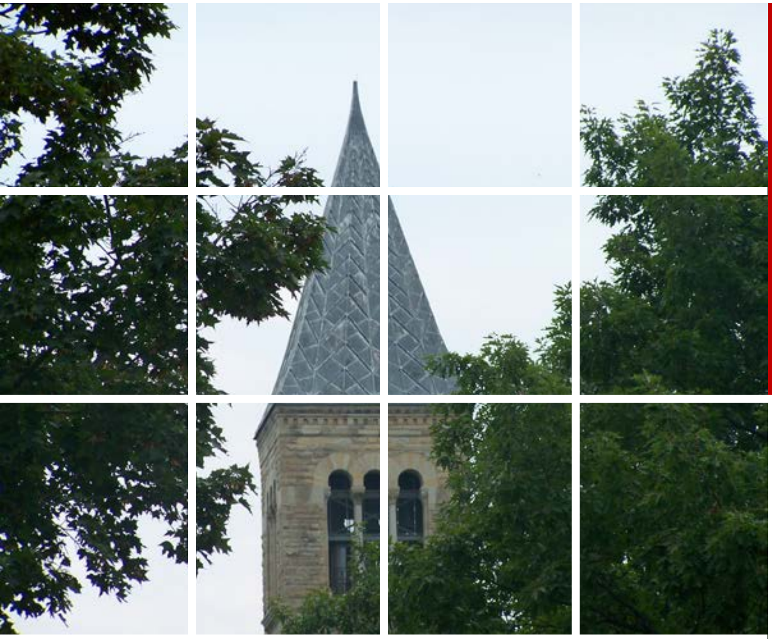
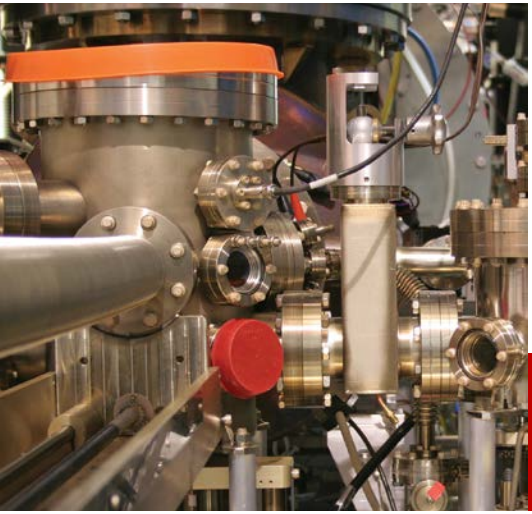


# Vacuum Science and Technology for Accelerator Vacuum Systems

*Yulin Li and Xianghong Liu*
*Cornell University, Ithaca, NY*

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



# Table of Contents

# SESSION 4.2-4.4: CAPTURE PUMPS

- *As named, these types of pumps operate by capturing gas molecules and binding them to a surface.*
- *The captured gases may be chemically bonded (chemisorbed), condensed (physisorbed), and/or buried.*
- *Capture pumps are naturally very clean. There are no moving parts, thus no lubrications, no noises. (But there may be particulates!)*
- *Most capture pumps have finite pumping capacity. After reaching the capacity, a pump has to be regenerated, or/and replaced. As such, a vacuum system needs to be 'roughed' down before a capture pump become functional.*
- *A good reference: Kimo M. Welch, "**Capture Pumping Technology**", 2nd Ed. Elsevier, North-Holland, 2006*

# *Capture Pumping – Category*

| | Pumps | Properties |
|---|---|---|
| Active Pumping | Sputtering Ion Pumps | 1. Pump all gases, including noble gases<br>2. Working range: $10^{-5}$ ~ $10^{-11}$ torr<br>3. Very high lifetime capacity |
| Passive Pumping Physi-sorption | Sorption pumps | 1. Pump most air gases<br>2. Limited capacity<br>3. Working range: atm. ~ $10^{-4}$ torr |
| | Cryo-pumps | 1. Pump all gases (except helium)<br>2. Working range: $10^{-5}$ ~ $10^{-11}$ torr<br>3. Very high capacity |
| Passive Pumping Chemi-sorption | Titanium sublimation pumps (TiSPs) | 1. Pump chemically active gases only<br>2. Working range: $10^{-6}$ ~ $10^{-11}$ torr<br>3. Capacity limited by Ti-covered surface area |
| | Non-evaporable getter pumps (NEGs) | 1. Pump chemically active gases only<br>2. Working range: $10^{-6}$ ~ $10^{-11}$ torr<br>3. Higher capacity than TiSPs, very high capacity for $H_2$. |

# SESSION 4.2: SPUTTER-ION PUMPS

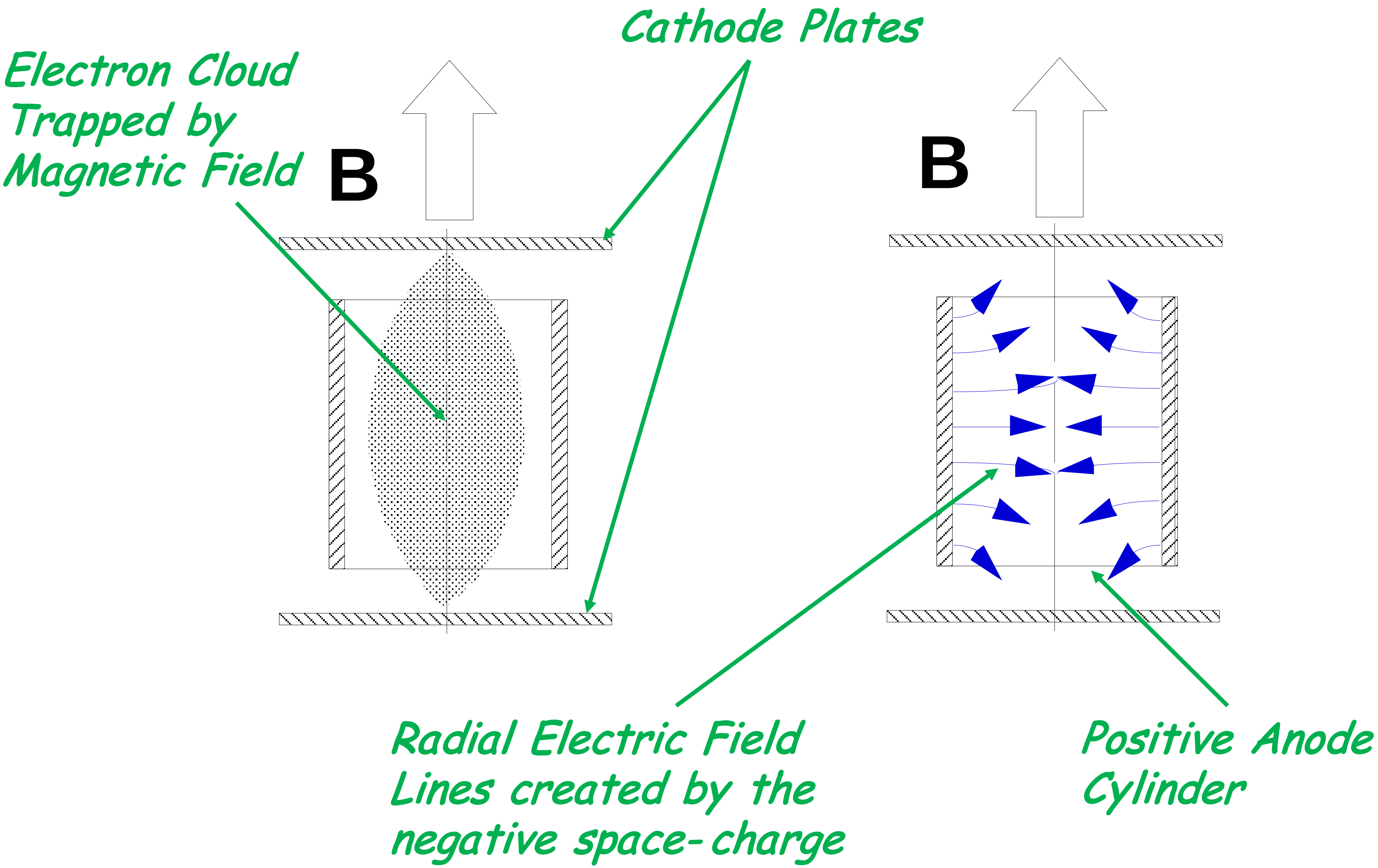
- *Sputter-ion pumps were first commercialized by Varian Associates (now Agilent Technologies, Vacuum Division) as VacIon pumps*

- *Ion pumps are made of a cluster of Penning cells, thus the pumping speed scales with number of cells.*

- *Advantages of ion pumps:*
  → *Very clean (UHV or chemically speaking)*
  → *Wide working pressure range, and for all gases*
  → *(Almost) unlimited pumping capacity*

- *Some concerns of ion pumps:*
  → *May generate particulates (metallic particles from cathodes)*
  → *Stray magnetic field may affect low energy particle beams*
  → *Space and weight*
  → *Radiation hardness of HV cables and controllers*

