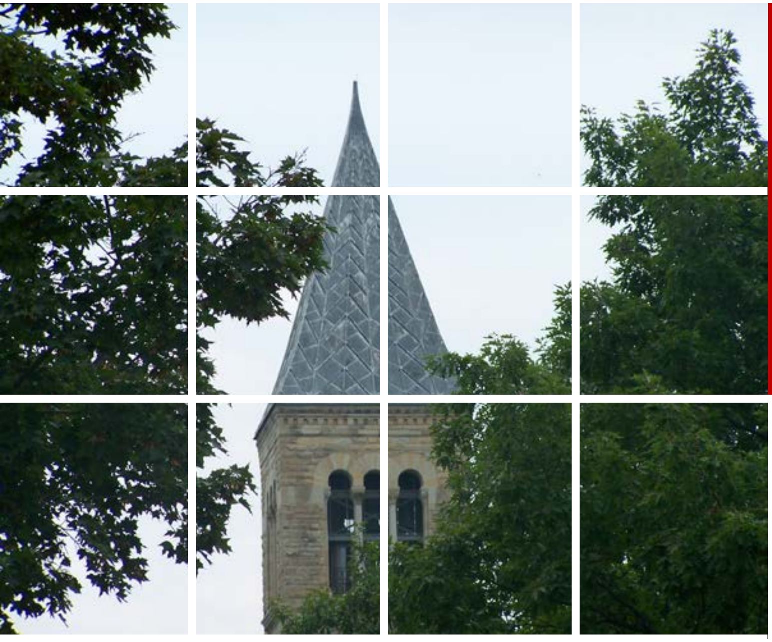

Vacuum Science and Technology for Accelerator Vacuum Systems

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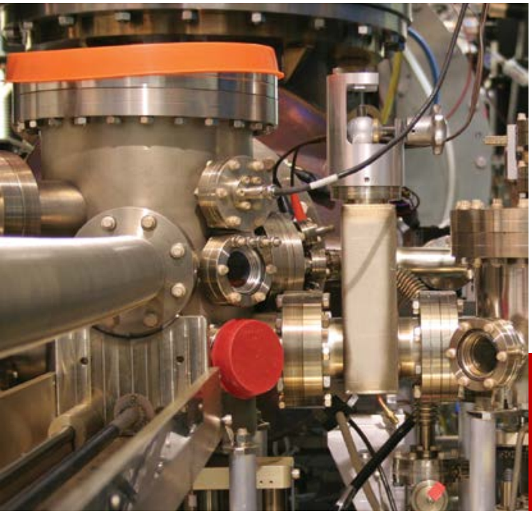


Table of Contents

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

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

SESSION 4.2: SPUTTER-ION PUMPS

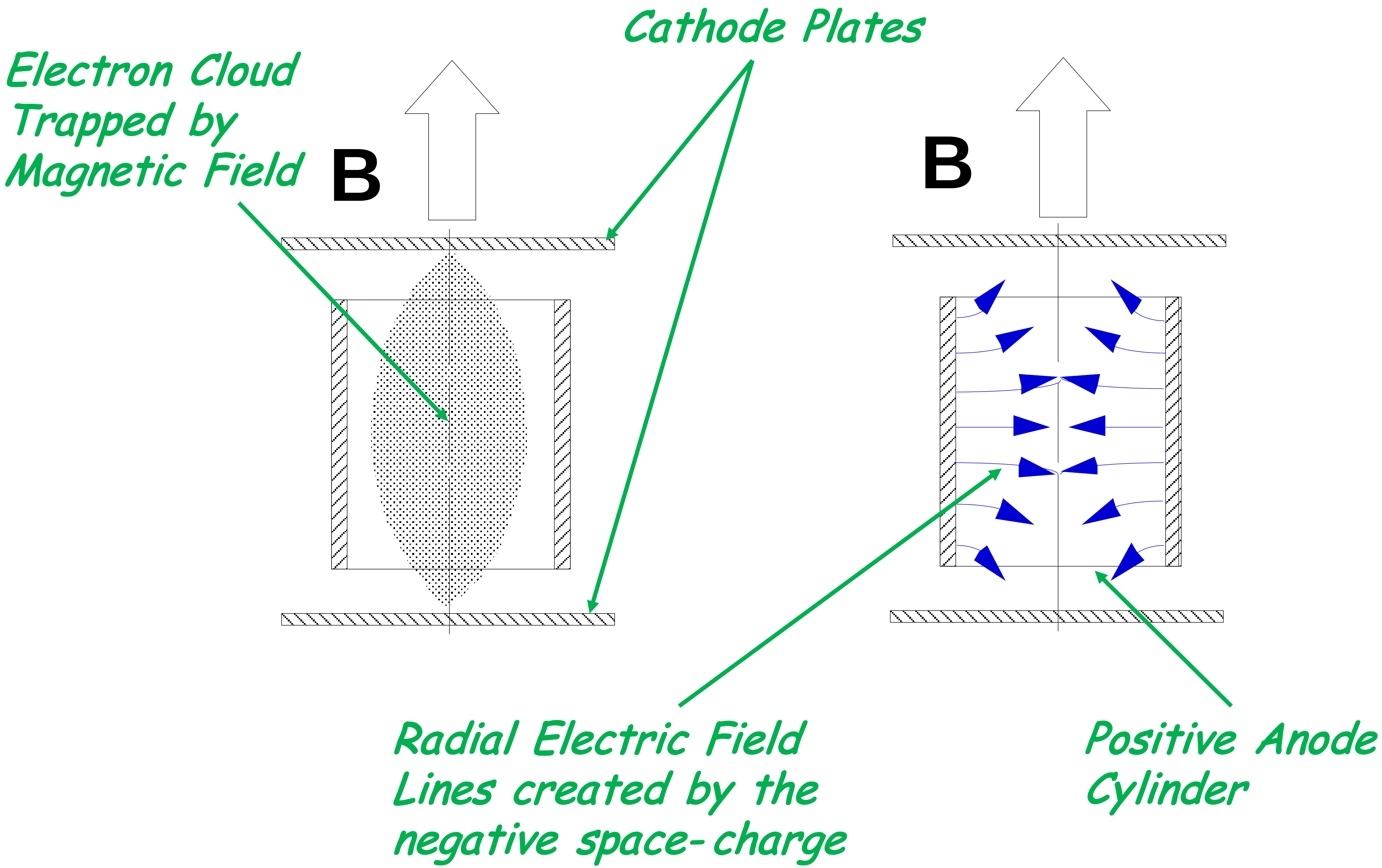
- *Sputter-ion pumps were first commercialized by Varian Associates (now Agilent Technologies, Vacuum Division) as VacIon pumps*

