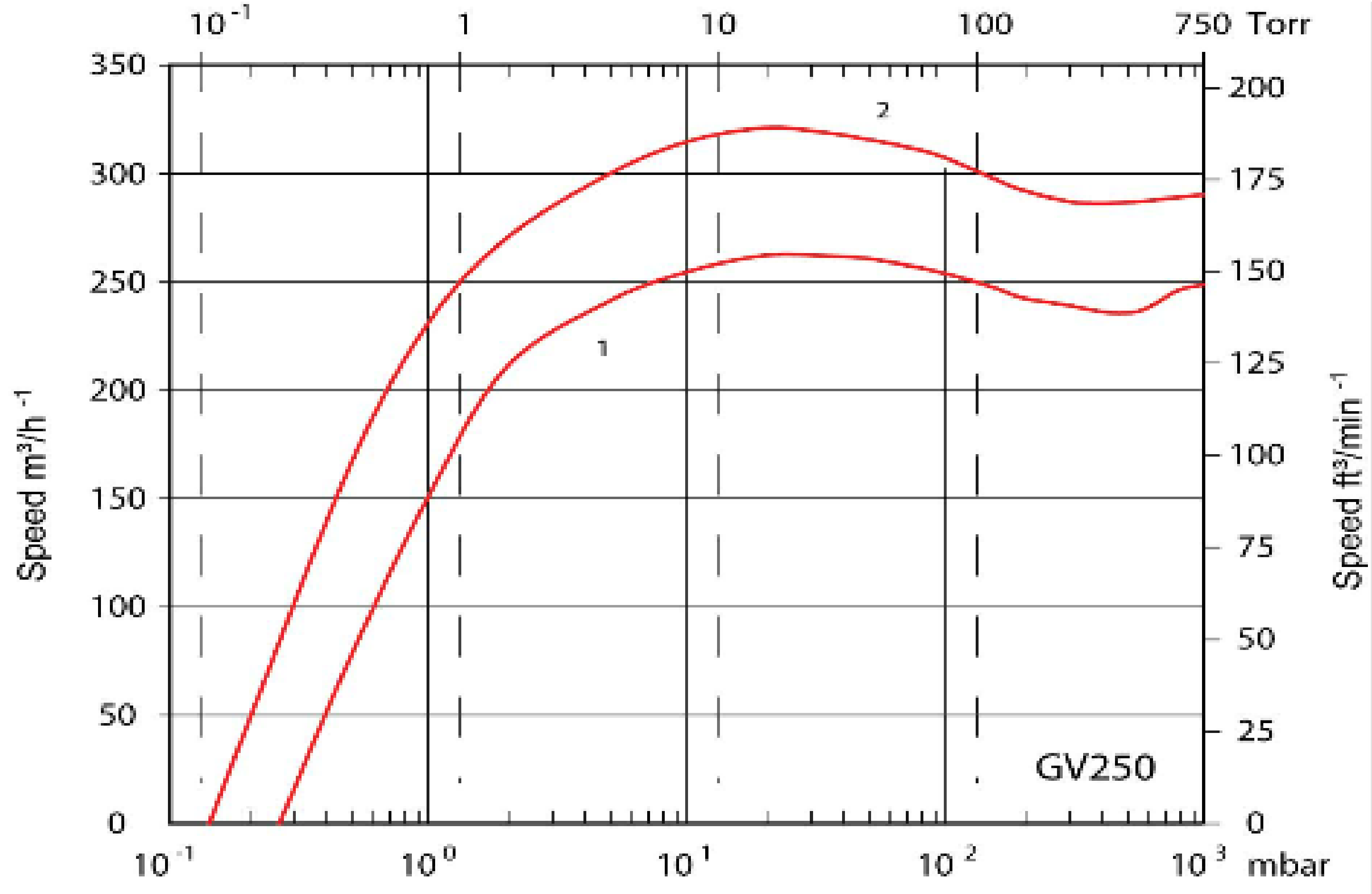


Claw Pumps – Principle



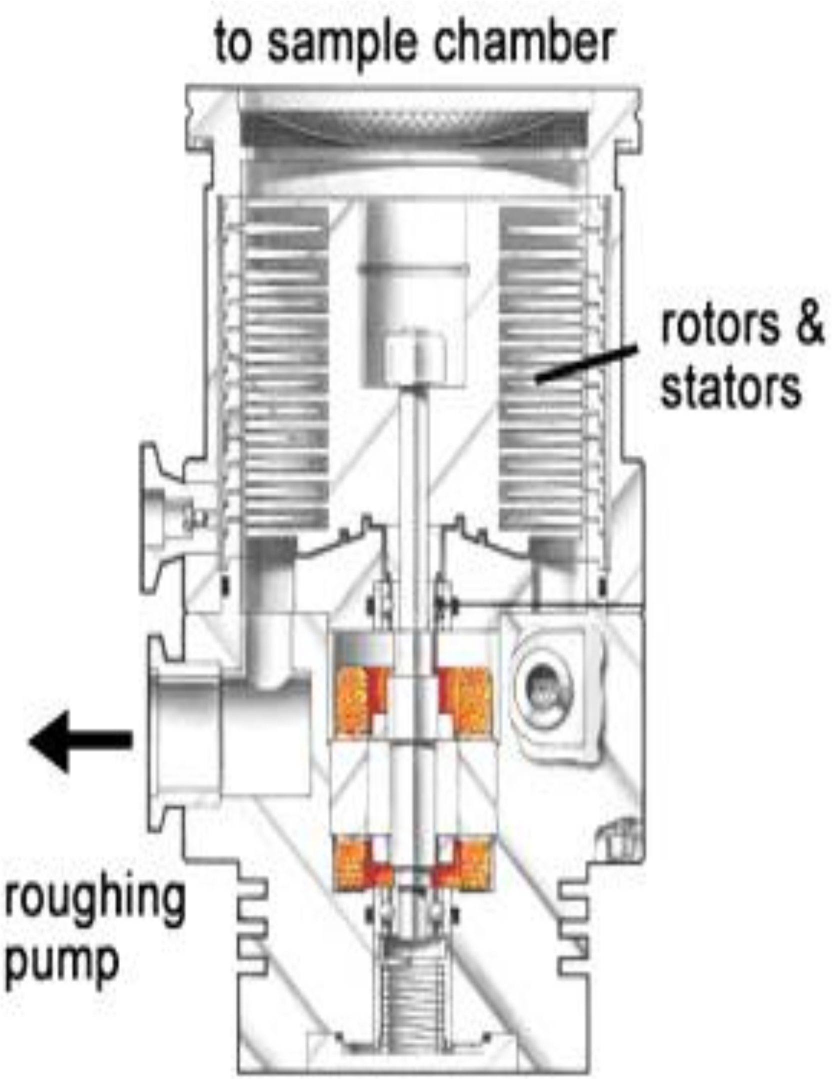
1 Rotors
2 Compression chamber
3 Intake space
4 Exhaust slot
5 Intake slot
6 Intermediate stage purge gas

Claw Pumps – Typical Parameters



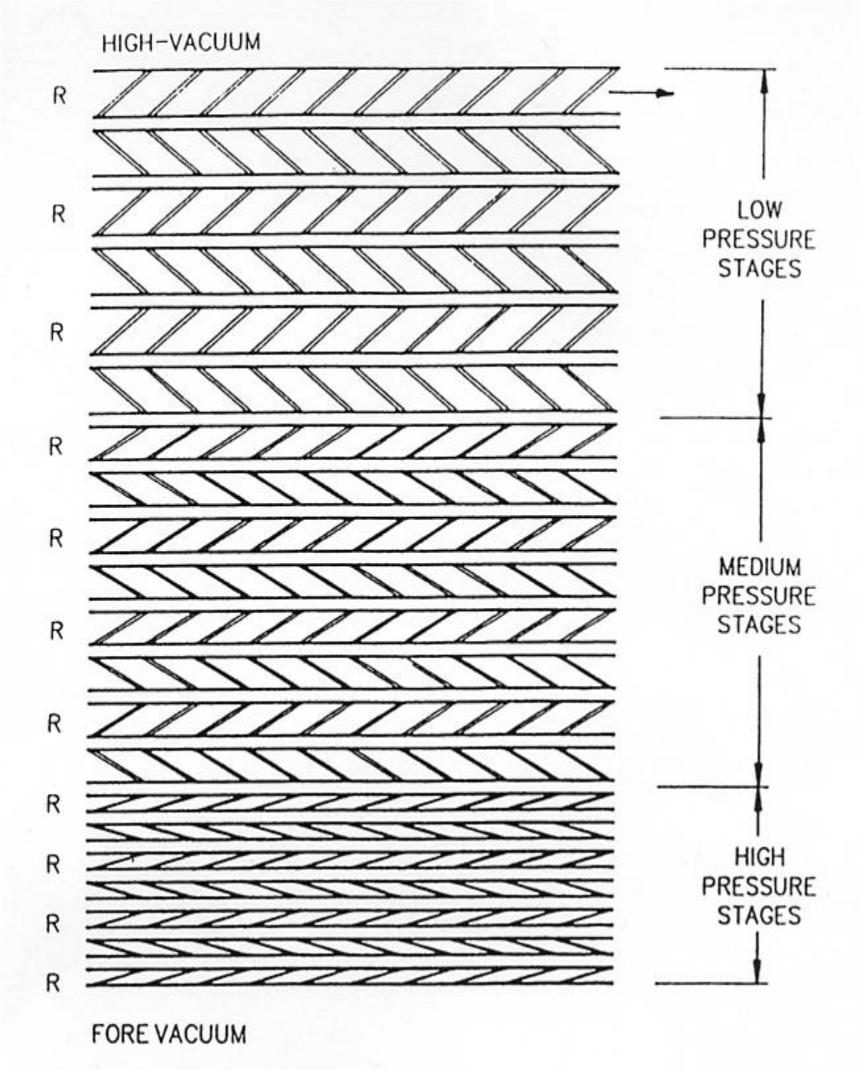
Turbomolecular Pumps (TMPs)

