CERN Accelerator School

Seminar on Getter pumps

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Outline

- What is a NEG and how it works : main chemico-physical features
- key properties and typical use of NEG pumps :
- Different types of NEG pumps
  - UHV Cartridge pumps
  - UHV NEG/sputter ion combination pumps
  - NEG modules and strip configurations
- NEG pumps outgassing properties
- Examples of applications for accelerators, experimental physics and industry
- Extending the use of NEG pumps into HV regime
- Particle issues in NEG pumps : compressed vs sintered materials

NEG pumps in a nutshell

- **NEG pumps** find widespread adoption in UHV applications such as :
  - Analytical equipment (QMS, SIMS, Surface science tools …)
  - Metrological and inspection tools (SEM, CD SEM, TEM)
  - Photolithographic equipment (e-beam equipment…)
  - Load lock and transportation
  - **Accelerators (colliders, light sources, FEL, ERL….)**
- They have **extremely large pumping** speed per unit volume.
- They can improve the **ultimate vacuum,** and provide a very **compact pumping** solution in any type of these equipment
- NEG pumps have **negligible power consumption** and **zero maintenance. They are therefore extremely easy to use.**
- **Overall, system reliability and vacuum performances are increased, with a lower total cost of ownership.**

2. What is a Non Evaporable Getter (NEG) : main chemico-physical properties

What is a Non Evaporable Getter ?

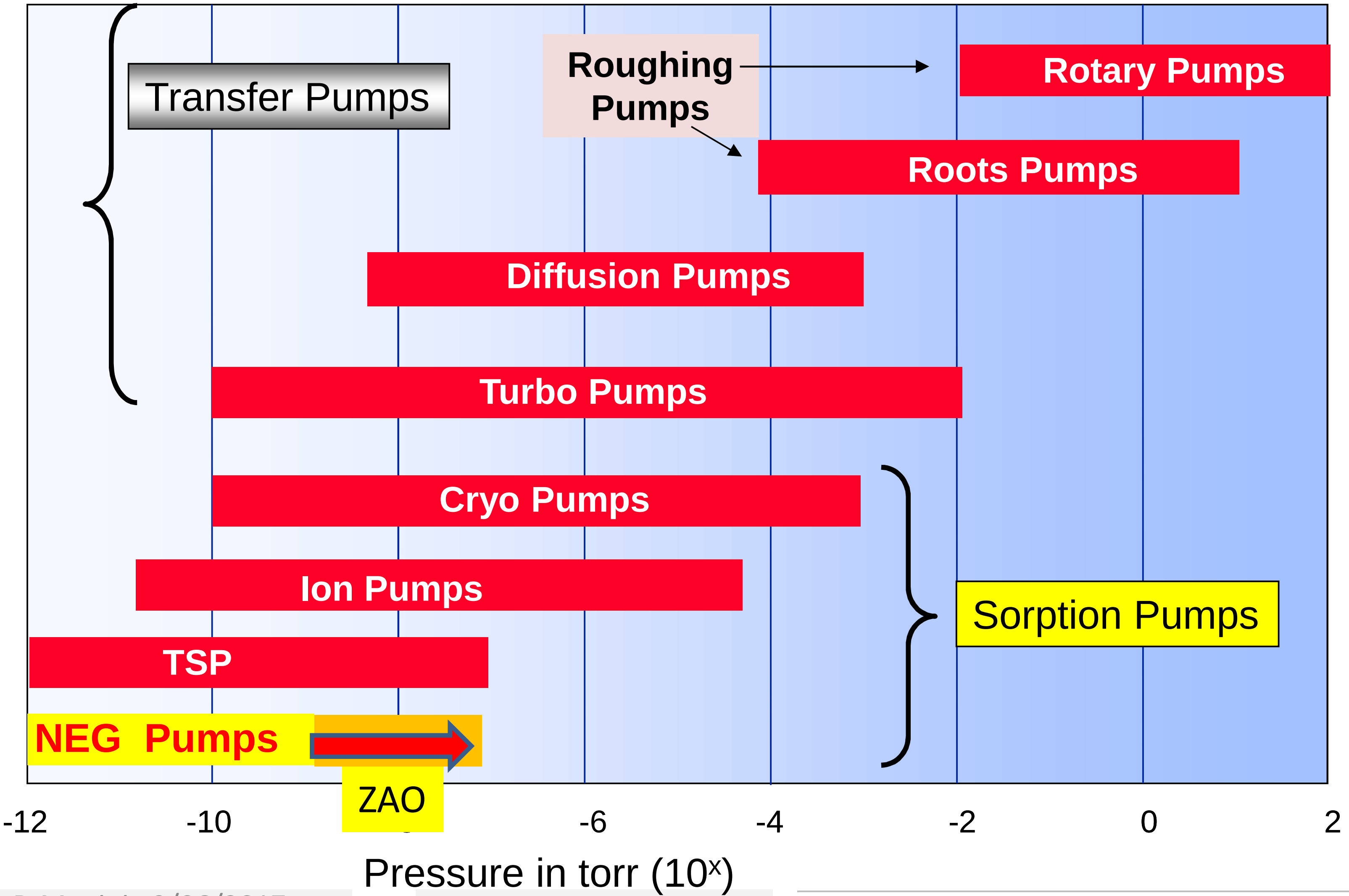
- NEG are reactive metals or alloys which capture gases , such as H_2O, CO, CO_2, O_2 and N_2 by a **chemical reaction** on their active surface.

- The reaction generates carbides/oxides/nitrides on the getter surface: Gases are **permanently removed** from the vacuum system.

- **Hydrogen** does not react to form a chemical compound but dissolves in the bulk of the getter forming a **solid solution**.

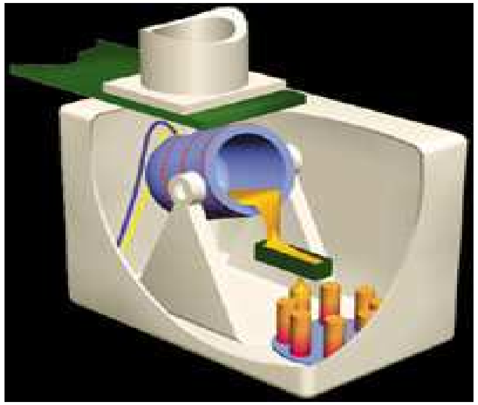
- A getter does not pump noble gases as they do not chemically react.

Pressure Range of Vacuum Pumps



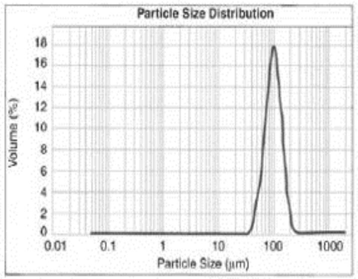
Getter Manufacturing Process

Alloy Ingot preparation

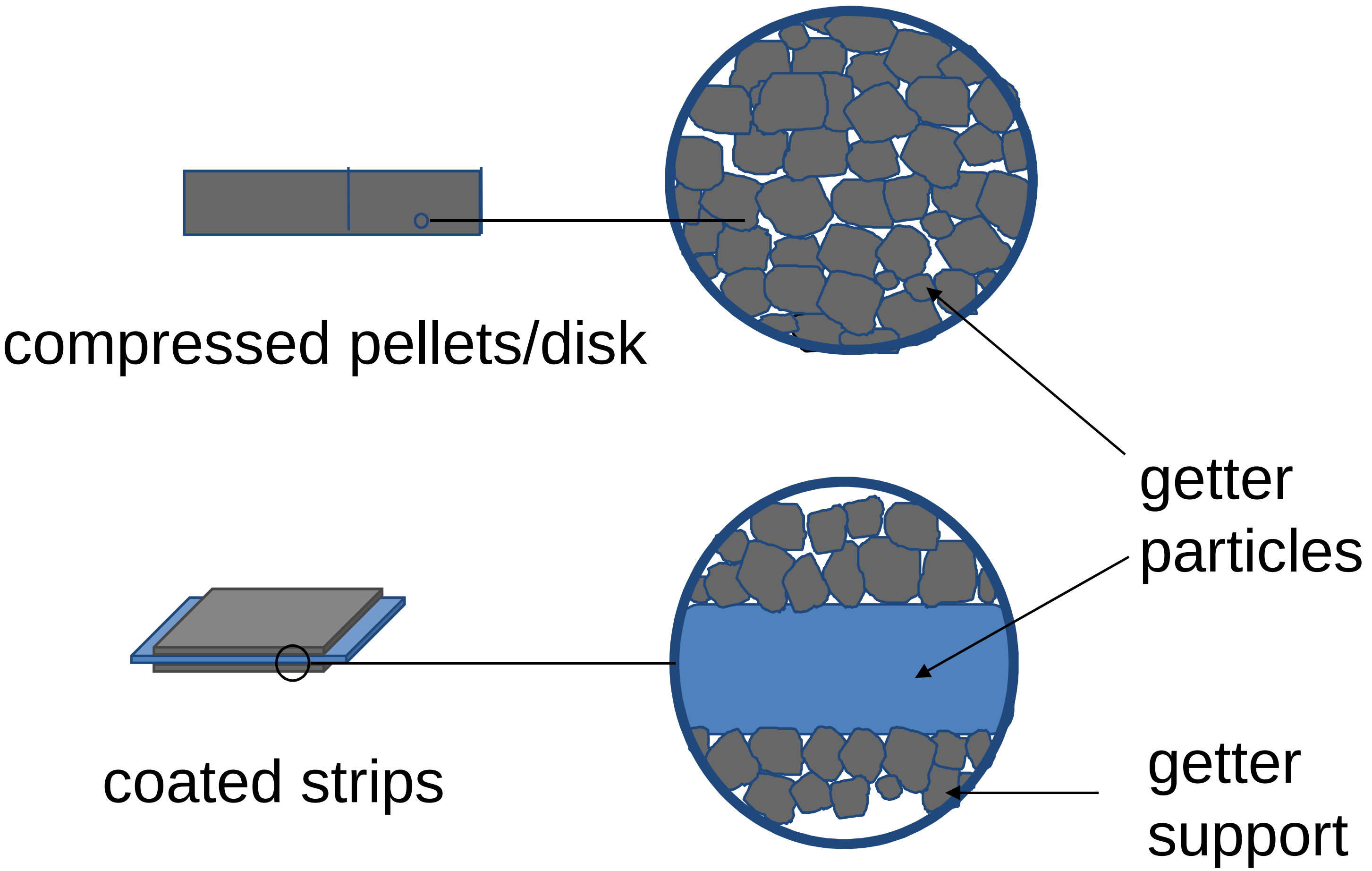


Alloy Ingots Grinding → Alloy Powder Sieving & Mixing → Getter Forming & Shaping

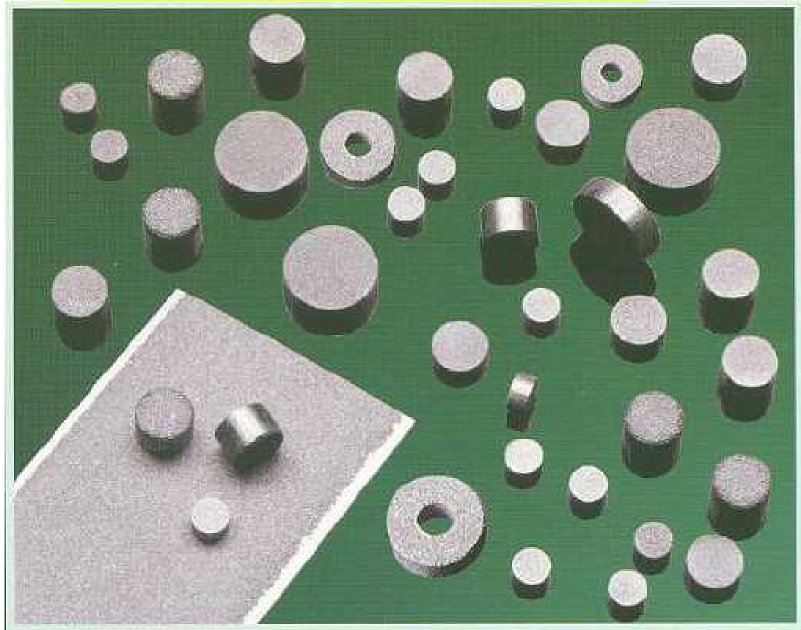
- Cold lamination
- Compression
- Sintering
- Screen printing
- Others….

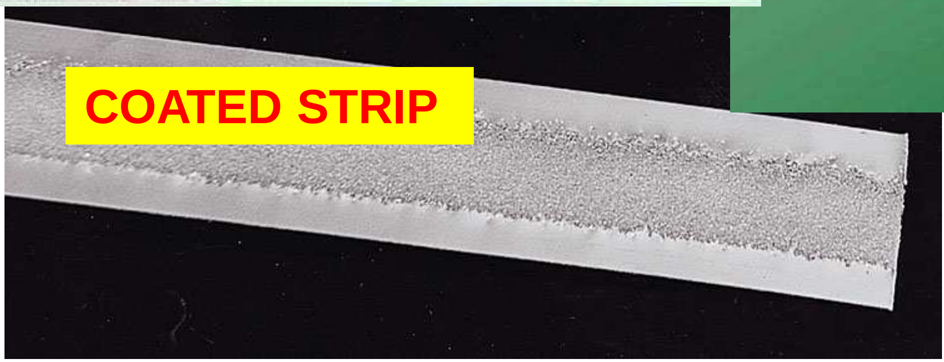


COMPRESSED getter configurations (St 707®)



Non evaporable COMPRESSED getters NEG (St 707®)

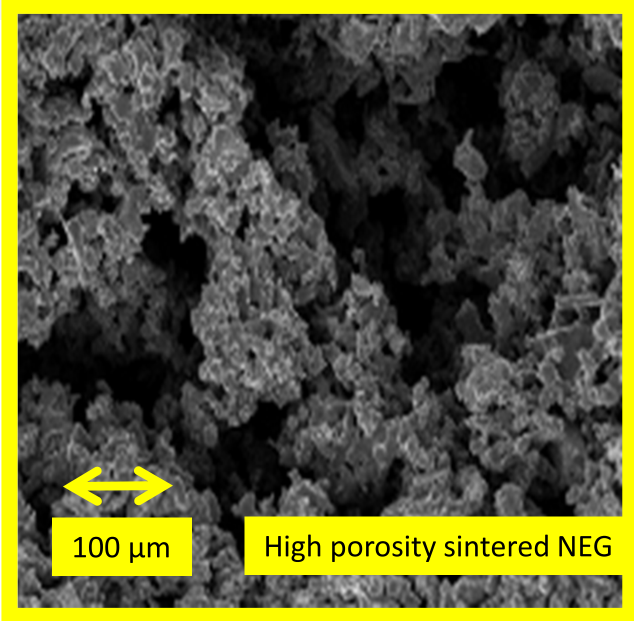


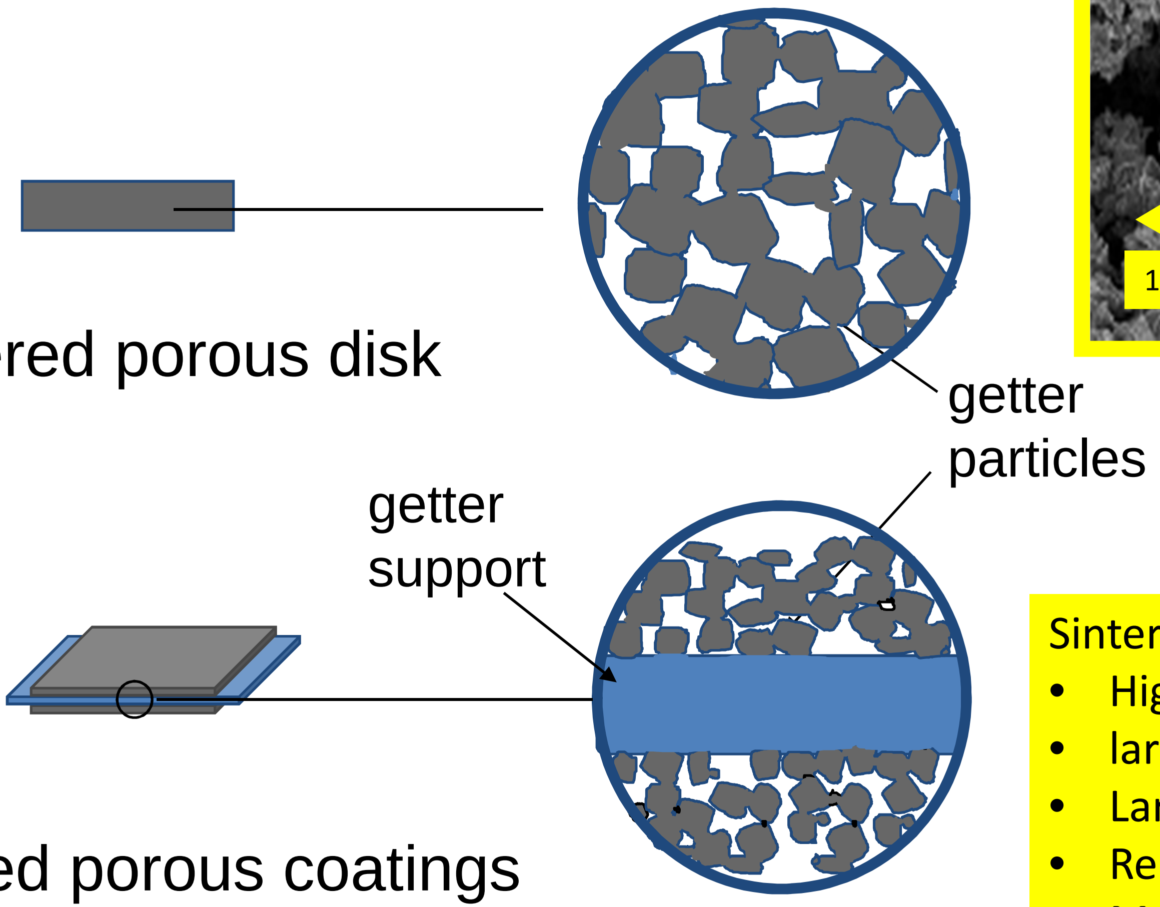


St 707®, St 172® , St 101 ® are SAES getters International registered trade marks

SINTERED getter configurations

In sintered getters (e.g. St 172) the getter structure is much more opened but getter grains are bound together.





sintered porous disk

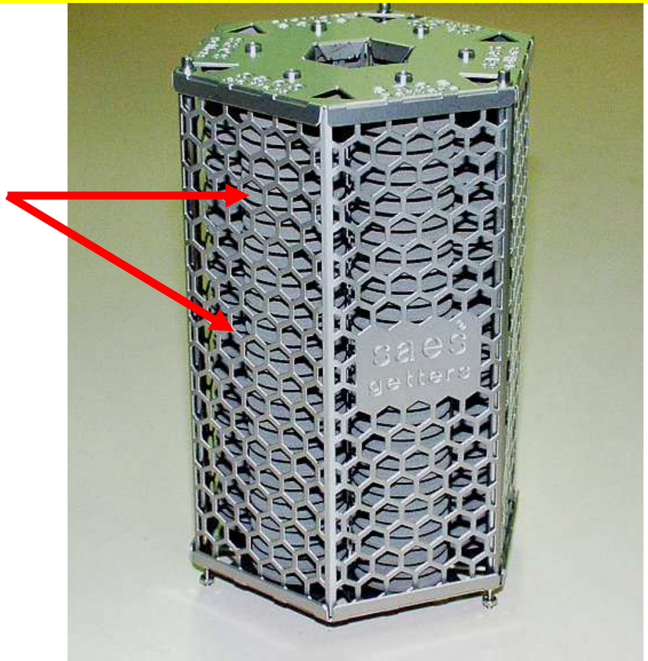
sintered porous coatings

Sintered St 172 getter disks have
- High conductance
- large porosity and voids
- Large sorption speed
- Reduced amount of material
- Marginal dust emission

Sintered Porous Getters

PELLETS, DISKS,WASHERS

POROUS GETTERS DISKS ASSEMBLED IN A OPTIMIZED STRUCTURE : NEG CARTRIDGE

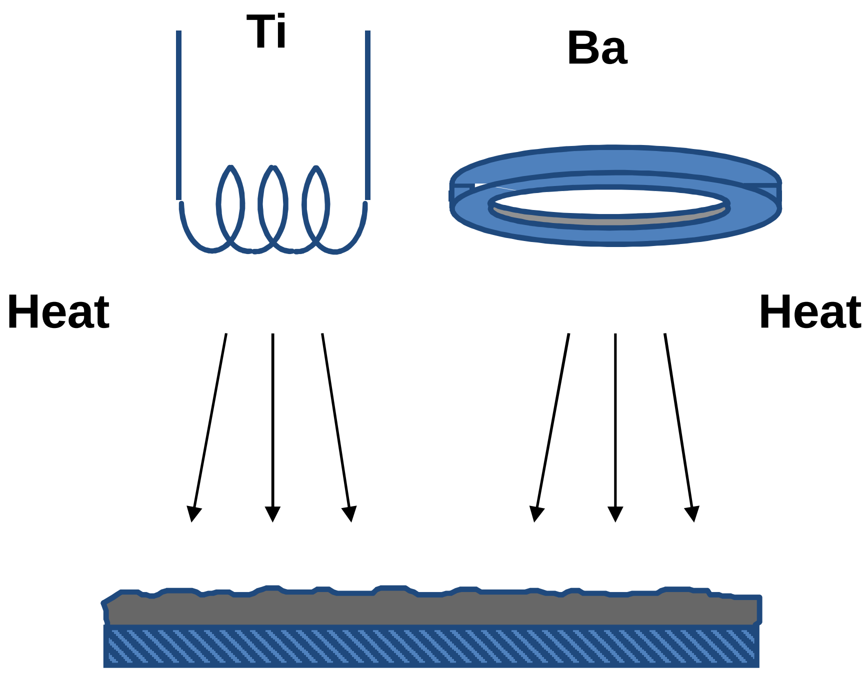


SINTERED GETTER DISKS

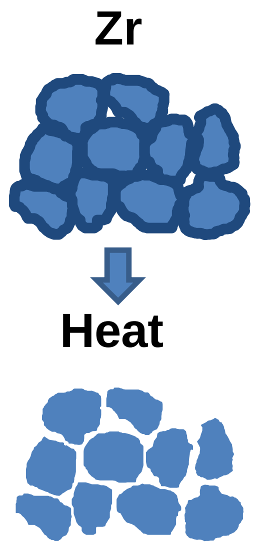
Families of getters

Evaporable
Ca, Sr, **Ba**, Ti*

Nonevaporable
Ti* , **Zr**, Th



Evaporation → TSP



Active getter material

Activation→NEG

Sorption mechanisms of getters

Adsorption → Physisorption

Adsorption → Chemisorption

Physisorption involves weak bonds (<10 kcal/mole), mainly due to Van der Waals forces.

Chemisorption involves stronger bonds, actual chemical bonds, localized in the adsorption sites, often leading to dissociation of the molecule

NEG operation

- ☐ NEG need to be heated **under vacuum** : **"ACTIVATION"**

a) Modest activation temperature : **400-500°C**
b) short time : **≈ 60 minutes**

- ☐ After activation, the pump sorb gases at room temperature without requiring power **(surface adsorption)**

- ☐ When the surface capacity is reached (or after a venting), the pump must be reactivated. This can be done many times (>100)

Getter Activation Process

Chemistry of the sorption processes

The sorption process is based on :

1. Cracking the molecule into atoms on the surface of the getter
2. Irreversible chemisorption of the atoms on the surface (metallic surface turns into carbides/oxides/nitrides)
3. In case of hydrogen sorption is reversible (equilibrum pressure)

$$Zr + O_2 \rightleftharpoons ZrO_2$$

at T=500 °C, Peq. ~10^{-60} mbar
at T=1000 °C, Peq. ~10^{-30} mbar
at T=2000 °C, Peq. ~10^{-10} mbar

$$Zr + H_2 \rightleftharpoons ZrH_2$$

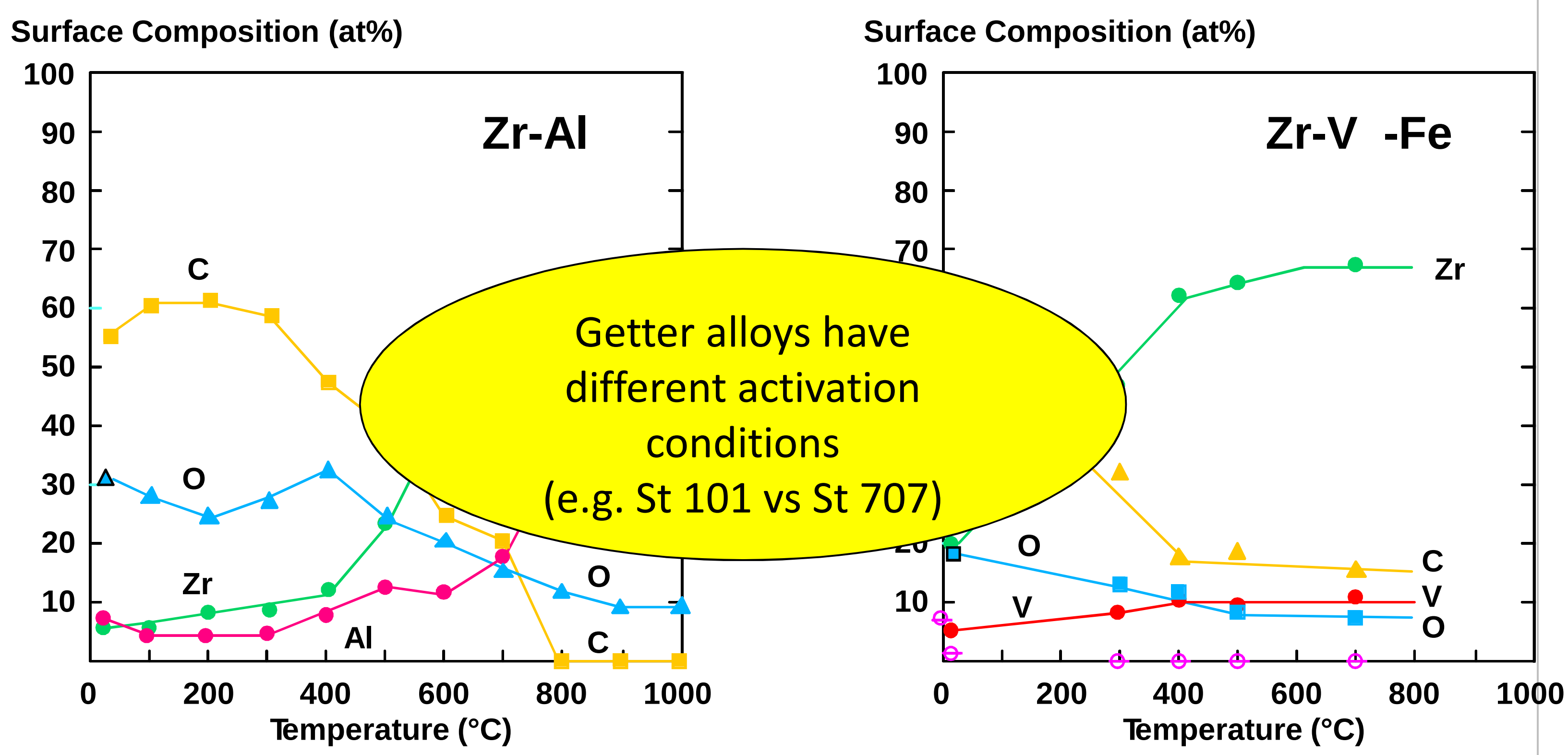
at T=21 °C, Peq. <10^{-15} mbar
at T=500 °C, Peq. ~10^{-2} mbar

Activation "Visualized" by Surface Analyses

(K. Ichimura et al., J. Vac. Sci. Technol. A 5(2), 220 (1987))

St 101®

St 707®



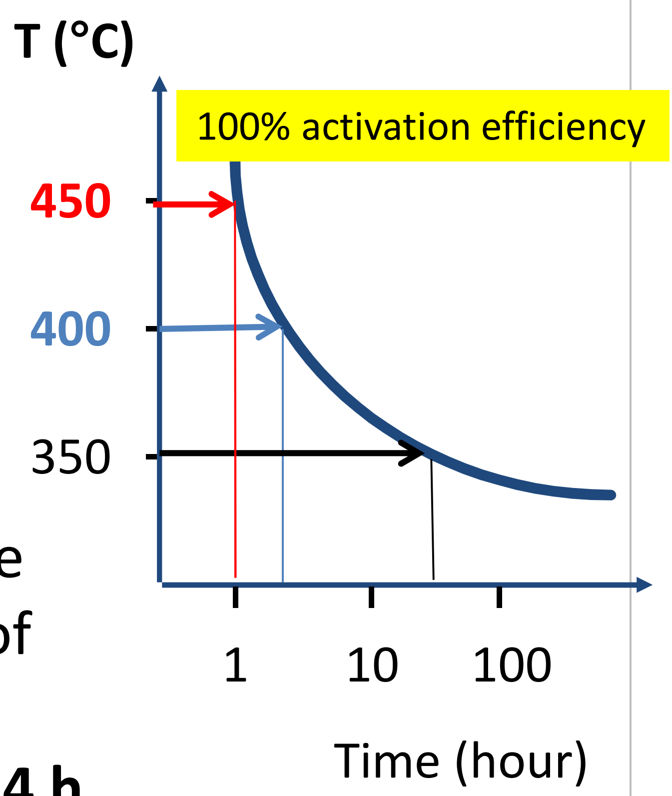
Getter alloys have different activation conditions (e.g. St 101 vs St 707)

St 707 and St 101 are SAES Group international registered trademarks

NEG Activation Process : T vs Time

***Activation*:**
- Diffusion of surface protective layer

Diffusion phenomena:
- Depend exponentially on the temperature: $D=D_o\exp(-E/KT)$
- Depend on the square root of the time

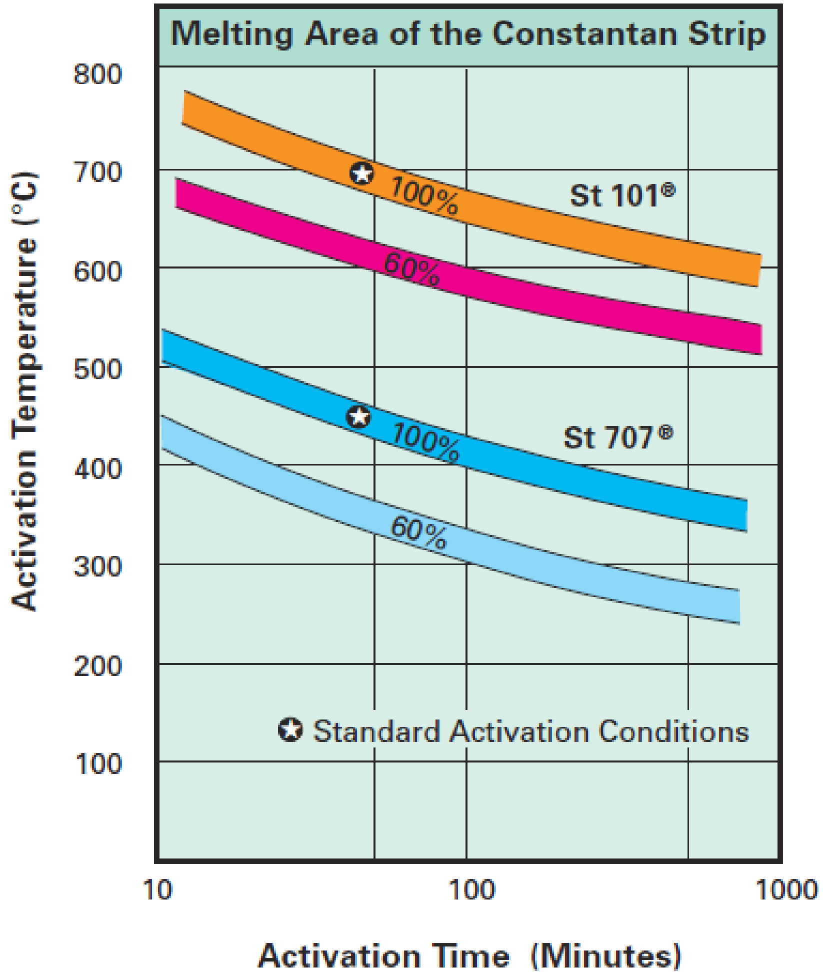


Thus, the same effect can be obtained with the increase of temperature or with the increase of time :

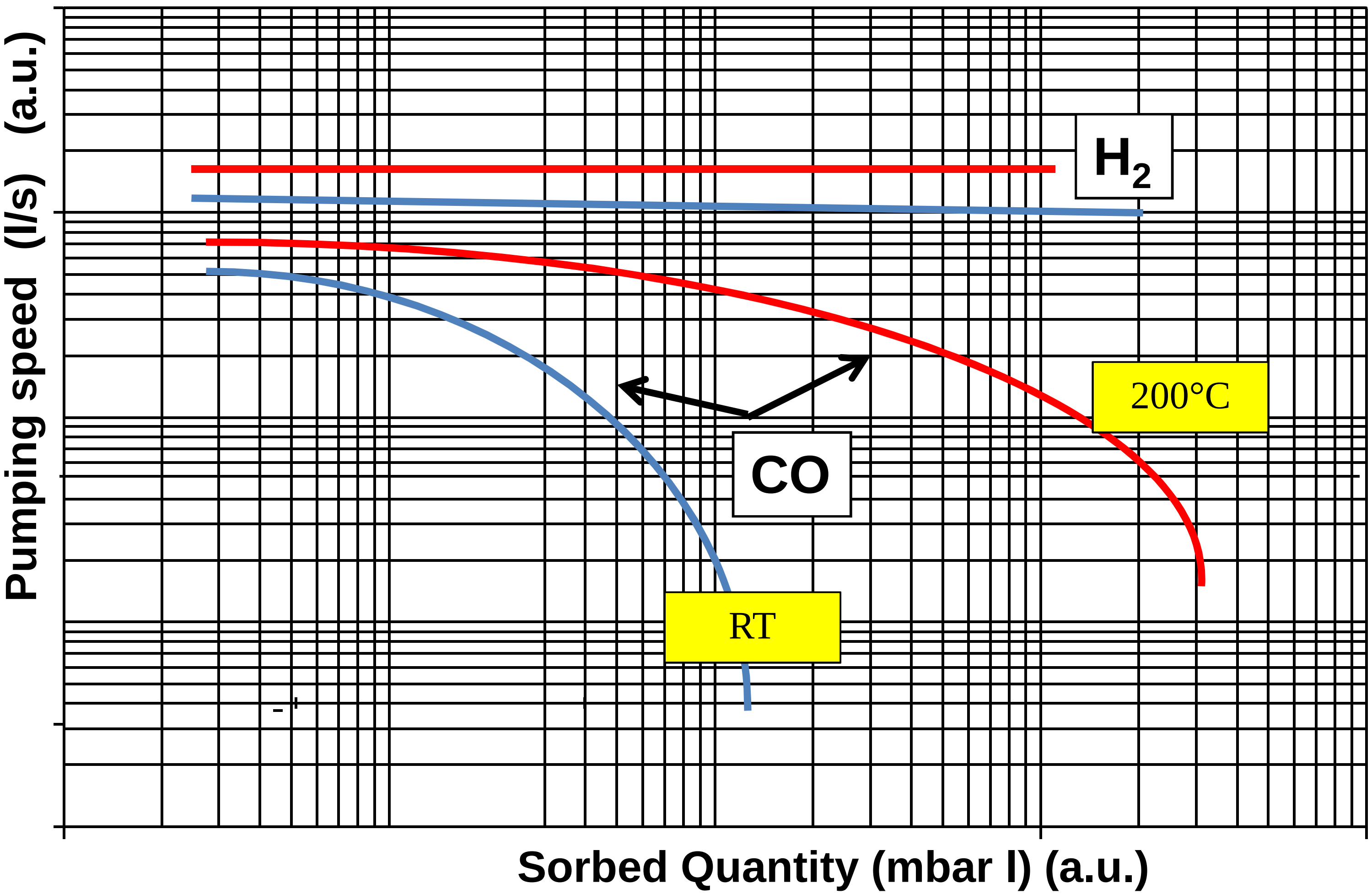
e.g. **450°C x 1 h ≈ 400°C x 4 h ≈ 350°C x 24 h**

NEG Activation efficiency

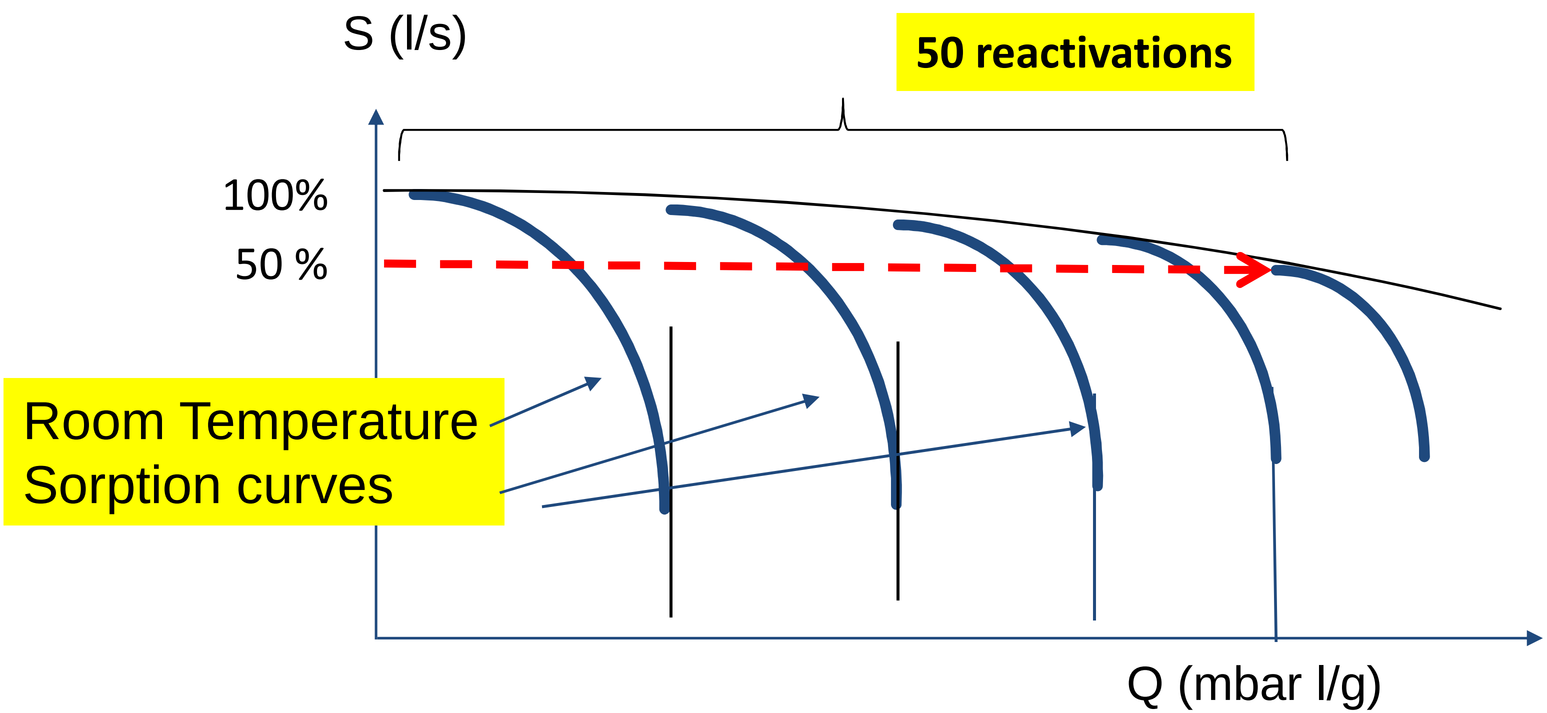
- In some situation it is not possible to achieve 100% activation efficiency due time or temperature constraints
- A “partial” activation can however be sufficient in some cases
- Example : a 60% partial activation of a 1000 l/s NEG pump simply means that the initial pumping speed of the pump is 600 l/s (maybe is still enough !)



