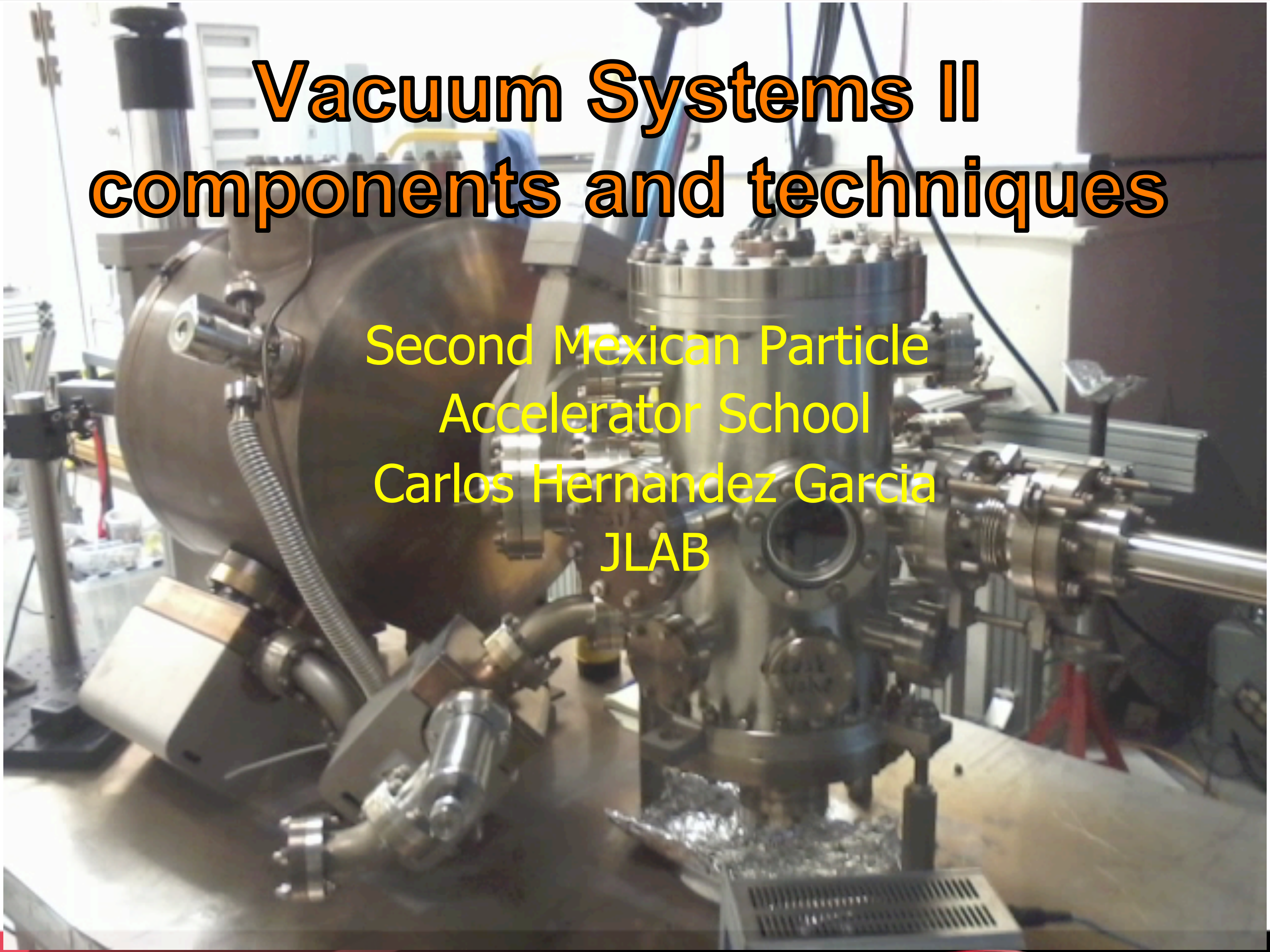
Vacuum Systems II components and techniques



Second Mexican Particle Accelerator School

Carlos Hernandez Garcia
JLAB

Outline

- The purpose of the vacuum system
  - Defining the required vacuum level
  - Defining the functions of the vacuum system
- The vessel
  - Vessel shape and dimensions (is it a box? Is it a tube?)
  - Material choice
  - Surface preparation
  - Surface cleaning
  - Interacting with the outside world: Viewports, feedthroughs, manipulators, etc.
- The pumping methods to achieve the desired vacuum level
  - Pumping mechanisms
  - Types of pumps and pumping speeds
  - Maintaining the vacuum level

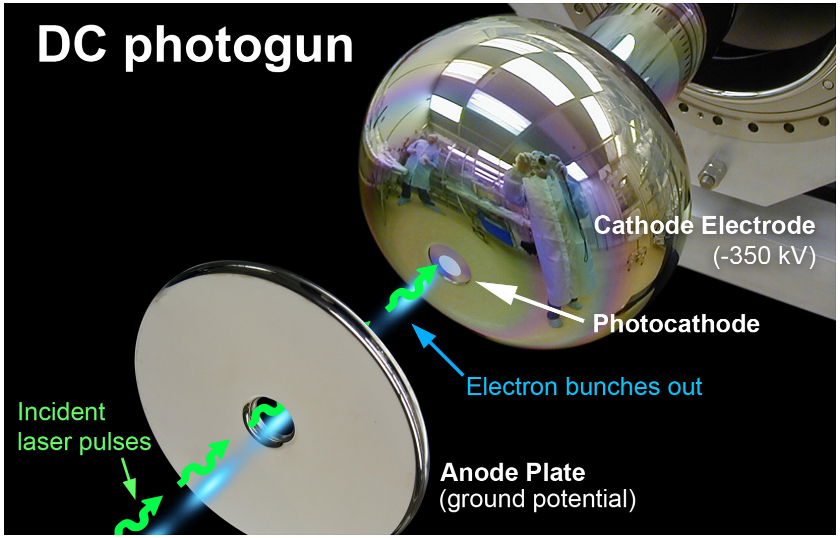
Outline

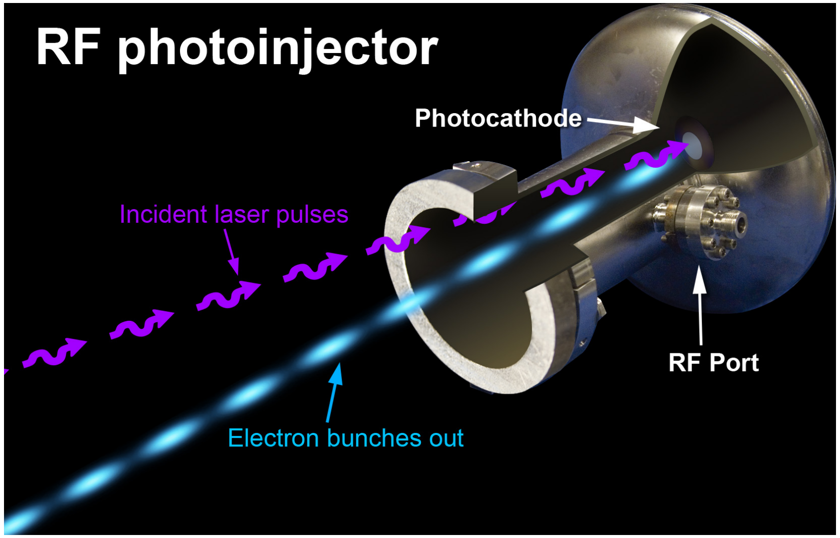
- Characterizing vacuum
  - The gauges (vacuum measurement)
  - Searching for leaks
  - Residual Gas Analysis
- Ultra High Vacuum techniques
- Resources and vendors

Defining the purpose of the vacuum system in accelerator applications

- Starting with the electron gun, vacuum is needed to prevent cathode contamination and to avoid electron beam scattering with gas molecules.

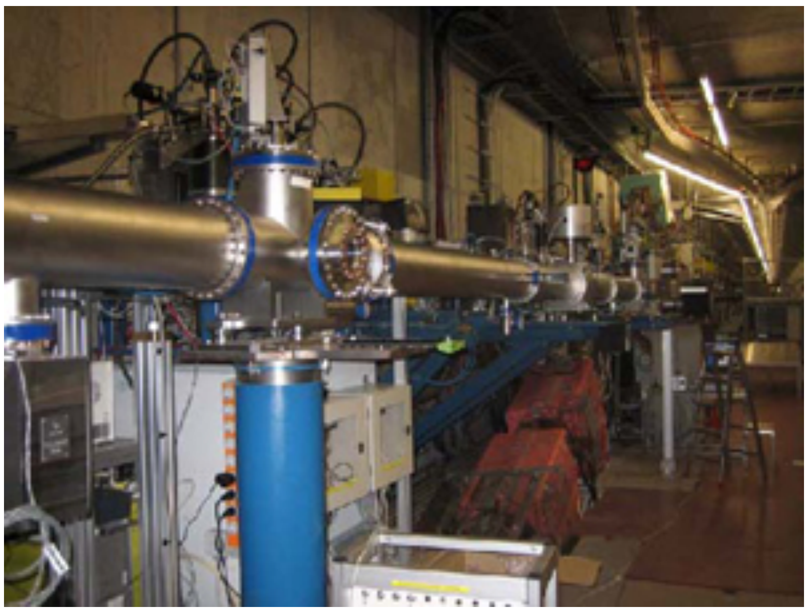
  - For example, depending on the type of electron gun, the vacuum level ranges from 10^{-6} to 10^{-9} Torr in RF guns, to 10^{-12} Torr in SRF and DC photoemission guns





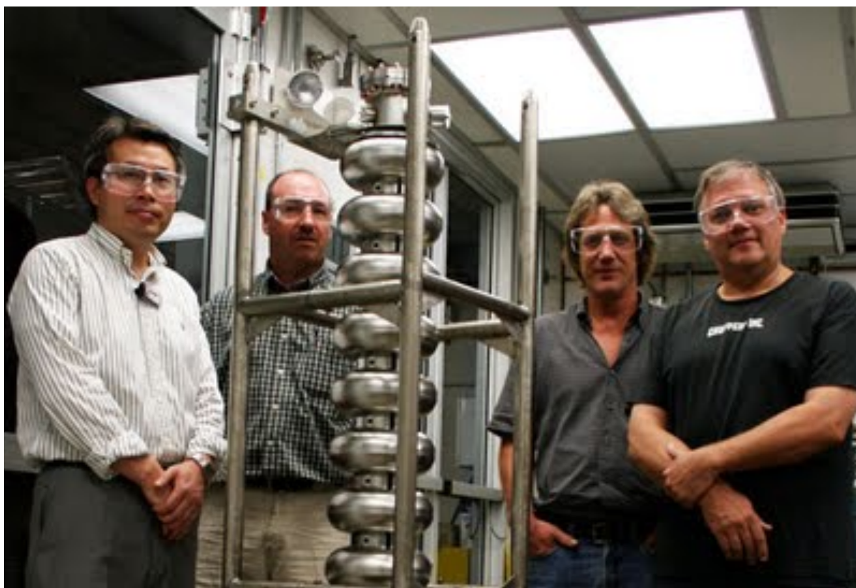
Defining the purpose of the vacuum system in accelerator applications

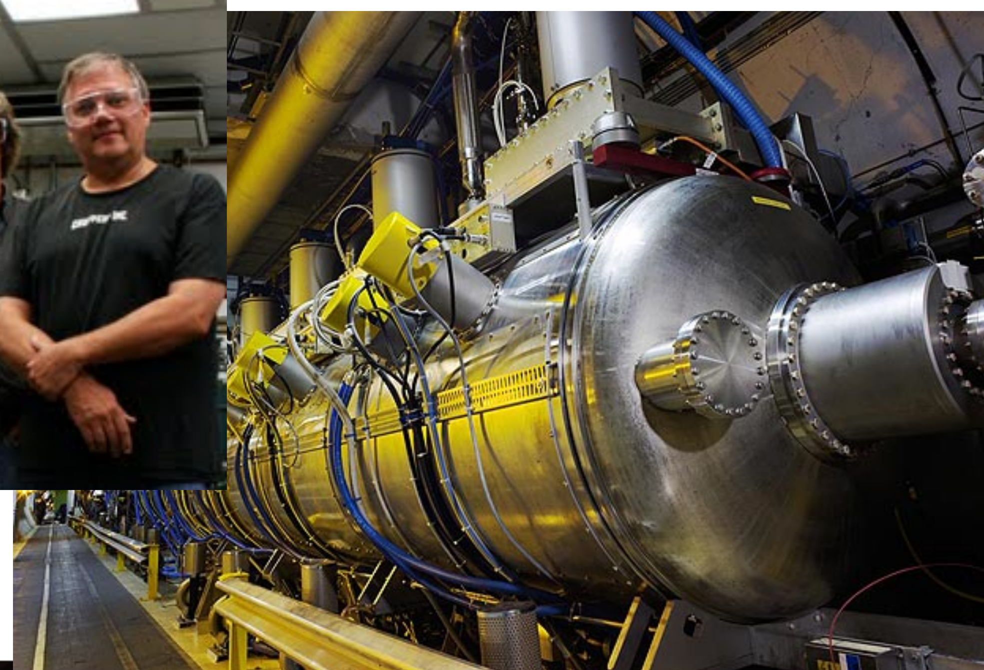
- Continuing with the transport of electron beam from the gun to the accelerating structures, the vacuum level required in the beam pipe to prevent electron beam scattering, is in the order of 10^{-8} to 10^{-9} Torr.



Defining the purpose of the vacuum system in accelerator applications

- In superconducting radio frequency accelerating structures, the vacuum level is typically 10^{-11} Torr or better thanks to the cryo-pumping action of the cold cavity. In NCRF accelerating structures like those used in most third generation light sources.