- TMPs are axial compressors designed for pumping gases in the molecular flow regime. So a backing pump is required.
- The gas molecules are transported towards to for-vacuum via momentum transfer from the rotating blades.
- Operation range: 10^{-2} to 10^{-11} torr
- Pumping speed: 10 to 10,000 l/s
- TPMs are throughput pumps, meaning infinite pumping capacity
- Blade rotation speed ranges from 14,000 to 90,000 rpm – making them mechanically vulnerable



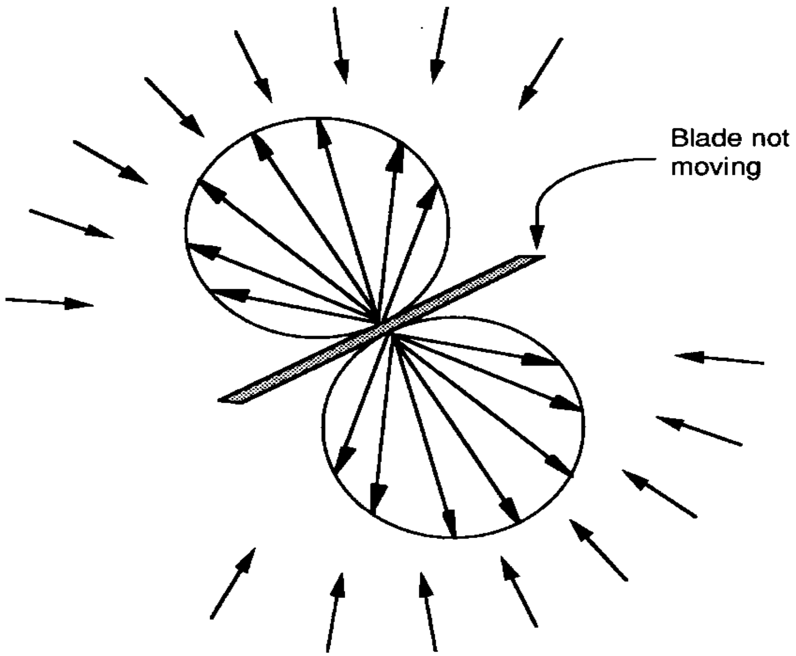
Turbomolecular Pumps (TMPs) Cont.

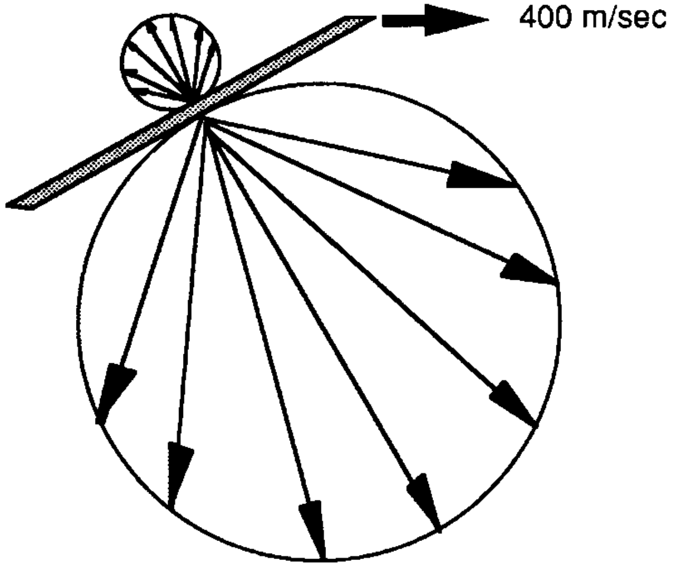
- *Axial compressor type pumps are very flexible designs:*
  → *# of stages*
  → *Various blade angles*
  → *Hybrid pumps*
- *Molecular flow exists through most of a TMP; however, transient and sometimes viscous flow occurs at the pump discharge.*
- *The key parameter of TMPs is compression ratio, which is gas mass dependent.*
- *Typical Compression ratios:*
  → N_2 – $10^8 \sim 10^{10}$
  → He - $10^4 \sim 10^7$
  → H_2 – $10^3 \sim 10^6$



TMP Pumping Mechanism (1)

- Rotating pump blades accelerate gas molecules in a preferred direction.
- To achieve effective compression, the blade tip speed needs to be comparable to the mean velocity of the gas molecules