Typical sorption curves for NEGs



The reactivation process



- **NEGs can be generally reactivated many times (e.g. >100)**
- **Each time active gases (CO, CO_2, O_2, N_2,..) are irreversibly sorbed and stored in the getter bulk**
- **Slight speed reduction (≈ 1%) each time.**

Why NEG are so effective for H2 : Sievert's law

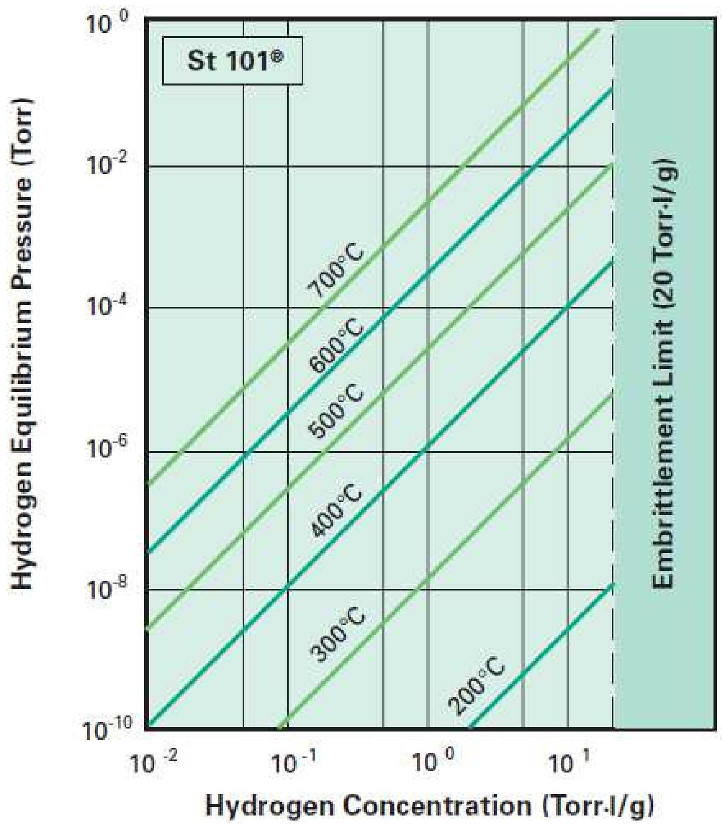


Figure 3 - Hydrogen Equilibrium Pressures of St 101 Alloy

H_2 goes in solid solution in the getter lattice. Equilibrium is established between the H_2 concentration in the getter volume and the partial pressure of H_2 in the gas phase. The equilibrium depends on temperature

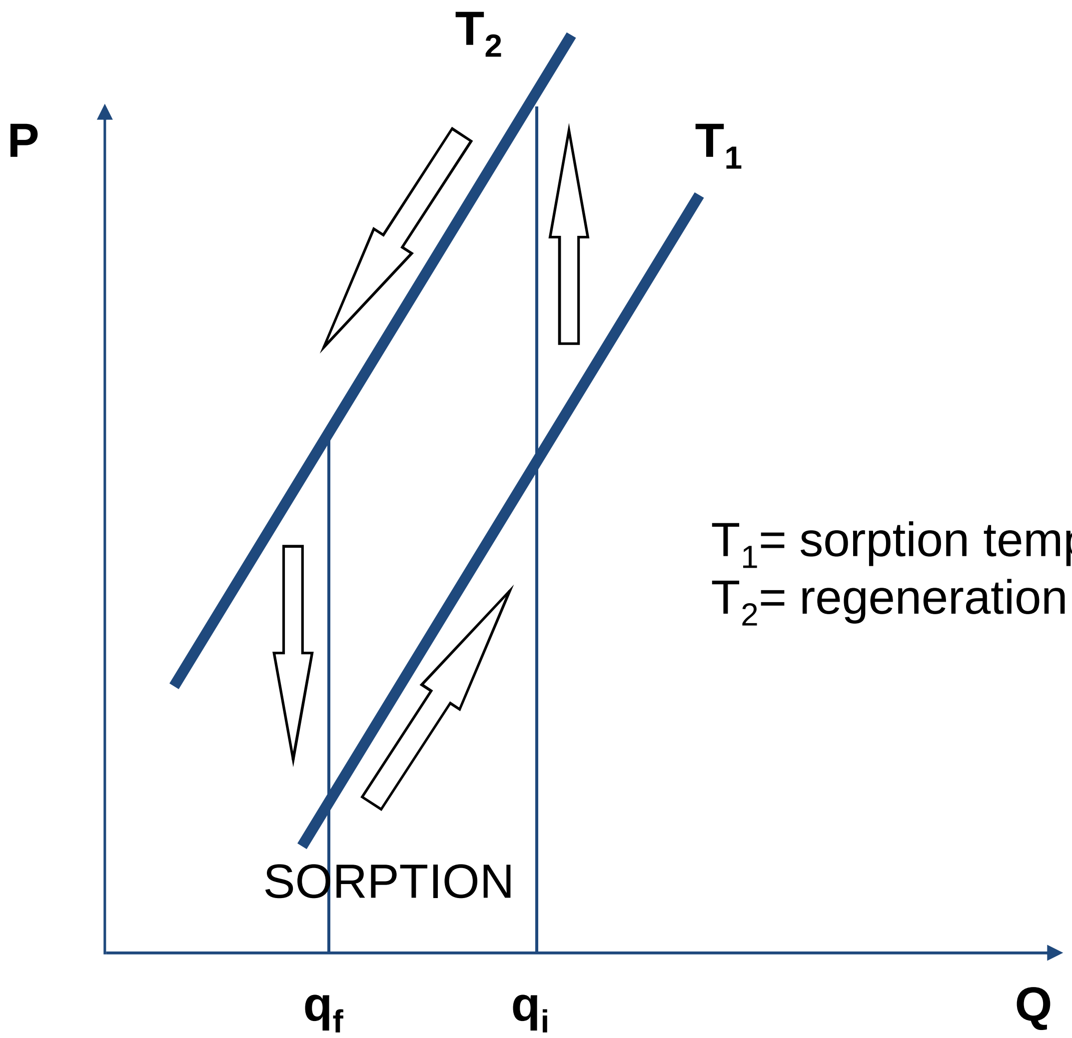
$$\log P = A + \log Q^2 + B/T$$

P= H_2 equilibrium pressure
Q= H_2 concentration
T= Getter temperature (K)
A, B = Sievert's parameters

The process is reversible: H_2 is preferentially sorbed or emitted depending on temperature (we will see later….outgassing properties of NEG)

At RT, estimated H_2 Eq. pressure of St 172 is $<10^{-15}$ mbar ….
the getter is a perfect sink for H_2 !!

Regeneration cycle: H2 removal



T_1= sorption temperature
T_2= regeneration temperature

Regeneration formula

$$t = \frac{M}{F}\left[\frac{1}{q_f} - \frac{1}{q_i}\right]10^{-A-B/T}$$

t=time, s
M=getter mass, g
F=back-pump speed, l/s
q_i=initial hydrogen concentration
q_f=final hydrogen concentration
A and B=Sieverts' plot parameters

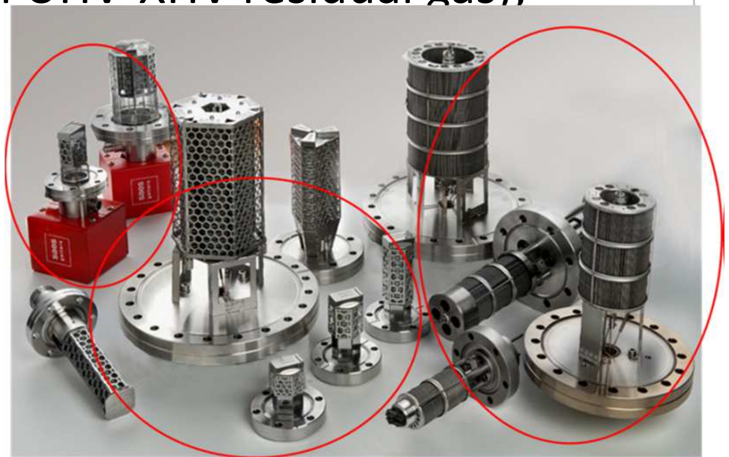
Regeneration is alloys dependent (Sievert's parameters)

Regeneration and reactivation are two different processes !

3. NEG pumps : key features

NEG pumps key features

- NEG pumps are extremely suitable for UHV applications as they provide :
  - very large pumping speed in a compact and light package;
  - High trapping efficiency for H2 (they main UHV-XHV residual gas);
  - Powerless operation;
  - Vibration free operation;
  - No maintenance;
  - Negligible magnetic interference (μ <1.002 for St 172);
  - Best vacuum on earth (10^{-12} Pa, Benvenuti et al.)



NEG pumps is a smart choice in those applications where light weight, compact package, high pumping speed, no vibration, no magnetism, reduced power consumption is key.

Why using NEG pumps in UHV-XHV?

- ☐ To achievement **better vacuum** level
- ☐ **More efficient pumping of H2**
- ☐ **To miniaturize** vacuum systems
- ☐ To **design** the vacuum system in a **more clever and cost effective** way
- ☐ To reduce the **pump down time**
- ☐ To reduce the **baking time or the baking temperature**
- ☐ To solve **specific issues** other pumps cannot address (e.g. space, weight, power consumption, vibration, magnetic interference…)

NEG pumps do not sorb noble gases so they are generally used in combination with TMP , Cryo or SIP

4. NEG pump typical designs

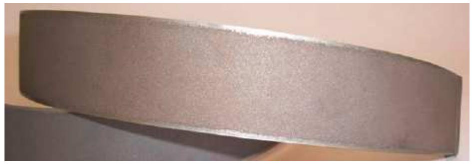
NEG products for vacuum systems

- ☐ **NEG strips**, to achieve distributed pumping
- ☐ **NEG Wafer modules**, based on NEG strips or sintered disks for distributed and discrete pumping
- ☐ **Cartridge pumps** for discrete pumping in UHV and HV
- ☐ SIP /NEG combined pumps : **NEXTorr** concept for discrete pumping
- ☐ **Custom NEG pumping** structures for specific and special pumping needs
- ☐ **NEG coating**

NEG pumps overview

Different applications → Several configurations

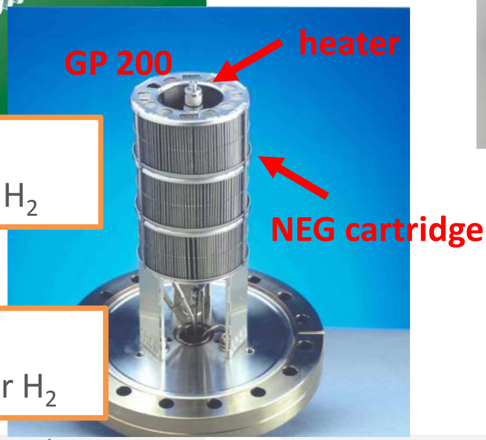
Laminated St707 ®strip



Porous sintered disks:
- **Dimensions**
- **Porosity**
- **Pumping speed**

SORB- AC® series

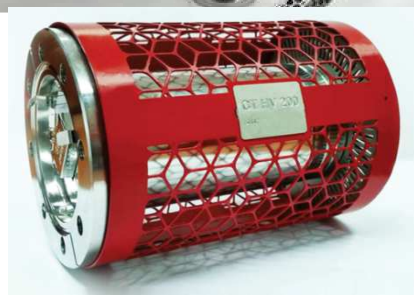
Wafer modules
300 to ***900 l/s*** for H_2

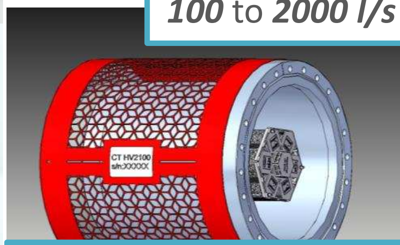


GP cartridges:
200 to ***2000 l/s*** for H_2

Cartridge type pumps:
50 to ***3600 l/s*** for H_2

The NEXTorr® family:
100 to ***2000 l/s*** for H_2

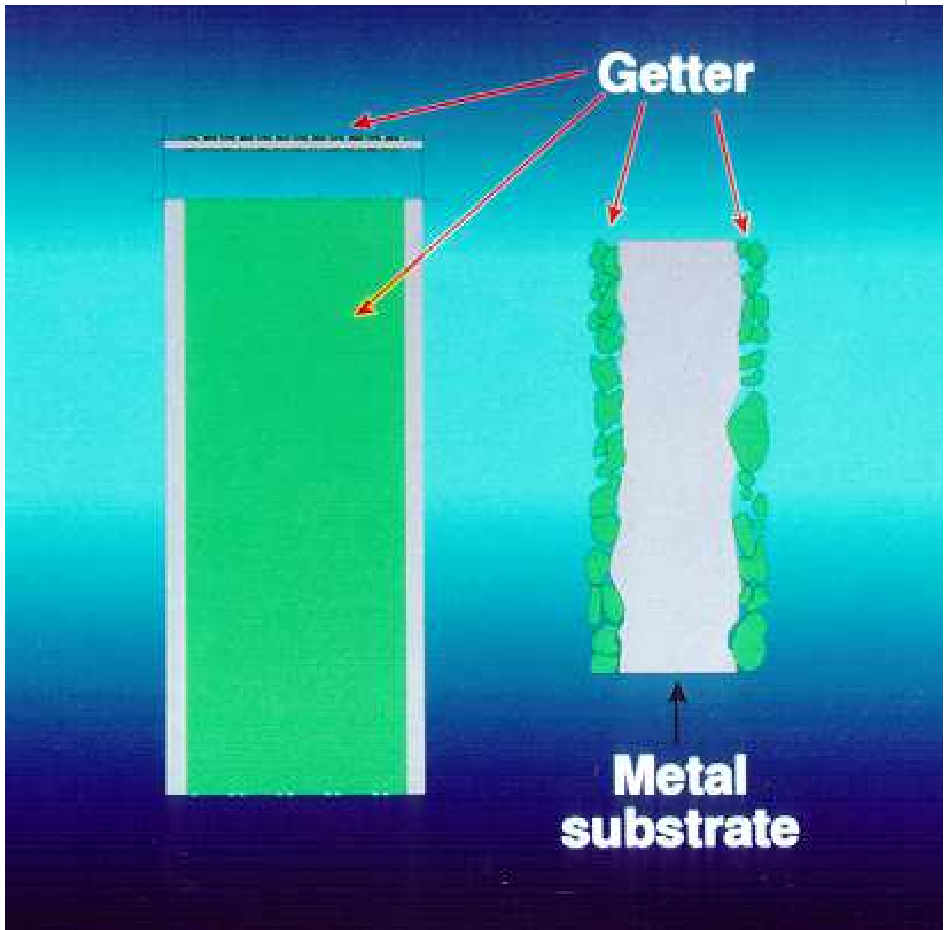




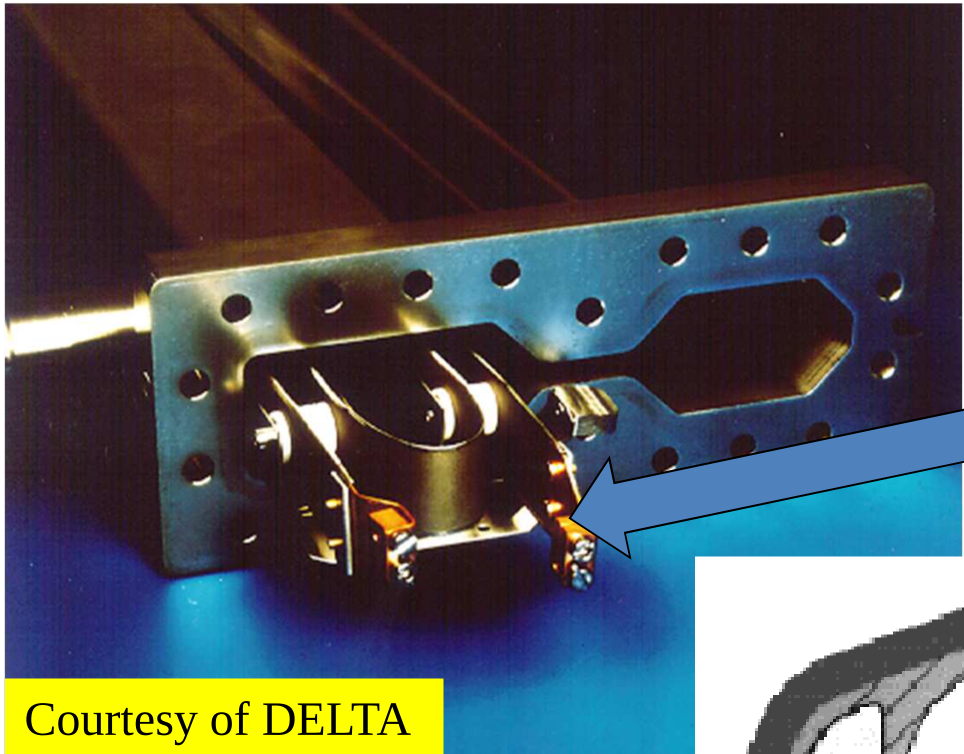
ZAO based HV pumps:
100 to ***2000 l/s*** for H_2

NEG Strip

- 75 micron of getter material laminated on both sides of a costantane (amagnetic) substrate
- St 101 (Zr-Al) & St 707(Zr-V-Fe) alloys
- It can be activated by passage of current or passively in a bake out
- It is flexible , it can be bended
- Magnetic permeability < 1.001
- pumping speed ≈3 l/s cm (H_2)

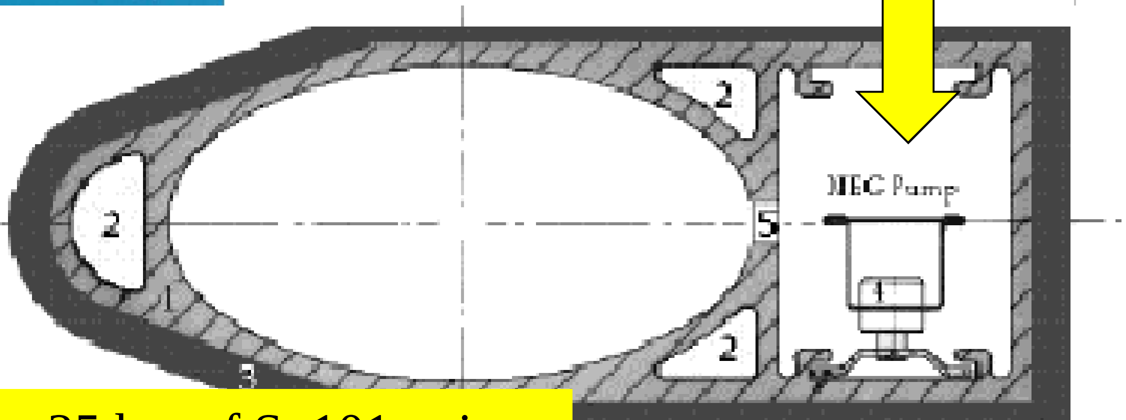


NEG Strip in particle accelerator - St 707



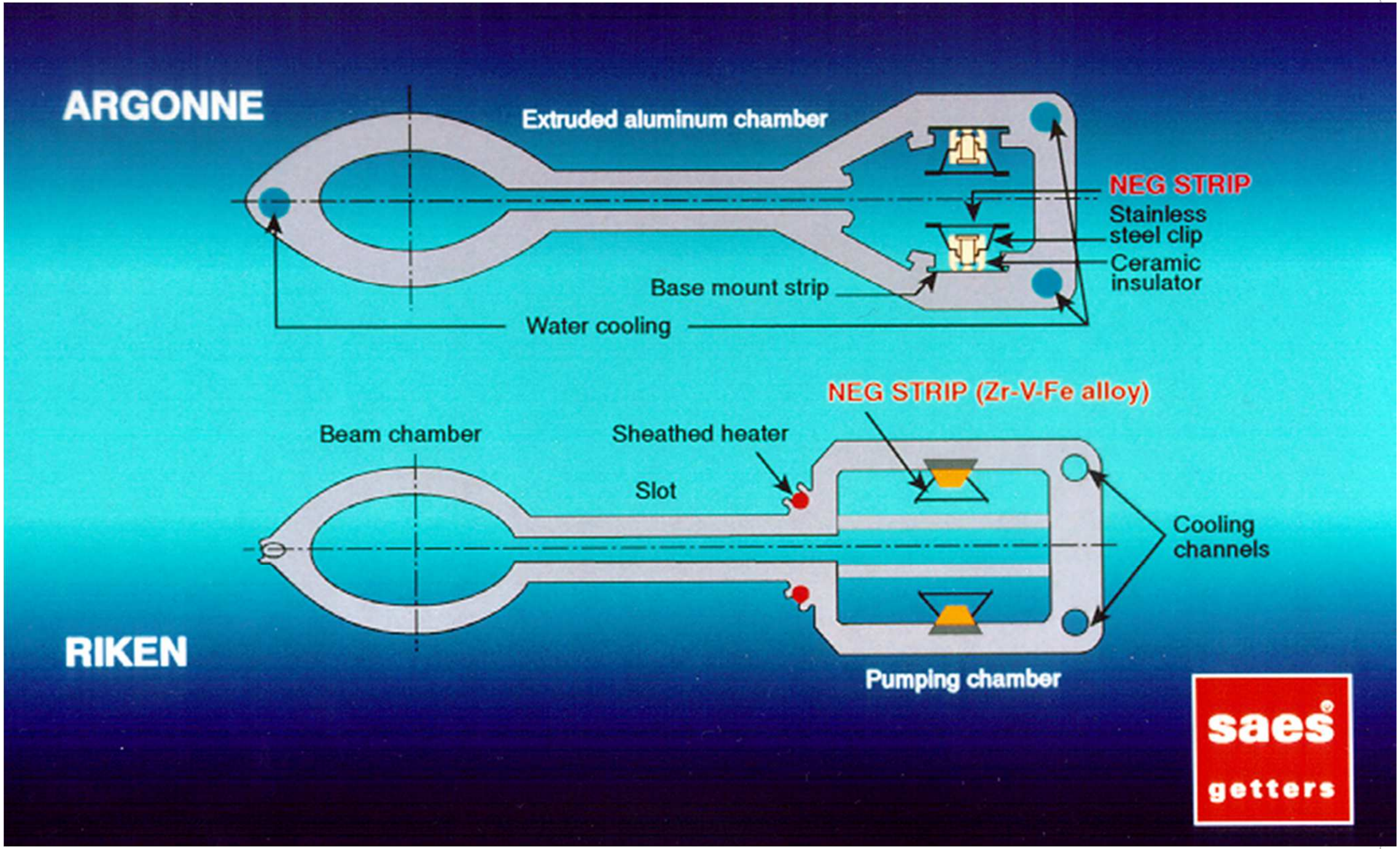
Courtesy of DELTA

The typical application is as distributed pump in a side chamber



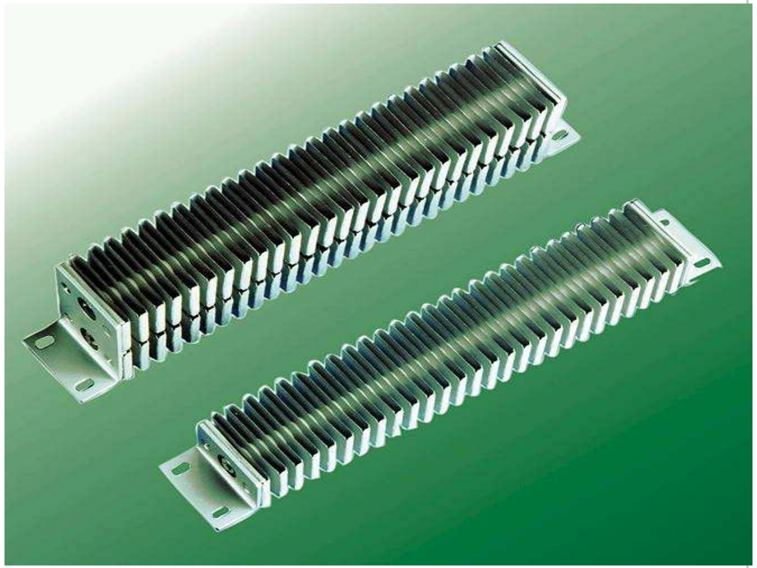
LEP : about 25 km of St 101 strip

NEG strip in APS and Spring-8 - St 707



NEG Wafer module features

☐ Wafer modules do not have flanges



☐ Mounting tabs are also electrical terminals (for activation by current)

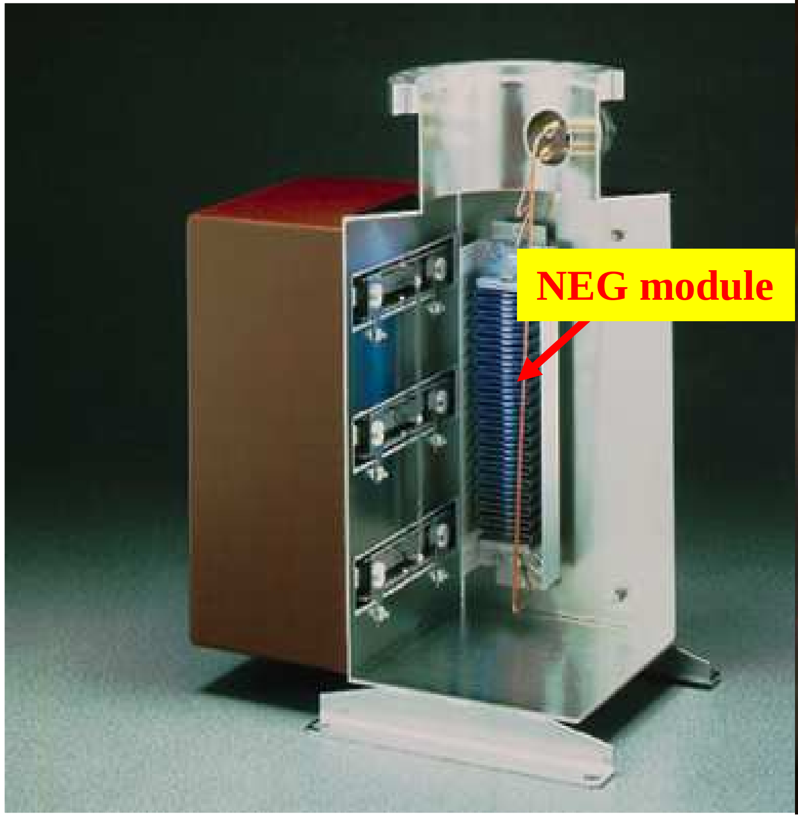
☐ Available with St 101 and St 707 and also with sintered ZAO disks

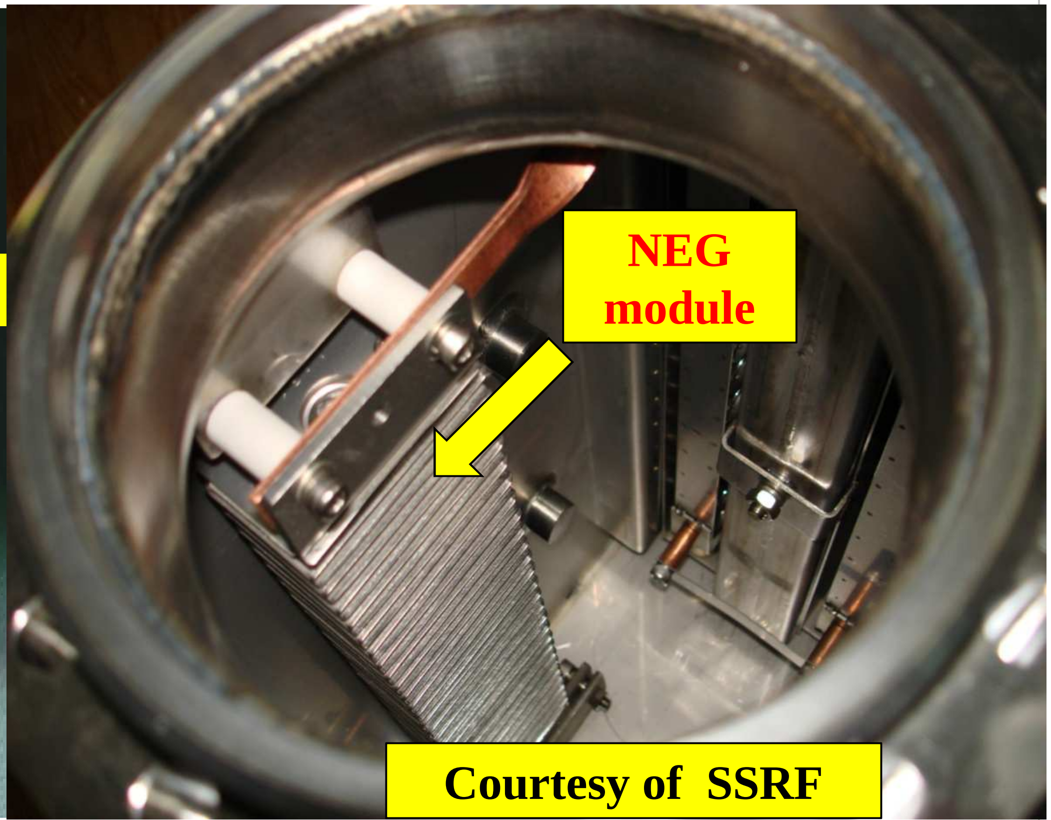
☐ Speed range from 300 to 2000 l/s (H_2)

☐ Small size : length from 200 to 400 mm

☐ Compact, cost effective solution ideal for in situ pumping inside chambers. Can be arranged in larger arrays (panels)

NEG wafer module inside SIP



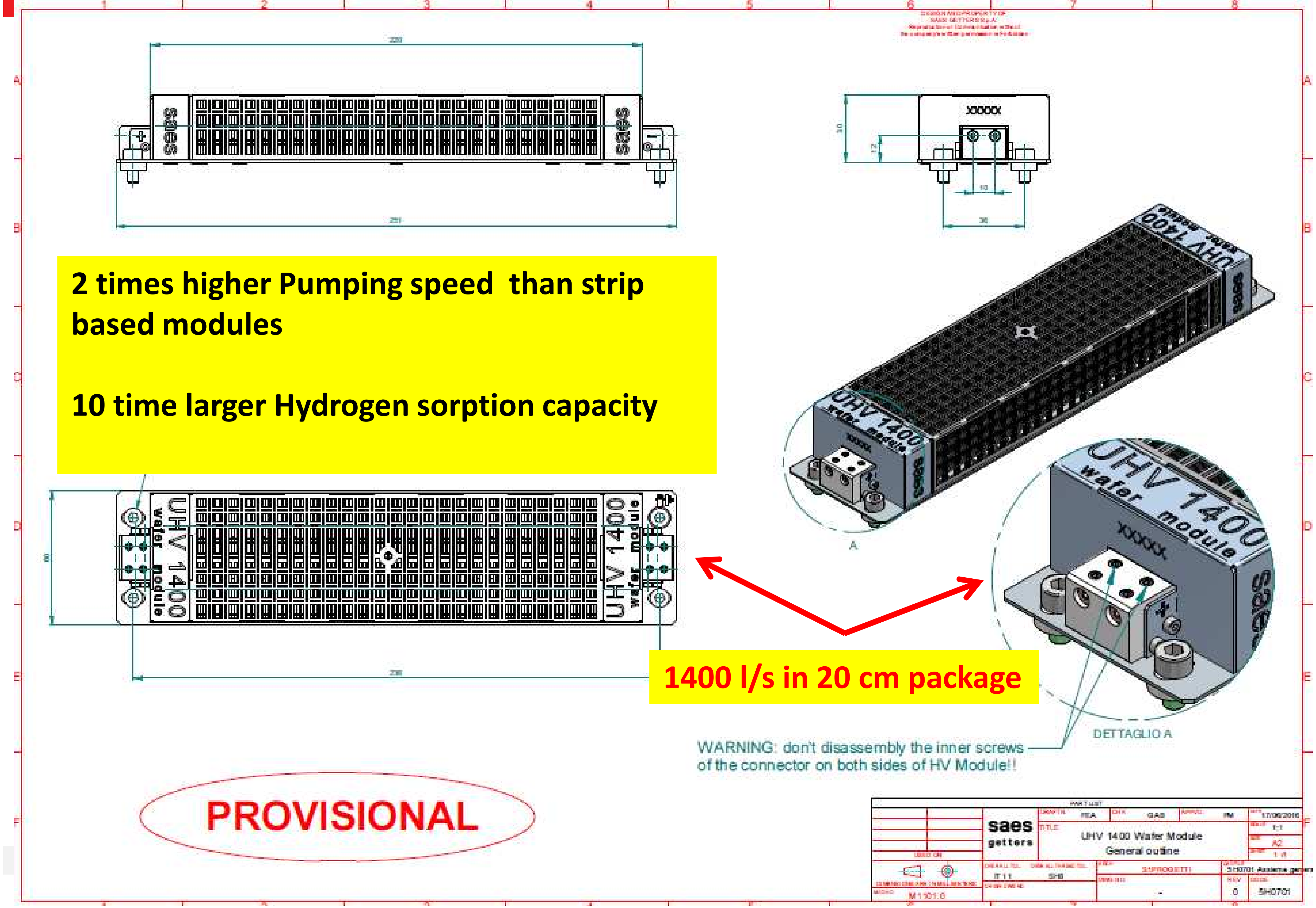


New NEG modules based on Sintered disks

2 times higher Pumping speed than strip based modules

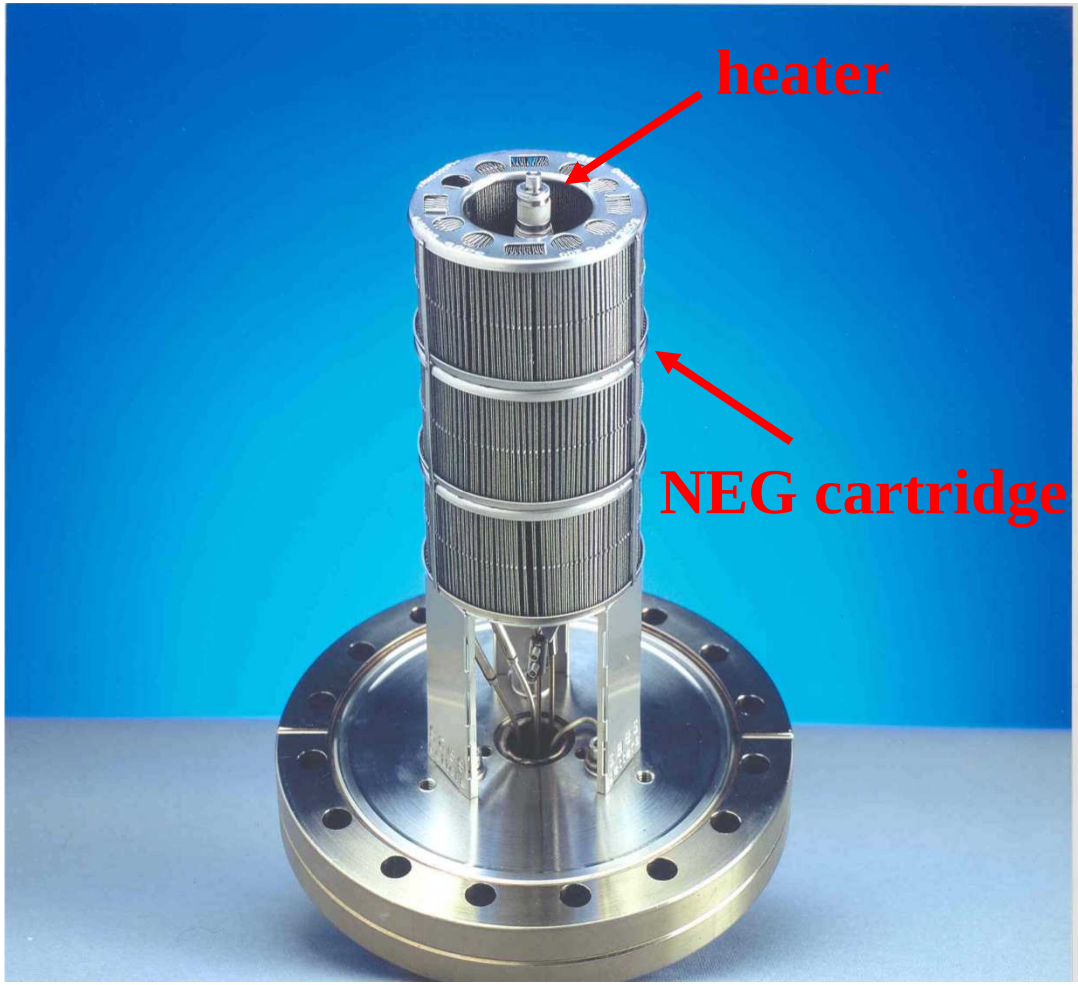
10 time larger Hydrogen sorption capacity

