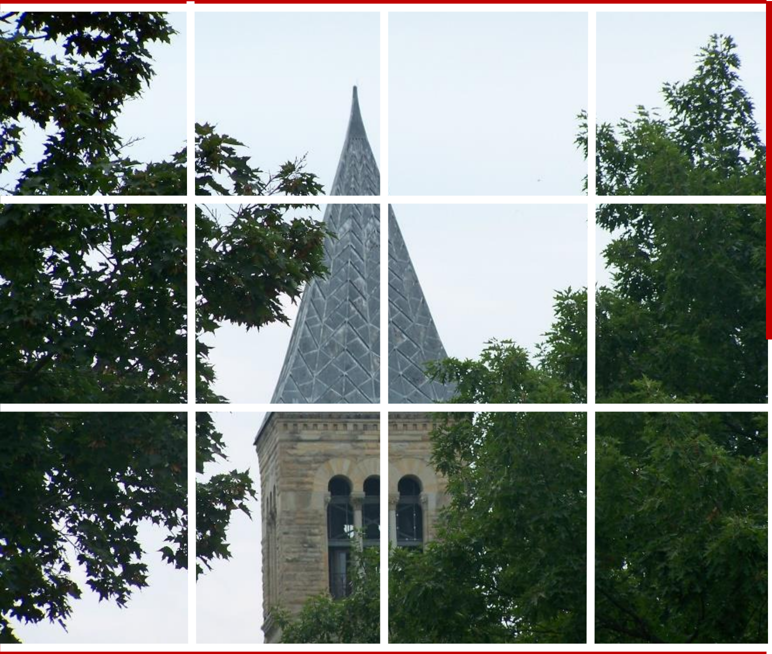

Vacuum Science and Technology for Particle Accelerators

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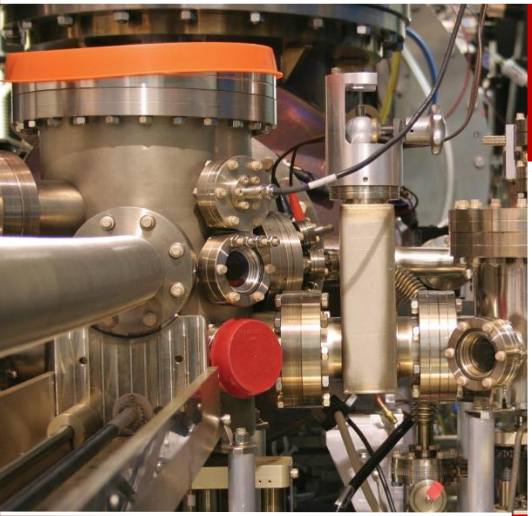
SLAC National Accelerator Laboratory

Albuquerque, New Mexico
June 17-28, 2019

Cornell Laboratory
for Accelerator-based Sciences
and Education (CLASSE)

SLAC NATIONAL ACCELERATOR LABORATORY



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

The US Particle Accelerator School
Cryosorption Pumps

Credit: Lou Bertolini
Lawrence Livermore National Laboratory

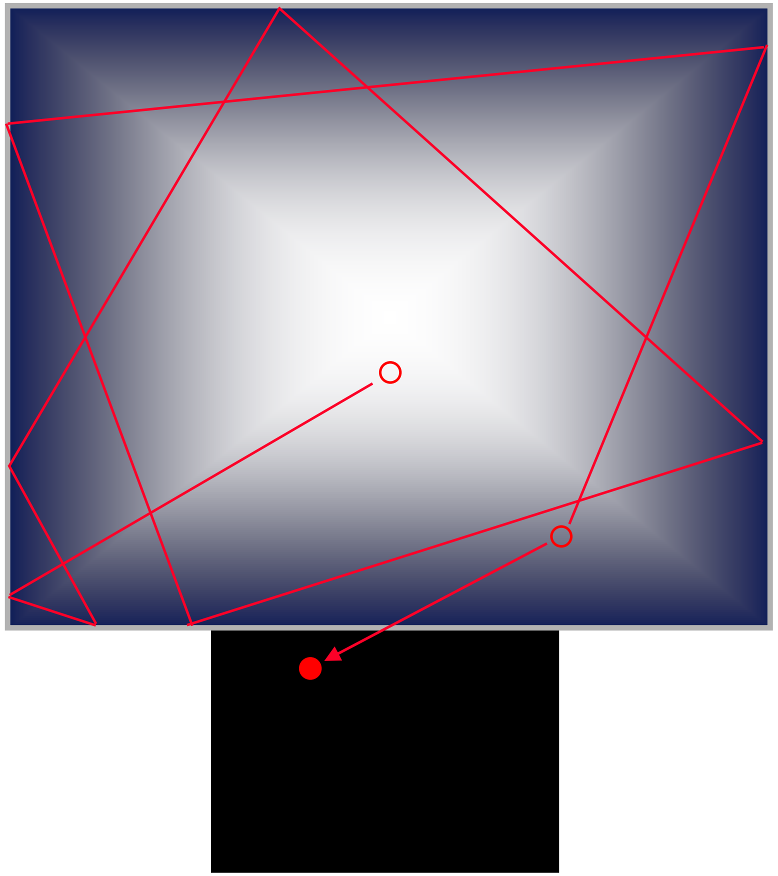
January 21-26, 2007

Updated: 5/1/2019 (Yulin Li)

Cryopumping Basics . . . Cryocondensation

Cooling gases to the extent that gas molecules lose sufficient energy to form condensation layers.

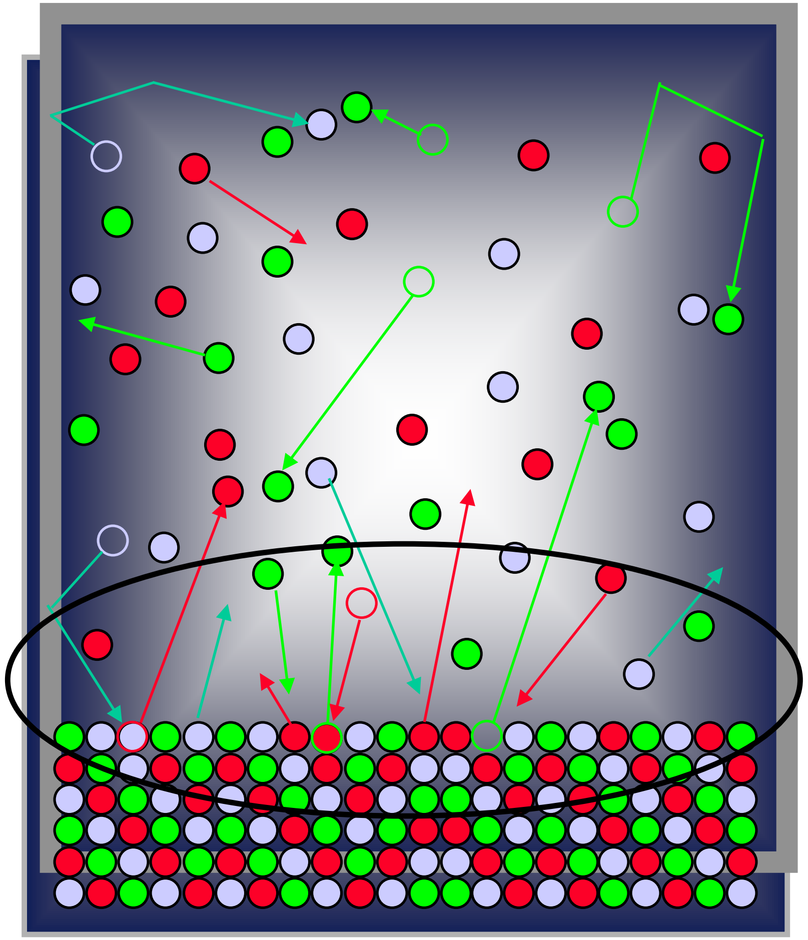
- A cryogenic surface will trap any molecule that contacts the surface if it is cold enough.



Cryopumping Basics . . . Equilibrium Vapor Pressure

Equilibrium vapor pressure is the state where as many molecules are condensing as are vaporizing.

Equilibrium occurs when the rate of gas molecules returning to the liquid/solid (condensing) is equal to the rate of energetic molecules becoming gaseous (vaporizing).

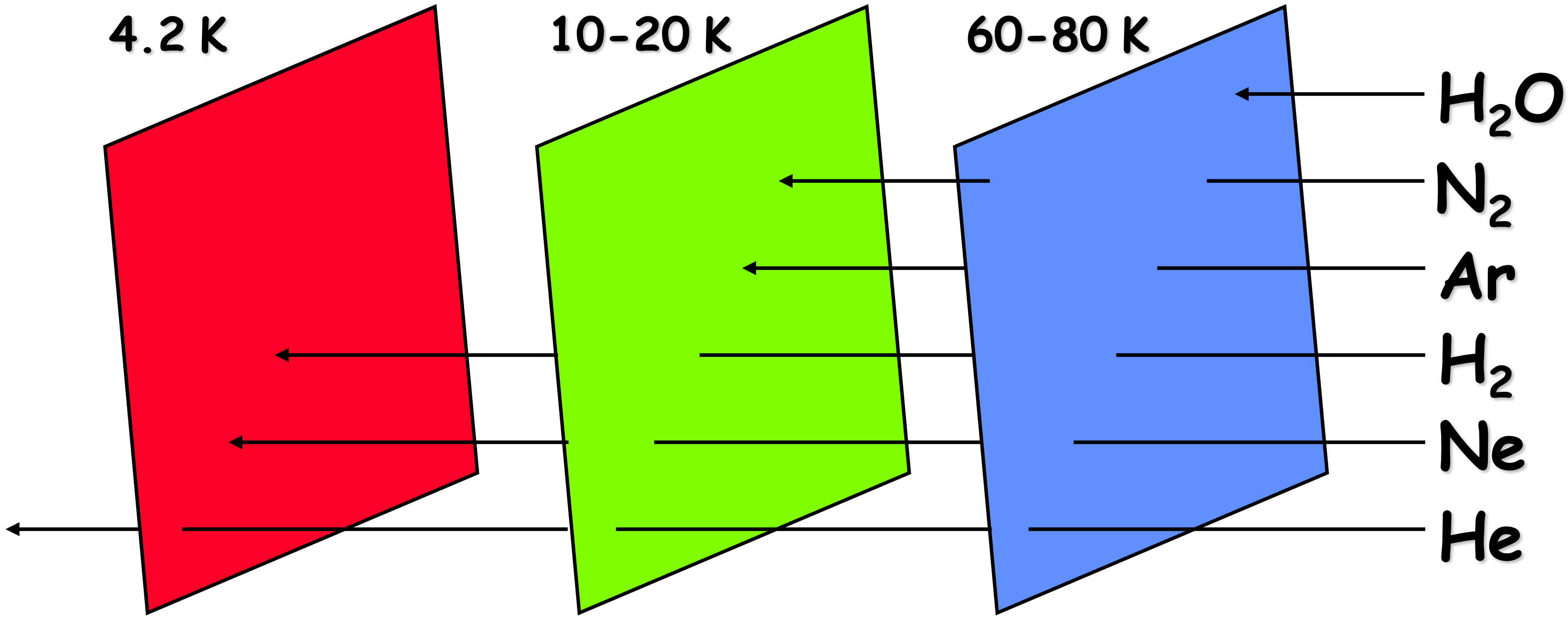


Cryopumping Basics . . . Pressure within a Cryopump

What determines the Pressure inside a Cryopump?

Surface Temp.	at 16K	at 25K	at 31K
•Nitrogen	> 10^{-12} Torr	> 10^{-7} Torr	> 10^{-4} Torr
•Argon	> 10^{-12} Torr	> 10^{-9} Torr	> 10^{-4} Torr
•Oxygen	> 10^{-12} Torr	> 10^{-10}Torr	> 10^{-4} Torr
•Hydrogen	> 10^{+2} Torr		
•Helium	> Atm.		