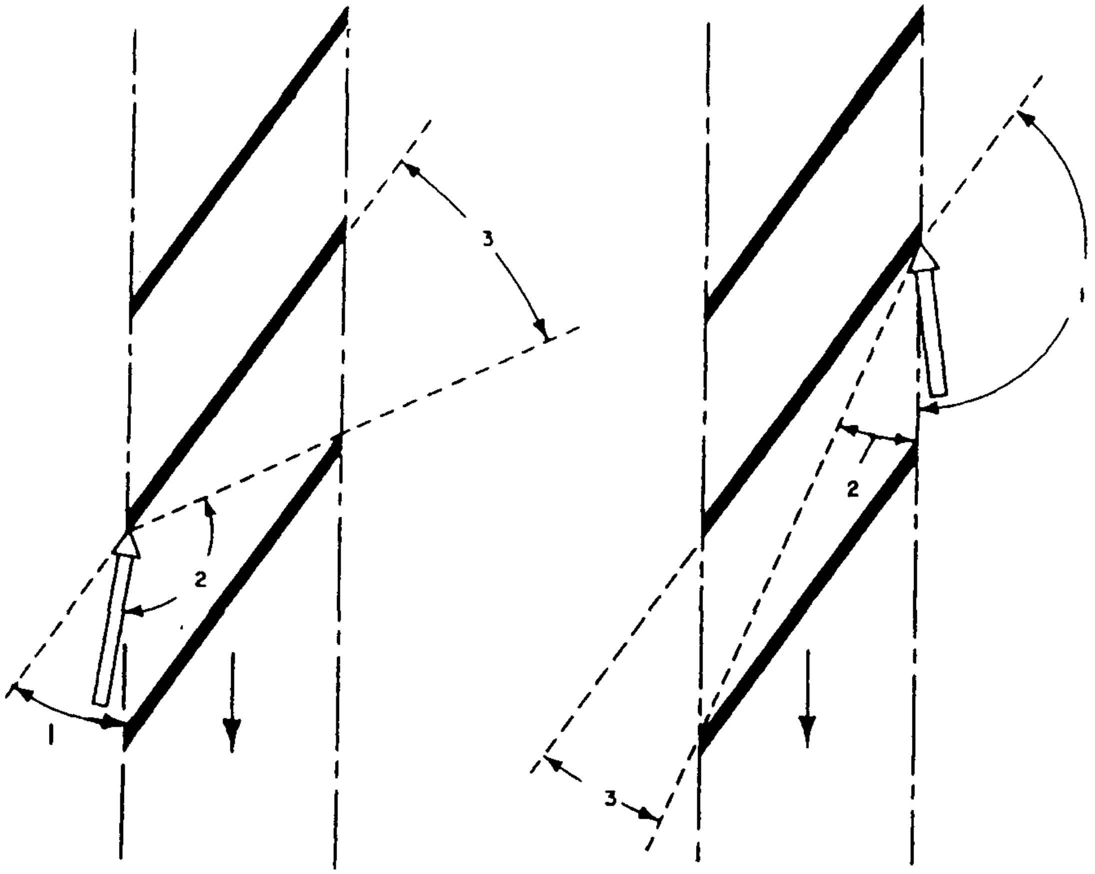




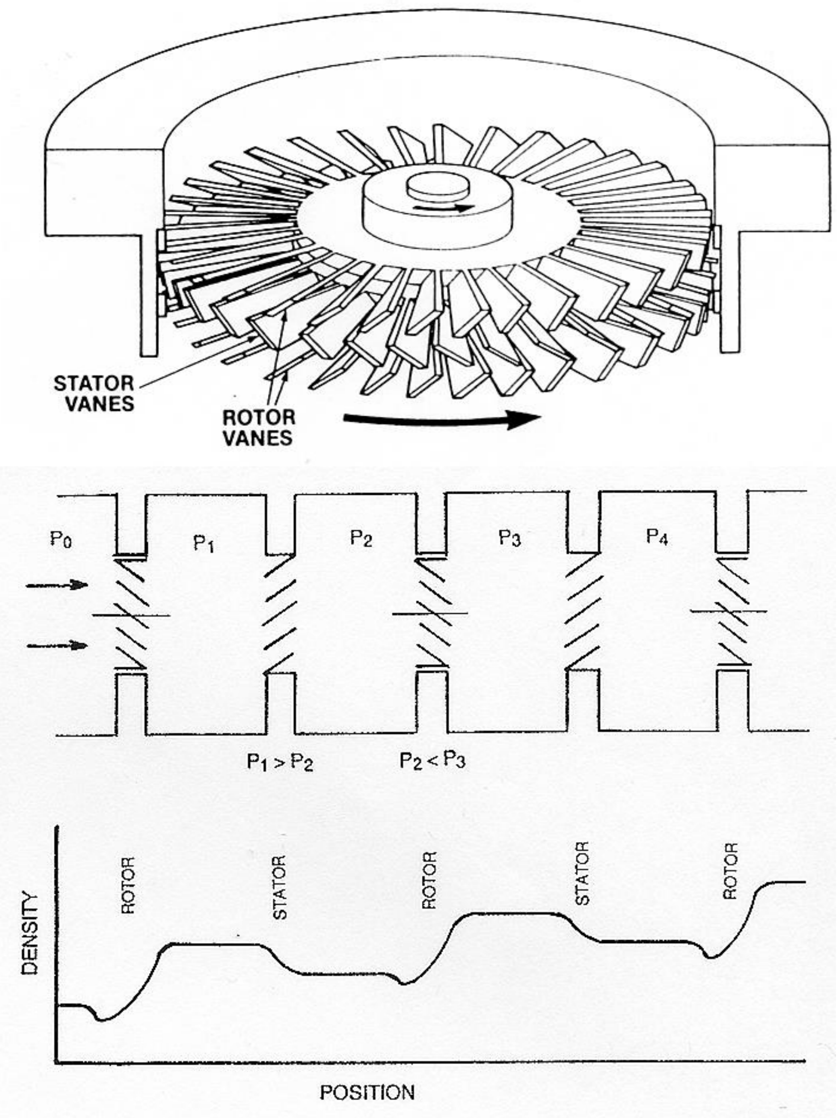
Velocity distribution from moving blades

TMP Pumping Mechanism (2)

- Another way of looking at it, is to consider the rotors as moving "chevron baffles". Their relative movement gives the baffles a higher conductance in one direction over the other.
- Steep rotor blade angles produce higher conductances, which produces higher pumping speeds.
- Shallow rotor blade angles produce higher compression ratios.



TMP Pumping Mechanism (3)



- The stator plays a complimentary role to the rotor.
  1. The stator thermalizes the gases, and
  2. Increases gas pressure without creating too much of a conductance limitation.
- The stator does it's job in as short a distance as possible.
- Rotors and stators are considered as a "pair" making up a "stage".

TMP Compression Ratio and Speed

Gas flow through TMP blades:

$$\boxed{F_1 W = F_1 a_{12} - F_2 a_{21}} \Rightarrow \boxed{\frac{F_2}{F_1} = \frac{a_{12}}{a_{21}} - \frac{W}{a_{21}}}$$

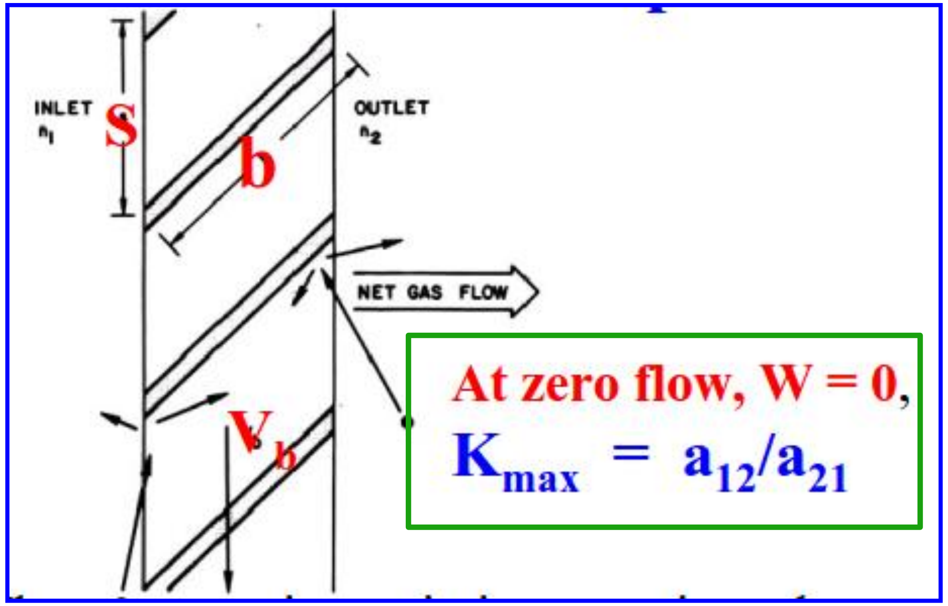
where, $F_{1/2}$: molecular flux at inlet/outlet
a_{12}: gas transmission probabilities from inlet-to-outlet
a_{21}: gas transmission probabilities from outlet-to-inlet

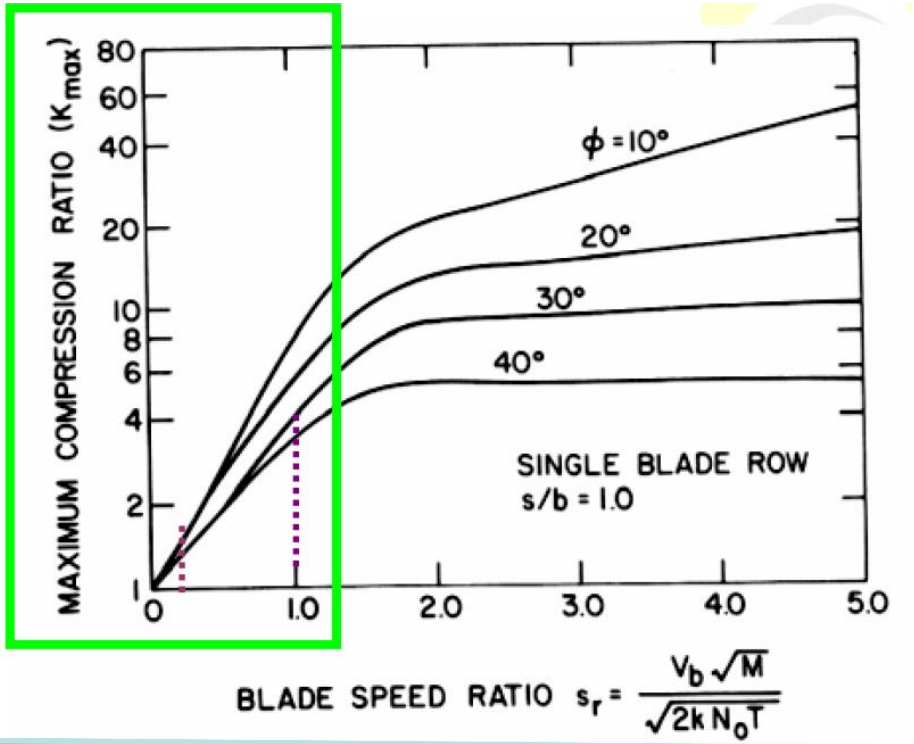
W: Ho coefficient, the ratio of net flux to incident flux

At uniform temperature, $\boldsymbol{F_i = P_i}$, the compression ratio $\boldsymbol{K}$

$$K \equiv \frac{P_2}{P_1} = \frac{F_2}{F_1} = \frac{a_{12}}{a_{21}} - \frac{W}{a_{21}}$$

TMP Maximum Compression Ratio – I





Using Monte Carlo method, Kruger & Shapiro calculated K_{max} *as function of*

→ *the blade angle (ø),*
→ *the blade spacing-to-cord ratio (s/b),*
→ *the normalized blade speed* $s_r = v_b/v_p$*, for single-stage (*v_p *is most-probable molecular speed).*

TMP Maximum Compression Ratio – II

- *"Flat" blades (small ø) yield higher compression ratio*
- *Compression ratio increases with blade speed exponentially up to molecular thermal speed, and levels off when $v_b \gg v_{rms}$.*