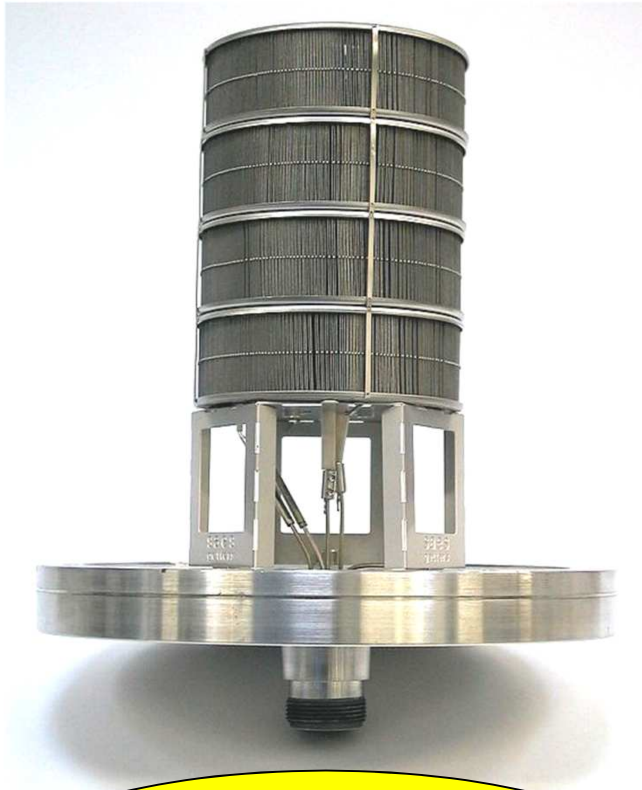
1400 l/s in 20 cm package



Cartridge types of NEG pumps

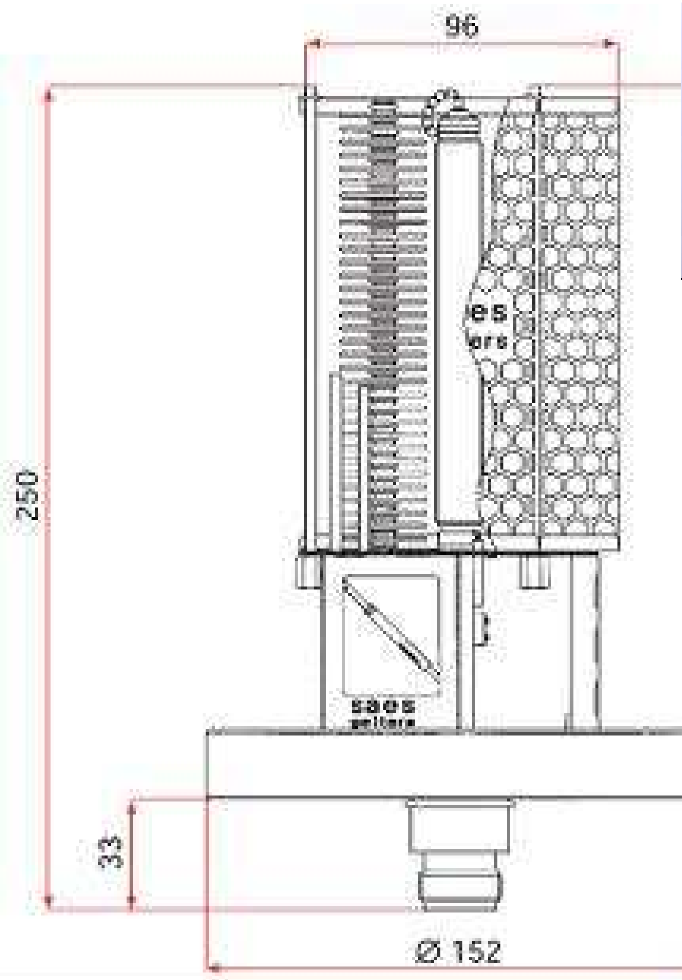
Cartridge pumps based on laminated strip (SORB AC MK5 series) speed from 100 to 2000 l/s H2





2000 l/s (H_2) on a CF 100/150 flange

NEG pumps based on sintered getters (Capacitorr MK5 serie) speed from 20 to 4000 l/s (H2)

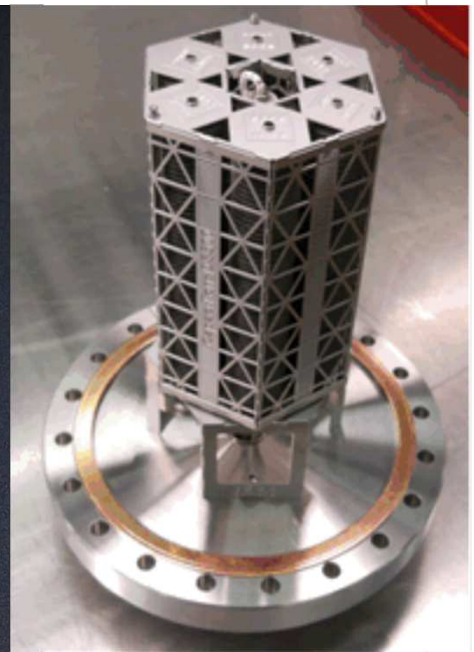


Sintered disk technology is key in particle sensitive applications, as we will see later…

Cartridge type pumps

Six models with speed from 50 to 3500 l/s for H_2

400 l/s | **1000 l/s** | **2000 l/s** | **3500 l/s**

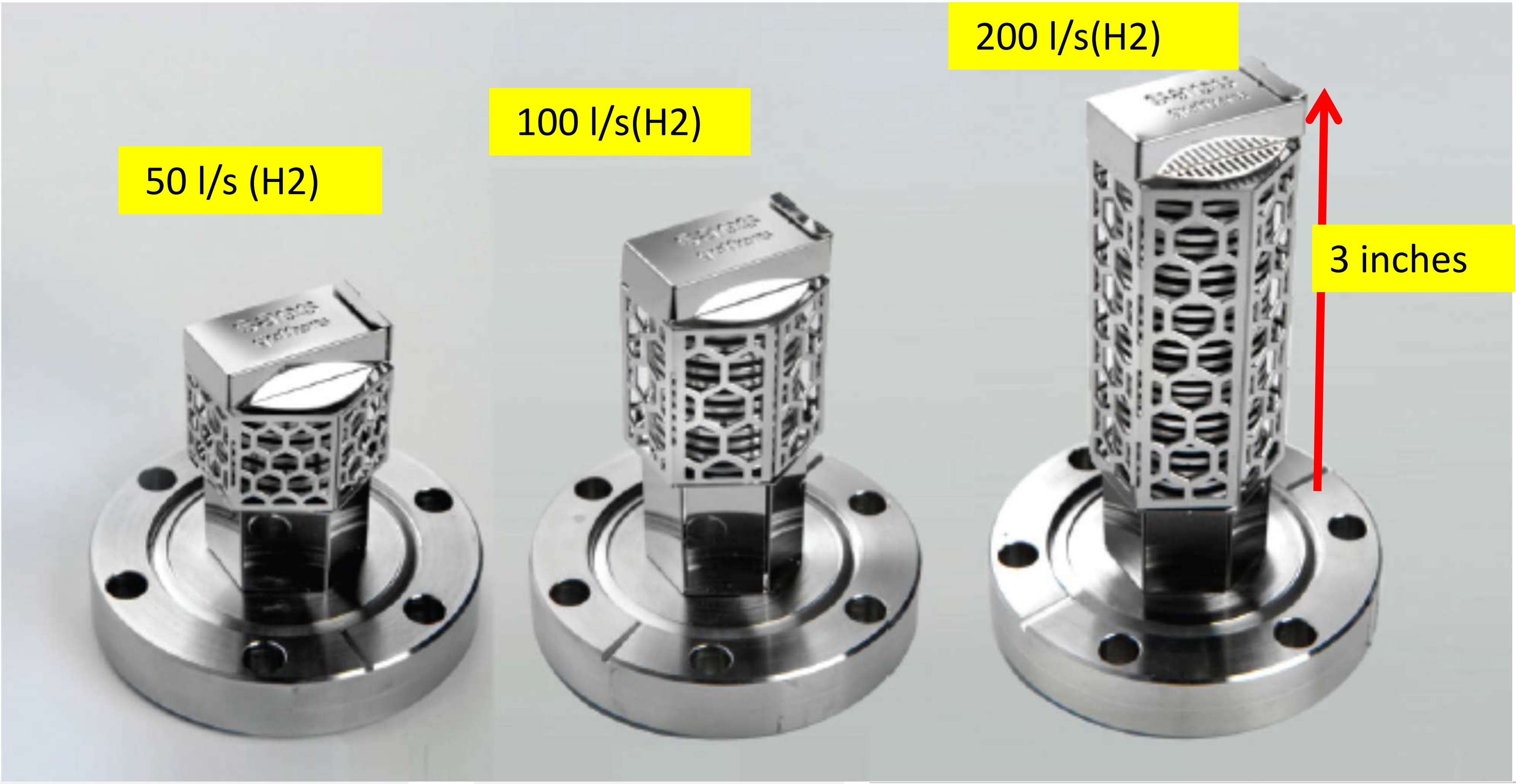


CF 35 | **CF63-100** | **CF 100-150** | **CF 150-200**

Compact size : 400l/s (H2) in a pen !

Ultra compact pumps

- 50 to 200 l/s speed in a few centimeter height and 100-200 g weight.
- **UHV –XHV vacuum systems, portable equipments, vacuum suitcases, semiconductor tools, SEM, FIB…**



NEG pumps outgassing properties

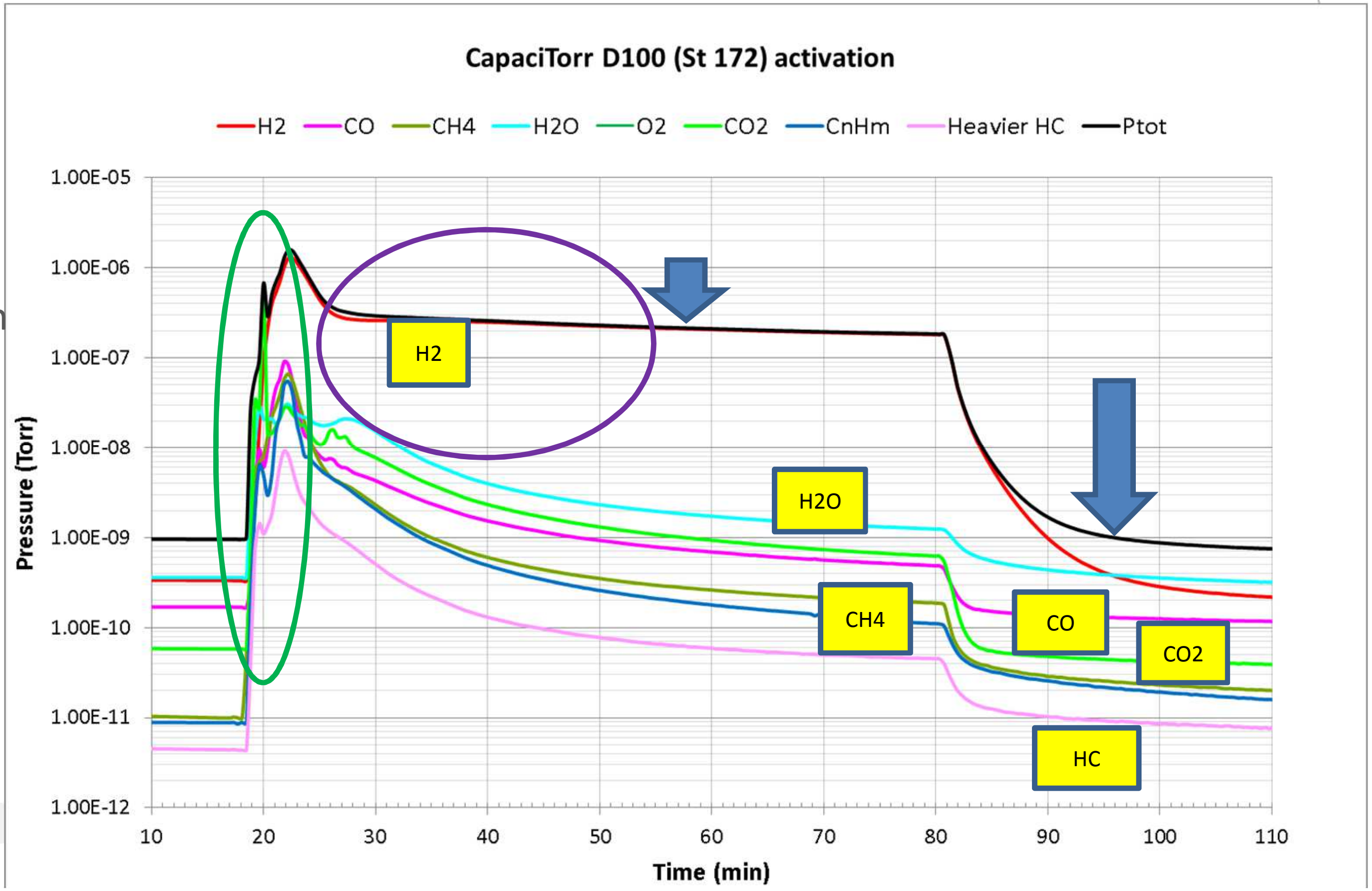
NEG pump outgassing during activation

- ***First desorption peak at 250°C - 300°C and approaching full activation temperature***
  Most of the phisysorbed species are released. H_2 peak followed by CO, CO_2, H_2O, CH_4 10 times lower (or more)

- ***Reaching full activation temperature***
  Within a few minutes species other than hydrogen start to decrease rapidly

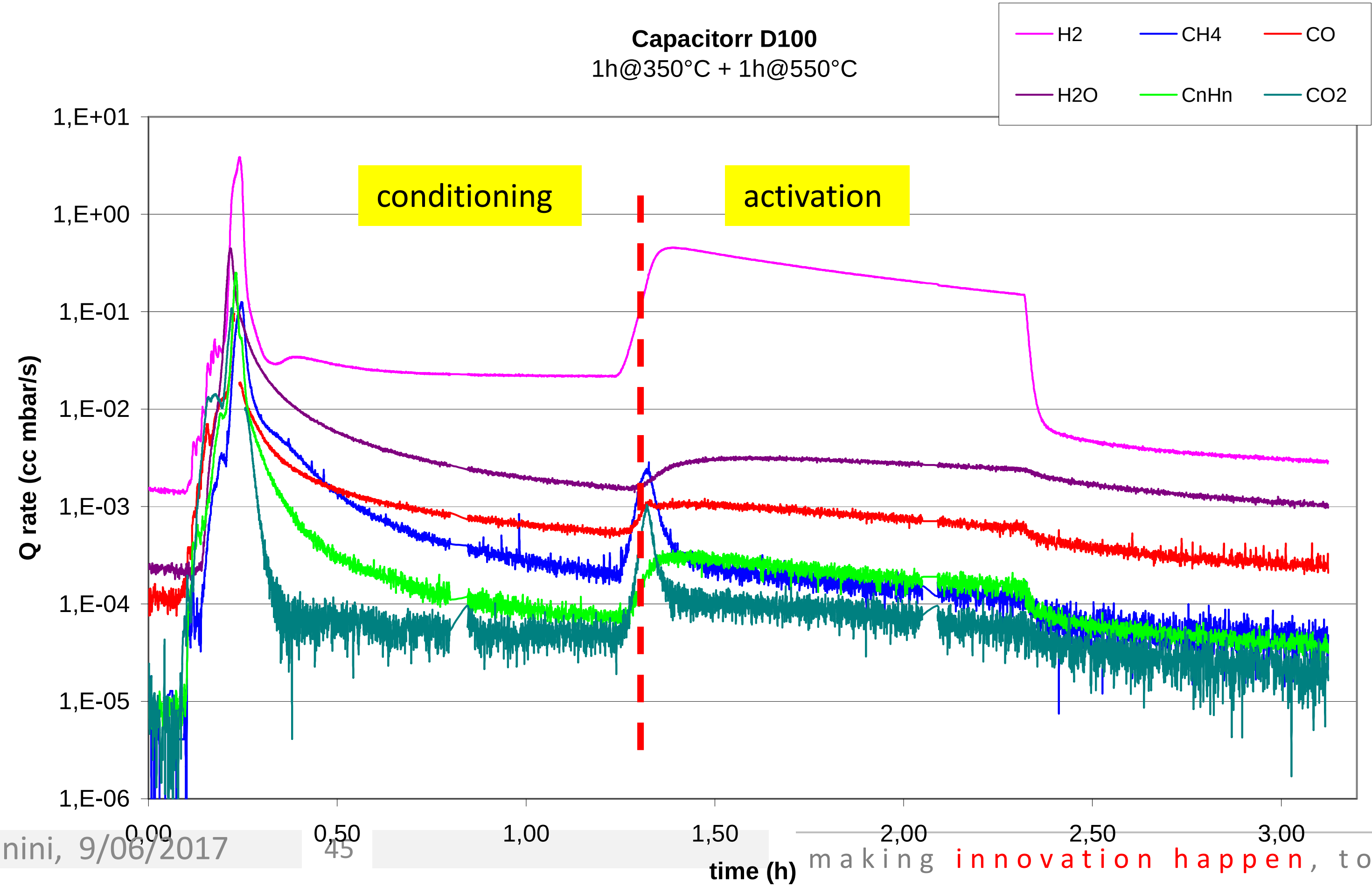
- ***H_2 plateau***
  Depends on :
  1)Equilibrium pressure
  2)Dynamic equilibrium between auxiliary pumping and H_2 desorption rate (diffusivity & recombination rate on the surface)

- ***H_2 re-pumping***
  Within minutes after the end of the activation, emitted H_2 is completely re-adsorbed



NEG outgassing during activation : a few hints

- If possible, apply a pre-conditioning step at 150-250 °C before the full activation to remove physisorbed species and reduce the amount of released gases. This is possible using the “conditioning” mode in the power supply. If this is not possible, a standard bake out is acceptable.



...Some more hints...

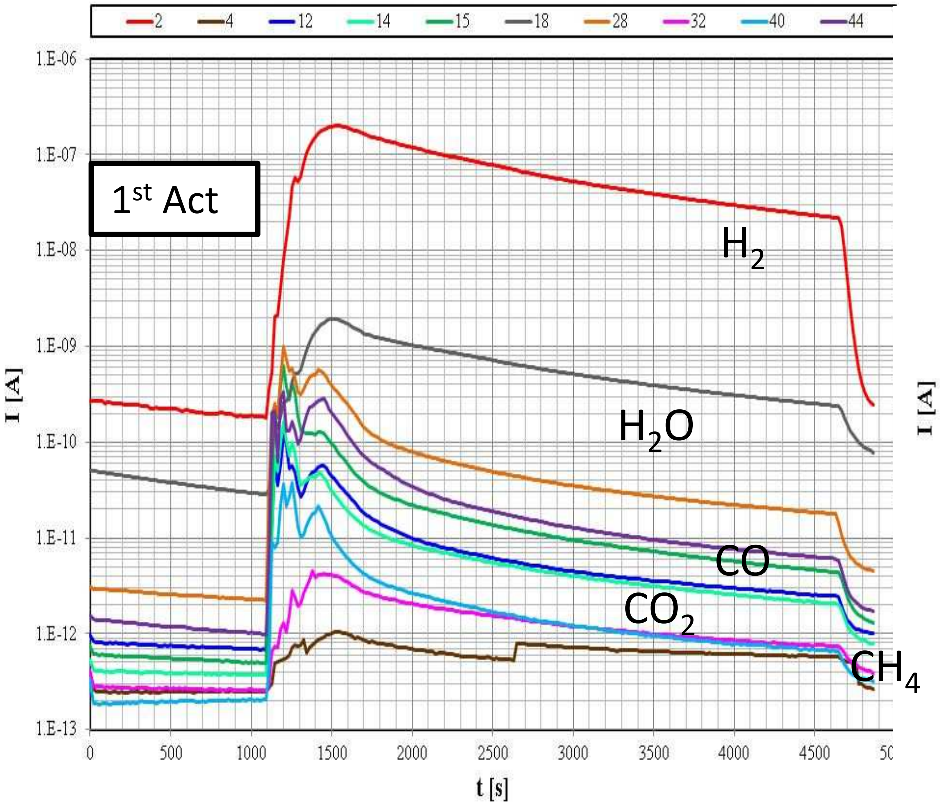
- As hydrogen is the main gas emitted by the pump, it is advisable to run the activation under TMP , keeping the ion pump off (to avoid H2 loading).
- The larger is the amount of getter material the more will be the gas emitted. To keep pressure down, longer conditioning or larger back up pumps might be required for massive NEG .

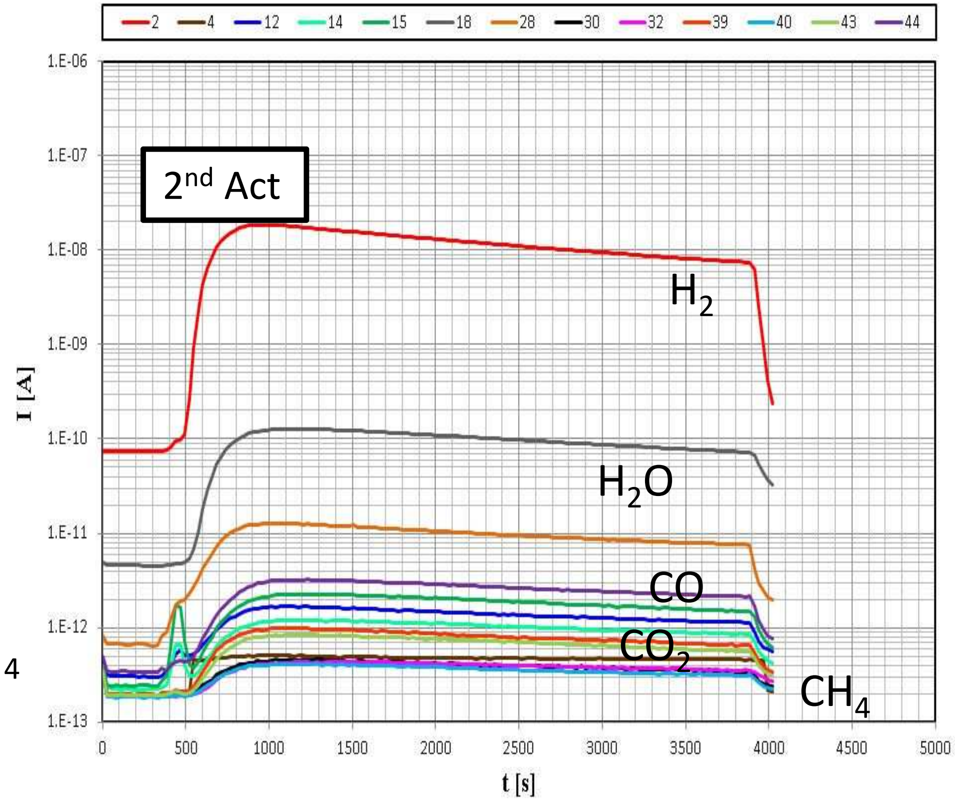
- A pressure increase during activation is normal, H2 originally present in solid solution in the getter and emitted during the activation will be quickly re-adsorbed...do not panic !

And finally…..

- If you do not vent the system, the following re-activation will emit much less gases (only hydrogen, basically) and can be even carried out without auxiliary pumping.

Gas desorption after the first activation





- Gas emission is about a factor 10-20 smaller
- The pump can be reactivated under isolated condition without ancillary pumps

Applications of NEG pumps

saes group

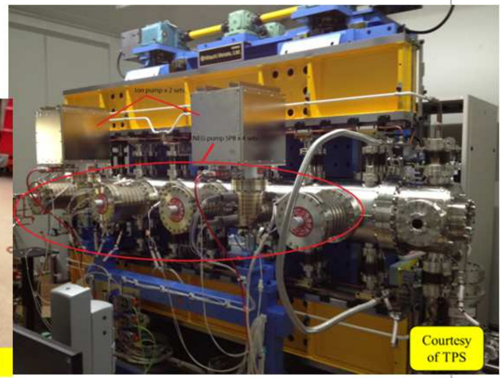
Use of NEG pumps in UHV-XHV systems

In the industry

- Scanning/Transmission electron microscopes
- Portable mass spectrometers
- Semiconductor lithographic & metrological tools
- X-ray inspection equipment, EDX analyzers ……

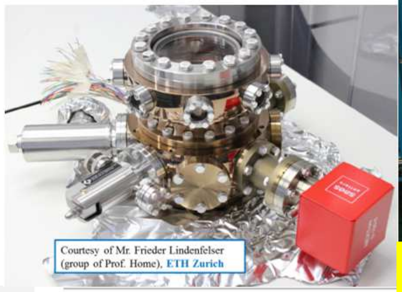
In large physics projects

- Synchrotron Light sources, FEL, ERL
- Colliders and accelerators
- Fusion devices
- Gravitational experiments….



In Scientific Laboratories

- Cold atom /ion trapping
- Atomic clocks
- Surface science, STM, MBE
- Vacuum suitcases

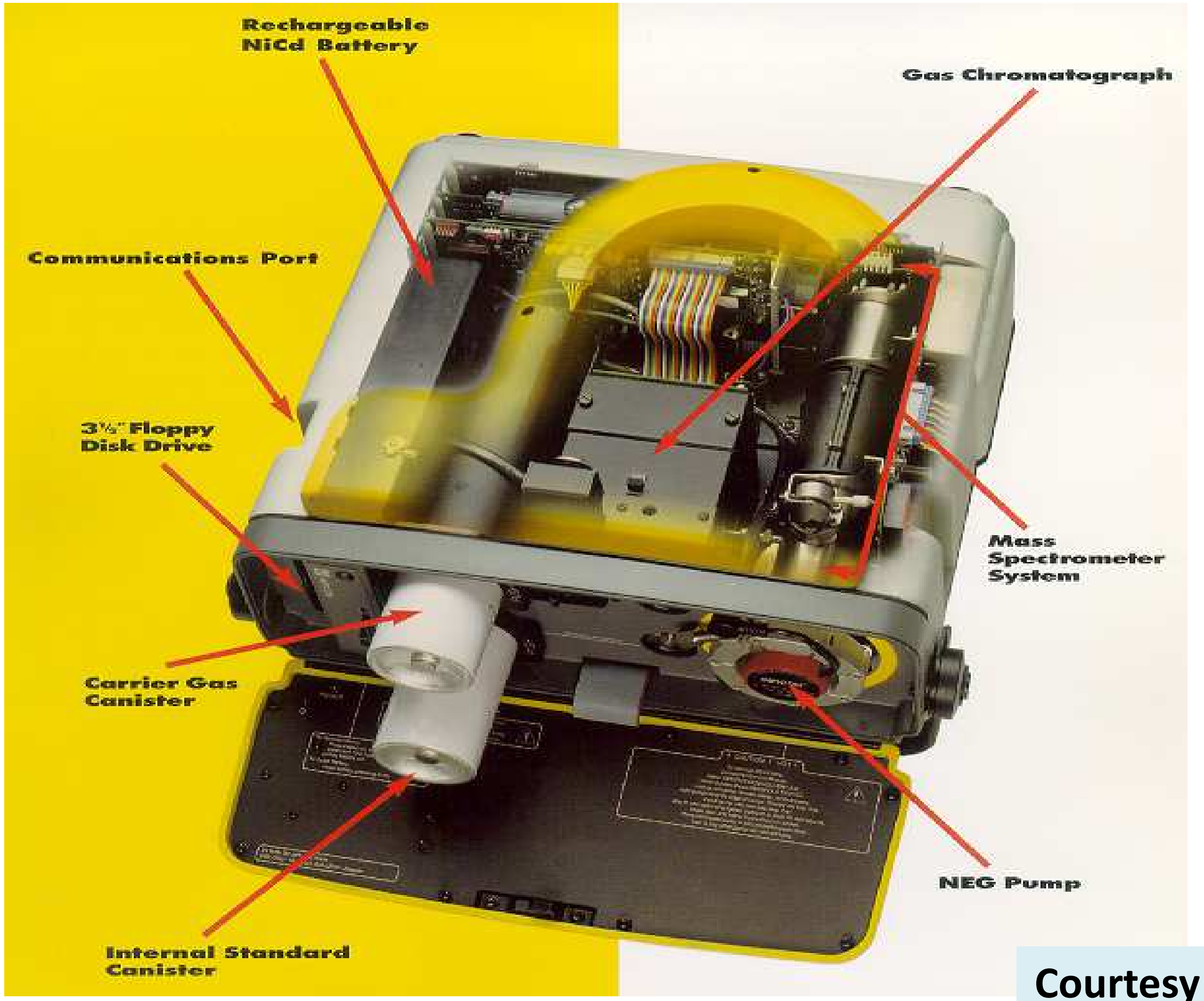


Portable analytical equipment

- NEG pumps are light, small and with high speed.
- They do not need power
- They are ideal for portable equipments and devices

Inficon MS-GCM system
for on site gas analysis

Inficon GCM/MS portable unit

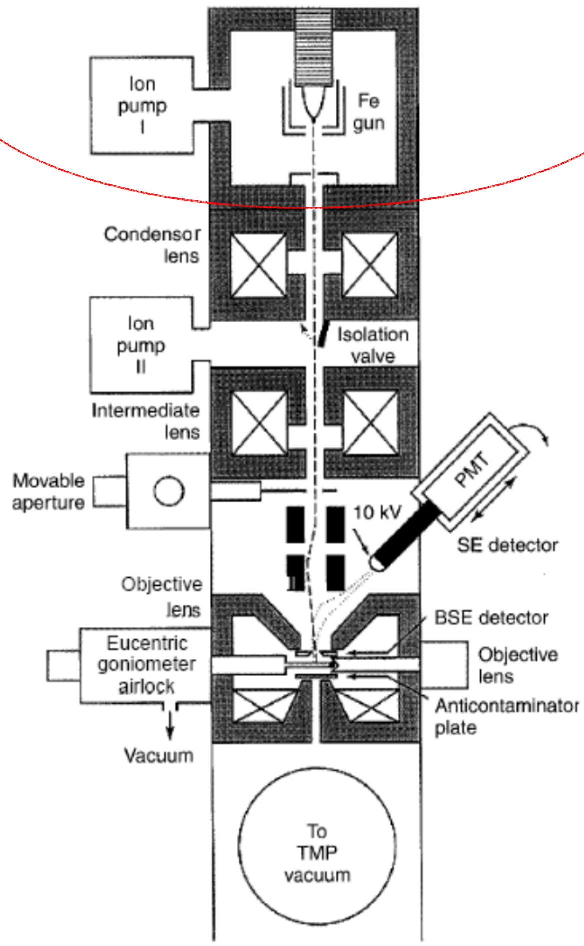


Courtesy of Inficon

SEM/TEM/ e-beam systems

Re-design of the SEM/TEM gun area, reducing weight and vibration and improving performances

Cold cathode emitters : better vacuum increases beam perfomance and prolonged stability **(1x10-10 Pa)**



Analytical equipments

E-beam based systems

Pattern Placement Metrology

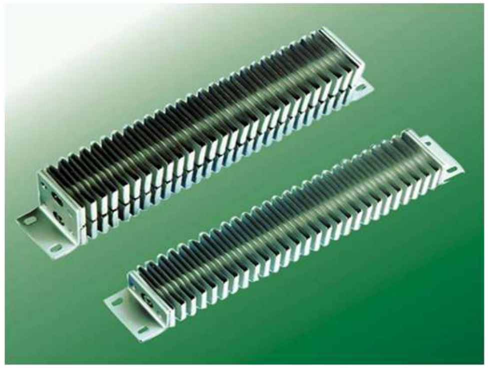
UHV systems

Photocathode guns for polarized electrons

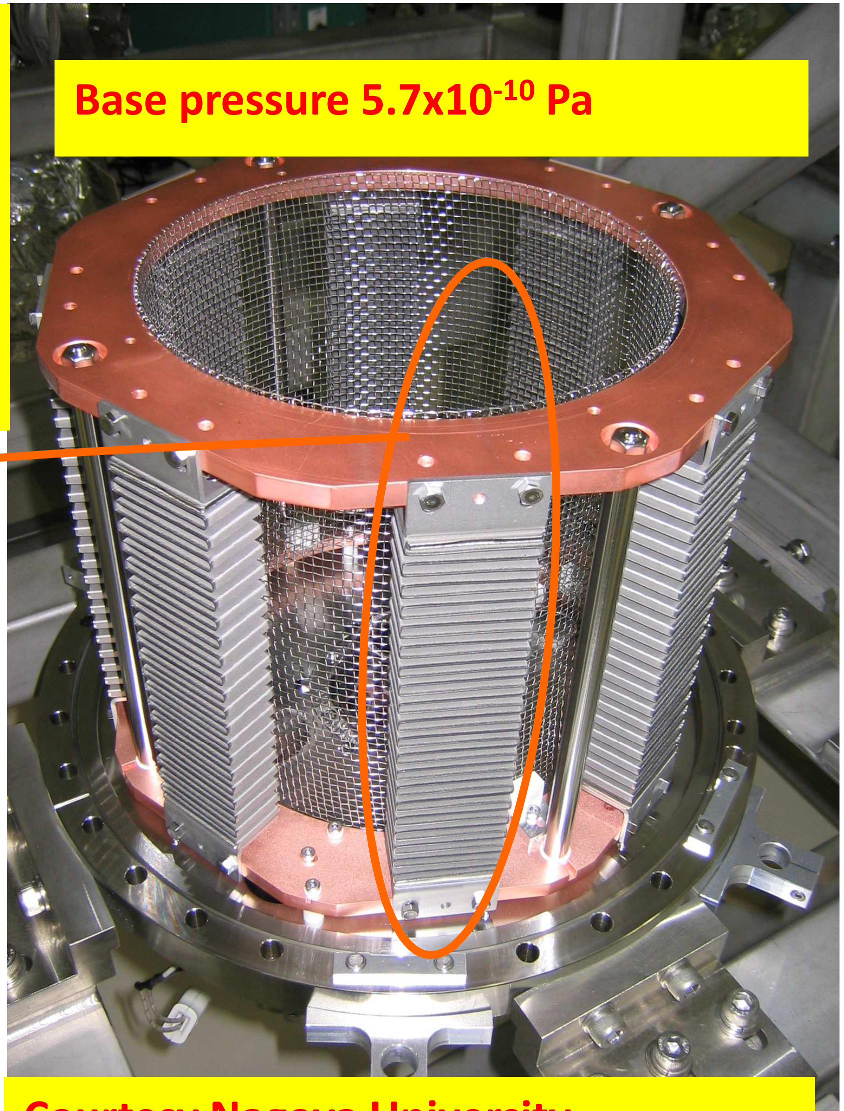
There is a need to generate intense pulsed electron bunches for material science investigation as well as for new light sources (X-FEL). High quality photocathode materials are used, which are extremely sensitive to gas poisoning

WP 950 st 707 NEG module

Total speed > 3400 l/s

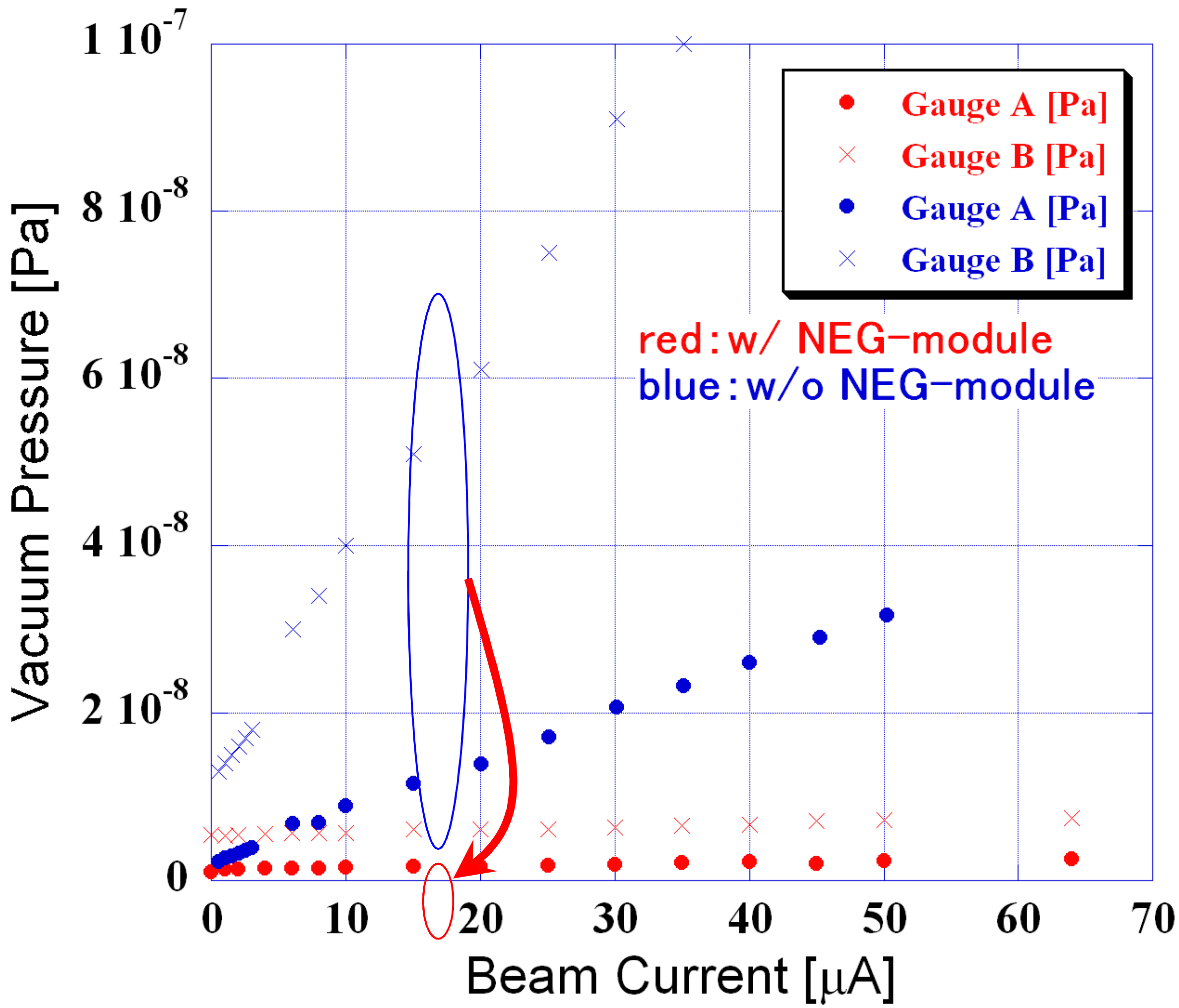


Base pressure 5.7x10^{-10} Pa



Courtesy Nagoya University

Better vacuum reduces cathode degradation



The degradation of the vacuum level is strongly suppressed to 1/10 or less by the NEG-modules.

Gun operational lifetime

25 hours @ 20μA

120 hours @ 50μA

M. Yamamoto, Nagoya University PESP2008

NEG pumps for transportation tools

- In the following slides we show the results obtained by INFN replacing a 60 l/s ion pump with a small Capacitorr D 100 pump (200 g weigh) in a photocathode transportation vessel.