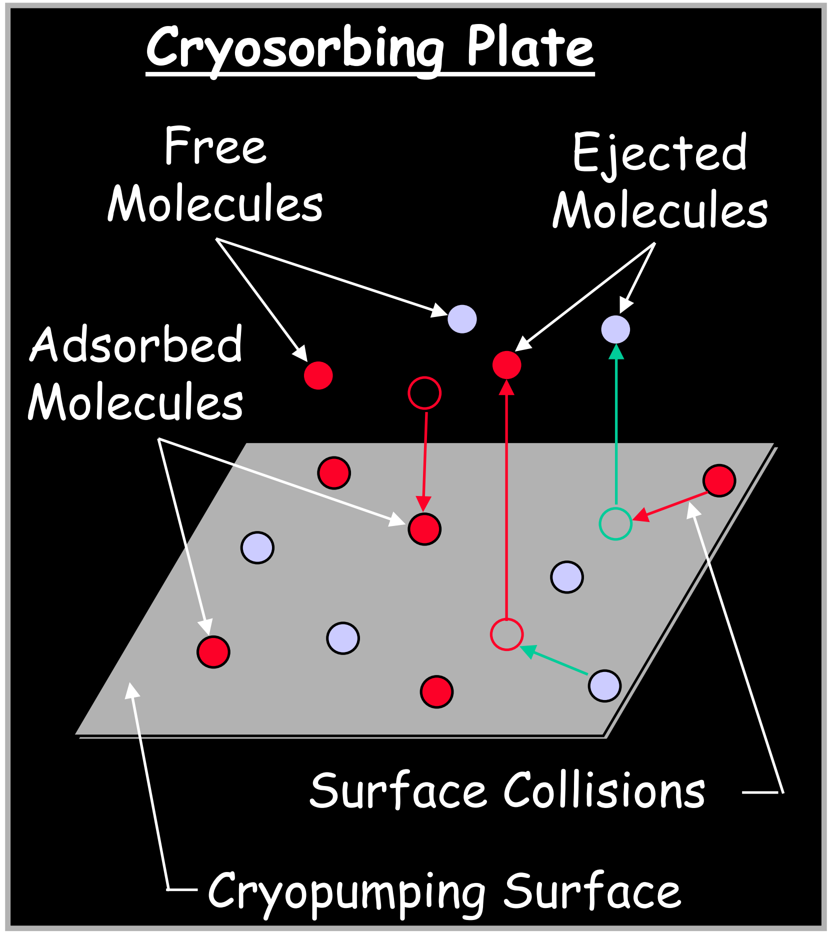
Cryopumping Basics . . . Cryocondensation



Cryopumping Basics . . . Cryosorption

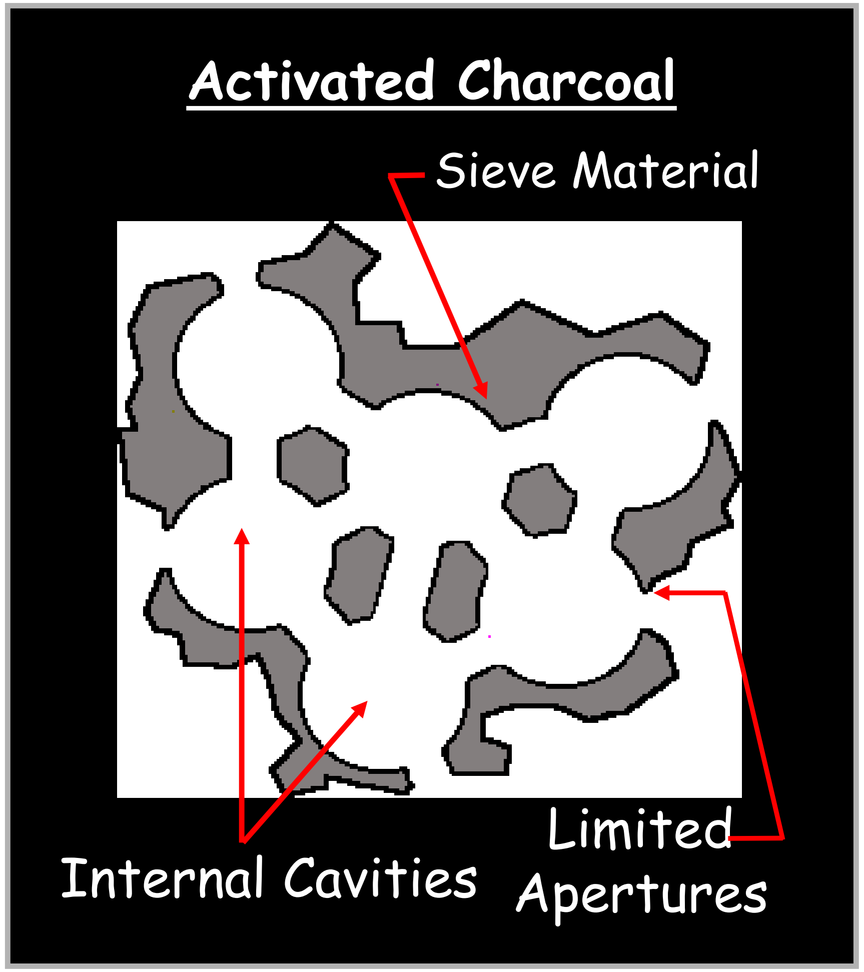
Cooling gas molecules to the extent that gas molecules, upon contacting a sufficiently cooled surface, lose enough energy to accumulate on the surface.

- A flat cryo-adsorbing plate retains some molecules.
- Flat surface allows molecules to continue moving.



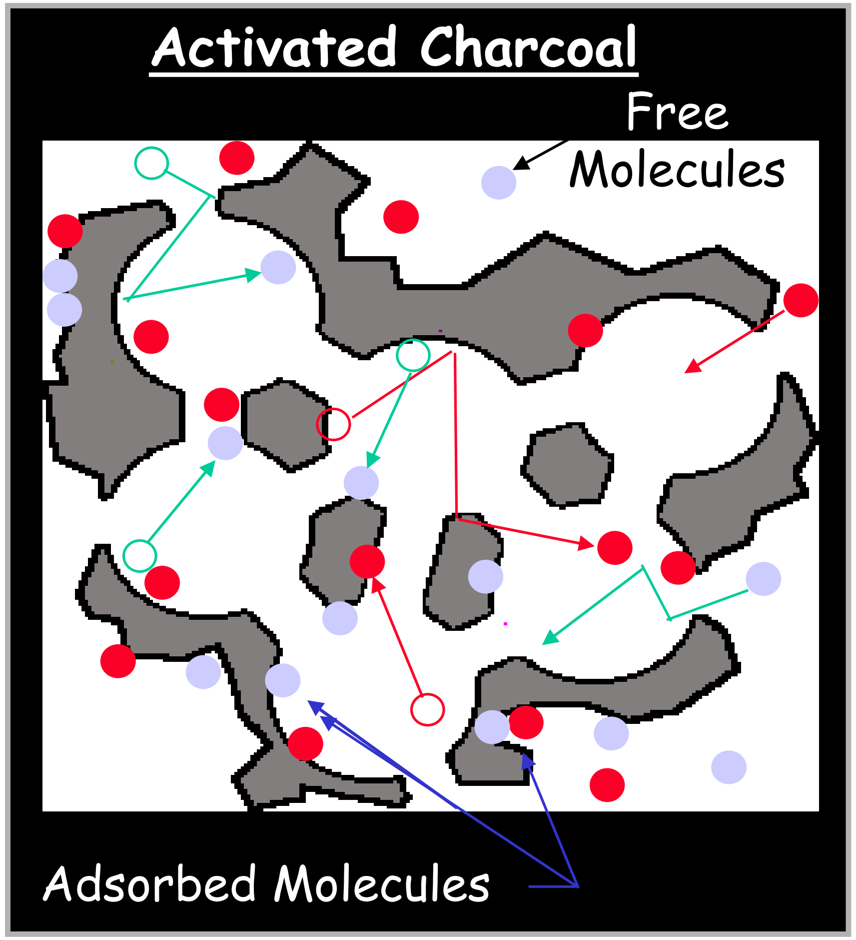
Cryopumping Basics . . . Cryosorption

- Sieve material, such as Zeolite, charcoal, provides greater surface area and limited apertures.
- Large surface area capacity; 1150-1250 m^2/gm



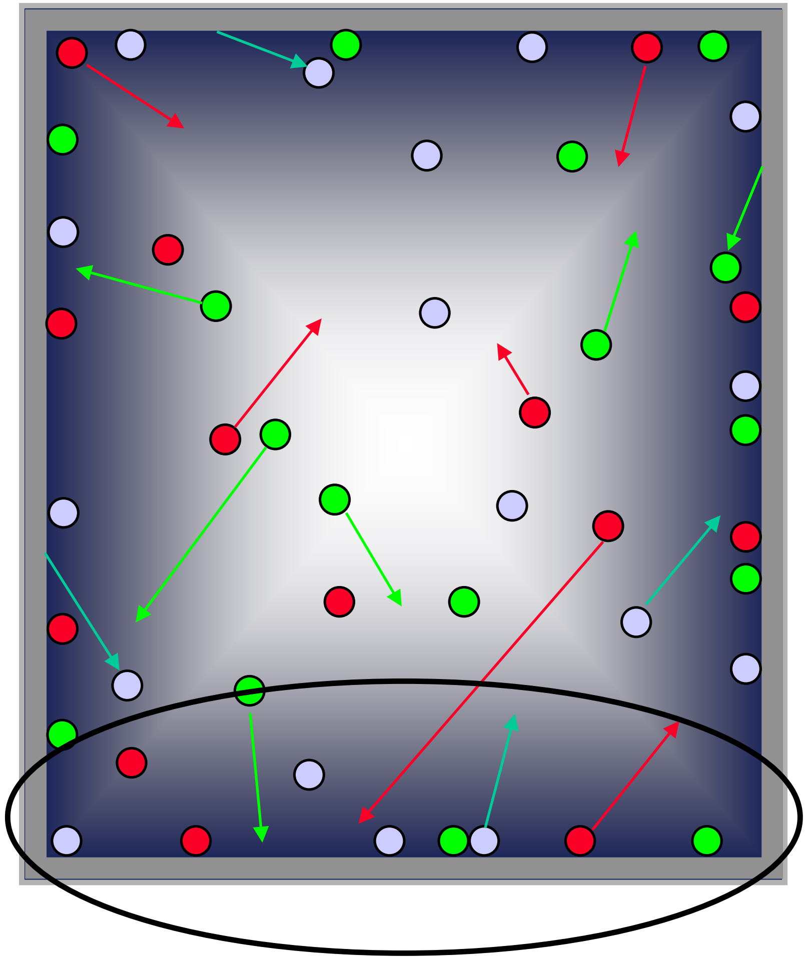
Cryopumping Basics . . . Cryosorption

- Increased surface area provides greater capacity.
- Released molecules remain confined.
- Irregular surface constricts motion.
- Cryosorption of hydrogen, neon, and helium accomplished.



Cryopumping Basics . . . Surface Equilibrium

When the number of molecules 'sticking' on the chamber surface (adsorbing) equals the number leaving the surface (desorbing), then the system is in "Surface Equilibrium".



Equilibrium

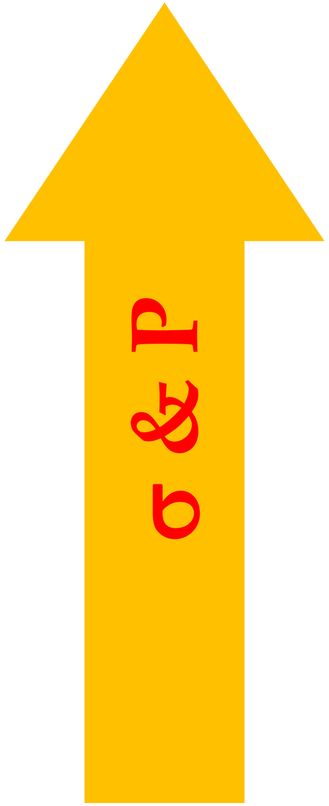
Equilibrium Vapor Pressure:

- CONDENSATION
- VAPORIZATION

Surface Equilibrium:

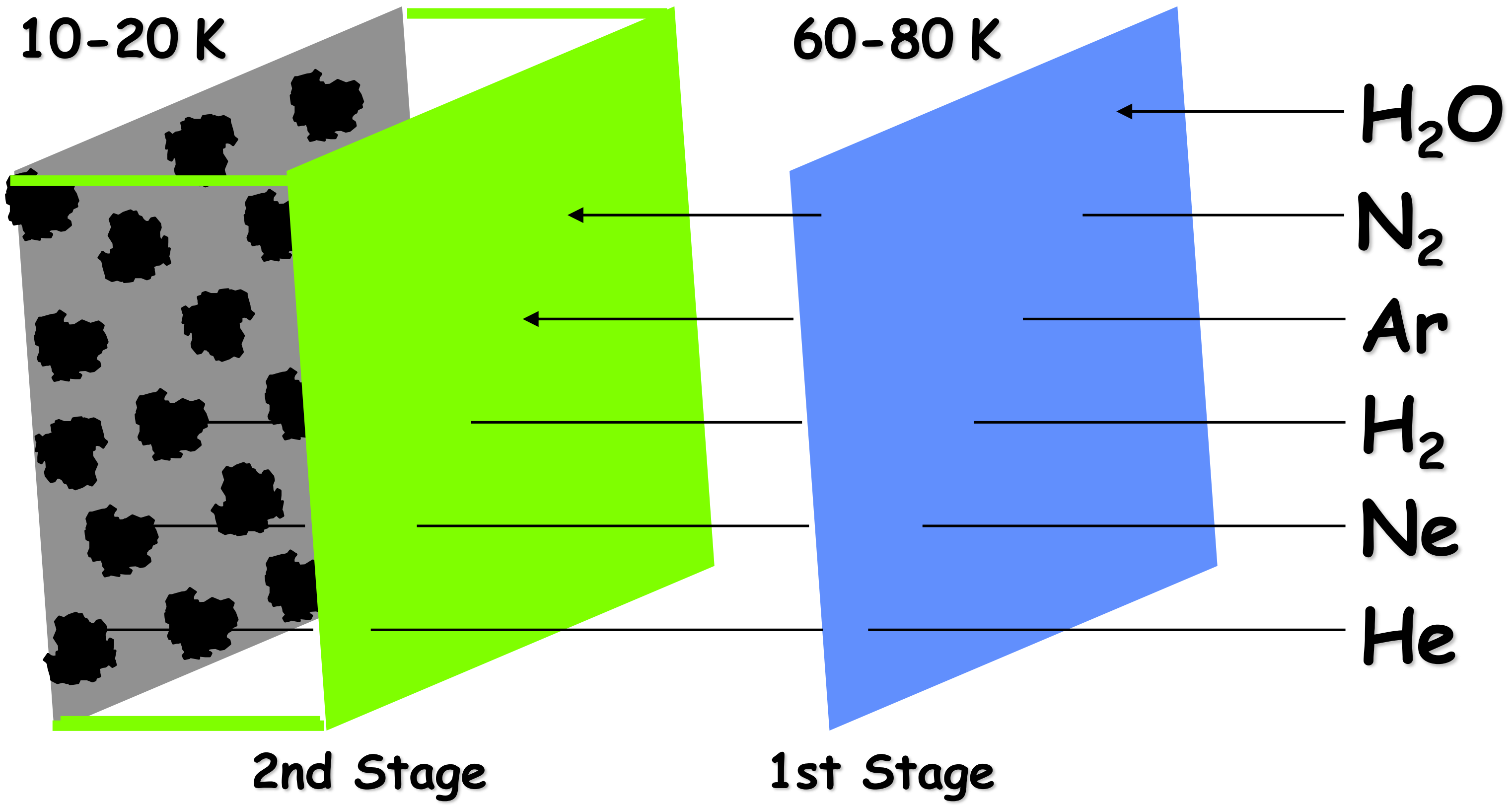
- ADSORPTION
- DESORPTION

σ < a few monolayers



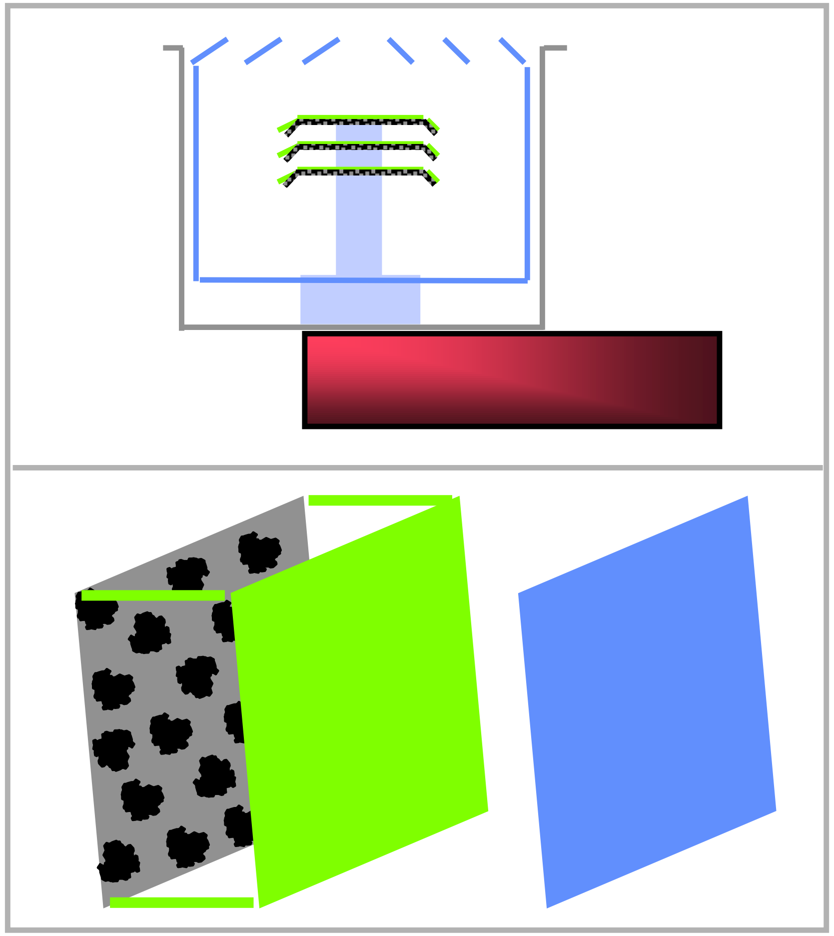
Cryopumping Basics . . . Cryosorption and Cryocondensation

Air gases and water vapor are condensed, non-condensible gases are captured.



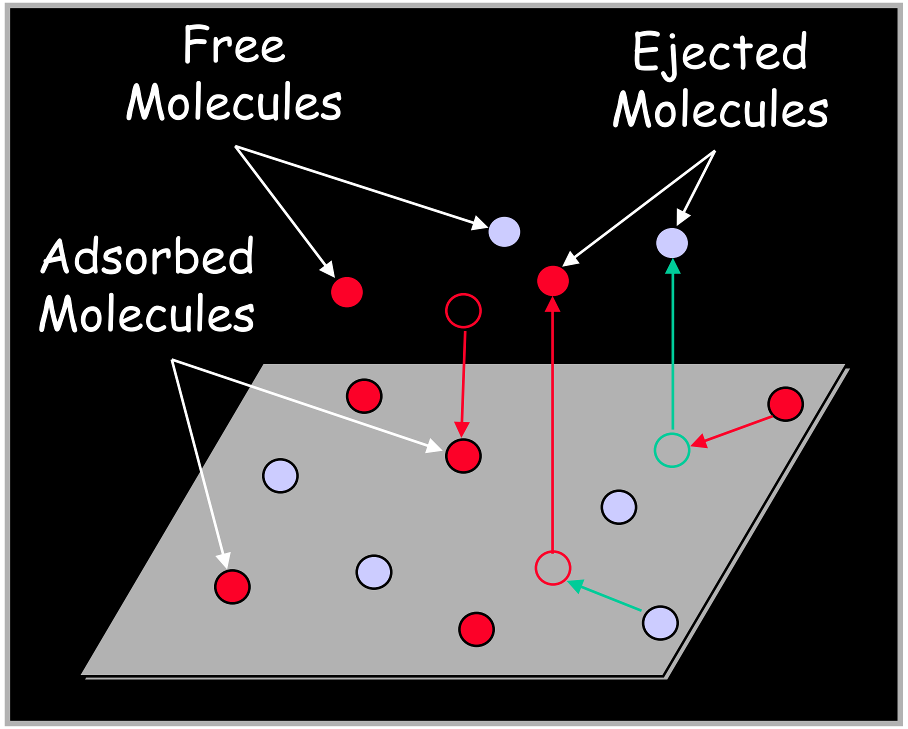
Cryopump Concept

- Cryopumps are designed to create these condensing and adsorbing surfaces.



Cryopumping Basics . . . Adsorption Isotherm

An adsorption isotherm is a measure of the surface population density of a gas at a constant temperature.

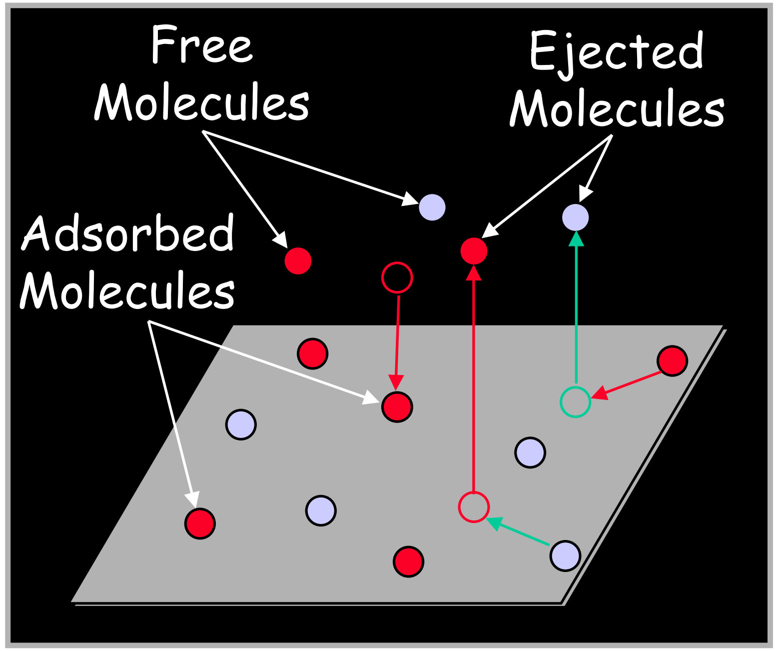


$$\sigma = f(P, T)$$

where σ = density of molecules of gas on a surface per cm^2
P = equilibrium pressure of system
T = system temperature

Cryopumping Basics . . . Adsorption Isotherm

Adsorption isotherms can be expressed several ways:



% Coverage

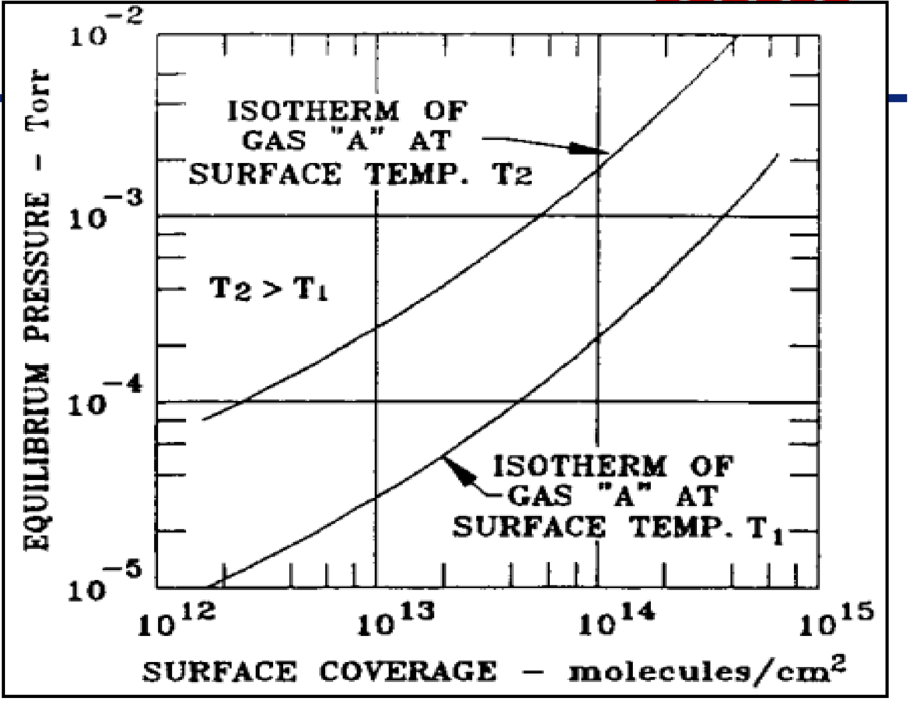
σ = 0.20 surface 20% covered
σ = 1 One monolayer (σ_m)
σ = 2 Two monolayers ($2\sigma_m$)

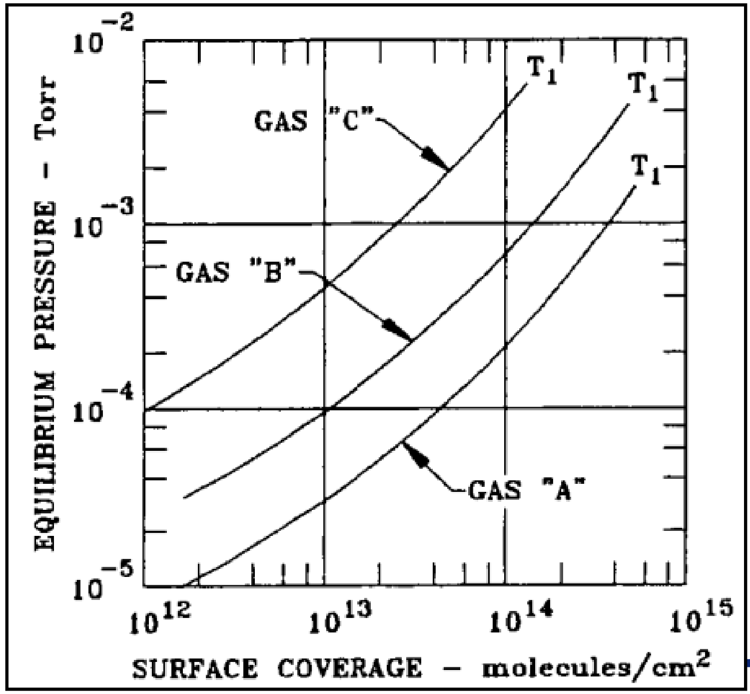
Molecules/cm^2

$\sigma = 10^{15}$ molecules/cm^2

Cryopumping Basics . . . Adsorption Isotherm

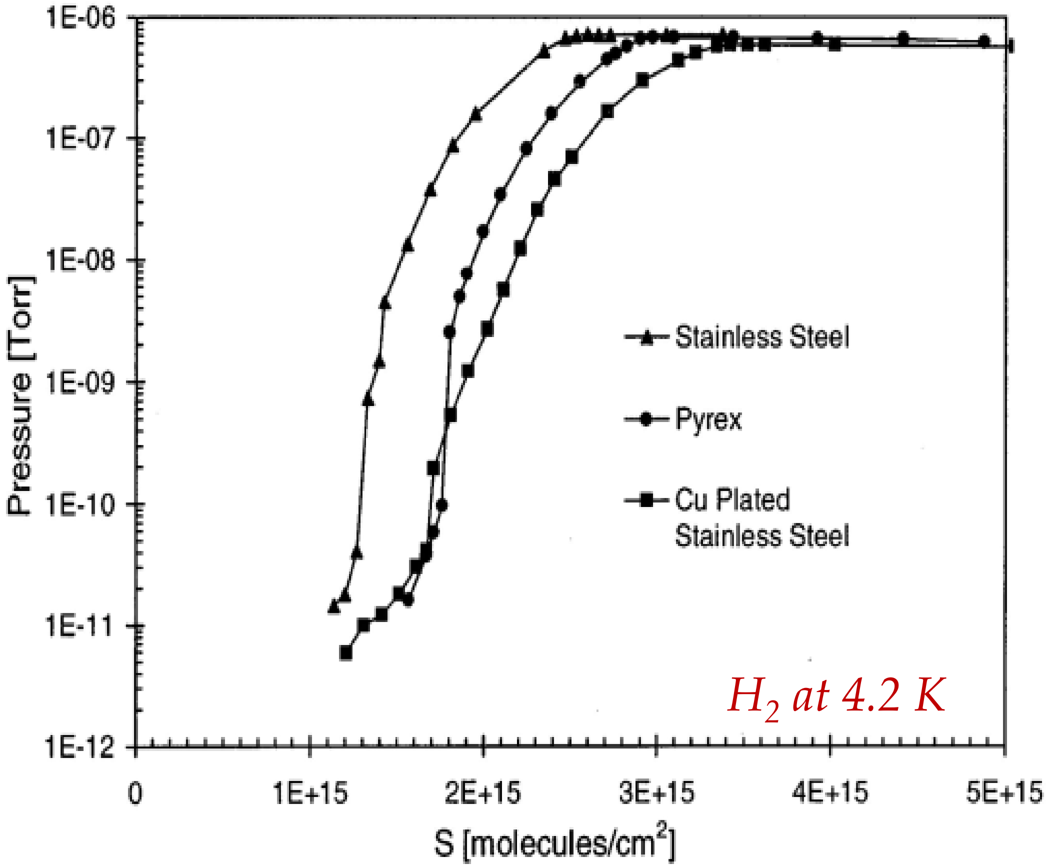
- Usually an adsorption isotherm represents pressure vs. coverage data at a specific temperature.
- As the temperature increases, the equilibrium pressure increases for a specific surface coverage.