# Penning Cell and Penning Discharge



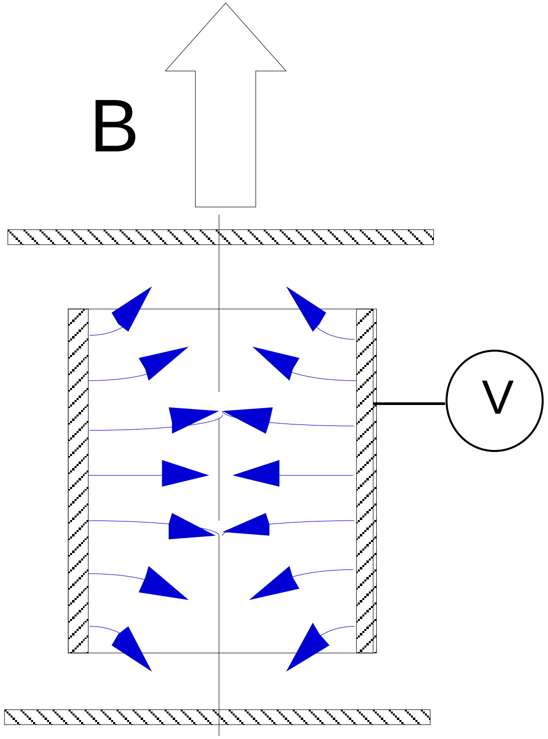
# Penning Cell Sensitivity

$$S = \frac{I^+}{P^n}$$

Where $I^+$ = ion current (Amps)
$P$ = pressure (Torr)
$n = 1.05 \sim 1.50$

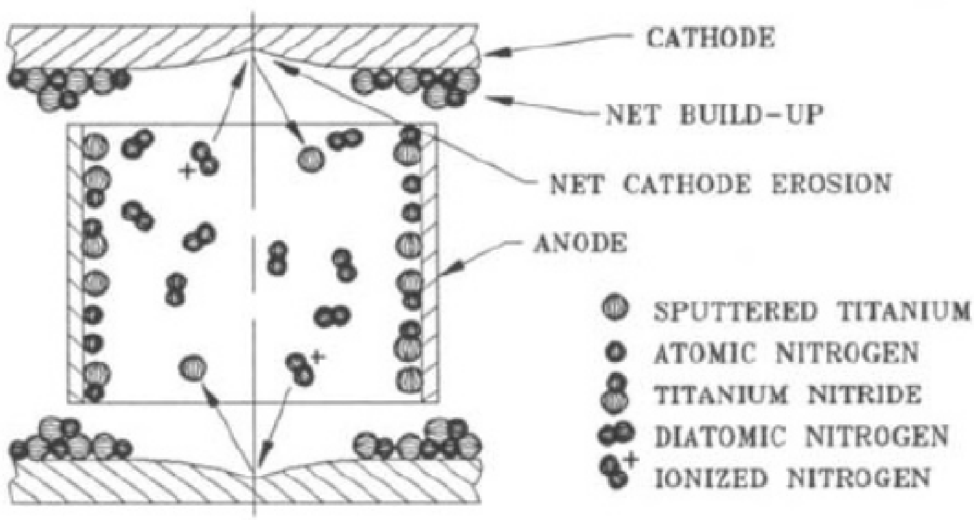
# Parameters Affecting Penning Cell Sensitivity

| | | |
|---|---|---|
| Anode Voltage | V | 3.0 - 7.0 kV |
| Magnetic Field | B | 0.1 - 0.2 T |
| Cell Diameter | d | 1.0 - 3.0 cm |
| Cell Length | $l$ | 1.0 - 3.2 cm |
| Anode-Cathode Gap | a | 0.6 - 1.0 cm |



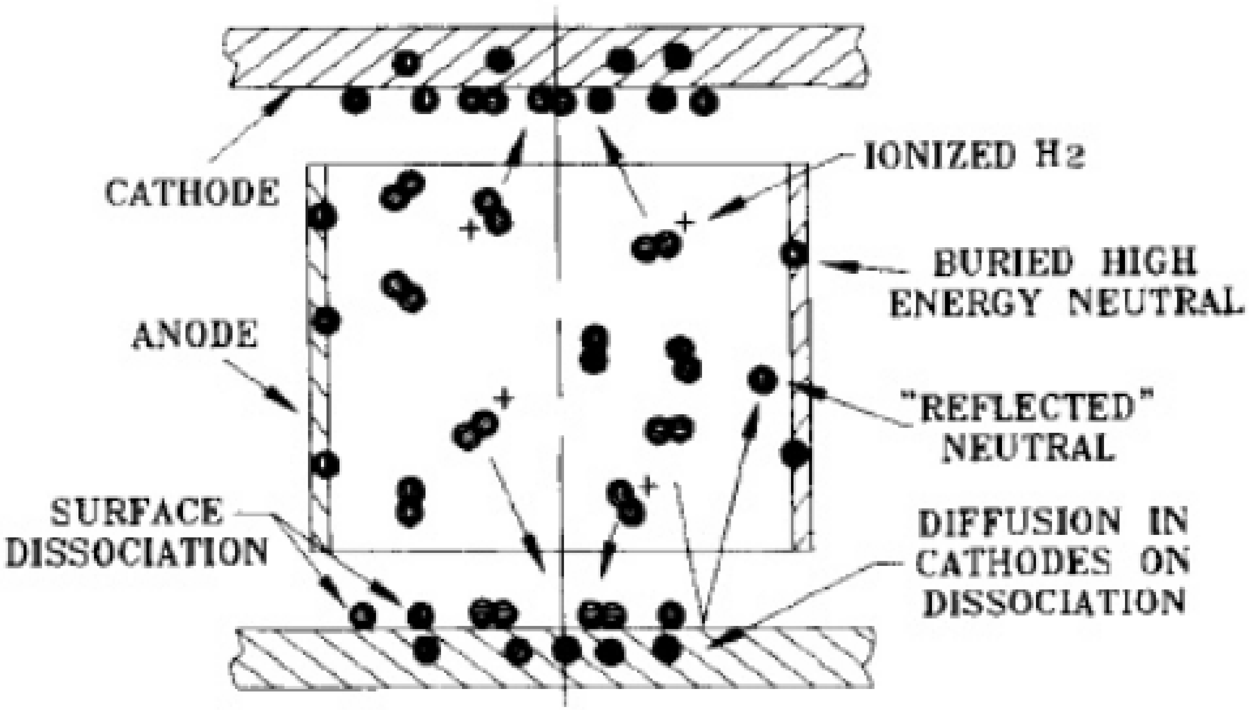
# SIP Pumping Mechanism – General

- *An electron 'cloud' build up inside anode cell in the cross-field. The electron cloud may be started with field-emitted electrons, photo-electrons or radiations.*
- *The electrons gain kinetic energy in orbiting trajectories, ionize gas molecules by impact.*
- *While electrons from ionization contribute to the e-cloud, ions are accelerated towards cathode plates, and sputter off cathode materials.*




- *Gas molecules may be bonded to the 'fresh' cathode material, that is,* ***chemi-sorption***
- *Or may be buried by the sputtered cathode atoms, that is, physical* ***embedment****. This is the main pumping mechanism for noble gases.*

# SIP Pumping Mechanism – Hydrogen




*Sputtering Ion Pumps pump hydrogen gas differently. Hydrogen pumping is a two-step process:*

- *Hydrogen molecules dissocatively chemisorb on fresh metallic cathode surface*
- *Adsorbed H atoms then diffuse into the bulk of the cathodes*