- *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



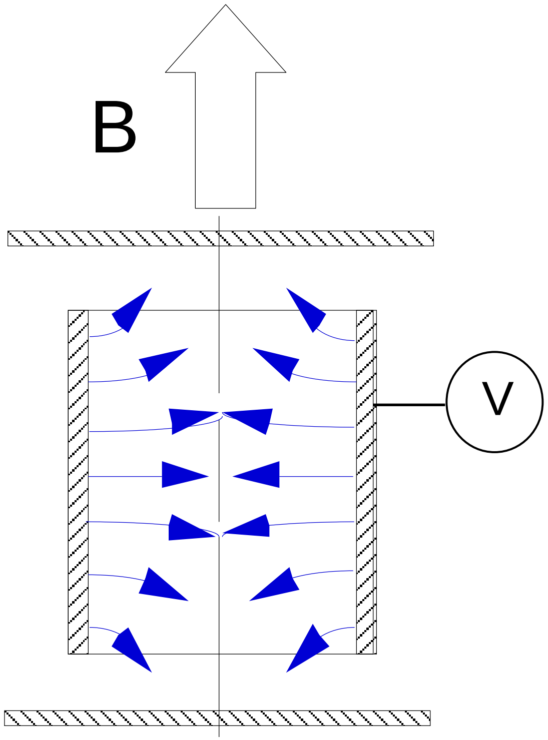
Penning Cell Sensitivity

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

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

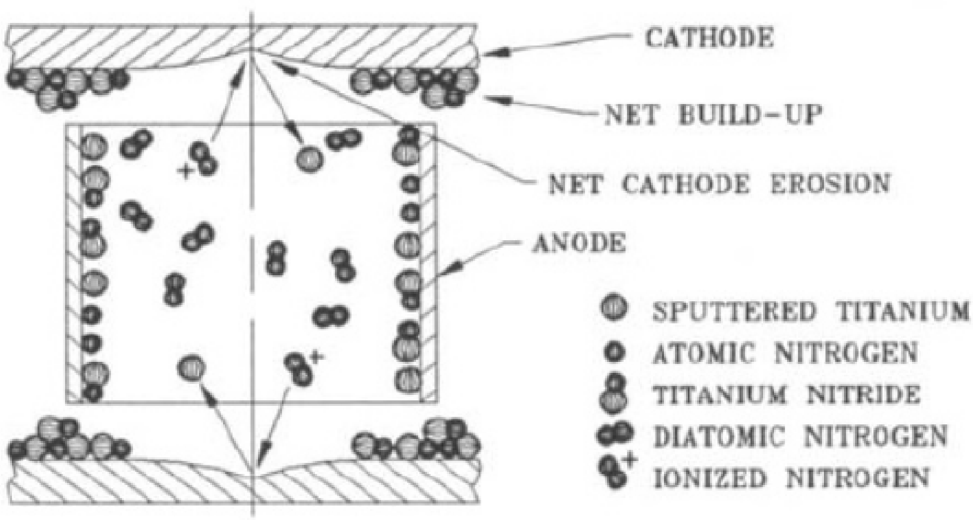
Parameters Affecting Penning Cell Sensitivity

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



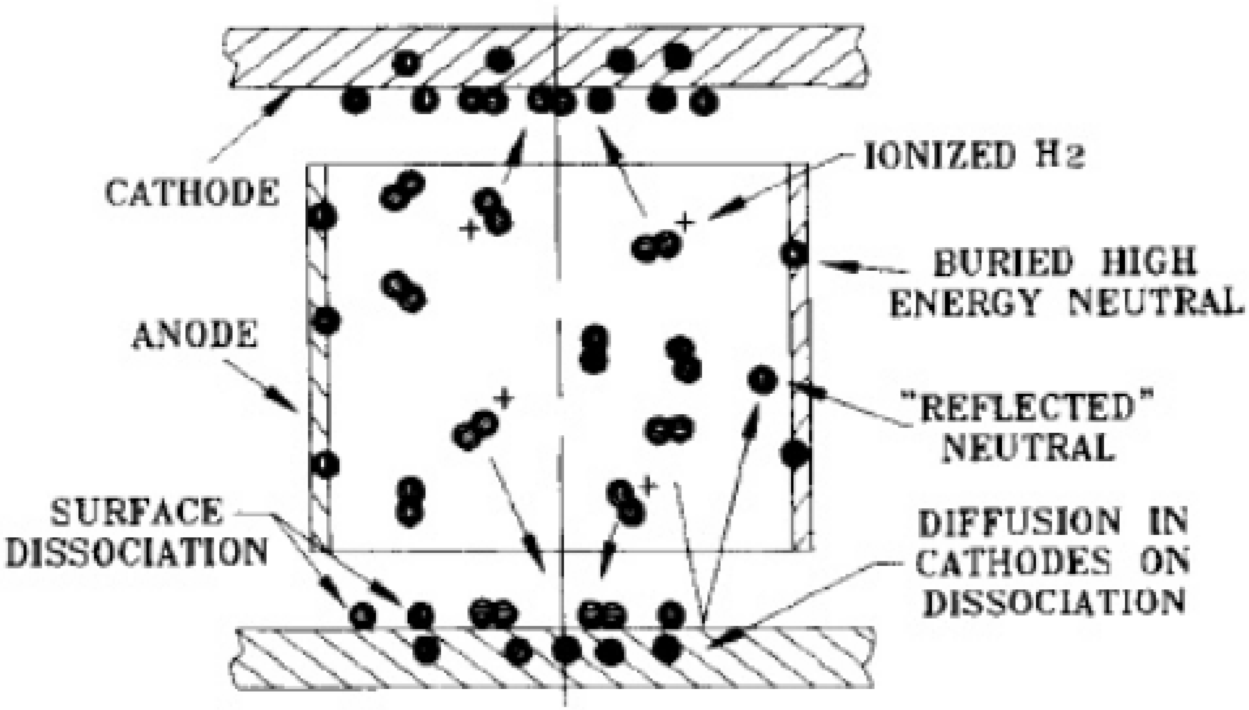
SIP Pumping Mechanism – General

- *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



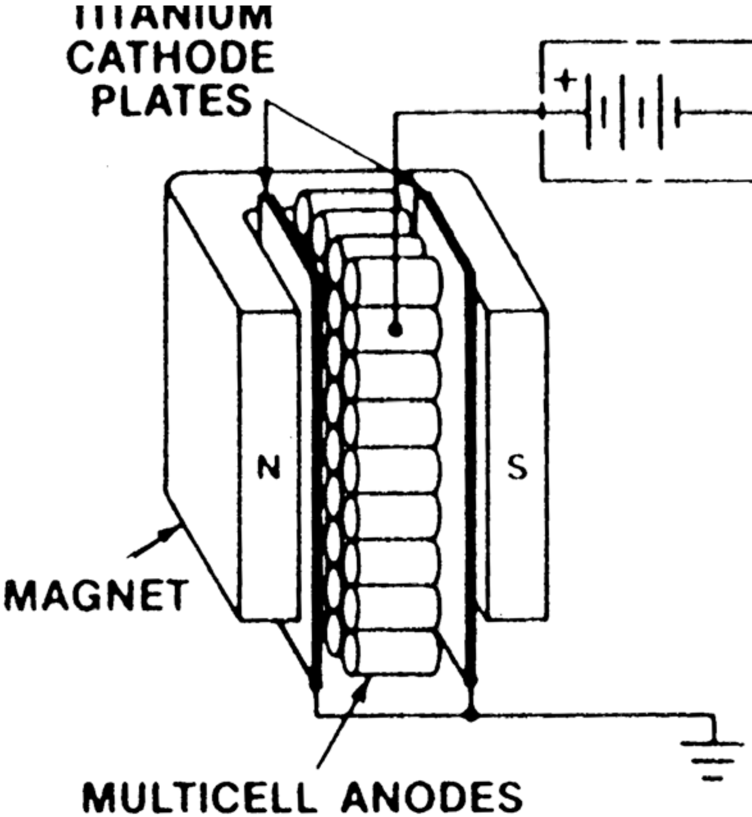
Sputtering Ion Pumps pump hydrogen gas differently. Hydrogen pumping is a two-step process:

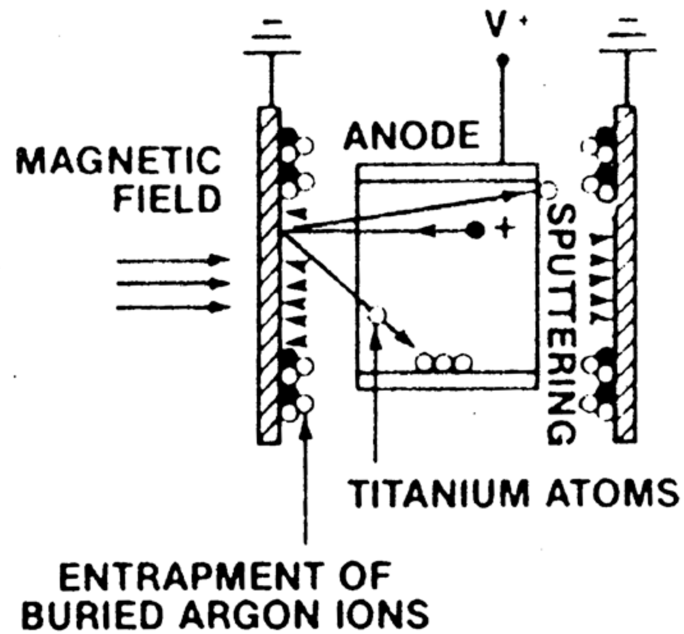
- *Hydrogen molecules dissocatively chemisorb on fresh metallic cathode surface*
- *Adsorbed H atoms then diffuse into the bulk of the cathodes*