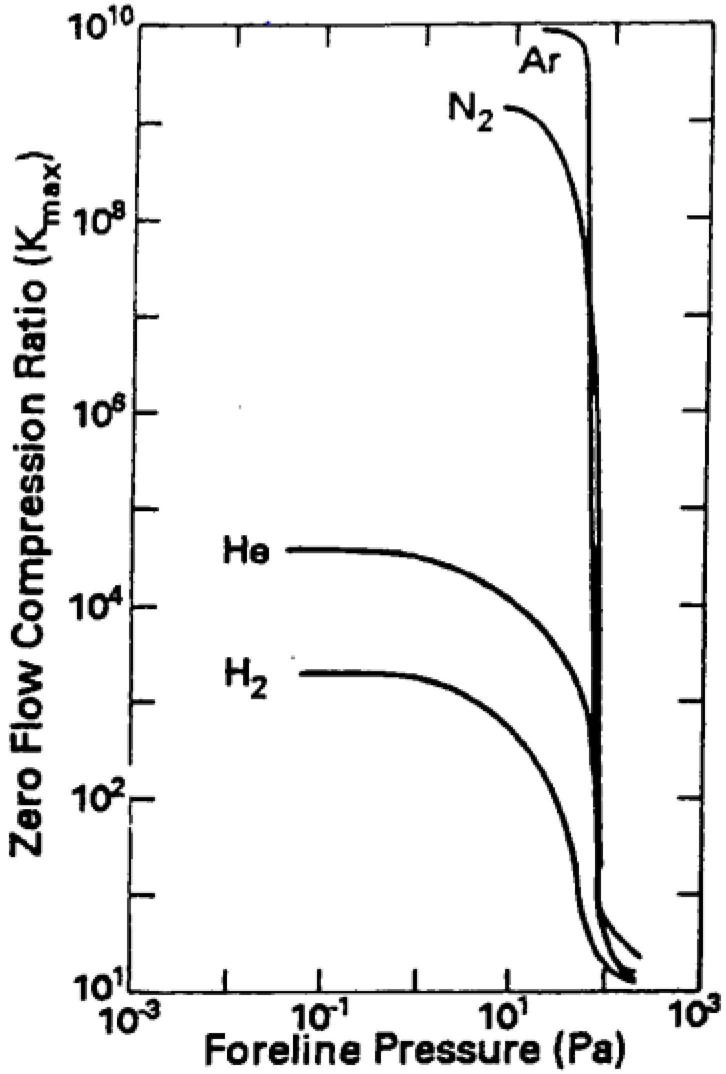
$$K_{\max} \propto \exp\left[\frac{v_b}{\sqrt{2kT/m}}\right] = \exp\left[\frac{v_b}{v_p}\right] \qquad (s_r \leq 1.5)$$

- *Outer edges of the blades contribute more with higher linear speed*
- *Compression ratio is also exponentially dependent on $m^{1/2}$.*

Example: *s/b=1, v_b(tip)=400 m/s, ø=30°*

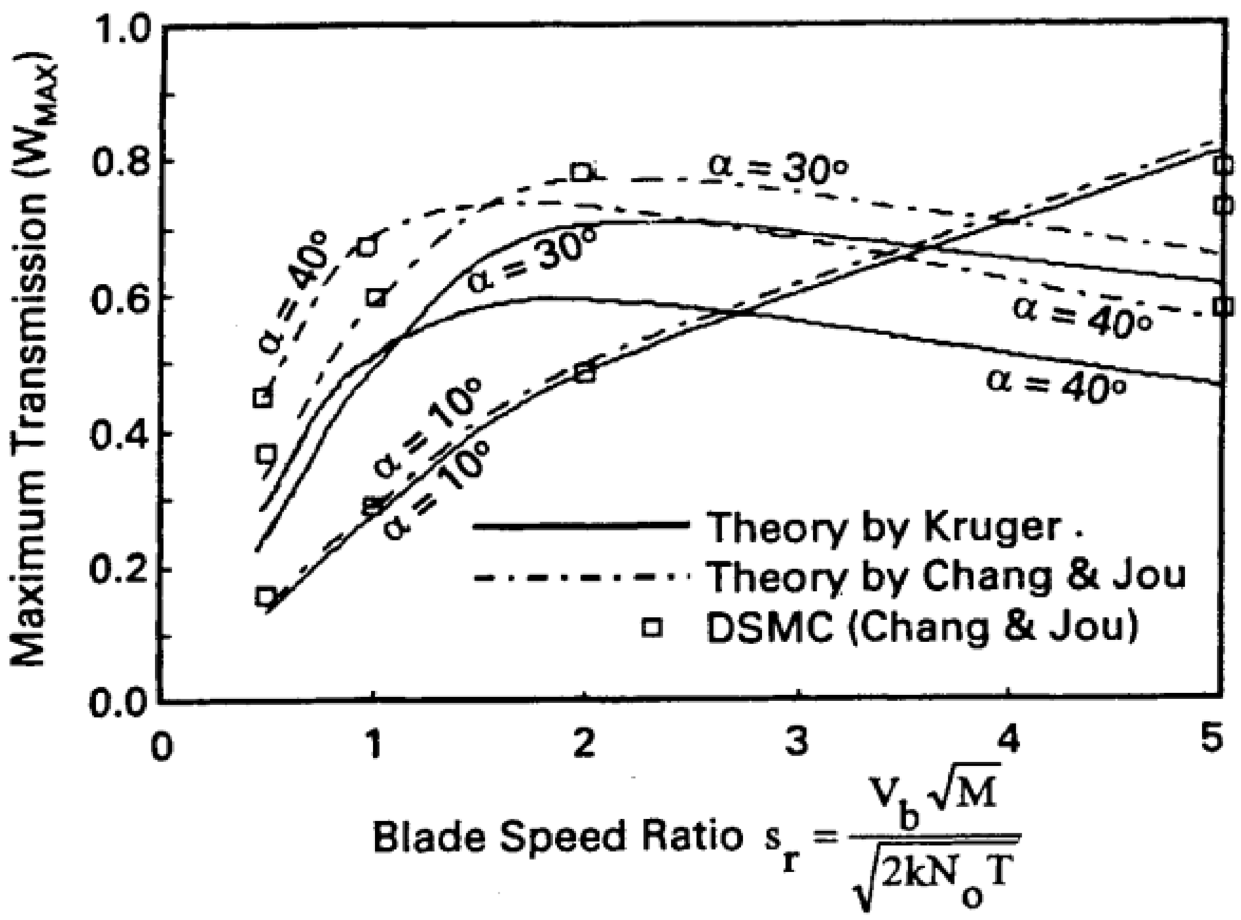
Gas Molecules	K_{max}		
	Single Stage	10-Stage	15-Stage
H_2	1.6	~100	~1000
Ar	4	~10^6	~10^9

TMP Maximum Compression Ratio – III



- *Experimentally measured compression ratios for a Pfeiffer TPU-400 pump*
- *In a blanked-off condition, gas is admitted to the foreline*
- *The measured compression ratio is the ratio of foreline pressure to inlet pressure*

TMP Maximum Pumping Speed – I



Kruger & Shapiro: (When K=1)

$$\boxed{W_{max} = a_{12} - a_{21}}$$

Chang & Jou [*JVST A19 (2001), p2900*]:

$$\boxed{W_{max} = \frac{a_{12} - a_{21}}{1 - a_{21}}}$$

TMP Maximum Pumping Speed – II

At $s_r \leq 1$ (or $v_b \leq v_p$) :

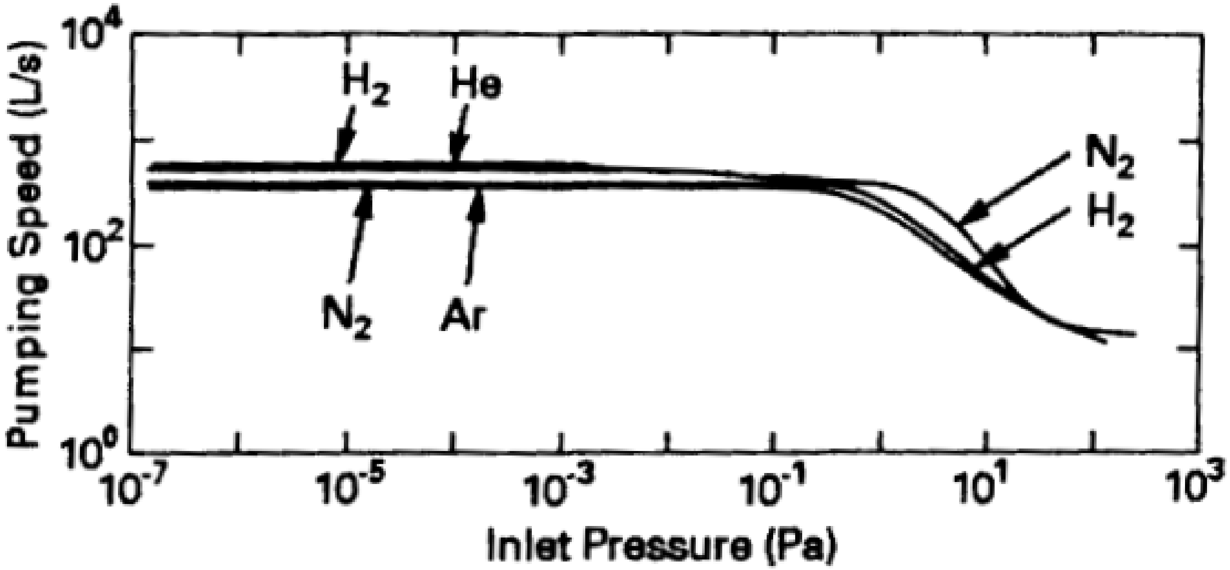
$$W \propto \frac{v_b}{\sqrt{2kT/m}}$$

Since pumping speed $S = F_1 \times W$
and molecular arrival rate $F \propto (kT/m)^{1/2}$