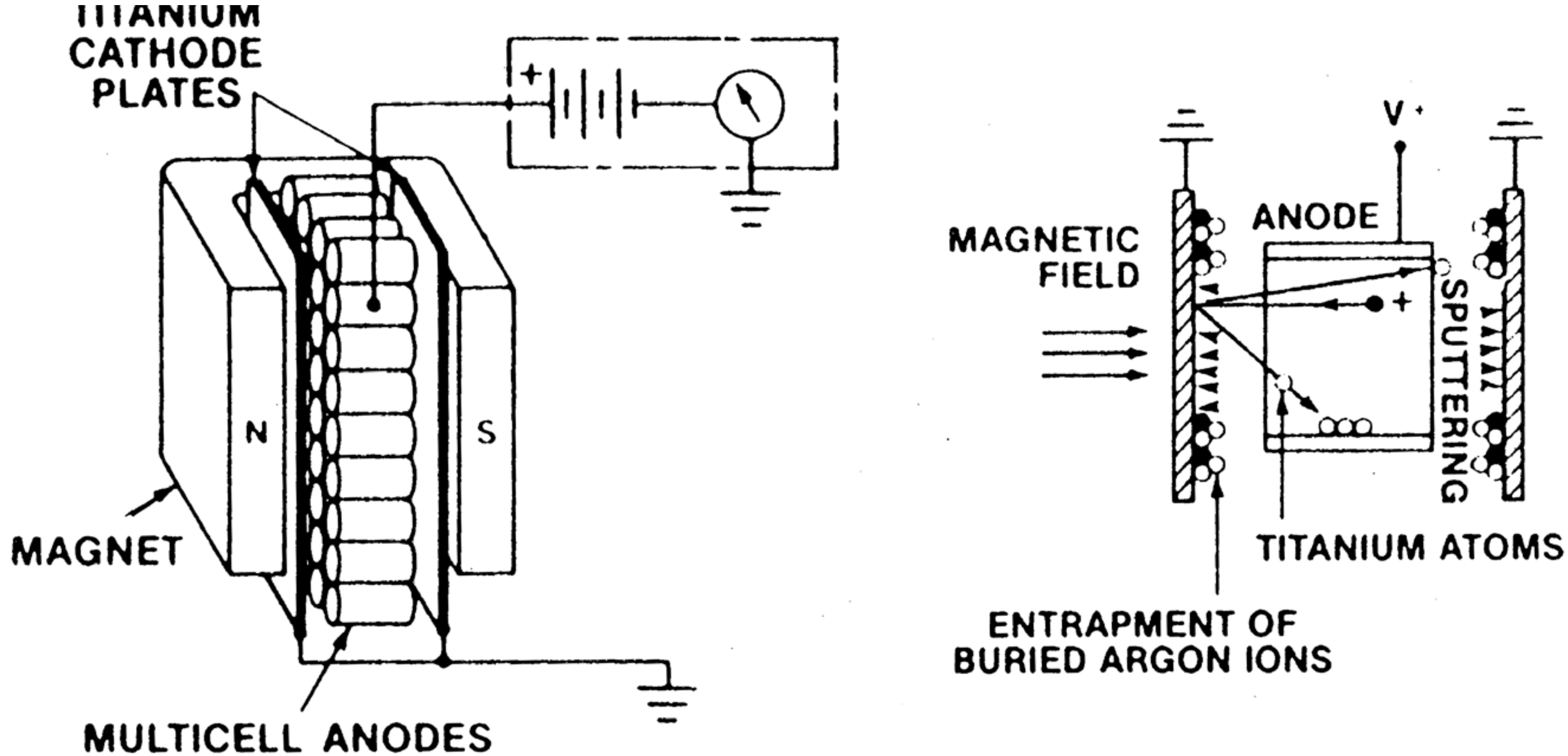
# Types of Ion Pumps

- **Diode** – Most commonly used. Best for UHV systems where 98% of the gas is hydrogen. Diodes have the highest hydrogen pumping speed.

- **Differential (Noble Diode)** – Optimized for pumping noble gases, with a compromise for hydrogen pumping speed. 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.

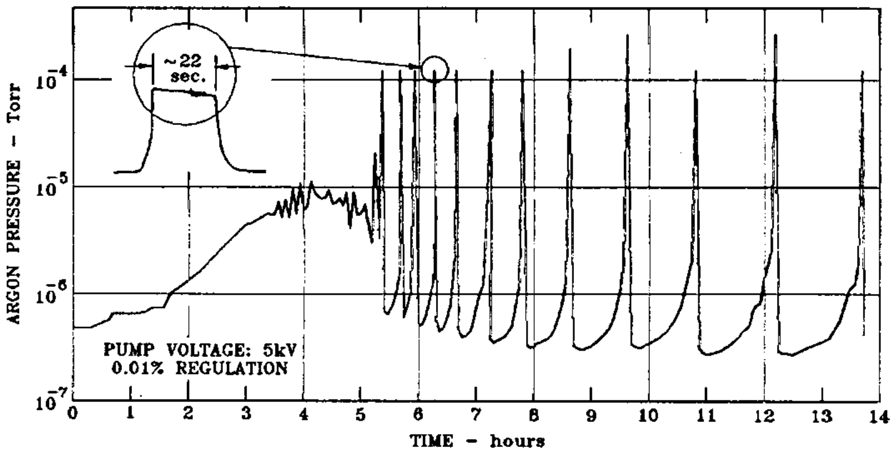
# Diode sputter-ion pump



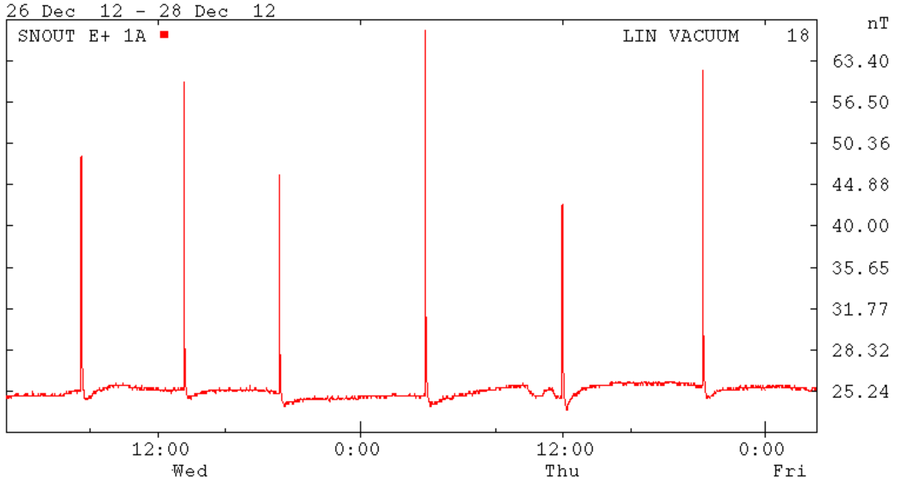

*In a diode ion pump, both cathode plates are commonly made of titanium, due to its high sputtering yields and chemical reactivity*

# Argon Instability of Diode Ion Pump

- Periodic pressure bursts observed for diode ion pump while pumping air or gas mixtures containing inert gases.
- This phenomena is usually referred as "argon instability", and the burst gas is mostly Ar.
- The sources of the argon bursts are believed from buried argon (or other noble gases) in the cathode, and then release by sputtering processes.




SLAC Ar-bursts




CESR LINAC Ar-bursts

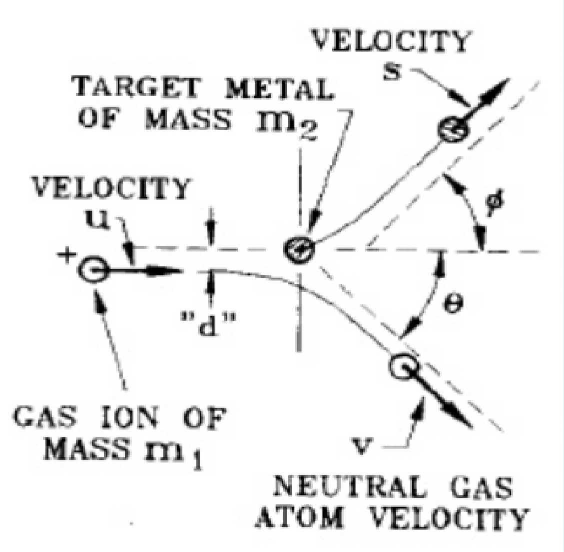
# Differential Ion (Noble Diode) Pumps

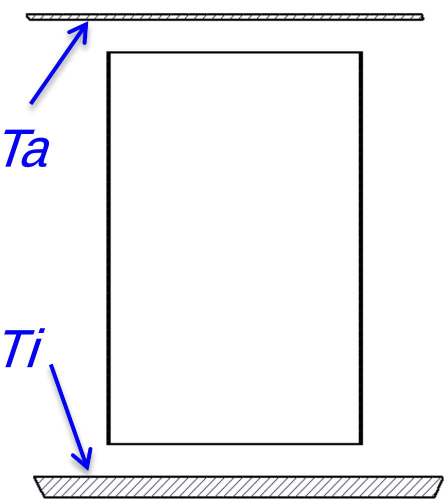
- In the so-called differential diode pumps, one of the Ti cathode plates is replaced with a heavy metal (commonly tantalum). The argon-instability is no longer an issue in the DI pumps.
- The enhanced noble gas pumping performance has been explained by a so-called fast neutral theory. The theory claims that the Ar+ neutralized on cathode surface, and Ar scatters and buried in anode surface. When this occurs on heavier metals, Ar neutral maintains higher velocity, thus buried deeper.