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

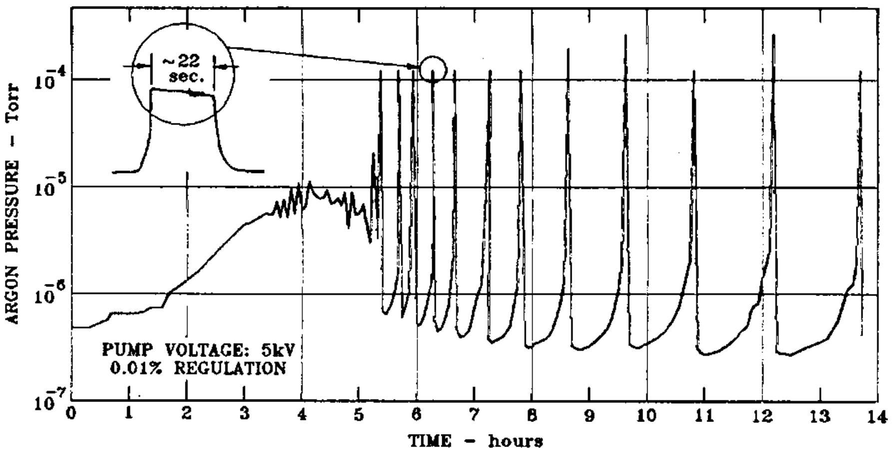




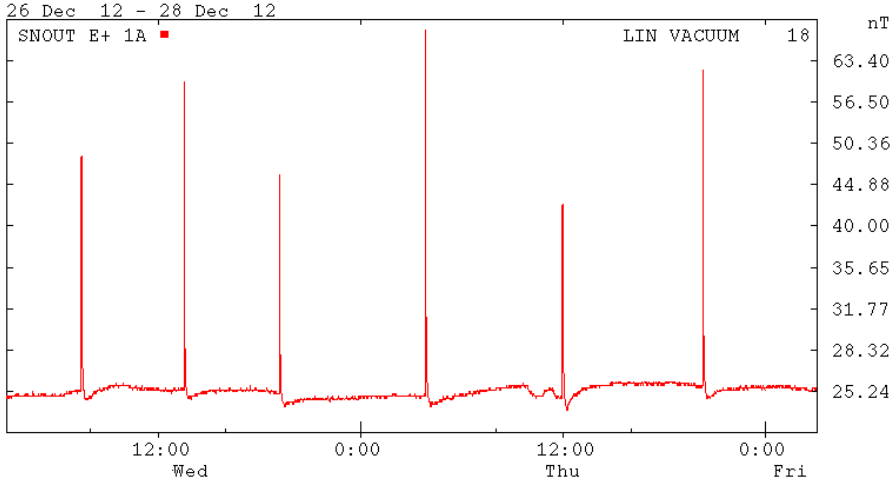
In a diode ion pump, both cathode plates are commonly made of titanium, due to its high sputtering yields and chemical reactivity

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

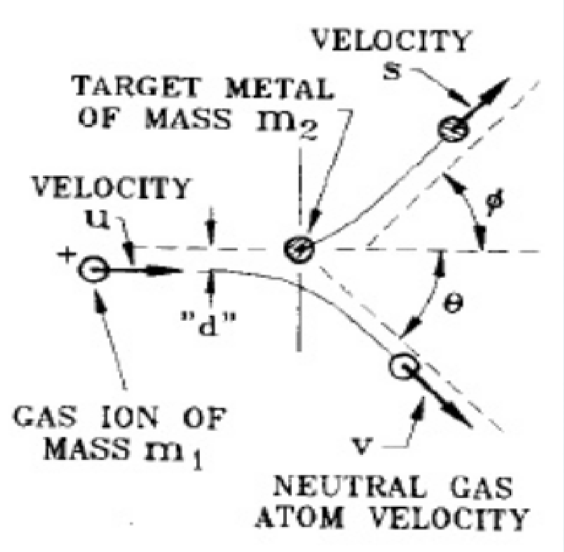
Differential Ion (Noble Diode) Pumps

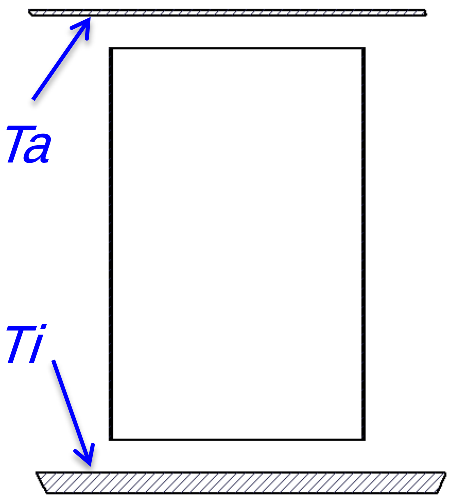
- *In the so-called differential diode pumps, one of the Ti cathode plates is replaced with a heavy metal (commonly tantalum). The argon-instability is no longer an issue in the DI pumps.*
- *The enhanced noble gas pumping performance has been explained by a so-called fast neutral theory. The theory 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