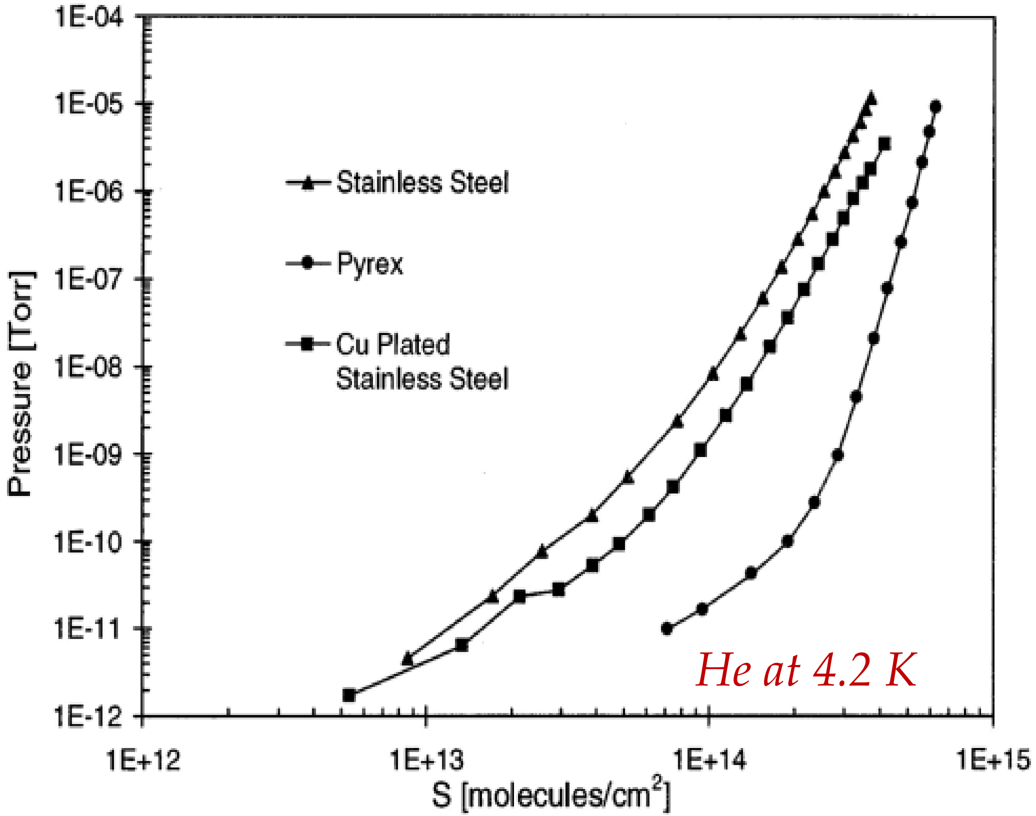




- For a given material surface, each gas has its own unique adsorption isotherm for the same temperature.
- For all gases, the equilibrium pressure of an adsorption isotherm is less than the vapor pressure at that temperature.
- As surface coverage goes up (to several monolayers), the equilibrium pressure will approach the vapor pressure.

Cryopumping Basics . . . Example Isotherms





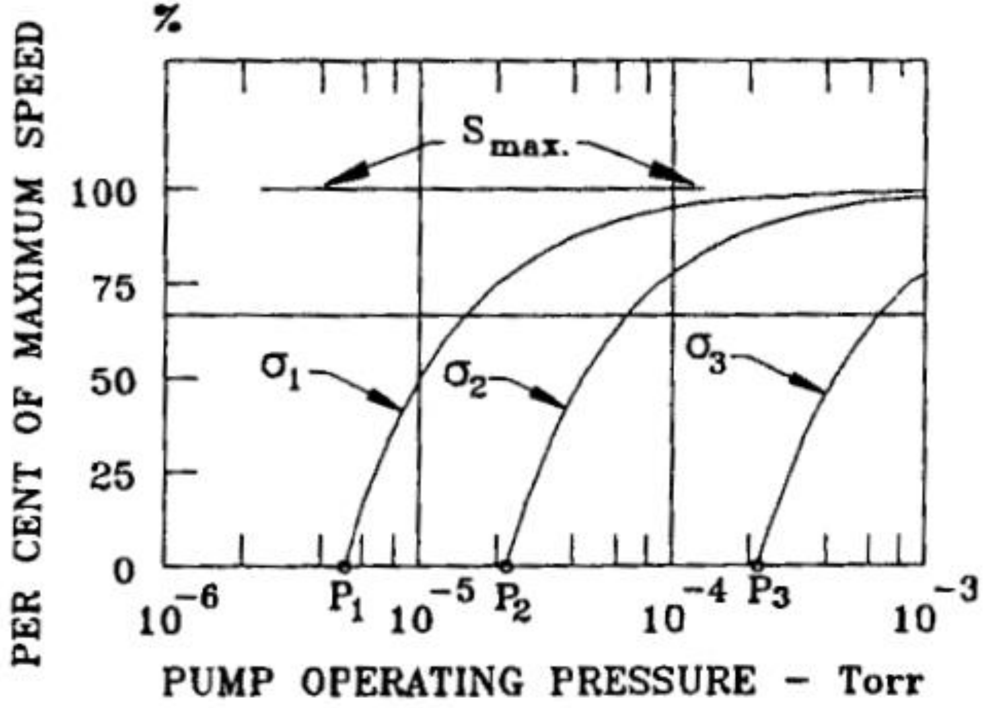
E. Wallen: "*Adsorption Isotherms of He and H_2 at Liquid Helium Temperature*", JVST **A15**, p.265

Cryopumping Basics . . . Pumping Speed

- A cold surface has a finite pumping speed for a gas as long as the pressure of the adsorption isotherm is less than the pressure of the gas.
- As the surface coverage increases, the equilibrium pressure (P_e) increases.

$$S = S_{max}\left(1 - \frac{P_e}{P}\right)$$

- S_{max} is set by the surface conductance limitations of the cryopump.



In cryosorption pumping, speed is dependent on the quantity of gas already adsorbed (σ) and the pressure. That is, a cryopump has a finite capacity.

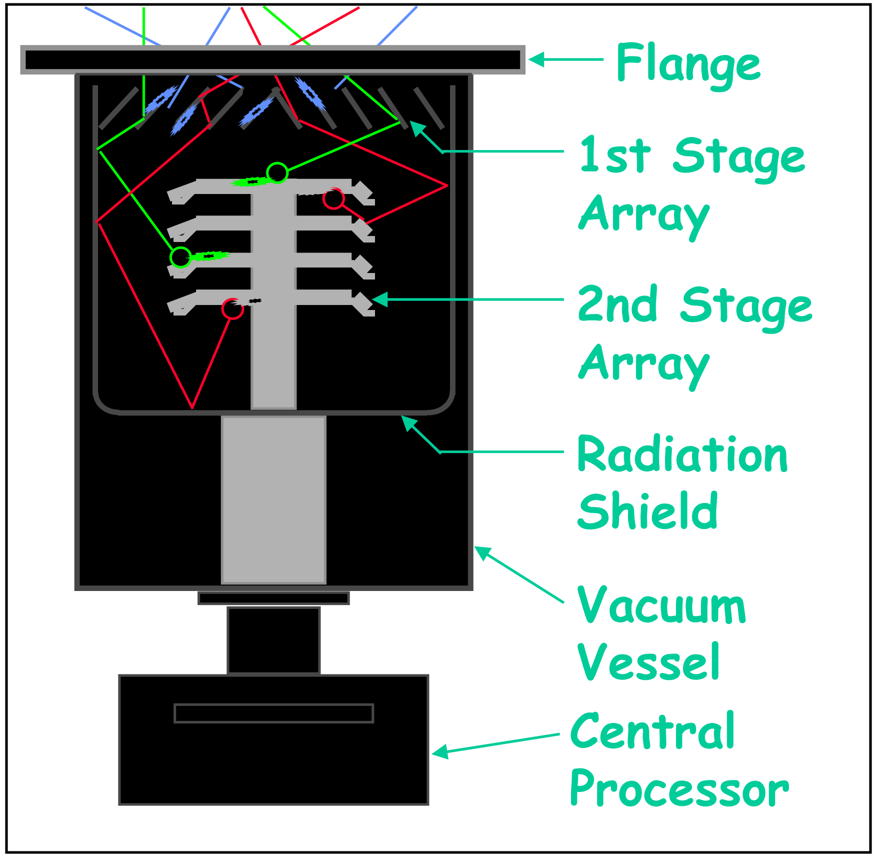
$$\sigma_1 < \sigma_2 < \sigma_3$$

Cryopumping Basics . . . Sticking Coefficients

CryoSurface Temperature (K)	Gas and Temperature									
	N_2		CO		O_2		Ar		CO_2	
	77 K	300 K	77 K	300 K	77 K	300 K	77 K	300 K	77 K	300 K
10	1.0	0.65	1.0	0.90			1.0	0.68	1.0	0.75
12.5	0.99	0.63	1.0	0.85			1.0	0.68	0.98	0.70
15	0.96	0.62	1.0	0.85			0.90	0.67	0.96	0.67
17.5	0.90	0.61	1.0	0.85	1.0	0.86	0.81	0.66	0.92	0.65
20	0.84	0.60	1.0	0.85			0.80	0.66	0.90	0.63
22.5	0.80	0.60	1.0	0.85			0.79	0.66	0.87	0.63
25	0.79	0.60	1.0	0.85			0.79	0.66	0.85	0.63
77									0.85	0.63

Ref. "Cryopumping", Dawson and Haygood, Cryogenics 5 (2), 57, (1965)

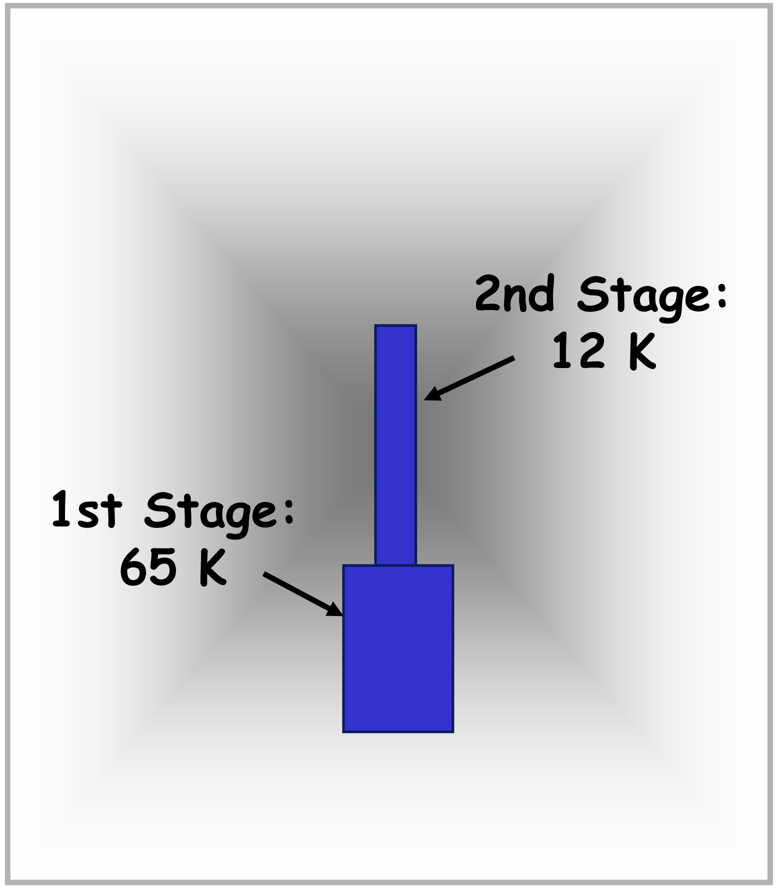
Cryopump Characteristics



- *No fluids, lubricants, or (in-vacuum) moving parts*
- *High crossover capability minimizes back-streaming*
- *High water pumping speed*
- *Tailorable pumping speeds*
- *Operate in all orientations*
- *Continuous backing not required*