## Fast Neutral Theory

$$\frac{v}{u} = \frac{\cos\theta + \left(R^2 - \sin\theta\right)^{1/2}}{R+1}$$

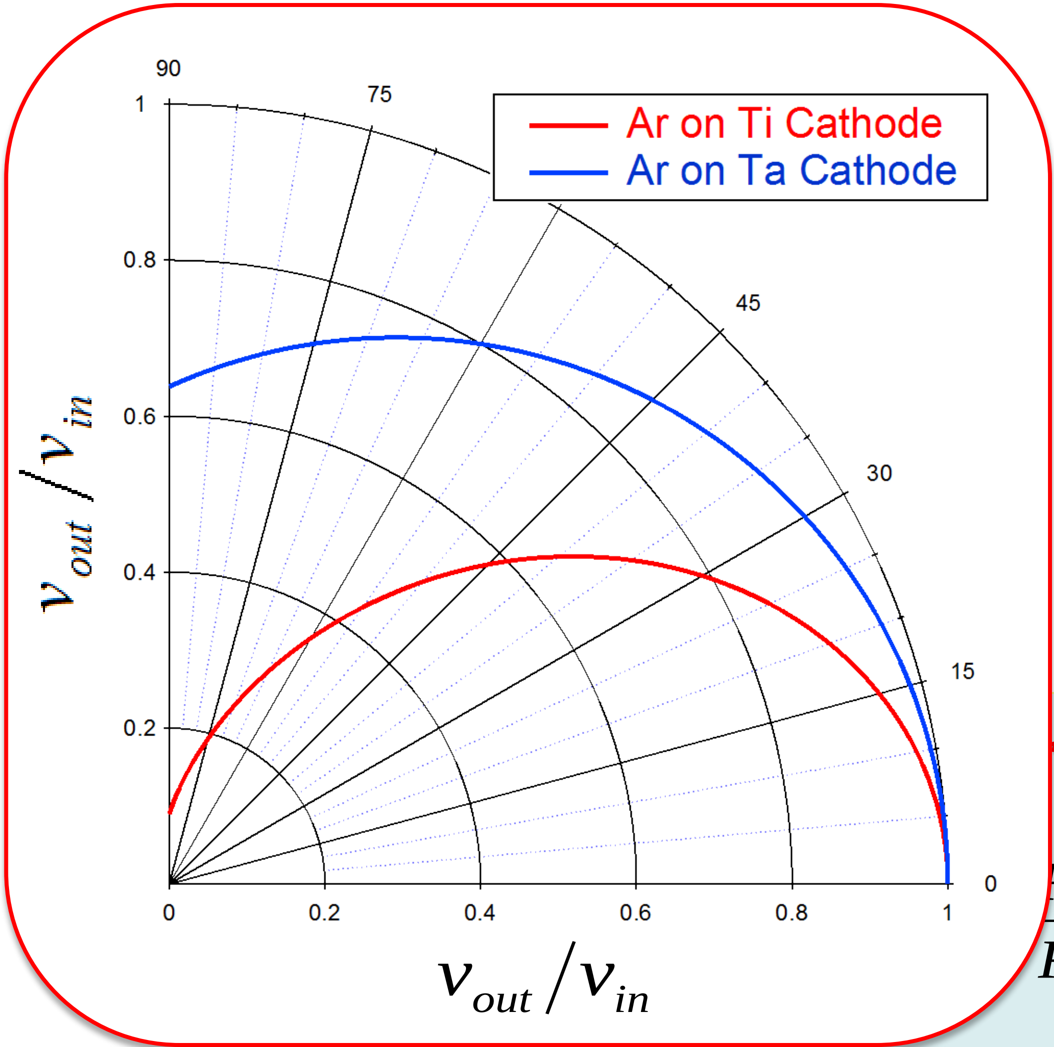
$$R \equiv m_2 / m_1$$




A D-I Cell

# *Neutral Ar Kinetic Energy – Ti vs. Ta Cathode*

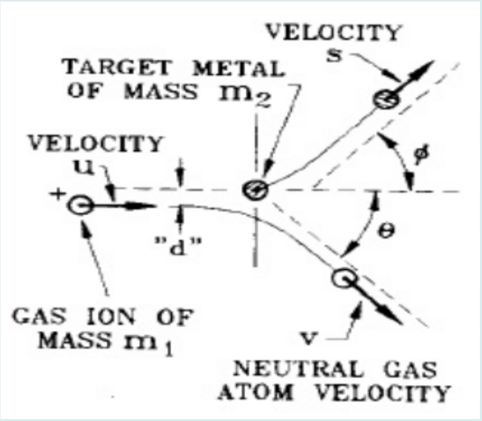



*Argon neutrals clearly maintain much higher kinetic energy upon interaction with a Ta cathode as compared to with a Ti cathode*

***al Theory***

$$\ldots R^2 - \sin\theta)^{1/2}$$
$$R+1$$

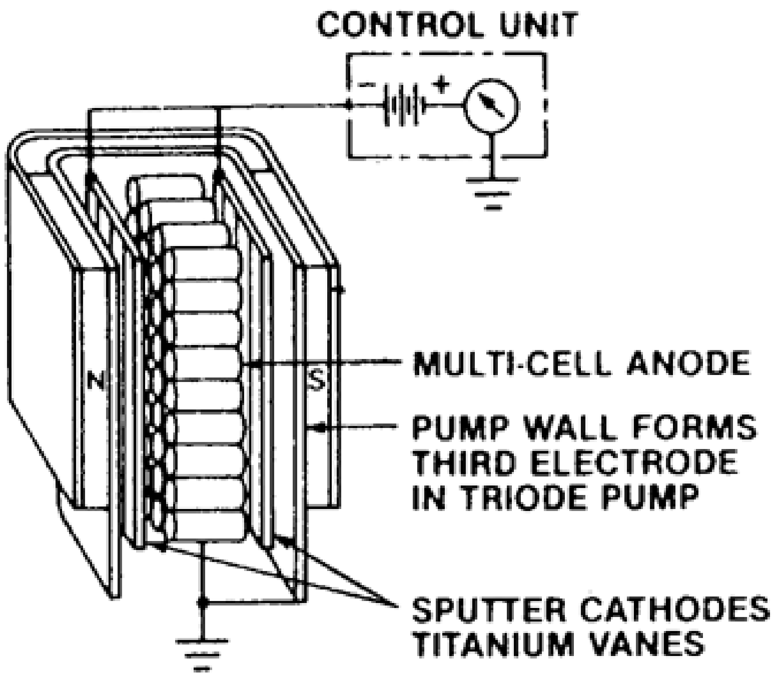
$$R \equiv m_2 / m_1$$



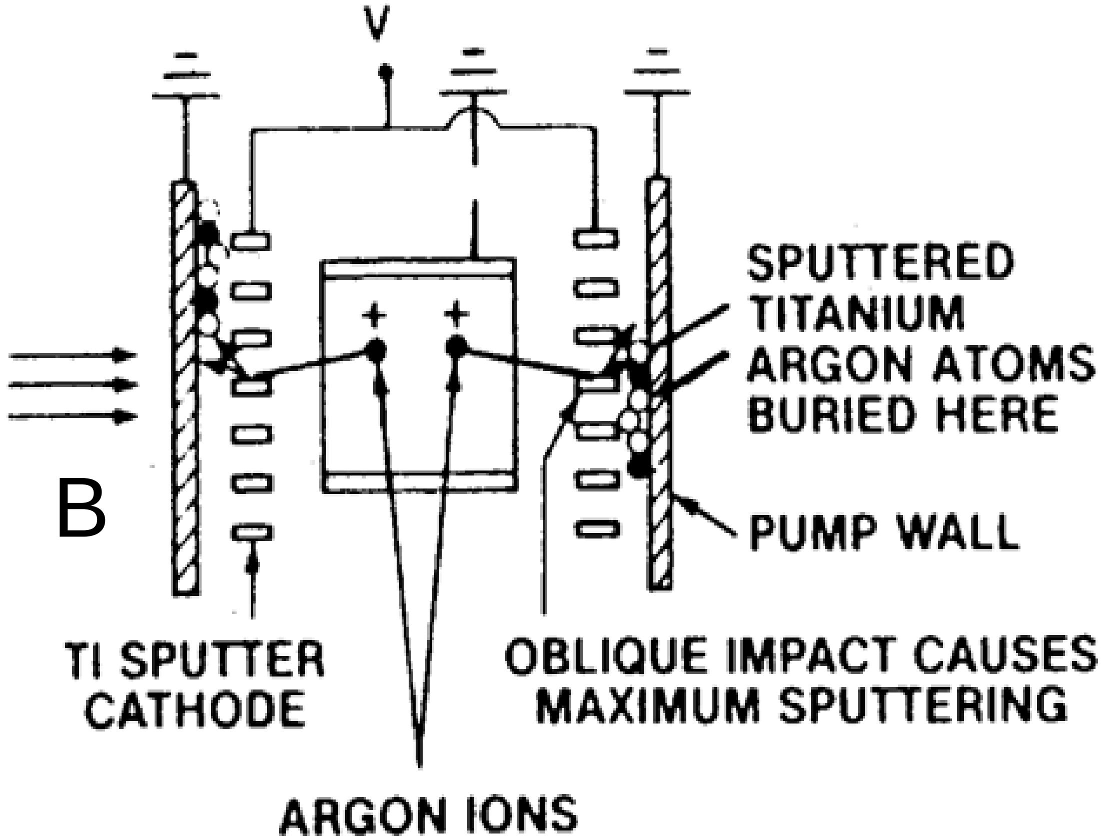
# Noble Diode vs. Diode Pumps

| Gas | Noble Diode | Diode |
|---|---|---|
| $H_2$ | 160% | 220% |
| $CO_2$ | 100% | 100% |
| $N_2$ | 85% | 85% |
| $O_2$ | 70% | 70% |
| $H_2O$ | 100% | 100% |
| Ar | 20% | 5% |
| He | 15% | 2% |
| Light Hydrocarbons | 90% | 90% |

