Vacuum components

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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

• The gauges (vacuum measurement)
• Characterizing vacuum
  – Finding leaks
• 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 $10^{-11}$ 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 SRF 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.
The vessel

• In accelerator applications, vessel material are non-magnetic, why?
  – 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, 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...
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.
The vessel: Surface Cleaning

• Basic principles:
  – Never touch internal surface of vacuum components with bare hands. Skin oils will outgass preventing achievement of desired vacuum. Always use powder-free latex gloves when handling components.
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.
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 installation must be cleaned too!
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 components clean

- 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
So, we have this pristine vessel. Now:

- How do we 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 cupper 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.
Viewportss

• 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.
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
Pumping mechanisms

• Throughput mechanisms:
  – Positive displacement: Molecules are compressed into a smaller volume, raising the pressure.
  – Momentum transfer: Molecules are given a preferred direction by very fast moving surfaces or oil molecules moving at high speeds.
Pumping mechanisms

• Capture mechanisms:
  – Chemical combination: Molecules react with active metal surfaces and are converted to a solid
  – Condensation: Molecules land on a very cold surface and freeze into a solid
  – Adsorption: Molecules land on a surface and stick there
  – Absorption: Molecules land on surface and dissolve into the bulk material
  – Ionization & burial: Molecules are ionized and accelerated into a surface with enough energy to get buried in the material.
Evacuation of a vacuum system

• It is performed in pumping stages, with different pumping mechanisms for each stage.
• The evacuation time depends on the pump’s speed, and the conductance from the vessel to the pump.
Evacuation of a vacuum system

• Stage 1: pumping from atmospheric pressure to 10-3 Torr.
  – Pumping mechanism: Positive displacement
  – Pump type: Mechanical Roughing Pump
  – Problem with some mechanical pumps: oil backstreaming
Dry mechanical pumps

• 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
• More reliable than roughing mechanical pumps
• More compatible with corrosive gases than oil pumps
• More expensive than oil pumps
Wide variety of dry pumps

- Multistage roots
- Claw
- Scroll
- Screw
- Diaphragm
- Reciprocating piston
- Molecular drag and diaphragm pump in series
Evacuation of a 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
Turbo-molecular pumps

- Turbopumps are axial compressors designed for pumping gases in the molecular flow regime.
- Operating range $10^{-2}$ to $10^{-10}$ 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 – making them mechanically vulnerable
Turbomolecular pumps

- Rotating blades accelerate gas molecules in a preferred direction
- The key parameter is compression ratio, not change in pressure
- Typical compression ratios
  - Nitrogen $10^8$ to $10^9$
  - Helium $10^4$ to $10^6$
  - Hydrogen $10^2$ to $10^5$
Turbo pump blades
Speed vs throughput for Turbomolecular pump
Turbomolecular pumps come in a wide variety of sizes and pumping speeds
Turbomolecular pumping stations allow to pump from atmospheric pressure to $10^{-9}$ Torr.
Evacuating a vacuum system

• Stage 3: Pumping from $10^{-9}$ Torr to $10^{-10}$ Torr.
  – Pumping mechanism: Chemical combination
    – Physisorption - atom burial deep within a lattice, atom
    – burial 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

•
Sputter ion pump characteristics

• Pumping speed - is sensitive to gas species, inlet size, pressure, and history of pump
• Starting pressure - ion pumps must be roughed to 20 milliTorr or less before starting (should be more like $10^{-6}$ 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
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.
Diode sputter-ion pump

Diagram showing the components of a diode sputter-ion pump, including titanium cathode plates, magnet, multicell anodes, magnetic field, anode, sputtering, titanium atoms, entrapment of buried argon ions.
H₂ Pumping speed curve for an ion pump
Commercial sputter ion pumps come in a wide variety of pumping speeds.
Sputter-ion pumps need controllers
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.
Example of putter-ion pumps in accelerator beamline
Evacuating the vacuum system

• Stage 4: Achieving Ultra High Vacuum: Pumping from $10^{-10}$ to $10^{-11}$ Torr, and maintaining the vacuum level.
  – Pumping mechanism: Absorption. Active gases are chemisorbed irreversibly by getter material.
  – This type of pump operates statically (no power is required), but it needs to be activated with heat.
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
Typical NEG cartridge by SAES Getters

NEG cartridges are made of alloys, typically consisting of titanium, vanadium, aluminum, and zirconium.

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

NEG coatings can be applied to the inner walls of chambers and beam pipes.
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 450°C 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.
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 $10^{-11}$ Torr UHV to 760 Torr atmospheric pressure. That’s 12 orders of magnitude!
Types of vacuum gauges used in accelerators are based on measurement of a gas property.

Indirect Gauges

Charge Generation (Ionization)
- Cold Cathode
  - Penning
  - Inverted Magnetron
- Triode
- Bayard-Alpert

Energy Transfer (Heat Loss)
- Hot Cathode
- Thermocouple
- Pirani
- STABIL-ION

Momentum Transfer (Viscosity)
- CONVEXTRON
- Spinning Rotor

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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
Heat-Loss transfer

• Heated element cools as molecules strike
• Higher pressure means increased cooling of sensor
• Gas species dependent
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
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.
Ionization Gauges

• At pressures below $10^{-5}$ Torr (high vacuum) direct measurement of pressure is very difficult
• Thermal conductivity gauges have exceeded their operational limits
• Primary method for pressure measurement from $10^{-4}$ to $10^{-12}$ 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
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
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

- Vertical stabilization coils (2)
- Permanent magnets (2)
- Sense coils (2)
- Drive coils (4)
- Lateral damping coils (4)
- Case & magnetic circuit
- Rotor
- Cylindrical Vacuum Tube
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: \( \text{N}_2^+ \ m/e=28.0061 \), \( \text{CO}^+ \ m/e = 27.9949 \)
Quadrupole analyzer
Analysis of Mass Spectra
Typical RGA spectrum of clean UHV
RGA are offered by various manufacturers
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 $10^{-11}$ 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 diffusing 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.
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....