$$S \propto v_b$$

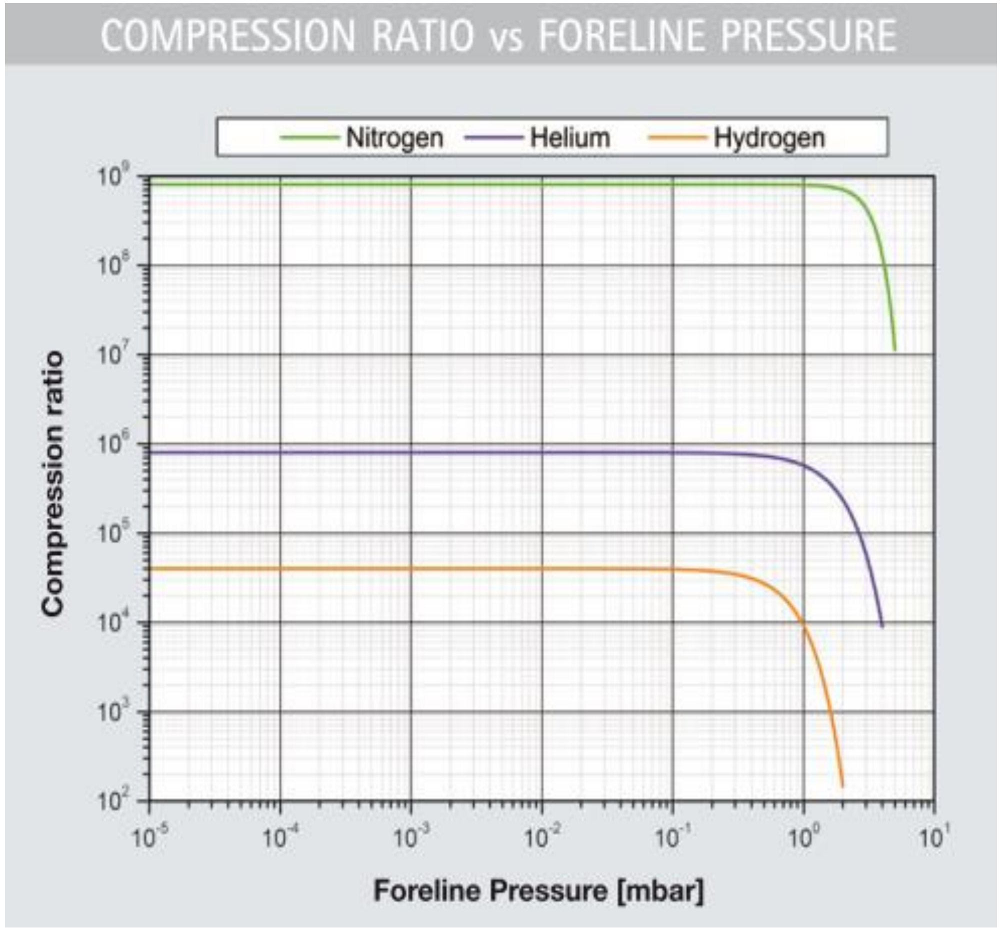
Thus TMP pumping speed is independent of type of gases and inlet pressure (in molecular-flow region)

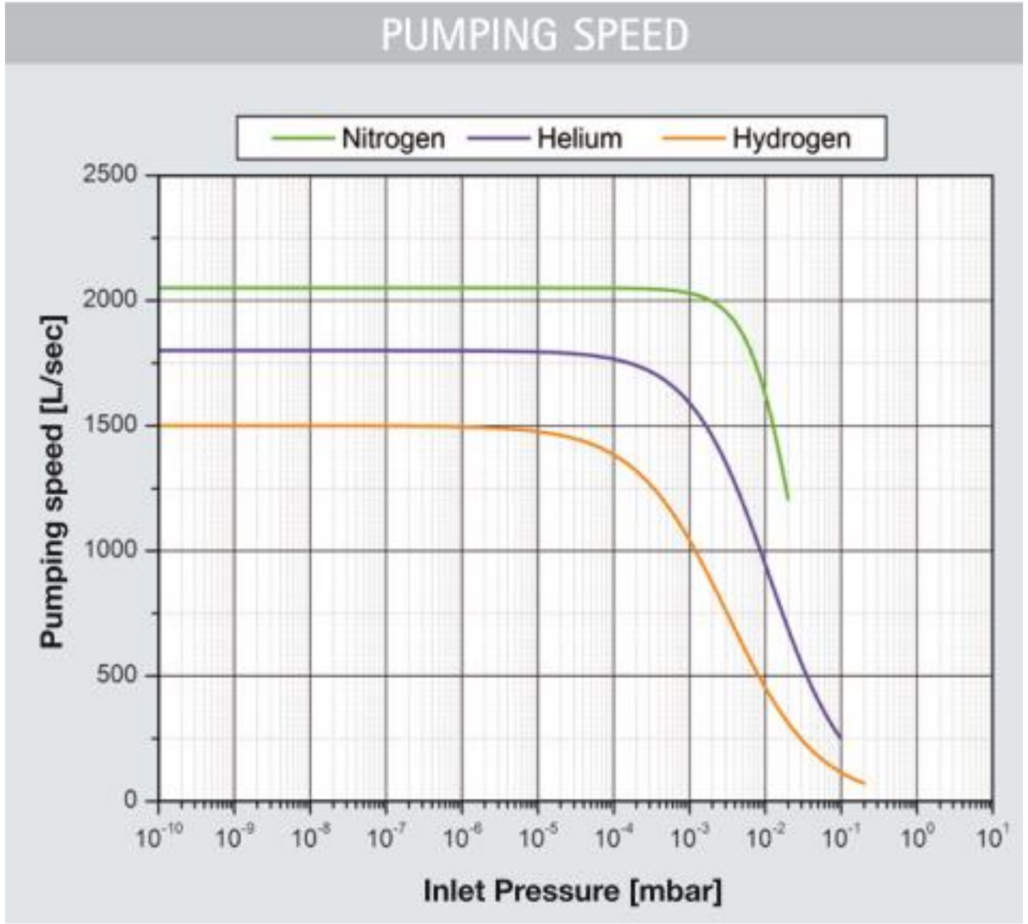
Measured Pumping Speed of Pfeiffer TPU-400 TMP



TMP Pumping Characteristics

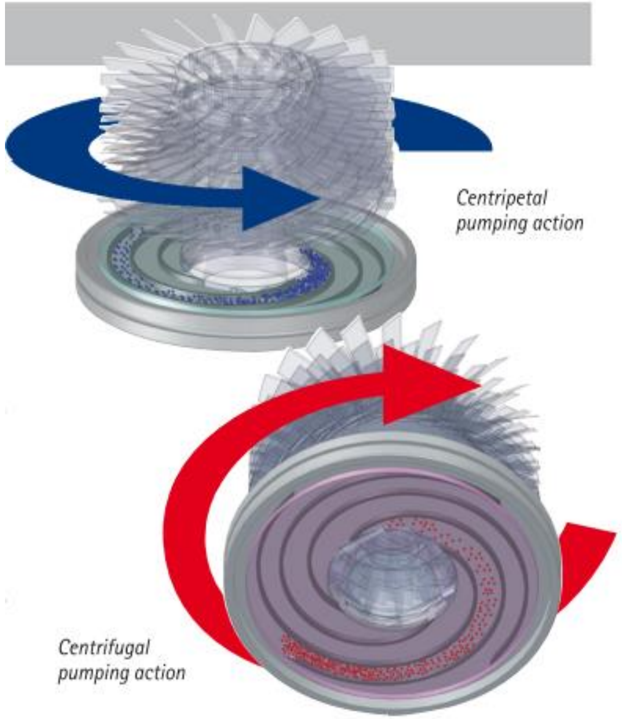
- Constant compression ratio (k) and pumping speed (S) for inlet pressure up to 10^{-5} torr.
- TMPs favor heavier gases. k has much stronger dependence on molecular mass, as compared to S.