# Triode Ion Pump



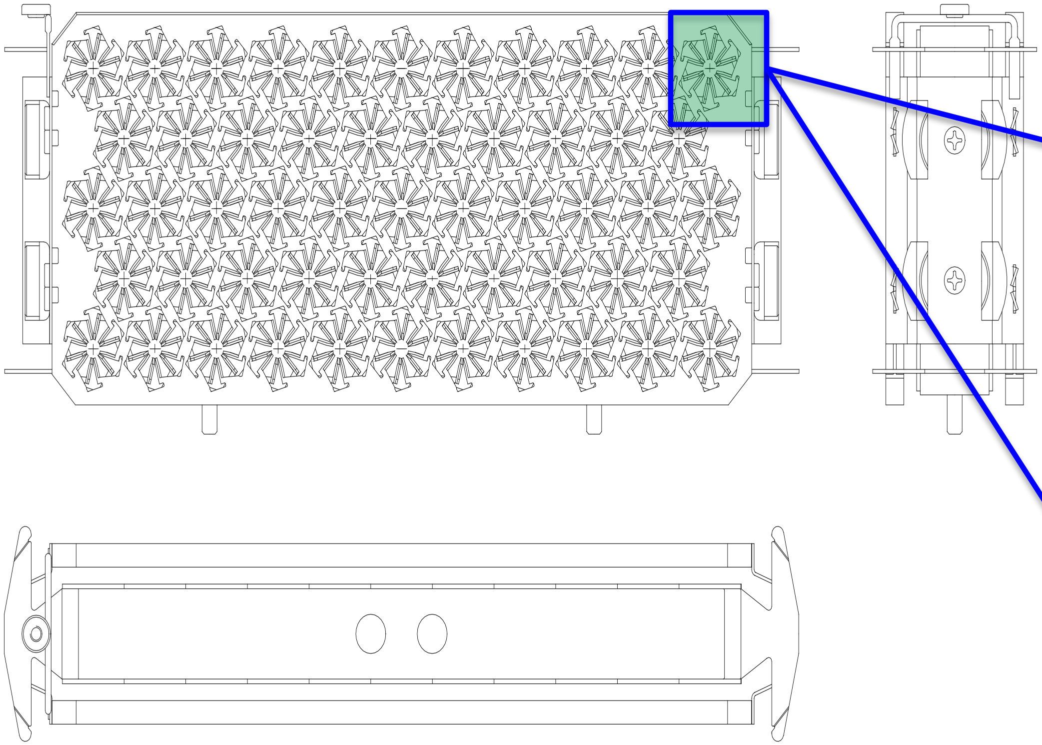

*Another type of ion pumps handle noble gases well. Usually the triode pumping elements exchangeable with diode elements.*

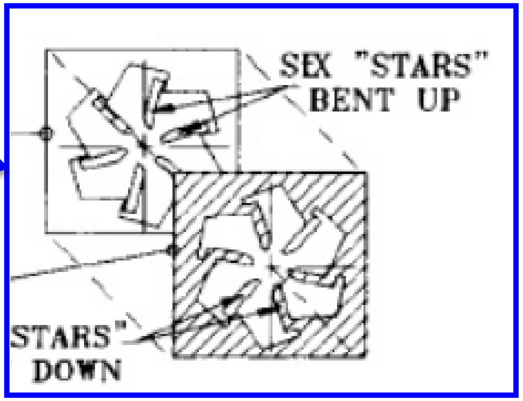


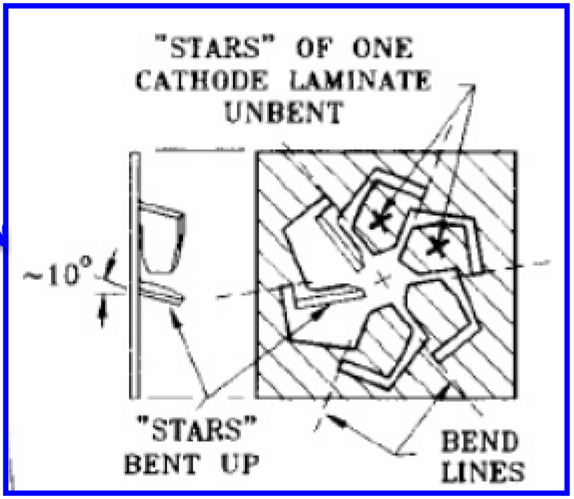

## Disadvantages:

- *Reduced pumping speed for all other gases.*
- *Expensive (due to complex assembling process)*
- *Cathode strips may cause short circuit.*

# Triode Ion Pump – StarCell Pumps

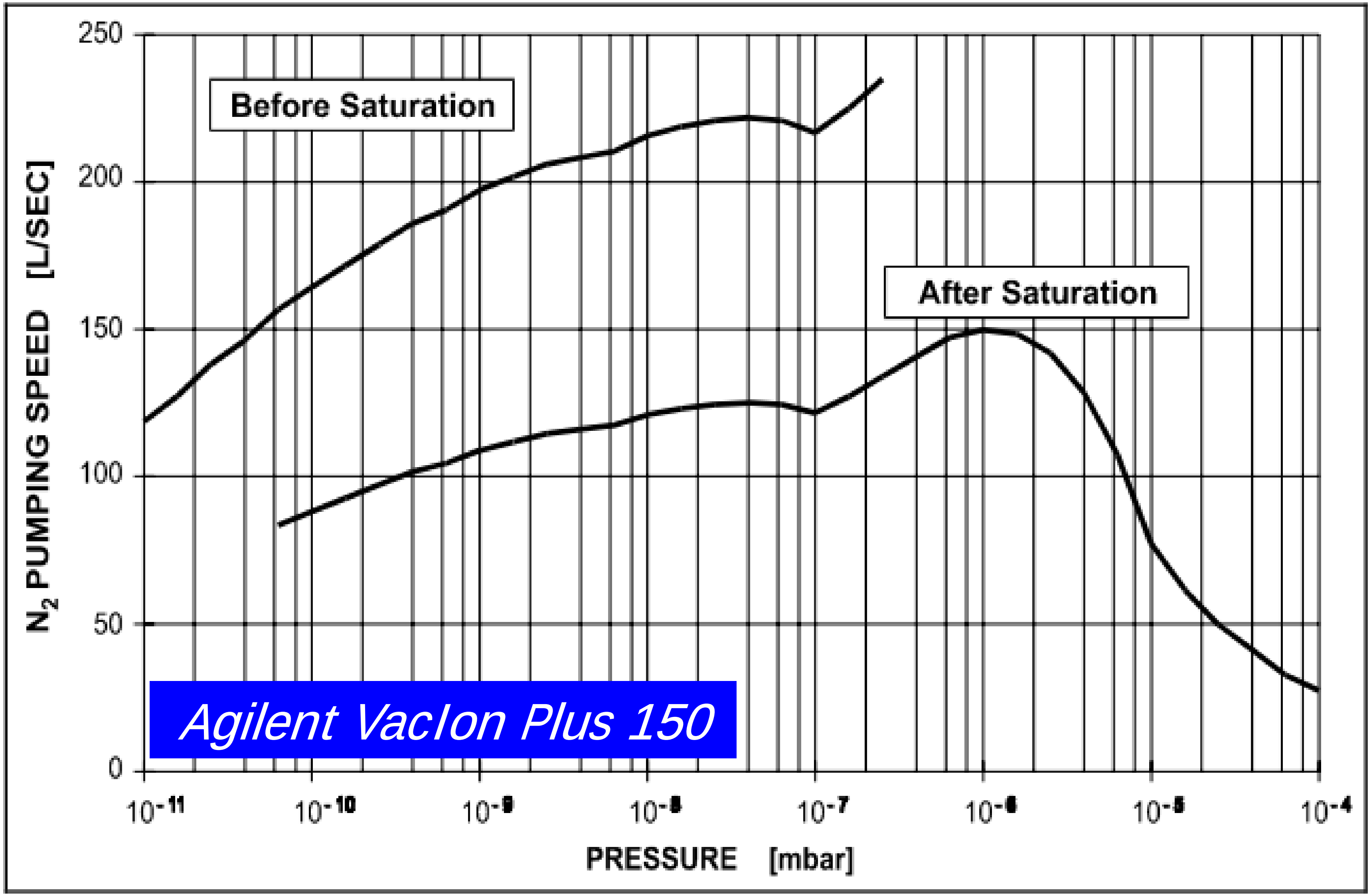




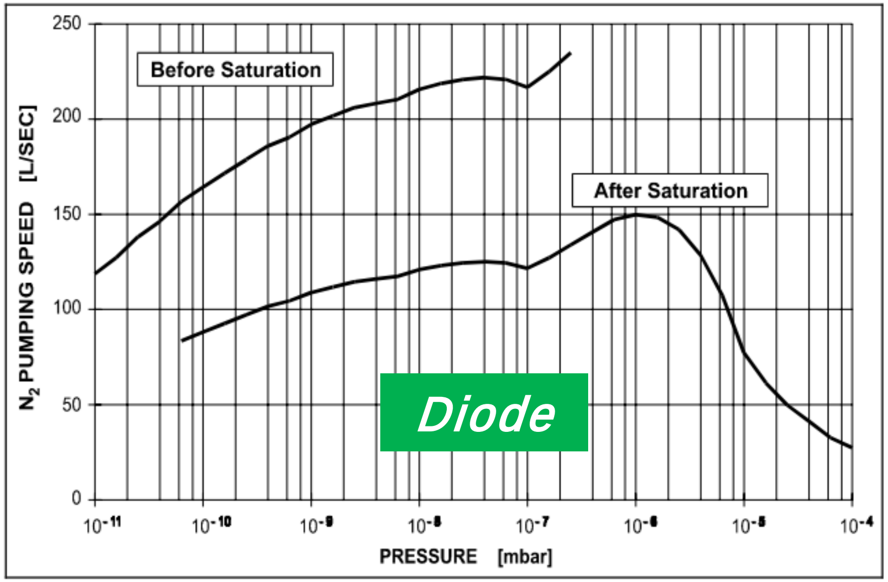



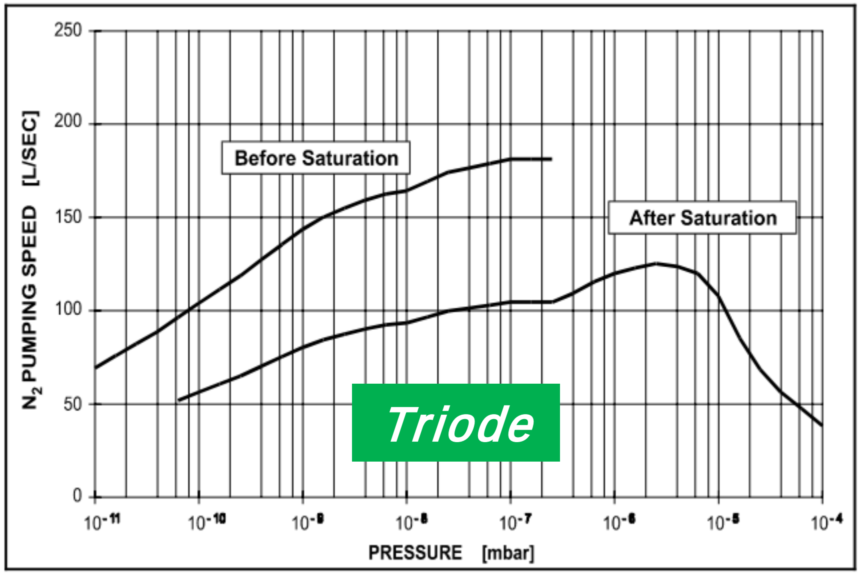

*A special type of triode pump from Agilent (Varian), with excellent noble gas pumping, and improved long-term performance over strip-style triode pump.*