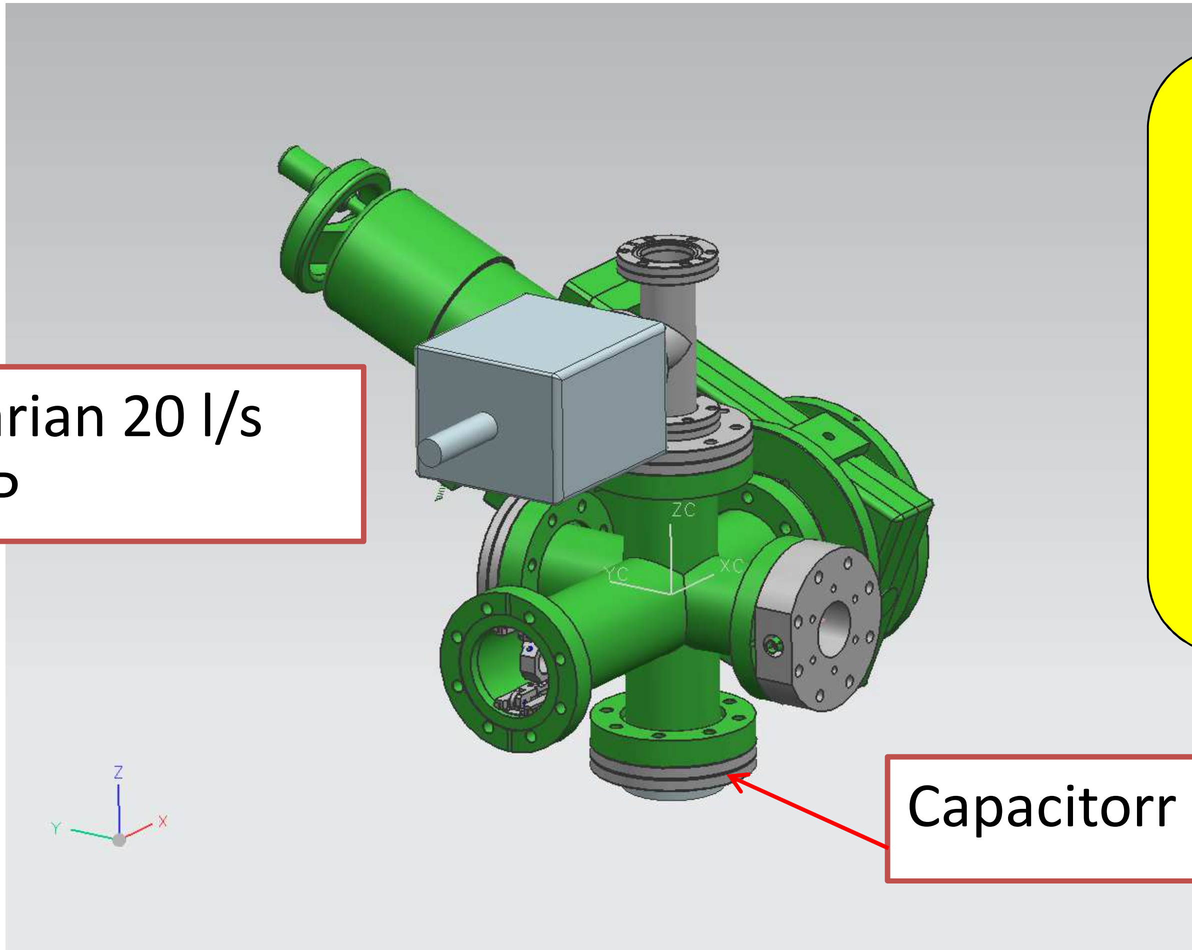
- The vessel was baked 7 days using the SIP and the vacuum achieved was 8x10-10 mbar.

- Using the Capacitorr D 100 , after 3 days bake, a pressure of 2x10-11 mbar was achieved.

- Such pressure could be maintained over several months even without any power.

UHV suitcases and transfer tools

Varian 20 l/s SIP



Capacitorr D100

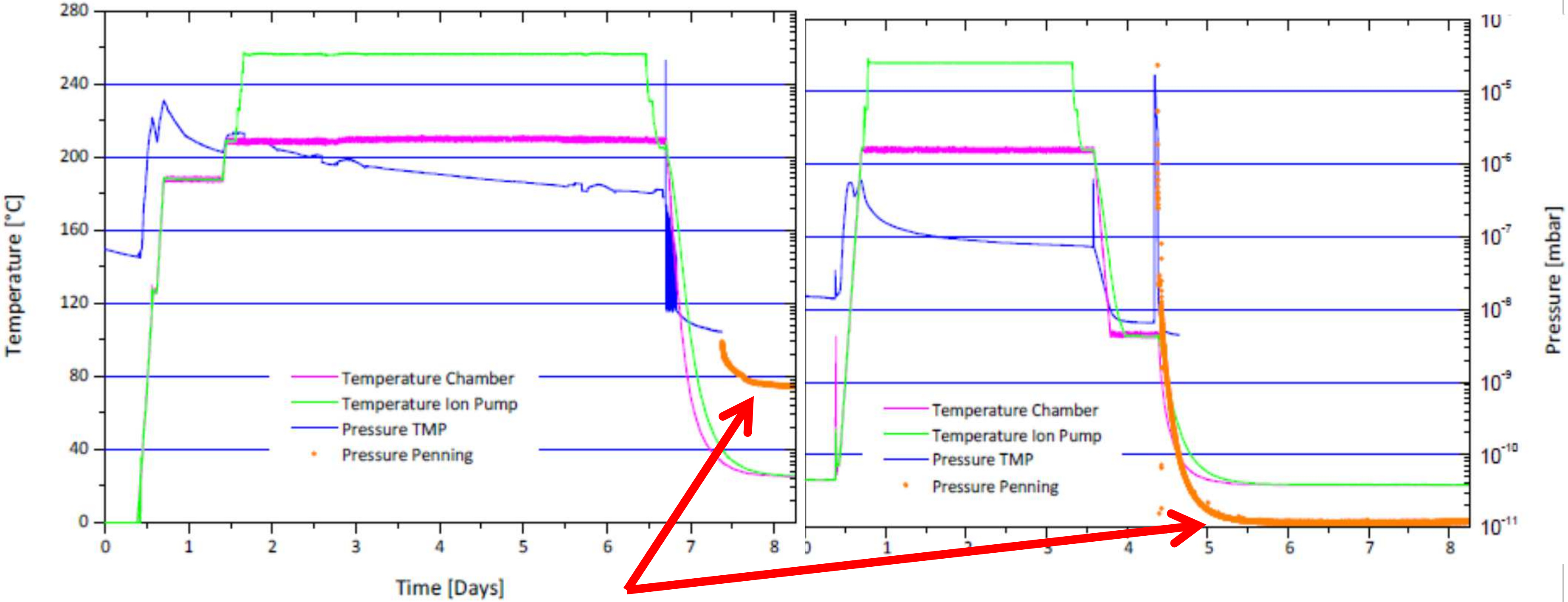
A 60 l/s SIP has been replaced with a Capacitorr D 100, this reduces significantly the weight & size of the system

"Ultra High Vacuum Transport System for high Quantum Efficiency Photocathodes", D. Sertore et al, proceeding IPAC 2011

Pump down curves with and w/o NEG

20l/s+60 l/s SIP, 7 days BO

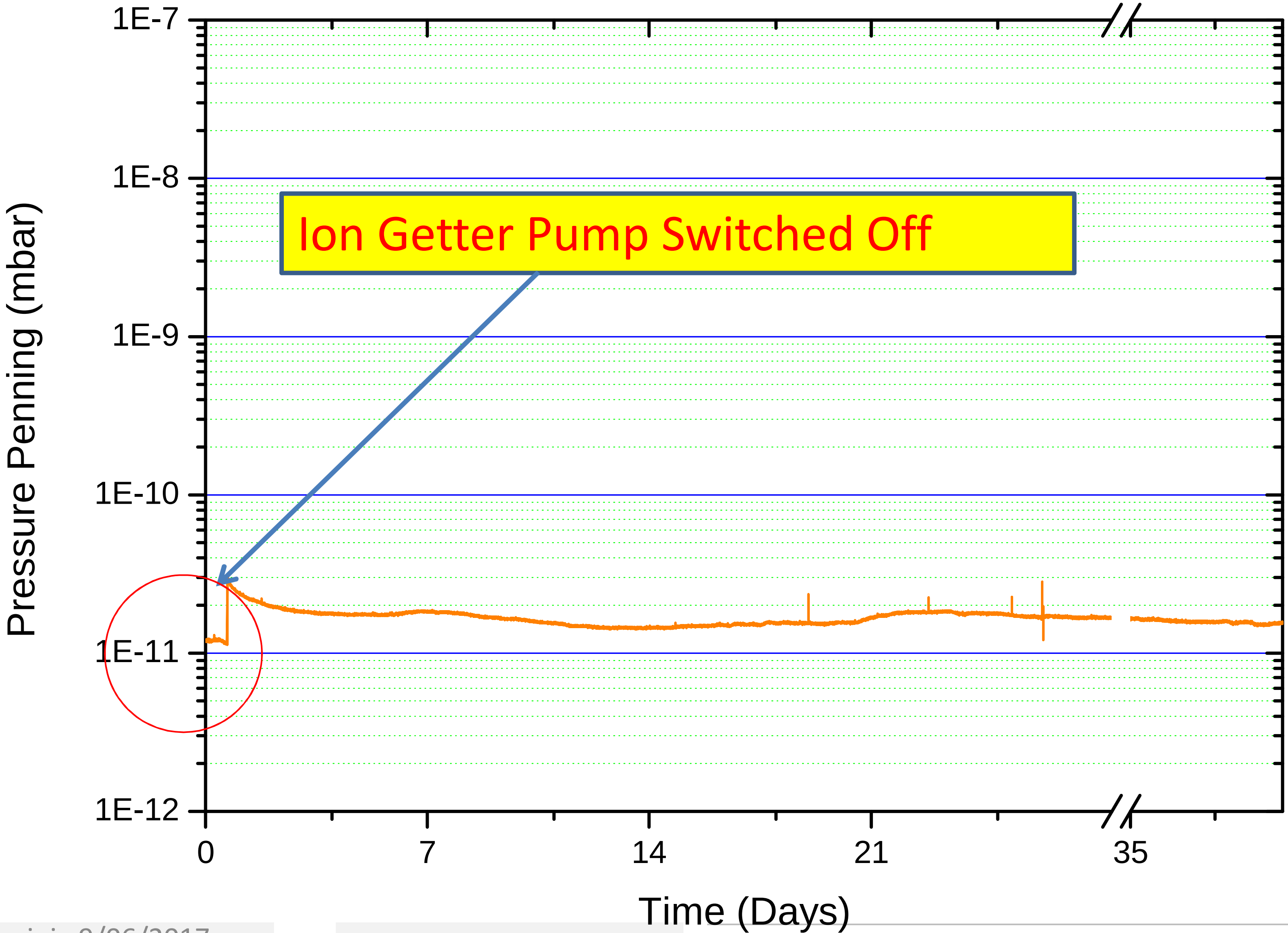
20l/s+CT D 100, 3 days BO



Vacuum 50 times better achieved in half of the time !!

"Ultra High Vacuum Transport System for high Quantum Efficiency Photocathodes", D. Sertore et al, proceeding IPAC 2011

Pressure stability after SIP switching off



Cs2Te photocathode long term stability

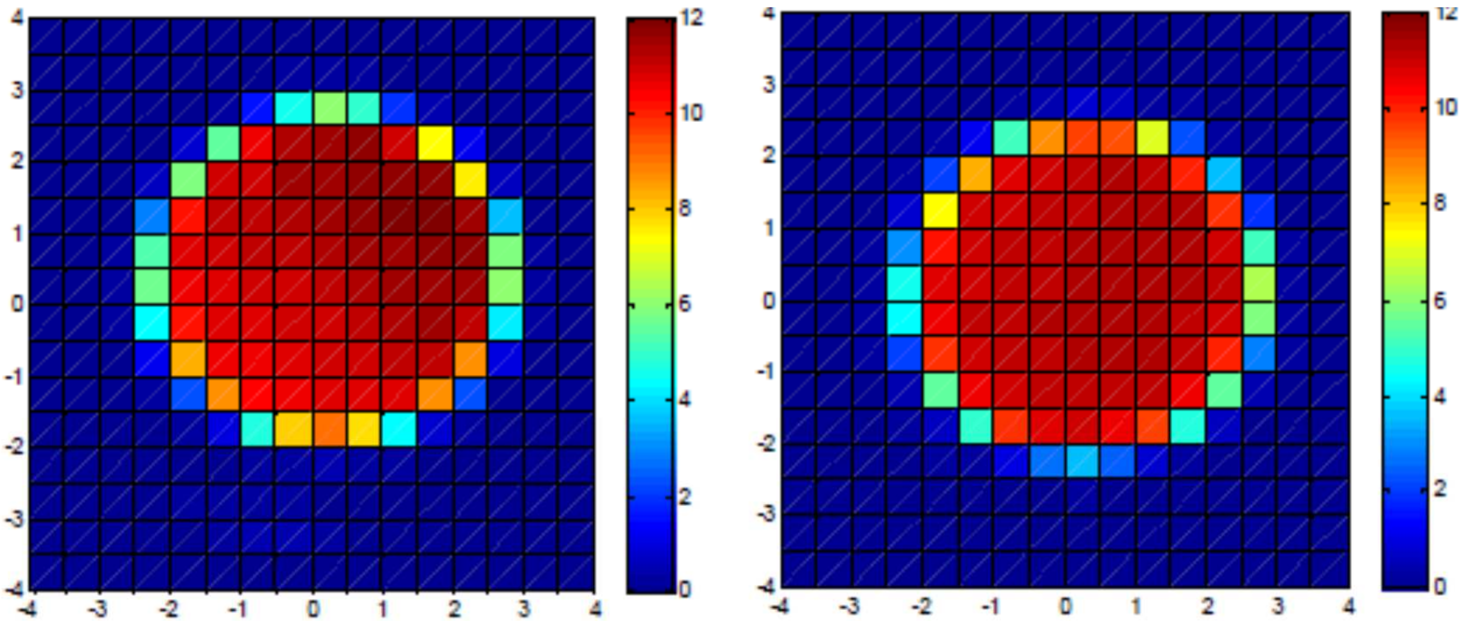


Fig. 6. QE maps at the 254 nm: after the deposition (right) and 5 months later (left).

QE maps clearly show that the photoemission properties have not changed after 5 months. As they depend on the surface state , this is a confirmation that the surface was not contaminate and that vacuum was excellent.

High energy physics

- Particle accelerators & Synchrotron Light Sources
  - Storage ring
  - In vacuum undulators
  - Crotch absorbers
  - Insertion devices
  - Beam lines

Use of NEG pump in the storage ring

Proceedings of EPAC 2004, Lucerne, Switzerland

THE VACUUM SYSTEM OF THE AUSTRALIAN SYNCHROTRON

E.Huttel, FZK, Karlsruhe, Germany
B.Barg, A.Jackson, B.Mountford, ASP, Melbourne, Australia

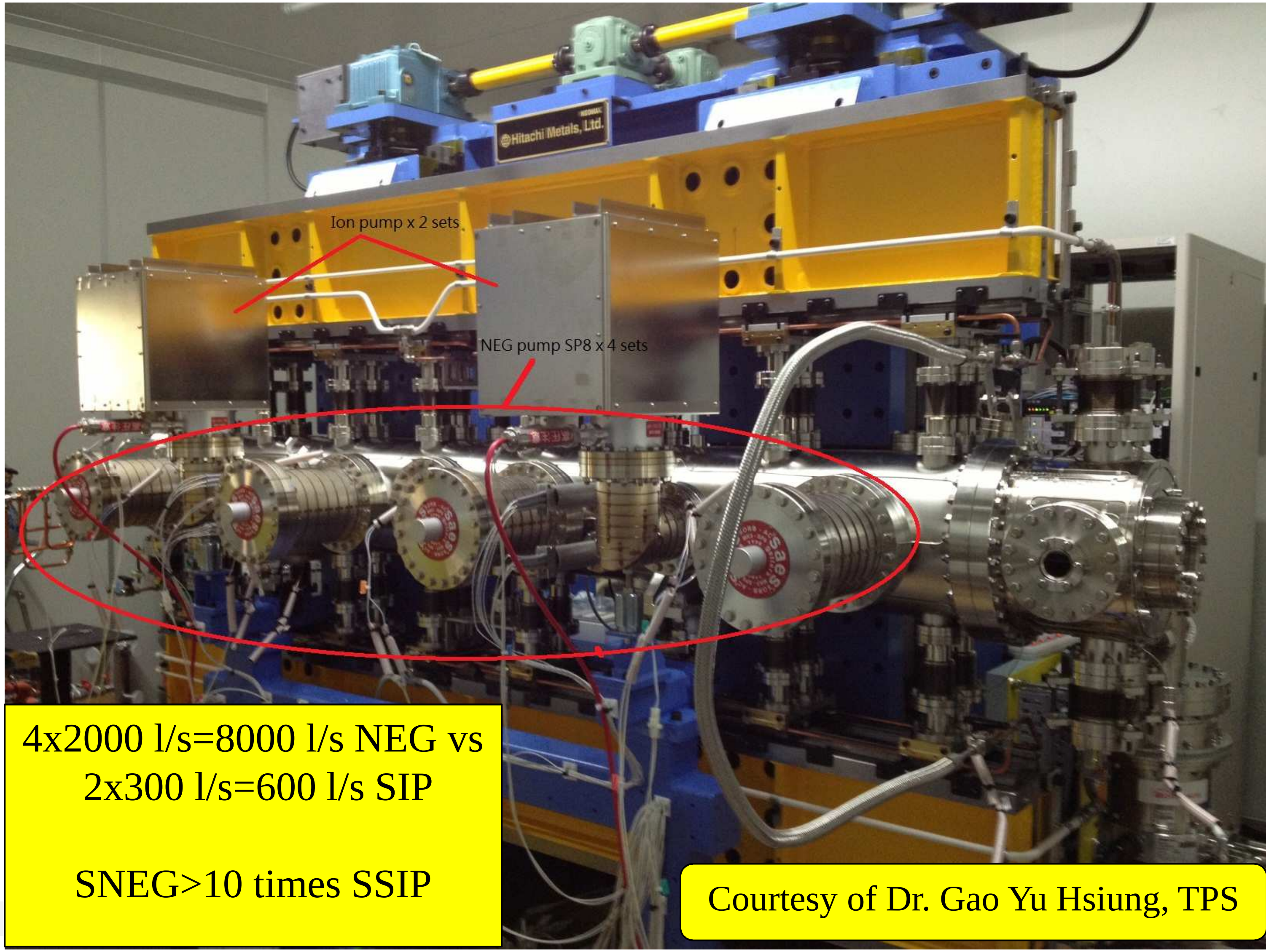
beam chamber. NEG cartridges are installed at two locations, where the installation of an ion pump was not possible due to space restrictions. Overall a pumping

All Storage rings built in the past 20 years , being upgraded or under design review have used or are considering extensive use of NEG pumps:

TPS, SSRF, ESRF II, APS U, SPring 8, Tohoku Ring, DLS, ALBA, ASP, SESAME…..

saes group

In vacuum undulators

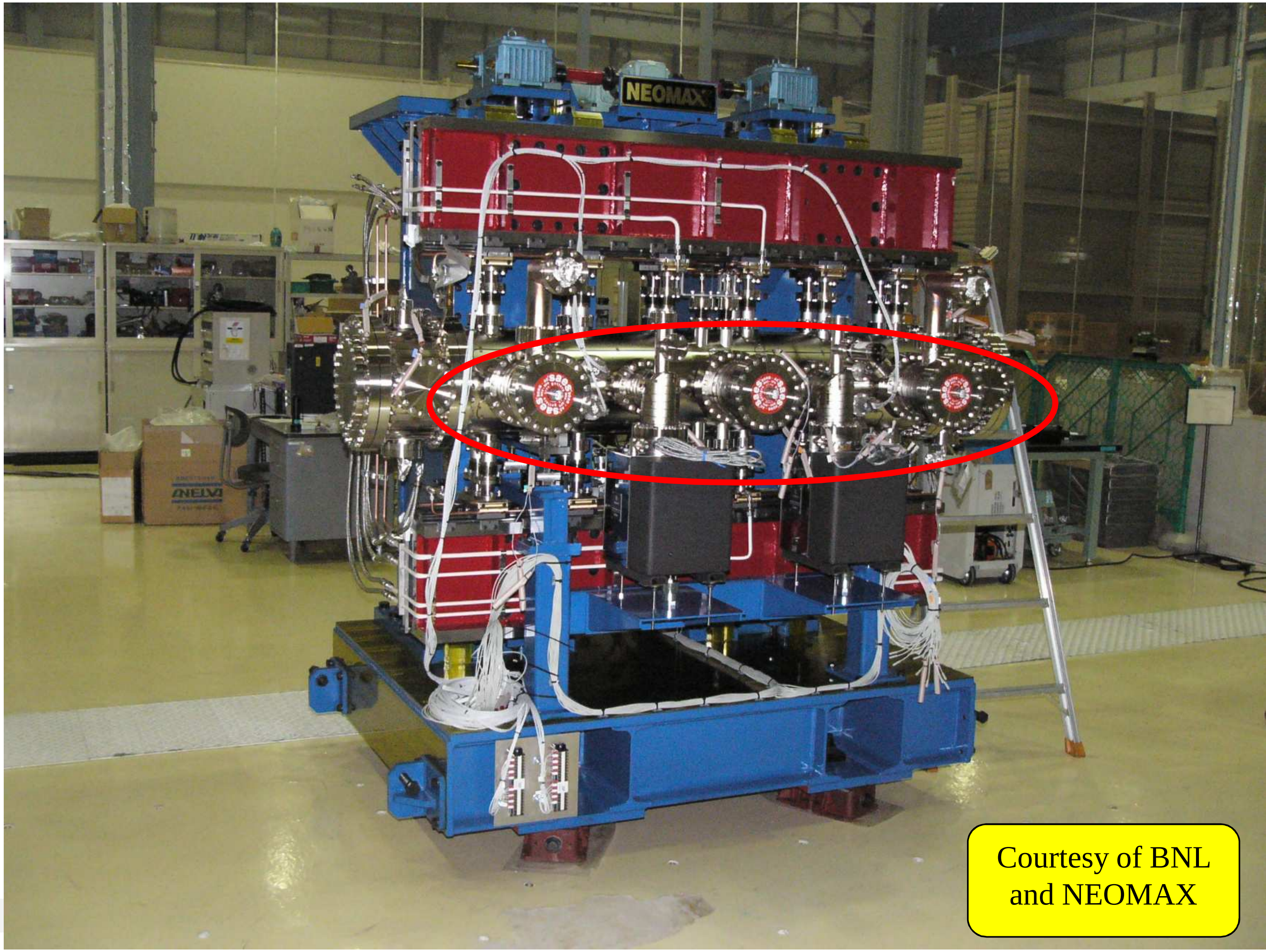


4x2000 l/s=8000 l/s NEG vs
2x300 l/s=600 l/s SIP

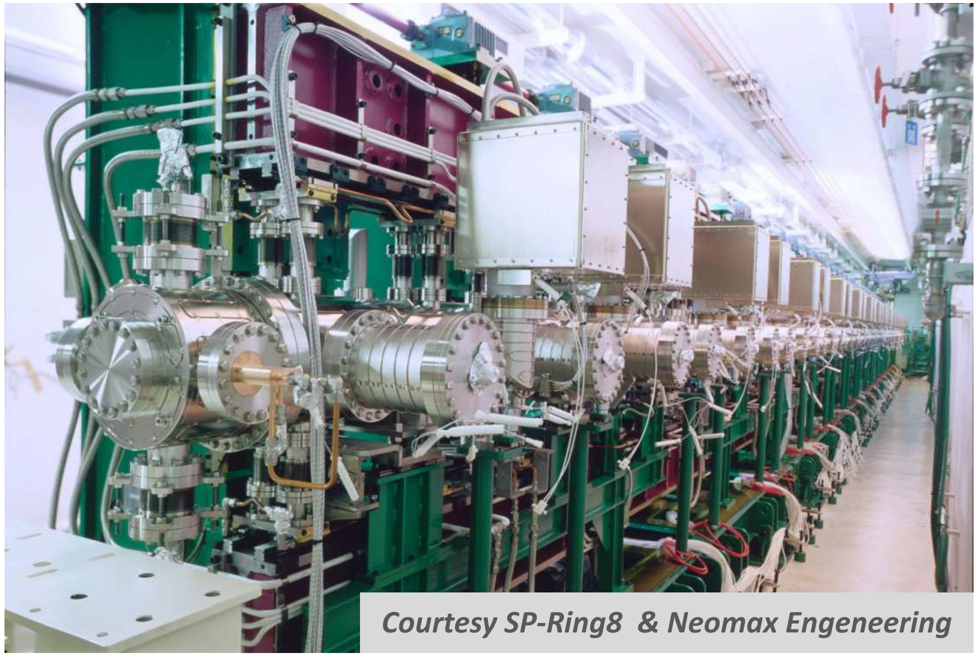
SNEG>10 times SSIP

Courtesy of Dr. Gao Yu Hsiung, TPS

In vacuum undulator @BNL

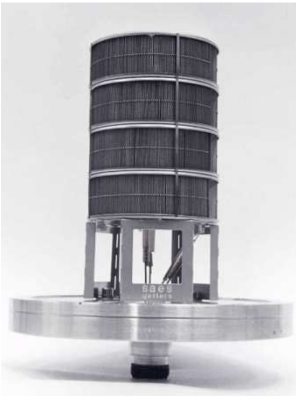


In vacuum undulators at X-FEL SACLA



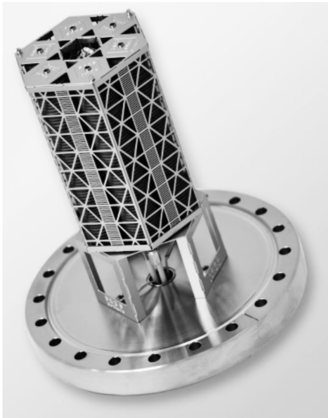
Courtesy SP-Ring8 & Neomax Engeneering

- The same in vacuum undulators have been used in the Taiwan Photon Source
- In the in vacuum undulators at BNL (NSLS-II) CapaciTorr® D3500 are installed. Provide double pumping speed compared to GP® 500



GP® 500

- Used at TPS, SPRING-8
- CF150
- Nominal pumping speed H2 2000 l/s



CapaciTorr® D3500

- Used at BNL
- CF150 and CF200
- Nominal pumping speed H2 3600 l/s

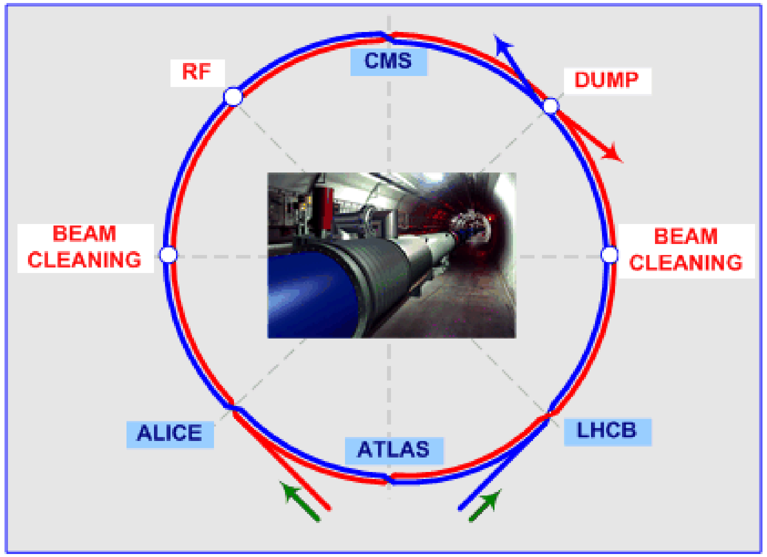
Colliders, B-factories, cyclotrons

Pressure (Torr)

10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11}

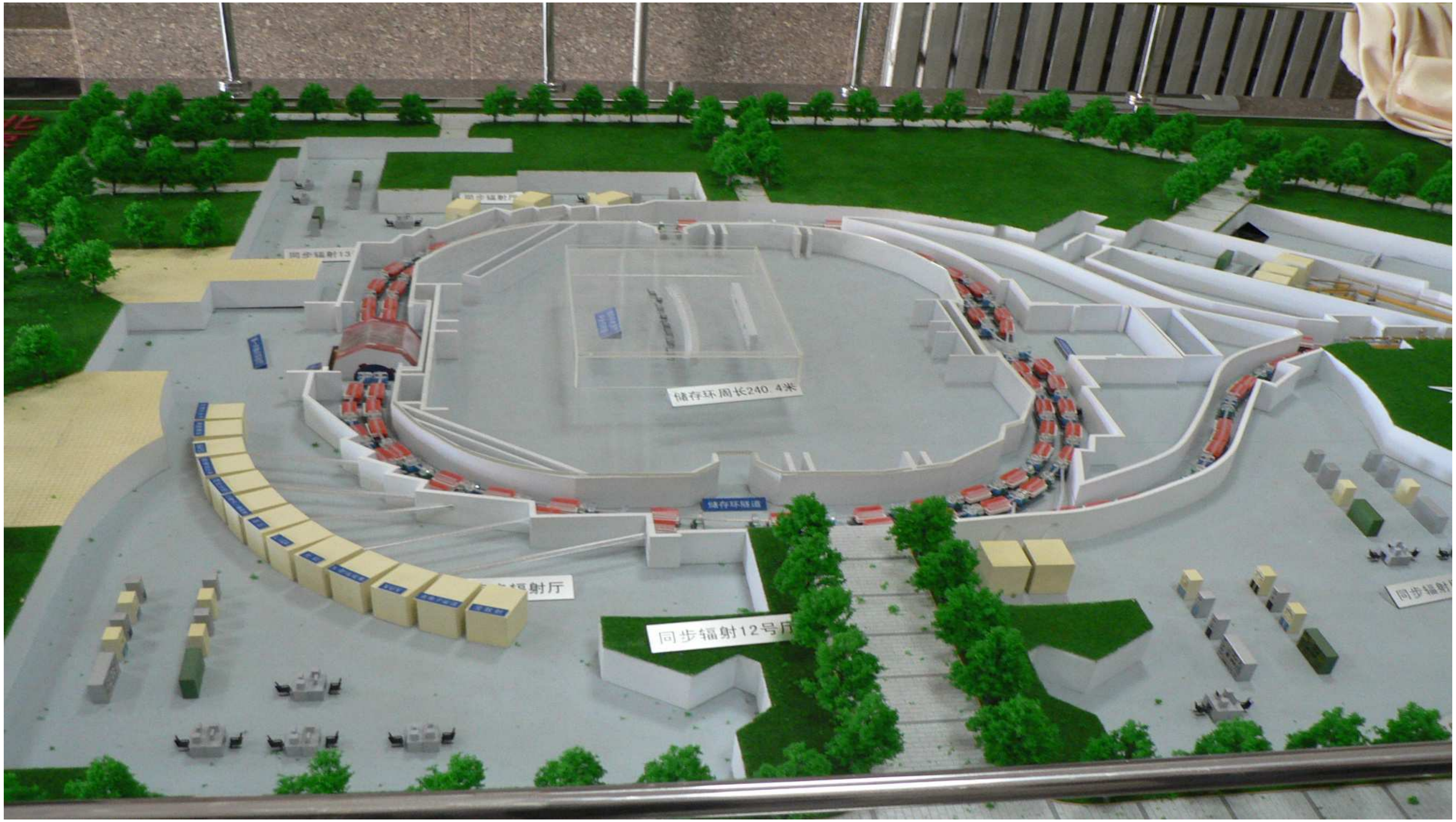
Vacuum level

LHC

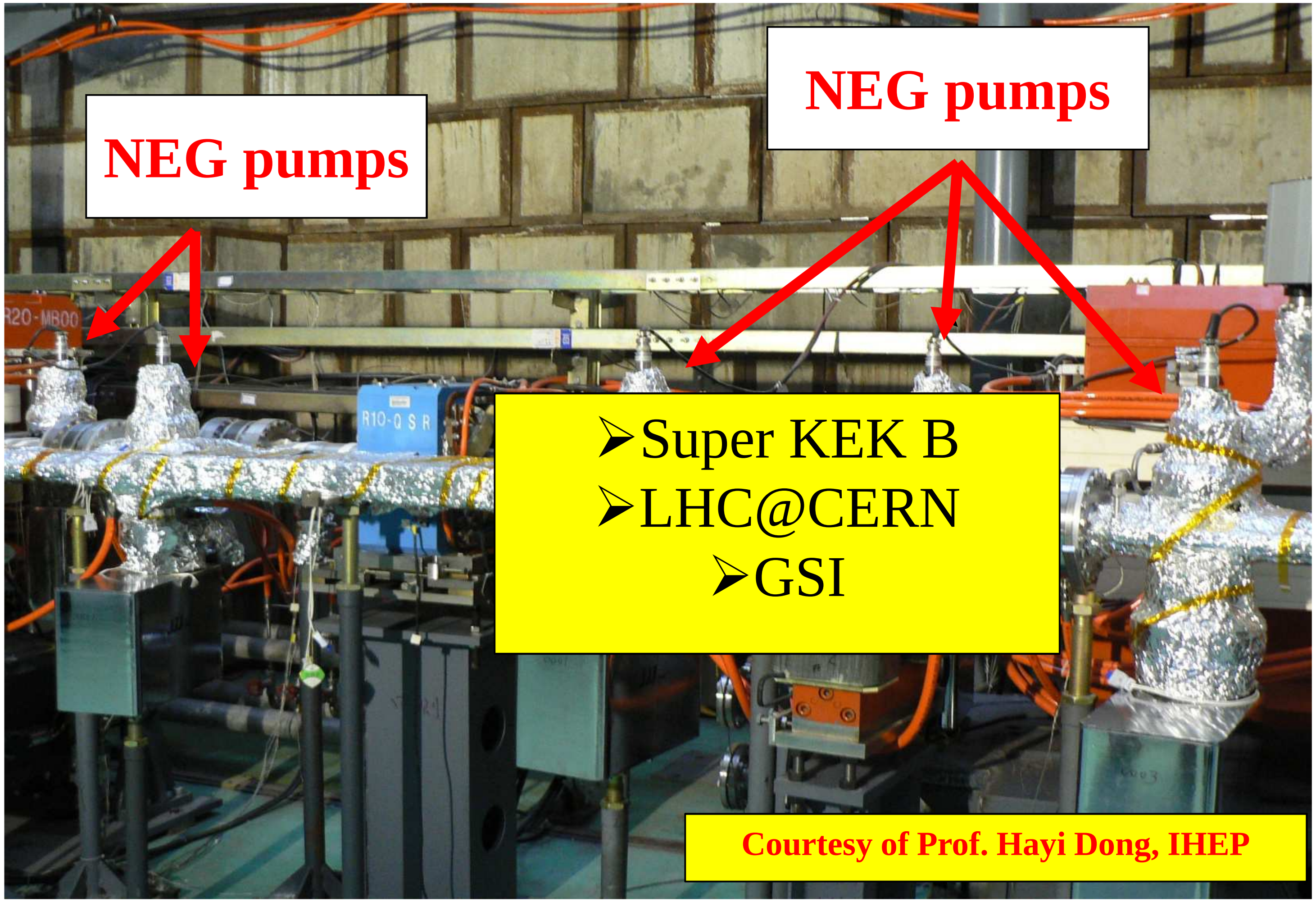


- **Vacuum requirements in colliders are even more demanding than in other accelerators**
- **Some machines (e.g. LHC, RHIC) uses NEG coating extensively**
- **NEG cartridges are also extensively used in high degassing area (LHC, BEPC2, Super KEKB)**
- **Other machines (e.g. Super-KEKB, COSY, BEPC II) mainly use distributed NEG strip + NEG pumps**

The largest Chinese collider
Beijing Collider (BEPC II)



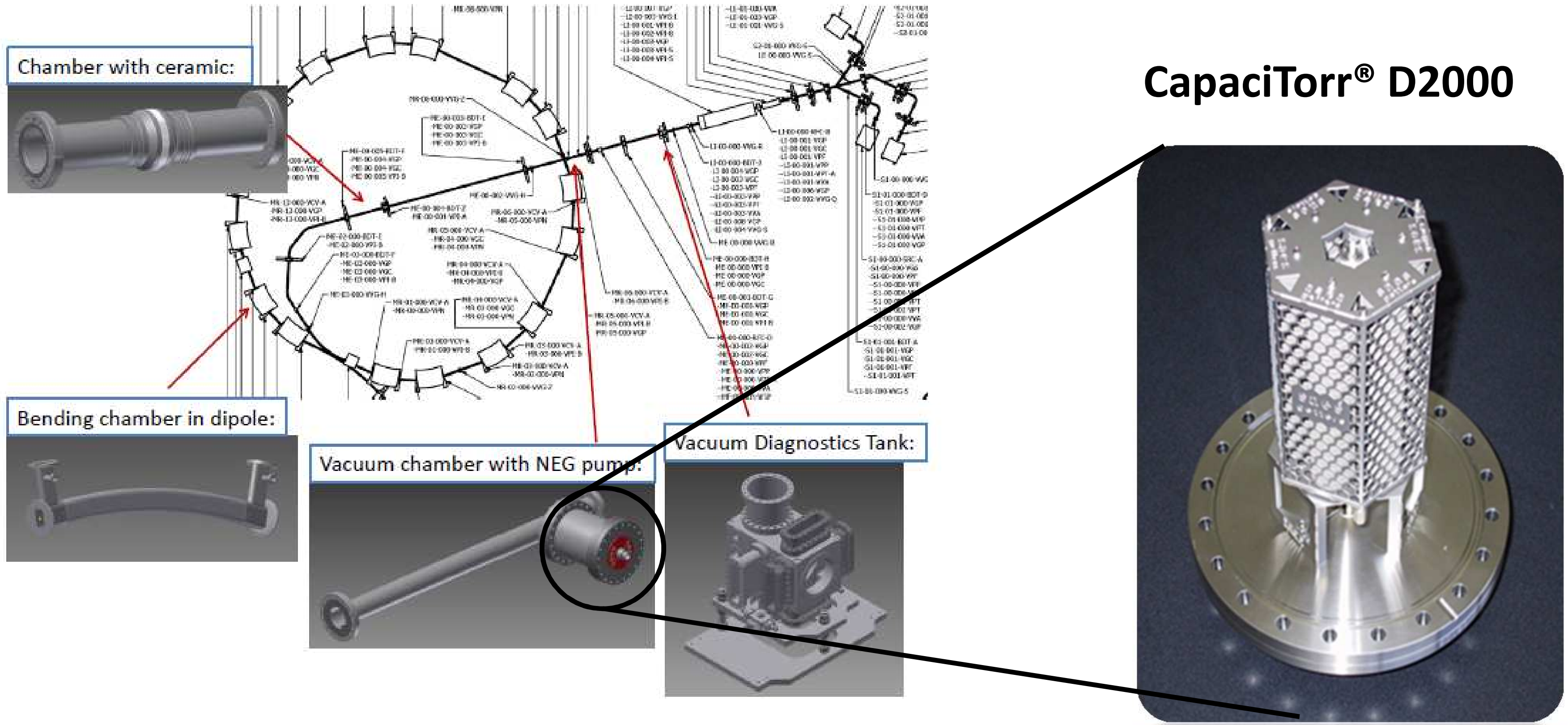
Beijing collider (BEPC II)



saes group

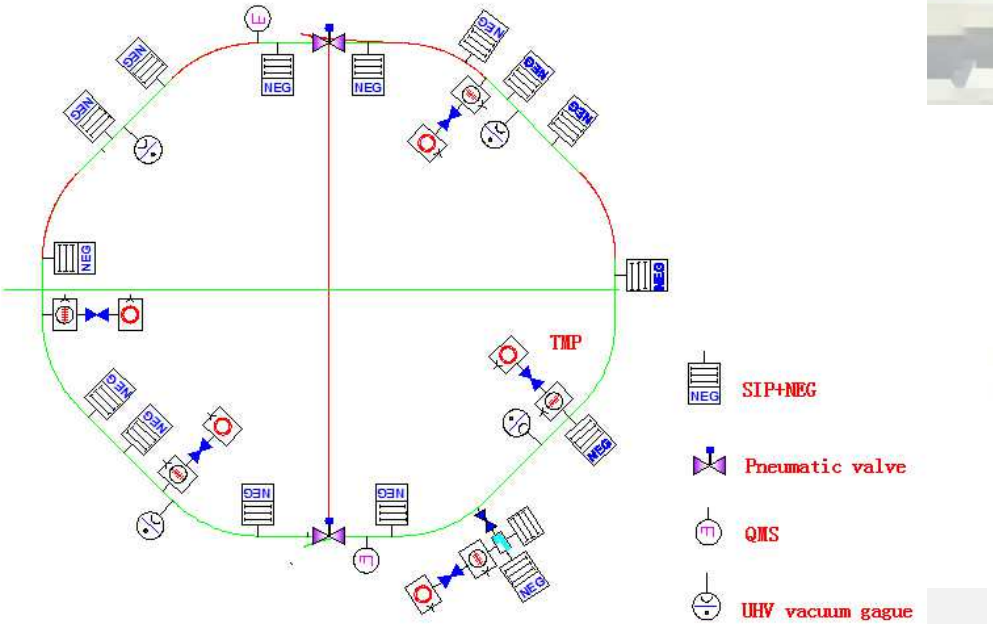
Medaustron Medical Accelerator

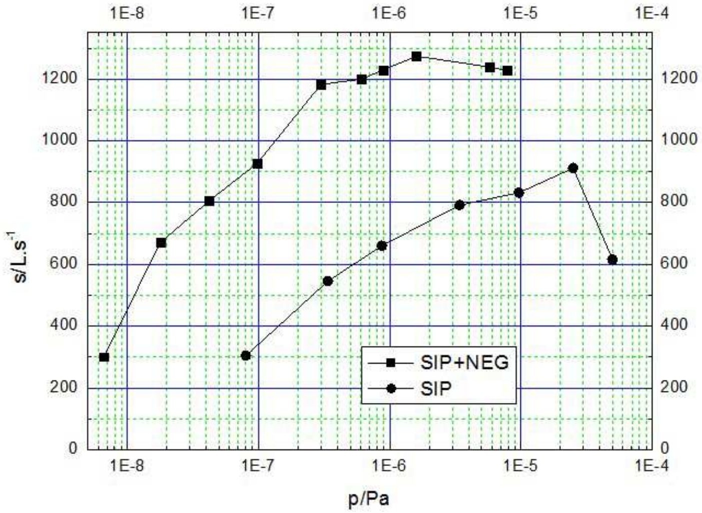
- In the accelerator and in addition to ion pumps, NEG cartridges will be installed to fasten recovery in case of vacuum venting to