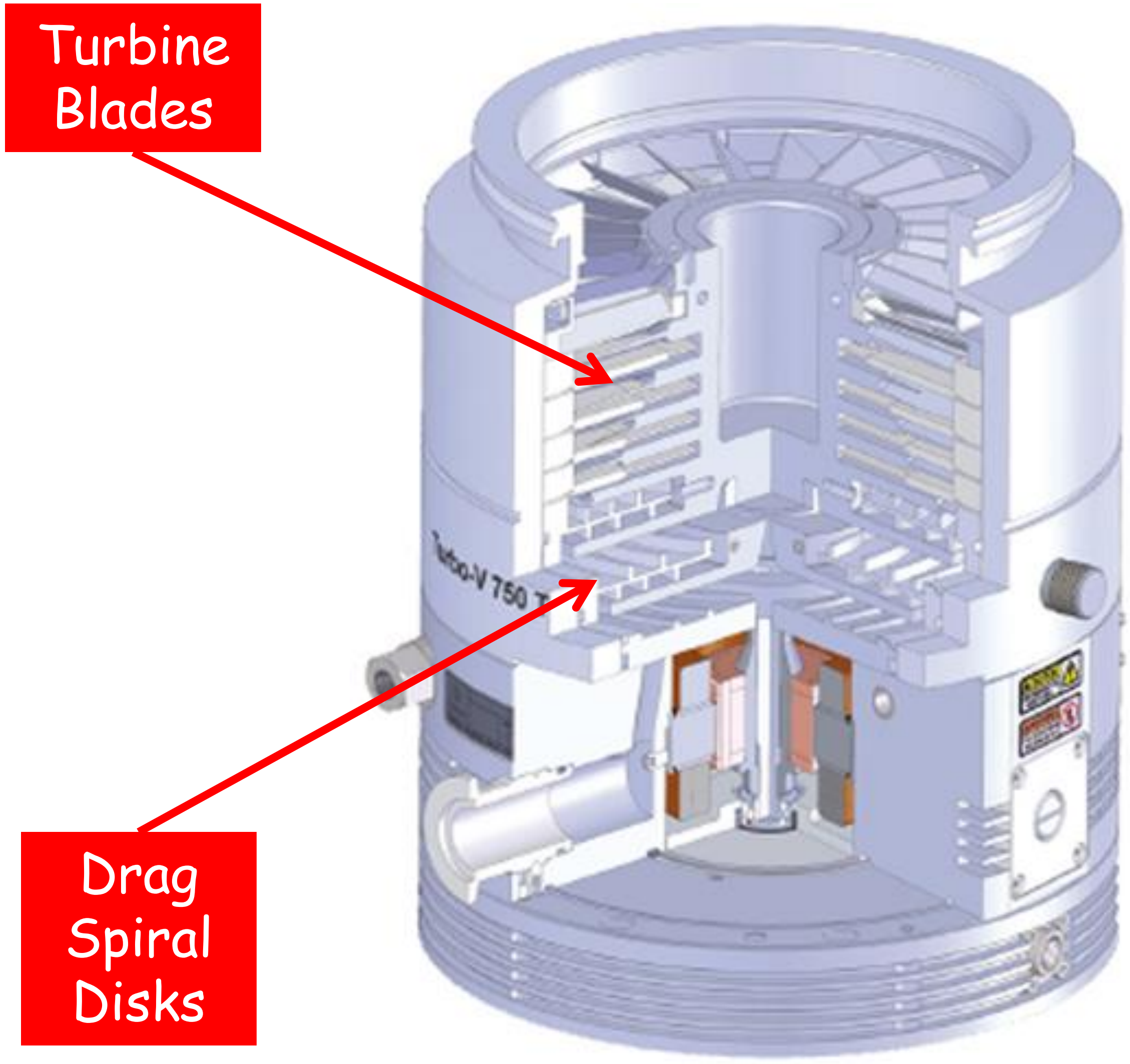




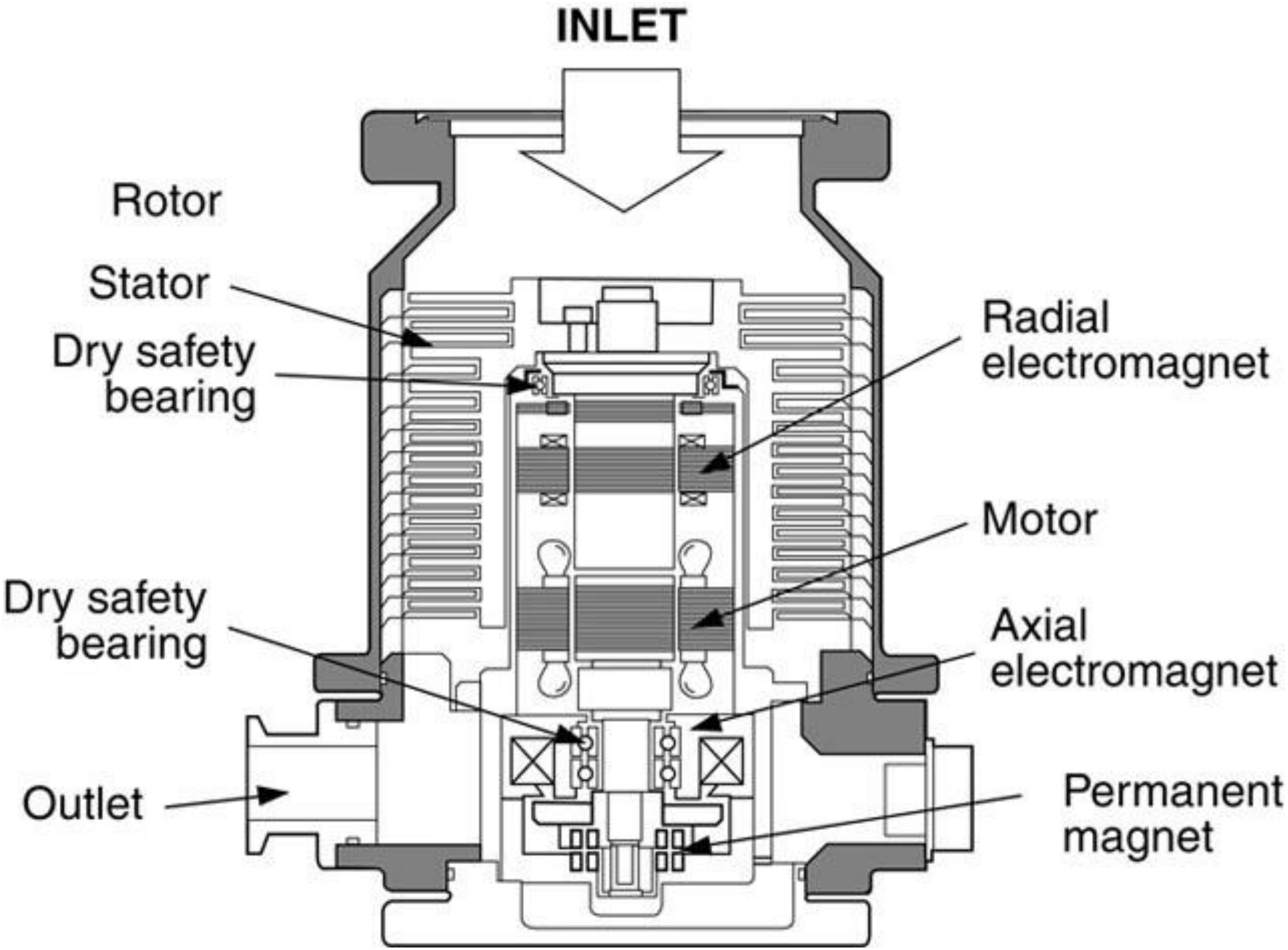
Hybrid TMPs with Molecular Drag Stage

- Most modern TMPs are combined with a molecular drag stage to in crease compression ratio.
- For the hybrid TMPs, backing pressure can be as high as ~ 1 torr.





TMPs – Drives and Bearings



TMPs – Types of Bearings

- *Typical turbine rotation speed range from 36,000 rpm for large TMPs, to 72,000 rpm for small TMPs. Such high speeds naturally raise questions as to a reliable bearing designs.*
- *There are three types of bearings from most TPM vendors*

> *Oil lubricated / steel ball bearings*
>
> \+ Good compatibility with particles by circulating oil lubricant
> -- Can only install vertically
> \+ Low maintenance

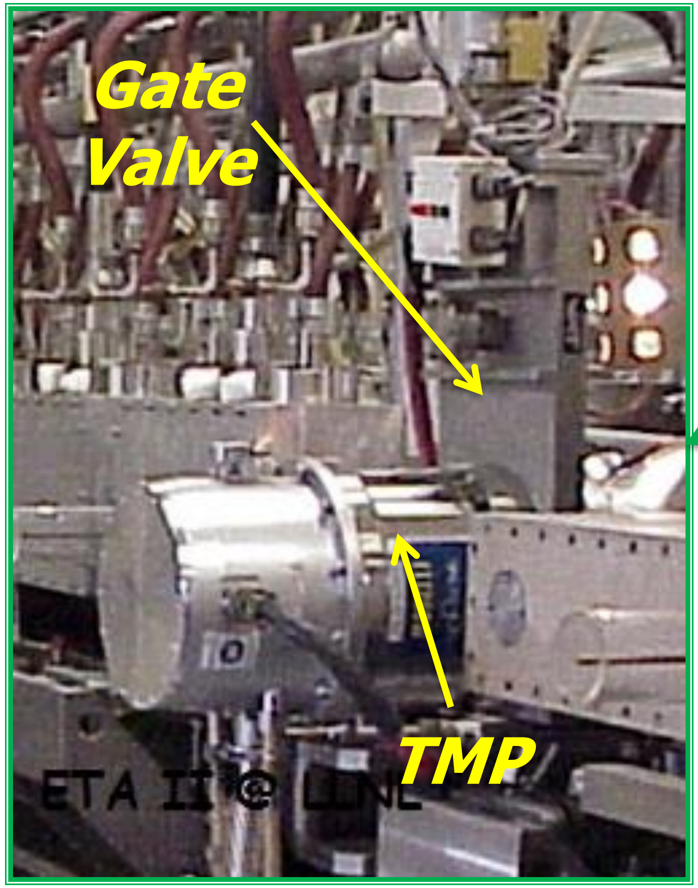
> *Grease lubricated / hybrid bearings*
>
> \+ Installation in any orientation
> \+ Suited for mobile systems
> \+ Lubricated for life (of the bearings)
> \+ Need cooling (forced air or water)