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

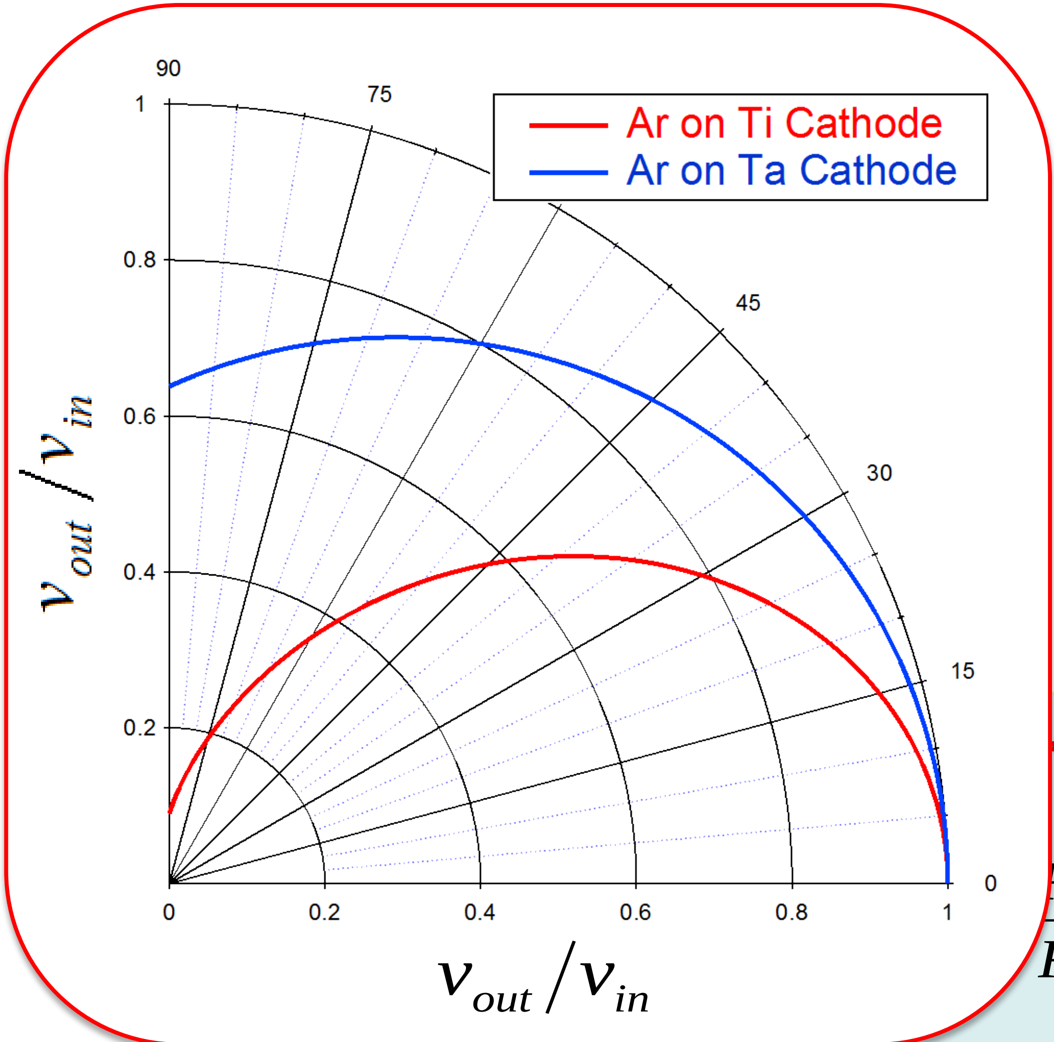
$$R\equiv m_2/m_1$$





A D-I Cell

Neutral Ar Kinetic Energy – Ti vs. Ta Cathode

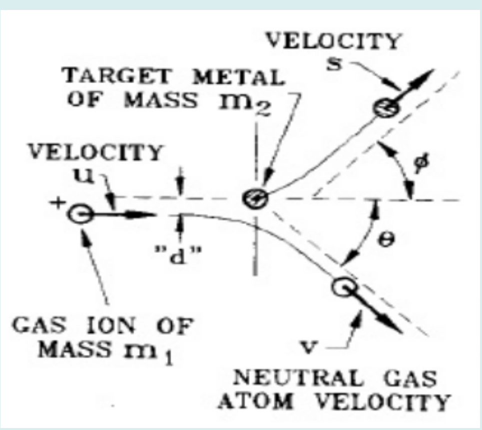


Argon neutrals clearly maintain much higher kinetic energy upon interaction with a Ta cathode as compared to with a Ti cathode

al Theory

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

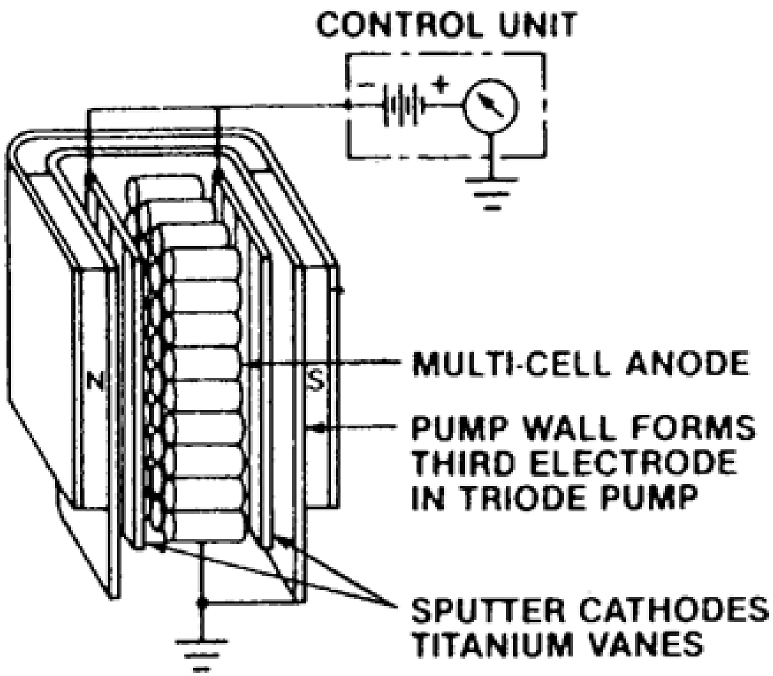
$$R \equiv m_2/m_1$$



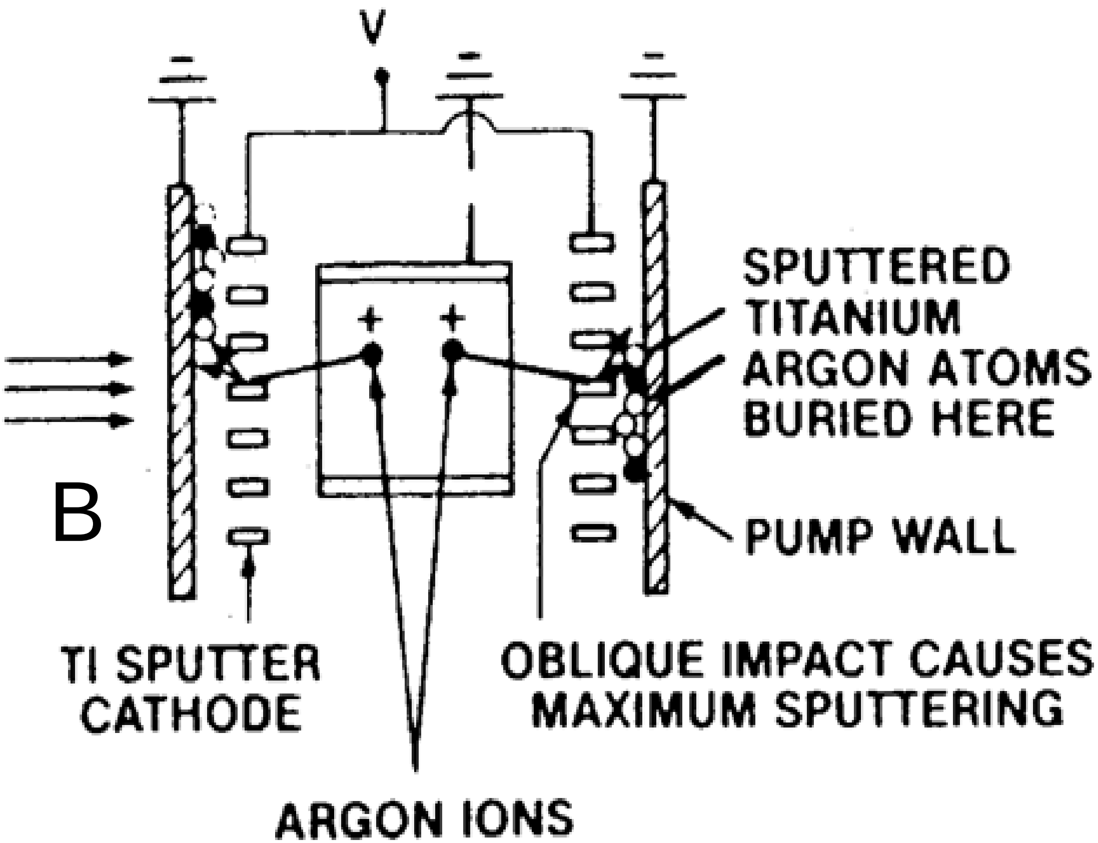
Noble Diode vs. Diode Pumps

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



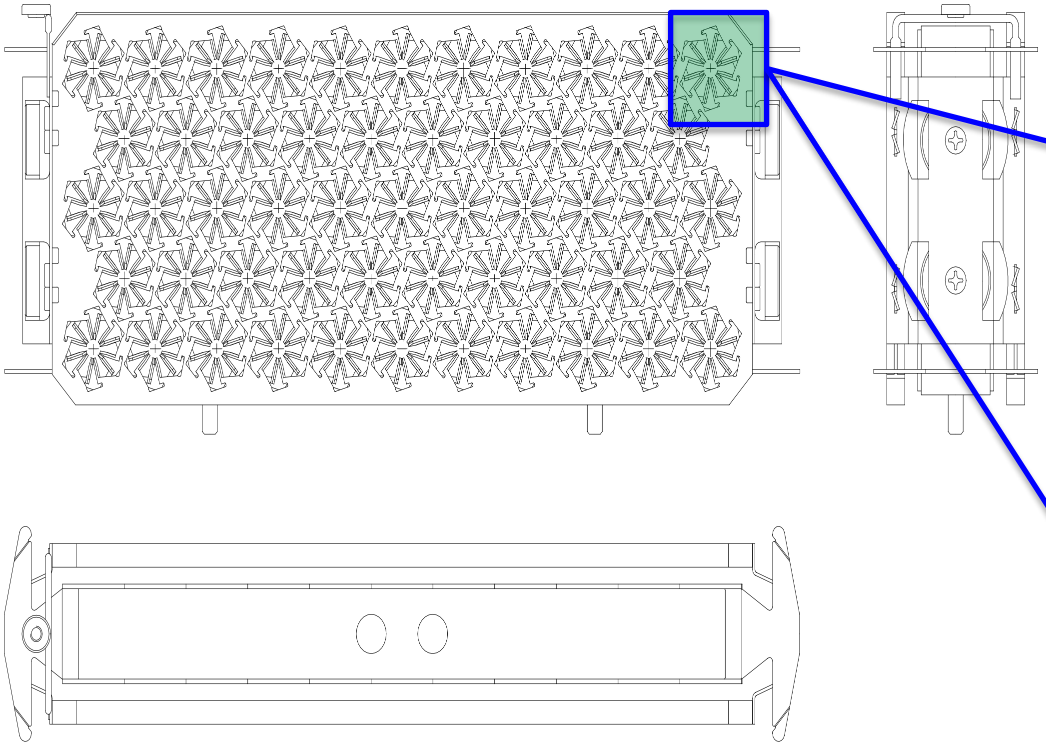
Another type of ion pumps handle noble gases well. Usually the triode pumping elements exchangeable with diode elements.