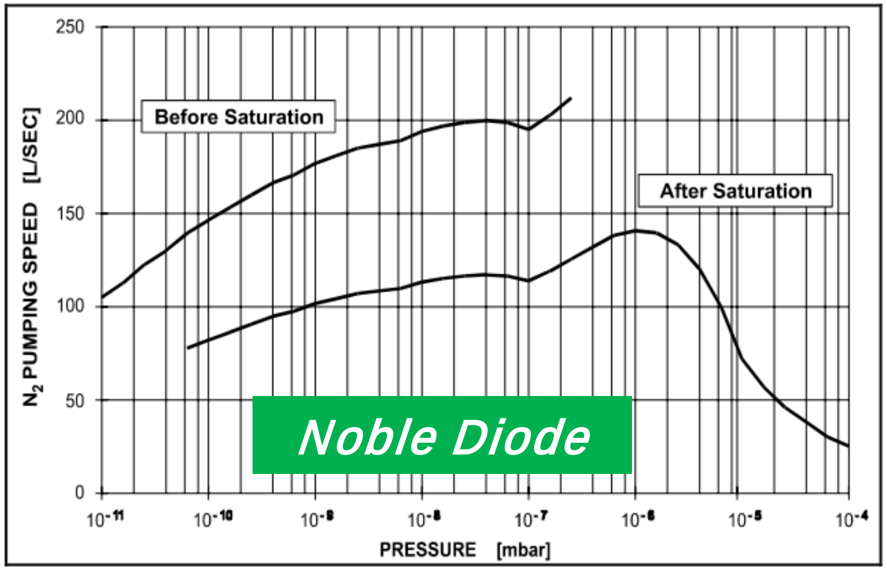
# Diode Ion Pump – Pumping Speed

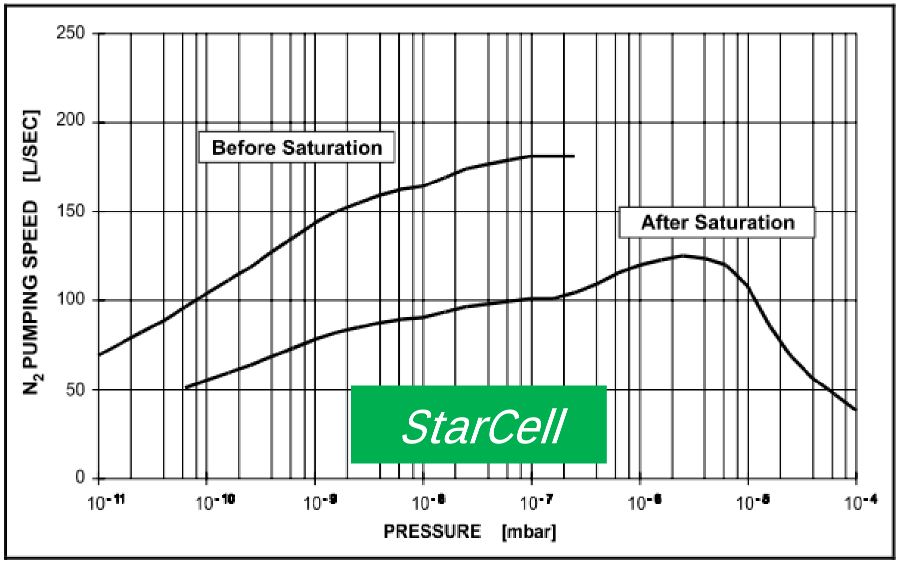


# $N_2$ Pumping Speed of Different Styles

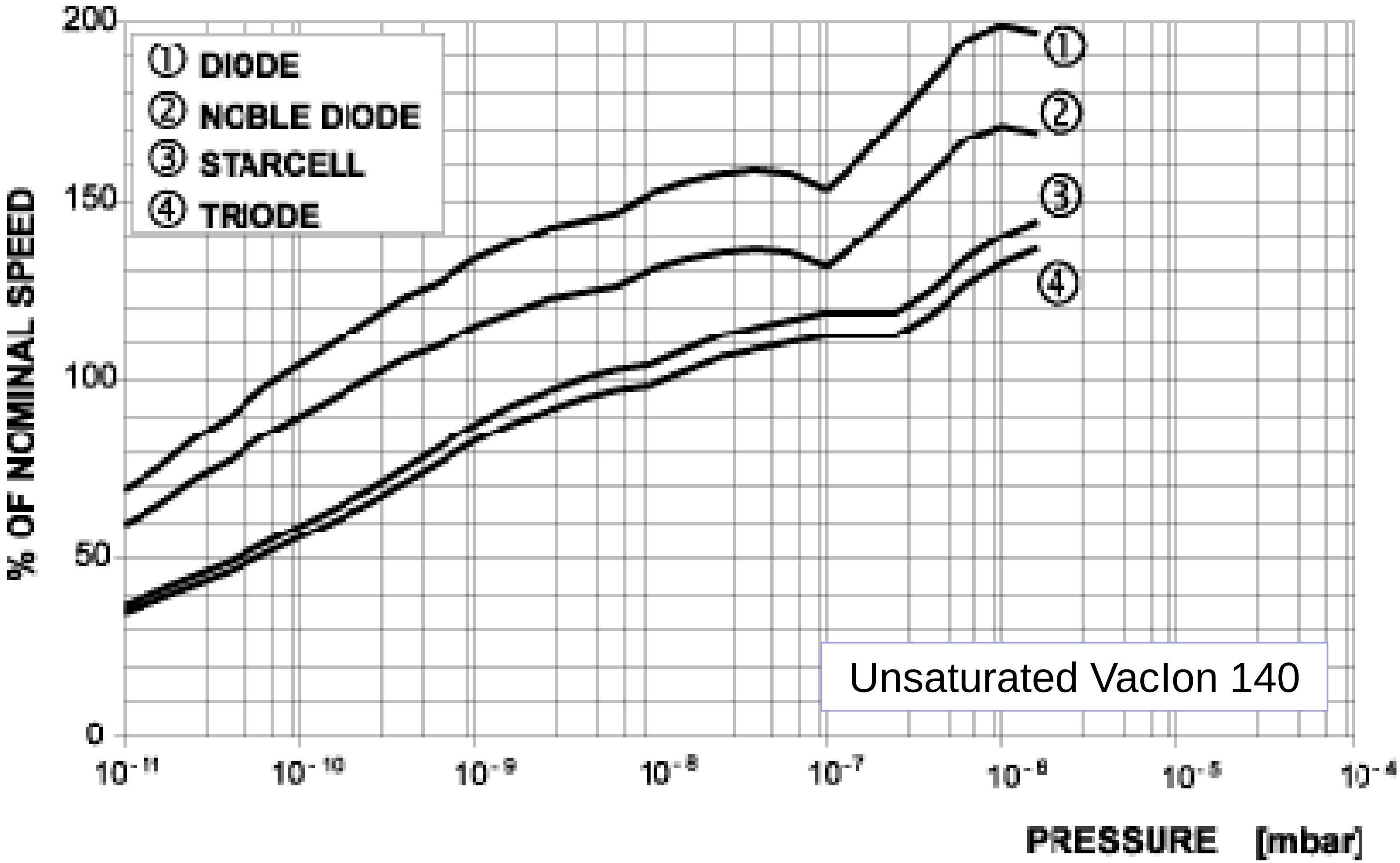


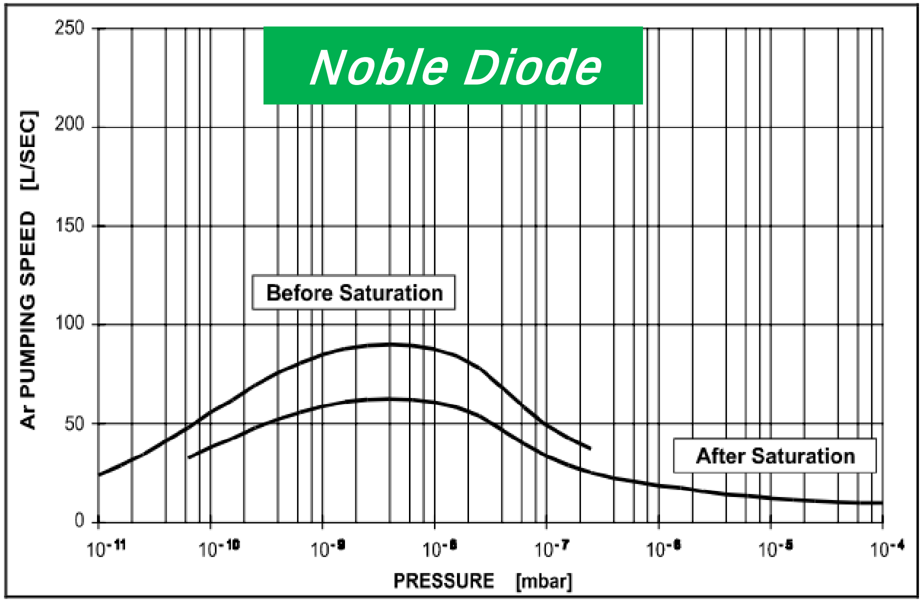



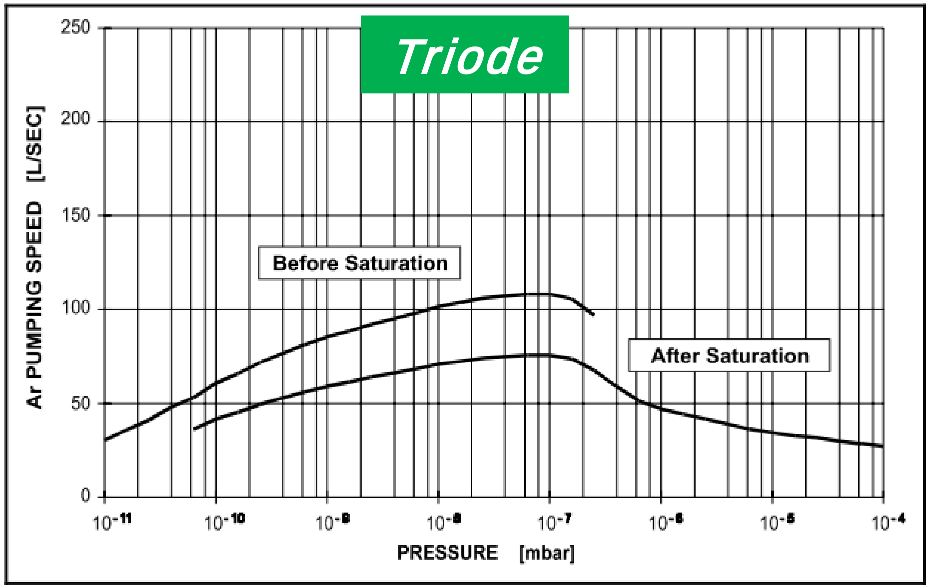
# $N_2$ Pumping Speed of Different Styles

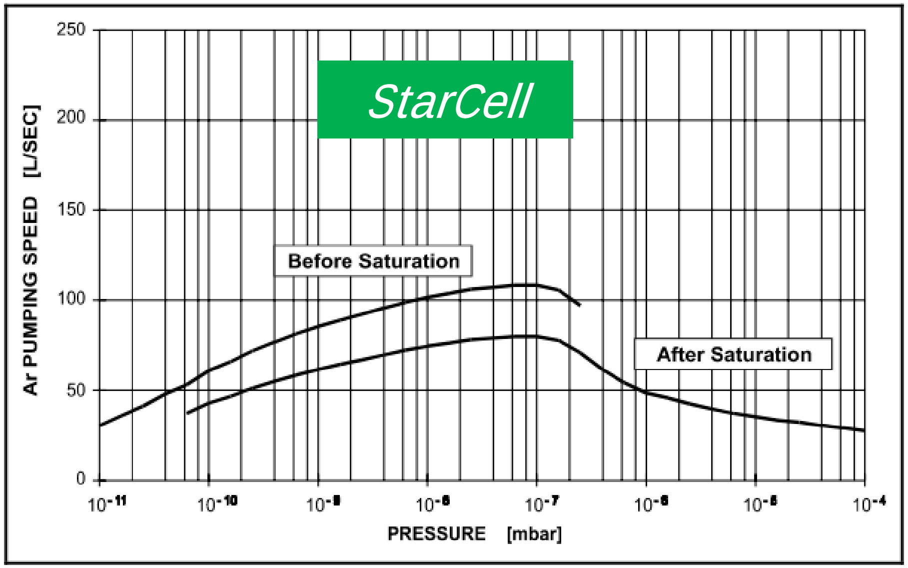



**(Ref. Varian Vacuum)**

# Argon Pumping Speed of Different Styles



# Ion Pump Performance for various gases

| Gas | Diode | Noble Diode | Triode | Starcell | TSP | NEG |
|---|---|---|---|---|---|---|
| $H_2$ | 3 | 1 | 1 | 2 | 3 | 4 |
| He | 1 | 3 | 3 | 4 | 0 | 0 |
| $H_2O$ | 3 | 2 | 2 | 2 | 3 | 3 |
| $CH_4$ | 2 | 3 | 3 | 3 | 0 | 0 |
| $N_2$ | 3 | 3 | 2 | 2 | 3 | 3 |