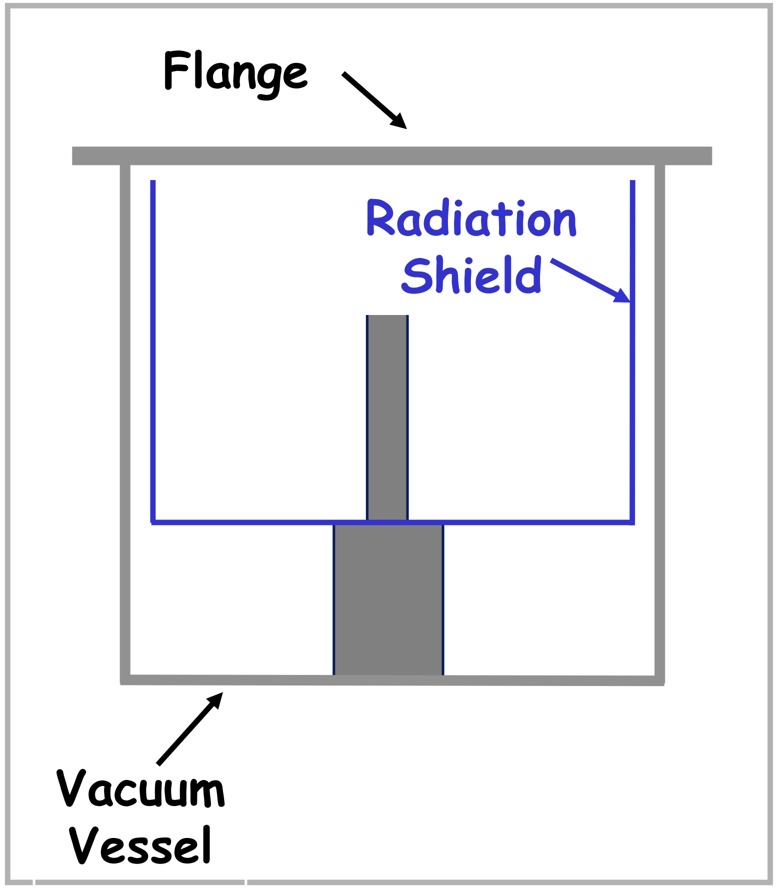
Cryopump Components . . .*The Cold-Head*

- A cryopump is built around the cold-head.
  - Creates the cold temperatures needed to condense and adsorb gases
  - Two stages, each at a different temperature
- Achieves these temperatures by the expansion of helium.



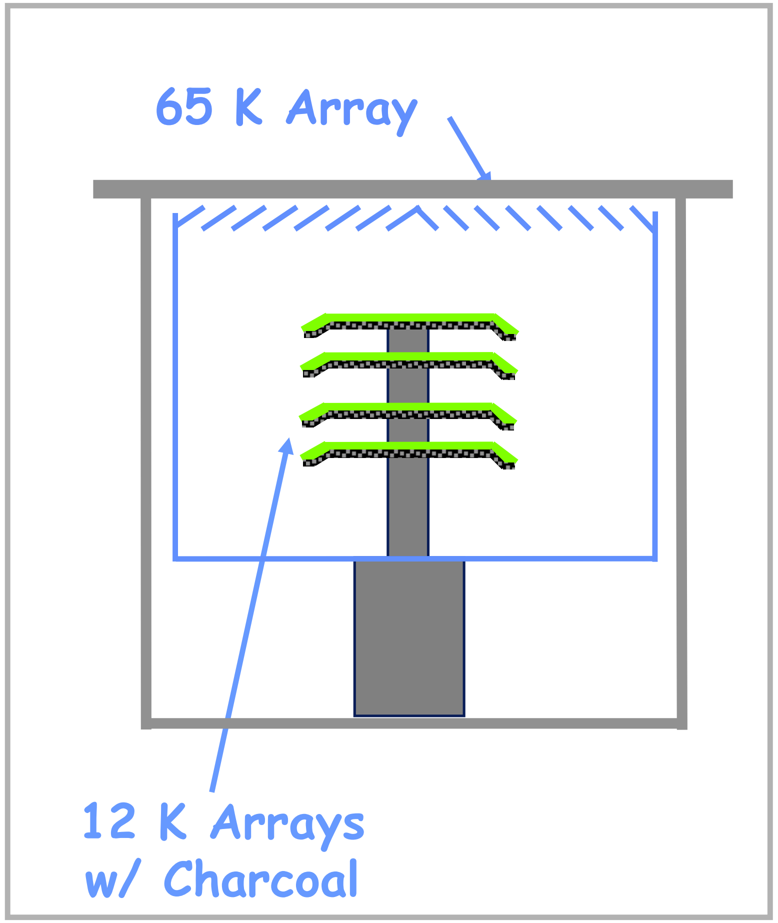
Cryopump Components . . .
shield, vacuum vessel, and flange

- A radiation shield is attached to the 1st stage of the cold-head.
  - Copper for conductivity
  - Nickel plating for protection
- The vacuum vessel isolates the cryopump.
- The inlet flange attaches to the chamber.

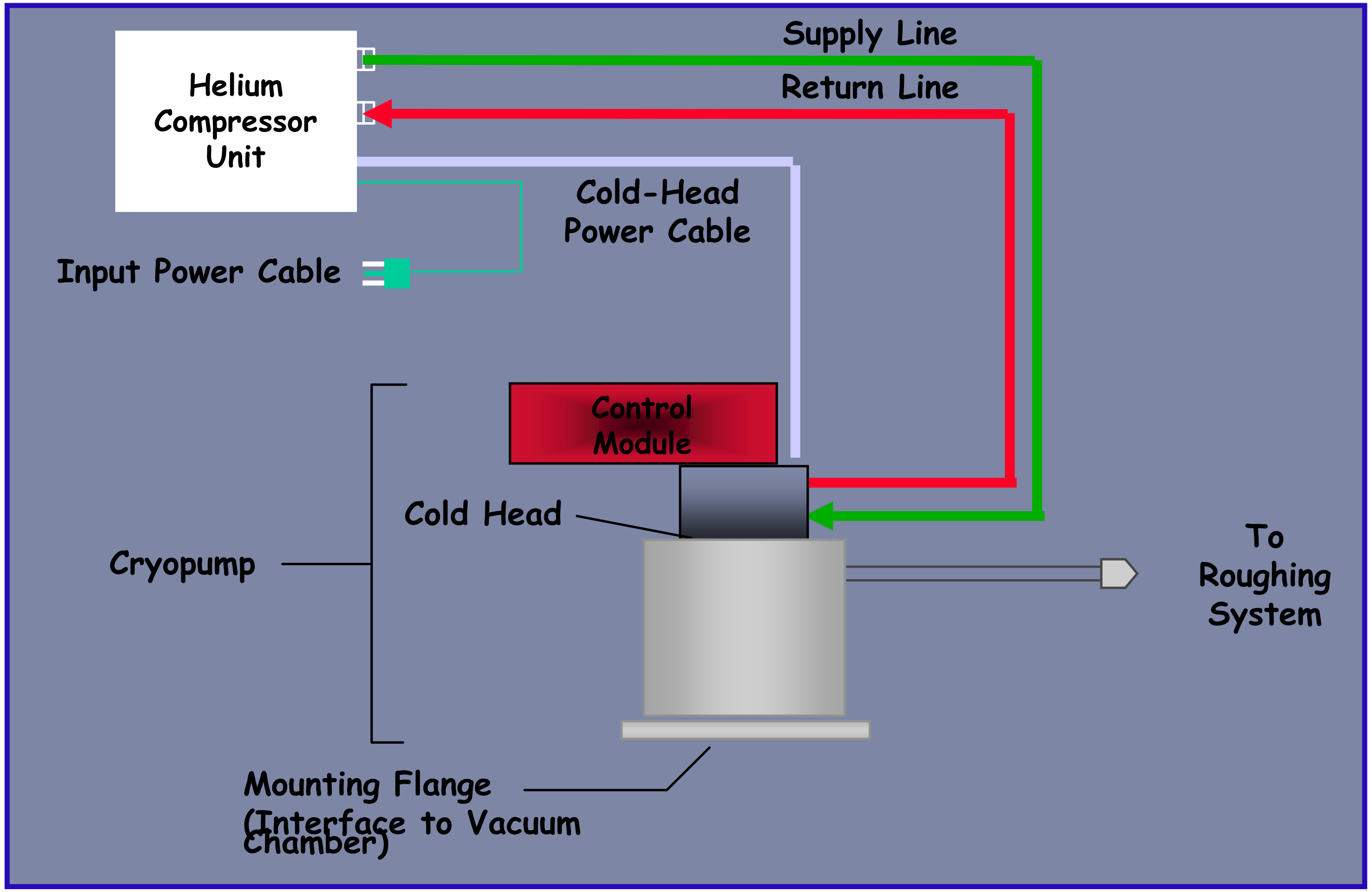


Cryopump Components . . . *1st and 2nd Stage Arrays*

- The 1st stage (65 K) array is attached to the radiation shield.
  - Condenses water vapor
- A series of arrays with charcoal are attached to the 2nd stage (12 K) of the cold-head.
  - Condenses O_2, N_2, Ar
  - Adsorbs H_2, He, Ne



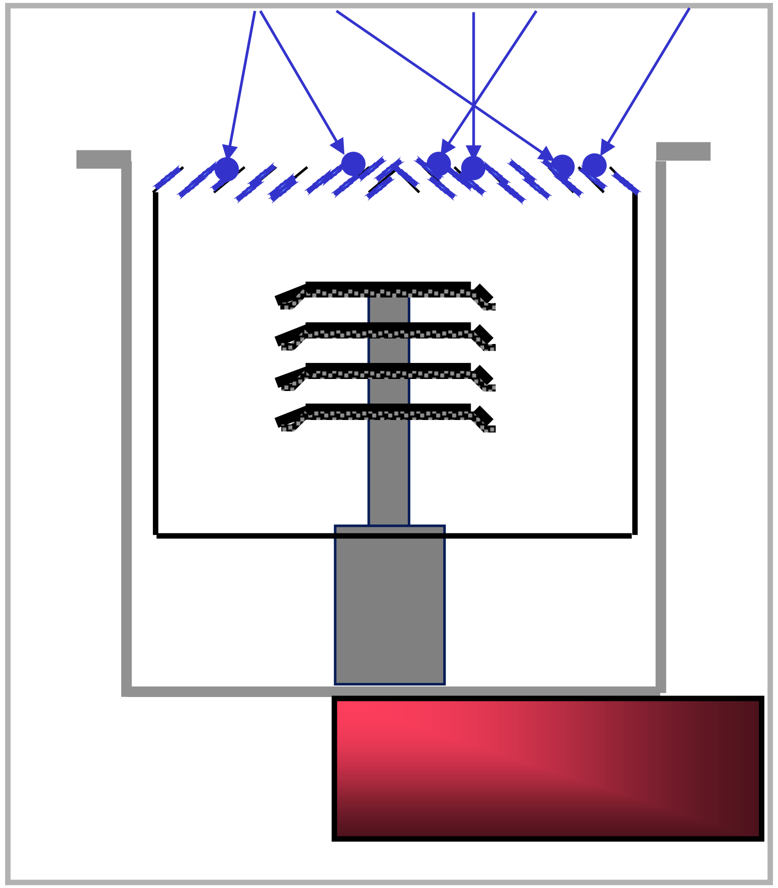
Cryopump System Overview



Cryopump Operation - *Cryocondensation*

- Water molecules collide with the cooled surfaces of the 65 K first stage array.

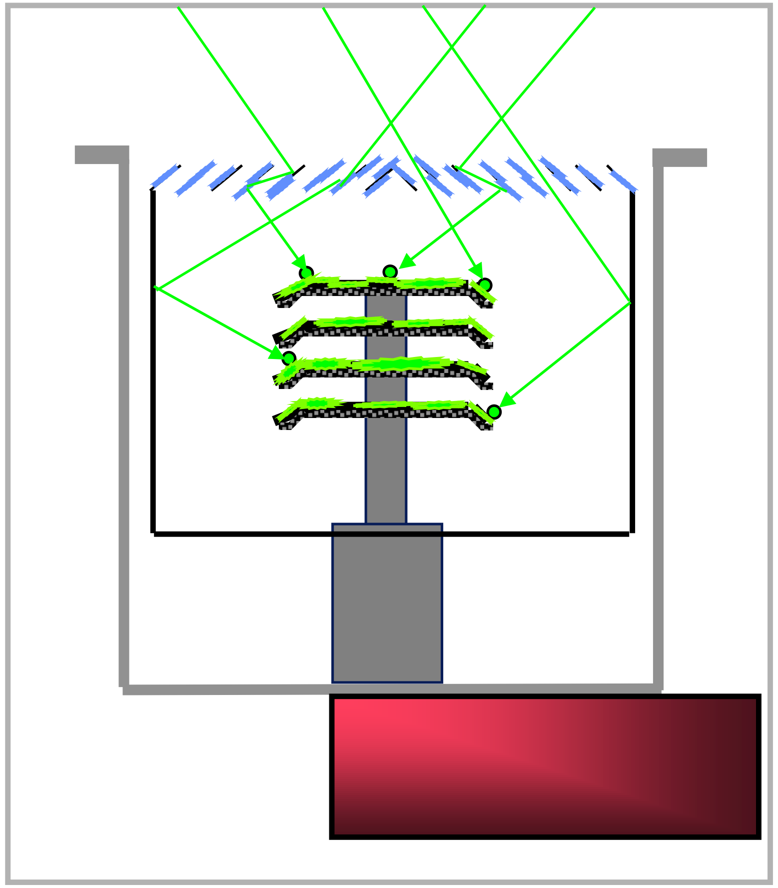
- Condensation layers form as more of these molecules collect.