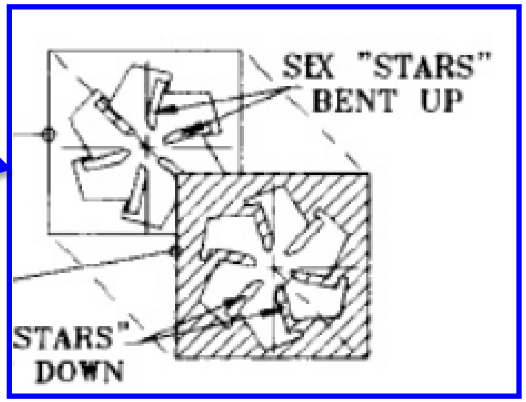


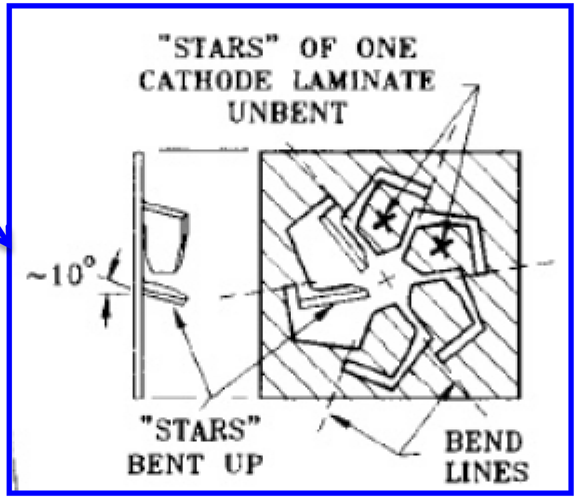
Disadvantages:

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

Triode Ion Pump – StarCell Pumps

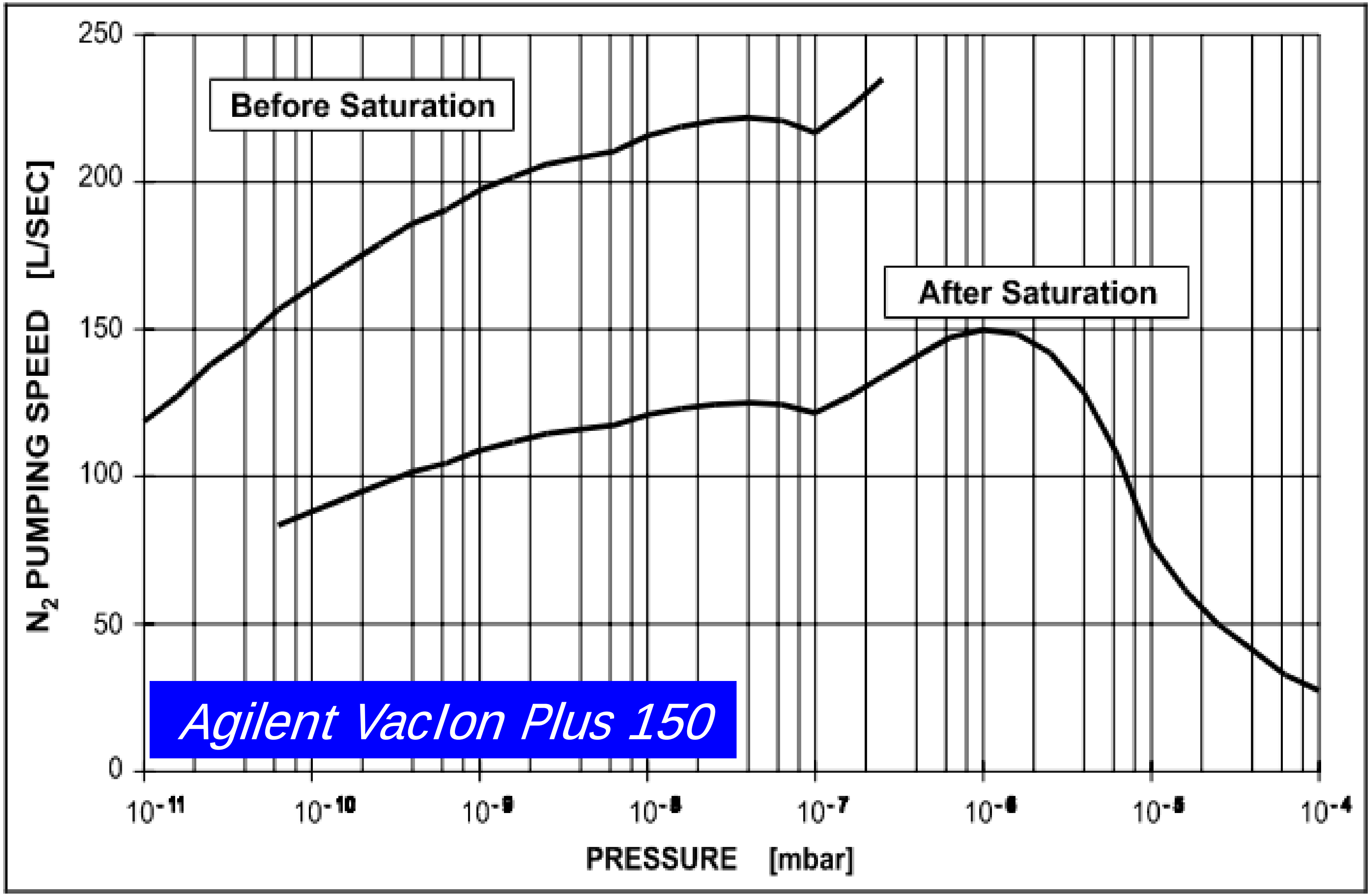




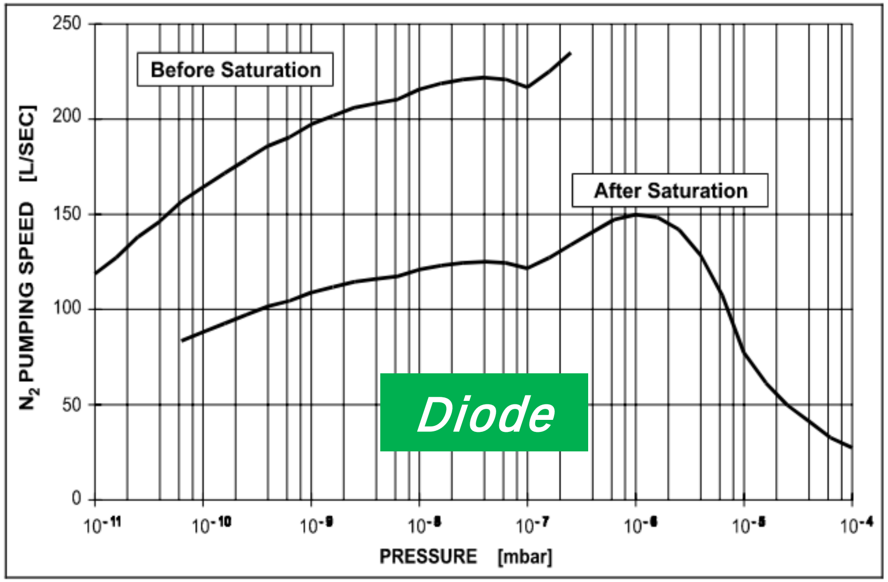


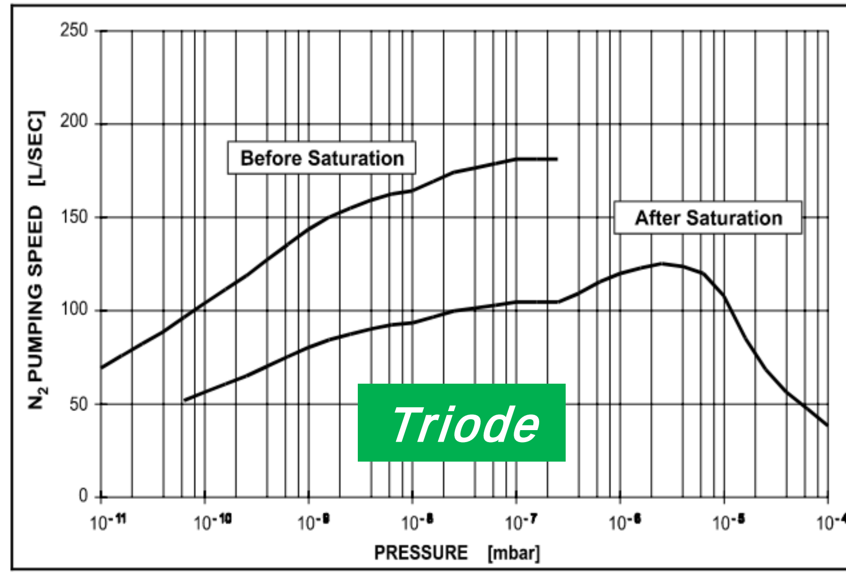
A special type of triode pump from Agilent (Varian), with excellent noble gas pumping, and improved long-term performance over strip-style triode pump.