| $O_2$,CO,$CO_2$ | 3 | 3 | 2 | 2 | 4 | 3 |
| Ar | 1 | 3 | 3 | 4 | 0 | 0 |

| | |
|---|---|
| None | 0 |
| Poor | 1 |
| Good | 2 |
| Excellent | 3 |
| Outstand. | 4 |

**(Ref. Varian Vacuum)**

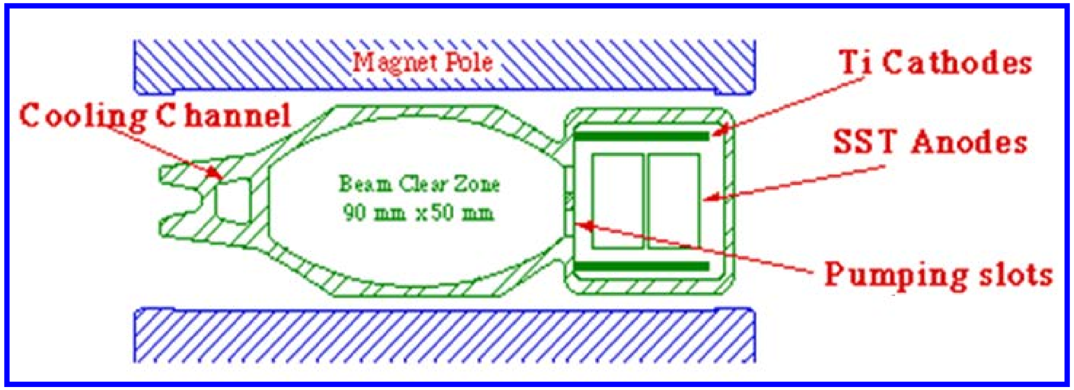
# Commercial Ion Pumps – Agilent (Varian)


- *Brand-named: VacIon (old) and VacIon Plus*
- *Pump sizes from 2 l/s up to 500 l/s nominal speed*
- *Diode, noble-diode, triode and StarCell styles are available*
- *Combination with NEG available*

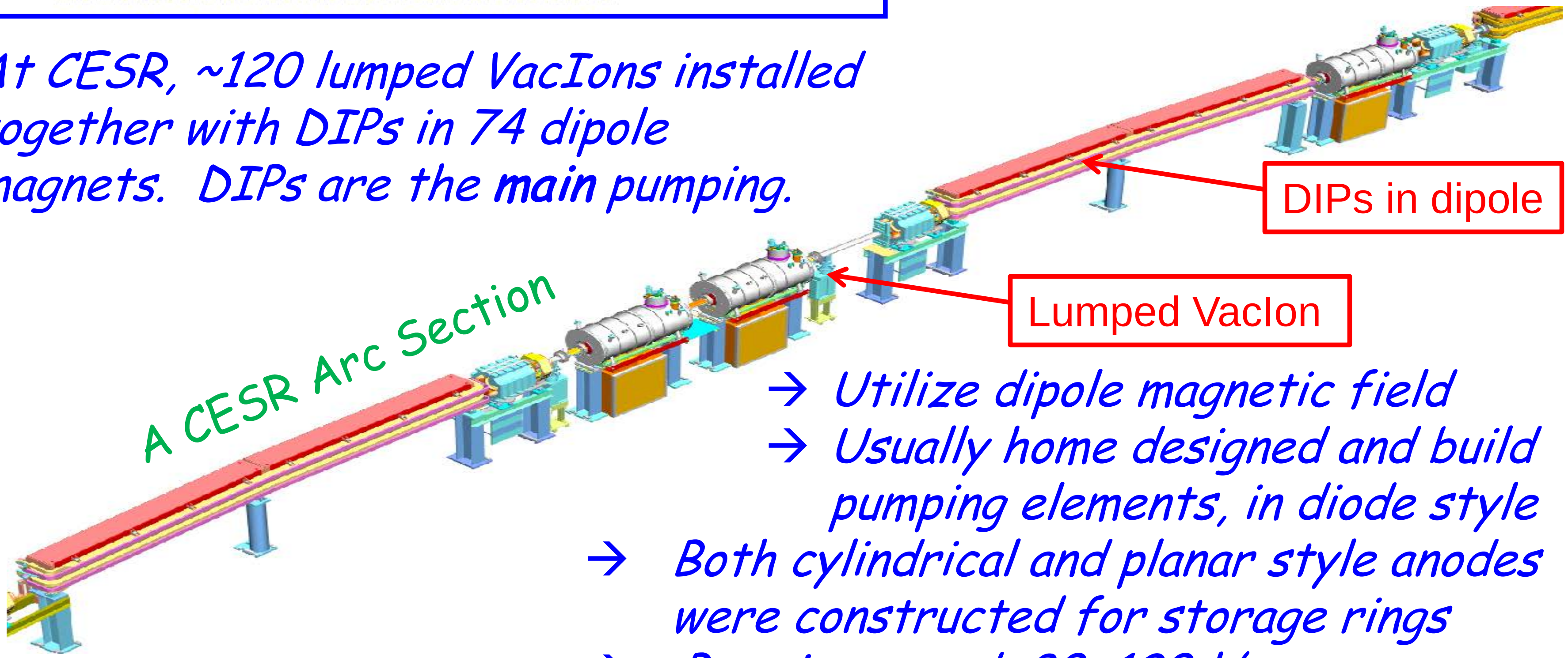
# Commercial Ion Pumps – Gamma Vacuum

- Formerly Perkin-Elmer, brand-named: TiTan Pumps
- Pump sizes from 2 l/s up to 1600 l/s nominal speed
- Diode, noble-diode and triode styles are available
- Combination with NEG available