Cryopump Operation - *Cryocondensation*

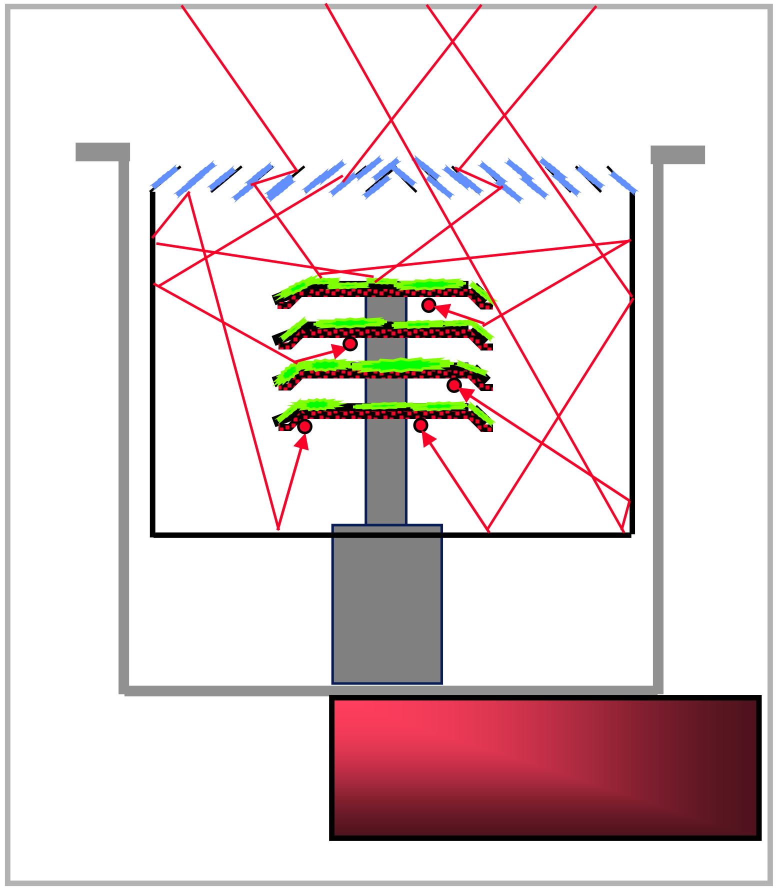
- Other molecules such as oxygen, nitrogen, and argon pass between the first stage arrays.

- By colliding with the 12 K second stage arrays, these molecules also form condensation layers.



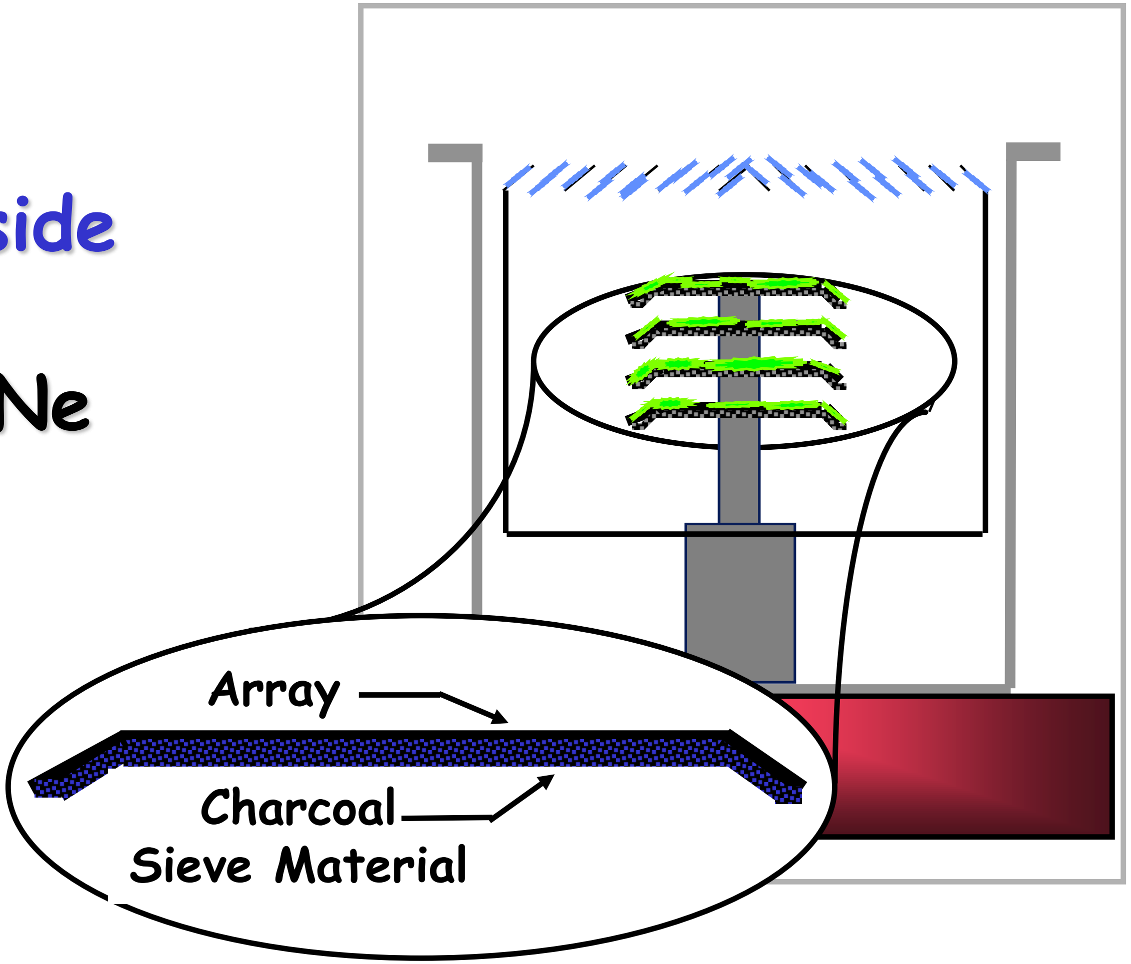
Cryopump Operation - *Cryoadsorption*

- The noncondensible H_2, He, and Ne molecules pass between the first stage arrays.
- Collide with walls and second stage arrays.
- Become adsorbed upon contacting the charcoal surfaces.



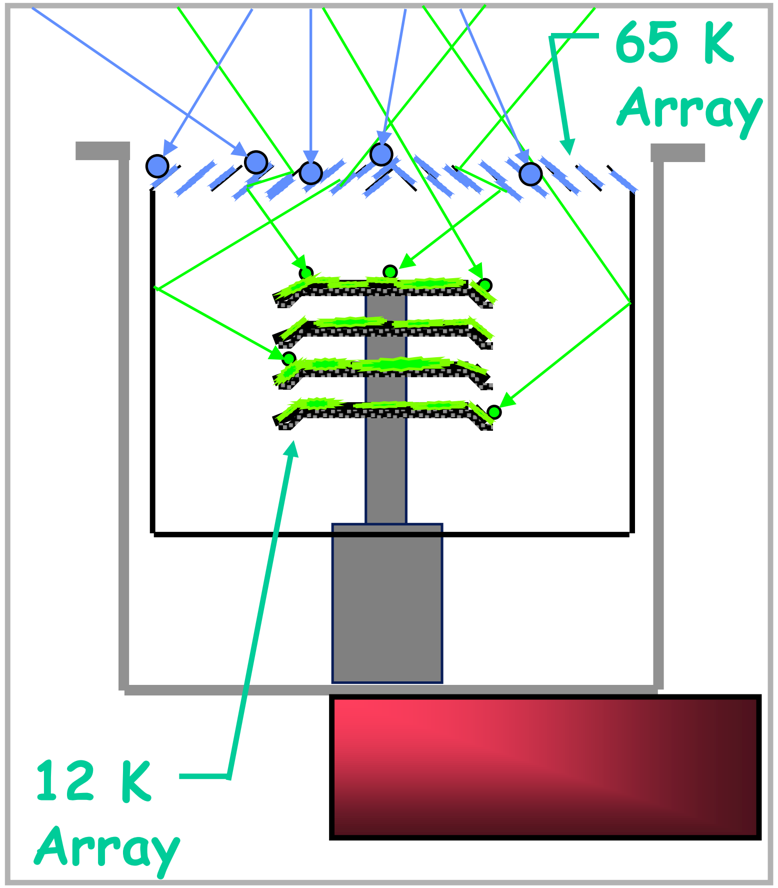
Cryopump Operation - Cryoadsorption

- Affixing activated charcoal sieve material to the underside of the 12 K second stage arrays, allows H_2, He, and Ne to be cryo-adsorbed.



Cryopump Operation – *Argon Hang-Up*

During normal operation, water vapor is condensed on the 65 K first stage array while oxygen, nitrogen, and argon are condensed on the 12 K second stage array.

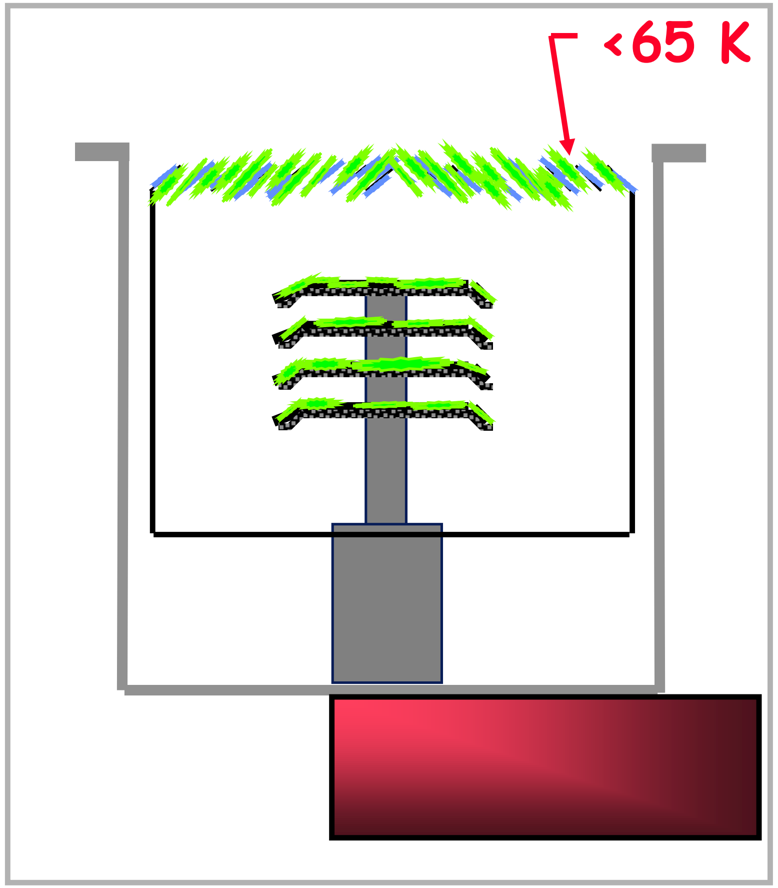


Cryopump Operation – *Argon Hang-Up*

- Argon Hang-Up can occur if the first stage gets too cold.

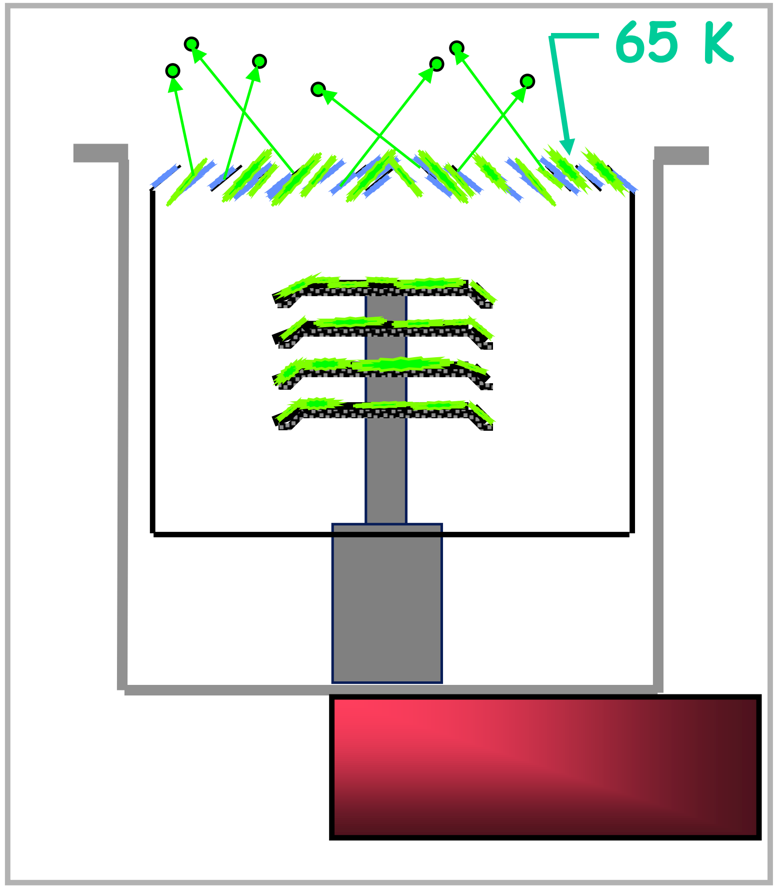
- Results in argon being condensed (pumped) on the first stage.

- Where it stays until lower partial pressures are reached.