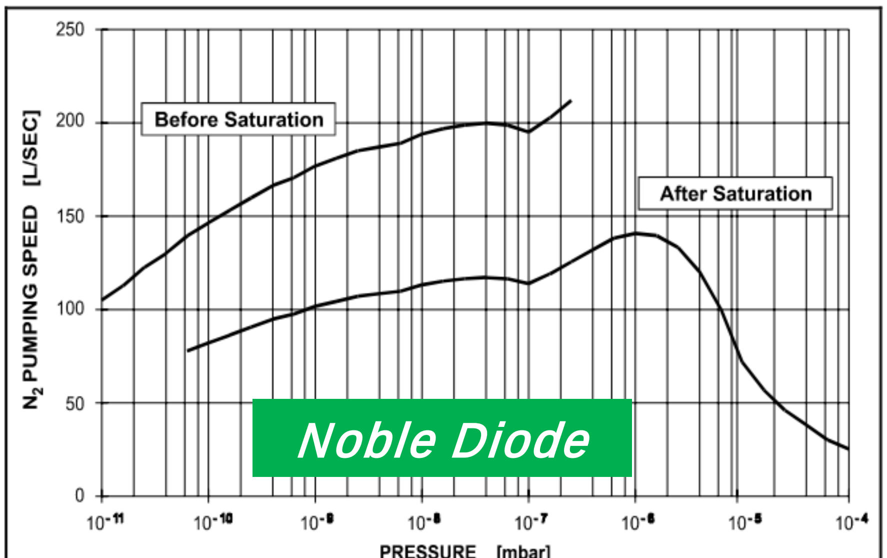
Diode Ion Pump – Pumping Speed

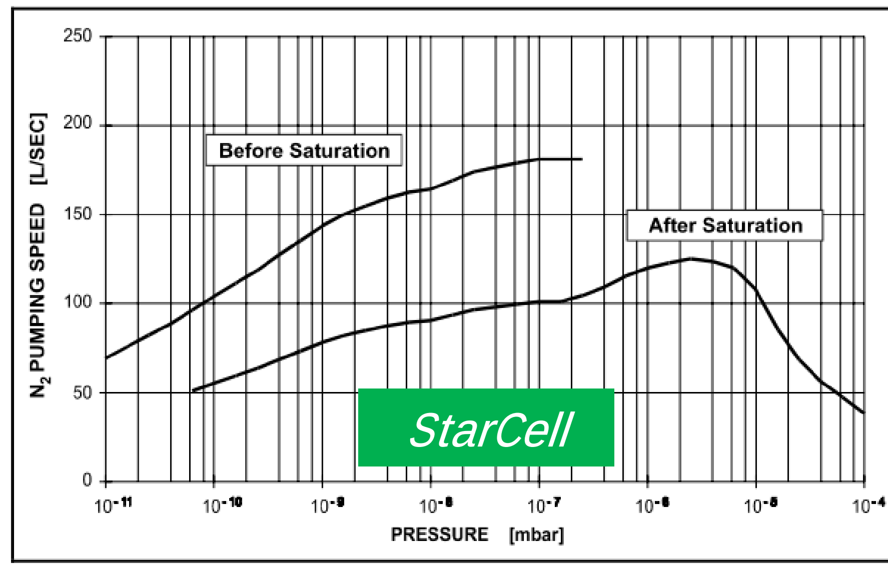


N_2 Pumping Speed of Different Styles



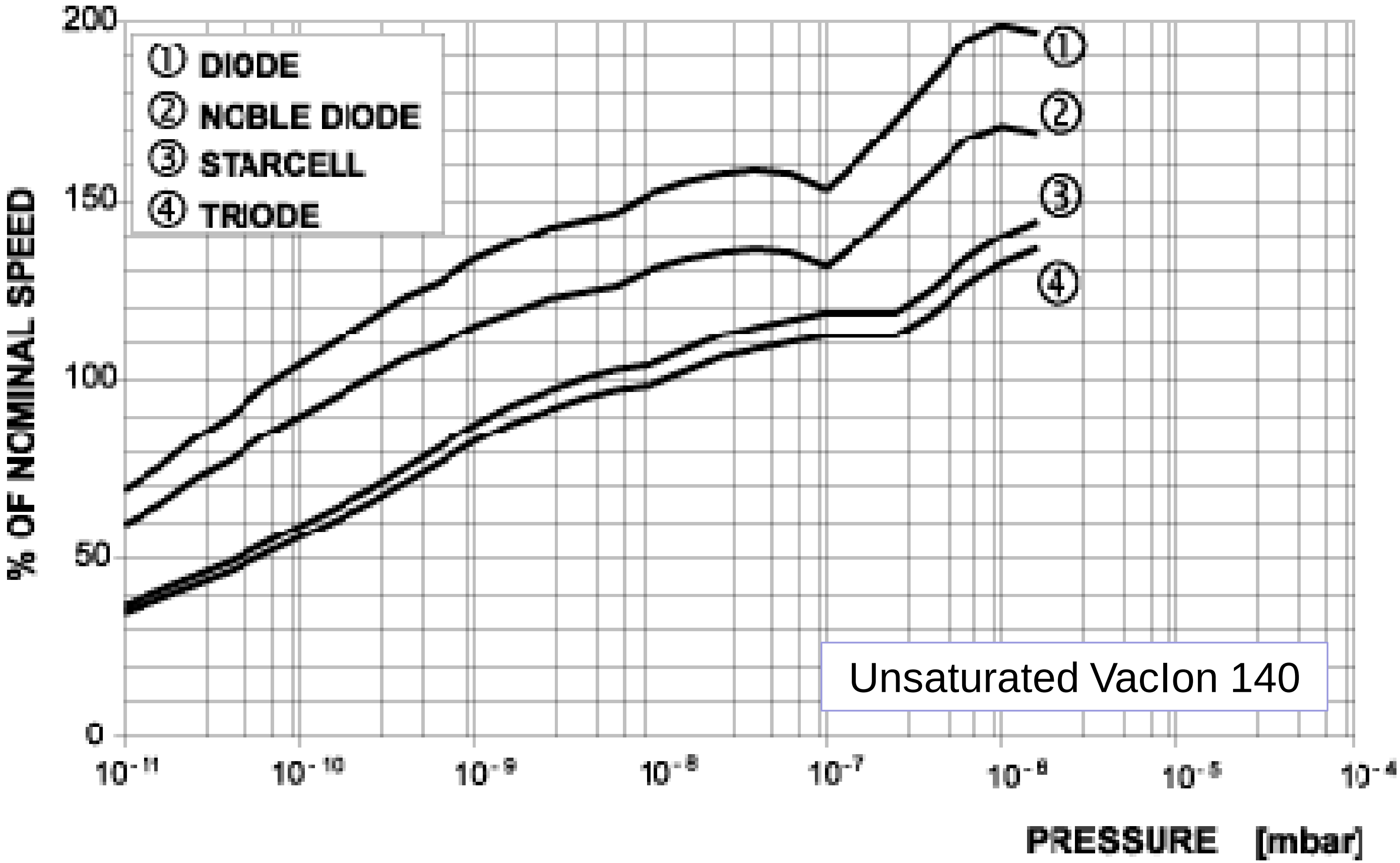






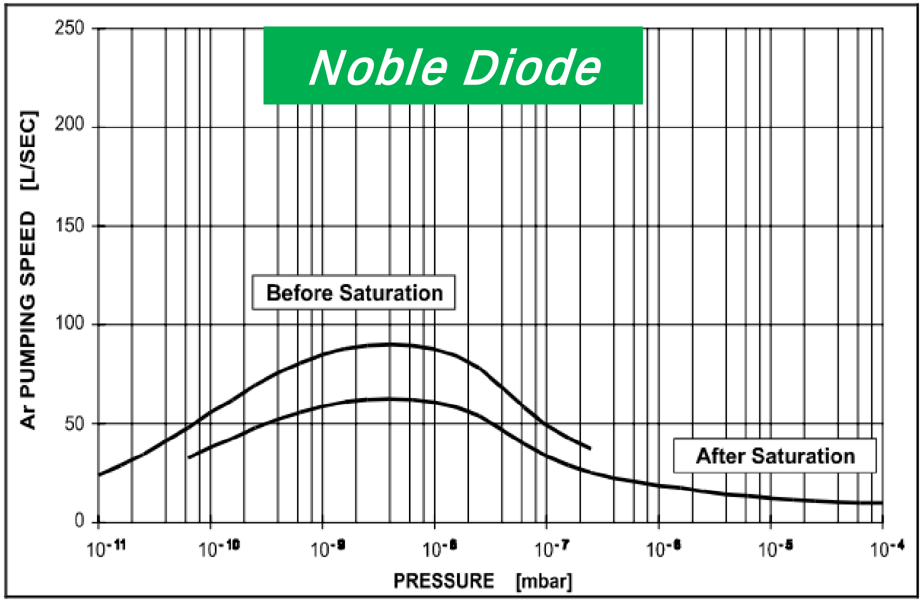
Agilent VacIon Plus 150

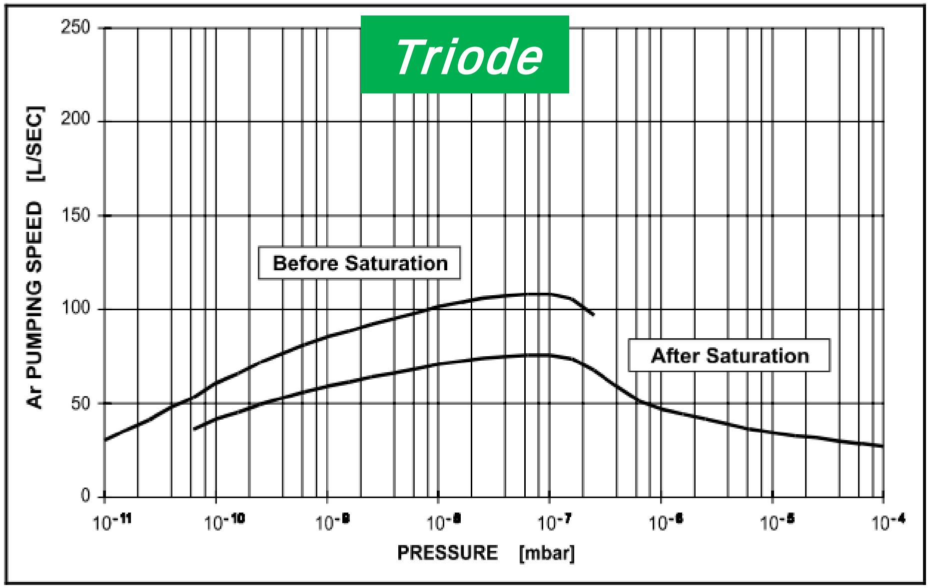
N_2 Pumping Speed of Different Styles

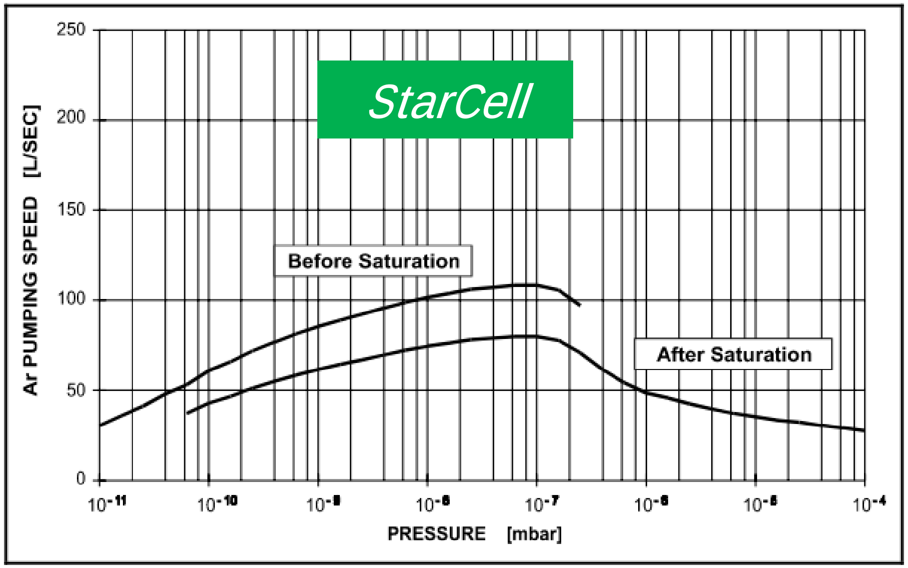


(Ref. Varian Vacuum)

Argon Pumping Speed of Different Styles







Agilent VacIon Plus 150

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)

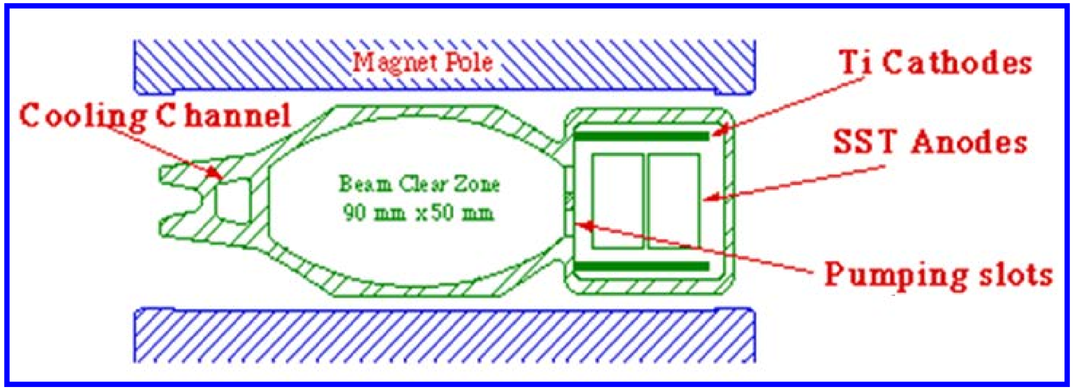
Commercial Ion Pumps – Agilent (Varian)