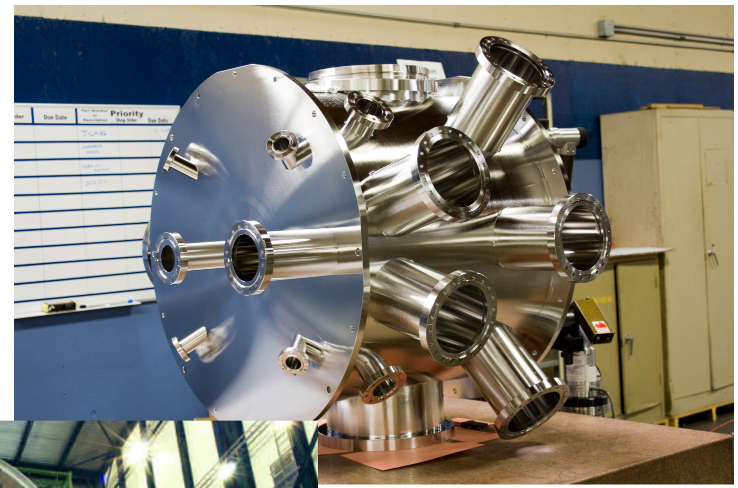


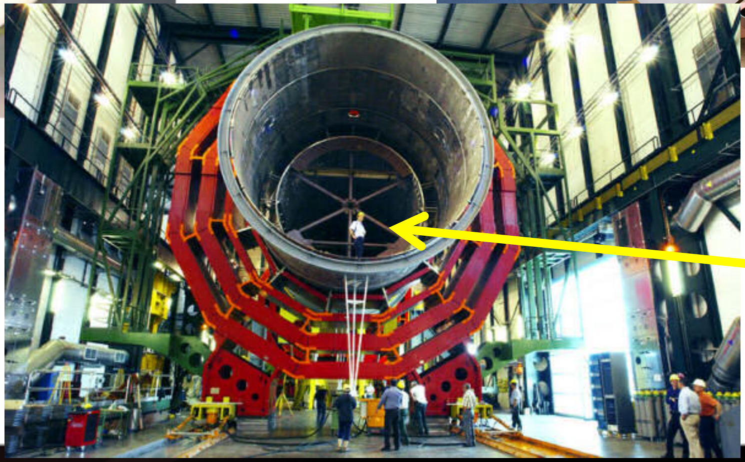
Defining the purpose of the vacuum system in accelerator applications

- In undulators and wigglers vacuum is also needed to prevent electron beam scattering, and is in the range of 10^{-9} to 10^{-10} Torr.

The vessel

- The shape, volume and surface area are some considerations to be used for defining the pumping methods.





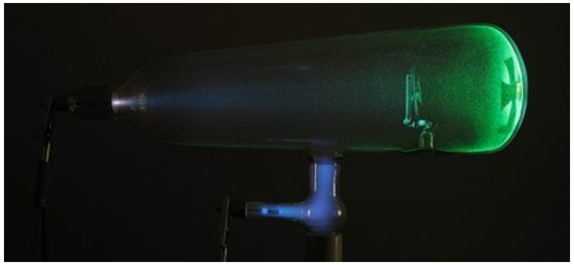
There is a person inside the vacuum chamber!

The vessel

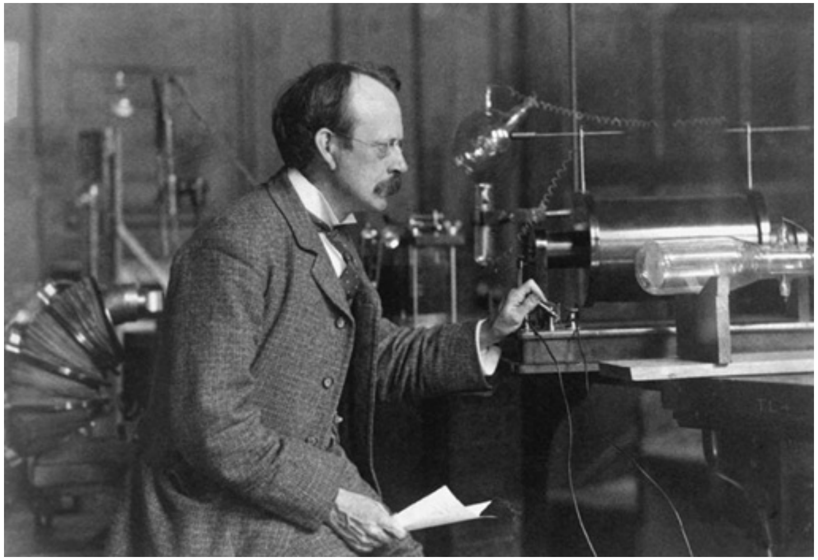
- In accelerator applications, vessel material has to be non-magnetic. *Think about why is this required?*
  - Typical material choices are stainless steel and aluminum. Accelerator structures often utilize copper for normal conducting RF, and Niobium for superconducting RF

The vessel

- The vessel material must be non-permeable, non-magnetic, have low outgassing, and be free of cracks and trapped volumes (true and virtual leaks)
- Glass would be a great example of an ideal material, if it not were for its mechanical properties…it is brittle!

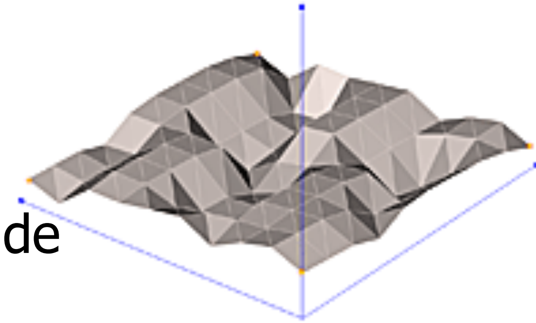


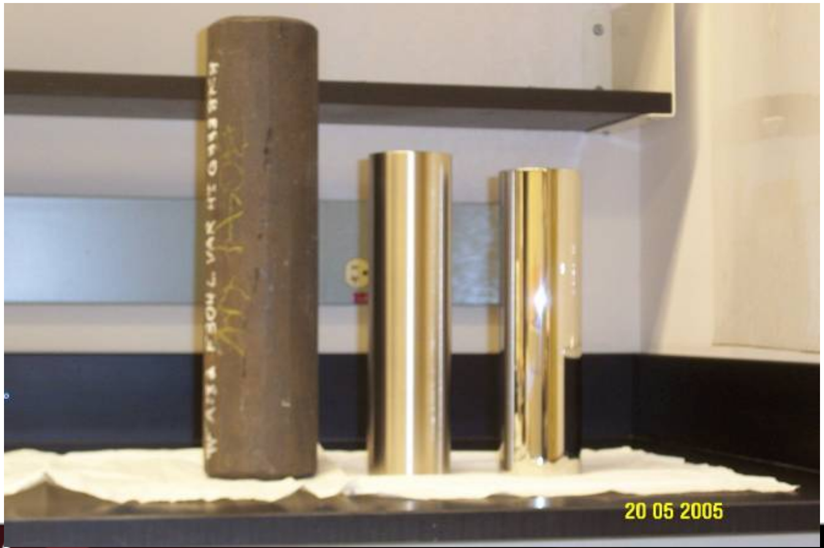
- But glass was used as the first vacuum vessel!!!

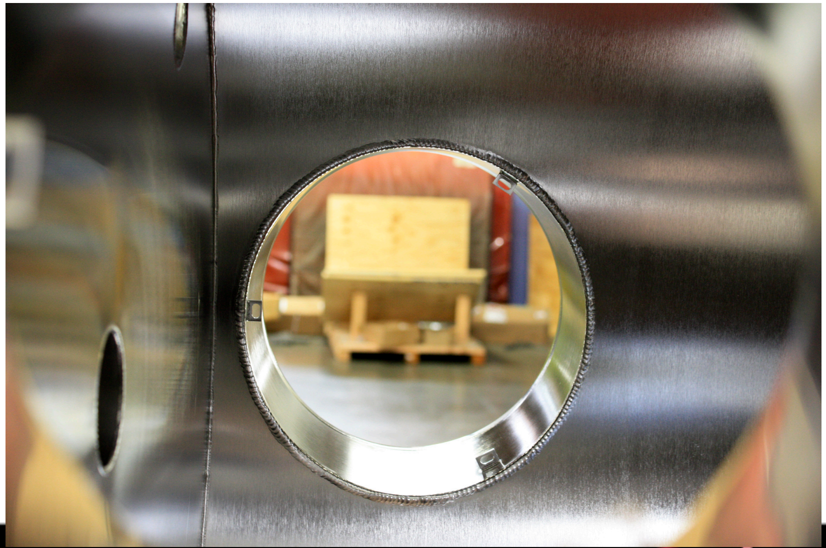


The vessel

- Surface preparation: The internal surface must be “smooth” and non-porous:
  - To minimize contamination from particulate traps
  - To minimize surface area for achieving lower vacuum levels
- For most accelerator applications, vacuum components are already fabricated with materials meeting rigorous specifications, unless custom made components are required.

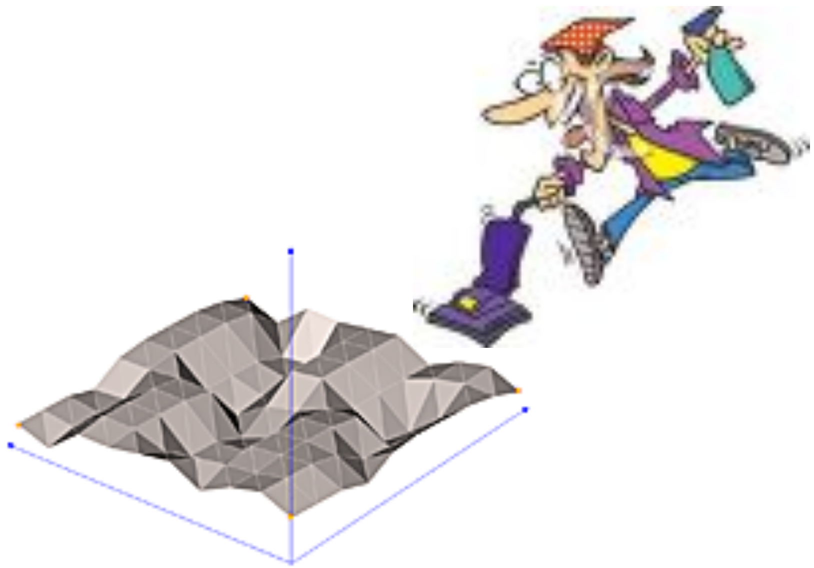






The vessel: Surface Cleaning

- Once components are chosen, surface cleaning is critical to achieving good vacuum.
- Procedures and techniques are available in the literature to achieve clean components suitable for ultra high vacuum.



Surface cleaning

- Solvents and detergents are ideal for removing hydrocarbon-based (for example, fingerprints, grease, oils) from components. There are a variety of detergent concentrates that must be diluted in filtered, de-ionized water. Typically, components are placed in a bath of this cleaning solution immersed in ultrasonic cleaners.

Typical Ultrasonic cleaner

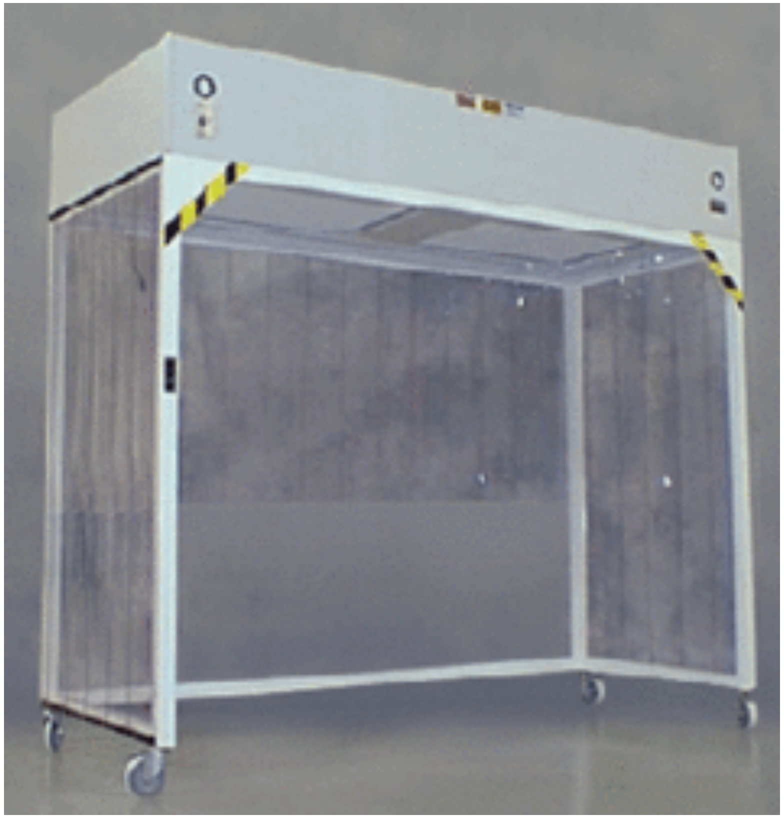
Surface cleaning

- After concentrated detergent is used, components are thoroughly rinsed in filtered, de-ionized water, then rinsed in the ultrasonic cleaner with fresh filtered and de-ionized water.