Cryopump Operation – *Argon Hang-Up*

- When the equilibrium pressure is reached.
  - Argon liberates
  - Pumpdown slows
  - Causes "False Full" condition

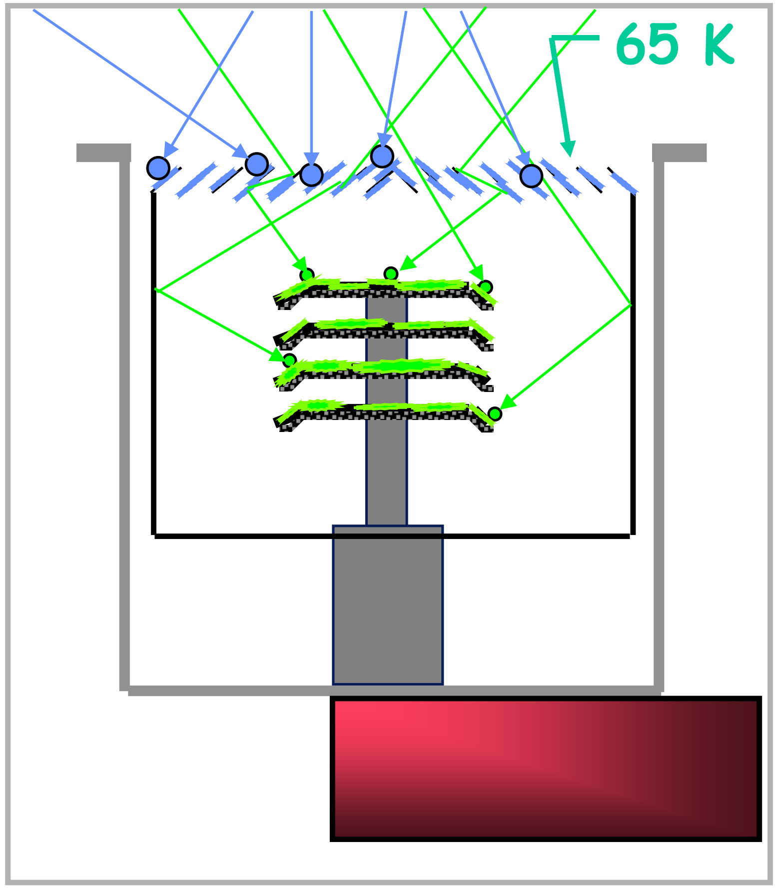


EQUILIBRIUM VAPOR PRESSURE

	10^{-10}	10^{-7}	10^{-4}	10^{-3}
Water	130K	153K	185K	198.5K
Argon	23.7K	28.6K	35.9K	39.2K

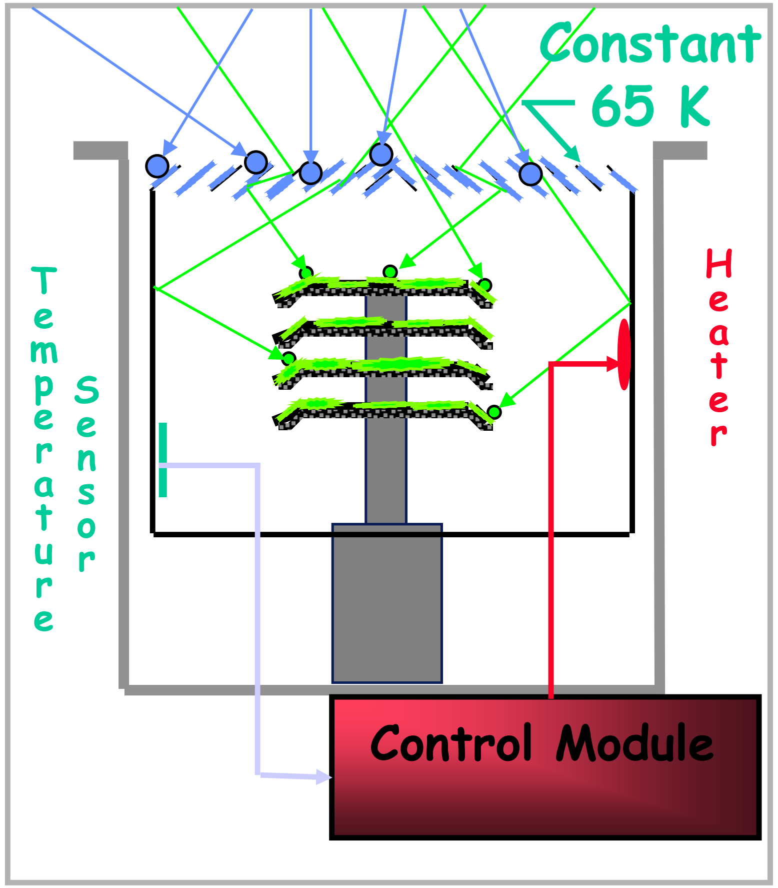
Cryopump Operation – *Argon Hang-Up*

- *Argon liberates until it is repumped onto the second stage where it should have been pumped.*



Cryopump Operation – *Argon Hang-Up*

- Argon Hang-Up can be avoided with modern controllers interfaced to the first stage sensor and heater.
  - Monitors and controls temperature
  - Prevents a "Too Cold" condition



Cryopump Example Parameters

Listed performance data (averaging from the catalogue of different manufacturers) for a typical 3000 l/s class two-stage cryopump

Parameter	Value
Pumping speed (l/s) water	9000–10500
Air	3000–3250
Hydrogen	4500–5200
Argon	2500–2700
Helium	1500–2300
Maximum throughput (Pa·m³/s) argon	1.0–2.5
Hydrogen	1.2
Pumping capacity (Pa·m³) argon	1.5×10^5–3×10^5
Hydrogen	1500–5000
Helium	10–100
Ultimate pressure (N_2 equivalent) (Pa)	$10^{-9} – 10^{-10}$
Cool-down time (h)	1.5–2.5
Crossover (Pa·m³)	35–50
Weight (kg)	30–50

Cryopump Operation . . . Crossover

During chamber evacuation, when should the high-vacuum valve be opened?

For cryopumps, the maximum crossover capability is specified as the impulsive mass input that causes the second stage to rise no higher than 20 K.

Cryopump Operation . . . Crossover

Example: Crossover Pressure Calculation

Crossover value for a CTI On-Board 8 = 150 Torr-liters

Crossover formula: $\frac{\text{Crossover value}}{\text{Chamber volume}}$ = P in Torr

$$\frac{150 \text{ Torr-liters}}{300 \text{ liters}} = .5 \text{ Torr or } 500 \text{ milliTorr}$$

Understanding crossover can produce faster pumpdown times and cleaner vacuum too.

Cryopump Operation . . . Regeneration

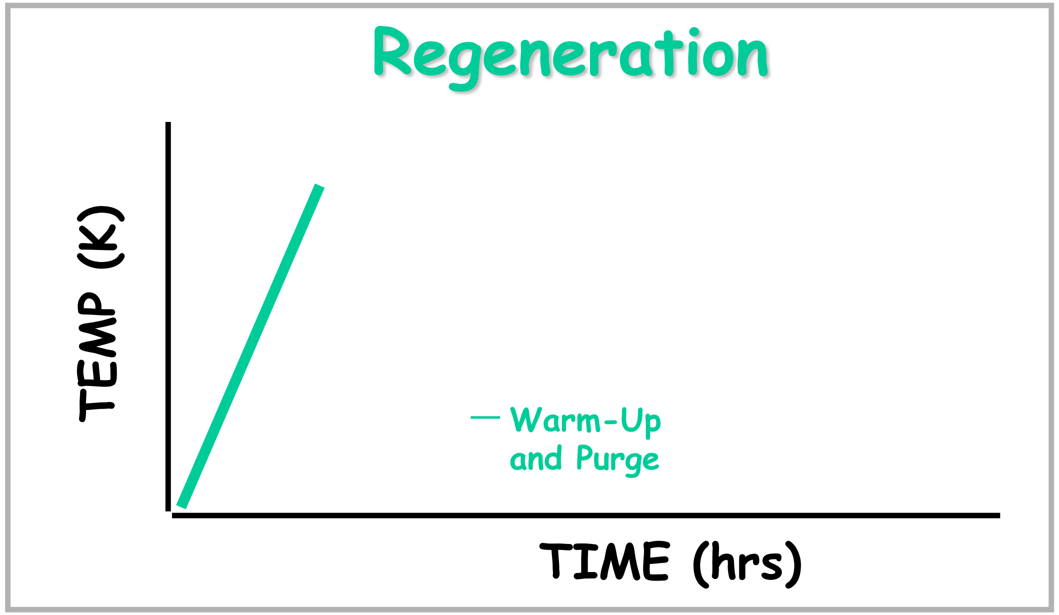
The objective of regenerating a cryopump is to remove the captured gases from the pump and restore its pumping capacity.

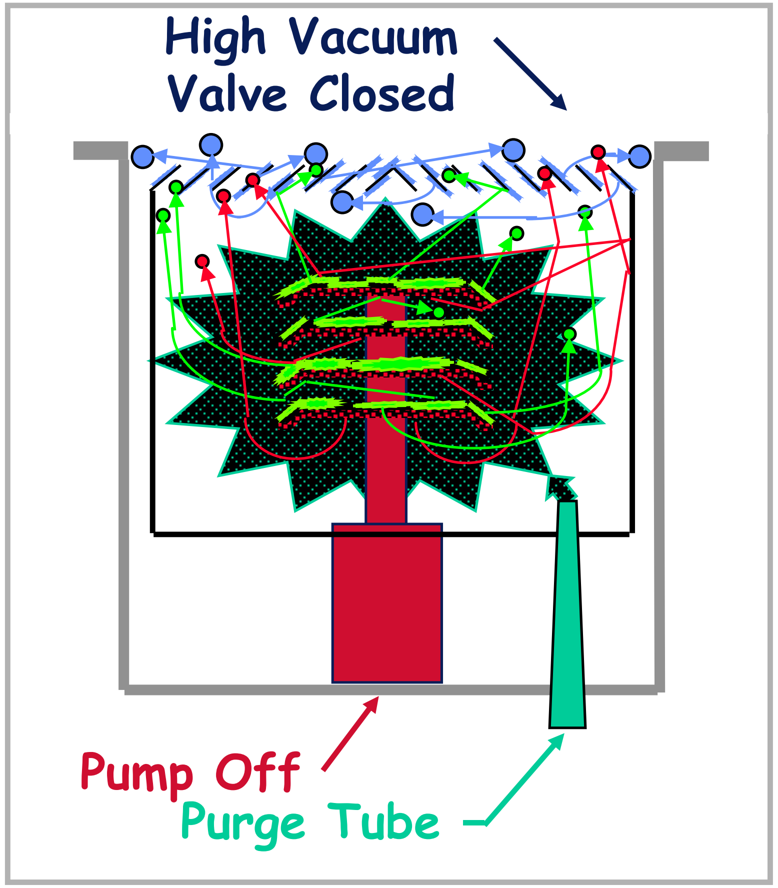
So . .. when should cryopumps be regenerated?

Whenever your system is down is a good opportunity to regenerate your cryopump without affecting your up-time.