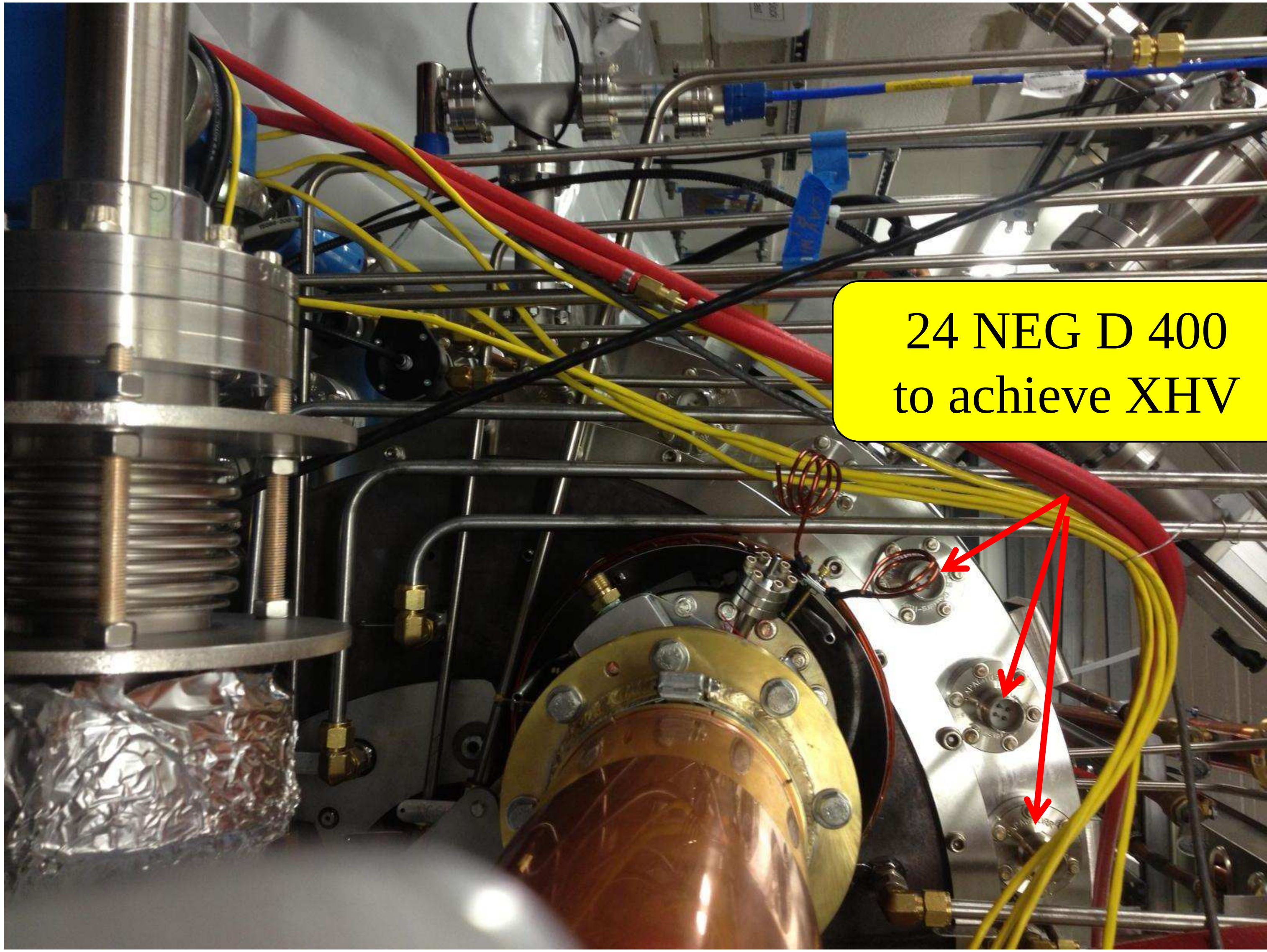
Medaustron Beam Vacuum System: from sources to patient treatment, Proceedin IPAC 2011, J.M. Jimenez et al.

The HIMM (Heavy Ion Medical Machine)

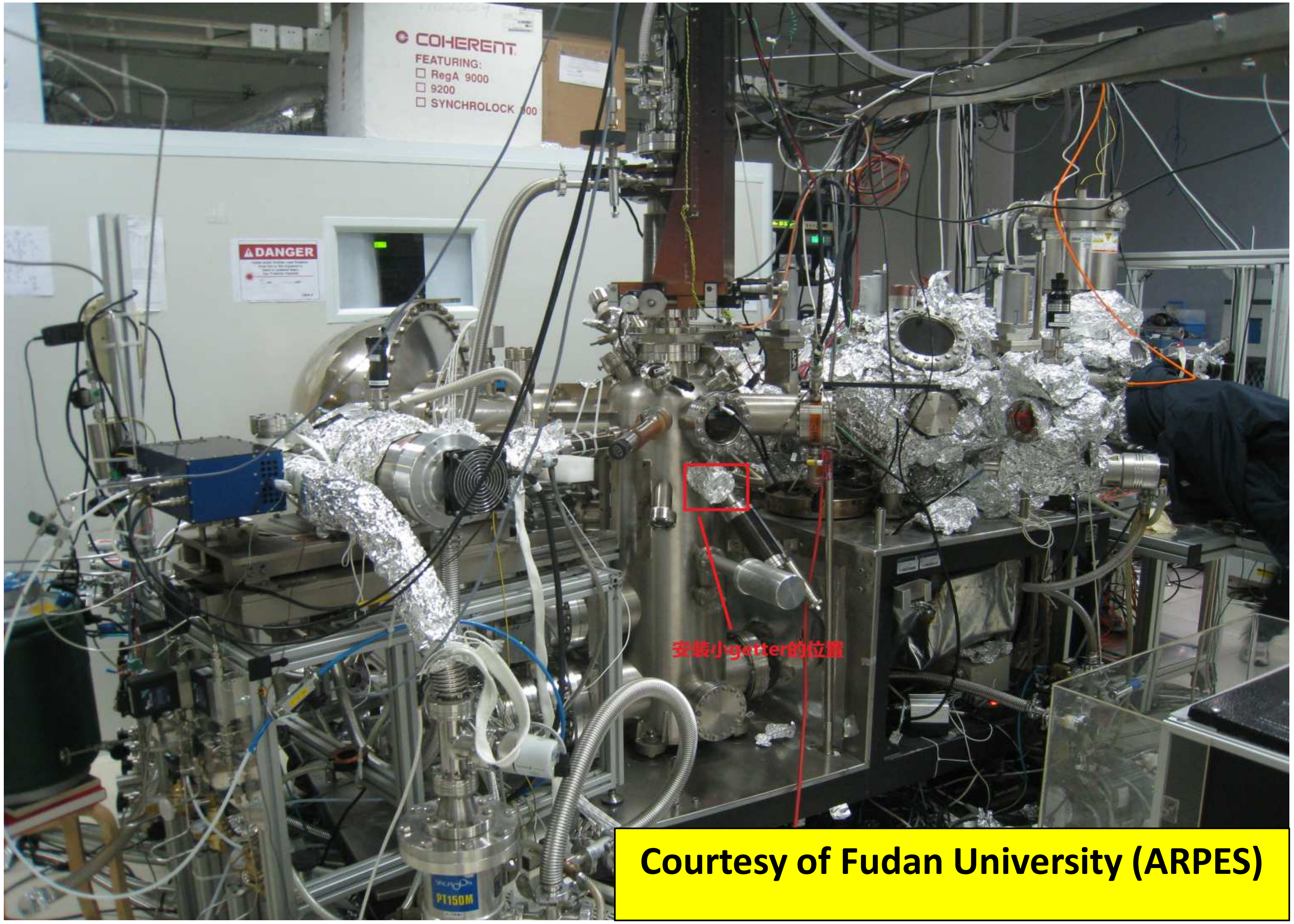




APEX photoinjector (LBL)

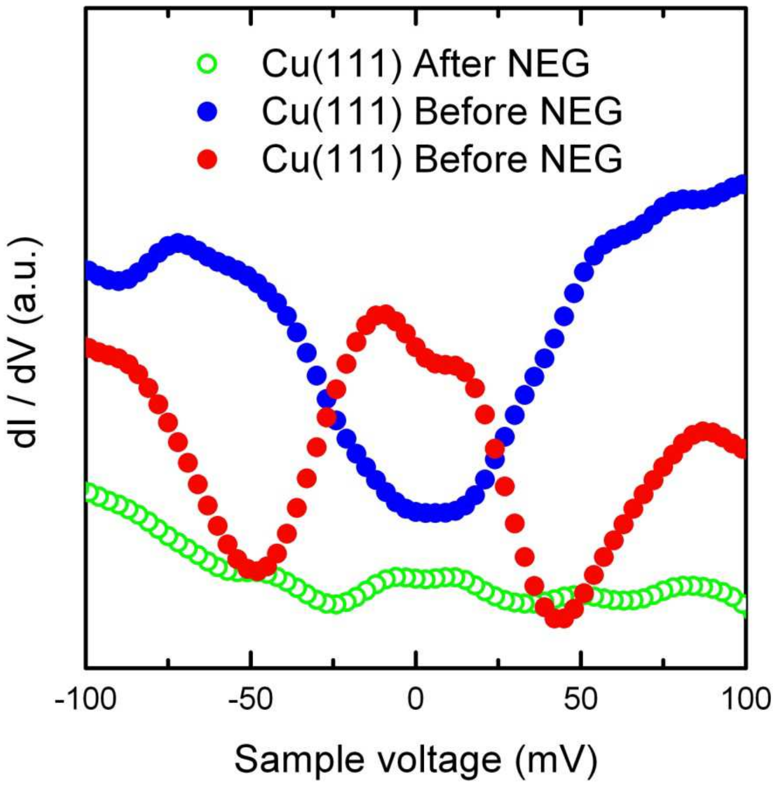


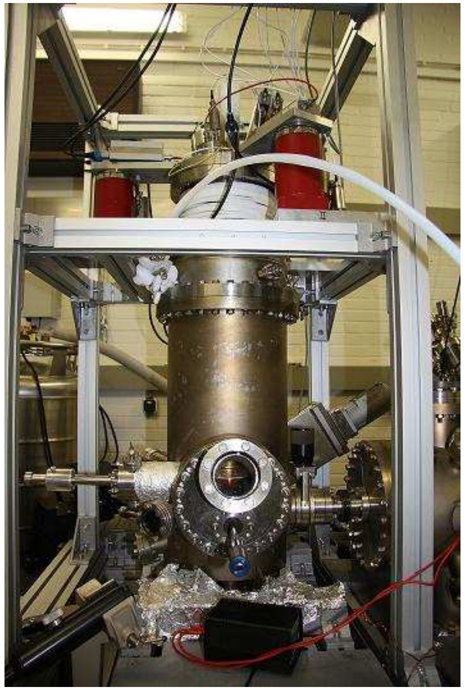
Surface science UHV systems



Courtesy of Fudan University (ARPES)

NEG pump in STM systems





front

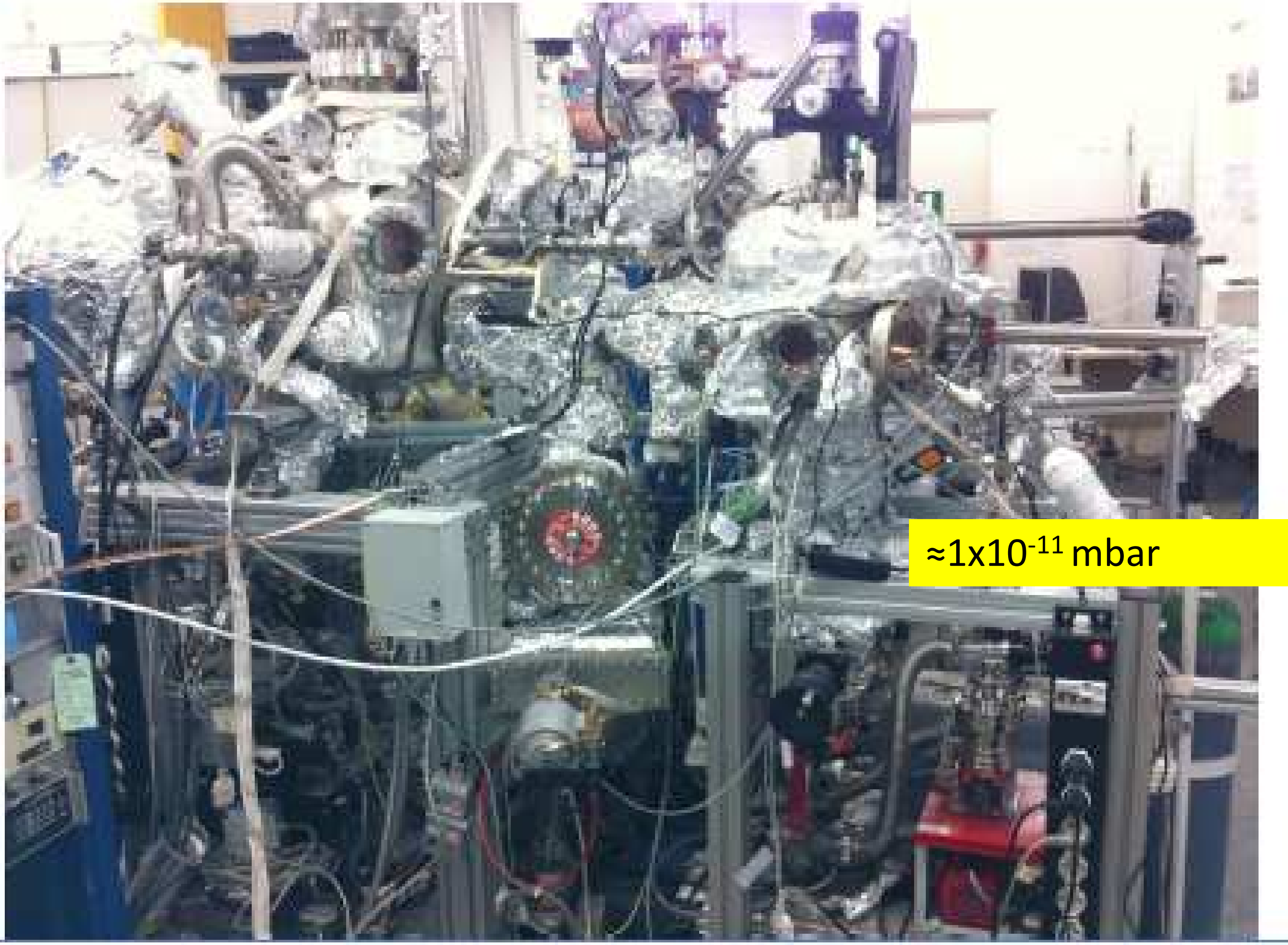
back

NEG pump: CF150 – 1900 l/s H_2

After using NEG pump, the H_2 features close to the Fermi Level disappeared!

Courtesy of University of Kiel (Dr. Schoeneberg, group of Prof. Berndt)

NEG in AES



A Capacitorr D-2000 is used in this complex AES system (courtesy of CNR Frascati, Italy)

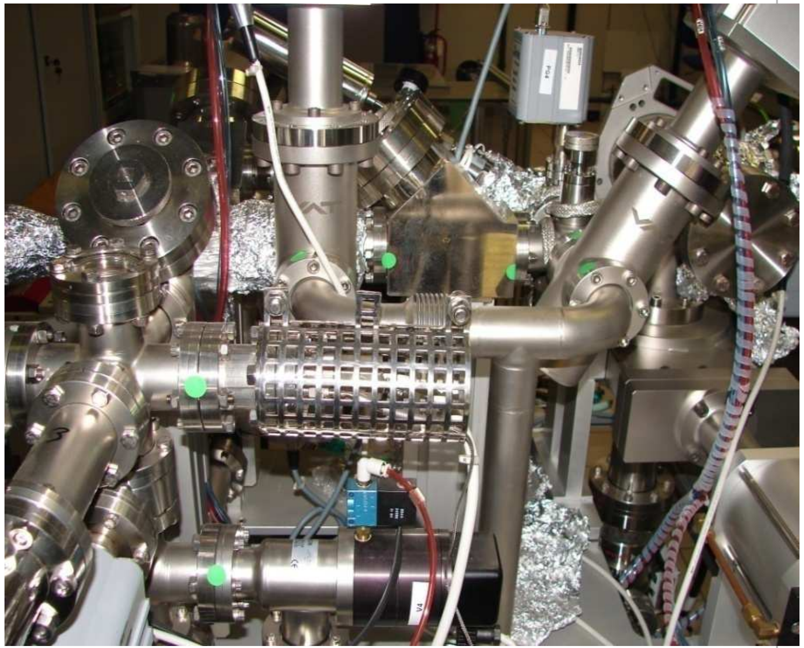
5. Combination of Ion and NEG pumps

Miniaturization : a key requirement in vacuum

- Equipment are getting more complex and “packed”. The demand to reduce the size and weight of vacuum systems is increasing for industrial and scientific equipment.

- Even in very large research vacuum systems, like accelerators & synchrotrons, magnets, diagnostic tools and diversified instrumentations limits the space available for pumps.

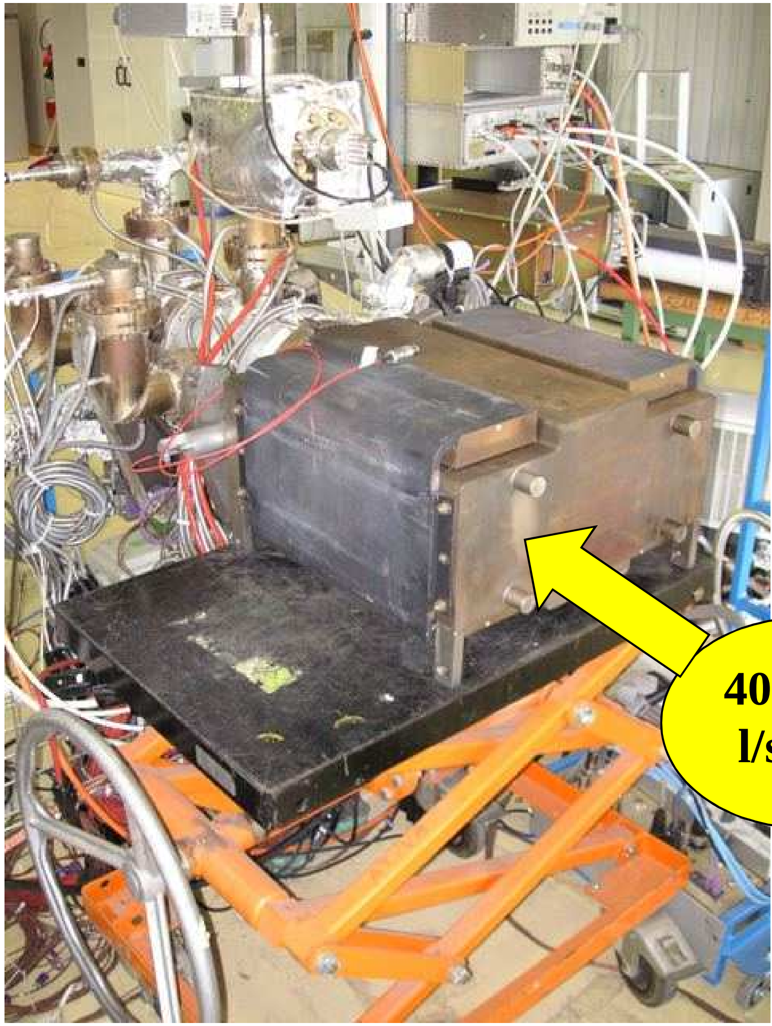
- Better vacuum and more effective pumping is on the other hand required.

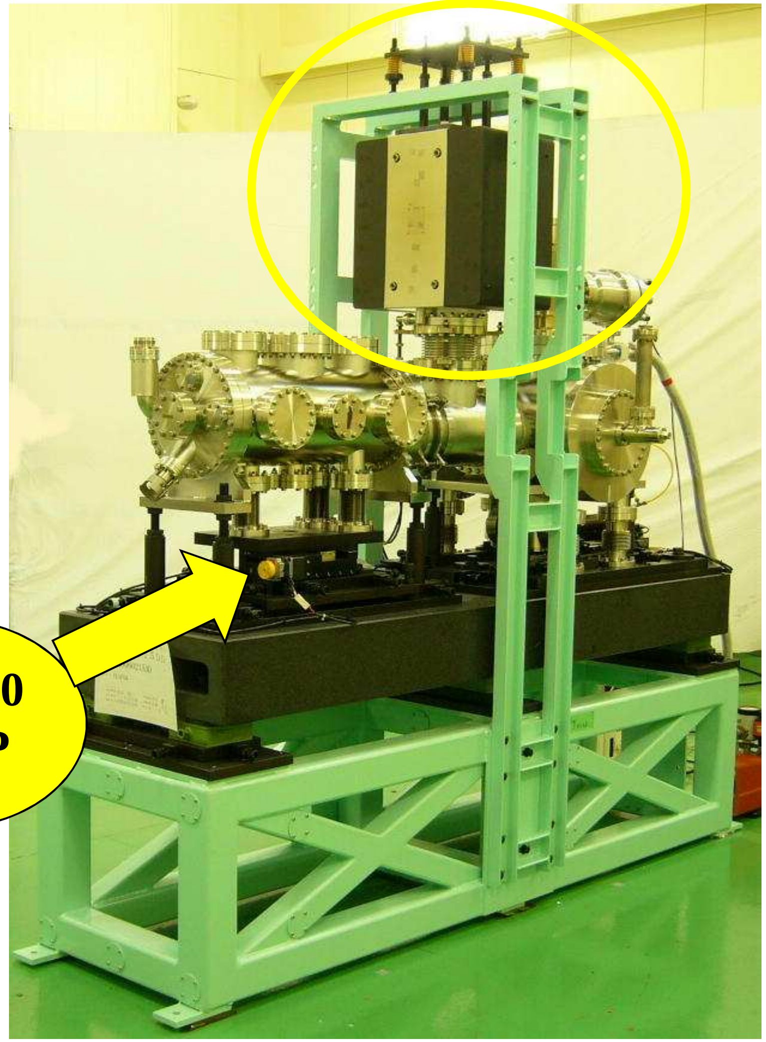


…conflicting issues…!

saes group

IP are large pumps…space and weight support needed





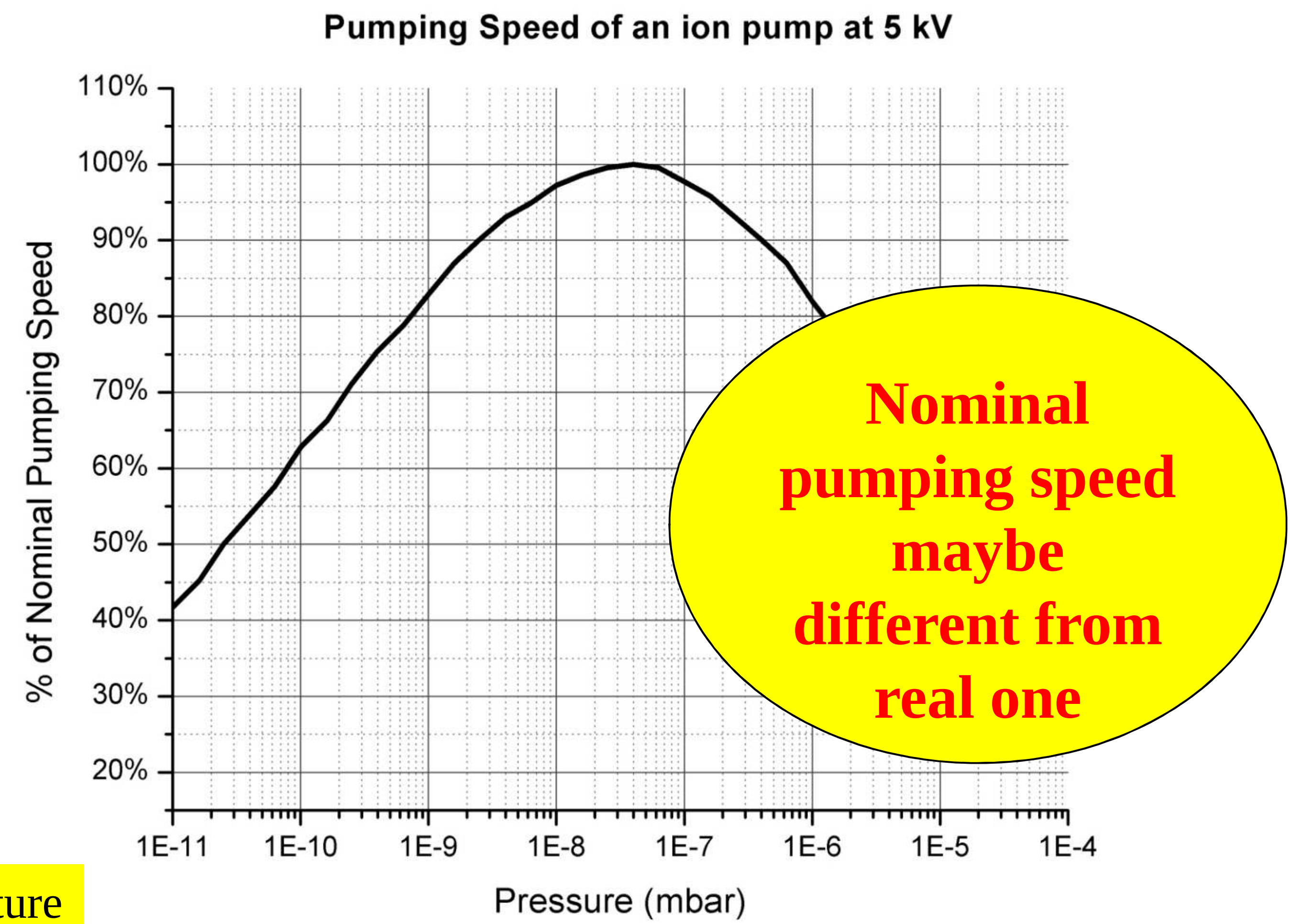
Sputter ion pumps (SIP) vs NEG pumps

- SIP is very popular technique to achieve UHV in vacuum systems. However, ion pumps have some limitations :

  - The **large weight and size**
  - The presence of **high voltages**
  - The **decrease in the pumping efficiency** below 10^{-8} mbar
  - The **low pumping efficiency for H_2** (main residual gas in UHV-XHV systems)

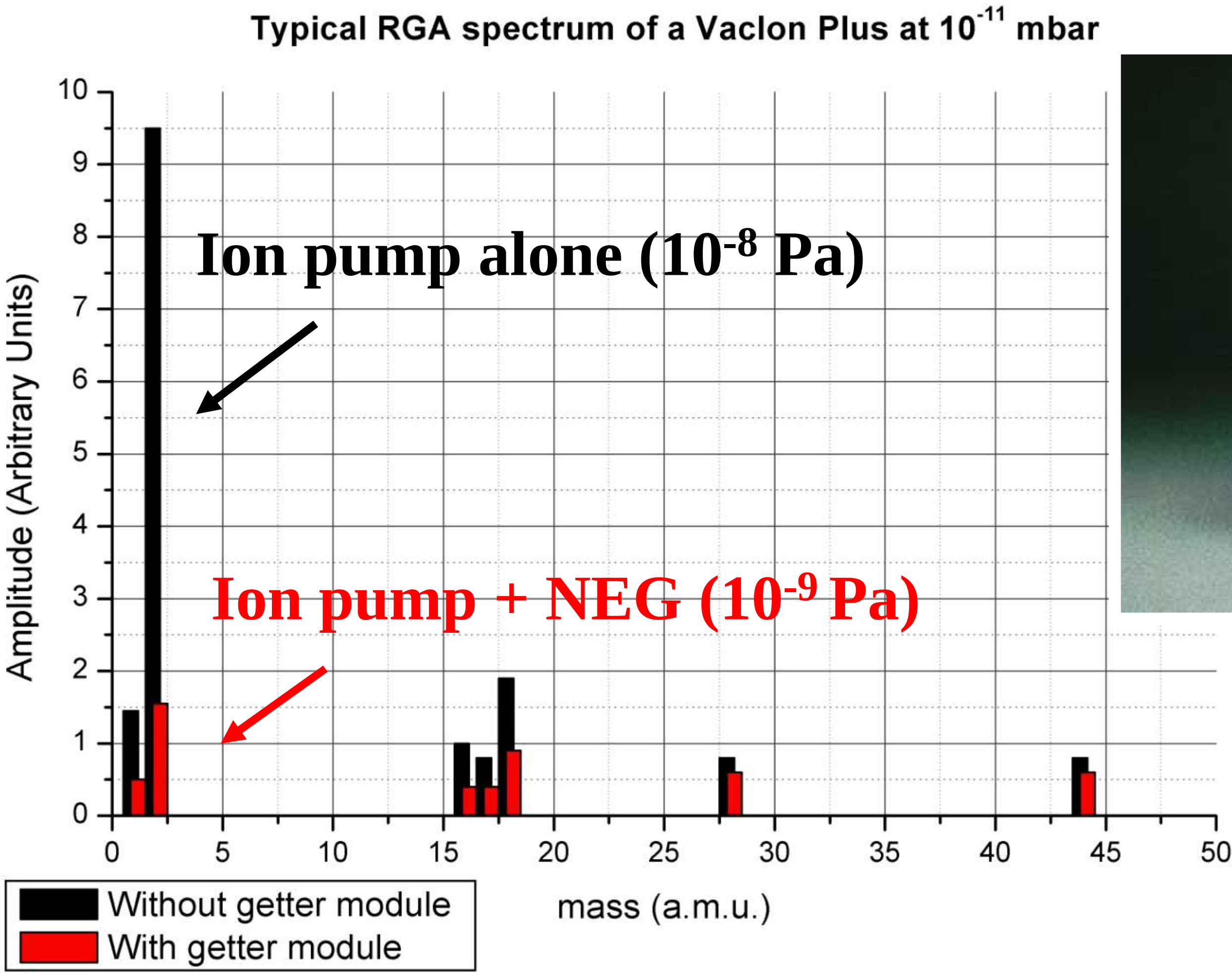
- This implies that to achieve 10^{-10}-10^{-12} mbar range, very large SIP have to be used.