- In a fresh, clean container, the component is then rinsed with acetone in the ultrasonic cleaner.
- The above process is repeated with iso-propanol.
- The iso-propanol is easily dried off using a flow of clean nitrogen, while holding the component on a clean surface table and wearing gloves.
- Once the component is dried, it is placed in a new, clean nylon bag, and heat sealed for transport and installation.
- All tools needed for assembly and insta

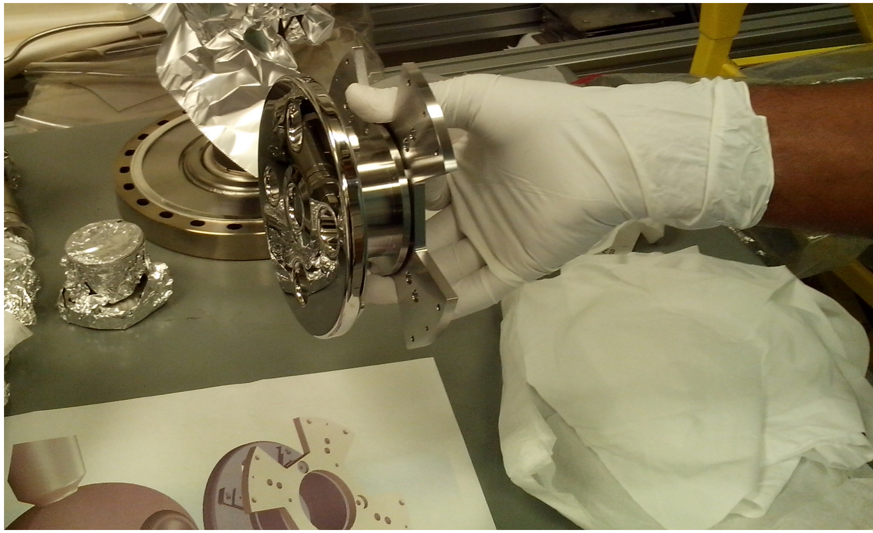
Keeping components clean

- Keep tools clean to prevent transporting contamination to clean components.
- Keep dust-free, grease and oil free working environment where vacuum components will be assembled and installed
- Portable clean enclosures with downward laminar airflow (to maintain positive pressure inside keeping dust particulates out) are ideal for most component installation in accelerators.



Keeping the components clean

- Basic principles:
  - Never touch clean vacuum components with bare hands. Skin oils will outgas preventing achievement of desired vacuum. Always use powder-free latex gloves when handling components.
  - Some components (like electron guns) require assembly and installation in full clean room enclosures, mainly to minimize dust contamination.



The vessel interacting with the outside world

- How do create a vacuum inside?
- How do we keep the vacuum?
- How do we measure and characterize the vacuum environment inside the chamber?
- What internal components are needed for its particular application, and how do we interface those internal components with the outside?
- How do we know where the electron beam is?
- How do we get the RF power inside the accelerating cavities' vacuum environment?
- How do we get laser light inside the electron gun vacuum environment?
- How do we get the generated x-ray beam outside the undulator's vacuum environment?

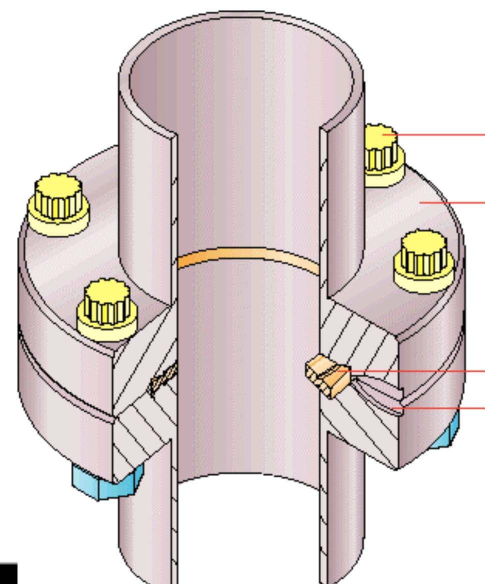
The vessel interacting with the outside world

All this translates into the capability of, and without compromising the vacuum environment

- Connecting the vacuum vessel to pumps via port with connecting flanges
- Transmitting electrical signals through the vessel walls via electrical feedthrough.
- Transmitting in or out optical (x-ray) beams via viewports.
- Maneuvering internal components from the outside via manipulators and bellows.

Ports and flanges

- All vacuum components are connected to each other via flanges of various sizes.
- The flanges ensure a leak tight seal via a rubber or copper gaskets, depending on the level of vacuum and operating conditions.
- A port is a hole made in the chamber body, where a tube is welded. The other end of the tube has a flange to accept other components.



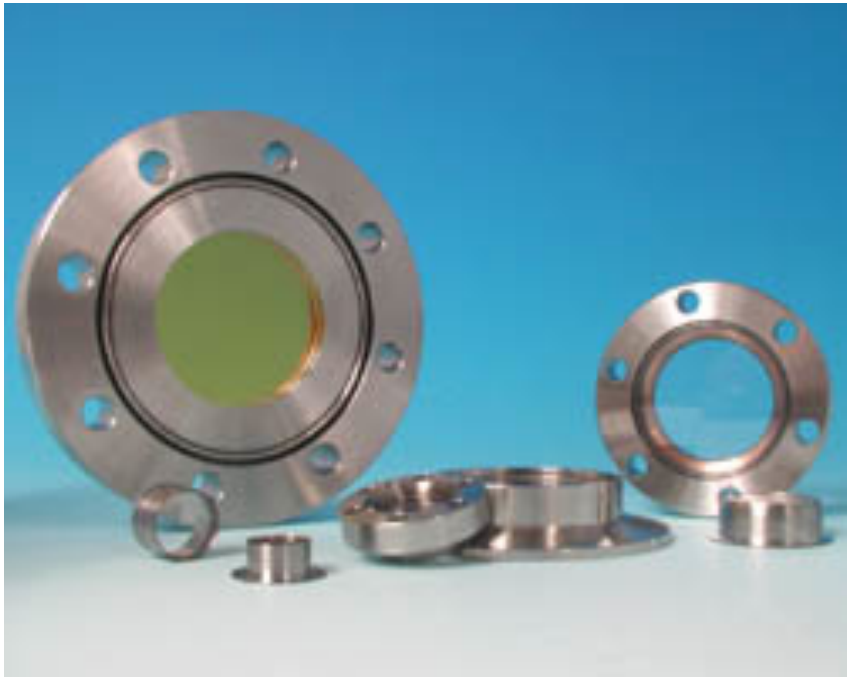
Electrical feedthrough

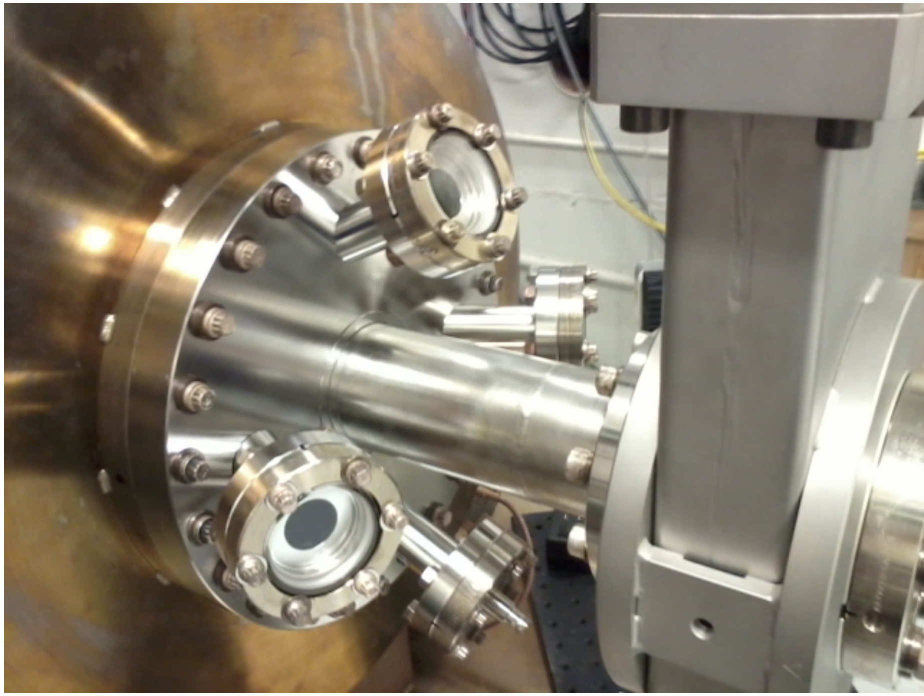
- Consist of a central conductor electrically isolated from its metallic holder (flange) by a ceramic. The vacuum seal is achieved by “brazing” the conductor to the ceramic, and the ceramic to its holder via Kovar seals.
- This type of feedthrough are used in vacuum pumps, gauges, beam position monitors, etc.

Viewports

- A viewport is a glass window that allows the transmission of light in and out of the vacuum system. The glass and coatings are designed for specific wavelength ranges.

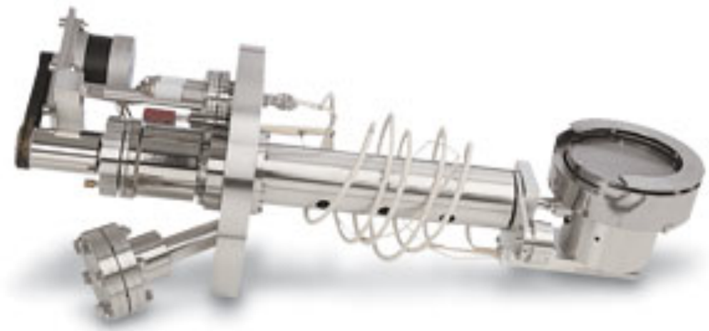
- The piece of glass is sealed to the metallic holder (flange) by brazing to a Kovar ring. The ring is then welded to the flange.





Manipulators and bellows

- There is a wide variety of manipulators to maneuver components inside the vacuum environment in all three axis.

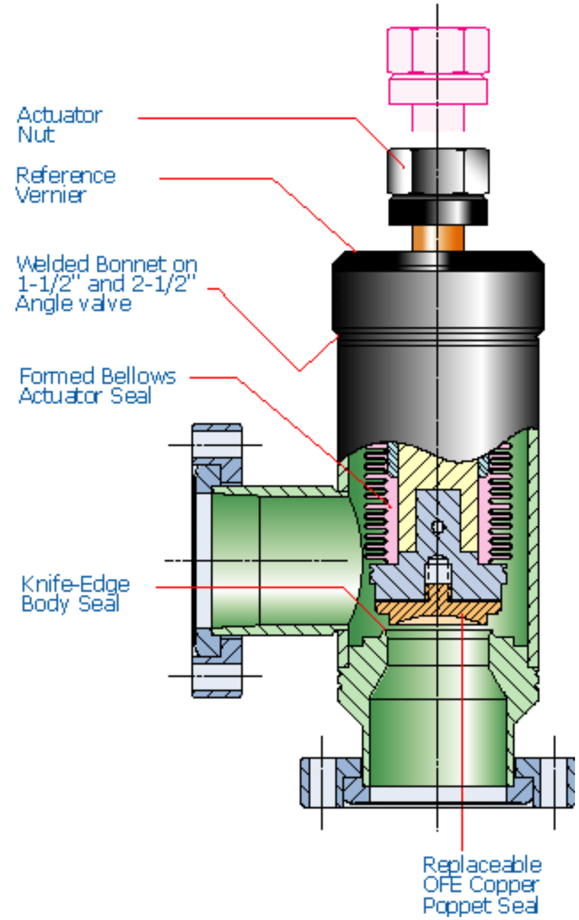




- Bellows allow longitudinal motion via a series of welded rings that can be collapsed and extended, much like an accordion.

Valves

- Right angle valves, all metal seal, are commonly used to isolate the vacuum system from the pumping stations, or from the atmospheric environment.

1-1/2"
All-Metal Angle Valve
Cross Section



Pictures from MDC V

Gate valves

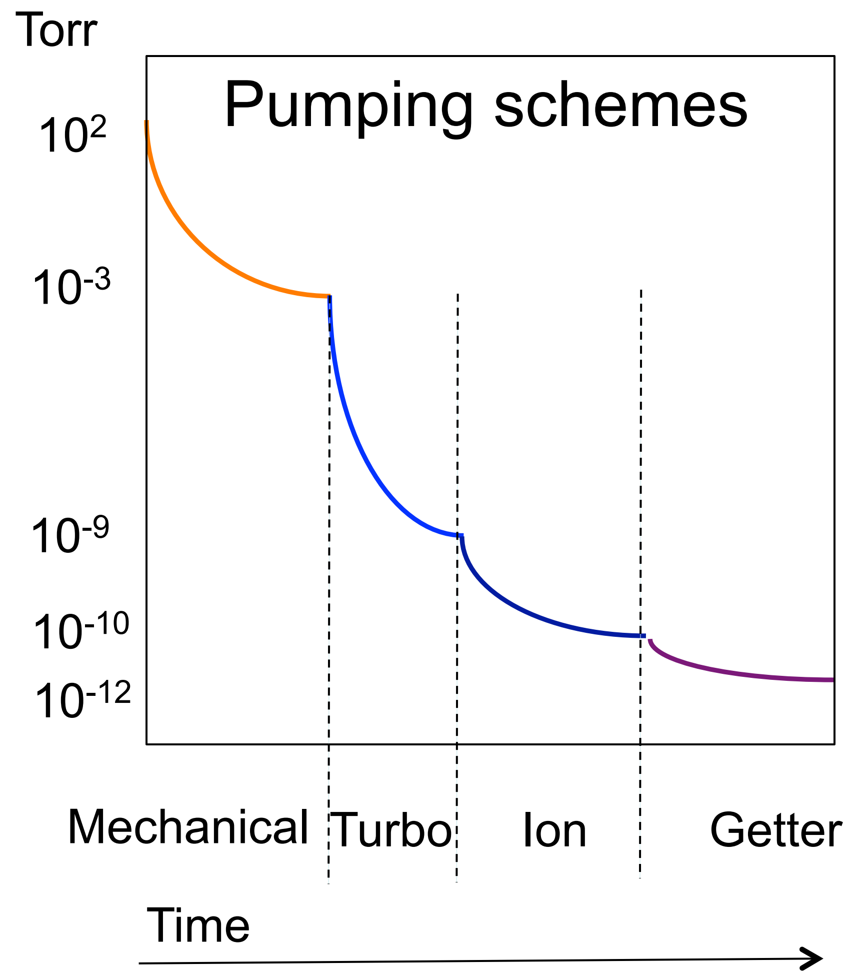
Allow isolating vacuum environments from one another

- There are manually and pneumatic operating options
- Most are bakeable to 250C
- There is a wide variety of sizes and options

So, we have this pristine vessel, now let's pump it down and make a vacuum…

… but WAIT!!! There are 14 orders of magnitude between the atmospheric pressure in the vessel and the desired vacuum level inside!!!