# *Distributed Ion Pumps (DIPs)*




*At CESR, ~120 lumped VacIons installed together with DIPs in 74 dipole magnets. DIPs are the **main** pumping.*




- → *Utilize dipole magnetic field*
- → *Usually home designed and build pumping elements, in diode style*
- → *Both cylindrical and planar style anodes were constructed for storage rings*
- → *Pumping speed: 80~120 l/s-m*

# Ion Pump Selection and Operation

- *For lumped ion pumps, noble gas pumping should be incorporated. Noble diode pumps are usually the best option, as the operating voltage polarity is same to regular diode pumps.*

- *In dipole magnet with sufficient field (> 0.1 T), DIPs are economical and reliable distributed pumping (as compared to NEGs).*

- *Extreme cares must be taken to protect HV electric feedthroughs of the ion pumps, both mechanically and environmentally (such as condensations and corrosions).*

- *For very long duration operations (30+ years in CESR), 'whiskers' may develop on anodes that cause partial shorting. These whiskers may be 'burnt' out by temporarily operating a pump at high pressure (~$10^{-5}$ torr)*

# Ion Pump Controllers

- *Ion pump controllers provide DC high voltage needed for the ion pump operation.*
- *There are many suppliers for ion pump controllers. These are generally in two basic designs: the linear power controllers with transformers, and switchers. The formers are more robust, often with higher output power, but bulky and heavy. The switcher controllers are more commonly used nowadays.*
- *Important parameters in selection ion pump controllers:*
  - ✓ *Output power and current (ranging from < 1W to 100s W)*
  - ✓ *Pump ion current read-out precision (down to μA or even nA) and response time (for interlocking etc.)*
  - ✓ *Programmability and computer interface features*
  - ✓ *Radiation hardness*

# Commercial Ion Pump Controllers


**Agilent 4 UHV**

Output Power: 400 W
Output HV: 3, 5, 7 kV
Current: up to 200 mA
Ion Current: 10 nA ~ 100 mA


**Agilent MiniVac**

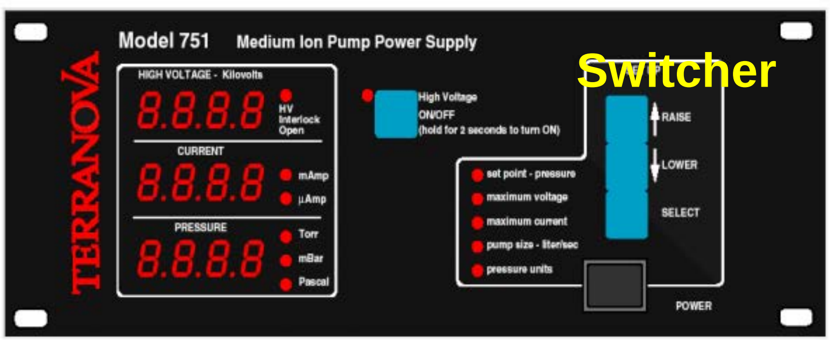
Output Power: 20~40 W
Output HV: 5 kV
Current: up to 20 mA
Ion Current: 10 μA~20 mA


**Gamma Vacuum LPC**

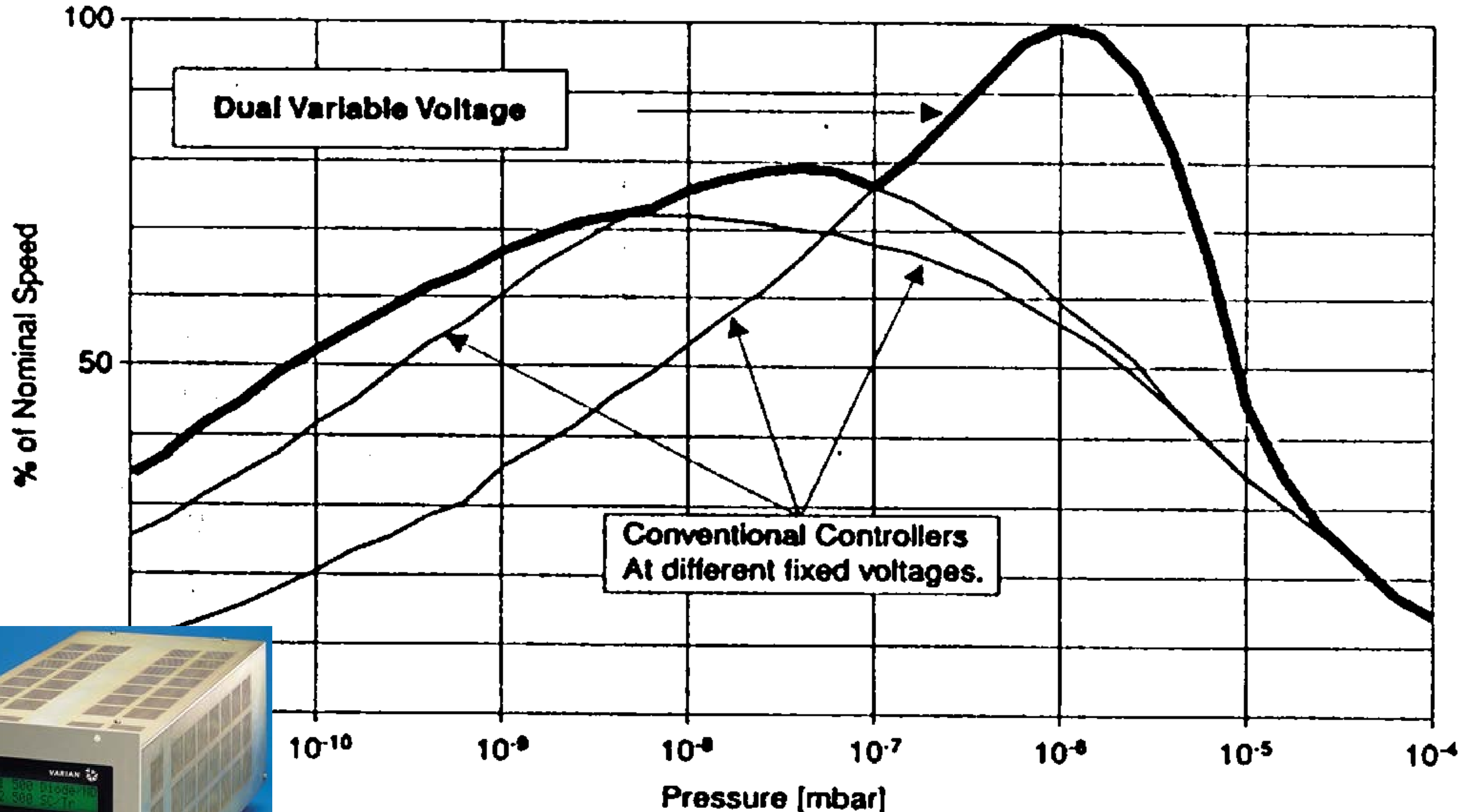
Output Power: 200 W
Output HV: 5.6/7.0 kV
Current: up to 100 mA
Ion Current res: 10 nA


**Gamma SPC**

Output Power: 40 W
Output HV: 3.5~7.0 kV
Current: up to 50 mA
Ion Current res: 1 nA



# "Step-Voltage" May Improves Pump Performance





(Ref. Varian Vacuum)

# Summary Notes

1) *Sputter-ion pumps are the primary UHV pumps for most modern accelerators, due to their cleanness and very high pumping capacity.*

2) *SIPs are most suitable at vacuum pressure < $10^{-7}$ torr. At these low pressures, their most efficient pumps, drawing almost no power.*

3) *As a capture pump, SIP has limited lifetime capacity. At extreme cases, ions may drill holes through cathode plates, resulting much poor performance and pressure spikes.*

4) *Starting SIPs should be done by experts, who understand the risk of thermal run-away in the pumping elements, especially in triode pumps.*

5) *Aged SIPs tend to have reduced $H_2$ pumping speed, at UHV conditions. Thus combination with NEGs is recommended.*

6) *Glow charge at high pressure may extend throughout a SIP, and potential metallic coating of sensitive surfaces may occur.*