SIP Pumping speed vs pressures



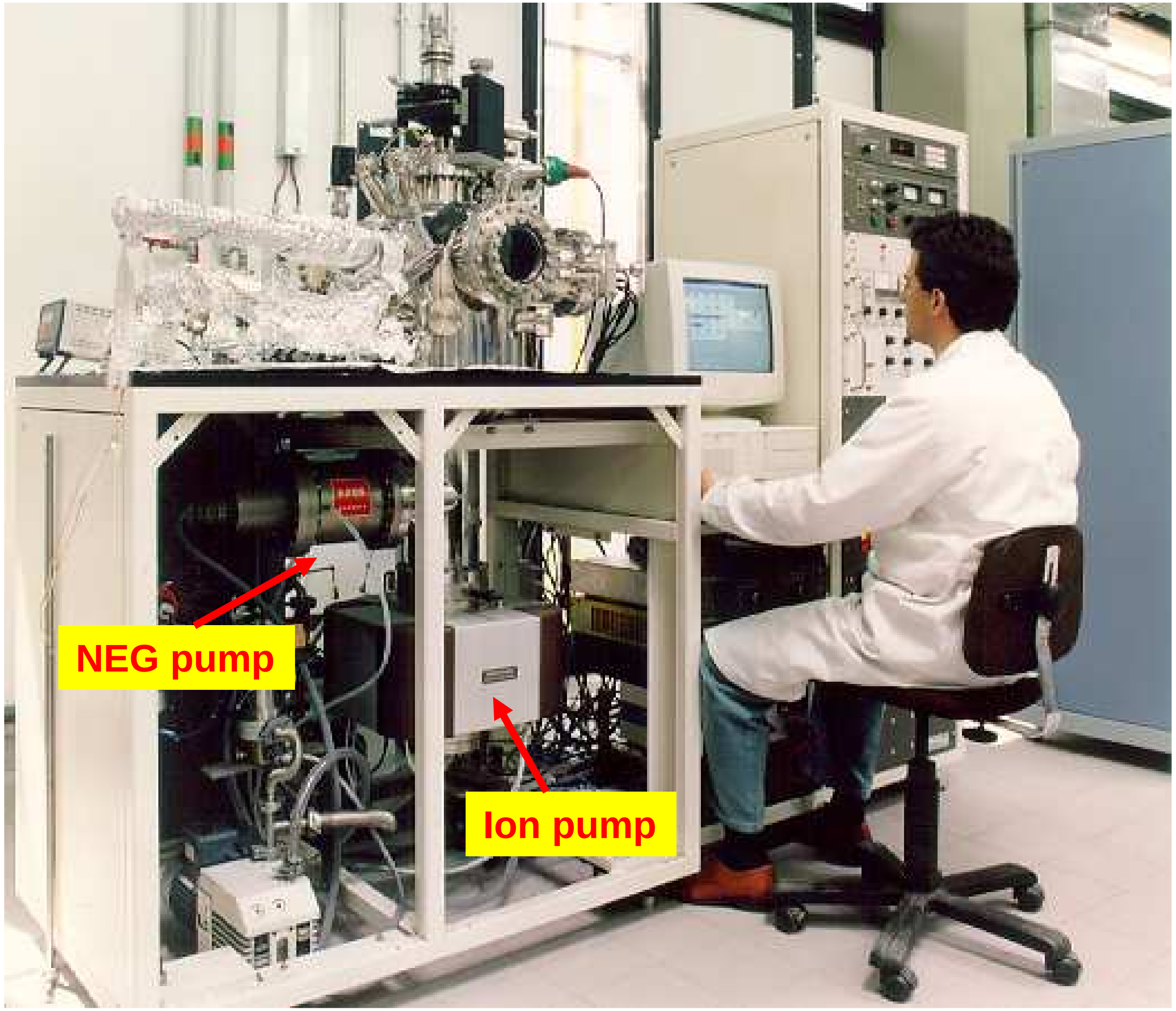
Varian literature

SIP+NEG combination

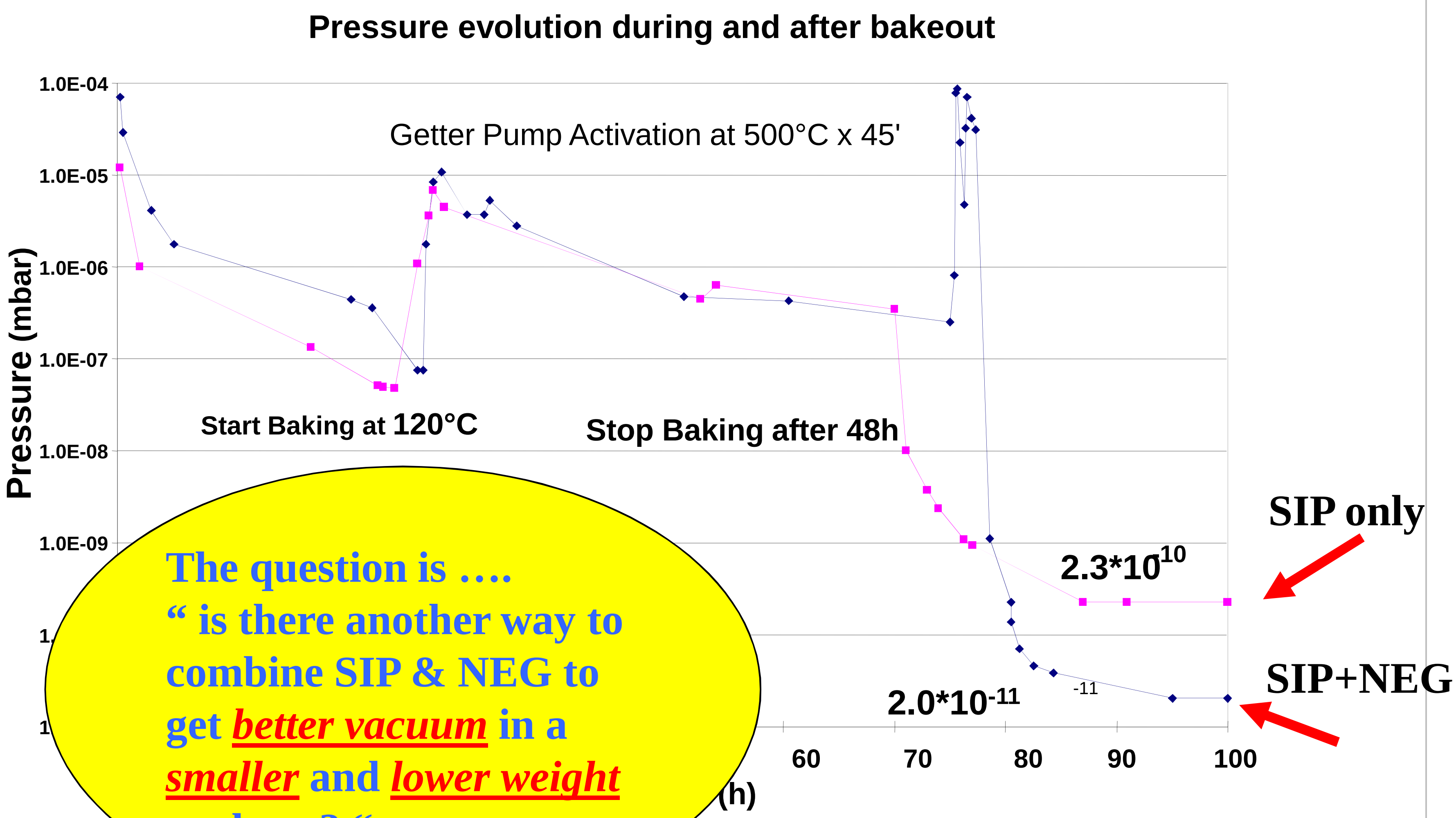


M. Audi and L.Dolcino, J. Vac. Sci. Technol. A 5(4), 2587 (1987)

Another traditional set-up



Ion pump-NEG pump combination
(UHV chamber for surface analysis)



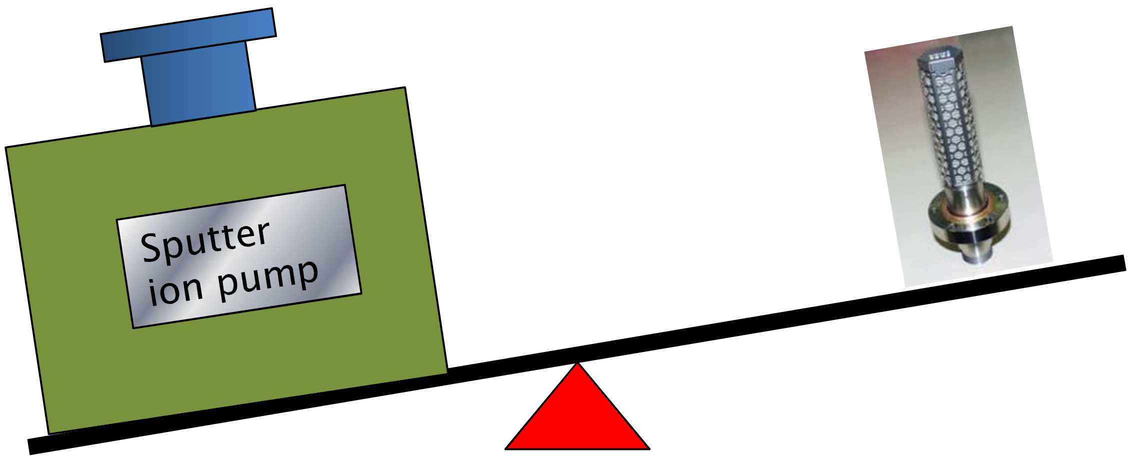
The question is ….
" is there another way to combine SIP & NEG to get *better vacuum* in a *smaller* and *lower weight* package? "

The traditional approach

Pumping speed requirements

Large SIP as main pump

Compact NEG to boost H2 performances

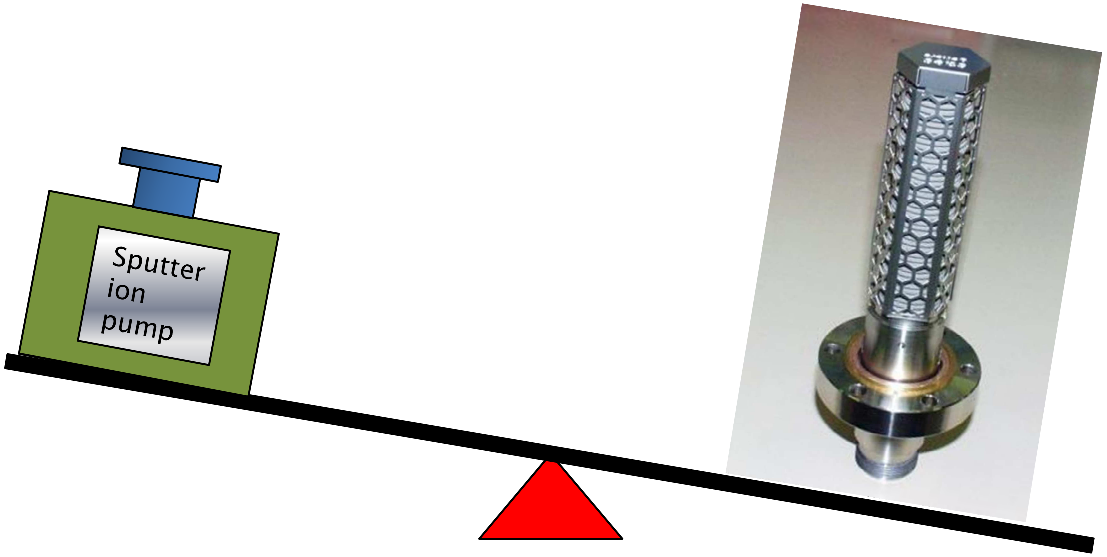


A different combination…

Pumping speed requirements

Small SIP for Ar and CH_4

Large pumping speed NEG as main pump (still compact)



Combination of NEG and Sputter-Ion Pumps for Particle Accelerator Vacuum Systems

P. Chiggiato, S. Meunier, I. Wevers
Vacuum, Surfaces and Coatings
CERN, 1211 Geneva 23, Switzerland

A.Bonucci, A.Conte, P.Manini, F.Siviero, L.Viale
SAES Getters SpA, Viale Italia 77, 20020 Lainate (Italy)

Introduction

NEG and sputter-ion pumps are usually combined in particle accelerators to attain UHV pressure specifications.NEG pumps provide very high pumping speed at a reasonable cost for most of the residual gases except CH_4 and rare gases, which amount to less than an hundredth of the total outgassing rate. Sputter-ion pumps remove all gas ... optimized design should be based on NEG assisted by sputter-ion p...

Not getterable gases are only 1% of the total gas composition….we can easily remove with a small ion pump

Thermal Outgassing		
Materials	Outgassing Rates of gasses pumped by NEG (mainly H_2) [Torr l s^{-1} cm^{-2}]	Outgassing Rates of Gasses Not Pumped by NEG (mainly CH_4) [Torr l s^{-1} cm^{-2}]
Stainless Steel	10^{-12}	$<10^{-14}$
Stainless steel (vacuum fired)	2×10^{-13}	$<10^{-15}$
Copper OFE	10^{-12}	$<10^{-14}$
Aluminium alloys	10^{-12}	$<10^{-15}$

P. Chiggiato et al., Poster VT-TuP6 AVS 58 Conference, Nashville 2011

Combining a NEG and a SIP on one flange

- ☐ **NEXTorr®** is a new generation of pumps which combines in a single, very compact - light package, a **NEG element** and a **small ion pump**.

- ☐ The getter element provides large pumping speed and acts as the main pump for the active gases, leaving to the ion pump the task of removing noble gases and CH_4, not pumped by the NEG.

A Bonucci et al, "The pumping synergies of integrated NEG and SIP pumps for UHV applications", 57^{th} AVS Conference, 2010.

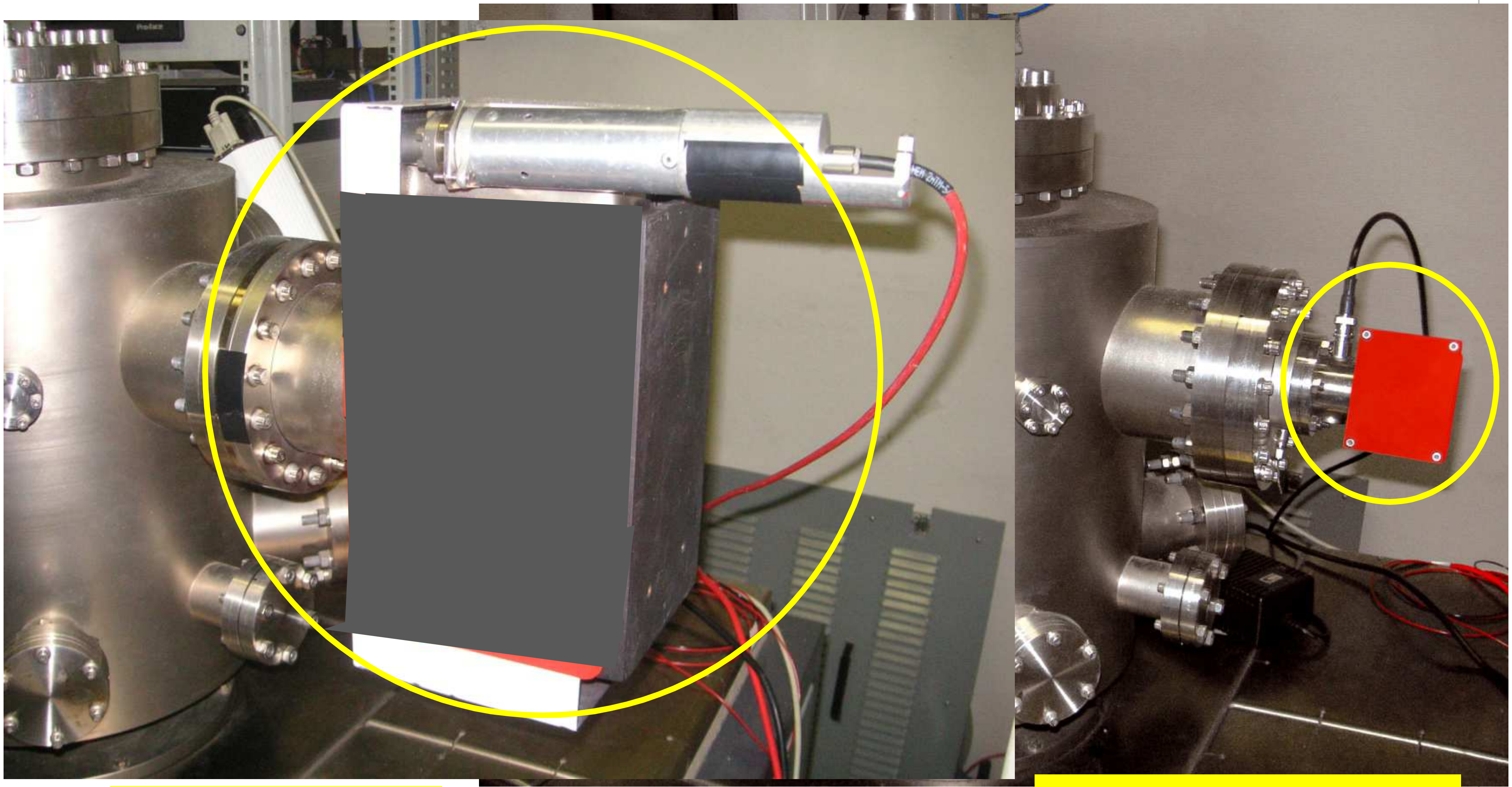
Combination pump main features

Total weight (magnets included)	2,2 kg
Volume	0,5 l

	Initial pumping speed (l/s)	
Gas	NEG activated	NEG saturated
O_2	100	3.5
H_2	100	-
CO	70	6
N_2	40	5
CH_4	15	7
Argon	6	6

NEXTorr® is a SAES registered Trade mark.
NEXTorr® is covered by international patents worldwide.

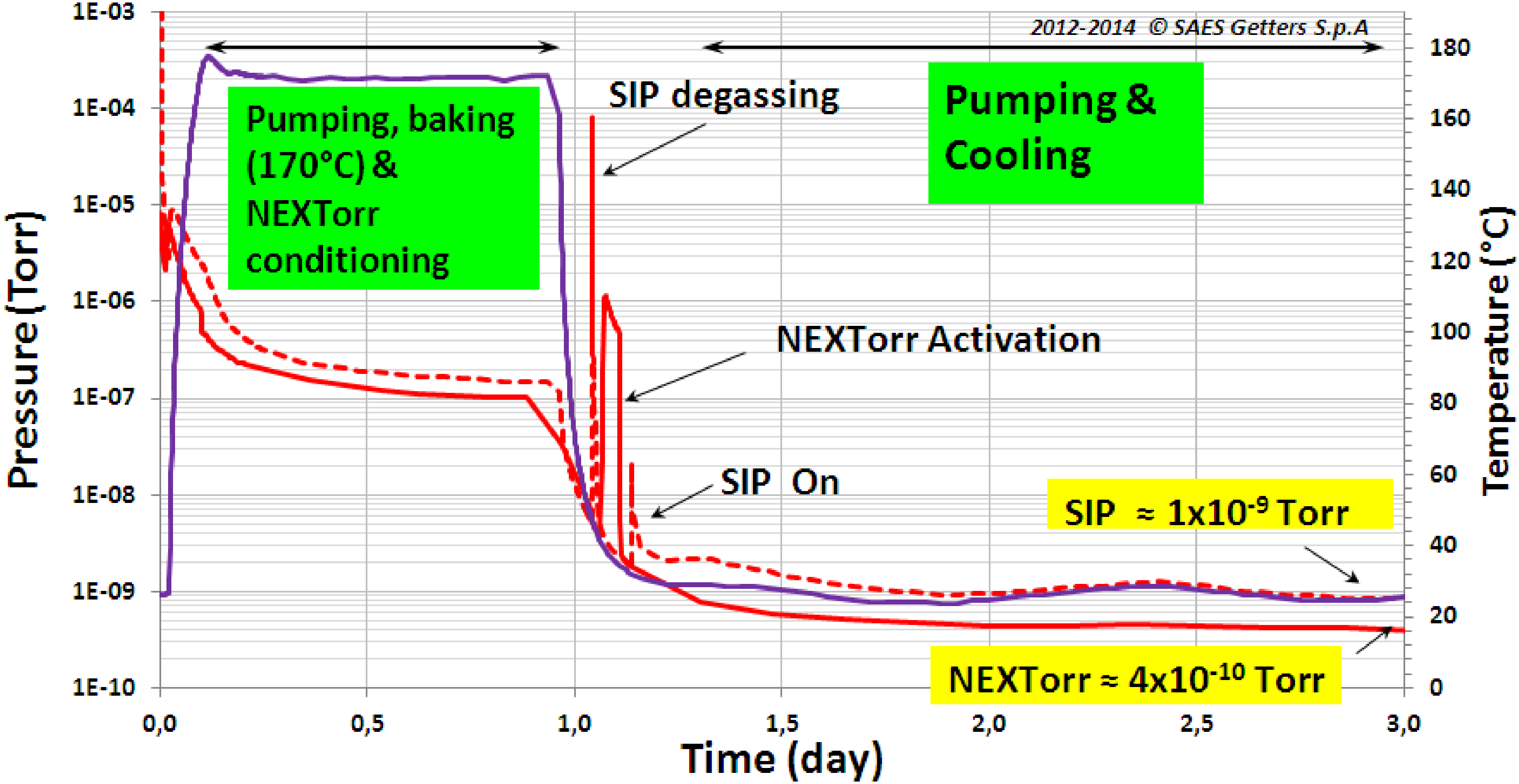
Combination pump vs SIP: experimental set-up



SIP - 120 L/s (H_2)

NEXTorr – 100 L/s (H_2)

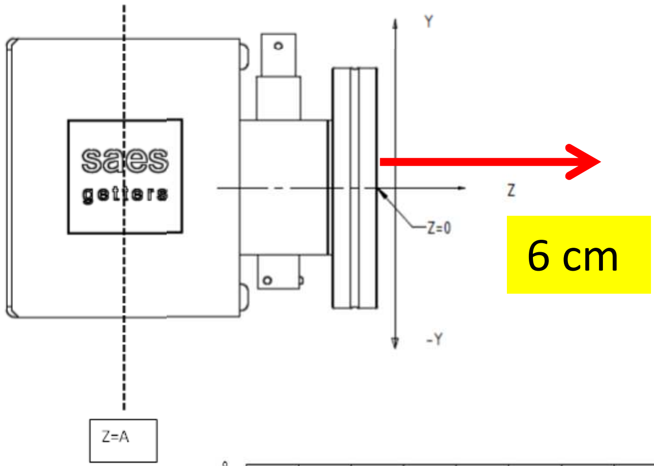
Pump down results

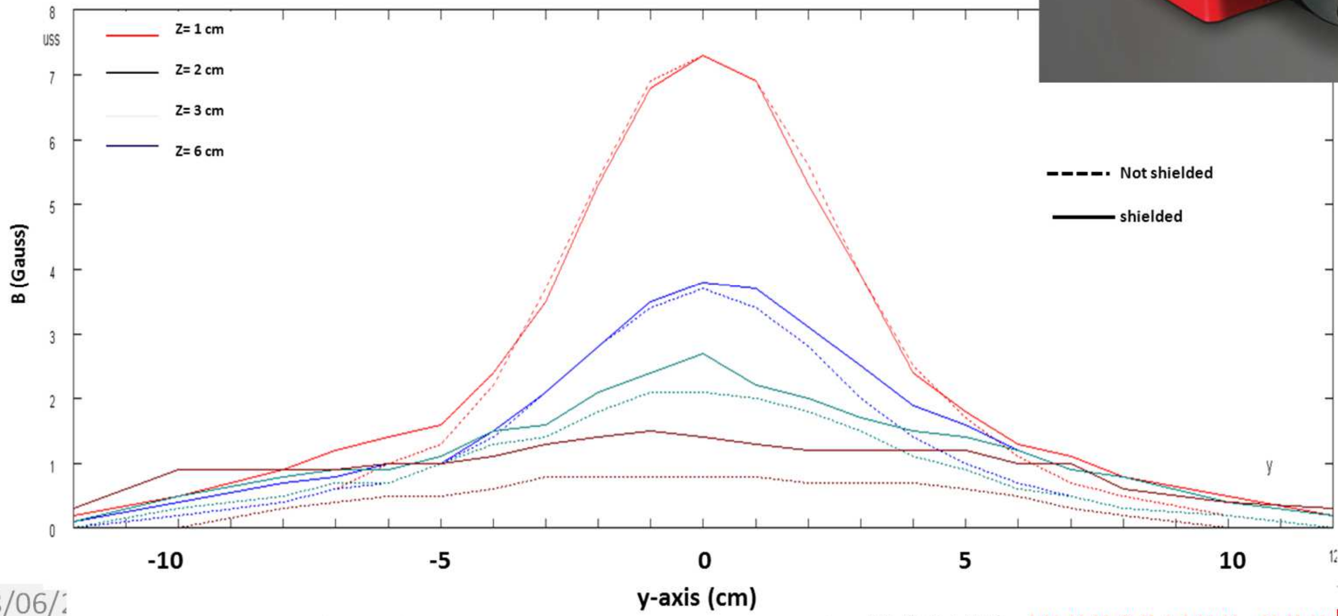


NEG/SIP combined pumps family

- Several models available from 100 l/s to 2000 l/s.
- Both diode and Noble diode available.
- SIP speed 5 l/s to 10 l/s (Ar)
- NEG cartridge based on two **sintered getter alloy disks** (St 172 or ZAO)
- The sintering process is key to ensure speed, capacity and particle retention.
- Weight from 2 to 7 Kg.

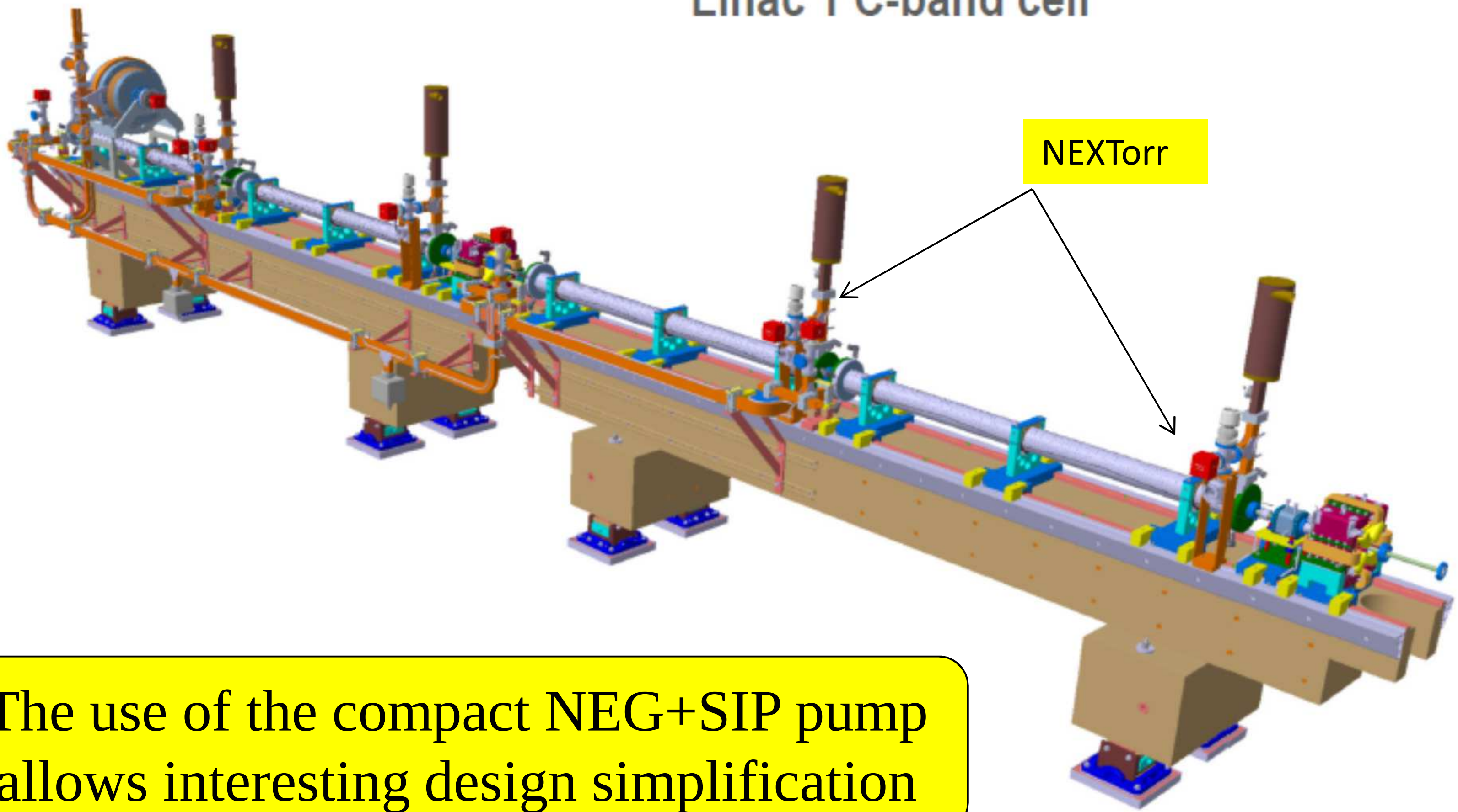
Negligible Magnetic field





Applications

Linac 1 C-band cell

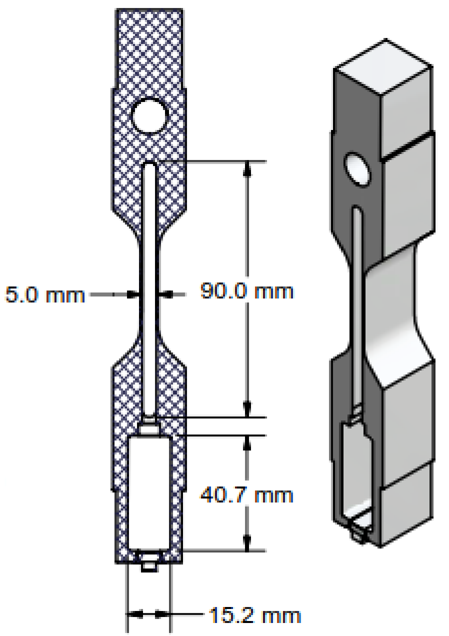


The use of the compact NEG+SIP pump allows interesting design simplification

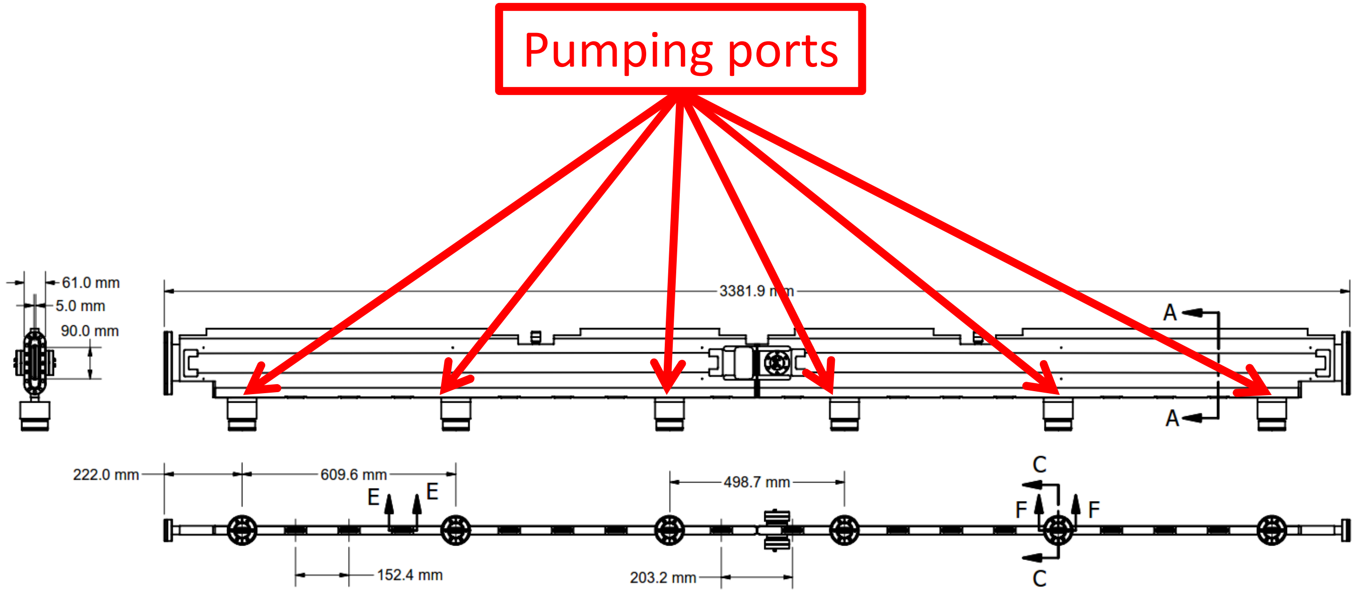
L. Schulz, ATK

Cornell Compact Undulators for CHESS

- Upgrade of Cornell High-Energy Synchrotron Source (CHESS): replacement of 1 wiggler with 2 **Cornell Compact Undulators** (CCUs).
- Vacuum chamber for CCUs: **5x90 mm** aperture, **~3.5 m** long.
- Made of **aluminium** for conductivity reasons.
- Chamber is water cooled (~1 kW SR power along the chamber).

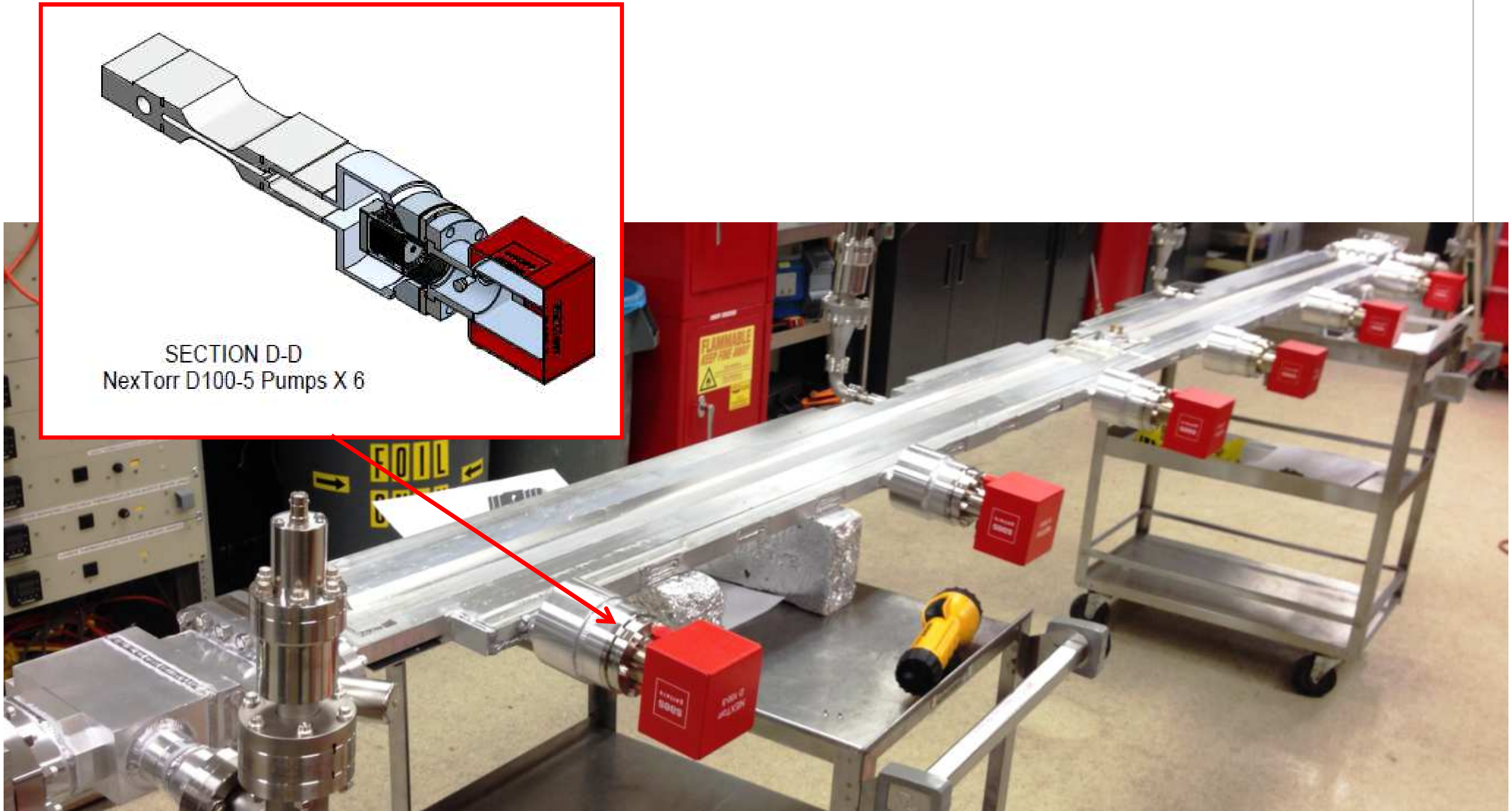


SECTION A-A
Beam-Pump Connection



Courtesy of Dr. Yulin Li, Wilson Synchrotron Lab., Cornell University.

Combined pump on Undulator Chamber



Courtesy of Dr. Yulin Li, Wilson Synchrotron Lab., Cornell University.

A simplified vacuum system for the new PC gun in the FERMI@Elettra project.

FERMI @elettra

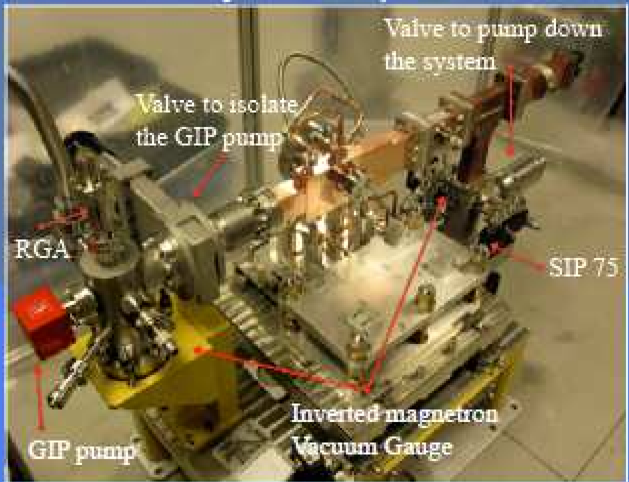
L. Rumiz, I. Cudin, E. Mazzucco, G. Pangon, M. Trovò, F. Zudini.
ELETTRA Sincrotrone Trieste S.C.p.A. - Trieste (Italy).

Corresponding author: Luca.Rumiz@elettra.eu

Elettra Sincrotrone Trieste

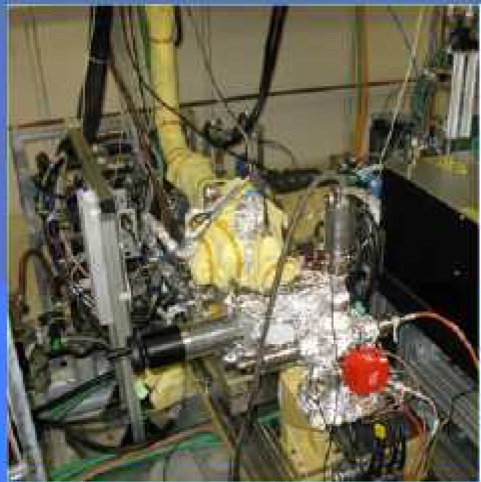
The new PC-Gun

A simpler vacuum system…



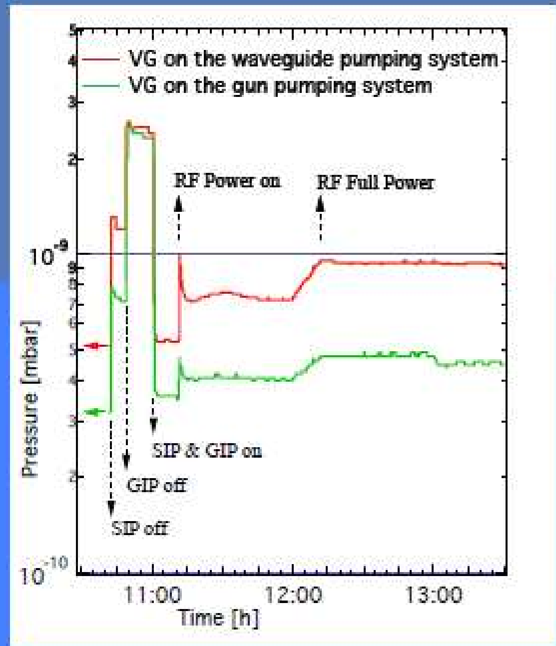
Thanks to our previous experience and to the avaibility of a new compact UHV pump which integrates a NEG and an ion pump, a simpler vacuum system was designed

…after the final installation!



When all auxiliary plants were installed, the space around the gun resulted truly accessible.

Vacuum performance



Switching on & off GIP &SIP: the NEG modules of GIP is able to keep the total pressure in the UHV range .

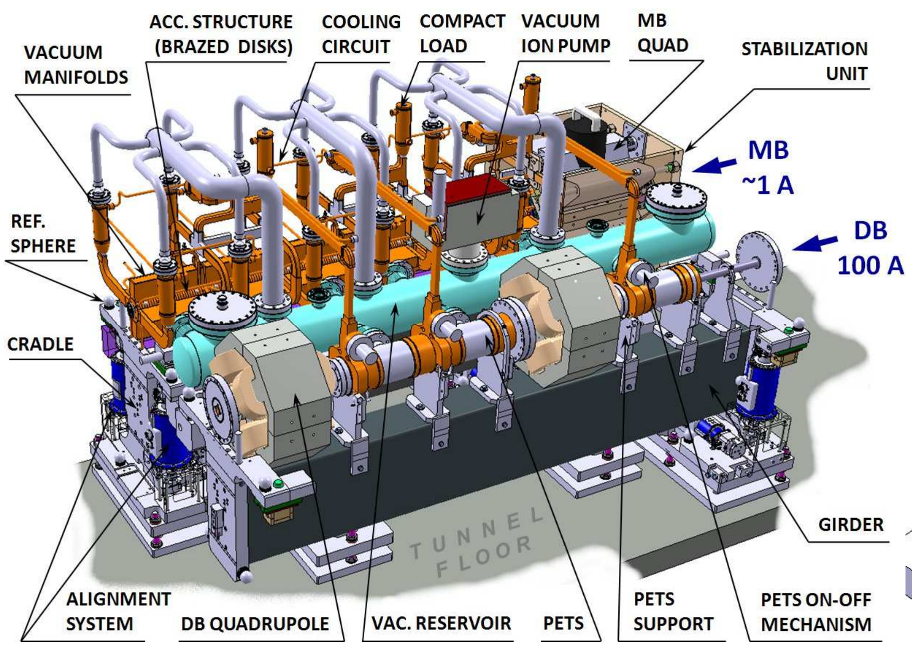
When it was necessary to upgrade the PC-Gun in order to increase the repetition rate to 50 Hz, it was necessary to change the vacuum system, too. Thanks to a new, compact and light vacuum pump which combines a 200 l/s NEG pump and a 6 l/s diode ion pump together (GIP 200), it is now possible replace effectively 2 large, heavier UHV pumps. The 75 l/s SIP installed on the waveguide and the GIP act as the main pumps of this new gun; the GIP is also an "emergency" pump in case of mains failure, thanks to its NEG module. It can be separated from the gun by a manual gate valve when a gun maintenance or a cathode cleaning process are required. Two inverted magnetron vacuum gauges (VG) are installed, one VG for each gun arm. The whole system is bakeable up to 120-150 °C.
This pumping system is able to keep the pressure in the 10^{-10} mbar range when full power (8 MW) radiofrequency is applied, and in the 10^{-9} mbar range when electrons are extracted from the mirror finished OFHC copper cathode. A quantum efficiency of $5 \cdot 10^{-5}$ e-/ph is usually achieved after a laser or ozone cleaning process. A bunch charge of 500 pC is normally extracted from a spot on the cathode of about 1.2 mm in diameter using a 40μJ pulse of a 260 nm laser.