- The pump down is performed in pumping stages, with different pumping schemes for each stage.
- The evacuation time depends on the pump's speed, the gas flow regime, the conductance from the vessel to the pump, etc.

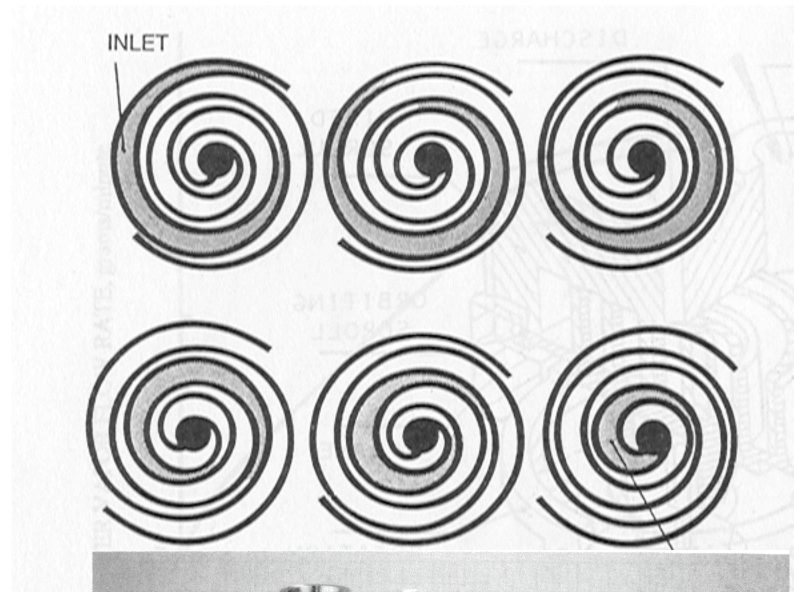


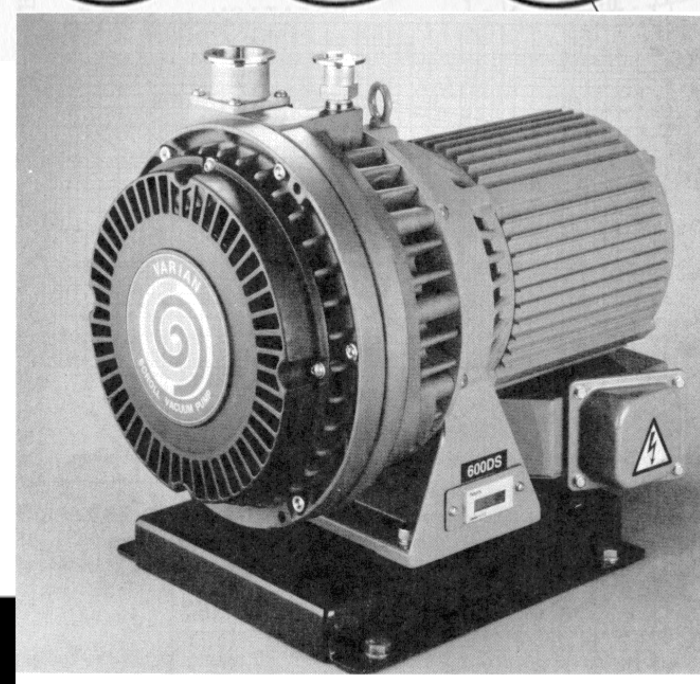
Pumping down the vacuum system

- **Stage 1**: pumping from atmospheric pressure to 10^{-3} Torr.
  - Pumping mechanism: Positive displacement
  - Pump type: Dry Mechanical Pump
  - No oils are exposed to the gas stream
  - Pumping by positive displacement and momentum transfer
  - Pumping range from 760 Torr to 10^{-3} Torr
  - Pumping speed 2 to 150 CFM

Stage 1: Wide variety of dry pumps

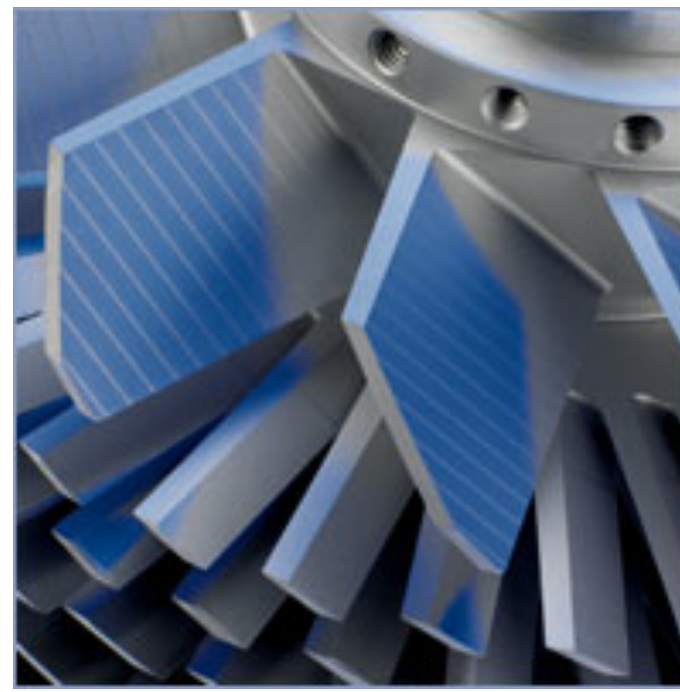
- Multistage roots
- Claw
- Scroll
- Screw
- Diaphragm
- Reciprocating piston
- Molecular drag and diaphragm pump in series





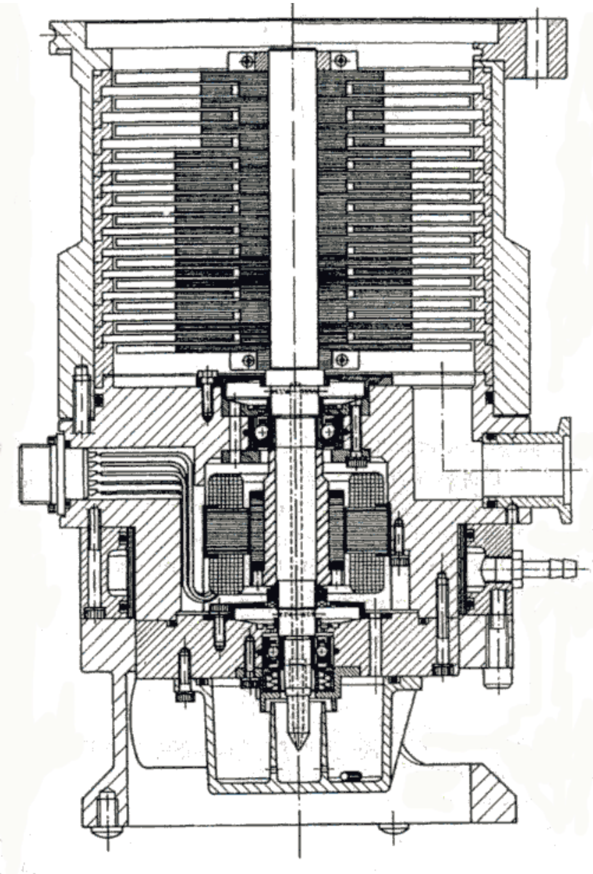
Pumping down the vacuum system

- **Stage 2**: Pumping from 10^{-3} Torr to 10^{-9} Torr.
  - Pumping mechanism: Momentum transfer
  - Pump type: Turbomolecular pump or molecular drag pump



Stage 2: Turbo-molecular pumps

- Turbopumps are axial compressors designed for pumping gases in the molecular flow regime.
- Operating range 10^{-3} to 10^{-9} Torr
- Pumping speed 10 to 10,000 l/s
- Infinite pumping capacity
- Turbopumps are throughput pumps meaning they have infinite capacity
- Blade rotation speed ranges from 14,000 to 90,000 rpm requiring magnetic bearings



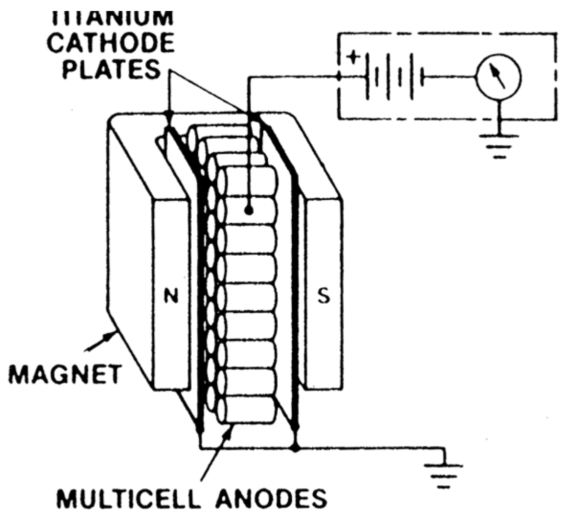
Pumping down the vacuum system

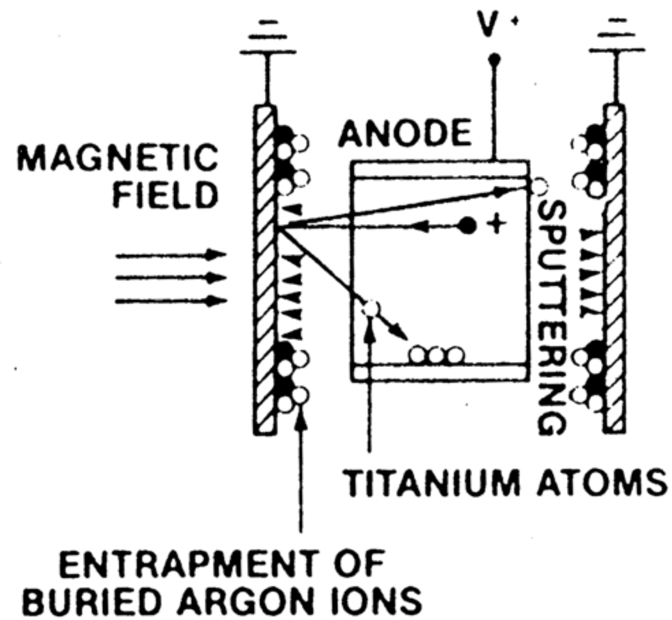
- **Stage 3**: Pumping from 10^{-9} Torr to 10^{-10} Torr.
  - Pumping mechanism: Chemical combination
  - Physisorption - atom burial deep under sputtered material.
  - Chemisorption - removal of atoms due to the formation of chemical bonds.
  - Diffusion - hydrogen diffuses into the bulk of the metal.
  - Pump type: Sputter Ion Pump

Stage 3: Sputter ion pump characteristics

- Pumping speed - is sensitive to gas species, inlet size, pressure, and history of pump
- Starting pressure - 10^{-6} Torr
- Capacity - sputter ion pumps are gas capture type pumps and do have a limited capacity
- Advantages
  - Ultra clean, quiet, high pumping speed for water and hydrogen
  - Essential to maintain 10^{-10} Torr vacuum in accelerator beam lines
- Disadvantages
  - Gas species sensitive, limited capacity

Stage 3: Diode sputter-ion pump





Pumping down the vacuum system

- **Stage 4**: Achieving Ultra High Vacuum: Pumping from 10^{-10} to 10^{-11} Torr, and maintaining the vacuum level.
  - Pumping mechanism: Abosrption. Active gases are chemisorbed irreversibly by getter material
  - Pump type: Non Evaporable Getter (NEG)
  - This type of pump operates statically (no power is required), but it needs to be activated with heat.