Cryopump Operation . . . Regeneration

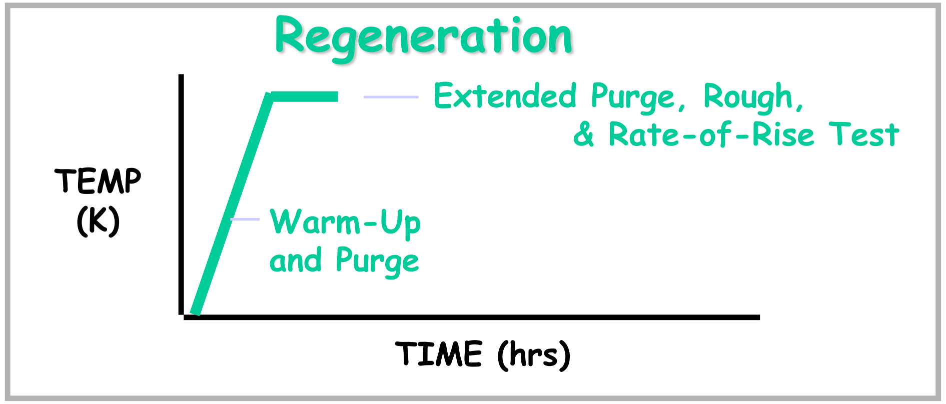
- Regeneration
  - Warm-Up and Purge

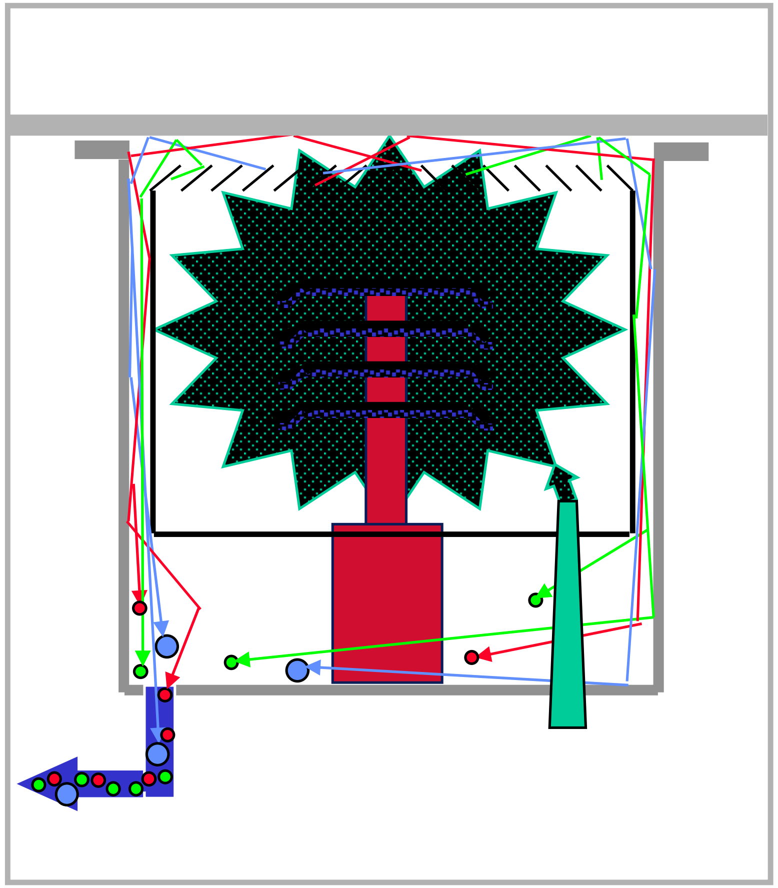




Cryopump Operation . . . *Regeneration*

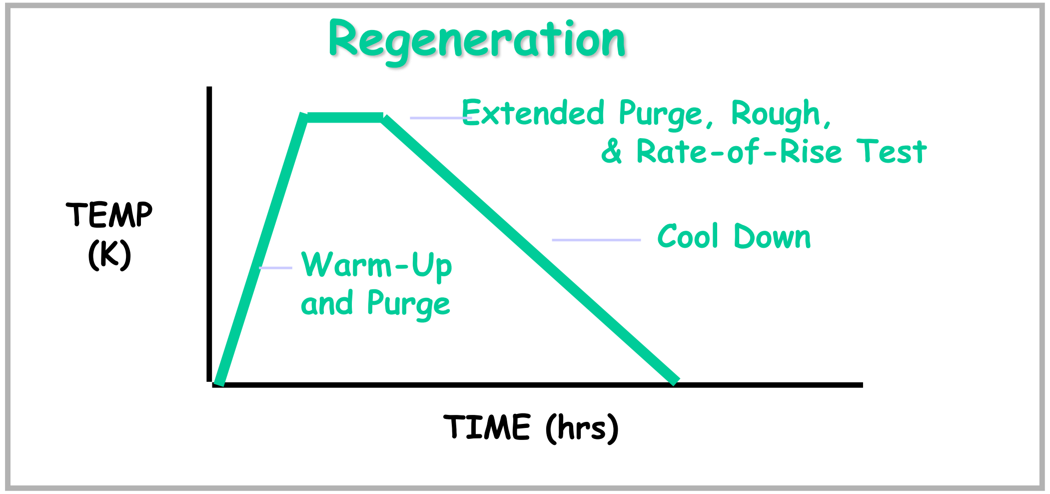
- Regeneration
  - Warm-Up and Purge
  - Extended Purge
  - Rough Out
  - Rate-of-Rise (ROR) Test

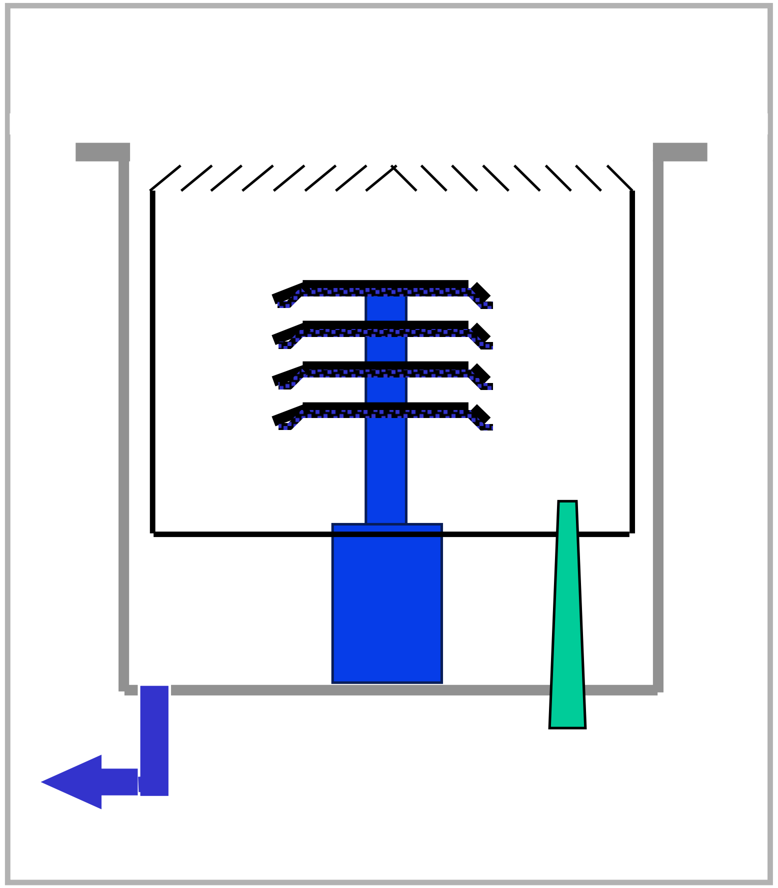




Cryopump Operation . . . Regeneration

- Regeneration
  - Warm-Up and Purge
  - Extended Purge
  - Rough Out
  - Rate-of-Rise (ROR) Test
  - Cool Down

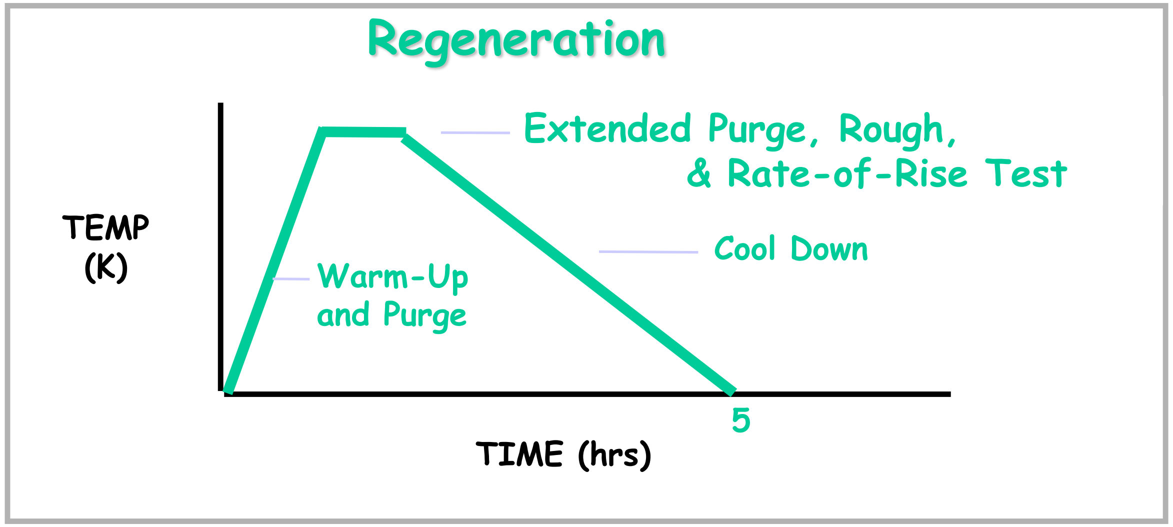


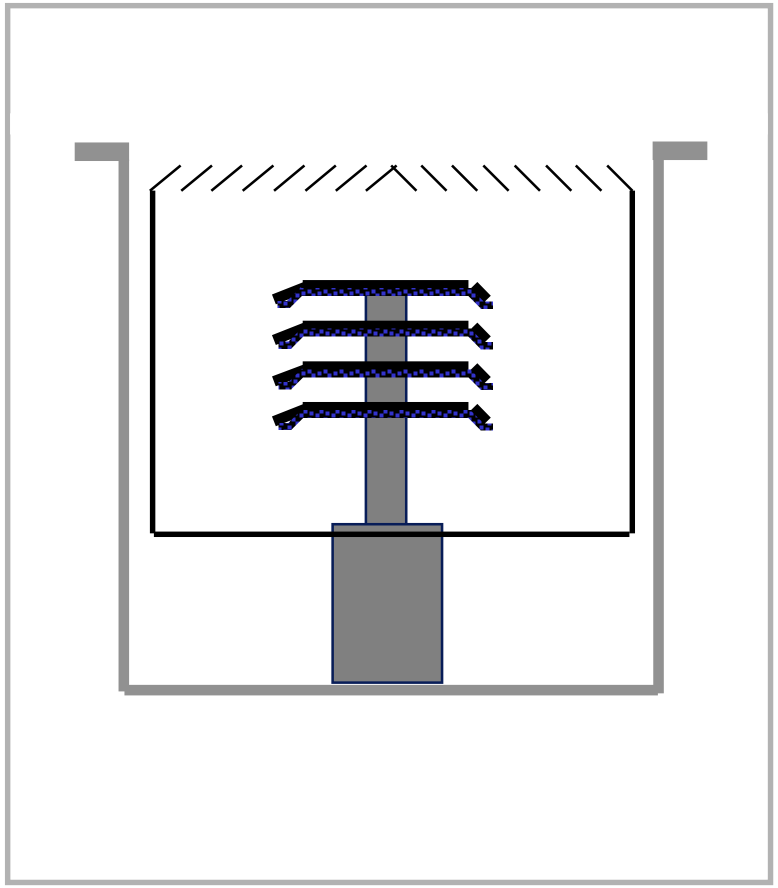


Cryopump Operation . . . Regeneration

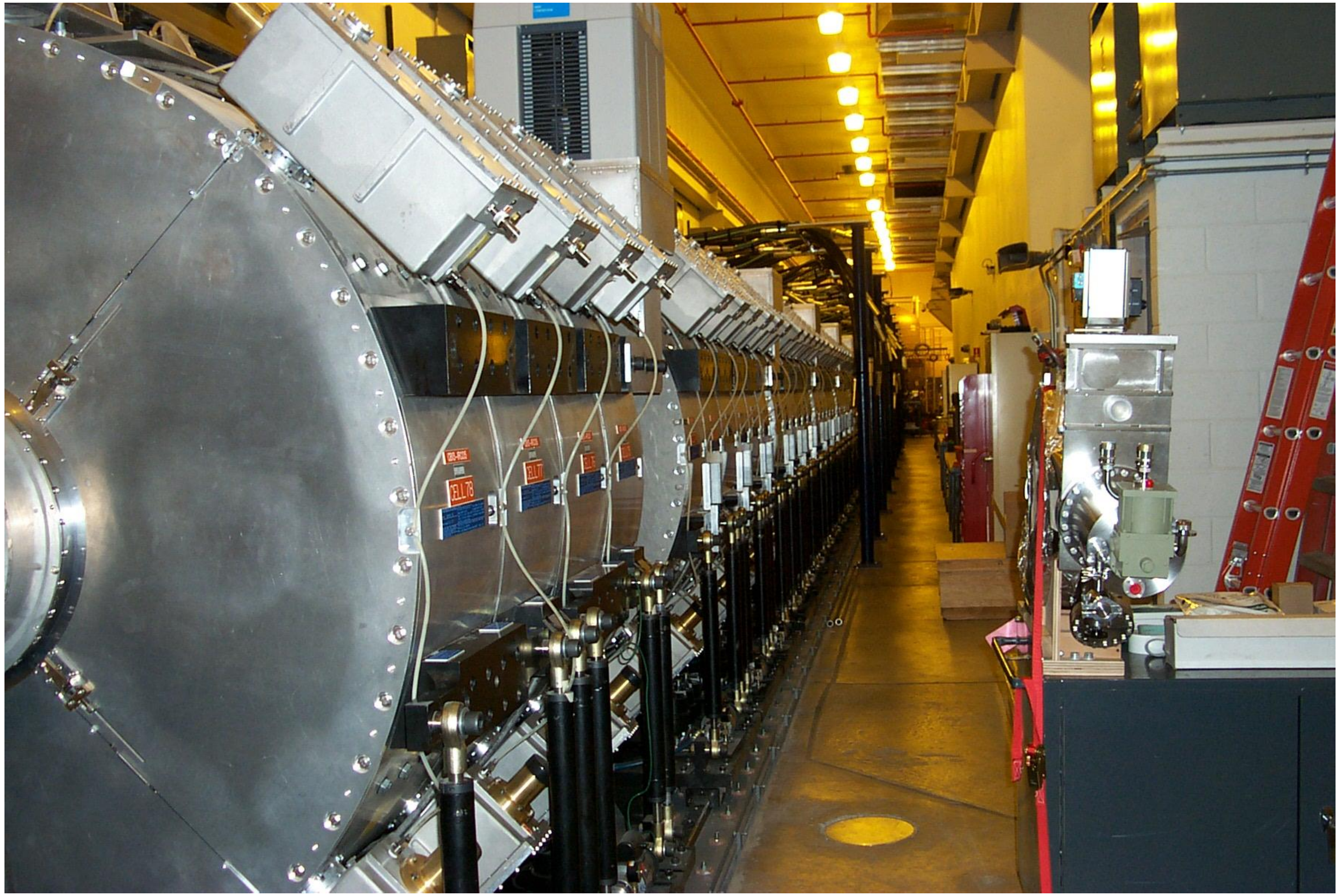
- Regeneration

Typically 5-6 hours cold-to-cold.





Example of Cryo-pumped Accelerator – DARHT II
(the Dual Axis Radiographic Hydro-Test)



Example of Cryopumped Accelerator – APT RFQ

- Cryogenic Pumping System for Cavity system, with H_2 Pumping Speed of 12,000 L/s
- This assembly was completed and successfully tested at LLNL Vacuum Lab. The whole system was then delivered and installed at the APT/LEDA facility.