Courtesy of Dr. Luca Rumiz, Sincrotrone ELETTRA, EIVC 2013

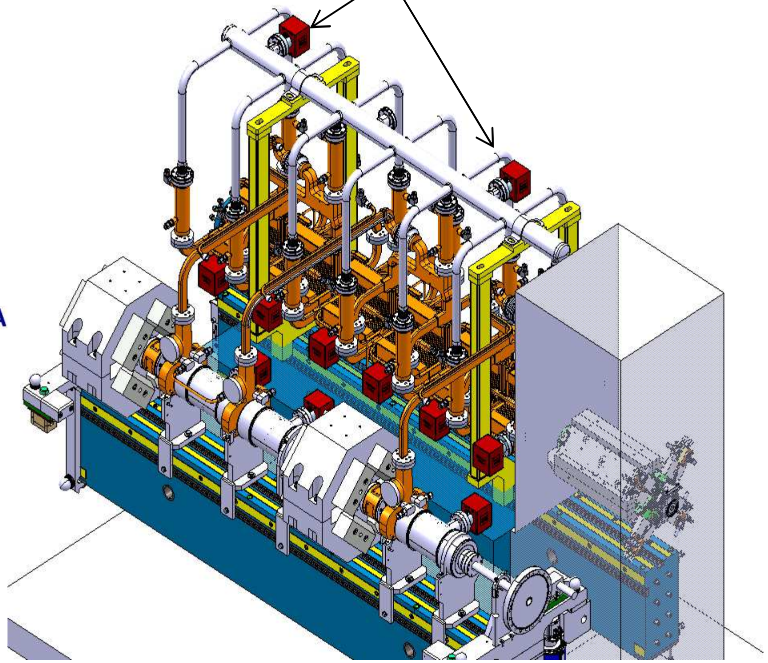
CLIC@CERN

- A compact package allows redesign the vacuum system !
- Improvement of the magnets design (more controlled beam focusing)
- Total cost reduction !

ION and Cryo- PUMP based system



NEXTorr based system



P. Chiggiato et al., Poster VT-TuP6 AVS 58 Conference, Nashville 2011

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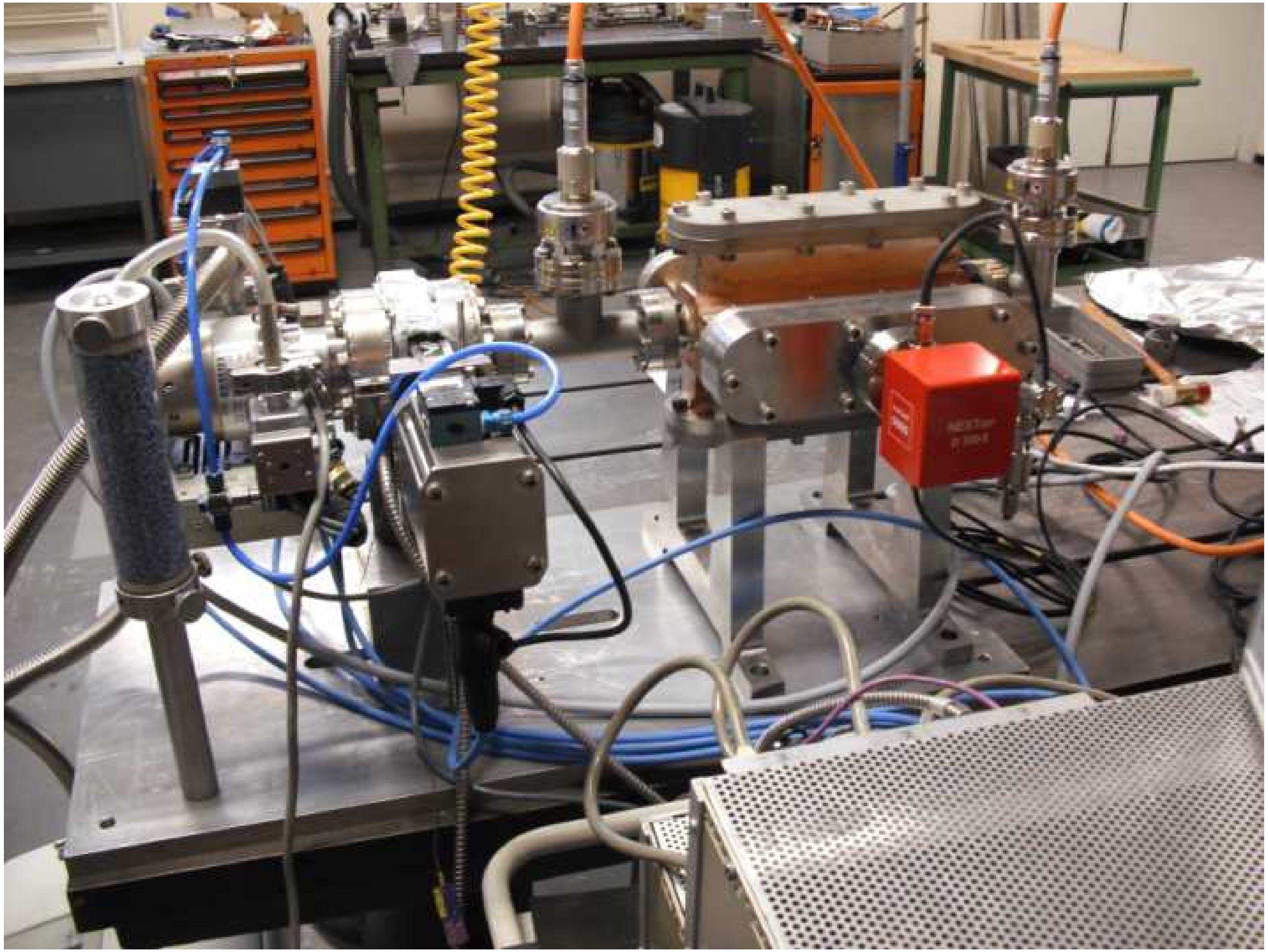
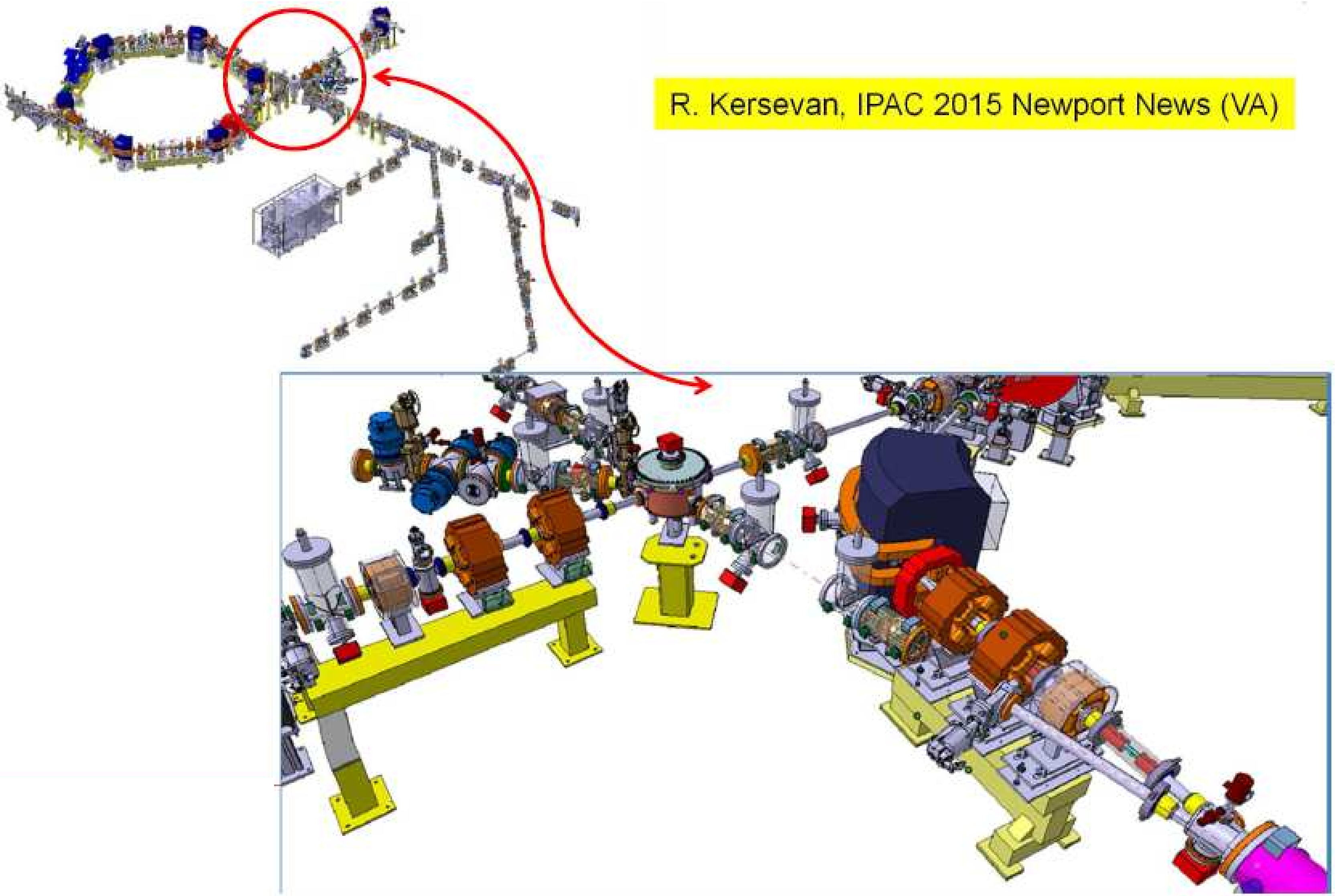
CLIC photocathode



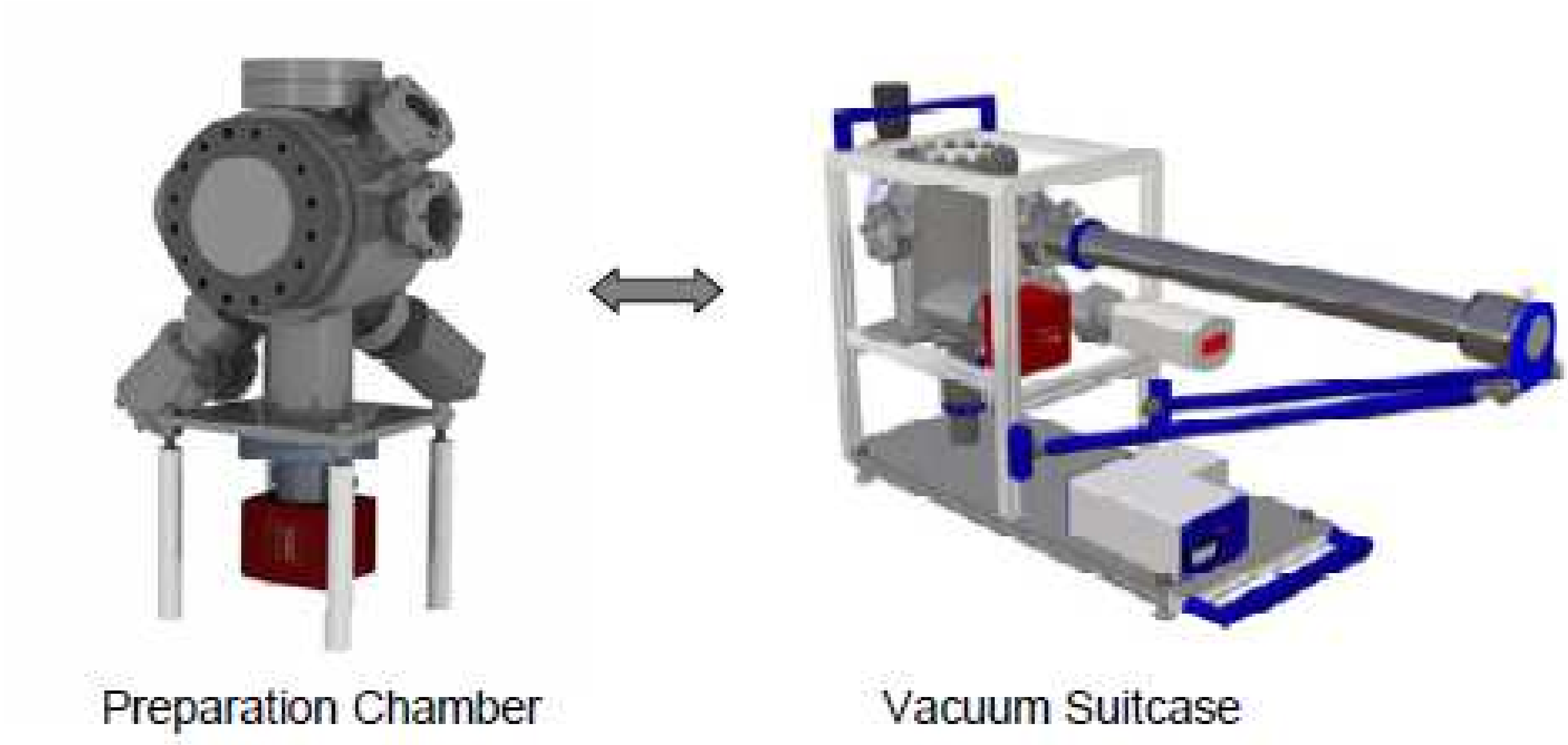
Proceeding at IPAC 2011, TUPS021

Elena at Cern: targeting 10-12 Torr

R. Kersevan, IPAC 2015 Newport News (VA)



SWISS FEL

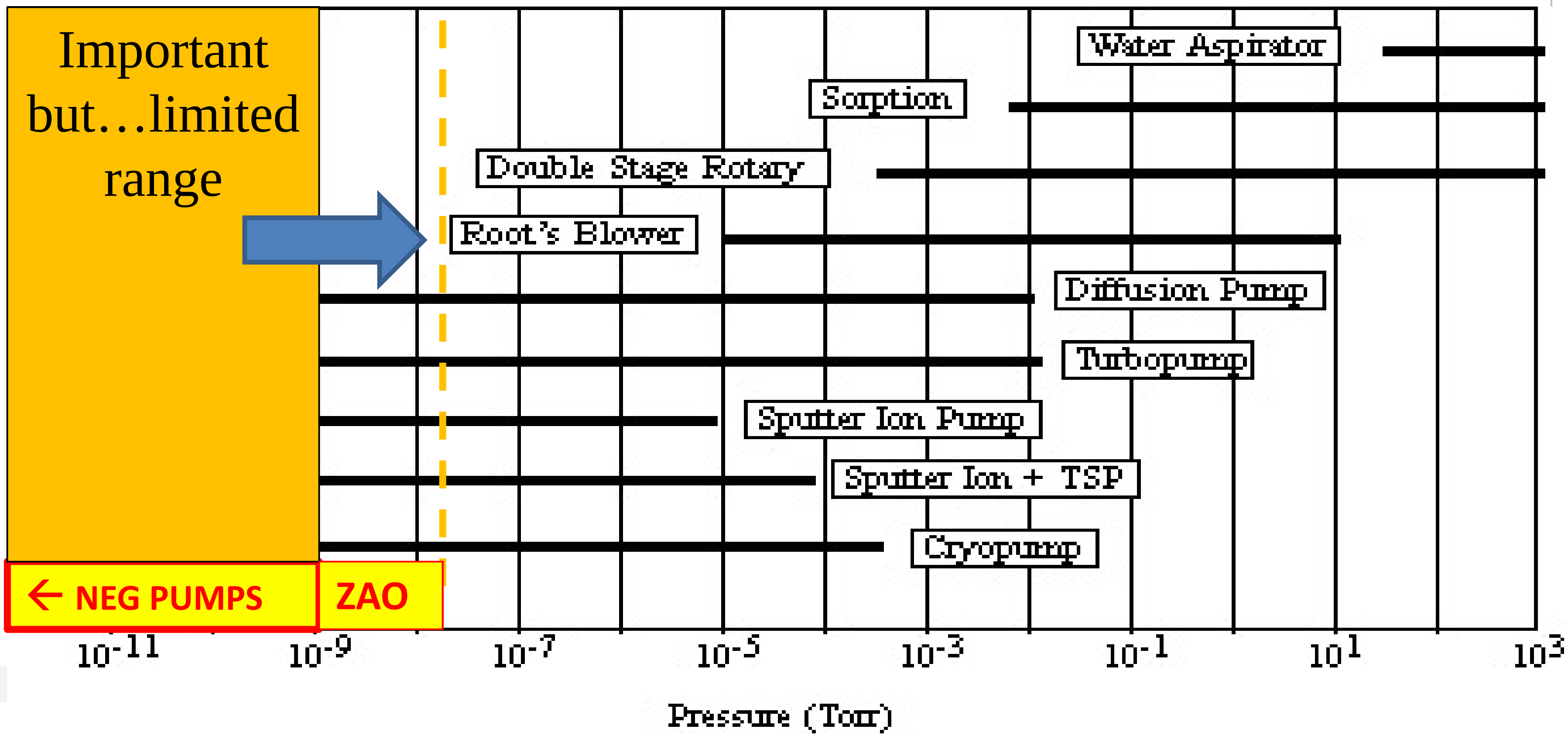


FEL conference 2013 (file 'photocathode Swissfel_FEL2013.pdf')

Extending the use of NEG pumps into HV regime

Vacuum pumps vs pressure range

- One of the main limitation of NEG pump is the **limited gas sorption capacity**.
- When exposed to high gas load, NEG surface gets saturated in a relatively short time (weeks-months). NEG use is therefore limited mainly to **UHV-XHV**(P<10-9 mbar).



A new getter alloy for HV : ZAO®1

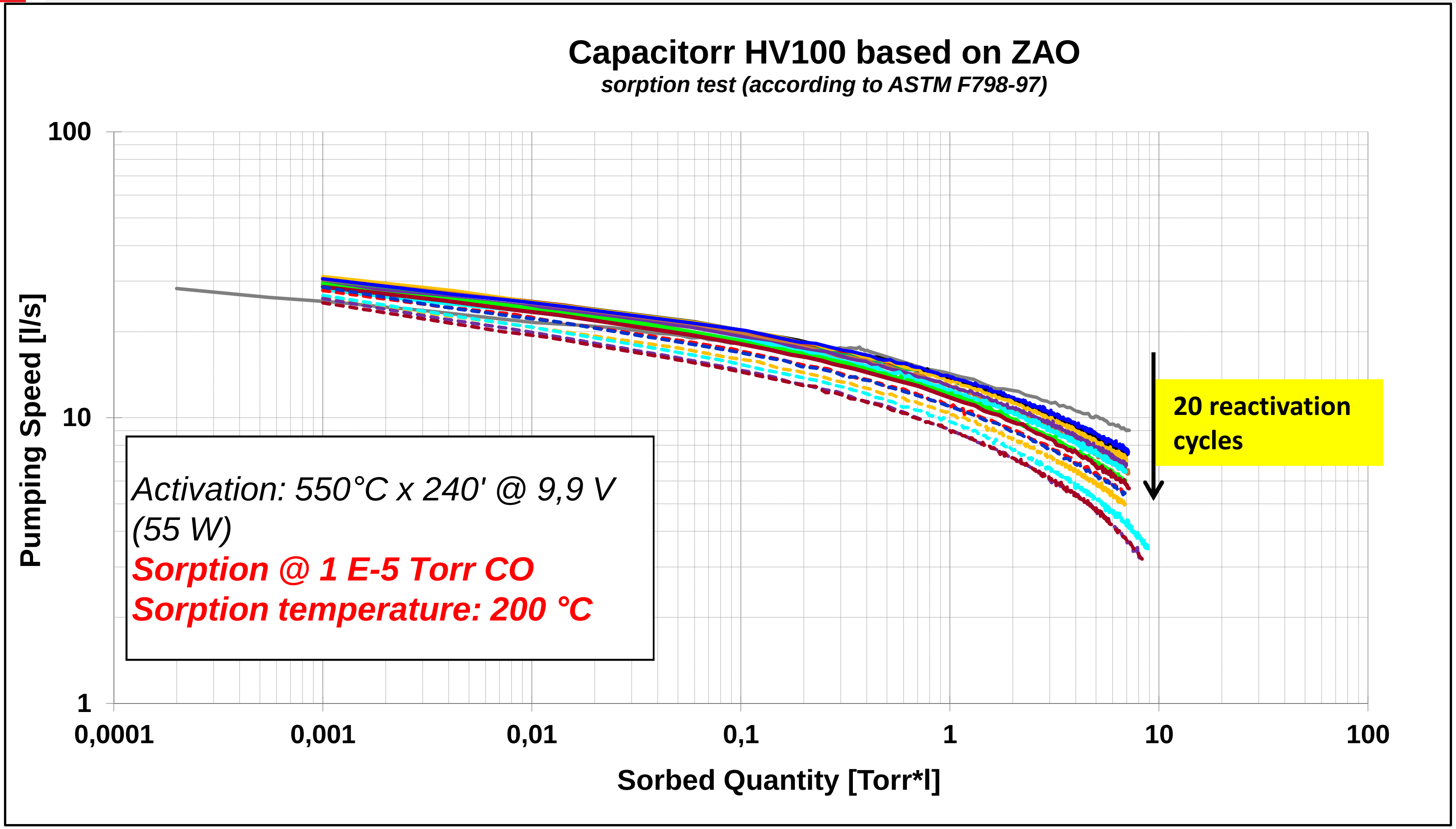
- ZAO 1 is a Zr-V-Ti-Al alloy with several specific advantages compared to the best getter material currently used (e.g. St 172 for Capacitorr® and NEXTorr® pumps).

  - **Larger sorption capacity** for all active gases
  - Ability to withstand **many more reactivation cycles** without loosing significant performances
  - **Lower equilibrium isotherm** (even at 200° C the equilibrium pressure of hydrogen is @1x10^{-10} mbar)
  - **Excellent mechanical properties** : sintered disks are intrinsically more robust, less prone to generate particles, with higher hydrogen embrittlement limit.

- Taking advantage of this, a range of novel NEG pumps has been developed which use ZAO® sintered disks (Capacitorr® HV).

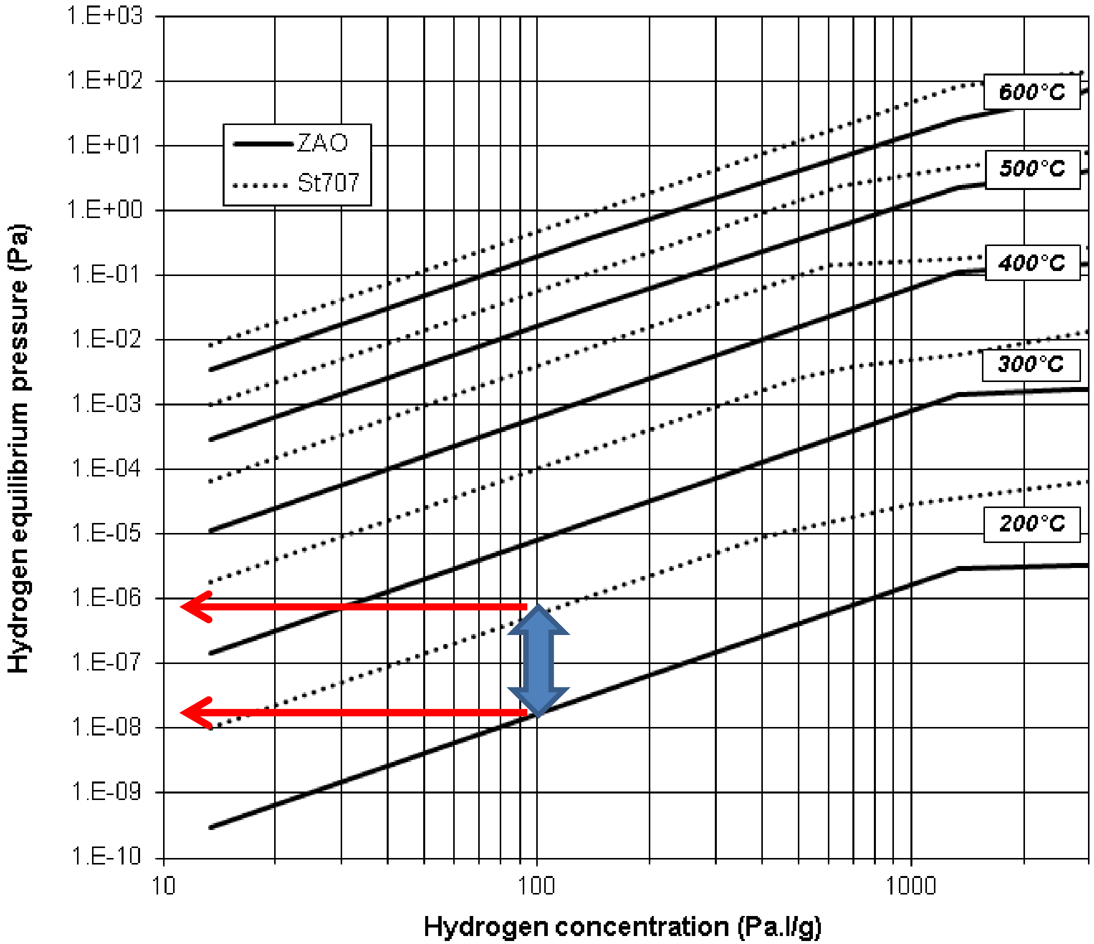
- To handle the large gas load of the HV environment, Capacitorr® HV operate at ≈150-200° C.
- Capacitorr® HV can also be used at room temperature for UHV applications.

Repeated sorptiont tests



- The sorbed quantity in each cycle corresponds to **1 year operation @ 3x10^{-8} mbar CO**.
- After 20 cycles of reactivations, CO speed decreases marginally vs the initial value.
- **Even better results obtained for N_2, H_2O, O_2 and H_2** for which ZAO has larger capacities

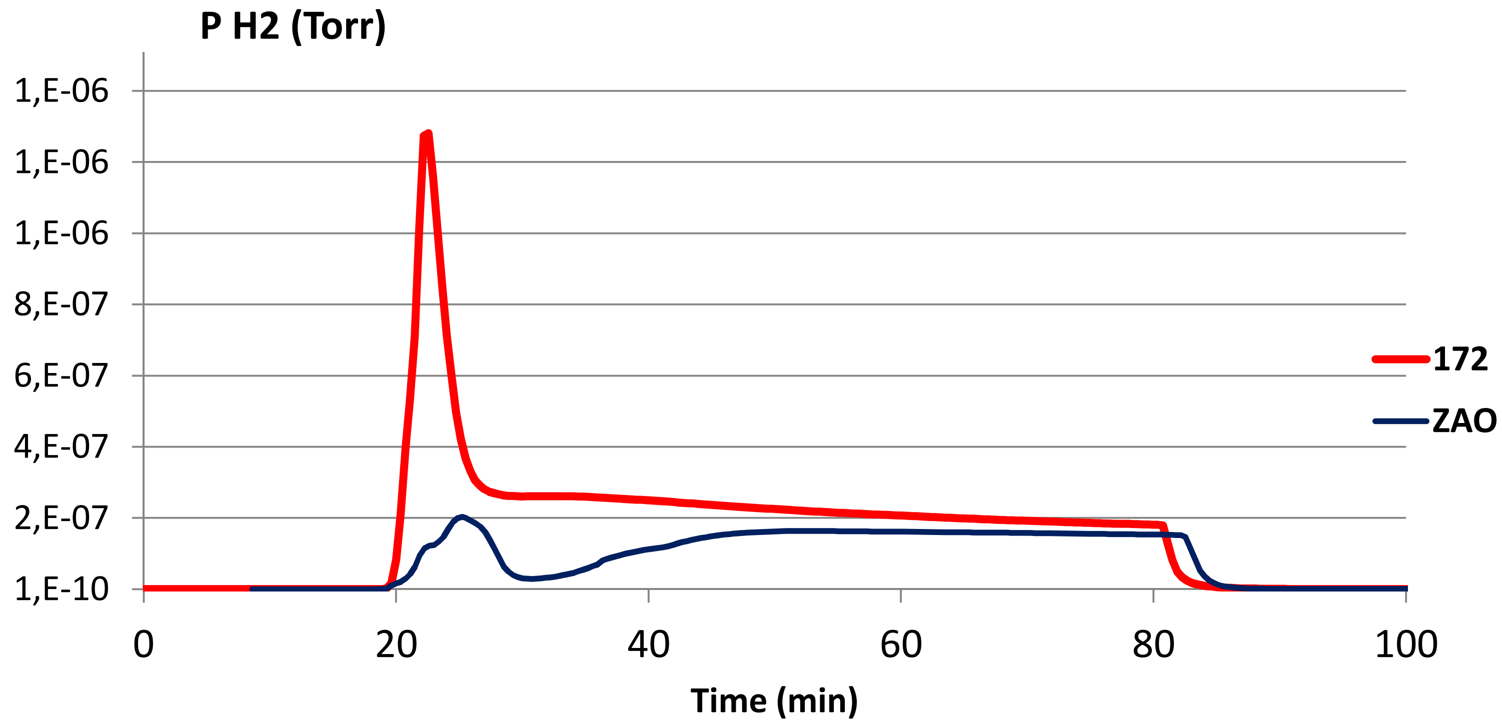
ZAO H_2 equilibrium isotherms vs St 707/St 172



ZAO has a lower H_2 eq. pressure and a larger H_2 storage capacity for each given **temperature**.

- **Eq. pressure at 200°C ≈ 10^{-10} mbar : ZAO pumps H_2O /H_2 effectively at this temperature**
- **St 707 and St 172 eq. pressure at 200°C ≈ 10^{-8} mbar, not suitable for HV pumping**

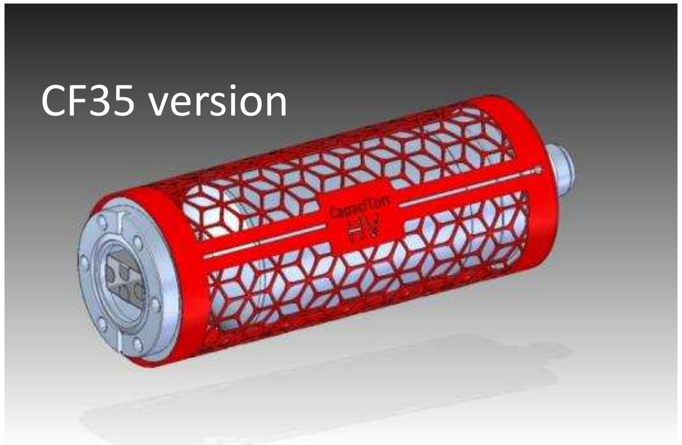
Outgassing comparison between St® 172 and ZAO®



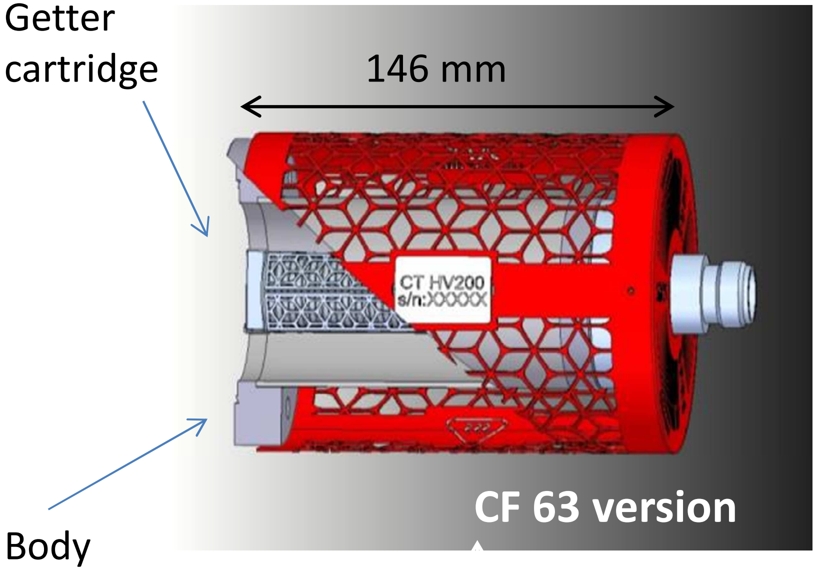
- The H_2 evolution during activation is about 5 times smaller for ZAO® than for St 172. The total amount of H_2 released is also a factor 2 smaller
- **ZAO® 1 based pumps are cleaner.**

ZAO®1 - based HV pumps (200-2000 l/s)

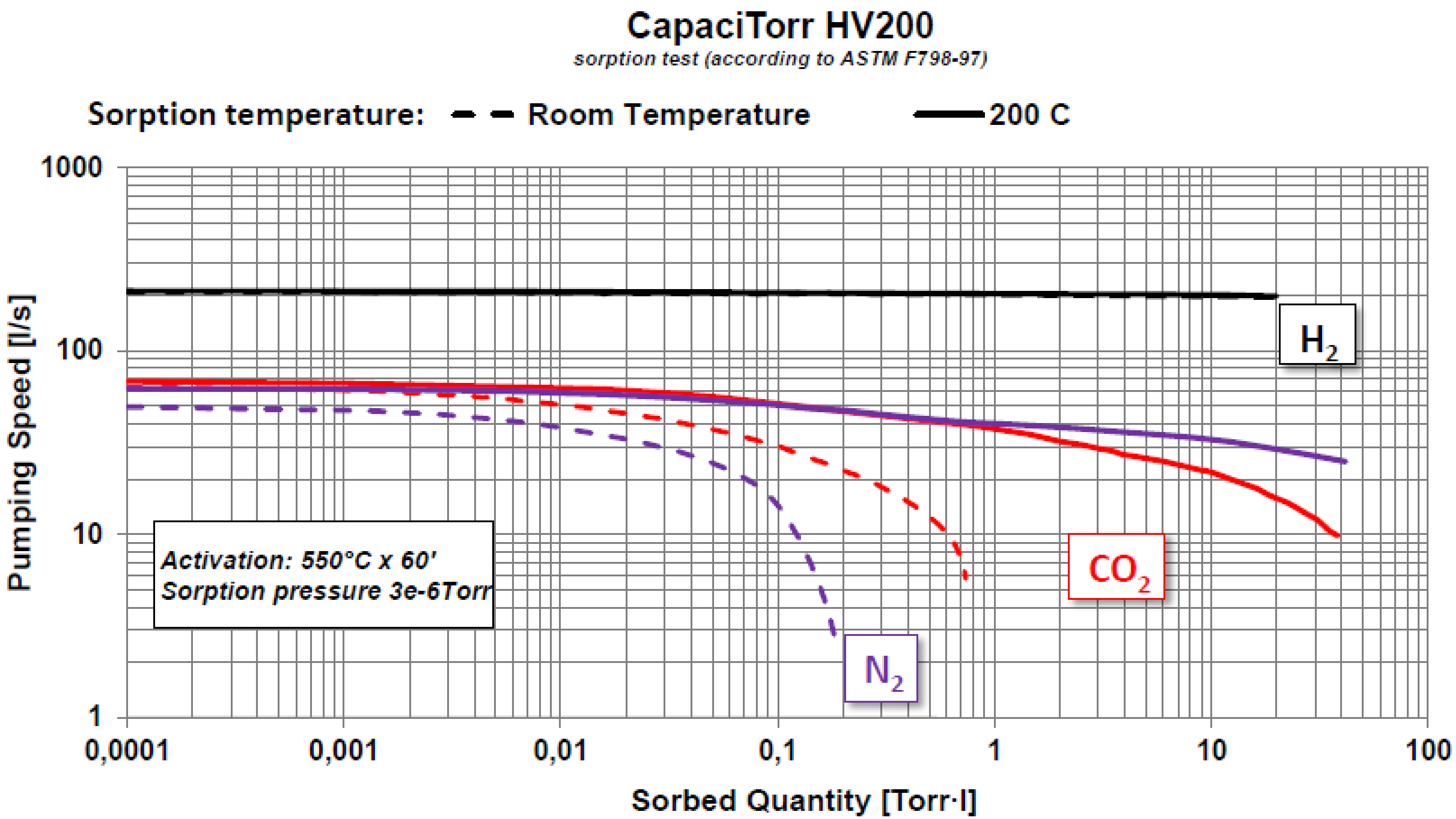
CapaciTorr® HV 200



- Body for thermal management
- CF63 and CF35 versions
- Power consumption: 8 W (~200°C)
- Up to 210 l/s for H_2
- It can operate at 7x 10^{-8} mbar (50% H2O-20% H_2 -30% air) for one year continuously. After that it has to be reactivated.
- At least 20 cycles of absorption

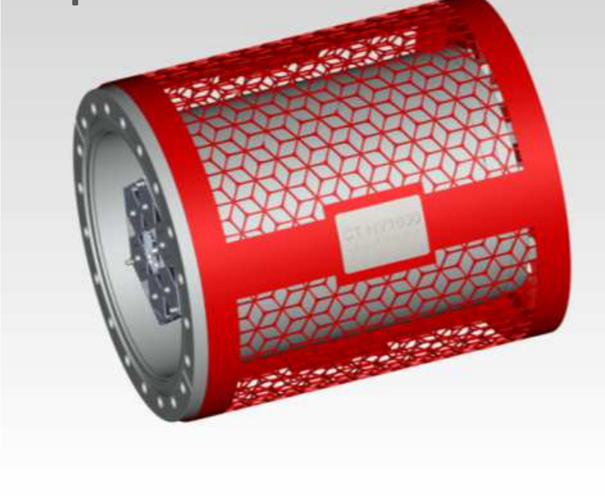


Pumping at RT vs. 200 °C

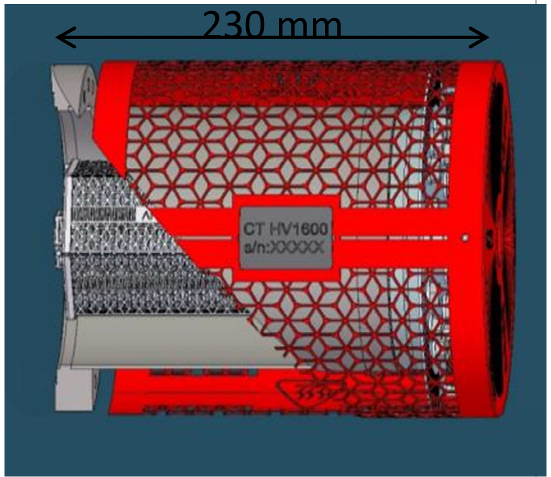


High gas load applications: larger HV pumps

CapaciTorr® HV 1600

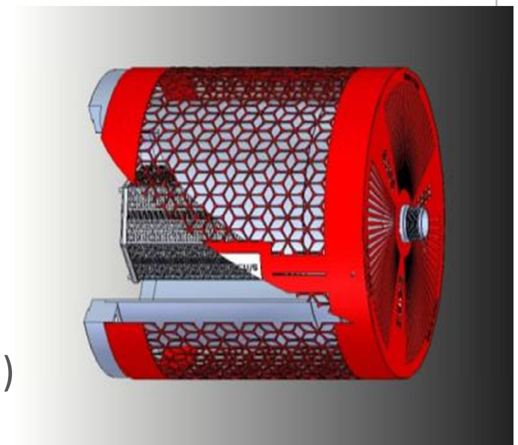


- Thermocouple control for optimal thermal management
- CF150
- Power consumption: 48 W
- 1600 l/s for H_2
- About one year operation at 5e-8 Torr (benchmark: 500 l/s SIP/TMP)
- At least 20 cycles of absorption



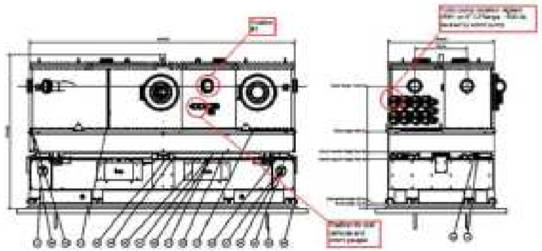
CapaciTorr® HV 2100

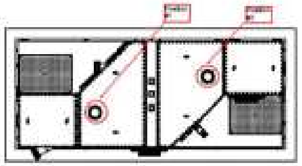
- Thermocouple control for optimal thermal management
- CF200
- Power consumption: *60 W (estimation)*
- 2100 l/s for H_2
- About one year operation at 5e-8 Torr (benchmark: 800 l/s SIP/TMP)
- At least 20 cycles of absorption



CapaciTorr HV pump in a large Monochromator chamber at LCLS—SLAC

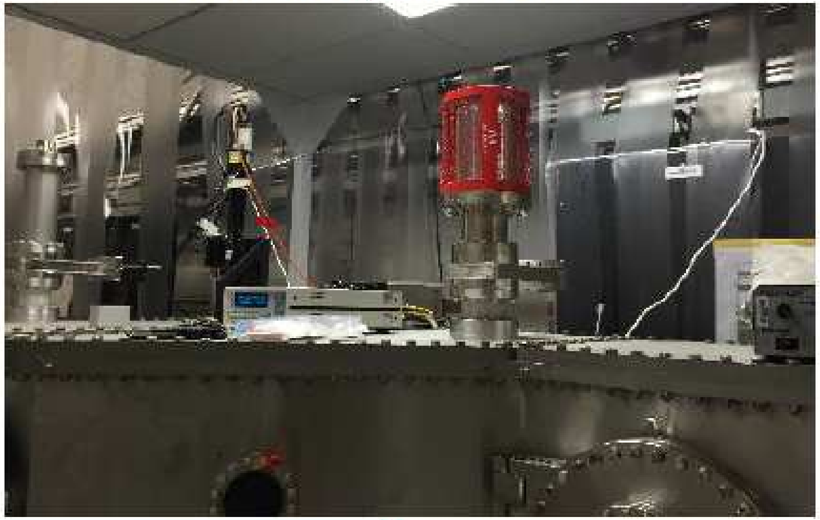
Monochromator Chamber Layout





Chamber approximate volume:
3 x 1.2 x 0.5 cu m
With high surface area components

Photo with CapaciTorr HV1600



Test environment courtesy of LCLS Hard X-Ray Department

Presentvacuum layout

- Two 600 l/s ion pumps + 500 L/s TMP.