Stage 4: Non-evaporable getters (NEG)

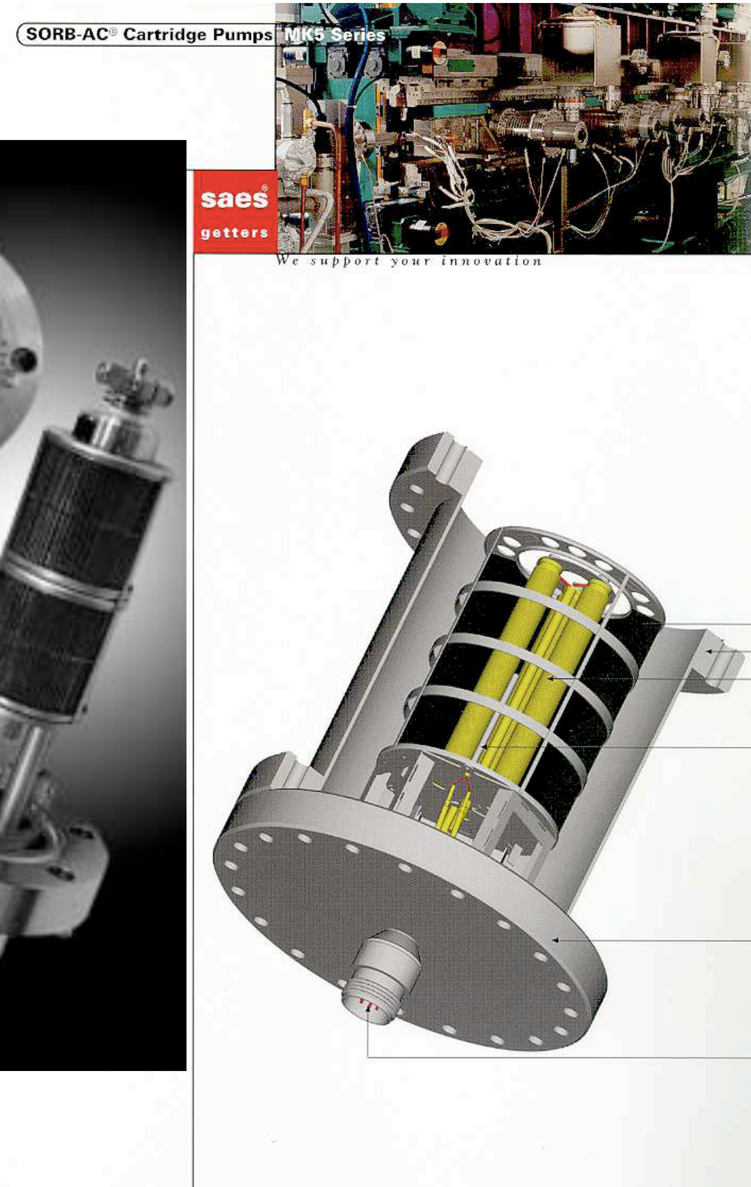
- Bulk Getters: Gases like CO, CO_2, O_2 and N_2 diffuse into the interior of the getter material
  - Noble gases are not sorbed at all (He, Ne, Ar, Kr, Xe)
  - The chemical bonds of the gas molecules are broken on the surface of the NEG
  - Various gas atoms are chemisorbed forming oxides, nitrides, and carbides.
  - High temperatures (activation) do not break these chemical bonds. High temperatures promote diffusion into the bulk of the NEG
  - Water vapor and hydrocarbons are “cracked” on the surface of the NEG

Stage 4: Typical NEG cartridge by SAES

NEGs are made of alloys, typically consisting on titanium , vanadium, aluminum and zirconium.

To increase the pumping capacity, NEGs rely on surface area. These NEG cartridge pumps use sintered plates to maximize surface area.

NEGs coatings can be applied to the inner walls of chambers and beam pipes.

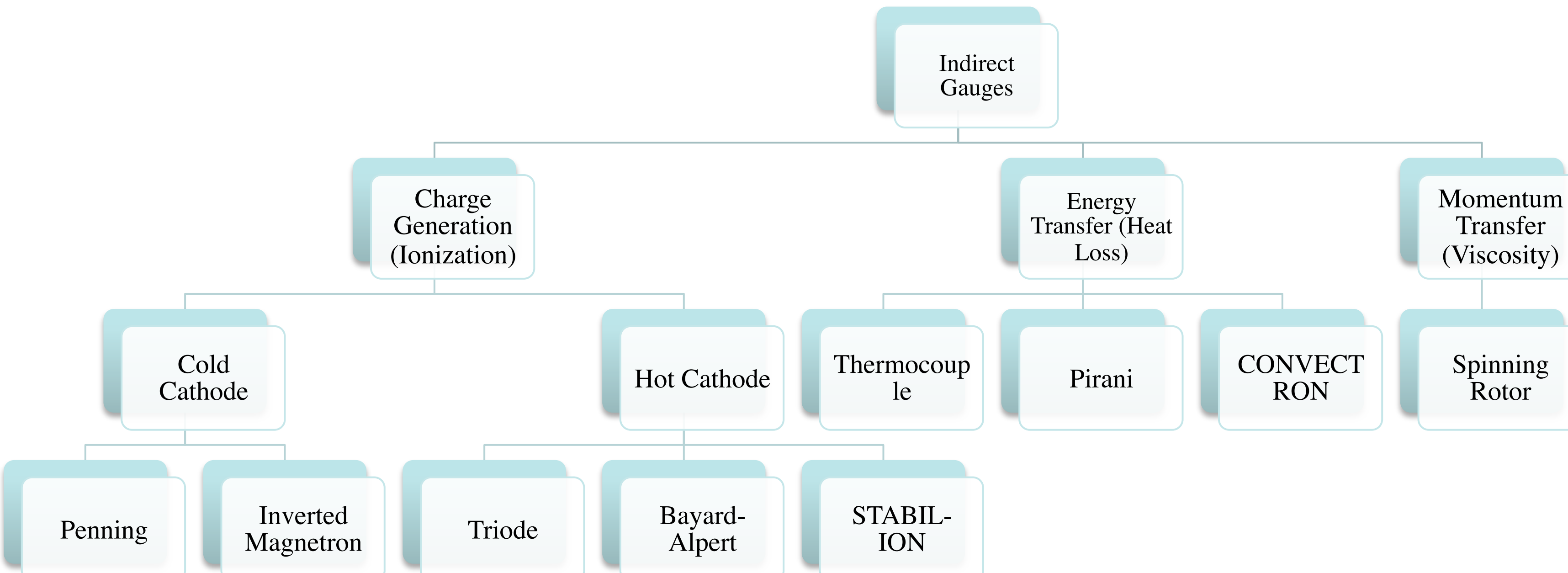


Vacuum Measurement

- Fundamentally, the measuring devices must interact with the vacuum environment in which it is immersed to measure the vacuum level.

- The pressure range measured in most vacuum systems is too large to be measured with a single gauge, it spans from 10^{-12} Torr UHV to 760 Torr atmospheric pressure. That’s 14 orders of magnitude!

Types of vacuum gauges used in accelerators are based on measurement of a gas property



Measuring Range of Vacuum Gauges

Medium and Low Vacuum: 10^{-3} Torr to 1000 Torr

- Direct Gauges
  - Displacement of a Solid Wall
  - Capacitance Diaphragm Gauge
- Indirect Gauges - Heat-Loss Gauges
  - Thermocouple Gauge
  - Pirani Gauge
  - CONVECTRON Gauge (Convection-Enhanced Pirani)

Ultra-High and High Vacuum: 10^{-11} Torr to 10^{-3} Torr

- Indirect Gauges - Ionization Gauges
  - Hot Cathode Gauge
  - Cold Cathode Gauge

CONVECTRON Gauge

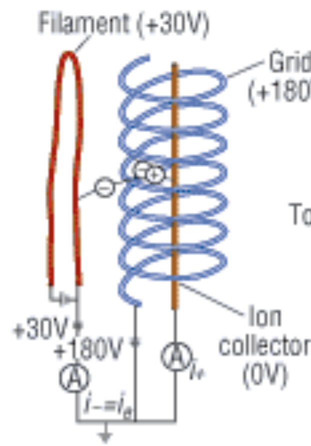
• Wide Measurement Range: 10^{-3} Torr - 1000 Torr.
• Individual calibration.
• Accurate, fast measurement.
• Long term stability.
• Recalibrate for contaminated gauge or after cleaning gauge.
• Very reliable - industry standard.
•At pressures below 10^{-5} Torr (high vacuum) direct measurement of pressure is very difficult

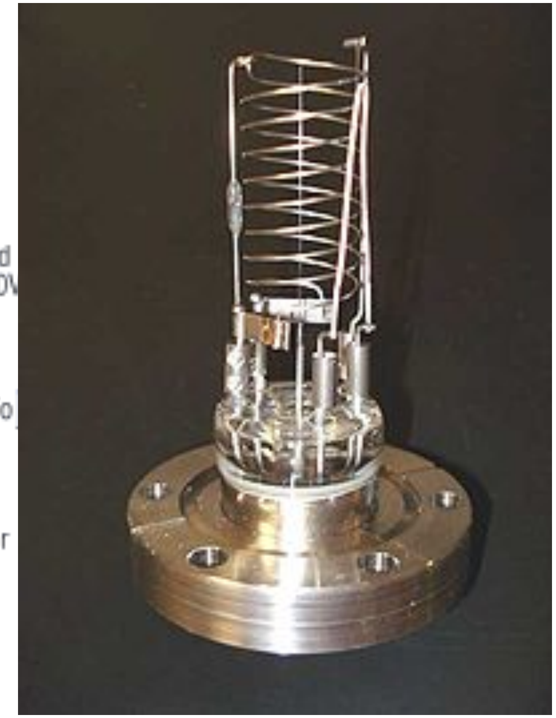
Ionization Gauges

- Primary method for pressure measurement from 10^{-5} to 10^{-11} Torr is gas ionization & ion collection/ measurement
- These gauges can be divided into hot & cold cathode types
- Most common high vacuum gauge today is the Bayard-Alpert
- A variation of the ionization gauge called "Extractor Gauge" is used to measure in the 10^{-12} Torr range, by shielding the collector from the filament. Very small currents are detected with the aid of an amplifier.

Hot cathode Ionization Gauge principles

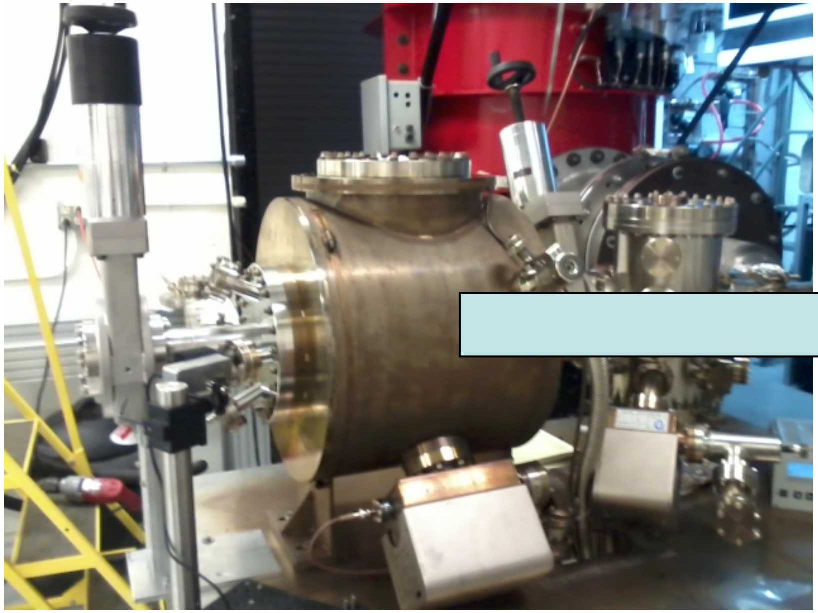
- Hot filament (cathode) emits electrons.
- Molecules are ionized and collected.
- Pressure reading is determined by the electronics from the collector current.
- This type of gauge is placed directly into the vacuum environment
- Filaments are replaceable





Characterizing Vacuum

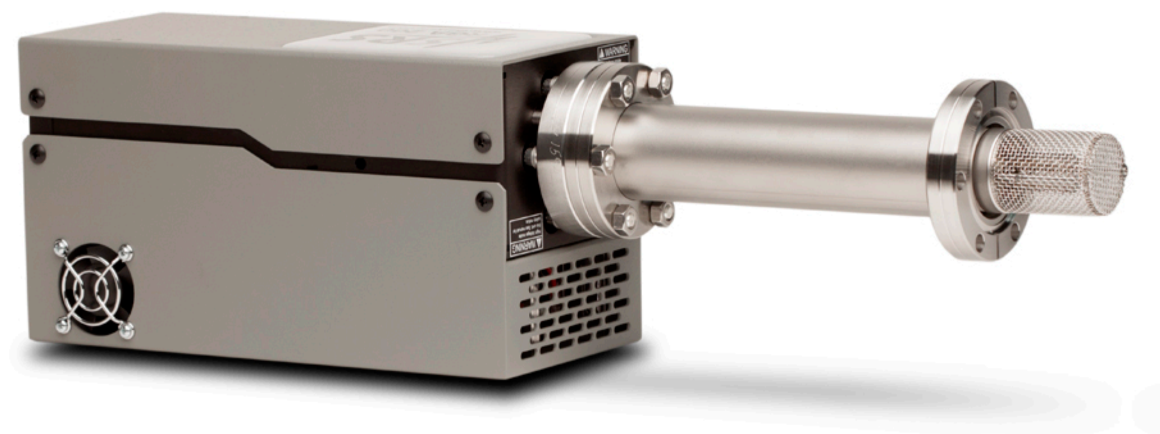
- Sometimes, it is not enough to know the vacuum level.
- Knowing the composition of the residual gases in the vacuum system if often useful to determine why the desired vacuum level is not achieved and what steps can be taken to achieve it.