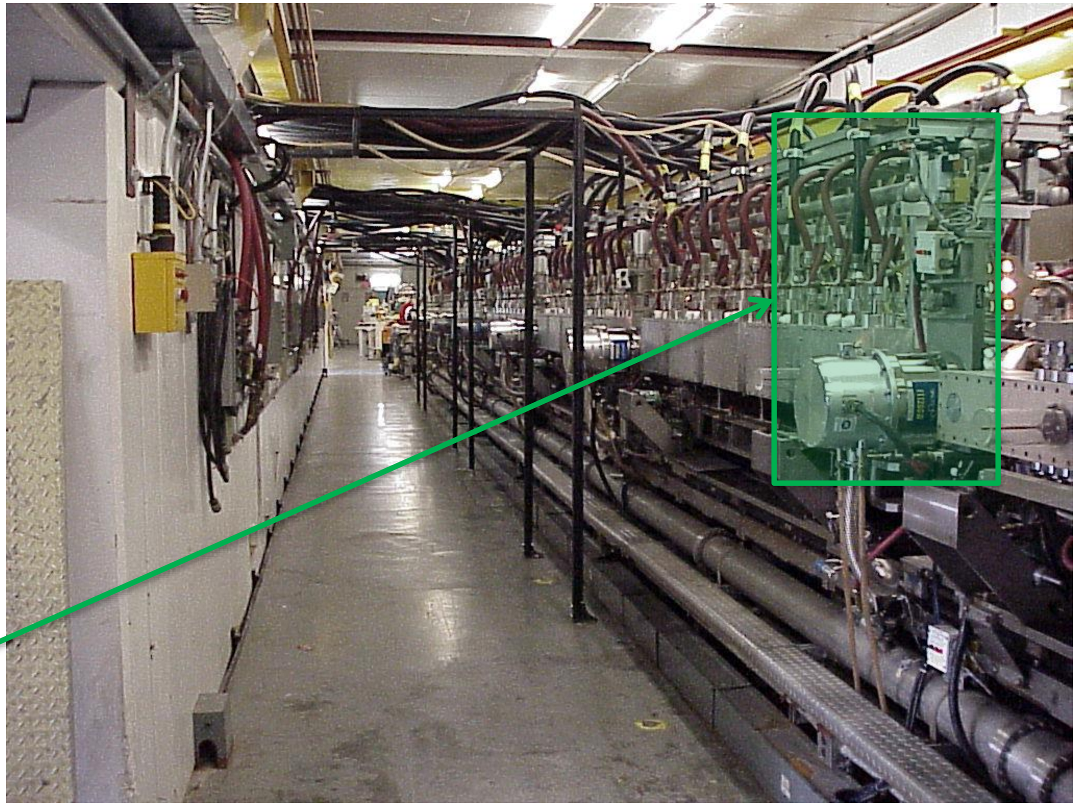
> *Free of lubricants / Magnetic suspension*
>
> \+ Installation in any orientation
> \+ Absolutely free of hydrocarbons
> \+ Low noise and vibration levels
> \+ No wear and no maintenance

TMPs for Continuous Operations

- Though capture pumps are preferred pumps for most accelerator vacuum systems, TMPs are suitable for long-term continuous operations for accelerator vacuum systems.
- Typical applications are for system with very high gas loads (such as ion beam sources), or specific gases (such as helium, hydrogen, etc. such as insolation vacuum of cryo-modules).
- Accelerator protection system is usually implemented to handle power failures, and for routine TMP maintenances. This include pneumatically actuated gate valve that can isolate the TMP from the accelerator vacuum system. Solenoid fore-line isolation valve should also be included in the inter-lock.

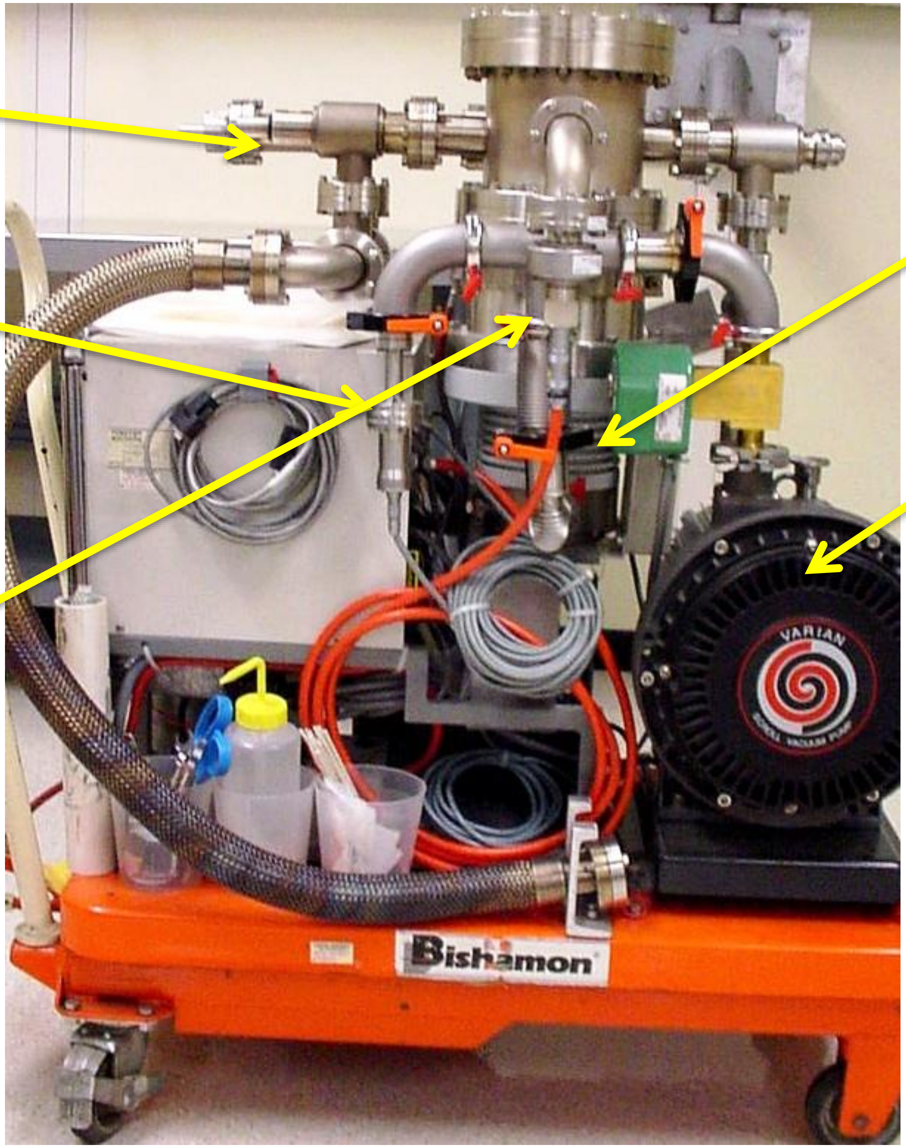
Example of a TMP Pumped Accelerator





ETA (Experimental Test Accelerator) II @ LLNL

A Typical Mechanical Pump Cart for CESR



Operating TMPs in a Magnetic Field

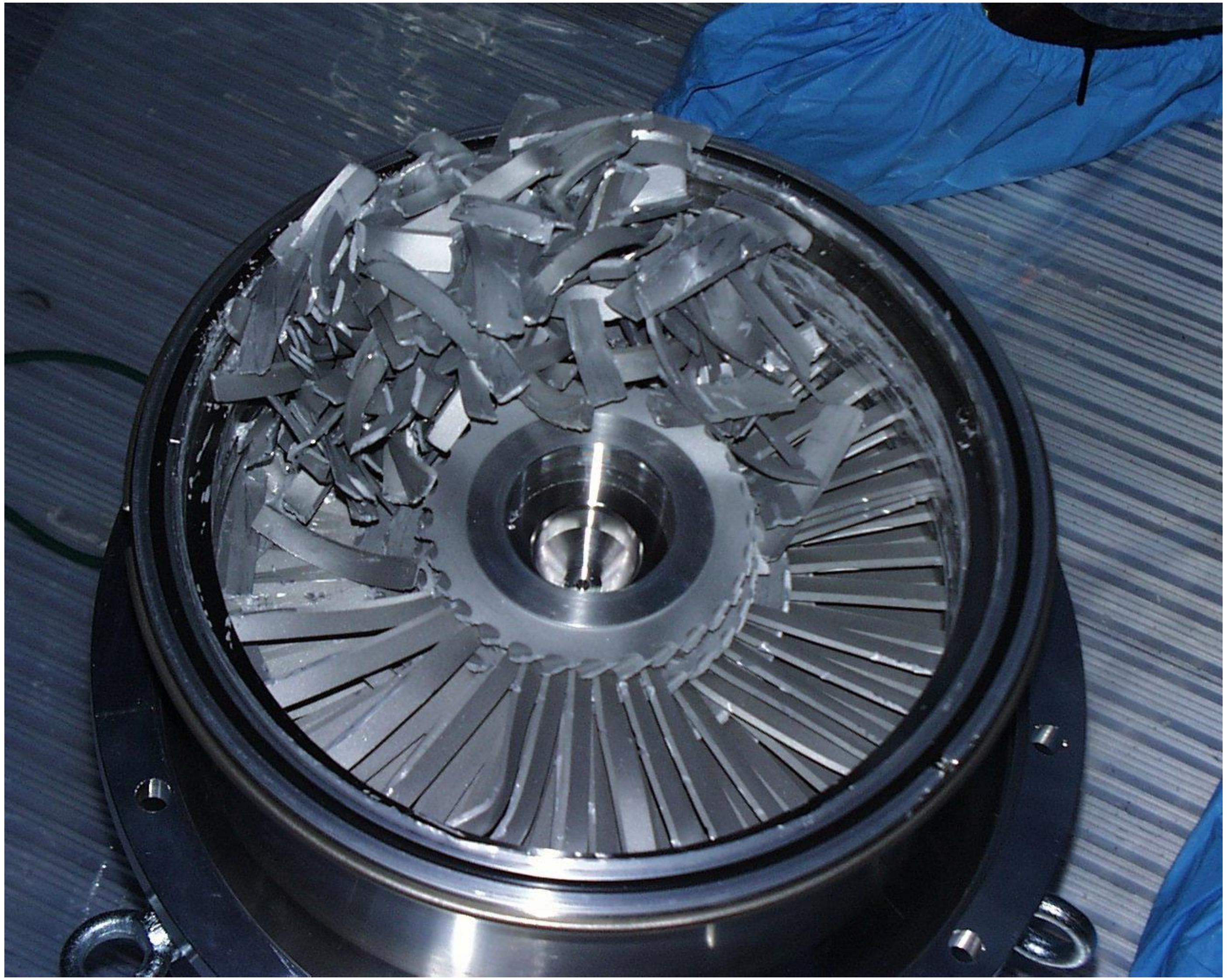
- *Magnetic fields induce eddy currents in the TMP rotor that tend to oppose its rotation. As a consequence the power delivered to the electrical motor is increased.*
- *Since the TMP's rotor is not in contact with the stator (and the TMP housing), all the heat generated by the eddy currents must be dissipated by radiation, so the rotor can be overheated even if the static parts remain cool.*
- *Eddy-current power loss, i.e. the amount of energy transformed by the eddy-current into heat is:*