Present system pumpdown

- 1-2 days of pumpdown with TMP for a chamber open to atmosphere for a week, to obtain 1e-6 Torr, the maximum pressure where the two ion pumps may be switched on.

Goal

- A quicker initial pumpdown of the chamber to 1e-6 Torr so that the two ion pumps may be turned on much sooner.

Results

- The CapaciTorr HV1600 was activated for 1 hour once the system reached 1e-5 Torr. Then, with the CapaciTorr HV1600 pump kept at 190 C, 13 hours were been required to achieve 1e-6 Torr in order to switch on the two ion pumps.

Note

- Ideally, the CapaciTorr HV1600 is installed directly on a chamber via a CF150 flange. Due to the system layout, the pump had to be installed on a CF100 with about 30 cm of extra ductwork. Therefore, a significant conductance restriction was introduced; the effective pumping speed was one third to one half of nominal, depending on the gas.

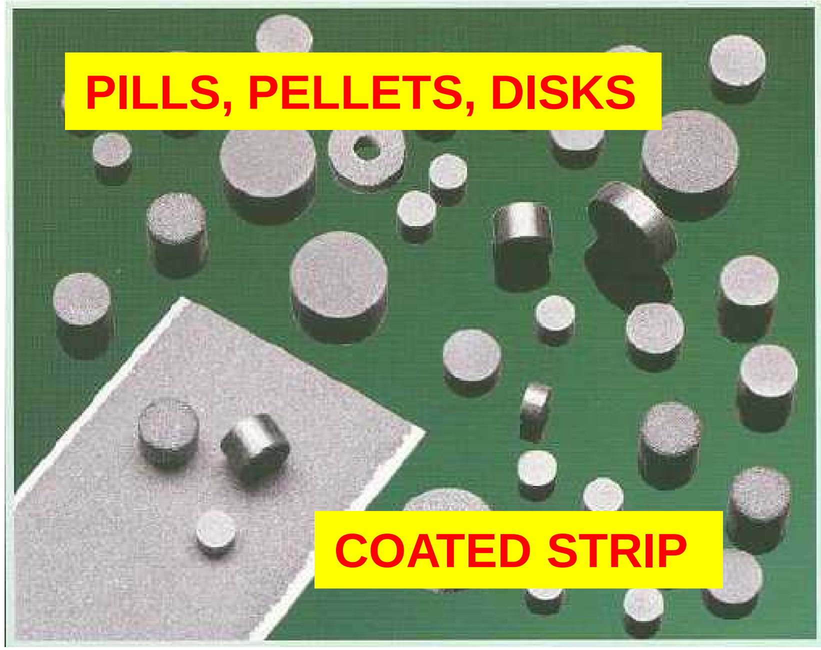
9. particle issues for NEG

Particle issues in Accelerators

- Particle accelerators are very clean systems and generation of particles is not welcome and can present various level of risks depending on the type of accelerating system :
  - Quenching in superconductive cavities (SRF)
  - Beam losses during operation
  - Charging effects with possible sparks and beam interference
  - Localised and uncontrolled outgassing
  - Movement of particles along the vaucum line, during venting/operation
- Preparation and cleaning of UHV components and subsystem is generally done according to high cleanliness standards and procedures and using ISO classes.
- Particles can however be introduced during the operation of the components in the accelerator. This can be minimized using sintered disks.

An historical perspective….

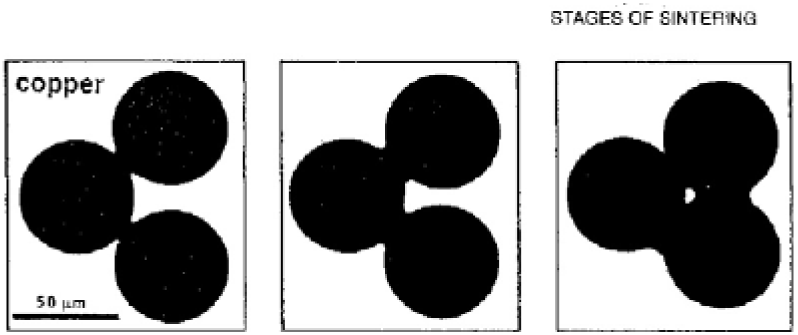
- First NEG pumps have been developed and proposed by SAES in the early **70s.**
- The typical design was based on St 707getter powder, **mechanically compressed**. St 707 pills, disks or NEG laminated strip could also be prepared by compression and shaped in a cartridge.
- The cartridge was mounted onto a flange with a heater for the NEG activation and a thermocouple to measure temperature



A major step forward…sintered getters

- To overcome the limitations of compressed powder pumps, SAES introduced in the **90s**' the use of sintered disks as main building block of a NEG cartridge.

- Sintering is a high temperature metallurgical process (below melting point) to consolidate, by surface melting, powders into a single body.



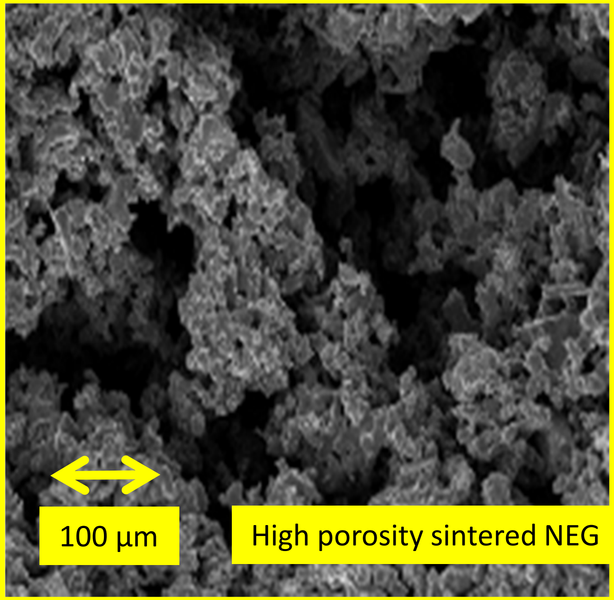
- In normal applications the aim of the sintering process is to create an extremely dense product, close to what can be achieved by cast melting.

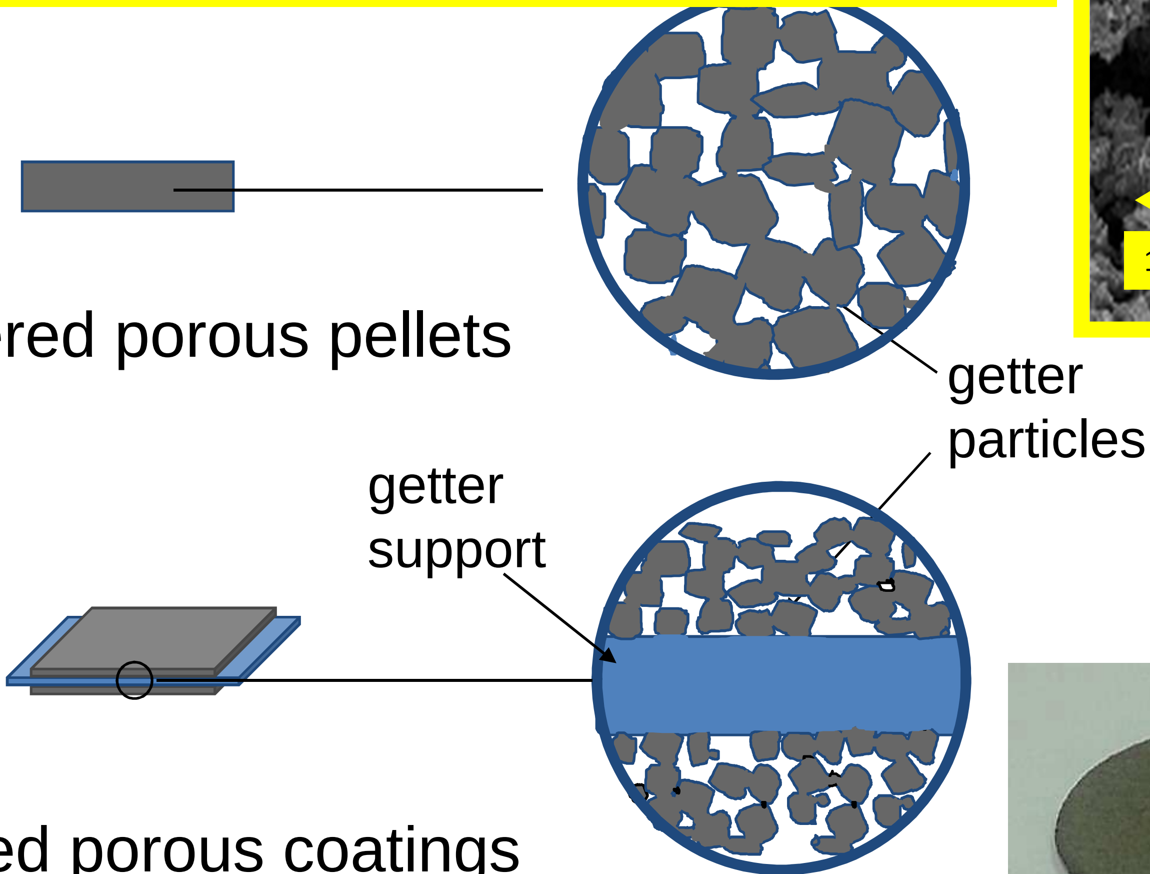
- In the case of a NEG material the objective is just the opposite :

" to consolidate powders leaving an extremely porous and open structure with a large internal surface area which can effectively capture molecules." Therefore the process has to be optimized to bound grains leaving large voids…

SINTERED getter configurations

Sintered getters were first obtained adding Zr powder to St 707 (St 172®) and applying specific proprietary manufacturing procedures to metallurgically bound the grains while retaining an open structure.





A second step forward : ZAO sintered disks

- More recently (**2010s**) a new class of high efficiency getter based on Zr-V-Ti has been made available (ZAO alloys). They are characterized by :

  - Larger sorption capacity and pumping speed
  - Hydrogen equilibrium pressure lower than St 172 and St 707
  - Less gas emission during activation
  - Better mechanical properties

- ZAO disks are sintered to provide high porosity mechanically robust bodies with negligible particle emission. They represent a natural replacement and an upgrade of St 172

- A remarkable amount of experimental evidence show that ZAO sintered disks are by far superior than compressed St 707. They also provide an order of magnitude improvement with respect to sintered St 172

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Dipping test in Ultrasonic bath

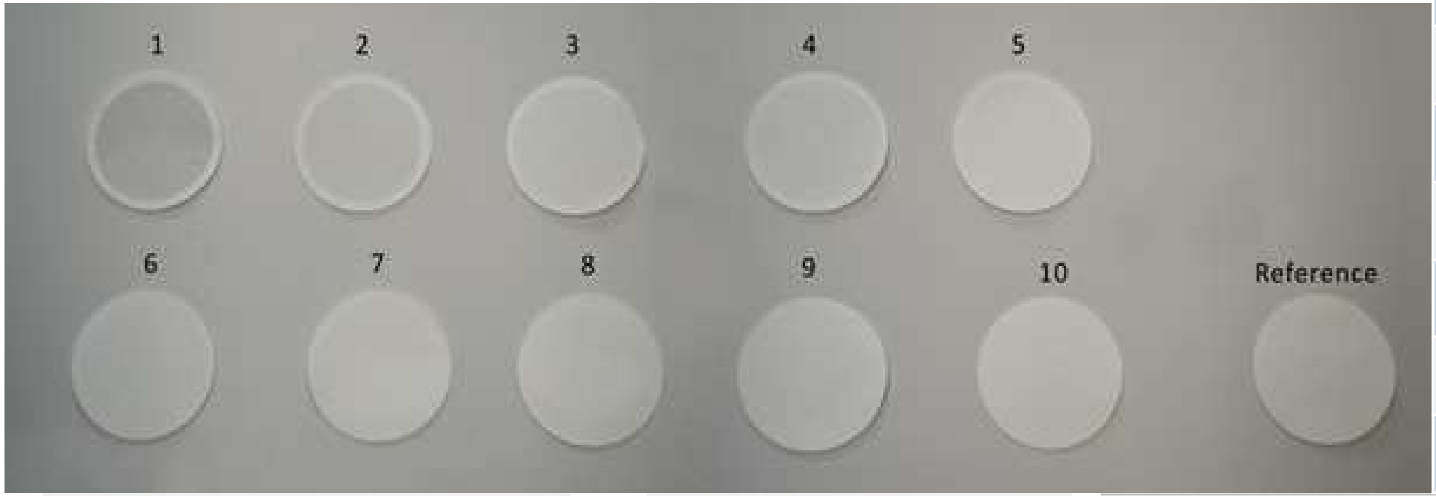
- The test pump was dipped in a solvent bath (99,8% pure). After each cycles (5 min long) the solvent is filtered and particles were collected on a paper filter and weighed (scale sensitivity 0,01 mg).
- Three NEG pumps were tested, mounting St 172 disks, ZAO disks or compressed St 707 disks.
- A blank run were carried out before and after each test.
- After the dipping test all pumps were dissassembled and inspected .

CapaciTorr D100 (St 172)

- No weight increase could be measured on the paper filter after 2 dipping. The total weight lost after three cycles : 1,25mg (unchanged after 10 cycles).

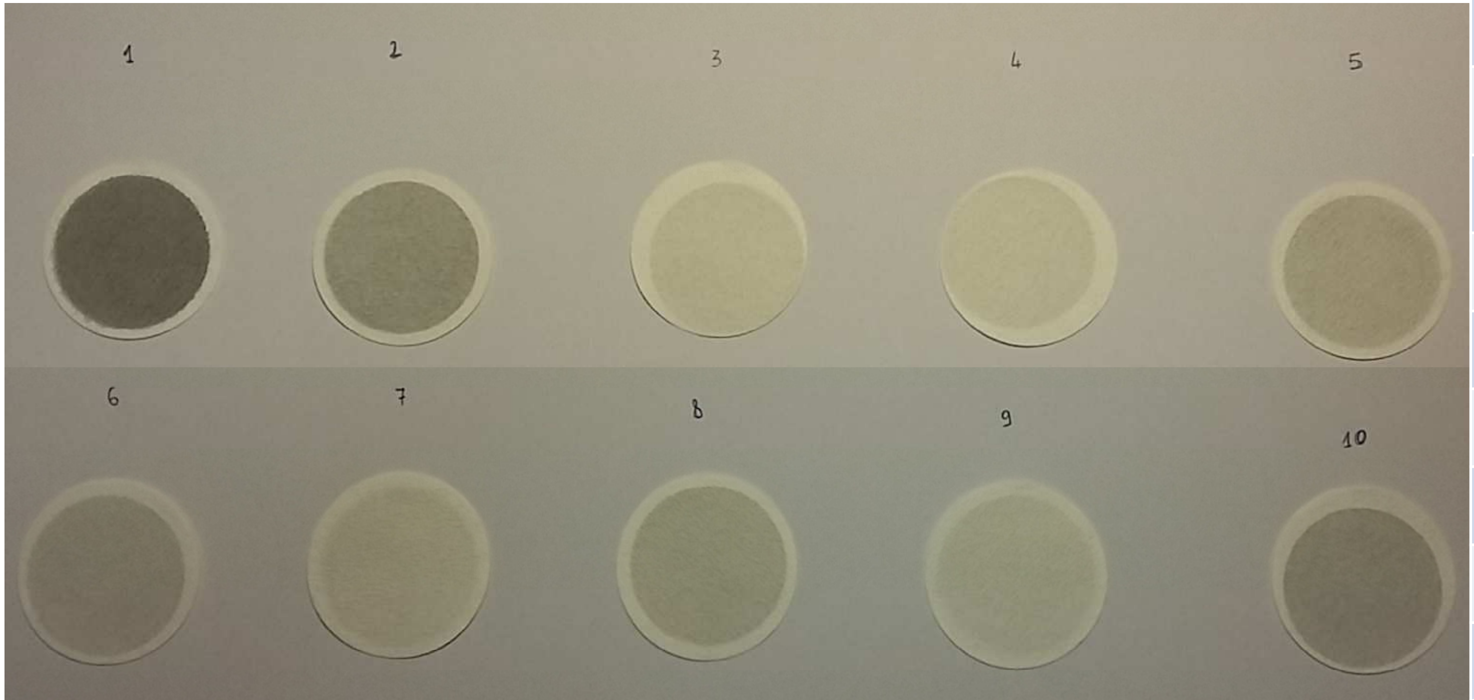
- After three dippings no differences could be noticed in the colour of the paper filter, confirming that additional released particles were a minor contribution.

Cycle number	Collected particles during each cycle
1	0,85 mg
2	0,41 mg
3	<0,01 mg
4	<0,01 mg
5	<0,01 mg
6	<0,01 mg
7	<0,01 mg
8	<0,01 mg
9	<0,01 mg
10	<0,01 mg
TOTAL	**1,25 mg**



Capacitorr with St 707 compressed disks

- Same procedure was applied in the case of the NEG pump with compressed St 707 disks.
- The amount of particles is significantly higher
- The particle emission process does not stop with time but it is a continuous process (10° cycle was comparable to first cycles).

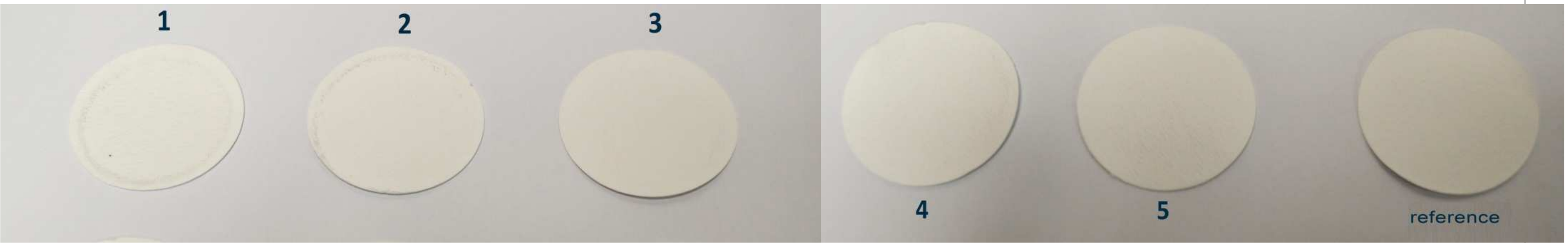


Cycle number	Collected particles during each cycle
1	7,9 mg
2	4,4 mg
3	1,4 mg
4	1,3 mg
5	2,0 mg !!
6	1,2 mg
7	1,2 mg
8	1,3 mg
9	0,9 mg
10	2,2 mg
TOTAL	23,3 mg

CapaciTorr D100 (ZAO)

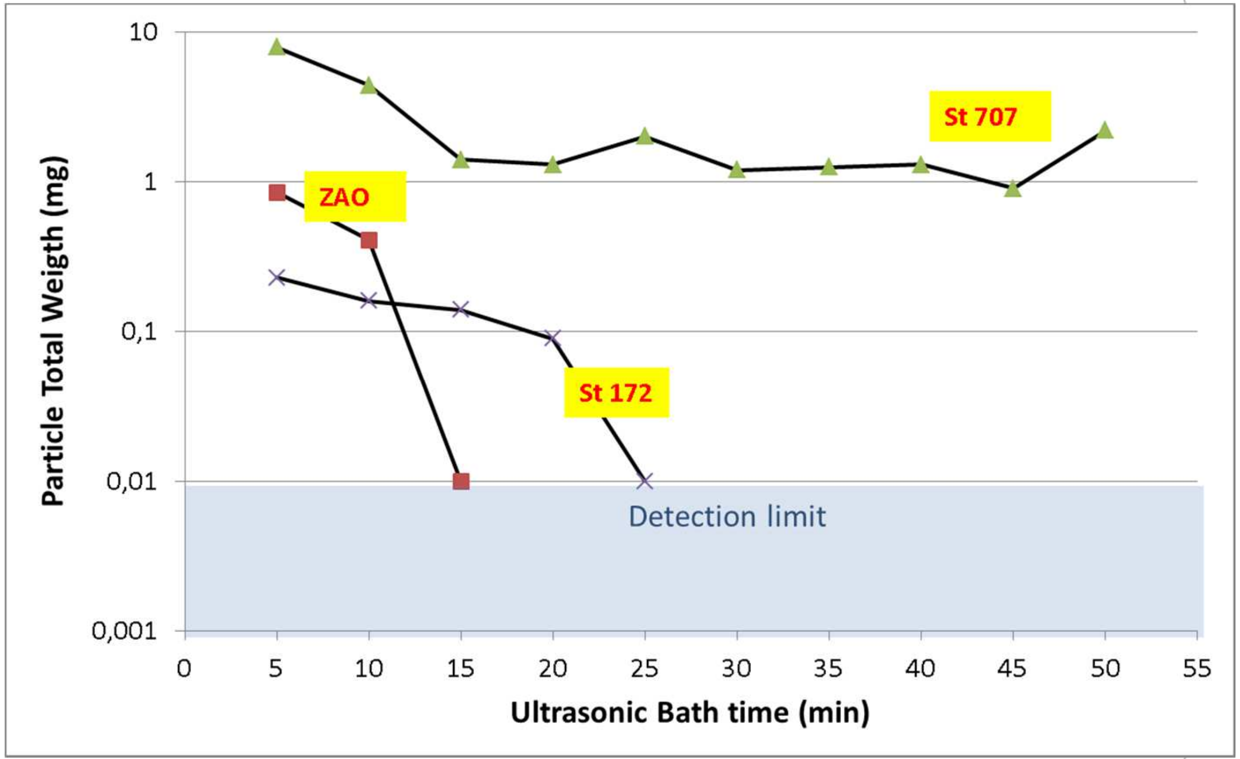
- No weight increase is measured on the paper filter after 3 dippings. The total weight lost after 3 cycles : 0,55mg (unchanged after 6 cycles).
- No color difference after the second dipping.
- Collected particles a factor 2-3 less than St 172

Dipping number	Collected particles during the cycle
1	**0,45 mg**
2	**0,06 mg**
3	**0,04 mg**
4	<0,01 mg
5	<0,01 mg
6	<0,01 mg
TOTAL	**0,55 mg**



Comments

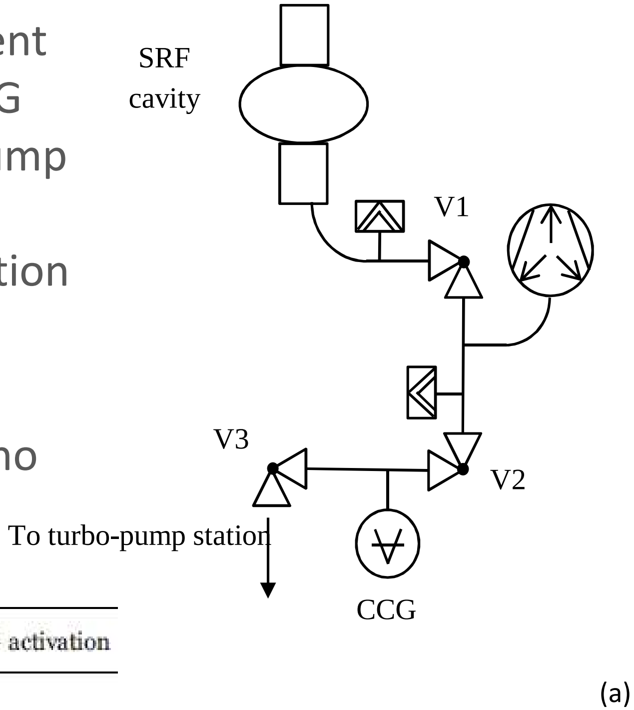
1. Dipping tests show that the total amount of dust released by sintered disks is much less.
2. Dust emitted by compressed disks does not to drop significantly with time.
3. ZAO drops faster than St 172



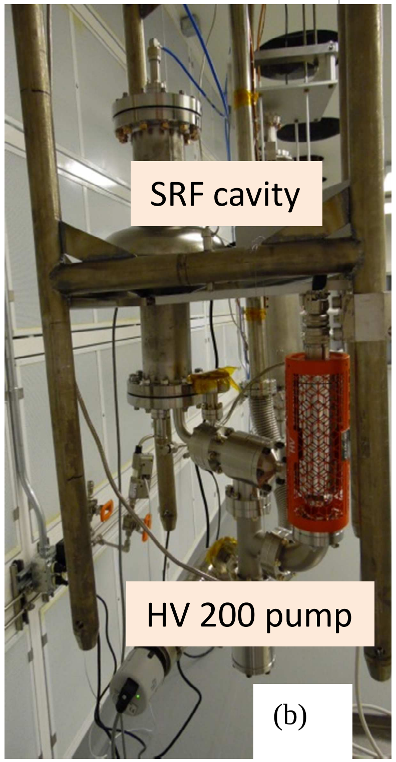
- The technique is quantitative : it collects all the particles released by the sample.
- Sensitivity (0,01 mg) of the technique is too small to assess pump usability in demanding dust free applications
- Specific tests have been carried out in ISO 5-ISO 4 environment using laser particle counters or exposing the pump in SRF cavities.

Tests in a SRF cavity (JLab, USA)

- Actual test with ZAO based pumps carried outat at JLab to check for compatibility with high gradient SRF cavities.
- The NEG pump was first sprayed for about 1 minute with ionized nitrogen to pre-clean it and then transferred in a ISO 5 clean room and connected to the SRF cavity manyfold.
- The cavity was pumped under different conditions, without activating the NEG pump (baseline) and with the NEG pump activated and kept under continuous pumping at 200°C. After each evacuation cycle the cavity performances were measured.
- Cavity performances were fine, with no quenching due to dust



(a)



(b)

Summary of evacuation conditions prior to each RF test.

Test number	Cleaned and assembled prior	Evacuation	NEG activation
1	Yes	Turbo-pump	No
2	yes	Turbo-pump	No
3	No	NEG, 3 days	Yes, 1 h
4	No	NEG, 5 h	No
5	No	NEG, 6 days	Yes, 2 h

«Operation of a high gradient superconductive radio frequency cavity with a NEG pump»
G. Ciovati et al. *Nuclear Instruments and Methods in Physics Research A 842 (2017) 92-95*

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Conclusions

- **NEG pumps** are finding widespread adoption in worldwide accelerators.
- They can improve the **ultimate vacuum,** and provide a very **compact pumping** solution **for miniaturization.**
- The **negligible power consumption** and the **zero maintenance** make these pumps very easy to use and improve the overall system reliability.
- Thanks to the small package the user can **re-design** the experiment and the machine in a more favorable way
- Very compact NEG/SIP combination (NEXTorr) have been developed to address **space issues in accelerators** and crowded systems
- A novel alloy, called **ZAO**, is a significant breakthrough in getter technology. It can be operated in UHV or HV with larger capacity and speed and possess much better compatibility with dust free applications.


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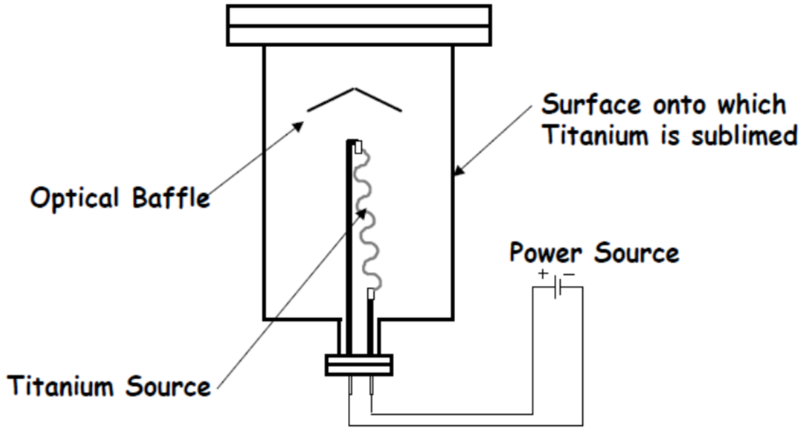
Comparison between TSP and NEG

TSP vs NEG



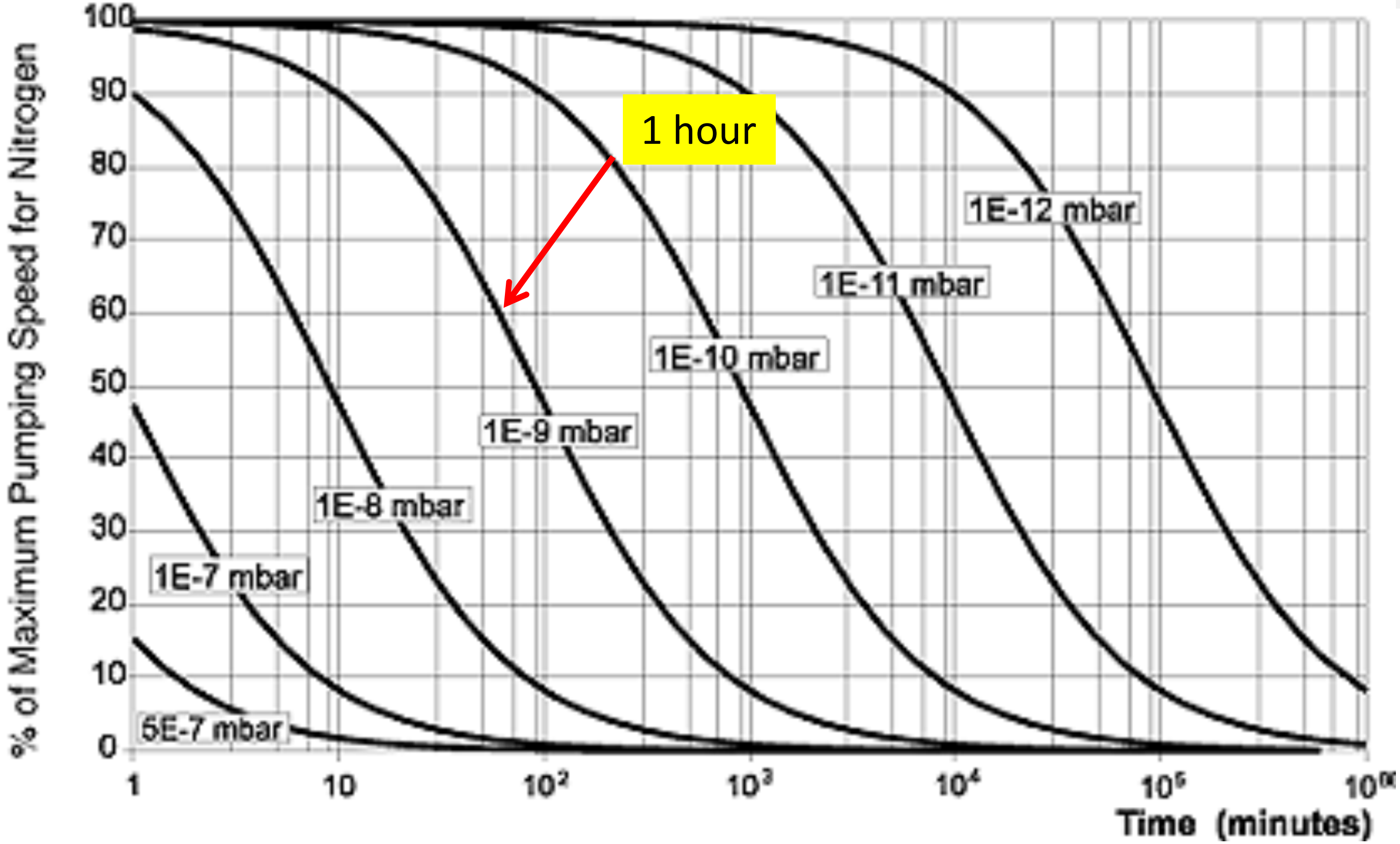
TSP ADVANTAGES

- limited up front investment
- high pumping speed for active gases
- Easy to use

TSP DISADVANTAGES

- Limited capacity (e.g. 3-5 g vs 200-500 g of NEG pumps)
- Higher power consumption
- May need a coolant (water /liquid nitrogen)
- Can generate Ti flakes and gas emission
- It requires a large evaporation volume
- Maintenance costs
- Pressure is not stable (50% speed drop @10^{-9} after 100 min)

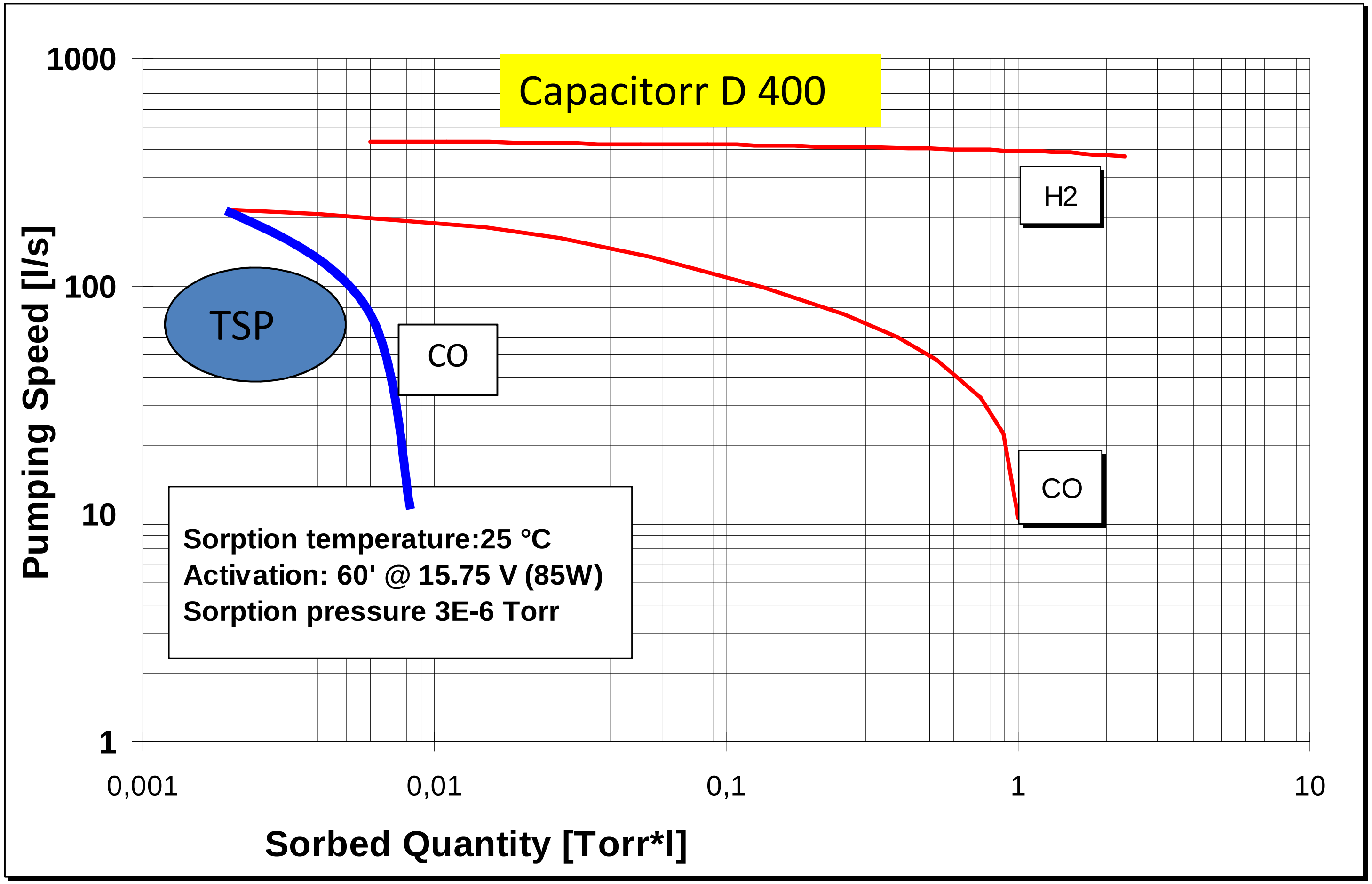
TSP vs NEG



With TSP you need to frequently evaporate Titanium, as the thin layer of evaporated getter is consumed rather quickly with time.

In the case of the NEG, the activated getter surface is > 100 times larger than a comparable TSP, so continued operation without power is possible for long time.

Comparison with TSP



This graph compares the pumping speed vs capacity for a NEG and a TSP having the same nominal initial pumping speed for CO (400 l/s). In the case of the TSP che film gets very fast saturated as compared to the NEG which continues to pump much longer