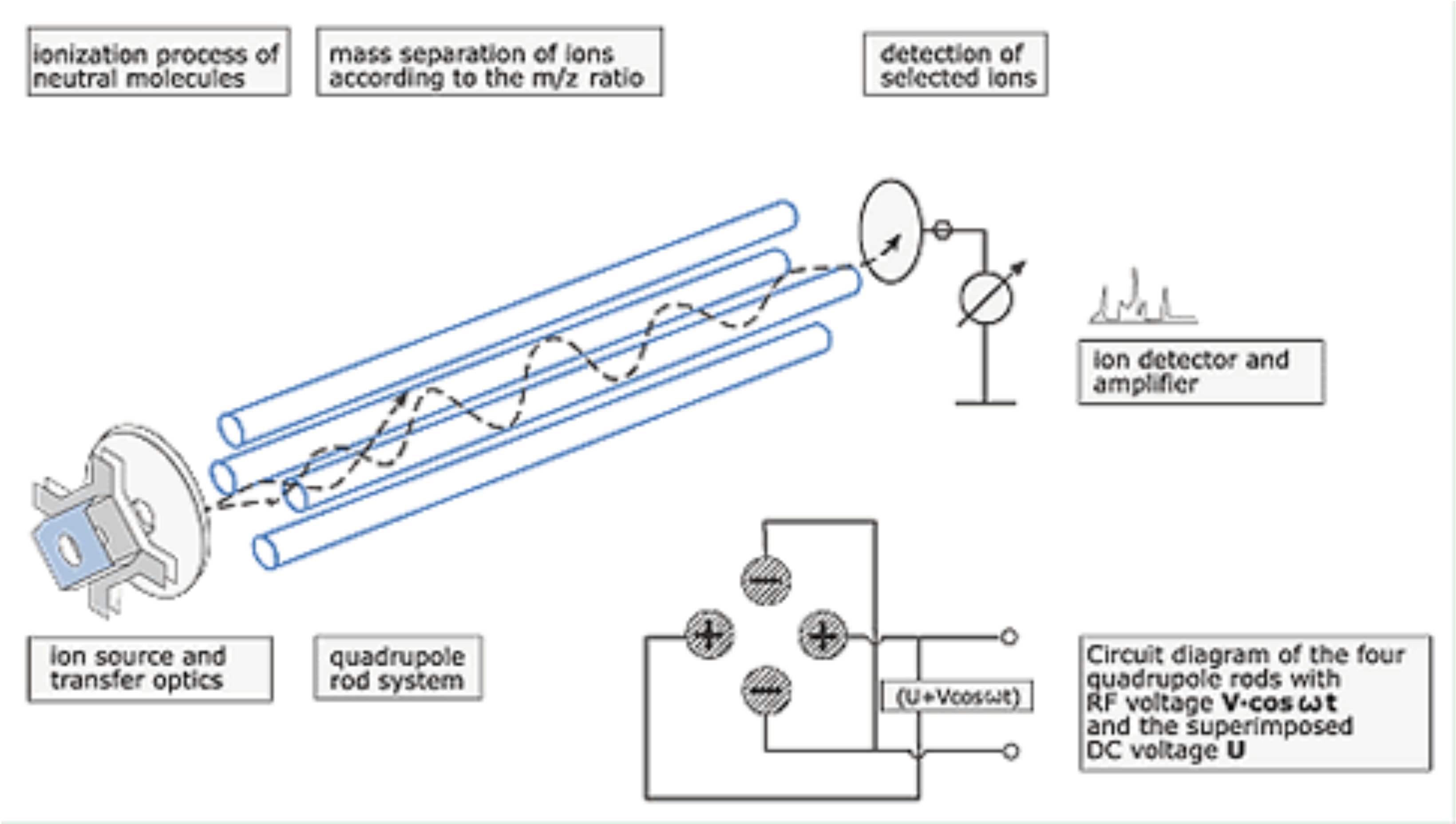
?

The most common tool is the residual gas analyzer

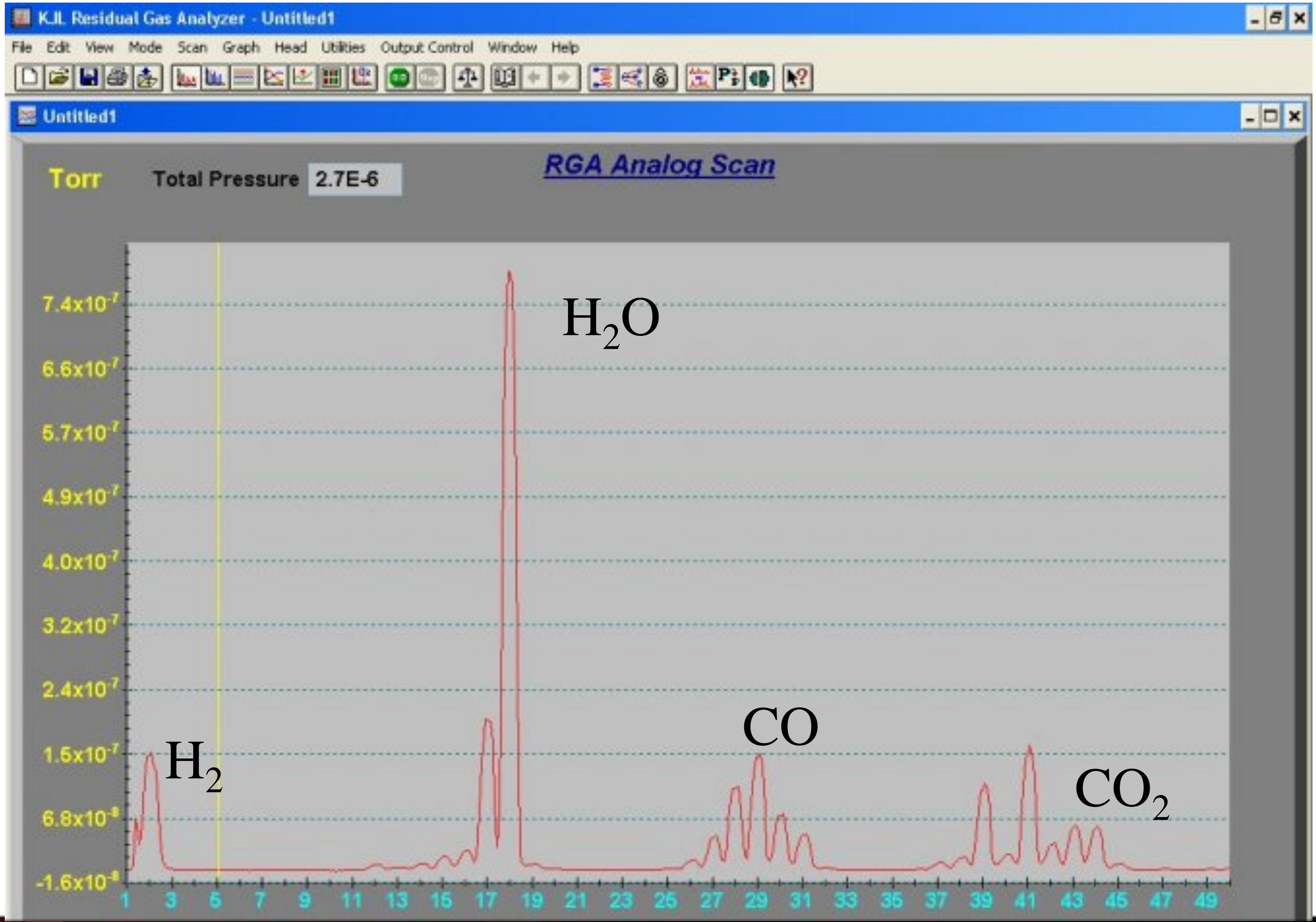
- It operates based on the amount of ions vs. mass/charge ration (m/e or m/q)
- The results for each species is reported in atomic mass units (AMU) C_{12} is exactly 12 AMU
- For example: N_2+ m/e=28.0061, CO+ m/e = 27.9949



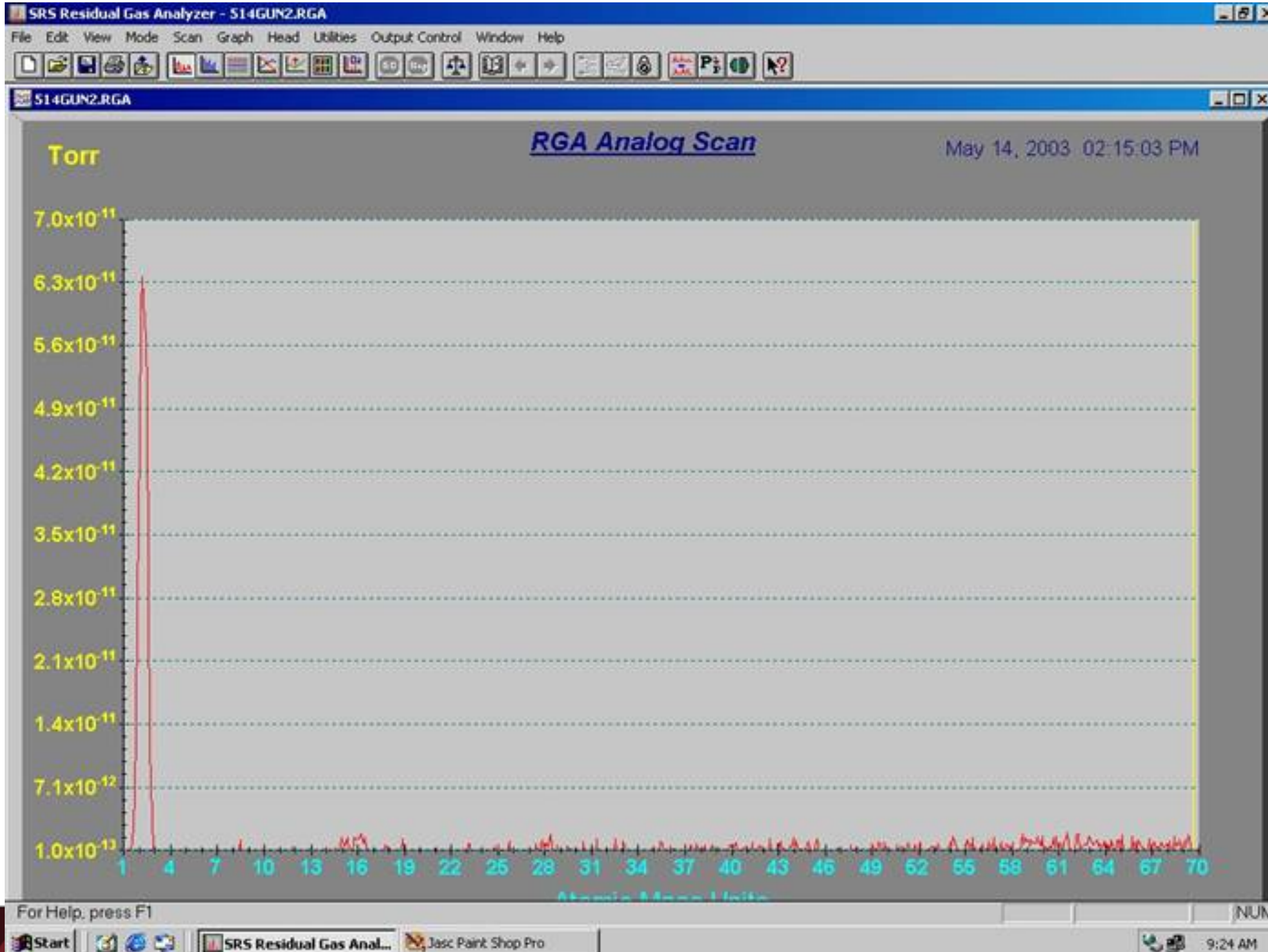
Quadrupole analyzer



Analysis of Mass Spectra

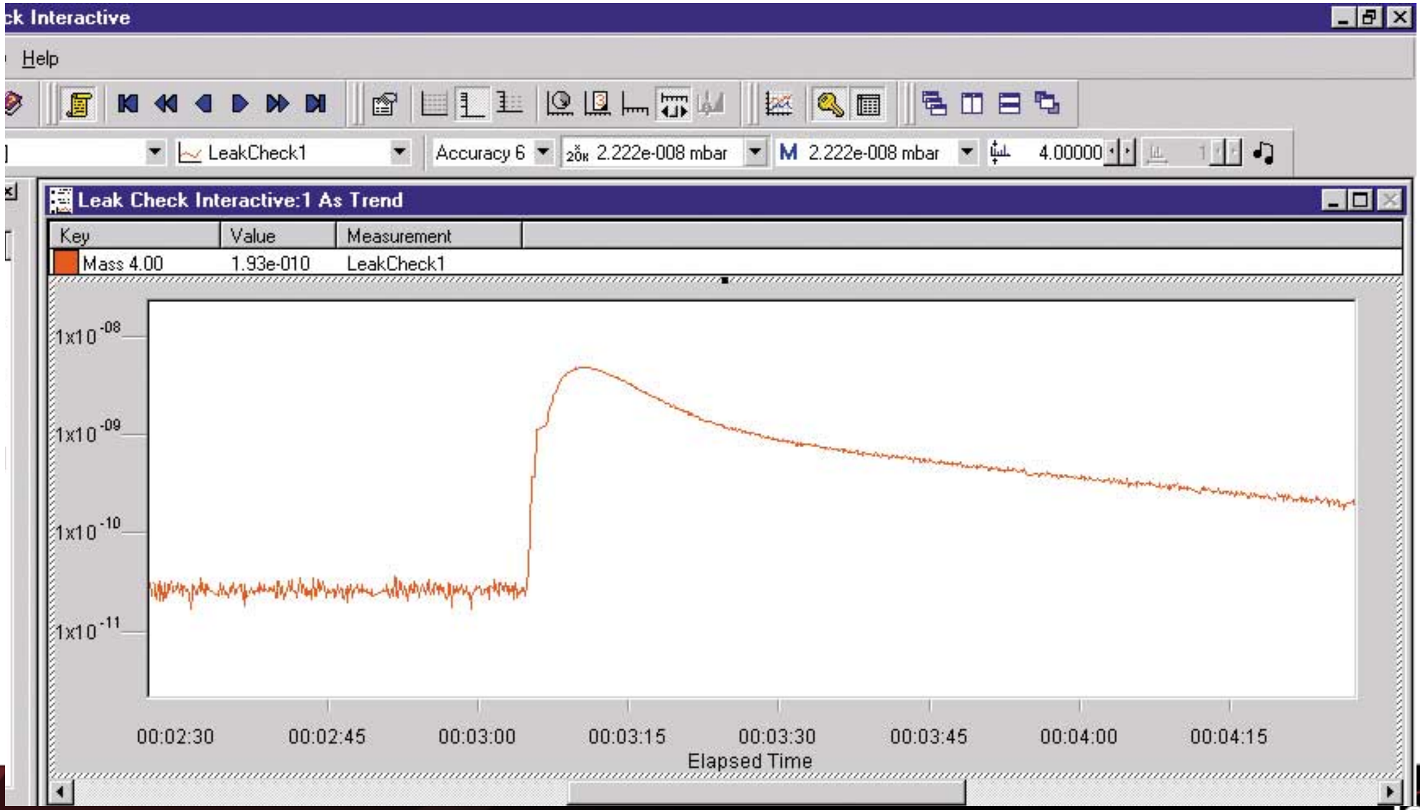


Typical RGA spectrum of clean UHV system



RGAs are very useful in finding leaks in vacuum systems

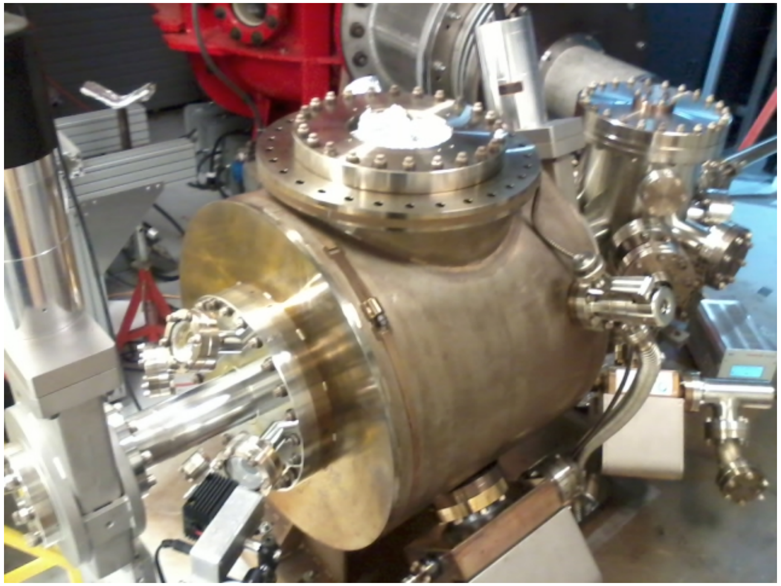
- RGA can be set to monitor Helium over time
- Helium has high mobility and is a very small molecule than can get "sucked in" the vacuum system through small gaps that cause leaking
- Using a nozzle with very slow helium flow one can pinpoint leaks while observing the rate of rise in the RGA.