$$W \sim \frac{B^2 \times f^2}{\rho}$$

B – Magnetic field flux
f – Rotor frequency
ρ - rotor electric resistivity

Most TMPs should not operate at magnetic field > 50 Gauss
(Considering Magnetic Shielding, if needed)

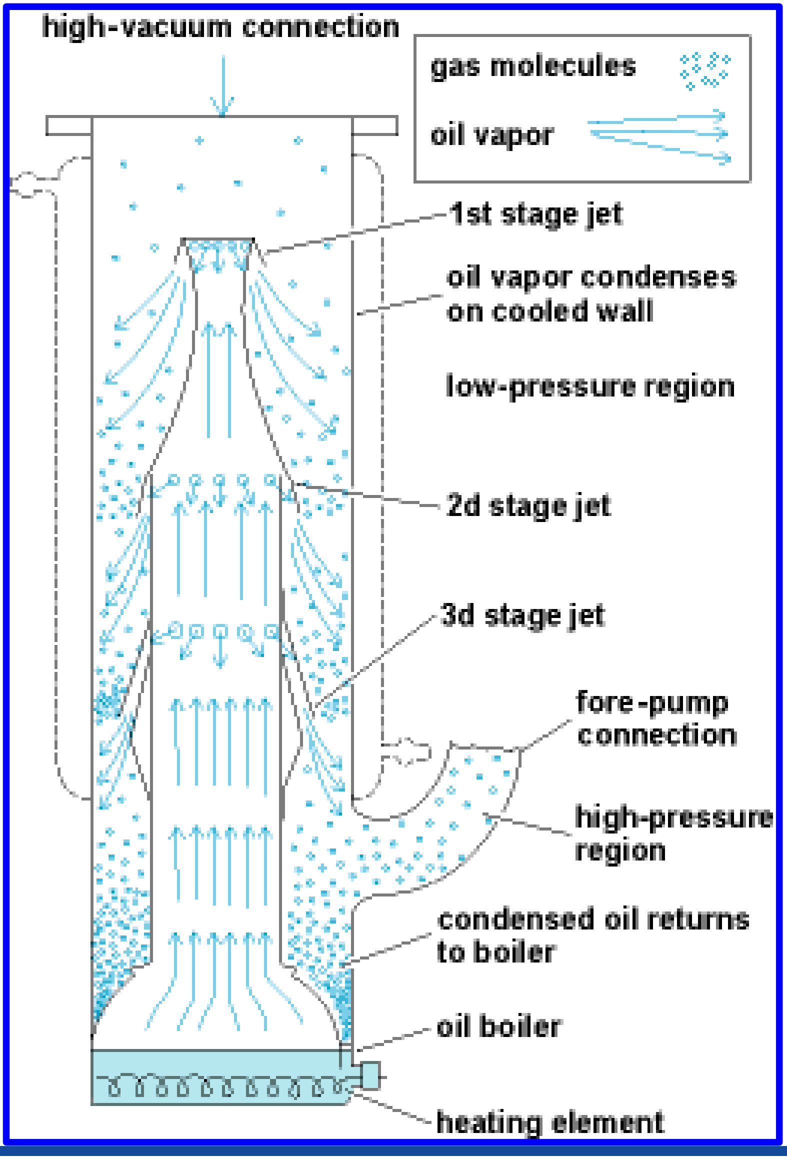
Really bad things can happen to a TMP



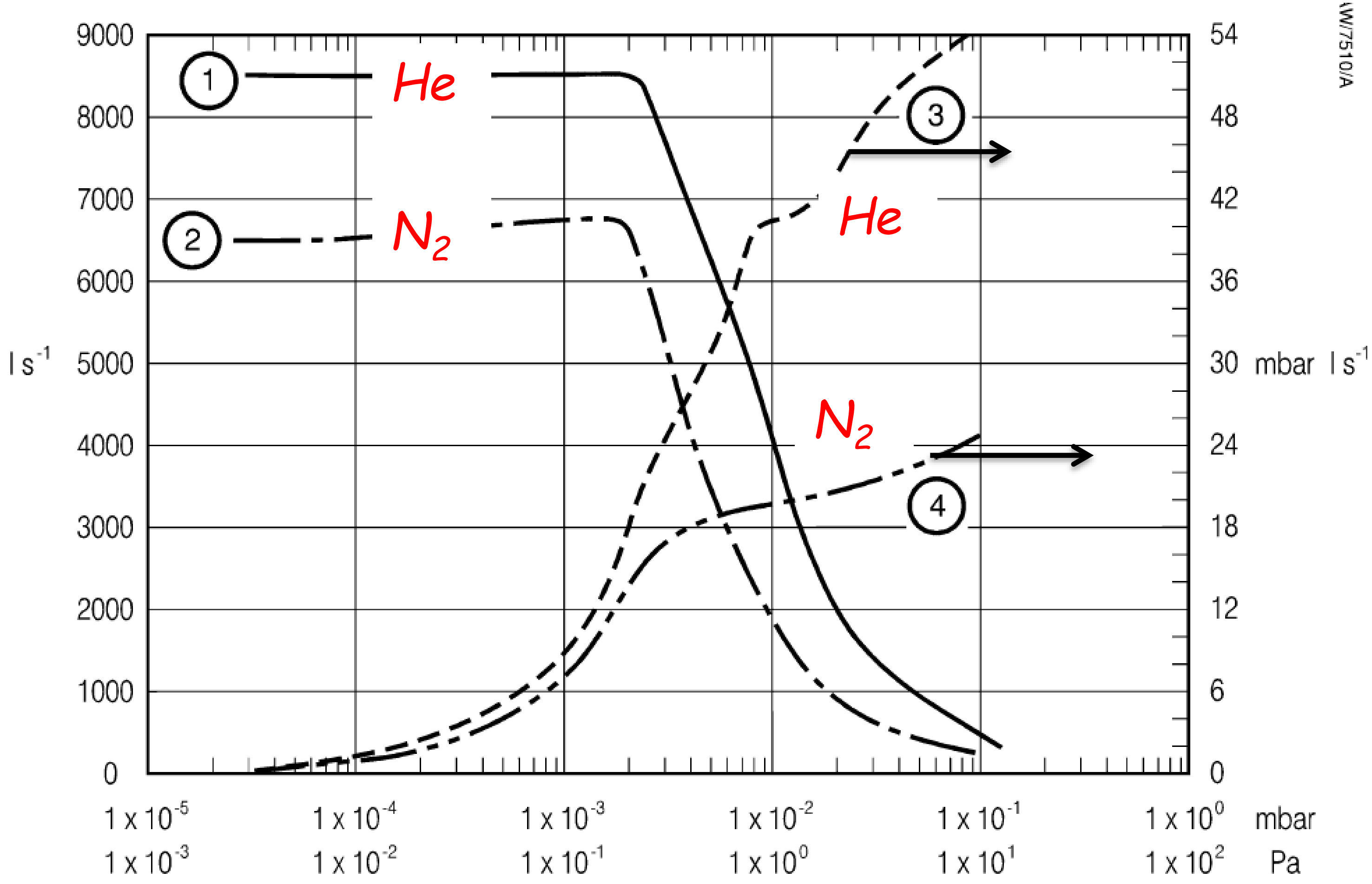
Use an inlet screen !

Diffusion Pumps

- *A diffusion pump is a vapor jet pump, which transports gas by momentum transfer on collision with the vapor stream.*
- *Commonly used pump fluids are hydrocarbons and fluorocarbon.*
- *Vapor back-stream can be a source of contamination.*
- *However, with proper cold traps, the vapor back-stream can be minimized significantly, so it can be used for HV and UHV systems.*
- *Diffusion pumps are extremely reliable, and require minimum maintenance. For example, for CESR's booster (the Synchrotron), we needed oil change every 30 years!*



Diffusion Pump Characteristics



Unlike TMPs, diffusion pumps favoring light gases