- 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

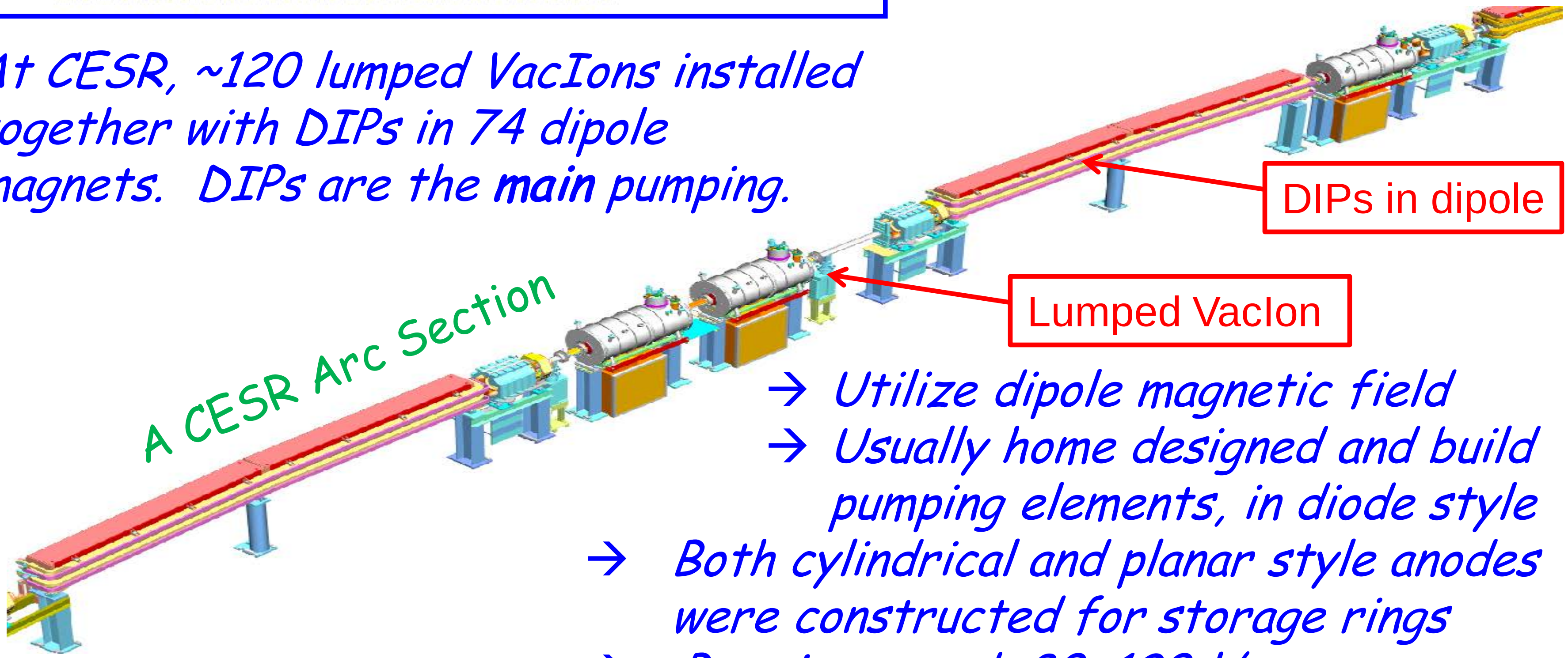
Commercial Ion Pumps – Gamma Vacuum

- 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*

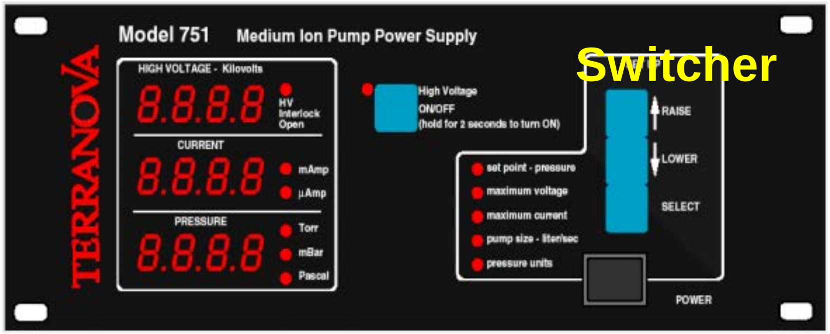
Commercial Ion Pump Controllers

Agilent 4 UHV
Output Power: 400 W
Output HV: 3, 5, 7 kV
Current: up to 200 mA
Ion Current: 10 nA ~ 100 mA

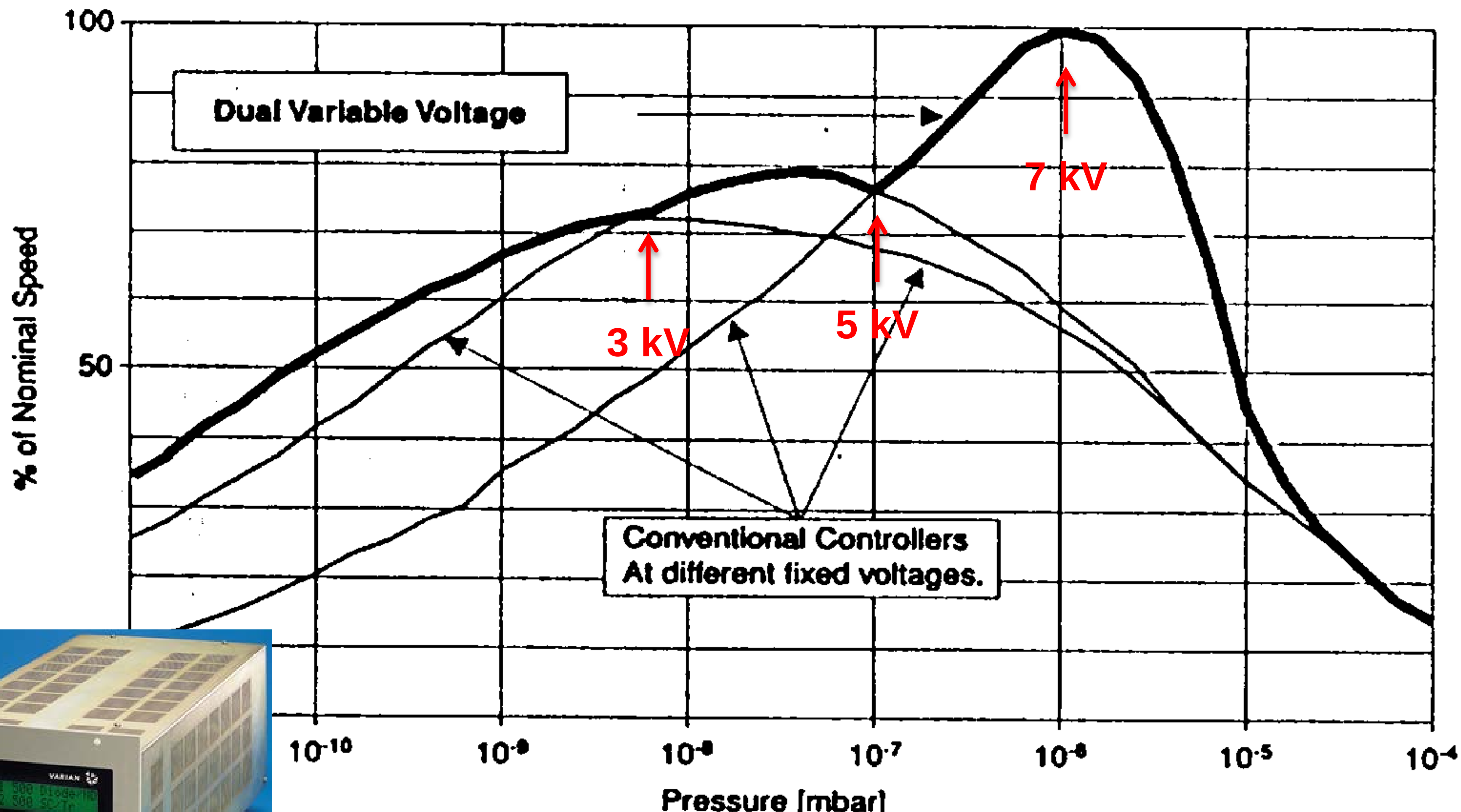
Agilent MiniVac
Output Power: 20~40 W
Output HV: 5 kV
Current: up to 20 mA
Ion Current: 10 μA~20 mA

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.*