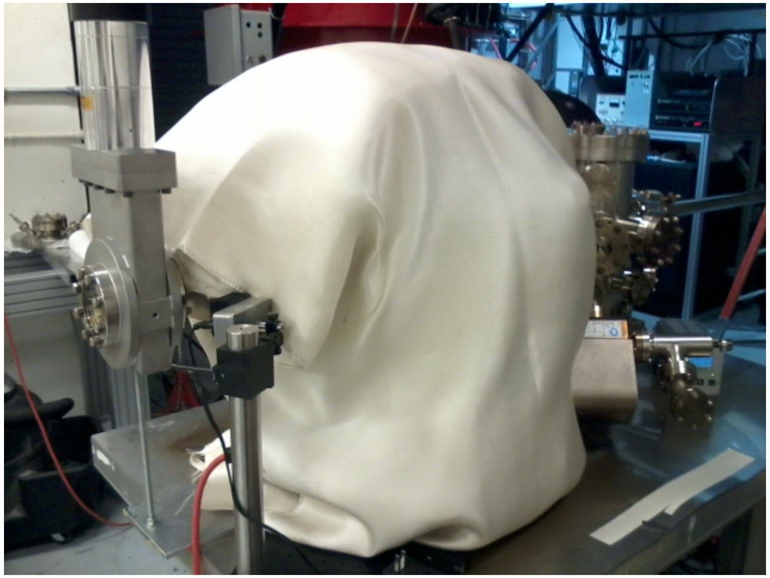


Ultra High Vacuum Techniques Achieving and maintaining 10^{-12} Torr

- Proper material selection for the vessel
- Internal surface finish and proper welding
- Wet cleaning procedures adding High Pressure Rinse with filtered and de-ionized water
- **Vacuum bake at 400 C to 900 C for a few hours to diffuse hydrogen out of the bulk material**
- Vacuum system assembly in Clean Room environment
- Vacuum system installation in accelerator using portable clean room
- Vacuum system initial pump down with turbo pumps
- NEG activation followed
- **Vacuum system bake at 250C with ion pump external to oven. Depending on the system size, it can take up to two weeks.** This steps desorb mainly water from the inner walls and is key to lower the vacuum level from 10^{-10} Torr to 10^{-11} Torr.

Vacuum bake is a critical final step to improve the vacuum level from 10^{-10} Torr to 10^{-12} Torr





Typically the system is baked at 250 Celsius for a few days

Resources and Vendors

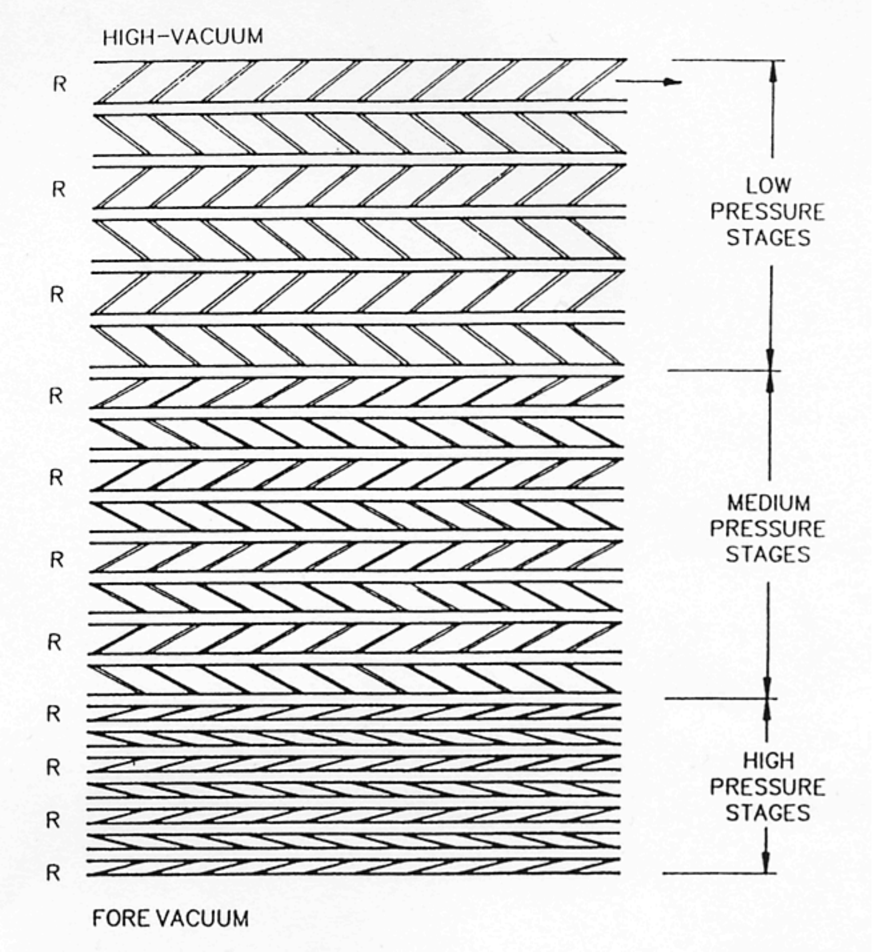
- AVS (formerly known as the American Vacuum Society)
- Journal of Vacuum Science and Technology
- MDC Vacuum
- Kurt J. Lessker
- Varian Vacuum
- Pfeiffer Vacuum
- Gamma Vacuum
- Stanford Research Systems
- …Many more exists….

…may the vacuum be with you…

Backup slides

Turbomolecular pumps

- Rotating blades accelerate gas molecules in a preferred direction
- The key parameter is compression ration, not change in pressure
- Typical compression ratios
  - Nitrogen 10^8 to 10^9
  - Helium 10^4 to 10^6
  - Hydrogen 10^2 to 10^5



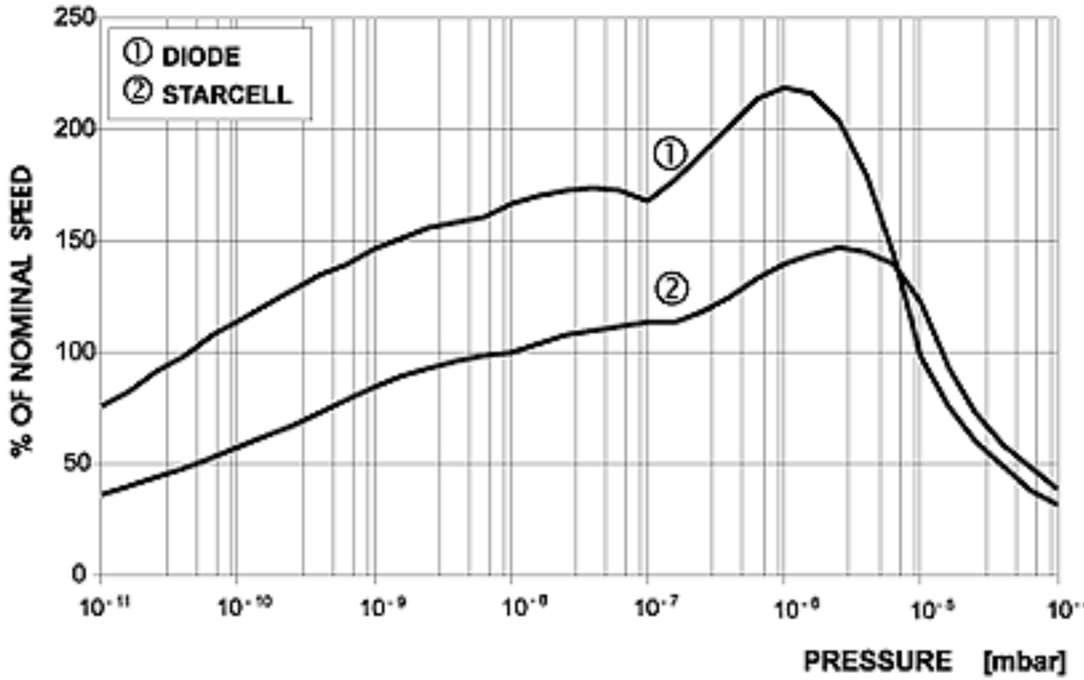
Turbomolecular pumps come in a wide variety of sizes and pumping speeds

Turbomolecular pumping stations allow to pump from atmoshperic pressure to 10^{-9} Torr

Types of sputter ion pumps

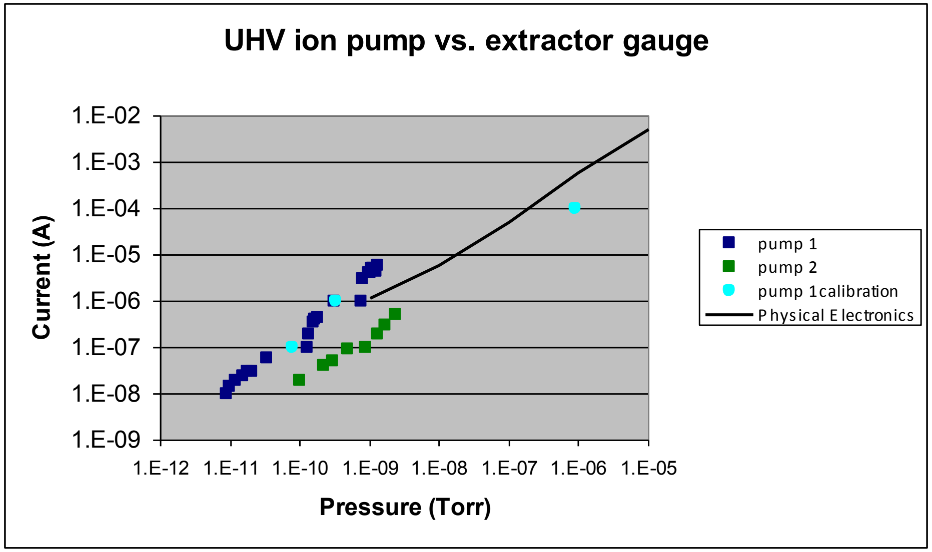
- Diode - best for UHV systems where 98% of the gas is hydrogen. Diodes have the highest hydrogen pumping speed.
- Differential (Noble Diode) – a compromise for hydrogen pumping speed with limited argon stability. This pump has reduced hydrogen pumping speed.
- Triode/Starcell - good hydrogen pumping speed, also pumps argon well. Good choice for pumping down from higher pressures often.

H_2 Pumping speed curve for an ion pump

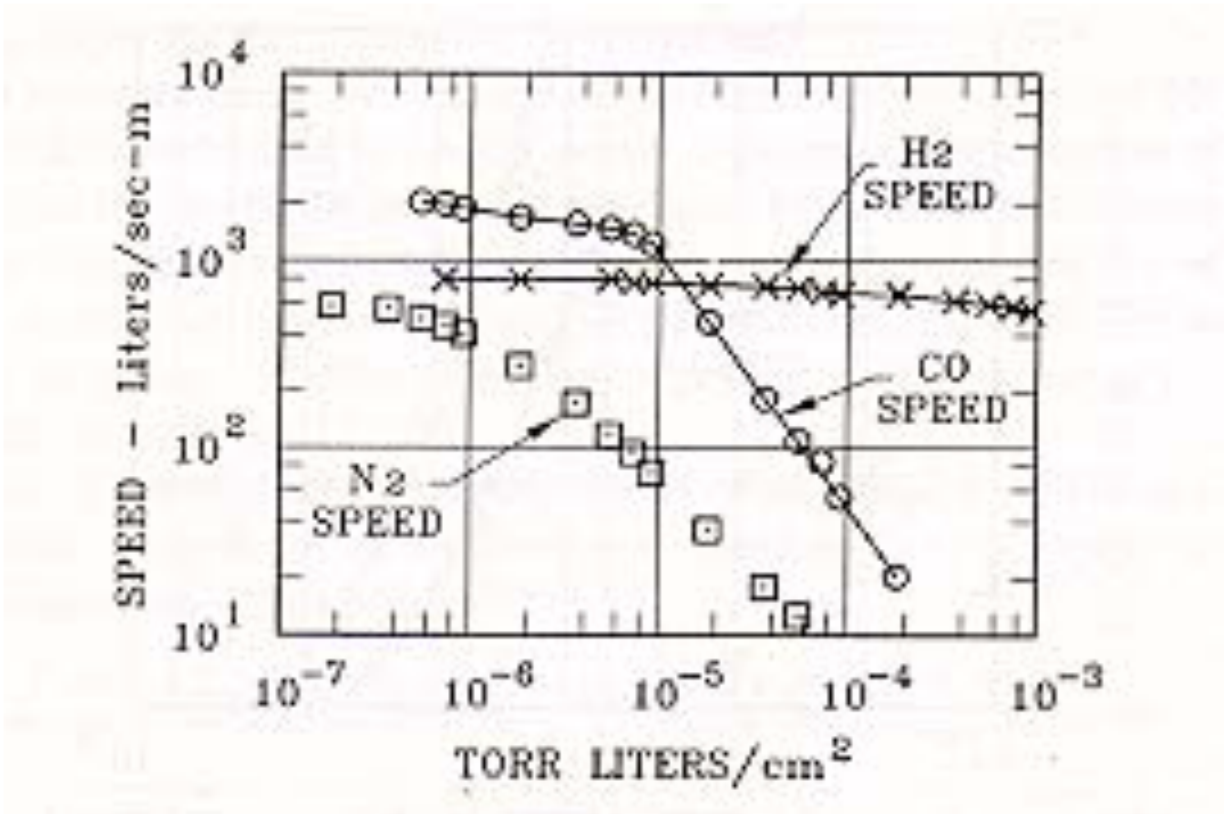


Sputter-ion pump current may be used to measure pressure in the vacuum system

- Pressure is linearly proportional to current.
- At low pressures ($<10^{-9}$ Torr), the leakage current effect the pressure reading.
- The displayed current is the total of the leakage in the power supply, cable connectors, feedthroughs, insulators, internal discharge, and working current.
- The new controllers with variable voltage capability improve this feature.

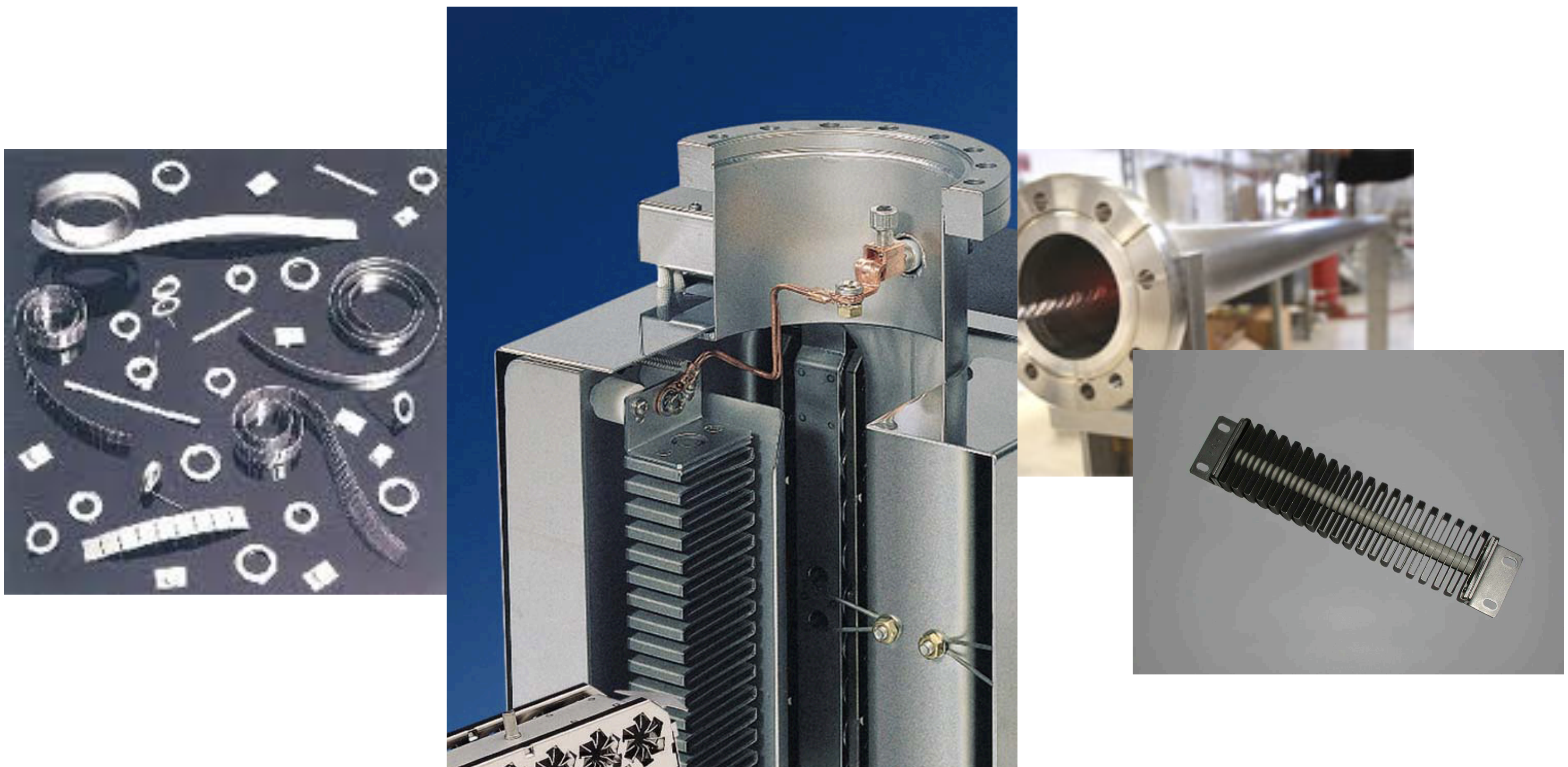


Pumping speeds vary with the type of NEG, here is just one example

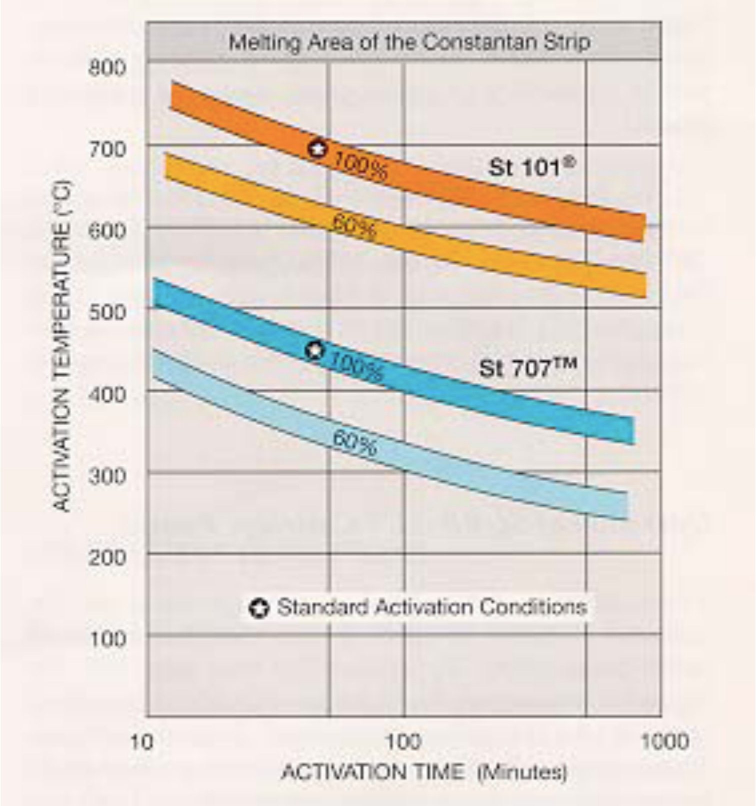


SAES ST101 Sorption graph

In a typical UHV system, there is a combination of ion pumps and NEG material on one or various forms (cartridges, strips, films, etc)



Most NEG pumps are activated at 450C for 45 minutes



Other types of pumps not covered in this lecture

- Cryo pumping: Wall temperature is so cold that gases lose all kinetic energy on contact and remain attached to the wall.

- Titanium Sublimation Pumps: Another form of getter, gases are pumped by chemisorption when titanium is evaporated inside the vacuum system forming a film in the inner walls.

Thermocouple Gauge

- Indirectly measured pressure via thermal conductivity of gases
- Operating range 1 Torr to 10^{-3} Torr
- Indicated value is gas dependent
- Constant current is delivered to a wire and its temperature is measured by a thermocouple
- Thermocouple is read on a pressure scale
- Rugged design but somewhat inaccurate and slow response

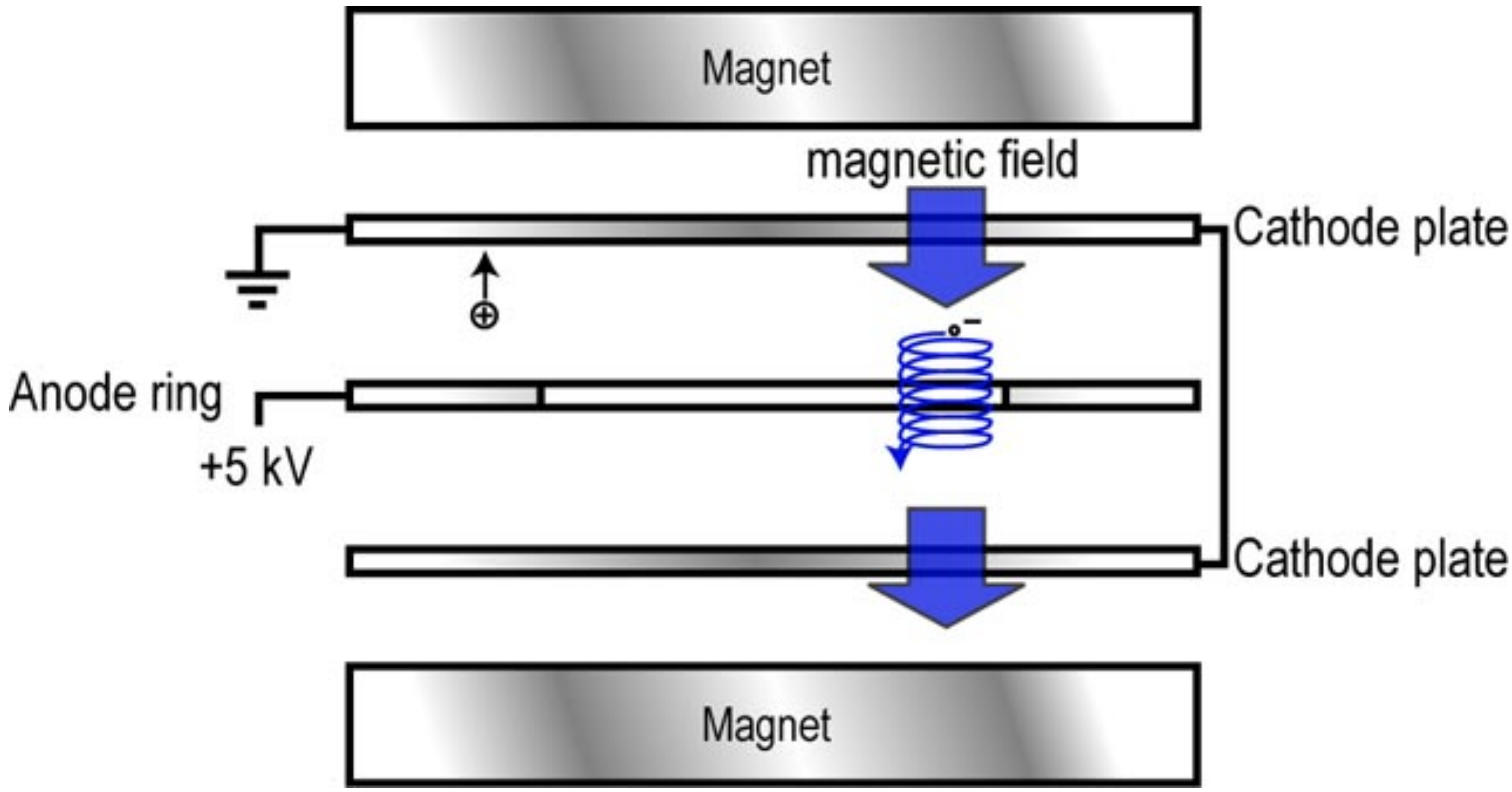
Pirani Gauge

•Indirectly measures pressure via thermal conductivity of Gases
•Operating range 100 to 10^{-4} Torr
• Indicated value is gas dependent
• Resistance heated wire which is part of a Wheatstone bridge
• Pirani gauge that is sensitive to convection heat losses is available

Penning Gauge

- Measured indirectly
- Operating range 10^{-2} to 10^{-7} Torr
- Indicated value is gas dependent
- Cold cathode, therefore does not produce gases like a hot filament gauge
- Based on crossed electrical & magnetic fields to enhance ionization efficiency
- Difficult to start & maintain discharge $<10^{-6}$ Torr
- Less accurate than ionization gauge

Penning gauge



Spinning Rotor Gauge

- Also called the molecular drag gauge (MDG)
- Measures pressure indirectly
- Operating range 10^{-2} to 10^{-7} Torr
- Indicated value is gas dependent (viscosity)
- Works by the principle of momentum transfer
- Utilizes a magnetically levitated, spinning, steel 4mm ball
- Ball rotation is slowed by gas collisions
- Vibration sensitive
- Requires 30 seconds to 5 minutes to make a measurement
- Very good accuracy and linearity
- Often used in laboratories for calibration transfer standard

Spinning Rotor Gauge